

**Relating Minimal Immersions With Critical Eigenvalue Metrics for Flat Line Bundles on Surfaces**

Santiago Adams

*Mentor: Antoine Song*

In the existing literature, there exists a strong connection between metrics whose first eigenvalue are critical on a surface and minimal immersions of that surface into a sphere of arbitrary dimension. We know that for a surface equipped with a critical metric, there exist a set of eigenfunctions of the Laplacian on that surface which define a minimal immersion into a sphere. We aim to use local arguments to extend this theory to the case of eigensections of a flat line bundle. That is, given a metric whose first eigenvalue is critical over a line bundle, we aim to define a minimal immersion of its universal cover into a sphere using the lift of its eigensections, and better understand if there exists a minimal immersion of our original surface into the sphere.

**Thermodynamic Properties of an Ising Ferromagnet at the Classical and Quantum Limits**

Sophia Adams

*Mentors: Thomas Rosenbaum and Daniel Silevitch*

This project is aimed at probing the thermodynamic properties of the model Ising ferromagnet  $\text{LiHoF}_4$  across the classical and quantum phase transitions. The classical transition is found at a critical temperature of 1.53 K and zero magnetic field, whereas the quantum transition occurs at a critical transverse magnetic field of order 50 kOe in the zero-temperature limit. We will use specific heat data to compare the critical exponents at the two transitions and the crossover between them.

**A Novel Approach to Generate and Pre-screen Proteins for Binding Affinity Using a Classifier-Based Generator**

Victoria Adams

*Mentors: Matt Thomson and Alec Lourenco*

Testing new engineered binding protein designs is highly ineffective due to the speed and scale at which current methods can screen protein binding efficacy. Quantitative rather than qualitative screening of new proteins would further contribute to efficiency. The Thomson lab has developed a high-throughput screening method for collecting information about binding proteins and enabling protein design. In my project, I have worked on developing a novel way of prescreening generated proteins using protein language models. Applying pre-existing protein large language models (pLLM) such as Evolutionary Scale Modeling (ESM) and AlphaFold 2 & 3, I am researching a way to generate and then prescreen proteins for their binding affinity. I have also had an opportunity to learn how to use the lab's high throughput screening assay to experimentally test protein designs. So far, I do not have a fully developed method/model, but I have the base classifier that needs to be finetuned and will require a generator for which the best parameters still need to be specified. I hope to be able to complete these programming improvements and perhaps be able to test them by applying the high throughput screening before the end of the summer.

**Time-Like Entanglement From Path Integral**

Zofia Adamska

*Mentors: John Preskill and Alexey Milekhin*

Most quantum mechanics formalisms treat space and time on different footings, which seems unnatural from the perspective of relativistic physics. To address this asymmetry, we propose a new definition of a spacetime density matrix, derived from the path integral approach, to better analyze quantum information in spacetime. Our motivation is based on observations in relativistic Quantum Field Theory, where the Renyi entropies of this density matrix coincide exactly with results derived via analytic continuation from space-like separation to time-like separation. We demonstrate how this density matrix can be used to bound spacetime correlation functions, and show that our bound is tighter than other approaches and obeys Lieb-Robinson bounds. Additionally, we test the predictions of this spacetime density matrix for a single-qubit system on a quantum computer. Spacetime entanglement calculated using our approach constitutes a novel probe of thermalization and can shed light on choosing an effective tensor network ansatz for time evolution of quantum many-body systems.

**Towards a Minimal Model for Virus Host Interactions Using Synthetic Cells**

Layla Adeli

*Mentors: Richard Murray and Zach Martinez*

The potential to utilize a minimal model to study viral infection using synthetic cells make them prime candidates for studying pathogens that are not well researched. In order to design a synthetic host for the PhiX174 bacteriophage, we have attempted to incorporate lipopolysaccharides (LPS) recognized by PhiX174, into a liposome membrane to potentially encapsulate a cell-free transcription, translation, and replication system (PURE Rep). Furthermore, a toehold switch designed to fluoresce when triggered by a PhiX174 gene within the liposomes can detect DNA transcription of the PhiX174 genome— our work currently includes designing one that has high efficacy. We have succeeded in producing liposomes, and are working towards incorporating the mechanisms of detecting

PhiX174 infection. The final steps of the project will include observing DNA infection, transcription, translation, and/or replication to show that PURERep is ideal for a synthetic cell environment, using the toehold switches and qPCR. Our work currently shows that making liposomes to encapsulate mixtures such as PURE is possible, meaning that using synthetic viral hosts has potential, but have found that it is difficult to produce because of the difficulty in measuring DNA transcription and replication in a synthetic host and ensuring proper viral lipopolysaccharide integration.

### **Investigating Weak Domain Mediated Protein-protein Interactions Between PU.1 and ICN-RBPJ-MAML Complex in the PU.1 and NOTCH Transcriptional Regulatory Network**

Joe Afful

*Mentors: Ellen Rothenberg and Boyoung Shin*

PU.1 and NOTCH signaling determine T cell lineage commitment at the DN3 stage of T-cell progenitor development. PU.1 and NOTCH signaling are known to form a mutually inhibitory network. PU.1 can downregulate the gene products of Notch signaling target genes, while Notch target gene products also repress PU.1. However, the direct effects PU.1 and Notch ICN (The transcription factor that mediates NOTCH signaling—forms an ICN-RBPJ-MAML complex functionally) have on each other are not known. This is interesting to explore since these two transcription factors are often associated in a variety of mutually inclusive transcriptional regulatory networks. While there has been research concerning this topic, there hasn't been the application of genome-wide sequencing such as CHIP-seq, RNA-seq and BET-seq in answering this question. My project aims to reveal the binding loci of PU.1 and Notch ICN across the whole genome, and subsequently the binding energy topography of the complexation of these factors and their binding sites in the absence of their known binding partners. Based on these findings, there would be inferences made on the nature of the direct interaction between PU.1 and the ICN-RBPJ-MAML complex.

### **Navigation of the Boston Dynamics Spot Robot in Extraterrestrial Planetary Environments**

Diya Agarwal

*Mentors: Dwayne McDaniel, Munim Rayhan, and Joel Burdick*

In planetary exploration, one of the greatest challenges faced by researchers is understanding how rovers will work on extraterrestrial environments, especially in rocky, unstable terrains and low-gravity systems. Thus, methods of virtual simulations can be implemented to test how robotic systems can function in alternate conditions using the Boston Dynamics Spot robot, an agile quadruped robot. This project aims to first create a code base for the Spot robot's simulation and navigation using ROS2 (Robot Operating System) and Gazebo, a robotic simulation software. Using this package, basic reinforcement learning (RL) techniques will be implemented to understand how the robot navigates on rocky surfaces that mimic lunar and martian surfaces. A simple RL algorithm will then utilize the data collected by running experiments in various simulated environments, allowing for a further understanding of the robot's navigation in extraterrestrial planetary conditions.

### **Diving Into the Oxygen Gradient World: Ultrastructure Analysis of *P. aeruginosa* PA14 Across Colony Biofilms Using High-Pressure Freezing Transmission Electron Microscopy**

Jana Carolina Aguirre Castañeda

*Mentors: Dianne Newman and Richard Horak*

Colony biofilms of *Pseudomonas aeruginosa* (*P.aeruginosa*) have been widely used as biological models to study the molecular dynamics of cells living in a fixed matrix. In this setting, bacteria in the bottom are nutrient-replete but oxygen-limited, while bacteria in upper parts of the biofilm are exposed to higher oxygen concentrations and scarce nutrients. Despite the knowledge we have on metabolic and molecular features of these populations, few studies have made a high-resolution spatial description of *P.aeruginosa* biofilms PA14 cell biology across the oxygen gradient. We used high-pressure freezing and freeze substitution techniques to obtain thin highly-preserved sections for subsequent Transmission Electron Microscopy of WT and  $\Delta phz1/2$  (a mutant strain that cannot produce phenazines) biofilms. Our images picture apparent poly-phosphate (Poly-P) granules in the longitudinal axis of cells in both types of biofilms as well as possible polyhydroxyalkanoates (PHA) and well-defined R-bodies. WT bacteria present one big white granule and smaller Poly-P compared to  $\Delta phz1/2$ , which displayed lighter granules and bigger Poly-P-like relative to the latter structures. Both WT and  $\Delta phz1/2$  showed R-bodies either at the top or bottom of the biofilms, however the cytoplasmic location of these structures varies between strains.

### **On the Existence of Harmonic, Finitely-Additive Measures Normalizing Paradoxical Subsets of the Free Group**

MohammedSaid Alhalimi

*Mentor: Omer Tamuz*

Neumann called a group  $G$  amenable if there exists a finitely-additive, left-invariant probability measure  $\mu: \mathcal{P}(G) \rightarrow [0,1]$ . Following Rosenblatt, we say  $G$  is supramenable if for every subset  $X \subseteq G$ , there exists a finitely-additive, invariant measure normalizing  $X$ , i.e.  $\mu(X)=1$ . Tarski showed this condition is equivalent to  $X$  being non-paradoxical, that is, there exists no disjoint  $X_1, X_2 \subseteq X$  where

$X_1, X_2, \dots$  and  $X$  are all finitely equidecomposable. In this work, we consider the free group on two generators  $\mathbb{F}_2$ . Given a probability measure  $\mu$  on the set of its generators, we say  $m: \mathcal{P}(\mathbb{F}_2) \rightarrow [0, 1]$  is  $\mu$ -harmonic if  $\sum_{\gamma=a^{-1}, b, b^{-1}} \mu(\gamma) m(\gamma X) = m(X)$  for all  $X \subseteq \mathbb{F}_2$ . We seek to establish sufficient conditions for the existence of a  $\mu$ -harmonic, finitely-additive measure normalizing a paradoxical subset of  $\mathbb{F}_2$ .

### Development of One-and-Two-Photon Radical Sensitizers for Polymerizations

Sulaiman AlKadi

Mentors: Harry Gray and Jay Winkler

Polymerizations are amongst the most versatile and useful reaction classes; producing a diverse range of useful materials such as plastics, coatings, adhesives, conductors, sensors, and more. However, there are still challenges in developing efficient and sustainable polymerization technologies, especially those utilizing light. We investigated the use of a diiridium complex that is a powerful excited state reductant, initially studied by the Gray group, to reduce methylmethacrylate and styrene, two common commercial polymer precursors. Initial investigations found that diiridium was not a powerful enough photoreductants to generate radicals from precursor molecules. We are planning to investigate more powerful excited state reductants such as tungsten(0) arylisocyanides.

### The Effect of Irradiation on the Isotopic Composition of Polycyclic Aromatic Hydrocarbons in the Interstellar Medium

Abdullah Almomtan

Mentors: John Eiler, Alexander Meshoulam, and Amy Hofmann

Polycyclic aromatic hydrocarbons (PAHs) are some of the most common sources of carbon in the universe. They are composed of multiple benzene rings fused together, forming systems with remarkably high delocalization and resonance, resulting in significant thermodynamic stability. Their ubiquity has put them in the forefront of the field of astrochemistry, as they can form on Earth, in hot circumstellar environments, and in cold interstellar molecular clouds. Zeichner et al. have determined that isotope clumping, or multiple substitutions of  $^{13}\text{C}$  and  $^2\text{H}$  atoms in PAHs can be used as an indicator of the environment in which these molecules form, as clumping is indicative of kinetically controlled reactions that occur in cold environments. However, secondary reactions such as fragmentation and isotope scrambling via irradiation also affect how isotopes are distributed in a PAH sample. Thus, in order to get a complete picture as to how to use isotope distributions to study PAHs, it is necessary to understand how irradiation influences them. We present a comparison of the doubly- $^{13}\text{C}$  substituted compositions of standardized pyrene with pyrene subjected to electron bombardment using gas chromatography-mass spectrometry (GC-MS), isotope ratio-mass spectrometry (IR-MS), and GC-Orbitrap mass spectrometry.

### I. Ab-Initio Study of High and Low-Field Electron Transport in Emerging 2D Materials Like Graphene and $\text{MoS}_2$ ;

### II. Design and Construction of Ellipsometer for Film Thickness Measurements

Ashutosh Krishna Amaram

Mentors: Austin Minnich and Benjamin Hatanpaa

I. 2D materials have created a buzz in the field of electronics especially when researchers are pushing the limits of science and technology to minimize the size of the transistors being fabricated. With the size of the devices becoming smaller and smaller it is important to understand the behavior of electrons at high fields. Modeling of electron transport in these 2D materials can be easily understood using an ab-initio approach where we calculate the electronic structure using Density Functional Theory calculations and consider phonons as scattering centers using Density Functional Perturbation Theory calculations. In order to compute the transport properties of these materials, it is necessary to interpolate the electron-phonon matrix to finer grids and also obtain the scattering rates using Perturbo. These two parameters are then taken as input to solve the linearised Boltzmann equation to understand the electron transport at both high and low fields. However, this approach cannot be used for graphene, hence for this special case we solve the real-time Boltzmann equation to understand the electron transport characteristics in the material.

II. Ellipsometry is one of the widely used non-destructive characterization techniques to compute the thickness of the film being deposited. The underlying principle behind the instrument is the change in the state of polarization when the incident light is reflected onto the analyzer. This change in the state of polarization can be characterized by two parameters which are  $\psi$  and  $\Delta$ , which can be obtained by fitting the output intensity plot given by the photodetector with the standard intensity equation. The experimentally determined values of  $\psi$  and  $\Delta$  are then taken as input values to a theoretical model where the  $\psi$  and  $\Delta$  values are computed using the snell's law and fresnel's equations with an initial guess for the thickness of the thin film. The iterations continue until the error between the theoretical and experimental values is minimized and the thickness at which this condition is achieved is the approximate value for the thickness of the thin film.

### **Development of a Qubit Module for Realizing Networks of Superconducting Quantum Processors**

Parthorn Ammwat

*Mentors: Oskar Painter and Piero Chiappina*

Quantum computers hold the promise of revolutionizing a wide range of scientific fields, including cryptography, drug discovery, and optimization. One prominent platform for constructing a large-scale quantum processor is superconducting quantum circuits. Despite recent developments in increasing the size and complexity of superconducting quantum processors, maintaining high coherence and fidelity control across a large chip remains a key challenge. One approach to scaling is to connect multiple small-scale quantum processors through optical fiber interconnects. Since superconducting qubits do not have a natural interface with optical photons, quantum transducers are needed to interface between microwave and optical photons. Moving forward, it is crucial to develop a qubit module that can efficiently capture photons coming from these transducers. In this work, we design, fabricate, and characterize a qubit module designed to capture incoming microwave photons. Using an existing qubit module as a prototype, we optimize the circuit geometry to achieve better photon absorption efficiency and implement asymmetric superconducting quantum interference devices to improve quantum coherence. The measured results mostly agree well with expectations. The qubit module in this work can be implemented in a future quantum network distributing entanglement across remote superconducting processors.

### **Matrix Product Operator (MPO) Representations of Sequential Quantum Circuits to Study the Mapping Between Gapped Phases**

Yuvan Anand

*Mentors: Xie Chen and Nat Tantivasadakarn*

Sequential quantum circuits of linear depth allow us to map between different gapped phases, for example between the product state and GHZ ground states of the Ising Model. Matrix Product Operators (MPO's) are useful tensor-network representations of operators that allow us to study the action of the circuit in terms of single-site operators. Thus, we look at adding modifications to the prototypical circuit of the transverse-field Ising model and studying the effect of the modifications on the Kramers-Wannier duality properties of the circuit, specifically, modifying the angle of rotation in the various components of the circuit. This analysis on the basic Ising model can then be applied to more complex topological models.

### **Searching for Reflected Returning Radiation in Black Hole X-Ray Binaries**

Sophia Andrews

*Mentors: Fiona Harrison and Edward Nathan*

An X-ray binary system is one consisting of a donor star orbiting a stellar-mass black hole. When sufficiently close, the immense gravitational pull of the black hole can begin to strip material from the donor star. As this stripped material rapidly spirals inward into the accretion disc, strong gravitational and frictional forces cause it to heat up to extremely high temperatures, which causes X-rays to be released. This process is known as an outburst. Furthermore, during an outburst, three kinds of spectral data can be observed, all of which come from the disc itself: disc, coronal, and reflection. This report focuses on reflection, which describes the reprocessing and reflection of X-rays from the accretion disc onto the black hole. Conventional reflection models often assume a power-law spectrum, in which X-ray intensity decreases with increasing X-ray energy. However, an interesting phenomenon can occur when the disc is particularly luminous. This is the observation of returning radiation, in which relativistic factors consequently cause some of the X-ray flux to be transmitted back to the disc. This report further examines the implications of such effects.

### **RadDiff: Describing Differences in Radiology Image Sets With Natural Language**

Sahithi Ankireddy

*Mentors: Serena Yeung, Yuhui Zhang, and Pietro Perona*

Which types of radiology images are most likely to lead to misdiagnosis? What traits distinguish patients with a lower likelihood of mortality? What are the hospital-specific artifacts in radiology images that hinder cross-hospital generalization? To tackle these challenges, we introduce RadDiff, a multi-modal AI tool that generates natural language descriptions to highlight differences between two radiology image sets, focusing on accurately capturing distinctions in set 1 over set 2. RadDiff first proposes candidate differences and then re-ranks them based on their effectiveness in distinguishing between the two sets. To validate RadDiff, we created RadDiffBench, a dataset comprising 133 paired image sets with ground truth difference descriptions. RadDiff contributes new knowledge and advancements to both the machine learning and healthcare communities.

### **Accounting for Power Budgeting During Orbital Eclipses for Lunar Trailblazer Mission**

Miina Anvelt

*Mentors: Bethany Ehlmann and Judy Adler*

Based on the geometry of the Earth, Moon, and Sun, the Lunar Trailblazer (LTB) spacecraft is on track to experience at least one long-duration eclipse while in its orbit around the Moon. The LTB mission aims to

investigate the presence of water on the Moon and the thermophysical properties of the lunar surface. During a long-duration eclipse, the spacecraft will spend three or more hours in the shadow of the Moon and Earth which puts the systems at risk due to the lack of solar radiation for recharging batteries. The purpose of this study is to outline the procedure of the LTB spacecraft to ensure successful power management through long-duration eclipse scenarios. The strategically planned procedure ensures that the spacecraft follows an autonomous software sequence prior to the eclipse, uses minimal battery power over the duration of the eclipse, and exits the eclipse to regain a nominal operation. Tests were performed to validate the template procedure on a virtual spacecraft simulation machine and FlatSat (a hardware bed composed of the same hardware as the spacecraft). The results followed the expected execution of the procedure and demonstrated the flexibility of the procedure to power considerations and timing of eclipses. By employing this procedure, the spacecraft can continue nominal operations after experiencing long-duration eclipse scenarios.

**Control of a Robotic Arm Using EEG**

Jafarbek Arifdjanov

*Mentors: Soon-Jo Chung and Yujin An*

This research project explores the development of a control system for a robotic arm using EEG signals, specifically designed to assist individuals with disabilities affecting their nervous system. The principal objective of this work is to create a reliable interface that allows users to operate a robotic arm through thought alone. Patients will wear an EEG device that captures neural activity as they imagine specific movements, such as using their right or left hand or performing actions like jumping. These neural signals are processed and translated into commands for the robotic arm, which is equipped with a camera to observe its surroundings, detect objects, and determine which items are within reach. The robotic arm will then execute the appropriate movements based on the user's intentions. Currently, we have developed a simulation model of the system and are in the process of integrating the camera into the simulation. Future work will involve refining the signal processing algorithms and conducting experiments to evaluate the system's accuracy and responsiveness.

**Cross-Modal Approaches for Characterizing Hypothalamic Line Attractor Neurons**

Iðunn Björg Arnaldsdóttir

*Mentors: David J. Anderson and Amit Vinograd*

The hypothalamus plays a critical role in regulating behaviors such as aggression and mating, with estrogen receptor 1-expressing (Esr1+) line attractor neurons in the ventrolateral ventromedial hypothalamic nucleus (VMHvl) being particularly significant. Identifying the specific subpopulations of neurons in the VMHvl that exhibit these characteristics and studying their morphologies, genetic profiles, and connections would allow for the development of more specialized markers for further optogenetic research and a deeper understanding of the physiology underlying aggressive emotional states. The primary objective of this research was to acquire an ex vivo sample of the VMHvl region housing these neurons. Various techniques were employed to optimize cryosectioning and align tissue sections for subsequent 3D reconstruction of the VMHvl. Future efforts will focus on refining these methodologies and improving the alignment of tissue slices to enhance the accuracy of the 3D reconstruction.

**Understanding the Superconductivity of Ultra-Thin Monoclinic LaSb<sub>2</sub>**

Alexis Ashby

*Mentors: Joe Falson, Adrian Llanos, and Reiley Dorrian*

At temperatures near absolute zero some materials become superconducting, their resistance decreases to zero and transports direct current without energy loss. In the ultra-thin limit, monoclinic LaSb<sub>2</sub>, 4nm thick, acts as a type II superconductor, when the resistance drops over a range of temperatures and begins forming an internal magnetic field. In this project, this transition region is analyzed for several ultra-thin monoclinic LaSb<sub>2</sub> samples at different applied perpendicular magnetic fields. This analysis includes determining activation energy, London penetration depth, full superconducting state, flux creep state, and paraconductivity state. Previous research indicates the London depth, describing the exponential decay of the applied magnetic field inside the film, can be found based on the exponential decay of the activation energy at different applied fields. The full superconducting, flux creep, and paraconductivity states can be estimated at 10%, 50%, and 90% of the initial resistance respectively.

In addition, Indium appears to improve the superconducting state of LaSb<sub>2</sub>. Several samples soldered using indium were found to have a higher transition temperature dropping to half the initial resistance, then transitioning to zero resistance in the expected region for LaSb<sub>2</sub>. Studying the diffusion of trace amounts of Indium could produce a more consistent way to improve the superconductivity of LaSb<sub>2</sub>.

### Search for Long-Lived Particles With HCAL Segmentation in CMS at the Large Hadron Collider

Katherine Avanesov

*Mentors: Harvey Newman and Kiley Kennedy*

Long-Lived Particles (LLPs), defined as particles with lifetimes greater than 0.1 nanoseconds, are predicted by both the Standard Model (SM) and many Beyond the Standard Model (BSM) theories, including those addressing dark matter, the matter-antimatter asymmetry in the universe, and supersymmetry. We search for the Higgs boson decay to a pair of such hypothesized heavy particles which subsequently decay to two pairs of bottom quark-antiquark jets  $H \rightarrow ss \rightarrow b\bar{b}b\bar{b}$ . The analysis exploits the new depth segmentation upgrade of the Compact Muon Solenoid (CMS) Hadronic Calorimeter (HCAL) to target the characteristic topology of a jet-cluster from an LLP that decays inside the HCAL and therefore whose decay vertex is displaced from the central beam line. Using Monte Carlo-generated signal samples against a  $W+$  jet background, we develop and compare the performances of various neural network (NN)-based classifiers. Among the explored architectures, we produce 3D convolutional neural networks (CNN) trained on images of the jet energy distribution across the HCAL depth-layers and in  $\eta$ - $\phi$  space. This motivates the use of Gradient-weighted Class Activation Mapping (GradCAM) to gain insight into the features learned by the CNN and to evaluate the reliability of the model.

### Regulation Mechanisms of Phenazine Biosynthesis in Phosphorus Limitation Conditions in *Pseudomonas synxantha*

Rogelio Avila

*Mentors: Dianne Newman and Reinaldo Alcalde*

Phenazines are redox-active metabolites produced by various bacteria in different contexts. Due to its high metabolic production cost, phenazine biosynthesis is a tightly regulated process that involves two main triggers in planktonic culture: quorum sensing and phosphorus limitation. Understanding these networks is crucial for developing microbial strategies that support sustainable farming practices. Recent observations made by the Newman Laboratory suggested a role for *phoB*, a phosphorus stress response gene, in phenazine production through a putative binding motif upstream of the phenazine biosynthesis genes, however, this has not been proved experimentally. We used deletion constructs of *phzI* and other quorum sensing genes to assess their impact on phenazine biosynthesis under phosphorus limitation conditions. Preliminary results confirmed that *phzI* is essential for phenazine production in *Pseudomonas synxantha* under these conditions. Additionally, we propose an experimentally validated model elucidating *PhoB*'s involvement in phenazine activation. Our findings suggest that *PhoB* may be inducing the quorum sensing activation pathway in phosphorus limited conditions.

### Physics Based Tests for CliMA Cloud Microphysics and Convection Parameterization

Diana Citali Avila Padilla

*Mentors: Tapio Schneider and Anna Jaruga*

Climate change is one of the biggest challenges humanity will face in the 21st century, with global damages from climate-related disasters exceeding 210 billion USD in 2020. Current climate models lack the accurate local information needed for adaptation, partially due to uncertainties in representing low clouds. Particularly, the behavior of stratocumulus clouds is critical; their increase could dampen climate warming, while their decrease could amplify it. However, there is no consensus on how these clouds will respond as CO<sub>2</sub> levels rise.

The Climate Modelling Alliance (CliMA) is developing a new parameterization for representing clouds and convection in climate models. The goal of this project is to test the new parameterization against high-resolution numerical simulations of stratocumulus clouds and to showcase the parameterization skill in capturing the behavior of drizzling vs non-drizzling stratocumulus clouds. This project is part of a broader effort to ensure CliMA's parameterization accurately captures the complex interactions between cloud droplet concentrations, resulting precipitation, and albedo.

### Characterization and Demonstration of Quantum Optoelectronic Systems With Squeezed Light

Pablo Backer Peral

*Mentors: Ali Hajimiri and Volkan Gurses*

Optoelectronic circuits combine photonics and electronics to improve sensing, communication, and computing systems. Quantum photonics, an emerging field, utilizes light's quantum properties to surpass classical limits. Quantum optoelectronic circuits further this by integrating quantum photonic and electronic functions, offloading tasks from photonic to electronic circuits. We showcase a variety of quantum optoelectronic designs, including an on-chip single photon detector and a tabletop setup with 2 squeezed light sources and 2 quantum-limited coherent receivers. Using this setup, we demonstrate a proof-of-concept generalization of classical phased arrays to the nonclassical domain by interfering two squeezed states of light. With the coherent receivers, we show an architecture to process quantum optical states coherently in the radio frequency (RF) domain after optoelectronic down conversion. To illustrate the capabilities of this system, we emulate an optical circuit that generates cluster state statistics through matrix multiplication. This is done with both RF and digital circuits, showing that some

processing of quantum information can be done through coherent optoelectronic down conversion and electronic processing.

### **Mechanical Behaviour and Failure of 3D-Printed Architected Photopolymers**

Alize Bakker

*Mentors: Julia R. Greer and Cyrus J.B.M. Fiori*

Additive manufacturing (AM) could be applied into several fields such as medicine, dentistry, and optics. Despite multiple applications, as of right now, these fabricated parts are limited from use as critical components in engineering, as they are manufactured with random defects and break in unpredictable ways. Architected materials are an enabling technology with continuously growing amounts of applications due to their customizable properties and ample benefits. They are especially amenable to AM fabrication, which makes them an exciting candidate for studying AM materials. This project aims to understand how the fabrication methods impact the material properties and to study the materials mechanical behavior and failure with random defects. In order to work towards these findings, first we created a program in Rhino/Grasshopper in order to input parameters to automatically have a sample created in under two minutes. After printing and post curing samples we tested them on the Instron MTS, some tests we run include: uniaxial tension of dog bone samples made of PR48, uniaxial tension of plane-stress lattices, stress relaxations of both dog bones and lattices and plane-stress fracture tests.

Additionally, we utilized differential scanning calorimetry to run tests on a PR48 square lattice at several different curing times. We found that there is no apparent correlation between the glass transition temperature and curing time (linear line of best fit slope:  $-0.0146$ ,  $R^2 = 0.0074$ ) but there is evidence that the glass transition temperature at every cure time is much higher than the experimental condition temperature (room temperature:  $22^\circ\text{C}$ ). The findings from this study help better predict how the material will behave despite its random defects.

### **Synthesis of Novel Anionic Ligands to Access Exotic Metal Oxidation States**

Aadarsh Balaji

*Mentors: Theodor Agapie and Meghan Bruening*

High oxidation-state metal centers are challenging to prepare and even more challenging to isolate. In the area of nickel organometallic chemistry, although high oxidation-states are proposed in reaction mechanisms, few such intermediates have been isolated and characterized. Recent studies have demonstrated that bulky ligands can stabilize Pd(IV) and it is hypothesized that the same may be true for Ni(IV). Additionally, interactions with Lewis acid cations have been found to influence reaction selectivity, and the presence of anionic ligands may enhance this effect. In this project, we synthesize an anionic phosphine ligand with a silicate backbone and investigate its metalation chemistry with nickel.

### **Measuring the Kinetics of DNA Hybridization**

Arjun Banerjee

*Mentors: Erik Winfree and Yancheng Du*

DNA hybridization, the formation of double-stranded DNA (dsDNA) from single-stranded DNA (ssDNA), underpins DNA nanotechnology, where nucleic acids are engineered to create intricate molecular systems such as logic gates, neural networks, and molecular walkers. The design of these sequences necessitates consideration of both thermodynamics (determining which structures will form) and kinetics (determining the rate of formation). While extensive datasets on DNA thermodynamics have enabled the development of highly accurate thermodynamics models, the experimental data on DNA kinetics is significantly less comprehensive. This makes it difficult to develop a model that accounts for a variety of parameters, such as secondary structure, guanine-cytosine content, salt concentration, and temperature. Here, we employ a universal fluorophore and quencher method to experimentally determine the rate constants of DNA hybridization across a range of parameters. We then compare our experimental results to existing prediction models and previous predictions of the influence of parameters, and discuss potential ways to improve modeling. Ultimately, we anticipate that our findings will contribute to the next generation of DNA kinetics models, including their integration into Bayesian inference frameworks for rate estimation in Monte Carlo Markov Chain simulations.

### **Unifying 3D Pose Tracking and Physics-Constrained Inverse Kinematics in Deep-Learning Animal Behavior Model**

Ava Barbano

*Mentors: Talmo Pereira, Eric Leonardis, and Ralph Adolphs*

Understanding behavior as a basis for neural activity involves examining how sensory inputs are processed and translated into actions within the body and environment. This project focuses on sensorimotor transformations within the framework of embodied control, addressing a key question in the field: how does biomechanical accuracy impact model fidelity? Previously implemented rodent forearm models with torque and simplified muscle actuators are compared to a newly integrated CAT-scan based muscle model in a reinforcement learning task. Using an actor-critic reinforcement learning architecture with Multi-Objective Maximum a Posteriori Policy

Optimization (MOMPO) in Acme, models are rendered using MuJoCo physics simulation and perform a target reaching task. Leveraging Fitts' Law, a predictive distance-accuracy relationship, kinematic performance with targets of varying sizes and locations are compared to this baseline. Comparing activation layers, the learned neural representations differ between representations, suggesting that the neural coding for motor control is dependent on the type of biomechanical actuator used.

### **Final Design, Testing, and Validation of the Assembly Tooling for the CMS BTL Detector at CERN**

Victoria Barry

*Mentors: Maria Spiropulu and Adi Bornheim*

This project encompasses the optimization of the assembly tooling for CMS BTL (Compact Muon Solenoid Barrel Timing Layer) detectors to be put on CERN's HL-LHC (High Luminosity Large Hadron Collider). Incorporating timing into CERN's HL-LHC is crucial for further understanding the science of high energy physics. It starts with the assembly of detector modules at Caltech. The CMS detector, and the BTL component, is to be installed on the HL-LHC by collaborators at CERN as an upgrade to the initial CMS detector which has been in operation since 2009. There are a range of physics goals for CMS and HL-LHC, including research on the Higgs Boson, dark matter, and physics beyond the Standard Model. The CMS experiment is residing on the LHC now and will utilize the upgraded HL-LHC starting in 2029. The experiments on the LHC detect interactions (collisions) between protons or nuclei as a principal tool to further our understanding of the fundamental laws of matter. The HL-LHC is an improved version of the LHC, creating five to ten times as many particle collisions as in the current data taking period. We have designed, and manufactured housing tools, and Assembly Test Stands to further the assembly.

### **Hexagonal Growth Algorithms for Irregular Architected Materials**

Kyrillos Bastawros

*Mentors: Chiara Daraio and Suyeong Jin*

Irregular architected materials are those which are built up from simple initial building blocks to form complex microstructures, and have been observed to have novel properties, "such as imperfection insensitivity, enhanced impact absorption, and stress redirection" (Liu et al., 2022). These materials have traditionally been made using a virtual growth algorithm, which assembles microstructures from basic building blocks using connectivity rules in an  $n \times m$  grid of square tiles. A novel approach to this algorithm assembles these materials using a hexagonal (or equivalently a triangular) grid, enabling a range of local and global coordination control, as well as domain size control. These samples are generated via three-dimensional printing from stereolithography (.stl) files. The aim of present work is to expedite this process through the use of python automation. This has been done for both the two-dimensional triangular algorithm and the three-dimensional octahedral algorithm.

### **A Model for the Chemical Kinetics of Cold, Gas-Phase Alkaline-Earth Monofluorides in a Cryogenic Buffer Gas Cell**

Adele M. Basturk

*Mentors: Nick Hutzler and Phelan Yu*

Understanding the chemical yield and stability of the processes inside a CBGC is critical in the design of brighter and colder molecular beams, which serve as the starting point for molecule laser cooling and precision measurement experiments. We model the chemical kinetics of alkaline-earth monofluorides, such as calcium monofluoride (CaF), produced in the gas phase within a cryogenic buffer gas cell (CBGC) with a set of 5-dimensional temporal differential equations. We solve the resulting set of equations numerically by utilizing a 4th-order classical Runge-Kutta (CRK) time-stepping. We study how the interspecies and intraspecies rate constants depend on temperature with the classical Langevin capture model, appropriate for temperature on the order of 0.1K - 10K. Further, we model the effect of helium density on the rate constants of third-body mediated reactions, such as the formation of calcium dimers and difluorides. Finally, we solve the equations for varying sets of initial fractional state populations at a fixed temperature, volume, and helium density to understand how the alkaline-earth monofluoride loss timescale depends on the chemical composition of the constituents inside the cell. From this, we learn that high neutral fluoride and difluoride concentrations lead to the shortest loss time scale.

### **Analyzing Fast-Moving Objects With ZTF and SRO Observations for Precise Orbit Determination**

Tanvi Batra

*Mentors: Tom Prince, George Helou, and Navtej Saini*

Near-Earth Objects (NEOs) pose a significant threat to Earth, making precise orbit determination critical. This project aims to refine NEO orbit data using a collaborative approach that leverages the strengths of Caltech's Zwicky Transient Facility (ZTF) and JPL's Sierra Remote Observatory (SRO). ZTF's extensive sky coverage and high-cadence streaks images, combined with SRO's robotically operated telescopes through optimal observing conditions, provide an integrated solution for enhancing our understanding of NEO orbits. The project employs several tools and techniques to streamline the detection, analysis, and reporting of NEO candidates to the Minor Planet Center (MPC). The ZStreak Web Interface aids in the initial identification of fast-moving objects (double or multiple streaks), while the Sat ID, Find Orb and IRSA Object Search verify and analyze detected objects. The FMO



(Fast-moving object) helper program and JS9 computational tool are used for visual inspection and further analysis. The SRO pipeline involves identifying candidate single streaks with ZTF, confirming detections with SRO's synthetic tracking algorithm, and performing parallax calculations. Ultimately, this combined effort will focus on refining these methods and ensuring a robust connection between ZTF and SRO, advancing our knowledge of NEO trajectories and potential impact risks.

### **Optimizing Retrieval-Augmented Generation and Information Retrieval to Design a Virtual Teaching Assistant for CS142 (Distributed Computing)**

Jayden Bautista

*Mentors: Kaniantha Mani Chandy, Sachin Adlakha, and Jeffrey Zhou*

Large Language Models (LLMs) such as OpenAI's ChatGPT and Anthropic's Claude have been trained with a broad range of internet data. These models have many hundred billion parameters to process and output content for a wide range of queries. However, for domain specific queries, these LLMs often generate incorrect or misleading answers. New methods known as retrieval-augmented generation (RAG) allow LLMs to improve by retrieving relevant data that is then passed to LLMs as "context". This allows LLMs to better respond to domain-specific queries. For this project, we built a chatbot with RAG to serve as a virtual teaching assistant for CS142. After extracting all text and images from the courses' website for data preprocessing, we implemented term frequency-inverse document frequency (tf-idf) and other semantic retrieval algorithms to provide context to various LLMs such as GPT-4o-mini and Gemini 1.0 Pro. We then tested their effectiveness on a list of questions we believe students would ask when taking CS142. We then incorporated the input from the user into the retrieval algorithms to allow for the ChatBot to engage in longer, more thoughtful conversations with the user.

### **Comparing the Efficacy of Different Deep Learning Approaches for Creating an Earthquake Catalog**

Alexa Baxter

*Mentors: Julian Bunn, Elizabeth Cochran, and Clara Yoon*

Earthquake catalogs, lists of the time, location, and magnitude of earthquakes, are an essential tool in the field of seismology. In recent years, machine learning models have taken over the job of analyzing and processing the data recorded by seismometers to output earthquake events. In this study, we compare the performance of two phase pickers, EQTransformer and PhaseNet, and two associators, PyOcto and GaMMA, on two days of West Texas earthquake data. West Texas has only started experiencing frequent earthquakes in the last decade due to oil and gas industry activities. We present preliminary results on how the models perform in comparison to each other and the data of the Advanced National Seismic System (ANSS) ComCat catalog. Our objective is to develop an accurate earthquake catalog to study the growth of seismic activity in West Texas in order to learn more about the sources of induced seismicity and help understand the resulting seismic hazard.

### **Engineering Synthetic Promoters for Robust Detection of TNF $\alpha$ and IL-1 $\beta$**

Patrick Bednarz

*Mentor: Mikhail G. Shapiro*

Abstract withheld from publication at mentor's request.

### **Investigation Into Weakly Coordinating Anions Comprised of Silicon Bearing Fluorinated Pinacolate Ligands**

Louis Bercaw

*Mentors: Theodor Agapie and Tianyi He*

The silylium cation ( $R_3Si^+$ ) can activate C-F bonds in many greenhouse gases via hydrodefluorination. The Agapie group has previously developed a weakly coordinating anion (WCA) comprised of a pentacoordinate silicon complex with perfluorinated pinacolate ligands containing  $C_{sp^3}-F$  bonds and an alkyl or aryl ligand,  $[^R SiF_{24}]^-$ . Due to the decomposition of this anion in the presence of highly electrophilic cations, such as silylium, a new WCA containing  $C_{sp^2}-F$  bonds,  $[^R SiF_{40}]^-$ , was targeted. Synthesis of the precursor to  $[^R SiF_{40}]^-$ , tetrakis(pentafluorophenyl)pinacol, was attempted via reductive coupling of decafluorobenzophenone using many different conditions. All attempts to prepare tetrakis(pentafluorophenyl)pinacol were unsuccessful, presumably due to the favorability of the formation of the uncoupled alcohol product, bis(pentafluorophenyl)methanol.

Given the lack of success in the synthesis of  $[^R SiF_{40}]^-$ , further investigation into  $[^R SiF_{24}]^-$  regarding its role as a counterion to various metal cations was pursued. The proposed  $[^R SiF_{24}]^-$  metal salts can serve as an effective additive to catalysts for  $N_2$  reduction into  $NH_3$  due to the Lewis acidity of metal cations. It was determined that  $[^R SiF_{24}]^-$  can serve as an effective counterion to  $Zn^{2+}$ . Investigations into  $Al^{3+}$ ,  $Ni^{2+}$ ,  $Y^{3+}$ ,  $Yb^{3+}$ ,  $Ga^{3+}$  are ongoing.

### Enhancing para-Ethyltoluene Selectivity for Toluene Ethylating Reaction via Hybrid Catalyst Design Strategies

Jack Bernhardt

Mentors: *Stephanie Kwon and Hosea Nelson*

Abstract withheld from publication at mentor's request.

### A Unified Framework for Multimodal Common Ground Tracking Demonstrations

Brady Bhalla

Mentors: *Nikhil Krishnaswamy and Eric Mazumdar*

In collaborative problem-solving tasks, Common Ground Tracking (CGT) identifies the shared beliefs of participants working towards a common goal. This is important when creating AI assistants for these types of tasks because a model of what participants currently believe is needed to provide effective feedback. Communication between participants is multimodal, so a system performing CGT must extract and utilize features such as speech, gestures, and gaze to track beliefs. In this project, we implement a fully functional CGT demonstration that runs both live and on prerecorded inputs of a group solving the "Weights Task," in which they work together to determine the relationship between blocks of different weights. Additionally, we create a Python library that can be used to easily build, extend, and test a variety of multimodal CGT demonstrations.

### Testing Neural Crest Enhancer Conservation Using Sea Lamprey

Srijani Bhattacharya

Mentors: *Marianne Bronner and Jan Stundl*

Vertebrate evolution is tightly linked to emergence of the neural crest, a group of migratory stem cells that give rise to distinct vertebrate traits. However, the early-branching group known as jawless vertebrates has neural crest cells without developing all neural crest-derived structures. The sea lamprey, in particular, is a jawless vertebrate that holds importance as the closest living evolutionary relative to jawed vertebrates. Neural crest development is governed by a gene regulatory network comprised of a series of signaling and transcriptional events. The goal of this project is to gain understanding of the neural crest gene regulatory network by comparing conserved and non-conserved aspects of enhancer function between lamprey and jawed vertebrates. We utilized enhancers identified in chicken embryos and injected them into one-cell stage of lamprey embryos. We screened for embryos with positive enhancer-driven fluorescent protein expression; one these embryos reached the desired developmental stage, they were processed by HCR *in situ hybridization* in order to visualize the neural crest cells. The cells that were positive for both neural crest cell markers and enhancer-driven reporter expression were then imaged. Processing these data will provide insight into the degree to which the neural crest gene regulatory network has been conserved across vertebrate evolutionary history.

### Enantioselective Palladium-Catalyzed Intramolecular Michael Addition and its Application in the Synthesis of Clovane

Sanzhar Bissenali

Mentors: *Brian M. Stoltz and Christian Strong*

The enantioselective synthesis of spirocyclic compounds is of interest to the synthetic community given it is a widespread motif found in many natural products. Generating all-carbon quaternary stereocenters containing spirocycles is especially challenging, and therefore it is a recent focus in the Stoltz group. Toward this end, we have developed a palladium-catalyzed enantioselective and diastereoselective Michael spirocyclization reaction. We show diverse examples of this reaction with various Michael acceptors to afford compounds with different ring sizes and side chains. We also present a possible application of this method in synthesizing Clovane, a classical target with a unique tricyclic carbon scaffold.

### Making Purer PURE

Lovisa Bjorn

Mentors: *Richard Murray and Yan Zhang*

OnePot PURE is a cell free expression system which takes the constituents and machinery of transcription and translation to produce proteins *in vitro*. The foundation of the system is in the 36 PURE proteins, which are grown in coculture and separated out from cell extract through His-tag-based metal affinity chromatography. His-tag-based purification has certain limitations in terms of specificity and purity, with metal binding endogenous proteins being purified with the target PURE proteins resulting in contaminants. These contaminants compromise the purity of the OnePot PURE. The identity of these contaminants will be determined using LC/MS. The proteins may be competing for the same substrates as PURE proteins and thus limit protein production, or even directly degrading the system. The goal of this project is to enhance the protein purification process in the One-Pot PURE system by replacing the traditional His-tag with a chitin/intein tag. This replacement aims to improve specificity and purity of the proteins produced. The project involves both computational and laboratory work to optimize the One-Pot PURE

protocol, enhance protein activity using the cleavable chitin tag, and develop fusion proteins to facilitate sequential reactions.

### **Scaling Up Binary Black Hole Merger Follow Up for the Rubin Era**

Aishah Blackmon

*Mentors: Matthew Graham and Kira Nolan*

In 2025, the Rubin Observatory's Legacy Survey of Space and Time (LSST) will transform transient astronomy by detecting approximately 10 million brightness changes nightly. As LIGO prepares for its O5 run, the combined data from Rubin and LIGO will present significant challenges for current binary black hole merger follow up methodologies. We leverage SkySurvey, a simulator traditionally used for supernovae, to enhance the follow up of binary black hole (BBH) mergers associated with electromagnetic (EM) counterparts in active galactic nuclei (AGN). By optimizing these methods, we aim to efficiently process the anticipated increase in data in the Rubin era.

### **Optimal Control of $^{171}\text{Yb}^{3+}$ Ions in $\text{YVO}_4$ for Multi-Emitter Quantum Nodes**

Jean-Michel Borit

*Mentors: Andrei Faraon and Chun-Ju Wu*

State-of-the-art quantum networks are limited to a single optically addressable qubit per node, hindering memory resources and quantum communication bandwidths. To overcome these bottlenecks, multi-emitter quantum nodes have been proposed. Among promising candidates,  $^{171}\text{Yb}^{3+}$  ions in  $\text{YVO}_4$  ( $^{171}\text{Yb}^{3+}:\text{YVO}_4$ ) are particularly attractive due to their long spin coherence times (16 ms), high gate fidelities (0.99975), and deterministic auxiliary nuclear spin memory. However, simultaneously addressing multiple qubits at different transition frequencies requires global control pulses with broadband fidelities. In this work, we design and optimize pulse sequences for broadband spin control of  $^{171}\text{Yb}^{3+}:\text{YVO}_4$  qubits. We characterize Hermite, composite, and gradient-ascent-optimized pulses, achieving control sequences with microwave infidelities below  $3 \times 10^{-4}$  across a spectral range of 1 MHz, a full order of magnitude improvement over conventional Gaussian pulses. Our results pave the way for scalable quantum networks based on rare-earth ions with multi-emitter memory nodes.

### **Probing Einstein's Equations Through Analogies With Electrodynamics**

Siddharth Boyeneni

*Mentor: Elias Most and Jiaxi Wu*

Numerical relativity (NR) is a powerful modeling tool for the dynamics of general-relativistic systems that cannot be analyzed analytically. Prior work has led to a non-standard tetrad formulation of the 3+1 decomposition of the Einstein field equations (EFE) that bears a striking resemblance to 3+1 electrodynamics. We expand this theory for known solutions of the EFE, developing tools that can be used to probe the gravitational effects of various astrophysically relevant systems such as the compact binary coalescence (CBC) problem. We run a set of simulations capturing these systems, via Einstein Toolkit, to directly verify the efficacy of these tools. Since these tools are defined similarly to Yang-Mills electric and magnetic fields, we open the possibility of applying insights from relativistic plasma physics to NR problems.

### **Effect of Task Stereotype on Racial Identity of Multiracial Individuals**

Ivy Brainard

*Mentor: Kirby Nielsen*

The objectives are to analyze how stereotype-confirming and stereotype-disconfirming feedback affect multiracial individuals' willingness to identify with specific racial groups. Participants are exposed to tasks associated with various racial stereotypes and receive performance feedback intended to either confirm or disconfirm these stereotypes. Their racial identity choices are then recorded to assess shifts in self-identification.

The study employs a multi-phase approach: initially assessing task-associated stereotypes, then evaluating racial identification in response to stereotype-related feedback. Preliminary results indicate strong stereotypes associated with different tasks and noticeable shifts in racial identity following feedback. These findings highlight how racial stereotypes influence self-perception and identity among multiracial individuals.

### **Electrochemical and Spectroscopic Determination of the Charge Compensation Mechanism in Metal-Deficient Sulfides**

Joshua Braun

*Mentors: Kimberly See and Colin Morrell*

This research aims to investigate the electronic factors that activate reversible anion redox chemistry in Li-rich transition metal sulfide cathode materials with the aim of surpassing current state-of-the-art Li-ion cathode materials which are limited to the theoretical storage of one electron per formula unit. A key focus towards achieving this aim is understanding how the charge compensation in these materials can be shifted between the anion and cation in the pristine state by preparing the materials such that they are electron deficient. A redox inert

metal is then aliovalent substituted into the material to study how the electron-deficiency can be handed-off between the cation and anion as the amount of redox-active metal is reduced. The study employs solid-state synthesis, galvanostatic cycling with potential limitation, galvanostatic intermittent titration experiments, and elemental analysis to understand the charge compensation mechanism in off-stoichiometric Li-rich transition metal sulfide materials. The preparation, compositional analysis, and electrochemistry of several materials prepared via aliovalent substitution into the pristine parent phase are presented. Ongoing and future experiments are focused on spectroscopic study of the charge compensation mechanisms in these materials.

### Control of Physical Parameters in Binary Black Hole Initial Data

Iago Braz Mendes

*Mentors: Mark Scheel, Nils Vu, and Saul Teukolsky*

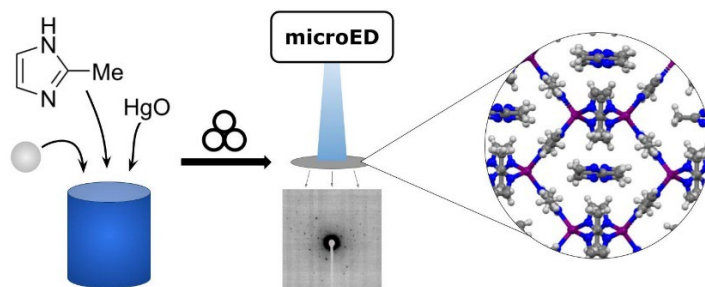
When solving Einstein's equations for Binary Black Holes (BBH) numerically, we split the four-dimensional spacetime into three-dimensional spatial slices and evolve them over time. The first slice is described by solving an Initial Data problem, which is cast as five elliptic partial differential equations in the extended conformal thin-sandwich (XCTS) decomposition. Prior to solving the XCTS equations, we must choose "free data" to impose boundary conditions and specify background quantities. This is the approach taken in SpECTRE, a parallel code that aims to simulate BBH for the new generations of gravitational wave detectors. After solving the XCTS system, SpECTRE runs a horizon finder that measures the masses and spins of the black holes. Additionally, our work extends SpECTRE's capabilities to calculate total energy, momentum, and center of mass as infinite-surface integrals using the Arnowitt-Deser-Misner (ADM) formalism. Typically, we want to choose these physical quantities before running a BBH simulation, but they can only be measured after numerically solving the XCTS equations. To address this, we implemented an iterative scheme in SpECTRE that drives the physical parameters to their desired values by adjusting the free data in a quasi-Newton-Raphson method that efficiently computes the Jacobian with Broyden's method.

### MicroED on Mechanochemically Generated Hg(II) Metal-Organic Frameworks

Theodore Bremner

*Mentors: Hosea M. Nelson and Kunal Jha*

Metal-organic frameworks (MOFs) are a useful class of material due to their modular and often porous properties. The solvothermal production of metal-organic frameworks requires high volumes of solvent and energy to heat the solution. Ball milling is a green alternative where the starting materials are milled in a jar as powders with one or more ball bearings. The ball bearings smash into each other, the milling jar, and the powder to generate mechanical energy to perform chemical reactions. The reaction occurs at room temperature with little to no solvent. This study investigates a mercury(II) 2-methylimidazolate framework synthesized via ball milling. Initial conditions yielded samples that revealed only starting material when characterized with powder X-ray diffraction (PXRD). The milling conditions were adjusted to input more mechanical energy into the system, resulting in a MOF and trace amounts of starting material. The crystal structure was then determined by microcrystal electron diffraction (microED).



### Atwood Number Effects in Statistically Stationary Rayleigh-Taylor Turbulence

Daniel Brito Matehuala

*Mentors: Guillaume Blanquart and Chian Yeh Goh*

The effect of Atwood number,  $A$ , on Rayleigh-Taylor (RT) turbulence is studied using a statistically stationary Rayleigh-Taylor (SRT) flow configuration. The SRT flow configuration represents the flow dynamics of late-time self-similar RT growth in the limit of small wavelength initial perturbations, and has been validated with the direct numerical simulation results of Cabot & Cook (2006) at  $A = 0.5$ . Due to stationarity, SRT flow can be simulated over a long time at the same flow condition, leading to excellent statistical convergence. This is particularly useful for higher Atwood number cases that are challenging to simulate in the traditional temporally evolving RT configuration. We present justifications for the validity of the flow configuration beyond  $A = 0.5$ , and apply it to Atwood numbers in the range of 0.01 – 0.8. Results are validated against others in the literature. Scalings are proposed for ensemble-averaged quantities to obtain normalized profiles that are independent of the Atwood

number, and analytical fits to these normalized profiles are examined. Finally, the consistency of the scaling analysis and model profiles are verified using the ensemble-averaged transport equations.

### **State Preparation and Detection for Quantum Simulation of Particle Collisions**

Sary Bseiso

*Mentors: John Preskill and Federica Surace*

One task in which quantum computers may exceed the performance of classical computers is the simulation of particle interactions and high-energy physics. These simulations are performed by preparing an initial quantum state, letting it time-evolve according to a model Hamiltonian, and measuring the final result. The state preparation and detection tasks are nontrivial and require robust and reliable methods. Here, we identify and benchmark protocols for the state preparation and detection of quantum states that represent particle configurations before and after a collision. These protocols have the potential to be tested on existing analog quantum simulators.

### **Probing LLMs for Encoded Syntactic Features Using Multi-Modal Analytical Techniques**

Aman Burman

*Mentors: Matilde Marcolli and Juan Pablo Vigneaux Ariztia*

Current Large Language Models (LLMs) have demonstrated remarkable capabilities in various linguistic tasks, including text generation, translation, and understanding context. However, a critical area of investigation is their ability to discern and interpret complex syntactic architectures. Inspired by Manning's paper "Emergent linguistic structure in artificial neural networks trained by self-supervision," which showcased the presence of dependency tree structures in BERT representations, this project investigates the encoding of syntactic features in decoder-only Large Language Models (LLMs). Recent research has increasingly focused on understanding the reasoning capabilities of LLMs through eXplainable Artificial Intelligence (XAI) techniques, shedding light on their inference processes. Due to LLMs being black boxes, probing their internal mechanisms is essential for gaining insight. Using mechanistic interpretability and XAI methods, we will reverse engineer the layers and multilayer perceptrons that make up the LLMs. Specifically, applying Layer-wise Relevance Propagation (LRP), neuron activation score analysis, sparse autoencoders, toy models of superposition, and linear probes to classify sentences as grammatical or not, we aim to uncover specific encoding of neurons to different grammatical structures in the Penn Treebank (PTB) Corpus as well as identifying latent features.

### **Improving the Efficiency of Wavefront Sensing and Control Algorithm for Broadband Coronagraphy for the High Contrast Spectroscopy Testbed (HCST)**

Maya Cadieux

*Mentors: Dimitri Mawet, Arielle Bertrou-Cantou, and Susan Redmond*

Direct imaging of exoplanets requires a high-performance coronagraph, a technology designed to suppress on-axis starlight while enabling the transmission of off-axis planet light. The High Contrast Spectroscopy Testbed (HCST) at Caltech demonstrated raw contrasts of the order of  $10^{-8}$  with a Vector Vortex Coronagraph (VVC) and by performing wavefront sensing and control (WFSC) with a deformable mirror (DM). Tests were conducted on the HCST to measure the execution times of software functions involved in the iterative wavefront control process. This analysis aimed to identify delays and eliminate unnecessary function calls, thereby enhancing the efficiency of the current algorithm. Moreover, we intend to implement a new WFSC algorithm that uses polychromatic images, rather than narrowband, to estimate the electric field and therefore apply DM corrections. This improved method aligns with the motivation of broadband coronagraphy to characterize exoplanetary systems across various wavelengths. The addition of a low-order wavefront sensor on HCST also requires broadband light, which will allow the correction of jitter and thermo-mechanical drift, in turn improving the overall stability of the testbed. With this method, we expect to reach the same level of contrast as with the current narrowband approach and improve the efficiency of the algorithm.

### **Quantification of Neural ZENK Expression Patterns in Songbird Brains Associated With the Motor Control of a Context-Dependent Courtship Display**

Beatrice Cai

*Mentors: Marc Schmidt, Natalia Aponte Borges, and Carlos Lois*

The neural circuitry controlling animal behavior and courtship displays is complex. In songbirds, an established neural circuit known as the "song system" gives insight into vocal production. While the "song system" circuit is well-characterized, the neural circuits for non-vocal courtship displays observed in male brown-headed cowbirds (*Molothrus ater*) and its synchronization with song remains unclear. Therefore, we propose using in situ hybridization technique to determine the expression of immediate early genes (IEGs) in motor areas of 9 cowbird brains during different courtship contexts: singing with wingspread, flight control, and silent control. By comparing the expression levels of ZENK, an IEG, we can identify brain areas that show differential activation depending on context-dependent postures to establish the postural neural circuit. The quantification of RNA expression in important song system neuroanatomical regions is conducted using an image processing software FIJI to calculate the expression ratio in the RA and AI<sub>d</sub>. We hypothesize that the RA region, crucial for song production, does not

influence motor control of courtship display while the AId region will show substantial expression. This research could reveal new insights into the neural circuits involved in postural control and their role in social interactions among songbirds.

### **Uranium Isotopic Composition of the Red Sea Seawater**

Runliang Cai

*Mentors: François Tissot and Haoyu Li*

Red Sea presents a unique case due to its isolation during the Last Glacial Maximum, which means less connection to global open ocean circulation. There is a possibly different evolutionary path of oceanic paleoclimate, especially on past extent of ocean anoxia in Red Sea that we know very little. Uranium isotopic ratio is a powerful tool on paleoredox reconstruction. The  $^{238}\text{U}/^{235}\text{U}$  ratio (expressed as  $\delta^{238}\text{U}$ ) serves as a sensitive proxy to redox extent of seawater which can offer a key insight to the oceanic anoxia. This summer we measured the seawater samples from a variety of locations and depths in Red Sea. Samples were processed and purified in a class 1000 clean laboratory. Double spike  $^{233}\text{U}$ - $^{236}\text{U}$  was added to sample solution for correction of fractionation introduced from column chemistry and instrument analysis. High-precision uranium isotopic ratio of seawater was determined via multi-collector inductively coupled plasma-mass spectrometry (MC-ICP-MS). We expect to establish a U isotopic composition-depth profile and gain average  $\delta^{238}\text{U}$  value of seawater in Red Sea. This result will be compared to well-known U isotopic composition of global open ocean, allowing us to gain a deeper understanding on evolution of isolated ocean and the effect of oceanic connection on extent of ocean anoxia.

### **Carbonization of Cement Paste in a Partially Filled Rotating Drum**

Luis Calyeca

*Mentors: Melany Hunt and Ricardo Hernandez*

With a projected increase in concrete usage,  $\text{CO}_2$  emissions resulting from its production have become a relevant issue that must be addressed. Studies have found that over decades, metal oxides in concrete react with atmospheric  $\text{CO}_2$  and form stable carbonates, capturing carbon and strengthening the concrete as a bonus. It has been found that this carbonization of concrete is accelerated when the process instead occurs during the mixing of cement paste for concrete creation. However, due to strict concrete production regulations, implementation of this finding on an industrial scale is restricted to merely injecting  $\text{CO}_2$  into the rotating drum that the cement paste is mixed in. Due to cement paste's strain rate dependent viscosity, it is a non-Newtonian fluid and its flow regime can thus be difficult to solve analytically and visualize. Hence, this project pursues a two-dimensional numerical modeling approach using COMSOL Multiphysics® software to investigate the flow regime of cement paste in a partially filled rotating drum subject to reactions with  $\text{CO}_2$  in order to determine the effectiveness of this mixing method in carbonizing the cement paste. Additional investigation on the rheological properties of cement paste will need to be performed for the continuation of this project.

### **Electrochemical Removal of Metal Byproduct From Molten Eutectic LiCl-KCl**

Arabella Camuñez

*Mentors: Michael Simpson, Courtney Eckley, and Jeffrey Mendez*

The presence of  $\text{ZrCl}_4$  in molten salt solution is required for chlorinating select metal oxides. In preliminary work done at the University of Utah,  $\text{ZrCl}_4$  has been generated in LiCl-KCl via reaction of  $\text{NiCl}_2$  and Zr. This reaction leaves a Ni byproduct which needs to be removed from the salt. In this project, galvanic coupling between a Zr anode and an inert cathode is being tested with  $\text{NiCl}_2$  or  $\text{FeCl}_2$  in the salt. This reaction is performed at  $500^\circ\text{C}$ , and the objective is to recover the metal byproduct (Ni and Fe) on a metallic cathode. Three experiments have been performed to date using either  $\text{NiCl}_2$  or  $\text{FeCl}_2$  as a chlorinating agent. In this first experiment, concentration of Ni and Zr were measured using ICP-MS on salt samples taken over a range of time. The results indicated that Zr concentrations reached 2.2%, equivalent to the solubility limit of  $\text{ZrCl}_4$ , and Ni concentration (as  $\text{NiCl}_2$ ) reached near zero. In the second experiment, concentrations of Fe and Zr were measured in salt samples, and the results indicated that the Zr concentrations reached 1.6% and the Fe concentrations reached near zero.

### **Development of Geant4/G4CMP Monte Carlo Simulations of Phonons and Quasiparticles Within Kinetic Inductance Detectors**

Matthew Cantor

*Mentors: Sunil Golwala and Karthik Ramanathan*

The existence of dark matter (DM) has been suggested by various astrophysical observations. Researchers are probing detection methods of low-mass DM candidates with masses less than 1 GeV. The interaction with these particular DM candidates is difficult to detect due to their low-energy reactions with nuclei, depositing small quanta of energy of only a few eV. To observe these reactions, the Golwala Group develops phonon-mediated detectors—Kinetic Inductance Detectors (KIDs)—that use thin superconducting aluminum films on silicon crystals. Potential DM interactions produce phonons that break Cooper pairs in the aluminum which are detectable as changes in inductance. This project utilizes the Geant4/G4CMP particle simulator package to conduct Monte Carlo simulations to understand the dynamics of phonons and quasiparticles through interactions with KIDs. Particularly, the impact

of phonon energy deposition on the performance and efficiency of KIDs will be investigated. Building off previous efforts in the Golwala Group, the research will continue to address gaps between simulation results and experimental data, notably the high phonon energy loss in the real-world detector. The RISQTutorial, developed by Dr. Linehan at Fermilab, will be utilized to incorporate the Golwala Group's single-KID detector geometry and integrate it with the existing particle physics framework. Additionally, the KaplanQP file, which governs quasiparticle physics, will be further developed and material absorption probabilities will be tuned to align the simulations with real-world data.

**Developing a Trigger Readout Mode for USRP Control for KIPM Detector Probes**

Chi Cap

*Mentors: Dan Baxter, Dylan J. Temples, and Jonas Zmuidzinas*

The kinetic inductance phonon-mediated (KIPM) detector deployed in the NEXUS helium dilution refrigerator, is probed using an Ettus Research x300 Universal Software-defined Radio Platform (USRP) unit, which in turn is controlled using the GPU\_SDR package. At the sampling rate of 100 MSps, we produce 6.4 GB per channel per second of raw data, excluding metadata. Long measurements are not feasible due to the amount of data amassed. Developing triggered readout mode such that only scientific data is saved is important data sparsification which would enable long runtimes for a potential future dark matter search. We have designed a trigger implementation that allows users to specify the time window of data to be saved, initiated using a keyboard press. This implementation lays the groundwork for the future goal of implementing a simple  $S_{21}$  phase quadrature threshold trigger. The trigger implementation is functional, with a 6.8s runtime for a 0.2s total time window; the runtime is dominated by deadtime, which is thirty times larger than the time window. Subsequently, the goal is to reduce the deadtime, aiming for <1% deadtime for any time window.

**Molecular Mechanism of the Nucleocytoplasmic Transport of cGAS**

Ioana Madalina Caraus

*Mentors: André Hoelz and Chia-Yu Chien*

Eukaryotic cells are subdivided into membrane-enclosed compartments, with the nucleus being a primary organelle that harbors the genetic information of the cell. The presence of DNA outside the nucleus is a sign of pathogenic infection. To counteract this, eukaryotic organisms have evolved a molecular sensor that detects DNA in the cytoplasm with great precision. Cyclic GMP-AMP synthase (cGAS) is the key factor that recognizes foreign cytosolic double-stranded DNA and further triggers downstream immune responses. Interestingly, cGAS is also found to tightly bind to nucleosomes. However, the function of cGAS in the nucleus and its shift of different cellular localization remain obscure. Deciphering the molecular mechanism of how cGAS is transported into the nucleus would illuminate its roles in different cellular compartments. Nucleocytoplasmic transport of molecules is tightly regulated and dependent upon interactions with transport factors that facilitate cargoes to pass through the diffusion barrier formed by the FG-nucleoporins of the nuclear pore complex. By extensive recombinant protein expression and purification, pull-down assays were carried out and multiple transport factors binding to cGAS have been identified. The screening result will further serve as a basis for structural elucidating of the cGAS•transport factor complexes.

**Using Machine Learning to Classify Sleep-Wake States in Zebrafish Through Micro-Behavior Analysis**

Maya Caskey

*Mentor: David Prober*

Sleep by definition encompasses all rest states of a rest-activity cycle universal to all animals. The zebrafish is a promising species from which to conduct studies into sleep. However, electrical activity recording approaches that are standard in defining different sleep stages in mammalian studies are difficult to perform on zebrafish. Thus, the way in which sleep-wake states are defined in zebrafish is entirely dependent on behavioral observation. Presently functional imaging experiments only use low-dimensional data, such as intensity changes in pixels, to quantify the behavior of head-fixed zebrafish larvae. Yet, given the rapidly expanding fields of machine learning and computer vision, a more advanced workflow has the potential to extract more nuanced behavioral states. We present a semi-supervised computational pipeline for the identification of periods of rest and activity in the zebrafish. Further development of this pipeline will include using additional machine learning techniques to identify the more complex micro-behaviors that comprise the broader behavioral states of rest and activity. This pipeline can then be used in future functional imaging experiments to better define the various stages of sleep in zebrafish.

**Revealing Hidden Star Formation and AGN in ESO 148-IG002**

Joahan Castañeda Jaimes

*Mentors: Jeff Rich and Lee Armus*

Ultraluminous infrared galaxies (ULIRGs) are galaxies which emit exceptionally high amounts of infrared radiation. Previous studies with the Spitzer Space Telescope have determined that enhanced star formation activity and active galactic nuclei (AGN) activity are the principle causes of such emission. ULIRGs at  $z < 0.1$  are dust obscured galaxy merger systems or merger remnant systems, making infrared spectral features important probes for

understanding late star formation in galaxies and merger phase gas kinematics. We present the preliminary results of analysis of the mid-infrared spectrum of the low redshift ULIRG, ESO 148-IG002, taken by the medium resolution spectrograph (MRS) aboard the James Webb Space Telescope (JWST) Mid Infrared Instrument (MIRI). JWST integral field spectroscopic observations will allow us to spatially map dust and gas features of ESO 148-IG002 for the first time. We investigate the spatial profile of several coronal lines, molecular hydrogen lines, and polycyclic aromatic hydrocarbon (PAH) features to determine the presence of any AGN-driven gas outflows and previously unresolved star formation regions. This work aims to further our understanding of the infrared emission sources of nearby ULIRGs by further developing gas and dust diagnostics to distinguish between pure starburst effects and AGN driven effects.

### **Understanding the Effects of Underlayer Materials on Dry Electron Beam Resists Through the Use of Monte Carlo Simulations**

David. A. Castillo Lozada

*Mentors: Axel Scherer, Scott Lewis, and Guy De Rose*

The ability to write structures at the nanoscale using lithography underpins all modern society. The electronic devices we take for granted contain integrated circuits, the key component being the field-effect transistors (FETs). They have reduced in size by a factor of two every two years for over fifty years, following "Moore's Law". This size reduction is dependent on the continuous development of materials and techniques that produce better line resolution. The technical program aims to apply a simulation tool called Excalibur to materials and processing problems critical to Applied Materials Inc. The Excalibur simulation suite can model the behavior of electrons and ions in the range of 100 keV to 3.6 eV. This software allows rapid prototyping of the next generation resists for electron beam lithography (EBL) and ion beam lithography (IBL) for the semiconductor industry. Although Excalibur currently does not simulate extreme ultraviolet (EUV) radiation, we propose that it can provide a first-order analysis and prediction of EUV based on e-beam behavior. In this project, we provide evidence that such prediction can be well modeled using the Excalibur tool. We also provide an alternative simulation, which we call Merlin, that aims to be more accurate and faster than its predecessor.

### **Symmetry Reduction and Truncation Techniques in Quantum Spin Systems**

Constantin J. Cedillo-Vayson de Pradenne

*Mentors: Efthimos Kaxiras and Xie Chen*

This research investigates the Heisenberg model on 2D hexagonal lattices through the method of exact diagonalization and group convolutional neural networks, leveraging the symmetries of the model to significantly reduce the computational overhead associated with large-scale quantum many-body systems. In parallel, we implement truncation methods that selectively exclude states that minimally contribute to lowering the system's energy. While this truncation alters the structural integrity of the wavefunction, the energy remains relatively unaffected, owing to the stability granted by the variational principle. However, such approximations introduce subtle distortions in the wavefunction, which manifest in observables that are sensitive to the underlying structure, such as spin-spin correlations. By investigating these correlations, we assess the fidelity of our approximations and ensure that the physical properties of the system are preserved. This combination of symmetry exploitation and state truncation allows us to extend our analysis to larger lattice sizes, offering deeper insights into the behavior of quantum spin systems and the inherent correlations within the Heisenberg model.

### **Earthquake Time-Series Analysis and Synthesis Using Machine Learning**

Cloudly Ceen

*Mentors: Domniki Asimaki and Grigorios Lavrentiadis*

The Generative Adversarial Neural Operator (GANO) is a framework that generates accurate synthetic seismic waves. In this direction, there is a similar framework called Conditional Ground Motion GANO (cGM-GANO) that creates these synthetic seismic waveforms based on various conditional variables. There are a few limitations with cGM-GANO and one of them is not accounting for filtering information which decreases the performance at the very high and low frequencies. This project is aimed toward modifying the framework to only focus on the information lying between the two corner frequencies. At the moment, there exists a shortage of empirical data and methods that either simplify ground motions or are computationally demanding. Our hope is to improve the accuracy of generating seismic waves which can unlock new capabilities in earthquake time-series analysis for researchers and engineering practitioners.

### **Synthesis of DNA Duplexes Containing Formaldehyde Induced Interstrand Crosslink**

Charlotte Chai

*Mentor: Dan Semlow*

DNA interstrand crosslinks (ICLs) are the covalent linkages between two strands of DNA, which significantly hinder DNA replication and transcription. Failure to repair ICLs may lead to bone marrow failure, growth abnormalities, and susceptibility to cancer. ICLs induced by endogenous metabolites, such as acetaldehyde, malondialdehyde, and formaldehyde, are known as endogenous ICLs. Previous research reveals that ICLs are typically repaired by



Fanconi Anemia (FA) pathway. Genetic evidence indicates that the inactivation of the FA pathway and alcohol dehydrogenase 5 (ADH5), an enzyme that detoxifies formaldehyde, results in synergistic synthetic lethal responses, suggesting that reactive formaldehyde in human body produces ICLs. However, whether the activation of the FA pathway is driven by endogenous ICLs remains unclear. In the past, research on the repair pathway of endogenous ICLs was only conducted on repair pathway of acetaldehyde-induced ICLs. To fill in the research gap of unveiling the repair pathway of formaldehyde-induced ICLs, this project involves: (1). use methylenediamine dihydrochloride, or methanediamine, to synthesize a DNA duplex containing ICL that is equivalent to a site-specific formaldehyde-induced ICL; (2). ligate the ICL containing duplex into a p48xLacO plasmid backbone; (3). monitor the repair of the ICL in a *Xenopus* egg extract system, which is a cell-free system that resembles the environment for vertebrate DNA replication, specifically whether the ICL can be repaired by the FA pathway.

### **Self-Organizing Map: A Data-Driven Method to Characterize Redshift Distribution of SPHEREx Photometry**

Jui-Kuan Chan

*Mentors: Olivier Doré and Yun-Ting Cheng*

SPHEREx, the Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer, will conduct the first all-sky near-infrared spectral survey using 102 bands from 0.75 to 5.00  $\mu\text{m}$ . Like other large-scale cosmological surveys, it will probe hundreds of millions of galaxies over a large cosmological volume. To constrain the physics of inflation, a 3-dimensional distribution of galaxies, and thus a precise and unbiased redshift distribution, is necessary. In this work, we use a data-driven approach called a self-organizing map (SOM) to characterize redshift distributions instead of traditional template-fitting codes. This algorithm can not only project high-dimensional data onto a 2-dimensional map but also preserve topological features, making analysis and visualization easier. Although this approach does not yet match the performance of the SPHEREx cosmological pipeline, it provides a potentially alternative method for the redshift estimation that is more data-driven than the current template-fitting approach. Furthermore, by training separate SOMs in the deep-field and all-sky photometry, we explore the possibility of leveraging the high-sensitivity SPHEREx deep-field photometric observations to improve the redshift estimation for the all-sky data.

### **Detecting the Moving Lens Effect in the Bullet Cluster**

Dwaipayyan Chanda

*Mentor: Jack Sayers*

The Moving Lens effect refers to distortions in the temperature of the Cosmic Microwave Background (CMB) radiation when passing through a time-dependent gravitational potential, particularly one which travels transverse to our line of sight. As massive objects, galaxy clusters with transverse velocities produce this effect, but the weak nature of the signal makes it notoriously difficult to detect.

We propose that the Bullet Cluster, a merging galaxy cluster system which travels at high transverse velocities, is an ideal candidate for the first detection of this effect. We have developed a Markov-Chain Monte Carlo (MCMC) fitting formalism to characterize the primary and secondary CMB anisotropies in the Bullet Cluster region using well-determined theoretical models, and we fit for the presence of the predicted moving lens signal using Planck and South Pole Telescope (SPT) data. Finally, we compare our fitted moving lens signal with the predicted moving lens signal in the Bullet Cluster region, the latter of which is obtained via the combination of existing gravitational lensing measurements of the potential and constraints on the transverse velocity from features identified in X-ray emission.

### **Leveraging Transformer Architectures to Learn Biologically Meaningful Cellular Representations**

Aditi Chandrashekar

*Mentors: Mariano Gabitto and Katherine Bouman*

Alzheimer's disease (AD) stands as a leading cause of dementia among the elderly, yet the precise molecular mechanisms driving the disease remain elusive. Single-cell technologies, allowing for detailed transcriptional profiling of individual cells, hold promise for uncovering the cellular and molecular alterations associated with AD. Nonetheless, there is a critical need for advanced computational approaches that effectively use single-cell data to explore AD at a cellular level. Variational Autoencoders (VAEs), capable of learning rich cellular representations from diverse data types, have been applied to the analysis of single-cell data sets for such annotation tasks (e.g., SCVI, MultiVI). Large Language Models, leveraging transformer neural network architectures, offer exceptional generalization capabilities across a variety of downstream tasks and datasets. In this study, we present VAEs that harness the power of transformer architectures to improve latent embedding learning and generalization capabilities in out-of-distribution data, demonstrating improved performance across various downstream tasks. By combining two prominent machine learning frameworks, we advance the analysis of single-cell AD datasets and facilitate the identification of relevant cellular populations impacted by AD.

### Exploration of Change Detection in the Periphery

Jacob Chang

*Mentors: Shin Shimojo, Matilda Cederblad, and Daw-An Wu*

Detecting change is an essential ability for survival. Humans use the detection of change within their vision, to aid decision-making and other important day-to-day processes. The resolution of human vision varies drastically across the visual field, separated into the fovea, the periphery, and the extreme periphery. Past research indicates that visual processing in the periphery and extreme periphery is not as straightforward as in the fovea. Utilizing a dataset of complex images, we create changes in these images that include the inclusion or exclusion of an object, or a change in color of an object. These changes happen at different eccentricities and saliency points. We utilize these stimuli with control stimuli in an experiment where the unchanged and changed images are displayed to participants in two transition methods: multi-shot and morph. In multi-shot, the stimuli flicker between the unchanged and changed image. In morph, the stimuli fade from the unchanged to the changed image. Building from this base, we have different versions of the experiment where we display the stimuli at varying eccentricities and sizes. Through analyzing the observations of participants and quantitative data such as reaction time, we hope to find conclusions to direct future research in change detection.

### Unveiling the Sulfation Code: Using Machine Learning to Uncover Glycosaminoglycan-Protein Interactions

Ardra Charath

*Mentors: Linda Hsieh-Wilson, Alex Sorum, and Hailan Yu*

Glycosaminoglycans (GAGs) are complex, linear polysaccharides that play a critical role in various biological processes, such as Alzheimer's progression, embryonic development, cancer metastasis, and pathogenic infections. We focus on heparan sulfate (HS)—a versatile and complex member of the GAG family known to interact with over 500 proteins. These interactions are highly specific and motif-dependent. The immense structural diversity and complexity of HS present significant challenges in isolating or synthesizing structurally defined poly- and oligosaccharides, impeding the understanding of their structure-activity relationships with proteins, which is crucial for advancing knowledge of their biological roles in health and disease.

Leveraging machine learning techniques, we developed an algorithm to predict the strength of heparan sulfate and protein binding based on gradient boosting and random forests, achieving an accuracy of 95.8% for the protein FGF2. Additionally, we constructed a comprehensive model to reveal the dependencies and importance of various factors contributing to a high protein binding score, employing hidden Markov models, interpolated Markov models, and neural networks to gain deeper insights into the binding mechanisms. Our research will enhance the understanding of molecular recognition processes and potentially lead to novel therapeutic strategies targeting GAG-protein interactions.

### CRISPR-Associated Transposase Expression and Detection in *Nicotiana benthamiana*

Paulina Chavira

*Mentors: Gözde Demirer and Kimberley Tanatswa Muchenje*

The CRISPR-Cas9 system has been widely utilized for targeted insertion of advantageous genes into plant genomes to address global climate change and the need to feed a growing population. However, its applications are limited by its reliance on the infrequent homology directed repair (HDR) system in non-dividing cells to mend generated double stranded breaks (DSB). Recently, CRISPR-associated transposases (CASTs) were identified in *Vibrio Cholerae* (VchCAST) and *Pseudoalteromonas* (PseCAST) and other bacterial species. CAST systems consist of Tn7-like DNA transposons that have co-opted the CRISPR RNA-guided (CASCADE). Vch and PseCAST systems achieve RNA guided transposition through a cut and paste mechanism allowing for targeted DNA insertion events without DSB creation or reliance on the HDR pathway. Our overall goal is to engineer CAST systems as a more efficient genome insertion tool in plants. As a part of this work, I am optimizing the expression and detection of CAST transposase proteins, TnsA and TnsB from the Vch and PseCAST systems in the model plant *Nicotiana benthamiana*. We are also working towards expressing all CAST proteins in *N. benthamiana* from a single plasmid to reconstitute CAST-mediated integration with diverse strong promoters and terminators. Our ongoing efforts are to optimize CASTs as a safe and efficient tool for widespread application in generating elite crops varieties.

### The Effect of Spatial Attention Allocation on Acuity in the Lower Visual Field

Ashley Chen

*Mentors: Shinsuke Shimojo and Matilda Cederblad*

Although the central visual field is considered the most vital aspect of our vision, clinical findings suggest the periphery also contributes significantly to visual information. Previous studies on the vertical periphery have proven that the lower visual field is more sensitive to details. When older populations stumble, it is usually due to the inability to detect obstacles in their lower visual field. The objective of this study is to investigate how the detection of stimuli in the lower visual field is affected by different spatial attention allocation conditions using two unimodal visual experiments. While maintaining their fixation in their central vision, participants in Experiment 1 are asked

to allocate their spatial attention to their lower visual field as a flashing stimulus will travel only in that area. In Experiment 2, the participant is told to allocate their spatial attention to their full vertical visual field as stimuli will flash in both the upper and lower visual field. The expected result is that allocating spatial attention to a larger area may hinder the ability to detect stimuli in the lower visual field. Understanding this phenomenon could lead to valuable aid devices to help older populations detect obstacles on the ground.

### **Super-High-Temperature Abrasion of High-Performance Fabrics for Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS)**

Belle Chen

*Mentors: Soon-Jo Chung and Lily Coffin*

The NASA Artemis mission aims to establish a permanent lunar settlement, necessitating frequent deliveries of personnel, materials, and other critical supplies to the lunar surface. However, rocket takeoffs and landings generate massively energetic plumes that disturb large quantities of lunar regolith with the potential to damage infrastructure and risk human health. To remedy this, we have proposed the Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS): a hollowed-out torus made of an inflatable, durable, heat-resistant fabric which aims to passively inflate and contain dust disturbed by lunar launches and landings. Materials selection and lifetime analyses are key components to guarantee the success and efficacy of PILLARS. Here, we design and construct a tribological system to abrade candidate materials at temperatures of up to 900 °C. Abraded samples are analyzed with 3D optical microscopy to estimate wear-loss performance and subjugated to ultimate strength and cyclic fatigue testing to estimate lifetime and performance. A recommendation is made among candidate materials and for future study. Additional analyses related to the performance of PILLARS as a standalone system and against other dust-mitigation options were also conducted.

### **Enabling the Synthesis of Spirocyclic Lactams via Machine Learning-Guided Reaction Development**

Difei Chen

*Mentors: Brian M. Stoltz and Melissa Ramirez*

This research involves the use of machine learning and high throughput experimentation to develop an enantioselective intramolecular Ni-catalyzed cyclization of lactams that generates spirocyclic scaffolds bearing a new quaternary carbon center and seven-membered ring. Our approach to reaction development involves the application of machine learning to predict combinations of five parameters (i.e., chiral ligand, aryl halide, solvent, temperature, reaction time) that provide high reaction yield and enantioselectivity. Our research group at Caltech (Stoltz laboratory) is testing machine learning predictions using high throughput experimentation and a model substrate, which I have focused on synthesizing. The laboratories of Gabe Gomes and Oles Isayev in the Department of Chemistry at Carnegie Mellon University are providing machine learning expertise on this project. Ongoing optimization studies involve the use of an automated liquid handling system and analytical instrumentation available in the Caltech Catalysis Center. Experiments will continue to be carried forward by my postdoc mentor, Melissa Ramirez, following my completion of my summer research experience.

### **Automatically Raising Mathematical Conjectures Without Expert Knowledge**

Jiacheng Chen

*Mentors: Yisong Yue and Kaiyu Yang*

Current research on mathematical reasoning via machine learning methods mainly focus on the forward reasoning process. That is, given a theorem, the goal of a reasoning agent is to derive a forward reasoning path that can lead to the proof-finished status. However, in our work, we mainly focus on how to raise novel mathematical conjectures and currently restrict the domain into inequality problems. For doing this, we developed a domain specific proving assistant for machines to learn elementary math and designed a machine learning based agent to derive new conjectures in an open-ended manner. Moreover, we develop an evaluating system to automatically measure the usefulness, novelty and interestingness of our generated conjectures, guiding the generating process. Finally, we further constructed a synthetic dataset which contains our derived conjectures and extracted proof step, then applied this dataset to train a forward-reasoning prover that achieve great performance inversely.

### **Improving Annealed Sub-trajectory Samplers**

Junhua Chen

*Mentors: Anima Anandkumar and Julius Berner*

Diffusion based strategies are becoming increasingly popular and studied for sampling from an unnormalized density. The core idea is to consider a diffusion process transporting the intractable data distribution to a tractable Gaussian, and then learning the time reversal of this process, using which we can then draw approximate samples from the target distribution. While often managing to achieve state of the art sample quality, Diffusion Samplers also frequently suffer from issues like mode forgetting/collapse and requiring large numbers of target evaluations to reach acceptable performance. With these limitations in mind, and based on the Controlled Monte Carlo Diffusions (CMCD) algorithm, we introduce a novel end-to-end trained particle-based sampling procedure. Moreover, we introduce the use of prioritized replay buffers to further improve training performance and sample

efficiency. These improvements culminate in our new Sequential Controlled Langevin Diffusions (SCLD) sampling framework, which show improved sample quality as well as computational speed on a wide range of density benchmarks.

### **Using Simulations to Investigate Earthquake Fault Rupture With Complex Geometry and High Normal Stress**

Kyle Chen

*Mentors: Jean-Philippe Avouac and Kyungjae Im*

Earthquakes, among the most destructive natural events, occur when energy is suddenly released in the Earth's crust due to fault movement. These faults, often not smooth but instead featuring bends and irregularities, can lead to complex patterns of their seismic activities. While much data on fault topology has been collected in laboratory and field studies, it has not yet been thoroughly analyzed. This project employs novel computer simulations to investigate the dynamics of fault sliding with a focus on the geometric complexities of faults. Using the newly developed Quake-DFN earthquake simulator, we explore the mechanisms underpinning epicenter location and slip variations. Specifically, we model earthquake sequences within a 3-D Discrete Fault Network based on rate and state friction principles. Using the 2019 Ridgecrest earthquake, the largest earthquake to hit Southern California in 20 years, as a model system, we simulate earthquake ruptures and aim to understand crustal deformation dynamics. Our results can help improve both the fundamental understanding of fault movement and also earthquake emergency preparedness. This study offers insights into the relationship between earthquake magnitude and fault zone complexity, spanning both scientific research and practical applications.

### **The Biology Mechanisms Behind Rational Inattention: Bridging Inferred Information Costs and Cognitive Workload**

Yen-Shan Chen

*Mentors: Colin Camerer and Zhenlin Kang*

Rational inattention (RI) theory suggests that people have limited attention spans and tend to selectively allocate mental effort to higher-priority tasks. Intuitively, individuals optimize the trade-off between the cost of acquiring information and the advantage more information can bring to decision-making. However, validating this theory is challenging due to difficulties in quantifying information acquisition costs. In this study, we address this gap by investigating the relationship between information costs and biological measures of cognitive workload, using eye-tracking (ET) and pupillometry (PDR) as indicators. Participants perform the Multiple Object Tracking (MOT) task under varying difficulty levels and incentive structures and their information costs are estimated through performances using the recovery theorem in RI theory. These costs are then correlated with ET and PDR data to determine how they reflect cognitive effort. Preliminary results indicate that increased task difficulty decreases accuracy and lowers inferred estimation costs, suggesting that when tasks become more challenging, participants have less incentive to exert full effort as their efforts do not guarantee substantial rewards. This research is significant in validating RI theories and elucidating the relationship between information costs and biological measures of cognitive workload, inspiring broader research into decision-making, attention spans, task prioritization, multitasking, and more.

### **Thermal Transport of Interlayer Excitons in a Magnetic Field**

Abhiram Cherukupalli

*Mentors: Gil Refael and Valerio Peri*

The thermal Hall effect, an analog of the classical Hall effect, involves the deflection of heat flow perpendicular to a temperature gradient when a magnetic field is applied. This phenomenon is well-understood in metals as a realization of the Lorentz force. However, its manifestation in insulators, where heat carriers are neutral, is fascinating, as any transverse current must be attributed to the topology of the underlying bands. This study explores the possibility of a thermal Hall effect with interlayer excitons—neutral electron-hole pairs bound by Coulomb interaction—as the heat carriers. By carefully considering the internal structure of the exciton, we aim to identify the conditions under which a transverse thermal current may emerge as a result of the Berry curvature of the excitonic bands.

### **Coupled Oscillatory Recurrent Neural Network: Modeling River Basins With Machine Learning**

Andrew Chiang

*Mentors: Tapio Schneider, Oliver Dunbar, and Katherine Deck*

The Coupled Oscillatory Recurrent Neural Network (coRNN) is a novel machine learning (ML) architecture based on a time-discretization of a system of second-order ordinary differential equations which can mitigate the exploding and vanishing gradient problem found in RNNs. The Climate Modeling Alliance (CliMA) aims to build an Earth System Model (ESM) capable of providing accurate and actionable scientific information to face Climate Change. This project aims to utilize the coRNN's ability to process complex sequential data to predict river stream flows from dynamic inputs (runoff) and static attributes. Hyperparameter turning, introducing nonlinear relationships, and increasing model flexibility were all used to optimize the coRNN's performance. The coRNN produced slightly

worse results than CliMA's long short-term memory (LSTM) model but did so with less than half the number of parameters

### **Constructing a Static Reflectance Spectroscopy Setup for the Investigation of Excitons in NiPS3**

Alexander Ching

*Mentors: David Hsieh and Vivek Pareek*

Van der Waals (vdw) materials have recently emerged as a versatile platform to study various interesting phenomena in solid state physics. A few examples of van der Waals materials include graphene, two dimensional semiconductors such as transition metal dichalcogenides, and magnetic insulators such as transition metal Phosphorus Trisulfide (e.g. NiPS3). NiPS3 is an antiferromagnetic material with interesting Coulomb bound electron-hole states called excitons that couple strongly to the magnetic ordering. In this project, we built a static reflectance spectroscopy setup with the goal to study the emergence of these excitons within NiPS3 as a function of temperature. This compact spectroscopy setup is all contained within an 18x18 inch breadboard with a tungsten halogen lamp as the light source and a home-built spectrometer to resolve the spectroscopic features in the visible to near IR range (400 – 1100 nm). The design of the setup also allows us to perform transmittance spectroscopy on thin film samples. We tested the setup by acquiring preliminary data on n-doped Gallium Arsenide (GaAs) and compared with other existing literature.

### **Deployment Design and Testing for Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS)**

Marie Choi-Schattle

*Mentors: Soon-Jo Chung and Lily Coffin*

PILLARS is an torus-shaped inflatable shield designed to protect the planned Artemis lunar base from abrasive regolith that is propelled by the force of a rocket plume during launch or landing. This system must be validated at Technology Readiness Level (TRL) 5, which requires testing in a relevant environment. Several protocols essential to the successful deployment of PILLARS were conceptualized and tested, such as unrolling, anchoring, and inflation. Methods used included experimentation using a custom-built test stand and simulation of anchoring in the lunar regolith in LPILE. Additionally, an anchoring and data acquisition system will be designed and implemented to determine the forces on PILLARS during a small-scale test with a rocket plume, which will provide valuable information regarding the loads PILLARS will have to withstand in the lunar environment.

### **Investigating the Detection of Asteroids in the Earth-Moon System**

Maleque Chouayekh

*Mentor: Michael E. Brown*

In 1772, Joseph-Louis Lagrange identified five specific equilibrium points within the context of the restricted circular three-body problem. At these points, termed Lagrange points, a particle of negligible mass can maintain a stable configuration relative to two larger bodies in constant circular rotation. Of these three points, designated as L1, L2, and L3, align along the line connecting the centers of the two larger masses. These collinear points are inherently unstable within the gravitational potential field, implying that any small perturbation results in the particle deviating from its equilibrium position. Conversely, the remaining points L4 and L5, which are defined as the Trojan points, are stable, lying within the orbital plane of the larger bodies and equidistant from them, effectively mirroring their separation. Notably, the L4 and L5 points in the Sun-Jupiter system host over 2,000 asteroids but no asteroid has been captured in the Earth-Moon system. We present in this project a novel methodology to investigate the mechanisms that could lead to the capture of asteroids into temporarily stable orbits in the Earth-Moon system.

### **Magnesite and Phyllosilicate Field Relations Developed During Alteration of Two Alluvial-lacustrine Sedimentary Analogs for Mars Deposits**

Maddy Christensen

*Mentor: Ted Present*

The solutions that form Mg-carbonate minerals in sedimentary systems can dissolve silicate minerals, producing mineralogically pure nodules, alteration rims, and veins in alluvial and lacustrine deposits on Earth and Mars. Elements released by silicate dissolution may reprecipitate as neoformed phyllosilicate minerals. These phyllosilicates often form elsewhere than the carbonates, requiring integrated studies across deposit scales to balance geochemical budgets. Here, we investigated the field-scale variability in carbonate and clay mineral assemblages with X-ray diffraction measurements in two terrestrial sedimentary magnesite deposits that share some mineralogical and field relation characteristics with Martian deposits.

In Queensland, Australia, Mg-rich groundwater ascends through unlithified alluvial sands, dissolving detrital silicates and producing magnesite nodules. Magnesite-bearing sands contain neoformed palygorskite and smectite-rich randomly ordered mixed layer illite-smectite clays. These sands are capped by up to 10 m-thick trioctahedral smectite soil dominated by the mixed layer clays and containing accessory authigenic quartz, iron/manganese

oxides, talc, and dolomite. The mineral distribution records the interactions between groundwater, soil water, and surface water: as the groundwater ascends, the activity of aqueous Mg decreases, pH decreases, and the activity of aqueous species derived from dissolution of detrital silicate minerals increases upwards due to the increasing influence of soil water and precipitation of magnesite. In comparison, the eastern Mojave Desert, USA hosts magnesite that formed in association with alluvial-lacustrine dolomite, jasper, shales, and intermediate volcanic rocks in a small extensional Tertiary basin. Here, both syndepositional hydrothermal processes and syntectonic metasomatic processes may control the distributions of Mg-carbonate and phyllosilicate minerals.

These two sites provide insight into how diagenetic and low-grade metamorphic processes produce the observed spatial distributions of carbonate and clay minerals in sedimentary deposits. On Mars, rover-scale field observations of carbonate and clay mineral distributions are necessary to understand geochemical budgets in sedimentary systems.

**Electrochemical Characterization of Na-MnPS<sub>3</sub> Framework for Applications in Next-Generation Batteries**

Po-Jui Chu

*Mentor: Kimberly See*

Next-generation batteries beyond lithium ion promise to reduce production costs and environmental concerns, and solid-state batteries in particular will improve battery safety and volumetric energy densities. However, sluggish conduction in post-lithium solid-state electrolytes has hindered the development of their all-solid-state batteries. Previous work from our group found that MPS<sub>3</sub> frameworks ( $M = \text{Cd, Mn}$ ) exhibit ionic conductivity between  $10^{-3}$  to  $10^{-4}$  S/cm for various solvated cations. This study focused on the Na-MnPS<sub>3</sub> material, addressing its detrimental reaction with the Na metal anode by inserting a Na<sub>3</sub>Zr<sub>2</sub>Si<sub>2</sub>PO<sub>12</sub> (NZSP) protective layer. Linear sweep voltammetry (LSV), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX) of samples after voltammetry demonstrated that the NZSP layer effectively decreased undesired side reactions and facilitated uniform sodium plating. Future work will involve symmetric cells and full-cell cycling Na|NZSP|Na-MnPS<sub>3</sub>|NaFe[Fe(CN)<sub>6</sub>] $\cdot$ nH<sub>2</sub>O to evaluate the practicality of Na-MnPS<sub>3</sub> as a solid-state electrolyte, with potential expansion to other cation systems.

**Optimizing Firing of Laser Printed and Reaction Bonded Alumina-Based Ceramics**

Audrey Chyung

*Mentors: Katherine Faber and Zachary Ahmad*

Alumina (aluminum oxide) ceramics have many industrial applications but are difficult to additively manufacture with net shape geometries. The Faber group is developing a processing method in which aluminum and alumina composites are printed via laser powder bed fusion, then fired to convert aluminum to alumina (reaction bonding) and to fuse particles (sintering), which densifies the bulk sample and mitigates thermal shock. Until now, firing temperature profile alterations have remained unexplored. Optimizing the firing procedure offers avenues to eliminate the possibility of molten aluminum leaching from the system, which would enhance the density of the samples. While increasing the ramp rate may reduce leaching, it could introduce cracking and incomplete reaction bonding. Additional isothermal holds may counteract these negative effects. To test this, samples are fired with an increased ramp rate and isothermal holds of varied temperature and time. Then, Archimedes' method, X-ray diffraction, and scanning electron microscopy are used to assess density and successful reaction bonding and sintering. Initial results suggest that holds at 450°C, 600°C, and 1100°C prevent cracking, leaching, and incomplete reaction bonding. If negative effects are minimized, increasing ramp rate may not only improve density, but also significantly decrease the time and energy costs of firing.

**Analysis of Simulations for Quasiparticle Physics in Thin Film Superconducting Detectors**

Thomas Cleveland

*Mentors: Sunil Golwala and Karthik Ramanathan*

The need to explain dark matter has led to the evolution of more precise particle detectors in the sub-kV range. With the advent of novel Kinetic Inductance Detectors (KIDs), there is now the job of predicting their behavior under standard physics. Geant4, G4CMP, and previous works have already developed tools to simulate KIDs. This however has not yet been connected to the real measurements produced by the hardware. This work composes the work beforehand and—by developing analysis tools for these simulations—we produce the expected measurements we would see under standard physics. In a future work, we hope to use these results to analyze the results of an 80-KID array in the search for WIMPs.

**Metabolic Profiling of the Early Murine Embryo: A Mass Spectrometry and Stem Cell Model Approach**

Chad Coen

*Mentors: Magdalena Żernicka-Goetz and Sergi Junyent Espinosa*

The role of metabolism in deciding cell fate has been previously studied in pluripotent stem cells, although its role in embryogenesis remains less understood. Embryonic stem cells (ESCs) cultured in 2D have been used as proxies of development in vitro, but they are not greatly representative of the in vivo environment as they are derived from pre- and post-implantation epiblasts. Thus, the metabolic landscape of pre-implantation embryonic cells is not yet known. Quantifying metabolites from cells is historically done using mass spectrometry which requires a great number of cells, presenting a unique challenge as the blastocyst is comprised of a small number of differentiated cells. To solve this issue we generated and optimized synthetic blastoids that closely resemble the blastocyst and have similar ratios of the blastocyst's 3 cell types: primitive endoderm (PrE), epiblast (EPI), and trophectoderm (TE). We also generated morula-like-cells (MLCs) from ESCs through use of the transgene GY118F, and then differentiated them into homogenous populations of PrE, EPI, and TE. Mass spectrometry was then used to quantify key metabolites and characterize the metabolic profile of not only the blastocyst as a whole, but also each of the individual cell subtypes present in a pre-implantation embryo.

**Verification and Validation of Inflatable Lunar Rocket Landing Infrastructure**

Lily Coffin

*Mentor: Soon Jo Chung*

The Plume-deployed Inflatable for Landing and Launching Abrasive Regolith Shielding is a low size, weight and power alternative to conventional landing pad solutions, which aim to prevent damage to the Artemis lunar base caused by regolith ejected by Lunar rockets. To reach technology readiness level 5, I designed a verification and validation protocol, traced to defined system requirements. Rocket plume-structure interaction was simulated in ANSYS Fluent and ANSYS LS-DYNA in both Lunar and Earth environments to understand the pressure and temperature of the impinging plume and to extrapolate Earth tests to a Lunar PILLARS. The expansion of the plume in vacuum was characterized experimentally to validate simulation results. Lifecycle testing of candidate materials was conducted to determine the degradation of tensile strength after cyclical abrasion and heating. Finally, a "dirty" vacuum chamber with Lunar regolith simulant was constructed to validate the dust shielding capability of the structure. Analysis and testing have shown that the PILLARS system is a compelling alternative to a more massive Lunar landing pad.

**Design and Optimization of a Photon Counting Detection Apparatus for Geotropic Fluctuations in Spacetime**

Rafael Crespo

*Mentor: Lee P. McCuller*

The pursuit of detecting geotropic fluctuations in the metric of spacetime has led to the development of an advanced photon counting apparatus designed to enhance sensitivity and distinguish the desired signals from background noise. The new apparatus leverages an atomic cavity, incorporating a laser-cooled cloud of Rubidium atoms within a 4-mirror setup. This configuration, featuring two curved mirrors and two flat mirrors, aims to minimize signal loss and optimize the filtering effect of incoming photons. By modeling various cavity designs using Finesse-3 on Python, the beam profile was refined to achieve a minimized waist, which is crucial for increasing the probability of photon-atom interactions. The simulation revealed that adjusting the angle of the curved mirrors effectively reduced the beam size, with an optimal minimum angle of  $6.34^\circ$  determined to avoid clipping. This advancement represents a significant step toward improving detection sensitivity for quantum gravity research and sets the stage for future exploration of more complex cavity geometries.

**Antimicrobial Efficiency of Locally Enhanced Electric Field Treatment and Copper (LEEFT-Cu) for Water Disinfection of Gram Positive and Gram Negative Bacteria**

Alex Crowley

*Mentors: Jared Leadbetter, Xing Xie, and Mourin Jarin*

Locally Enhanced Electric Field Treatment (LEEFT) is an emerging technology that employs electric fields to inactivate harmful bacteria in water. Compared to traditional chlorine based disinfection, LEEFT allows for water disinfection at low energy costs and prevents the formation of harmful byproducts (DBPs). Furthermore, when combined with copper, a material recognized for its antimicrobial properties, LEEFT-Cu has demonstrated increased bacteria inactivation efficiency. By suspending each species in solution and running it through the LEEFT-Cu reactor, we have demonstrated the effectiveness of LEEFT-Cu across a wide range of bacteria species that reside and are found in different environments. Bacteria with different growth conditions were used and multiple growth phases were tested for each to ensure results represent LEEFT-Cu's ability to inactivate pathogens in any environment at any point in their lifecycle. The inactivation was measured through the standard plate count method and the copper release was measured using an Atomic Adsorption Spectrometer. We primarily focused on the effectiveness of LEEFT-Cu against gram-positive vs gram-negative bacteria as their contrasting

membrane structures reflected in different inactivation results. This research fills a significant knowledge gap for further understanding the capabilities of LEEFT-Cu for application in water disinfection.

**Applying Click-Electron Microscopy to Examine ANME-SRB Consortia**

Abigail Curtis

*Mentors: Victoria Orphan and Daniel Utter*

Anaerobic methanotrophic (ANME) archaea and sulfate reducing bacteria (SRB) are symbionts found in deep sea methane seeps. They are thought to play a large role in the anaerobic oxidation of methane (AOM), which in turn helps regulate oceanic release of carbon into the atmosphere. Understanding ANME-SRB consortia is integral to conceiving the unique homeostasis of deep sea, anaerobic environments. Many questions about ANME-SRB's physical and nutritional interdependencies remain. Click-electron microscopy (Click-EM) is a burgeoning technique synthesizing click chemistry, which utilizes non-protein biomolecule analogs with an azide or alkyne moiety and Diels-Alder chemistry to fluorescently label incorporated analogs, and electron microscopy (EM), by using chemically altered dyes that produce singlet oxygen, discernable in EM when photooxidized and stained. In turn, this results in fluorescence and EM images that can be used to probe the spatial relationship between labelled cellular components and organisms.

Here, an application of Click-EM techniques to image vesicle formation and transport using a clickable glycerol analog in *Methanosarcina* (MA), a archaeon similar to archaea found in ANME-SRB consortia, is presented, with results providing precedent for future applications in ANME-SRB rich sediments. Additionally, the potential comparative advantage between using analogs with alkyne or azide moieties within sulfur-rich, anaerobic environments is examined, and recommendations for optimization of the Click-EM protocol for its application to non-pure culture samples are developed.

**Improving the Sensitivity and Thermostability of iNicSnFR12 Through Consensus Design**

Sophie Dalfonzo

*Mentors: Steve Mayo and Nick Friesenhahn*

The nicotine-sensing protein iNicSnFR12 consists of a periplasmic binding protein (PBP) engineered for nicotine specificity and a green fluorescent protein (GFP), fused in such a way that when nicotine binds the PBP, the GFP will fluoresce. Two design goals for this protein are to increase its sensitivity to low nicotine concentrations and to increase its thermostability. In this study, we used consensus design to address these goals: using a large dataset of similar proteins, we identified 22 residues that appear to be positively selected for during evolution, and thus likely to play an important role in function and stability. We constructed variants of iNicSnFR12, each with a mutation at one of these positions where the residue was changed to the most common amino acid at that position in the dataset. We screened these variants for nicotine-sensing activity and purified promising variants, including H68T, W343Y, V18L, I420L, N428G, and W436Y. We then tested them for nicotine sensitivity via dose-response experiments and for thermostability via differential scanning fluorimetry. Further replicates are needed to establish consistency in these results and determine whether these variants improve upon the current iNicSnFR12 design.

**Mice in Manhattan Maze: Navigation and Rapid-learning Without a Cortex**

Anwasha Das

*Mentors: Markus Meister and Jieyu Zheng*

In humans, the interplay of the neocortex and hippocampus is vital for forming and retaining memories. Whether these structures are crucial in rodents is taken for granted. To explore the role of these structures in navigation and spatial learning, acortical mice — structural mutants born without a neocortex and hippocampus — are placed in a novel 3D 11x11 reconfigurable maze. Over two days, the mice learn three new maps. While 3x slower than their wildtype counterparts, surprisingly, the acortical mice learned multiple maps and solved them even after 2 months. This suggests a neocortex and hippocampus-independent model of learning in rodents.

Data was collected from four additional acortical mice that demonstrated learning of multiple maps over the long term. Additionally, a double-home cage experiment was designed to test the role of home cage odor in navigation behavior. Six wild-type and two acortical mice were tested on the two-day protocol. As we prepare to collect neural recordings to gain further insight, the remaining SURF period will be spent designing a new maze and piloting experiments.

**Introducing Time Evolution Into a Parameterised YSO Accretion Disk Model and Predicting Changes in Observational Signatures**

Gautam Das

*Mentors: Lynne Hillenbrand and Adolfo Carvalho*

Young Stellar Objects (YSOs) are known to undergo a sudden rise in luminosity by a few orders of magnitude over time scales of a few months, followed by decay on decadal timescales. Modelling the lightcurves of these objects is crucial to understanding how different components of these systems evolve during outburst. For this purpose we



are using a simple parameterised model called YSOpy which couples an irradiated dust disk, viscously heated gas disk, magnetospheric accretion shocks, and stellar photospheric emission. We develop a pipeline to reproduce lightcurves for outbursting objects and aimed at determining accretion rate variation with time. We used this pipeline for sources like Gaia17bpi, HBC722, V960Mon to understand how the observational signatures evolve with time. This provides important insights into the disk-magnetospheric interactions throughout the cycle by enabling us to predict which parts of the model can best be observed at each point of the outburst cycle.

### **Machine Learning Analysis of Helium-3 Rich Solar Energetic Particle Events Using ACE/SIS Data in the Context of Recent Observations**

Soham Dasgupta

*Mentors: Allan Labrador and Ashish Mahabal*

This goal of this study is to address the challenge of identifying Helium-3 (He-3) rich periods during Solar Energetic Particle (SEP) events, using data from the Advanced Composition Explorer's Solar Isotope Spectrometer (ACE/SIS) from 2017 to 2024. Utilizing a novel approach that combines supervised neural networks and unsupervised K-means clustering, we aim to improve the accuracy and reliability of detecting these helium 3 rich events. The research initially focuses on ACE/SIS data due to its relevance and accessibility, but the methods are designed to be applicable to other datasets, such as those from STEREO and the Parker Solar Probe, facilitating broader validation and comparative studies. By integrating these advanced machine learning techniques, we not only aim to enhance the identification of He-3 rich periods but also contribute to a deeper understanding of the solar phenomena influencing the environment. Ultimately, this approach is expected to provide a foundation for integrating insights across multiple spacecraft measurements, offering a comprehensive perspective on SEP events and their implications for space weather forecasting.

### **Mechanism Behind NAC Multitasking in Protein Biogenesis**

Pratiman De

*Mentors: Shu-ou Shan and Radoslaw J. Gora*

Protein biogenesis involves the maturation of nascent chains (NCs) into functional proteins through proper folding and translocation to cellular locations such as the endoplasmic reticulum (ER) or mitochondria. Ribosome-associated protein biogenesis (RPB) factors guide NCs to their cellular destinations and protect them from misfolding and aggregation. However, it's not completely understood how RNCs recruit the correct set of RPBs and how multiple RPBs coordinate with each other in the crowded space near the ribosome tunnel exit. Previous studies have established that nascent-polypeptide-associated complex (NAC) acts as a gatekeeper of the ribosome exit tunnel that recruits appropriate RPBs (e.g., SRP) that then direct elongating polypeptides into their correct biogenesis pathway, adding yet additional layer of complexity to the maturation process. It appears that one mechanism by which NAC steers these complex interactions is through the recognition of specific sequences on the nascent chains. Preliminary results indicate that these sequences might appear at the beginning of the new domain sequences. Here, using the single-molecule FRET technique, we're trying to understand how NAC exhibits varying affinities for different lengths of human cytonuclear protein, hRPL4, and if there indeed are any specific sequences within those proteins to which NAC preferentially binds.

### **Random Surfaces, Non-Commutative Tori and Their Spectral Geometry**

Vinicius de Alcantara Nevoa

*Mentor: Matilde Marcolli*

Inspired by known relations between partition sums of random stepped surfaces and localization sums of algebraic-geometric invariants, the present work employs non-commutative differential geometry to characterize a certain "quantum" line bundle  $\mathcal{Q}$  that refines the saddle point of a (classical) random surfaces over a graph. This line bundle is realized as the kernel of an operator constructed from the non-commutative 3-torus algebra  $\mathcal{A}_\theta$ , and upon completing it into a self-adjoint operator  $D$  on an appropriate Hilbert space, we compute the Fredholm index of different projectors in  $K_0(\mathcal{A}_\theta)$  corresponding to twistings of the original spectral triple. These indices are related to the Hilbert polynomial of  $\mathcal{Q}$ , understood as a linearization of its geometry, and thus help characterize this quantum line bundle beyond its usual commutative aspects. Moreover, the zeta function associated to this spectral triple is closely related to the index, and its significance is discussed. Future directions include relating the present work to mirror symmetric aspects of  $\mathcal{Q}$  and conjectures therein, which entails discussing the appropriate commutative limit of the results obtained.

### **Computer Vision for Airborne Imaging of Antarctica: Creating a 75-year Record of Surface Change**

Sani Deshmukh

*Mentors: Jay Dickson and Bethany Ehlmann*

Airborne imaging of Antarctica exists dating back to 1947, but the data are not registered to the surface, preventing efficient comparisons between the surface 75 years ago and today. This project examines the efficacy of various contemporary Computer Vision (CV) algorithms—namely SIFT, AKAZE, KAZE, SURF, and ORB—in

registering high-resolution (<10 m/pixel) time-series airborne imagery to cartographically accurate elevation models. To address this, we employed an iterative feature-matching approach that aligns simulated terrains generated from a high-resolution Antarctic elevation model (REMA) with aerial images, enhancing the precision of feature matching by cumulatively retaining accurate matches and discarding outliers. Matching aerial images with an elevation model involved fine-tuning CV algorithm parameters, refining outlier detection techniques, and optimizing iteration and matching processes for matching on inconsistent shadows while disregarding the snow and debris outcrops. Our findings indicate that the SIFT and AKAZE algorithms demonstrate superior performance in matching aerial images, particularly when these images are similarly oriented relative to a larger base map elevation model. These results represent a successful proof-of-concept that will allow accurate georeferencing of historic overflight imagery and extend the temporal analysis of Antarctic surface changes from a few decades to nearly a century.

### **X-Ray Reflection Spectroscopy in Thick Accretion Disks**

Indie Desiderio-Sloane

*Mentors: Fiona Harrison and Joanna Piotrowska*

In this project, we study the influence of assumed disk geometry on the resulting X-ray spectra of the accretion disks of black holes. To this end, we conduct a thorough comparison of different disk geometry models to draw meaningful conclusions about the physical properties of the systems challenging current X-ray reflection models. We are using the RELXILL (a razor thin disk model) and FENRIR (a model with pressure-supported disk height) models. For these models, we test the influence of disc geometry on a set of different scenarios for the illumination source in the black hole-accretion disc systems. We analyze the models through statistical comparisons across the whole parameter distributions. We are finding significant similarity (where the difference between the models was no greater than 5% at any time) between the models for different parameter sets. These findings advocate against using the razor-thin disk assumption for modelling X-ray reflection spectroscopic signal in accreting black hole systems.

### **Bridging the Stars: Gamified Learning for Astronomy Enthusiasts**

Naman Dharmani

*Mentors: Ashish Mahabal and Theophile Jegou du Laz*

The primary objective of this project is to extend the current Android app, ZARTH (ZTF Augmented Reality Transient Hunter), to other platforms such as iOS and desktop, allowing more enthusiasts to learn about astronomical transients interactively. The methodology involves developing a Progressive Web App (PWA) using modern web technologies to target these platforms with a single codebase while also supporting device-native features and experiences. The development process included transforming an outdated library (VirtualSky.js) designed for displaying night skies by adding layers for transient objects and interactive functionality supported by a backend database. The app successfully combines educational content with various gamified add-ons and experiences to make complex scientific information accessible. In the future, it can be further extended to desktop and tablet devices and expand its educational content. This project illustrates the potential of gamification in making scientific learning enjoyable and effective for everyone.

### **Shock Simulations in Euler Equations Using Neural Operators**

Reva Dhillon

*Mentors: Anima Anandkumar and Zongyi Li*

The current machine learning models utilised to learn the solution to the Euler equations and capture supersonic flow fields with shockwaves are the geometry-aware FNO, Geo-FNO and the geometry-informed neural operator, GINO. While each of these models may be applied to partial differential equations with discontinuities and irregular grids, errors still persist near the discontinuities as in each case the sampling points are not tailored to the location of the discontinuity. In this work, we introduce a model capable of learning an adaptive mesh based on the gradients of the flow field variable under consideration. An FNO is used to learn the mesh by modulating the distance between the grid points based on the location of the discontinuity. This model may then be used in conjunction with the existing architectures to produce a more accurate simulation of the flow field. This work also introduces a new model which combines Geo-FNO and GINO with the aim of exploiting the advantages of the deformation map in Geo-FNO and the interpolations in GINO. We demonstrate the effectiveness of the models proposed on the steady state solution to the Euler equations for an airfoil database with transonic flow over the airfoils.

### **Assessing Scalp Sensitivity in Laser Speckle Cerebral Blood Flow Measurement by Occluding the Temporal Artery and Measuring Blood Flow Changes at Different Source-to-Detector Distances**

Maya Dickson

*Mentors: Changhuei Yang and Simon Mahler*

Monitoring cerebral blood flow (CBF) non-invasively is challenging due to the difficulty of overcoming the scalp and skull layers protecting the brain while maintaining an effective signal-to-noise ratio. We recently designed a laser

speckle device capable of measuring CBF optically. This project aims to assess the device's sensitivity to scalp blood flow and demonstrate its effectiveness in measuring cerebral blood flow. To do this, I designed a multi-channel version of the device, with some channels configured to measure scalp blood flow and others to measure cerebral blood flow. By occluding the temporal artery (a safe medical intervention), we temporarily reduced blood flow in the scalp. Observing the effects of the occlusion across the different channels, we found that channels configured for cerebral blood flow were significantly less affected by the occlusion than channels configured for scalp blood flow. This suggests a lower sensitivity to the scalp layer and a higher sensitivity to the brain layer. This demonstration is crucial for advancing future research in non-invasive CBF monitoring, with potential applications in stroke detection, traumatic brain injury examination, and neurological disease detection.

### **Optimizing Sparse SYK**

Matthew Ding

*Mentors: John Preskill, Robbie King, and Eric Anschuetz*

The Sachdev-Ye-Kitaev (SYK) model is a chaotic fermionic Hamiltonian with randomized Gaussian coefficients over all  $q$ -local interaction terms. We consider the optimization problem of finding approximate ground states for the sparse SYK model where terms are randomly discarded with probability  $1 - p$ . Gaussian states are a common ansatz used for this task with some approximation ratio between the best Gaussian state energy and optimal energy depending on  $p$ . It was previously only known that they achieve at most a  $1/\sqrt{n}$  approximation ratio in the densest case ( $p = 1$ ) and optimal energy up to a constant approximation in the sparsest case ( $p \sim 1/n^3$ ). In this work, we provide the first results on Gaussian state approximations for values of  $p$  between these two limits. We prove the upper bound that with high probability, Gaussian states cannot achieve better than an approximation ratio of  $\max(1/(n^{3/2}\sqrt{p}), 1/\sqrt{n})$ . We also show that the Hastings-O'Donnell quantum algorithm achieving optimal energy on  $p = 1$  SYK-4 remains optimal for all  $p > 1/n$ , extending this quantum-classical separation to the sparsified regime.

### **Revisiting Foundational Transformer Models for Thermal Image Retrieval and Localization**

Kevin Do

*Mentors: Soon-Jo Chung and Xingxing Zuo*

Foundational Transformer models have found their place in the image retrieval task, however we believe they could be leveraged more effectively. This research investigates the use of foundational transformer models for improving thermal image retrieval and localization tasks, focusing on enhancing existing methodologies to achieve more accurate and efficient results. Traditional approaches, such as mutual nearest neighbors similarity and contrastive loss functions, face significant limitations in computational efficiency and the confidence of matching results. To address these challenges, this project employs optimal transport techniques, specifically using the Sinkhorn algorithm, to refine feature assignment between images. Preliminary results demonstrate that the application of optimal transport in training and evaluation phases yields promising improvements in retrieval accuracy and processing speed, all while introducing limited extra parameters.

### **Emotional Expression in 24 Month Olds With Agenesis of the Corpus Callosum Compared to Typical Development**

Olivia Dods

*Mentors: Ralph Adolphs and Lynn Paul*

Evidence suggests that temperament is an important factor in early behavioral development and may serve as an indicator of future neurodevelopmental diagnoses such as Autism Spectrum Disorder (ASD). Previous work reported blunting of both positive and negative emotionality in 6- and 12-month-old children with isolated agenesis of the corpus callosum (ACC) compared to neurotypical children. Likewise, the current study found blunted positive emotionality in ACC at 24-months, but no difference from neurotypical children on negative emotionality or emotional control. However, confirmatory factor analysis suggests that scores from the ACC group poorly fit with the published model, raising concerns about measurement invariance and need for future exploratory modeling to understand temperament in young children with ACC.

### **Design and Implementation of a Heating Stage for Transient Extreme Ultraviolet (XUV) Spectroscopy of Small Polaron Formation**

Belinda Dong

*Mentors: Scott Cushing and Jocelyn Mendes*

Transient XUV spectroscopy can probe core-to-valence transitions in different materials, which makes it a powerful technique for studying polaron formation. Polarons, a type of quasiparticle that form when excess charge couples with deformations in the surrounding atomic lattice, are theorized to trap charge carriers and limit photoconversion efficiencies of different photocatalyst materials. We hope to investigate the effect of different temperatures on polaron formation, as tuning material properties can tune the properties of polaron formation. This project aims to design and construct a heating stage that can be integrated into the Cushing Lab's tabletop XUV setup. The heating stage operates in high-vacuum conditions and will ideally be able to reach temperatures up to 670°K. Temperature

sweeps of different samples over a range of 20–670°K will be conducted to identify if there exist any critical thresholds or temperature ranges that reduce polaron formation. If polarons are discovered to be inhibited at a certain temperature threshold or range, then by designing solar technologies to operate at those temperatures, their photoconversion efficiencies and impact could be dramatically improved.

**Task-Switching During Mouse Hunting**

Ha Dong

*Mentors: Markus Meister and Daniel Pollak*

The nervous system's dynamic internal state fluctuates in response to environmental changes to control behavioral task switches. Investigating this phenomenon during complex tasks like hunting presents opportunities, particularly in replicating naturalistic conditions within laboratory settings while collecting comprehensive data. We developed an integrated pipeline for experimentation, data collection, and analysis to elucidate if there are internal states governing visually-guided hunting in mice. Our approach utilizes a real-time interactive platform that simulates naturalistic hunting scenarios. An artificial prey was programmed to evade the mouse subject following a probabilistic escape strategy in which the escape trajectory is sampled according to a von Mises distribution of escape angles. We recorded the subjects' trajectories and behavioral kinematics using a bird's-eye view video data while simultaneously recording high-density neural activity in the superior colliculus (SC) using a Neuropixel 1.0 probe. Given the SC's role in locomotion, orientation, and visual responses during hunting and escape behaviors, we hypothesize that neural activity in SC contains decodable states reflecting approach and quiescence behaviors. We used cluster analysis to detect patterns in mouse behaviors, and to test our hypothesis, we employed a Generalized Linear Model – Hidden Markov Model to predict internal and behavioral states from SC activity and kinematic data. Future work will incorporate looming as a predatory signal during hunting to stimulate escape responses, potentially revealing robust state transitions. This paradigm also enables future investigation into naturalistic hunting dynamics in mice.

**Data Partitioning in Causal Inference**

Jeff X. Duan

*Mentor: Frederick Eberhardt*

Although causal discovery algorithms are well understood, it is unclear how to split data consisting of subsets with varying causal graphs, leading to misinterpretation of data. We aim to produce an algorithm that recursively splits a dataset based on graph difference, until the resultant leaves cannot be decomposed into subsets that better fit the data. This demands two conditions be met: to develop a loss function that effectively measures how closely a graph fits data, and to construct a framework for optimizing partitions that subverts the combinatorial number of possible partitions. Two approaches have been adopted to meet these conditions: visual/"graphical" approaches based on clustering, and "pointwise" approaches based on randomly generating sets of points. We have shown that graphical methods are ineffective for these purposes, but might be implemented into the pointwise approach through means such as dendrogram clustering. After much consideration and experimentation, the most promising loss functions are Average Standardized Residuals (ASR) and BIC score. Meanwhile, the current candidate for optimization framework is "Graph Probing", in which we start with predetermined graphs and evaluate how likely they are to reside in the dataset. An implementation of probing is being coded to enable testing of the complete pipeline.

**DiStruction for Bayesian Machine Unlearning Without Repair**

Zack Dugue

*Mentors: Alexandra Brintrup and Georgia Gkioxari*

Machine unlearning is the task of teaching a machine learning model to "forget" a subset of its training data, known as the forget set, without compromising performance on the rest of the data, known as the retain set. This task has become increasingly important as privacy concerns around the data used to train machine learning models have grown. At the same time, the size of such models makes simply retraining them on the retain set impractical. Many algorithms to implement machine unlearning utilize repair steps, which involve tuning the model on a subset of the original dataset in order to maintain performance. Our Distributional Reconstruction (DiStruction) method instead works by representing the parameters of the original model as independent Gaussian distributions. To ensure good performance on the retain set through the forgetting process, we introduce Kullback–Leibler divergence penalty between the distributions of the two models' parameters. This allows the model to forget the required data without compromising its performance on the retain set.

**Reinforcement Learning-Based Agents to Study Fear and Anxiety Responses in Gamified Environments**

Hudson Kaleb Dy

*Mentors: Dean Mobbs and Noah Okada*

Fear and anxiety are critical emotions which play an integral part in human decision making, equipping us with the survival instincts necessary to safely navigate our surroundings and continuously adapt. Despite the prior studies done on these emotions, there is a need for larger scale studies to better generalize results across broader

populations within society. This project focuses on enhancing the Survivors Platform, a series of simulations designed to mimic real-world predatory scenarios. By leveraging Google Firebase, C# scripts, and Unity, the project optimizes the platform's infrastructure, upgrades server capabilities, and boosts user engagement, ensuring the game's smooth transition to large scale experiments and handling of increased traffic and data collection. By developing reinforcement learning-based agents through Proximal Policy Optimization (PPO) with Curriculum Learning, the project allows for the modeling of behavioral phenotypes, providing deeper insights into fear responses and decision-making processes. These developments contribute to a broader understanding of fear and anxiety, facilitate the progression of gamified environments as tools to study human behavior, and ultimately advance the intersection between cognitive science and machine learning.

### **Development and Characterization of Physical and Solid-State Electrochemical Gas Sensors for Respiratory Analysis**

Freyr Víkingur Einarsson

*Mentors: Wei Gao and Wenzheng Heng*

The project aims to develop a device for measuring respiratory parameters such as humidity, temperature, airflow, CO<sub>2</sub> amount and O<sub>2</sub> levels, which all give insight into a person's respiratory health. Monitoring respiratory health can help detect and diagnose various conditions such as asthma, chronic obstructive pulmonary disease (COPD), and sleep apnea. Building on previous work by Professor Gao's research group, which focused on wearable sensors and continuous monitoring algorithms, this project applies that foundation to respiratory monitoring. Respiratory health can be monitored not only through human breath but also through the skin. This project focuses on examining the two ways of measuring respiratory health and the sensor selection for that task through a thorough evaluation to ensure the upmost quality for the final respiratory monitoring device.

### **Entanglement Swapping With CW-Source**

Claire Ellison

*Mentors: Maria Spiropulu and Raju Valivarthi*

Quantum internet, a network that transports qubits containing information through entanglement, has potential to change the field of secure information. Quantum key distribution (QKD) is a protocol that offers secure communication via entanglement. We experimentally demonstrate high-visibility entanglement swapping using polarization-entangled photons produced by spontaneous parametric down conversion (SPDC) with continuous-wave light. A Mach-Zehnder interferometer is used to ensure stable interference of the non-degenerate photon pairs. To detect the photons a superconducting nanowire single-photon detector with low jitter was used. The research process consisted of testing a multitude of different optical components and optimizing different variables for maximum visibility of entanglement such as temperature, voltage, filtering, and polarization. An entanglement visibility of 99.5% was measured, a promising result for a compact source for free-space quantum communication.

### **Solution of Coupled Fokker-Planck Equations in F1-ATPase Model Exhibits Michaelis-Menten Kinetics**

Josiah Emerson

*Mentors: Sándor Volkán-Kacsó and Rudolph A. Marcus*

The rotation of the molecular motor F1-ATPase, which participates in ATP synthesis and hydrolysis, can be modeled through a system of coupled Fokker-Planck equations. The solution to these equations yields a probability density function for the system to be found in some chemical state, angle, and time, which is used to find the expected angle trajectory over time. For one full rotation of the motor, 12 chemical states must be implemented, and each added state increases the calculation time immensely, which imposes limitations on the length of the trajectory. The complexity of the system of equations requires the solution to be found numerically. We utilize the 'pdepe' function in Matlab to solve the equations at different concentrations of ATP. Comparing the slopes of these trajectories we extract the reaction rate for the motor as a function of ATP concentration, and show that the enzyme follows Michaelis-Menten enzyme kinetics.

### **Understanding Intelligent Predictive Systems Through a Comparative Analysis of Latent Spaces**

Sam Fatehmanesh

*Mentors: Matt Thomson and James Gornet*

Prediction is a task shared by various intelligent systems, from engineered machine learning models to animals. To understand the general laws underlying intelligent system prediction, we gathered representations from various systems performing the same video prediction task. These include time series of mouse cortical neural representations, a video prediction model's latent representations, and neural culture representations. The latent spaces of these systems will be compared using simple linear regression and MLPs to identify shared features. By doing so, we aim to identify universal shared features and structures across intelligent systems.

**Detection of Converted Phases With a CNN Trained on Synthetic Traces From Southern California's Seismic Velocity Model**

Ethan Feng

*Mentor: Rob Clayton*

Seismic phases undergo refraction whenever they pass through a new medium. Earthquakes that are detected by receivers in the Los Angeles basin traverse the San Gabriel Moho into the sedimentary basin. This change in medium causes refractions, resulting in a strong converted wave signal. We present a convolutional neural network (CNN), trained on synthetic traces generated from the Southern California's Seismic Velocity Model to detect specifically the SP converted phase.

**The Development of Thermal Distribution Systems for Radio Frequency Integrated Circuits on Flexible Boards**

Nerissa Finnen

*Mentors: Ali Hajimiri and Oren Mizrahi*

When radio frequency integrated circuits (RFICs) operate at their maximum capabilities for prolonged periods of time they generate substantial amounts of heat that can deteriorate its functionality and lifespan. Developing the necessary thermal distribution system for electronics is essential for proper operations. Traditional heat sinks are large and/or dependent on rigid structures. Additionally, convection is typically the primary cooling method of RFICs in most circumstances. However, these are insufficient methods in specific situations; in space, convection cannot assist with cooling, flexible boards can unstick from a heat sink when bent, and lightweight design restrictions prevent the use of typically dense highly thermally conductive metals employed in heat sinks. We use flexible and highly thermally conductive and emissive graphite with glass-fiber backing to develop a flexible, thin, and lightweight thermal distribution system that is integrable on a flexible board without the presence of convection. By co-curing the board's surface with the composite material we emulate an isothermal surface capable of transferring the RFIC's heat to the board for radiative cooling to reduce the RFIC's temperature. This provides a novel technique for radiative cooling in space for flexible electronic boards and greater radiative cooling applications.

**The Role of KATP Channels in Retinal Ganglion Cell Function in a Model of Dominant Optic Atrophy**

Lucas Flach

*Mentors: Steven Barnes and Markus Meister*

The eye disease called Dominant Optic Atrophy is a hereditary optic neuropathy linked to mutations causing reduced mitochondrial efficiency. This project examines the function of KATP channels in human stem cell-derived retinal ganglion cells with Dominant Optic Atrophy. KATP channels are voltage-gated potassium channels that are inhibited by ATP and produce outward, hyperpolarizing currents. We hypothesized that reduced ATP output in mutants leads to less inhibition of KATP channels and is thus responsible for the weakened visual signaling in mutant ganglion cells.

To test this hypothesis, we measured voltage-clamped potassium currents in control and mutant cells. This involved attaching an electrode to an individual cell, rupturing the patch of the cell beneath the electrode, then inducing voltage steps and measuring the resulting currents. Using a KATP channel inhibitor called glibenclamide, we isolated KATP channel currents, revealing differential KATP channel activity in cells with the Dominant Optic Atrophy mutation.

**Modeling Wind Speeds Over Lake Arrowhead**

Nicholas Flach

*Mentors: Dave James and John O. Dabiri*

In order to combat drought, the implementation of indirect potable reuse through surface water augmentation (SWA-IPR) is useful. SWA-IPR is a method of augmenting drinking water supplies that involves mixing highly treated wastewater effluent into an environmental buffer such as a lake or aquifer to reduce contaminant concentrations before further treatment. In order to determine the effectiveness of the environmental buffer in this process, it is vital per state regulations to estimate the mixing of treated effluent within the buffer. For surface water reservoirs, where mixing is largely driven by wind, modeling wind speeds is one important factor in calculating accurate hydrodynamic model estimates of potential contaminant concentrations. Using Lake Arrowhead as a case study, we compare computational fluid dynamics models WindSim 11.0 and Meteodyn WT as well as interpolation models (inverse distance weighted and kriging) to see which of the models estimate wind speeds with the least error. We also compare various weather station combinations for input into these models to help answer the question of how many stations are useful for minimal error and which locations may be more optimal.

### **Developing Wildlife Behavior Classification Process Using Machine Learning**

Brendan Flaherty

*Mentors: Devis Tuia and Katie Bouman*

Advanced computer vision and machine learning methods are powerful tools when applied to conservation and ecology efforts, enabling the analysis and understanding of individuals and species. New collection techniques have produced immense datasets of animal behavior, and the analysis of these datasets is revolutionized by machine learning. We investigate and develop these methods further by studying a proprietary dataset of camera trap videos captured from the Swiss National Park by the ECEO lab of EPFL. The dataset consists of more than 3,700 videos and represents eight species with many different behaviors. The data ingestion pipeline we developed involves several key steps: detecting animals using MegaDetector, trimming raw videos, tracking individuals with ByteTrack, manually correcting tracks using CVAT, and generating targeted tublet videos. Metadata generated throughout the process is analyzed and representative behaviors are annotated. Additionally, various methods will be tested for behavior inference and analysis. Overall, we have developed a general, multi-purpose codebase to process fieldwork for behavior analysis. The project will be invaluable for conservationists and ecologists who seek to analyze animal behavior in the future.

### **An Analysis of the Hall Probes in, and the Magnetized Solenoid Beneath, the Cryostat**

Jessica Fox

*Mentors: Saptarshi Chaudhuri, Joelle-Marie Begin, and Sunil Golwala*

In the Princeton axion experiment, we are constructing a cryostat, known colloquially as "Maggie," with a high magnetic field in order to detect the presence of axions. However, before finishing the cryostat construction the Hall probes inside the cryostat must be tested for accuracy. To do so, a solenoid was placed beneath the cryostat and had a current run through it. We measured the magnetic field with each of the two Hall probes and graphed and fit the results. Furthermore, to test the accuracy, we did pen-and-paper calculations of the magnetic field of the solenoid. Lastly, we ran a simulation of the solenoid and its magnetic field in COMSOL Multiphysics and compared it to the measurements we collected from the Hall probes.

### **Diving Into Structure to Function in ActiveDROPS**

Jazzer Francisco Uncal

*Mentors: Matthew Thomson and David Larios*

The cytoskeleton is essential for driving motion in living organisms, with kinesins and microtubules being key components of the eukaryotic cytoskeleton. These elements have been extensively studied to understand how cells utilize molecular machines for complex tasks. Recently, the ActiveDROPS system has shown that the genetic expression of different kinesins in a TXTL and stabilized microtubule mixture can generate diverse dynamics. However, the underlying mechanisms for these differences remain unknown. In this study, we combined domains of kinesins with known dynamics, tested their behavior in ActiveDROPS, and compared their structural 3D predictions from AlphaFold3. Our results reveal specific structural differences that may explain the observed variations in their behavior.

### **Designing an Updated SuperSpec: A High Instantaneous Bandwidth, Cryogenic, sub-mmWave Spectrometer**

Ron Freeman

*Mentor: Charles Bradford*

Spectroscopy in the sub-mmwave regime is a useful tool to understand star formation rates and early galactic evolution. These measurements require a sensitive, tileable spectrometer that is both able to resolve these spectral lines and is small enough to allow for a spectrometer array, important for sky mapping. SuperSpec is a cryogenic spectrometer on a chip, using Kinetic Inductance Detectors (KIDs) and a superconducting niobium filterbank to simultaneously measure  $\sim 300$  discrete spectral channels in the 180-320 GHz band. KIDs are a new detector technology that uses an LC resonator where the inductor is made of a high  $T_c$  superconductor such that when a photon hits it, it has enough energy to break Cooper pairs in the inductor, modifying its inductance by the kinetic inductance effect. This can then be read out by measuring the shift in the resonant frequency of the resonator. The goal of this project was to design and demonstrate an updated SuperSpec chip using a new amorphous silicon dielectric developed by JPL Microdevices Laboratory. This work also shows a new antenna feed for the spectrometer, using an inline split-block horn to waveguide to chip transition to allow for a future spectrometer array.

### **Extension and Lifting Properties of Sobolev Maps From $\mathcal{W}^{1,p}$ in the Study of Yang-Mills Connections**

Ania Freymond

*Mentors: Riccardo Caniato and Antoine Song*

Donaldson's insights into the geometry of 4-manifolds and the moduli space of solutions to Yang-Mills equations follows largely from the results of Uhlenbeck, who proved that a gauge exists in which the Sobolev  $\mathcal{W}^{1,2}$ -norm of

the connection 1-form  $\mathcal{A}$  is controlled for curvature  $\mathcal{F}$  as  $\|\mathcal{A}\|_{L^2} \leq C\|\mathcal{F}\|_{L^2}$ , where  $\mathcal{A}$  can satisfy the Coulomb condition  $d^*\mathcal{A} = 0$ . The control of  $\mathcal{A}$  for higher norms, however, remains ripe for exploration, which motivates our proof of a small energy extension theorem in  $\mathcal{W}^{1,p}$ . We define  $\mathcal{U}_{p,\varepsilon}$  as the  $n$ -Dirichlet energy  $\varepsilon$ -sublevel in  $\mathcal{W}^{1,p}(\mathbb{S}^n, N)$  and establish its path-connectedness for small  $\varepsilon$  by constructing a homotopy path within the tubular neighbourhood of  $N$ . We then define  $\mathcal{V}_{p,\varepsilon,C} \subset \mathcal{U}_{p,\varepsilon}$  as the subset of maps  $u \in \mathcal{U}_{p,\varepsilon}$  with control on  $|du|$  such that there exists an extension  $\tilde{u} \in \mathcal{W}^{1,p}(B^{n+1}, N)$  with  $\tilde{u}|_{\mathbb{S}^n} = u$  in the sense of traces, showing that its closure follows naturally from weak compactness and embedding theorems. More interestingly, we prove  $\mathcal{V}_{p,\varepsilon,C}$  is open by studying the behaviour of solutions to the equation  $d^*(\tilde{u}^{-1}d\tilde{u}) = 0$ , inciting the need of local linearisation of Fredholm operators. These results motivate further applications to the gluing of gauges within the study of minimisers' regularity for stationary Yang-Mills fields in  $\dim > 4$ .

### Charge Asymmetry and Sequence Effects on Self-Coacervation of Intrinsically Disordered Proteins

Kelsey Fu

*Mentors: Zhen-Gang Wang, Shensheng Chen, and Pierre J. Walker*

In aqueous environments, intrinsically disordered proteins (IDPs) can undergo liquid-liquid phase separation (LLPS), forming protein rich coacervates coexisting with dilute supernatant phases. While previous studies have primarily considered proteins with equal positive and negative charges, natural IDPs often exhibit charge asymmetry. This study uses molecular dynamics (MD) simulations to examine how sequence disorder, charge asymmetry, and salt concentration influence IDP self-coacervation. Our findings indicate that, in salt-free systems, only IDPs with moderate disorder can self-coacervate. Among these, the inclusion of charge asymmetry diminishes the IDP's ability to self-coacervate due to increased repulsive electrostatic forces. The balance between electrostatic attractions and entropic effects is crucial. However, the addition of salt can have different effects on the self-coacervation behavior of IDPs. For neutral IDPs, salt inhibits coacervation by screening attractive interactions. In contrast, for charge-asymmetric IDPs, initial salt addition enhances coacervation by reducing electrostatic repulsions, even enabling coacervation in some non-coacervating IDPs. However, excessive salt screens favorable interactions, thereby inhibiting coacervation. We have fully mapped-out the phase space of IDPs in terms of charge asymmetry, sequence disorder, and salt concentration. By mapping these variables, we provide a framework for designing systems with desired coacervation properties, offering significant insights for various applications.

### Computational Design of Binders for the Toxin-Antitoxin RelE-RelB System

Jessie Gan

*Mentors: Amy Keating, Steve Mayo, and Lindsey Guan*

In recent years, machine learning models have greatly accelerated the progress of protein prediction and design. With the development of diffusion-based models, software such as RFDiffusion and AlphaFold2 have improved to predict and verify *de novo* protein and binder designs. In this work, we used the protein design model RFDiffusion to generate peptide binders for the RelE-RelB toxin-antitoxin system. Toxin-antitoxin systems can protect resistant bacterial colonies from antibacterial phage therapy via abortive infection, where bacterial systems self-exterminate to save bacterial colonies. Our peptide binder design goal is to inhibit natural toxins that prevent the spread of phage therapy, to eliminate resilient bacterial colonies. We are not only interested in binders for the sake of generating effective antibiotics, but also as a way to develop narrow-spectrum antibiotics that preserve as much of the native microbiome as possible and prevent future antibiotic resistance. We draw on investigation of previously designed binders to inform the design of *de novo* binders, with a focus on specificity between RelE orthologs.

### Biophysical Study on the Kinetics of Cooperative DNA Hybridization

Tanvi Ganapathy

*Mentors: Lulu Qian and Matthew Plazola*

Machine learning models, such as neural networks that model the interactions between neurons in the mammalian brain, have taken inspiration from the computational abilities of biological systems to perform more complex artificial intelligence tasks. DNA-based neural networks enable complex artificial intelligence tasks in molecular systems. Previous studies have designed neural networks to perform pattern recognition tasks through a winner-take-all (WTA) layer that performs pairwise annihilation of signals through cooperative DNA hybridization. Critically, annihilation requires fair competition between the input signals to enable accurate WTA behavior. However, previous models for annihilation have limitations in explaining the reasons underlying unfair competition in WTA. Moreover, we discovered that the previously implemented annihilation reaction was not fully irreversible, which further contradicts the existing model. Here we perform a biophysical study on the kinetics of cooperative DNA hybridization to improve the model for annihilation. A better understanding of the annihilation reaction kinetics informs the molecular design. For example, we explore a new molecular design that improves the irreversibility of annihilation, which could enable more accurate molecular pattern recognition.



### **Characterizing Changes in Neutron Beam Polarization and Transmission (P/T) of Cryogenic Neutron Electric Dipole Moment Apparatus**

Xinyi Gao

*Mentors: Bradley Filippone and Robin Zhu*

The CP violation in the Standard Model is currently insufficient to explain the presence of an excess of baryons over antibaryons. Measuring permanent electric dipole moments provides insights into the elementary particle interactions. The present neutron electric dipole moment (nEDM) experiment utilizes the cryogenic apparatus that significantly improves the sensitivity of the measurements. The current P/T neutron experiment on the 8.9 Å beamline at the Spallation Neutron Source aims to eliminate the discrepancy between measured and expected neutron transmission and polarization rate after the neutron beam goes through a series of magnetic and thermal shieldings to reach downstream. The measurement system consists of a polarizer upstream of the beam, a detector and an analyzer downstream. In addition, the spin of the neutron particles is to be aligned with the B0 magnetic field in the east-west direction generated by a modified saddle-shaped  $\cos \theta$  coil while optimizing the gradient and the effects of the ambient field that is  $\sim 10^{11}$  time larger than the changes in the magnetic field of interest. Field compensation (FCS) coils, magnetic shield enclosure (MSE) coils, and additional magnets were installed to optimize the magnetic field and magnetic gradient of the ambient and B0 field. Eventually, the absolute transmission and polarization of only the neutron beam without the magnet, and followed by both the neutron beam and the magnet will be measured.

### **A Flexible Flying Surface for Multimodal Flight**

Diego Garcia

*Mentors: Mory Gharib and Ioannis Mandralis*

Unmanned Aerial Vehicles (UAVs) are quickly gaining in popularity in a range of fields such as search and rescue, exploration, as well as package delivery. However, the rigid design of these systems limits the possible flight modes that can be explored. By loosening these restrictions, we can hope to design flying vehicles that can achieve more agile and energy efficient flight. In this work, we utilize a set of embedded brushless motors, inertial measurement units, and thin mylar sheeting to produce a flexible flying surface that flies in both a folded and unfolded configuration. This mechanism possesses the ability to achieve multi-modal flight (flapping and hovering) while also allowing freedom for shape manipulation. We investigate the controls necessary for this mechanism, with current results showing that a modified proportional-integral-derivative (PID) controller can achieve basic flight. More experimentation will be conducted to produce stable flight with smooth shape control.

### **Adapting Gaussian Splatting for Thermal Imagery in Autonomous Robotics**

Ricardo Garcia

*Mentors: Soon-Jo Chung and Xingxing Zhuo*

This research project aims to extend 3D reconstruction techniques, particularly Gaussian splatting, to the thermal imaging domain for use in autonomous robots and drones operating in low-light conditions. While methods like Structure from Motion (SfM) and Neural Radiance Fields (NeRF) have proven effective for RGB imagery, their application to thermal data presents unique challenges due to the inherent characteristics of thermal images, such as high dynamic range and lower signal-to-noise ratios.

The project adapts Gaussian Splatting techniques to work with thermal imagery by leveraging sparse landmarks and poses obtained through SfM. It explores methods to accurately model the thermal image rendering process, and methods to improve the three-dimensional mesh reconstruction output of Gaussian Splatting. The effectiveness of these adapted techniques is evaluated and benchmarked against existing methods using public datasets, with the goal of improving 3D reconstruction capabilities for autonomous systems relying on thermal vision.

### **Mechanical Behavior of Interlocking Polycatenated Architected Materials**

Jabri Garcia-Jimenez

*Mentors: Chiara Daraio, Sujeeka Nadarajah, and Wenjie Zhou*

Polycatenated architected materials (PAMs) consist of linked particles with repeating geometries whose mechanical and physical behaviors are determined by their geometric features beyond those of the material microstructure. This project focuses on 1D chain-like PAMs whose particles interlock when a tensile load is applied, giving the chain a rigid-body-like form. Then, it unlocks when compressed, returning kinetic freedom to the particles. Three geometries of 1D PAMs were analyzed: locking, quasi-locking, and non-locking chains where the locking chain's particles more firmly lock and can hold its rigid state even after shaking, the quasi-locking chain's particles gently lock, and its rigid state more easily falls apart, and the non-locking chain retaining kinetic freedom and not interlocking at all. Each PAM was additively manufactured using thermoplastic polyurethane (TPU), with each 1D PAM having a rough and smooth surface finish variant. Experimental methods included tensile and compressive tests at different strain rates and three-point bending tests. The resulting data shows how particle geometry, surface finish, and strain rate may affect mechanical behaviors such as force absorption, stress-strain behaviors,

and the locking of particles. Conclusions display potential applications in robotics or energy-absorbing systems for locking and quasi-locking chains.

### **Enhancing Equity in AI: Improving Tools for Inspecting and Mitigating Social Bias in Large Language Models**

Tyler Gatewood

*Mentors: Animashree Anandkumar, Mike Alvarez, and Rafal Kocielnik*

This study presents an innovative methodology for mitigating social bias in large language models (LLMs) via advanced synthetic dataset generation. We propose a dual-component system consisting of a prompt-based issue detection classifier and an iterative self-refinement model. The classifier employs target prompts to identify categorized issues in LLM generated synthetic data while the self-refinement model iteratively optimizes the synthetic data generation using its own concrete and actionable feedback following self-refinement framework. This approach aims to produce more diverse, high-quality, and balanced datasets for LLM bias testing and fine-tuning, addressing limitations to current debiasing techniques. Additionally, we integrate this enhanced synthetic data generation capability into the open-source BiasTestGPT tool hosted on HuggingFace.co, expanding its functionality for bias testing and mitigation. These capabilities aid synthetic dataset generation that can be used to test a multitude of models for presence of social bias. This study contributes to the broader research agenda of improving fairness and equity in artificial intelligence by developing more sophisticated tools for addressing social bias in contemporary language models.

### **Tracing the Milky Way Circum-Galactic Medium With Optical Spectroscopy**

Abra Geiger

*Mentor: Vikram Ravi*

The gaseous halos surrounding galaxies are crucial to informing our understanding of galaxy evolution and the universal baryonic fraction. This circumgalactic medium is primarily studied through analysis of ultraviolet spectral absorption induced by cool circumgalactic clouds, using stars and quasars as background sources. In this work, we probe the Milky Way halo through optical spectroscopy, using globular clusters as background sources, since both the Milky Way and the optical band are less studied in this context. Through simulation using the spectral synthesis code Cloudy, we explore the optical absorption and emission induced by circumgalactic clouds varying in temperature, density, depth, metallicity, and grain abundance, focusing on the NaI, CaII, and MgII absorption line doublets. We find the relative strengths of these lines to be highly dependent on the depletion of gas-phase metals onto grains. Additionally, for globular clusters with pulsars, we have dispersion measures, which provide additional context to our analysis. We find our simulated cloud dispersion measures to be significantly higher than those observed, suggesting that the circumgalactic medium is more neutral than currently accepted. Finally, we compare our simulation results to observed spectra for the distant globular clusters NGC 7089, Laevens 3, M53, NGC 7006, and Palomar 14.

### **Assessing the Effect of Fluorinert, Fomblin, and Krytox Coatings on Oxidation of Fe Nanoparticles Using Mössbauer Spectroscopy and X-Ray Diffraction**

Sophie Gershaft

*Mentors: Brent Fultz and Channing Ahn*

Mössbauer spectrometry is used to study iron nanoparticles (Fe NPs) that were synthesized in this project. The oxidation of Fe nanoparticles (NPs) is examined and compared under different coatings, intended to slow oxidation. Fe NP samples are prepared by thermal deposition with varied inert gas pressures during deposition to affect NP size. NP samples are prepared, coated with Fluorinert, and Fomblin and Krytox diffusion pump oils and X-ray diffraction (XRD) is used to determine phase fractions and NP size by examining broadening of the peaks using the Scherrer equation for the full-width-at-half-maximum (FWHM). More samples must be examined before conclusive results can be obtained. Fe NP samples will be prepared with coatings of Fluorinert, Fomblin, Krytox and control and will be tested with exposure to inert gas only and with exposure to atmosphere. Characterization will be performed using XRD and Mössbauer Spectroscopy. Mössbauer Spectroscopy is an experimental technique which finds applications in identifying the composition of iron (Fe) oxides on the moon. Further work would involve developing a technology readiness level 3 concept for a mission to the moon involving measurement of oxidation and oxygen kinetics in lunar conditions by Mössbauer Spectroscopy of custom coated Fe NP samples prepared in the lab.

### **Aqueous Electrochemical Ammonia Synthesis Using a Solid-State Electrolyte**

Dagemawi Getachew

*Mentors: Karthish Manthiram and Anukta Jain*

The Haber-Bosch process, the current conventional method to produce ammonia, is highly energy-intensive, operating at extremely high temperatures and pressures. Furthermore, the process leaves a detrimental carbon footprint due to the use of steam reformation of methane to produce hydrogen. The lithium mediated nitrogen reduction reaction (Li-NRR) is an attractive alternative that can achieve ammonia synthesis at ambient

temperatures and pressures electrochemically. During this process, lithium protons are reduced into lithium metal, which then reacts with nitrogen gas to form lithium nitride, and finally forms ammonia through protonation. This project focuses on using water vapor as a proton source to overcome solvent decomposition challenges associated with liquid electrolytes and employing the solid-state electrolyte  $\text{Li}_{6.4}\text{La}_3\text{Zr}_{1.4}\text{Ta}_{0.6}\text{O}_{12}$  (LLZO) for its ability to remain stable upon contact with water, conduct lithium ions, and be an environmentally-friendly alternative to the conventional tetrahydrofuran (THF). For this method to be applicable, the system must be able to plate lithium on the cathode efficiently at high rates. This project explores interfacial engineering methods to decrease interfacial resistance and promote lithium plating. It primarily investigates different cathode materials, ionic liquids, and electrolyte synthesis methods.

### **Developing an Annealing System to Tune Transmon Qubit Frequencies**

Mark Gherghetta

*Mentors: Mohammad Mirhosseini and Omid Aligholamioskooee*

Superconducting quantum processors are proving to be a promising hardware platform for achieving full-scale quantum computers. They rely on Josephson junctions, a non-linear inductive element that allows for usable quantum bit (qubit) states. Further scalability for this platform relies on the precise tuning of superconducting qubit frequencies. Imperfections during chip fabrication prevent qubits from hitting their target value. Thus, a method for post-fabrication tuning of qubits is desired. In this project, techniques for post-fabrication tuning of individual Josephson junctions are studied. Previous literature on various annealing methods demonstrates precise frequency tuning without compromising key metrics such as qubit coherence. We develop a robust system for alternating-bias assisted annealing (ABAA) proposed by Pappas et al. to selectively tune Josephson junction resistance, which is directly related to the qubit frequency. Significant changes in junction resistance are observed, and statistics are developed over multiple junctions. This system for post-fabrication qubit tuning will allow for improvements across a wide range of qubit experiments. Future work will involve perfecting and testing this system on physical chips to be used for novel qubit experiments.

### **The Roles of *stk32a* and *gpr156* in Zebrafish Sleep Regulation**

Madelyn Gilbert

*Mentors: David Prober and Jasmine Emtage*

Despite being vital for survival, the genetic mechanisms that govern sleep regulation remain largely undiscovered. Zebrafish (*Danio rerio*) are a convenient sleep model because they are diurnal vertebrates that exhibit similar sleep behaviors to mammalian sleep. The zebrafish ortholog of the human gene *stk32a* was found to increase sleep upon mutation. Although its function is unknown, *stk32a* is endogenously expressed in the neuromasts of the lateral line (LL) system, a system that identifies water flow changes via sensory hair cells (HCs). We hypothesize that *stk32a* and *gpr156*, two genes that work in the same pathway to confer directional sensitivity to HCs, are implicated in sleep regulation by altering LL function and subsequently zebrafish arousal. Utilizing behavioral assays in conjunction with fluorescence imaging, we investigated two inquiries: 1) if the *stk32a*<sup>-/-</sup> sleep phenotype results from atypical LL function and 2) if *gpr156*<sup>-/-</sup> fish exhibit a disordered sleep phenotype. Work is ongoing to determine if any additive behavioral effect to the *stk32a*<sup>-/-</sup> sleep phenotype will result from LL disruption. We found that mutations to *gpr156* result in increased sleep at night, similar to the *stk32a* mutant phenotype. This suggests that they act in the same pathway within the LL to regulate sleep.

### **Leveraging Open-Source Large Language Models for Encoding Social Determinants of Health Using an Intelligent Router**

Akul Goel

*Mentors: Matthew Thomson and Belinda Waltman*

Lifestyle choice and sociodemographic factors are crucial to patient outcomes, yet are often underrepresented in patient's Electronic Health Records (EHRs). The Center for Disease Control's (CDC's) introduction of Z-codes, a subset of ICD-10 codes, aims to address this gap, but these codes are rarely annotated and often need to be inferred from clinical notes. Although large language models (LLMs) show promise in extracting unstructured data from EHRs, selecting the optimal model for Social Determinants of Health (SDOH) coding is challenging due to the variety of available models, each with unique architectures and datasets. Furthermore, the use of closed-source models raises privacy concerns due to the presence of trusted health information, highlighting the need for effective open-source alternatives. We propose an intelligent routing system that directs EHR data to the most suitable open-source LLM for specific SDOH codes. Our system achieves 97.4% accuracy across five SDOH codes (which includes factors like homelessness and food insecurity) matching the performance of leading closed-source models as a proof of concept. Additionally, we introduce a synthetic data generation framework to train and validate the system without using protected medical records, demonstrating a robust architecture for high-performance SDOH coding.

**Towards Compact Gas Vesicle Gene Circuits Using the SEMPER System**

Arul Goel

*Mentors: Mikhail Shapiro and Ishaan Dev*

Abstract withheld from publication at mentor's request.

**COMAP Joint Analyses: Interloper Emission in the HETDEX Catalog of Lyman-Alpha Emitters**

Ashiria Goel

*Mentors: Kieran Cleary and Delaney Dunne*

The study of galaxy formation relies on understanding the interactions between different phases of gas, traced by different spectral lines. Hydrogen Lyman-Alpha ( $\text{Ly}\alpha$ ) emission from galaxies traces neutral hydrogen, and Carbon monoxide (CO) indicates dense molecular gas that is the precursor to new stars, making the interaction between the two important to understanding galaxy formation. The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) is a survey that has produced a catalog of information on thousands of  $\text{Ly}\alpha$ -emitting galaxies in the distant universe (about 10 billion light-years away). This project focused on the characterization and elimination of false positive detections from the catalog in order to use it as input for algorithms that attempt to draw conclusions about galaxies based on the interactions between their  $\text{Ly}\alpha$  emissions and CO emission from the Carbon Monoxide Mapping Array Project (COMAP).

**Fully Underactuated 3DOF Parallel Mechanism Gripper Design for Passive, Highly Adaptable Robotic Grasping**

Alexander Gogola

*Mentor: Joel Burdick*

Parallel jaw and suction cup grippers are the most widely used robotic end effectors due to their simplicity and reliability. While they are effective, these gripper designs are unable to reliably grasp objects with complex shape and surface properties, even with state of the art grasp planners. Soft grippers are a common solution due to their high adaptability, but this comes at the cost of a limited grasp force magnitude. The use of passive compliance and underactuated mechanisms in a gripper design offers the potential of the best of both worlds, keeping the design simple and highly adaptable while maintaining a strong grasp force. We have designed a fully passive gripper by arranging four underactuated 1T2R parallel mechanisms in a 2x2 grid. The natural stability and grasp force optimization that arises through the use of these add-on mechanisms can help alleviate the computational burden of conventional grasp planners. The design of a mechanical gripper that can effortlessly grasp any object is still an open problem. The add-on gripper design modules developed in this project offer a potential avenue for a practical solution to this problem.

**Increasing the Light Output of Extruded Polystyrene Scintillator Bars**

Victor Gomez

*Mentors: David Hitlin and James Oyang*

The Light Dark Matter eXperiment (LDMX) is designed to probe the lower thermal mass range ( $\sim$  MeV to GeV) for dark matter particles. Dark matter could present itself as missing momentum carried away by the non-interacting dark matter particle. In LDMX, high-energy electrons are fired at a target and scatter. The energy and angle of all the outgoing radiation products are measured to find a missing momentum caused by the non-interacting dark matter. One component necessary in doing so is a hadron calorimeter (HCal), composed of alternating layers of steel absorber and POPOP-doped polystyrene scintillator bars with a wavelength-shifting fiber passing through the center. The polystyrene bars are produced at Fermilab by co-extruding with a  $\text{TiO}_2$  coating. However, measurements of the  $\text{TiO}_2$  reflectance show a drop-off across the POPOP emission spectrum. This motivates using a  $\text{BaSO}_4$  reflective coating which maintains a high reflectance throughout the POPOP emission spectrum. Furthermore, the transmission of the polystyrene pellets currently used at Fermilab has been measured to be poor when compared to polystyrene pellets produced by the Taita Chemical Company. From initial Monte-Carlo simulations, it has been shown that making these two changes promises a 4-times improvement in the photoelectron yield per scintillation event.

**Variability of Io's Volcanism on Orbital Timescales**

Haonan Gong

*Mentors: Katherine de Kleer and Tina Seeger*

Gravitational forces from the other Galilean moons and Jupiter makes Io the most volcanically active body in the Solar System. It has given Io unique internal mechanisms that churn out hot magma all over the surface of the moon. We will focus on constraining the effect of gravitational tidal forces on Io's volcanic activity. First, evidence of volcanic activity, which is captured by thermal emission data from both terrestrial and space telescopes, is collected. Emission data from different telescopes is currently scattered in different formats among different research groups. We provide the first effort in aggregating this emission data into one unified dataset. Second, we analyze this evidence for volcanic activity alongside a model, pyALMA3, which calculates the stress and strain Io

feels across its surface from tidal forces. With the new aggregate dataset, it is now possible to find correlations between surface stress/strain and volcanic activity on timescales of single orbits around Jupiter. Better understanding how Io reacts to tidal forces may also allow us to gain further insight into the inner workings of the moon, such as how magma interacts with and travels through Io's interior.

**Predicting Biological Traits of Mammals From Nitrogen Stable Isotope Ratios of Amino Acids**

Mia Gonzalvo

*Mentor: Julia Tejada*

Nitrogen stable isotope ratios of glutamate and phenylalanine can be used to reconstruct the trophic positions of extant and extinct mammals. We sought to determine if nitrogen stable isotope ratios of other amino acids are as predictive of trophic position as glutamate and phenylalanine and of other biological traits, such as fermentation, basal metabolic rate, body mass, stomach, herbivory, and locality. All possible amino acid combinations using glycine, alanine, proline, valine, glutamate, and phenylalanine were generated, and top predictors were extracted for each trait using Akaike Information Criterion. Generalized linear models were fitted for each trait. We found that no other amino acid pair was equivalent or better at predicting trophic position than the nitrogen stable isotope ratios of glutamate and phenylalanine (AICc weight = 0.998). No other nitrogen stable isotope ratios of amino acids were suitable for predicting fermentation and basal metabolic rate. Further investigation is warranted to determine the utility of other amino acids and their stable isotopes for reconstruction of biological traits in extant and extinct mammals.

**Regular Functions and Arakelov Degree on Formal Analytic Arithmetic Surfaces**

Samuel Goodman

*Mentor: Vesselin Dimitrov*

In this project, we seek to understand the regular functions on a formal analytic arithmetic surface. By construction, most of the complication is in the infinite places, for which Riemann surfaces are attached at each place, and relating the gluing at the infinite places to the finite data gives rise to regular functions on the formal analytic arithmetic surfaces and thus a rich array of holomorphicity questions. The notion of Arakelov degree happens to be the natural notion to express the size of the ring of regular functions on the f.a. arithmetic surface, as conjectured by Bost and Charles. We prove a conjecture of theirs where, under the assumption that the Riemann surfaces (with boundary) are chosen to be any compact subsets of  $\mathbb{C}$  containing a neighborhood of 0 and having smooth boundary and the Arakelov degree of the normal bundle of the surface is negative, the ring of regular functions has cardinality the continuum.

**Voice vs. Text: Assessing the Persuasive Power of Large Language Models**

Isha Goswami

*Mentors: Diyi Yang, Chenglei Si, and Chris Umans*

This review of previous works and analysis of methods used to study the persuasive abilities of large language models (LLMs) focuses on comparing voice and text modalities. Many of the works reviewed study various aspects of LLMs in the context of persuasion, how they compare to human persuasion, and the different tasks or subjects the persuasion is being used for. Spoken words are much more complex than written words, especially with factors like trust, ease of interaction, and likeability. Numerous studies observed persuasion on political issues and the use of personalization with demographic and political characteristics. We find that large language models are equally as persuasive as humans, but this is not always the case when LLMs become personalized. The artificial aspect of LLMs is not received well by users, so synthetic voice is usually the least persuasive. Additionally, the persuasive effect and conversation quality are found to be much lower when users are aware that they are interacting with an LLM.

**Analysis of Angular-Differential Post-Processing Algorithms for Exoplanet Direct Detection**

Suvinay Goyal

*Mentors: Dimitri Mawet and Yinzi Xin*

Exoplanet research is crucial to understanding planetary formation and potential life outside of our solar system. Over the years several methods have contributed to the detection and characterization of those exoplanets resulting in around 5500 detections. The direct imaging method typically uses coronagraphs which blocks out the stellar host's light and allows us to characterize the planets atmospheres and features to a high degree. A newer kind of instrument, Photonic Lantern Nuller (PLN) attempts to do the same but for planets at closer separations to the stellar host, which is something that the coronagraphs can't do well. One common data analysis approach for the coronagraphic data to detect the planets leverages rotational symmetry of the planets' signal around the stellar host. However, PLNs don't show this symmetry. During the summer, I have reformulated that data analysis technique such that it may detect planets hidden in the PLN data.

### Effect of Molecular Structure on Autoignition Temperature of Jet Fuels

Colin Gray

Mentors: Joseph E. Shepherd and Charline Fouchier

Jet fuels are regulated by several strict standards on various properties; one such property is the autoignition temperature (AIT). The AIT is the minimum temperature at which a material ignites, causing combustion without an external ignition source. If the AIT of a fuel is too low, there is a risk of spontaneous ignition. However, the exact relationship of jet fuel composition to AIT is not well understood, and investigation would augment the synthesis of sustainable fuels with desired properties. The ASTM-E659 test is the industry standard for measuring AIT, and the previous projects in Prof. Shepherd's laboratory have created an automated injection apparatus to increase repeatability. Using this mechanism, we can measure the AIT of different fuel compositions with distinct characteristics and study the correlation between specific structures and the subsequent AIT. For example, investigation into aromatic content has shown higher aromatic content results in higher AIT. The relationship between compactness/branching of fuel components and the subsequent AIT is also investigated. Results from this project will improve the current understanding of AIT and provide some guidance for future development of sustainable fuels.

### Investigating the Relationship Between Reproduction and Induced Regenerative Responses in *Drosophila melanogaster*

Elisa Grillo

Mentor: Lea Goentoro

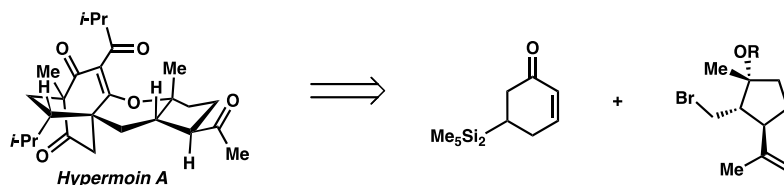
The idea of latent regeneration, hypothesized by Thomas Morgan, indicates that regeneration can be "turned on" for any species, regardless of typical capabilities. Due to many reasons including continually growing species tending to regenerate well, energy expenditure is implied to be a factor in regenerative ability. Moreover, Abrams et al. found that a surplus of energy in the form of nutrient supplementation can induce a regenerative response in many species, including *Drosophila melanogaster*. In order to deepen the understanding of the mechanisms behind induced regeneration and increase the regenerative response rates, the relationship between regeneration and reproduction, a major energy expenditure for female *Drosophila*, was explored. By inducing regeneration in virgin and control female flies of differing strains and dissecting and imaging their ovaries, it was determined that it is highly likely that there is a tradeoff between reproduction and successful induced regeneration.

### Progress Toward the Total Synthesis of Hypermoin A

Zoe Grogan

Mentors: Brian Stoltz, Kali Flesch, and Ruby Chen

This project is dedicated to synthesizing the natural product Hypermoin A. This molecule is a nor-polycyclic polyprenylated acylphloroglucinol (norPPAP) demonstrating promising biological activity, including reversal of multidrug resistance activity for HepG2/ADR and MCF/ADR cancer lines. Since their isolation in 2021, there have been no syntheses of any of the Hypermoins reported to date. Our approach to this synthesis involves retrosynthetic disconnection of the molecule into two fragments, an enone and a functionalized cyclopentane, that can be synthesized separately and joined together at a later stage. Our current efforts are aimed toward the development of these two fragments. This includes experimentation with a wide variety of possible functional handles on each fragment, which must all be compatible with later steps of the synthesis. The identification of compatible substrates will facilitate the successful synthesis of the molecule.



### Concept-based Explanations for Video Models

Emily Gu

Mentors: Pietro Perona, Markus Marks, and Neehar Kondapaneni

The interpretability of machine learning models has become an important field of study over the past few years, especially the explainability of image models. However, fewer studies have attempted to analyze models for video data, primarily due to the challenges brought by the additional temporal dimension. This project first attempts to extend CRAFT, a framework that comprehensively answers "where" and "what" an image model looks at when making classifications. The extended framework, VideoCRAFT, provides a simple way to extract concepts with importance scores from 3D CNN-based models. The project focus then shifts to VTCD, a recently developed concept-based explainability framework for video transformers. Specifically, the effectiveness of VTCD in lab

settings was assessed, including its ability to localize behavioral differences in mice and how well domain experts could explain the extracted concepts. Experiments on various models and datasets demonstrate the effectiveness of both VideoCRAFT and VTCD to provide human-interpretable concepts. To further investigate the impact of the temporal dimension on features learned by models, a metric for quantifying how much a concept encodes temporal versus spatial information is being developed and tested, which can serve as a useful addition to future video model explainability methods.

### **Optimization of Programmable Computer Networks Using Machine Learning**

Pranit Gunjal

*Mentors: Harvey Newman and Mariam Kiran*

The largest scientific programs, such as the Large Hadron Collider, face the challenges of distributing exabytes of data per year among hundreds of sites throughout the world where it can be processed and collaboratively analyzed, on the road to the next round of discoveries. The challenges continue to grow as the data volumes generated and expand by an order of magnitude every few years and are projected to match and soon outstrip the available capacity of the world's research and education networks, which must also support the network traffic on which the at-large academic and research communities rely. There is therefore a clear need for low-latency networks that can distribute the data as effectively as possible, coordinating the use of the available network resources with the computing and storage resources at the various sites, and responding dynamically to a "river" of requests, taking priorities and policies, fair sharing among different programs, approaching deadlines and other constraints into account while seeking an effective operational optimum. With the advent of the P4 language and programmable networks, engineers can now control how networks respond, learn to intervene, and optimize their behavior to make them more efficient and responsive to the needs. The goal of this study is to determine if a reinforcement learning strategy can enable an agent to route flows through a complex network topology in the most optimal way. The methods developed will aim to deal with simulated traffic surges by delaying the queues on certain switches. To simulate the disabling of routes, manual intervention will be done to simulate a route being disabled.

### **Phase-Encoding Mask in Photoacoustic Computed Tomography for Transcranial Human Brain Imaging**

Wenhan (Danny) Guo

*Mentors: Lihong Wang and Manxiu Cui*

Abstract withheld from publication at mentor's request.

### **Multi-Modal Self-Supervised Learning for Surgical Feedback Effectiveness Assessment**

Arushi Gupta

*Mentors: Anima Anandkumar and Jiayun Wang*

During surgical training, real-time feedback from trainers to trainees is important for preventing errors and enhancing long-term skill acquisition. Accurately predicting the effectiveness of this feedback, specifically whether it leads to a change in trainee behavior, is crucial for developing methods for improving surgical training and education. However, relying on human annotations to assess feedback effectiveness is laborious and prone to biases, underscoring the need for an automated, scalable, and objective method. Creating such an automated system poses challenges, as it requires an understanding of both the verbal feedback delivered by the trainer and the visual context of the real-time surgical scene. To address this, we propose a method that integrates information from transcribed verbal feedback and corresponding surgical video to predict feedback effectiveness. Our findings show that both transcribed feedback and surgical video are individually predictive of trainee behavior changes, and their combination achieves an AUROC of  $0.70 \pm 0.02$ , improving prediction accuracy by up to 6.6%. Additionally, we introduce self-supervised fine-tuning as a strategy for enhancing surgical video representation learning, which is scalable and further enhances prediction performance. Our results demonstrate the potential of multi-modal learning to advance the automated assessment of surgical feedback.

### **Probing Changes in Neural Representations During Training of Complex Decision Tasks: From Novice to Mastery**

Ashug Gurijala

*Mentors: John P. O'Doherty and Sneha Aenugu*

Skill improvement has been a recently trending topic, but the difference between a novice and an expert in a field cannot easily be pinpointed. A key aspect of skill improvement is the development of efficient state-space encodings. As a human learns a task, they understand which information to focus on, and which irrelevant details can be abstracted away. This study aims to provide an understanding of how neural representations evolve over time, through a proposed platform allowing measurement of detail abstraction abilities over time. Furthermore, machine learning models are used as a comparison benchmark to verify if neural agents are indeed viable models of human skill improvement. If the evolution of detail abstraction can be pinpointed to specific neural circuitry, learning systems can be developed to allow humans to more efficiently improve at general tasks.

### **Investigating the Effect of Membrane Composition on a Synthetic Cell-Based Biosensor Utilizing the NarX-L Two-Component System**

Dylan Hakken

*Mentor: Richard M. Murray*

Synthetic cells are non-living biomimetic vesicles with the potential to sense external stimuli and propagate the signal. Using the two-component system NarX-L, a synthetic cell is able to sense nitrate and fluoresce in response by expressing GFP. Because synthetic cells can be designed to fit a specific purpose, understanding how the composition of the synthetic membrane affects the function of membrane proteins is crucial. This project explores how membrane features such as chain length and the ratio between different lipids affect the function of the NarX membrane protein. A total of 25 compositions have been evaluated including vesicles made of 100% DMPC, DPPC, and DLPC to elucidate the role of chain length, as well as 90:10, 50:50, and 10:90 ratios between POPC and DOPC, DMPC, DPPC, DLPC, POPE, POPG, and *E. coli* polar lipid extract. We have demonstrated that nitrate negatively affects the natural fluorescence of the *E. coli* cell lysate TXTL, and DOPC vesicles enable greater total fluorescence over vesicles made of a mixture of 70% POPC and 30% POPE or POPG.

### **Vision-Language Transformer for Prediction of Homeostatic States and Behavior in Mice**

Jadon Hale

*Mentors: David Anderson and Aditya Nair*

Achieving a quantitative understanding of naturalistic animal behavior is a critical preliminary step in neuroscience, essential for correlating behavior with neural activity. Traditional approaches to behavioral analysis, which aim to generate annotations of behavior, often involve estimating animal pose. This process is not only time-consuming and computationally demanding but also faces challenges in generalizing across different environments. Consequently, contemporary machine-learning assisted methods still require labor-intensive manual verification of model generated annotations. In this work we introduce a new paradigm of transformer-based behavioral classification and discovery using Contrastive Language-Image Pretrained (CLIP) vision-language transformer models to produce visual embeddings of images of mice homeostatic behaviors. Lightweight regression models can then be trained to predict frame-wise behavioral labels or homeostatic states of hunger from those embeddings. Preliminary results show that with merely 20k frames sampled across six different videos of resident-intruder interactions, our pipeline is able to achieve state of the art accuracy in distinguishing eating behavior from social behaviors and is able to distinguish the hunger state (fed vs. fasted) of the resident mouse with upwards of 96% accuracy on relatively little training data. We aim to produce a software platform to both classify mouse behavior in naturalistic assays as well as leverage language models to perform behavioral reasoning and unsupervised discovery of novel behaviors from raw video.

### **DSMC Analysis of Rocket Plume on PILLARS**

Kieran Hale

*Mentors: Soon-Jo Chung and Lily Coffin*

The Caltech Air and Outer Space Club was a finalist in the 2024 NASA Big Idea Challenge with our proposal titled PILLARS (Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding)—a technology designed to enable a sustained lunar human presence by shielding lunar infrastructure from the destructive high velocity lunar regolith that rocket plumes dislodge during landings and launches. In this work we present a numerical analysis of the interactions between rocket plumes, the lunar surface, and PILLARS. We use the direct simulation Monte Carlo (DSMC) method which is a fast and accurate simulation technique for rarefied flows to determine the temperature, pressure, and heat transfer coefficients that PILLARS will experience from rocket plumes under lunar conditions, simulated as the combustion product from three SpaceX Raptor Vacuum engines using LOX / CH<sub>4</sub> propellant. We estimate the variation of temperature, pressure, and heat transfer with the radius of the dust shield by performing simulations over a range of radiuses and interpolating over these data. Finally, we determine the optimal radius that minimizes the weight of PILLARS while maximizing its longevity and durability. Our work helps to validate the efficacy of the PILLARS technology in the lunar environment.

### **Characterizing Extended Lyman-Alpha Emission of Faint, High Redshift QSOs**

Charis Hall

*Mentors: Chuck Steidel and Evan H. Nunez*

Investigating the circumgalactic medium (CGM), of distant galaxies with actively accreting supermassive black holes (QSOs) is important for understanding the role of extended cold gas in galaxy evolution. Observing bright emission lines such as Lyman-Alpha (Ly $\alpha$ ) is particularly useful for detectability. Due to its role as a tracer of photoionized gas, the presence of diffuse Ly $\alpha$  emission can tell us more about the structure of cool gas within the CGM and the sources responsible for ionizing it. Studying Ly $\alpha$  emission from low luminosity, broad-line QSOs will aid in our understanding of why these intrinsically faint objects still exhibit characteristics of hyper-luminous QSOs. In this study, we characterize the spatially extended Ly $\alpha$  emission of a sample of faint QSOs, using integral field unit (IFU) data cubes provided by the Keck Cosmic Webb Imager (KCWI). We aim to make a comprehensive comparison of Ly $\alpha$  emission within the sample, investigating:



- the kinematics of the extended emission and their velocities relative to the QSO rest frame
- the spatial extent, surface brightness distribution, and asymmetry of the emission
- the luminosity of the extended emission compared to the central QSO

This analysis would ultimately contribute to the broader goal of defining exactly what constitutes a faint QSO – i.e., whether these objects represent low level activity in a massive black hole, high-level activity in a much lower mass black hole, or perhaps something else altogether.

### **Exploring the Role of Colibactin-Induced DNA Damage in the Pro-Inflammatory Signaling**

Farah Hasanain

*Mentors: Daniel Semlow and Shuangshuang Xie*

Polyketide synthase *Escherichia coli* (pks+ *E. coli*) are bacteria implicated in inflammatory bowel disease (IBD) and colorectal cancer (CRC). These bacteria produce colibactin, a genotoxic secondary metabolite that induces DNA interstrand cross-links (ICLs) through the reaction of its cyclopropane groups with the N3 positions of deoxyadenosine in DNA. This leads to significant DNA damage, triggering inflammatory responses.

Chronic inflammation is a factor in the progression of IBD and CRC. DNA damage can provoke an immune response, activating specific inflammatory signaling pathways. Persistent DNA damage may result in the release of DNA fragments within the cell, further amplifying inflammation. A crucial pathway in this process is the cGAS-STING pathway.

This study aims to elucidate the connection between colibactin-induced DNA damage and the activation of the cGAS-STING pathway, which influences inflammatory responses. We hypothesize that unresolved colibactin-induced DNA damage activates the cGAS-STING pathway, leading to the activation of downstream inflammatory signaling, particularly the IRF3 and NF- $\kappa$ B pathways.

To test this hypothesis, HT29 (colorectal cancer cells) will be treated with hydroxyurea, which will serve as the control and colibactin, the experimental main target, along with a cGAS inhibitor. We will use qPCR to measure the expression fold change of type I interferon transcripts, TNF-Alpha, and IL-6 transcripts to assess the activation of the IRF3 and NF- $\kappa$ B signaling pathways, respectively. We expect colibactin-treated cells to show increased levels of type I interferon transcripts, TNF-Alpha, and IL-6, indicating IRF3 and NF- $\kappa$ B pathways activation through inducing the cGAS-STING pathway. In addition, this increase should be reduced when cells are co-treated with a cGAS inhibitor.

Our current findings show that upon treating cells with hydroxyurea, the cGAS-STING pathway is activated, and the levels of type I interferons, in addition to IL-6 and TNF-alpha, were significantly increased. Further experiments will be conducted in the following weeks to examine the activation of the cGAS-STING pathway upon treating the cells with colibactin.

This research will enhance our understanding of how colibactin-induced DNA damage leads to inflammation, potentially contributing to the progression of IBD and CRC.

### **Probing the Weak Interaction With Intermediate Mass Sterile Neutrinos in the Early Universe**

Blake Hawkins

*Mentors: Chad Kishimoto and Elias Most*

Neutrino oscillation experiments suggest that the active (left-handed) neutrino species have non-zero masses, hinting at the existence of a fourth, sterile (right-handed) neutrino species. Unlike active neutrino species, sterile neutrinos do not interact via the weak nuclear force except through a sub-weak interaction arising from active-sterile neutrino mixing, making them extremely difficult to probe in Earth-based laboratories. We simulate the effects of intermediate mass sterile neutrinos that are thermally populated in the early universe and that decay into Standard Model particles around the time of Big Bang Nucleosynthesis. As the sterile neutrinos decay, they deposit a significant amount of entropy into the plasma which is tractable in observations of anisotropies in the CMB. Our simulation can be leveraged alongside CMB stage 4 observations of cosmological observables such as the effective number of active-neutrino species and primordial abundances to permit improved constraints on, or indications of, Beyond Standard Model (BSM) physics.

### **A Platform for Arbitrary Vortex Pair Generation to Study the Cylindrical Crow Instability**

Axel Haydt

*Mentors: Joseph Shepherd and Michael Wadas*

A vortex ring is a closed loop of fluid within which rotation dominates straining-type motion. When vortex rings collide head on, they create an expanding vortex pair subject to the Crow instability (CI), which famously results in the reorganization of the original two rings into a series of evenly spaced secondary ringlets. Experiments exploring

these physics, however, face significant spatiotemporal alignment challenges and are constrained in the types of vortex pairs that may be produced. Our objective is therefore to overcome these limitations with a novel platform for generating arbitrary vortex pairs. In our new radial-jet approach, two circular plates are separated, and fluid is injected through a hole in the top plate, expanding radially outwards through the space between the plates. As the fluid exits the plates, its interaction with the stationary surrounding fluids causes it to roll up into a vortex pair. These design choices allow for easier vortex collision testing and rapid collection of a large variety of vortex collision data. An inward-pointing radial jet further enables the examination of the CI with a reversible base flow, uncovering novel vortex behavior.

### **Liquid Shock Absorber Impact Force Attenuation in Helmets for Prevention of Traumatic Brain Injury During Impacts With Free Motion**

Claire Hays

*Mentors: David Camarillo, Jessica Towns, and Wei Gao*

Personal protective equipment (PPE) like helmets can play a crucial role in preventing traumatic brain injuries (TBIs) during sports or other activities. Since rotational forces are believed to be the primary cause of mild TBI, it is essential to test helmets under conditions that allow for such motion. In this study, we developed and tested a drop test setup that allows unrestricted motion of the helmeted headform following impact. This setup was used to evaluate the performance of novel liquid shock absorbing technology integrated into commercial equestrian helmets at two impact locations (side and back of the head). During an impact, the liquid is forced through an orifice, resulting in a pressure drop that partially contradicts the impact force, potentially reducing angular kinematics. The helmet prototypes were tested in comparison to unmodified control helmets. The results validated the new drop test setup, demonstrating its effectiveness and repeatability for future tests, and allowing for the assessment of impacts with more range of motion, similar to real-world scenarios. Additionally, this study offered valuable insights into the potential for liquid shock absorber units to reduce the negative implications of an impact when used in helmets.

### **Using Conditional Generative Models to Solve Inverse Problems**

Aaron Henslovitz

*Mentor: Ricardo Baptista*

When solving an inverse problem through Bayesian inference, a closed form of the posterior distribution is often not directly known. Instead, sampling algorithms such as Markov chain Monte Carlo (MCMC) are used to generate samples of the posterior distribution so that it may be characterized. However, MCMC-based sampling is computationally inefficient with each new set of observations and can lead to high correlation between samples. Conditional generative adversarial networks (cGAN) offer an alternative by learning a mapping from a simple, easily sampled distribution to the desired posterior distribution. Evaluating the cGAN enables the generation of independent samples from the posterior for any observation, thereby amortizing the cost of inference over the data. This work aims to solve a set of 11 benchmark inverse problems in science and engineering using both MCMC and cGAN methods. The performance of the cGAN framework will be evaluated under various settings, including the number of model parameters and the number of model evaluations, to assess its efficiency and accuracy compared to traditional MCMC methods.

### **Point of Zero Charge Analysis of Oxide-Coated Copper Electrocatalysts for CO<sub>2</sub> Reduction Reaction**

Noah Hicks

*Mentors: Raffaella Buonsanti, Petru Albertini, and Nathan Lewis*

The electrochemical CO<sub>2</sub> reduction reaction (CO<sub>2</sub>RR) holds the promise of closing the carbon loop while utilizing renewable energy sources. Previously, the host group has shown that inorganic/organic hybrid oxide coatings grown via colloidal-ALD (c-ALD) confer stability to copper nanocatalysts during CO<sub>2</sub>RR. In this work, we investigate the impact of these coatings on the point of zero charge (PZC) of the copper nanocatalysts. The PZC provides information on the surface charging and thus is connected to electronic effects which can impact catalyst selectivity. In particular, we compare coatings with different porosity to enhance our understanding of the copper|metal oxide interface. We use staircase potentiostatic electrochemical impedance spectroscopy to measure the PZC. We employ both single frequency impedance measurements and complete impedance spectra fit to an equivalent electrical circuit to extract the capacitance values. Finally, we connect the PZC analysis to the demonstrated selectivity of the copper nanocatalysts covered by the oxide coatings. This work contributes to advancing our understanding of copper|oxide interfaces in electrocatalysts for CO<sub>2</sub>RR so to further optimize their reactivity and stability.

### **3D Raman Spectroscopy and Laser-annealing for Perovskite/Silicon Tandem Solar Cells**

Hana Hisamune

*Mentors: Albert Polman, Harry Atwater, and Robin Schot*

Perovskite/silicon tandem solar cells, which combine a high-energy photon-absorbing perovskite top cell and a low-energy photon-absorbing silicon bottom cell, have the potential to exceed the maximum theoretical efficiency of

single-junction solar cells by harnessing a broader range of the solar spectrum. However, since perovskites tend to decompose when exposed to moisture, oxygen, excessive illumination, and heat, there is a major need for structural and compositional analysis of perovskite/silicon tandem solar cells. In this project, we explore confocal Raman microscopy with 532nm laser excitation as a contactless method to analyze the compositional variations and integrity of lead halide perovskites. Our results demonstrate that the high intensities involved in micro-Raman spectroscopy lead to burning and degradation of the perovskite samples. We perform Raman spectroscopy on perovskite precursor solution to investigate their crystallization dynamics and laser annealing as a potential fabrication technique. Furthermore, we examine the various layers of the tandem solar cell using Raman spectroscopy and acquire depth scans on 3D structures to lay the groundwork for comprehensive 3D Raman imaging of perovskite/silicon tandems.

**Tuning of Human Inferotemporal Cortex Responses in the Latency Domain**

Qianhui Hong

*Mentors: Ueli Rutishauser and Yingxi Jin*

Rate coding (the average number of spikes per unit time) and temporal coding (the precise timing of single spikes) are the two common neural coding mechanisms. While rate coding mechanisms have been extensively studied, the potential information carried by temporal coding remains underexplored. This project investigates the role of spike timing in the human inferotemporal cortex (IT cortex) to determine how neurons utilize latency differences to encode visual information beyond traditional rate coding. It aims to close this gap by analyzing the latency of neuronal responses to visual stimuli and comparing these responses to traditional rate metrics. Data were collected from 17 patients with depth electrodes for seizure monitoring while they performed serial reversal learning tasks. In each task, subjects were shown one of four unique images and had to discover what the correct response for each image was. Tempotron is used to decode latency codes to see if neurons can decode image categories after being trained with input spike trains. Preliminary results show that latency code can distinguish between image categories of the four stimuli. Future work will involve correlating these latency patterns with specific visual attributes of the stimuli.

**Observation of Parametric Multisolitons in Optical Microcavities**

Hanfei Hou

*Mentors: Kerry J. Vahala and Qing-Xin Ji*

Kerr solitons are ultrashort pulses with comb-like spectra generated in optical microcavities via a balance between Kerr nonlinearity and cavity dispersion. In recent years, they have been shown to display rich nonlinear dynamics and have revolutionized a wide series of frequency comb applications thanks to their integrated nature. However, certain specific applications including terahertz generation require special spectrum structures which are previously hard to realize for Kerr solitons. We observed and investigated a new dynamical behavior of Kerr solitons named parametric multisolitons, where a new soliton is derived from a pump soliton via Kerr parametric gain under specially designed dispersion. The solitons are also demonstrated to possess good tunability and controllability, and their spectra are well suitable for terahertz comb generation. This work provides new insight into nonlinear soliton dynamics in optical microcavities and points out a possible method to realize chip-based terahertz comb sources. Further demonstrations are needed to exploit the potential of parametric multisolitons for the application.

**Testing Carbon Absorption and Desorption of Potassium Carbonate Sorbents**

Noah Howell

*Mentors: Melany Hunt, Ricardo Hernandez, and Hannah Szentkuti*

Capturing carbon emissions at their source in power plants is a promising way to reduce emissions globally. The main challenge for point source capture is creating an effective, reusable, and cheap sorbent. Potassium carbonate has shown promise for capture, but current formulations have poor capacity and kinetics. Here we placed the sorbents in a reactor flowing with 10% CO<sub>2</sub> and 90% Ar and water vapor at 65°C and recorded the absorption by measuring the ratio of CO<sub>2</sub> to Ar with mass spectrometry. We have developed sorbents using a potassium bicarbonate/potassium carbonate mixture and bentonite clay as the main active ingredients. This formulation performs 2-3 times better than mixtures without bicarbonate or bentonite clay. When dried at 600°C rather than the standard of 180°C, the sorbents behave oddly, some with exceptional capacity and others with poor capacity in the same batch, which stimulated further investigations. Dissolution tests show that the 600°C sorbent does not dissolve easily in water unlike the 180°C sorbents, implying a chemical reaction having happened during drying.

**Investigating the Flexure Joint's Response to Forces in *Drosophila* and Blowflies**

Renee Hsu

*Mentor: Michael H. Dickinson*

Insects are the most species-rich group of metazoans in the history of life and their ability to fly is undoubtedly the secret to this success. Unlike birds, bats, and pterosaurs, insect wings did not evolve from their legs, but rather represent an entirely novel structure. One of the reasons behind the speedy flight of Dipteran organisms is the presence of an elastic material called resilin in distinctive patches across the ventral and dorsal areas of Dipteran

wings and at the base of the *Drosophila* fly wing specifically. The *Drosophila* flexure joint is a recently discovered structure that stores and recovers initial elastic energy from resilin at the wing base. It is probable that this flexure joint is present in other Dipteran species such as the blowfly. This project aims to 1) determine if the flexure joint is present in blowflies and 2) to evaluate the flexure joint's response to forces across these two types of Dipteran insects through measurements of torque and angle.

### **Optimization of Gelatin Methacrylate Hydrogels for 3D dHL-60 Culture: Effect of Mechanical Cues on Neutrophil Differentiation and Activation**

Annie Hu

*Mentors: Kaustabh Ghosh and Mitchell Guttman*

Diabetic retinopathy (DR) is a diabetes-induced microvascular complication of the retina, and the primary cause of vision loss in the working age population. In inflammatory pathways leading to early-stage DR acellular vessel formation, activated retinal endothelial cells (ECs) bind to leukocytes and cause them to release cytotoxic factors. Among leukocytes, neutrophils are a major contributor to EC death in DR, releasing cytotoxic neutrophil elastase. Our lab has recently discovered that lysyl oxidase (LOX), a matrix crosslinking and stiffening enzyme which mechanically activates retinal ECs, also activates neutrophils in its soluble form. Interestingly, recent immunostaining of mouse bone marrow (BM), which houses the neutrophils, shows significant LOX upregulation in diabetes. Since neutrophils originate from the BM, it is possible that LOX activates neutrophils in the BM even before they enter circulation and reach the retina. Further, since LOX crosslinks and stiffens collagen-rich matrix, it may 'mechanically' activate neutrophils via an increase in BM stiffness. We aim to use 3D BM-mimicking hydrogels to determine whether matrix stiffness can mechanically activate and differentiate neutrophils. The main focus of this study is to optimize HL-60 (neutrophil-like) cell viability within 3D gelatin-methacrylate hydrogels, which is a prerequisite for using these 3D hydrogels to promote HL-60 differentiation. Initially we found lower viability readings for cells encapsulated in 3D culture when compared to a 2D suspension control. However, subsequent experimentation revealed that the unfavorable result was an artifact of the hydrogel, which had hindered penetration of the viability reagent. Despite this success, we have found low viability readings (30% of initial luminescence) for HL-60 in 3D hydrogels, compared to a 3D standard curve, after a longer period of time (3 days). Testing different gel formulations to optimize 3-day viability, we currently have findings which implicate that increased stiffness of GelMA hydrogels causes lower HL-60 viability.

### **Video-based Analysis of Social Behaviors in Children With Autism**

Chia-Yu Hu

*Mentors: Ralph Adolphs, Lynn K. Paul, Shuo Wang, Xiangxu Yu, and Mindi Ruan*

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by difficulties in social interactions. The standard diagnostic method, the Autism Diagnostic Observation Schedule - 2 (ADOS-2), is time-consuming and requires trained clinicians. This study aims to apply computer vision and machine learning to analyze the behavior of children with ASD. Our dataset consists of 247 videos from participants with ASD and 215 videos from controls, with each recording featuring parents performing assigned interactions with their children. The data was evaluated in both audio and video aspects. For audio analysis, we used Deepgram to transcribe the conversations and obtained timestamps of parents saying keywords to observe children's responses. The coordinates of 25 body keypoints of people in the videos were extracted using OpenPose, although OpenPose tended to misdetect background objects as humans. After preprocessing, the children's skeleton data was analyzed using a pre-trained MMSkeleton model for action recognition, combined with a self-defined classifier to distinguish ASD from the control group. Taken together, various problems were addressed to yield a useful pipeline for the analysis of audiovisual features from videos that machine learning algorithms are able to use to detect autism.

### **Creating a Ray-Marching Mesh Renderer in Taichi Lang to Generate Two-Tone Mooney Image Stimuli**

Jennifer Hu

*Mentors: Ilker Yildirim, Hakan Yilmaz, and Pietro Perona*

Psychophysics experiments have been used multiple times to inform the robust ability of the human visual system to form strong 3D percepts of degraded image modalities, such as silhouettes or two-toned "mooney" images. One experiment observed this ability using realistic 3D models of human bodies physically rendered as 2D images, then thresholded by an average light value to form a two-tone mooney image. To improve on the speed and realism of stimulus generation for this experiment, we attempted to replicate the mooney image rendering pipeline by building a ray-marching renderer in Taichi Lang, a parallel programming language embedded in Python. Using a SIREN model to fit a signed distance function to an obj mesh resulted in slower renders which sometimes lacked articulate limbs and had artifact surface holes. Voxelizing the mesh resulted in clear and quick renders, but reduced the realism of the stimuli. For similar psychophysics experiments using familiar stimuli outside of human bodies as well, some mooney images of tetris-block shaped objects were rendered.

### **Using Causal Machine Learning to Explore the Role of Climate Change, Air Pollution, and Genetics in the Aging of People With HIV**

Ryan Hu

*Mentors: R. Michael Alvarez and Cong Cao*

Individuals living with HIV (PLWH) demonstrate an expedited aging process in comparison to their counterparts without HIV (PLWoH) of the same age. Studies have attempted to investigate the impact of DNA methylation age and external factors in environmental epidemiology. Despite these efforts, there is a gap in research focusing on pinpointing significant epigenetic and environmental alterations linked to aging in PLWH. There exists data suggesting climate change and air pollution may speed up this process. This project aims to explore this relationship to find out if climate change and air pollution speeds up the aging process in PLWH faster than it does in PLWoH. Preexisting data has already been collected from men living with HIV and men living without HIV which informs us how fast these people are aging. Combining that data with historical data on air pollution and weather in areas where those people live, we apply various feature selection and causal machine learning approaches including gradient-boosting trees to explore this relationship. Ultimately, we will provide information that may guide both climate and public health policies for mitigating the effects of climate on the aging of PLWH.

### **Investigating Amygdala Function With Naturalistic Movie-fMRI**

Simon Hu

*Mentors: Ralph Adolphs and Zach Diamandis*

Traditionally, the amygdala has been known as the “fear center”, acting as the part of the brain responsible for processing threats. However, recent studies suggest that this role of the amygdala is outdated, and research suggests that its role is clearer in social domains. Functional magnetic resonance imaging (fMRI) is a commonly used imaging paradigm in cognitive neuroscience to study the brain’s structure and activity, but a majority of studies typically focus on cortical structures of the brain while subcortical regions, like the amygdala, have yet to be deeply explored. In this study, we scanned the brains of participants while they watched the movie *Forrest Gump* with the purpose of analyzing brain responses to emotions in naturalistic conditions. Encoding models were fit to explain the participants’ brain activity as a function of various semantic features, which included the movie’s portrayed and elicited emotions, arousal (level of emotional response), valence (positive or negative), and music. Through feature engineering and various data quality checks, initial data hints at a significant amygdala response in response to the movie’s portrayed emotions. Understanding the neuronal mechanisms underlying emotion can help illuminate the psychopathology of psychiatric disorders, paving the way for improved treatments and diagnoses for patients with these disorders.

### **Volume Growth of One-Relator Cayley Graphs and Complexes**

Dongming (Merrick) Hua

*Mentor: Antoine Song*

Recent work has highlighted the importance of understanding how varying a Riemannian metric on a thin tubular neighborhood of a smooth curve can change the volume entropy. A similar question in a more discrete setting, the growth of a Cayley graph obtained by quotienting a free group by a single relation, is understood in the generic case (with high probability as the length of the relation goes to infinity) due to work of Shukhov.

We study an intermediate problem, namely the growth of weighted one-relator Cayley graphs where different generators may be assigned different weights. We confirm that the results from the unweighted setting still hold, so that generically the growth of the weighted Cayley graph approaches that of the corresponding weighted free group. As a further step towards the manifold setting, we also study the volume growth of one-relator complexes, where we attach a 2-disc to a bouquet of circles along the given relator. We show that if the diameter of the disc does not grow sufficiently fast, then the volume entropy diverges to infinity as the length of the relator grows.

### **A Model Predictive Control Framework for Legged Robotics Systems**

Gavin Hua

*Mentors: Aaron Ames and Zachary Olkin*

Model Predictive Control (MPC) is a form of optimization-based control that is widely used by researchers in legged robotics control to plan and execute trajectories, especially in tasks that require dynamic gaits, where transitions are not statically stable. Existing MPC libraries focus on implementing its general mathematical form and are either not specialized for robotics systems or provide one type of reduced order model. This project aims to design and implement a Toolbox for Optimization, Robotics and Control (TORC) specifically for MPC’s robotics applications. Through interfacing with required libraries such as nonlinear optimization solvers (IPOPT), auto-differentiation (CppAD), and efficient rigid-body algorithms (Pinocchio), as well as including a suite of commonly used reduced order models, this framework provides control stack designers with a simple interface to define and implement MPC controllers.

**Wearable Sensor Chip Validation Testing and Characterization**

Fangyao Huang

*Mentors: Azita Emami and Shawn Sheng*

The ONR chip developed in the Mixed-mode Integrated Circuits (MICS) Lab is a collaborative effort with Professor Wei Gao's lab to develop a novel wearable sensor that is capable of noninvasive drug delivery and sweat analysis. The design and fabrication of the asic is complete, but in order to advance to the next stage of testing, the chip needs to undergo extensive testing and characterization in order to ensure safe and predictable operation. This project seeks to bring all functionalities online and obtain a complete characterization of the various onboard sensors.

**Image-Plane Correction for the OVRO-LWA Radio Telescope**

Zachary Huang

*Mentors: Gregg Hallinan, Casey Law, and Liam Connor*

The Owens Valley Radio Observatory's Long Wavelength Array (OVRO-LWA) images the entire visible night sky at low frequencies (from 15 MHz to 85 MHz) at up to once every 10 seconds. However, the measurements made are imperfect due to the refraction of radio waves caused by the ionosphere. Correcting for refractive shifts is critical to producing accurate all-sky maps, which helps to facilitate the search for transient radio signals produced by exoplanets, coronal mass ejections, stellar explosions, neutron star mergers, etc. The goal of this project is to explore different dewarping algorithms and apply them to OVRO-LWA data to correct for refraction in the image plane. The existing Fits\_Warp dewarping algorithm introduced by Hurley-Walker & Hancock is implemented and verified as a baseline. We also introduce a new approach based on optical flow to directly infer pixel offsets representing refractive shifts in an image. This approach can also be extended to extrapolate to out-of-band frequencies and/or infer ionospheric electron densities. The models will be evaluated on their effectiveness, computational efficiency, and applicability to real-world data.

**Investigating Potential PCNA-Binding Motifs on NEIL3 Using Co-Immunoprecipitation Assays**

Dung Huynh

*Mentor: Daniel Semlow*

During eukaryotic interstrand cross-link repair, cross-links are resolved by DNA interstrand crosslinks (ICLs) are highly toxic DNA lesions where opposite DNA strands are covalently linked, significantly hindering DNA replication. As such, there are multiple replication-coupled ICL repair pathways. The NEIL3-dependent pathway uses the glycosylase NEIL3 to cleave the N-glycosyl bond of the ICL, resolving the lesion and resulting in an abasic site in its place. NEIL3 contains two domains: a catalytic glycosylase domain and a disordered C-terminal domain. Previous studies suggest that interactions between NEIL3's glycosylase domain and proliferating cell nuclear antigen (PCNA) is required for NEIL3 recruitment to the ICL, although the interaction surface is unmapped. Using AlphaFold, the Semlow lab predicts an interaction motif on NEIL3 that binds to PCNA's hydrophobic pocket. With a co-immunoprecipitation assay, we show that despite AlphaFold's predictions, mutating the interaction motif does not obstruct NEIL3's interactions with PCNA, suggesting another unmapped interaction motif on NEIL3. We then synthesized 12 mutants across NEIL3's glycosylase domain in search for the interacting motif, to further investigate this interaction.

**Neural Mechanisms Underlying Hunger-Driven Modulation of Social Behaviors in Mice**

Sophia Huynh

*Mentors: David Anderson and Jineun Kim*

In natural environments, animals frequently encounter multiple, often conflicting stimuli that require adaptive behavioral responses. Our study explored how hunger influences territorial aggression and mating behaviors in male mice when they encounter conspecific intruders and available food. We found that male mice that fasted for over 24 hours exhibited suppressed aggression and decreased sexual drive. In contrast, those who fasted for less than 22 hours displayed heightened aggressive behaviors, characterized by a reduced latency to the first attack. We aimed to understand how neurons within the ventrolateral subdivision of the ventromedial hypothalamus (VMHvl), known for regulating social behaviors such as mating and aggression, integrate environmental cues with internal physiological states like hunger. Our behavioral and neural observations led us to hypothesize that VMHvl neurons may be modulated by hunger-regulating Agouti-Related Peptide (AgRP) neurons in the arcuate nucleus (ARC). Using chemogenetics to manipulate ARC<sup>AgRP</sup> activity, we observed that this neuronal activity plays a significant role in aggression and mating behaviors modulated by hunger. Our results suggest that ARC<sup>AgRP</sup> neurons significantly influence VMHvl-governed social behaviors in hungry mice, highlighting the importance of integrating circuit-level models of individual internal states into a systems-level understanding of behavior in response to complex stimuli.

**A Hartree-Fock Study of Quenched Disorder in Sachdev-Ye-Kitaev Models**

Amir Ibrahim

*Mentors: Siddharth Parameswaran and Olexei Motrunich*

The Sachdev-Ye-Kitaev (SYK) model has emerged as a paradigmatic model in both condensed matter and high-energy physics: originally introduced as a model for quantum spin glass behavior, in recent years it has attracted renewed interest as a solvable model of holography as well as intriguing properties linked to quantum information scrambling, black holes physics, and non-Fermi liquid behavior. The SYK model is a disordered quartic Hamiltonian defined in terms of Gaussian-distributed random couplings, and, as such, it is subject to the usual difficulties involved in exact computation of quantum many-body systems, and precise results are difficult to come by. Bearing this in mind, in this project, I have applied standard many-body self-consistent mean-field techniques (Hartree-Fock-Bogoliubov) to benchmark the extent to which quantum variational methods can capture non-Fermi liquid behavior, and I will present a detailed comparison of the numerical results from both the variational algorithm and exact diagonalization.

**Exploring New Constructions of Quantum Codes With Low-Weight Measurements**

Jun Ikeda

*Mentors: John Preskill, Nathanan Tantivasadakarn, and Margarita Davydova*

Floquet code is a family of quantum correction code defined on  $D + 1$  colorable  $D$  dimensional graph whose mutually anticommute check measurement operators associated with the colors are periodic in time. Its smaller weight makes it easier to be physically realized. In this project, we generalized a procedure to first construct a color code from homological product codes, and then to Floquetize it. We also aim to generalize the color code construction of 2D product code to 3D product code. In this report, we present the generalized floquetization and its some disappointing properties, and our current attempt to construct a color code from 3D homological product code.

**Transit Timing Variations Reveal a Second Planet in the Kepler-1624 System**

Haedam Im

*Mentors: Heather Knutson and Morgan Sidel*

The presence or absence of nearby low-mass planetary companions can be used to constrain the formation and migration histories of gas giant planets on close-in orbits. While transits of a planet in a Keplerian orbit are strictly periodic, the timing of transits may deviate for dynamically interacting systems with multiple planets. In this study, we measure transit timing variations (TTVs) of Kepler-1624b, a Neptune-like planet orbiting a low-mass M star, which reveal the presence of a non-transiting outer companion. We reanalyze the transits from archival Kepler data and combine these with a new transit observation obtained using the Wide-field InfraRed Camera (WIRC) on the 200-inch Hale Telescope at Palomar Observatory. Our transit midtimes display clear variations, indicating the presence of a less massive planet in an exterior orbit. We fit these TTVs with a dynamical model in order to reveal the physical properties of the outer companion, and to constrain the mass and bulk density of the inner planet. We conclude that if both planets migrated inward from a more distant formation location, they must have done so via viscous interactions with the protoplanetary gas disk in order to avoid destabilizing the system and ejecting the lower mass companion.

**A Type System for LaTeX-Written Proofs in Discrete Mathematics**

Divin Irakiza

*Mentor: Adam Blank*

Writing rigorous discrete mathematical proofs is a challenge for students who have not taken proof-intensive courses. Similar to how a compiler checks the types of variables and is able to infer the types of some expressions in a programming language, this project builds a type system to perform type classification, type checking, type inference, type consistency checks, and type-error detection on mathematical expressions. The tool is specifically designed as a platform for students enrolled in CS13 (Mathematics for Computer Science) at the California Institute of Technology, a course that requires constructing rigorous proofs in discrete mathematics. Given that the proofs in this class must be written in LaTeX, the tool processes LaTeX-written proofs by using common proof patterns to match and extract relevant textual and mathematical content. The type system is then employed to ensure the proof is type-error free. The tool highlights any issues in the LaTeX document as detailed feedback to help students learn and improve their proof-writing skills.

**Investigating the Biological Mechanism of N<sub>2</sub>O Omissions From Arid Southern Californian Drylands**

Emma Isella

*Mentors: Dianne Newman and Lydia Varesio*

Nitrous oxide (N<sub>2</sub>O) is a powerful greenhouse gas, each molecule capable of warming the atmosphere 273 times more effectively than CO<sub>2</sub>. Arid soils after rainfall events have the highest N<sub>2</sub>O emission rates recorded globally. Recent work has shown that the majority of these emissions are biologically produced. While these emissions have

classically been attributed to denitrification, measured  $N_2O$  isotopic fingerprinting (site preference, SP) more closely matches enzymes involved in detoxification. We hypothesize that nitric oxide (NO) detoxification pathways are responsible for the initial burst of  $N_2O$  production after rainfall, with denitrification only becoming dominant after a few hours. Using coupled measurements of soil oxygen concentration and  $N_2O$  production, we show  $N_2O$  production begins only once the added water depletes the soil of oxygen. We plan to use targeted mass spectrometry to observe the ratio of Fhp over NOR proteins as  $N_2O$  is produced and assess the SP fingerprint of the produced  $N_2O$ . We expect the Fhp:NOR ratio and the SP value to decrease over time post-wetting, indicating a shift from detoxification to denitrification. We thus suggest that previously overlooked detoxification pathways can have dominant roles in observed biogeochemical events, as is the case with these  $N_2O$  emissions.

### **Nickel-Catalyzed Enantioconvergent Cross-Coupling of Racemic Tertiary Alkyl Reagents**

Kyra Jackson

*Mentors: Gregory C. Fu and Jason Rygus*

Pharmaceutical success is increasingly correlated with the architectural complexity of molecules, and quaternary stereocenters ( $sp^3$ -hybridized, all-carbon junctions) provide rich scaffolds for such discoveries. Despite their promise, strategies for forming these quaternary centers are limited; tertiary-tertiary couplings are sterically hindered, making them difficult to accomplish. Further, developing a stereoconvergent method for this coupling—one that controls the stereochemical configuration of the product using readily available, racemic starting materials—is even more challenging and powerful. Using a chiral nickel catalyst, we have made progress coupling tertiary  $\alpha$ -bromoester electrophiles and racemic tertiary organozinc nucleophiles to form and control quaternary stereocenters. Condition optimization to maximize product yield and enantiomeric excess is ongoing. Once fully developed, the reaction would help unlock synthetic access to a new variety of highly dimensional bioactive agents.

### **Forward Flux Sampling of DNA Tile Self-Assembly Programmed to Nucleate Combinatorial Decisions**

Ritali Jain

*Mentors: Erik Winfree and Cameron Chalk*

The complexity of signals and interactions in molecular environments suggests that biological systems are capable of high-dimensional processing and computation. The field of molecular computing has demonstrated concrete mechanisms that could equip biology to solve combinatorial problems, including stochastic chemical reaction networks and exponentially parallelized DNA tile assembly systems. However, current constructions depend on exponential space requirements, whereas we suspect that the spatial dimension of the problem can be reduced by packing computation into geometry via local binding interactions. Inspired by the direct mapping between programmable DNA tiles and mathematical Wang tiles—which can serve as primitives for formulating NP-complete problems—we provide evidence that passive DNA tiling systems can solve computationally hard problems within constrained space. We designed a set of DNA tiles that nucleates via self-assembly to explore solutions to the bounded tiling problem. We characterized our tile sets via nucleation kinetics and trajectory-based analysis under the forward flux sampling (FFS) model for rare event characterization. Our computational results showed that successful assemblies generally search and find solutions to input tiling instances. We also consider caveats of sampling methods for nucleation processes, as well as properties of critical nuclei, with valuable implications for nucleation theory. In doing so, our work not only provides support for solving NP-complete problems on the other face of the space-time tradeoff, but also lifts the study of NP-complete problems from a thermodynamic to a kinetic standpoint. Further refinement and experimental validation of these tiling systems would reinforce our evidence that by embedding computational power into geometry, nucleation is a viable mechanism for biology to perform complex functions.

### **Geochemistry of the Skalbreydur Volcano, Iceland**

Mehul Jangir

*Mentors: Saemundur Halldorsson and Simon Matthews*

Iceland has an extensive rock record of volcanic activity due to its position above the Mid Atlantic Ridge. Mid ocean ridge magmatism has led to both fissure and vent style eruptions that record geochemical signatures that trace the origin and evolution of parent magmas. In this paper, we examine these processes through a geochemical study of the Skalbreydur volcanic dome in Iceland's Western Volcanic Zone. We used previously obtained major and minor element chemistry and conducted IPCMS analysis to obtain trace element data for our sample suite. We also obtained lead isotope data. Geochemical indicators, such as  $K_2O/TiO_2$  and  $La/Yb$  ratios, and  $MgO$  content vary over time as the Skalbreydur eruption evolves, providing insights into the volcanic plumbing of the Western Volcanic zone. Variance of several indicators suggests that mantle material recharged the magma chamber underneath Skalbreydur.

### **Enantioselectivity Access to $\beta$ -Amino Acids via Selective C-H Bond Amination**

Ana Jaramillo

*Mentors: Frances Arnold and Julia Reisenbauer*

Abstract withheld from publication at mentor's request.



**Accelerated Medical Imaging With One-for-All Neural Operator Models**

Armeet Jatyani

*Mentor: Anima Anandkumar*

Traditional clinical imaging methods are bottlenecked by long test times, particularly in scenarios where patients cannot remain still for extended periods, leading to motion artifacts and unreadable results. In compressed sensing, imaging is accelerated by acquiring a small fraction of the original measurements, significantly reducing test times. Subsequent data-driven machine learning approaches are then used to reconstruct fully sampled images. However, current state-of-the-art methods are dependent on specific subsampling pattern methods and acceleration factors, necessitating training separate models for each setting. We propose a novel imaging framework that leverages the discretization invariance of neural operator component layers, enabling the training of universal models invariant to subsampling techniques. We show that our framework can be applied to existing architectures and pipelines for accelerated MRI, CT, and PACT imaging modalities. By reducing imaging times from hours to minutes and minutes to seconds, our approach could extend the utility of these modalities to new applications, such as real-time imaging of dynamic processes within the body.

**Understanding the Light Dark Matter eXperiment's Sensitivity to Visibly Decaying Axion-Like Particles**

Nathan Jay

*Mentors: David Hitlin and Sophie Middleton*

The proposed Light Dark Matter eXperiment (LDMX) will probe the MeV to GeV range in the search for dark matter, using the missing momentum approach. LDMX is theorized to be sensitive to axion-like particles (ALPs), but it must be shown that these particles can be discriminated against from the background. This project simulates photon-coupled ALPs and a photo nuclear background that originates from the electromagnetic calorimeter. Then, we utilize LDMX simulation software to reconstruct the generated samples. After determination of features that can discriminate between signal and background, a boosted decision tree is trained to separate ALP decay events. Optimizing the input variables will improve the model, working towards the eventual goal of obtaining a sensitivity estimate for these samples of ALPs.

**A Deep, Archival Search for Tidal Disruption Events and Rate Constraints**

Thuwaragesh Jayachandran

*Mentors: Vikram Ravi and Jean Somalwar*

Tidal Disruption Events (TDEs) occur when a star is shredded by the tidal forces of a supermassive black hole (SMBH), resulting in multiwavelength flares that provide crucial insights into quiescent black holes in distant galaxies. Despite their significance, TDE rates and their correlation with host galaxy properties remain unconstrained. Previous constraints have restricted the domain of TDEs, but recent discoveries suggest they could occur beyond traditional definitions. This project aims to address these challenges using re-processed archival data from the Zwicky Transient Facility (ZTF). By developing software and utilizing a novel approach of exponentially smoothed moving average (ESMA) filters to detect and classify flares from light curves, we aim to build a comprehensive and inclusive catalog of flares. These flares will be analyzed to extract physical parameters and study their correlations with host galaxy properties, ultimately forming a broader and more precise definition of TDEs to better understand them.

**Study of Cell-Cell Competition in a Human Epiblast Model**

Heather Jensen

*Mentors: Magdalena Žernicka-Goetz and Ikbal Choudhury*

The incidence of aneuploidy, or an abnormal number of chromosomes, is 73% during pre-implantation stages of development, but only 0.6% in live births. Trisomy (TS) is a type of aneuploidy in which there is an additional chromosome in a diploid cell. Most cases are lethal, unable to make it to term. The rarity of successful aneuploid fetuses indicates that there is an error correcting mechanism in embryos, which is under investigated. To make progress, we created lumenoids, which are stem-cell derived models of the human post-implantation epiblast to study cell-cell interaction between diploid and aneuploid cells at an unprecedented resolution. We created lumenoids from diploid cells using lines Hnes1 and Shef6 as well as ones originating from specific aneuploidies: TS12 and TS21. Then, we created mosaic lumenoids by adding 50% aneuploid cells and 50% fluorescently labelled diploid cells and analyzed the proportion of each type as they progress along the developmental trajectory. We found that there is an increased proportion of diploid cells in these mosaic structures, highlighting the fact that there is depletion of aneuploid cells caused by cell-cell competition. Surprisingly, we also noted that the cells in later stage lumenoids undergo epithelial-to-mesenchymal transition (EMT), a phenomenon reminiscent of gastrulation. We hope to expand on this data and discover the physical and molecular mechanisms underpinning cellular competition between normal and diseased cells using live-imaging and statistical analysis.

### **Intuitively Teleoperating a Mobile Robot With Eye Gaze Tracking and Brain Computer Interface**

Jihyun Jeon

*Mentors: Soon-Jo Chung and Yujin Ahn*

The development of brain-computer interface (BCI) has introduced a new possibility in helping those with severe motor disabilities by enabling users to control devices to aid in daily tasks by merely thinking about the task they want performed. However, many of the current BCI research requires the user to make many lower-level commands, such as turning left and right, instead of providing an intuitive way to utilize the robot with higher-level decisions, such as moving to a table. In this project, we aim to overcome this limitation by creating an intuitive way of controlling a robot through a Virtual Reality (VR) interface. The VR interface will use eye tracking data from the user to recognize user intent, which will be combined with the BCI data as inputs to a Sequential Convex Programming (SCP) based motion planner. Future work on this project will include comparing the use of the VR interface with BCI to direct control and to the use of only BCI.

### **Mapping Fragile Geological Features With UAVs**

Yunha Jo

*Mentors: Zachary Ross and Zhiang Chen*

Precariously Balanced Rocks (PBRs) offer valuable insights into seismic hazards due to their sensitivity to ground motion. Our research focuses on developing an autonomous UAV system for mapping PBRs in California. The UAV system uses advanced algorithms for approach, detection, exploration, and mapping. During the approach stage, the UAV takes off and utilizes the Fast Planner algorithm to navigate to a desired PBR. After that, the UAV uses object detection algorithms (e.g., YOLOv8) to detect PBR candidates. An identification algorithm is then used to identify the desired PBR from the candidates. Alternatively, when detection and identification fail due to lighting limitations, we provide a user decision support system to help the UAV identify the PBR target. Once the desired PBR is identified, the UAV uses an exploration algorithm to find an obstacle-free path to collect complete camera perspectives for mapping, which is implemented by a Simultaneous Localization and Mapping system (e.g., RTAB-Map).

### **Identifying Constraints From Safe Demonstration Trajectories Using Gaussian Processes**

Adam Johansson

*Mentors: Soon-Jo Chung, John Lathrop, and Fengze Xie*

It is typical for robotics tasks to have constraints that must be satisfied, such as obstacles which must be avoided or a region that the robot must stay inside. Manually defining these constraints can be time-consuming and requires prior knowledge of the constraints. We propose a statistical model that can learn the most probable constraint set using only a set of safe expert demonstrations, by modeling the constraint function as a Gaussian process with latent inducing points, whose values are determined as the maximum a posteriori estimate conditioned on the demonstration trajectories. A gradient ascent algorithm with phantom Monte Carlo trajectories is then used to compute this estimate. The results show that the model is capable of learning smooth constraint sets that are safe, while also providing meaningful uncertainty quantification using the Gaussian process posterior.

### **A Learning Approach to Stochastic Dynamic Tubes for MPC in High-Dimensional Robots**

Cole B. Johnson

*Mentors: Aaron Ames and Will Compton*

Safe trajectory planning is fundamental in the development of autonomous robotic systems, particularly in navigating through cluttered or dynamically changing environments. The challenge escalates when the environment's elements, like obstacle locations, and goal or task identities are unknown prior to execution, potentially rendering a priori pathfinding intractable even in static environments. Thus, successful planning relies on developing planning methods which balance computational and movement efficiency with robust safety guarantees. In this project, we approach the problem by training trajectory tracking RL-based walking controllers, collecting massively parallelized data, and learning stochastic estimations on the error between the planning and tracking models of different robots. We demonstrate this pipeline in simulation using quadrupedal, bipedal, and hopping robots, utilizing a variety of planning models. We also perform sim-to-sim and sim-to-real transfer to show the efficacy of the system in different environments and on hopper hardware.

### **Emulating X-Ray Reflection Spectroscopy With Machine Learning**

Rahel Joshi

*Mentors: Fiona Harrison and Asia Piotrowska*

X-ray observations of astronomical objects like black holes and neutron stars allow us to constrain, with parameters, the most energetic processes in the universe. Currently, physics models, like XILLVER, can simulate X-ray emission from compact objects, allowing astrophysicists to create tables of template X-ray spectra resulting from different combinations of input physical parameters, used to fit observed spectra. Since a perfect fit is unlikely, the current standard is to linearly interpolate the closest spectra. However, due to the non-linear nature of

X-ray spectra, linear interpolation can result in inaccurate results. Here, machine learning can be a powerful alternative approach due to its ability to capture non-linearity. Previous studies demonstrate the potential use of neural networks for this use case. In this project, we investigate how neural networks perform in emulating complex spectra with rich emission line signals, exploring different network architectures and data preprocessing techniques. We then compare the results of emulation with standard interpolation techniques evaluating the potential inaccuracies with the conventional approach.

### **Hydrogel Infusion Additive Manufacturing (HIAM) of Oxide Dispersion-Strengthened Alloys**

Kitty Joyce

*Mentors: Julia R. Greer, Thomas T. Tran, and Wenxin Zhang*

Hydrogel infusion additive manufacturing (HIAM) is an additive manufacturing technique in which hydrogels are infused with metal salts and converted to metals through a series of heat treatments. Previous studies of HIAM-fabricated Cu-Ni alloys resulted in highly twinned, equiaxed grains which were strengthened by localised hierarchical oxide structures resulting from incomplete reduction. This study leverages the compositional tunability of HIAM to investigate oxide retention behaviour in a system which does not fully reduce. Cu-Y<sub>2</sub>O<sub>3</sub> honeycomb lattices are fabricated with a variety of compositions and heating profiles to provide insight into the microstructural evolution of HIAM-fabricated oxide dispersion-strengthened alloys. Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and electron backscatter diffraction (EBSD) reveal a bimodal grain size distribution in lower-Y compositions. This is likely due to Cu being reduced from two different oxide phases, revealed by X-ray diffraction (XRD) to be CuO and Cu<sub>2</sub>Y<sub>2</sub>O<sub>5</sub>. Unusual morphologies are observed, including layered structures which may emerge due to void coalescence between print layers, and highly patterned surfaces which may be partially due to differences in cross-linking density. Future work will focus on improving sintering and porosity removal; it is anticipated that grain refinement and oxide nanoparticle pinning may enhance mechanical properties.

### **Learning Helmholtz Operator for High Frequency Applications**

Krishna Kamalakannan

*Mentors: Hossein Salahshoor and Mikhail Shapiro*

Neural operators are machine learning models that demonstrate remarkable speed, accuracy, and adaptability in solving many high-dimensional partial differential equations (PDEs). Much work has been put into using it to solve effectively the Helmholtz equation  $\Delta u + k^2 u = -f$ , especially for the large  $k$  regime, which is known to be very difficult even for the best classical solvers. This equation is of great importance due to its use in modeling mechanical waves. For this project we had in mind the applications to ultrasound modeling. Going forward, we wish to experiment with the use of Sobolev norms when training neural operators. We hope that such norms will more reliably capture the nature of highly oscillatory solutions that arise in the large  $k$  regime. We also wish to experiment with the Neumann Series Neural Operator (NSNO), first presented in a January 2024 paper by Chen et al. NSNO solves the Helmholtz equation by learning mappings from both  $k$  and  $f$  to the solution  $u$  as opposed to the input simply being  $k$  or  $f$ , as in most other neural operators, and this added flexibility is desirable for cases of inhomogeneous media.

### **Characterization and Comparison of Aggressive States in Lactating and Virgin Female Swiss**

**Webster Mice**

Zara Kanold-Tso

*Mentors: Tomomi Karigo, Drishti Soneja, and Markus Meister*

Aggression is a highly conserved state that can be observed in both female and male mice. Male aggression has been widely studied, but female aggression has rarely been studied in non-lactating female mice, as it has been previously believed to only occur during lactation as a parenting mechanism. It is unclear whether the internal states behind aggression in lactating and non-lactating female mice differ. Therefore, we aim to characterize and compare the behaviors leading up to and during aggression in order to deduce the motivations behind aggression. We utilize the deep-learning based platform Social LEAP Estimates Animal Poses (SLEAP) in order to extract pose data of the free behaving animals and analyze for differences in their confrontations. Characterizing the internal emotional states behind animal behavior can be done through the analysis of facial expressions. Hence, using Behavior Ensemble and Neural Trajectory Observatory (BENTO) and machine-learning techniques, we decipher the differing internal states between seemingly similar outward aggressive states and are able to create an ethogram of facial expressions regarding behaviors relating to aggression.

### **Optimizing Methods for High Resolution Mass Spectral Data Analysis**

Gautham Kappaganthula

*Mentors: Paul Wennberg and Kat Ball*

The Wennberg Lab recently deployed a new chemical ionization mass spectrometer with a much higher resolution than their previous mass spectrometer, calling for new data analysis techniques to process field, laboratory, and air data collected by the new instrument. We relied on lock mass calibration with an isotopically labeled ethylene glycol

clustered with  $\text{CF}_3\text{O}^-$  and the analysis of the mass spectrometer's timing errors to correct for the shifting of signals away from their true mass. Using these new calibrated mass axes, we applied linear and cubic spline interpolation methods as well as exponential fitting to filter out non-zero baseline signals from the mass spectra. We then used peak integration, deconvolution, and lineshape approximation to understand the amount of signal present for chemical species of interest. These refined analysis techniques will be used to selectively identify trace gas species observed during NASA's Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) and Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA) campaigns, which conducted airborne sampling in East/Southeast Asia and North America, respectively. This improved dataset can then be utilized to understand factors leading to worsening air quality in various parts of the world.

### Searching for Pulsation in Low Mass Stars Using Unsupervised Learning Techniques

Waly M Z Karim

Mentors: Gregg Hallinan and Rocio Kiman

M-dwarfs, the most prevalent stars in our solar neighborhood, remain poorly understood due to inconsistencies between theoretical models and observational data regarding their radii and effective temperatures. Asteroseismology, the study of stellar oscillations, offers a promising solution. Despite previous challenges in detecting pulsations in M-dwarfs, TESS light curves provide new opportunities with their red sensitivity and low observing cadence. We have developed an unsupervised algorithm to classify M-dwarf light curves and identify pulsations by retraining a convolutional autoencoder on a catalog of variable stars using TESS 2-minute cadence data. Dimensionality reduction was achieved through the neural network, followed by clustering the latent space using K-Means and visualizing it with UMAP. Our model has reached 80% accuracy in classifying pulsators, with 20% misclassified as non-pulsators. We are now advancing to 20-second cadence TESS light curves to further classify low-mass variable stars. This work will present our clustering results, accuracy, sources of variability, and the potential detection of M-dwarf pulsations, offering a method to reconcile theoretical and observational discrepancies.

### Synthesizing and Examining the Quantum Spin Liquid Properties of $\text{Pr}_2\text{Ta}_6\text{O}_{19}$

Bisrat Kassahun

Mentors: Linda Ye and Zili Feng

The Kitaev model is a theoretical framework that describes spins on a two dimensional honeycomb lattice structure with bond-dependent interactions. Since it leads to an exactly solvable state, this model is of high interest to researchers in realizing quantum spin liquids (QSLs). Due to the applicability of Kitaev QSLs in quantum computation and topological study, finding such a compound would be useful to further a number of other fields. Here, we attempt to synthesize  $\text{Pr}_2\text{Ta}_6\text{O}_{19}$ , a compound that could theoretically serve as a Kitaev QSL. We used an oxygen flowing tube furnace to synthesize a stoichiometric ratio of  $\text{Pr}_2\text{Ta}_6\text{O}_{19}$  from  $\text{Pr}_6\text{O}_{11}$  and  $\text{Ta}_2\text{O}_5$ . The compounds were mixed with a mortar and pestle, then shaped into a quarter inch die with a hydraulic press at 50 bar. After cooking the puck in the furnace for 48hr at 1000C, it was removed and crushed to be sampled in the XRD machine. Data from the XRD plot shows that the compound we formed remained in the 3+ state, not 4+ state. It appeared to be due to the compound not oxidizing enough or being under high enough pressure. The first synthesis of this compound was unsuccessful in realizing a potential Kitaev QSL. Future steps include attempting to synthesize the compound under new initial conditions, namely 1 bar of pressure in the furnace and at 400C instead of 1000C.

### Factors Influencing the Fabrication and Stability of $\text{Li}_2\text{FeS}_2$ Electrodes

Isabella Kedikian

Mentors: Kimberly See and Victoria Davis

Today's commercial lithium-ion batteries are based on cathode materials that can only store one equivalent of lithium per formula unit.  $\text{Li}_2\text{FeS}_2$  is a promising cathode material for next-generation lithium-ion batteries because of its ability to store more than one equivalent of lithium per formula unit. Understanding the stability of  $\text{Li}_2\text{FeS}_2$  to different levels of oxygen and humidity conditions as well as how to optimize the  $\text{Li}_2\text{FeS}_2$  casting procedure is of significant interest towards making this material commercially relevant. Solvent amount, coating amount, and solvent type were varied to thicken slurries and increase active mass loadings. Controlled oxidation studies were carried out to assess how exposure to various relative humidity (RH) conditions influences both the electrochemical and structural properties of  $\text{Li}_2\text{FeS}_2$ . Results demonstrated that propylene carbonate is the best solvent to use for  $\text{Li}_2\text{FeS}_2$  casting as it has a high viscosity, results in high dissolution of electrode binder, and does not react with the  $\text{Li}_2\text{FeS}_2$  material. Immediate exposure to 11% RH atmosphere results in a dramatic increase in the open circuit voltage. Upon assessing the results of 0% RH atmosphere experiments, we will be able to determine the compatibility of  $\text{Li}_2\text{FeS}_2$  with dryroom operations.

### **Developing a Machine Learning Powered Semi-Automated Custom Grading Tool for CS Core (CS 2, CS 3, CS 24)**

Maya Keys

*Mentor: Adam Blank*

The current grading systems for CS 2 and CS 24, foundational courses in Caltech's Computer Science Core Curriculum, lack the efficiency, adaptability, and customization necessary for optimal student learning and engagement. These courses, which cover essential topics like data structures and computer systems, suffer from the limitations of existing platforms, which hinder the provision of detailed feedback and ability to revise and regrade assignments. This project aims to develop a custom grading platform tailored to these courses, incorporating feedback from course staff and students to enhance teaching efficiency and learning experience in each of these courses. Utilizing large language models to analyze student responses, our grading platform will preliminarily categorize student answers based on semantic similarity and hierarchical/k-means clustering which allows for new features such as search, automated group creation, and automated grading with provided rubrics. This will improve feedback and instructional quality, as teaching assistants will have more time and ability to leave specific, accurate feedback on assignments, exams, and projects. The implications of this research extend beyond these courses, potentially benefiting other disciplines requiring robust and adaptive grading systems.

### **Learning Keypoints for Multi-Agent Behavior Analysis Using Self-Supervision**

Daniel Khalil

*Mentors: Pietro Perona and Markus Marks*

The study of social interactions and collective behaviors through multi-agent video analysis is crucial in biology. While self-supervised keypoint discovery has emerged as a promising solution to reduce the need for manual keypoint annotations, existing methods often struggle with videos containing multiple interacting agents, especially those of the same species and color. To address this, we introduce B-KinD-multi, a novel approach that leverages pre-trained video segmentation models to guide keypoint discovery in multi-agent scenarios. This eliminates the need for time-consuming manual annotations on new experimental settings and organisms. Extensive evaluations demonstrate improved keypoint regression and downstream behavioral classification in videos of flies, mice, and rats. Furthermore, our method generalizes well to other species, including ants, bees, and humans, highlighting its potential for broad applications in automated keypoint annotation for multi-agent behavior analysis.

### **Wearable Enzymatic Electrochemical Sensor for Non-Invasive and Continuous Monitoring of Ketone Bodies for Metabolic Syndrome**

Arya Khokhar

*Mentors: Wei Gao and Soyoung Shin*

Metabolic syndrome is a cluster of interconnected conditions including high blood pressure and high blood sugar that significantly increase the risk of heart disease, stroke, and type 2 diabetes and affects approximately one-third of adults in the United States. Continuous monitoring of key biomarkers such as ketone bodies, such as beta-hydroxybutyrate, is crucial for the early detection and management of metabolic syndrome. This project proposes a sweat-based, non-invasive, continuous monitoring system for beta-hydroxybutyrate that utilizes a hydrogel medium for cofactor diffusion. Our primary objective is to optimize this monitoring system. Our sensor design requires the optimization of three components: the gold layer, the mediator layer, and the enzyme layer. NADH detection was tested using a spiked amperometric i-t curve to evaluate the 0  $\mu\text{m}/\text{mm}$  concentration point, sensitivity, and stability of the sensor. For the hydrogel system, our focus is on optimizing and controlling the diffusion of NAD<sup>+</sup> by employing a hydrogel with a modified lower critical solution temperature (LCST). Looking ahead, we aim to integrate these optimized components to fabricate our final biosensor design, offering a promising tool for the continuous and non-invasive monitoring of metabolic syndrome biomarkers.

### **Optimization of *Agrobacterium*-mediated Transient Transformation in Different Plant Species**

Tuyako Khristoforova

*Mentors: Gözde Demirer and Yuan Geng*

Global warming demands the development of crops that can withstand increasingly harsh environmental conditions. *Agrobacterium*-mediated transient transformation is a promising technique for delivering genome-editing reagents into plant cells to optimize genetic traits in plants. However, the process of getting gene-edited offspring is usually tedious and time-consuming necessitating the development of a transient transformation method to quickly assess gene editing reagents, ensuring their efficacy in producing desirable genetic modifications in plant cells. In Demirer lab's previous research, they have successfully developed an efficient *Agrobacterium*-mediated transient transformation method in the model plant *Arabidopsis thaliana*. This study aims to optimize and extend the same method to other plant species, including economically important crops. So far, we have successfully applied the method to two tomato cultivars, achieving high levels of protein expression in the leaves of one cultivar. In our future work, we plan to further test and optimize this method in additional plant species, and to demonstrate its robustness in evaluating the effectiveness of gene editing reagents.

**Real-Time Semantic Video Editing Interface With Language Model-enabled Image Grammars**

Ashley Kim

*Mentors: Matt Thomson and Surya Narayanan*

An important goal in Mixed Reality is creating real-time interactive experiences that cohesively mix physical reality with AI-generated content. This kind of real-time semantic video editing allows humans to unite their imaginations with physical reality, which opens applications for users to not only picture their imaginations under constraints that would otherwise be fundamentally impractical to view in real-time - such as having AI render the image of a city as an aftermath of a tsunami or during the Iron Age - but also save and collaborate on them in the future.

To enable this real-time semantic editing, a technology platform must operate under many features of the human brain implicated in scene processing. This involves decomposing videos in real-time to recognize scenes, tag objects by their semantic qualities, and invoke precise AI loops to create the desired images. The lab has developed Thalamic, a bio-inspired interface incorporating Meta's segment anything platform with large language models to create 'semantic image graphs' that provide real-time, graph-based representations of a video. The platform separates spatial and semantic processing into independent computing streams and then uses image graphs to construct an integrated representation of object identity and locations. Using these generated image graphs, Thalamic opens gateways to perform search, prediction, and editing over visual scenes.

**Incorporation of Gas Vesicles in Silk Fibroin Scaffolds**

Minho (Jimmy) Kim

*Mentors: Mikhail G. Shapiro and Yuxing Yao*

Abstract withheld from publication at mentor's request.

**Thermal Vision Models for Spacecraft Detection**

Sulekha Kishore

*Mentors: Soon-Jo Chung, Hannah Grauer, and Sorina Lupu*

Space debris and uncooperative targets pose significant threats to operational satellites, necessitating advanced detection techniques in low-light space environments. Detecting these objects is challenging due to the lack of prior knowledge about their features, trajectories, or even existence. Recent advancements in computer vision models enhance current tracking methods, reducing reliance on ground support while improving robustness and reliability. Long-range infrared (IR) sensors, which detect thermal signatures, are particularly promising for this task, though the lack of IR datasets for spacecraft identification presents a challenge.

We aim to improve spacecraft operations by autonomously detecting and classifying satellites using diverse datasets. We train and test a novel vision model, DINO+FastSCNN, leveraging foundational vision models and knowledge distillation for effective performance on IR and spacecraft datasets. We create custom short-range and synthetic long-range IR datasets, prepare the software stack, and ensure model readiness for on-orbit operations on Aerospace Corporation's EdgeNode Lite satellite mission in early 2025.

 **$SL(2, \mathbb{R})$  Symmetries in the JT/SYK Correspondence**

Stavros Klaoudatos

*Mentors: Maria Spiropulu and Joe Lykken*

The AdS/CFT correspondence is a duality that has had a profound impact on theoretical physics over the last decades. This project is concerned with the study of a pair of theories that fall under a similar classification, namely  $NAdS_2/NCFT_1$  (Nearly- $AdS_2$ /Nearly- $CFT_1$ ). The bulk theory is a 2d dilaton gravity called JT gravity, where the spacetime is asymptotically described by  $AdS_2$ , and wherein an interaction between the two boundaries is considered. The gravitational modes correspond to the boundary dynamics, governed by a Schwarzian action. This theory bears the interpretation of an eternal wormhole which is rendered traversable by the topological-censorship-evading non-local interaction of the boundaries. The boundary theory is described by two coupled SYK models. Both theories have the same low-energy effective description, which allows for the interpretation of SYK observables as those of a gravitational sector. In the low-but-not-too low energy limit, the system exhibits modes whose spectrum is governed by a  $SL(2, \mathbb{R})$  symmetry, which has interpretations in both SYK and JT theory. This symmetry is analyzed and examined, and relevant simulation data is also presented.

**Modeling Interactions of Squeezing With the Laser Interferometer Gravitational Wave Observatory at High Frequencies to Improve Sensitivity**

Umran Serra Koca

*Mentors: Lee McCuller and Sander Vermeulen*

The Laser Interferometer Gravitational Wave Observatory (LIGO) uses quantum squeezing to improve its measurement precision. However, this squeezing is degraded upon interactions with the optical components of the

interferometer (IFO). This is true especially at high frequencies where the interferometer response to the squeezed state is poorly understood. In this project, we use a simulation package called Finesse to examine how squeezing interacts with the aLIGO interferometers at high frequencies. We use non-vacuum sidebands to simulate what happens to squeezed light. By comparing the modeled IFO response to squeezed light to real data on the quantum noise at high frequencies, we will be able to gain understanding about the mode matching of the arm cavities among other things. This will allow for diagnostics of the issues that limit aLIGO's sensitivity in the signal band where it is operated.

### **Creating Predictive Knee Injury Models From Biomechanical Data**

George Andrew Koclanes

*Mentor: Michael Alvarez*

From November to April of the 2022-2023 NBA season, out of the approximately 500 players in the NBA, there were an estimated 800 instances where a player was placed on an injury list, indicating that a player was receiving treatment for an injury and was unable to play. Whether a minor or serious injury, these events can impact a player's career and salary, as well as a team's overall success and future. Given this high injury rate, many experts have attempted to identify the main indicators of injury. However, research has been largely ineffective at actually predicting player injuries prior to their occurrence. P3 Peak Performance (P3), a company started in 2006, believes that biomechanics is the key to both predicting and preventing injuries in professional athletes. This project combined P3's biomechanical expertise with cutting edge data science techniques. The biomechanical data of NBA athletes was gathered and processed in an effort to create a machine learning model capable of predicting future knee injuries. This involved establishing injury guidelines, web scraping, feature addition, multiple imputation, and feature selection. Eventually, multiple machine learning methods (regression, gradient boosting, graph neural networks, bayesian networks) were applied to the final dataset in order to find a model that was both accurate and explainable.

### **Annotation and Unsupervised Discovery of Mouse Social and Innate Behaviors Through Fine-Tuning of a Large Multimodal Language Model**

Rohan Kolhe

*Mentors: David Anderson and Aditya Nair*

Behavioral studies provide a visible manifestation of activity of the CNS and brain mechanisms underlying behavior such as complex decision making. In studying mouse behavior, precise annotation and interpretation of video data are crucial for understanding the intricate dynamics of different activities. This project leverages machine learning techniques for annotation and interpolation of a variety of mouse behaviors. We fine-tune a vision transformer (CLIP) on a custom dataset of annotated mouse behavior videos, optimizing it to accurately identify and label specific behaviors. The embeddings from the CLIP are then processed through a classifier to assign precise labels per frame. Additionally, we employ a fine-tuned version of LLaVA, a vision-language model, to generate descriptive annotations and discover previously unrecognized behaviors. This dual approach not only improves the accuracy of behavioral labels but also provides rich, contextual descriptions, facilitating a deeper understanding of the observed behaviors. Our method has already demonstrated significant potential for social behaviors, achieving high accuracy for classification of behavior such as attack & mounting. Furthermore, our unsupervised approach demonstrates potential in identifying subtypes of behaviors, including various forms of sniffing. This finding suggests that vision-language models may offer a novel avenue for segmenting and interpreting mouse behavior.

### **Asteroid Characterization Through Space-Based Telescopes: Thermophysical Modeling and Image Differencing**

Manaswi Kondapally

*Mentor: Joseph Masiero*

Asteroids, also known as minor planets, are the remnant debris from the inner solar-system formation. Unlike the planets which have undergone significant geological and atmospheric changes, many asteroids have remained relatively unchanged for billions of years. This makes them valuable time capsules, preserving information about the conditions and materials present in the early solar system. This project focuses on studying asteroids from two perspectives: characterizing their physical properties and analyzing their orbits.

Near-Earth Asteroids (NEAs) are a critical area of study due to their proximity to Earth. We use data from the NEOWISE mission to characterize these asteroids' physical properties. Employing a ThermoPhysical Model (TPM) that utilizes a Monte Carlo Markov Chain, we derive parameters such as albedo, diameter, and thermal inertia. Understanding the orbits of these asteroids is also essential, particularly for space missions like the Roman Space Telescope. The upcoming mission will use image differencing to detect transient objects, making it crucial to distinguish asteroids from background sources. To achieve this, we use the NEOSPY software on simulated data from Roman, enabling the identification of variable objects in the given RA/Dec coordinates.

**Highly Precise Evaluation of Scattering by Means of the Rectangular-Polar Method**

Elianna Kondylis

*Mentors: Oscar Bruno and Sabhrant Sachan*

The accurate modeling of wave propagation and scattering is necessary for a multitude of applications, including electromagnetism, fiber optics, and remote sensing. Specifically, when an incident electromagnetic field impinges on a body, we wish to compute the resulting scattered field. To achieve this, the Bruno Lab has developed the Rectangular-Polar Method (RPM), a novel numerical integration technique designed to evaluate singular and near-singular integrals on a boundary surface. Using RPM, a boundary is partitioned into non-overlapping patches which are then parametrized. The integral is evaluated over each patch, with any singularities pre-computed using a window function in the parametric space. However, an error remains as singular points near the edge of one patch affect neighboring patches. Thus, we define small overlapping patches near the edges of other patches and use a partition of unity to correctly evaluate the integral over the entire boundary. This approach allows for highly accurate and fast computation of scattering fields in a variety of problems, and opens the door for low-memory computations using interpolation.

**Automatic Classification and Anomaly Detection of Supernova Spectra in ZTF Bright Transient Survey**

Abhiram Krishna

*Mentors: Shrinivas R. Kulkarni and Yu-Jing Qin*

The ZTF Bright Transient Survey (BTS) represents a pioneering endeavor in systematically identifying and characterizing extragalactic transients. One of the primary missions is to acquire optical spectra to classify and study extragalactic transients, including supernovae and tidal disruption events. We develop an automatic supernovae classification tool using machine learning by designing a series of binary classifiers for different types of supernovae using ensemble classifiers, primarily the Random Forest Classifier and XGBoost Classifier.

Furthermore, due to the extensive collection of spectra from the survey and the community, there could be rare cosmic transients and uncommon events that can deepen our understanding of the evolution of stars and activities of supermassive black holes. We employ an unsupervised Isolation Forest algorithm and various dimensionality reduction techniques to identify these novel, unusual events. This approach allows for detecting significant anomalies, potentially revealing rare and extraordinary supernovae within the dataset.

**Wearable Nanocomposite Kinesiology Tape for Characterizing Ankle Movement During Running**

Aurelia Kuester

*Mentors: Kenneth Loh, Elijah Wyckoff, and Wei Gao*

The movement of the ankle while running is complex and difficult to quantify without large expensive motion capture systems. To address this, we utilized wearable fabric-based distributive strain sensors to measure the change in strain at four distinct locations on the ankle throughout the running cycle. The sensors are composed of piezoresistive multiwalled carbon nanotubes layered on kinesiology tape. Placing the sensors on the top of the ankle, spring ligament, and the medial and lateral sides of the achilles allows us to quantify the four main movements the ankle-joint complex makes throughout the running cycle, plantarflexion, dorsiflexion, inversion, and eversion. In order to identify inaccuracies in running form, we used the results of stationary ankle movement tests to create a system of equations to estimate the angle of the ankle while running. By comparing these results to contemporary models of ankle movement, we aim to identify issues in running form.

**Identifying Circumbinary Planets Using Precession Analysis**

Diya Kumar

*Mentors: Ben Montet and Lynne Hillenbrand*

Circumbinary planets, which orbit two stars, make up a small discovered population. All 15 systems have been found via the transit method: observing the light from a star for periodic dips in brightness caused by a planet passing in front of it. However, this method can only detect planets that directly pass in front of their host stars and are not inclined to our observational plane, limiting our understanding of system geometries. We search for circumbinary planets through precession, a method unaffected by this bias. Precession is observed as slight changes in the orbital axis of the stars from the gravitational tug between the stars and planet, rotating the orbit around the system's center of mass. We investigate how the relative timing of primary and secondary eclipses evolve over decades for 586 binary systems, combining data from ground and space-based photometry surveys. I present preliminary results of systems with observed precession larger than can be caused by general relativity and tidal effects. These findings will help us better understand the architectures of circumbinary systems, determine whether they only form in flat, aligned configurations, understand the conditions allowing these planets to form, and explore the types of binaries that host planets.



**LeanBot: Dynamic Theorem Proving**

Adarsh Kumarappan

*Mentors: Anima Anandkumar and Chaowei Xiao*

Large language models (LLMs) have shown promise in assisting with theorem proving in interactive proof assistants like Lean, but existing approaches rely on static training datasets, limiting their ability to leverage new mathematical knowledge. We introduce a novel framework, LeanBot, that enables LLMs to dynamically retrieve and integrate knowledge from a diverse range of sources, including Lean repositories, research papers, textbooks, and mathematical knowledge bases. Our approach extends retrieval-augmented architectures and progressive training paradigms to identify and incorporate relevant definitions, premises, and insights from growing Lean codebases. The dynamic knowledge retrieval and progressive training mechanisms are central to our framework, which allows LeanBot to continuously update its knowledge base as it encounters new repositories and theorems. We conduct extensive experiments on a diverse set of Lean repositories, covering various mathematical domains, demonstrating LeanBot's superior performance compared to existing theorem-proving techniques. Our research introduces novel techniques and insights that have broader implications for interactive theorem proving and AI-assisted reasoning, significantly enhancing LLMs as interactive assistants for exploring and formalizing new mathematical domains through cooperative human-AI reasoning. To this end, we release our codebase and include our progressive training paradigm in LeanCopilot.

**Understanding Transversal Gate Limitations for Quantum Codes**

Colin La

*Mentors: Zi-Wen Liu and Christopher Umans*

Quantum information is extremely delicate, necessitating quantum error correction (QEC) to protect the information. An important problem that is not well understood is the processing of encoded information on QEC codes. The main bottleneck is the implementation of logical non-Clifford gates, which is pertinent to achieving universal quantum computation. Thus, it is pressing to understand their limitations. In previous works, it has been proven that 'transversal' implementation, a basic form of fault-tolerant implementation, of non-Clifford gates is fundamentally prohibited in various simple code architectures, such as two-dimensional topological and hypergraph product codes. In this project, we extend the consideration of these works to more general classes of quantum codes, attempting to formalize the feasibility and limitations on quantum topological and low-density parity-check (LDPC) codes with better code performance, using tools from linear and homological algebra. The results advance our understanding of the cost of executing computation on a much wider range of quantum codes that are key elements of practical quantum computation.

**Modeling Polymer-based Bacterial Aggregation for Treatment of Intestinal Bacterial Overgrowth**

Henry Lane

*Mentors: Rustem Ismagilov and Kathy Gopalakrishna*

Intestinal bacterial infections are a major and widespread antagonist to human health and represent a major unsolved problem in the developing world. Bacterial aggregation through antibodies is known to clear out bacteria within the human small intestine, but in diseases and disorders such as environmental enteropathy, this mechanism is impaired, leading to bacterial overgrowth of the small intestine. Interventions, such as antibiotics and elemental diets have not been universally effective in treating these diseases. We investigated whether dietary polymers (fibers) may aggregate and clear bacteria from the small intestine. We analyzed various relevant physiological parameters (osmolality, viscosity) of the small intestines and physical properties of both bacteria and dietary polymers. From this analysis, we identified a range of optimal polymer concentrations for driving aggregation and confirmed its safety profile. We also identified probiotic species and food particles to increase particulate concentrations to levels relevant for aggregation driven by depletion forces in physiologically relevant contexts. These results will enable us to design mouse-model experiments to demonstrate potential treatment/supplement options to prevent bacterial overgrowth in the small intestine in humans.

**Development of Computational Tools to Quantitatively Characterize Non-equilibrium Active Matter**

Edgar Larios

*Mentors: Matt Thomson and David Larios*

This study presents an activedrops system for expressing motion-generating motor protein genes using cell-free transcription-translation (TXTL) and microtubules, categorizing kinesins into fast-acting (producing motion within 1 hour) and slow-acting variants. We developed an algorithm to quantify fluorescence data from experiments, enabling determination of protein concentration over time through a calibration curve. To model system dynamics, we proposed a 14-parameter mathematical model describing transcription and translation processes. Using least squares regression, we fit experimental data to this model and identified parameter regimes yielding optimal fitting. Analysis revealed highly conserved ribosome concentration across samples, suggesting consistent translational capacity, while protein degradation exhibited the greatest percentage variation, indicating high variance in protein stability. As proteins in our activedrops system either degrade or accumulate, this model provides insights into protein stability and expression dynamics in cell-free environments. The combination of the

activedrops system, quantification algorithm, and mathematical model offers a toolset for studying protein expression and motor protein activity in synthetic biological systems. This approach has potential applications in synthetic biology, particularly in the design and optimization of biomolecular systems, and may contribute to advancements in drug delivery, biosensing, and development of artificial cellular components.

### **Investigating the Role of p53 and Myc in Aneuploidy Elimination Using Stem Cell-Derived Embryo Models**

Dillan Lau

*Mentors: Magdalena Zernicka-Goetz and Laura Amaya*

Humans have a remarkably low ability to produce an abundance of offspring. Aneuploidy, the presence of an abnormal number of chromosomes, is largely responsible for implantation failure, miscarriage, and congenital defects. Fertilization gives rise to a mosaicism of euploid and aneuploid cells. As development proceeds, the occurrence of aneuploidy decreases from 73% in pre-implantation stages to 0.6% in live births, suggesting a selective loss of aneuploid cells over time. Previous studies have shown that aneuploid cells are eliminated in pre-implantation stages via apoptosis in the epiblast. However, the mechanisms of aneuploidy elimination in post-implantation stages and other cell lineages such as the visceral endoderm and trophectoderm remain largely unexplored. This project seeks to address this gap by analyzing the effects of aneuploidy during these later stages using a stem cell-derived embryo model that recapitulates mouse embryo development up to day 8.5 post-fertilization. Specifically, we aim to elucidate the functional roles of p53 and myc, key markers involved in cell competition and apoptosis. We intend to generate CRISPR knockout lines for these genes, and through detailed analyses using immunofluorescence imaging and flow cytometry, we will investigate how these knockouts affect aneuploidy elimination in post-implantation stages and various cell lineages.

### **Fairaccord: Balancing Fairness With Accuracy to Automate Bias Mitigation in Deep Learning Models**

Jonayet Lavin

*Mentors: Gias Uddin and Ricardo Baptista*

Deep Learning (DL) models are being increasingly deployed in critical applications, including criminal justice, banking, and personalized medicine, making unbiased and fair inference a critical social requirement. However, recent research reveals that state-of-the-art (SOTA) DL models carry the risk of exacerbating existing social stereotypes by implicitly learning protected demographic attributes like race, age, and gender. Efforts have been made to mitigate bias in DL models, but they incur a notable tradeoff between fairness and accuracy, ultimately diminishing the overall effectiveness of the model. Therefore, we explore the notion that bias is inherent to the architecture design and hyperparameter selection itself. To do so, we leverage AutoML systems, which aim to automate the machine learning (ML) workflow. Neural Architecture Search (NAS) is a key component of AutoML that automates the design and optimization of neural network architectures by exploring a vast search space to find the best-performing model. Thus, we propose a novel methodology for balancing fairness and accuracy in DL models by implementing a bi-objective cost function. This cost function, which simultaneously considers both fairness and accuracy metrics, guides the NAS process within SOTA AutoML pipelines.

### **A Systematic Search for Ultraluminous X-Ray Transients in Nearby Galaxies in SWIFT/XRT Observations**

Ai-Dan Le

*Mentor: Murray Brightman*

X-Ray transients (XRTs) are high energy outbursts of x-ray radiation, and a subset of those are ultraluminous X-ray sources (ULXs) that are of special interest to those modeling compact systems (i.e. powered by accretion onto a neutron star or black hole) due to their unusually extreme luminosities. ULXs are unique because of this extreme luminosity, orders of magnitude higher than  $10^{38}$  ergs and other XRTs, which exceed even the expected Eddington luminosity of neutron stars or stellar black holes. Systematically searching through the 2XPS catalog, sources were examined for transient behavior. In order to further characterize these sources, analysis of the light curves can be completed in order to determine possibilities of the physical sources creating the ULXs, which are created using HEASOFT's XSPEC, cross-referenced with already existing data to confirm accuracy. These findings revealed several transient ULXs, confirming previous publications, and include a newly discovered source in M83.

### **Log-Concavity and the Lorentzian Condition for Alexander Polynomials of 2 and 3-Bridge Links**

Ryan Leal

*Mentor: Yi Ni*

The Alexander polynomial was proven to be log concave for two-bridge knots and links. We study the Lorentzian property of the multivariable Alexander polynomial of two-bridge links, motivated by results from Huh that connect the Lorentzian property to log concavity. We enumerate all of the first 4200 links whose multivariable Alexander polynomials are Lorentzian. We consider and enumerate walks on integer lattices with the aim of recovering the multivariable Alexander polynomial for 2-bridge links, motivated by Christoffel words generated by Schubert's normal form of 2-bridge links. We consider derivations of the Alexander polynomial using spanning trees on MOY

graphs and attempt to relate these to the characteristic polynomial of a matroid. We consider 3-bridge links and characterizations of this family motivated by Schubert's normal form.

### **Calcium Concentration and Isotope Composition in Nails as a Biomarker of Bone Health**

Carlynda Lee

*Mentors: François Tissot, Théo Tacail, and Dan Razonale*

Osteoporosis is a prevalent disease resulting in a decrease in bone density and mass. While dual-energy X-ray absorptiometry (DXA) is the "gold standard" for determining bone density, because DXA is a measurement of areal bone density, individuals with smaller bones are more likely to be diagnosed with an overestimated risk of bone fracture. Therefore, a more consistent method of assessing bone density and mass loss is necessary. In this study, we propose that human nail samples offer a viable alternative to determining bone health by measuring nail calcium concentrations and isotope composition, where we compared the effects of abrasion and sonication on nail calcium concentrations before assessing the changes in nail calcium concentration over time. All samples were digested using a microwave digestion system: to assess the viability of the microwave digestion method, urine samples that were previously characterized for calcium isotope composition were digested in the microwave and remeasured. Finally, the calcium was purified using automated low-pressure ion exchange chromatography, and the calcium concentrations were measured via ICP-MS to determine the changes in nail calcium concentration over time. This study will be the first step of many to assessing the potential of calcium concentrations and isotope compositions in nails as a diagnostic biomarker of bone health.

### **The Role of VCP/p97 in Nuclear Trafficking**

Deng Siang Lee

*Mentors: Tsui-Fen Chou and Chai Foong Lai*

We are investigating the cofactors that regulate the nuclear trafficking of Valosin-Containing Protein/Transitional Endoplasmic Reticulum ATPase, commonly known as p97 in mammals and CDC48 in yeasts. VCP/p97 is a member of AAA+ ATPase family and is involved in ubiquitin-proteasome system and mitochondrial quality control. VCP/p97-associated proteinopathy includes the inclusion body myopathy with early-onset Paget disease and frontotemporal dementia, as well as autosomal-dominant childhood-onset neurodevelopmental disorder. It has also been shown to have an indirect relationship in cancer, neurodegenerative diseases, and viral infections. Cofactors are vital to the correct functioning of VCP/p97, however, the specific mechanism of VCP/p97 in nuclear trafficking is still unclear. Therefore, our goal is to identify specific cofactors that regulate the nuclear trafficking of VCP/p97. Using western blot analysis, we found that p97 is more localized/upregulated in the nucleus of DAOY cells under DNA damage induced by doxorubicin and hydrogen peroxide ( $H_2O_2$ ). Furthermore, we performed immunoprecipitation coupled with liquid chromatography-mass spectrometry (IP-MS) to investigate the interactome of VCP/p97 in nuclear extraction under DNA damage. IP-MS analysis showed that VCP/p97 pull-down is enriched with proteins related to membrane trafficking and mRNA splicing, suggesting that the nuclear trafficking of VCP/p97 is interlinked with other important cellular processes.

### **Active Learning of Molecular Properties**

Eric Lee

*Mentors: Sarah Reisman, Yisong Yue, Jules Schleinitz, and Raul Astudillo*

The ability to predict molecular properties is crucial in tasks like drug discovery. However, obtaining these properties through high-fidelity simulations or wet-lab experiments is slow and resource-intensive. Machine learning models have shown exceptional capabilities in learning complex input-output mappings inherent in molecular prediction tasks. Yet, traditional deep learning methods are data-intensive, posing significant challenges in this domain.

Active learning, a subfield of machine learning, addresses data scarcity by employing probabilistic models to strategically select data that maximizes predictive performance. Traditional models like Gaussian processes, though effective, falter in high-dimensional chemical spaces that are often non-smooth and contain numerous small clusters of optimizing molecules.

In optimization tasks, where the aim is to identify molecules that maximize a specific metric, Variational Autoencoders (VAEs) have successfully reduced these complex spaces to more manageable lower-dimensional representations. This project aims to investigate whether VAEs can also enhance active learning tasks by enabling global learning of molecular properties in data-scarce environments.

### **$c_{\text{eff}}$ and the Other Side of BPS $q$ -Series Invariants**

I-Kwan Lee

*Mentors: Sergei Gukov and Mrunmay Jagadale*

We are interested in the effective central charge  $c_{\text{eff}}$  of a family of strongly coupled three-dimensional superconformal field theories  $T[-\Sigma(p_1, p_2, p_3)]$  that arise from 3d-3d correspondence. The BPS  $q$ -series invariants  $\hat{Z}$

associated with the Brieskorn sphere  $\Sigma(p_1, p_2, p_3)$  are well-known and are a linear combination of false theta functions  $\tilde{\Psi}_p^{(a)}(q)$ . Nevertheless, the BPS  $q$ -series invariants  $\hat{Z}$  on the other side, i.e. the orientation-reversal Brieskorn sphere  $-\Sigma(p_1, p_2, p_3)$ , are much more complicated. A newly proposed resurgence technique uniquely determines the dual  $q$ -series and does not rely on modular properties. Assuming that the coefficients of the  $q$ -series are integer-valued, we compute the dual false theta function  $\tilde{\Psi}_p^{(a)}(q)^v$  for several  $(p, a)$  and discuss the effective central charge  $c_{\text{eff}}$  for different three-dimensional superconformal field theories  $T[-\Sigma(p_1, p_2, p_3)]$ .

### Investigating the Stability of a PEO Protective Film Over Lithium Metal Anode Batteries

Sebastian Lee

*Mentors: William A. Goddard III and Boris Merinov*

Lithium metal as an anode exhibits the highest energy density possible. However, it is highly reactive towards most solid-state electrolytes. The inclusion of a polyethylene oxide (PEO) layer between the electrolyte and the anode may prevent these reactions from occurring. However, PEO's stability against lithium metal is not very well described. In this report, we present the preliminary AIMD results of the stability of PEO against lithium metal at different monomer lengths. After adjustments to the experimental parameters, it has been seen that 3 monomer PEO is stable against temperatures as high as 600K, whereas the periodically connected PEO is only stable up to 400K. Further adjustments and investigations are required to ensure that the experimental parameters are appropriate to the system and accurate to real-life experiments.

### Improved Synthetic Cell Division

Trinity Lee

*Mentors: Richard Murray and Manisha Kapasiawala*

Cells are the smallest autonomous building blocks of life. However, the composition, function, and interactions of proteins and cellular machinery necessary for a cell to live have remained elusive. To determine the catalysts of life, building an autonomous synthetic cell from the bottom-up is imperative. Previous work in the Danelon Lab at Delft University has shown the FtsZ protoring system is capable of asymmetric synthetic cell budding. This project takes great strides towards an autonomous synthetic cell by working towards symmetric division using microtubules and the FtsZ protoring system. By using cell-free expression systems to express both these microtubules and protoring in liposomes, we aim to create liposomes that will exhibit budding behavior to form a symmetric "dumbbell" shape. Ultimately, achieving synthetic cell division will advance the field of synthetic biology, paving the way for novel applications in nanomedicine and material science.

### Development and Improvement of an Open-Source Motor Controller Package for Brushless Direct Current Motors Used in AMBER Lab Robots

Steven Lei

*Mentors: Aaron Ames and Gary Yang*

Modern robots use brushless direct current motors (BLDC) as the primary source for joint manipulation. BLDC motors provide a robust form factor while also maintaining high efficiency, power, and reliability. A combination of software and firmware packages already exist to control and optimize BLDC motors for robotics applications, but not all of them are open source and easy to use. This work aims to create a low cost, open source motor controller package that includes the hardware, firmware, and software necessary to operate BLDC motors specifically used in AMBER Lab robots. We will use MIT's custom mini cheetah motor controller as a base model and make improvements such as increasing cost efficiency and updating hardware components like the motor encoder. Once a prototype controller is built, the controller performance will be benchmarked for revisions. The end goal of the project is to have a final PCB to package all components in a small form factor along with a code base that will make usage of the controller simple while also allowing room for customization in the future.

### Describing Phonon Dynamics in Density Matrix Formalism With Phonon-Phonon Interactions

John Leung

*Mentors: Marco Bernardi and Kelly Yao*

Phonons are quantised sound waves which are essential in determining the electrical and thermal properties of a material, driving structural phase transitions and thermalization via electron-phonon (e-ph) and phonon-phonon (ph-ph) interactions. At room temperature or higher, these processes happen on an ultrafast timescale on the order of femto- to nano-seconds in systems driven by external fields, where quantum effects such as coherence become significant. However, no theoretical formalism has yet been developed in order to simulate the dynamics of phonons with ph-ph interactions beyond the semiclassical Boltzmann transport equation. This project aims to derive quantum equations of motion for phonon populations and coherences in the presence of ph-ph interactions.

With the Heisenberg formalism, we derived the kinetic equations for elements of the 1-particle phonon density matrix, which include both populations and coherences under e-ph and ph-ph interactions. Our formulas correctly reproduce the Boltzmann transport equation in the semi-classical limit. This work lays the theoretical ground for future implementation of first-principles simulation of phonon dynamics.

**Computing Degrees of Projections of Rank Loci**

Guanxi Li

*Mentor: Paolo Aluffi*

In the last decade, algebraic-geometric techniques have been increasingly applied to study problems in complexity theory. One such example is the variety of matrices of  $r$ -border rigidity,  $R[n, r, s] = U_S J(\sigma_{\{n,r\}}, L_S)$ , which is an important formulation for the Matrix Rigidity problem. In this project, we seek to compute the degree of  $J(\sigma_{\{n,r\}}, L_S)$ , which provides qualitative descriptions for the defining equations of the  $r$ -border rigidity variety. In his paper, Professor Aluffi has translated the problem into computations of Segre classes utilizing Fulton MacPherson Intersection theory and successfully computed the degrees for some small cases. In this project, we seek to extend the computation to more general cases. In the process, we discovered formulas for Segre class of reduced reducible schemes, with the condition that the irreducible components intersect transversally, or the condition that the irreducible components are zero schemes of regular sections of vector bundles. We also proved a combinatorial fact regarding the degree: the degree of projection of rank  $r$  determinantal variety of  $n \times n$  matrices with the center to be  $(n - r)^2$  boxes placed along the diagonal is the number of  $n \times n$  standard Young Tableaux.

**A Geometry-Aware Text-Structure Multimodal Framework for Molecule Discovery**

Haorui Li

*Mentors: Anima Anandkumar and Shengchao Liu*

In the field of AI for Molecule Discovery, much attention has been focused on improving the effectiveness and capability of molecular representations using machine learning methods. However, there has been limited exploration of the rich textual descriptions available in numerous molecular databases. Based on previous work, this work aims to leverage both the 3D structural information and the textual description of the same molecule to significantly enrich the information encapsulated in its latent representation. This improvement is intended to benefit various downstream tasks, leading to better performance and outcomes.

In this work, a novel 3D structure-text dataset is constructed, which is then used for text-structure contrastive learning pretraining. By employing this approach, the textual and structural latent representations of the same molecule are integrated into a unified space. Additionally, two downstream tasks are designed to validate the superiority and effectiveness of the proposed method: Reaction-Guided Editing and Text Description of Molecule Changes. Notably, in the editing task, a generative model for 3D molecule is utilized, which greatly improves the quality of the generated molecules.

**Investigating the Radiation Pattern of a Millimeter Wave Hierarchical Phased Array Antenna**

Richard Li

*Mentors: Sunil Golwala and Jean-Marc Martin*

The optimal pixel size for radio telescope detectors depends on the frequency being observed. To achieve more optimal pixel sizes for a broadband detector, a hierarchical phased array antenna was developed, which consists of smaller pixels for higher frequencies which can be coherently summed, acting as a larger pixel for lower frequencies. However, upon testing the antenna, it was found that the characteristics of the antenna did not exactly match what was predicted. Thus, this project works to understand these differences, specifically the differences between the predicted radiation pattern and the measured radiation pattern.

To accomplish this, various hypotheses for the cause of the differences were proposed, then tested using computer simulations. Such hypotheses included that the gap between subpixels in the antennas caused a shoulder in the radiation pattern, or that the wide bandwidth of each frequency band observed by the detectors smoothed out the radiation pattern. The resulting computer simulations were then compared with the experimental data to determine the best explanation for the differences between the predicted and measured radiation pattern. Knowing this, the next iteration of the antenna may be designed to correct the radiation pattern.

**Reconstructing Early Trophectoderm Development in Mouse Embryonic Stem Cell-Derived Blastoids**

William Li

*Mentors: Magdalena Zernicka-Goetz and Wenqi Hu*

Understanding early embryonic development is essential to congenital disease research and provides insight into fertility issues arising near conception. Accordingly, mouse embryo models are powerful tools that elucidate mammalian embryonic morphogenic events *in vitro*. Mouse embryos consist of epiblast (EPI), trophectoderm (TE), and primitive endoderm (PrE) cells following the second lineage segregation at 3.5 embryonic days (E3.5). Of particular interest, TE cells give rise to the placenta and are instrumental in embryo implantation in the uterus. Several groups have created blastocyst-like structures (blastoids) *in vitro* using various combinatorial methods to capture these three cell fates. However, they wholly fail to implant *in vivo* and do not develop into post-implantation stages *in vitro*.

In this study, we collect single-cell RNA sequencing (scRNA-seq) data from E3.5-E5.5 natural embryos and compare their transcriptomes to existing blastoids. We find that most blastoids possess asynchronous developmental stages between the three lineages with particularly overdeveloped TE lineage cells. However, a model using inducible *Cdx2* (iCdx2) overexpression exhibited improved synchrony and a more complete representation of cell fates observed *in vivo*. Thus, we use iCdx2 cells to construct blastoids and illustrate the early development of TE lineage cells *in vitro*.

### Sub-Manifold Method for 3D PDEs

Xinyi Li

Mentor: Anima Anandkumar

This paper introduces the Sub-Manifold Method, a novel approach developed for solving 3D partial differential equations (PDEs) where solutions are confined to 2D sub-manifolds. This method is particularly beneficial for large-scale simulations in complex systems, such as automotive aerodynamics and propeller dynamics, where the critical solutions—like surface pressure fields—are confined to two dimensions. By leveraging optimal transport to create transition maps between 3D physical and 2D computational charts, the method facilitates the use of 2D PDE solvers. This strategy significantly reduces the computational demands associated with high-fidelity simulations, which are vital for realistic modeling in computational fluid dynamics (CFD) and structural analysis.

### Dissecting the Role of *Cdh12* Within the Developing Chick Trigeminal Ganglion

Zhikai Li

Mentors: Marianne Bronner and Hugo Urrutia

The trigeminal ganglion transmits sensory stimuli from the vertebrate head to the brain and is comprised of both the cranial neural crest and ectodermal placode. While previous studies have focused on the interaction and condensation of these two cell populations within the developing ganglion, the pivotal adhesion molecules mediating gangliogenesis remain to be elucidated. Here, we identify and characterise *Cdh12* as a possible adhesion molecule required for trigeminal gangliogenesis. We show by *in situ* hybridisation chain reactions *Cdh12* is expressed within the developing ganglion. Preliminary results show ectopic expression of *Cdh12* hinders migration and drives aggregation of cranial neural crest cells. Moreover, CRISPR-Cas9-mediated knockout of *Cdh12* at later stages altered otic vesicle development and migration of the neural crest cells within the epibranchial ganglion. Our results implicate *Cdh12* in driving condensation of cranial neural crest and placodal cells during trigeminal gangliogenesis, whilst also inviting investigation of other adhesion molecules which may act as interaction partners.

### Monte Carlo Neural PDE Solver to Learn PDEs With Probabilistic Representation

Sarah Liaw

Mentors: Anima Anandkumar and Julius Berner

Training neural partial differential equations (PDEs) through unsupervised learning is important in scenarios with limited availability of high-quality data. Prior work developed the Monte Carlo Neural PDE (MCNP) Solver to train unsupervised neural solvers using a Monte Carlo framework, where macroscopic phenomena are represented as ensembles of random particles. While this approach demonstrated robustness against spatial-temporal variations and allowed for coarser time steps, we extend it by incorporating learned interpolation to avoid Fourier interpolation. Since losses based on stochastic differential equations (SDEs) exhibit high variance due to their inherent stochasticity, we propose control variate methods by relying on gradient estimators with low variance to reach convergence accurately and quickly. We also extend the diffusion loss to larger temporal discretization steps, utilizing more than one-step rollouts and the full solution trajectory to enforce the consistency of the PDE solution. We apply our proposed methodology to experiments on 1D diffusion-advection and 2D Navier-Stokes equations and compare our method to other unsupervised baselines.

### Brownian Thermal Noise of Thin Dielectric Coatings and Optimizations of Mirror Shapes

Cindy Lin

Mentor: Yanbei Chen

Dielectric optical coatings are ubiquitous in measurement devices, such as gravitational-wave detectors, quantum optomechanical oscillators, and atomic clocks. Upon the applications of these coatings, mirrors can become highly reflective and be used to form optical cavities, which provide significant enhancement of sensitivity. However, thermal fluctuations of these coatings can result in coating thermal noise, which can create issues such as limited sensitivity to displacements and diminished stability of laser frequencies. The level of coating thermal noise can theoretically be altered through reshaping the mirror's substrate because that changes the response of the mirror to the random thermal stresses within. We seek to identify a more optimal shape for the substrate through generating models of the substrate that deviate from its conventional cylindrical shape, computing the thermal noise that would be present in the coating, and comparing that to the thermal noise of a model of the conventional shape. To cut down on the computation power necessary for such a calculation, only the substrate is modeled numerically, whereas the coating is modeled analytically. For mirrors like those used in

Advanced LIGO detectors, the optimal shape determined from the findings of this work reduces thermal-noise power by 31%.

### **Enzyme-Catalyzed Dearomative Amination of 2D Naphthols to Form Enantioenriched 3D Scaffolds**

Ethan Lin

*Mentors: Frances Arnold and Kathleen Sicinski*

Abstract withheld from publication at mentor's request.

### **Learning Solution Operators of Partial Differential Equations on Irregular Domains With Physics-Informed Losses**

Ryan Lin

*Mentors: Anima Anandkumar and Julius Berner*

Partial differential equations (PDEs) are crucial for modeling complex real-world science and engineering problems, such as molecular dynamics or turbulent flows. Successfully capturing these phenomena requires high-resolution solutions, but there are often no analytical solutions for PDEs with practical applications. Traditional numerical methods struggle with generating high-resolution solutions due to excessive computational requirements. Existing machine learning approaches, while promising, typically only solve individual instances of PDEs, requiring retraining or finetuning for each new case. We address the challenge of solving PDEs with irregular and varying geometries using Neural Operators. Unlike other machine-learning methods, Neural Operators learn the solution operator for an entire family of PDEs, eliminating the need for retraining with each new instance. In this work, we apply the Physics Informed Neural Operator (PINO) and Geometry Informed Neural Operator (GINO) to the nonlinear Poisson equation, marking the first application of this physics-informed architecture to irregular and large-scale problems with varying geometries. By training purely on the boundary loss and physics loss—both of which are known calculatable quantities—we eliminate the need for numerical solvers that rely on resource-intensive methods like the Finite Element Method (FEM). This approach significantly improves the efficiency and scalability of machine-learning methods for solving PDEs.

### **Rotational Diffusion of Dipole Emitters: Improving Accuracy via Physical Theory and Computational Imaging**

Erik Lindeman

*Mentors: Matthew Lew and Sunil Golwala*

Using fluorescent molecules, super-resolution fluorescence microscopy allows for nano-scale-precision measurements; it has invaluable applications in fields such as biophysics and material science. However, the precision of measurements is limited by the finite number of fluorescent photons emitted since observations are subject to Poisson shot noise. This issue can be mitigated by modifying the optical elements used to image the dipole (i.e., fluorescent molecule). One such optical element is the phase mask, which applies a position-dependent phase-shift to the collected fluorescence before it is focused onto a detector. Moving beyond fixed imaging systems, we propose an adaptive approach, whereby two different phase masks are used during a single image acquisition, to measure a dipole's rotational diffusion during the acquisition. Monte Carlo simulations show that this two-mask technique (TMT) leads to 25% or higher improvement in measurement precision for some dipole orientations over standard fixed imaging systems. Our methods therefore improve precision of rotational mobility measurements where it is possible to image dipoles on an individual basis, allowing for more insight into the molecules or system being studied. We demonstrate the improved performance of the TMT by imaging fluorescent markers attached to glass in both air and within a polymer film.

### **A Study of the Reaction Kinetics of Ti-mediated NRR to Discover a More Sustainable Ammonia Synthesis Pathway**

Alexis Lindenfelser

*Mentors: Karthish Manthiram and Channing Klein*

The Haber-Bosch process produces most of the world's ammonia, but it is incredibly carbon and energy intensive. Ti-mediated nitrogen reduction (TiNRR) for ammonia synthesis has been proposed as a cleaner alternative because it can operate at ambient pressures and temperatures. TiNRR was mediated by sodium in this study. Naphthalene, time, current, pressure, and sodium-concentration dependency screens were performed on the electrolytes to study reaction kinetics. The salicylate assay was used to determine ammonia yield and calculate Faradaic Efficiency (FE). Sodium-based electrolytes achieved maximum of FEs of around 21%, and no clear reaction-dependencies were established. A greater understanding of reaction kinetics and the reaction's dependence on the identity of the alkali metal is needed to further optimize FE and yield.

### **Expressive Variational Inference With Score-based Priors**

Christina Liu

*Mentors: Katherine Bouman and Berthy Feng*

Inverse imaging problems require solving for an unknown image given limited or noisy measurements. The distribution of reconstructed images given a set of measurements is known as a posterior. Variational inference for complex posterior distributions, particularly those involving high-dimensional images, remains a challenge. Existing methods that are expressive are often computationally expensive in both optimization and inference. We want to find a variational method that gives an expressive posterior in a computationally efficient manner. The recently proposed Diff-Instruct method transfers knowledge from pre-trained diffusion models to efficient generators without using original training data, with the aim of training the generator to sample from the same prior distribution as that of the pre-trained diffusion model. We propose to extend this method to posterior sampling. Our method allows the generator to learn to sample from the posterior distribution given a set of measurements with the prior of the pre-trained diffusion model, solving the challenge of approximating the posterior with a rich yet efficient variational distribution. We have successfully modified Diff-Instruct to perform posterior sampling for denoising MNIST images and reconstructing MRI scans from accelerated MRI measurements.

### **Simulation of Spin Configuration in $CoTa_3S_6$ Under Varying External Conditions and Investigation of Topological Properties of $CP^2$ Skyrmions**

Fangyan Lucy Liu

*Mentors: Linda Ye and Takashi Kurumaji*

The Hall effect is a well-known phenomenon where an electric current induces a Hall voltage proportional to the magnetization. Typically, this effect occurs spontaneously in antiferromagnetic materials. However, a spontaneous Hall effect was observed in  $CoTa_3S_6$  without an external field. Theoretical studies suggest that this effect results from the non-trivial spin configuration in  $CoTa_3S_6$ , specifically the all-in-all-out spin configuration. Experimental results have confirmed this theory. In  $CoTa_3S_6$ , Co atoms significantly contribute to the Hall effect, making their spin configuration particularly interesting to investigate. Our project employs computational methods, including Monte Carlo simulations, to validate the all-in-all-out spin configuration. We discovered a relationship between the deformation of the  $CoTa_3S_6$  lattice and its spin configuration, enabling the investigation of changes in magnetic properties relative to lattice deformation.

Additionally, skyrmions are vortex-like configurations protected by an energy barrier, a feature known as topological protection. As topological solitons, skyrmions are characterized by parameters such as the skyrmion number. In an  $SU(3)$  system, compared to an  $SU(2)$  system, a new term related to single-ion anisotropy in the Hamiltonian introduces an 8-component vector field instead of the 3-component vector field found in an  $SU(2)$  system. Our project calculates the  $CP^2$  skyrmion number by simulating and visualizing both the dipole and quadrupole moments for further investigation.

### **Leveraging Language Model-enabled Image Grammar for Real-Time Semantic Video Editing and Counterfactual Generation in Cancer Therapeutics**

Jiun You Rex Liu

*Mentor: Matt Thomson*

A major goal in Augmented Reality and Mixed Reality is to create interactive experiences that seamlessly blend physical reality with AI-generated content in real-time. The crux of achieving this lies in real-time semantic video editing, a process that allows users to dynamically visualize, interact with, and manipulate AI-enhanced scenes. Our research focuses on integrating AI-based visual editing with cognitive models of human perception. To this end, we have developed Thalamic, a platform that combines object segmentation models with large language models to generate semantic image graphs, capturing complex spatial relationships and attributes within a scene. By embedding these graphs using graph neural networks (GNN), Thalamic facilitates efficient manipulation and recall through a retrieval-augmented generation (RAG) framework, inspired by the hippocampus memory-indexing theory. This approach ensures temporally consistent and coherent content across dynamic scenes. In the context of biomedical research, Thalamic holds potential for discovering novel cancer therapeutics by enhancing our lab's Morpheus framework. Morpheus generates counterfactual explanations of tumor spatial proteomes, and by incorporating image grammar, it accurately models important spatial relationships between cell types in the tumor microenvironment. For instance, understanding the proximity of macrophages to tumor cells informs therapeutic perturbations that enhance T-cell infiltration, thereby improving immunotherapy efficacy.

### **Investigating the A-to-N Editing Activity of Adenine Transversion Base Editors in Mouse Retina Explants and Their Potential in Cell Lineage Tracing**

Linlu Liu

*Mentors: Michael B. Elowitz and Martin Tran*

Embryonic development and tissue homeostasis involves cells proliferation and differentiation into specialized cell types which are designed to perform certain functions. It remains unclear how these processes are coordinated over time. The Elowitz lab has recently developed a technique termed memory by engineered mutagenesis with optical in situ readout (MEMOIR) to record cell lineage by randomly introducing heritable A-to-G mutations. The editing patterns across multiple barcode repeats per cell can be read out via imaging and analysed to reconstruct the phylogenetic tree. To increase the memory capacity of the system and yield more accurate lineages, newer



versions of ABE variants which mediate A-to-C/T/G transversions can potentially be used to create a 4-bit system. Due to variations in editing efficiencies across different species, cell types and gRNA sequences, the overall editing efficiency in the tissue-of-interest should be examined to identify the editor(s) which can be used in future work. We transfected E18.5 mouse retinal explants with plasmids containing sequences for the barcodes, editors and gRNAs to allow *in vitro* editing, followed by barcode sequencing and edit rate analysis. Since results did not identify suitable editors due to low editing rates across all samples, future studies could focus on identifying mechanisms for increasing editing efficiencies.

### **Simulating Rocket Exhaust to Inform Design and Testing of 1/10 Scale Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS)**

Marcel Liu

*Mentors: Soon-Jo Chung and Lily Coffin*

PILLARS is a torus-shaped berm intended to protect lunar infrastructure from high-velocity lunar regolith launched into the air during the takeoff and landing of a rocket. A major goal for PILLARS is to reach Technology Readiness Level (TRL) 5, which is characterized by relevant field testing. A small-scale test involving a scaled prototype and a small rocket is scheduled for August 17. Computational fluid dynamics (CFD) simulation is crucial to inform design choices for the scale model and validate the relevance of this field test. Simulations varying parameters such as size, wall shape, and material of PILLARS were conducted using Ansys Fluent, and their relationships with temperature, pressure, and heat transfer coefficient at the surface of the wall were determined.

### **Engineering Phosphorylation-Driven Phase Separation for Synthetic Proofreading Circuits**

Meryl Liu

*Mentors: Michael Elowitz and Dongyang Li*

Core cellular processes such as codon recognition and immune response activation require high specificity, achieving low error rates beyond thermodynamic equilibrium limits. Kinetic proofreading is a mechanism that amplifies biochemical reaction fidelity through non-equilibrium multi-step pathways, wherein irreversible exit steps prematurely eliminate incorrect products. Drawing from receptor-ligand proofreading in T-cell signaling, kinase-driven phosphorylation offers a dynamic multi-step paradigm for enhanced specificity and robustness in synthetic protein circuits. The previously-developed SPARK (separation of phases-based activity reporter of kinase) system induces fluorescent protein phase separation by introducing multivalency through multi-site phosphorylated homooligomers. Here, we harness multi-site phosphorylation-dependent phase separation to engineer a synthetic kinetic proofreading circuit that differentiates binding affinities. We developed a high-throughput image analysis pipeline for quantifying fluorescent condensates at a single-cell level and constructed split Src kinases that reconstitute through dimerizing domains with varying binding affinities, modeling ligand-receptor interactions. To determine the circuit's two-phase coexistence regime, we are titrating the number of "empty" SPARK monomers for critical multi-site phosphorylation proofreading levels that activate condensate formation. Our work seeks to advance the understanding of kinetic proofreading principles and protein circuit modularity. Future efforts will expand the orthogonality of synthetic condensates and explore additional quantitative readouts of phase separation in cells.

### **Hyper-Heisenberg Scaling Quantum Super-Resolution Microscopy**

Wenyu Liu

*Mentors: Lihong V. Wang and Chieng Ying Huang*

Abstract withheld from publication at mentor's request.

### **Probing Gas Giant Origins: Chemistry of Exoplanet Atmospheres in the $\beta$ Pictoris Young Moving Group**

Yurou Liu

*Mentors: Dimitri Mawet and Yapeng Zhang*

2M0249-0557 c is a  $11.6 M_{\text{Jup}}$  gas giant planet in the  $\beta$  Pictoris young moving group (YMG). It orbits a pair of brown dwarfs at a wide separation of approximately 1950 AU. Its mass places it at the intersection of gas giant planets and brown dwarfs, making it an interesting target for constraining formation pathway. Using spectroscopic data of the planet acquired with CRILES+ (The CRyogenic InfraRed Echelle Spectrograph Upgrade Project) mounted on VLT (Very Large Telescope), we conduct atmospheric retrieval with radiative transfer code petitRADTRANS and nested sampling tool PyMultiNest. With the retrieved C/O ratio, metallicity, and  $^{12}\text{CO}/^{13}\text{CO}$  ratio, we conduct a comparative study with other members of the  $\beta$  Pictoris YMG to infer its formation mechanism.

### **Optimization of Conditional Guide RNA (cgRNA) Circuits for Monitoring Microbial Gene Expression in the Undisturbed Rhizosphere**

Kara Lo

*Mentors: Niles Pierce and Eric Lei*

Conditional guide RNAs (cgRNAs) enable spatiotemporal regulation of CRISPR/Cas activity by forming functional Cas/cgRNA complexes only upon encountering specific nucleic acid triggers. While ON- $\rightarrow$ OFF and OFF- $\rightarrow$ ON cgRNAs

have been successfully implemented with exogenously expressed triggers, inducing synthetic responses to cgRNAs controlled by endogenous cellular triggers can be a powerful tool to reveal gene expression dynamics in vivo, such as in rhizosphere microbes. This project aims to link the endogenously expressed mRNA for nitrous oxide reductase (*nosZ*) to signal molecule secretion in *E. coli* expressing cgRNAs, triggers, and silencing dCas9 as the protein effector. We optimize OFF->ON cgRNA circuits and measure conditional response by targeting red fluorescent protein (RFP) for reduction in response to cgRNA and trigger titration. Our goal is to maximize the conditional response while maintaining a clean OFF state, specifically by testing the impacts of ribosome binding site (RBS) presence, comparing two-plasmid and three-plasmid circuits, finding the best RFP targeting sequence, and improving cgRNA sequence designs with NUPACK software. Such circuits create a platform for aboveground optical readout of microbial gene expression dynamics in an undisturbed rhizosphere. These insights can then be applied to enhance sustainability-relevant processes like nutrient cycling optimization and greenhouse gas emission reduction.

**Revealing Possible Microtubule/Mitochondria Interaction With CryoVIT Segmentation Method**

Stephen Lo

*Mentors: Wah Chiu, Gong Her Wu, and Zhen Chen*

CryoVIT is a new, cutting-edge approach to Cryogenic Electron Tomography (CryoET) segmentation developed by the Chiu Lab. It is powered by a vision foundation model with over a billion parameters, which accurately segments pleomorphic 3D structures across diverse sample conditions. The model is trained in a semi-supervised fashion and can learn from sparsely labeled tomogram slices, significantly reducing the manual effort involved in training the model and cleaning up false positives post-annotation. Here, we attempt to utilize CryoVIT to build efficient, accurate models for segmentation of microtubules (MT) and mitochondria in CryoET imaging. Specifically, we are analyzing tomograms of Huntington's Disease-expressing iPSC-derived and mouse model neurons, in an effort to discover possible interactions between the two organelles. Gaining insight into the involvement of microtubule-mitochondrial interaction in Huntington's Disease may lead to future experimental therapeutic methods. Once we have achieved accurate segmentation of MT and mitochondria with CryoVIT, we hope to utilize subtomogram averaging software, such as EMAN2, to discover signs of interaction by visualizing the complex at subatomic resolutions (single particle analysis, SPA).

**Feature Selection via Common Weight Pruning for Supervised Learning in DNA-Based Winner-Take-All Neural Networks**

Yi-Cheng Lu

*Mentors: Lulu Qian and Matthew Plozala*

Recognizing molecular patterns is crucial across organisms, from the simplest bacteria to complex beings like humans. To accurately respond to environmental changes, learning is a fundamental process observed across various biological scales. Therefore, incorporating learning and pattern recognition into artificial molecular systems, such as DNA circuits, has the potential to revolutionize molecular technologies. Due to their well-understood thermodynamic and kinetic properties, as well as their biological compatibility, DNA holds promise for building sophisticated molecular neural networks. Previous work has successfully constructed a DNA neural network capable of supervised learning by utilizing an activable memory in a winner-take-all architecture. However, the competition relies solely on the relative difference of input compared to all memories, and thus, the shared features among different classes of patterns result in redundant information that slows down computation and increases background noise. Here, we aim to enhance pattern recognition performance through a novel feature selection mechanism within memory storage. We explored different designs of a novel annihilator motif to specifically prune activable memories and addressed challenges such as unwanted hairpin formation and signal loss. Simulation and experimental results demonstrate promising outcomes on feature selection and neural network performance, paving the way for further scalability on larger networks.

**Natural Language Automated Proof-Checking Assistant**

Gosha Lubashev

*Mentor: Adam Blank*

Checking the validity and assisting students with the composition of proofs in high volumes in proof-based math and computer science classes can become quite a chore. Much of proof-writing is formulaic, leading to repetitive work for graders, and assisting students with diagnosing logical or structural issues in their proofs is not an efficient use of a teaching assistant's time. Identifying inconsistencies in a proof is a strictly simpler and less instructive task than designing its high-level logical construction. We are therefore investigating the automation of partially verifying proofs written in natural language for use by both graders and students. In addition to the problem of validating the logic of a proof, difficulties arise from the inconsistent format of written proofs, as well as the redundancy and ambiguity of natural language. Though the intricacies of natural language make the complete deterministic parsing of a proof impossible, we develop a multi-pass pattern matching system to heuristically parse a proof into an abstract syntax representation describing the proof in terms of structural proof units (a variable declaration, for instance) and a program to analyze this representation for fundamental issues such as inconsistency of a variable's type or the non-termination of an induction algorithm.

**Synthetic Data for Animal Models for Point Tracking**

Justin Luo

*Mentors: Pietro Perona and Markus Marks*

Point tracking has shown remarkable performance in translating synthetic training data to real testing data. As such, large synthetic datasets such as PointOdyssey have begun to emerge with diverse subjects and environments. However, current datasets are made up of a majority of human subjects which results in issues when trackers are applied to foreign/specialized settings such as mice in a lab environment. In order to address this, we will use various methods including reinforcement learning in order to synthesize data for animal models, then train a state-of-the-art point tracking model (CoTracker) on this data. We then present an analysis of the impact realism has on the effectiveness of the trained model, and the need for realistic training data for synthetic datasets.

**Exploring the 2D Antiferromagnet NiPS<sub>3</sub>: Challenges in Device Fabrication and Potential for Photoelectric Applications**

Pei-Rui Parry Luo

*Mentors: Harry Atwater and Miles Johnson*

Nickel-phosphorus trisulfides (NiPS<sub>3</sub>), a novel 2D antiferromagnetic material, exhibits unique excitonic properties with an ultra-narrow linewidth of 0.4 meV, making it promising for advanced photovoltaic applications. This research aims to fabricate devices to explore the electrical properties of NiPS<sub>3</sub>, focusing on investigating its magnetization and conductivity. Our methodology includes mechanically exfoliating NiPS<sub>3</sub> crystals, fabricating devices using photolithography and e-beam evaporation, and performing conductivity measurements with a physical property measurement system (PPMS). Preliminary findings indicate progress in transfer techniques and thermal deposition, with initial conductance measurements from prototype devices aligning with numerical estimations. However, challenges remain in optimizing the fabrication processes and ensuring observable conductance signals. Future work will involve detailed magnetization and electrical measurements, along with photoelectric characterization under various conditions. Despite current challenges, NiPS<sub>3</sub>'s unique optical properties highlight its potential for photovoltaic technologies.

**Learning k-Body Hamiltonians via Compressed Sensing**

Muzhou Ma

*Mentors: John Preskill, Yu Tong, and Steven Flammia*

Learning the many-body Hamiltonian of a physical system from the dynamics of its corresponding quantum system is a fundamental task in physics. The complexity of this task can be characterized by how long we need to let the system evolve to generate the samples necessary for reconstructing the Hamiltonian. In this work, we analyze the total evolution time required to learn a k-body Hamiltonian consisting of M Pauli terms. We proposed a protocol using compressed sensing that can learn unknown Hamiltonians with total evolution time that scales polynomially with M, logarithmically with the number of qubits, and linearly with the inverse of the error, reaching the Heisenberg limit. On the other hand, we establish a lower bound for the total evolution time in the Hamiltonian learning problem, showing that it scales at least linearly with M. We further investigate the operational interpretation of Hamiltonian learning under different error metrics. Our results answer important open questions on characterizing quantum systems with non-local interactions.

**Electrical Impedance Tomography in 65 nm CMOS With On-Chip Cavities and Electrodes**

Antônio Victor Machado de Oliveira

*Mentors: Ali Hajimiri and Debjit Sarkar*

Electrical Impedance Tomography (EIT) is a tomographic imaging technique that reconstructs conductivity distributions by solving an ill-posed inverse problem using boundary voltage-current data, with a wide range of applications which include cancer detection, fluid flow monitoring and neuron activity monitoring. This project employs a 65nm CMOS process to design and test a microscale on-chip EIT chamber for 2D imaging of single cells. The system architecture features a multi-electrode array, a differential stage, and a multiplexing stage, with all components integrated on-chip. By miniaturizing the EIT system and integrating its structures on-chip, this project aims to push the limits of traditional EIT devices, enhancing portability, reducing power consumption, and improving signal-to-noise ratio.

**High Accuracy Methods for Computing Gravitational Potential and Gravitational Force Fields Near the Surface of Irregularly Shaped 3-Dimensional Bodies**

Thomas MacLean

*Mentor: Al Barr*

Accurate gravity field calculations are necessary for landing on planets, moons, asteroids, or other irregularly shaped bodies, but current methods become increasingly inaccurate near the surface. We present a set of high

accuracy methods for computing gravitational potential and gravitational force fields, which is needed for future missions. Notably, gravitational force and potential computation are simplified with high accuracy levels retained by bringing the derivative inside the gravitational potential integral, using coordinate systems—where cylindrical coordinates have special advantages—tailored to shape, using new bounds in the gravitational potential integral, not trying to fit smooth basis functions to non-smooth curves, and harnessing new computational tools where tasks are sometimes migrated to GPUs. In addition, we present a new gravitational field “calculus,” which lets us combine simpler potentials and force fields to create more complex ones without accuracy loss. Several examples are provided, for instance, where we subtract different shapes from a spherical body making a variety of craters. We have created preliminary MATLAB and Mathematica toolboxes utilizing these methods and the gravitational calculus. These methods are newly customizable for necessary high-accuracy gravity computations in future missions planned by JPL and other space agencies to irregularly shaped bodies like asteroids.

### **Mapping Antibody Responses Elicited by Intercladal Sarbecovirus Receptor-Binding Domains**

Indeever Madireddy

*Mentors: Pamela J. Bjorkman and Alexander A. Cohen*

Sarbecoviruses are a subgenera of coronaviruses widely prevalent in bats and other animal species globally. Sarbecoviruses are classified into four clades (1a, 1b, 2, 3) based on their spike receptor-binding domain (RBD). The recent pandemic and the continued evolution of new SARS-CoV-2 variants are evidence of the need for a pan-sarbecovirus vaccine that can protect against current variants and future spillover events across clades. The mosaic RBD-nanoparticle vaccination strategy is one way to achieve this goal. A mosaic vaccination includes a nanoparticle with up to 8 distinct RBDs from different viruses attached to its surface. Due to avidity effects, a mosaic vaccine encourages the immune system to develop antibodies against conserved viral epitopes. This means a mosaic vaccination can protect against related viruses not present on the nanoparticle. While it is known that mosaic sarbecovirus vaccination generates more broadly neutralizing antibodies than traditional homotypic vaccines, it is unclear which sarbecoviruses should be present on the vaccine to elicit the broadest protection across all clades. This work aimed to elucidate the antibody breadth elicited by vaccination with different sarbecoviruses to inform the design of a pan-sarbecovirus mosaic vaccine that confers the broadest protection.

### **A Heat Equation-Inspired Neuromorphic Algorithm for Graph Navigation**

Raaghav Malik

*Mentors: Markus Meister and Zeyu Jing*

Many problems in cognition can be formulated as search on a graph. Examples include spatial navigation, where the graph represents paths through the environment, or games, where the graph represents states and actions during the game. The recently formulated *Endotaxis* algorithm uses a two-layer neural network to compute all-pairs shortest paths (APSP) on graphs. However, the goal signal vanishes exponentially at large graph distances, making the model performance highly prone to noise and dependent on specific parameter tuning. To enhance robustness and biological plausibility, we present a heat equation-inspired alternative that replaces the adjacency matrix in the original *Endotaxis* network with the graph Laplacian matrix. This can be understood as integrating the discrete heat diffusion equation and thus provides an intuitive interpretation of goal signal as temperature. Numerical simulations across various graph types demonstrate that the Laplacian formulation is indeed far more robust under noise than the adjacency approach under several metrics. The Laplacian formulation leads to up to 100 times smaller average path lengths, 30 times greater probability of taking shortest path, and 3 times greater the log-units of valid parameter regimes. Theoretically, we derive several proofs showing that the Laplacian formulation eliminates local optima for the full parameter range, guaranteeing optimality on trees, and that its asymptotic behavior approximates exact graph distances for small parameter values and expected hitting distances for large parameter values, indicating a wider range of valid parameter values under noise. Finally, we show that this Laplacian formulation admits a simple neuromorphic implementation that involves a modified local synaptic learning rule compared to the *Endotaxis* model. In summary, we developed an alternative Laplacian-based graph navigation algorithm based on the *Endotaxis* model, which is more noise-robust, less sensitive to parameters, and simple to implement with biological neural networks.

### **Compressing the Phonon-Phonon Interaction**

Dhruv Mangtani

*Mentors: Marco Bernardi and Yao Luo*

A central goal in solid-state physics is to understand the dynamics of phonons — bosonic quasiparticles carrying collective excitations of atomic vibrational modes. The scattering interactions between phonons (ph-ph interactions) modify the macroscopic properties of materials, such as thermal conductivity. In particular, three-phonon and even four-phonon scatterings have prominent effects, leading to a vast number of possibilities that all need to be accounted for. In recent years, it has been possible to accurately compute these dynamical non-equilibrium properties through first-principles calculations due to the enhanced efficiency of supercomputers. In this work, we further tackle the high dimensionality of the interactions by leveraging the singular value decomposition (SVD), a popular compression technique. By performing a truncated SVD on the interaction tensor, we are able to maintain accuracy with only 10% of the memory and time traditionally required to compute phonon

lifetimes, thermal conductivity, and phonon dynamics under the coupled Boltzmann Transport Equation. This indicates that these properties are lower dimensional than previously thought. The findings of dominant interactions can also help better understand the recently discovered Phonon Hall Effect, which is not yet accurately analytically described.

### Higher-order Blow-up Finite Elements

Michael Manta

*Mentor: Yakov Berchenko-Kogan*

Finite element methods (FEMs) are numerical techniques for solving partial differential equations (PDEs) by reducing the space of solutions from an infinite-dimensional space to a finite-dimensional space. These methods are implemented in various fields, including structural analysis, fluid dynamics, heat transfer, electromagnetics, and biomechanics. Berchenko-Kogan and Gawlik recently introduced new finite element spaces, called blow-up finite elements. These spaces contain the classical finite element spaces but also allow certain kinds of singularities that make them conducive to simulating flows on curved surfaces, such as lava flows or the lubrication of mechanical parts. Berchenko-Kogan and Gawlik developed the lowest-order version of these spaces; in our work, we generalize these spaces to higher order. Higher-order finite element methods are coveted for improving the efficiency of implementations in terms of resources and accuracy. In this talk, we will go over the basics of finite element spaces, give an overview of the blow-up finite element spaces, and discuss the novel higher-order blow-up finite element spaces we propose. References: <https://yashabk.github.io/talks/blowupfeec-siam-handout.pdf>

### Assessing the Influence of Strongly Peraluminous Granites on Positive Excursions in the Marine Sr Isotope Record, and Development of Plagioclase Reference Materials for In Situ Sr Isotopic Analysis

Rory Mapletoft

*Mentor: Claire Bucholz*

The seawater Sr isotope record (expressed as  $^{87}\text{Sr}/^{86}\text{Sr}$ ) exhibits temporally finite, positive excursions. The most recent positive excursions over the last  $\sim 40$  million years have been linked to the rapid exposure and erosion of metamorphic and igneous core of the Himalayas, increasing the riverine flux of radiogenic Sr to the oceans. Specifically, the strongly peraluminous granites (SPGs), widely exposed in the Himalayas, likely acted as a first order source of radiogenic Sr to seawater. This is due to the critical transformation during collisional metamorphism, where radiogenic Sr from sedimentary rocks is transferred to a more labile source in SPGs (plagioclase). This study aims to better constrain the influence of SPGs from these collisional orogens on the observed positive excursions.

Rock-chips and hand-picked plagioclase grains from Neoproterozoic to Mesoproterozoic SPGs were mounted, polished, and analysed using electron probe microanalysis (EPMA) and laser-ablation multicollector inductively coupled plasma tandem mass spectrometry (LA-MC-ICP-MS/MS) for major element and Sr isotopic composition, respectively. The data collected, along with future analysis of unprocessed mounts and a global compilation of SPG Sr isotope composition is expected to elucidate the contribution of SPGs to the flux of radiogenic Sr flux to oceans through Earth history.

Additionally, five plagioclase specimens with varying major element concentrations were selected for characterisation and potential development as in-house reference materials to mitigate and correct for matrix effects during future LA-MC-ICP-MS/MS analyses of plagioclase.

### Superfluid Helium-4 Acoustic Gyroscopes: Loss Analysis and Prototyping

Isaac A. Marchant

*Mentor: Keith Schwab*

Superfluid helium-4 devices, such as Josephson junction-based quantum interference devices and acoustic ring gyroscopes, hold significant promise to realize some of the most precise rotational sensors manufactured to date. The Schwab group is focussed on producing the next generation of such devices able to operate well below the superfluid transition temperature ( $T_\lambda=2.17\text{K}$ ) where dispersive losses are near zero, enabling a rotational sensitivity on the fractional order of  $10^{-9}$   $\text{rads}^{-1}$ . To engineer superfluid acoustic-ring gyroscopes, a strong theoretical understanding of superfluid acoustic behaviour in fluidic circuits and the ability to test prototype devices at room temperature ahead of precision manufacture are required for efficient progress. This project seeks to provide those foundations. First, we outline a theoretical pathway to understanding the coupled superfluid-elastic tubing system using analytic elastic shell theory to characterise the system behaviour with a view to estimating energy losses in the device tubing. Future work will focus on confirming these estimates using finite element analysis software such as ElmerGUI. Second, we describe the development and construction of a tabletop acoustic ring gyroscope for use as a prototype in future superfluid device development.

**Progress Towards the Total Synthesis of Cassiabudanol A**

Priscila Marquez

*Mentors: Sarah E. Reisman and Katelyn S. Gallagher*

Diterpenoids are a large class of natural products, many of which exhibit significant biological activity. These molecules often contain complex oxidation patterns that synthetic chemists can leverage for chemical discovery. In 2016 and 2019, ryanodol and perseanol were synthesized in minimal steps and have unique scaffolds that provide keen insights on natural product synthesis. (+)-Cassiabudanol A is an isoryanodane diterpenoid that exhibits potential immunostimulant activity. Its unique scaffold contains a highly oxidized 5/6/6/5 ring system, and includes a quaternary center at the bridgehead of the bicyclo-[3.3.1]nonane core. Herein, we investigate the first five steps towards the total synthesis of (+)-cassiabudanol A. Our strategy involves a Ni-catalyzed reductive electrophile cross coupling approach to install an isoprenyl moiety necessary for a future Pd-catalyzed cascade key step. These efforts will establish the successful total synthesis of Cassiabudanol A.

**Photoinduced, Copper-Catalyzed Enantioconvergent Alkylations of Secondary Amines by Racemic Secondary Electrophiles**

Laura C. Martínez-Leal

*Mentors: Gregory C. Fu and Feng Zhong*

Tertiary alkylamines are ubiquitous in pharmaceutical and agrochemical agents, natural products and small-molecule biological probes. However, classical methods of nucleophilic amine substitution of an alkyl electrophile are not generally amenable to enantioselective variants that employ readily available racemic electrophiles. Fu group already accomplished enantioconvergent carbon–nitrogen bond constructions by a photoinduced copper catalytic system, breaking through the limited scope of traditional substitution reactions using activated tertiary electrophiles and anilines as nucleophiles, and unactivated electrophiles with primary amides. We now intend to use photoinduced copper catalysts to perform a cross-coupling between an unactivated secondary alkyl electrophiles and secondary amines.

**Political Orientation and Social Choices: A Study on Political Orientation and Risky Financial and Social Decisions for Others at Varied Social Distance**

Samuel Mathews

*Mentor: Kirby Nielsen*

This study analyzed how political orientation affects social decisions. The riskiness of individuals from different political orientations is studied when risky financial decisions are made on the behalf of themselves, anonymous participants, and participants of the aligned and misaligned political orientation. Inequality and risk aversion was measured for social risk preferences with health gains for anonymous groups and groups of specified political orientation. For financial risky decisions participants of all political orientations took the most risk when investing on behalf of themselves. Participants of all political orientations invested more on behalf of participants aligned to their political orientation than those misaligned. They also invested a similar amount on behalf of people of aligned political orientation as they believed the person would invest on behalf of themselves compared to investing much less for the misaligned person than what they believed the misaligned person would invest on behalf of themselves. For the choice with options for total risk or no risk, Republicans had no change in risk averseness for anonymous groups versus groups of specified political orientation, while Democrats became less risk averse when political orientation was introduced. For the choice with options for total inequality versus no inequality, both political orientations became less inequality averse when the aligned political party was favored and more inequality averse when the misaligned political orientation was favored. More complex results followed.

**Assessing the Scalability and Interpretability of the L-Pattern Identification Problem**

Ishita Mathur

*Mentors: Pablo Moscato and Shinsuke Shimojo*

With datasets containing hundreds of thousands to millions of features, innovative data mining initiatives have been taken to identify the most influential features. This not only streamlines datasets by being able to remove irrelevant or redundant features but also enhances interpretability in the context of explainable artificial intelligence (XAI), addressing the limitations of traditional black-box models. While the  $(\alpha, \beta)$ -k-Feature Set Problem has been extensively studied for feature selection through feature identification, the L-Pattern Identification Problem focuses on capturing richer contextual information through *pattern* identification.

Our research advances this field by exploring the scalability and optimization of algorithms for the L-Pattern Identification Problem. We propose using a memetic algorithm, an evolutionary AI method, that provides high-quality, near-optimal solutions, effectively balancing solution quality with scalability in comparison to constraint programming methods. Additionally, we utilize advanced matrix operations and vectorization techniques to improve performance. The proposed algorithm is tested across diverse datasets, including presidential elections, molecular toxicity, and divorce predictions, demonstrating its scalability and versatility. Performance benchmarks show our

algorithm achieves results 540 times faster than constraint-programming on the small-scale presidential dataset. Studies on larger-scale datasets are still in progress.

### **Simulating and Mitigating Potential Anomalies in Transit for the Lunar Trailblazer**

Mahak Mathur

*Mentors: Bethany Ehlmann and Judy Adler*

The Lunar Trailblazer (LTB) project is a NASA Small, Innovative Missions for PLANetary Exploration (SIMPLEx) mission intended to better understand the form, abundance, and distribution of water on the Moon. However, before the satellite can actually take data from a lunar orbit, it needs to successfully travel from the Earth to the Moon, performing various maneuvers along the way. Naturally, this requires detailed procedures to be put in place to cover as many scenarios as possible based on likelihood and consequence. In order to construct these crucial procedures, a careful analysis of potential anomalous situations was first conducted to consolidate a list of solutions potentially needed by LTB. Based on this list, contingency procedures were developed and rigorously tested via software simulators that closely resemble spacecraft conditions to determine their efficiency and effectiveness in resolving the anomaly. The results of this project were put into practice during the Off-Nominal Operations Readiness Test, ensuring their readiness for actual spacecraft operations.

### **The Small-Energy Extension Problem**

John Griffith Mattson, Jr.

*Mentor: Riccardo Caniato*

Sobolev spaces generalize notions of differentiability. They are useful tools in functional analysis and in the study of partial differential equations (PDE), particularly because of the Sobolev embeddings. In this project, we explore methods of extending Sobolev maps with domain  $S^n$  and co-domain  $G$  to all of  $B^{n+1}$  in such a way that we can uniformly control the energy of the map. Our goal is to find that there are constants  $\varepsilon$  and  $C$  depending only on the dimension  $n$  and the co-domain  $G$  such that any Sobolev map  $W^{1,n}(S^n, G)$  with energy  $E(u) < \varepsilon$  can be extended to  $B^n$  such that the energy of the extension is bounded above by  $E(u)C$ . We call this property "admitting a controlled extension."

To prove this claim, we consider the set  $U$ , the set of  $W^{1,p}$  functions (for some  $p > n$ ) with energy smaller than  $\varepsilon$ , and the set  $V$ , the subset of  $U$  of functions who admit controlled extensions. We then just need to prove that for some fixed  $\varepsilon$  and  $C$  (which, again, may depend only on the dimension  $n$  and the target  $G$ )  $U$  is connected and  $V$  is open and closed as a subset of  $U$ . Future work should finish the last details of proving that  $U$  is connected and give a proof that  $V$  is open in  $U$ .

### **Building a Stellar Radio Catalog of Sources With TESS Flares**

Klara Matuszewska

*Mentors: Gregg Hallinan and Ivey Davis*

Stellar magnetic activity, characterized by phenomena such as flares, plays a pivotal role in understanding stellar evolution, magnetic field dynamics, and the history of planetary evolution. Currently, the relationship between radiation and particle flux is poorly constrained for stars other than the Sun. To address this, we use data from the Transiting Exoplanet Survey Satellite (TESS) to construct a catalog of solar-type stars (characterized by temperatures between 5000-6000 K) exhibiting flares. We processed approximately 130,000 stars from TESS data, identifying around 3,500 exhibiting flaring activity. Concurrently, we utilized Very Large Array Sky Survey (VLASS) data to identify radio emissions corresponding to these flares to gain insight to the particle acceleration. For the stars identified with both flare activity and radio emissions, we delve into analyzing specific stellar properties that influence the likelihood of these magnetically-active stars not only producing radio emissions but also accelerating particles to relativistic velocities. By analyzing the correlation between stellar properties and the likelihood of radio emissions, we address a gap in current research which has predominantly focused on cooler stars.

### **Strong Gravitational Lensing With Upcoming Wide-Field Radio Surveys**

Samuel McCarty

*Mentor: Liam Connor*

The number of strong lensing systems will soon increase by orders of magnitude thanks to sensitive, wide-field optical and infrared imaging surveys such as Euclid, Rubin-LSST, and Roman. A dramatic increase in strong lenses will also occur at radio wavelengths. The 2000-antenna Deep Synoptic Array (DSA-2000) will detect over  $10^9$  continuum sources with a high mean redshift ( $\langle z \rangle = 2$ ) and the Square Kilometer Array (SKA) will observe a large sample of extragalactic sources with sub-arcsecond resolution. We forecast lensing rates, finding that the DSA-2000 will discover a few hundred thousand strongly lensed systems, many of which will be galaxy group and cluster lenses. We propose strategies for strong lensing discovery in the limit where the Einstein radii are comparable to the PSF angular scale, taking advantage of multiwavelength information and modern computer vision techniques. We also forecast synergies with optical and infrared surveys, which will provide redshifts as well

as multiwavelength information about the lens systems. Finally, we describe applications of radio strong lensing systems, including time-delay cosmography with transient and variable sources. Several hundred time-variable flat-spectrum AGN lenses discovered by the DSA-2000 could be used to constrain  $H_0$  at sub-percent level with follow-up by the Next Generation Very Large Array (ngVLA).

### **Fabrication of Dual Gated Twisted Bilayer Molybdenum Ditelluride Heterostructures**

Maverick McKown

*Mentors: Stevan Nadj-Perge and Hyunjin Kim*

Recent works have theorized that twisted bilayer  $\text{MoTe}_2$  possesses two topologically distinct phases that can be tuned in-situ via varying electrostatic gating. In this project we pattern graphite gates with nanoscale precision to border two different correlated phases within a single twisted bilayer  $\text{MoTe}_2$  sample. The interface between two phases are expected to host exotic quasiparticles such as anyons due to bulk-boundary correspondence. We demonstrate this is possible using controlled nanoscale oxidation of graphite gate using contact-mode AFM. We also present the techniques required for the construction of van der Waals heterostructures, as well as exfoliation and stacking techniques specific to dual-gated, twisted bilayer  $\text{MoTe}_2$ .

### **Sensitivity to CP Violation at the DUNE Far Detector**

Jude McLean

*Mentor: Ryan Patterson*

As Fermilab's premier neutrino beam experiment, NOvA, nears the end of its life cycle, more work is now being dedicated to its successor, DUNE. This up and coming neutrino beam experiment will operate over a much larger distance and should help to rectify the ambiguities associated with its predecessors, Fermilab's NOvA and Japan's T2K experiments. Most importantly, it should help to confidently resolve the value of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix's  $\delta_{\text{CP}}$  parameter that governs the degree to which neutrinos and antineutrinos are treated differently. Our ability to reject minimal CP (Charged-Parity) violation is largely dependent on the beam exposure and event reconstruction at the far detector. DUNE's technical design reports suggest that it may take upwards of thirteen years before we can conclude with  $5\sigma$  significance that  $\delta_{\text{CP}}$  lies away from minimal CP violating values for 75% of possible true  $\delta_{\text{CP}}$  values. By performing multidimensional sensitivity studies of the same data sets used in this TDR, we aim to find parameters that may help to reduce the exposure time required to reach these significance levels, and effectively reduce the time required to make meaningful conclusions about the underlying physics governing neutrinos.

### **CellCutLER: Unsupervised Cellular Image Segmentation**

Aditya Mehta

*Mentors: Pietro Perona, Markus Marks, and Neehar Kondapaneni*

Cells are fundamental building blocks of biological systems. Accurately segmenting cells is crucial for a wide range of microscopy image analyses. While deep learning has significantly advanced this field, it relies heavily on large annotated datasets, which are often unavailable for new imaging conditions. Since cellular images can vary with respect to cell size, shape, imaging modality, and staining, new setups usually require users to annotate new training data. To address this, we propose a novel zero-shot/few-shot cell segmentation method. By exploiting the rich feature representations of large vision foundation models, we extract and compare patch-level similarities within cell images. We use these similarities to iteratively cut out individual cells and thereby create pixel-level mask annotations of cells. Finally, we use these masks to fine-tune a cell-detection model and show how it improves performance on the new dataset. Our method eliminates the need for extensive manual annotations, accelerating high-throughput image analysis and enabling broader applicability of cell detection and segmentation models.

### **Identifying Phages for Use Against Antibiotic-Resistant Bacteria**

Divan Mejia Gonzalez

*Mentors: Smruthi Karthikeyan and Cathryn Holmes*

Antibiotic-resistant bacteria are becoming increasingly prevalent as a threat to human health. The most notable of these are the ESKAPE (*Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella* sp., *Acinetobacter* sp., *Pseudomonas aeruginosa*, and *Enterobacter* sp.) pathogens, which have potential to be multi-drug resistant (resistant to at least one antibiotic in three classes of antibiotics) and extensively drug resistant (resistant to almost all approved antibiotics). Bacteriophages, viruses which infect bacteria, and in particular jumbo phages, are being explored as a potential therapy for antibiotic-resistant bacteria. Jumbo phages, which have genomes of greater than 200 kbp, have been shown to be effective against extensively drug resistant bacteria. Here, we aim to isolate new phages that can effectively lyse a multi-drug resistant *Pseudomonas aeruginosa* strain. These phages will be sourced from wastewater samples shown to be enriched in antibiotic resistance genes. Simultaneously, we aim to optimize protocols for the isolation of phages from wastewater by comparing various methods. Characterization of the isolated phages through efficiency of plating assays, sequencing, and genomic annotation will be used to determine the effectiveness of the phages for therapeutic use against drug-resistant bacteria.



### **Advancing Ground-Based Exoplanet Characterization Instruments: MODHIS and HIRAX**

William Melby

*Mentors: Dimitri Mawet and Ashley Baker*

Detecting and characterizing exoplanets requires advanced instruments on some of the world's largest ground-based telescopes. At the upcoming Thirty Meter Telescope, the Multi-Objective Diffraction-limited High-resolution Infrared Spectrograph (MODHIS) is an instrument that will enable precise spectroscopic measurements of exoplanets and other targets. In this work we update MODHIS's performance simulation package, *specsim*, to more accurately estimate the signal-to-noise ratio (SNR) for the science case of direct imaging spectroscopy of exoplanets. For this, a fiber coupling profile database was generated and made compatible with *specsim*, allowing efficient SNR calculations across observing conditions.

The second part of this project visits Palomar Observatory's 200-inch Hale telescope, where HIRAX, a multi-band optical photometer that targets transiting hot, gassy exoplanets, will be used to detect atmospheric sodium using three ultra narrow bandpass filters. We identified a temperature-dependent throughput shift of 2.8 pm/°C in these filters, which could affect future science observations. To counteract this, we developed a compact temperature control system that can maintain a stable elevated filter temperature to within <0.1°C. These improvements in MODHIS's SNR calculation and HIRAX's temperature stability advance both instruments' capabilities, contributing to more accurate exoplanet characterization.

### **Hollow Cathode Plasma Ion Source Design for Atomic Layer Etching**

Aramis Mendoza

*Mentors: Austin Minnich and Ivy Chen*

Atomic layer etching (ALE) is a developing nanofabrication technique used by the semiconductor industry to fabricate their electronic circuits with nanoscopic precision. Recently, ALE has also shown promise for the development and fabrication of superconducting and integrated photonic devices. To expand the capabilities of ALE, it is necessary to extend beyond commercial plasma etching chambers to develop novel etching chemistries for various materials. Derived from Sobell et al., the proposed hollow cathode plasma (HCP) ion source design seeks to aid the mitigation of the nanofabrication precision gap. The HCP ion source produces plasma through the following steps: an ionization event, ion acceleration within the cathode tube, electron oscillation inducing further ionization, and the emission of an ion beam. The design uses two DC circuits to drive ion generation. The first circuit consists of the positively biased anode and the less positively biased hollow cathode. The second circuit operates between the positively biased hollow cathode and the negatively biased molybdenum mesh grid. To measure the produced ion saturation current and density, custom Langmuir probes were designed to evaluate the capabilities of the proposed HCP ion source design.

### **A Primordial Venus Moon Might Explain That Planet's Slow Rotation**

Mira Menezes

*Mentor: David J. Stevenson*

Earth's slow rotation period (24 hours) arose because of the tidal recession of the Moon. A more typical formation period for large bodies forming from random collisions of embryos is 5 hours or even less. Venus has a rotation period of 243 days, long for a body that lacks a moon. Tidal forces from the sun have a large uncertainty but could take 100x the solar system lifetime to cause this angular momentum reduction. The formation of Earth's moon gives evidence that planetary embryo impacts can lead to moon formation, and it is possible that a similar scenario could have occurred on Venus. Tidal torque scales with distance<sup>-6</sup>, creating extremely powerful interactions early on, when a moon is in low orbit. If early Venus also formed a moon, as is likely on standard accretion scenarios, this moon could quickly drain the angular momentum of Venus—However, this theory requires that Venus lose its early moon.

This may happen because the early solar system environment had many planetary embryos on intersecting paths with the terrestrial planets. Close encounters with planetary embryos cause a moon's semi-major axis to do a random walk. This creates a "tidal ratchet", where random encounters may bring the moon into a low orbit again, allowing a moon to sap angular momentum multiple times. A close encounter or collision with a planetary embryo would later on be able to eject this moon. A similar fate is avoided for earth with a late moon formation.

### **Designing a Learning Controller for a Bipedal Robot's Walking**

Jade Millan

*Mentors: Soon-Jo Chung and Sorina Lupu*

This project aims to design and train a machine learning model that can be trained and implemented onto a controller. The controller (referred to as the policy) will be tested in simulation and have its robustness verified before being implemented on the bipedal robot hardware. The effectiveness of the policy will be verified in comparison with an "expert", which allows the robot to walk via a capture-point inverse kinematics system and

inverse dynamics system. A successful test and implementation of this controller will result in the robot being able to walk autonomously and be able to learn how to walk on different surfaces other than the smooth and firm lab surface.

### **Compiling Qunity: Optimized Compilation of a High-Level Quantum Programming Language**

Mikhail Mints

*Mentors: Robert Rand and Michael Vanier*

This work focuses on implementing a new quantum programming language called Qunity, proposed in 2023 by Voichick et al., which has a central design goal of treating quantum computation fully as a generalization of classical computation. In contrast to most existing quantum programming languages, which are based on the quantum circuit model, Qunity has a compositional denotational semantics defined in terms of quantum operators and superoperators. It extends constructs from classical programming, such as algebraic data types and try-catch statements, into the domain of quantum computing, allowing many complex quantum algorithms to be expressed in a natural way. The main goal of this project is to design a compiler that translates Qunity into the quantum assembly language OpenQASM 3, which is not a trivial task due to Qunity's high level of abstraction from the quantum circuit model. We develop various optimization techniques for multiple stages of the Qunity compilation procedure, including post-processing circuit optimizations as well as methods that consider the high-level structure of a Qunity program to reduce the number of qubits and gates used by the compiler. These optimizations significantly improve the efficiency of the generated circuits compared to the originally proposed compilation algorithm.

### **Construction and Testing of a Galvo-Based Single Mode Fiber Switcher**

Anya Mischel

*Mentors: Nick Hutzler, Phelan Yu, and Madison Howard*

The failure of the Standard Model to explain the cosmologically observed matter-antimatter asymmetry is a longstanding problem in fundamental physics. Experimental searches for charge parity (CP) symmetry-violating shifts in the spectra of cold molecules under laboratory magnetic and electric fields could shed light on the physical mechanisms that created this imbalance. A technical challenge in these precision experiments is the large number of independent laser frequencies needed to address the internal quantum states of the science molecule. In the most advanced cold molecular experiments, over a dozen laser frequencies can be needed to achieve full quantum control, with individual wavelengths spanning hundreds of nanometers. Monitoring and controlling these frequencies requires fast and scalable single-mode fiber switches; however, most off-the-shelf, commercially available systems are both limited in number of input sources ( $\leq 8$  channels) and have limited wavelength operating ranges. To remove these limitations, I constructed and tested a 2D galvo-based single mode fiber switcher that leverages the flexibility of free-space fiber optical coupling. Through the construction phase, I 3D printed, machined, and soldered a protective container for the galvo's power supply unit, assembled the optics for the input laser sources, and modified the galvo's controller software to correctly move to the desired locations of the input sources. This galvo setup is able to be expanded to any number of mirrors and will be helpful in improving the range and scalability of current optical setups.

### **Designing a Wearable Chemical Sensor for the Discovery of Non-invasive Chronic Kidney Disease Biomarkers**

Ashley Mo

*Mentors: Wei Gao and José A. Lasalde-Ramírez*

Globally, 800 million people are estimated to have chronic kidney disease (CKD). However, 90% of patients with CKD remain undiagnosed. CKD is traditionally assessed by generating an estimated glomerular filtration rate (eGFR) through the analysis of blood creatinine, which is invasive. Using wearable sensors to assess CKD biomarkers in sweat can enable CKD to be diagnosed and monitored remotely and in real time, providing more accessible methods of CKD assessment. This project aims to build and optimize a wearable sensor that can quantify creatinine in sweat. It can provide a tool to validate the correlation between sweat and blood creatinine. Once this correlation is established, the sensor can be used to generate eGFRs using sweat creatinine. A cascading enzymatic reaction is used for the detection of creatinine. We optimize the redox mediator and enzyme concentrations to enhance the sensitivity. The sensors show good linear range calibrations for clinically relevant levels of creatinine. Further experiments are needed to assess the sensor's robustness in different sweat profiles before it can be tested in on-body studies.

### **Differential Aging of the Degenerative Spine: Characterizing the Functional, Radiographic, and Genetic Features of the Paraspinal Muscle of Patients With Lumbar Back Pain**

Maxwell Montemayor

*Mentors: Michael Safaee, Vinay Duddalwar, and Shinsuke Shimojo*

Back pain is the leading cause of disability worldwide. Traditional models on lumbar spine disease have focused on the disc degeneration, however the paraspinal musculature remains a poorly understood mediator of pain.

Increased intramuscular fat (IMF) and reduced cross sectional area (CSA) of the paraspinal muscles is correlated with increased back pain. A recent study has shown that radiomics, the extraction of quantitative features from medical images, can be used to extract data from cervical MRIs that correlates with the clinical degree of spondylotic myelopathy. This suggests that radiomics can be used to extract meaningful clinical data from imaging studies alone. Our project seeks to find what relationship the radiomic features of the paraspinal muscles, the IMF and CSA of these muscles, and the patient's age, sex, BMI, and physical activity has with the biological age and transcriptional profile of the muscle. Using the T1 and T2 MRIs of patients undergoing lumbar back surgery, we have measured IMF and CSA with ImageJ, and are currently extracting radiomic features of the paraspinal muscles using pyradiomics. Epigenetic and transcriptional data from the paraspinal muscle has been obtained from tissue acquired during surgery. We hope to develop a better understanding of the biomarkers of back pain and aid clinical decision making.

### **Investigating RF Harmonic Fluctuations Associated With Ice Grain Formation in a Weakly Ionized Plasma**

Robert Morgan III

*Mentors: Paul Bellan and Andre Nicolov*

The Caltech Ice Dusty Plasma Experiment studies the dynamics of ice grains suspended in a weakly ionized plasma at  $T=80-150K$ . The dusty plasma is a capacitively coupled discharge driven at a radio frequency (rf) of 13.56 MHz. Nonlinear sheath oscillations generate harmonics of the driving frequency. For a silane-argon dusty plasma, it had been observed that the amplitude of these harmonics abruptly changes as the dust particles transition from an accumulation to a coagulation growth mechanism. Investigations of the silane-argon plasma utilize similar nucleation and growth models applicable to the Caltech Dusty Ice Plasma Experiment at equivalent size scales (nanometers), so the analysis is expected to be transferable. The effects of the ice grains on the plasma are examined by monitoring the Fourier Transform of the time-varying voltage at the powered electrode. While the ice grains are on the order of nanometers, the charge accumulated by the grains is insufficient to alter the plasma's impedance. Consequently, when the ice grains are at this size scale, variations in the rf harmonics should directly correlate with the growth mechanism. Analysis of the rf harmonics are used to isolate ice grain nucleation and growth and assess working models for the phenomena.

### **Negligible Group Cohomology Over Fields of Characteristic $p$ and Eventually Negligible Classes in Integral and Mod $n$ Group Cohomology**

Samuel J. Moss

*Mentor: Matthew Gherman*

Let  $F$  be a field,  $K/F$  a field extension with  $\Gamma_L := \text{Gal}(K_{\text{sep}}/K)$ ,  $G$  a finite group,  $j: \Gamma_L \rightarrow G$  a continuous group homomorphism, and  $M$  an abelian group. Then there is an induced map  $j^*: H^n(G; M) \rightarrow H^n(K; M)$ . We say an element  $u \in H^n(G; M)$  is negligible over  $F$  if  $j^*(u) = 0$  for all such  $j$  and field extensions  $K/F$ . The space of negligible elements forms a subgroup  $H^n(G; M)_{\text{neg}, F} \subseteq H^n(G; M)$  containing information about group invariants and Galois embeddings over  $F$ . Given a unital commutative ring  $R$ , we can form the graded anticommutative cohomology ring  $\mathcal{H}(G; R) := \bigoplus_n H^n(G; R)$ . We say an element  $u \in H^n(G; R)$  is eventually negligible over  $F$  if there exists some  $k \in \mathbb{N}$  such that with respect to the ring multiplication on  $\mathcal{H}(G; R)$ ,  $u^k \in H^{nk}(G; R)_{\text{neg}, F}$ . In this project, we compute the second degree negligible cohomology of cyclic  $p$ -groups with coefficients in the Prüfer Group over arbitrary fields for  $p$  prime. We prove several results concerning negligible cohomology over fields of characteristic  $p$  for arbitrary groups; in particular, we provide a complete description of negligible cohomology for a  $p$ -group  $G$  over fields of characteristic  $p$  with coefficients in arbitrary finite abelian groups,  $\mathbb{Z}$ , and direct limits and sums of these. We show that every element of degree at least one is eventually negligible in the cohomology ring  $\mathcal{H}(G; \mathbb{Z})$ . Finally, we explore the feasibility of connecting homomorphisms in providing a natural description of negligible group cohomology.

### **Mutation Transfer for Improved Robustness in Enzymatic Cyclopropanation**

Orna Mukhopadhyay

*Mentors: Frances Arnold, Jae Kennemur, and Yueming Long*

Abstract withheld from publication at mentor's request.

### **Full-Sky Maps With SPHEREx for Studies of the Interstellar Medium**

Giulia Murgia

*Mentors: Jamie Bock and Ari Cukierman*

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) is a NASA mission designed to survey the entire sky over a two-year period, capturing data in optical and near-infrared light. SPHEREx aims to address fundamental cosmic questions by observing more than 450 million galaxies and over 100 million stars within the Milky Way. This project focuses on constructing arcminute-resolution full-sky HEALPix maps from SPHEREx exposures, with a scientific emphasis on the study of the interstellar medium (ISM) and components such as diffuse Galactic light (DGL) and polycyclic aromatic hydrocarbons (PAHs). We developed a

reprojection function to accurately map SPHEREx data onto a HEALPix grid, and we implemented source masking and zodiacal light removal techniques. These efforts aim to produce high-quality maps for cross-correlation with other surveys, contributing to a deeper understanding of the ISM and the universe's large-scale structure.

### **$O_2$ A-Band Parameters From Photoacoustic Spectroscopy**

Linus Murphy

*Mentor: Mitchio Okumura*

Anthropogenic carbon emissions have resulted in potentially catastrophic changes in the global climate, and year-by-year atmospheric  $CO_2$  absorption variability has eluded explanation. The Orbiting Carbon Observatory (OCO) project is currently studying this variability in orbit, measuring regular  $CO_2$  dry air mole fractions through reflected-sunlight spectroscopy of  $CO_2$ , with the goal of resolution on the scale of 1 ppm. The measurements require precise path length, temperature and pressure parameters, which are calculated from spectroscopy of the  $b^1\Sigma_g^+ \leftarrow X^3\Sigma_g^-(0,0)$  vibrational transition in  $O_2$  at 762 nm, commonly known as the A-Band. However, a better understanding of collision induced effects is required to achieve a more complete picture of the carbon cycle. Photoacoustic Spectroscopy (PAS) is a compelling method of studying these A-Band parameters, as it is broadband, considerably low-noise, and can measure in varied temperature and pressure conditions. We thus utilized PAS to measure collision induced lineshape broadening and linecenter shifting parameters. We measured broadband spectra from the P29P29 transition to the R29Q30 transition, at pressures varying from 50 torr to 1000 torr in increments of 50 torr. Our results vary marginally from literature values, and will be helpful in improving the resolution of the OCO satellites.

### **Materials Optimization of Lattice-Driven Fermi-level van Hove Singularities**

Samuel Murray

*Mentors: Linda Ye and Tao Lu*

The revitalization of superconductivity interest has recently produced into these novel van Hove singularities (vHS) subtle investigation since the divergent density of states brought by the vanishing of the wavevector gradient in the electronic band structure facilitates unconventional high-temperature superconductivity; in quantum materials with strong electronic correlations, such as heavy fermion systems or those with various transition metal complexes, they may enjoy enhanced spin-density wave formation or antiferromagnetism, for example. When such singularities coincided with the Fermi level, this research observed accelerated electron-electron interactions, which amplified the aforesaid properties. The foremost endeavor of the research was held to superconductivity and any new patterns pertaining to it: some candidate materials of particular interest that suggested an appreciable increase in critical temperatures were  $AV_3Sb_5$  kagome structures, FeGe, NiTe<sub>2</sub>, PdTe<sub>2</sub>, and the newly explored Co<sub>5</sub>Se<sub>6</sub>. These compounds were synthesized and grown, analyzed by HRXRD measurements, magneto-infrared spectroscopy, and electron-transport measurements. The results of such confirmed the presence of vHS and its superconductive manifestations, suggesting some predictability good for a more holistic model. LaNiO<sub>3</sub>-based perovskites, NbSe<sub>2</sub>, and Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8+x</sub> are very likely subjects for prospective examination, with special attention to any others that which are organized in a clover lattice structure.

### **Comprehensive Analysis of Urban Aerosol Pollution Dynamics and Health Impacts at Pico Rivera Using Advanced SMPS Measurements**

Ramona Wanjiru Murugu

*Mentor: Richard Flagan*

The Atmospheric Science and Chemistry Measurement Network (ASCENT) project is a comprehensive initiative aimed at monitoring and understanding the evolution and pathways of air pollution across the United States. Within this framework, our study focuses on the Pico Rivera site, one of three strategic monitoring locations within the Los Angeles basin. Pico Rivera provides insights into aerosols from urban activities, volatile chemical products, and wildfires. Complementing this, the Rubidoux site captures aged aerosols as they move downwind, while Joshua Tree serves as a background site in Southern California. Although this study primarily concentrates on Pico Rivera, we aim to enhance the spatial resolution of air quality assessments across these locations. To achieve this, we utilize Scanning Mobility Particle Sizer (SMPS) data and apply Python code to quantify aerosol size distributions, analyze temporal variations, and refine data analysis processes. By adapting the initial SMPS processing code and developing versatile Python scripts, we enhance the accuracy and applicability of air pollution assessments.

### **Supersymmetric Wormhole Teleportation**

Damian R. Musk

*Mentors: Joseph Lykken and Maria Spiropulu*

Our research extends previous work on simulating supersymmetric quantum mechanics to supersymmetric field theory. Beginning with a 1D Kitaev model as a warm-up, where we use Majorana fermions to perform an energy spectrum and entanglement power analysis, we further extend the Gao-Jafferis protocol for wormhole teleportation between copies of supersymmetric SYK models. We show in finite- $N$  simulations that the supersymmetric SYKs exhibit signature holographic features of wormhole teleportation, including those related to size winding. In

particular, the analysis indicates superior teleportation as compared to that of the non-supersymmetric original. This work represents a first step in incorporating supersymmetry into the “quantum gravity in the lab” program.

**Finiteness Problems on Simple CM Abelian Varieties With Rational Field of Moduli**

Kenji Nakagawa

*Mentor: Matthias Flach*

The study of elliptic curves has historically been a central part of number theory and currently the theory of the higher dimensional analogues of them form an important branch of modern number theory. The higher dimensional analogue is given by abelian varieties which enjoy nice algebraic and geometric properties as well as having a group structure tied to the geometric aspect of it. For simple abelian varieties, the endomorphisms form a ring, and one can derive a field from it. For elliptic curves with complex multiplication, this derived field is referred to as a CM field, and the field having class number one, the curve having rational field of moduli, and the curve having a rational field of definition are all known to be equivalent. By the fact that the class number must be one and the CM fields are all imaginary quadratic, it follows that there are only finitely many elliptic curves with this property. Although classification for 1,2 and 3-dimensional varieties has been done, this project attempts to investigate finiteness for the general case with special attention to 5-dimensional varieties.

**Deep Learning for Detection of Surgical Feedback Instances in Real World Surgeries**

Firdavs Nasriddinov

*Mentors: Anima Anandkumar, Rafal Kocielnik, and Andrew Hung*

The manual annotation of surgical feedback in real-world settings is a challenging, costly, and imperfect process. To address this, our study focuses on the development of deep learning models that can automatically detect feedback instances in extensive urology surgery recordings performed using the da Vinci robotic system. These models will enable the training of subsequent models, paving the way for a variety of applications, such as determining trainee behaviors based on feedback, identifying teaching tasks to gain insights into the relative difficulty of specific tasks, and ultimately developing an automated feedback delivery system. The dataset comprises extensive audio and video feeds capturing interactions between trainee surgeons and supervising trainers during surgeries. We propose two primary approaches: (1) A binary classification approach that distinguishes feedback from no-feedback instances, with inference on entire surgery recordings performed using a fixed-length rolling window technique to capture feedback instances across lengthy sessions. (2) A dialogue-based approach where the entire conversation between trainer and trainee is modeled which includes separating conversations, identifying speakers, and evaluating speaking rounds of variable lengths BERT and/or GPT-4. This research aims to advance the automatic detection of feedback in surgical training, thereby providing valuable insights for improving surgeon performance and training protocols.

**Applying Filtration and MEM to Low Bacterial Load Samples**

Paulina Naydenkov

*Mentors: Rustem Ismagilov, Christopher Nieman, and Ojas Pradhan*

The interactions between humans and their associated microbiome have been associated with health through the use of microbial taxonomic profiling through 16S ribosomal RNA gene sequencing. However, some insights cannot be uncovered partially due to the high host to microbe DNA in some samples. Recently the Ismagilov group developed a microbial enrichment method (MEM) which enabled high-throughput characterization of microbial metagenomes by reducing host DNA more than 1,000-fold. However only roughly 90% of taxa had no significant differences between MEM-treated and untreated control groups. General bacterial loss is also observed due to the necessary buffer exchange steps. We would like to increase the bacterial retention in these samples by using filtration instead of centrifugation for buffer exchanges. We see that using a filter does not significantly affect the bacterial loads when performing MEM on moderate loads of cultured cells and filters can capture a low load of cells. We will further see if the filter is compatible with tissue samples.

**Automatic Fiber Polarization Adjuster**

Miruna Neacsu

*Mentors: Andrei Faraon and Rikuto Fukumori*

Quantum networks represent a new communication infrastructure that provides increased security and computational power. Microwave-to-optical quantum transduction can aid in the construction of such networks, by enabling the remote connection of superconducting qubits via optical fibers.

In the transduction setup in the Faraon lab, polarization drift in these fibers can cause reduced conversion efficiencies. This can be solved using a custom-built automated fiber polarization adjuster, involving a combination of electronic and optical components featuring an Arduino control unit with digital-to-analog converters (DACs), arbitrary waveform generators, and an electronically-driven polarization controller.

An Arduino IDE coding system using the I2C protocol supported by a Python code sends different voltages to DACs/waveform generators. This procedure changes the polarization by adjusting the voltages applied to four magnets in the polarization controller.

To measure the polarization state, we send the light through a linear polarizer and measure the output power using a photodetector and digitally monitor with an oscilloscope. Using this signal as feedback, an algorithm is used to stabilize the polarization to be aligned with the polarizer.

This setup will enable the polarization stabilization in transduction experiments conducted in cryogenics settings, optimizing the transduction process for long-distance quantum communication.

**Enantioselective Cobalt-Catalyzed Homo Diels-Alder Reaction: Expansion of Scope and Application Toward the Total Synthesis of Pedrolide**

Gabriel Negrao de Morais

*Mentors: Sarah E. Reisman and Cedric Lozano*

Metal-catalyzed homo Diels-Alder (hDA) reactions are powerful tools for the construction of complex polycyclic scaffolds, serving as an efficient alternative for accessing compounds of biological relevance. Methods for metal-catalyzed hDA cycloadditions of norbornadienes and partners, such as olefins, butadienes, and acetylenes, have been reported in the literature. Aiming to further contribute to these initial efforts, herein, we report a method for an enantioselective cobalt-catalyzed hDA of norbornadienes and acetylenes. Additionally, an investigation of the functional group tolerance of this method was performed by employing a wide range of substituted acetylenes. Building on the discoveries from the reaction scope investigation, the method has been utilized to conduct synthetic studies toward an enantioselective total synthesis of *pedrolide*, a tigliane-type diterpenoid natural product that has revealed promising results for the reversal of multidrug resistance (MDR). Ultimately, the objective of this cobalt-catalyzed hDA method, along with its extensive scope exploration and reaction optimization, is to expand the tools of chemists in organic synthesis to build challenging core structures in an efficient and enantioselective way.

**Searching for Pulsation Signals in Low-Mass Stars With TESS Through Light Curve Analysis**

Sajia Shahrin Neha

*Mentors: Gregg Hallinan and Rocio Kiman*

Asteroseismology is an important technique for extracting the intrinsic properties of pulsating stars. Previous research has shown that high-mass stars have pulsations, and theoretical work suggests low-mass stars can also pulsate. Despite this, previous Kepler K2 data failed to detect pulsations in M dwarfs. In this project, we aim to identify solar-like pulsations in low-mass stars, particularly G, K, and M dwarfs, using Transiting Exoplanet Survey Satellite (TESS) 20 second and 2-minute cadence data. We extract and analyze light curves from our target stars to identify and investigate noteworthy signals. We examine these signals in detail using Lomb-Scargle periodograms and power spectrum plots. Our analysis has revealed various phenomena, including stellar flares, eclipsing binaries, variable stars, pulsations from nearby higher-mass stars, and rotation periods in the light curves of our target stars. Our goal is to detect significant oscillation signals and utilize them to determine the fundamental properties of these low-mass stars.

**Biochemical and Structural Analysis of the HsGet3 Protein and Its Inhibition by Retro Compounds: Implications for Targeting Retrograde Trafficking**

Anna Huyen Ngo

*Mentors: William M. Clemons, Jr., and Juliet Lee*

Fundamental cellular processes encompass the recognition and insertion of membrane proteins into the lipid bilayers of cells and organelles, which are crucial for cellular metabolism and disease progression. Among these membrane proteins are tail-anchored (TA) proteins, which reach the endoplasmic reticulum (ER) through obligatory posttranslational targeting via the guided entry of TA proteins (GET) pathway. At the core of this pathway lies the Get3 ATPase, which binds to and mediates the targeting of TA proteins to destination membranes. Some SNAREs, a type of TA protein, are involved in retrograde trafficking, a transport mechanism exploited by pathogens and toxins to infiltrate cells. Previous studies have demonstrated the therapeutic potential of the GET pathway, showing how Retro compounds and their analogs hinder TA protein targeting by redirecting them towards degradation. Using cryo-EM, we aim to obtain a structure of HsGet3 in complex with Retro-1 and its more potent derivatives. Through site-directed mutagenesis, we will characterize specific amino acids implicated in the putative drug binding site of the protein. This work extends beyond elucidating the human GET pathway by laying the groundwork for further optimization of small molecules to impede retrograde trafficking.

**Using Price History, Forecasts, Risk Attitudes, and Emotional Measures to Predict Experimental Asset Bubble Crashes**

Cady Ngo

*Mentors: Colin Camerer and Thomas Henning*

Integrating biometric data into an experimental asset pricing market, this study seeks to enhance our understanding of asset bubble dynamics. By combining skin-conductance responses with traditional market behavior and expectations, we examine individual risk preferences during bubble formation, price forecasting, and risk elicitation. This novel approach analyzes the cognitive and emotional drivers behind market decisions, particularly during bubble crashes. Preliminary findings suggest that physiological responses can forecast asset bubble crashes – a notoriously difficult task – offering valuable insights into market dynamics and risk management. These findings have the potential to contribute to both academic discourse and practical applications in the financial industry.

### **Mo-Catalyzed N<sub>2</sub> Reduction to NH<sub>3</sub> With SmI<sub>2</sub> and Multidentate Alcohols Towards Photodriven Samarium Turnover**

Bao Nguyen

*Mentors: Jonas C. Peters and Emily Boyd*

The reduction of nitrogen to ammonia with well-defined molecular transition metal catalysts is of great interest for opportunities to better understand mechanisms of N<sub>2</sub> reduction and for offering a possible alternative to the energy-intensive Haber-Bosch process. Work from Nishibayashi and coworkers has demonstrated that SmI<sub>2</sub> and ethylene glycol serve as effective sources of electrons and protons, respectively, for N<sub>2</sub> reduction with a range of Mo catalysts. While capable of selectively producing high yields of ammonia, this system requires stoichiometric amounts of SmI<sub>2</sub> and produces ill-defined Sm<sup>III</sup>-alkoxide species. These species include oxygen-bridged polysamarium complexes with a strong chelate effect, resulting in a thermodynamic sink and rendering Sm turnover very difficult. Herein, we demonstrate that pairing stronger chelating higher-order (poly)ethylene glycol monomethyl ethers with SmI<sub>2</sub> produces higher yields of ammonia with the Chatt-type catalyst **Mo**. These monoprotic ligands are more conducive to photodriven nitrogen reduction with SmI<sub>2</sub> and **Mo**, as their Sm<sup>III</sup>-alkoxide byproducts are more amenable to turnover than their ethylene glycol analogs. Thus, we also present the results of attempts at photodriven Sm turnover in this system utilizing a photocatalyst (**[Ir]**) and a sacrificial reductant (HEH<sub>2</sub>).

### **From Benamou-Brenier Optimal Transport to Triangular Velocity Fields**

Minh Nguyen

*Mentors: Franca Hoffmann and Ricardo Baptista*

We consider the Benamou-Brenier formulation of optimal transport, but with a modified weighted Euclidean norm and prove convergence to a triangular velocity field. We show that a proximal/soft-constraint of the weighted Benamou-Brenier also converges to a triangular velocity field, and that the solution to the soft-constraint weighted Benamou-Brenier converges to the solution to the normal weighted Benamou-Brenier. Then we discuss a Hamilton-Jacobi formulation of the problem, how the Hamilton-Jacobi decouples in limit and some regularity at the end. Numerical results are provided at the end.

### **Estimating Impacts of Future Change in Extratropical Cyclone Activity on Precipitation Using Machine Learning**

Thanhthanh Nguyen

*Mentors: Edmund K. M. Chang, Cheng Zheng, and Katherine Bouman*

Across North America, precipitation events caused by extratropical cyclones (ETCs) are responsible for destructive disasters such as floods and landslides. We aim to gain better understanding of the relationships between ETCs and precipitation by confirming findings from an earlier study using linear methods, and by using novel nonlinear machine learning (ML) methods to possibly discover additional, more robust relationships. Using linear regression prediction to create a point-by-point correlation map, 100 CESM2 (Community Earth System Model 2) ensembles confirmed a strong relationship between the precipitation in California and storm tracks in the Eastern North Pacific, and a somewhat-weaker relationship between Northeastern United States precipitation and storm tracks in the Northwestern Atlantic Ocean. Additionally, PCA (principal component analysis) modes of storm tracks, which represent the leading spatial patterns of storm track variability, are used in a multiple linear regression model to discover potentially stronger relationships. Neural networks are currently being utilized to explore whether nonlinear ML prediction methods can be leveraged to find more robust relationships between storm track and precipitation, especially over regions where linear regression methods suggest weak linear correlations, such as over the east coast of the U.S. and the Midwest.

### **Text-Guided Protein Sequence and Structure Co-Design**

Zhanghan Ni

*Mentors: Anima Anandkumar and Shengchao Liu*

Language models have been successfully repurposed for protein design by modeling the distribution of amino acid residues. While these models can generate a diverse family of plausible sequences, the function of a protein in its biochemical environment is directly determined by its three-dimensional structure. Empirical protein research has also accumulated an extensive reservoir of functional annotations for proteins designed through natural evolution.

Our project aims to utilize these textual descriptions to more efficiently navigate the vast protein space for designing coherent sequence and structure pairs. Benchmarking of existing multimodal approaches suggests that structure-based models, despite their limited capacity to leverage textual information, outperform sequence-based models in enhancing structural stability through point mutations.

### **Simulating the Effects of Dust on Multiwavelength Emission From Tidal Disruption Events**

Nitya Nigam

*Mentors: Vikram Ravi, Jean Somalwar, and Hazel Yun*

Tidal disruption events (TDEs) occur when stars get close enough to a massive black hole (MBH) to be shredded by the MBH's tidal forces, producing luminous radiation flares across the electromagnetic spectrum. These flares can reveal otherwise quiescent MBHs, aiding in their identification and study.

TDE samples selected at different wavelengths show intriguing differences. Notably, IR-selected TDEs often lack optical flares. Dust, which diminishes optical light but emits in the IR, could cause this discrepancy. Differences in dust geometries might explain the variety in TDE light curves and spectral energy distributions (SEDs) across the EM spectrum. Dust's role in TDE emission, however, has never been theoretically explored.

This project simulates the effects of dust on multiwavelength emission from TDEs. We model the propagation of UV radiation through dust and gas near the MBH, using an iterative Python algorithm based on a model of IR dust echoes from binary neutron star mergers. Assuming standard ionization physics and dust grain size distribution, we generalize to azimuthally symmetric dust geometries. We expect IR lightcurves and SEDs generated from UV input to match TDEs observed in both wavebands. This work will allow us to distinguish between dust geometries based on their IR emissions.

### **Tracking and Characterizing Flocculation and Settling Velocity**

Brayden Noh

*Mentors: Michael Lamb and Kimberly Miller*

This study investigates methods for in-situ tracking and characterization of flocculation and settling velocity in freshwater environments. We use an in-lab mixing tank equipped with an optical camera system to observe particle behavior. The analysis focuses on identifying flocs based on two key parameters: fractal dimension (internal structure) and aggregate count (number of constituent particles). Particles with lower fractal dimension and higher aggregate count, deviating from the theoretical settling velocity predicted by Stokes' Law, are considered potential flocs. This method has potential applications in studying the effects of varying organic matter content and shear stress on flocculation and sediment dynamics.

### **Constraining How Sediment Properties Control Organic Carbon Transport in Arctic Rivers**

Alison Norton

*Mentors: Michael P. Lamb and Yutian Ke*

Rivers play a major role in transporting sediment and its associated organic carbon (OC) from mountainous sources to ocean sinks, significantly impacting the global carbon cycle. In Arctic landscapes, permafrost stores substantial amounts of OC, which rivers receive as permafrost thaws. Consequently, suspended sediment in Arctic rivers may have a higher OC carrying potential compared to other large rivers worldwide. Characterizing the physical and mineralogical features of suspended sediment is crucial for unravelling the mechanisms controlling OC loading. Thus, we analyzed grain size distribution and OC content of suspended and bed sediments from various depths in the water columns in the Koyukuk River in Huslia, Alaska and the Yukon River in Beaver, Alaska, during Spring and Fall. This study also aims to differentiate the POC loading between a sand-bedded meandering river (Koyukuk) and a gravel-bed braided river (Yukon). Preliminary findings show that as grain sizes become coarser from the river surface to the bottom, OC content becomes more depleted. Furthermore, OC content increased on average from Fall to Spring in both rivers. By investigating the controls on OC loading, we can deduce the sources and fates of OC, providing insight into the role of permafrost rivers in the carbon cycle.

### **Designing and Implementing Thrust Vectoring Systems for Novel Scale Kerosene-LOX Rocket Engines With the Goal of Application on a Self-Landing Vehicle**

Reid Nussbaum

*Mentors: Morteza Gharib and Jack Caldwell*

Thrust vectoring via engine gimbaling has been utilized in the space industry for launch vehicle attitude corrections and maneuvers for decades. More recently, commercial companies have started implementing thrust vectoring to enable controlled, powered rocket landings of launch vehicles. While large commercial space companies have proven that thrust vectoring is a viable method of landing launch vehicles, the concept has only been implemented on a select few large-scale rockets and the academic analysis of a system is not well documented by current literature. The implementation of a thrust vectoring system on a novel-scale liquid-biprop engine was explored, using perpendicularly set PID-controlled linear actuators to manipulate an engine mounted on a spherical bearing.



The design was able to not only exceed the minimum travel requirements for flight maneuvers, but also provided an adequate response rate for flight stabilization purposes with an analytically solved inverse kinematics system allowing edge computing of control inputs. A continuation of the project would include designing a flight-ready version with a reduced mass budget, more redundancy of critical parts, and the integration of the control scheme with full vehicle controls.

**Understanding the Rotational Behaviors of M Dwarfs**

Khant Nyi Hlaing

*Mentors: Gregg Hallinan and Rocio Kiman*

Low-mass stars, or M dwarfs, are the most common type of star in the Galaxy and the most likely host of Earth-like exoplanets. One of the main unresolved problems about M dwarf properties is that the rotational period evolution is not well understood. In this work, we studied the bimodal distribution of the rotational period of field low-mass stars, particularly the fast rotators. There are several explanations to this bimodality such as magnetic dynamo, initial conditions, magnetic field topology or binarity. In this work, we tested the binarity explanation. We compiled low-mass stars from the literature with rotation period measurements and cross-matched them with Gaia EDR3. For binary classification, we used three different binary indicators from Gaia: RUWE (Renormalised Unit Weight Error),  $rv\_amplitude\_robust$  (variability in radial velocity), and  $ipd\_frac\_multi\_peak$  (an indicator for unresolved companions). Among two hundred thousand stars, we selected the single, main sequence stars that are older than 500 Myr with rotation periods faster than 7 days. Our final sample contained 37 stars. We found that single M dwarfs stay rotating fast for at least about 2 Gyr before they start to spin down. Finally, I will work on a supervised classification algorithm I developed to improve the binary classification.

**Variable Area Pintle Injector for Rocket Engine Throttling Applications**

Max Oberg

*Mentors: Mory Gharib and Jack Caldwell*

The pintle rocket engine injector has existed since the 60s, however, any progress made on variable area pintle injectors has not been well researched and work has mostly been limited to the commercial space and as such is hard to get access to. Two different pintle injectors were developed in this study. The first was a stationary pintle meant to act as a test article to verify discharge coefficients and flow characteristics of a pintle injector. Using this injector, the assumptions used to design the pintle were analyzed and tweaked to account for experimental data. The second injector is currently still being designed. Once the design is finalized, a similar testing of the flow characteristics of propellant and oxidizer through the injector can occur before being tested on a hot firing of a rocket engine.

**Gradient-Based MCMC Methods for Uncertainty Quantification in Climate Models**

Kota Okuda

*Mentors: Tapio Schneider, Oliver Dunbar, and Eviatar Bach*

Climate Modeling Alliance (CliMA) is developing new data-driven climate models by leveraging recent machine learning and statistical tools to enhance the predictive accuracy and uncertainty quantification. Therein, sampling techniques such as Markov Chain Monte Carlo (MCMC) are key methods for expressing uncertainties in parameter estimation. However, the MCMC stage in modelling becomes computationally prohibitive as the number of parameters increases. Our project is focused on accelerating the MCMC sampling by using the fact that the machine-learned models utilised in climate models are frequently meant to be differentiable, and hence that the gradient information of the models are available. One of the computational problems behind the gradient-based MCMC is that the optimally fast sampling could be realised only if some tuning parameters in MCMC algorithm is finely conditioned. To overcome this issue, we adopt the Barker proposal, which is tuning-robust in a sense that the enhanced performance of gradient-based sampling does not degenerate in varying the tuning parameters compared to the ordinary gradient-based MCMC. Our contribution is that we incorporate the Barker proposal into the sampling from the emulated Gaussian Processes and develop Julia codes for easier implementations.

**Generating Transgenic *D. melanogaster* by Adult Abdomen Injections With Recombinant Tol2 Transposase and a Target Plasmid**

Emma Olinger

*Mentor: Bruce Hay*

Methods currently available to generate transgenic *D. melanogaster*, more commonly known as the fruit fly, are labor intensive and inefficient. Transposons are segments of DNA that have the ability to integrate into the genome of an organism using the transposase enzyme. We hypothesized that injecting a mixture of transposase, a transposon plasmid with a gene of interest, and an endosomal release agent (EER) could be a more efficient and less laborious method of generating transgenic *D. melanogaster* offspring. To test this hypothesis, we assembled a plasmid construct containing the transposon *pminiTol2*, which has shown to have high cargo capacity in vertebrates, and an EGFP (green fluorescent protein) coding sequence as a selection marker to determine successful integration of the plasmid into the fly's genome. After adult flies were injected, they were mated to

white-minus flies to ensure offspring production, which were then scored to determine successful plasmid integration.

### **Engineering Plasmonic Nanostructures for Azobenzene Molecular Switches, and Predicting Their Reaction Rates**

Brian Olsen

*Mentor: Axel Scherer*

This summer I have worked on two projects because I was not satisfied with purely experimental work.

The objective of the experimental side of this project is to construct nanostructures on the order of tens of nanometers that produce distinctly high electric fields, which in turn can be used to modulate the reaction rate of an azobenzene molecular switch. We use a typical nanofabrication process of electron beam lithography, wafer development, ion milling, and sputtering-based deposition to produce the structures, and then adsorb azobenzene molecules onto them for further testing. Currently, we have not achieved any data, but we have produced structures on the order of 50 nanometers in size and in gap, producing sufficiently small cavities for the "field enhancement" to occur. We will conclude the quality of the nanostructures' field effects when the azobenzene treatment has finished, as well the field's effect on molecular switches' reaction rates.

The purpose of the theoretical side of this project is to produce a general mathematical model that accurately predicts the reaction rates of two-state systems in plasmonic nanojunctions. The analysis was done ab-initio by describing the explicit Hamiltonians for the system at hand, and numerically solved under the assumption of equilibrium condition before the plasmonic enhancement occurs. The model, if verified by the experiment, has large implications for the possibility of optimizing molecular switches to be orders more sensitive, and many other applications.

### **Designing an Outward Propagating Relay Network on a Chip**

George Ore

*Mentors: Kwabena Boahen and Glen George*

Designing a network on a chip needs to prioritize simplicity and slowly move toward more complicated designs, especially when there are only a handful of individuals working the full stack. The network developed over the last four weeks has seen significant growth, but still needs more. Uncertainties in the manufacturing requirements make design more challenging but prioritizing simplicity and focusing on abstract methods will make pivoting easier when the time comes.

### **Anomaly Detection and Factorization in Collider Physics**

Emily Pan

*Mentors: Maria Spiropulu and Raymond Wynne*

The Large Hadron Collider is a particle accelerator that produces the highest energy particle collisions ever made in a lab. Factorized Observables for Regressing Conditional Expectations (FORCE) is a method to study these collisions and detect general deviations from the Standard Model. The FORCE method is based on factorization—the inductive bias that the physics governing high and low energy scales are approximately independent. Given a dataset with approximately factorized objects with kinematics  $p_T$  and scale-/boost-invariant substructure  $O$ , we can train a machine learning model to learn  $p_T$  from  $O$  and classify anomalous objects using the results. Our objective is to expand our understanding of the FORCE method and employ it to recover variables of interest from our simulated dataset. We show how anomaly detection performance varies with changes in the signal and background distributions. We explore implementing a functional form of the conditional expectation of simulated analytical distributions to learn the average  $p_T$  and signal fraction of our dataset.

### **Uncertainty- and Grid-aware DER Control via Deep Learning Robust Optimization**

Yiyuan Pan

*Mentors: Steven H. Low and Yiheng Xie*

The capacity expansion and subsequent optimal scheduling help power system reduce emissions and improving electricity efficiency, which has attracted considerable attention in recent years. This sequential decision problem can be formulated as a two-stage robust optimization model. The study of this model provides decision support for the resolution of the optimal power flow (OPF) problem in real power grids and the deployment of distributed energy resource (DER) devices in the future. Nevertheless, the real-time price (RTP) and nodal daily demand during the grid operation are subject to significant uncertainty, which may negatively impact the model's performance. To this end, we have designed an end-to-end (E2E) hybrid neural network-optimization architecture for the study of Linear Distflow-based three-phase circuit models. The framework incorporates an additional uncertainty calibration layer, which transforms the predictive distributions into convex constraints. Furthermore, the model solution results are utilized for gradient propagation, enabling the updating of network parameters.

Ultimately, our model is evaluated on data derived exclusively from the real world. The findings demonstrate that our model is capable of attaining optimal solutions for grid operation while accurately estimating the parameters.

**Superconducting Quantum Sensors in Dark Matter Search: Improving Phonon Collection Efficiency in Phonon Mediated Kinetic Inductance Detectors (KIDs)**

Hanna Park

*Mentors: Sunil Golwala, Brandon Sandoval, and Osmond Wen*

The lack of evidence for weakly interacting massive particles above 10 GeV have prompted investigations into lower keV mass scales, where dark matter interactions produce energy depositions under 1 eV—too small for standard detection techniques such as scintillation or ionization. Phonon-mediated microwave kinetic inductance detectors (KIDs), which are thin-film superconducting microwave resonators featuring an interdigitated capacitor and a meandering inductor, are effective for detecting these low-energy interactions. KIDs detect dark matter by capturing the energy deposited into the substrate from dark matter particle collisions. This energy generates phonons that disrupt Cooper pairs within the resonator, increasing the inductance and lowering the resonance frequency.

This project aims to improve phonon collection efficiency in KIDs, currently below 1%, through two main strategies: adding thin-film quasiparticle-trapping aluminum fins to maximize phonon collection area and guide phonons into the resonator, and redesigning the KID box mount to reduce phonon loss. We use Sonnet, an electromagnetic simulation software, to test and analyze these improvements along with circuit geometry modifications, focusing on current density distributions and changes in resonant frequency and Q factor. The redesigned box features a new mounting configuration with wire bonding to minimize phonon loss through surface area and provide thermal connection, ensuring effective thermal anchoring and enabling the detector to reach the low temperatures required in the cryogenic refrigerator.

**A Robust MRI Reconstruction Approach for 2D Overlapping (SSFSE) Liver Images to Enhance Usability**

Deepro Pasha

*Mentors: Shreyas Vasanawala, Ali Syed, and Lihong Wang*

Optimal evaluation of abdominal organs such as the liver has been enabled by the continuing technological growth of MRI techniques, with 3D MRI methods providing arbitrary plane reformatting and higher spatial resolution. However, due to relatively longer acquisition time, these methods have high sensitivity to motion such as common respiratory and cardiac motion, thus creating ghosting artifacts, signal loss, and blurred images. In this work, we propose utilizing 2D MR image slices, which are faster and relatively motion insensitive, but are unable to reformat into arbitrary planes due to slice misalignment instead creating through-plane artifacts. We aim to realign stated slices to remove such artifacts. We additionally utilize overlapping slice information to cure areas of signal voids present within select slices due to cardiac pulsation. We implemented this via a supervised deep learning augmentation-based technique that, based off augmented diagnostically perfect data, works to perceive levels of unalignment and detect slices that contain signal voids. We thus return motion-robust MR images of liver.

**Developing GMM-Consistent Velocity Profiles With 1D Wave Propagation: An Ensemble Kalman Inversion Approach**

Amrita Pasupathy

*Mentors: Domniki Asimaki and Grigorios Lavrentiadis*

Site-response analyses characterize how seismic waves are amplified near the surface due to the entire velocity profile by providing the shear-wave velocity as a function of depth. However, in ground motion models (GMMs), the shallow crustal amplification is simplified to just a function of the time-average shear-wave velocity at the top 30 m ( $V_{s30}$ ). Determining  $V_{s30}$ -consistent velocity profiles is important in applying GMMs to regions where the full profiles are inconsistent with the dataset. Past efforts to determine these profiles fell victim to certain oversimplifications that affect the fit of the amplification factors, such as assuming profile smoothness or ignoring full wave propagation and the reflection of waves at the surface. Our project aims to address these issues by employing Machine Learning methods to develop velocity profiles that more accurately account for site amplification. To do this, we defined a reference profile for  $V_{s30}$  of 100 m/sec and then iteratively inverted the velocity profiles for other  $V_{s30}$  values using the Ensemble Kalman method, a derivative-free optimization approach with fast convergence.

**AI-Generated Images and Messages to Determine Behaviors for Risky Decision-Making in the Stag Hunt Game**

Ria Patel

*Mentor: Colin Camerer*

This project aims to understand how AI-generated pre-play messages and images influence players' decisions in the stag hunt game, a classic coordination problem in game theory. The research explores the role of assurance in promoting risky choices through various factors, including tone of voice, emotion, celebrity status, and

demographics. Methodology involves a series of experiments starting with diverse faces, followed by audio and text messages, combined face-audio clips, and lifelike deepfake videos. Preliminary results indicate that facial characteristics significantly affect participants' willingness to choose the risky option, supporting hypotheses on social biases and non-verbal cues. The goal is to use the collected data to train a predictive model that identifies the characteristics most likely to encourage risky decision-making. This research aims to contribute to a deeper understanding of strategic interactions and social perception.

### **Leveraging Machine Learning for Source Classification With the NASA ROMAN Telescope**

Heramba Patil

*Mentors: Ashish Mahabal and Roberta Paladini*

This project focuses on developing an autoencoder machine learning model to identify and classify transient objects in astrophysical images from the NASA ROMAN Telescope. The telescope is scheduled to launch in 2027, so the model is currently using simulated image pairs containing non-variable and transient objects, coupled with key information such as magnitude and celestial coordinates from accompanying catalog files. A grid-based scanning method was applied to select transients within snapshots for training, followed by magnitude difference calculations using aperture photometry. The core of the project involves constructing an autoencoder model designed to reconstruct the locations and brightness of transients using generated Point Spread Function (PSF) images as ground truth. Initial results show that the model is in progress, with ongoing experimentation involving various hyperparameters and loss functions to optimize performance. Future work includes refining the model with a larger dataset and implementing more advanced preprocessing techniques for artifact detection. This work aims to contribute to the broader goal of building a robust machine-learning pipeline for the identification and classification of celestial events from the ROMAN Telescope.

### **Understanding Sums of Linear Orders Through Their Structure**

Eric Paul

*Mentor: Garrett Ervin*

The study of sums of linear orders has many classic theorems. One by Aronszajn classifies exactly the linear orders whose sum commutes and another by Lindenbaum provides a sort of Euclidean algorithm for sums of linear orders. The proof of each of these theorems uses very different techniques. We use a single structural decomposition of linear orders to prove each of these results in the same way. We further extend this approach to show a new identity for sums of linear orders. The overall strategy is to follow one of two paths. If a linear order is isomorphic to two copies of itself, then many of the theorems regarding its sums become straightforward to prove. If a linear order is not isomorphic to two copies of itself, then we take advantage of this extra rigidity to more deeply understand its structure and use that to prove theorems about its sums.

### **Using Protein Language Models to Engineer a Zinc Finger Based Transcriptional Activator as a Dravet's Syndrome Therapeutic**

Jean Sebastien Paul

*Mentors: Xiaojing Gao and Niles Pierce*

Human Zinc Finger (ZF) proteins offer a compact, non-immunogenic alternative to CRISPR activation (CRISPRa) for epigenetic therapies. We used human ZF proteins to engineer an initial humanized transcriptional activator targeting the SCN1A gene associated with Dravet's Syndrome. By employing evolutionary protein language models, we enhanced the construct's transcriptional activation efficacy. To maintain non-immunogenicity, we screened mutations using MARIA, an established machine learning model that predicts peptide antigen MHC presentation. We validate our evolved transcriptional activator's overexpression of SCN1A in human HEK 293T cells via qPCR. These findings highlight the potential of human ZF proteins, optimized by protein language models, as efficient and safe gene activators, indicating a promising therapeutic strategy for haploinsufficient genetic disorders. Further optimization and testing in neuronal cell lines are essential to confirm clinical applicability and therapeutic potential.

### **Roman RAPID Team: Analysis of Astronomical Data Through Image-Differencing**

Anushka Paulchoudhury

*Mentors: Mansi Kasliwal and Lin Yan*

The RAPID team's goals include an efficient process of image-differencing between reference images and novel Roman images, public alerts regarding transients in the aforementioned difference images, records of source match-files regarding the candidate photometry for instances of Roman source being observed multiple items with the same filter; using Roman data to investigate photometric history at a given location in the sky. Our approach to accomplish these goals is to focus on image-differencing development to simulate what the Roman telescope will observe once launched. The eventual goal is to ensure that reality is simulated with the image-differencing process between reference images and novel Roman images so after launch the telescope's identification abilities are as accurate as possible.

**Performance Estimates for Hybrid Rayleigh-Sodium Laser Guide Star System**

Brianna Peck

*Mentor: Richard Dekany*

Adaptive optics (AO) is a technique used by ground-based telescopes to correct aberrations in astronomical images caused by the turbulence in Earth's atmosphere. A hybrid Rayleigh-sodium laser guide star system combines economical low-altitude Rayleigh beacons with costly high-altitude sodium ones. This hybrid system provides a cost-effective solution for wavefront correction compared to a system composed solely of sodium laser guide stars. However, based on current performance simulations, a hybrid AO configuration does not meet quality requirements for large optical telescopes such as the W. M. Keck Observatory. For our trade study, we choose to work with the open-source Multi-Threaded Adaptive Optics Simulator (MAOS) due to its highly configurable nature. We present the results of our hybrid AO simulations with and without the photometric effects of the guide stars. Ultimately, more work is needed to determine the highest performing regime for hybrid AO, such as with smaller telescopes or more powerful mid-altitude Rayleigh beacons.

**Biocatalytic Methods for Vinyl Cation Generation: Evolving the Catalytic Promiscuity of an Oleate Hydratase**

Grace Perna

*Mentors: Hosea Nelson and Yan Liu*

In efforts to improve the design of organic synthetic pathways, engineered biological enzymes have been introduced as a sustainable alternative to traditional chemical catalysts. Enzymes can be both catalytic and stereoselective in nature; biocatalysis has been associated with higher yields, higher selectivity, and mild reaction conditions. Oleate hydratases, which catalyze the hydration of oleic acid to 10-(R)-hydroxystearic acid, are thought to proceed through a carbocation intermediate and are of interest for biocatalytic methods development. Consequently, enzymes are subjected to directed evolution: a synthetic process mimicking natural selection to engineer a catalyst with the desired substrate scope, reaction conditions, and catalytic mechanism. This project seeks to develop a methodology using site-saturation mutagenesis for probing catalytic promiscuity (i.e., alternative pathways) of an oleate hydratase from *Marinitoga hydrogenitolerans*, with the goal to generate vinyl cation intermediates from phenylacetylene derivatives. The biocatalytic approach expands the utility of vinyl cation pathways, which have previously been limited. Here we present the current substrate scope and preliminary mutants, identified by gas chromatography mass spectrometry (GCMS), that will undergo further iterative mutagenesis to achieve the hypothesized intramolecular C-H insertion via a vinyl cation intermediate.

**Investigating the Role Metabolic Transitions Play in Early Murine Embryonic Development Using Stem Cell Models**

Hannah Perry

*Mentors: Magdalena Žernicka-Goetz and Sergi Junyent Espinosa*

While the roles of genetic and morphogenic factors in specifying early embryonic development are relatively well characterized, the role of metabolic transitions in this process remains essentially unstudied. My project investigates the existence of a functionally important lactate shuttle mechanism between Epi (future embryo body) and PrE (future yolk sack) cells during the rosette stage of mouse blastocyst development. I hypothesize that the transfer of lactate from PrE to Epi cells leads to increased ERK activity in Epi cells, supporting the vital transition of Epi cells from a naïve to primed pluripotency state. I developed novel embryonic stem cell models of the embryonic rosette to overcome the intrinsic challenges of studying embryos at this stage. To ensure effective use of these models, I optimized the structure formation protocol and prepared an analytical pipeline. I assessed lactate transfer between cells, ERK signalling activity, and changes in morphology and gene expression using immunofluorescence staining and biosensors. In the future, inhibition of ERK signalling, modulation of the metabolic environment, and blocking of lactate transfer will be used to further explore the existence and importance of an Epi/PrE lactate shuttle mechanism in mouse blastocyst formation.

**Optimizing and Understanding the Steady Streaming Jet in Relation to the Turbulent Drag Reduction Effect**

Joseph Pieper

*Mentors: Cong Wang and David J. Stevenson*

The turbulent drag force is the major limiting factor for the energy efficiency of large-scale transportation systems, such as container ships, commercial airplanes, and oil pipelines. As such, effective turbulent flow control and drag reduction can substantially increase energy efficiency. Recently, a novel dynamic free-slip surface method, which employs an array of actuated deformable free-slip interfaces, was developed at Caltech, which can reduce drag effect by more than 40%. However, the physics of the drag reduction mechanism is unclear. In addition, the design and control (e.g., geometrical design and actuation frequency) of this promising technique can be further optimized. To better understand the steady streaming jet, we constructed a fish tank and underwent 2D PIV on the jet being produced by a 20Hz, 30Hz and 50Hz frequency. We constructed a box with a speaker at the top of the box and a tiny hole at the bottom of the box (which was able to have an oscillating membrane or just a tiny hole)

and put it inside of the fish tank. We took phase averages of our data for 20 different phases at different frequencies and with membrane or no membrane. We found that vorticity is very pronounced with an oscillating membrane. This mechanism and data from PIV help us understand how the steady streaming jet is created. With the experiments and data, we have recorded inside of our lab we now can take the observations on the most optimal conditions for this steady streaming jet. Our results tell us that the steady streaming jet is best created using a speaker at a frequency of 20Hz and an oscillating membrane. In the future, with this data we can use our results to make more observations about drag reduction created from the steady streaming jet. We are anticipating that with these observations our experiment can be related to energy efficiency and potential providing a way for large scale transportation systems to conserve energy with the help of the turbulent drag reduction effect.

### **Impact of Herbivory on the Primary Productivity and Microbial Communities of *Racomitrium lanuginosum* in the Icelandic Heath**

Gigi Pistilli

*Mentors: Bastien Claude Jean Papinot and Ingibjörg Svala Jónsdóttir*

Across Iceland and other high latitude ecosystems, bryophytes such as the dominant *Racomitrium lanuginosum* play essential roles as drivers of terrestrial net primary productivity and habitats for a diverse community of fauna and microbiota. To understand the response of *R. lanuginosum* and its bryosphere to sheep trampling and grazing, we investigate protected or unprotected heath in an eight-year field experiment set up in the degraded Icelandic highlands. This project examines changes in primary productivity by herbivory through various methods, linking carbon dioxide fluxes from three distinct moss segments – the green, autotrophic top, the grey middle, and the brown decomposing bottom - to *in situ* measurements of the intact moss carpet and underlying soil. By quantifying carbon exchange of extracted microbes and identifying microbial abundance in each moss segment through flow cytometry, we analyze herbivory's effects on bryosphere productivity. Our findings reveal the role of the top, green segment as responsible for the bulk of respiration, carbon sequestration, and C content, home to a smaller but metabolically active microbial community. We also observe plots exposed to herbivory capable of greater carbon sequestration, potentially due to observed increases in the respiration, microbial abundance, and microbial respiration in the brown segment.

### **Optimizing Optical Control for Quantum Emitters in Silicon-based Nanophotonic Devices**

Alexander P. Plekhanov

*Mentors: Andrei Faraon and Adrian Beckert*

Silicon-based quantum technologies offer a promising pathway for scalable quantum information processing, leveraging the well-established silicon semiconductor industry. We focus on the T-center, a telecom-compatible color center in silicon. It exhibits a coherent spin-1/2 ground state with spin-selective transition and an associated nuclear spin-1/2 which features second-long coherence and the potential to serve as quantum memory. Building on the prior successful creation of ensembles of T-centers in industry-standard silicon-on-insulator wafers, we aim to achieve precise optical control over single T-centers embedded in nanophotonic resonators for their characterization and manipulation. I constructed an optical setup to establish precise polarization and power control for optical pulse driving. This was achieved via careful optimization of system polarization extinction ratio and laser beam characteristics. Additionally, I designed and assembled a versatile grating-spectrometer setup with single and multimode fiber inputs for single and ensemble quantum emitter spectrometry. In the future, this setup will be used for characterization of lifetimes, coherence, and spectral diffusion of the T-center electron spin as well as further T-center-like defects in silicon.

### **The Switch From Cell Proliferation to Differentiation in the *Drosophila* Testes**

Juni Polansky

*Mentors: Margaret Fuller, Hannah Vicars, and Lea Goentoro*

The switch from cell division to cell differentiation is crucial for reproduction, tissue regeneration, and the prevention of cancer. Using the *Drosophila* testes as our model system, we aim to investigate several different avenues underlying the switch from proliferating spermatogonia to differentiating spermatocytes. Previous research in the Fuller lab has shown that the main role of Bam (Bag of Marbles) is to block expression of HOW (Held Out Wings) to allow spermatogonia to end mitosis, switch to meiosis, and differentiate. We investigate two possible ways in which HOW plays a role in this system. Cyclin B is a known cell-cycle regulator that may be a target of HOW, so by conducting FISH (fluorescent *in situ* hybridization) using fluorescent probes against cyclin B mRNA in the *Drosophila* testes, we hope to determine the effect that overexpression of HOW has on cyclin B expression. We also aim to investigate the potential role for HOW in alternative splicing by conducting FISH experiments on genes that are significantly alternatively spliced in spermatogonia when HOW is present compared to spermatogonia when HOW is absent. We are pairing our biochemical investigations with a bioinformatics analysis to investigate differential protein isoform expression at various developmental timepoints in spermatogenesis.

### Characterization and Validation of a Fatigue Monitoring Wearable Biosensor

Chris Pope

Mentors: Azita Emami and Shawn Sheng

Advances in sensor-receiver signaling and in efficiently powering biosensors in a way that is compatible with normal biological functions have paved the way for further development of versatile devices that can monitor a variety of different parameters important for human health. Our work is concerned with the characterization and validation of a newly designed application specific integrated circuit (ASIC) used to analyze sweat for fatigue monitoring, which is paired with a wearable sensor component to measure data. The ASIC is able to acquire multi-channel biomarkers, conduct signal processing like digitization, wireless data transmission, filtering, and amplification. We validated each component of the ASIC in conjunction with the ingested component of the biodevice by using function generators, test signals, and sample solutions. These were used to produce expected inputs for the biodevice, which then allowed us to ensure the ASIC's received and processed outputs matched previously simulated values. These successful tests of the biodevice mark another step in the development and testing of a device with important potential in predicting and monitoring the health of individuals in intense situations, be they athletes, soldiers, or emergency service workers.

### CrazyPong: A Ping-Pong Playing Quadcopter Test Bed for State-of-the-Art Control Research

Leonid Pototskiy

Mentors: Soon-Jo Chung, John Lathrop, and Fengze Xie

Quadcopters have become a very popular type of flying robot over the years, continuously becoming more powerful and agile. The ability of performing fast and aggressive maneuvers makes the quadcopter a viable alternative to robotic arms for making a ping-pong playing robot. Being able to reach a specific target point at a specific time also has many applications, such as docking in strong winds, formation flying and aerial defense. In this project, we implement a full pipeline from predicting the path of the ball to hitting the ball back using a Crazyflie quadcopter. A Vicon vision system was used to track the position of the ball and drone at a rate of 100Hz and we utilized an Extended Kalman Filter to predict the path of the ball within millimeter accuracy. To account for changes in the ball prediction, a real-time polynomial spline trajectory planner was implemented. This simple pipeline produces very consistent results, making it a good starting point for future testing of state-of-the-art algorithms for time-critical UAV trajectory planning.

### Progress in the Total Synthesis of Euphonoid E

Camilla Power

Mentors: Brian M. Stoltz and Adrian de Almenara

Nearly 7% of anticancer treatments are natural products, and over 17% are derived from these compounds. A group of natural products known as *ent*-atisane diterpenoids have displayed cytotoxic activity, which suggests potential in novel anti-tumor treatments. Euphonoid E is an *ent*-atisane C<sub>20</sub>-diterpenoid first isolated from *Euphorbia fischeriana*, a perennial herb found in the grasslands of Siberia, Mongolia, China, Korea, and Japan, in 2019. In recent years, Euphonoid E was found to be cytotoxic against human C4-2B prostate cancer cells (IC<sub>50</sub> = 16.1 μM) in vitro. The compound is also effective against enzalutamide resistant C4-2B cells (IC<sub>50</sub> = 22.1 μM) in vitro. However, only ten milligrams of Euphonoid E can be isolated from fifteen kilograms of *E. fischeriana* roots, thus producing a 0.0007% isolation efficiency.<sup>1</sup> Despite its biological potential, the low natural abundance of the target compound prevents further pharmacological studies. We attempt to improve the yield and scalability of the early steps in the planned synthesis of Euphonoid E. Additionally, we are exploring an alternative cyclopropanation mechanism using Simmons-Smith conditions.

### Directed Evolution of Therapeutic Molecular Chaperones for Neurodegenerative Diseases

Architesh Prasad

Mentors: Shu-ou Shan and Arpit Gupta

Molecular chaperones are a class of proteins with numerous functions including ensuring correct protein folding and preventing protein aggregation. Current work in the Shan Lab at Caltech has concentrated on using directed evolution to design chaperone proteins with higher activity toward specific protein aggregates. One of these "tailor-made-molecular chaperones" (TMMCs), an evolved cpSRP43 chaperone, has shown increased anti-aggregation activity toward amyloid-β-peptide (αβ) aggregates found in Alzheimer's disease. This Surf project concentrated on further developing the cpSRP43 for continued research. Two structural variants of cpSRP43 were tested for their activity against alpha-synuclein aggregates. Using the TMMC with higher activity, a plasmid library was constructed. This library was codon optimized for expression in mammalian cells and incorporated random mutations in order to produce additional cpSRP43 variants. These evolved proteins will be tested for their anti-aggregation activity.

**Inverse Lagrangian Modeling of Methane Source Distribution and Variability in the Los Angeles Basin**

Ruotong Qi

*Mentor: Yuk Yung*

With growing concerns about greenhouse gas emissions, it has become increasingly important to understand the spatiotemporal variability of sources of methane (CH<sub>4</sub>), the second largest contributor to greenhouse warming, in urban environments. The Los Angeles basin, characterized by its diverse and intense anthropogenic activities, presents a unique case study for this objective. The complexity of accurately locating methane sources and quantifying their emission rates in such an environment arises from the intricate interactions between various emission sources and atmospheric processes including transport and dispersion. Previous studies have typically used low-resolution data to investigate mean methane concentrations over regional spatial scales and short timescales. With this approach, the spatiotemporal variations of the concentrations and emission rates of methane within urban settings are often overlooked.

High-resolution, decade-long methane observational data over Los Angeles from the CLARS-FTS instrument, combined with inverse Lagrangian modeling of atmospheric transport and turbulent dispersion with the Stochastic Time-Inverted Lagrangian Transport (STILT) model, allows us to constrain the spatiotemporal distribution of methane emissions across the Los Angeles area. Our preliminary findings correlate atmospheric transport of methane with seasonal wind patterns in the region.

By combining the existing data of methane concentrations and the sensitivity of observed methane concentrations to emission rates in the upstream region as informed by the inverse Lagrangian modeling, we estimate average emission rates at a number of landfills. Preliminary analysis reveals a significant decreasing trend with increasing distance between emission sources and receptors (where methane measurements are made) and their impact on observed methane concentrations, due to a stronger dispersion effect over longer distances of transport. Motivated by these preliminary insights, we carry out a thorough investigation for areas within the Los Angeles basin where notable trends in methane concentrations are observed from the CLARS-FTS data and quantify the associated trends in methane emission rates in nearby emission sites. Through a detailed analysis of these temporal trends and spatial patterns of methane emission rates, our findings enhance the understanding of methane concentration variability, providing vital information for devising effective mitigation strategies for methane emission in urban settings like Los Angeles.

**Hybrid Transfer Reinforcement Learning via Cross-Domain Adaptation**

Chengrui Qu

*Mentors: Adam Wierman and Laixi Shi*

In many real-world reinforcement learning (RL) applications, learning a good policy requires a large amount of data and can be costly. It is thus desirable to reuse knowledge from a different domain or task to enable faster learning. In this work, we introduce a Hybrid Transfer RL setting, in which the agent has access to both the target environment and an offline dataset collected from a different source domain. By constructing the lower bound sample complexity for general Hybrid Transfer RL, we demonstrate that algorithms with source domain knowledge cannot beat pure online RL. Further, we show that, under two mild assumptions, we can quickly recognize the dynamics differences and select source-domain data in order to provably reduce the sample complexity needed for the target domain as compared to online RL. Our proposed framework is built on reward-free exploration and UCB-VI algorithms with revised analysis. Our experimental results show that our proposed algorithms improve upon state-of-art online RL baselines.

**Engineering Protein-Nucleic Acid Interactions Using Deep Learning**

Dhruva Rajwade

*Mentors: Animashree Anandkumar and Shengchao Liu*

Protein-Nucleic acid interactions play a pivotal role in regulating gene expression. Controlling these interactions is key to modulating gene regulation and potentially cure many diseases and conditions. Deep Learning has revolutionized the field of Protein Science, with new models like AlphaFold3 and ESM3 advancing the field every day. We use pre-trained domain-specific LLMs to obtain representations of Proteins and Nucleic acids at a sequence level. We use 3D structural datasets of Protein-Nucleic acid complexes to learn interactions between constituent amino acids (Proteins) and nucleotides (DNA/RNA) at a single-element level. We plan to use this interaction model to further generate 3D structures and apply conditioning using textual descriptors. We plan to use Flow matching in the Latent space of the interaction model, allowing us to generate binding-aware complex embeddings and follow textual constraints. The grand vision of this project is to explore text-based molecule editing and the design of RNA/Protein targets that can be validated in vivo and used for gene therapy and the development of vaccines.



### **Spatial Transformation Capabilities in Image Editing via Diffusion Models**

Tejas Ram

*Mentor: Matt Thomson*

Diffusion models, particularly those applied to image generation, have shown incredible capabilities in creating high-fidelity images. However, these models often lack the ability to recreate images based on significant changes to the spatial orientation of image features. In this project, we use the Instruct Pix2Pix diffusion model to reorient the distribution of objects within images, leveraging instructive prompts that direct the model to shift the positions of targeted shapes. The model incorporates and builds on the standard U-Net framework, utilizing the latent diffusion process to create potential pathways for object reorientation. We fine-tune this model using a curated dataset from Pillow, a Python imaging library, which includes many synthetic image transformations. The model will then be continuously improved/refined based on an evaluation of the model accuracy.

### **Compositional Tuning of Li-rich Iron Sulfide Multielectron Cathodes, Targeting Mechanistic Alterations of Anion Redox Processes**

Nayantara Ramakrishnan

*Mentors: Kimberly A. See and Eshaan S. Patheria*

Increasing the energy density of Li-ion batteries while using earth-abundant elements is essential to facilitate a global transition to renewable energy. Multi-electron redox in Fe-and-Al-based sulphides has been developed as a way to achieve this, but current major challenges include large hysteresis and capacity fade. Here, we expand the phase space of these sulphides by making solid solutions with compounds that share the same anion sublattice. Addition of Cu is shown to maintain long-range order and mitigate capacity loss. Addition of Si is reported for the first time, and the groundwork is laid for future investigation. Addition of Ti is also attempted. All the syntheses are rationally motivated by a comparative structural analysis, and the resulting materials are examined by X-ray diffraction and galvanostatic cycling. We find that our novel solid solutions can tune the electrochemical properties of the materials towards developing design rules for decreasing hysteresis and capacity fade in Fe-based sulphide multielectron redox cathodes.

### **Mixing Time Bounds for Quantum Gibbs Samplers**

Akshar Ramkumar

*Mentors: John Preskill and Mehdi Soleimanifar*

A quantum Gibbs sampler is a quantum algorithm designed to prepare the stationary state, or Gibbs state, of a general quantum system left to thermalize at a fixed temperature. In 2023, Chen, Kastoryano, and Gilyén introduced a quantum Markov chain algorithm that provably converges to the Gibbs state. However, the convergence time, or mixing time, of this algorithm remains uncertain for many quantum systems of interest. In this work, we establish bounds on the mixing time for several "single particle" quantum systems, where a particle follows a quantum walk on a graph. For these systems, we determine the optimal parameters for the Gibbs sampling algorithm to maximize its efficiency. An efficient Gibbs sampling algorithm has numerous applications. At low temperatures, the Gibbs state is a low energy state of a quantum system, which is particularly useful in condensed matter physics and quantum chemistry. Additionally, Gibbs sampling of single-particle systems may provide a quantum advantage in solving optimization and graph problems.

### **Ignition of Sustainable Aviation Fuels in Hot Air Atmospheres: Parametric Analysis on the ASTM Injection System**

Hannah Ramsperger

*Mentors: Joseph E. Shepherd and Charline Fouchier*

The ignition properties of aviation fuels must be thoroughly examined before use. Their autoignition temperature is assessed using standardized ASTM-E659 tests, where 0.1-0.5 mL of liquid fuel is injected with a syringe into a flask inside a temperature-controlled furnace. Given that the test results strongly depend on injection characteristics, we use an automatic injection system to control the height, speed, and duration of the syringe's needle inside the hot atmosphere. We investigated how injection parameters influence ignition behavior using the temperature signals inside the flask. After conducting one hundred tests, we found that different injection parameters significantly affect the initial temperature condition and fuel volume in the flask. If the needle stays inside the flask for more than 10 seconds, approximately 150% of the initial fuel volume vaporizes. We also found that vaporization influences the temperature decrease more than the needle itself. To prove this, we visualized the injection jet with a high-speed camera in a transparent rectangular cell heated by a hot plate. This test showed that vaporized fuel enters the container even without injection, validating our hypothesis. This finding suggests that the injection in the standardized ASTM-E659 test should last less than 10 seconds to have accurate results.

### **Isotopic Measurements to Determine the Origins of the Pala Pegmatites in the Northern Peninsular Ranges Batholith**

Lillian Randall

*Mentors: Claire Bucholz and Paolo Sanchez*

In the northern Peninsular Ranges batholith (NPRB) in San Diego County, CA, Li-rich pegmatites occur and are an economic source for gem and Li minerals, however their origin is unclear. Lithium-cesium-tantalum (LCT) pegmatites typically originate from granites which have formed through the melting of metasedimentary rocks. In some cases, due to their ability to form dikes and distribute up to kilometers from their source, LCT pegmatites are found large distances from their parent granites. In the NPRB LCT-pegmatites are frequently found as dikes within the mafic San Marcos gabbro and never found hosted in peraluminous granites. Previous hypotheses suggest the pegmatites are fractionated products of the host gabbros or they are related to the metasedimentary rocks in the surrounding area. We have collected samples of the pegmatite and gabbro from the Tourmaline King Mine in the Pala mining district, alongside peraluminous gneissic granites from the Harper Creek Suite and Julian Schist samples to determine the genetic relationship of the metasedimentary rocks, pegmatite and gabbros. We aim to investigate the genetic relationship between all these units beginning with examining  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of plagioclase found in each unit.

### **Investigation of Ultra-High-Quality Factor Germano-Silicate Optical Resonators**

Avani Ranka

*Mentors: Kerry Vahala and Haojing Chen*

Ultra-high-quality factor (Q factor) optical resonators are optical microcavities that circulate light along a closed path with little loss of energy. The overall Q factor of a device is dependent on the losses from radiation, scattering, material absorption, and contamination. Minimizing these losses through careful fabrication is therefore vital in achieving ultra-high-Q values. Germano-silicate, a mixture of fused silica ( $\text{SiO}_2$ ) and germania ( $\text{GeO}_2$ ), has an ultra-low-material-loss window in the  $1.55 \mu\text{m}$  telecommunication band, making it a promising substrate for the fabrication of ultra-low-loss optical resonators. Significant progress in the development of ultra-high-Q resonators over the past few decades has culminated in the production of photonic integrated circuits (PICs), which have broad applications for fields ranging from quantum computing to optical telecommunications. In this paper, we describe progress toward the fabrication of PICs through the investigation of ultra-high-Q waveguide resonators in a novel germano-silicate platform.

### **Selective Enhancement of Rydberg Excitons in Monolayer MoS<sub>2</sub> by Twisted Light**

Beining Rao

*Mentors: Nai-Chang Yeh and Duxing Hao*

We use photocurrent spectroscopy (PCS) technique to measure the photocurrent (PC) spectrum generated in MoS<sub>2</sub> under varying wavelengths of light with orbital angular momentum (OAM) to study the selective enhancement of Rydberg excitons corresponding to the specific OAM order. Since no one have used vary wavelength light with OAM to develop measurement before, the spatial light modulator (SLM) used to generate OAM light should be calibrated to ensure that the OAM light spot pattern should be same under different wavelength in our experiment. Because the PC is proportional to the incident light power, we should also calibrate the laser power to ensure the laser irradiating on sample has uniform power with wavelength ranging from 500nm to 680nm. Since the laser output is a nonuniform power output spectrum, a continuous neutral-density filter (Thorlabs ND1-25C-2) moved by a computer-controlled precision translation stage is applied to adjust the output laser power.

### **Modeling the Secure Key Rate of Measurement Device Independent Quantum Key Distribution**

Tisya Rawat

*Mentors: Maria Spiropulu and Raju Valivarthi*

Quantum Key Distribution allows two authenticated users to distribute secret keys among them even in the presence of an eavesdropper. QKD in conjunction with one-time-pad provides information theoretic secure communication. Measurement Device Independent Quantum Key Distribution has been proposed that is not only immune to all detector side channel attacks but generates a high key-rate. Through this project, we model the secure key rate of MDI-QKD based on realistic experimental parameters using Python and analyze this simulation. We study the secret key rate equation:  $S = Q11Z.(1-h2(e11X))-QmuZ.(h2(emuZ))$  and study the components that limit or enhance the secret key generation rate. By modeling MDI-QKD, we try to see which initial parameters should be selected to optimize secret key rate. Using the simulation, we first study the symmetric case of MDI-QKD, where the distance between both communicating parties from a common point is equal, and then studied the asymmetric case, where the transmission distance between the two communicating parties from an intermediary are not equal.

**Designing Hands for the Humanoid Robot Achilles**

Juan Renteria

*Mentors: Aaron Ames and Adrian Boedtke Ghansah*

Caltech's AMBER Lab has a long history of working with bipedal humanoid robots. Most recently, the lab has worked on ADAM and Achilles. ADAM is the world's first point foot humanoid robot capable of walking in 3D. Whereas ADAM was used to test walking algorithms of underactuated robots, Achilles, its successor, has ankles which allows us to reuse the algorithms used on ADAM but with the additional stability provided by the feet. This project focuses on designing a humanoid hand for Achilles so that algorithms that involve hand manipulation and general locomotion can be tested. The design for the four fingers is complete and the next steps are to finalize the thumb design and test the actuation and tracking of the hand.

**The Identification of Strong-Ligand Binders to the Amyloid-Beta 42 Tetramer in Alzheimer's Disease**

Aarya Riasati

*Mentors: William Goddard and Soo-Kyung Kim*

In this SURF, we have identified several novel ligand binders that are able to effectively bind to the A $\beta$ -42 tetramer with  $\mu$ M and sub  $\mu$ M potency. This was done by screening several ligand databases with AUTODOCK-VINA using blind-docking. We find that these ligands bind best to the N-terminus of the A $\beta$ -42 tetramer and can be used for further applications such as in PROTAC design for A $\beta$ -42 breakdown. These compounds may have several uses in other applications as well, particularly in the design of new inhibitors, therapeutics, or molecular warheads.

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**Time-Resolved Raman Spectroscopy of the Soft Pseudospin Magnet Sr<sub>3</sub>Ir<sub>2</sub>O<sub>7</sub>**

Eleanor Richard

*Mentors: David Hsieh and Hoon Kim*

Magnetic order in antiferromagnetic Mott insulators is highly sensitive to the optical injection of free charge carriers – dubbed photo-doping. Interesting out-of-equilibrium phenomena have been predicted to occur ranging from ultrafast demagnetization to metastable spin configurations. However, studying light-induced spin dynamics on short (femto- to pico-second) timescales is technically challenging. Here I will introduce time-resolved Raman scattering as a novel technique for measuring ultrafast light-induced changes in the spin excitation spectra of materials. By applying this technique to the strongly spin-orbit coupled Mott antiferromagnet Sr<sub>3</sub>Ir<sub>2</sub>O<sub>7</sub>, we resolve rapid changes in the energies and lineshapes of both phonons and magnons upon photo-doping, suggesting a short-lived state with structural and magnetic conformations different from those in thermal equilibrium. As the charge carriers relax back to equilibrium on longer timescales, the antiferromagnetic order remains partially suppressed due to the nearly flat magnon dispersion of Sr<sub>3</sub>Ir<sub>2</sub>O<sub>7</sub>, resulting in a red-shift and broadening of the magnons. Our results uncover the fast dynamical interplay between charge, spin and lattice degrees of freedom in Sr<sub>3</sub>Ir<sub>2</sub>O<sub>7</sub>, and potentially shed light on the nature of its magnetic order, which remains unsettled due to its proximity to a quantum critical point.

**Analyzing the Impact of Olfaction on Hunting Behavior in Mice: Behavioral Insights and Sensory Contributions**

Alexa Rios

*Mentors: Markus Meister and Daniel Pollak*

Predators such as mice rely on various senses to navigate their environment and pursue targets. However the degree to which mice rely on olfaction compared to vision, somatosensation, and audition is not known. Understanding how olfaction contributes to mice's ability to hunt is crucial to understanding the underlying cues of natural behaviors. This study utilizes two tests: a dig test consisting of a food-deprived mouse tasked with locating a food pellet that is buried and a hunt test which requires a food-deprived mouse to be placed in an arena to pursue a live *Blaptica* roach. These tests embody natural behavior a mouse would perform in the wild. Nasal Ablation is a technique that temporarily removes olfactory input to the brain, inducing anosmia. It was refined and resulted in an improved survival rate from 33% to about 85%. Preliminary experiments indicate that mice do not exhibit reduced hunting efficiency when deprived of their olfactory sense. This research aims to give evidence on mammalian animals' primitive behavior and address a knowledge gap in neuroscience by studying instinctual behaviors over trained behaviors.

**Development of a Liquid Culture Method for *Steinernema hermaphroditum***

Nathan Rodak

*Mentors: Paul Sternberg and Chieh-Hsiang Tan*

*Steinernema hermaphroditum*, the only characterized hermaphroditic entomopathogenic nematode (EPN), offers a unique model for symbiosis research. Its distinct evolutionary, ecology, and morphological features diverge from common laboratory nematodes, and with forward and reverse genetic tools, it allows the study of various biological fields such as genetics and developmental biology. Although solid culture methods exist, the absence of a liquid culture method hinders scalability, reproducibility, and the control and manipulation of nutrients in experiments. Here, we describe a bacterial-based liquid culturing method for *S. hermaphroditum* using concentrations of *Comamonas aquatica* ranging from 200  $\mu$ L per mL of solution to 1 mL of a 10x stock solution of *C. aquatica* grown overnight.

**The Moduli Space of Stable  $n$ -Pointed Curves, Its Grothendieck Class and Log-Concavity**

Eduardo Henrique Rodrigues do Nascimento

*Mentor: Paolo Aluffi*

The class of the fine moduli space of stable  $n$ -pointed curves of genus 0,  $\overline{M}_{0,n}$  in the Grothendieck ring of varieties encodes its Poincaré polynomial. Aluffi-Chen-Marculli conjecture that the Grothendieck class of  $\overline{M}_{0,n}$  is real-rooted (and hence log-concave). The conjecture is supported by substantial numerical data, and they were able to prove an asymptotic log-concavity result for these polynomials. We use Lagrange inversion and Manin's functional equation for an exponential generating function  $\underline{M}$  for those Grothendieck classes to find explicit formulas for the Grothendieck class of  $\overline{M}_{0,n}$  and use it to improve on the previous asymptotic log-concavity result. We also show that the logarithmic derivative of  $\underline{M}$  has palindromic coefficients, and that it is uniquely determined by this property (under some assumptions). We hope the methods used can be extended to prove log-concavity for the class of  $\overline{M}_{0,n}$  for all  $n \geq 3$ .

**Studying the (Spin) Holstein Polaron Using Diagrammatic Monte Carlo**

Alexandre Roger

*Mentors: Marco Bernardi and Yao Luo*

The Holstein Hamiltonian incorporates electron-phonon interactions to describe lattice polarons. The lattice is one-dimensional with each site possessing a single vibrational degree of freedom, and contains a single excess electron (or hole). This Hamiltonian can be solved using approximations, but Diagrammatic Monte Carlo (DMC) allows us to extract polaronic properties exactly without approximate methods. DMC relies on a Markov Chain Monte Carlo method to sample from the diagrammatic expansion of the Matsubara Green's function, interpreting it as a multivariate probability distribution function. The DMC algorithm was successfully implemented in Julia, correctly reproducing the analytical solution of low order Green's functions. In future work, we look towards a modified spin-Holstein Hamiltonian, which would consider the spin degrees of freedom of phonons and electrons.

**AI-Driven Prediction of Type 2 Diabetes Mellitus Risk**

Ashlyn Roice

*Mentors: Rohan Khera and Adam Wierman*

Diabetes affects around 11.6% of Americans, but around 23% of US adults with diabetes are unaware of their diagnosis. Among Americans with diabetes, 90-95% have type 2 diabetes mellitus (T2DM), a chronic metabolic condition characterized by the body's inability to use insulin effectively. T2DM is a serious condition and can lead to serious damage to the eyes, feet, and heart. With early diagnosis, T2DM patients can manage their condition through medication, diet, and exercise. Therefore, this project aims to use Fitbit and EHR data from the All of Us Research Program to train a machine learning model that can predict patient development of T2DM within 1 year. The data from All of Us ( $n = 9454$ ) features data derived from accelerometry (step count, exercise activity), photoplethysmography (heart rate, heart rate variability, rhythm), polysomnography (sleep length, quality), and specialized physiological measures (such as those from 1-lead ECGs). Analyzing how this data varies over time for each patient can lead to conclusions on a given patient's risk for developing T2DM in the near future. Machine learning models will be developed and evaluated for their performance in predicting whether a patient could be diagnosed with T2DM within a year based on the All of Us data. From there, patterns in sleep, exercise, and heart rate variability that are indicative of T2DM risk can be inferred, leading to less invasive and more efficient measurement of T2DM risk and further elucidation of the risk factors for T2DM.

**Characterizing Pulsar Distances Using HI Kinematics**

Steven Romero-Ruiz

*Mentors: Vikram Ravi and Stella Ocker*

Pulsars are fast rotating neutron stars that are used to study the interstellar medium (ISM). We only have distance measurements for a fraction of the known pulsar population, many of which are derived through HI kinematics. The last major catalog of  $\sim 70$  pulsar kinematic distances was published in 1990 using a Galactic rotation curve based on HI and CO distances. We have applied the Reid et al. (2019) rotation curve model, which is based on maser parallax measurements, to archival HI radial velocity data and estimated new pulsar kinematic distances. We find a typical difference of  $< \sim 5\%$  between the old kinematic distances and those derived with the updated rotation curve, where our updated distances tend to be closer for negative HI radial velocities and farther for positive HI radial velocities. We are exploring a Bayesian inference approach to derive the uncertainties of our new distances. Our updated catalog of pulsar distance measurements will aid in future development a Galactic electron density model.

**Analysis of a Vacuum Beam Guide for Quantum Communications**

Hannah Rose

*Mentors: Rana Adhikari and Aaron Goodwin-Jones*

Current solutions for quantum communication channels such as telecom fibers and satellite relays face significant issues such as high loss and disrupted transmission. Huang et al. have introduced a vacuum beam guide as a promising new solution designed to provide a low-loss and stable quantum channel, with less than  $10^{-4}$  dB/km loss not subject to atmospheric variability. This system uses a periodically spaced array of lenses within an evacuated tube to propagate a coherent electromagnetic field over long distances with minimal loss. The initial proposal is limited to analyzing a confocal vacuum beam guide and calculates only absorption loss and a preliminary estimate of alignment loss. Our analysis further examines the performance of a generalized class of vacuum beam guide configurations with the inclusion of physical imperfections using computer optics simulations. These simulations were developed into software tools that allow for detailed evaluation and optimization of different vacuum beam guide configurations. By identifying a configuration's alignment tolerances, this work enables the development of a system that is suitably insensitive to realistic constraints. These results advance the vacuum beam guide closer to potential implementation as a quantum communication channel and contribute to the realization of reliable, continental-scale quantum communications with low loss and high throughput.

**Developing a Suite of Simulation Tools to Maximize EMIT Science Returns**

Anwesh Saha

*Mentors: Christian Frankenberg and Suniti Sanghavi*

Retrieving atmospheric properties like aerosol, trace gas profiles, and surface reflectance is crucial for constraining Earth's radiative budget. Using a fully vectorized and linearized radiative transfer model vSmartMOM, we simulate EMIT observations and perform retrievals. The forward model begins with an arbitrary guess of state parameters, iteratively updating them using measured radiances until the model fits the measurements, determining the "true" state parameters.

We develop tools to retrieve EMIT measurements for any location and time. Location data stored as pixel coordinates are georeferenced to obtain location-specific measurements. This helped us visualize how absorption patterns vary under different conditions (clear, cloudy, hazy skies). Simulated EMIT radiance observations are generated using vSmartMOM for various albedo and aerosol optical depths.

A key goal for NASA's EMIT and the upcoming Carbon-I mission is investigating aerosol impacts on CH<sub>4</sub> and CO<sub>2</sub> retrievals and mitigating photon path length changes using proxy gases (O<sub>2</sub> for EMIT, N<sub>2</sub>O for CarbonI). We evaluate the effects of varying atmospheric compositions and spatial distributions of trace gases, aerosols, and clouds on global radiative impact. These efforts will culminate in developing an Orbital Simulator for current (e.g., EMIT) and future (e.g., Carbon-I) satellite measurements.

**Design and Creation of Dataset for Nickel-Reductive Cross Coupling Reactions Utilizing High Throughput Experimentation**

Aryan Saha

*Mentors: Sarah Reisman, Danielle Mantin, and Jules Schleinitz*

Nickel Reductive Cross Coupling reactions are an effective mechanism used to create C(sp<sup>2</sup>)-C(sp<sup>3</sup>) bonds between electrophiles with application in the pharmaceutical industry. With the complexity of this reaction, choosing optimal substrates which yield substantial products proves difficult. As a result, my project utilizes a process called High Throughput Experimentation (HTE) to create a large, scientifically accurate, and substantial dataset which we can apply predictive machine learning models to aid in choosing substrates. In addition to collecting data on product yields through (HTE), we also seek to develop molecule descriptors to assist machine learning models such as linear regression, logistic regression, and other models at predicting reaction results.

## Studying Mars as an Exoplanet

Xianlei San

Mentors: Yuk L. Yung, Siteng Fan, and Stuart J. Bartlett

The study of single-point spectral light curves of terrestrial planets is a vital technique for understanding their spatial features, atmospheric processes and habitability, given that most current and near-future observations will likely not be able to spatially resolve exoplanet features (Fan et al., 2019). Mars, as Earth's sister planet, serves as an excellent model in this context. The Emirates Exploration Imager (EXI) on the Emirates Mars Mission (EMM) Hope probe captures approximately 5000 fully sunlit images of Mars every Earth year (Jones et al., 2021). In this work, we analyze single-point light curves produced by integrating these full-disk images. These light curves show noticeable increases in the RGB bands (centered at 635nm, 546nm, 437nm) and significant decreases in the UV bands (centered at 320nm, 260nm) during dust storms. This may be due to dust being brighter in visible wavelengths, and the fact that clouds are less prevalent when global temperature increases. Further, by applying Principal Component Analysis (PCA) to the light curves, we found that the first three principal components explain more than 90% of the total variance. Variability due to clouds is primarily contained in PC2 and PC3, and that due to ice caps in PC4. The characteristics of red and black terrain are clearly discernible in PC3. Additionally, we deployed a technique from complexity science to assess the 'statistical complexity' of martian light curves (Bartlett et al., 2022). With this metric, we compared Earth, Mars, and Jupiter, revealing distinct differences among these planets. This study enhances our ability to deduce properties of distant exoplanets from non-spatial measurements, which could inform our estimates of their habitability and internal complexity.

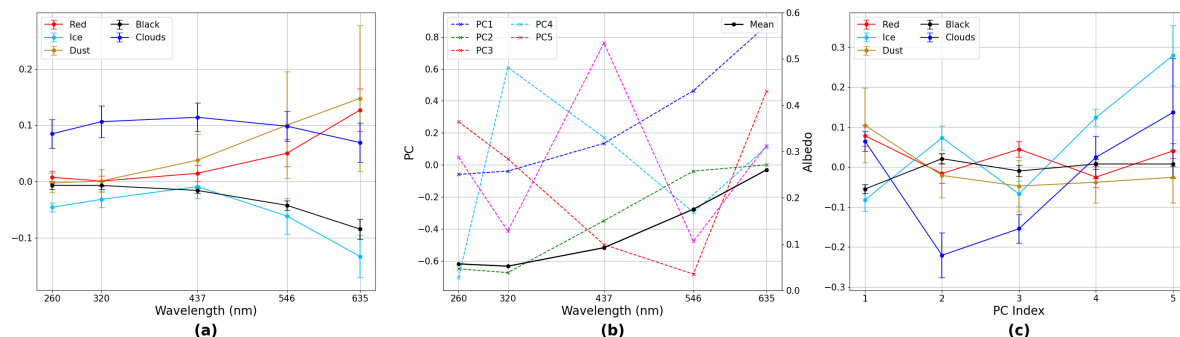


Fig. 1. (a) Spectra of the five characteristic reflectors on Mars are subtracted by the mean spectrum, each extracted from nine characterized images. (b) Left five lines shows unit vectors of PCs in original coordinate (PCs' spectra), while black line is mean spectrum. (c) The spectra from (a) are projected onto the principal component (PC) coordinate. The magnitude indicates the significance of each component in this PC.

## High-throughput Analysis of Urinary Calcium Isotopes for Noninvasive Bone Health Monitoring

Kate Sanderson

Mentors: Francois Tissot, Dan Razonale and Théo Tacail

Osteoporosis leads to a bone fracture every three seconds globally, primarily due to reduced bone mineral density (BMD) and mass. Measuring BMD has faced challenges, as the standard method has limited sensitivity and is difficult to standardize. This study aims to develop a noninvasive and cost-effective biomarker for monitoring bone health by utilizing naturally occurring stable calcium isotope abundances and compositions in urine. When the rate of bone resorption exceeds formation, isotopically light calcium is released back into soft tissue, causing a shift in lighter urinary calcium isotope values ( $^{44}\text{Ca}/^{42}\text{Ca}$ ). Here we use microwave digestion, automated chromatography for calcium separation, and a Neptune multi-collector inductively coupled plasma mass spectrometer to measure calcium isotopes in a high-throughput manner. This large-scale analysis of healthy individuals across several factors, such as gender, age, and lifestyle, demonstrates the potential of calcium isotope ratios as a stable and informative biomarker. These findings may prove valuable in assessing net bone calcium gain or loss, thereby enhancing bone health diagnostics.

## Measuring Irrationality of Deterministic Choice

Alec Sandroni

Mentors: Kota Saito and Yi Xin

It is well known that every choice function may be represented as the sum and difference of choice functions that may be rationalized by a single preference over all alternatives. A natural measure of irrationality is the minimum number of preferences required in the sum. We demonstrate the relationship between this measure and the number of violations of the independence of irrelevant alternatives axiom. We devote special attention to choice functions which admit a nested representation.

### **Commissioning a Muon Detector For Cross-Comparing Radio-Based and Muon-Based Cosmic Ray Detection Techniques at the OVRO-LWA**

Alianna Santisteban

*Mentors: Gregg Hallinan and Kathryn Plant*

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) is a standalone radio antenna array that can distinguish the radio emissions of a cosmic ray air shower from the noisy radio background without the use of particle detectors. The benefits are that radio detection is cheaper and the cosmic ray air shower data the array outputs is easier to model than some techniques that rely on particle detection. Muons in the atmosphere are produced almost exclusively by cosmic rays so muon detectors are often paired with radio. The objective of this project is to integrate a muon detector with the OVRO-LWA. In the future it will be used to verify that events flagged by the cosmic ray radio detection system are coincidental with muon events. This will be a cross-comparison of the two detection techniques.

### **Needles in a Haystack: Mapping the Universe with Ly- $\alpha$ Dropouts in Euclid**

Sage Santomenna

*Mentors: Ranga-Ram Chary and Andreas Faisst*

The epoch of reionization within the first billion years of the Universe is a critical phase of cosmic evolution still under active investigation. Quasars, extremely luminous galactic nuclei, promise to expand our understanding of reionization and help us trace out the large-scale structure of the Universe. The distant, faint quasars of interest are observable only with some of the largest telescopes on the planet, but ground-based telescopes suffer from source confusion that compromises their ability to detect high-redshift quasars by themselves. We use joint processing to combine deep, high-resolution ESA Euclid Space Telescope data with ground-based observations, enabling us to use spatial priors to deconfuse distant sources. In this work, we present the discovery and characterization of high-redshift ( $z > 6$ ) galaxy and quasar candidates near the Abell 2390 cluster. In the future, the same methods will enable us to characterize reionization over large parts of the universe as data becomes available.

### **Characterizing the Impact of Spatially-Dependent Redshift Errors on $f_{NL}$ for SPHEREx**

Aaditya Sarma

*Mentors: Olivier Doré, Spencer Everett, and Henry Gebhart*

The Spectro-Photometer for the History of the Universe, Epoch of Reionisation, and Ices Explorer (SPHEREx), due to be launched in early 2025, is a near-infrared space telescope that will survey the entire sky every four times in its 2.5-year mission. SPHEREx aims to probe cosmic inflation (exponential expansion of the universe from  $10^{-32}$ s to  $10^{-36}$ s after the Big Bang) by looking at the statistical properties of the three-dimensional clustering of galaxies where any deviations from the simplest inflationary models is captured by the parameter  $f_{NL}$ . Multiple systematics must be considered that can contribute to potential errors in determining the redshift of detected sources and can have a drastic impact on achieving one of the main objectives of the SPHEREx mission. This project aims to provide a quantitative measure of the impact of source crowding on  $f_{NL}$  which is needed to ensure the success of the SPHEREx mission. We measure SPHEREx photometry using synthetic COSMOS survey SEDs mapped into a region of interest to calculate redshift across three bins of median, high and low source density. This preliminary work is building towards a comprehensive map of the redshift error distribution across the whole sky as a function of source density.

### **Integrating Selective Gradient Information in Consensus Based Optimization**

Anagha Satish

*Mentor: Franca Hoffmann*

In this study, we devise a novel algorithm for integrating gradient information into Consensus Based Optimization (CBO), a recently proposed multi-particle gradient-free optimization method.

The CBO algorithm is modeled as a system of stochastic Differential Equations (SDE) that mimics interacting agents communicating over a weighted mean. The particles are then expected to build a consensus at the position of the weighted mean that is located near the global minimizer of the objective function. Unlike many current optimization algorithms, it does not involve the evaluation of a gradient, making it ideal for situations where the gradient cannot be evaluated for all function values or is too computationally expensive.

Motivated by the success of gradient based methods in machine learning and previous efforts to integrate gradient-based and gradient-free methods, we devise a modified hybrid CBO algorithm. On each iteration, we integrate gradient information into a select number of particles' update steps. We answer two questions: 1) How to select particles for this hybrid update step and 2) How best to incorporate gradient information into the already existing CBO structure. We further study the minimum number of gradient evaluations required to substantially improve the optimization solution.

### **Radiative-Convective Equilibrium Model Intercomparison and Sensitivity Tests With the CliMA Atmospheric Model**

Cameron Schmitt

*Mentors: Tapio Schneider, Zhaoyi Shen, and Akshay Sridhar*

Radiative-convective equilibrium (RCE) models idealize the climate system by balancing radiative cooling with convective energy transport. The lack of extraneous dynamics allows for a simple diagnosis of climate sensitivity and emergent dynamic behavior. The RCE model intercomparison project (RCEMIP) set forth by Wing et al. established a framework for RCE implementation in single column, general circulation, and cloud resolving models. We applied this framework to the CliMA atmospheric model by imposing RCEMIP surface temperature and insolation boundary conditions, enabling the CliMA model for future contribution to RCEMIP. Then, we tested a matrix of sphere and box models with varying sea surface temperature setups and analyzed the effect on the equilibrium state.

### **Characterization and Nanofabrication of Electro-Optic Lithium Niobate Photonic Metasurfaces**

Elisabetta Schneider

*Mentors: Harry Atwater and Martin Thomaschewski*

Metasurfaces, with their ability to manipulate light at subwavelength scales, offer transformative solutions for various optical applications, including sensing, imaging, and communication. These ultra-thin surfaces can control light's phase, amplitude, and polarization, potentially replacing bulky optical components with more compact, efficient alternatives. The two primary types of metasurfaces are passive and active. Passive metasurfaces have fixed functionalities defined during fabrication, while active metasurfaces can dynamically adjust their optical properties in response to external stimuli, providing real-time control and tunability. This project focuses on fabricating and characterizing passive and active electro-optic lithium niobate (LN) metasurfaces. Leveraging LN's unique electro-optic properties, we aim to achieve precise dynamic beam steering, a critical application for optical communication and sensing systems. Our approach combines advanced nanofabrication techniques to construct the metasurfaces with meticulous characterization of the material properties and geometry after each fabrication step.

Finite element simulations complement our experimental work, allowing us to model the metasurfaces' optical responses and optimize their geometries for high-quality resonances. Our findings highlight the significant advantages of active metasurfaces in terms of tunability and performance, demonstrating their potential to revolutionize beam steering applications. This research advances the fundamental understanding of light-matter interactions in nanostructures and contributes to developing next-generation, dynamically tunable photonic devices.

### **Implementing In-Context Learning in Latent Diffusion for Unsupervised Keypoint Generation Using Text Embedding Optimization**

Jin Schofield

*Mentors: Pietro Perona, Rogério Aristida, and Guimaraes Junior*

Latent diffusion model training is a computationally heavy process that prevents flexible instilling of expert knowledge after the process' completion. In-context learning is a form of learning in transformer-based language models where information can be taught to the model through an input prompt without having to re-train weights. An important problem in computer vision is that of keypoint generation, often applied in tasks such as pose estimation. This research applies a process analogous to in-context learning to unsupervised keypoint generation using latent diffusion to allow keypoint generation to benefit from added knowledge without having to re-train the model. This is accomplished by appending an initially randomized embedding (which is later optimized by a loss function) to the original embedding conventionally used in cross-attention during latent diffusion. This randomized embedding is trained on a small new dataset of five images paired with attention maps whose maxima are desired keypoints. After optimization, this new embedding guides the cross-attention mechanism to create attention maps concentrated on a specific desired object in test images. Keypoints are the coordinates most impacted by attention in an image. The embedding is created using a loss function minimizing mean squared error between pixels of predicted and ground truth desired attention maps, optimizing localization of gaussians in the attention maps, and maximizing equivariance of the keypoints between transformed versions of the same image. This research allows us to understand and improve how diffusion models create robust and modular abstract representations that meaningfully and efficiently encode semantic information in images.

### **Realtime Extreme Atmospheric Conditions Sensing With Fixed-Wing Drones**

Jacob Schuster

*Mentors: Morteza Gharib and Xiaozhou Fan*

The increasing utilization of drones across various fields necessitates advancements in their safety and control, especially for fixed-wing drones navigating in highly dynamic environments. This research addresses the challenge of navigating through desert tornadoes, called twisters, which pose severe risks to drone stability and functionality. The primary objective is to develop a machine learning-based system that enables drones to detect twisters, path



plan around them, and maintain stability within their intense flow fields. Central to this research is the development of a multi-hole pitot tube system, which measures flow direction and magnitude, providing data for understanding and adapting to wind conditions. Once assembled, a robotic arm orients the tube in many positions facing incoming airflow, collecting data on individual pressure sensor readings. To provide a clean flow to calibrate the multi-hole probe, a settling chamber was designed, ensuring minimum turbulence level and flow uniformity, which is then used to provide ground truth for the calibration process. Short-term goals include mounting two pitot tubes to the pressure side of the drone's wings and conducting testing in the wind tunnel and fan array. In the future, we will build lower profile, more lightweight pitot tubes and integrate them onto more robust drones.

**Modeling and Analysis of PILLARS for Off-Nominal Rocket Landings Using LS-Dyna**

James Scott

*Mentors: Soon-Jo Chung and Lily Coffin*

Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS) acts as a parachute, inflating via the plume of a rocket, providing a barrier against the abrasive lunar regolith disturbed by rocket launches and landings. In the case of an off-nominal rocket landing, the plume and force of the rocket are unevenly distributed into the structure, potentially leading to system failure if the anchoring mechanism is unable to support the force received by the plume. To address this challenge, modeling is being done on the inflation behavior of PILLARS using LS-Dyna. This modeling will simulate lunar conditions under both ideal and off-nominal scenarios to determine the maximum loads and stresses on the anchors and structure. The goal is to reinforce these components adequately to ensure they can handle both cases effectively, enabling PILLARS to reach TRL 5.

**Barrel Timing Layer Assembly in CMS for the High Luminosity Update of the Large Hadron Collider**

Kristina Sevier

*Mentors: Maria Spiropulu and Adi Bornheim*

The High Luminosity update for the Large Hadron Collider at CERN will allow for the detectors in the Large Hadron Collider to manage more data collection from particle collisions than previously. The Barrel Timing Layer (BTL) within CMS was added in the tracking section of the detector to increase particle resolution. Assembly of the Barrel Timing Layer included assembling and testing for proper light yield/thermal cooling of sensor modules, detector modules, and cold plate trays. Afterward, 72 detector modules are installed onto each cold plate tray with 6 readout units that relay detector module data to computers for physics analysis. These trays are then evaluated for proper cooling and installed into a mockup of the BTST or the outermost layer of the tracking section. BTL is made of 72 completed cold plate trays that line the inside of the cylindrical BTST. The assembly process and its adjustment are smooth, but the testing of completed cold plate trays has manifested thermal issues (non-uniform cooling of the tray) in specific detector modules caused by thermal conductive material used in its copper housing. Further work includes changing this material and modifying the assembly process to make it more concise, efficient, and consistent.

**X-ray Microdiffraction Analysis of the Structural Gradient in the Semicrystalline Polymer Poly(L-Lactide) for Improving Bioresorbable Vascular Scaffolds**

Faiza Shabibi

*Mentors: Julia Kornfield and Tiziana Di Luccio*

The principal objective of this research is to analyze the microstructure of poly(L-lactide) (PLLA) and PLLA-tungsten disulfide nanotubes (WSNT) nanocomposites, which are a promising route for developing thinner, stronger, and safer bioresorbable vascular scaffolds (BVS). Cardiovascular disease treatment with BVS aims to provide temporary arterial support as opposed to permanent metal stents that increase the risk of late-stent thrombosis and restrict arterial vasomotion, but PLLA's brittleness and processing-induced strains pose challenges. Understanding PLLA's structural response to strain is essential for ensuring safer yet effective BVS. The methodology involves using Python and MATLAB scripts to organize previously acquired raw data at the Argonne Advanced Photon Source and analyze microdiffraction SAXS and WAXS data. Initial results indicate that using X-ray scans acquired above and below the sample provides the correct background correction and significantly improves data clarity. This study has also used polarized light microscopy to visualize crystalline and amorphous regions, supplementing the X-ray analysis with visual observations. Ongoing work focuses on refining detection functions and implementing masking in data analysis. Future goals include completing the code implementation and extending data analysis to a larger set of samples to understand the material's structure under different processing conditions.

**Exploring Fourier Neural Operators for Predicting Dynamics in Quantum Spin Systems**

Freya Shah

*Mentors: Anima Anandkumar, Taylor Patti, and Julius Berner*

The Fourier Neural Operator (FNO), due to its remarkable PDE-solving capabilities and discretization invariance, presents a novel approach for simulating the time evolution of quantum wavefunctions, specifically in intricate quantum spin models like the Heisenberg Model. This project tackles the computational challenge of modeling the dynamics of quantum spin systems, which typically demand substantial computational resources due to their

exponential complexity. The project explores two distinct FNO architectures: one holding significant physical meaning and the other optimal for discretization invariance. The project investigates their ability to learn time evolution and extrapolate it to later time steps using random and low-energy input states. Additionally, the use of Pauli observables as inputs is explored, aiming to extend the model's applicability to larger qubit systems. This research lays the groundwork for further exploration of FNOs in predicting dynamics at later time steps, potentially contributing to advancements in quantum computing and condensed matter physics.

### **Photoreductions of Cr(III) & Ti (IV) Using Various Photosensitizers**

Sanjana Shah

*Mentors: Jonas C. Peters and Christian Johansen*

Metal reductants (e.g. Sm(II), Cr(II) and Ti(III)) have applications in organic synthesis and methodology. Photochemical strategies can be used to recycle the oxidized metals but most examples use an explicit photocatalyst. We analyzed Cr(III) to Cr(II) and Ti(IV) to Ti(III) by UV Visible spectroscopy to determine if chromium or titanium could even be reduced by a photoreductant without a photocatalyst to define a system that can more selectively couple substrates. Once we were able to successfully observe Cr (III) to Cr (II) we tried more specific catalysis. We have performed catalytic photoreductive Nozaki-Hiyama-Kishi (NHK) coupling with chromium as the catalytic metal reductant, dihydrophenanthradine as the photoreductant and aromatic aldehydes (4-fluorobenzaldehyde) and allyl bromide as the coupling partners under Blue LED (456 nm). A similar study has been reported (Calogero, Francesco. "A photoredox nozaki-hiyama reaction catalytic in chromium." *European Journal of Organic Chemistry*, vol. 2022, no. 29, 2022) but they use a photocatalyst that requires the use of aliphatic aldehydes. In their system with a photocatalyst they have not observed success with aromatic aldehydes because they observe pinacol coupling. By removing the photocatalyst from our system we have opened the possibility of coupling these aromatic aldehydes. We will continue to explore the mechanism of the interaction between Chromium and dihydrophenanthradine and how it is successfully recycling the chromium.

### **Searching for Circumbinary Planets Through Apsidal Precession**

Arden Shao

*Mentors: Benjamin Montet and Elias Most*

Probing for transiting planets around binary stars has long been a difficult task, with stellar activity from two stars often masquerading or hiding planetary transits. We present a new method of detection in which we aim to find planets by observing their dynamical effects on stellar orbits over a decades long baseline. We investigate a sample of 500 eclipsing binary targets across multiple surveys in the past 20 years to identify those with unexplained precession, in which their orbits are potentially being modulated by an unseen companion. To do so, we measure the relative timing of primary and secondary eclipses of the various datasets folded on periods derived just from the primary eclipses or the secondary eclipse, aiming to see a phase shift in eclipse timings. Since precession causes an elliptical orbit to rotate in its orientation, we expect these eclipses to occur earlier or later in time. From a preliminary search, we have identified five candidates with unambiguous evidence for precession. We first verify that for these identified targets, the effects of general relativity and tidal perturbations cannot fully account for the observed precession rate, so that an additional orbiting in the body in the system is required to explain the observed signal. Next, we will model each candidate system to determine if the source of unexplained precession is indeed a planet or a brown dwarf or star.

### **Progress Towards a Fully Coupled General Circulation Model For Uranus's Atmosphere: Dynamical Core and Radiative Transfer**

Kevin Shao

*Mentors: Yuk L. Yung and Chen Sihe*

General Circulation Models are a class of 3D atmosphere models that can resolve the dynamics, chemistry, radiative transfer, and latent heat processes in full spatial detail. Observational studies of Uranus have revealed drastic seasonal variations in its atmosphere, particularly in its polar regions (Rages 2004). This observed change is thought to result from the melting of methane ice crystals or a decrease in aerosol levels, driven by shifts in atmospheric circulation. In this study, we employed the simulation within the framework Simulating Nonhydrostatic Atmospheres of Planets (SNAP), under a cubed-sphere configuration (Li & Chen, 2019, Chen & Li, 2024). The goal is to develop a sophisticated GCM model for Uranus to investigate its seasonal variations, which can also be applied to the atmospheres of other bodies.

### **X-Ray Active Red Giant Stars in the Milky Way**

Domani Sharkey

*Mentors: Kareem El-Badry and Antonio C. Rodriguez*

The release of the first eROSITA all-sky survey marked an unprecedented expansion in the capabilities of X-ray astronomy. Red giant stars (RGs) in systems like X-ray binaries and RS CVns are highly interesting X-ray sources in need of broadened classification. Here we cross-match eROSITA data with  $\sim 10^6$  *Gaia* DR3 RGs with high-quality astrometric solutions to construct a sample of 6,497 RGs that are likely emitting soft X-rays (0.2-2.3 keV). We

observe a notable increase in the relative number density of X-ray active RGs inside the Red Clump region of the Color-Magnitude Diagram (CMD), in conflict with the theory that the expansion and subsequent deflation of giants prior to the Red Clump stage should significantly limit X-ray activity. Additionally, we probe a distinct variety of optically-selected RS CVns— those fainter in X-rays and thus potentially not previously detected. The distribution of RS CVns does not align with our X-ray-emitting RGs, suggesting that either the X-ray selection is more reliable or the RS CVn catalogs target distant systems. We also compute orbital period solutions for 10 sources. Our work broadens existing knowledge of RG X-ray emission and presents a new puzzle on the CMD evolution of X-ray active giants.

### **Evolution of Black and Brown Carbon (BC and BrC) in the Los Angeles Basin**

Nimish Sharma

*Mentors: Paul Wennberg and Haroula Baliaka*

Carbonaceous aerosols account for a large portion of atmospheric pollutants. The light-absorbing carbon species have emerged as potentially critical contributors to atmospheric warming. This study examines the emission sources and temporal variations of absorptive black and brown carbon (BC and BrC) in the Los Angeles basin. For our analysis, we have used the aethalometer measurements from the Multiple Air Toxics Exposure Study (MATES-V) in Central Los Angeles from May 2018 to April 2019 and the Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT) site in Pico Rivera, Los Angeles from July 2023 to April 2024. We apportion BC to biomass burning and fossil fuel emissions based on its optical absorption properties, using the absorption Ångström exponent (AAE) approach. We further utilize the strong spectral dependence of BrC absorption to estimate its levels in the atmosphere. We find that the estimated BrC level has increased in the past five years in the Los Angeles basin, with the median  $b_{\text{abs},370,\text{BrC}}$  value being  $2.04 \text{ Mm}^{-1}$  during 2018-19 compared to  $3.12 \text{ Mm}^{-1}$  during 2023-24. The increase in BrC levels was unexpected as the BC concentration declined by 9.2 % at the same time, with a median of  $0.69 \mu\text{gm}^{-3}$  during the ASCENT campaign from  $0.76 \mu\text{gm}^{-3}$  during the MATES campaign, making BrC an interesting research topic to investigate.

### **Prediction of Damaged Locations in Buildings Using Machine Learning**

Jaylen Shawcross

*Mentors: Domniki Asimaki, Monica Kohler, Yaozhong Shi, and Gabriel Pizarro*

This project aims to use machine learning to predict the location of damaged locations in a 15-story skyscraper. We use a data set previously created by our lab consisting of the acceleration of each floor on said skyscraper in response to an earthquake. There are 1000 simulations, each with a different set of connectors randomly damaged. We then process the data using PyTorch to create a data set for machine learning. We feed the dataset into a multilayer perceptron to predict the location of damage in our testing data and analyze the performance of our machine learning model. This project is useful because it aims to be able to detect damaged connections between beams in a building which may not be visible but will improve safety. Future work can continue to optimize our model or apply it to other building frameworks.

### **Improvement of Biosensing and Stimulating Implants Using Biocompatible Materials**

Humza Sheikh

*Mentors: Yu-Chong Tai and Suhash Aravindan*

When designing implantable biostimulating electrodes, materials must be both biocompatible and durable when used in the body. As these devices are utilized, there needs to be a balance between impedance of the electrode and durability. Platinum black coated electrodes fill this role when creating electrodes that require low impedance and improved signal quality. When deposited to create a porous structure for an electrode the surface area of the electrode increases, as well the charge transfer capacity. When choosing this method of fabrication, however, the porous structure of the electrode leads to a fragile product. To counter this, porous platinum black layers on an electrode can be mixed with adhesive and polymer layers such as parylene, which increases the durability of the final product. This project is aimed at determining a suitable combination of parylene and platinum black coating that reduces the increase in impedance while creating an electrode that is able to last for long periods without the need for replacement.

### **Simulating a Charged Particle on a Disordered Discrete Lattice Under a Time-Varying Electric Field for the Purpose of Optimization**

Karen Shekyan

*Mentor: Gil Refael*

On a disordered lattice, a particle will tend to become localized in potential wells. A charged particle's motion may be altered by an applied electric field, but the particle may still become localized since it cannot gain arbitrary quantities of momentum. While previous work has focused on dynamic localization of the particle in order to alter the transport properties of materials, we aim to delocalize and direct the particle toward a target location. We present a simulation designed to model and optimize this process with respect to time. By applying basic principles of quantum mechanics and Kalman control theory, we predict the behavior of the system and use observable

quantities to dynamically adjust an applied electric field while accounting for errors due to noise. As our approach involves creating a model of charged particles on a discrete lattice, our work may be extended to study or alter the properties of semiconductors.

### **Evolution of the Accretion Flow Properties of Black Hole X-ray Binaries in Outburst: MAXI J1820+070**

Paul Shen

*Mentors: Fiona Harrison and Oluwashina K. Adegoke*

During an outburst, a black hole X-ray binary (BHXB) experiences sudden increase in luminosity, by several orders of magnitude, transitioning through different spectral states over several months before returning to quiescence. While hard X-ray photons, presumably from a hot corona, dominate the hard state, softer disk blackbody emission are believed to dominate the soft state. This standard thin disk picture, in the soft state, generally holds true for moderate range of luminosities ( $< 0.3L_{Edd}$ , where  $L_{Edd}$  is the Eddington luminosity). For higher luminosities, it has been argued that the disk tend to deviate from a standard disk. Using data from the X-ray telescope NICER, the goal of this project is to probe the evolution of accretion disk properties in the bright BHXB MAXI J1820+070 in relation to those of a standard disk.

### **Rippling Through Fluid Dynamics: Unveiling Collective Motion in Brine Shrimp**

Siddhartha Shendrikar

*Mentors: John Dabiri and Nina Mohebbi*

Brine shrimp exhibit intriguing collective motion, utilizing fluid structures to optimize their movement efficiency. Studying and analyzing their behavior can provide valuable insights into improving engineering systems that rely on fluid dynamics. In order to analyze this movement, we conducted experiments on the movement of collectives of brine shrimp using particle tracking velocimetry (PTV), a methodology that allows for volumetric velocity measurements within a fluid flow by imaging the motion of suspended micron-size particles [1]. We simultaneously measure 3-dimensional (3D) flow using particle image velocimetry (PIV), a technique that compares consecutive video frames to analyze fluid flow, with 3D swimmer tracking. We segmented the images to isolate individual shrimp, tracked their centroids over time, and calculated their velocities. This dataset allowed us to track the position and velocity of each shrimp over time, providing insights into their collective behavior. Using metrics such as curvature analysis, velocity analysis, and nearest neighbor distance, we observed the shrimp's behavioral patterns and interactions. Our findings reveal a complex coupling between the collective behavior of the shrimp and surrounding fluid dynamics, where the shrimp impact the flow, and the flow impacts their movement. These results not only further our understanding of biological collective motion, but also have applications in optimizing fluid dynamics for engineering systems, such as optimizing wind turbines and other mechanical systems influenced by fluid flow.

### **Real-Time 6DOF Pose Estimation With Limited Priors**

Dhruv Sheth

*Mentors: Joel Burdick and Ersin Das*

The Learning Introspective Control (LINC) program under DARPA, in association with Caltech, aims to develop machine learning-based introspection technologies on various systems to respond to events that are not predicted at design time. One of the important goals of this program is to robustly detect an object with unknown geometry with very limited prior information about the object. 6DOF pose estimation is widely researched and current SOTA methods require prior information such as geometry and texture of the object in the form of CAD model but still aren't robust to complete occlusion and outliers in the form of incomplete CAD model of the object. We explore robustification of the current 6DOF pose estimation pipeline in the SOTA by integrating a Video Object Segmentation (VOS) network with top-down object-level memory reading which allows robust tracking of the prompted object even after complete occlusions. To integrate this into 6DOF pose estimation framework, we design a 'segmentation-conditioned cropping' module which provides coarse pose initialization to the 6DOF tracking module that allows the framework to track the object robustly during reappearance after complete occlusion. We also deploy this on the Jetson AGX Orin and perform TensorRT optimization on the VOS modules as well as pose estimation modules to improve the performance on an embedded device and enable real-time processing. An additional goal explored in this research is performing one-shot Neural Radiance Field (NeRF) training of the object from sparse ( $\sim 3$ ) views of the object and using the partial NeRF reconstruction to perform pose estimation with state estimation using Extended Kalman Filter and iteratively improving the NeRF reconstruction upon availability of novel views of the object. To construct an end-to-end framework, we also explore Uncertainty Quantification (UQ) on the pose estimation obtained from the framework and integrate the quantified uncertainty into the EKF using an adaptive filter to improve state estimation predictions and be robust to outliers.

### **Exploring, Modeling, and Fitting Spectral Energy Distributions for Young Stellar Objects**

Ahaan Shetty

*Mentor: Lynne Hillenbrand*

Stars in their early evolutionary stages provide critical insights into star formation processes, and are most readily analyzed through spectral energy distributions (SEDs). SEDs represent the energy distribution over a wide range of wavelengths, resulting from radiative transfer of photons originating from the central source and propagating through the circumstellar dust. The Hyperion codebase is a dust continuum radiative transfer code that is able to model SEDs given several stellar parameters. Theoretical and computational complication arises from the disk and envelope accretion, dust parameters and ambient mediums. This project aims to comprehensively utilize this infrastructure and consequently explore the influence of specific parameters on SED data. We also use the SED fitter tool to compare real data from interesting young stellar object cases such as RNO 54 to thousands of theoretical models. Different dust structure geometries heavily influence SED shapes. The physical intuition that Hyperion develops along with mathematical and statistical techniques helps to appreciate and parse through potential stellar parameters. A future application of this is to use Young Stellar Object Corral (YSOC) data to determine and evaluate parameters from SEDs and gain parametric information about otherwise elusive stars.

### **Performance of the Deep-Learning Phase Picker PhaseNet on Magnitude 3+ Earthquakes in Southern California**

Benjamin Shimota

*Mentors: Gabrielle Tepp, Ettore Biondi, Allen Husker, and Weiqiang Zhu*

Machine learning models are being considered for use in operational seismic monitoring. Seismic networks currently possess automated real-time systems; however, machine learning models could improve the systems by increasing the accuracy of detection algorithms and decreasing the workload of analysts. The machine learning model chosen for this study is PhaseNet, a deep-learning neural-net model that is currently used in post-processing within the Southern California Seismic Network. Before integrating PhaseNet into real-time monitoring, its performance with larger earthquakes must be evaluated. I have compared events from 50 earthquakes with magnitudes greater than 3 that were made by PhaseNet, the current real-time system, and the analysts. For the analysis, I focused on arrival time differences and whether PhaseNet was able to pick events in comparison to current systems, using analyst picks as a ground-truth. Preliminary results indicate that on average PhaseNet makes fewer picks within a short distance of an earthquake, as was expected based on experience from previous applications. In addition, PhaseNet seems to pick events earlier in the waveform. Overall, the analysis suggests that PhaseNet could be useful in real-time seismic monitoring when used in conjunction with other pickers or after being retrained for larger magnitude earthquakes.

### **Oxygen Isotope Ecology of Western Amazonian Mammals: Insights Into Behavior and Habitat**

Alyssa Shin

*Mentor: Julia Tejada*

Oxygen isotope ratios ( $\delta^{18}\text{O}$ ) in mammalian tissues reflect an animal's water intake and metabolism, providing valuable insights into animal ecology and environmental conditions. This study analyzes  $\delta^{18}\text{O}$  in teeth from Western Amazonian mammals in Peru (147 specimens from 43 species), complementing previous carbon and nitrogen isotope ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) research to develop a comprehensive isotopic profile of species in one of Earth's most biodiverse closed-canopy rain forests. The relationship between  $\delta^{18}\text{O}$  and various factors, including diet, habitat, body mass, and energy intake, is examined through statistical analyses and data visualization techniques. Preliminary results reveal that while individual factors show weak correlations with  $\delta^{18}\text{O}$ , multivariate models incorporating canopy height, elevation, energy intake, and body mass yield stronger predictive power. By advancing our understanding of mammalian ecology and isotopic signatures in modern ecosystems, this research establishes the foundation for future paleoenvironmental studies.

### **An Analysis of Standard Foundation Models for the Modeling of Irregular High-Dimensionality Astronomical Data**

Pratyush Singh

*Mentors: Ashish Mahabal, Lisa Guan, and David Liu*

Prior research has clearly shown the promise of the application of machine learning models to irregular datasets, demonstrating the efficacy of machine learning algorithms in dichotomous classification of variable sources. This has allowed for the rapid classification of variable astronomical objects using the extensive time-series data gathered by the Zwicky Transient Facility (ZTF). This project aims to evaluate the baseline performance of various foundational time series models for these irregular light curves. Beyond this, the study aims to analyze how the inherent modularity of these models can be used to adapt them to the light curve data in order to improve their accuracy and overcome the irregular nature of the light curves. The outcomes of this work aim to refine automated approaches for analyzing large-scale time-domain surveys, contributing to the broader understanding of stellar and galactic variability.

### **Search for Gravitational Wave Technosignatures Using Complexity Theory**

Pritvik Sinhadc

*Mentors: Yuk L.Yung and Stuart Bartlett*

We investigate the potential of Complexity Theory to analyze Gravitational Wave (GW) time series, having developed a novel, agnostic method for identifying technosignatures or signs of extraterrestrial technology. We also use Complexity Theory to identify physical characteristics of merging astronomical masses that are not easily decipherable through a general relativistic approach for extracting information from a given GW-producing event. The statistical complexity of a GW signal can be regarded as the information content of the most compact, optimal model of that signal. Processes for computing complexity metrics primarily employ causal state-splitting reconstruction (for constructing so-called epsilon machines), zip compressibility, and estimates of Kolmogorov complexity. This provides a new way to distinguish and compare GW sources, constrain possible spin-mass ranges involved in the GW event, and simulate time series from unmodelled bursts. We also study signal randomness of a given GW time series using Shannon entropy. Combining these results, Complexity-Entropy (CE) values are acquired for a given merger event's time series and used to distinguish the structure of different GW sources. We also simulate potential technologically-generated GW sources and predict the differences in CE values between technosignature GWs and abiotic GWs. We predict that GWs produced from abiotic sources consist of one of four predictable, noisy, low-complexity signal types. We further suspect that in the case of GW technosignatures, signals would likely not follow one of the abiotic signal types. For borderline cases, wherein signals still appear similar to abiotic GWs, we observe a greater degree of less predictable signals, a higher degree of periodicity, entropy, and complexity, as well as the signal lasting significantly longer than abiotic time series. This approach promises significant contributions to the fields of astrobiology and the search for extraterrestrial intelligence, while also potentially offering a new paradigm in understanding and interpreting GW phenomena.

### **Analyzing Potential Regulators of Centriole Number Control**

Sophia Slora

*Mentor: David Glover*

Supernumerary centrioles are a common cellular issue found in cancerous cells. The connection between extra centrioles and cancer is poorly understood and warrants additional investigation. A recent genome-wide screening in the Glover Lab has identified several unexpected genes as potential regulators of centriole count, including Rab8a and Nde1. In this study, we did a reconfirmation screening of Rab8a and Nde1 using knockdown testing and fluorescence imaging. We found that both genes play a role in regulating centriole count, and knockdown results in a higher ratio of centrioles per cell and a higher percentage of phenotypically atypical cells. We also analyzed the impact of Rab8a, a potential regulator for cilium length, on cilia through fluorescence imaging under various conditions. Analysis of common correlates of cancer such as with centrioles could help to expand treatment options for patients and increase our awareness of the complex interactions that underlie the condition. To continue our work, the next step would be to utilize cell sorting to analyze the average cell size for knockdowns of each gene compared to a control, as cells with supernumerary centrioles appear to have significant increases in mass.

### **Characterization of Microbial Metabolites Disease Pathology and Pathophysiology in $\alpha$ -Synuclein Overexpressing Mice**

Sam Small

*Mentors: Sarkis K. Mazmanian and Manxuan Zhou*

As evidence emerges highlighting the role of the gut-brain axis in Parkinson's Disease (PD), new doors to potential treatments are opening. This project seeks to investigate the role of microbial metabolites, specifically p-cresol sulphate (pCS) and indoxyl sulphate (IS), in PD pathology using  $\alpha$ -synuclein overexpressing (ASO) mice. Our work aims to understand how these metabolites influence  $\alpha$ -synuclein pathology, dopaminergic neurodegeneration, microglia activation, neuroinflammation, and apoptosis. In order to complete this, we have utilised methods such as Western blotting, immunofluorescent staining, and ELISA assays to assess and visualise p- $\alpha$ Syn, Tyrosine Hydroxylase and many other markers implicated in neuroinflammation and apoptosis, such as TNF- $\alpha$  and IL-6. We hope to show a clear link between pCS and IS treatment and increased PD pathology, providing insights into the role gut-brain axis in PD and identify potential new therapeutic targets.

### **Improving the Modeling of Cement Carbonation and Carbon Uptake**

Logan Smith-Perkins

*Mentor: Melany Hunt*

The production process of concrete is a substantial contributor to carbon emissions; however, due to a set of carbonation reactions, cement also acts as a carbon sink by absorbing atmospheric CO<sub>2</sub>. The current estimate of the mass of CO<sub>2</sub> that can be absorbed by cement is 40-50% of the CO<sub>2</sub> emitted in manufacturing cement. However, the model used in this estimate is an approximation with assumptions that are inconsistent with the real world. Our research develops a refined model incorporating more realistic porosity and atmospheric CO<sub>2</sub> concentrations.

By employing a volumetric numerical method (finite volume method FVM), we simulate the CO<sub>2</sub> diffusion throughout a block cement and incorporate the carbonation reactions that are missing in the approximate model. This improved FVM model provides a more accurate assessment of the amount of carbon absorbed through time and matches experimental data more accurately than the approximate model. Ultimately, this research will support the development of sustainable concrete production and utilization strategies to mitigate climate change.

### **Stabilization of Defect Centers in Silicon Carbide**

Jennifer Solgaard

*Mentors: Jelena Vuckovic and Alireza Marandi*

Defect centers in silicon carbide (SiC) are a promising platform for quantum information science because they can leverage well-established and scalable photonic device fabrication techniques to enable spin-photon entanglement and the generation of non-classical states of light. Within bulk silicon carbide crystals, these defect centers (such as the silicon vacancy) have narrow intrinsic linewidths and are optically-addressable, emitting photons at convenient wavelengths through their zero-phonon decay pathway. However, the emission spectrum of these vacancies is highly sensitive to external electric fields. As such, changes in the external field caused by the movement of charge carriers near the defect rapidly shift the center frequency of the defect centers emission spectrum, resulting in an effective broadening of the defect linewidth. This effect is especially pronounced when the defect center is located near a crystal surface, which is necessary for integration into nanophotonics. In this project we investigated and demonstrated a method for stabilizing the silicon vacancy's optical linewidth using Schottky diodes to create a depletion region near the emitter. In parallel, we develop and demonstrate a whispering gallery mode resonator compatible with our electrical control scheme. We expect to find that adding Schottky contacts narrows the optical linewidth of silicon vacancy centers close to the surface of bulk silicon carbide crystals, and the addition of identical contacts on photonic structures has little impact on the quality factor of the optical mode. With these findings, the path towards spectrally stable silicon vacancies in photonic cavities is clear.

### **Development of a Family of Copper-Metallated Bimetallic Molecular Quantum Bits**

Alan Song

*Mentors: Theodor Agapie and Matt Espinosa*

Few examples of multimetallic molecular quantum bits currently exist in the literature. This work demonstrates the synthesis of bimetallic copper quantum bits from the <sup>Mes</sup>N<sub>6</sub> ligand units previously synthesized by the Agapie lab. These rigid, square planar coordinating ligands have previously been metallated with copper(II) to make quantum bits known to be coherent at room temperature ( $T_2=0.47\mu\text{s}$ ). Two equivalents of <sup>Mes</sup>N<sub>6</sub>-quinone were condensed across aromatic bridges of several different lengths and metallated the subsequent products with copper. The reaction products were characterized by single crystal X-ray diffraction and nuclear magnetic resonance spectroscopy to ascertain their structures and establish their paramagnetism. We recommend that future work characterize the quantum bits by electron paramagnetic resonance spectroscopy to probe the electronic structure and interactions between spin centers. Furthermore, these quantum bits should be characterized by Raman spectroscopy in order to probe the vibrational modes of the quantum bits. In this vein, we hope to demonstrate the room temperature coherence of these synthesized quantum bits, as well as the specific vibrational modes associated with the spin decoherence of the quantum bits.

### **Observations of the Spatial and Power Distributions of Io's Hotspot-Sourced Heat Flux**

Michael Sowell

*Mentor: David J. Stevenson*

The Jovian moon Io is the most volcanically-active body in the Solar System, and these volcanic sources source over half of Io's total heat flux. Recent global maps of hotspots compiled from ground and space-based measurements allow us to analyze spatial and power trends in Io's volcanic sources. Estimated hotspot heat flux and rank for the largest 100 known hotspots follows a power law  $N(\phi) \propto \phi^{-\alpha}$ , where  $\alpha = 2.15$ . Assuming this trend is consistent across hotspot sizes, smaller hotspots should dominate the total heat flow of Io. In order to characterize the spatial distribution of Io's global heat flux without arbitrary binning, we performed a spherical harmonic expansion on hotspot distribution. Both the spherical harmonic coefficients and the angular power spectrum of Io's volcanic heat flux were found to be statistically insignificant beyond the monopole term. In degree-2, we find stronger longitudinal ( $f_{2-2} = 5.4 \text{ TW}$ ,  $f_{22} = -4.7 \text{ TW}$ ) than latitudinal preferences ( $f_{22} = -2.9 \text{ TW}$ ). Even though previous literature has focused on the discrepancy between the polar and equatorial flux, we find that latitudinal heterogeneities may not be as important as previously assumed.

### **Calculating Quasi-Particle Spectra in Mott Insulators Using First-Principles Methods**

Aditya Srinivasan

*Mentors: Marco Bernardi and Khoa Le*

First-principles calculations are incredibly important to advancing our understanding of condensed matter systems and go hand-in-hand with experimental progress in the field. First-principles calculations are crucial for interpreting experiments by providing physical insight into the quantum behavior of materials, while, in turn, experiments

validate simulations and enhance the modeling of quantum phenomena in matter. Such calculations involve computationally solving the Schrödinger equation to analyze the behavior of electrons and various quasi-particles. Understanding the behavior of quasi-particles can provide novel insight into quantum materials. In this work, I calculate both the magnon dispersion relations and exciton absorption spectrum of a Mott Insulator, Lanthanum Cuprate (LCO), using Yambo, a code that applies GW-BSE methods to a Hamiltonian and computationally solves the Schrödinger equation to describe the excited state properties of materials. LCO is an especially interesting compound as it displays exotic electronic and magnetic properties, and even serves as the parent compound to high-temperature superconductors when chemically doped. Eventually, the goal of this project is to use the calculated spectrum to help motivate physical conclusions from nonlinear optical spectroscopy experiments being performed on LCO.

### **Noise Analysis and Implementation on a Millimeter-Wave Kinetic Inductance Detector Camera for Long-Range Imaging Through Optical Obscurants**

Sage Stanton

*Mentor: Jack Sayers*

Kinetic Inductance Detectors (KIDs) can be used to develop an effective image of a target through optical obscurants where other imaging techniques might struggle. KIDs are highly effective detectors which can be tuned to atmospheric infrared windows, as is the case for this project. However, due to the fact that the KIDs are very sensitive they can be susceptible to noise. Filtering and modeling the noise of independent sources is required to allow the system to detect the signal as accurately as possible. To analyze the noise the detector is run with no external data source, then the noise is examined to determine what is electronics noise, thermal noise, or from other expected sources. However, after this process there is still residual noise in the system. This project aims to empirically model and reduce this noise to improve the current noise filtering process. To accomplish this we split the noise data from several experimental runs into subsections and analyze them separately over multiple domains before recombining them.

### **Experimental Study of Propeller Flow Air Ventilation**

Alexi Stapf

*Mentors: Cong Wang and Morteza Gharib*

There are different factors that cause air ventilation of propeller that allow air to be entrained into the propeller and decreased thrust. This experiment is run using Proportional Integral Derivative (PID) control system to keep the propeller at a target RPM while we are running the experiment and using 2D Particle Image Velocimetry (PIV) to examine the flow motions around the propeller during ventilation to get a better understanding of the mechanics behind this phenomenon. Further work on this topic could include a study on how to incorporate design choices into propellers that are based on results from further experiment to see what aspects of propeller geometry make propellers less susceptible to air ventilation.

### **The Origin of Hot Jupiters Revealed Through Their Age Distribution**

Elin Stenmark

*Mentors: Andrew Howard and Luke Bouma*

When and how hot Jupiters (HJs), gas giant exoplanets with orbital periods <10 days, arrive on their close-in orbits has been a mystery since their first discovery in 1995. The HJ age distribution may provide valuable insight as the arrival timescale for HJs differs across migration models. We define a brightness-limited sample of 417 hot Jupiters, and search it for stellar rotation periods using data from a NASA satellite (TESS) as well as archival data from the literature. We use these stellar rotation periods as age indicators, since the spin-down rate of Sun-like stars has been calibrated by other work. We compute ages for 60 HJ systems from literature. The resulting age distribution suggests a paucity of hot Jupiters younger than 0.5 Gyr, relative to the abundance of hot Jupiters at older ages, a result consistent with high-eccentricity migration. Additional work is needed to assess the potential impact of both the Milky Way's star formation history and completeness of the rotation period catalog on the observed HJ age distribution.

### **Adapting Operations of the 3 x 50 cm Colibri Telescope Array for Exoplanet Detection**

Sophia Steven

*Mentors: Stanimir Metchev and Lynne Hillenbrand*

The United States National Aeronautics and Space Administration (NASA) has funded the Transiting Exoplanet Survey Satellite (TESS) Follow-up Observing Program (TFOP) to address the findings of the original TESS mission. The Colibri Telescope Array (CTA), a three-telescope observatory located in London, Ontario, has the potential to enhance the follow-up efficiency of the TESS-TFOP mission. However, the current software capabilities of the CTA do not include the ability to schedule and execute requested observations, thereby limiting the observatory's accessibility and value to the mission. To enable the TESS-TFOP mission to utilize the increased efficiency of the CTA, we designed a graphical user interface (GUI) and scheduling software code package. This package allows users to scheduling night sky observations and integrate these observations into the existing observing schedule of



the CTA. The software package employs Python to develop a GUI that accepts observation data—such as right ascension and declination values, start and end times, number of exposures, exposure duration, etc.—and saves the data to a comma-separated value (CSV) file. Additionally, the package utilizes JavaScript in conjunction with DC-3 Dreams' ACP Observatory Control Software to extract the observation request data from the CSV file. This data, along with astrometry and weather constraints, are used to filter and rank each observation request, allowing the CTA to schedule and execute requested observations around the current observations of Kuiper Belt Objects (KBOs).

### **Quantum Physics of Real Quadratic Fields**

Harry Stoltz  
Mentor: *Matilde Marcolli*

Hilbert's 12<sup>th</sup> problem asks how to generate the maximal abelian extension of a number field. This project aims to find connections between the approach of Manin and Bost-Connes. Manin's approach includes constructing 2-D noncommutative tori associated with a pseudolattice and mirrors the theory of the solved complex multiplicative case. The C\*-dynamical system developed by Bost-Connes exhibits some interesting symmetry-breaking properties, and its partition function is the Riemann zeta function. We have examined methods of integrating theta functions in the upper half plane over geodesics connecting real quadratic irrationalities, as well as relations between the universal C\*-algebras representing tori and the construction of Bost-Connes. Further research is needed to establish a more concrete connection.

### **Enhancing Traffickcam Search Queries Through Embedding Projection**

Noreen Sultan  
Mentors: *Robert Pless and Steven Quartz*

In the pursuit of more efficient machine learning models, Parameterized Overlap Subspaces (PoS) offers a novel perspective on the internal structure and functioning of neural networks. This approach leverages the geometric properties of neural network parameter spaces to identify and exploit shared subspaces across different tasks, ultimately facilitating the transfer learning process. To isolate unwanted visual noise, one can project a CLIP (Contrastive Language Image Pertaining) embedding onto the subspace or its orthogonal component. For evidence in human trafficking images, it becomes pertinent to be able to identify images across a variety of different conditions such as poor lighting or extreme messiness. Our research seeks to enhance current Traffickcam capabilities by applying said new technique.

### **Establishing Strong Spatial Mixing for List Colorings**

Bharathan Sundar  
Mentors: *David Gamarnik and Houman Owhadi*

A key problem in algorithmic counting and sampling is approximately counting the number of proper colorings of a graph and sampling from this set. Such approximation algorithms can be used to estimate the partition function and sample from the Gibbs measure of discrete spin systems. Strong spatial mixing (SSM) is a property of such models that says that the correlation between vertices decays exponentially fast in graphical distance, conditioned on arbitrary pinnings of vertices to colors. SSM is highly connected to the design of efficient algorithms for counting and sampling. On trees, SSM has been long conjectured to hold whenever the number of colors  $q$  is greater than or equal to  $\Delta+2$ , where  $\Delta$  is the degree. We numerically simulate the well-known recursion for list colorings and verify that this property does hold via contraction of the recursion. We use this to provide an analytic proof of SSM in trees when  $q$  equals  $\Delta+2$ . We also modify the recursion for general graphs and remark on analogous mixing properties.

### **An Extension of CFTs to Non-Riemannian Manifolds**

Kai Svenson  
Mentors: *Maria Spiropulu, George Fleming, and Joseph Lykken*

We seek a generalized procedure for creating a conformal field theory (CFT) over an arbitrary smooth  $n$ -manifold. Our approach performs a discretization of the manifold by locally approximating its curvature with an affine-transformed lattice. On such a lattice we can define a conformal action, which we expect to remain conformal in the continuum limit. In this work, we perform a numerical analysis of the 3d Ising model on the affine-transformed FCC lattice. The critical surface is mapped by sweeping the 6d coupling parameter space and locating the divergence in energy fluctuations. At the critical point, the coupling parameters can be mapped to geometric distances via the correlation functions. Such a mapping can then be used to construct a conformal action given a discretized manifold as described above. The construction of a CFT over an arbitrary manifold would serve as a powerful tool to study field theories in exotic spacetimes and may also serve as a proto-model for quantum gravity.

**Grating Couplers and Photonic Crystals in 65nm Bulk CMOS**

Aaban Syed

*Mentors: Ali Hajimiri and Debjit Sarkar*

Description: Integration of on-chip electronics with photonics has the potential to revolutionize a variety of fields such as communications, sensing, and LiDAR. Approximately 90% of the market uses bulk CMOS, of which there hasn't been an integrated electronic-photonic solution until recently. In 2023, Ives et. al. demonstrated low loss waveguides in a commercial bulk CMOS process using the method of subtractive photonics. This results in a glass-air interface that allows for the refractive index contrast necessary to create a waveguide. To interface with these waveguides, light must be coupled into and out of the chip. In this project, we designed grating couplers and photonic crystal waveguides to be fabricated using a commercial 65nm bulk CMOS process at communication and near-infrared wavelengths. These structures can potentially allow for a higher density of photonic components on chip. In addition, a design for a novel coupler that takes advantage of the multiple layers in the 65nm bulk CMOS process is proposed and has been simulated to more efficiently couple light on chip than traditional grating couplers.

**Optimization of Placement of Amplitude-Only Proximal Phase Sensors**

Imaad Syed

*Mentors: Ali Hajimiri and Alex Ayling*

Microwave phased arrays have many applications, including wireless communications, RADAR and wireless power transfer. Since phased arrays steer microwave beams electronically with varied phase excitations, they require precise timing and phase alignment to maintain coherence, making phase-state information crucial. Prior work has obtained phase state information using magnitude only near-field sensors and a neural network for the problem of phase retrieval, with the sensor placement being a critical parameter to minimize the phase-state error. In this work, we present a near-field sensor placement optimization method based on genetic algorithms to reduce the RMS error of the phase-state measurements. This method will be used to inform the placement of sensors on the next iteration of magnitude only proximal phase sensors on a patch antenna phased array.

**Analytical Solutions for the Fokker-Planck Equation in the Context of F1-ATPase Rotary Motor Dynamics**

Alexandra Szolnoki

*Mentors: Sandor-Volkán Kacsó and Rudolph Marcus*

This project focuses on solving the Fokker-Planck equation by finding analytical solutions to complement computer-generated ones. My research is part of a broader study on the F1-ATPase rotary motor conducted by our group. This motor performs ATP hydrolysis or synthesis depending on its rotational direction, rotating in 120-degree segments with dwell periods induced by the binding and release of substrates and products during the catalytic cycle. These biochemical events lead to pauses in rotation, corresponding to different biochemical states. Single-molecule imaging data of the motor's trajectory presents challenges that can obscure the true nature of the motor. Therefore, our research group is investigating methods to resolve the issues found in single-molecule imaging data and uncover the hidden biochemical states of the motor.

One of the primary issues we are addressing involves using analytical methods to calculate the Michaelis-Menten curve from single-molecule experiments. We have developed a model that we apply to these single-molecule experiences, aiming to calculate the Michaelis-Menten curve analytically. This approach is critical to accurately interpreting the motor's biochemical states and understanding its functionality in greater detail.

**Convergence Guarantees for Particle Swarm Optimization**

Ritvik Teegavarapu

*Mentors: Franca Hoffmann and Dohyeon Kim*

Particle-based approaches are widely used in solving global optimization problems, using an ensemble of particles governed by coupled stochastic differential equations to explore the energy landscape. A classical method called particle swarm optimization (PSO) is available in many state-of-the-art optimization toolboxes. Despite widespread adoption, no theoretical guarantees currently exist for the algorithm to recover even approximately the desired global optimum. Such guarantees are available for the related consensus-based optimization (CBO) algorithm. The goal of this paper is to investigate to which extent the approaches that have shown fruitful for CBO are expected to apply in the PSO setting. We provide theoretical analysis on parameter ranges and algorithm set-ups for which we expect exponential convergence to hold and present numerical simulations to illustrate our results.

**Monte Carlo Simulations for Low Voltage Secondary Electron Resist Exposure**

Eric Thomassen

*Mentors: Axel Scherer and Scott Lewis*

Electron beam (E-beam) lithography is an alternative to currently used optical and X-ray lithography processes in semiconductor manufacturing. Existing E-beam methods have focused on 100+ keV high accelerating voltages for

primary electron beam exposure, where scattered electrons reduce minimum feature size. However, these secondary electrons present another viable option for resist exposure. Using Monte Carlo simulations, we are able to demonstrate the underlying exposure method of various semiconductor resist materials. These results are validated using known material properties and through direct observation of collected E-beam data across different resist materials and accelerating voltages. Using these simulations at <1 keV, we demonstrate the potential for secondary electrons to be used as a primary method of exposure in future semiconductor processes to achieve lower feature size with reduced complexity.

**Optimizing Chemical Sorbents for Point Source Carbon Capture**

Jordan Threat

*Mentors: Melany Hunt, Ricardo Hernandez, and Hannah Szentkuti*

Chemical sorbents can be used to efficiently capture carbon dioxide gas directly from point sources such as power plants. Our research aims to maximize the amount of carbon dioxide that is absorbed by these sorbents. The particles should have high surface area and porosity, be easily producible on a large scale, and be able to be regenerated repeatedly. Extrusion and spheronization form the material into two-millimeter diameter balls, which are then dried. The surface area and pore size are determined using BET testing. We found that increasing the percentage of potassium bicarbonate and bentonite clay as well as drying the sorbents for longer times greatly increased the area available for capture. The 75% to 25% ratio of potassium bicarbonate to potassium carbonate had the highest surface area with 1.7641 m<sup>2</sup>/g. This was also supported by reactor data, which showed that this ratio captured the most CO<sub>2</sub>, allowing us to build from the sample to discover an optimal sorbent for carbon capture.

**Unsupervised Identification of Behavior Motifs Linked to Surgical Outcomes in Sheep**

Vansh Tibrewal

*Mentors: Pietro Perona, Markus Marks, and Neehar Kondapaneni*

Accurate animal action recognition is crucial for understanding both behavior and the brain, with significant implications in fields like bioengineering, nature conservation, pharmaceutical experimentation, and brain research. Manual distinction of animal behaviors is labor-intensive, time-consuming, and susceptible to human biases. To address these challenges, we present a machine learning method that combines web-scale pre-trained vision models alongside an Autoregressive Hidden-Markov-Model (AR-HMM) to identify animal behaviors in an unsupervised manner. Our approach utilizes a fine-tuned image foundation model to derive video embeddings of animal movements and employs an AR-HMM to temporally cluster these embeddings into behavioral states. This method offers distinct advantages over single-species models by enabling multi-species action recognition with versatile applicability. Our work investigates the limitations of generalized pre-trained language-vision models such as CLIP and X-CLIP for precise action recognition in the animal domain, and utilizes low-resource self-supervised fine-tuning of image foundation models, namely DINOv2, to attempt to overcome these limitations. We validate our approach by analyzing behavioral differences in sheep that underwent neurosurgery, using the number of occurrences of behavioral states and their transition matrices to describe these differences. Our method will enable researchers to automatically analyze animal behavior and assess behavioral shifts in animals in an unsupervised manner.

**Optimizing Plasticity, Crosslinking, and Ultrasound Absorption in Biocompatible Shape Memory Polymers**

Everett Tolbert-Schwartz

*Mentors: Chiara Daraio and Gunho Kim*

Crosslinked poly-cyclooctene is developed as a shape memory polymer for several medical applications. Varying chemical additives are introduced to the system to produce a range of effects: ultrasound heating sensitization, UV-induced crosslinking, and variable plasticity. To synthesize the polymers, uncrosslinked poly-cyclooctene was fully dissolved, combined with additives, and then the solvent was removed to produce a homogeneous precursor sample that could be crosslinked using either heat or UV-A radiation. Samples were mechanically characterized by stretching under hot water and measuring deformability and shape recovery. Samples were chemically characterized using FTIR and DSC. These methods yielded samples which could be deformed by >1000%, with >95% recovery. In the heat-crosslinked samples, the thermocrosslinker was found to be producing unintentional plasticizer effects. The quantities of thermocrosslinker were fine-tuned to eliminate these effects and produce more consistent samples. Additionally, the chemical additives yielded samples that had controllable plasticity, and were increasingly sensitive to ultrasound heating effects. Finally, although UV-induced radical crosslinking successfully occurred, the UV-A radiation could not sufficiently penetrate into the sample, leading to uneven crosslinking. Various photoinitiators that absorb in the blue and near-UV will continue to be tested to determine if penetration depth can be improved.

**Pattern-Based Design and Fabrication of PILLARS Inflatable Prototype for NASA BIG Idea Challenge**

Angelina Torres

*Mentor: Soon-Jo Chung*

As a part of the Artemis program, rockets will launch and land on the lunar surface, and fine, abrasive, high-velocity particles of lunar regolith will be kicked up, sandblasting lunar infrastructure. As a part of the 2024 NASA BIG Idea Challenge, Caltech's Plume-deployed Inflatable for Landing and Launch Abrasive Regolith Shielding (PILLARS) aims to mitigate this threat. PILLARS inflates passively using only the plume of a rocket to contain any disturbed regolith. The shield must be able to withstand the heat and pressure of a rocket plume, as well as survive the extreme abrasion of lunar regolith. To verify the feasibility of the PILLARS system, candidate materials with high tensile strength and high melting point were investigated, as well as heavy-duty methods of construction. Various fabric materials, fabric weaves, stitching patterns, and seam finishes were tested in the expected thermal, load, and abrasive conditions. Through this testing, we can determine which materials and construction methods will give PILLARS the longest usable lifetime, driving system design and creating a more optimal solution than landing pads.

**Evaluating the Influence of Magnetic Field Sweeps on Human Visual Perception**

Matthew Torres

*Mentors: Shinsuke Shimojo and Lara Krisst*

Many organisms can sense Earth's magnetic field, but most humans are not aware of geomagnetic stimuli. Recent research, however, found a human brain response to Earth-strength magnetic field sweeps in an experimental setting (Wang, 2019). Previous research on multisensory integration has shown a complex interplay between distinct sensory modalities. Under this premise, we examined whether magnetoreceptive information can influence visual perception. We studied the interaction between magnetoreceptive and visual information by measuring subjects' responses during a visual motion detection task while they were exposed to Earth-strength magnetic field sweeps. Subjects were asked to report the direction of visual motion on a random dot kinetogram while simultaneously being exposed to a magnetic field sweep that was either congruent or incongruent with the direction of visual motion. Preliminary results from this study suggest that magnetic field sweeps may have an effect on visual perception, as subjects' responses varied in a systematic way to the magnetic field sweep direction.

**Simulating the Creation and Maintenance of Lunar Bases**

Thang Tran

*Mentors: Yuk Yung and Jonathan Jiang*

Through several proposed lunar missions within the next decade, global space agencies plan to land humans on the surface of the moon and establish lunar colonies, leveraging lunar resources for the goal of planetary exploration and habitation. Given the complexities and high costs associated with lunar missions, testing base designs poses significant challenges. To address this, we present a detailed simulation environment to evaluate potential lunar base scenarios and challenges as a cost-effective alternative to physical testing. Based on an analysis of NASA's proposed Artemis mission sites, our simulation environment depicts the Lunar South Pole from 87.5 °S to 90 °S, with the flexibility to replace it with a custom area the user wishes to analyze. The simulation features a hypothetical landing system that models the Lunar Excursion Module (LEM) and a building system at user-selected sites, whose viabilities are determined by the terrain's slope and surface roughness. Our key features encompass resource management and life support systems, infrastructure planning and construction, and dynamic facility operations. Overall, our simulation serves as an interactive, detailed visualization of lunar colonization, allowing users to adjust a set of input parameters, experiment with several base designs, and monitor their base over time.

**Observation of Collective Electronuclear Modes About a Quantum Critical Point in a Disordered Magnet**

Josephine Tsai

*Mentors: Thomas Rosenbaum and Daniel Silevitch*

Disorder is known to have profound effects on the macroscopic properties of materials. In strongly disordered systems, the critical exponents of the phase transition can be modified or suppressed, and the transition itself can be suppressed or broadened. We characterize the ferromagnetic-paramagnetic quantum phase transition in the disordered Ising magnet  $\text{LiHo}_x\text{Y}_{1-x}\text{F}_4$ , with  $x = 0.65$ , via microwave spectroscopy. A magnetic field applied transverse to the Ising axis tunes the quantum transition. The measurements are made in a loop-gap resonator compatible with a helium dilution refrigerator, permitting us to study the system at milliKelvin temperatures. Whereas the lowest electronuclear energy level of  $\text{LiHoF}_4$  has been found previously to go to zero at the quantum critical point, our results point to this "soft mode" being gapped by the disorder in the system. Moreover, we characterize the effects on the electronuclear levels of a magnetic field applied parallel to the easy (Ising) axis of magnetization, and attempt to observe the non-linear response at high power levels.

**Design and Implementation of an Inductively Coupled Plasma Source for Atomic Layer Etching**

Chloe Isabella Tsang

*Mentors: Austin Minnich and Ivy Chen*

Inductively Coupled Plasmas (ICPs) are highly ionized gases generated by electromagnetic fields, commonly used in various nanofabrication processes due to their high ion density and uniformity. ICPs are key in applications such

as etching and deposition, where precise control over material removal or addition is needed. In this project, ICPs are utilized for Atomic Layer Etching (ALE), a process that allows for the atomic-scale precision etching of materials. We have designed and constructed a custom ICP source, aimed at advancing ALE techniques. Starting with a conceptual design, we identified and sourced all necessary components, ensuring compatibility and functionality. The design process included detailed research on plasma generation, power supply requirements, and the configuration of the ICP system. After procuring the components, we assembled the system while addressing challenges related to component integration and operational stability. The resulting ICP source aims to demonstrate effective plasma generation, providing a key component for precise and controlled ALE processes.

**Sensory Cues for Social Behaviour in Mice**

Ruby Tseng

*Mentors: David Anderson and Lindsey Salay*

The detection of sensory cues is important for animals to display relevant behaviours during mating and aggression. The loci for both male aggression and mating behaviours have been well studied: aggression is mediated by ventrolateral subdivision of the ventromedial hypothalamus (VMHv1) and mating by the medial preoptic area of the hypothalamus (MPOA) (Lin et al., 2011; Karigo et al., 2020). Artificial activation of these nuclei using optogenetics can evoke a range of instinctual behaviors that can be divided into appetitive and consummatory phases. The former brings an animal in close proximity to a target (e.g. chase) and the latter facilitates the elicitation of stereotyped actions (e.g. attack). Notably, optogenetically-evoked behaviours can even be directed toward three-dimensional inanimate target objects that lack any olfactory pheromonal cues. What sensory cues are required for the different phases of mating and aggression under both natural and hypothalamic stimulation conditions is currently not well understood. Understanding the sensory cues for mating and aggression would provide insight into the complex behaviors necessary for animal survival.

**Measuring Irrationality of Choice Using Network Flow Theory**

Saikhanbileg Tsogtgerel

*Mentor: Kota Saito*

Traditional models of economics are based on the belief that choices of an agent could be rationalized by one single linear order, satisfying IIA (Independence of Irrelevant Alternatives). Real-world decision-making typically violates this axiom due to effects like compromise and attraction. The goal of this work is to characterize choice functions that are irrational with sets of linear orders as small as possible. We built a theoretical framework and computational algorithm using network flow theory to find minimal such sets. We will map the choices to paths and cycles in directed graphs using Block Marschal polynomials and flow networks. Our algorithm is illustrated on a dataset of choice functions for quantifying the degree of irrationality in individual behaviors, looking for correlations with demographic factors. Our findings provide strong, firm justification for the use of small sets of linear orders as a good metric toward the assessment of choice rationality.

**In Vivo Directed Evolution of a Multi-Protein CRISPR-Associated Transposition System**

Emily Tu

*Mentors: Kaihang Wang and Jolena Zhou*

Mobilizing large fragments of DNA with a clustered regularly interspaced short palindromic repeats (CRISPR) associated transposon (CAST) system is a foundation for the efficient construction of chimeric genomes. CAST is a multi-protein complex designed to mobilize and insert a DNA payload onto a designated location on a recipient genome; coupling CAST with a conjugation system enables megabase-scale integration in one step. With the inclusion of a mutagenesis plasmid, we aim to evolve the CAST protein complex and increase the rate of successful integrations. During each round, CAST passes from a donor to a recipient genome via conjugation and cells with correct insertions are new donors in the subsequent round. Only the protein of interest accumulates mutations thus eliminating background noise, and characterization of the resulting protein will elucidate the proficiency of this novel directed evolution scheme.

**Safe Autonomous Mapping of Seagrass Distribution and Health by USV**

Idil Turasi

*Mentor: Victoria Orphan*

Seagrass habitats are increasingly at risk due to shoreline development, the growing intensity of storms, and the spread of non-native species. Autonomous uncrewed surface vehicles (USVs), equipped with advanced safety and control mechanisms, are ideal for navigating densely populated coastal zones, including beaches and harbors. To upgrade a USV that is controlled by an operator on the shore, we mapped its motor controllers to a Blue Robotics Navigator Flight Controller, established a stable wireless connection through routers, and created autonomous mission using QGroundControl. Testing in the Caltech Pond and at Kerckhoff Marine Laboratory was used to confirm successful autonomous operation. In addition, a realtime data interface for the USV's science payload was developed, including an Ecotone underwater hyperspectral imaging spectrometer and a Star-Oddi DST CT Online conductivity/salinity/temperature logger. With autonomous operation and scientific data collection capabilities, the

USV can be used to image the seagrass study area by Kerckhoff Marine Laboratory. In the next phase of the project, hazard detection and safety and control mechanisms for autonomous operation will be added.

### **Anomalous Hall Crystal Hosts**

Avi Vadali

*Mentors: Ashvin Vishwanath, Xie Chen, Tomohiro Soejima, and Junkai Dong*

Within two-dimensional systems of charged particles, the quantization of the system's resistance is a well-known phenomenon and is attributed to the quantum Hall effect (QHE). The QHE conventionally quantizes resistance in the presence of an external magnetic field; however, resistance quantization has been observed in the absence of an external field. This phenomenon is called the quantum anomalous Hall effect (QAHE), and it is a result of the topological properties of the system's energy band structure. Recent experiments have observed the quantum anomalous Hall states in rhombohedral pentalayer graphene in the absence of a moiré potential. Such a state is called the anomalous Hall crystal (AHC), and it is a many-body electron state spontaneously breaking time-reversal symmetry and translation symmetry.

We investigate several platforms potentially capable of hosting AHC states including rhombohedral multilayer graphene, surface states of 3D topological insulators, and a simplified model with highly concentrated Berry curvature. We aim to elucidate the physical mechanism behind the spontaneous crystallization and time-reversal symmetry breaking characterizing anomalous Hall crystals.

### **Graph-Assisted Data Clustering With Generalized Euclidean Distance**

Eric Verheyden

*Mentors: Konstantin Zuev and Michele Coscia*

In data analysis, clustering data serves as a vital toolset for uncovering patterns, structures, and relationships latent within datasets. Traditionally, clustering is performed on Euclidian or other non-Euclidian spaces like hyperbolic space. However, as datasets increase in complexity, traditional Euclidean-based geometry fails to encompass all aspects of the data. Luckily, graphs are ubiquitous in modeling complex systems such as social networks, biological networks, and recommendation systems, and they can explicitly map arbitrary non-Euclidean spaces. However, presently analysis involving graphs is more concerned with describing the graphs themselves, rather than the data that lives on the complex space they define. We present a machine learning-based data clustering method utilizing the Generalized Euclidian measure, which can use the graph to define the space of the analysis, as a basis for its loss function.

### **Quantifying Forced and Internal Components of Observed Precipitation Changes**

Sydney Vernon

*Mentors: Tapio Schneider, Dave Bonan, and Ronak Patel*

A central goal of climate science is to understand how anthropogenic emissions affect climate processes, including precipitation, at regional scales. However, it is difficult to attribute regional precipitation changes to anthropogenic emissions due to the strong influence of natural variability. Therefore, identifying the impacts of human activity on historical precipitation changes is of great academic and societal interest, and would fill a gap in the literature. Here, we use a novel statistical method called low-frequency component analysis (LFCA) to quantify the anthropogenic and internal components of observed changes in regional precipitation. We do this by identifying precipitation variability that co-varies with sea surface temperature variability, which exhibits a stronger anthropogenic signal. We find that the long-term mode of variability identified by LFCA exhibits characteristics associated with anthropogenic global warming, including amplified warming in the Arctic. This long-term pattern is associated with a Northward shift of tropical rainfall. Subsequent modes exhibit different degrees of variability associated with other known climate modes, including Pacific and Atlantic decadal variability and the El Niño-Southern Oscillation. This decomposition of precipitation and temperature patterns allows for a quantification of the relative importance of anthropogenic forcing and internal variability in regional precipitation changes.

### **Application of Active Learning to Analyze Nickel-Catalyzed Reductive Cross-Coupling Reactions**

Julie Vinh

*Mentors: Sarah Reisman, Danielle Mantin, and Jules Schleinitz*

Nickel-catalyzed reductive cross-coupling (RCC) reaction examines the catalytic role of Nickel in producing a coupled product. In high-throughput experimental fashion, various substrates are simultaneously screened through multiple reaction plates under consistent conditions to evaluate the reproducibility of the experiment. The conditions that the reactions are placed under are the following: CyBioX as the ligand, nickel complex with diglyme ( $\text{NiBr}_2$ ) as the metal catalyst and trimethylsilyl chloride (TMSCl) as the stabilizer and Ethylbenzyl chloride (EtBnCl) as the solvent. Complementary to the HTE, our project focuses on implementing active learning using the database generated by screening the RCC reactions. Using the retention times of the substrates we created a model to predict the response factor using data on various molecular descriptors including the types of atoms, bonds, cyclic rings and bond energies present. Our findings of the consistent product turnout across multiple plates shows

promise in enhancing the efficiency and accuracy of nickel-catalyzed reductive cross-coupling reactions. While the active learning aspect of the project is still a work in progress, the integration of machine learning shows potential in paving the way for more automated and intelligent design of chemical processes; therefore, revolutionizing the field of synthetic chemistry.

### **A Generative Surrogate Model Framework for Efficient Malaria Transmission Simulations**

Annika Viswesh

*Mentors: Youssef Marzouk, Yisong Yue, and Matthew Levine*

Effective malaria control requires the optimization of limited resources due to insufficient funding. Achieving this optimization depends on a deeper understanding of the complex interactions between human immunity, such as antigen capacity, and the transmission dynamics of the *Plasmodium falciparum* parasite. These intricate interactions complicate the prediction of the impact of immunity on malaria risk and transmission, necessitating mathematical modeling to inform resource allocation strategies. The agent-based Epidemiological MODELing software (EMOD) facilitates this by simulating mosquito-human interactions, immune responses, and within-host parasite dynamics over extended periods to capture the full progression of malaria transmission, which is crucial for understanding the spread of the disease and guiding resource allocation. However, generating the initial population conditions for long-term simulations using EMOD is computationally demanding, especially for large populations. This work introduces a generative surrogate modeling framework designed to optimize the synthesis of initial population states, thereby reducing the computational burden of EMOD while preserving the accuracy of population state projections. We thus aim to enhance the speed and precision of long-term malaria simulations and provide detailed metrics to evaluate the efficiency and success of the model, ensuring its reliability and robustness.

### **Waves Resonances and Eigenstates in Periodic Structures**

Kieran Vlahakis

*Mentors: Oscar Bruno and Manuel Santana*

In this work, we focus on the problem of finding the resonant and near-resonant acoustic frequencies of periodic structures. Mathematically, this descends to an eigenvalue problem for the Laplacian operator, in particular we are interested in finding values of  $k$  satisfying

$$\nabla^2 u = -k^2 u$$

Finding these eigenvalues and eigenfunctions depends on the geometry of the problem. Except in simple (separable) geometries, this problem cannot be solved analytically, therefore, this project aims to develop an efficient numerical method for computing these resonant frequencies for periodic structures. These resonant frequencies have important physical applications such as in antenna design, particle accelerators and medical imaging.

### **Membrane Stability Analysis for Nanomechanical Quantum Transducers**

Adam Wajed

*Mentors: Mohammad Mirhosseini and Han Zhao*

This project focuses on simulating the stability of the silicon-on-insulator platform that supports on-chip nanomechanical quantum transduction. Quantum information processing, with superconducting qubits at cryogenic temperatures, and room temperature communications systems are respectively reliant on electromagnetic radiation at microwave and optical frequencies, separated by a factor of  $10^5$  Hz. Subsequently, forming a distributed quantum network to realise scalable quantum computers necessitates coherent microwave-optical transducers. In the Quantum Engineering Lab, a piezoelectric-free electro-optomechanical interface accomplishes this non-linear process by exploiting acoustic vibrations as an intermediary degree of freedom. The device platform is a  $220 \mu\text{m}$  silicon-on-insulator substrate released from a  $3 \mu\text{m}$  silicon dioxide layer using hydrofluoric (HF) acid. However, residual stresses in the device and capillary forces from liquid HF acid, can sometimes cause geometric failure of the membrane. This project explores the membrane structural mechanics using a finite-element analysis, through an eigenvalue buckling analysis and a nonlinear post-buckling analysis. Comparisons with optical images show the simulation appears to capture the observed behaviour and provides insight into the effects of residual stress. The investigation concludes there is strong evidence suggesting that the dominant collapse mechanism results from the capillary forces, consistent with empirical observations of liquid versus vapour HF fabrication processes. Therefore, this project ultimately provides a solution to unpredictable geometric failure by producing simulations of membrane stability and proposing optimised designs for realising more efficient devices with greater fabrication yield.

### **Integration and Control of Musculoskeletal and Exoskeleton Models for Optimizing Wearable Lower-Limb Exoskeleton Rehabilitation**

Keyu Wan

*Mentors: Aaron Ames and Kejun Li*

Wearable exoskeleton devices have become crucial tools in aiding therapists with the rehabilitation of neurological patients suffering from paralysis. We mainly focus on lower-body robotic assistive devices designed to help in the recovery and rehabilitation of patients' disabled legs. These wearable lower-limb exoskeletons aim to restore mobility to individuals with lower-body paralysis. Accurate muscle prediction is essential for optimizing rehabilitation training with robotic assistive devices, especially for individuals with hemiplegia. Users of exoskeleton devices require different rehabilitation regimens based on their specific paralysis and muscle signals. By identifying specific muscle issues, these devices can customize therapy to meet each patient's unique needs. However, the relationship between exoskeletons and human muscles is not well understood. It is unclear how the movement of an exoskeleton influences the rehabilitation of human muscles. We propose a solution through the integration of musculoskeletal and exoskeleton models, which simulates how exoskeleton movement would influence muscle activation. By applying reinforcement learning methods, we develop and refine the exoskeleton controller that results in muscle signals closely resembling the desired activation patterns for targeted rehabilitation.

### **Evaluating Parameter Recovery Algorithms Applied to Chaotic Systems**

Ashley M. Wang

*Mentors: Franca Hoffmann and Elizabeth Carlson*

This project explores the effectiveness of various parameter recovery algorithms applied to chaotic systems, specifically focusing on the Lorenz '63 and Lorenz '96 systems. We compare deterministic methods, including the Carlson-Hudson-Larios (CHL) and Pachev-Whitehead-McQuarrie (PWM) algorithms, with stochastic methods, such as the combination of the Ensemble Kalman Filter (EnKF) and the Expectation-Maximization (EM) algorithm, and Ensemble Kalman Inversion (EnKI). Using a predictor-corrector scheme that incorporates the Adaptive Multi-step Differential Transform Method (adaptive MsDTM) and Implicit Euler Method to numerically construct synthetic data, our detailed comparisons highlight the robustness of the CHL and PWM methods. Our findings show that for our chosen noise level, deterministic parameter recovery algorithms are more accurate and stable. Additionally, deterministic parameter recovery methods have demonstrated greater speed and efficiency, requiring less computational power than stochastic methods, which need multiple ensembles to extract useful information. This suggests that future work should consider exploring the full potential of deterministic parameter recovery algorithms.

### **An Ensemble Langevin Diffusion Sampler for General Noisy Inverse Problems**

Austin Wang

*Mentors: Yisong Yue and Hongkai Zheng*

Diffusion models have seen recent use as strong data priors for Bayesian inverse problems, owing to their powerful generative capabilities and flexible sampling process. However, many diffusion-based inverse problem solvers rely on assumptions about the problem setting, such as access to gradient or pseudo-inverse information of the data measurement model. These assumptions rarely hold true in complex real-world inverse problems, such as those in the scientific domain, thus limiting the applicability of diffusion-based methods. To this end, we propose a derivative-free Markov chain Monte Carlo algorithm that sequentially refines an ensemble of samples by alternating between solving a Langevin dynamic for measurement consistency and performing a standard denoising diffusion step for sample quality. By approximating the forward measurement model gradient with ensemble differences, we extend the applicability of our method to non-differentiable inverse problems. We demonstrate the quality and robustness of our algorithm on various image reconstruction tasks and non-differentiable scientific inverse problems.

### **Diffusion-Based Functional Ultrasound Imaging: An Inverse Problem Perspective**

Bobby Wang

*Mentors: Anima Anandkumar and Bahareh Tolooshams*

Functional Ultrasound Imaging is a popular medical imaging technique that creates neural activity maps through the measuring of changes in blood volume as a spatio-temporal function: Tracking changes in blood flow can infer neural activity. Functional ultrasound works by exposing the brain to pulsed ultrasonic waves, subsequently recording echoes back-scattered by the blood and tissue. Then, the crux of the functional ultrasound imaging problem is the deconvolution of the blood flow volume signal from the tissue signal. Classical methods are computationally expensive: They require a larger number of time frames, begetting an extended period of data acquisition. Deep-learning frameworks attempt to address this issue by learning a mapping between a fixed small number of frames to the Doppler image; however, many deep learning techniques do not support inference given a variable number of time frames. The challenge, then, is formulating a statistical prior to separating tissue and blood, through a method that is robust to the number of frames. We propose to treat functional ultrasound reconstruction as an inverse problem and to learn the statistical priors governing the decomposition of the



measured signal into its blood flow and tissue components at each frame through the use of a functional ultrasound-tailored diffusion-based generative model. We thus propose the use of a dual-track temporal diffusion model to solve the functional ultrasound reconstruction problem.

### **Structural Studies of Viral Antigens and Antibodies to Characterize Protective Immune Response Against HIV-1 and Coronaviruses**

Eric Ji Da Wang

*Mentors: Pamela Bjorkman and Edem Gavor*

Most successful protective vaccination strategies elicit neutralizing antibodies as the primary mode of protection. However, effective HIV-1 or pan-coronavirus (SARS-CoV-2 and MERS-CoV) vaccines remain elusive due to viral antigenic diversity. A successful vaccination strategy would effectively elicit broadly neutralizing antibodies (bNAbs) that target conserved epitopes on the surface antigens of these viruses. In this project, we seek to further our understanding of the mechanisms of bNAb-antigen interactions to aid design of immunogens to elicit bNAbs. We carried out biophysical and structural characterization of antibodies against HIV-1 Env, SARS-CoV-2 and MERS-CoV spike proteins isolated from immunized animals. Cryo-EM structures of anti-HIV Env V3 loop binding antibodies reveal structural determinants of V3-targeted bNAb binding. Comparative analysis of the V1 loop conformations between Env based immunogens 5MUT-3fill-DS, -4Del, -8Del, RC1 and 11MutB provides insight into structural determinants guiding the maturation of V3-targeting bNAbs in non-human primates, thereby informing vaccine design. We also evaluated antibodies isolated from mice immunized with a MERS-S2 subunit nanoparticle using Cryo-EM. Given that the S2 subunit is more conserved than the receptor-binding domain (RBD) between coronaviruses, insights from the mechanisms of bNAb cross-reactivity between sarbecovirus and merbecovirus S2s can inform design of a pan-coronavirus vaccine to combat future emerging zoonotic pathogens.

### **Atmospheric Retrievals of a Cloudy L Dwarf With the Keck Planet Imager and Characterizer**

Gavin Wang

*Mentors: Dimitri Mawet, Jerry Xuan, and Yapeng Zhang*

Brown dwarfs are objects more massive than planets but lighter than stars, with masses of roughly 13 to 80 times that of Jupiter. However, whether a brown dwarf formed like a planet through core accretion or like a star through disk fragmentation is often ambiguous. CD-35 2722 B, an L dwarf orbiting the 0.4 solar mass M dwarf CD-35 2722 A, is one such example, with a mass of  $31 \pm 8$  Jupiter masses that lies at the low end of the brown dwarf mass regime. We analyze high-resolution (resolving power 35,000) K band (2.10-2.49 microns) spectra of the companion and its host star from the Keck Planet Imager and Characterizer (KPIC). The high signal-to-noise spectra allow us to retrieve precise carbon-to-oxygen ratios, atmospheric metallicity, and  $^{12}\text{CO}/^{13}\text{CO}$  isotopologue ratios for both objects. From these measurements, we test whether the brown dwarf companion and its host star share similar chemical abundances, which is expected for a star-like formation mechanism. In addition, L dwarfs are among the cloudiest of brown dwarfs, and we find significant evidence for clouds in the atmosphere of CD-35 2722 B. Finally, we explore the clouds' properties by jointly analyzing the KPIC data with archival spectra from 1-2.5 microns.

### **Enhancing Predictability in RNAi Screening Through Cross-Protein Correlation Integration**

Jasmine Wang

*Mentors: Mark Bathe, Reuven Falkovich, and Henry Lester*

The effective operation of synapses in the brain relies on a system of intricate molecular networks, making it crucial to be able to predict gene knockdown effects in RNAi screens especially with significant experimental variability. Here, we use support vector machines (SVMs) trained on synaptic data to determine the predictability of proteins and genes across experiments. Initially, SVM models based solely on average protein levels resulted in weak predictability due to plate-to-plate differences. However, with the addition of protein-protein correlation values, the predictability significantly improved, highlighting their consistency across plates of neurons. This approach utilizes the Probe-based Imaging for Sequential Multiplexing (PRISM) technique to produce multiplexed imaging of synaptic proteins. This underscores the potential of cross-protein correlations to improve predictive machine learning models in genetic studies and the future possibility of applying this to gene knockdowns associated to psychiatric disorders like autism and schizophrenia.

### **Building a DNA Part Library for Entomopathogenic Nematode Symbiont *Xenorhabdus griffinae***

Olivia Wang

*Mentors: Richard Murray and Elin Larsson*

*X. griffinae* is a bacterium that lives inside the gut of the *S. hermaphroditum* nematode and partners with the nematode to infect and kill insect hosts in the soil. The construction of gene circuits, like sensors, in *X. griffinae* would provide a better understanding of their symbiotic relationship and develop soil engineering principles to enhance pesticides to improve agricultural production. However, because *X. griffinae* is not a model organism like *E. coli*, there is little information about gene circuit construction in *X. griffinae*. The development of a DNA part library similar to CIDAR MoClo extension library for *E. coli* would allow for greater predictability and efficiency while

creating complicated circuits in *X. griffinae*. Therefore, twenty TurboRFP expressing strains with eleven different constitutive Anderson promoters and ten different ribosome binding sites (RBS) were designed and constructed to quantify promoter and RBS strengths in *X. griffinae* with TurboRFP fluorescence. Furthermore, two large operons, the lux operon genes for bioluminescence and phz operon for phenazine-1-carboxylic acid production, were added to the part library to create an orthogonal marker to fluorescence, as well as produce a toxic compound known to kill nematodes.

**Characterizing Band-Pass Filter Performance in Millimeter-Wave Hierarchical Phased-Array Antennas**

Sylvia Wang

*Mentors: Sunil Golwala and Jean-Marc Martin*

To achieve optimal results with mm/sub-mm telescope detectors, the pixel size should be adjusted according to frequency. A proposed solution to achieve this is with a hierarchical phased array antenna, which can coherently sum signals from individual pixels to provide frequency-dependent pixel scaling. Band-pass filters (BPFs) are necessary for coherent summing of frequencies at the correct junctions, but measured spectral response of BPFs on existing hierarchical antenna models exhibit ripples that do not appear in simulated responses. This project aims to understand these differences by incorporating elements that are not included in the current model, such as the optical window between the devices and the measurement source. This was done by calculating the transmission and reflection of the optical stack using the transfer-matrix method as well as using Altair Feko, a high-frequency simulation software. Various methods of improving transmission were simulated, such as replacing low-transmission layers and tilting internal layers to reduce standing waves. These results may provide guidance on how to improve the hierarchical antenna model to better match original simulations.

**Role of U1 snRNA Dysregulation by Disease TDP43 and FUS Variants in ALS Progression**

Yu Wang

*Mentors: Mitchell Guttman and Drew Honson*

Amyotrophic Lateral Sclerosis (ALS) is a fatal neurodegenerative disease that causes progressive motor neuron degeneration in the central nervous system leading to loss of motor control, paralysis and death. Recent studies suggest that U1 snRNA, a key regulator of pre-mRNA splicing and transcription, may be dysregulated in ALS. Two RNA binding proteins frequently mutated in ALS, TDP43 and FUS, regulate U1 snRNA biogenesis and function. TDP43 regulates the formation and function of Cajal bodies, cellular compartments important for U1 maturation, while FUS directly binds to U1 and may affect U1's localisation and regulation of pre-mRNA synthesis. Despite regulatory links between TDP43, FUS, and U1, it is unclear if disease variants of TDP43 or FUS contribute to ALS progression through U1 dysregulation. In our study, we use fluorescence imaging and Covalent Linkage & Affinity Purification – Sequencing (CLAP-Seq) to investigate how expression of disease variants of TDP43 or FUS affect U1 biogenesis and function.

**Comparing the Human Health Effects of Urban Heat and Climate Change in LA County**

Kaylee Wei

*Mentor: Hannah Druckenmiller*

Since the Industrial Revolution, Earth's global climate has warmed to unprecedented levels, driven largely and unequivocally by anthropogenic activities. This warming has led to wide-ranging consequences, including increased extreme weather events and poorer public health. Extreme heat in particular has become a key concern, due to its large role in public health as well as its prevalence in urban areas due to the urban heat island effect, in which the built environment elevates local temperatures. However, while the temperature increases associated with urban heat islands are comparable to those projected by end-of-century climate change scenarios, the impacts of urban heat have received relatively less attention from the public and policymakers, and there is limited work empirically comparing the two. We aim to address this gap by estimating the human health effects of urban heat on mortality and morbidity across LA county at the zipcode level, using regression analysis that incorporates social vulnerability and prolonged heat exposure from socio-demographic and high-resolution, near-surface air temperature data. We perform a similar analysis on end-of-century climate change projections, before comparing the health effects of the two phenomena to help empirically inform mitigation measures at the local level.

**Investigating the Interactive Effect of CFH(Y402H) and Oxidative Stress in Lipid Metabolism and Age-related Macular Degeneration**

Nova Wei-Navarro

*Mentors: Deborah Ferrington, Dennis Dougherty, and Peng Shang*

Age-related macular degeneration (AMD), characterized by the degeneration of retinal pigment epithelia (RPE) and photoreceptors, causes severe and irreversible blindness. Complement factor H (CFH) polymorphism (Y402H) is one of the most significant genetic risk factors for AMD, with smoking being a notable environmental factor. Angiogenesis, which often occurs in AMD, is when new blood vessels begin growing from existing blood vessels. This process can be regulated by many pathways, including sphingolipid metabolism, highlighting a potential role for lipid metabolism in AMD pathology. In this study, we utilized induced pluripotent stem cells (iPSC) derived RPE

cells from human donors and cigarette smoke extract (CSE) treatment to investigate lipid metabolism in AMD pathology. Cells with either high risk CFH (402H) or low-risk CFH (Y402) treated with or without CSE were collected for protein analysis. From our initial review of the proteomics data from the analysis of 16 cell lines, we observed several lipid-related proteins were altered by either CSE or genotype. My project involved validating the changes in protein content through Western blots. Confirming the changes of these lipid related proteins with the effects of CFH genotype and oxidative stress will provide novel insight into AMD pathology.

### Nickel-Catalyzed Copolymerization of Ethylene and Isocyanides

David Welt

Mentors: Theodor Agapie, Paramita Saha, and Adjeeda Tekpor

The incorporation of polar monomers into polyethylene improves desirable properties of the material, and we hypothesize that copolymerizing ethylene and isocyanides may form a polyketone derivative that improves the photodegradability of the material. The incorporation of functional groups is industrially achieved via a radical mechanism or post-polymerization functionalization, which require high temperatures and pressures and do not offer control over polymer microstructure. A possible alternative is the use of nickel catalysts, which operate under milder conditions and allow for control over the microstructure, improving the cost and sustainability of the process. However, we hypothesize that isocyanides will form a deactivating 3-membered chelate upon addition to the catalyst (Fig. 1). We investigate the behavior of two nickel catalysts in the presence of isocyanides and ethylene, and the effect of steric bulk from the catalyst and from the isocyanide on the deactivation pathway (Fig. 1).

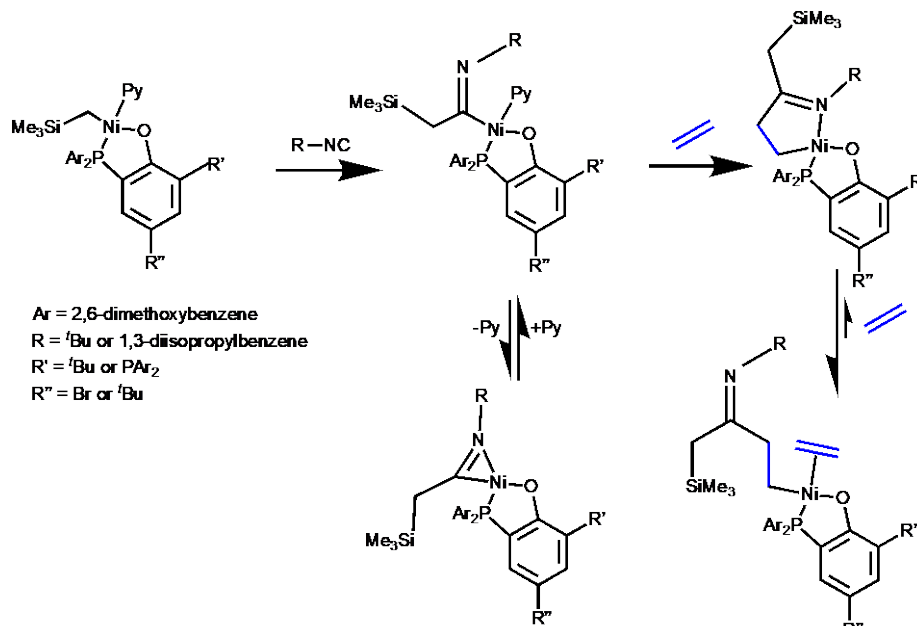


Figure 1: Proposed catalytic pathway for nickel catalysts and isocyanides

### Human Ultrasound Imaging Using Physics-Informed Machine Learning

Weishan Weng

Mentors: Lihong V. Wang and Aborahama Yusuf

Ultrasound imaging has significantly evolved since its inception in the mid-20th century, revolutionizing medical diagnostics by offering rapid and cost-effective insights into tissue structure and function. Despite advancements in transducer and electronic technologies, current ultrasound systems still face challenges in visualizing features behind bone or air pockets and are limited to narrow field-of-view images. To address these limitations, we propose a novel whole-body human ultrasound tomography (UST) system utilizing a custom circular array with 512 receiver elements and a rotating single-element transmitter. This setup enables the acquisition of 2D isotropic images of reflectivity, speed of sound, and attenuation profiles with full 360° viewing angles, thus penetrating tissues previously obscured by acoustic limitations.

The primary focus of this study is to enhance the image quality obtained from the UST system using physics-informed machine learning (PIML). Compared to traditional numerical methods and conventional machine learning, PIML offers robust, interpretable solutions that integrate noisy data more effectively. We employ a physics-informed neural network (PINN) to solve the inverse problem, leveraging the flexibility and scalability of PIML to improve image quality.

### **Characterization of KLF6 Coding Region and 3' UTR Knockouts in Breast Cancer Cells**

Grace Wilson

*Mentors: Mary Hynes, Ze Yang, and Bruce Hay*

Breast cancer is the most diagnosed cancer globally, with over 2.3 million new cases reported in 2020 and 685,000 associated deaths (Arnold et al., 2022). A significant contributor to breast cancer mortality is metastasis, which is often characterized by epithelial-to-mesenchymal transition (EMT), a process that enhances the mobility of cancer cells. Disruption of the KLF6 gene, a known tumor suppressor in the Kruppel-like factor family, is linked to EMT and aggressive metastatic disease. This study aims to deepen our understanding of KLF6 by elucidating the roles of its coding DNA sequence (CDS) and 3' untranslated region (UTR). A library of CRISPR-Cas9 constructs targeting the KLF6 CDS and 3' UTR will be generated for transfection into MDA-MB-231 breast cancer cells. Successful transfection will be confirmed through FACS sorting, followed by the growth of single knockout colonies. Western blots and PCR will be used to verify the generation of knockout cell lines. A variety of assays will be used to characterize the morphological changes and expression-level effects resulting from the knockouts. By examining the roles of KLF6 CDS and 3' UTR, we hope to gain insight into how KLF6 downregulation contributes to breast cancer development and metastasis, potentially identifying new therapeutic targets for the disease.

### **Analyzing the Use of Quantitative Susceptibility Mapping for Deep Brain Stimulation Surgery to Treat Parkinson's Disease**

Cherise Wong

*Mentors: Melanie Morrison, Lee Reid, and Markus Meister*

Deep brain stimulation (DBS), a neurosurgical procedure used to treat Parkinson's Disease (PD), involves the delivery of electrical stimulation to the brain by electrodes carefully positioned at target brain regions (the subthalamic nucleus and globus pallidus for PD). Magnetic Resonance Imaging (MRI) guides neurosurgeons in positioning the electrodes appropriately. Quantitative Susceptibility Mapping (QSM), an advanced MRI technique sensitive to iron content, provides quantitative measurements and allows for remarkable visualization of target brain structures of DBS for PD that are difficult to resolve on standard clinical images. The Morrison Lab is developing a pipeline that processes raw patient QSM data to produce a QSM image, and my goal was to test its accuracy. I used ITK-Snap software to create an atlas of regions of interest (ROIs) in PD on a template brain. I wrote a bash script that uses ANTs (Advanced Normalization Tools) to register the template to a patient's T1, register the patient's T1 to their QSM image, and apply the resulting transformations to transform the template ROIs to the patient QSM space. It automatically samples QSM values from each ROI to be compared to reference QSM values from previous studies to analyze the accuracy of the QSM processing pipeline.

### **Design of a Planetary Gearbox and Thruster Test Stand for Bi-Pedal Robots, Achilles and Harpy**

Brittany Wright

*Mentors: Aaron Ames, Adrian Boedtke Ghansah, and Sergio Esteban*

Achilles is a bipedal robot developed by the AMBER Lab as a testbed for advanced walking research. Walking simulations show that the torque supplied to certain locations on Achilles' legs is insufficient for proper movement. To address this, 3:1 planetary gearboxes will be mounted onto these locations. These gearboxes meet specific mass and size constraints and are designed to have low friction and internal stress. This helps improve the gearbox's efficiency and longevity. After the gearbox is manufactured, robustness and holding torque tests are performed to evaluate the effectiveness of the design.

Harpy is another bipedal robot used by the AMBER Lab to study thruster-assisted bipedal locomotion. The thrusters allow Harpy to perform agile motion by offsetting the loads experienced by the legs. To characterize the performance of these thrusters, a test stand is designed to measure the thrust and torque output in response to PWM commands. This allows for a relationship between desired thrust, which is set by the PWM commands, and actual thrust, which is measured by a load sensor, to be established. This relationship aids in the use of model-based control, whereby Harpy's motion may be predicted from input PWM commands.

### **Hydrogel Infusion Additive Manufacturing (HIAM) of Oxide Dispersion-Strengthened and Anisotropic Alloys**

Anna Wu

*Mentors: Julia Greer, Thomas Tran, and Wenxin Zhang*

Hydrogel infusion additive manufacturing (HIAM) is a novel additive manufacturing (AM) technique that allows more versatility in the metal and metal oxide lattices fabricated. Hydrogels are infused with metal salts and undergo calcination to form a metal oxide and then reduction to form a metal lattice. In previous studies, a reducible (Cu) and an irreducible metal (Y) oxide were chosen to form oxide dispersion-strengthened metal alloys such that nanoparticles of the metal oxide phase will provide structural reinforcement to the metal matrix, improving mechanical strength of the system. The main challenges were the high pore fraction and inhomogeneity of the samples due to trapped air and reduction from two different oxide phases. In the first part of this

investigation, the thermal treatment process is tuned to separate the effects of reduction and sintering to allow better understanding of when each microstructural feature such as porosity and grain growth occurs. Cu-Y and Cu-Al systems are explored to test the hypothesis of bimodal grain size distribution because of Cu reducing from two different Cu oxide phases. In the second part of the investigation, by taking advantage of inhomogeneity of different compositions, anisotropic alloys were created as a time study through a two-step infusion process. Where the hydrogels are first swelled in  $\text{Cu}(\text{NO}_3)_2$  and then swelled in nitrate solutions of the following nominal compositions:  $\text{Cu}_{98}\text{Y}_2$ ,  $\text{Cu}_{50}\text{Ni}_{50}$  or  $\text{Cu}_{50}\text{Co}_{50}$  for different amount of time. This allows study of the composition profiles across the bulk of the sample to understand how local microstructure is affected. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) reveal bimodal grain size distributions for Cu-Al ODS alloys and an increase in %alloying phase from the sample center to sample edge for alloys created using two-step infusion method. Future work will focus on continuing to optimize thermal treatment profiles for improving densification of ODS alloy and controlling where an interface occurs in anisotropic alloys.

### **Study of Fusion Rules of Defects in Topological Phases Using Category Theory**

Linqian Wu

*Mentors: Xie Chen and Wenjie Ji*

It is known that fusion processes exist among quasiparticles in trivial or nontrivial topological phases. From the holographic perspective, these quasiparticles are regarded as 0d defects in a nD phase. Analogous to quasiparticles, defects of higher dimensions can also be fused into (the superposition of) new defects of the same dimensions. Moreover, phases of lower dimensions can be regarded as defects of higher dimensions, which on the other hand means defects of lower dimensions can exist in or between defects of higher dimensions. We explicitly calculated fusion results in 2+1D trivial system with global symmetry and 2+1D toric code, especially those of two 1d defects each with or without 0d defects, using the condensation completion approach in the language of category theory. Comparing these results with those from the physical approach recently proposed by Chen et al., we precisely matched categorical and physical descriptions. In these cases, the precise correspondence between "non-integer coefficients" and algebraic data (module maps, etc) in higher categories was conjectured. Higher dimensional cases such as 3+1D toric code is being studied as well.

### **Constructing Si-Centered Chirality With Biocatalytic Carbene Transferases**

Sophia Wu

*Mentors: Frances Arnold and Ziqi Li*

Silicon-centered chirality is a significant synthetic challenge in pharmaceutical chemistry. Traditional methods often involve harsh conditions and extensive use of toxic chemicals. Here, we present an engineered carbene transferase, derived from a bacterial cytochrome P450, that is capable of catalyzing Si-centered chirality formation with high efficiency and selectivity. Initial screening identified a promising variant, which was further optimized through site-saturation mutagenesis, resulting in the final P411 variant capable of producing chiral tertiary silanes with an enantiomeric excess of 89%. The construction of fully substituted silicon-centered stereocenters with phenyl, ethyl, and methyl groups highlights the enzyme's remarkable selectivity. A comprehensive substrate scope study demonstrates the biocatalyst's compatibility with diverse steric and electronic properties of aryl substituents, structural diversity of dialkyl substituents beyond methyl-ethyl, and trialkyl substituted silanes. This biocatalytic method offers a sustainable alternative to conventional chemical synthesis, providing a valuable tool for the production of chiral silicon-based pharmaceuticals.

### **Predicting Windowed Power Spectrum for the SPHEREx Inference Pipeline: A Deep Learning Approach**

Tianrui Wu

*Mentors: Olivier Doré, Chen Heinrich, and Henry Gebhardt*

We develop a neural network-based approach to predict the impact of window functions on cosmological power spectrum (PS) measurements, enhancing the precision of the cosmological parameter inference pipeline for the upcoming SPHEREx survey. Leveraging the ResUNet convolutional neural network architecture, the model accurately predicts windowed PS multipoles from non-windowed ones. The training and testing datasets are derived from simulated lognormal mock catalogs that incorporate SPHEREx survey masks, with PS measurements obtained through the Yamamoto estimator. Preliminary results demonstrate the model's capability to accurately reproduce the window function effects with significant precision. Future work will extend these methods to bispectrum modeling, deepening our insights into the early universe's inflationary dynamics.

### **A Rapid-Response System for Mapping Earthquake Surface Fractures Zones Using UAVs and Deep Learning**

Frank Xiao

*Mentors: Zachary Ross and Zhiang Chen*

Efficient and accurate mapping of complex surface fractures after earthquakes is essential for advancing earthquake research and improving rapid response efforts. However, current InSAR methods struggle with decorrelation where displacements exceed the radar wavelength. Additionally, finer fractures may erode and

change with afterslip, motivating the need for rapid and accurate data collection. We propose deploying autonomous UAVs with edge computing capabilities as a solution to these challenges. By leveraging UAV camera systems, we propose and train deep neural networks to enable the probabilistic 3D reconstruction of damage zones on a digital elevation map. Additionally, we implement a finite state machine framework leveraging both autonomy and human-robot interaction to improve system robustness and enable a spline-based trajectory planner. Using UAV data from recent earthquakes in California and Turkey, we demonstrate in simulation the capabilities of UAVs to perform accurate autonomous on-board decision making and accurately estimate the damage zone of a given earthquake through visible faults, and plan to do the same on hardware at Ridgecrest. We aim to significantly improve the accuracy and speed of earthquake damage assessment, thereby aiding in disaster response and scientific efforts.

**Uncovering the Neural Mechanisms of *Drosophila* Odor Formation: A Study of Early Life Olfactory Sense Modification Process With a Chronic Natural Odor**

Zihang Xiao

*Mentors: Elizabeth J. Hong and George Barnum*

Like humans, olfactory experience in early life can alter how *Drosophila melanogaster* behaves towards odors later in life. Understanding how early life experience affects olfactory function provides insights into understanding the development of the nervous system and the role of the sensory environment in shaping this process. Prior work showed that chronic exposure to natural odors increases the attraction of flies to familiar odors when measured in a free-walking assay. However, the neural mechanisms that mediate this increase in attraction are known. Here, we optimized a tethered treadmill setup for flies, to replicate the same upwind attraction in transgenic flies that enable two-photon imaging of defined neural populations. Additionally, we use the same flies to investigate the contribution of dopaminergic function to odor experience-dependent plasticity.

**Improve the Design of Non-Orographic Gravity Wave Parameterization**

Xiaoyang Xie

*Mentors: Tapio Schneider, Zhaoyi Shen, and Dennis Yaturin*

Gravity waves are waves generated in a fluid medium or at the interface between two media when the force of gravity or buoyancy tries to restore equilibrium following certain perturbations. They are crucial to the climate system, yet their small scales and short periods present challenges for resolution in global climate models (GCMs). Consequently, we need to employ parameterization schemes to capture these physical processes. At CliMA, people are trying to incorporate the influence of gravity waves into atmospheric models. My research project aims to improve the design of non-orographic gravity wave parameterization. Firstly, I refactored the entire code for non-orographic gravity wave parameterization to reduce excessive memory allocations and ensure compatibility with GPU processing. The next phase involves optimizing the parameterization based on mathematical derivations and the physical processes that generate gravity waves. The optimization process begins by removing invalid or physically constrained gravity waves from the spectrum before computation. Additionally, the gravity wave parameterization will be coupled with convection parameterization. As convection is a key source of gravity waves, the model's accuracy is expected to improve by integrating these processes.

**Enhancing Electoral Predictions With LogisTiCC Models: Analyzing Senate Election Dynamics**

Allison Xin

*Mentors: Jonathan Katz and Daniel Ebanks*

This research project aims to improve the accuracy of electoral predictions by utilizing the LogisTiCC (Logistic-Student t with Contemporaneous Correlation) model within the ElectIt package. The primary objective is to address the complexities and nuances of Senate elections by applying advanced Bayesian hierarchical modeling techniques. The methodology involves constructing models that account for contemporaneous correlations and varying electoral dynamics, incorporating factors such as missing data, uncontested races, and custom priors. Initial results indicate that the LogisTiCC model significantly enhances predictive accuracy compared to traditional approaches. The principal conclusion highlights that incorporating contemporaneous correlation improves the robustness of electoral predictions. Recommendations for further research include exploring additional modeling features and expanding the application to other electoral contexts to validate and refine the approach.

**Exploring Meteorological Contributions to Wildfires in Different Parts of the World and Enhancing Global Wildfire Prediction Using Machine Learning Techniques**

Yi Xiong

*Mentors: Yuk L. Yung, Yuan Wang, and Minghao Qiu*

Nowadays, with the increasing impact of climate change, the probability of wildfires is rising due to extreme weather conditions. Due to the nonlinear and spatially variable relationship between human and natural factors and wildfire occurrences, predicting wildfires remains challenging. After visualizing global wildfire conditions from 2002 to 2023 using the open fire dataset from GWIS, we selected nine representative parts of the world for separate analysis. Our initial findings illustrate that the correlations between the total annual burned area and both the

annual number of wildfires and the average burned area vary across regions, which indicates that the contributions of the latter two to the overall burned area differ among different areas. Therefore, we plan to select regions with significant increasing or decreasing trends in the annual number of events and use machine learning methods to build region-specific fire models. These models will quantify how each meteorological factor contributes to wildfire dynamics, thereby affecting the total burned area in different parts of the world.

### **Investigation of Resonance-Stabilised Radicals by Cavity Ringdown Spectroscopy**

Amy Xu

*Mentors: Mitchio Okumura and Zachary Auvil*

Resonance-stabilised radicals (RSRs) have relatively long lifetimes and high concentrations, and are therefore prevalent and significant in both our atmosphere and in interstellar medium.  $\pi$ -conjugated systems have particularly high resonance stabilisation energy. In interstellar medium, they are proposed to be the primary precursor for forming benzene and other polycyclic aromatic hydrocarbons through various self-reactions, as well as heterocyclic rings, which are the basic building blocks of pre-biotic molecules, through reactions with cyanide compounds.

In this work, we aim to use a homemade pulsed laser photolysis cavity ringdown spectroscopy (PLP-CRDS) system to detect the presence of certain RSRs, analyse their spectrum, and investigate their kinetics. Radicals are generated *in situ* in a gas reactor cell by photolysis before being probed by CRDS, a highly sensitive technique. By changing either the wavelength of the probe laser or the time delay between photolysis and probing, spectroscopic or kinetic data can be taken respectively. Previous work has investigated the 1-methylallyl and 2-methylallyl radicals; further work includes pentadienyl and hydroxypentadienyl radicals, as well as the hexadienyl radicals, as the final intermediates in the pathway to benzene formation.

### **Sub-GeV Direct Dark Matter Detection: Improving Phonon Collection Efficiency in Phonon-Mediated Kinetic Inductance Detectors Using Simulations and Analysis**

Emily Xu

*Mentors: Sunil Golwala, Brandon Sandoval, and Osmond Wen*

Unsuccessful searches for dark matter for masses above 1 GeV have motivated the development of technologies that can probe deposited dark matter masses on the meV-eV scale. Phonon-mediated Kinetic Inductance Detectors (KIDs) are well suited to read out phonon vibrations in sub-eV resolutions. Each KID is a superconducting thin film patterned to include an interdigitated capacitor and a thin meandering symmetric coplanar inductor. When low-energy depositions occur on the substrate, phonons are generated, breaking Cooper pairs in the resonator. This increases inductance and lowers the resonance frequency of the KID. The phonon collection efficiency observed is currently below 1%, and this SURF aims to increase this by changing the KID geometry to include thin-film quasiparticle-trapping fins and redesigning the KID box. We replace the physical contact between the KID and the gold-plated copper frame with wire bonds to decrease phonon loss through the conducting frame. By adding aluminum quasiparticle-trapping fins to the KID, we increase the phonon collection area to direct more phonons to the inductor where they can break Cooper pairs. Using the RF simulation software Sonnet, we observe how changes in geometry affect the current density through the KID and changes in the resonance frequency and quality factor.

### **Enhancing Gross Primary Productivity Estimation Through Solar-Induced Chlorophyll Fluorescence in Urban Vegetation**

Wenleyuan Xu

*Mentor: Yuk L. Yung*

Solar-induced Chlorophyll Fluorescence (SIF) serves as a reliable proxy for photosynthesis, given its proven linear relationship with gross primary productivity (GPP) in empirical studies. SIF effectively illustrates the energy allocation within photosynthesis and facilitates the remote monitoring of GPP on a large scale, reflecting the physiological state of plants and their responses to environmental changes. This capability is instrumental in studying the carbon and water cycles within terrestrial ecosystems. In this study, we focus on urban vegetation in the Los Angeles (LA) basin, utilizing data from the California Laboratory for Atmospheric Remote Sensing - Fourier Transform Spectrometer (CLARS-FTS). We compare the retrieved SIF data with GPP measurements to deepen our understanding of urban vegetation dynamics. Moreover, we address the significant impact of aerosols and solar geometry on SIF by employing a state-of-the-art atmospheric radiative transfer model 2S-ESS (Natraj et al. 2023) with aerosol information from AERONET observations in LA. This model helps quantify and correct for the effect of urban aerosol scattering on the SIF retrievals from CLARS data, refining our GPP estimates by mitigating aerosol effects.

**Optimization of Multiplexed Induction Memory Circuit**

Ellie Yamada

*Mentors: Kaihang Wang and Bryan Gerber*

T7 RNA polymerase (T7 RNAP) interacts with its pT7 promoter to form an auto-expression positive feedback loop in a bistable circuit with induction memory. Initially, T7 RNAP is transcribed as two separate polypeptides with associated inteins, which splice to produce a functional T7 RNAP. The constitutively expressed extein acts as a "resource allocator" for the other pT7-driven extein. Transcriptional leakage from the auto-expression loop is addressed by setting a threshold with an inhibitor. Three inhibitors were tested at variable plasmid copy numbers: T7 lysozymes, Cas7-11 RNAi, and a dummy site containing multiple pT7 sites to sequester T7 RNAPs. The mature circuit is kickstarted by a pBAD-driven full T7 RNAP, which upregulates the expression of the pT7-driven extein. Multiple versions of the kickstart mechanism were tested with varied ribosome binding site strength and presence or absence of a degradation tag. Mutant regions of the split extein were introduced synthetically using overlap PCR and Gibson assembly. Four orthogonal variants interact independently with mutant pT7 promoters to drive expression of disparate fluorophores in a single reporter plasmid. This multiplexed memory circuit could reduce the cost and volume of inducers required for sustained protein expression or become a biosensor for multiple molecules over time.

**Photogalvanic Effect and Supercontinuum Generation on Ultralow-Loss Germanosilicate Integrated Waveguide**

Hongrui Yan

*Mentors: Kerry Vahala and Kellan Colburn*

The photogalvanic effect enables materials without a second-order nonlinear susceptibility ( $\chi^2$ ) to exhibit second-order nonlinear optical effects. Supercontinuum generation, on the other hand, leverages a material's inherent third-order nonlinear susceptibility ( $\chi^3$ ) to generate higher frequency waves. Both phenomena rely on  $\chi^3$  to produce nonlinear optical effects. Recent developments in fabrication techniques by Prof. Kerry Vahala's group have achieved ultralow-loss devices made from Germanosilicate glass, a material characterized by non-zero  $\chi^3$  but lacking  $\chi^2$ . This project aims to utilize these low-loss, high-quality devices as platforms for higher frequency generation, exploring both the photogalvanic effect and supercontinuum generation to generate UV light from wavelength around 800nm.

**Two-Dimensional Fourier Continuation on Non-smooth Domains With Corners**

Allen Yang

*Mentor: Oscar Bruno*

The "two-dimensional Fourier continuation" (2D-FC) method for constructing smooth biperiodic extensions of nonperiodic functions combined with existing partial differential equation methods have showed great promise in several applications like the Poisson equation and time-domain wave equation within a bounded domain. However, this existing method only works over smooth two-dimensional domains. In this project, we present a means of constructing biperiodic extensions of smooth nonperiodic functions defined over general two-dimensional domains with corners. The boundary regions of the non-smooth domain are first decomposed into the union of overlapping "corner" and "smooth" patches. Once this is done, each patch is transformed into parameter space, simplifying the geometry of the region, and the one-dimensional Fourier continuation method is applied in parameter space to generate extensions that vanish along an interval beyond the boundary. These extensions are then evaluated on the original Cartesian grid with an efficient, high-order, polynomial interpolation algorithm, thus generating smooth biperiodic extensions. The highly precise Fourier series representation can then be computed directly by an application of the two-dimensional fast Fourier transform (FFT). Combined with existing boundary-integral methods, we also demonstrate a use of the revised 2D-FC method by solving the Poisson problem on these non-smooth domains.

**I. Subcellular Visualization of Glycogen in Endothelial Cells and Probing Metabolic Switch to Other Carbon Sources Under Glucose Starvation in Endothelial Cells Using SRS Microscopy;  
II. Highly-Multiplexed Live-Cell Vibrational Metabolic Imaging**

Benjamin Yang

*Mentors: Lu Wei and Rahuljeet (RJ) Chadha*

I. Endothelial cells (ECs) are highly glycolytic and rely on aerobic glycolysis of glucose for most of their energy. Under excess glucose conditions, ECs are thought to store glycogen although there is a scarcity of literature on visualization of glycogen storage in ECs and its role in ECs remains poorly understood. Therefore, in this work, we employ non-invasive stimulated Raman scattering (SRS) spectro-microscopy to visualize subcellular glycogen in ECs using two different glucose isotopologues. We further exploit a genetic target to modulate glycogen synthesis in ECs.

We also investigate the metabolic reprogramming that occurs in ECs under glucose starvation conditions in the absence or presence of glycogen. Our data support that endothelial cells switch to metabolic reliance on glutamine or lactate in place of glucose under glucose-starvation, although cells with glycogen stores require less glutamine



or lactate metabolism. Our data suggest that these alternate metabolites are important for cell growth and proliferation, which may be key during cell migration and angiogenesis. Notably, this data also represents the first live-cell visualization of glycogen and lactate metabolism in ECs.

II. Visualizing subcellular dynamic metabolic changes is valuable in understanding cellular metabolism. However, current methods to image multiple metabolites are limited: fluorescence microscopy is limited by the color barrier and mass spectrometry imaging is highly invasive and incompatible with live-cell imaging. To overcome these challenges, we use non-invasive SRS microscopy to multiplex metabolites in live cells to perform spatial metabolomics in different mammalian cell lines. To the best of our knowledge, this is the largest number of metabolites concurrently visualized in live cells using vibrational imaging and proves a technique capable of advancing the understanding of spatiotemporal dynamics of metabolites in living systems.

### **Text-Alignment for Diffusion-Based Action Recognition**

Marco Yang

*Mentors: Pietro Perona, Markus Marks, and Neehar Kondapeni*

Current state-of-the-art video action recognition models struggle with viewpoint and domain shift across videos, as demonstrated by poor performance on cross-view evaluation protocols on various datasets and benchmarks such as BEAR. Recently, diffusion-based vision models have performed well on object detection, image segmentation, and depth estimation, suggesting that pre-trained diffusion backbones have strong perceptual capabilities. It has also been shown that text-image alignment for the diffusion backbone can improve both single-domain and crossdomain performance. In this project, we aim to utilize the cross-domain, scene-understanding powers of text-aligned diffusion-based perception to overcome the weaknesses of current video action recognition models by extending one such framework (TADP) to videos, generating features for each frame using TADP as input to a transformer-based classification head. We also experiment using feature maps and cross-attention maps from text-to-video diffusion models on the same task to see if they can improve performance over text-to-image models as they have been shown to encode information about motion. We then evaluate our new models on the BEAR unsupervised domain adaptation (UDA).

### **Enhancing Plant Drought Resilience With Engineered Hydrophobic Biofilms for Improved Water Retention**

Nicole Yang

*Mentors: Gözde Demirer and Catherine Griffin*

The increasing frequency and severity of drought stress due to climate change is a major threat to global agricultural productivity. To address this growing concern, we hope to enhance drought resilience in crops by genetically engineering *Bacillus subtilis* biofilms to improve water retention. *B. subtilis* is a bacterium commonly found in the rhizosphere that forms biofilms which are structured communities of microorganisms that adhere to surfaces such as plant roots. *B. subtilis* biofilms have been found to demonstrate a hydrophobic nature, primarily due to the presence of BslA and extracellular polymeric substances (EPS). In this study, we manipulated *B. subtilis* biofilms by targeting BslA, TapA, EpsD, and EpsL. These genes play crucial roles in the biofilm's hydrophobicity and structural integrity. We used plasmid-based transformation and homology-directed repair to knock out and overexpress these genes, followed by characterizing the biofilm phenotype, conducting growth curves, and coculturing engineered strains with *Arabidopsis thaliana* for root imaging. Our preliminary results show successful manipulation of BslA, with ongoing efforts to characterize other strains. This study not only addresses the immediate need for drought resilience in agriculture but also paves the way for future projects aimed at optimizing biofilms for applications in plant-microbe interactions, ultimately contributing to sustainable agricultural practices.

### **Stabilizing Transient Oligomers for Structural Characterization of Skd3**

Vanessa Yang

*Mentors: Shu-ou Shan and Wren Stiefel*

Proper protein folding is essential for cellular survival and proliferation. Molecular chaperones recognize and remediate unfolded, misfolded, or aggregated proteins, allowing the cell to maintain a healthy proteome. Skd3 is a ring-forming mitochondrial chaperone found in humans, with disaggregase and refoldase activities that have been attributed to distinct higher-order oligomer states. However, the mechanism by which Skd3 identifies and interacts with client proteins is poorly understood. Here, we sought to covalently stabilize transient Skd3 oligomers in order to obtain high-resolution cryo-electron microscopy structures of the Skd3 active state. Denatured firefly luciferase was loaded onto Skd3 as a substrate to encourage oligomer assembly, and covalent crosslinkers such as glutaraldehyde were used to capture and stabilize the active refolding state. Mass photometry was used to evaluate crosslinking efficiency and screen for optimal reaction conditions by measuring the relative distribution of Skd3 across its monomeric and oligomeric states. We have identified conditions that improve glutaraldehyde crosslinking efficiency and increase the abundance of stable, soluble Skd3 oligomers. The next steps of this project will require negative stain electron microscopy in order to visualize the oligomers and verify sample homogeneity, a prerequisite for cryo-EM structural characterization.

**Formation of Ultracompact X-ray Binaries in Globular Clusters**

Yi Wei (William) Yang

*Mentors: Kyle Kremer and Philip Hopkins*

Globular clusters are host to a large range of stellar remnants such as white dwarfs (WDs) and black holes (BHs) that undergo dynamical processes connected to a variety of astrophysical transients. Using N-body simulations performed with the Cluster Monte Carlo (CMC) cluster dynamics code, we study the formation of ultracompact binaries similar to observed Galactic (and extragalactic) sources in which a stellar black hole accretes material from a white dwarf companion. These binary systems are prime multimessenger targets, as they are both very luminous X-ray sources and emitters of millihertz gravitational wave sources detectable by the Laser Interferometer Space Antenna (LISA). We find that BH+giant collisions are the primary mechanism through which such systems form. After weighting the N-body models according to the observed properties of local globular clusters, we estimate a BH+WD formation rate of roughly  $60 \text{ Gyr}^{-1}$  in the Milky Way and  $6000 \text{ Gyr}^{-1}$  extragalactic sources out to 20 Mpc. Last, we estimate their gravitational wave strain, and the mass transfer rate and corresponding luminosity using the binary stellar evolution code COSMIC. We predict roughly 6 Galactic sources with X-ray luminosities of  $>10^{34}$  erg/s and 1 ultraluminous source out to 20 Mpc with luminosities of  $>10^{39}$  erg/s.

**Using Spectroscopic Imaging Techniques to Investigate the Dynamics of Weakly-ionized Dusty Plasma**

Zhe Yang

*Mentors: Paul Bellan and Andre Nicolov*

A cryogenically cooled, weakly-ionized laboratory argon plasma contains growing ice grains. Previous research suggests that ice grain morphology have a notable influence on its dynamics. Planar laser-induced fluorescence (PLIF) imaging will be used to map the three-dimensional temperature/density of the argon neutral species within the plasma volume. The correlation between neutral and ice grain maps will be examined across various time scales and plasma initial conditions. These maps will be used to relate thermophoresis and drag forces acting on ice grains to the flow of argon neutrals, thereby identifying the momentum transfer mechanisms within the plasma.

**A Tool for Creating Customized Reference Genomes From VCF Files for Variant-Aware Genomic Analysis**

Jessica Yin

*Mentors: Lior Pachter and Delaney Sullivan*

Constructing reference genome sequences that incorporate specific genetic variations is a key task in genomics research. We present a user-friendly and efficient tool, part of the 'splitcode' program, designed to generate new reference genome sequences in FASTA format. This tool uses information from VCF files, which contain data on genetic variations such as SNPs (single nucleotide polymorphisms), indels (insertions and deletions), and mutations. By incorporating these variations, researchers can create modified genome sequences, such as diploid genomes for F1 hybrids from different mouse strains, or modified reference sequences to reflect mutations observed in cancer samples. Written in C++, this tool is not only easy to install and run but also performs the sequence construction quickly and accurately. We showcase this tool's capability of creating diploid mouse genomes that we then use to perform allele-specific expression analysis on single-cell RNA-seq data from different mouse strains. Altogether, our tool provides an accessible and reliable option for scientists working on projects that require customized reference genomes.

**Smooth Knots With Odd Term of Their Quadratic Conway Polynomial Have Inscribed Trefoils**

Jonah Yoshida

*Mentors: Cole Huguemeyer and Yi Ni*

An *inscribed knot* is formed by first polygonally connecting points lying on a knot  $\gamma$  in parametric order, then closing the path by connecting the first and final points. The *stick-knot number* of a knot type  $K$  is the minimum number of line segments needed to polygonally form some knot with the same homotopy type. For a trefoil, it is 6. Cole Huguemeyer studied the manifold  $M$  consisting of 6 points lying on a triangular prism and found that by intersecting a perturbation of  $M'$ , twisting the top of the prism, with  $Q_\gamma$ , the manifold of 6-tuples of points lying on  $\gamma$ , any analytic knot with nontrivial quadratic term of its Conway polynomial has an inscribed trefoil. We show that by using a perturbation of the double-cover of the orientation class  $[M \cap Q_\gamma]$  and analysis of planar configurations, an analogous result holds for a class of smooth knots. We also show that in the analytic case, both inscribed left and right-handed trefoils may be found.

**Biochemical Validations of the *Chaetomium thermophilum* Nup120-Nup37-ELYS-Nup85 Complex**

Emily Yu

*Mentors: André Hoelz and Narek Yousefian*

The nuclear pore complex (NPC) is a large protein complex that permits selective transport of molecules between the nucleus and the cytoplasm. The NPC's outer rings are formed by Y-shaped coat nucleoporin complexes (CNCs) anchored atop both sides of the nuclear envelope. We utilize *Chaetomium thermophilum*, a thermophilic fungus, to understand the binding between the proteins of the Nup120-Nup37-ELYS-Nup85 complex of the CNC. To

understand the residues through which the bindings are mediated, we use size-exclusion chromatography with multi-angle light scattering. While fungal and human CNCs share similar overall structure and shape, there are also architectural distinctions observed across species. Our findings will facilitate the detailed characterization of CNCs from various species which is important for understanding how evolutionary differences have shaped this subcomplex.

### **Visualization and Perception Package for Humanoid Robots**

Hanjiang Yu

*Mentors: Aaron Ames and Lizhi Yang*

The operation of humanoid robots traditionally relies on expensive inertial measurement units or environment-constrained optical tracking systems, necessitating the exploration of more versatile and cost-effective alternatives for robot control and interaction. This project aims to enhance the teleoperation capabilities of the AMBER Lab's humanoid robot, ADAM, by developing an advanced visualization and perception package. The research addresses limitations in current motion tracking systems by integrating Visual-Inertial Tracking (VIO) stereo cameras, Virtual Reality (VR) technology, and innovative software solutions. A VR-based interface using the Oculus Quest 3 headset was developed, enabling operators to view the environment from ADAM's perspective and control the robot with intuitive hand tracking. The system utilizes Unity for VR development and interfaces with ROS for robot communication. The solution is tested in simulation with the MuJoCo library integrated with VR visualization. We explored various approaches to rendering stereo images, ultimately achieving a solution that provides excellent depth perception and low latency. We demonstrate significant potential for improving operator situational awareness and control precision in robotic teleoperation. This research contributes to creating a more robust and versatile teleoperation system for humanoid robots, with potential applications beyond ADAM.

### **Activation Mechanism of Smoothed G Protein-Coupled Receptor**

Ryan Yu

*Mentors: William A. Goddard III and Soo-Kyung Kim*

Smoothed (SMO), a class F G Protein-Coupled Receptor and important member of the Hedgehog signaling pathway, is an oncoprotein implicated in causing basal cell carcinoma. To understand more about its activation mechanism, the precoupled state of SMO with its Gi protein is elucidated through molecular dynamics simulations starting from a Cryo-EM structure. This validates the G protein first theory in which the Gi protein binds to SMO before its ligand, a state that can potentially be a target for drug development. Additionally, ligand binding in each of the two binding sites in SMO during its precoupled state is investigated to explore the effects of binding site and potential SMO activation on this precoupled state.

### **Investigation of the Strain and Light-Induced Effects on the Optoelectronic Responses of Monolayer MoS<sub>2</sub> by Optically Assisted Scanning Tunneling Microscopy and Spectroscopy**

Yi-An Yu

*Mentors: Nai-Chang Yeh and Akiyoshi Park*

Two-dimensional (2D) material, particularly the family of monolayer (ML) semiconducting transition metal dichalcogenides (TMDCs) such as MoS<sub>2</sub>, possess unique electronic and optoelectronic properties that stimulate intense research interest. Notably, the strong Coulomb interaction between electrons and holes in ML-TMDC can lead to the formation of quasiparticles known as excitons. These excitons can cause significant bandstructure renormalization, up to 500 meV, offering a novel method to modify the bandstructure and density of states (DOS) of ML-TMDCs. Furthermore, it has been reported that the exciton concentration increases in strained region. This project aims to investigate novel the light-induced effects on strained ML MoS<sub>2</sub> experimentally by the scanning tunneling microscopy and spectroscopy (STM/STS) and different polarization/orbital angular momentum of light, combined with theoretical computation including density functional theory (DFT) calculation and molecular dynamics (MD) simulation, to understand the effect of strain and light excitation on the local DOS for ML-MoS<sub>2</sub>.

### **Optical Study of Magnetization in a Magnetic Weyl Semimetal**

Nathan Yue

*Mentors: David Hsieh and Dan Van Beveren*

Weyl semimetals (WSMs) host topologically interesting electronic states, including gapless low-energy excitations in the bulk and Fermi arc states on the surface, which are allowed only within materials that break inversion and/or time-reversal symmetries. The latter occurs in magnetic Weyl semimetals (MWSMs) which combine Weyl physics with magnetic phenomena, and in which walls between magnetic domains can introduce topologically interesting defects that may host exotic electronic states localized on domain boundaries. Our previous work on Co<sub>3</sub>Sn<sub>2</sub>S<sub>2</sub> provides evidence of such states, but in order to confidently attribute these results to Weyl physics it is necessary to rule out other effects, e.g. domain-induced sample demagnetization. In this project we use spatially-resolved, single-spot Kerr rotation to quantify such demagnetization of the sample due to domain formation, providing a correction necessary to accurately attribute electronic effects to the domain walls themselves.

### **The Origin Story of the Enigmatic Double Peaked Supernova, SN 2022hgk**

Gene Yun

*Mentors: Mansi M. Kasliwal and Kaustav K. Das*

In this project, I analyze the lightcurve of an unusual supernova - SN 2022hgk discovered by Zwicky Transient Facility (ZTF). Unlike other normal Supernovae (SNe) that shows a single-peaked lightcurve, SN 2022hgk shows double-peaked lightcurve that are clearly separated. This peculiarity can be described through a separate power source energizing the last burst of energy. Some possible candidates are magnetar, circumstellar medium (CSM), double Ni-distributions. To investigate these possible power source, we utilize Modular Open Source Fitter for Transients (MOSFiT) to adjust parameters and create a possible fit for each candidates. Complete History of Interaction-Powered Supernovae (CHIPS) code has also been used to model and fit for CSM interactions. Fitted lightcurves are then analyzed to find the most likely candidate to create both the peaks of SN 2022hgk. Currently we are in process of creating good quality fits and plots for each candidate and are planning to uncover the origin story of SN 2022hgk.

### **Development of a Synthetic-Cell Based Biological Ink**

Pierre Zeineddin

*Mentor: Matthew Thomson*

We have made progress in making a synthetic cell platform that can sense its environment, select the production of cell free expressible proteins, and release it payload into a liquid and gel environment. Concretely we have a) tested and formed lipid bilayer vesicles known as Giant Unilamellar Vesicles (GUVs) with varying concentrations of several lipid species, b) conducted preliminary testing on pH sensitive lipids as a release mechanism, as well as c) encapsulated our vesicles in a variety of biological hydrogel materials.

For further research and design testing, we envision environmental sensing with a calcium concentration dependent system, where piezo1, a mechano-sensing transmembrane protein will filter in selective amounts of calcium; an interior calmodulin-transcription factor system converts concentration signals to specific gene expression patterns. To release our proteins after transcription, we have researched an underused yet effective pore protein Perforin, a larger variant of the pore forming toxin  $\alpha$ -Hemolysin. We anticipate this protein's advantages to be threefold: it will i) be formed only after the necessary proteins synthesize in the synthetic cell, ii) will enable proteins to freely pass into the exterior while keeping ribosomes, DNA within the system, and finally iii) will remain trapped in the vesicle's lipid bilayer, allaying concerns of cytotoxicity (with detergent micelles being the only method of removal from their firm embedding). We hope that this design platform will enable researchers, engineers to design experiments that delve deeper into specific cell secretion patterns (among other topics), therapies to regrow damaged or previously deemed irreparable tissues in the human body such as cartilage or even one day brain tissue.

### **Investigation of the Mechanical Behavior of Locking, Quasi-Locking, and Non-Locking Chains**

Eloise Zeng

*Mentors: Chiara Daraio, Wenjie Zhou, and Sujeeka Nadarajah*

Polycatenated Architected Materials (PAMs) represent a new class of materials comprising of topologically interlinked particles, such as rings, polygons, and polyhedra. The mechanical properties of PAMs can be extensively tuned by altering the contact mechanics between individual particles. This study aims to introduce metastability into PAMs through the parametric design of inter-particle contact geometries. These geometries enable a transition between a flexible state, where certain kinematic degrees of freedom are preserved, and a locked state, which restricts any kinematic movement. In this study, we explore two distinct configurations of 1D PAMs, namely the locking chain and the quasi-locking chain, and compared their performance against a conventional non-locking chain. Each chain variant is additively manufactured using thermoplastic polyurethane (TPU), with one set featuring a rough surface and the other a smooth finish. The locking chain exhibits a unique mechanical response; under tensile load, it transitions into a rigid state akin to a solid rod, maintaining rigidity even under lateral shaking. The quasi-locking chain exhibits a similar behavior; however, its links only gently lock into place and can loosen when shaken. In contrast, the non-locking chain behaves like a typical chain, exhibiting no locking behavior. Experimental analyses, including tensile, compression, and three-point bending tests, were conducted using the Instron 3000 apparatus at variable loading rates. These tests facilitated a comprehensive evaluation of force-displacement behaviors, energy dissipation characteristics, and the sequential locking of links. The experimental data sheds light on the influence of particle geometry and surface finish on the overall mechanical behavior of the chains. The findings suggest that the locking and quasi-locking chains have potential for applications in robotics and adaptive structural systems, marking a promising avenue for future technological integrations.

**A Machine Learning Approach to Retrieve Aerosols From Orbiting Carbon Observatory-2 Measurements**

Antong Zhang

*Mentors: Yuk L. Yung and Jiani Yang*

Anthropogenic activities have caused atmospheric carbon dioxide concentrations to increase drastically. To ascertain the pace at which our planet is heating, it is imperative to acquire accurate measurements of CO<sub>2</sub>. The raw values of column-averaged dry air mole fraction of CO<sub>2</sub> reported by the Orbiting Carbon Observatory (OCO-2) contains substantial biases due to the challenge posed by aerosol light scattering effects. Here we use a novel two-step machine learning approach to retrieve aerosol parameters from OCO-2 observations, which can then be used to improve CO<sub>2</sub> retrievals. We studied several orbits in the African and Middle Eastern region and our results show a significant improvement compared to the operational OCO-2 Level-2 retrieval. The model has applications for scenarios with large concomitant emissions of CO<sub>2</sub> and aerosols, such as megacities and volcanos, enhancing the reliability of global space-based CO<sub>2</sub> emissions monitoring.

**Development of a Wearable Sensor for Real-Time Monitoring of Chronic Wound Biomarkers**

Charlotte Zhang

*Mentor: Wei Gao*

The objective of this research project is to develop a non-invasive wearable patch capable of assessing wound healing by measuring key biomarkers in real-time. We aim to monitor parameters including pH, temperature, and hydrogen peroxide concentrations, as these are important indicators of infection, metabolic status, and inflammation in chronic wounds. This project focuses on creating a multiplexed bioaffinity sensor array to detect multiple inflammatory and physiological biomarkers in the wound bed. The outcome could improve wound management, enhance patient health, and potentially reduce healthcare costs.

To achieve this, the sensor will be fabricated using an electrochemical deposition approach based on an inkjet-printed carbon electrode. The sensitivity and stability of each electrode material will be evaluated using amperometric and potentiometric methods to determine the optimal choice. Following the selection of the electrode material, the sensor will be designed and optimized for detecting skin pH, temperature, and ion concentrations. Various sensing materials and configurations will be tested to enhance the sensor's performance and accuracy. Future advancements could involve integrating drug agents within the sensing platform to create a multifunctional closed-loop system for monitoring and treating chronic wounds.

**Achieving Dosage Compensation With Tunable Protease-Based Incoherent Feed-Forward Loops**

Evan Zhang

*Mentors: Michael B. Elowitz, Andrew C. Lu, and Lukas Moeller*

Gene dosage compensation is a mechanism used by nature to maintain balanced protein expression despite variations in gene copy number between cells. The incoherent feed-forward loop (IFFL) motif, which uses two competing activating and repressing regulatory pathways to control a downstream target's expression levels, can provide a simple mechanism for synthetically inducing dosage compensation in cells. Recent work has shown that dosage compensation can be achieved using IFFL designs that operate on the transcriptional or post-transcriptional level. However, it has not yet been shown that an IFFL which operates at the protein level can also induce a dosage compensation effect. Here, we present a protease-based IFFL protein circuit that can induce dosage compensation in HEK293 cells. Furthermore, we show that these circuits can be delivered to cells as mRNA transcripts and can be easily modified to tune the target protein's expression level. Overall, these results provide the foundation for an alternative dosage compensation mechanism that has applications in synthetic biology and gene therapy.

**Engineering Exotic Quantum Phases in Twisted Bilayer Graphene Through Floquet-Induced Topological Manipulations**

Hongu Zhang

*Mentors: Gil Rafeal, Iliya Esin, and Gal Shavit*

Van der Waals (vdW) materials, characterized by their layered structures, have revolutionized materials science by enabling the creation of novel materials with tailored electronic, optical, and magnetic properties. Twisted bilayer graphene (TBG) stands out due to its unconventional superconductivity at "magic angles," making it an ideal platform for exploring strongly correlated phenomena and quantum materials. Floquet engineering, which uses time-periodic fields such as lasers to dynamically alter a material's topological properties, has emerged as a powerful technique. This research focuses on leveraging Floquet engineering to stabilize Fractional Chern Insulators (FCIs) in TBG. We aim to elucidate the conditions under which these exotic phases can be realized. Through numerical simulations and analytical methods, we investigate the electronic band structure of TBG under periodic driving fields. By solving the time-dependent Schrödinger equation and using the Magnus expansion, we derive the effective Floquet Hamiltonian and will identify indicators of FCI states, derived from the Berry curvature and Fubini-Study metric. This study could provide a theoretical foundation for future experimental efforts to observe and utilize these exotic states, advancing the understanding of quantum materials and their potential applications.

### **Investigation of Transition Metal Oxides as Catalysts for Electrochemical Oxidation of Methane to Methanol in Membrane Electrode Assembly**

Ruijia Gabo Zhang

*Mentors: Chengxiang Xiang, Sol A. Lee, and Yong Kim*

Methane is a greenhouse gas that is 80 times more potent than carbon dioxide. In 2021, the largest annual increase in methane was observed. Electrochemical conversion of CH<sub>4</sub> is a sustainable pathway to upgrading methane into value-added liquid fuels (CH<sub>3</sub>OH, C<sub>2</sub>H<sub>5</sub>OH). However, the low solubility of methane in aqueous electrolytes poses a significant challenge, limiting mass transfer and hindering large-scale production with high current density. In this project, we investigate an electrochemical oxidation approach with transition metal oxide catalysts to efficiently and selectively convert methane into methanol (CH<sub>3</sub>OH). Gas diffusion electrodes act as anodes and are prepared by spray-coating metal oxide catalysts on a porous substrate such as carbon paper. We screened various catalysts in an H-cell to identify the one that produces the highest amount of methanol. The most promising catalyst was then further optimized. We introduce a membrane electrode assembly cell with the selected catalyst to enhance yield and rate of methanol production. Future studies will focus on increasing methanol selectivity by examining various controllable factors, including anode preparation (e.g., the ionomer concentration in the catalyst spray solution, the amount of catalyst loading, the catalyst deposition method) and operational conditions (e.g., electrolyte solutions, cell pressure).

### **Floquetifying the Domain Wall Color Code: Low Weight Parity Checks for Biased Noise**

Christine Zhang

*Mentors: John Preskill and Nathanael Tantivasadakarn*

Noise in physical systems that perform quantum computation often have certain structure, such as the dominance of dephasing noise in bosonic systems encoded in the so-called cat code. Error threshold is a decoder-dependent upper bound on the physical error rate such that the logical error rate scales down as system size, or distance of the code grows larger. In this work, we explore the possibility of making a sequence of weight two parity checks that dynamically generates a set of stabilizers which achieve a higher threshold under biased noise. This is inspired by the domain wall color code, which turns the decoding of error syndrome into an effective one dimensional problem that resembles the classical repetition code. In our approach with Floquet codes, we use the CSS honeycomb code under a set of local Hadamard rotations. Preliminary results show improvement after this change of basis. Possible extensions to the work includes finding bias preserving gate sets to maintain this high threshold, as well as looking for inspirations from constructions such as fiber bundle code with twisted geometries to increase the effective distance.

### **The Role of Sediment Cohesion on the Threshold Shear Stress and Entrainment Rates of Muddy Rivers**

Jonathan Zhao

*Mentors: Michael Lamb and Maria Schmeer*

Understanding the mechanisms of sediment entrainment by river flows is critical for predicting riverbed evolution and managing sediment-related environmental challenges. For flowing water to entrain and transport sediment, it must have a bed shear velocity that exceeds a threshold shear stress, which is dependent on a complex interplay of factors, such as grain size, cohesive properties, and the presence of organic matter. Despite a majority of meandering and braided rivers banks containing a significant fraction of cohesive clays, the role of clays on bank erosion is not well understood, and previous studies conducted primarily using triaxial shear tests have been inconsistent. This project aims to isolate the role of kaolinite clay with an average diameter of less than a micron on both the threshold shear stress and the entrainment rate of sand-clay mixtures with various clay fractions. In contrast to the previous studies, we replicate the shear stress exerted by moving water on a sediment bed using a motor driven PVC mill, in which the circular flow of the water will deliver a known shear stress to the underlying sediment bed. We measure the lux of our light source passing through the water as a proxy for the turbidity, indicating the amount of sediment that has been entrained. The threshold shear stress of the sediment is characterized by a pronounced increase in sediment concentration with a small change in the applied shear stress. We measure the entrainment rate by sampling the turbid water for sediment concentration each time the system reaches a steady state for select shear stresses. We define the steady state to be when the entrainment rate is equal to the settling rate, and the settling rate can be obtained by measuring the increase in light intensity after the motor is turned off. Preliminary observations indicate a peak in strength with clay fractions between 25% and 50%, although results are inconclusive and vary due to a heavy dependence on initial conditions of this dynamical system.

### **Investigating the Role of Cold Circumgalactic Gas in Galaxy Star Formation With the IllustrisTNG Simulation**

Zhiyi Zheng

*Mentors: Lars Hernquist, Scott Lucchini, and Rana Adhikari*

The presence of cold gas in the CGM (circumgalactic medium), characterized by a temperature below 10<sup>4.5</sup> K, indicates a ready supply of material that can be accreted onto the galaxy, replenishing its gas and sustaining star

formation over time. In this project, we utilize the high-resolution TNG50 magnetohydrodynamic simulation in the IllustrisTNG project, alongside the AREPO Voronoi tessellation-based algorithm, to investigate the role of cold gas clouds within a Milky Way-like galaxy at a low red-shift range ( $z \approx 0.5$  to  $0.25$ ). Our analysis focuses on the causal relationship between the number of cold clouds and the star formation rate, aiming to provide insights on how cold gas influences key processes such as star formation and its subsequent impact on galaxy evolution. Preliminary findings suggest that the star formation rate is predictively linked to changes in the number of clouds as a function of redshift. We plan to further characterize this correlation by examining the evolution of cold cloud radial positions, as well as the impact of galaxy merger events on the abundance of cold clouds.

### **Modeling in the Multi-Stage Stern–Gerlach Experiment by Frisch and Segrè for the Study of Nonadiabatic Spin Transitions**

Boyan Zhou

*Mentors: Lihong V. Wang and Kelvin Titimbo*

The Stern-Gerlach (SG) experiment, pivotal in quantum mechanics, demonstrated the quantization of angular momentum and electron spin. The multi-stage SG experiment by Frisch and Segrè explored spin flip fractions in potassium atom beams under magnetic fields generated by a current-carrying wire. Using the co-quantum dynamics (CQD) theory, we modeled this setup, simulating electron and nuclear magnetic moment dynamics. Our numerical simulations aligned with experimental data for beam paths near the wire but diverged at greater distances, suggesting either experimental inaccuracies or the need for CQD adjustments. This research employed various numerical modeling techniques to fit the experimental data, aiming to refine the CQD theory or identify uncertainties in the original experiment.

### **Leveraging ML Techniques to Identify and Classify SEP Decay Phases in Time-Series Flux Data From NASA's ACE/SIS Instrument for Inferred Charge State Candidates**

Jeffrey Zhou

*Mentors: Allan Labrador and Ashish Mahabal*

Solar Energetic Particles (SEPs) are a significant phenomenon in space weather research, as they are not only capable of disrupting infrastructure on Earth, but also provide insights into solar phenomena through their ionic charge states. Although NASA's Solar Isotope Spectrometer (SIS) does not measure charge states directly, mean states can be inferred using a technique pioneered by Sollitt et al. (2008), given extended time periods of well-behaved, exponential decay profiles in particle flux. Current methods for extracting these decay profiles for charge state inference involve manual and semi-automated algorithms that are time-consuming, susceptible to noise in the data, and are prone to implicit bias. We leverage machine learning techniques, specifically Multilayer Perceptron (MLP) classifiers and regressors, as well as time-series analysis with Long Short-term Memory (LSTM) based recurrent neural networks to streamline and improve the accuracy of identifying SEP decays and their decay constants. Initial efforts to develop a sliding window algorithm to aid in the creation of a candidate dataset for MLP training yielded exceptional results. We present a novel methodology for automated elemental flux decay phase classification, improving efficiency of SEP charge state inference, and eliminating the need for manual fitting.

### **Modeling the Circularization and Concatemerization of Double-Stranded Deoxyribonucleic Acid Molecules**

Jinhuang (Jin) Zhou

*Mentors: Kaihang Wang and Jianyi Huang*

Plasmids, circular double-stranded Deoxyribonucleic Acid molecules (dsDNA), are widely used in research for procedures such as molecular cloning. In the last step of plasmid construction, namely the circularization of dsDNA through ligation, a single dsDNA can either circularize, by binding with itself, or concatemerize, by binding with another dsDNA. At low concentrations and short lengths of dsDNA, concatemerization, the formation of concatemers, is not a problem; however, at higher concentrations and longer lengths, concatemerization becomes a problem. This work seeks to understand the relationship between the length and concentration of dsDNA and its effects on the probability of circularization and concatemerization through the use of computer simulations and mathematical modeling. On one hand, we calculate the probability of circularization and concatemerization independently. While on the other hand, we calculate the probabilities of circularization and concatemerization together in one model. In addition, we use oxDNA, a coarse-grain model of dsDNA, to more realistically simulate circularization and concatemerization. Future work should improve upon current models and verify the results with real world circularization experiments.

### **Unsupervised Machine Learning for Analysis of Young Star Photometric Light Curves**

Karen Zhou

*Mentor: Lynne Hillenbrand*

Time series data such as stock market prices in finance or light curves in astronomy present a notoriously challenging problem in machine learning. Spectral clustering is a type of unsupervised machine learning that transforms data points into a graph structure where each point is a node and edges represent the similarity

between nodes. We apply spectral clustering to the normalized flux of light curves in the Upper Scorpius and Taurus clusters in the K2 and TESS datasets to obtain a nuanced understanding of stellar variability and characteristics beyond those available using standard lightcurve metrics. We utilize quantile graphs for dimensionality reduction, capturing the general motion of the light curves while remaining robust to attributes such as amplitudes, period, and phase as well as fluctuations in the data. By applying an unsupervised method to a traditionally supervised task, we aim to uncover novel insights in the light curves.

### **Investigating the Interaction Between the Hantzsch Ester and Sm<sup>III</sup> in the Photodriven Generation of Sm<sup>II</sup>**

Luke Zhou

*Mentors: Jonas Peters, Emily Boyd, and Christian Johansen*

The usage of light to harvest electrons for the reduction of unactivated substrates has motivated investigations into photoreductants with strong excited state reduction potentials. The Hantzsch ester (HEH<sub>2</sub>) is one such photoreductant whose reactive excited state (\*HEH<sub>2</sub>) is accessible by visible light but suffers from a short lifetime, hindering its activity in diffusion-limited reactions. As such, HEH<sub>2</sub> typically requires an interaction with an oxidant for productive electron transfer to occur. Recent work from the Peters group has shown that a hydrogen-bonding interaction from HEH<sub>2</sub> to 2,4,6-trimethylpyridinium sets up electron transfer from \*HEH<sub>2</sub> to 2,4,6-trimethylpyridinium, mitigating the low lifetime of \*HEH<sub>2</sub>. The Peters group has also expanded this strategy towards reducing Sm<sup>III</sup> Lewis acids with \*HEH<sub>2</sub> to generate SmI<sub>2</sub>, a versatile and selective single-electron reductant commonly used in organic synthesis. However, the mechanism by which HEH<sub>2</sub> and Sm<sup>III</sup> generates SmI<sub>2</sub> has not been extensively photophysically characterized. Herein, we report our efforts in investigating the HEH<sub>2</sub>-Sm<sup>III</sup> interaction. Spectroscopic evidence supports a HEH<sub>2</sub>-Sm<sup>III</sup> interaction at the carbonyl functionalities. A Stern-Volmer experiment yields a constant describing the quenching of \*HEH<sub>2</sub> by Sm<sup>III</sup>. Furthermore, addition of I<sup>-</sup> and base to HEH<sub>2</sub> and Sm<sup>III</sup> generates SmI<sub>2</sub> and leads to further fluorescence quenching.

### **Solving Inverse Problems With Low-Rank Gradient Approximation-Based Diffusion**

Rayhan Zirvi

*Mentors: Anima Anandkumar and Bahareh Tolooshams*

Recent advancements in diffusion models have demonstrated their potential as powerful tools for solving inverse problems in various domains. However, these models often exhibit high sensitivity to measurement error feedback, leading to performance degradation and artifact introduction in reconstructed images. We propose a gradient approximation method to enhance the robustness of diffusion models to the choice of guidance hyperparameters in solving inverse problems. Our approach leverages singular value decomposition (SVD) to approximate the gradient in a lower-rank subspace defined by the current (latent) image representation, effectively filtering out artifact-inducing components. We introduce an adaptive rank selection mechanism based on a fixed variance retention threshold, allowing the method to dynamically adjust to the changing complexity of the image representation throughout the diffusion process. We evaluate our method on a range of inverse problems, including box inpainting, random inpainting, super-resolution, and deblurring, using the FFHQ 256 dataset and a pre-trained LDM-VQ-4 model. Our results demonstrate improved robustness to abnormal measurement error feedback while maintaining comparable performance under normal conditions, suggesting a promising direction for enhancing the reliability of diffusion-based inverse problem solvers.



**Mass Spectrometry-Based Bulk and Single-Cell Proteomic Profiling of CB-5083 Resistant Colon Cancer Cells**

Amina Abdalla

*Mentors: Tsui-Fen Chou and Marion Pang*

Cancer is caused by dysfunction of cellular processes responsible for growth, differentiation, replication, and death. The enzyme p97 is an important cancer target as it mediates vital clearance pathways for misfolded proteins. A specific p97 inhibitor, CB-5083, has been shown to induce antitumor activity; however, Phase I clinical trials of the drug were halted due to off-target effects and the emergence of drug-resistant cells. We present a mass spectrometry-based proteomics study probing the proteomic differences between CB-5083 resistant and sensitive colon cancer cells at the bulk and single-cell level. By assessing the cellular proteome changes with and without drug treatment, we aim to elucidate the mechanism by which p97 mutations drive CB-5083 resistance, and to discover alternate strategies for treating the resistant cancer. This work contributes to ongoing efforts in assessing the therapeutic utility of p97 inhibitors in cancer.

**Replicating River Morphodynamics: Calibration of Hydraulic and Sediment Transport Parameters in a Laboratory Flume**

Raisha Abubo

*Mentors: Michael P. Lamb, Kimberly L. Miller, and Maria N. Schmeer*

Riverbank erosion play a crucial role in shaping Earth's landscape, affecting a wide range of geologic, ecological, and socio-economic issues. As such, riverbank erosion has been subject to a vast array of studies and applications. However, the inherent complexity of river systems often makes it challenging to isolate the impact of individual factors on river behaviors in the field. To address this challenge, my project utilized a laboratory flume, allowing for a controlled environment where riverbank erosion can be isolated and observed in detail. Here we present the initial hydraulic and geometric conditions and parameters required to simulate a straight river channel eroding through a bank composed of a mud-sand mixture in the flume. We find that to simulate a river channel with an initial width of 20 cm eroding through the bank and maintaining a dynamic equilibrium at a width of 40 cm in the flume, the channel requires a bed slope of 0.003, water discharge of 0.0017 m<sup>3</sup>/s, and a sea level height of 4 cm, to minimize backwater effects. Future work in the lab will apply these initial parameters in experiments to determine the erosion rates of riverbanks composed of various mud-sand mixtures.

**Characterization of Neural Crest-Derived Cells in Newt Tail Regeneration**

Barera Ajaz

*Mentors: Marianne Bronner and Miyuki Suzuki*

Iberian ribbed newt can perform complete regeneration of amputated appendages. It has been suggested that when the tail is amputated, the cells adjacent to the amputation plane dedifferentiate into progenitor cells, contributing to the regrowth of the tail. Most spinal ganglia and melanophore cells are derived from neural crest cells in development; however, it is unclear how neural crest-derived cells contribute to regeneration. This project aims to characterize neural crest-derived cells in tail regeneration and examine their necessity for regeneration. Neural crest-derived cells are characterized by double staining of the regenerating tail with neural crest markers (*Sox10*, *HNK1*) and tissue-specific markers (notochord, muscle, melanophore, spinal cord, epidermis) by immunohistochemistry and *in situ* hybridization chain reaction. Live imaging of *Sox10* expressing cells was performed using *Sox10::tdTomato* transgenic newt during tail regeneration. Further characterization of the neural crest-derived cells will be performed by using several neural stem cell markers. After completing cell characterization, neural crest-derivatives in regeneration will be ablated by targeted laser ablation using *Sox10* reporter transgenic newt. We will then observe regeneration to examine the necessity of neural crest cells for complete regeneration, allowing for novel insights into the regeneration process.

**Advances in Terahertz Time-Domain Spectroscopy (THz-TDS): From Carbonaceous Chondrites to Next-Generation Batteries**

Elizabeth Ballmann

*Mentors: Geoffrey Blake and Jax Dallas*

In this investigation, we aim to advance THz-TDS techniques through two interconnected studies. The first project involves developing and constructing an ultra-broadband coherent THz-TDS instrument using spintronic terahertz emitters manufactured at the Kavli Nanoscience Institute. We standardize the performance of these fabricated films by comparing their broadband terahertz emission spectra to that of commercial TeraSpin1 emitters. This system is also utilized to investigate the broadband phonon frequency modes of carbonaceous chondrites from numerous parent sources largely composed of silicates. The second project investigates the optimization of a tunable ultrafast THz spectrometer to probe the low-frequency phononic occupation of compressed powder Li-ion conducting solid-state electrolyte ceramic (LLTO) pellets, which is critical for next-generation of lithium-ion solid-state batteries. Using transmission grating pairs in a THz-TDS system, we generate tunable THz pulses using a Mach-Zehnder interferometer, acquiring variable frequencies and spectral bandwidths spanning the 0.5-7 THz range. These efforts

highlight the adaptability of sophisticated THz spectroscopy in the analysis and characterization of various materials, as well as providing insights for future scientific and technological advances.

**Measuring Power Loss in Millimetric and Submillimetric Wavelengths of Hydrogenated Amorphous Silicon Dielectric of Microstriplines in the Be231102d2 Device Through Fourier Transform Spectroscopy: Data Treatment and Comparison**

Pedro Beron-Vera

*Mentors: Sunil Golwala and Jean-Marc Martin*

The Next-generation Extended Wavelength-MULTiband Sub/millimeter Inductance Camera (NEW-MUSIC) device relies on the use of superconducting slot dipole antennas, coupled to photolithographic bandpass filters. Light picked up by these antennas is then routed to microstripline-coupled, parallel-plate capacitor, lumped-element kinetic inductance detectors (MS-PPC-LEKIDs). Measurements of loss in the microstriplines of these devices are important for understanding how effectively millimetric and sub-millimetric wavelength optical power is being transmitted to the kinetic inductance detectors (KIDs). The Be231102d2 device employs a loss test antenna and an index test antenna. We measure the frequency response of the antenna as well as the microstripline loss over different frequency bands. Fourier Transform Spectroscopy (FTS) is vital in these measurements, therefore we also compare algorithm speed and signal fidelity of different techniques for FTS raw data treatment.

**Modulation of 6-*exo-trig* Cyclization With Neutral Aminyl Radicals in Olefins**

Leonardo Birriel-Rodríguez

*Mentors: Sarah Reisman and Omar Santiago-Reyes*

Piperidines are saturated nitrogen-containing hexacycles whose synthetic derivatives possess a wide spectrum of biological activity, such as anticancer, antiviral, antimicrobial, and antimalarial. A potential strategy to synthesize piperidines is through the 6-*exo-trig* cyclization of an aminyl radical and an alkene. However, there are few reports in the literature of successful 6-*exo-trig* cyclization owing to the tendency of radicals to perform 1,5-hydrogen atom transfer (1,5-HAT). In this project, we propose to study the use copper catalysts to favor 6-*exo-trig* cyclization of alkyl aminyl radicals over 1,5-HAT. Moreover, we wish to develop a methodology for the carboamination of unactivated alkenes, in which the radical intermediate after the nitrogen-centered radical addition into the alkene could react with carbon-based radical traps, such as electron deficient alkenes. The understanding and modulation of the 6-*exo-trig* cyclization will lead to new complex synthetic transformations incapable of being realized through traditional methods.

**Formal Languages, Automata, and Topological Quantum Field Theories**

Luisa Boateng

*Mentor: Matilde Marcolli*

A series of recent papers provided a construction of 1-dimensional topological quantum field theories with defects from finite state automata, which compute regular languages. In this project, we explore the logical properties of subregular languages and their corresponding interpretation in the TQFTs constructed, as well as the next most restrictive class in the Chomsky hierarchy, context-free languages.

**Mechanistic Modelling Unveils an Implementation of Line Attractor Dynamics Based on Long-range Neuropeptide Release and Local Connectivity**

Isabela Camacho

*Mentors: David Anderson and Aditya Nair*

Mechanistic modeling is crucial in theoretical and computational neuroscience as it provides a framework for understanding the causal mechanisms governing neural systems. Unlike empirical models, which rely on statistical correlations, mechanistic models strive to replicate real-world functioning by detailing underlying mechanisms. Our project focused on developing three mechanistic models of line attractor dynamics underlying aggressive behavior in mice: local neuropeptide modulation, long-range neuropeptide release, and a hybrid model combining both. Model parameter tuning suggests that both the local and long-range models fail to accurately approximate the data. Instead, both mechanisms need to be combined for accurate modelling. Our results suggest that hypothalamic line attractor dynamics utilize non-canonical mechanisms to achieve long time-scale integration. Furthermore, they provide specific testable experimental predictions about anatomical connectivity and neuropeptide receptor expression and thus advance our understanding of the neural basis of aggression.

**Assessing the Role of TRPA1 in the Detection of Iridoids in Rove Beetles**

Jenasis Campbell

*Mentors: Joe Parker and Hayley Smihula*

The evolution of species interactions is essential to understanding the evolution of species and biodiversity, however this process is poorly understood on a mechanistic level. Rove beetles are one group that has potential to shed light on how species interactions evolve because they have an abundance of interspecies relationships.

*Sceptobius lativentris* and *Dalotia coriaria* are two species of rove beetle with opposing relationships to the *Liometopum occidentale* ant, in which *Liometopum* preys on *Dalotia* but has developed a symbiotic relationship with *Sceptobius*. These relationships are partially mediated by the beetles' detection of and response to iridoid compounds that *Liometopum* produces for its foraging trails. Here, we assess the role of TRPA1 (transient receptor potential channel subfamily A member 1) in the avoidance or attraction that *Dalotia* and *Sceptobius* respectively exhibit towards iridoids. To achieve this, we genetically manipulated TRPA1 expression through CRISPR and RNAi with the goal of testing the resulting knockout/knockdown beetles in a T-maze behavior assay. Additionally, we designed machine learning models to analyze the behavioral outputs. This work establishes the genetic and analytic groundwork for determining if TRPA1 plays a functional role in the beetles' species-specific behaviors, and more generally, their evolutionarily divergent lifestyles.

### **Progress in Enzymatic Carbon-Carbon Bond Formation With Boronic Acids**

Kamila Cano-Giraldo

*Mentors: Frances Arnold, Deirdre Hanley, and Edwin Alfonso*

Biocatalysis offers a promising avenue for achieving sustainable and selective routes to valuable compounds. Organoboron compounds play a vital role in organic synthesis and catalysis. They are widely available, have notable functional group tolerance, and are non-toxic. Enzymatic conversion of boronic acids to carbon-carbon bonds may offer benefits over chemo-, regio-, and stereoselectivity compared to traditional approaches. My project involved identifying enzymes that convert boronic acids to alkyl compounds through carbon-carbon bond formation. Specifically, heme proteins (proteoglobins) were tasked with transferring carbenes to boronic acids and esters. By systematically screening diverse proteoglybin enzymes and employing substrate walking approaches, we aim to identify novel enzyme variants with activity toward the desired transformation.

### **Numerical Sound-Hard Scattering: Applying the IFGF Method to Neumann Boundary Conditions**

Noah Conner

*Mentors: Oscar Bruno and Sebastian Lamas*

The direct scattering problem seeks the evaluation of the scattered wave for a given incident wave and inhomogeneous medium – a closed surface in our case. Solutions to the direct scattering problem have broad applications in engineering that utilize acoustic and electromagnetic wave theory. The scattered wave can be calculated via the evaluation of particular integral operators; in the case of a complex object, an analytic evaluation is intractable. Thus, it is standard practice to implement numerical methods for these calculations. The interpolated factored green function (IFGF) method is a recent advancement in this area, where it has since been applied to the Dirichlet sound-soft scattering problem. The IFGF method has many advantages over previous methods: a low computational cost ( $O(N \log N)$ ), a small memory footprint, a simple implementation, and the ability to be effectively multi-threaded. In this work, we will develop a novel implementation of the IFGF method for the Neumann sound-hard scattering problem, utilizing two different techniques: differentiation of Chebyshev coefficients and repeated application of the algorithm over several dimensions. We will study the computational costs and errors of both approaches and show that we can retain the original advantages of the method.

### **Examining SynGAP1's Intrinsic Disordered Domain Through an Evolutionary Lens**

Carla D'Amato

*Mentors: Mary Kennedy and Giovanni Juarez*

SynGAP1 is a Ras/Rap GTPase-activating protein (GAP) that has garnered significant attention in spheres of synaptic plasticity research due to its abundance in both human and murine postsynaptic densities (PSDs). Recent studies have shown that the protein's intrinsic disordered domain (IDR), C-terminus coiled-coil domain, and PDZ ligand appear heavily implicated in displacing other proteins (such as TARP- $\gamma$ 8) from PSD-95 clusters; such processes can in turn regulate the size and strength of a synapse during long term potentiation. Furthermore, the Kennedy Lab has generated unpublished data that suggest SynGAP1's IDR plays an important role in the formation of protein condensates at concentrations that exist *in vivo*. To gain greater insight into how the IDR facilitates SynGAP1's protein interactions and function, we have analyzed protein sequencing data from SynGAP1 homologs across vertebrate and invertebrate species to identify how the IDR has evolved over time. By examining both highly conserved regions within the disordered domain, in addition to areas that have changed from organism to organism, we hope to not only gain a better idea of the IDR's role in regulating synaptic plasticity but to also understand the evolution of distinct learning mechanisms in distantly related vertebrates and invertebrates.

### **Engineering Reversible Proliferation Arrest in Mammalian Cells to Uncover the Fundamentals of Multicellular Population Dynamics**

Isaiah Demetri Diggs

*Mentors: Michael Elowitz, Jacob Parres-Gold, and Dhiraj Indana*

Nature's intricate cellular networks showcase a remarkable balance between growth and regulation, inspiring us to unravel the complexities of multicellular systems and harness their principles to advance biomedical solutions. Our goal is to synthesize biological circuits to understand nature's complex and dynamic designs. Building these

synthetic multicellular systems we aim to engineer & test different multicellular circuits experimentally in order to explore the performance and tradeoffs of different designs. Although some multicellular circuit designs have previously been studied through simulations, synthetic multicellular circuits would allow these designs to be studied experimentally, including all the real-life limitations of biological systems. Our study focuses on engineered multicellular systems to control mammalian cell proliferation using proteins p21 and p27, regulated by synthetic signals. We demonstrated that overexpression of these proteins halts cell proliferation, with cells resuming growth after protein removal. Future work will refine protein degradation methods to prevent potential toxicity from their over-expression, as well as inhibiting the mTOR pathway to prevent the growth arrest from leading to cellular senescence. By bridging the gap between theoretical models and practical applications, we can pave the way for innovative solutions in biomedicine and synthetic biology.

### **Towards the Structural Characterization of Predicted Carboxyl-terminal Dimerization Domain of *Giardia intestinalis* Get 5 Like Protein**

Deron Donald Jr

*Mentors: Bil Clemons and Victor Garcia*

Membrane proteins are integral to the function of cells. They facilitate regulatory processes critical for maintaining cellular homeostasis. Notably cell-to-cell communication, vesicle fusion, and apoptosis regulation. Most membrane proteins are transported to the endoplasmic reticulum (ER) by way of the Signal Recognition Particle (SRP) pathway co-translationally. One class of proteins that are exempt from the SRP are TA (tail-anchored) protein due to their C-terminal transmembrane domain (TMD). This property of TA proteins requires them to be transported to the ER post-translationally by way of the Get pathway (guided-entry of TA proteins). The Get pathway is found in all lineages of life. In yeast, the GET pathway is composed of several proteins, Sgt2 a chaperone protein that shields the TA protein, Get4/Get5 a heterodimer that facilitates the handoff of TA proteins from Sgt2 to Get3, Get3 a homodimer responsible for transporting the TA protein to the ER, and Get1/Get2 which are membrane receptor proteins for Get3 that are localized in the ER. Currently, all of our understanding of the GET pathway, both structural and biochemical, is held to only the yeast and human pathways. Recently homologues of the GET pathway were discovered in the organism *Giardia intestinalis*. In this research, we aim to characterize the structure of the predicted Get 5-like homodimerization domain of *G. Intestinalis*. Characterizing this Get 5-like dimerization domain structure will give us insight on how conserved the Get pathway is outside of opisthokonta.

### **A Comparative Physiology of Dipteran Wing Motors**

Marissa Douglas

*Mentors: Michael Dickinson and Samuel Whitehead*

Flight is essential to the evolutionary success of insects. Flying insects obtain food, find mates, and evade predators with great efficacy, through their increased travel distance and speed. For small insects to create lift, they must flap their wings at speeds faster than typical muscles. This is accomplished through asynchronous muscles that fire more than once per neural impulse. These fast motors are well defined in the Dipteran species *Drosophila melanogaster* (common fruit fly). We seek to understand how asynchronous flight muscles evolved by studying a distantly related Dipteran, *Aedes aegypti* (yellow-fever mosquito). Mosquitoes have existed longer than fruit flies and exhibit different wing beat frequencies and wing stroke amplitudes. Through electrophysiological methods and high-speed video recordings, we have found that mosquitoes also have quantitatively different flight motors. Both the muscles that power and that steer mosquito flight fire differently than those in fruit flies. We show that asynchronous flight has mutated over time within insects, and further studies into more species may reveal its evolutionary history.

### **Computational Modelling of a Quantum Ferromagnet**

Matilda Eriksson

*Mentors: Thomas F. Rosenbaum and Daniel M. Silevitch*

Experiments on the magnetic and thermal properties of materials can give useful insight into their quantum nature, but rarely feature spatial resolution suitable for analysis on the microscopic scale. Using Monte Carlo simulation methods, we computationally model the rare-earth ferromagnet Lithium Holmium Tetrafluoride (LiHoF<sub>4</sub>) semi-classically. We are able to probe the system's configurations on a spin-by-spin, spatially-resolved scale. In addition, the simulation calculates local field distributions throughout the sample, which can be used in the analysis of spin glass and spin liquid energetics. Finally, progress has been made towards a full quantum-mechanical treatment of the LiHoF<sub>4</sub> Ising ferromagnet in transverse magnetic field.

### **Exploring Liquid Layer Formation and Ion Cluster Generation in Extreme Water Jet Conditions**

Shiyue Feng

*Mentors: Morteza Gharib and Sean Mendoza*

Research shows that extremely fine, high-speed water jets impacting surfaces can generate ion clusters through triboelectric charging and intense hydrodynamic shear mechanisms. Although the formation of liquid layers by such jets has been widely studied, most studies are limited to larger diameters and lower flow velocities. This study

explores the thickness distribution of these liquid layers under extreme conditions using experiments with stained liquids and grayscale analysis, which is crucial for understanding the dynamics of ion cluster formation. Our experimental procedure consists of three main stages: first, analyzing the radial variation in liquid thickness; second, examining the effect of the jet spray angle on ion cluster shape and comparing it with thickness data; and third, inferring flow field characteristics from thickness measurements to identify regions responsible for ion cluster generation.

Our findings indicate that variations in liquid thickness significantly impact the dynamics of flow fields and ion cluster formation. Ion clusters predominantly form in the initial thin film layer, where shear forces are high, and thickness is low, a condition applicable within a 30-degree spray angle. This research provides valuable insights for optimizing industrial processes and enhancing our understanding of the physical properties of liquid films under extreme conditions.

### **Synthesis and Ring-Opening of Reactive, Biologically Important Aziridines**

Leanne M. Fuentes Ruiz

*Mentors: Brian Stoltz and Elliot Hicks*

Aziridines, which are three-membered heterocycles comprised of one amine group and two methylene groups, are potentially useful intermediates in the synthesis of more complex molecules as a consequence of the reactivity attributed to their ring strain. The presence of the aziridine functional groups in naturally occurring molecules has been shown to result in potent biological activity. Because aziridines contain two potential sites of reactivity, when attacked by a nucleophile their ring opening often yields a mixture of constitutional isomers. However, a key discovery in a recent total synthesis from our group showed that the ring opening can give only one outcome under the correct reaction conditions. This project aims to further research the regioselectivity previously observed by synthesizing simple, analogous compounds and testing their ring opening reactions. Current efforts are focused on synthesizing three aziridine-containing molecules and testing their ring-opening reactions with an array of nucleophiles and electrophiles with the goal of determining if a common regioselectivity exists for most aziridines of this type.

### **Measuring the Electrochemical Characterization of 3-D Architected Electrodes for Li-ion Batteries**

David Goba-Rivera

*Mentors: Julia Greer and Yingjin Wang*

Energy storage devices are essential for many modern technologies, such as smart phones, power grid storage, and electric vehicles. The traditional 2-D slurry batteries struggle to support electric aerial vehicles and long-range electric cars. With improving power density and decreased weight in mind, this project aims to fabricate 3-D batteries whose geometry can be optimized to support the transport of lithium ions. Through additive manufacturing, the electrode was fully configured and subject to hydrogel infusion, transforming the polymer scaffold into a lithium iron phosphate (LFP) lattice, which was then assembled to create a half cell battery. A 2-D slurry was then prepared and assembled in the same manner. By applying Electrochemical Impedance Spectroscopy (EIS), the Nyquist plots created displayed less impedance and a higher rate of Li diffusion for the 3-D batteries. Additional geometries were created and will be analyzed to maximize the battery's performance effectively. These results suggest that 3-D additively manufactured batteries show a promising potential to increase energy storage capabilities.

### **Autonomous Car Kinematics Simulator for the Indy Autonomous Challenge Project Team**

Muskaan Gupta

*Mentors: Soon-Jo Chung and Matt Anderson*

The Indy Autonomous Challenge is a race series featuring self-driving cars running on student-programmed vehicle software. Every team uses the challenge's IAC AV-24 racecar equipped with cameras along with LiDAR and RADAR sensors that enable teams to develop complex autonomous racing software. This summer, I created a kinematics model to simulate and visualize the car's trajectory using Robot Operating System 2 (ROS2) with a C++ backend and a simulation in rviz2. The kinematics simulator subscribes to data outputted from the upstream controller node. It interprets the vehicle commands to calculate the updated position of the vehicle which it publishes to the rviz2 graphical simulation software to display the car's trajectory. Additionally, this update informs future controller action. This simulator supports the preliminary development of the autonomy algorithms before utilizing them on the real race car. Final adjustments include fine-tuning the model towards a goal condition to create a closed-loop model.

### **Psychological Symptoms of Agenesis of the Corpus Callosum in Early Childhood**

Wilder Hartwell

*Mentors: Ralph Adolphs and Lynn Paul*

Agenesis of the corpus callosum (ACC) is a collection of congenital neurodevelopmental disorders in which the bundle of nerve fibers that connects the two hemispheres of the brain is either completely or partially absent. This study compared parent-reported emergence of common behavioral and psychological symptoms in 138 children

with isolated ACC and 235 typically-developing (TD) community-based participants. For two summary scores from the Child Behavioral Checklist (CBCL) - Preschool version, internalizing (problems within the self) and externalizing (social conflict and behavioral problems), the mixed linear effect model showed that symptoms increased with age. The ACC group scored higher than the TD group on some symptom subscales, including withdrawal from social contacts. These results indicate that ACC participants are on par with their TD peers in their overall internalizing and externalizing development, but the ACC group faces greater psychological symptoms in some areas.

**Testing the Coherence of Periodicity in Supermassive Black Hole Binaries**

Alice Heranval

*Mentor: Matthew J. Graham*

Supermassive black hole binaries (SMBHBs) occur in active galactic nuclei (AGN), and emit low-frequency gravitational waves (GWs) that will be observable by the Laser Interferometer Space Antenna (LISA). However, at separations small enough to emit detectable GWs, these binaries cannot be resolved optically. Periodicity in electromagnetic emissions from AGN has been linked to the presence of SMBHBs, but it can be misleading due to the presence of stochastic noise. We aim to identify strong SMBHB candidates by studying coherence times for periodicity in both simulated and real light curves from AGN with the intention of using them to separate real signals from noise.

**Simulation of a Swimming Origami Millirobot Using the Immersed Boundary Lattice Green Function**

Tryphena Ho

*Mentors: Tim Colonius, Caroline Cardinale, and Wei Hou*

The Immersed Boundary Lattice Green Function (IBLGF) is a computational method for simulating fluid dynamics around complex boundaries. It combines the immersed boundary method, which allows for fluid flow simulation around non-conforming geometries, with lattice Green's functions for efficient computation on a fixed Cartesian grid. We use IBLGF to analyze the propulsion mechanism of a magnetically-actuated swimming millirobot developed by the Zhao Lab at Stanford. The primary feature of interest is its unique Kresling origami design, characterized by a hollow hexagonal body with radial cuts along tilted triangular panels. A rotating magnetic field spins the body, inducing an internal flow through cutouts in the body. The mechanisms by which this propulsive flow is created are not well understood. First, we test a non-rotating millirobot in a steady flow to establish a baseline drag force. We then examine how the drag force is reduced, and eventually, thrust is generated as a function of the spin rate. Understanding the fluid dynamics around such a geometry may give us insight into fully optimizing the Kresling pattern—or potentially similar tessellations—for a broader range of applications.

**Autonomous Deployment of a High Packaging Efficiency Inflation System**

Peijuan Huang

*Mentors: Soon-Jo Chung and Matt Anderson*

My team's goal is to create a prototype for the PILLARS (Plume-deployed Inflatable for Landing and Launching Abrasive Regolith Shielding) system that effectively reduces lunar dust impact, enhancing the safety and functionality of the Artemis base. The challenge lies in autonomously deploying a large structure from a stowage package without astronaut assistance. This system must also withstand extreme high temperatures and pressures from rocket plumes, ensuring the structure's integrity and functionality. This project investigates the effectiveness of two deployable mechanisms for the prototype: an inflatable bladder using compressed gas and a self-deploying super-elastic alloy. By exploring both approaches individually and in combination, we aim to determine the most reliable and efficient method for autonomous deployment. Preliminary results indicate that while the inflatable bladder can be easily scaled up, it may compromise the structure's low mass goal. Conversely, the super-elastic alloy with a strategic folding pattern could constitute just 10% mass of the fabric or less, providing a simpler yet effective and consistent self-deployable mechanism.

**In utero Cortical Manipulation Using AAV Mediated CRISPR**

Carrie Jackson

*Mentors: Viviana Gradinaru, Cameron Jackson, and Elisha Mackey*

Adeno-associated viruses (AAV) are a viral vector used for gene therapy. They have the potential to mitigate congenital brain disorders if used as a method for in utero gene therapy. Mouse embryos expressing endogenous Cas9 were injected with AAVs containing guides against the Reelin gene, a key player in cortical lamination. We aim to investigate the efficacy of the gene edits by quantitative analysis of cell presence and position. We hypothesize that in Reelin knockout mice, neural cells in layers 1-6 of the cortex will be mislayered. This work aims to use AAVs to investigate approaches for in utero gene therapy in the developing brain. The project serves as a model for our ability to use AAVs to knockout genes in the brains of animals during embryonic development.

**Orbital Purr-Suits: An Analysis of Orbital Variations in Cygnus X-3 Using StrayCats**

Ollie Jackson

*Mentors: Fiona Harrison and Brian Grefenstette*

Cygnus X-3 is a well-studied and unique high mass x-ray binary consisting of a Wolf Rayet companion star orbiting either a neutron star or black hole with an orbital period of 4.8 hours. NuSTAR's focal plane and aperture stop allow for stray light that hasn't been focused by the optics to reach the detectors, resulting in a shadow of the aperture stop. Stray light observations of Cygnus X-3 with NuSTAR allow for long exposures that capture multiple orbital periods, providing the opportunity for unique analysis of orbital variations. Here we present results affirming the need to track changes in the orbit of Cygnus X-3 over time for epoch folding, as well as analysis in how the spectrum of Cygnus X-3 changes throughout its orbital period. We find that an absorbed power law with a Gaussian component fits the spectra well, with the most significant changes in the normalization of the power law and photon index throughout the orbital period. This gives possible insights into the geometry of Cygnus X-3, which is still not well understood.

**Determining the Trophic Dynamics of Velvety Ant Colonies by Stable Isotope Analysis**

Bianca Jaramillo

*Mentor: Julia Tejada*

The collective evolutionary pressure exerted by eusocial ant species, from Cretaceous to present, has allowed them to become hegemonic sculptors of their ecological communities. Other arthropod species had to adapt to their presence through strategies that include avoidance, coexistence, and direct symbiosis. This case study focuses on niche partitioning in the biome shaped by *Liometopum occidentale* (velvety tree ant) colonies, which are host to rove beetle symbionts *Platyusa sonomae* and *Sceptobius laviventris*. Despite the significance of *L. occidentale*'s role in shaping nearby species' diets, little is known concerning its feeding behavior and those of the hormonally integrated beetles it supports. We therefore aimed to determine the trophic dynamics of terrestrial arthropods within a small-scale ecological system in order to better comprehend evolutionary diet shifts in response to *L. occidentale* colonies. This was accomplished through nitrogen stable isotope ratios ( $^{15}N$ ) of specific amino acids, a process that can provide accurate estimates of an organism's trophic level. This study will provide critical data as to the diet of *L. occidentale*, its symbionts, and other arthropods while contributing to the adoption of a promising, under-utilized methodology in terrestrial arthropod research.

**Characterizing Aggressive Behavior Using Automated Deep-Learning Behavioral Annotation Algorithms and Its Underlying Cortical Neuronal Dynamics**

Chenyu Lisa Ji

*Mentors: David Anderson and Ho Namkung*

Aggression, while an innate social behavior essential for survival, is costly and must be tightly regulated in a context-dependent manner. The anterior cingulate cortex (ACC) has been particularly highlighted for its role in the context-dependent, top-down regulation of aggression in both humans and animals by modulating subcortical circuits. However, to our knowledge, no study has investigated the *in vivo* neuronal activity of this cortical region and its population dynamics underlying aggressive behaviors. To address this gap, we first applied *in vivo* micro-endoscopic imaging of ACC neurons during aggressive behaviors in mice using resident-intruder behavioral assays. In parallel, to analyze specific behaviors, we used a deep-learning-based algorithm, A-SOid, which allows for high-throughput, automated behavioral annotation with high precision. Based on these neuronal and behavioral data, we will discuss both the activity of individual ACC neurons and the dynamics of neuronal populations in correlation with specific aggressive behaviors.

**Investigating Odor-Evoked Upwind Walking in *Lucilia cuprina***

Penelope Juarez

*Mentors: Elizabeth Hong and Pratyush Kandimalla*

*Lucilia cuprina*, the Australian sheep blowfly, relies on olfactory cues to rapidly seek their main food source and reproductive site: animal protein. They are of particular interest to forensic entomologists because their rapid arrival aids in establishing the time of death. Furthermore, understanding their olfactory behavior can demonstrate how this animal species may be adapted to the distribution of odors in their natural environment. To quantitatively measure the behavioral sensitivity and olfactory preferences of the blowfly, we confined them to a 5 mm high laminar wind tunnel adapted from *Drosophila melanogaster*. Within the wind tunnel, we presented them to a panel of odors to observe if these stimuli would elicit upwind orientation and walking. The odorants that are quantitatively deemed attractive to blowflies will allow us to compare this panel to that of *Drosophila*, serving as a step towards comparative olfactory coding and behavior in different animal species.

### **Simulating and Characterizing CMOS Detectors for UVEX Mission**

Grace Kallman

*Mentors: Fiona Harrison, Hannah Penn Earnshaw, and Brian Grefenstette*

The Ultraviolet Explorer (UVEX) is a proposed medium-class explorer (MIDEX) mission that will advance UV studies of the universe. To prepare for the mission, we need to know the limitations of complementary metal-oxide semiconductor (CMOS) detectors, the camera detectors that UVEX will use. We simulated detector images by generating random Gaussian-filtered point sources, adding the point sources to a blank image, binning that image by a factor of 10, and adding noise (dark current noise, shot noise, and read noise) to the binned image. We created images with different gain modes and exposure times. We then implemented Earnshaw's (2022) HDR technique that combines unsaturated pixels from at least three combinations of exposure time and gain mode to create higher quality images. Furthermore, we used point spread function (PSF) photometry to analyze the accuracy and limitations of the detector. Additionally, we evaluated the detector in the lab by measuring the detector-specific dark current noise and read noise values. We ultimately determined the following: the accuracy of UVEX photometry, how to optimize the HDR algorithm for UVEX, and the properties of the CMOS detectors.

### **Investigating the Role of Phosphatases in the Fanconi Anemia Pathway for DNA Interstrand Crosslink Repair**

Jade Konsler

*Mentors: Daniel Semlow and Victoria Mackrell*

Interstrand crosslinks (ICLs) are covalent bonds that form between nucleotide bases on opposite strands of the DNA double helix. The presence of an ICL completely stalls the replication fork, a crucial structural intermediate in DNA replication, making ICLs highly cytotoxic. Elucidating the repair pathways and the roles of specific proteins involved in ICL repair is important for understanding the biological implications of DNA damage. The Semlow lab utilizes extracts derived from *Xenopus laevis* eggs, which are a powerful cell-free tool for studying eukaryotic DNA replication in the absence of a nucleus. This project aims to purify two protein phosphatases to utilize in replication experiments and for raising polyclonal antibodies for use in future experiments. Expression vectors containing our phosphatases have been cloned and one phosphatase was expressed in both *E. Coli* and *Spodoptera frugiperda* (SF9) insect cells using IPTG induction and baculovirus infection, respectively. We are currently optimizing the expression conditions, which will inform expression and purification protocols for the second phosphatase of interest. Once enough protein is purified, it will be utilized for replication reactions in the presence of an inhibitor to determine if DNA replication functionality can be regained by addition of the protein.

### **Using Modeling to Predict Ultrafast Electron Energy Loss Characterization of Photoexcited Carrier and Thermal Dynamics in Strontium Titanate Photocatalysts**

Ezra Korican-Barlay

*Mentors: Scott K. Cushing and Levi D. Palmer*

Nanoparticle photocatalysts are ideal for water splitting and renewable hydrogen generation. A photocatalyst's composition is often modified using dopants that shift the bandgap to match the solar spectrum and suppress defect states and co-catalysts that introduce sites for counter-reactions. Ultrafast electron microscopy (UEM) and ultrafast electron energy loss spectroscopy (EELS) are promising techniques for probing and imaging the carrier excitation, transport, and recombination. An EELS probe has the unique ability to measure a wide range of energetic transitions and dynamics, excite transitions via momentum transfer that cannot be accessed using photon-based spectroscopies, and is performed in a TEM with sub-atomic spatial resolution. This wealth of information can lead to convoluted transitions in ground-state spectra and the excited-state dynamics also typically overlap. Thus, theoretical approaches are necessary for data interpretation and assignment of spectral features. Here we use a density functional theory and Bethe-Salpeter equation approach to calculate the electronic structure and ultrafast EELS spectra of the water-splitting photocatalyst SrTiO<sub>3</sub> (STO). We use a 2x2x2 supercell to simulate the effects of dopants in the STO lattice and simulate how the Ti L<sub>2,3</sub> edge, and low-loss EELS shift with temperature. Lastly, we apply these methods to InP, another water-splitting photocatalysts.

### **Design and Evaluation of a Tilt Rotor Mechanism for Autonomous Hybrid Aircraft**

Alicia Lin

*Mentors: Soon-Jo Chung, Matthew Anderson, and Joshua Cho*

In many applications of transportation, vertical take-off and landing (VTOL) uninhabited aerial vehicles (UAVs) demonstrate a competitive advantage over their airborne and land-based competitors. One particular field where VTOL UAVs show promise is the medical domain, in which an autonomous flying ambulance (AFA) could avoid obstacles and help injured patients receive medical care quicker than traditional methods. The design of our AFA is an autonomous hybrid aircraft, which benefits from the advantages of both lifter rotors and fixed wings. Lifter rotors enable VTOL, a necessary feature for navigating urban environments, and fixed wings provide higher energy efficiency for cruise flight. In this project, we develop a tilting mechanism to the lifter rotors, enabling them to change orientation to generate forward thrust during flight. Not only do these tilting rotors reduce the number of motors on the vehicle, and thus the overall weight, they also increase the available control authority in yaw. We



evaluate the effects of tilting motors on aerodynamic performance and its potential role in further autonomy research.

### **Evaluating the Effects of RNA Protective Elements in Increasing the Stability of Highly Structured RNA**

Arie Lin-Goldstein

*Mentors: Niles Pierce and Heyun Li*

The use of RNA in synthetic biology is hindered by its susceptibility to degradation in a physiological environment. RNA protective elements (PELs) have been shown to help prevent degradation of linear RNA, but their protective effect on highly structured RNA is still unknown. Fluorescent aptamers are a class of highly structured RNA that emit fluorescence when bound to a fluorogen. The fluorescence levels provide a measure for the state of degradation of the aptamers, making them an optimal vehicle for evaluating the effect of PELs. This project designs and optimizes protocols to test whether PELs can prevent the degradation of RNA fluorescent aptamers *in vitro* and *in vivo*. Several variations of the RNA aptamers Broccoli and Pepper were produced, and their stability was tested with and without PEL *in vitro* through an exonuclease digestion test, and *in vivo* in HEK293T cells through fluorescence-activated cell sorting. We will discuss the effect of appending PELs to the aptamers in increasing their resistance to degradation both *in vitro* and *in vivo*. These findings could be broadly applicable to increasing the stability of RNA aptamers and other highly structured RNAs, expanding their use in synthetic biology.

### **An Isoperimetric Inequality for Graphs With Non-Negative Ricci Curvature**

Isaac M. Lopez

*Mentors: Thomas Hutchcroft and Antoine Song*

The Ollivier-Ricci curvature extends the definition of the Ricci curvature from Riemannian geometry to metric spaces, namely graphs. The curvature of a graph gives us some important information about its geometry, including the behavior of the random walk on the graph's vertices. The isoperimetric profile of a graph helps measure the decay of the return probabilities of the random walk. In this paper, we prove an estimate for the isoperimetric profile of a non-negatively curved graph with bounded degree and discuss some of its consequences.

### **Understanding and Tuning Earthquake Models With Data Assimilation**

Rileigh Mansfield

*Mentors: Franca Hoffmann, Elizabeth Carlson, and Lianghao Cao*

Every year fault fault-lying lands have to combat frequent earthquakes. Scientists can only take measurements from the surface of the earth, making it difficult to better understand the phenomenon. Data assimilation is a method used to direct mathematical models by making corrections with real-world data. Previous research has proved data assimilation to be an effective method for forecasting with the most popular use being weather forecasting. During this study, we will be using a specific form of data assimilation called particle filter to understand and tune earthquake models. Using this algorithm, sparse data on the upper boundary of our domain, and a one-dimensional viscoelastic partial differential equation model we can recover the state of our problem. We present evidence of this methodology working in one dimension which can possibly evolve to an applicable three-dimensional problem that can utilize the data scientists collect.

### **Investigating the Interaction Between UFD-3 and DCAP-1**

Arianna McKnight

*Mentors: Tsui-Fen Chou and Yanping Qiu*

Several highly common neurodegenerative disorders, including Parkinson's and Alzheimer's disease, result from pathological accumulation and aggregation of aberrant proteins in the brain. The Transitional Endoplasmic Reticulum ATPase p97 unfolds and shuttles aberrant proteins for proteasomal degradation and has inspired great interest from researchers seeking to cure these diseases. Research in *C. elegans* has identified UFD-3, a cofactor to p97 that supports endoplasmic reticulum-associated degradation and mitophagy, as potentially related to these diseases. Moreover, various neurodevelopmental diseases are causally tied to mutations in UFD-3. Recent findings in the Chou lab have implicated a relationship between UFD-3 and DCAP-1, a major cofactor involved in mRNA degradation and post-transcriptional regulation, which has implications in aberrant protein aggregation. Using liquid chromatography-mass spectrometry, we analyzed the protein-protein interactions in the UFD-3-DCAP-1 complex to learn more about the structure and function of these proteins. Furthermore, we engineered a deletion of the evolutionarily conserved intrinsically disordered region in UFD-3, which lacks a stable three-dimensional structure and facilitates protein folding and complex formation. By studying these altered structures and investigating differential interactivity, we hope to explore the mechanisms underlying protein aggregation. Ultimately, these data will provide greater insight into targeted gene therapies aimed to enhance intracellular protein regulation.

**Processing and Characterization of Superconducting Niobium Nitride**

Sela Murphy

*Mentors: Austin J. Minnich and Azmain A. Hossain*

Superconducting quantum devices are plagued by loss and defects stemming from nanofabrication techniques, and there is a need for novel processing technology to address the current limitations. Niobium Nitride (NbN) is a superconducting metal of interest due to its relatively high kinetic inductance and critical temperature in comparison to common materials of interest. Atomic layer etching (ALE) is a self-limiting isotropic process with ultra-low damage etching properties compared to conventional etching methods like reactive-ion etching and wet-etching. One of the most interesting characteristics of ALE is that it allows etch control on the order of Angstroms and reduces surface roughness. We worked towards developing an ALE recipe for NbN using oxidation and selective removal of the oxide using an H<sub>2</sub>/SF<sub>6</sub> plasma. Compared to other common superconductors like aluminum and titanium nitride, niobium possesses many more oxidation states which leads to complicated surface chemistry. We examined the effect of different oxidation procedures on the surface chemistry of NbN and the subsequent effect of plasma etching. The study resulted in a cyclic, self-limiting ALE recipe for NbN which is relevant to applications of NbN in quantum devices.

**Exploring Variability and Correlated Astronomical Parameters in the 5MUSES Galaxy Sample**

Vaennessa Nickell

*Mentor: George Helou*

The field of extragalactic astronomy has significantly advanced with improved infrared observational capabilities, providing deeper insights into galaxy formation and evolution. This research focuses on analyzing the 5MUSES galaxy survey, comprising 330 galaxies observed by the Spitzer Space Telescope. The primary challenge is to understand the factors contributing to galactic variability in both the infrared and visible spectra, which is crucial for comprehending galaxy evolution dynamics. Previous studies have shown that some galaxies exhibit emissions that vary over weeks to years, driven by star formation or black hole accretion processes. This project aims to expand on these findings by integrating additional astronomical parameters like redshift, luminosity, and color indices. Methodology includes compiling data from archival sources, integrating new data with existing variability estimates, and analyzing the relationships between galaxy variability and other parameters. Initial results will lead to the development of models predicting variability based on these parameters, providing a comprehensive understanding of galaxy variability and its underlying mechanisms.

**Assessing Individual Differences in Habit Propensity via Resting-State Functional Magnetic Resonance Imaging (rs-fMRI), Integrated Laboratory, and Real-World Behavioral Data**

Cadence Maria O'Donnell

*Mentors: Colin Camerer and Rani Gera*

Neural pathways underlying habitual and goal-directed behaviors are investigated using resting-state functional magnetic resonance imaging (rs-fMRI). The dual-process theory of action control differentiates habitual behavior, characterized by automatic responses to prior cues, from goal-directed behavior, which involves deliberate actions to achieve specific outcomes. Existing research is constrained by the artificial nature of laboratory settings and the short durations of training periods.

To address these limitations, we utilize a Single Session Laboratory Task and a Habit Induction Mobile Application. This application allows participants to engage voluntarily throughout the day, fostering real-life habit formation. Both methods incorporate devaluation outcome periods, where previously rewarding outcomes are reduced in value to assess habit persistence. Participants who have established habits are expected to exhibit reduced sensitivity to these devalued outcomes. Additional field data are collected through daily diaries using the Social Rhythm Metric (SRM) and real-time mood and behavior tracking via Ecological Momentary Assessment (EMA).

Behavioral data will be analyzed alongside rs-fMRI data using the FMRIB Software Library (FSL). The analysis will focus on functional connectivity between regions of interest (ROIs), including the supplementary motor area (SMA) to the posterior lateral putamen, premotor cortex to the posterior lateral putamen, and anterior caudate to the ventromedial prefrontal cortex (vmPFC), with the objective of identifying neural pathways involved in habitual behaviors and their real-world relevance.

**Quantitative Analysis of Morphometrics for Stromatolites From the Paleoproterozoic Rocknest Formation, Northern Canada**

Jaden Olah

*Mentors: John Grotzinger and Emily Geyman*

Stromatolites are sedimentary structures that are thought to form via interactions between sedimentation rate, mineral precipitation, and microbial activity, growing by generating thin laminae that build upon each other, forming a diverse array of macroscopic morphologies in the geological record. Stromatolite growth factors are modulated by the physical and chemical conditions of the ancient seafloor. However, the ways these factors

interact with each other to produce specific morphologies remains poorly understood from a quantitative perspective. Obtaining this understanding is significant for the active study of carbonate structures on Earth and Mars. Previous research has used stochastic growth equations such as the Kardar-Parisi-Zhang equation to model the formation and morphology of individual stromatolites, but these studies have yet to address the growth dynamics of a spatiotemporally robust stromatolite group. We focus on the problem of large-scale stromatolite growth using x-ray fluorescence microscopy to map elemental abundances for stromatolites of the Rocknest Formation exhibiting a diverse array of morphologies. We have found that Rocknest stromatolite laminae are abundant in calcium, iron, silicon and potassium. Potassium abundance in particular represents a novel discovery that holds geological significance. We thus demonstrate the viability and significance of analytical geochemistry contributions towards understanding stromatolite morphometrics.

**Water Solubility in Calcium Aluminosilicate Melts**

Emilia Pelegano-Titmuss

*Mentors: Edward Stolper and Michael Baker*

Water, an important volatile constituent of magmas, has a dramatic effect on the physical properties of silicate melts (e.g. lowering their viscosities and liquidus and solidus temperatures, allowing them to erupt more easily). Much effort has been devoted to determining water solubilities in silicate liquids of geologic interest (generally at pressures >1 atm). Extensive 1-atm water solubility data in simple silicate systems exists in glass and slag literature. For this study, H<sub>2</sub>-CO<sub>2</sub> gas mixtures in a 1-atm furnace were used to impose a fixed pH<sub>2</sub>O on silica-rich melts in the CaO(C)-Al<sub>2</sub>O<sub>3</sub>(A)-SiO<sub>2</sub>(S) system at 1200 to 1400°C. Compositions included the Wollastonite-Silica-Anorthite (An) eutectic, a composition on the An-silica join, and additional compositions in the CAS ternary. Water contents in the glasses were determined using Fourier Transform Infrared Spectroscopy. We found that temperature has an inverse relationship with CAS eutectic water capacity [water content/√pH<sub>2</sub>O], and water capacities in the CAS system change as a function of melt composition. We will compare our findings to results in the literature (much of which appears to be inconsistent), investigate simple relationships between water capacity and composition, and compare our data with the predictions of an existing thermodynamic model.

**Advancements in Robotic Design: Improving Structural Integrity and Functionality**

Angelica Pena

*Mentors: Soon-Jo Chung and Matthew Anderson*

The design of experimental testbeds is essential to develop the next generation of control systems for autonomous robots. There are key challenges in designing systems that are functional for scientific experimentation. The primary focus is enhancing the robotic system's structural integrity, optimizing component integration, and designing for easier manufacturing. The first system is LEONARDO, a control testbed designed to showcase balance. It is a bipedal robot that can perform both ground and aerial locomotion. To protect LEONARDO's components during testing, shieldings and electronics need to be reliably mounted to the robot's body. To address this, we redesigned the armor shields, the tracking camera mount, and the head to make them easier to assemble and manufacture. The second system is a volcano sampler designed to navigate around volcanic fumaroles and collect gas samples to inform us about volcanic activity. We needed to upgrade the motor in the mechanism that autonomously lowers the sampler from a drone to ensure it could perform effectively in varying conditions. Lastly, for future long-range operations, we needed a tripod mount for a Yagi antenna that could tilt and pan. These improvements have led to more robust and manufacturable systems, enhanced performance in various applications, and overall effectiveness. Collectively, these advancements contribute to the adaptability of our technologies, supporting ongoing research development.

**Characterizing Sediment Microbial Communities and Investigating the Impact of the Physicochemical Environment on Methane Cycling Across Methane Seeps in the Gulf of Alaska**

Nalani Quintana

*Mentors: Victoria Orphan and Daniel Utter*

Ocean floor methane seeps are essential to global methane cycling and climate control. However, the environmental factors impacting anaerobic oxidation of methane (AOM) powered by anaerobic methanotrophic archaea (ANME) and sulfate-reducing bacteria (SRB) consortia at these seeps remains largely understudied. By investigating the sediment microbial communities and geochemical conditions from varying depths and habitats (e.g. clams, frenalates), we explored the composition and function of ANME-SRB consortia at methane seeps in the Gulf of Alaska. Sediment samples were collected via a deep-sea research submersible and studied using DNA extraction, 16S rRNA PCR amplification, and FISH microscopy to profile microbial communities and their distribution. Porewater was geochemically analyzed to grasp the environmental conditions influencing AOM. Our results reveal variability in microbial community composition and activity, particularly at depths of 6 to 15 cm below the seafloor, where high DNA concentrations and microbial aggregates were observed, suggesting active AOM processes. This study enhances our understanding of microbial interactions at oceanic methane seeps, offering insights into the relationship between AOM consortia and marine ecosystems. Further research on the ecological implications of ANME-SRB consortia will prove instrumental to understanding the role of seafloor carbon cycling on climate change.

**Un-Obscuring the Obscured: The Feeding Habits of Supermassive Black Holes**

Krystyn L. Roldan

*Mentors: Fiona Harrison, Peter Boorman, and Elias Kammoun*

Supermassive black holes are believed to reside at the centers of all large galaxies. These black holes grow by accreting material that not only fuels but also obscures them. A subset of these sources exhibit the most extreme levels of obscuration, where the obscurer and accretion disc are thought to be viewed at edge-on orientations. As fuel reservoirs for black holes, obscurers also play a crucial role in their growth mechanisms. Their high obscuration levels are linked to two main growth channels: black holes that feed on material from their own galaxy are expected to have obscurers aligned with the galaxy, whereas black holes that have grown from merging with other galaxies often have misaligned obscurers. Using the largest compilation of the most obscured accreting supermassive black holes, we investigate their evolutionary paths by comparing the orientations of obscurers and their galaxies. We estimate galaxy inclinations from ground-based infrared imaging and derive the underlying distribution of inclinations for the sample using a flexible Hierarchical Bayesian Model. Our results will enhance our understanding of the complex co-evolution between supermassive black holes and their encompassing host galaxies.

**Numerical Simulations Comparing the Effects of Viscosity in Driven RMHD Turbulence**

Anuranj Roy

*Mentors: Elias Most and Sarah Habib*

Relativistic gas hydrodynamics is a well understood phenomena that is known to exist in many astrophysical systems such as accretion and jet flows in Active Galactic Nuclei (AGN) or small compact objects like neutron stars and stellar mass black holes. For turbulence, however, the standard scenario is limited to the accretion disk; where the magnetic field and hot gas can create instability and cause turbulence. Below we show our results from our cooling and driving implementation on 2D and 3D relativistic hydrodynamic simulations. This provides an in-depth study of the driving conditions and cooling parameters to achieve turbulence and correlate to physical systems. We find that our cooling and driving implementation returns parameters that align with our theoretical understanding, and that our transition to GPU simulations achieve numeric stability.

**Cationic Carbon Nanodots for the Delivery of Nucleic Acid**

Robert Russum

*Mentors: Gözde Demirer and Jesus Galeana*

The changes in climate due to the dramatic increase of anthropogenic carbon dioxide and other greenhouse gases have attracted widespread public attention in recent years due to their impact on global surface and atmospheric temperatures. Global climate change is causing environmental stresses to occur far more often; if nothing is done, crop yields could decline by nearly 25% by 2050, according to the most severe projections. Something novel must be done to improve crop yields by making crops more resilient in unstable conditions and improving their productivity. In working towards a solution to these issues, tools to deliver nucleic acids for genetic engineering applications in plants are being developed. The genetic engineering of plant cells using CRISPR Cas-9 for example has the potential to be a highly effective solution; the introduction of genes that allow for greater crop productivity and improve their resistance to both biotic and abiotic stressors is something that could achieve the goal of protecting crops and improving their yield. To tackle this problem Carbon dots (CDs) for their simple synthesis, high water solubility, biocompatibility, low toxicity, nano size, and luminescence properties make them highly suitable candidates for gene editing applications. We have managed to functionalize CDs with PEI, following the precedent of chemistry in carbon nanotubes, to enable them to enter plant cells. Our results lay a foundation for future work in creating CD gene delivery systems and in this presentation, we will discuss the advancements in designing different size and charged carbon dots for genetic engineering applications.

**Detecting Type-2 Spectroscopic Binaries in High-Resolution Spectra With KPF**

William Salazar

*Mentors: Andrew Howard and Steven Giacalone*

Roughly half of Sun-like stars have a binary companion. Detection of such systems includes methods such as visual, spectroscopic, and eclipsing detection. We focus on detecting spatially unresolved binary stars in spectroscopic data via the type 2 spectroscopic binary (SB2) method. An SB2 binary is a system where the stars are too close to resolve using visual methods, but can be identified via careful inspection of high-resolution spectra. Detection of such stellar systems is crucial for planet searching surveys as such systems are less likely to host exoplanets. Using spectrographic data collected and processed by the Keck Planet Finder (KPF) spectrograph on the 10-meter Keck-I telescope, we prepare a Python pipeline to process and detect binary star systems. For our algorithm, we focus on computing the cross-correlation function (CCF) using a binary stellar line mask. We focus on a peak detection algorithm that is sensitive to binary stars with radial velocity shifts relative to the primary star. Injection-recovery tests are used to determine the sensitivity of our algorithm to binary systems and calculate the probability of a binary star existing in a system in which none are detected.

### **Hot Fire Test Bed for the Plume-deployed Inflatable for Launch and Landing Abrasive Regolith Shielding (PILLARS)**

John Manuel Santana

*Mentors: Soon-Jo Chung, Matt Anderson, and Lily Coffin*

PILLARS is designed to shield the lunar Artemis base from unconsolidated, abrasive regolith kicked up by rockets landing on the lunar surface. In order to test candidate materials and prototypes in a simulated rocket plume environment, a test stand with a 500,000 BTU/hr propane torch facing down to an 80-pound cement block was constructed. The test stand's goal is to (a) aid the design of the PILLARS system, heat transfer mitigation strategies such as intermediate mesh layers of different pore sizes and materials can be tested, (b) a vertical linear actuator was implemented in the test stand to simulate a landing/launching rocket, which achieves TRL 4 of the PILLARS shield inflation mechanism, and (c) the stand also enables testing of different prototypes to determine the optimal configuration for minimum heat transfer and stress. PILLARS is trying to validate the inflation mechanism under hot fire conditions because it is necessary to advance the technology readiness level of the PILLARS system. Since PILLARS will also be under extremely hot temperature and high-pressure conditions on the lunar surface, finding the best materials to help shield against the excessive heat and pressure is crucial for PILLARS to survive and go on multiple missions.

### **On the Current and Future Capability of Compact Binary Coalescence Parameter Estimation Methods**

Sterling Scarlett

*Mentors: Alan Weinstein and Jacob Golomb*

We introduce, understand, and interpret parameter estimation (PE), examining its role in analyzing Compact Binary Coalescence events (CBC) via their emission of Gravitational Waves (GW) and the measured GW strains by instruments such as LIGO, VIRGO, and the future detector Cosmic Explorer (CE). We explain and list all fifteen parameters that characterize of CBC. Understanding and looking at current methods of parameter estimation (Bayesian inference, Fisher Matrix), we investigate how each method is currently used (Bilby), future possibilities of the methods via machine learning (Dingo), and advancements in detectors (Cosmic Explorer). Conducting a comparative quantitative analysis with a methodology considering the speed, accuracy, and precision of the different methods and detectors, we aim to assess their efficiency and capabilities, offering insight on the future of PE of CBC events. We evaluate simulated events developed from a IMRPhenomXPHM waveform approximation and similar phenomenological frequency-domain waveform approximations to develop our injections of a full spectrum of CBC events. Doing this allows us to measure greater accuracy, precision, and characterization of potential strengths and weaknesses of each waveform model and detector.

### **Characterizing Bacterial Amyloid Proteins in Parkinson's Disease Pathogenesis**

Meilin Scott

*Mentors: Rustem Ismagilov and Natalie Wu-Woods*

Parkinson's Disease (PD) is a neurodegenerative disease characterized by the formation of Lewy bodies, aggregates of alpha-synuclein in neurons. Previous studies have demonstrated a link between the human gut microbiome and the brain, although precise mechanisms are not understood. A recent study found that patients with PD have a higher abundance of bacterial biofilm-associated proteins (BAP) in fecal samples. However, a direct causative mechanism between BAP gene abundance and PD pathology or progression has not been established. The Mazmanian and Ismagilov labs are utilizing Parkinson's mouse models (alpha-synuclein overexpressing; ASO) to begin discovering mechanistic links between the gut microbiome and PD pathology. The labs have previously performed metagenomic sequencing of ASO and Wild Type (WT) mice of various ages and sample types (mucosal and luminal samples along the gastrointestinal tract and fecal samples). Now, in this current WAVE project, we are using bioinformatics tools to explore the role of BAP genes in PD pathology by comparing gene abundances across age, disease, and location. This knowledge can help develop future studies investigating the connection between the microbiome and Parkinson's Disease.

### **Total Synthesis of (+)-Cyanocycline A**

Hanna Shan

*Mentors: Brian Stoltz and Camila Suarez*

Natural product synthesis is a major field of organic chemistry research that aims to find efficient synthetic pathways to the total synthesis of complex natural products. Natural products are defined as compounds produced by living organisms. Cyanocycline A is a natural product isolated from the cultures of the soil bacterium *Streptomyces flavogriseus* and it exhibits antimicrobial and antitumor activity. Previous synthesis pathways for cyanocycline A are linear and rely on electrophilic aromatic substitution making them inflexible to adjustments for synthesizing derivatives of cyanocycline A.

This project aims to accomplish the total synthesis of (+)-cyanocycline A by synthesizing highly complex coupling partners and utilizing a Pd-CMD (concerted metalation deprotonation) C–H cross-coupling to nearly complete the full carbon skeleton. I will be studying the cross-coupling step by synthesizing the coupling partners with different functionalization such as different protecting groups. The synthesis of the dihydropyrrole coupling partner has been completed and I will be testing its intermediates in the CMD. We are studying the importance of the functionality on the dihydropyrrole coupling partner in the CMD to learn more about its mechanism. Preliminarily we see that the coupling works without the oxazoline group and shuts down when the primary alcohol is protected.

### **Control Barrier Functions Through SLAM: A Probabilistic Approach**

Pascal Sikorski

*Mentor: Aaron Ames*

In autonomous robotics, ensuring robust and safe navigation within uncertain environments is critical. This research focuses on implementing a novel Belief Control Barrier Function (BCBF) framework with simultaneous localization and mapping (SLAM) to achieve risk-aware control in autonomous systems. By utilizing the belief of an environment and the robot's position, a BCBF can incorporate probabilistic constraints into a control strategy, ensuring safety under uncertainty.

Our control strategy is formulated as a quadratic program that minimizes the difference between a teleoperation input and a safe input while ensuring the probability of collision remains below a predefined threshold. The probability of collision is determined through belief (such as positional mean and covariance dynamics) of the system in the surrounding environment, under either a discrete or continuous form.

Development with simulation in ROS2 can yield strong early results, prompting our further testing in real-world situations. These include not only mobile and aerial robots but also bipedal and quadrupedal robotic systems. With this research, we can ensure the safety of autonomous robots through a reliable and robust BCBF in SLAM with the potential of scalability for broader applications in numerous robotic platforms.

### **Numerical Modeling of Shock-Powered Transients From Neutron Star Mergers**

Ananda Smith

*Mentor: Elias R. Most*

The gravitational and electromagnetic emission from binary neutron star (BNS) mergers provides exciting opportunities for multi-messenger astrophysics. Recently, it was found that under certain conditions, the collapse of the BNS merger remnant into a black hole launches some of the most powerful shocks in the Universe. In this work, we investigate the interaction between these "monster shocks" and the cloud of debris ejected during the BNS merger using special relativistic magnetohydrodynamic (SRMHD) simulations. We track the monster shock from its initial formation as it traverses through and deposits energy into the ejecta cloud on long time scales. To make predictions about the distinguishability of this monster shock scenario from other proposed post-merger outcomes, we pay particular attention to the signatures imprinted by the shock-ejecta interaction on the infrared-emitting kilonova afterglow.

### **On-Orbit Training of Spacecraft Detection and Segmentation Models Using Thermal Imagery**

Cailyn Smith

*Mentors: Soon-Jo Chung and Hannah Grauer*

Detection and segmentation of spacecraft on-orbit enables proximity operations, including rendezvous, on-orbit servicing, and debris removal. Existing neural networks on satellites with onboard training capabilities have focused on Earth-based objects and previously have not demonstrated training with a GPU. We present a novel software architecture for onboard GPU training of space-based object detection and segmentation algorithms to be deployed on Aerospace Corporation's Edge Node Lite mission in 2025. Dino + Fast-SCNN, a segmentation model using knowledge distillation proposed in Grauer et al., and YOLOv8, a convolutional neural network (CNN) based detection model, were trained on long-wave infrared imagery to increase their robustness in the varied lighting conditions of space. These models were deployed and adjusted for performance on a Nvidia Jetson TX2 and tested in the Caltech Autonomous Robotics and Control Lab's spacecraft simulator. We demonstrate the capability to run spacecraft detection and segmentation on-orbit as well as training of these algorithms using a GPU for the Edge Node Lite mission.

### **Optimization of Ni-Pd Catalyzed Cross-Coupling for the Total Synthesis of (-)-isodocarpin**

Chaw M. Soe

*Mentor: Sarah Reisman*

(-)-Isodocarpin is an *ent*-kaurene diterpenoid, a class of molecules characterized by complex and highly oxidized structures along with rich biological activities. As such, *ent*-kaurene diterpenoids have been the targets of synthetic chemists aiming to explore their chemical and biological properties. Envisioning (-)-isodocarpin retrosynthetically, it is envisioned that the central lactone ring can be bisected into a vinyl iodide fragment and 3.2.1 bicycle vinyl

triflate. These fragments can be joined via  $sp^2$ - $sp^2$  C-C bond formation via Ni-Pd catalyzed cross-coupling, with nitrogen ligands for the Ni catalyst and phosphine ligand for the Pd catalyst. This fragment cross coupling approach would allow for the rapid assembly of isodocarpin structure. Thus, optimization of an Ni-Pd catalyzed cross-coupling is crucial for synthesizing isodocarpin efficiently. Bayesian optimization has been employed to enhance optimization efforts. A variety of conditions have been explored including nitrogen ligands for the nickel catalyst and phosphine and nitrogen ligands for the palladium catalyst as well as general reaction conditions. It is through these effects that we aim to develop a better understanding of the cross coupling and develop a more efficient reaction overall.

**Modeling Thermomechanical Shape Memory Polymer Deformation Using a Parallel-Phase Constitutive Relation and the Finite Element Method With Computational Parameter Optimization Techniques**

Kamakshi Subramanian

*Mentors: Chiara Daraio, Suyeong Jin, and Gunho Kim*

Smart materials called shape memory polymers can independently regain a memorized permanent shape from a temporary deformed shape under exposure to an external stimulus, such as heat or light. Computational modeling is essential to effectively understanding and utilizing this behavior. In this study, we used a constitutive relation which combines parallel rubbery and glassy rheological models to develop a finite element method simulation to predict the measured stress in a sample when extended at high temperature, held and cooled to a lower temperature, released slowly and freely, and heated back to high temperature. We determined the optimal values of equation parameters using one dimensional experimental data for each phase separately by running parameter sweeps and comparing residuals in stress-strain curves while analyzing the physical effect of each parameter. We then calculated the temperature parameters and combined the two phases into a single program with temperature dependence. To further improve the model, parameters of the added shape memory strain element will be refined, and more advanced optimization algorithms, such as machine learning, will be explored for greater accuracy. A robust model for shape memory effect will benefit shape programming in manufactured devices such as biomedical stents, self-deployable structures, and heat-shrinkable coverings.

**Establishing Direct Regulation of *decommissioned* Laccase by Hox Gene *AbdB* Through CRISPR Knockout in *Dalotia coriaria***

Primrose Tanachaiwiwat

*Mentors: Joseph Parker, Yuriko Kishi, and Veronica Muller*

Rove beetles (*Staphylinidae*) possess the remarkable novelty of a tergal gland that evolved synchronously with a complex interspecies relationship to ants. One species, *Dalotia coriaria*, possesses a defensive tergal gland containing benzoquinones (BQ) specified by Hox gene *AbdB*. Knockdown of *AbdB* in the adult leads to loss of BQ production because it affects the expression of enzymes known to act in the BQ synthesis pathway. However, the mechanism by which *AbdB* regulates BQ production and BQ cell enzymes is unknown. The laccase *decommissioned* (*dmd*) is of interest because when silenced, it leads to an almost complete loss of BQ in *Dalotia's* secretions and therefore may be directly regulated by *AbdB*. To assess this, we knocked out putative *AbdB* binding sites in regulatory regions upstream of *dmd* via CRISPR injections. The putative binding sites are in the intergenic region and knocked out via guide RNAs that map the beginning and end of the region. Injections are performed biweekly onto wild-type eggs that are reared until eclosion. The adult beetles are then crossed to produce F1s. The F1s will be genotyped, and if loss of *dmd* expression occurs after knockout, a connection between *AbdB* and direct regulation of *dmd* will be established.

**Geochemical Analysis of Pegmatitic Rare-Earth Element Granites From the Eastern Egyptian Desert**

Mattox Telwar

*Mentors: Paul Asimow and Oliver Wilner*

The standard whole rock analysis method relies on the creation of a homogenous glass pellet using a lithium-borate flux to prepare the sample for X-Ray Fluorescence (XRF) analysis, and often dissolving the sample in hydrofluoric acid for Inductively Couple Mass Spectrometry (ICP-MS). This method erases the possibility of analyzing the natural lithium or fluorine concentration of the rock sample. The increasing demand of lithium in global supply chains is prompting the search for lithium-rich deposits, and therefore relying on the ability to analyze the natural lithium concentration of rock samples. We implement a novel flux- and acid-free pressed pellet method to analyze the whole rock composition of a specific sample suite of pegmatitic, A-type granites that contain rare-earth elements collected from the Eastern Egyptian Desert. The goal is to provide a resource assessment of this locality to contribute to Egypt's green energy effort by potentially identifying a substantial lithium reserve. We conclude that the samples contain significant concentrations of rare-earth elements, specifically uranium. However, there is not a substantial lithium reserve at the locality in which these sample were collected.

**Understanding Biological Metabolism in Biotic-Electrochemical Interface of Bacteria: *S. oneidensis***

Jayden K. Thomas

*Mentors: Karthish Manthiram and James Wang*

Nature uses electrochemistry to catalyze metabolic reactions essential for cell growth. To gather insight into metabolic factors influencing cell growth, we focused on the bacterium *Shewanella oneidensis*. While observing a *Shewanella* culture mid-exponential growth phase, we observed curious fluorescence oscillations using a redox active dye. These oscillations could disprove popular assumptions that cell metabolism is steady state, yet the causes of these oscillations are contested, with too many conflicting phenomena for one to be determined as domineering. The development of experimental tools equipped to deconvolve these oscillations is crucial. Hence, we shifted focus to the expression of genetically encoded voltage indicators (GEVI's) in bacterium to investigate if metabolism is non steady state. GEVI's are biological sensors, equipped with a fluorescent protein (FP) that emits fluorescence due to changes in transmembrane potential. The goal of this project is to engineer GEVI's to express in various strains of bacteria to gather further insights into growth behavior. Additionally, techniques in microscopy for these sensors will be described.

**CHEX-MATE: The Generation and Analysis of Mock Galaxy Cluster Observations**

Mina Thoresen

*Mentors: Jack Sayers and Adriana Gavidia*

The Cluster HEritage project with *XMM-Newton* – Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX-MATE) is an observational study of 118 galaxy clusters sampling the low- $z$  ( $0.05 < z \leq 0.2$ ) and high mass ( $M_{500} \geq 7.25 \times 10^{14} M_{\odot}$ ) populations. It was designed to study the clusters' matter distribution shapes and the effects of baryonic physics on their global properties (CHEX-MATE Collaboration et al. 2021). In this work, we prepare and fit mock observations of clusters that span the range of morphologies in the CHEX-MATE sample in order to study the non-thermal pressure fractions at larger radii than previous studies, where accretion, rather than AGN feedback, dominates. In particular, we use the 3d triaxial fitting methods of Kim et al. 2023 to fit data that we have generated from mock observations of simulated clusters based on the ACT telescope and Planck satellite.

**In-Silico Designed Glucose Transport Protein Incorporation Into the Synthetic Cell Membrane**

Denys Vasyutyn

*Mentor: Richard M. Murray*

Synthetic cells are an important area of research within the field of synthetic biology. It relies on bottom-up building of biological structures in order to have a high degree of their control and understanding. One of the crucial systems for the development of functional synthetic cells is the network of membrane proteins that receive nutrients and chemical signals from the extracellular environment. The efforts on incorporation of many such proteins have been done over the years, incorporating existing proteins from living organisms into synthetic cells. The goal of this project was to use recently developed machine learning tools for protein engineering to design novel sequences for glucose transporter membrane proteins and test them in vitro. The sequences were developed using TRILL software and its underlying algorithms and tested within droplet interface bilayers (DIBs). Out of 2199 in-silico designed sequences, 20 passed in-silico testing and 7 were selected for in-vitro testing. 1 of the 7 sequences showed great capabilities for the transport of glucose across the bilayer, as compared to the naturally occurring glucose transport proteins. The results show increasing potential for machine learning utilization within the field of protein engineering and synthetic biology.

**Effect of Dipole Asymmetry on the Interfacial Potential Gradient of Water**

Ananya Venkatachalam

*Mentors: Zhen-Gang Wang, Samuel Varner, and Pierre J. Walker*

Despite its simple molecular structure, water exhibits diverse anomalous properties, one of which is its ability to generate a strong electric field at its interface with air despite being a neutral molecule. Recent research employing first-principles molecular dynamics has shown that water can catalyze critical and climate-impacting atmospheric reactions. Many studies have used atomistic simulations to examine water structure at the air-water interface. However, due to the unique hydrogen bonding network and characteristics of water, the results are often self-specific. We postulate that the anomalous interfacial behavior exhibited by water arises from dipole asymmetry. Our study generalizes this idea, focusing on the underlying mechanisms for strong polarization and ion adsorption at the vapor-liquid interfaces of polar fluids. We use coarse-grained molecular dynamics simulations to gain a broader understanding of interfacial phenomena across the chemical space, employing our own modified Stockmayer fluid model for asymmetric polar molecules. This model allows us to vary the dipole strength and the degree of asymmetry, or dipole offset, to observe effects on the interfacial polarization and electric field. Introducing molecular asymmetry results in preferred dipole orientations at the interface, producing a finite electrostatic potential and electric field. Our analysis indicates that higher dipole moments increase the density and structural organization within the fluid, while greater dipole offset asymmetry leads to more distinct alignment and stronger electric fields at the interface. These findings contribute to a better understanding of interfacial



polarization and could be valuable for developing predictive models for climate change and sustainable environmental technologies.

**Seamless Interface of Implantable Bioelectronic Devices Through Bioadhesion and Shape-Morphing Actuation**

Mya Verrett

*Mentors: Wei Gao and Dickson (Richard) Yao*

Bioelectronics have greatly expanded its use in health through monitoring and treatment of chronic disorders. However, current implanted devices can be rejected by the body leading to chronic immune reactions. In efforts to improve the interface between an implantable device, we developed tissue adhesive that can be programmed to morph into the shape of various types of tissue for a seamless and conformal interface. By incorporating this, we can program a device to spiral or naturally grip around tissue to become less intrusive and remain intact through covalent bonding of both surfaces. We demonstrated the potential of this material by integrating various bioelectronics onto this shape morphing bioadhesive platform, including strain sensors, glucose sensors, and stimulation electrodes. When testing, the material was able to closely actuate around the artery in a spiral and adhere the surface of the sensor to tissue, even when submerged in water for long periods of time. Ultimately, we aim to apply this device for closed-loop monitoring and management of cardiometabolic disorders.

**The Genetic Link Between Chondrules and Matrix in Primitive Meteorites From Nucleosynthetic Isotope Anomalies**

Katie Victor

*Mentors: François Tissot and Teng Ee (Tony) Yap*

As remnants of the primordial Solar System, meteorites are time capsules containing valuable information about the formation of planetary materials. The objective of this study is to uncover this information by finding Zn and Ti nucleosynthetic isotope anomalies - mass-independent variations in isotopic abundance resulting from stellar processes - of a selection of chondrites. This work focused on carbonaceous chondrites CV3 Allende and CM2 Murchison and ordinary chondrites L/LL4 Bjurböle and LL4 Soko-Banja. To find the anomalies the chondrules and matrix of these samples needed to be separated, which was accomplished through freeze-thaw disaggregation - the process of repeatedly freezing a sample in Milli-Q water with liquid nitrogen and thawing the sample. This disaggregation technique is highly effective, breaking apart the chondrules and matrix of our samples within 50-70 cycles. Although this work has led to success, this study is far from complete. This project should be continued by performing acid digestion on separated matrix and chondrules, finding elemental concentrations using the quadrupole iCAP RQ ICPMS and performing isotopic analysis using the Neptune MC-ICPMS.

**Doctor Blade Automation for Thin Film Hydrogel Biosensors**

Xiaoli (Shelli) Wang

*Mentors: Julia Kornfield, Raj S Mukkamala, and Dennis Ko*

Phosphorus is an essential nutrient for crops and crucial for feeding the world's growing population. As phosphorus is a finite resource, precision agriculture is vital for sustainability, reducing waste, and preventing environmental damage like eutrophication caused by excessive nutrient applications. At Caltech, an interdisciplinary group aims to encapsulate genetically engineered bacteria into hydrogels to create a wireless biosensor for detecting bioavailable phosphorus in soil. This device can provide real-time, remote measurements, helping farmers decide when, where, and how much phosphorus fertilizer to apply, minimizing waste. The bacteria must remain encapsulated in hydrogels and not be released into the environment due to regulatory requirements. Additionally, the hydrogels must be under 300 microns thick to allow the bacteria to access oxygen and produce fluorescent protein signals in response to phosphorus limitation. We use the doctor blade method for hydrogel spreading due to its low material consumption, simplicity, and cost-effectiveness. However, manually spreading thin hydrogels with consistent thickness is challenging. Therefore, we aim to design and build an inexpensive automated setup to spread hydrogel solutions at user-defined speeds, conducting experiments to determine the optimal speed for uniform thickness. The success of this project will provide a crucial tool for consistently making thin hydrogels for our biosensor, enabling accurate phosphorus detection. This tool can also benefit the broader scientific community in applications such as membrane research.

**Lattice Matching Thin Films to Experimentally Viable Substrates**

Sivanjali Elena Williams

*Mentors: Joseph Falson and Reiley Dorrian*

Molecular beam epitaxy (MBE), a thin film growth technique, involves growing a crystal film on top of a different substrate. However, not all crystals are geometrically compatible with all substrates. Too much mismatch between the lattices of the substrate and film creates strain, resulting in defects and inconsistent growth orientations (domains). Focusing on commercially available and inexpensive substrates, we are developing an application which identifies promising substrates for a material or set of materials from the Materials Project database. The tool generates a weighted Voronoi diagram describing the lattice constants best matched to each substrate. It also

includes filters and parameters to allow a user to tune the matching conditions. The application can help researchers choose the best-matched substrate for a particular film, the best combination of substrates for a group of films, or identify promising candidate films to grow on a particular substrate. Finally, we experimentally explore whether lattice-matched substrates can improve the quality of cerium diantimonide (CeSb<sub>2</sub>) films grown through MBE.

**Optimization of Thin-Film Kirigami Springs for Use in Tensioning Solar Panels in the Space Solar Power Project**

Rachel Willick

*Mentors: Sergio Pellegrino and George Popov*

Kirigami is a variation of origami, altering the appearance and behavior of a thin sheet of material using folds and cuts. Kirigami is used to create ultralightweight, bi-directional springs that will be used to maintain the orientation of photovoltaic panels in the Space Solar Power Project. The spring design is optimized by creating iterative patterns of springs using b-spline curves characterized by three control points and a ribbon-width scalar. Each design is then characterized using a numerical solver to determine the force necessary for a given displacement of the spring. Force and displacement are then measured experimentally for selected patterns to confirm model accuracy. This will create a library of springs from which we can choose the desired amount of tension on the PV panels.

**Improving Posterior Predictive Checks for Gravitational Wave Population Analyses**

Sophia Winney

*Mentors: Simona Miller and Katerina Chatziioannou*

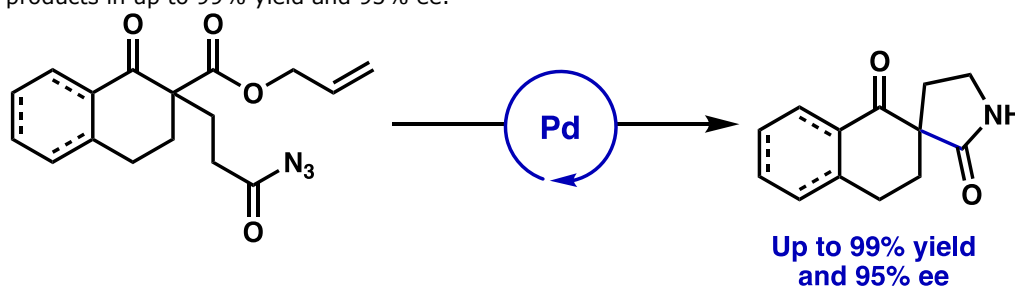
In population analyses of gravitational waves emitted by merging binary black holes (BBH), spin magnitude and tilt angle distributions provide key insights regarding BBH evolutionary histories and formation channels. Therefore, developing reliable BBH spin population models is essential. However, the effects of spin magnitude and tilt on gravitational wave signals are subdominant. Measurements of these parameters tend to be poorly constrained, posing challenges when assessing the accuracy of proposed population models. Posterior predictive checks (PPCs), a widely used model-checking method in gravitational wave science that compares observed data to the population model's predictions, demonstrate limitations when used on events with high uncertainties. We implement data-level PPCs and partial PPCs on simulated populations with known underlying parameter distributions to determine whether they perform better than traditional PPCs when evaluating inaccurate models. We have demonstrated the inability of traditional PPCs to identify inaccurate models when individual event measurements are highly uncertain. Additionally, we have shown that data-level PPCs are more discerning of deviations of the observed data from inaccurate model predictions than traditional PPCs. With certain choices of test statistics, data-level PPC  $p$ -values better reflect model misspecification, and traditional PPC  $p$ -value distributions can help to infer characteristics of the true population.

**Development of an Asymmetric Spirocyclization of Pd-Enolates and Isocyanates**

Rakel Ang

Mentors: Brian Stoltz and Jay Barbor

The synthesis of enantioenriched spirocyclic building blocks bearing an all-carbon quaternary center remains an ongoing challenge in the field of organic synthesis. Inspired by the Pd-catalyzed decarboxylative asymmetric allylic alkylation (DAAA) reaction developed in the Stoltz group, we now seek to utilize the chiral Pd-enolates generated under these reaction conditions to deliver spirocyclic  $\gamma$ -lactams *via* an interrupted allylic alkylation. Substrates bearing an acyl azide are subjected to a Curtius rearrangement which, following treatment with a chiral Pd catalyst, undergo decarboxylative enolate formation. Intramolecular cyclization with the pendant isocyanate delivers the spirocyclic  $\gamma$ -lactam products. The inclusion of a Meldrum's acid derivative was found to be essential for turnover, both protonating the lactam and engaging in reductive deallylation at the metal center. Preliminary scope yields products in up to 99% yield and 95% ee.

**Understanding the Squid-Vibrio Symbiosis via Nuclear Proteomics**

Stella Baldwin

Mentors: Margaret McFall-Ngai and Sonia Gasmi

Scientific understanding of host-microbe symbioses has increased over recent years. Beneficial microbes are now recognized as critical drivers of animal physiology (i.e., the human gut microbiome). Model systems like the squid-vibrio symbiosis, a beneficial partnership between the Hawaiian bobtail squid (*Euprymna scolopes*) and *Vibrio fischeri*, can reveal the biological and molecular mechanisms behind host-microbe communication, allowing for a better understanding of symbiosis establishment and maintenance. Previous studies indicated that  $^{15}\text{N}$ -labelled biomolecules of *V. fischeri* cells traffic strongly to the *E. scolopes* nucleus. However, the type and function of these biomolecules are still unknown. Our project focuses on locating and identifying *V. fischeri* proteins that target the light organ central core (CC) nuclei, where the squid hosts the symbiont cells. We first worked on separating the nuclei from the cytoplasm, and then we extracted and quantified the total amount of soluble nuclear proteins. These first steps let us choose the adapted proteomics technique to analyze our samples. Indeed, we had to find a high-sensitivity method, RAP-MS, to overcome the low amount of proteins extracted from the CC nuclei. Future directions involve employing this method to prepare our samples for mass spectrometry analyses.

**Investigating Phenazine-Mediated Interactions Between Bacteria, Fungi, and Wheat**

Miki Chiang

Mentors: Dianne Newman and Hannah Jeckel

Phenazines, secondary metabolites produced by many bacteria species, are known antibiotic and antifungal agents. But while the mechanism and utility of antibiotics have long been studied for therapeutic purposes, the native roles they play in shaping the plant rhizosphere are comparatively unexplored, despite these metabolites' widespread presence in soil (Perry and Newman, 2022). Developing an understanding of phenazines' influence on microbial interactions in the rhizosphere is particularly relevant to agriculture, as this knowledge may inform future farming practices or technologies for improving crop health. Furthermore, phenazines' impact on the relationship between bacteria and fungi could have ever broader relevance to native ecosystems and medicine, in areas where mixed bacterial and fungal communities are prevalent (Dahlstrom and Newman, 2022). Thus, the question that guides my research is "How do phenazines instigate or influence relationships between bacteria, fungi, and plants?" To pursue this question, I have established protocols for isolating fungi from wheat seeds and creating fungal spore suspensions for their long-term storage. I then characterized the fungal isolates' susceptibilities to phenazine-1-carboxylic acid (PCA) and pyocyanin (PYO) as well as the level of disease severity they cause in wheat plants to identify the most relevant candidates for further study. These results provide the basis for ongoing experiments to investigate how phenazine and fungal presence impacts the abundance of individual species in bacterial communities. Finally, I plan to explore the role of phenazines in induced systemic resistance (ISR) of plants by administering purified phenazines or phenazine-producing bacteria to wheat roots in the presence of fungi, thereby observing the simultaneous interactions between bacteria, fungi, and plants.

**Mitophagy Independent of Dynamin-Related Protein 1**

Robert Davis

*Mentors: David Chan and Yogaditya Chakrabarty*

Mitochondria are dynamic organelles essential for cellular energy production and regulation of metabolic pathways. These dynamic organelles consistently undergo fission and fusion processes which are essential to maintaining their productivity. Mitochondrial dynamics are crucial to maintaining a healthy mitochondrial population. Mitophagy, a crucial cellular process, preserves the overall quality of the mitochondria population through the selective degradation of mitochondria via lysosomes. However, the known mitochondrial fission factors, dynamin-related proteins Dnm1 in yeasts, and DNMI1/Drp1 in mammals are dispensable for some pathways of mitophagy. This protein selectively divides mitochondria to allow for autophagosomes to encapsulate and degrade. Our primary focus is unraveling the fission and fusion factors that are present in Drp1 dispensable mitophagy pathways. Drp1 knockout (KO) cell lines will be generated using the CRISPR-Cas9 system and mitophagy will be observed through fluorescence microscopy. These findings will provide more insight into the role of fission and fusion factors in the mitophagy process.

**Structural Determination of *Chaetomium thermophilum* POM152 Ig Domains**

Katelynn Horvath

*Mentors: André Hoelz and Sema Ejder*

The Nuclear Pore Complex (NPC) is the only bidirectional pathway for transport of macromolecules across the nuclear envelope. The fungal species *Chaetomium thermophilum* is used as a model organism for the human NPC because the overall shape and architecture is evolutionarily conserved. POM152 is an integral membrane protein in the NPC thought to provide structural support, regulate transport, and participate in signal transduction. At approximately 120kDa, ctPOM152 is too large to be crystallized as a whole and was thus separated by domain. The objective of this project is to produce optimized crystals for Ig3 and Ig9-10 to complete the structural dataset for ctPOM152. Ig3 and Ig9-10 were purified in a multistep process to minimize contaminants: first nickel affinity, then ion exchange, and finally size exclusion chromatography. Purified samples were used to set both commercial screens for new crystals and optimization screens. Crystals for Ig1-3 and Ig9-10 have been obtained but require further optimization. To this end, the purification process is being optimized and new constructs are being generated to increase yields. Complete and robust structural determination of ctPOM152 will begin to elucidate underlying mechanisms of essential functions carried out by the NPC.

**Concentration Robustness Inducing Invariant Biocircuit Signaling**

Max Janssen

*Mentor: Richard Murray*

The design of artificial biological circuits is a crucial component in the bottom-up construction of synthetic cells. Due to the nanoscale nature of the cells, large variations across compositions is an inevitable hurdle in the creation of scalable circuits. An early, invariant signal within the cell would provide the opportunity to build robust circuits by guaranteeing the strength of the inner signal regardless of the strength of the original signal. By introducing the two component *E. Coli* phosphorylation pathway EnvZ-OmpR to a synthetic cell, we can take advantage of the known concentration robustness that arises within the phosphorylated form of OmpR. The OmpC promoter that canonically is induced by phosphorylated OmpR can be assembled to mediate the expression of GFP as a proxy for the internal signal. The EMeRALD system is a synthetic reception system demonstrated in *E. Coli* that serves as an initial signal from transmembrane signaling. Here, we present the modulation of the EMeRALD system and the EnvZ-OmpR pathway to produce an invariant signal for synthetic cells in the presence of variant extracellular ligand.

**Reconstituting FGF Signaling In Vitro to Study Differential Signaling Dynamics Resulting From Ligand-Receptor Specificity**

Jasmine Murray

*Mentors: Angela Stathopoulos and Vince Stepanik*

Fibroblast Growth Factor Receptors (FGFRs) have tyrosine kinase activity that initiates a phosphorylation cascade that activates MAPK (Mitogen-activated Proteins Kinase) signaling, which is crucial for cellular behaviors like adhesion, migration, and division. This project focuses on two homologous FGF ligands, Pyr and Ths, which signal through the common FGFR Htl (Heartless). Despite sequence homology in their receptor binding FGF domains, Pyr and Ths have distinct functions, likely due to differences in how they activate Htl. Preliminary findings indicate that the kinetics of MAPK signaling activation differ: Pyr shows a rapid peak in MAPK response followed by a sharp decline, whereas Ths exhibits a slower and more sustained MAPK response. To investigate this further, we used western blot analysis to measure MAPK signaling levels at various concentrations and time points for both ligands to understand how MAPK signaling may differ based on these factors. To understand on a cellular level how Pyr and Ths may activate and interact with Htl in unique ways, we also utilized light microscopy to capture the colocalization of mCherry-tagged Pyr and Ths with Htl-GFP within cell vesicles over a similar time course. Furthermore, to investigate the role of Dof, an signaling adaptor protein that associates with Htl in the FGF

signaling pathway, we again examined MAPK signaling levels when Htl is exposed to either ligand. This study aims to dissect the molecular mechanisms of FGF signaling *in vitro* to understand how this signaling mechanism is diversified *in vivo* to induce a variety of cellular behaviors.

### **The Fluorescent Visualization of Cell Surface Molecules *in vivo***

Kevin Rostam

*Mentors: Kai Zinn and Shuwa Xu*

Neural circuits that regulate motor control are formed in a highly stereotyped manner and enable precise movements in both vertebrate and invertebrate systems. The efferent components of these circuits are motor neurons, which extend their axons to innervate specific muscular targets. While previous research has shown that terminal axon branching in the *Drosophila* neuromuscular system is mediated by protein interactions between two members of the DIP/Dpr cell surface molecule family, DIP- $\alpha$  and Dpr10, the signaling dynamics of these molecules are yet to be elucidated. Despite a wealth of genetic and molecular tools having been developed to alter and examine the morphology of motor neurons after the genetic knockout of these molecules, a method for visualizing their individual molecular dynamics remains elusive. While immunostaining is the most prevalent method, the process of generating numerous molecule-specific antibodies is difficult and often unsuccessful. More problematically, during later developmental stages as in the adult, the cuticle impedes antibody permeabilization, with attempts at dissection distorting tissue integrity. In characterizing the dynamics of these proteins, a peptide partner system has been employed to fluorescently tag cell surface molecules through a secretory process. Current results demonstrate successful tagging of cell surface molecules *in vivo* at larval, pupal, and adult stages of development.

### **Exploring Chaperone cpSRP43 Interactions With LHCP Transmembrane Domains via Crosslinking-Mass Spectrometry**

Abigail Strausbaugh Hjelmstad

*Mentors: Shu-ou Shan and Alex Siegel*

Chloroplast signal recognition particle 43 (cpSRP43) acts as a chaperone for light harvesting chlorophyll proteins (LHCPs) by preventing their hydrophobic transmembrane domains (TMDs) from aggregating in the stroma and delivering them to the Alb3 insertase at the thylakoid membrane. While interactions between the LHCP L18 loop at cpSRP43 Tyr204 is well characterized, the cpSRP43 interactions with LHCP TMDs that prevent their aggregation are poorly understood. Crosslinking-mass spectrometry (MS) was used to identify sites of cpSRP43 interaction with LHCP TMDs. Crosslinking was performed using p-benzoyl-L-phenylalanine (pBpa), a site-specific, photoinducible crosslinker, incorporated into the LHCP TMDs. The cpSRP43 interaction regions identified for each LHCP pBpa site may provide insights into cpSRP43 protection of LHCP TMDs.

### **Investigating the Impact of Dietary Tryptophan on Homecage Spontaneous Behavior in Mice**

Alyssa Vidal

*Mentors: Yuki Oka and Wongyo Jung*

Tryptophan, an essential amino acid, is a precursor to neurotransmitters and hormones including melatonin and serotonin, which play an important role in appetite, sleep and gut-microbiome regulation. Previous studies have reported that a tryptophan-rich diet can reduce depression and anxiety-like behaviors and enhance cognitive function, while a tryptophan-deficient diet can lead to gut microbiota dysbiosis and intestinal inflammation. In this study, we analyzed spontaneous behavior patterns in mice across three dietary groups: tryptophan-rich, normal tryptophan, and tryptophan-deficient. Preliminary results indicate that mice on a tryptophan-deficient diet experienced significant weight loss, reaching approximately 90% of their initial weight within 5 days, despite similar food intake compared to other groups. Additionally, the tryptophan-deficient group exhibited increased locomotor activity. For the remainder of the project, we will investigate potential factors contributing to this significant weight loss using machine learning algorithms to analyze their spontaneous behaviors in the home cage. This research aims to deepen our understanding of how dietary tryptophan affects spontaneous behavior, with potential applications in broader biological contexts.

### **Spectral Analysis Using BayesWave for Characterizing Remnant Outcomes in Binary Neutron Star Mergers**

Lana Alabbasi

*Mentors: Isaac Legred and Katerina Chatziioannou*

Neutron stars provide critical insights into the extreme physics of stellar structures. The detection of GW170817 initiated multimessenger astronomy by revealing both gravitational and electromagnetic signals. However, the sensitivities of current gravitational wave detectors limit the detection of the postmerger, which contains crucial information about the remnant's characteristics and the equation of state (EoS) of the neutron star's dense matter. This research project addresses this gap by analyzing postmerger frequency modes and their implications for different EoS by using simulated waveforms from numerical relativity. Employing BayesWave with Sine-Gaussian wavelets, gravitational wave signals are reconstructed to the sensitivity level of future detectors, such as Cosmic Explorer. Results show that BayesWave is effectively reconstructing the signals and is capturing peak and secondary frequency modes. This motivates further understanding of remnant evolution and the transition from a neutron star remnant to a ringdown indicating the formation of a black hole remnant. By exploring these modes across various simulations with varying total mass, including short-lived and long-lived neutron stars and simulations undergoing delayed collapse, this study aims to deepen our understanding of binary neutron star mergers.

### **Automating LIGO Glitch Witness Identification With OmegaNeuron**

Bri Aleman

*Mentor: Derek Davis*

The developing field of gravitational wave astronomy has seen significant progress thanks to instruments like the Laser Interferometer Gravitational-wave Observatory (LIGO), which has greatly expanded our knowledge of the collisions between black holes and neutron stars. However, the high sensitivity of these detectors and the vast amount of data produced both pose a challenge in distinguishing transient gravitational waves from transient noise, or glitches. Current processes involve Omega Scan, a tool used to provide detailed information on the transients and channels of interest, and GravitySpy, a citizen-science project that leverages machine learning and human input for glitch classification. OmegaNeuron, an innovative machine learning based tool, integrates datasets from both Omega Scan and GravitySpy to enhance glitch classification and elimination methods. In effectively identifying glitches and their witnesses in gravitational wave data, it contributes to detector improvements, which will provide deeper insights into the characteristics of compact binary coalescences (CBCs). OmegaNeuron indicates an advancement and a shift towards utilizing machine learning techniques in detector characterization and gravitational wave astronomy.

### **Seismic, Acoustic, and Electromagnetic Background Assessments for Future Cosmic Explorer Site Tests**

Carlos Campos

*Mentors: Michael Landry and Robert Schofield*

From June 11<sup>th</sup> to August 16<sup>th</sup>, we worked on preparing equipment, kits, and action plans in order to be used for Cosmic Explorer CE site testing. This needed to be done so that the CE surveyors are prepared and know what to do and look for when they get to potential sites. We worked on calibrating and configuring seismometers, magnetometers and microphones. These are used to read the environmental background noise. When configuring the seismometer, we discovered that it has an electronic lock that is controlled digitally. Its other functions are controlled the same way. This differs from prior models where there were physical buttons to activate its different abilities. With the magnetometer, we found some limitations with the digital to analog converter (ADC)'s software. To mend this issue, a Python code was written to widen our data analysis capabilities. We also had to construct hardware in order to connect our seismometer to the ADC as they were not compatible. After getting the equipment working, we created travel-ready kits for the surveyors to easily take from site to site. We also set out to identify transient noise in the area. This will be used to compare against the data collected at the site surveys, as well as giving the surveyors an action plan for how to conduct their surveys. These surveys will greatly decrease the amount of trouble shooting and calibrating that CE will have to undergo as they will be made familiar with the transient noise in the area.

### **Frequency Locking a Laser to Rubidium-87**

Briana Chen

*Mentors: Ian MacMillan and Lee McCuller*

To prevent frequency drifts over time, lasers are frequency-locked to reduce unwanted degrees of freedom in a system. This has applications in projects ranging from improving filter cavities in LIGO and GQuEST to atom trapping experiments. Lasers are typically locked, as in LIGO, using the Pound-Drever-Hall technique, which passes modulated light through a cavity to form a feedback loop tuning the laser frequency back onto resonance. However, the cavity only acts as a relative reference because its constituent mirrors are susceptible to fluctuations in distances, reflectivity, and transmissivity. In contrast, atoms have absolute transitions that enable them to be an absolute locking reference. Thus, we locked a laser to the D2 780 nm transition of Rb-87 via a similar feedback

loop as PDH locking. By passing a modulated probe beam and counterpropagating pump beam through a vapor cell of Rb-87, we can increase the resolution of locking and sharpen frequency discrimination. We also aim to use second harmonic generation to lock a 1560 nm laser to the vapor cell. Future work includes incorporating a specialized controller into the feedback loop to correct frequency drift with minimal overshoot.

### Quantum Noise Locking on Squeezed States

Jacob Cherry Sam

*Mentors: Rana Adhikari, Shruti Maliakal, and Koji Arai*

Gravitational wave detectors are highly sensitive instruments and are affected by a large number of noise sources. Quantum noise, originating from the vacuum field fluctuations that enter the anti-symmetric port of the interferometer, is one of the fundamental sources that affect its sensitivity. Squeezed states are used to tackle this problem as they can have lower fluctuations in a desired quadrature (squeezed quadrature) than the vacuum state. Squeezed states are represented as an ellipse in the quadrature plane. Noises in the interferometer can alter the orientation of this ellipse, which can result in coupling to the anti-squeezed quadrature which degrades the detection. This project aims at characterising a technique called Noise Locking to lock the squeeze angle and thus maintain the orientation of the ellipse. This technique can be used for vacuum-squeezed states and does not involve another phase reference other than the squeeze angle, which makes it experimentally simpler. This technique is modelled in an electronically simulated system of squeezing to investigate its performance. The future aim is to acquire and impart this technique onto the squeezed state in a Waveguide Optical Parametric Amplification (WOPA) system.

### Investing Methods of Fitting Quasinormal Modes in Numerical-Relativity Ringdown Signals

Erin Coleman

*Mentor: Eliot Finch*

The ringdown of a black hole merger can be decomposed into quasinormal modes (QNMs), and it has been suggested that the subset of QNMs known as overtones can contribute significantly. This work aims to measure the contribution of each overtone to the ringdown via fits to numerical-relativity waveforms, which has implications for analysis of ringdown signals and tests of general relativity (GR). We employ both least-squares and Bayesian fitting methods, and use several different metrics to determine each overtone's importance. The first metric used is the earliest time at which a model with  $N$  overtones is a good fit (i.e., the ringdown start time). Each additional overtone allows an earlier fit, however the change in start time decreases with  $N$ . The second metric introduces deviations from the GR frequency of each overtone. We found that the effect of deviations decreases rapidly with overtone index  $n$ . This implies it becomes harder to perform tests of GR with each additional overtone. The third metric is the stability of mode amplitudes between fits with different ringdown start times. It is known that least-squares fits are not optimal for studying amplitudes, and here we perform a Bayesian analysis for more robust results.

### Upconverted Light for GW Detector Control and Readout

Dhatri Raghunathan

*Mentors: Rana Adhikari and Radhika Bhatt*

The LIGO detectors, which are designed to measure the incredibly small disturbances caused by passing gravitational waves, must maintain a stable locked configuration. LIGO and its 40m prototype locks and stabilizes the primary laser to the arm cavity by using an auxiliary (AUX) laser as a reference. Noise budgeting catalogs all relevant noise sources to explain the observed noise, enabling targeted improvements to enhance the interferometer's stability and sensitivity. The first phase of the project aims to identify contributors to the noise spectrum through noise budgeting.

The LIGO Voyager upgrade aims to enhance high-frequency sensitivity by using high-power operation and highly squeezed vacuum states, with a strict squeezing loss budget requiring quantum efficiency (QE) of at least 99% at the 2  $\mu\text{m}$  operating wavelength. Sum-frequency generation (SFG) offers an alternative to improve photodetection QE by upconverting 2  $\mu\text{m}$  fields to 700 nm, allowing the use of traditional photodetectors like InGaAs or Si with QE of  $\geq 99\%$ . The second phase of the project is to demonstrate a single pass of SFG using a PPLN crystal and a pump of 1064  $\mu\text{m}$ .

### Using Nonlinear Crystals to Improve Gravitational Wave Detectors

Sarah Gates

*Mentors: Rana Adhikari, Shruti Maliakal, and Koji Arai*

To improve high-precision optical measurements, two components are required: reducing noise in the signal, and employing a sensitive, low-loss detection scheme. Nonlinear PPLN crystals are effective for both objectives. For example, optical vacuum states are squeezed in their observable quadrature to minimize intrinsic quantum measurement noise. Here, squeezing is simplified through the use of a PPLN crystal as a waveguide to create squeezed states through Spontaneous Parametric Down-Conversion. Waveguide squeezing is challenging because

beams must be mode-matched into a waveguide with a 4-micron aperture; yet, this was accomplished, allowing squeezing to be observed. Additionally, an electronic simulation was developed to model the control loop and lock onto noise in the signal, as is necessary to observe vacuum states. PPLN crystals also improve detector sensitivity under cryogenic conditions. In systems using 2000nm light, where the best photodetectors have only 85% quantum efficiency, PPLN crystals can initiate Sum Frequency Generation to convert 2000nm light into 700nm. An External Cavity Diode Laser was assembled as a 2000nm source, and both the signal and pump beams were mode-matched into the PPLN crystal's oven with a beam waist ratio of 200:70 micrometers. The process efficiency was then calculated.

### **Constraining the Precession of Binary Black Hole Systems Using New Parameters**

Charles Gibson

*Mentor: Javier Roulet*

The precession of Binary Black Holes (BBHs) can be informative of the formation channel of the system weakly/non-precessing systems are likely to have formed through binary stellar evolution, while strongly precessing systems may have formed dynamically. Despite the growing number of LIGO sources, evidence of precession is strongly debated in the literature. The parameter  $\chi_p$  is currently used to evaluate the precession of observed BBH systems. However,  $\chi_p$  is difficult to constrain to a narrow range of values for most events and can yield vanishing prior probability density at the aligned-spin configuration. We present an alternative spin precession parameter, the cosine of the angle between the total spin and the orbital angular momentum  $\cos(\theta_{LS})$ , that provides better localization of a precession value and allows a non-zero probability of aligned spins. We begin by testing  $\cos(\theta_{LS})$ ,  $\chi_p$ , and other parameters against synthetic data with known values to determine the best statistical measurement of precession. We then use  $\cos(\theta_{LS})$  to evaluate the precession in events from O3, the third observing run of LIGO and Virgo.

### **BayesWave++: Implementing a Bayesian Inference Package for Gravitational Waves in C++**

Maven Holst

*Mentors: Katerina Chatziioannou and Sophie Hourihane*

Gravitational waves (GWs) are minute ripples in spacetime detectable only by a global network of interferometer observatories that sense length changes on the scale of a proton. Despite the careful engineering of these observatories, GW signals are notoriously difficult to extract and characterize, often mimicked or masked by the significant detector noise caused by terrestrial events, meteorological interference, and instrument glitches. BayesWave++ is an improved C++ implementation of BayesWave, a Bayesian inference software written to enable signal modeling in this noisy environment. Using a transdimensional Reversible Jump Markov Chain Monte Carlo (RJCMC) algorithm, BayesWave++ fits sine-exponential wavelets to burst signals of both GW events and instrument glitches, and specific waveform templates from compact binary coalescence (CBC) simulations to GW events. Here, pipeline support for automated analysis of real GW data is added to BayesWave++, and a thorough review is conducted of the GW/glitch wavelet and CBC models to ensure proper algorithm performance. From this review, new issues throughout the BayesWave++ software are identified and corrected, and bounds are determined on the subset of parameter space in which the algorithm works well.

### **High Frequency Gravitational Wave Detection by Detuning GEO 600**

Christopher Jungkind

*Mentors: Brian Seymour and Andrew Laeuger*

We investigate whether the GEO 600 interferometer can be sensitive to gravitational waves in the kilohertz frequency range. Typically, most gravitational wave instruments are optimized for sensitivity around 100 Hz. However, a Michelson interferometer also has sensitivity near the half integer free spectral range peaks ( $\sim 62.5\text{kHz}$  for GEO). GEO's short arms and lack of Fabry-Perot cavities make it a sensitive interferometer at high frequencies. The key idea is that detuning the signal recycling mirror allows the first resonant peak to scan over the kilohertz range. Using Finesse, we create a noise budget for GEO 600 in the high frequency range for various detuning angles. We investigate how detectible boson clouds, sub-solar mass primordial black holes, and binary neutron star post-merger remnants would be for these setups. Using common waveform templates for these systems and optimizing the high frequency sensitivity of the interferometer, we determine the feasibility of detecting them with GEO 600.

### **Decoding the Effects of Varying Frequency Bands on GW Source Characterization**

Sena Kalabalik

*Mentors: Rhiannon Udall, Lucy M. Thomas, and Derek Davis*

Gravitational-wave (GW) science has opened new avenues for understanding astrophysical phenomena, with precise signal characterization being essential for interpreting these cosmic events. However, short-duration terrestrial noise transients, known as "glitches," complicate this task. A common strategy for mitigating the impact of glitches involves restricting the analysis to a reduced frequency band. In my work, I utilize a neural posterior estimator, a deep learning (DL) model, to investigate how varying frequency bands influence GW parameter



estimation for compact binary coalescences. I perform parameter estimation on artificial data, which include both simulated waveforms and noise realizations. By examining different frequency ranges, I aim to characterize the typical effects of these restrictions on the inference of the source parameters. Additionally, I focus on evaluating the use of a DL model in the GW parameter estimation pipeline. By comparing results obtained with the DL model and the conventional pipeline, I explore the effectiveness of deep learning approaches in improving analysis speed and accuracy. My ongoing work involves refining the network's capabilities and analyzing the impact of varying frequency bands on the reliability of parameter estimation.

### **The Impact of Astrophysical Population Model Choices on Post-Newtonian Deviation Tests of General Relativity**

Ruby Knudsen

*Mentor: Ethan Payne*

The Laser Interferometer Gravitational-wave Observatory detects gravitational waves and uses them to test the theory that predicts their existence: Einstein's theory of general relativity. Testing general relativity using gravitational waves can be done at the individual event level and the population level. Most current tests of general relativity are not inferred jointly with a population model to describe the astrophysical distribution of the sources. The omission of a population model describing the astrophysical population of binary black hole mergers inscribes an implied population model that may be inaccurate. This inaccurate population model could lead to biases in supposed deviations from general relativity. This investigation used injected signals of simulated binary black hole systems to infer the probability distributions for population model parameters. These probability distributions are constructed using Markov Chain Monte Carlo analysis. A family of mass population models was injected and recovered using each of the different models as the population distribution to determine whether biases in deviations from general relativity and population misspecification can be observed. Further research is needed as more gravitational wave events are detected and our understanding of the mass population distribution evolves.

### **Optical and Near-Infrared Searches for Gravitational Waves: Exploring Efficiencies**

Anurathi Madasi

*Mentors: Tomas Ahumada and Shreya Anand*

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is able to detect ripples in spacetime caused by a binary black hole or binary neutron star mergers known as gravitational waves (GW). Some of these GW events can have an electromagnetic(EM) counterpart, which can be seen optically using a telescope. This is known as multi-messenger astronomy, and having multiple sources of the same event provides insight into what the object is, where it from, etc. In our project, we aimed to test the efficiency of the Zwicky Transient Facility(ZTF) at detecting kilonovae. We populate a skymap with kilonovae, and test how many kilonovae ZTF can detect compared to how many we simulated. We updated our code from *simsurvey*, which is no longer being maintained, to *skysurvey*.

### **Vacuum Beam Guide for Quantum Communication**

Prakhar Maheshwari

*Mentors: Rana Adhikari and Aaron Goodwin-Jones*

Quantum communication at large distances is pivotal for the advancement of secure communication channels in various fields, offering unparalleled security. This technology's potential is exemplified in applications requiring low photon losses over vast distances, such as long-distance baseline interferometry. Our approach focuses on minimizing these losses through the innovative use of Vacuum Beam Guides. These guides offer a promising alternative to methods like satellite-based systems and quantum repeaters, potentially revolutionizing long-distance quantum communication. A Vacuum Beam Guide functions as a vacuum-sealed pipe that facilitates the transmission of quantum states over long distances with minimal loss. In this study, we focus on determining the optimal parameters for the practical implementation of Vacuum Beam Guides to facilitate quantum communication from the west coast to the east coast of the United States. This research provides key insights into the construction and operation of Vacuum Beam Guides, including critical parameters like lens separation and focal length for a given length of the vacuum tube. By addressing these challenges, we aim to pave the way for a more robust and efficient quantum communication infrastructure.

### **The Impact of the Differential Arm Length Servo on Photo Calibrator Comparisons**

Emmanuel Paluku Makelele

*Mentors: Richard Savage and Dripta Bhattacharjee*

The detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) are enhanced Michelson interferometers with four-km-long arms and 40 kg suspended mirrors. They detect differential arm length (DARM) fluctuations as small as  $10^{-19}$  m. A DARM servo maintains the interference condition and the servo error point and control signals are used to compute relative length changes induced by gravitational waves. To provide accurate absolute calibration, a Photon Calibrator (Pcal) system has been implemented at the end of each interferometer arm. By leveraging the insensitivity of the interferometer to which arm length is changing, calibration uncertainty

can be reduced by comparing Pcal fiducial displacements at two closely separated frequencies using a signal from the DARM servo. This comparison has been calculated continuously using the reconstructed *external* length variation signal by the LIGO group at Kenyon College since the beginning of the ongoing O4 observing run. Drifts as large as 0.2 % were observed in the LIGO Hanford Observatory (LHO) data over a year-long interval. To investigate the potential impact of changes in the DARM servo response at the two Pcal excitation frequencies, the Kenyon group also calculated the comparison using the DARM loop error signal. The ratio of the comparison calculated using the two methods yields the suppressed DARM loop sensing ratio. Data from May 2023 that includes the first six days of the ongoing O4 observing run reveal that the relative changes in the ratio of the response of the DARM servo at the two Pcal excitation frequencies were smaller than 0.0022 %. This may indicate that DARM servo response variations are not a significant contributor to the 0.2 % drifts observed in the Pcal calibration comparison factor. Efforts to extend this investigation to the rest of the O4 run are ongoing.

### **Mapping and Correcting the Wavefront of GQuEST End Mirrors**

Erin McGee

*Mentors: Lee McCuller and Daniel Grass*

GQuEST, or Gravity from the Quantum Entanglement of Space-Time, is an experiment with the goal of measuring fluctuations in space time using an ultra-sensitive tabletop Michelson Interferometer. This experiment requires high precision optics, including extremely thin high-reflectivity mirrors. This makes the optics extremely sensitive to small changes in their radius of curvature which can cause a misalignment in the modes of the light in the system. This can, in part, be mitigated by imaging the mirrors and matching the modes and by applying pressure to the mirror in a custom mount. The goal of this project is to develop a process for imaging and correcting the curvature of the mirror and analyzing how well the modes of different mirrors match.

### **Reinforcement Learning for Lock Acquisition of the LIGO 40-Meter Interferometer**

Kenny Moc

*Mentors: Rana Adhikari and Chris Whittle*

The current locking scheme at the LIGO 40-Meter Interferometer uses closed control loops to guard against noise and acquire lock. However, this linear control method is inefficient and time-consuming for a nonlinear system. In this paper, we present reinforcement learning as an alternative approach for lock acquisition, known as intelligent control. We first develop a neural network simulation of FINESSE 3, an interferometer modeling software, achieving a significant increase in simulation speed at the expense of some accuracy. This simulation is evolved in time with the noise forces present in the 40-meter laboratory. We then train a Proximal Policy Optimization (PPO) agent to acquire lock in the simulated environment. Our results demonstrate that the agent surpasses traditional methods by [to be determined], especially in regimes far from the operational point, due to its exploratory nature. This work is particularly relevant as future upgrades in laser power and interferometer complexity are expected to increase the frequency of lock loss. Intelligent control can reduce detector downtime, and our research lays the groundwork for a prototype implementation at the 40m interferometer.

### **Investigation of Narrow Spectral Artifacts and Lockloss Tagging**

Iain Morton

*Mentors: Camilla Compton and Ansel Neunzert*

LIGO data is imperfect, largely due to ongoing phenomena that interfere with data detection. As such, investigating certain disruptions in this gravitational wave detection is important for run analysis. This is true for both analyzing narrow spectrum artifacts over long searches (relevant to continuous wave searches), and for refining existing tools, which tag potential reasons for losing lock.

More specifically, change-point detection methods are proposed for identifying lines over LIGO noise. Our project incorporates using a window-sliding method to detect abrupt change-points over specified dates, which allows for understanding of narrow spectral artifacts.

Over the O4 run, a considerable number of locklosses are for unknown reasons. The Locklost tool correlates certain reasons for locklosses using Python plugins that tag events. This project involves developing a glitch plugin which establishes an amplitude threshold within a certain frame prior to the lockloss event itself. Furthermore, we are developing plugins that check for lockloss times in the input mode cleaner. These practices will ensure further refinement for detecting and analyzing various reasons for lockloss.

### **Using Symbolic Regression to Characterize Degeneracies in CBC Parameter Space**

Andres Nava

*Mentors: Aaron Johnson, Lucy Thomas, and Simona Miller*

Gravitational waves, detected by observatories like LIGO (Laser Interferometer Gravitational-Wave Observatory), carry rich information about astrophysical phenomena such as compact binary coalescences. Interpreting these signals is challenged by parameter degeneracies. Characterizing these degeneracies is difficult in practice,

especially during the merger phase of compact binary coalescences where approximate solutions to Einstein's equations break down. We address this by combining data-driven Symbolic Regression with machine learning to characterize degeneracies in binary black hole systems. We employ a deep neural network to predict the mismatch between gravitational wave signals and analyze the local geometry of the mismatch function with symbolic regression to uncover analytic dependencies between parameters. This approach aims to improve parameter measurability and enhance gravitational wave signal interpretation, advancing our understanding of binary black hole dynamics.

### **Reinforcement Learning for Lock Acquisition of the LIGO 40 Meter Interferometer**

Anubhav Prakash

*Mentor: Rana Adhikari*

Reinforcement learning (RL) offers an alternative approach to achieving lock acquisition in the LIGO interferometers, known as intelligent control. This project works on the application of intelligent control to the LIGO 40m laboratory interferometer, serving as a prototype for the full-scale implementation. We do this by first developing a neural network that replicates the simulation outcome of FINESSE 3, an interferometer modelling python package. Our neural network achieves an order of magnitude increase in simulation speed, for lowest order of Laser HG modes. Subsequently, we employed this neural network to train an Proximal Policy Optimization (PPO) agent to achieve lock. We then utilized this agent to lock the LIGO 40m Interferometer. Our results demonstrate that the agent surpasses traditional methods by [to be determined], and our agent was particularly effective in regimes far from the operational point, due to its exploratory nature. Thus, decreasing detector downtime. This work is especially pertinent as future upgrades in laser power and interferometer complexity will increase the frequency of lock loss.

### **Analysis of a Vacuum Beam Guide for Quantum Communications**

Hannah Rose

*Mentors: Rana Adhikari and Aaron Goodwin-Jones*

Current solutions for quantum communication channels such as telecom fibers and satellite relays face significant issues such as high loss and disrupted transmission. Huang et al. have introduced a vacuum beam guide as a promising new solution designed to provide a low-loss and stable quantum channel, with less than  $10^{-4}$  dB/km loss not subject to atmospheric variability. This system uses a periodically spaced array of lenses within an evacuated tube to propagate a coherent electromagnetic field over long distances with minimal loss. The initial proposal is limited to analyzing a confocal vacuum beam guide and calculates only absorption loss and a preliminary estimate of alignment loss. Our analysis further examines the performance of a generalized class of vacuum beam guide configurations with the inclusion of physical imperfections using computer optics simulations. These simulations were developed into software tools that allow for detailed evaluation and optimization of different vacuum beam guide configurations. By identifying a configuration's alignment tolerances, this work enables the development of a system that is suitably insensitive to realistic constraints. These results advance the vacuum beam guide closer to potential implementation as a quantum communication channel and contribute to the realization of reliable, continental-scale quantum communications with low loss and high throughput.

### **On the Current and Future Capability of Compact Binary Coalescence Parameter Estimation Methods**

Sterling Scarlett

*Mentors: Alan Weinstein and Jacob Golomb*

We introduce, understand, and interpret parameter estimation (PE), examining its role in analyzing Compact Binary Coalescence events (CBC) via their emission of Gravitational Waves (GW) and the measured GW strains by instruments such as LIGO, VIRGO, and the future detector Cosmic Explorer (CE). We explain and list all fifteen parameters that characterize of CBC. Understanding and looking at current methods of parameter estimation  $\textit{\{Bayesian inference, Fisher Matrix\}}$ , we investigate how each method is currently used  $\textit{\{Bilby\}}$ , future possibilities of the methods via machine learning  $\textit{\{Dingo\}}$ , and advancements in detectors  $\textit{\{Cosmic Explorer\}}$ . Conducting a comparative quantitative analysis with a methodology considering the speed, accuracy, and precision of the different methods and detectors, we aim to assess their efficiency and capabilities, offering insight on the future of PE of CBC events. We evaluate simulated events developed from a  $\textit{\{IMRPhenomXPHM\}}$  waveform approximation and similar phenomenological frequency-domain waveform approximations to develop our injections of a full spectrum of CBC events. Doing this allows us to measure greater accuracy, precision, and characterization of potential strengths and weaknesses of each waveform model and detector.

### **Characterization and Modeling of the LLO Squeezing System**

David A. Smith

*Mentor: Begum Kabagoz*

The introduction of frequency dependent quantum squeezing has allowed the LIGO interferometers to operate below the standard quantum limit dictated by shot noise, through the injection of squeezed quantum vacuum. As

an increase in the injected squeezing improves the astronomical detection range, it is imperative to track and reduce sources of loss within the squeezing system. This project utilizes the interferometer simulation programs, GWINC and Finesse, to build tools to model loss sources within the squeezing system informed by measurements. We use GWINC based interactive quantum noise fitting to make relatively fast and accurate quantum noise models from DARM spectra. Markov Chain Monte Carlo (MCMC) simulations are then used to determine quantum noise parameters and their confidence ranges. A comparison between both quantum noise inference methods is made using data gathered during O4b. After gaining insight on the parameters that affect frequency dependent loss, a Finesse model of the LLO Squeezer is made. The outcomes of this project will inform future commissioning efforts in the quest to improve quantum noise reduction.

### **Using the Binary Black Hole Population to Study Cosmology and the Stochastic Gravitational-Wave Background**

Jake Summers

*Mentors: Jacob Golomb and Alan Weinstein*

The stochastic gravitational-wave background is the overall signal of gravitational waves produced by a superposition of all binary black hole coalescences in the universe. We use new results from LIGO-Virgo-KAGRA to analyze the population of binary black hole coalescences and the gravitational-wave background expected to be caused by them. In analyzing the population of binary black hole coalescences, we consider several mass and redshift population models, using hierarchical Bayesian inference to infer the population. Using these population models, we compute the expected stochastic gravitational-wave background, finding agreement between the newest LIGO-Virgo-KAGRA catalogs and previous analyses. We also find that including the results from LIGO-Virgo-KAGRA O4a reduces the uncertainty in both the population models and the predicted gravitational-wave background. However, since the catalogs are limited to low-redshift binary black holes, there is significant uncertainty in the empirically predicted gravitational-wave background. Finally, using a phenomenological model for the merger rate as a function of redshift, we explore how changing the model behavior at high redshifts affects the predicted gravitational-wave background spectrum.

### **Seismic, Acoustic, and Electromagnetic Field Tests and Site Assessments for Cosmic Explorer (CE)**

Milena V. Tsioma

*Mentors: Michael Landry and Robert Schofield*

Cosmic Explorer (CE) is a concept for a future, third-generation gravitational wave observatory comprising two widely separated, large scale interferometers, up to 40 km in length, situated in North America. CE will be 10 times larger than the current Laser Interferometer Gravitational Wave Observatory (LIGO). Potential CE sites must have low environmental noise including seismic, acoustic, and electromagnetic backgrounds. In order to assess the suitability of potential Cosmic Explorer locations, we performed a series of initial tests of seismic, acoustic, and magnetic instrumentation and hardware. Tests were carried out at LIGO Hanford Observatory and at nearby offsite locations.

Our overarching goal of this project is to create a portable kit containing the necessary site-assessment instrumentation, such as a seismometer and magnetometer, while ensuring the equipment is accurate, reliable, weather-proof, and simple to transport and use for CE site testing. Another aim is to write a 'CE Kit Setup on Site Surveys' user manual to serve as a Quick Guide (QG) for setting up the instruments in the field and analyzing data on the go. The experiments performed in this project are a pathfinder in evaluating environmental noise at potential Cosmic Explorer sites.

### **Investigating Inspiral Gravitational Waveform Models With Eccentricity and Precession**

Isaiah Tyler

*Mentors: Lucy Thomas and Taylor Knapp*

Large banks of waveform templates are needed for both modeled gravitational wave searches, and for use in parameter estimation of signals. Having waveform templates that include both the effects of eccentricity and precession is important for increasing the physics output with parameter estimation. Furthermore, the same gravitational wave events can show evidence of eccentricity when analyzed with an eccentric model and show precession when analyzed with a precessing model since the effects on the waveform can mimic each other. Thus, models that include both effects are needed to discern which effects are present. In the present work, we attempt to generate waveform templates for the inspiral phase of compact binary coalescence that include both the effects of eccentricity and spin-induced precession. We investigate the features and limitations of current waveform models that have either eccentricity or precession exclusively. Orbit averaged spin and orbital evolution equations are used to calculate the time evolution of orbital quantities for a binary system with a set of initial conditions, which is then used to calculate the  $h_+$  and  $h_\times$  gravitational polarization modes.

**Improving Posterior Predictive Checks for Gravitational Wave Population Analyses**

Sophia Winney

*Mentors: Simona Miller and Katerina Chatziioannou*

In population analyses of gravitational waves emitted by merging binary black holes (BBH), spin magnitude and tilt angle distributions provide key insights regarding BBH evolutionary histories and formation channels. Therefore, developing reliable BBH spin population models is essential. However, the effects of spin magnitude and tilt on gravitational wave signals are subdominant. Measurements of these parameters tend to be poorly constrained, posing challenges when assessing the accuracy of proposed population models. Posterior predictive checks (PPCs), a widely used model-checking method in gravitational wave science that compares observed data to the population model's predictions, demonstrate limitations when used on events with high uncertainties. We implement data-level PPCs and partial PPCs on simulated populations with known underlying parameter distributions to determine whether they perform better than traditional PPCs when evaluating inaccurate models. We have demonstrated the inability of traditional PPCs to identify inaccurate models when individual event measurements are highly uncertain. Additionally, we have shown that data-level PPCs are more discerning of deviations of the observed data from inaccurate model predictions than traditional PPCs. With certain choices of test statistics, data-level PPC  $p$ -values better reflect model misspecification, and traditional PPC  $p$ -value distributions can help to infer characteristics of the true population.

### **Estimating Sea-level Fingerprints Using the Ice-sheet and Sea-level System Model With GRACE and GRACE-FO Data Over the Gulf of Mexico**

Alex Chung

*Mentors: Felix W. Landerer and Daniel Cheng Jet Propulsion Laboratory/California Institute of Technology*

The Ice-sheet and Sea-level system Model (ISSM) is a computer model that simulates the evolving polar ice caps in Greenland and Antarctica, and their impact on regional sea levels. It uses advanced numerical methods and tools to create Fingerprints for various regions of the world. Fingerprints describe how regional sea level changes depend on the location of changes in mass elsewhere over land. Gravity Recovery and Climate Experiment (GRACE) observed changes in gravity to infer mass changes within the Earth's water reservoirs, ice sheets, sea level and solid Earth. By implementing ISSM to GRACE data of the Gulf of Mexico, the Fingerprints pertinent to the Gulf of Mexico can be constructed, using techniques such as automatic differentiation. These models help us understand how sea level changes evolve regionally, and which processes are the most important ones that drive these changes. With these insights, mitigation and adaptation approaches for sea level changes can be implemented.

### **Detecting Organic Molecules in Star-Forming Regions With Markov Chain Monte Carlo Inference**

Kahaan Gandhi, Haverford College

*Mentors: Dariusz Lis and William Langer, Jet Propulsion Laboratory/California Institute of Technology*

Spectroscopic observations enable studies of chemical composition of star-forming regions based on their distinct molecular emission and absorption spectra. The difficulty of detecting complex organic molecules, which probe chemical complexity, scales with their size — emission from heavy molecules is distributed over many lines, too weak to detect individually. To address this, we adapt and implement a Markov Chain Monte Carlo (MCMC) algorithm to enhance signal detection in radio spectra from the Deep Space Network's (DSN) 70-m antenna in Canberra. We benchmark the MCMC algorithm on HC<sub>3</sub>N observations of the prestellar core Chamaeleon C2, demonstrating faster convergence and more efficient exploration of high-dimensional parameter space compared to the CASSIS spectral analysis package. Leveraging shared source properties, we use HC<sub>3</sub>N posteriors as priors for more complex molecules, improving the detection process for longer cyanopolyynes and elusive ring species such as benzonitrile. We develop a robust and scalable open-source software tool for MCMC inference of spectra, to be released alongside a publication reporting DSN observations of Chamaeleon, facilitating future research in molecular detection through sparse observations. This work contributes to NASA's abiogenesis program and is synergistic with the James Webb Space Telescope's infrared observations by providing complementary radio-frequency spectra of gas-phase species.

### **Analyzing JunoCam Images to Investigate Colors in the Jovian Atmosphere**

Shan Gupta – California Institute of Technology

*Mentors: Glenn Orton and Tom Momary – Jet Propulsion Laboratory, California Institute of Technology*

As the Juno spacecraft orbits Jupiter, its on-board push-frame camera, JunoCam, captures images of the planet's clouds. We use images of Jupiter taken by JunoCam over four years spanning both the polar and equatorial regions to investigate colors in the Jovian atmosphere. We conduct both clustering analysis and principal components analysis (PCA). Building on prior work using Hubble Space Telescope (HST) data, we find that Jovian colors can be broken into three components. The first appears gray and comprises approximately 90% of the images' variance; the second appears to be blue-absorbing and accounts for most of the remainder; the third component has a large green loading and makes up less than 1% of the variance. We observe that the variance captured by the second component, which represents a blue-absorbing chromophore or set of chromophores, varies spatially. We hold that equatorial regions, which have red-tinted clouds, strongly display the blue-absorber, while polar regions, which appear blue, have reduced intensities of that chromophore or set of chromophores. We also investigate the third component, which may be signal that adds green brightness. This study confirms that prior HST work holds at smaller scales.

### **Design of a Single Board Control System for Mössbauer Spectroscopy**

Ethan Labelson

*Mentors: Risau Toda, Mina Rais-Zadeh, Jet Propulsion Laboratory/California Institute of Technology*

Mössbauer spectroscopy provides new capabilities to a growing suite of sensors aboard off world missions. The ability to easily determine the oxidation state of iron makes it a powerful tool for geologic analysis on the surface. However, many Mössbauer spectroscopy units currently available are large and use many discrete components, making them impractical for use on missions off world. This project aims to implement a system which has a high-performance drive for the piezo actuator used in current Mössbauer setups, as well as data capture and acquisition. Instead of being separate, proprietary units, the entire system will be on a single PCB which is small enough to easily fit with the rest of the setup in a handheld container.

### **Describing and Simulating Rainbow Hazes in Jupiter's Atmosphere Using JunoCam**

Jeylin Lee, California Institute of Technology

*Mentors: Glenn Orton and Thomas Momary, Jet Propulsion Laboratory/California Institute of Technology*

JunoCam is a visible-light pushframe camera on board NASA's Juno spacecraft, designed to capture high-resolution images of Jupiter's atmosphere. JunoCam has repeatedly detected translucent "rainbow" hazes, which have a distinct separation of colors and always appear near Jupiter's terminator. The specific absorption and dispersion of colors through the rainbow hazes remain to be measured, which this project aims to quantify. A search through the JunoCam image gallery identified images with clear evidence of rainbow hazes. The U. S. Geological Survey's ISIS (Integrated Software for Imagers and Spectrometers) code was then used to process the raw archival data and identify the Sun azimuth line through each rainbow haze. Python-based code was created to analyze the data, using the brightness values for the red, green, and blue channels to generate quantitative signatures of color dispersion. A consistent pattern was detected with greater contributions from the blue channel on the sunward side and the red channel on the anti-sunward side of the beam. The physical distance over which the color dispersion takes place appears to depend on the size of the haze feature itself. The results of this project will enhance our understanding of the unique atmospheric features on Jupiter detected by Juno.

### **Accelerating Models for the Extragalactic Background Light in Preparation for SPHEREx**

Sean Lewis, Yale University

*Mentors: Tzu-Ching Chang and Jordan Mirocha, Jet Propulsion Laboratory/California Institute of Technology*

The light between resolved objects in images, known as the "Extragalactic Background Light" (EBL), encodes important information about our universe. The EBL Power Spectrum reveals this information by tracking features in the EBL as a function of the angular separation between them. Galaxies from the Epoch of Reionization, diffuse halos of stars (Intrahalo Light or IHL) and satellite galaxies around galaxies, and the diffuse galactic light (DGL) of the Milky Way all contribute to the shape of EBL power spectrum. The soon-to-launch satellite SPHEREx (Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer) will provide a detailed look into the EBL by taking near-infrared spectra of the entire sky in 6" x 6" pixels. Along the celestial poles, SPHEREx will take deep spectra that will allow us to create power spectra at 10 wavelength bands from 0.75 - 5  $\mu\text{m}$ . Modeling the EBL power spectrum to understand its make up is a challenging task; N-body simulations take extreme computational time while analytical models are quicker but have many parameters (around 40) to constrain. Emulators are a method of speeding up these initial wide parameter space searches by taking a database of model runs and fitting or interpolating between them. We created an emulator using a deconvolutional neural network that can accurately mimic EBL power spectrum models from the Python package ARES and decrease the time of individual model runs by orders of magnitude. We demonstrate its use in reconstructing parameters through Markov Chain Monte Carlo (MCMC) methods and show its uncertainty in reconstructing these parameters at different masking depths. We will use this emulator or its improved versions in interpreting data from SPHEREx and using it to provide insight into the properties of galaxies across cosmic history.

### **Measuring Heat Stress in Southern California**

Carolina Lopez, California Institute of Technology

*Mentors: Colin Raymond and Huikyo Lee, Jet Propulsion Laboratory/California Institute of Technology*

The rise of global warming has led to an increase in heat stress around the world, posing a threat to local communities in Southern California. Analyzing climate and Earth system processes on regional scales is essential for assessing the impacts of climate change on people and our natural resources. Traditional methods of capturing meteorological variables such as temperature and humidity show disparities between neighborhoods. However, multivariate heat stress across Southern California has not been previously documented. We apply the Universal Thermal Climate Index (UTCI) metric, which combines air temperature, humidity, wind, and radiation, to measure the effects of each variable on neighborhoods during heatwaves and establish a pipeline for environmental justice and heat mitigation efforts. By utilizing NASA's MERRA-2 reanalysis data and Argonne's ADDA downscaled data, we integrate UTCI parameters into high resolution model output to better understand heat stress at each layer and the effects each variable has on the UTCI. We also explore overlaying findings with socioeconomic data to identify disadvantaged communities and advise tailored heat mitigation policies. Our approach offers a more accurate prediction of heat stress and targeted heat mitigation strategies in the wake of rising global temperatures.

### **Inferring the Presence of Habitable Worlds in Multi-Planetary Systems Observed by Kepler**

Moises Mata (Columbia University)

*Mentor: Yasuhiro Hasegawa (Jet Propulsion Laboratory/California Institute of Technology)*

The over 5,000 confirmed exoplanet population has allowed the statistical analysis of observed planetary system characteristics (e.g. planet radius, semi-major axis, inclinations) however we cannot constrain intrinsic features of these systems (e.g. the presence of habitable planets, true multiplicity) due to the bias inherent to observational techniques. We utilize existing distribution functions of the planetary system characteristics to generate thousands of systems that represent the intrinsic state of the in-situ model of planetary formation. We produce a pipeline that uses this simulated data, applies an observation simulator to create a "biased" dataset, and finally trains

classification models that predict whether a biased system will contain planets in habitable zones. We attempt the application of these models to observed systems found likely to be formed via in-situ formation and predict the presence of habitable worlds within them. Within our unbiased data, we find separations between habitable and uninhabitable systems when plotting measures like average eccentricity, ratio of semi-major axes between the inner and outermost planets, and dynamical mass as notable — we set out to find these separations through different biasing scenarios as well and identify which observed systems are likely to host habitable exoplanets.

### **Mars Helicopters With Payloads: A Study of Single-Rotor Coaxial vs Multi-Rotor Helicopter Designs for Chopper**

Giannka Picache, Stanford University and Jet Propulsion Laboratory/California Institute of Technology  
*Mentors: Laura Jones-Wilson and Clara O'Farrell, Jet Propulsion Laboratory/California Institute of Technology*

In 2021, Ingenuity demonstrated a first-of-its-kind extraterrestrial helicopter flight on Mars with a single-rotor coaxial design. However, Ingenuity was not designed to carry a payload or perform science. As NASA looks to leverage Ingenuity's resounding success into a science platform, the Chopper study is dedicated to exploring Mars helicopter designs with a payload mass of 3 kg and a traversal distance of 3 km/sol. A major question about the helicopter design is the rotor count—should the Chopper design stay with a single-rotor or go to a multi-rotor configuration? Our analysis indicates that multi-rotor designs generally scale better and have better margins in the design environment compared to single-rotor designs, given a set of constraints (i.e. aeroshell size). A published JPL-led study for a Mars Science Helicopter (MSH) converged on a hexacopter design, suggesting that other studies of this type came to similar conclusions. However, a discussion of the practical limits of the single-rotor coaxial design—and a direct comparison to multi-copters—have not been documented in literature. In this study, we compare the sensitivities of a single-rotor to a multi-rotor and characterize how different design elements influence performance metrics such as payload mass. We use flight performance and mass models, along with informed margin policies, to directly compare different designs and to guide a discussion of why large payloads drive us toward multi-rotor configurations. These results inform a fundamental architectural question in Mars helicopter evolution while justifying a multi-copter design as the next iteration of a science-capable Martian aircraft.

### **Noise Reduction and Computational Analysis of Thermal Imaging of Jupiter to Deduce Atmospheric Properties**

Arjun Pradhan, California Institute of Technology  
*Mentors: Glenn Orton and Thomas Momary, Jet Propulsion Laboratory/California Institute of Technology*

This project focuses on improving thermal images of Jupiter captured by the Mid-Infrared Imager and Spectrometer (MIRSI) at NASA's Infrared Telescope Facility, which often suffer from vertical striping that affects atmospheric details. To address this noise, our team developed and tested several algorithms, including a Convolutional Neural-Network algorithm, a boxcar-averaging algorithm, a grid-search algorithm, and a gradient-descent algorithm. After extensive comparisons, we selected the gradient-descent algorithm due to its superior performance in reducing stripe noise efficiently while preserving image granularity. Initially developed in Python, the code was later adapted for integration into the Data Reduction Manager (DRM), a graphical user interface within JPL's server infrastructure that operates in the Interactive Data Language (IDL). Integrating the algorithm into DRM required substantial modification, as IDL code does not have the same optimization and morphological packages as Python. After completing this integration, and refactoring our algorithm, our team is now processing and destriping years' worth of planetary data from Jupiter through a user-friendly interface. The scope of the code will be further extended to work on archival datasets from Saturn and Venus, allowing our team to destripe years of data from these planets as well.

### **ENDURANCE Hazard Assessment: Validation and Integration of OBKS Algorithm**

Zhonghe (Catherine) Zheng, California Institute of Technology  
*Mentor: Ashish Goel (Jet Propulsion Laboratory/California Institute of Technology)*

In the recent Planetary Science and Astrobiology Decadal Survey, NASA identified the EnduranceA mission concept for collecting samples from South Pole-Aitken (SPA) as one of its top priorities. The proposed Endurance rover will autonomously traverse ~2000 km on the far side of the Moon, through a wide variety of terrains under varying illumination conditions. A crucial part of autonomous driving is hazard assessment and avoidance: given a path, how does the robot know if the path is collision and hazard free, in the presence of both positive and negative obstacles? Past projects at JPL had developed Optimization Based Kinematic Settling (OBKS), that evaluates the rover at discrete points along a potential path and determines if the rover is in a "safe" configuration. This presentation focuses on the adaptation of the algorithm for Endurance, validation against a physics-based simulation (DARTS) and its integration with a state lattice planner.