



2025 Student Abstract Book



Cloud watching in the simulated circumgalactic medium

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Mentors: Lars Hernquist, Cameron Hummels, and Scott Lucchini

The circumgalactic medium (CGM), the diffuse halo of multiphase gas surrounding the galaxy, is crucial for regulating accretion and feedback processes. Despite temperatures reaching $\sim 10^7$ K within the CGM, cool clouds ($< 10^{4.5}$ K) could play a key role in renewed star formation. However, due to small scale structure, studying these clouds in hydrodynamical galaxy simulations is difficult. We utilize the new cosmological zoom simulation suite, ENhanced Galactic Atmospheres with Arepo (ENGAWA) with IllustrisTNG physics to study a Milky Way-like galaxy at four different resolutions, including the highest resolution of 200 pc within the inner CGM. Through analysis of how temperature, metallicity, and other properties shift across the cloud boundary layer, we present an improved understanding of the transition between gas within the cloud and the surrounding medium. We quantify the differences in these cloud-centric radial profiles as a function of cloud size, as well as resolution, to better understand the effect of these variables on gas mixing around galaxies.

Evaluating late-time nebular spectral features for progenitor mass in stripped-envelope supernovae

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Mentors: Mansi M. Kasliwal and Kaustav Das

Determining the progenitor masses of supernovae are crucial to understanding the processes that underlay their formation. Of particular interest are stripped-envelope core-collapse supernovae (SESNe), which have their hydrogen and/or helium layers stripped. Two methods are currently in use to determine their progenitor mass: a correlation between the ratio of [O I] $\lambda\lambda 6300, 6364$ and [Ca II] $\lambda\lambda 7291, 7323$ and the kinetic energy of the explosion, and a fitting using the fractional flux of the [N II] $\lambda\lambda 6548, 6583$ line. However, these methods have only been tested in models and small sets of supernovae, meaning a more comprehensive approach is needed. By comparing these methods on a large database of supernovae, we find that the [O I]/[Ca II] method is more consistent and applicable towards a larger range of spectra, while the [N II] method is only applicable to a smaller set of supernovae and has less reliable results.

Studying detector noise properties for precise EBL measurements for SPHEREx

Iori Adachi

Mentors: James J. Bock and Chi Nguyen

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) is a telescope that aims to answer key questions about the history of the universe, galaxies, and ices on exoplanets by observing and studying the Extragalactic Background Light (EBL). SPHEREx is equipped with 6 H2RG detectors which allows the telescope to capture precise spectral information. Although the amplitude of the detector read noise is low, the noise is correlated on spatial scales comparable to astrophysical signals we aim to measure. This correlation makes it particularly difficult to study as it can introduce artificial fluctuations that mimic real cosmic signals. The goal of this project is to evaluate the noise performance of flight detectors by comparing calculated detector noise from flight data to pre launch noise data. First, we validated the noise of optically dark pixels, also known as reference pixels, using pair-differenced images. Next, we calculated the per-pixel noise estimates of optically active pixels and found they matched expectations, though some residual photon signals in the noise estimates require further analysis.

Bootstrapping methods for matrix quantum mechanics and quantum field theory

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Mentors: Xi Yin, David Simmons-Duffin, and Joshua Sandor

This project is aimed at improving bootstrapping methods for matrix quantum mechanics and quantum field theory. The bootstrap method is an analytic alternative to Monte Carlo simulation that produces rigorous bounds on the expectation values of observables. The large N limit of the two-matrix anharmonic oscillator is of particular interest since it is conjectured to be a minimal truncation

of BFSS dual to a string theory of black holes. Energy eigenvalues of the single particle anharmonic oscillator, large N one-matrix case, and large N two-matrix case were bounded without logarithmic relaxation using the Quantum Information Conic Solver.

Optimization of iontophoresis drug delivery device for surpassing the blood brain barrier

Layla Adeli

Mentors: George Malliaras, Azita Emami, and Andrew Setley

Glioblastoma treatment is heavily limited by the blood-brain barrier (BBB), as it prevents the majority of effective chemotherapeutics, such as Doxorubicin, from reaching brain tissue. However, iontophoresis is a method that uses electric fields to drive charged drug molecules, and offers a promising approach for the controlled and localized delivery that bypasses the BBB. This project aims to optimize an iontophoretic drug delivery device by varying the pore size of permeable cellulose membranes to improve drug delivery efficiency and is structured in three phases, including device fabrication, evaluation of various membranes using saline solutions, and in vitro testing using Rhodamine 6G and Doxorubicin. Early results indicate that membrane pore size and surface chemistry have less of an influence on drug transport than previously hypothesized, and that they have varying effects on the electric field dynamics. Challenges such as drug adsorption in cellulose membranes and reduced current output have been addressed continuously by modifying the pre-treatment of the membrane, reducing channel resistance, increasing electrode surface area, and adjusting pH for conductivity. This work as it progresses contributes to the development of implantable systems for targeted drug delivery to glioblastoma tissue, offering a potential alternative to standard chemotherapy.

Identifying differential methylation of distinct T cell intra-lineage sub-populations

Joe K. Afful

Mentor: Ellen Rothenberg

In the T-Cell lineage commitment program, there are three phases of differential transcriptional expression that corresponds to major shifts in cellular identity. This research aims to use Enzymatic Methyl-seq to build epigenetics landscape across these three phases. This could reveal novel potential regulatory regions in the genome required for change in cellular identity. Furthermore, the expression levels of PU.1 a non-T-lineage (myeloid) transcription factor would be perturbed to distinguish its role in diverting lineage fate epigenetically.

Experimentation and development of a snake robot jamming gait

Diya Agarwal

Mentors: Howie Choset, Gunter Niemeyer, Andy Vu, and Bhaskar Vundurthy

Modular snake robots are essential tools for search and rescue applications due to their flexible structure and diverse locomotion capabilities. While existing gaits—modeled after biological snakes—allow the snake to navigate on flat surfaces and pipes, they often fail in unstructured environments, such as in rubble-filled voids or complex truss structures. This research addresses that gap by developing a biologically-inspired jamming gait, where the snake creates anchor points to move forward by pressing itself against uneven surfaces. This jamming technique supports the snake's weight and facilitates forward motion. The main objective is to use these static friction holds to develop a stable and controlled way to reach elevated surfaces in irregular or non-planar environments. To characterize this behavior, our main methodology involves a series of controlled experiments to determine optimal jamming configurations, strength, and repeatability by varying joint angles and contact forces. An adjustable 3D testing structure will be designed and constructed to facilitate these tests. While results are pending, this project will define parameters for a reliable jamming gait. This work will provide a foundational understanding of this novel locomotion and the capabilities of the snake robot, and offer further recommendations for its implementation in autonomous systems.

LLM-driven intelligent biomarker data extraction

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Mentors: Ashish Mahabal and Sean Kelly

The Early Detection Research Network (EDRN) is a national consortium of scientists and institutions led by the National Cancer Institute, focused on the discovery, development, and validation of biomarkers for cancer risk assessment and early detection. EDRN maintains a range of biomedical datasets, including a Biomarker Database that is made available to partner institutions such as Caltech and JPL for research and analysis. This EDRN Biomarker Database contains rich, descriptive entries critical for biomedical research and clinical applications. However, these descriptions are often verbose, making it difficult to directly utilize important details—such as biomarker status, associated disease, and assay methods—for structured analysis or querying. In this project, we aim to develop a large language model (LLM)-powered agentic system to extract and organize key biomarker attributes from descriptive texts. The current system uses a chain of prompt-engineered LLMs to interpret the natural language content and produce structured output that we can use to add and populate additional fields in the EDRN database, enhancing their quality and usability. Extracted information is currently verified manually, with the long-term goal of enabling systematic validation through consistency checks. Ultimately, we aim to extend this system to extract structured biomarker information directly from published literature, reducing manual curation effort and accelerating the integration of new biomarker findings into structured repositories.

Integration and testing of components for the ATLAS high luminosity upgrade to the Large Hadron Collider

Mitchell J. Agris

Mentors: Caterina Vernieri and Michele Papucci

The High-Luminosity LHC (HL-LHC) upgrade will significantly increase the luminosity of proton-proton collisions, requiring substantial upgrades to the ATLAS detector. By focusing on pre-production integration and testing, this project supports the development of the new all silicon Inner Tracker (ITk), which senses the products of colliding protons in the LHC. The objective was to develop a procedure to assemble detector support structures and testing boxes in addition to testing modules and connecting electrical services to testing boxes. Methods included assembling 3D-printed mechanical rings into carbon-fiber frames and installing them into a quarter shell, mounting the cable tray, and preparing a service box for high-voltage, low-voltage, and temperature-sensing connections. Additionally, we built a testing chamber to validate the electrical and mechanical properties of loaded supports. Over the course of the project, we observed improved dew point performance in the small testing boxes, successfully integrated rings into the first quarter shell, and identified procedure inconsistencies requiring a detailed updated procedure. Future goals include full shell integration and finalization of electrical service assembly. This work provides procedural insight for streamlining full-scale production and integration of the ATLAS ITk detector.

Enhancing Motion and Sash Height (MASH) alarms to increase fume hood energy efficiency

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Mentors: Julia A. Kornfield, Dennis L. Ko, Maximilian Christman, and Tasha Cammidge

Fume hoods account for 40-70% of a laboratory's total energy consumption, with each unit consuming the same amount of energy as 3.5 households in the US per year. Furthermore, when fume hoods are left open without a user present, energy usage increases unnecessarily. To address this problem, others developed the Motion and Sash Height (MASH) sensor, a fume hood monitoring device with active feedback to alert lab users when a fume hood has been left open and unused for a set amount of time, which helped labs save energy. Our work addresses limitations in the original design by improving performance, data transfer, visualization, design, and scalability. These enhancements not only streamline deployment and usability but also support educational outreach to reinforce best practices among fume hood users. Upon the deployment of the improved sensor, we observed a measurable decrease in average sash height and overall energy consumption. These results suggest that this advancement lays a strong foundation for reducing energy usage across laboratories worldwide.

Characterizing WISEA J064750.85-154616.4, a new L/T transition binary system

Ethan A. Alderete

Mentors: Trent Dupuy and Andrew W. Howard

Brown dwarfs cool over time, evolving through distinct spectral types. The transition from L-type to T-type is of particular interest due to its rapidity and poorly understood physical mechanisms. We aim to provide more insight into these processes by quantifying the physical and spectral characteristics of WISEA J064750.85-154616.4 (J0647), a binary whose components lie near or in this transition. Direct images of J0647 were taken by the Near-infrared Camera, Second Generation (NIRC2) instrument on the Keck Observatory between 2015 and 2024. By reducing these images, we obtain Separation and Position Angle measurements in milliarcseconds and degrees, respectively. We use the open-source Orbits from Radial Velocity, Absolute, and/or Relative Astrometry (orvara) Python package on those measurements to obtain an orbit profile of J0647, containing physical parameters such as the orbital period and total dynamical mass. Using absolute astrometry measurements from the Wide-field InfraRed Camera (WIRCam) Canada-France-Hawaii Telescope (CFHT), we find the binary's parallax and proper motion; combining this with the orbit fit from orvara, we calculate the individual masses of each companion and other physical parameters. In addition to imaging analysis, we have a total spectrum of J0647, obtained from the Keck Observatory. As Keck's spectrometer cannot resolve the binary's components, we estimate the individual spectra using a reduced Chi-Squares technique which attempts to re-create the total spectrum of J0647 from binary addition of single spectra taken of field brown dwarfs. We intend to use these new-found physical and spectral properties to test the efficacy of different brown dwarf evolutionary models, thereby helping understand what may lead to and cause the brown dwarf L/T transition.

Scalable second-life battery management system for stationary energy storage

Jacob R. Alderete

Mentor: Runar Unnthorsson

The rapid growth of electric vehicles has generated an abundance of end-of-life lithium-ion cells, presenting an opportunity for cost-effective stationary energy storage if reliable second-life management systems can be developed. This project develops and validates a scalable battery management system (BMS) for repurposed electric-vehicle cells in stationary energy storage applications. Starting with a 4-cell proof-of-concept, we have refined both hardware and firmware to support 30 V and 50 V assemblies, including improved current and temperature sensing, enhanced thermal management, and reliable relay control. We have adapted existing control software for automated cycling and balancing validation, and designed compact enclosures that integrate factory thermistors and BMS electronics. These 30 V and 50 V modules are designed to be deployed in parallel banks, allowing capacity to be scaled to multi-kilowatt-hour levels for grid-tied or off-grid applications. Ongoing work encompasses comprehensive capacity and cyclability testing under IEC 61960-3 protocols, the development of passive balancing strategies for idle periods, and field deployment at off-grid sites. Together, these efforts aim to demonstrate a cost-effective, reliable second-life energy storage solution that advances sustainable, circular-economy practices.

Comparative analysis of relative earthquake relocation methods: ReSpair and GrowClust3D.jl applied to the Bárðarbunga volcanic region

Levi J. Alderete

Mentors: Elias Heimisson and Ylse Anna De Vries

This project investigates two computational approaches for improving the relative relocation of seismic events: ReSpair, a MATLAB-based optimization method, and GrowClust3D.jl, a Julia-based clustering algorithm. The primary objective is to evaluate how each tool performs when applied to real seismic data, using the Bárðarbunga volcanic region in Iceland as a test case. The project integrates differential travel-time data with velocity models and applies iterative relocation routines under various threshold parameters. The ReSpair codebase was modified to enhance scalability and efficiency, allowing for systematic experimentation with event inclusion criteria. Preliminary results suggest that relocation accuracy and coverage are sensitive to parameter tuning, particularly

threshold values controlling event clustering. Future work will refine these parameters and conduct quantitative comparisons of output catalogs from both tools. This study contributes to ongoing efforts in high-resolution earthquake mapping by providing insight into the comparative and strength of a widely used relocation method and the developing ReSPair method.

Photophysics and photochemistry of a thioxanthone dimer

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Mentors: Daniel G. Nocera, Ryan G. Hadt, and Matthew Drummer

Organic photoredox catalysis has emerged as a powerful tool to drive a myriad of challenging chemical transformations. A notable organic photoredox catalyst is thioxanthone, which is competent for energy transfer, single-electron transfer, and hydrogen atom transfer reactivity through its triplet excited state. Thioxanthone, however, suffers from a low triplet quantum yield (TQY), particularly in polar solvents, which are often necessary in synthetic applications, making it less attractive compared to ruthenium and iridium based polypyridyl complexes. A potential strategy to enhance TQY is through H-dimerization, where multiple chromophores are stacked in an offset side-by-side arrangement. In this work, H-dimerization is successfully exploited as a strategy to achieve near unity (97.5%) TQY in a molecular thioxanthone dimer ("TXXanth") in benzene. The ultrafast excited state dynamics and reactivity of TXXanth were then probed with a range of femtosecond and nanosecond transient absorption measurements and a suite of complementary photophysical techniques.

Chiral allene formation via vinylcation intermediate

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Mentors: Hosea Nelson and Yucheng Fu

Allenes are unique π -conjugated systems with axial chirality that make them valuable precursors for materials with circularly polarized luminescence and self-assembly properties. Current strategies for enantioselective allene synthesis rely heavily on metal-catalyzed transformations of alkynes, while purely organocatalytic approaches remain underdeveloped. In this work, we investigate a novel pathway to chiral allenes through vinyl cation intermediates, a high-energy species traditionally generated via solvolysis or vinyl triazene protonation. Building on recent advances in vinyl cation stabilization through strong Lewis acids and tailored leaving groups, we aimed to design ion-pairing catalysts capable of both promoting vinyl cation formation and imparting high enantioselectivity. Our synthetic efforts focused on preparing protected ion-pairing precursors, including MOM- and Me-protected dibromo intermediates, with characterization confirmed by NMR and high-resolution mass spectrometry. Although attempts at final catalyst formation using carborane coupling encountered challenges, our progress demonstrates the feasibility of stabilizing vinyl cations for asymmetric transformations. Ongoing work will optimize protecting groups and catalyst design to enable efficient, enantioselective chiral allene synthesis via this underexplored β -H elimination pathway.

Design of an electromagnetic cat qubit and development of Josephson junction fabrication process

Parthorn Ammawat

Mentors: Oskar J. Painter and Piero Chiappina

Superconducting quantum processors are inherently susceptible to decoherence due to unavoidable interactions with their environment, leading to frequent bit-flip and phase-flip errors. While the theory of quantum error correction (QEC) and its fault-tolerant implementation addresses this issue, the required hardware overhead remains challenging. Cat qubits, which encode quantum information in superpositions of coherent states in a resonator, have recently emerged as a promising alternative as they allow for exponential suppression of bit-flips, significantly reducing the need for active correction. In this work, we design and fabricate an electromagnetic-based cat qubit with a modified architecture to further reduce the hardware overhead and to establish the group's cat qubit measurement capabilities. This will also serve as a first step toward realizing a hybrid acoustic-electrical cat qubit

incorporating a mechanical quantum memory, which offers significantly longer lifetimes and smaller footprints and thus presents a promising new direction for building scalable and robust quantum processors. We also developed a new Josephson junction fabrication process to enhance the coherence and overall performance of future superconducting devices in the group.

Observable-projected ensembles

Yuvan Anand

Mentors: John P. Preskill, Alexey Milekhin, and Sara Murciano

We investigate the observable-projected ensemble, an ensemble of subsystem states conditioned on measuring an extensive bath observable, in order to study quantum thermalisation. While the conventional projected ensemble forces us to perform a full projection onto the set of states in the bath, and therefore scales exponentially with bath size, the observable-projected ensemble circumvents this by projecting only onto the quantum numbers of a Hermitian operator on the bath.

We are interested in the closeness of the k -th moment of the ensemble to the Haar ensemble, the uniform distribution over the total set of states. By bounding its Lipschitz constant, we find that the k -th moment of this ensemble clusters closely around its expectation value in a predictable way. Where we encounter complications, however, is trying to find its expectation value over the Haar ensemble. In particular, we project onto observable outcomes with projectors that have rank ≥ 1 , which tells us that the reduced density matrix of the ensemble and its associated probability are not independent. We derive conditions under which we can assume them to be independent. Despite this, we find that our ensemble exponentially diverges from the Haar ensemble as our bath size grows.

Thus, we consider instead focusing on eigenstates of chaotic hamiltonians, rather than the broader information theoretic approach used before. This allows us to use the tools of ETH (eigenstate thermalisation hypothesis) to derive the Haar random behaviour we expect. We use the so-called 'Many Body Berry Conjecture (MBBC)', from Lu, Grover (2018); treating overlaps with the bath and the eigenstates as independent random Gaussians could reproduce Haar-like behaviour, and could remedy the divergence of the observable ensemble from the Haar ensemble. We show that the MBBC, along with basic ETH assumptions, produce Scrooge-like behaviour, a deformation of the Haar ensemble.

Investigating the HD 984 system with the Keck Planet Imager and Characterizer

Anica J. Ancheta

Mentors: Dimitri P. Mawet and Katelyn Horstman

Different types of substellar companions, such as brown dwarfs and planets, have different formation pathways. Investigating these pathways is key to understanding how these objects form, and therefore understand if our own solar system possesses unique conditions to support life. HD 984 A is a 1.2 solar mass F7V star known to host a hot brown dwarf companion, HD 984 B, previously imaged with the Keck Planet Imager and Characterizer (KPIC) between August 2022 and November 2024. This project investigates the possibility of a second brown dwarf in the HD 984 system, which could classify the system as a brown dwarf binary (BDB). We leverage KPIC's unique capabilities of combining direct imaging and high-resolution spectroscopy ($R \sim 35,000$) over multiple epochs of data, and utilize the KPIC data reduction pipeline in conjunction with the Broad Repository for Exoplanet Analysis, Detection, and Spectroscopy (BREADS) to extract radial velocities over time. Through cross correlating spectra with models and modeling orbital solutions, we look for the presence of a second substellar companion.

Design and analysis of a 3D-printed gaseous oxide/liquid nitrogen resonance igniter in a bipropellant engine

Sophia-Marie N. Andrews

Mentor: Morteza Gharib

This project focuses on the design and testing of a gaseous oxide (GOX)/liquid nitrogen (LNG) resonance igniter and cavity. Moreover, we investigate its feasibility and performance for rocket propulsion applications, specifically focusing on its ability to provide reliable and efficient ignition. Ignition through a resonance igniter consists of sending compressed oxygen (GOX) through a nozzle, which travels at supersonic speed as an underexpanded jet; this is then sent into the cylindrical cavity, also known as the resonator, where both the temperature and pressure of the GOX rise significantly due to emission of shock-waves. Once mixed with the fuel in the combustion chamber, due to the oxidizer now being at an incredibly high temperature and pressure, this becomes sufficient enough to combust when coming into contact with the fuel. Therefore, the objective is to design, conduct CFD-based thermal-fluid analysis, and fabricate a Hartmann-Sprenger type resonance igniter under controlled gas inlet conditions, as well as a test setup with adjustable nozzle-cavity spacing. Experimental data suggests that such geometry amplifies acoustic pressure oscillations and thus enhances ignition potential. Future work will focus on transient high-speed diagnostics and refining the nozzle-cavity design to further validate reliability and efficiency.

Search for long-lived particles with HCAL segmentation in CMS at the Large Hadron Collider

Katherine A. Avanesov

Mentors: Harvey B. Newman and Kiley E. Kennedy

A search for long-lived particles (LLPs) with lifetimes greater than 0.1 ns is presented, using data from the Compact Muon Solenoid (CMS) experiment. Such particles are predicted by various theories beyond the Standard Model (BSM) that address phenomena such as dark matter and supersymmetry. The search targets Higgs boson decays to a pair of massive LLPs (X), which subsequently decay to a final state with two bottom quark- antiquark pairs: $H \rightarrow XX \rightarrow b\bar{b}b\bar{b}$. The analysis utilizes the depth segmentation of the CMS Hadronic Calorimeter (HCAL) to identify the distinct topology of LLPs decaying within its volume. Two neural network (NN) classifiers are employed: a "depth" tagger, which uses information on the jet's decay depth in the calorimeter, and an "inclusive" tagger, which does not. This paper optimizes the signal region for an "asymmetric double-tag" strategy that requires at least one LLP to decay in the HCAL. Thresholds on the depth and inclusive scores are chosen to maximize statistical significance. We find that signal events for different LLP mass points populate distinct regions of the score space, favoring either high depth and low inclusive scores, or vice versa. Further investigation focuses on defining a unified optimal signal region boundary.

Creating an optimal neural tissue microenvironment through mechanosensing

Alize G. Bakker

Mentors: Julia R. Greer and Peter Serles

Millions of people worldwide suffer from neurodegenerative diseases and traumatic brain injuries, however, the impact can be subsided through human stem cell-derived neural tissue engineering, with a focus on repairing damaged nerves. There are currently a vast amount of studies in neural tissue engineering, primarily mammals or non-human primates cells are utilized rather than human cells thus lacking critical application to human medical assistance. This project aims to open avenues to treat nervous system injuries through designing optimal neural tissue growth scaffolds which incorporate 2D, 2.5D, and 3D geometric effects including controlled pore size, beam size and cell density to enhance cell proliferation through the use of mechanosensing and substrate engineering utilizing human neural tissue.

To accomplish this, hydrogel samples of 18 geometries are printed with two-photon photopolymerization on the Nanoscribe, then post-processed with ethanol and stored in phosphate buffered saline salt solution. After that, 4-5 month old dorsal cortical organoids derived from human induced pluripotent stem cells, which are synthesized in the Quadrato lab at USC Stem Cell, are dissociated into single cell suspensions then plated onto the hydrogels and left to adhere for 48 hours. After that, the cells are fixed and stained with immunofluorescent markers of SOX2, DAPI, TBR2, GFAP

to identify neurons, primary and secondary neural progenitors, astrocytes and astroglial cells, respectively. The cells are imaged on the Thunder Live Cell and 3D-Assay microscope (LEICA) and cell counting is performed using ImageJ and a MATLAB image analysis code. Additionally, live calcium ion imaging is performed to observe the neuron electrophysiology in some samples. To observe geometric implications different sample geometries such as grids, gyroids, pillars, walls, staple and T shapes are tested. These geometries allow us to gain insight on different cell types feature spacing, stiffness and surface area favorability. From the data collected, the different cells show distinct characteristic preferences of the varying hydrogel samples.

The electronic structure of Holm clusters

Aadarsh Balaji

Mentors: Garnet K. Chan and Chenghan Li

It is only within the last two decades that the molecular structure of the nitrogenase enzyme has become well understood, and only in the last decade that progress has been made in describing its electronic structure via *ab initio* methods. Because of the complexity of nitrogenase's electronic structure, and due to the presence of dense, low-lying excited states that can contribute to room-temperature chemistry, a rigorous understanding of the dinitrogen reduction mechanism has not yet been developed. Currently, our goal is to describe the FeMoco active site of nitrogenase, but describing large systems that have many open-shell metal atoms is challenging due to the multi-reference nature of the ground state wavefunction. For qualitative insight, we begin by focusing on the so-called Holm clusters, which are synthetic "cubane" metal-iron-sulfur clusters that we use as model systems. We study the ground states of these clusters using several post-Hartree Fock methods and additionally describe the theory and computational implementations of some of these methods as well.

Impact of bacterial community structure on plasmid conjugation efficiency assessed through colony-forming units

Ava K. Balanon

Mentors: Sujit Datta, Danielle Sclafani, and Pablo Bravo

By 2050, antibiotic resistance is projected to cause 10 million deaths annually, largely driven by horizontal gene transfer through plasmid conjugation. While conjugation dynamics are well studied in liquid cultures, natural microbial communities often grow in structured environments where spatial confinement and restricted motility may alter transfer efficiency. Thus, in this project, we analyze how bacterial community structures affect conjugation efficiency under the stress of antibiotics. We quantify plasmid transfer under three conditions: liquid LB media, well mixed granular hydrogel, and 3D-bioprinted hydrogel clusters of varying densities. We use *E. coli* strains expressing different fluorescent proteins to distinguish between recipient and donor cells. Then, we quantify conjugation efficiency by comparison of colony-forming unit counts on agar plates with and without antibiotics. We hypothesize that conjugation efficiency will be optimal at an intermediate hydrogel concentration where cells are confined long enough to interact but not so restricted that motility is inhibited, decreasing the total number of cell-cell contacts. This approach is used to clarify how spatial structure influenced the spread of plasmids and provided insight into the role of bacterial community structure and the evolution of antibiotic resistance.

Constraints on the orbital parameters of stellar flybys of the early solar system

Avni Bansal

Mentors: Konstantin Batygin and Ian Brunton

The Cold Classical Kuiper Belt (CCKB) has an unexcited dynamical structure, with low inclinations and eccentricities that have persisted since its formation. The CCKB is thus a constraint on proposed perturbation events such as stellar flybys, because any perturbation must leave the CCKB undisturbed. Here, N-body simulations are carried out to explore whether different trajectories of hyperbolic stellar flybys preserve the observed Rayleigh distribution of free inclinations in the CCKBs. Using a random forest classifier, the impact parameter and inclination of the flyby were found to be the best predictors of whether Rayleigh-ness is preserved. In particular, it was found that encounters with perihelion distance $q < 160$ AU and inclinations far from 0, 90, or 180 degrees almost always

destroy the CCKB's structure, and are thus unlikely. These results provide a useful constraint on the Sun's birth environment, ruling out long residence times in dense clusters where such disruptive encounters would be likely.

A fully integrated optical alignment system for the Andor Spectrometer

Jonathan G. Barata

Mentors: George R. Rossman and Helen V. Evans

The Andor Spectrometer is a spectroscopy system that uses a wide range of wavelengths to analyze the absorption spectra of any mineral. The biggest hurdle in using the spectrometer is the fact that in order to focus light into the fiberoptic detector a series of stages need to be manually aligned to even get close to a smooth signal and proper alignment. To remedy this, we switched to a microscope that focuses light through a custom-made made optical system, using two concave lenses, into a 3D printed set up. The setup not only holds the detector at just the right distance from the lenses but also has a built-in compartment for a polarizer, which allows for comparison between polarized and unpolarized light. The microscope has a singular stage that can be manipulated via a joystick, meaning less room for error and more precise control over alignment. The stage, however, still needs to be aligned in a way that maximizes light through any given sample. We came up with a system that uses a photodiode, transimpedance amplifier, and a microcontroller to measure light output from the microscope and compare it with pre-calibrated values for every possible lens setting. This would then be run through a microcontroller to output an audible pitch scaled to the lens that indicated maximum alignment and thus proper light input to the detector.

Identifying the circuit for odor-induced visual valence in *Drosophila*

Ava O. Barbano

Mentors: Michael H. Dickinson and Ivo Ros

Multimodal sensory integration is essential for adaptive behavior, yet the neural circuits that mediate cross-modal interactions remain poorly understood. When the fruit fly, *Drosophila melanogaster*, encounters an attractive odor during flight, its behavioral response to visual stimuli can switch from aversion to attraction. This odor-mediated switch in visual valence is also observed in *Aedes aegypti* mosquitoes, suggesting a conserved neural mechanism among dipterans. While the neural circuitry underlying olfactory processing and visual pathways in *Drosophila* are well characterized, far less is known about how olfactory signals modulate visuo-motor pathways. To address this, we measure visual attraction in a psychophysics arena that allows precise control over sensory input by recording behavioral output. We combine optogenetic activation of olfactory receptor neurons using the Q-system with targeted silencing of candidate visual-motor neurons via the orthogonal Gal4/UAS system. Through this genetic approach, coupling fictive odor presentation with neuronal silencing, we can determine the necessity of a candidate neuron to switch the valence of the stimulus response, thus changing the behavioral mode. This approach aims to probe the neural mechanism in the fly brain responsible for odor-mediated changes in stimulus response.

Final design, testing, and manufacturing of the Compact Muon Solenoid-Barrel Timing Layer assembly for integration at CERN

Victoria E. Barry

Mentors: Maria Spiropulu and Soham Bhattacharya

I have assembled 357 CMS-BTL (Compact Muon Solenoid-Barrel Timing Layer) Sensor Modules, worked with the lab's QA/QC mechanisms, and designed technical parts which were then 3D printed for the lab. Sensor modules are the first manufactured part of the process of creating detector modules then after trays are assembled. 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.

Computational and experimental study of irregular architected metamaterials

Kyrillos A. Bastawros

Mentors: Chiara Daraio and Chelsea Fox

Irregular networks are found in a variety of biological materials, resulting in a diversity of structurally dependent mechanical properties. An algorithm based on a lattice of truncated octahedra has been developed to generate irregular pseudo-random structures. These structures are examined both computationally and experimentally, and in both quasi-static and dynamic compression.

Distribution of tidal disruption event debris around a spinning black hole

Maya A. Basu

Mentors: Fiona A. Harrison and Elias Kammoun

After a tidal disruption event (TDE) the stellar debris stretch out into a stream which winds around the supermassive black hole (SMBH). For a spinning black hole, relativistic precession can cause the stream to miss itself for several orbits until stream widening causes an explosive self-intersection, eventually leading to the formation of an accretion disk. By modeling the geodesic motion of the approximately ballistic motion before this first intersection, we calculate the rough distribution of stellar debris around the SMBH at the time of self-intersection, putting a lower bound on how much the later accretion disk is aligned with the SMBH spin.

Noninvasive monitoring of cardiovascular and endometriosis biomarkers using an engineered acoustic biosensor

Patrick T. Bednarz

Mentors: Mikhail G. Shapiro and Elizabeth Hughes

Abstract withheld from publication at mentor's request.

Extending BayesRays for reliable spatial uncertainty in ill-posed inverse problems

Kyle T. Berkson

Mentors: Katherine L. Bouman and Brandon Zhao

Spatial uncertainty quantification is indispensable when implicit neural representations are used to solve ill-posed inverse-imaging problems. We investigate—a post-hoc Laplace-approximation method originally designed for 3-D NeRFs—as a drop-in estimator for 2-D and 3-D imaging pipelines whose reconstructions are parameterised by coordinate MLPs. On synthetic Fourier- and Radon-based data, BayesRays exhibits two systematic failure modes: (i) an inverse correlation with ensemble variance that over-confidently scores high-frequency structure while inflating uncertainty in flat regions, and (ii) “marbling” artefacts that arise from the diagonal Fisher approximation. We trace both pathologies to a mismatch between BayesRays’ deformation grid and the geometry of general inverse problems, where the forward operator breaks the one-to-one mapping between image and measurement domains. Using this diagnosis we propose a banded-Hessian variant that suppresses marbling without sacrificing computational efficiency, and outline a roadmap for extending these ideas to VLBI and dynamic black-hole tomography. These results show that naïvely transplanting BayesRays is insufficient, but that a geometry-aware adaptation can yield trustworthy spatial error bars for scientifically critical reconstructions.

Turning light into flow: Active matter driven microfluidic pumps

Rishi Bhargava

Mentors: Matthew W. Thomson and Hao Wang

Physiological processes like vascular remodeling and embryonic development occur under slow interstitial flow ($\sim \mu\text{m/s}$). Conventional microfluidic pumps rely on rigid, non-biocompatible materials, limiting their use in live-cell biological models. This project introduces a new paradigm for biological modeling by developing a biocompatible, programmable microfluidic pump powered by a microtubule kinesin motor solution.

Five pump geometries were simulated *in-silico* and fabricated via Polydimethylsiloxane (PDMS) soft lithography. Negative control trials using M2B buffer and tracer beads ($1 \mu\text{m}$) showed low average speeds ($1.5 - 3.6 \mu\text{m/s}$), minimal directionality, and near zero flow rates ($0.0001 - 0.0021 \mu\text{L/min}$). One-way ANOVA revealed significant differences among controls ($F(4,86) = 3.11$, $p = 0.019$), likely due to residual loading pressure. A Welch's t-test confirmed that flow from a microfluidic syringe pump (average speed: $30.96 \mu\text{m/s}$) was significantly greater than from any negative control ($t \approx -200.5$, $p < 10^{-120}$), demonstrating that any future flow observed in active matter experiments will result from active matter activity rather than experimental artifacts.

Active matter trials will continue once microtubule supply is restored. This work establishes validated experimental and computational frameworks. Future efforts will aim to optimize device performance and incorporate cells within PDMS to establish novel models for pathology.

Search for invisible Kaon Long decays in Light Dark Matter eXperiment (LDMX)

Rohan Bhattarai

Mentors: Bertrand Echenard and David G. Hitlin

The search for invisible decays of long-lived neutral kaons K_L provides a sensitive probe for physics beyond the Standard Model, including scenarios with light dark matter or dark photons. In the Standard Model, such decays occur with an extremely small branching ratio, making any measurable signal a potential indication of new physics. This work develops an analysis framework for the Light Dark Matter Experiment (LDMX) to identify invisible K_L decays by reconstructing the accompanying K_S and recoil electron from simulated events generated in the GEANT4 framework. The methodology includes kinematic reconstruction, calorimeter hit clustering, and background rejection strategies to maximize signal efficiency while suppressing visible decay backgrounds. Preliminary results yield a total efficiency of 4.54% and a single-event sensitivity of 4.41×10^{-8} , demonstrating LDMX's strong potential to constrain or discover invisible K_L decays in future runs.

Investigating the effect of electrochemical potential on proteins

Kadambari U. Bhide

Mentors: Karthish Manthiram and Evan Miu

Proteins are versatile biomolecules performing vital functions in all living systems. Given the diversity of the cellular environment they work in, many proteins are inherently sensitive to redox conditions. Proteins such as nitrogenase can transfer electrons in their catalytic cycle while others like the fumarate and nitrate reductase regulator (FNR) can regulate bacterial metabolism based on oxygen availability. Redox dependence and the effect of electrochemical potential on protein function remain underexplored, which is what this project focuses on. Specifically, we developed an enzyme-linked immunosorbent assay (ELISA) that evaluates protein-protein binding and its disruption by electrode-free electrochemical potential. We set up a library of redox buffer solutions to precisely set a range of potentials in which the assays are performed. Buffer performance was evaluated using open circuit potential measurements, redox titrations, and cyclic voltammetry. Additionally, we confirmed the robustness of ELISA components like substrate interactions and probe stability in the given scope of experimental variations. Future work will correlate changes in protein function observed in ELISA to changes in protein structure, revealing the mechanisms by which redox transformations to proteins can alter their function. This could, for example, provide insights into the electrochemical sensitivity of proteins that function in complex electrochemical microenvironments, relevant to modern immunology and biochemistry research in general.

A multiscale differential programming framework with local neural operator of accretion and feedback applications

Nihaal Bhojwani

Mentors: Anima Anandkumar and Chuwei Wang

Supermassive black holes (SMBH) at the center of galaxies coevolve with their host galaxy through accretion and feedback. Direct numerical simulations modeling the feeding and feedback of the black holes across the black hole horizon to the galactic scale is computationally infeasible. Recent development in computational frameworks and the applications of GPUs have made such kinds of computations possible, however, with significant costs of approximately 100k GPU hours per run. Here, we introduce a novel framework that integrates a Local Neural Operator (LocalNO) as an inner boundary condition, coupling two-level, multi-scale direct numerical simulations. We demonstrate this approach in both magnetohydrodynamic (MHD) and general relativistic magnetohydrodynamic (GRMHD) contexts, achieving accurate modeling of black hole feeding and feedback with dramatically reduced computational overhead. This method is generally applicable to all of the central accretor problems, including black hole formation, star formation, and central engine in the supernovae remnants.

Investigating Changing-Look AGN subpopulations with unsupervised machine learning techniques

Sufia Birmingham

Mentor: Matthew J. Graham

Changing-Look Active Galactic Nuclei (CLAGN) are a rare subset of AGN that exhibit dramatic changes in the flux of their broad Balmer emission lines, accompanied by strong photometric variability. There are about 1500 confirmed CLAGN to date; this population is almost certainly heterogeneous. We investigate whether differences among CLAGN arise from natural internal variations within a population, or are indicative of distinct CLAGN subgroups that have different underlying physical mechanisms. We construct recurrence plots (RP) from the Zwicky Transient Facility light curves of the CLAGN population to capture the dynamical structure of these nonlinear and irregularly-sampled optical time series. We devise a new technique to construct RPs that utilizes the Wasserstein distance. To investigate possible subpopulations of CLAGN, we feed these Wasserstein RPs (WRP) into the t-SNE and UMAP algorithms to perform a high-to-low dimensional projection. We apply DBSCAN to the projected space to identify WRP clusters. Additionally, we train an unsupervised Siamese neural network on augmented images of our WRPs, and apply DBSCAN to the learned embeddings to identify clusters of CLAGN. We identify clusters of CLAGN which display distinct dynamical behavior, suggesting the existence of subpopulations of CLAGN driven by different underlying physical mechanisms.

Deterministic single atom loading into optical tweezers

Sanzhar Bissenali

Mentors: Jeff Thompson, Andrei Faraon, and Michael Peper

Neutral atom quantum computing is a promising platform for scalable quantum information processing. One of the key challenges in the field is achieving high-probability single-atom loading into optical tweezer traps. The current standard method—parity projection—has several drawbacks, including millisecond-scale time and limited efficiency. We propose an alternative, deterministic approach for atom loading that overcomes these limitations. By utilizing the rich electronic structure of ^{171}Yb and exploiting collective many-body Rabi oscillations, we computationally demonstrate that highly efficient single-atom loading is achievable, provided sufficient laser power and a long-lived Rydberg state.

Development of an artificial urine standard for stable calcium isotope analysis for geochemical applications

Priscilla Boo

Mentors: François Tissot, Rebecca J. Ryan, and Theo J. Tacail

Calcium (Ca) isotopes in urine are rising in popularity as a non-invasive biomarker for bone mineral balance. However, there is currently no reference material that reflects the complexity of the urine matrix while also being appropriate for isotope work. This hinders inter- and intra-lab comparability and complicates troubleshooting across workflows. This project aims to develop and validate an artificial urine standard specifically for $\delta^{44/42}\text{Ca}$ (‰) analysis by Multi-Collector Inductively Coupled Plasma-Mass Spectrometry (MC-ICP-MS) that is both biologically and geochemically robust. Two batches of standards were synthesized: one artificial urine standard and one matrix-only standard (without Ca). The validation of the artificial urine standard using matrix-only standard involved two main parts: (1) running replicates of the different aliquots of the artificial urine standard and (2) assessing how the urine matrix affects isotope measurements on the MC-ICPMS. The data shows that all the synthesized artificial urine produced homogenous $\delta^{44/42}\text{Ca}$ values. The matrix-only standard spiked before the workflow showed the same $\delta^{44/42}\text{Ca}$ ratios as the artificial urine standard and that the Ca recovery throughout the process was within error. Finally, the blank matrix-only standard yielded negligible $\delta^{44/42}\text{Ca}$ values or quantifiable $\delta^{44/42}\text{Ca}$ values.

Mitigating decoherence in superconducting qubits via a floating merged-element transmon embedded in a phononic shield

Benjamin L. Boone

Mentors: Oskar J. Painter and Matthew Davidson

The development of long-lived superconducting qubits is challenged by decoherence due to both Two Level Systems (TLSs) in dielectric materials and quasiparticles in superconducting films. Current research in the Painter Lab focuses on the development of a new qubit design, a merged-element transmon (MET) embedded in a phononic shield, to minimize TLSs and maximize qubit lifetime. The effect of quasiparticle participation can also be reduced by removing the qubit's connection to the superconducting ground plane, a major reservoir for quasiparticle generation. This project investigates the design implications surrounding the creation of a floating qubit. We demonstrate the theoretical equivalence between a grounded and ungrounded MET and confirm it computationally. We analyze the relationship between the required qubit drive voltage and capacitance. We simulate the electrostatic and quantum-mechanical properties of the device to arrive at optimal geometries and drive based on our analysis. Findings indicate that a floating MET is both a feasible and reasonable implementation strategy for our novel qubit design.

Experimental study of new flexible solar array

Maxwell B. Braithwaite

Mentors: Sergio Pellegrino and Maria Kechri

The Caltech Space Solar Power Project aims to launch a 60m x 60m solar structure into space, harvesting solar energy, and then sending that energy back to earth via microwaves. To do this, a large deployable space structure was designed to accommodate size constraints of launch vehicles. The design of the structure includes four triangular quadrants composed of trapezoidal strips, filled with solar panels, with hinges and diagonal tapes connecting them. The diagonal tapes provide prestressing, while the hinges are there to couple the strip kinematics. Alternate hinge designs and locations were used to study the interactions between the hinges and the diagonal tapes. The information collected was used to pursue decreasing the space between the strips of solar panels. The space between the strips is unproductive, since no photo voltaic cells can be mounted there, and the amount of power lost due to the area of the gap has a significant effect. A 20% decrease in the space between strips of the solar structure has been achieved, but more is possible once a deeper understanding of the relationship between the hinges and the diagonal tapes is found that reduces contact interactions. The interactions between the strips, the new hinges, and the diagonal tapes continues to be studied to see how these factors will affect the characteristics of the deployment of the flexible structure.

Stochastic memory backgrounds within LISA

James Buda

Mentors: Yanbei Chen and Kwinten Franssen

Gravitational-Wave (GW) memory is a permanent distortion in spacetime from a GW merger. This phenomenon is not only theoretically interesting but also elusive, with no strong evidence of detection within current GW interferometers. The space-based LISA mission, operating in the 10^{-5} - 10^{-1} Hz band, is well-suited to probe memory from massive black hole binary (MBHB) mergers, whose memory amplitudes scale with total mass. While prior work has focused on single-event detectability, we extend the analysis to the cumulative, unresolved contribution in the form of a stochastic GW memory background (SGWMB). Using both agnostic and astrophysically informed MBHB population models, we recover known single-event SNR forecasts and simulate long-term LISA realizations to assess background properties. We quantify how the characteristic strain and the statistics of the background depend on population assumptions, and evaluate the validity of the Heaviside step approximation for memory waveforms. We find the SGWMB lies below LISA's sensitivity, with predicted background SNRs $O(0.1-10)$ and variance driven by population uncertainties. We discuss the implications of this background and chosen population models on the LISA noise curve and data analysis.

Quantifying the energetic costs of chemical gradients in biology

Tarik Burlingham

Mentors: Rob B. Phillips and Henry Greenside

Biology operates far from equilibrium. This is evident in spatial gradients, which are ubiquitous. For example, the proton gradient in mitochondria powers ATP synthesis, a critical process in biology. The Bicoid morphogen gradient in *Drosophila* directs cell differentiation. However, a unified framework linking theoretical energetic costs of gradients to empirical data remains incomplete. How much energy must life expend to create and maintain spatial gradients? To investigate this question, we used a discrete and continuous form of Gibbs entropy to quantify entropy and Helmholtz free energy dissipation as the gradient relaxes. We first analyzed a toy model of ATP synthase, looking at the electrochemical potential difference between compartments to find a per-proton energy yield. Next, we analyzed exponential gradients like the Bicoid morphogen gradient to find the energy required to maintain the shape of the gradient. This work is part of a broader question about quantifying energy flow through biology. A precise understanding of energetics in biology has implications for bioengineering and synthetic biology and could elucidate the physical constraints that shape life.

Investigating the roles of macrophage sources in mouse digit tip regeneration and scarring

Beatrice K. Cai

Mentors: Kai Mesa, Lea A. Goentoro, and Emily A. Polk

Macrophages are essential for digit tip regeneration in mammals, yet the distinct roles of monocyte-derived versus tissue-resident macrophages remain unclear. Using a mouse model of distal (regenerative) and proximal (non-regenerative) digit amputations, we examined spatial and temporal distribution of macrophages and how macrophage origin influences regenerative outcomes. Two-photon live microscopy of *Csf1r-EGFP* mice reveals that regenerative wounds form a blastema enriched with rounded macrophages positioned near the wound edge, while non-regenerative wounds exhibit elongated macrophages and horizontally aligned extracellular matrix. To test the role of monocyte-derived macrophages, we use *Ccr2-RFP* (knock-in/knock-out) mice, which lack efficient *Ccr2*-dependent monocyte recruitment. Digits from heterozygous and homozygous mice are amputated and analyzed via cryosectioning, immunofluorescence, and image quantification using FIJI and Imaris. Preliminary results show smaller blastemas in homozygous mice along with diminished bone regrowth. These findings suggest that monocyte-derived macrophages promote blastema formation and structural regeneration, while resident macrophages alone may be insufficient to support full tissue repair. Understanding the distinct roles of macrophage subsets may inform future strategies to regulate the immune response and improve regenerative outcomes in mammalian wound healing.

Probing spin-orbit coupling in bilayer graphene via symmetric proximity coupling from WS₂ encapsulation

Matthew J. Cantor

Mentors: Stevan Nadj-Perge, Ankan Mukherjee, Nastasija Conic, and Siu Chi Wang

Two-dimensional van der Waals heterostructures provide a highly tunable platform for investigating novel quantum phenomena, as charge carriers are confined to atomically thin planes and interlayer coupling can be controlled. The studied device architecture sandwiches bilayer graphene (BLG) between two monolayer WS₂—a transition metal dichalcogenide (TMD)—which allows dual-side proximity coupling. Previous studies have shown that a single WS₂ device can induce strong Ising spin-orbit coupling in BLG, lifting spin degeneracies and generating nontrivial Berry curvature. A consequence of this Berry curvature is a nontrivial Chern number, enabling topological phenomena such as the anomalous Hall effect, fractional quantum Hall states, and fractional Chern insulating states that have anyonic excitations.

Low-temperature magnetotransport measurements are conducted to map Landau fan diagrams and identify signatures of symmetry-broken quantum Hall states and gate-tunable topological insulators with chiral edge states. Dual graphite gates enable independent tuning of carrier density and displacement field, allowing access to spin-polarized and valley-polarized electronic states in BLG. This dual WS₂ device provides a controlled system to study spin-orbit induced topological phenomena in BLG, giving a path to investigate exotic quantum Hall physics, including fractional Chern insulating behavior and the emergence of anyonic quasiparticles with Abelian statistics.

Structural and functional characterization of the nucleocytoplasmic transport of MAPK14

Ioana M. Caraus

Mentors: André Hoelz and Chia-Yu Chien

Cells have evolved to thrive in constantly changing living conditions by rapidly detecting and responding to extracellular stress. The mitogen activated protein kinases (MAPKs) play a key role in the cellular response to a wide range of stimuli, by translating extracellular signals into a cascade of intracellular phosphorylation events. MAPK14 is one of the most extensively studied member of the MAPK family. Initially, it was believed that MAPK14 acts as a tumor suppressor, yet recent studies have revealed its tumor promoter activity. The apparent dual role of MAPK14 as a tumor promoter and suppressor made the attempts to develop anti-cancer therapies against MAPK14 unsuccessful, outlining the gaps in knowledge regarding the MAPK14 pathway – such as the transport of this protein through the nuclear pore complex. 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 conducted and multiple transport factors binding to MAPK14 have been identified. These screening results will further serve as a basis for the structural elucidation of the MAPK14•transport factor complexes.

Soft contact normal quantification using Flow Matching

Nils Jonathan Andreas Cederlund

Mentors: Joel W. Burdick and Emily A. Fourney

Robotic grasping has proven to be quite challenging, and the best approaches achieve a rate of around 90%. To improve this, we propose giving uncertainty quantification on the force normals, which in turn would allow for risk quantification of the grasp. The current state-of-the-art methods for calculating force normals provide only a single estimate without offering any risk metric. We present a Flow Matching (FM) model that samples from the distribution of normals conditioning on a point cloud. The ability to sample from the posterior distribution gives a confidence range of the force normal. The model is trained on cups, mugs, and bowls from the Shape-Net dataset. To bridge the sim-to-real gap, we use a synthetic depth image pipeline with noise models based on the ZED mini stereo camera. Our 95% confidence cone has a single angle of 18.2 deg and a mean error to the true force normal of 6.5 deg.

Categorification of Stokes coefficients for Brieskorn sphere invariants

Constantin J. Cedillo-Vayson de Pradenne

Mentors: Sergei G. Gukov and Mrunmay Jagadale

We construct a homology theory $H^{\{*,*\}}(\Sigma(p,q,r))$ for Brieskorn spheres $\Sigma(p,q,r)$, whose graded Euler characteristic matches the power-series invariant Z_b of Gukov–Pei–Putrov–Vafa. This invariant, defined via resurgence in complex Chern–Simons theory, encodes Stokes coefficients from steepest-descent expansions around flat connections. Using plumbing descriptions, we compute integer series $I^{\{S\}_{\{S'\}}}(q)$ and categorify them into Poincaré polynomials representing candidate homology groups. Initial computations agree with known cases but show discrepancies in higher examples, suggesting refinements are needed. The project advances the categorification of quantum invariants of 3-manifolds.

A unified phase-space framework for measurement-device-independent quantum key distribution

Sujay Champati

Mentors: Maria Spiropulu and Raju Valivarthi

We develop a unified theoretical framework for measurement-device-independent quantum key distribution (MDI-QKD) that combines phase-space modeling with realistic system imperfections. Coherent state pulses are represented as Gaussian states with covariance matrices and displacements, and their evolution through beamsplitters, phase modulators, and lossy channels is described via symplectic transformations. Using this formalism, we derive analytic coincidence probabilities for Hong–Ou–Mandel interference at the measurement station, incorporating detector dead time, dark counts, and partial temporal overlap between time bins. These results yield closed-form expressions for basis-dependent gains and error rates, providing a foundation for decoy-state analysis and secure key-rate estimation under realistic conditions. Our optimized key rates outperform previous simulations due to the improved accuracy of phase space computations. To complement the physical model, we implement high-speed classical post-processing with LDPC and Cascade reconciliation, followed by GPU-accelerated Toeplitz hashing for privacy amplification. Finally, we outline extensions of this framework to model longer-distance MDI-QKD using two-mode squeezed vacuum sources and to generalize the protocol to multi-party scenarios based on GHZ-state measurements.

Quality assessment of skydata from the OVRO-LWA radio telescope

Aaron W. Chan

Mentors: Gregg W. Hallinan and Nivedita Mahesh

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) operates at low frequencies approximately from 13MHz to 82MHz, and captures images of the sky at various times throughout the day. However, these sky images can be distorted and inaccurate due to charged particles in the ionosphere interfering with the radio waves being captured by the array. This is one of the issues we hope to fix. While existing data from the OVRO-LWA can be used for data analysis, there is no streamlined way to create images from the captured data. Using Python with Jupyter, in addition to numerous Python libraries, we aim to create a program to efficiently bridge the gap between telescope data stored in directories and the individuals who analyze the generated sky images. The completion of this project will allow for improved OVRO-LWA data analysis by providing a program to easily generate sky images from OVRO-LWA data. Additionally, this project enables future opportunities such as a program for pattern recognition or predicting trends in subsequent data sets.

Verification of a next generation 65 nm CMOS multi-modal wearable sensor prototype for simultaneous monitoring of 10 physiochemical biomarkers

Christine T. Chang

Mentors: Azita Emami and Shawn Sheng

Wearable sensor systems offer a promising platform for continuous, non-invasive health monitoring, particularly in high-stress environments where real-time physiological data can improve human performance and safety. This project develops a multi-modal, low-power wearable device capable of simultaneously tracking biochemical and physiological stress markers through analysis of sweat collected during physical exertion or iontophoresis. The system integrates a 65 nm CMOS-based sensing chip onto a flexible printed circuit board (flex PCB) and communicates wirelessly via a BLE module to support untethered data collection. Recent efforts have focused on refining both the hardware and software of the wearable system to support reliable, low-power multi-modal sensing. A redesigned flex PCB was fabricated to reduce form factor and improve integration with the BLE communication module. Initial testing under controlled conditions revealed inconsistencies in sensor outputs, leading to a reevaluation of prior calibration protocols and electrode configurations. The goal is to extract clear and reproducible characteristic curves from the sensor data under controlled conditions, enabling the transition to human subject trials and advancing toward a field-deployable health monitoring system.

Profiling misinformation susceptibility in the American electorate

Samantha Chang

Mentors: R. Michael Alvarez and Mitchell Linegar

Misinformation has become a persistent influence in American political life, with false claims spreading widely especially during elections, public health crises, and major news events. This study investigates which groups within the American electorate are most susceptible to misinformation by using the Misinformation Susceptibility Test (MIST) index, a validated measure based on how people respond to news headlines. Drawing from a large, nationally representative survey, we analyze how susceptibility varies by age, education, political affiliation, ideology, and media consumption. We find that while many Americans accurately identify false claims, a significant portion struggles to do so, especially on politically charged topics. Regression models show that susceptibility is not evenly distributed: Republicans and very conservative respondents are more likely to believe misinformation and misidentify factual statements as false, especially on items aligned with their ideological views. In contrast, Democrats and liberals tend to score higher, especially on items involving public health and political narratives. These patterns reveal how misinformation belief clusters within certain groups, providing insights into how misinformation intervention strategies can be better tailored towards these groups.

Monte Carlo modeling, experimental, and theoretical study of the Stern-Gerlach experiment

Ya-Cheng Chang

Mentors: Lihong Wang, Suleyman Kahraman, and Xukun Lin

In our Stern–Gerlach experiment with potassium atoms under small magnetic field gradients, we observe discrepancies between simulated and experimental beam profiles, particularly in the form of blurring and background shoulders. On the simulation side, I modified the Monte Carlo code to include 2D convolution with Gaussian and Lorentzian kernels. This improved agreement near the center but did not capture the extended shoulders. I also explored hard-sphere collision models, but the high relative velocities produced sharper features than observed, suggesting the cross section could be better modeled.

On the experimental side, I investigated various sources of background. After ruling out laser noise and camera artifacts, we identified reflections from uncoated chamber windows as a major contributor. I also found that increasing the oven temperature from 200 °C to 220 °C improved the signal-to-noise ratio by a factor of five, making the central peak more prominent relative to the background.

For the theory, I studied classical spin dynamics to understand how the Bloch equation arises from the equations of motion. I simulated the precession of nuclear and electron spins and explored how to interpret the Breit-Rabi equation classically.

These combined efforts help clarify the sources of background and beam profile distortion, improving the comparison between theory and experiment.

Mechanism of DNA2-dependent replication fork degradation

Anusha K. Chatha

Mentors: Daniel R. Semlow, Maria Altshuller, and Victoria MacKrell

During interstrand crosslink (ICL) repair, replication forks must be restored after fork reversal and lesion unhooking. The nuclease-helicase DNA2 has been implicated in the restoration step, but its exact activity at the replication fork remains unclear. Hyperactivation of DNA2 leads to degradation of 3' ends of fork structures generated during ICL repair, although it is not yet known whether this affects both the reversed fork and the fork abutting the ICL. This raises the hypothesis that DNA2 can resect a nascent leading strand at a replication fork. This project aims to test whether DNA2 can degrade a base-paired 3' end at a replication fork and whether this activity is aided by RPA, a single-stranded DNA-binding protein known to influence DNA2 resection. We will express and purify DNA2 and RPA from insect cells, validate their activity using known flap substrates, and assemble a synthetic Y-shaped DNA substrate that mimics a stalled fork. Using gel electrophoresis and phosphorimaging, we will assess whether DNA2 resects the labeled leading strand in the presence of RPA. These studies will provide insight into the mechanism by which DNA2 processes replication fork structures during ICL repair.

Framing the future: Textual analysis of political discourse on AI and technological change

Arjun S. Chatha

Mentors: R. Michael Alvarez and Beatrice Magistro

From early computerization through the internet revolution to today's generative AI, technological advancements have repeatedly transformed labor markets. Historically, technological advancements have improved productivity but also exacerbated economic inequality by benefiting some groups while displacing others. Understanding how technology has been framed in political discourse over time is essential for predicting how policymakers will respond to the new challenges arising from AI. In this project, we applied Natural Language Processing Techniques to identify how political elites discuss technological change. We built a dataset consisting of the US Congressional Record and the Canadian Parliamentary Record (1995-2024). First, we utilized Large Language Models to identify instances of technology-related discussion. Our next steps include frequency analysis to track how often technology-related themes appear over time and across different technological waves (e.g., computerization, internet, automation, AI), comparative analysis to examine differences in how political parties discuss technological change, and sentiment analysis to evaluate how technology is portrayed: whether as an opportunity or a threat. Future work will compare technology discourse to how politicians have discussed other economic disruptions, such as trade. These analyses will help us understand how political discourse around modern AI and technology is likely to evolve based on historical patterns.

Existence and stability of traveling-wave solutions to a generalized Korteweg-de Vries-Burgers equation

Dora Chatterjee

Mentors: Jared C. Bronski, Omer Tamuz, and Vera Hur

This project expands upon the existence and stability of traveling-wave solutions to a generalized Korteweg-de Vries-Burgers equation. To be specific, the equation that we are looking at is the following: $(\Phi^2/2) - (1/2) = \Phi_x + v\Phi_{xxxx}$ which is a 5th order ODE. A related model, the Korteweg de Vries (KdV)-Burgers equation: $u_t + (u^2/2)_x = u_{xx} + vu_{xxx}$ with conditions $u(x, 0) = \Phi(x)$ was proposed by Whitham as a model for undular bores, a natural phenomenon where high tides at a river mouth lead to waves propagating upstream against the flow of the river. An undular bore is a type of

dispersive shock wave that is formed when a disturbance in fluid evolves into a series of oscillations due to dispersion and nonlinearity. The reason why we would like to understand non-monotone bores is that they consist of complex wave structures that are difficult to capture in standard shock models. We have numerically constructed the bore profile and used it to verify the spectral condition that Blake, Bronski, Hur, and Zhao found in their paper. Specifically, we use spectral methods such as series expansion to conduct a matching of the left and right sides of $\Phi(x)$.

A LEEM study on graphene growth

Yan Che

Mentors: Joseph L. Falson, Ivan S. Bespalov, and Joseph L. Falson

The discovery of graphene, a one-atom-thick layer of carbon atoms, by Geim and Novoselov has triggered intense research on two-dimensional materials (2DM). Due to their exceptional properties, these materials hold great potential for applications in next-generation electronics. However, for practical use, a major requirement is the ability to synthesize individual 2DM islands on a device-compatible scale. One promising approach for large-scale synthesis involves combining layer-by-layer growth with tools for *in-situ* monitoring of the growth process, allowing observation of 2D material formation at every stage. In the present research, we employ Molecular Beam Epitaxy (MBE) together with Low-Energy Electron Microscopy (LEEM), area-selected Low-Energy Electron Diffraction (μ LEED), and LEEM I-V to study the growth and structure of graphene and graphene-based heterostructures, providing a unique platform for real-time, real-and reciprocal-space observation of 2DM at the device-relevant scale. The growth and evolution of graphene islands were monitored by LEEM, while μ LEED provided information about the atomic structure, and LEEM I-V yielded information about local work-function variations. The controlled and scalable synthesis presented in this work enables exploration of large-scale graphene and graphene-based heterostructures growth, which, when performed on semiconducting substrates, can provide a usable platform for measuring 2D material transport properties.

Characterization of TiO₂ electron transport layers for transition metal dichalcogenide photovoltaics

Belle L. Chen

Mentors: Harry A. Atwater, Jr., and Rachel Tham

Transition metal dichalcogenides (TMDs) are a class of 2D semiconductor materials that possess high optical absorption, passivated surfaces, and favorable mechanical and electrical properties that are well-suited for applications requiring light, flexible, and efficient solar cells. However, the highest performing TMD theoretical power conversion efficiencies expected of these materials, primarily due to recombination losses at the TMD and electrode interface. High efficiency solar cells with other photoactive semiconductors, such as silicon or perovskites, typically incorporate carrier-selective contacts, or transport layers. These layers facilitate the movement of the photogenerated charges from the photoactive layer to improve the device carrier collection and thereby increase the overall device efficiency. Here, we investigate TiO₂ as an electron transport layer due to its favorable band alignment and wide bandgap properties. TiO₂ films were deposited through atomic layer deposition atop numerous stack geometries and subjugated to a suite of post-processing conditions. Film quality and composition were verified through techniques such as Raman Spectroscopy, X-Ray Photoelectron Spectroscopy, and Atomic Force Microscopy. The TiO₂ optical constants were also measured with ellipsometry. Finally, the viability of the TiO₂ electron transport layer in a TMD solar cell was assessed.

Redesigning Caltech CS 2 to support all students' experience

Ellie Chen

Mentor: Adam Blank

Data Structures college courses fall into two types: "implementation" and "client." Implementation-type courses focus on teaching implementing data structures, while client-type courses focus on teaching applying data structures. As of last year, Caltech's CS 2 course, "Introduction to Programming Methods," was heavily weighted toward the "implementation" side. In recent years, the percentage of CS students in CS 2 has decreased significantly. Hence, our project redesigns the

course to be more directly applicable to non-CS major students as well. We created many new projects and labs, as well as revised previous assignments to transition CS 2 to weigh heavily toward the “client” side. Moreover, because interacting with teaching assistants (TAs) is a major aspect of the student experience, we also wrote documentation for teaching assistants on various domains and duties they must perform. This research will allow teaching assistants and the course itself to support and benefit CS 2 students in the near future, as well as future students of other core computer science courses.

How do multimodal language models reason about space and time?

Hongqiao Chen

Mentors: Pietro Perona, Georgia Gkioxari, and Raphaela H. Kang

Spatiotemporal reasoning about visual input in the brain proceeds through a multi-step, structured process. With VLMs we have the unique opportunity to decompose latents and uncover exact mathematical mechanisms by which such reasoning can take place. In this work, we investigate whether spatiotemporal structure emerges in the textual activations of autoregressive vision-language models (VLMs), both with and without reinforcement learning-based reasoning strategies, and if they can be mechanistically disentangled and manipulated in the latent space. We show that VLMs without explicit supervision emergently employ a multi-hop mechanism for spatial and temporal queries, wherein intermediate spatiotemporal IDs, which are ubiquitous across the model, are encoded as linearly decomposable latents in textual activations. Perturbing these IDs in key modality alignment layers significantly steers the model’s output, revealing their causal role in reasoning. We show that spatiotemporal IDs can serve as a diagnostic tool for pinpointing limiting reagents in the VLM pipeline, or as an internal learning signal that encourages structured reasoning. Monitoring these IDs also reveals that explicit reasoning traces enhance robustness to incorrect internal beliefs. By identifying and analyzing spatiotemporal IDs, we offer new insights into the internal reasoning mechanisms of VLMs, with implications for interpretability and the principled design of more aligned and capable models.

Monte Carlo simulation of the $\text{LiHo}_x\text{Y}_{1-x}\text{F}_4$ quantum Ising magnet

Jiakai Chen

Mentors: Daniel Silevitch and Thomas F. Rosenbaum

This project investigates the quantum dynamics of the disordered Ising magnet $\text{LiHo}_x\text{Y}_{1-x}\text{F}_4$, an archetypal system realizing the transverse field Ising model with long-range interactions. Depending on holmium concentration, the system forms a variety of states including a disordered ferromagnet, a spin glass, or a dilute ensemble of spin clusters. In the quantum regime at low temperatures, spin dynamics are driven by quantum tunneling instead of thermal fluctuations. Hence, we developed a Monte Carlo simulation framework incorporating quantum tunneling via a field-dependent Metropolis update rule. This framework was used to simulate the dynamics of $\text{LiHo}_x\text{Y}_{1-x}\text{F}_4$, in the spin glass and ferromagnetic phases to obtain spatial resolution of individual spins otherwise inaccessible to experimental measurements. In the spin glass phase, we successfully reproduced the rejuvenation and relaxation effects experimentally observed in the quantum memory dip procedure, as well as partial memory loss from negative field cycle experiments. The spin-by-spin spatial resolution also enabled correlation analysis of spin configurations during rejuvenation and relaxation. Finally, we simulated the ferromagnetic phase at lower disorder using the same framework. Our investigations of the hysteretic properties and the statistics of Barkhausen noise produced by plaquette growth during domain wall tunneling were limited by finite computational sample size.

Numerical analysis of low-Mach time-integration schemes for 3D variable density flows

Kyle Y. Chen

Mentors: Guillaume Blanquart and Aaron Nelson

The low-Mach limit gives rise to numerical challenges in turbulent flows where density changes over time and space. We study the performance of an iterative time-integration scheme for such flows using direct numerical simulations of a stationary homogeneous buoyant turbulent flow in a triply periodic domain. The parameters tested include the Courant–Friedrichs–Lewy (CFL) number, scalar

transport scheme, scalar rescaling to enforce conservation, number of subiterations, and grid resolution. Results show that the effects of rescaling and transport scheme depended on the CFL and subiteration settings, where rescaling improved density conservation at low CFL but could greatly increase equation-of-state error, and the semi-Lagrangian scheme tended to yield slightly lower residuals than the Eulerian scheme but was less stable in some high-CFL cases. Additionally, while both had similar convergence rates for low CFL, the semi-Lagrangian scheme had a much faster convergence rate than the Eulerian scheme at high CFL, with rescaling amplifying the effects. These findings provide guidance for selecting parameters that balance accuracy, stability, and computational cost in low-Mach turbulence simulations. Future work will extend this study to shear-generated variable-density turbulence.

Enhancing astronomical spectrographic efficiency through automated and modular mask-cutting software infrastructure

Maylin D. Chen

Mentors: William Schoenell and Charles C. Steidel

Mask-cutting is a crucial component of multi-object spectroscopy and astronomy as a whole. Spectrographs capture light from far-away objects to analyze a variety of phenomena, such as velocity dispersions and chemical makeup. With multiple objects often within the capturing scope of spectrographs, masks are extremely important to eliminate interference from other objects. Despite its importance, the current process for cutting masks remains largely manual, time-consuming and prone to human error because there is no way to automate the process, which requires many specific parameters to be input repeatedly. In this project, we aim to create an open-source, modular software framework that incorporates existing applications to create a more efficient workflow by enabling automation and more rigorous error-checking through an API and web interface. While our goal is to eventually support multiple mask-cutting softwares in our infrastructure, we're focused on first creating a working proof-of-concept for Carnegie Observatory's two spectrographs: IMACS and LDSS3. I'll be using a popular Python framework called Django, which has extensive infrastructure to create REST APIs, which are uniquely suited for interactions from website interfaces due to the HTTP protocols they use. Moreover, Django has an app-based organizational system, where apps are groups of code contributing to the same goal. By simply creating a modifiable app template that specifies all the API functions a mask cutting program would need, this system allows support for additional spectrographs to be instantaneously integrated with the existing codebase. In our finalized prototype, we simplified the workflow into one continuous process that implemented stronger organizational conventions such as naming restrictions and mask grouping, while also retaining all of the original functionality of the mask cutting software. We also added more user feedback, such as a visual schematic showing the slit placements overlaid on sky catalog images. Given its modularity, ease of integration, and improved user experience, this system holds strong potential for broader implementation across observatories.

On foundation models for proton-proton collisions

Michael H. Chen

Mentors: Maria Spiropulu, Abhijith Gandrakota, Jennifer Ngadiuba, and Raghav Kansal

Foundation models have transformed machine learning by leveraging large-scale pre-training on unlabeled data, achieving remarkable success across natural language processing and computer vision. We explore the adaptation of foundation model approaches to particle physics, specifically for proton-proton collisions in the CMS experiment at the LHC. Using immense collision datasets and transformer architectures, we comprehensively investigate the efficacy of self-supervised learning for capturing substructure topology through reconstruction-based methods, contrastive learning, and physics-motivated augmentation strategies, while establishing supervised and transfer learning baselines. We further train and distill a series of large physics foundation models. Broadly, we focus on fundamental questions about representation learning in high-energy physics and the ability of data-driven approaches to discover relevant physical invariances. The unique challenges of collision data present both opportunities and limitations for modern deep learning paradigms.

Tropical Hodge Conjecture for abelian fourfolds

Nancy Chen

Mentors: Tony Yue Yu, Shaowu Zhang, and Thorgal G. Hinault

The Tropical Hodge Conjecture posits that every tropical Hodge class arises from a tropical cycle via the cycle-class map. This project investigates the tropical Hodge conjecture for abelian fourfolds, an open question in tropical geometry. I began by explicitly constructing the eigenwave map on tropical chains and computing its matrix representation. I then computed the intersection of the kernel of this map over the reals with the domain lattice. The Hodge classes lie in this intersection, and I found exactly three such classes, which is consistent with results found in literature. To examine their algebraicity, I studied the cycle-class map. Preliminary results suggest these classes may correspond to actual tropical cycles, although the verification remains ongoing. This work contributes to a deeper understanding of tropical Hodge theory and offers insights towards the classical Hodge Conjecture, one of the most mysterious problems in algebraic geometry.

Studying the spin-liquid behavior in iridate $\text{Ba}_4\text{Ir}_3\text{O}_{10}$

Yanxin Chen

Mentor: Sandeep Sharma

Spin liquid, as a quantum state characterized by high frustration, long-range entanglement and absence of normal spin orders, attracts great attention. Several models are believed to have a spin-liquid ground state, and experiments are conducted to find the spin-liquid candidate in real materials. Recent study reveals that $\text{Ba}_4\text{Ir}_3\text{O}_{10}$, with a high frustration factor and observed spinons, has a high probability to have a spin-liquid ground state. However, the mechanism of the observed high frustration factor, combined with other experimental observations, still remains a mystery. Here, we would like to employ first-principle calculation methods to identify the underlying mechanism. Our calculation successfully finds that the magnetic atom in this material is Ir atoms and the most important atomic orbitals are Ir-d and O-p orbitals. For our future work, we'd like to use CASCI method based on DFT orbitals to calculate the exchange energy in $\text{Ba}_4\text{Ir}_3\text{O}_{10}$ and try to build an effective model of it.

Steering diffusion policy for controllable actions in robot manipulation

Yen-Ru Chen

Mentors: Aaron D. Ames, Albert Li, and Damiano Marsili

Learning-based control under the imitation learning paradigm offers a promising alternative to classical model-based control for robotics. Unlike model-based approaches, which require explicit and complete modeling of the robot's environment, learning-based methods can acquire complex, multimodal behaviors directly from human demonstrations—even in settings without full observability or detailed task specification. Diffusion Policy has emerged as a leading method for behavior cloning in this context. In this work, we investigate strategies to flexibly control a Diffusion Policy's behavior in robot manipulation by incorporating additional visual inputs as conditioning signals. Our experiments highlight both the challenges and opportunities of steering robot actions via enhanced sensory guidance.

Evaluation of the glycomic profile of p97 disease-associated mutants

Yun-Shan Chen

Mentors: Tsui-Fen Chou and Chia Yen Liew

Protein glycosylation is a fundamental post-translational modification that governs the protein folding machinery. Aberrant glycosylation leading to protein malfunction may contribute to endoplasmic reticulum (ER) stress and disrupt cellular homeostasis. The ubiquitous AAA+ ATPase p97/VCP is an essential protein that plays a central role in protein quality control, involved in diverse ubiquitin-associated pathways such as ER-associated degradation (ERAD) and chromatin-associated degradation. Pathogenic missense mutations in p97/VCP are implicated in rare diseases, multisystem proteinopathy-1 (MSP1), and intellectual disability & developmental delay (IDDD). Although the role of p97/VCP in protein quality control is well-established, the impact of p97/VCP variants on protein

glycosylation remains underexplored. This research employs cutting-edge mass spectrometry to investigate the glycoproteomic and *N*-linked glycan profiles in cellular models expressing p97/VCP variants, thereby advancing our understanding of p97-related disease mechanisms.

Probing correlated dark matter signals in pulsar timing arrays might lead to promising bounds on substructure

Abhiram Cherukupalli

Mentors: Kathryn M. Zurek, Kim V. Berghaus, and Vincent Lee

Dark matter models predict very different small-scale structure: WIMPs exhibit damping below $\sim 10^{-6}M_{\odot}$, while (post-inflationary) QCD axions can produce an enhanced microhalo abundance via isocurvature fluctuations. Conventional probes like microlensing rapidly lose sensitivity to extended subhalos because their low surface densities smear the lensing signature. We revisit the detection of this diffuse substructure with pulsar timing arrays by targeting the correlated stochastic signature of dark matter subhalo flybys. Projecting timing residuals onto the dipolar spatial mode isolates a dark-matter signal from the dominant stochastic gravitational-wave background and the intrinsic pulsar red noise. Using a gauge-invariant treatment of Doppler, Einstein, and Shapiro effects, we forecast constraints on the subhalo mass function in the $\sim 10^{-12} - 10^{-6}M_{\odot}$ range. Such bounds could sharply discriminate between cold, axion-like, and warm/free-streaming dark matter scenarios.

Creating chimeric BMP receptors with novel combinations of affinity and specificity

Chloe Chong

Mentors: Michael B. Elowitz and Maire Gavagan

Bone Morphogenetic Protein (BMP) is a developmental signaling pathway with a combinatorial, many-to-many architecture. A large repertoire of BMP ligands promiscuously form complexes with different combinations of type I and type II receptors. The amount of each receptor complex that forms is determined by the affinity and activity of each receptor for each ligand. Previous work from the Elowitz lab showed that this combinatorial design allows the pathway to compute complex responses to combinations of ligands. Here, we aim to create chimeric receptors by swapping the extracellular and intracellular domains of existing type I BMP receptors to create receptors with mix-and-match specificity and activity. When tested in cells, the response of chimeric receptors to five BMP ligands matched expected results based on previously measured wild-type binding preferences. These chimeric receptors have a combination of specificity and activity towards different BMP ligands that does not exist in nature. In future work they can be used to explore how combinatorial signaling architectures produce complex computations by expanding our toolkit of BMP receptors to explore receptors with new combinations of affinity and activity.

Unsteady inertial effects in cardiovascular flows: Experimental observations and analysis

Malia A. Christy

Mentors: Michael Plesniak, John O. Dabiri, and Kartik Bulusu

Cardiovascular diseases linked to carotid artery dysfunction remain a significant global health concern, with wall shear stress playing a critical role in atherosclerotic plaque formation. Understanding the hemodynamics that give rise to such stresses requires accurate modeling of unsteady pulsatile flow in arterial geometries. We investigated inertial effects in a 180-degree curved artery model under physiological flow conditions using the dimensionless Womersley number to characterize the influence of pulsatile flow. Due to the multi-harmonic nature of blood flow, a range of Womersley number is expected, which may introduce distortions in experimental measurements and complicate correlations with human vascular flow conditions. Utilizing a custom-built flow loop with a programmable pump, pressure transducers and flow rate sensors, we use water as a Newtonian blood analog to simulate arterial flow. The system was designed using dynamic similarity principles and analytical solutions to the unsteady Navier-Stokes equations. Through combined measurements of pressure gradients, flow rates and wall shear-stress, this work enables more accurate replication and analysis of complex cardiovascular flow environments.

Gradient-controlled and templated TBA-based freeze casting of porous prismatic SiOC scaffolds

Audrey S. Chyung

Mentors: Katherine T. Faber and Wesley D. Patel

Tert-butyl alcohol-based freeze-casting yields scaffolds with a prismatic pore morphology, which is highly permeable along the axis of pore orientation and not achieved using common freeze-casting solvents. However, tert-butyl alcohol's tendency to supercool leads to rapid, uncontrolled nucleation and crystal growth upon freezing. The resulting off-axis pore domains reduce bulk permeability. A double-sided, gradient-controlled freeze-casting setup is hypothesized to reduce supercooling and encourage growth in the direction of the imposed temperature gradient. A templated bottom surface may further reduce supercooling and control initial crystal nucleation to select for vertically-oriented grains. In the current research, we obtain a phase diagram of the tert-butyl alcohol-polymethylsiloxane system using differential scanning calorimetry to quantify the degree of supercooling occurring during freezing and better inform freezing profile design. We develop a gradient-controlled freezing profile and template. Image analysis techniques are used to measure freezing front velocity. Scanning electron microscopy and a variable-pressure fluid flow apparatus are used to evaluate pore morphology, pore alignment, and permeability. Mercury intrusion porosimetry is used to measure porosity and pore size distribution. Compressive strengths and permeabilities of prismatic, lamellar, and dendritic structures are measured to compare flow properties, energy input, and mechanical stability of the scaffolds for applications in filtration.

Optimizing transient recovery and analysis for simulated Roman observations

Daria Alice Ciobanu

Mentors: Jacob Jencson and Lin Yan

The Roman Alerts Promptly from Image Differencing (RAPID) pipeline is being developed to enable near-real-time discovery of astrophysical transients and a broad range of time-domain science for the upcoming Roman Space Telescope, set to launch before May 2027. To test and validate the pipeline's performance, RAPID makes use of the OpenUniverse2024 data set of simulated images with injected transient events based on the planned Roman High-Latitude Time-Domain Survey. We began by assessing photometric accuracy using manual aperture photometry on the difference images produced by the pipeline and comparing results to automated photometry and the "true" injected transient light curves, identifying systematic biases due to aperture size and residual background structures. As the project progressed, the focus shifted to evaluating detection completeness and reliability across two state-of-the-art subtraction algorithms, ZOGY and SFFT. Using matched catalogs and diagnostic cutouts, we found that SFFT recovers fainter injected sources at the cost of more false positives, while ZOGY provides cleaner samples but misses a larger fraction of dimmer transients. These findings inform ongoing development of detection thresholds, masking strategies, and subtraction methods in the RAPID pipeline, thereby optimizing future transient science with Roman.

Understanding black hole accretion flow properties in GX 339-4 using NICER and NuSTAR

Cyrus Clabeaux

Mentors: Fiona A. Harrison and Shina Adegoke

This project investigates the accretion flow properties of the black hole X-ray binary (BHXB) GX 339-4 during its 2021 outburst using data from the NICER and NuSTAR telescopes. While BHXBs traverse a unique track on the hardness-intensity diagram (HID) during an outburst, deviations from this path are not uncommon. The origin of these deviations, as well as their effect on the accretion flow properties of BHXBs, is not well understood. A probe of the outlier dataset may hold important clues towards a better understanding of how BHXBs evolve through different spectral states over the course of an outburst. Using X-ray data from the 2021 outburst of GX 339-4, which lasted for close to one year, we study the hard-state spectral evolution of the black hole as well as the similarities/differences in spectral properties for the dataset on the track relative to those off the track in the HID while the source was in the hard state.

Asymmetric reverse prenylation of 3-substituted indoles

Tommaso Colombo

Mentors: Brian M. Stoltz and Jonathan Farhi

The enantioselective construction of all-carbon quaternary centers is longstanding challenge in synthetic organic chemistry. Even more challenging is the formation of vicinal all-carbon quaternary centers. To this end, we have developed a protocol to install a "reverse-prenyl" group at the C3 position of C3 propargyl indole enantioselectively via an iridium-catalyzed allylic alkylation. The reaction will be optimized with a variety of solvents, reactant concentrations and bases to afford the C3 reverse-prenylated propargyl indole in high yields.

Pulse check: Biotic and abiotic drivers of the Birch effect

Oliver T. Crofts

Mentor: Woodward W. Fischer

Despite their pivotal importance in the global carbon budget, terrestrial carbon fluxes are poorly constrained and are sources of uncertainty in future climate projections. Despite containing the largest terrestrial reservoir of organic carbon, soil is a major contributor to such uncertainty, particularly in arid environments. In Mediterranean systems such as Southern California, moisture content varies dramatically throughout the year resulting in a high variability of the rate of organic matter remineralisation. It has been empirically demonstrated that there is a large pulse of CO₂ following rainfall events on such dry soils, known as the Birch effect. Various hypotheses have been postulated for the mechanisms behind the Birch effect, with previous studies suggesting that it is driven almost exclusively by biotic effects. In stark contrast, a suite of laboratory and field experiments highlight a transient abiotic pulse of CO₂ upon rainfall.

Wetting experiments on carbon free soil analogues demonstrate a near instantaneous increase in soil CO₂ concentration, which can only be driven by an abiotic response to simulated rainfall. The amplitude of this response is increased when the specific surface area is artificially raised, implying a crucial role of desorption of CO₂ from the surface of soil particles. When this is repeated with organic rich soil added, the amplitude and decay time of the pulse increases, due to the combined effects of greatly enhanced surface area and superimposed soil carbon remineralisation. Laboratory studies were complimented by field experiments on the Caltech campus and at the Jalama Canyon Ranch, Lombok. Together, the Birch effect is closer to being untangled; the combined influence of an instantaneous pulse of CO₂ rich gas from the soil coupled with a delayed increase in soil carbon remineralisation.

Towards formal verification of neural networks in Lean

Jennifer A. Cruden

Mentors: Anima Anandkumar and Robert Joseph George

Modern neural networks are increasingly deployed in safety-critical domains, yet empirical testing alone leaves potential failures undetected. We present a machine learning framework in Lean, an interactive theorem prover, that supports both rigorous proofs of network behavior and concrete execution. The framework provides a flexible tensor library and modular layer definitions for common architectures such as multilayer perceptrons, convolutional networks, and transformers. Networks are defined over a generic scalar type. This allows the same model to be analyzed with real numbers for formal proofs or executed with rationals or floats for computation and interoperability with tools like PyTorch. To illustrate feasibility, we specify and run a two-layer perceptron in both Lean and PyTorch, while reasoning about its properties over the reals. Although current results focus on idealized reals, future work aims to address floating-point semantics. This unification of proof and execution within a single system lays the foundation for end-to-end formal verification of neural networks in Lean, offering a basis for trustworthy AI.

Verifying a continuum approximation for architected materials in two and three dimensions

Carl J. Crum

Mentors: Julia R. Greer and Cyrus Fiori

Nonporous, solid materials respond to applied forces in such a way that can be reliably modeled by continuum mechanics theory, enabling scientists and engineers to measure strain, calculate stresses, and predict failure in their constructions. However, a new theory presented by Cyrus Fiori, my SURF mentor, asserts that porous substances, such as architected materials and aerogels, can still be modeled as continuums beneath a threshold porosity, and thus be trusted for engineering applications. Through computer simulations, critical porosities were obtained for two geometries: a planar lattice composed of triangular cells, and a rectangular prism composed of octet cells. During this project, we aimed to design mathematically precise lattices with CAD software, fabricate samples via stereolithographic 3D printing, and perform tension and compression tests in order to develop a constitutive relationship for our samples. Such data would help verify the theory, expanding the realm of continuum mechanics and paving the way for novel applications of porous materials.

Thin or monolayer 2D conducting metal-organic frameworks by exfoliation

Katie M. Dao

Mentors: John Anderson and Jonas C. Peters

Metal-organic frameworks offer great potential for various electronic and physical applications due to their modular nature and tunable structures. However, and despite these known benefits, observing unusual physical phenomena in MOFs is often limited by their poor crystallinity. Trimming down 2D systems in other materials has shown unusual behavior and moving to thin or monolayer 2D MOFs would similarly avoid issues with crystallinity. However, such similar studies in potentially interesting MOFs have been quite limited. 2D nanosheets of MOFs might enable different properties compared to their bulk. This allows for the ideal properties of the materials to be utilized and studied. In this work, we synthesized our base MOF linker, SnTHT, from which we make the MOF NiTHT. With this material, we have used a range of techniques; sonication, exfoliation, and Scotch tape method; to find the best resulting nanosheets.

Converting carbon dioxide into useful chemicals and fuels

Daniel C. Darahdgian

Mentors: Harry B. Gray and Aisulu Aitbekova

Lowering carbon dioxide emissions while also reducing demand for fossil fuels is made possible through the catalytic hydrogenation of carbon dioxide into hydrocarbons. However, few catalysts are capable of hydrogenating CO₂ while not reducing the carbon-carbon double bonds characteristic of olefins or unsaturated hydrocarbons. Therefore, we studied a carbon nanotube supported iron-potassium catalyst, which has previously been reported to have high CO₂ conversion while maintaining great olefin selectivity. In our experiments, carbon monoxide and methane were our major gaseous products. However, we did not produce any liquid olefins but instead made mostly alcohols and carboxylic acids. We investigated the cause of these unexpected results with particular interest in how catalyst loading may affect what sort of products are made in the hydrogenation reaction.

Neural operator-based reconstruction for low-dose sparse computed tomography

Aujasvit Datta

Mentors: Anima Anandkumar and Jiayun Wang

Computed tomography (CT) enables high-resolution cross-sectional imaging but requires dense angular sampling, which increases radiation exposure. In this work, we embed neural operators within a UNet backbone to learn continuous, rotation-equivariant mappings across sinogram, frequency, and image domains, enabling resolution-agnostic reconstruction from sparsely sampled projection data. We evaluate this approach on the KiTS abdominal CT dataset under fixed and variable downsampling schemes, demonstrating consistent gains in peak signal-to-noise ratio (PSNR) over a standard UNet baseline, particularly when explicit sinogram inpainting is employed. By treating the Radon transform and its inverse as smooth operators, our method generalizes to unseen sampling patterns and

suppresses artifacts more effectively than traditional convolutional techniques. These results underscore the promise of operator-centric architectures for sparse-view CT and motivate future work on learned filter design and structure-preserving convolutional bases for low-dose imaging.

Enhancement of heat transfer in porous materials with polymer solution flows

Grace F. Davis

Mentors: Sujit Datta and Craig Singiser

Convective heat transfer plays a vital role in energy, industrial, and environmental processes, many of which depend on fluid flow through porous materials. Chaotic, turbulent flows can enhance heat transfer, but small length scales and low fluid velocities suppress conventional turbulence in confined geometries characteristic of porous media. Polymer solutions, however, have been shown to increase solvent mixing in porous materials, as stretching and coiling of dissolved polymers generate elastic instabilities that drive turbulent-like chaotic flow fluctuations despite pore-scale confinement. Therefore, we hypothesize that this elastic turbulence may also enhance convective heat transfer in confined systems. In our study, we prepare a thermo-responsive dye to fluorescently probe the temperature distribution in flow channels representative of porous materials. Paired with confocal fluorescence microscopy, we directly observe thermal gradients in situ while varying the geometry, fluid properties, and imposed heat flux at the boundaries of our devices. Thus, we aim to establish viscoelastic fluid flows as an alternative approach to enhance heat transfer with elastic turbulence in confined environments.

Combining magnetic susceptibility measurements with a mathematical approach to modeling inductive coils to approximate the London penetration depths of superconductors

Jonathan Dawit

Mentors: Joseph L. Falson and Reiley J. Dorrian

Two-dimensional quantum materials have been shown to exhibit a multitude of effects that are of great significance. Superconductance is one of the aforementioned properties that has applications in the fields of quantum computing, magnetic resonance imaging, and far more. However, to analyze the properties of these superconductors, one must find their London penetration depths, a measure of how deeply external magnetic fields penetrate the surface of superconductors. Here, we present a technique to measure the London penetration depth based on changes in the magnetic fields of three inductive coils through the Meissner effect. We created a 3D-printed mount for the superconducting sample, and created an adjacent rod with three inductive coils, which allows us to measure the changes in the magnetic field. We then analyze our findings with a Python program, made to convert these changes in the magnetic field to the London penetration depth.

3D micron-resolution brain tractography via scattered light imaging

Derek W. Days

Mentors: Michael M. Zeineh and Ellen Rothenberg

This project aims to generate the first complete 3D tractography of a human brain specimen at micrometer resolution through Computational Scattered Light Imaging (ComSLI). While existing methods like diffusion magnetic resonance imaging (dMRI) and 3D-Polarized Light Imaging (3D-PLI) are limited by resolution or the inability to resolve crossing fibers, ComSLI can map multiple crossing nerve fiber orientations in 2D sections with resolutions down to a single micrometer.

First, ComSLI was applied to histology slides to determine nerve fiber orientations. These 2D sections were then coregistered to high-resolution photographs of the tissue block surface with MRI data. Key computational tools, including the Scattered Light Imaging ToolboX (SLIX), Advanced Normalization Tools (ANTs), and Tensor Image Registration Library (TIRL), were used for data analysis and 3D reconstruction.

This novel approach will allow for the detailed visualization of key hippocampal pathways, offering critical insights into the brain's connectivity and the microstructural changes associated with neurodegenerative diseases like Alzheimer's.

Computations of and upper bounds on the optimal t-pebbling of graphs with rate r

Jacob de Juan Millon

Mentor: Matthew M. Gherman

Given a distribution of pebbles on the vertices of a graph G and some $r > 1$, a fractional pebbling move with rate r removes rx pebbles from a vertex and adds x on a single neighbor, for some $x \in \mathbb{R}_+$. The fractional optimal pebbling number with rate r , denoted $f^*(G, r)$, is the minimum real number k such that some distribution of k pebbles permits reaching each vertex by at least one pebble via fractional pebbling moves. With $r > 1$ an integer, a rate r pebbling move is a fractional pebbling move with rate r and $x=1$. The optimal t -pebbling number with rate r , denoted $\pi_t^*(G, r)$, is the minimum number k such that some distribution of k pebbles permits reaching each vertex by at least t pebbles via rate r pebbling moves. All prior work in this field fixed the rate at $r=2$. We give a sharp upper bound for $f^*(G, r)$ in terms of $|V(G)|$ and the graphs for which the equality holds. We compute every $\pi_t^*(P_n, r)$ value and certain $\pi_t^*(G, r)$ values for cycles and trees with degree at most $r+1$. To bound $\pi_t^*(G, r)$ in terms of $n=|V(G)|$, we provide values of t such that $\pi_t^*(G, r) \leq \pi_t^*(P_n, r)$ for any graph G .

Probing the weak interaction with early universe physics: The effects of sterile neutrinos in hot and dense environments

Eddily M. De La Cruz

Mentors: Chad Kishimoto and Ryan B. Patterson

Neutrinos are tiny, nearly massless fundamental particles. Despite only interacting weakly, they strongly influence the evolution of our universe. We analyze the observational consequences of a model that introduces a population of sterile neutrinos that decay roughly one second after the Big Bang, when the early universe was hot, dense, and the weak interaction played an important role in the dynamics of the universe. Sterile neutrinos are hypothetical electrically neutral particles that interact only through gravity. The hot and dense early universe provides an optimal setting to study sterile neutrinos because the conditions at this time allow for more interactions between elusive particles. In this work, we examine this model's effects on large-scale structure formation and cosmologically-inferred neutrino mass measurements. At the same time, we explore how the model influences the formation of the first light elements during Big Bang Nucleosynthesis.

Neural operators for dissipative relativistic magnetohydrodynamics

Ansh V. Desai

Mentors: Anima Anandkumar, Chuwei Wang, Elias R. Most, and Valentin Duruisseaux

Relativistic dissipative magnetohydrodynamics is essential for modeling high-energy astrophysical systems such as black hole accretion flows, where non-equilibrium effects like shear stress, heat flux, and magnetic conduction play a critical role. While these dissipative contributions are necessary for accurate simulations, their repeated evaluation in large-scale numerical solvers is prohibitively expensive, often requiring hundreds of millions of GPU hours. In this work, we utilize a Fourier Neural Operator based framework to bypass this computational bottleneck by learning a surrogate model for the evolution of dissipative quantities from easily computed local fluid states. This approach takes advantage of the remarkable discretization-invariance and generalization capabilities of neural operator to predict small-scale dissipative dynamics with high efficiency, enabling rapid integration into global simulations.

Knowledge transfer in ResNet and vision transformers: Investigating asymmetric data distributions and alternative training paradigms for computer vision

Shravani A. Deshmukh

Mentors: Pietro Perona and Fengqing Yu

In real-world settings, data often follows a long-tailed distribution, where a few "head" classes contain abundant examples while the majority of "tail" classes remain underrepresented. This imbalance raises critical questions about whether knowledge learned from head classes can transfer to improve tail-class recognition. In this project, we rigorously evaluate two leading architectures—ResNet-50 and Vision Transformers (ViTs)—across a range of head-tail splits. Our findings demonstrate that head

classes do not aid tail classes in either architecture, confirming that no meaningful transfer of learning occurs from head to tail. This result highlights a fundamental limitation in current approaches to imbalanced classification and underscores the need for methods explicitly targeting the tail regime. As a step in this direction, we also implement a custom class-conditional GAN to generate synthetic images for tail classes, in place of large-scale diffusion models. While the impact of these GAN-based augmentations remains under evaluation, their inclusion provides a concrete pathway to test whether targeted synthetic data can address the lack of transfer and improve learning under extreme class imbalance

Testing accretion disk geometry with X-ray reflection spectroscopy

Indie E. Desiderio-Sloane

Mentors: Fiona A. Harrison and Joanna Piotrowska-Karpov

The geometry of accretion disks plays a crucial role in shaping the X-ray signal observed in black hole systems, which we rely on for inferring the fundamental physics governing black holes. As of today, most state-of-the-art X-ray spectroscopic models assume an idealized disk with a razor-thin geometry, despite its widely recognized inconsistency with predictions from full-physics numerical simulations. In this project, we examine how this assumption influences our interpretation of X-ray observations by comparing two relativistic reflection models: RELXILL, which assumes an infinitesimally thin disk, and FENRIR, which includes pressure-supported vertical structure. We simulate a range of illumination scenarios and statistically compare the resulting spectra across a comprehensive set of physical input parameters, focusing on spin and inclination which are, typically, of interest in X-ray reflection analysis. We find that distinct geometric assumptions can produce remarkably similar spectra for different parameter combinations, revealing degeneracies among disk thickness, spin, and assumed inclination. This result underscores the risk of biased parameter inference when simplified geometries are adopted and highlights the need for incorporating physically motivated disk structure in future high-resolution X-ray modeling.

Quasi-periodic pattern detection in patients with brain lesions

Aamina Dhar

Mentors: Haris I. Sair and Henry A. Lester

The intrinsic activity of the brain can be explored using resting state functional magnetic resonance imaging (rs-fMRI). Analysis of time-varying activity of rs-fMRI connectivity discovered the existence of quasi-periodic patterns (QPP) in humans, rats and mice. The most prominent QPP reflects a recurring pattern of large-scale anti-correlation between the Default Mode Network and the Task-Positive Network. Studying these QPPs provides a new approach to investigating bold-oxygen level dynamics and their disruptions, since changes in functional connectivity have been reported in neurological and psychiatric diseases, which could subsequently be used as clinical biomarkers. As such, our project aims to investigate the relationship between QPPs and tumor severity in human patients with varying diagnoses. We will extract QPPs from patients with brain lesions and use QPP-derived features to predict the tumor severity of patients to characterize the deviations in intrinsic brain activity.

Quench dynamics and metastability of intertwined orders

Francesca Di Cecio

Mentors: Gil Refael and Gal Shavit

False vacuum decay is a process of considerable interest in settings such as quantum field theory and quantum condensed matter theory. In previous work, a bubble nucleation formalism based on Ginzburg-Landau theory was used to show that coupling two systems such that their ordered phases could not coexist could extend the false vacuum lifetime by orders of magnitude. This was applied to observe non-equilibrium superconductivity in graphene multilayers. Here we numerically investigate the effect of such intertwined orders in a model of intricately coupled quantum Ising chains, each at the vicinity of phase transitions of differing orders. The time evolution of spin expectation values and nearest-neighbour correlations upon sudden quenches in the longitudinal magnetic field is presented in which the metastable state is seen to last longer with coupling between the chains. Such richness in

the phase diagram and quench dynamics could suggest avenues for realising novel phenomena and materials in the future. A Ginzburg-Landau free energy description of the system is proposed and validated, with the aim of applying the bubble nucleation formalism in the quantum mechanical regime using the imaginary time action to predict decay rates.

Boosting generalization in neural CFD surrogates through FIGConv refinement

Yichen Di

Mentors: Anima Anandkumar and Valentin Duruisseaux

We develop methods to improve the accuracy and generalization of neural operator architectures for computational fluid dynamics (CFD) prediction. Building on the Factorized Implicit Global Convolution (FIGConv) framework, we explore architectural refinements, optimized training schedules, enhanced conditioning strategies, and the integration of geometric priors. Controlled overfitting experiments confirm strong model expressiveness, while tests on varied geometries reveal a generalization gap that motivates ongoing optimization. These advancements aim to enable scalable, reliable surrogates for complex fluid systems, supporting downstream applications such as shape optimization.

Prediction selection in two-player games

Yuehan Diao

Mentors: Adam C. Wierman and Tinashe Handina

In a two-player game setting, it is often hard for players to obtain information about the reality, so they have to take actions based on game state predictions that can contain inaccurate information. Assuming players treat the given prediction as the reality and act accordingly to maximize their utilities, we observe that sometimes more accurate predictions lead to worse equilibrium payoffs. This motivates us to formulate a new optimization problem for state prediction selection. We frame the problem into a multi-armed bandit optimization question, where each prediction is treated as an arm with an unknown equilibrium payoff. We then construct confidence bounds over the expected loss incurred by each prediction and use successive elimination to discard predictions whose estimated losses exceed the error bound. The resulting no-regret algorithm, after running for T time steps, can distinguish near-optimal predictions from the set of all predictions. We also conduct numerical experiments to prove our algorithm is applicable in real game settings. Our discovery suggests the need to balance accuracy and equilibrium payoff and provides an effective way to determine the most desirable game state predictions.

Metabolic contributions of *Lactobacillus brevis* ATCC 367 in adult *Drosophila melanogaster*

Hanna K. Diop

Mentors: Lea A. Goentoro and Judah Bates

This project investigates how the gut bacterium *Lactobacillus brevis* can alter the metabolic profile in *Drosophila melanogaster*. Previous work in the Goentoro lab showed that a combination of leucine, insulin, and glutamine induces partial tibia regrowth in adult flies, which normally do not regenerate. Building on this finding, we focus on *Lactobacillus brevis* ATCC 367 (Lb6). *L. brevis* is heterofermentative, so it produces lactate and acetate. The Lb6 strain also expresses the arginine deiminase (ADI) pathway and secretes ornithine, an amino acid potentially linked to increased protein synthesis and therefore, growth. Since *Drosophila* has low baseline levels of ornithine, we hypothesize that Lb6 supplementation could increase ornithine levels, signal nitrogen availability to the fly, and support cell growth. To test this, I am conducting ornithine and acetate assays to quantify metabolite levels in flies treated with *L. brevis* versus untreated controls. This work contributes to understanding how microbe-derived nutrients may support regenerative responses to injury in non-regenerating host models.

3D photonics in CMOS and transistors in silicon photonics

Belinda W. Dong

Mentors: Ali Hajimiri and Debjit Sarkar

The monolithic integration of electronics with photonics, which aims to combine electronic and photonic systems within the same chip, is a promising avenue for realizing next-generation communication, sensing, and computational platforms. In this work, we approach the challenge of monolithic integration from both the electronics and photonics viewpoints. Starting from a 65nm bulk CMOS electronics process, we use an inverse design approach to design photonic components such as visible and near-IR filters for wavelength-division multiplexing (WDM), polarization rotators, and Y-splitters. Using the technique of subtractive photonics, these components can then be manufactured directly in bulk CMOS without any process modifications, enabling more complex electronic-photonic systems. From the photonics viewpoint, we also characterize transistors such as JFETs, MOSFETs, and BJTs that have been fabricated in a silicon photonics process. The characterization of these devices will help advance our understanding of how electronic circuits can be integrated into silicon photonics, as well as the design limitations of silicon photonics.

AprilTag-based vision system for arm-guided object probing with a RealSense depth camera

Randolph L. Douge

Mentors: Joel W. Burdick and Yacine Derder

In order for robots like the Multi-Modal Mobility Morphobot (M4) to handle real-world fieldwork tasks, such as probing high-voltage electrical boxes or diagnosing solar array faults, they need a reliable method of sensing and interacting with objects in their environment. One critical missing piece in M4's design is a fine-manipulation system that allows for accurate, autonomous interaction with physical components. My project directly supports this capability by building a vision-based spatial recognition system using an Intel RealSense D405 depth camera, paired with AprilTag fiducial markers to serve as visual reference points in 3D space. Over the course of my work, I developed a Python-based pipeline that allows the RealSense camera to detect AprilTags in real time, extract their XYZ coordinates using calibrated depth data, and link this information to motion commands for a custom-built robotic arm. Unlike many robotic systems that rely on inverse kinematics or preset poses, this setup simplifies the movement logic by directly mapping camera-derived coordinates to arm positioning actions. The probing action is defined not just as reaching a point but also as confirming the presence of the tagged object, which reflects the kinds of spatial reasoning M4 will need in deployment. While developing this system, several challenges had to be overcome, including tuning the depth camera to deliver reliable distance measurements and ensuring smooth integration with OpenCV-based tracking. To test the system's robustness, a modular rail-based test stand was built to simulate a variety of object positions and tag orientations. The resulting pipeline enables accurate visual localization and motion triggering with centimeter-level precision, demonstrating the system's potential for real-world application. This foundational vision system is designed to eventually be integrated into M4's robotic arm platform, helping expand the robot's capabilities beyond locomotion and into active, autonomous manipulation. As we look ahead, this framework will be key in M4's goal of navigating and servicing hazardous electrical environments safely and intelligently.

Mechanistic study of N₂ activation on intermetallic surfaces

Chrystal Duan

Mentors: William A. Goddard III and Sejun Kim

The development of an efficient, environmentally friendly method for ammonia synthesis has long been a subject of interest. NH₃ plays a crucial role in fertilizers, food production, and holds promise as a long-term energy carrier and carbon-neutral fuel. Industrially, NH₃ is synthesized through the Haber-Bosch process, which requires extreme temperatures and pressures, resulting in significant energy consumption and environmental impact. A major challenge in developing alternative catalytic routes is the activation of chemically inert nitrogen gas (N₂). In this work, we employ computational methods, such as Density Functional Theory (DFT), to investigate the catalytic behavior of LaCoSi and related rare-earth intermetallic compounds. Through a stepwise analysis of the reaction mechanism on the catalyst surface, we demonstrate how the distinct electronic and structural characteristics of these materials facilitate N₂ activation and reduce the energy barrier for NH₃ formation.

Safe offline reinforcement learning in noisy environments with digital twin-supported medical decision making

Aaron M. Dumas

Mentors: Rose Yu, Eric V. Mazumdar, and Aysin Tumay

Mean aortic pressure (MAP) is a primary factor in systemic hemodynamics and organ perfusion. Developing safe strategies for weaning cardiogenic shock patients from mechanical circulatory support (MCS) flow devices requires sequential decision-making under uncertainty. Offline reinforcement learning (RL) offers a promising framework to learn such strategies with retrospective data, avoiding the safety risks of online exploration. However, offline RL faces challenges such as distribution shift, where learned policies recommend actions not represented in the clinical dataset, and noisy signals from sensor error, medication effects, and changing patient states. A major barrier to clinical implementation is the lack of a safe online environment to test learned policies. To address these issues, we pair offline RL with a Transformer-based digital twin (TDT) of the circulatory system to simulate the environment. We show that our TDT outperforms baseline models on predictive accuracy and uncertainty. We evaluate offline RL policies with medically grounded metrics: physiological reward based on MAP, heart rate, and pulsatility; Action Change Penalty (ACP) to discourage abrupt pump-level changes; and Weaning Score (WS) to capture appropriate flow reduction. This work highlights the current limitations of offline RL and provides a practical methodology for rigorously testing policies prior to deployment, addressing safety and reliability challenges.

Optical phase stability in large-scale quantum networks

Elizabeth C. Ellison

Mentors: Maria Spiropulu, Andrew Cameron, and Si Xie

Quantum entanglement is a powerful feature of quantum mechanics that has valuable implementations within quantum communication. Quantum networks rely on quantum mechanical properties of single photons to transfer data between nodes, using entanglement to overcome classical limitations. Other encodings, such as the dual rail encoding, enable long distance communication but require strict control of the stability of the optical phase in fiber. Within our group, INQNET (Intelligent Quantum Networks and Technologies), entanglement has been achieved through multiple means (polarization, time-energy, etc.). There is a powerful new quantum key distribution protocol, twin-field, that can increase communication distances. The protocol only relies on a single photon making it through a fiber rather than requiring two photons to both successfully pass through fibers. Phase stabilization has significant implementation complexity, with our group previously only maintaining stabilization over centimeters in distance. This project aims to analyze phase fluctuations over a 2.5 km link at Fermilab. With an understanding of the magnitude and frequency of phase fluctuations in the link, a feedback loop can be built using QICK (Quantum Instrumentation Control Kit), a FPGA based system with closed loop controls capable of operating up to 1 MHz in rate.

Sparse graphical designs and the Kolm Pollak-EDE: Investigating the equity of spectral geometry

Jawhara A. Emhemed

Mentors: Catherine Babecki and Drew Horton

A graphical design is a framework that uses the eigenvectors of the graph Laplacian to find a small subset of nodes that efficiently represents the entire network, analogous to a quadrature rule for numerical integration. These designs are computationally tractable as they can be found by solving a linear program. In contrast, the Kolm-Pollak Equally Distributed Equivalent (EDE) is a metric that balances average outcomes with a penalty for inequality. We seek to understand if the graphical design solution is inherently equitable. To investigate this hypothesis, we compare our graphical designs to a facility location model that directly finds the most equitable placement of resources by optimizing the Kolm-Pollak EDE with an integer program. We test both models on theoretical and real-world graphs. Our results show that on highly symmetric graphs, the graphical design method can be suboptimal compared to the KPL model due to eigenspace multiplicity. However, in realistic models and even in these suboptimal cases, a graphical design is often fairly equitable and saves greatly on computational costs. This makes it a practical alternative for large-scale networks where both efficiency and fairness are desired.

Utilizing nuclear magnetic resonance spectroscopy and machine learning for tree health monitoring

Shrila Esturi

Mentors: Jeffrey Reimer, Paul O. Wennberg, and Sophia Fricke

Trees play a crucial role in maintaining the health of Californian ecosystems but have been impacted by natural disasters such as forest fires and droughts, and there does not exist a reliable method to quantitatively measure their health, which is representative of climate health. We aim to utilize Nuclear Magnetic Resonance Spectroscopy (NMR) to understand how the molecular composition of tree resin, a terpene-rich compound that trees emit due to an external stress, correlates with the environmental stresses the tree is subject to. We collected tree resin samples from over sixty trees across forests all over California, subjected to varying drought and wildfire exposure, and performed 1D Proton NMR and 2D Correlation Spectroscopy (COSY) experiments on each of the samples. We fed the 1D and 2D results into separate neural networks, where both successfully classified the trees' environmental exposure based on their spectra. The activations from these models were then inputted into a Principal Component Analysis (PCA), and we observed clustering of different trees exposed to the same level of environmental stress. This clustering is indicative of the connection between tree health and tree resin composition and showcases how NMR serves as a reliable method for future climate health monitoring.

A novel application of a frequency tracking technique to nanomechanical resonators for mass sensing

Thomas E. Eyres

Mentors: Michael L. Roukes, Batu Kaynak, and Mert Yuksel

Nanoscale resonators have emerged as a promising technology for performing mass spectrometry of large biomolecules and nanoparticles. As nanoscale objects land on the resonator one by one, they induce resolvable shifts in the resonance frequency of the sensor proportional to their weight. This mechanical system must be controlled by an electronic frequency locking system. The current method employed is a phase-locked loop (PLL). However, this has a key limitation that it is not operable above 80K. I have found that the Pound-Drever-Hall (PDH) technique – a method designed for high precision laser systems – can control the resonator at room temperature. I plan to perform comparison measurements between PLL and PDH down to the 4K level.

A mathematical model of neuronal rewiring after perturbation

Saga M. Fagerström

Mentor: Michelle Effros

In a study out of the Lois group, the brain of a zebra finch demonstrates an ability to restore learned behaviors following neuronal injury. In the experiments described there, zebra finches exhibit song loss after large-scale perturbation of neurons in the high vocal center (HVC). Song capability then spontaneously recovers over time. The mechanisms underlying this recovery remain incompletely understood. While previous work has suggested recovery mechanisms on a network level, this work considers whether plasticity mechanisms at the level of individual neurons may contribute to function restoration in the zebra finch. To investigate such mechanisms, we construct a simplified three-neuron model in which two presynaptic HVC neurons project to one postsynaptic RA (robust nucleus of the arcopallium) neuron. Relying on a mathematical framework developed by Effros and Li, we analyze the long-term behavior of a spiking neuron model with spike-timing-dependent plasticity and homeostatic stabilization. By studying the behavior of the postsynaptic RA neuron before and after one presynaptic input is perturbed, we seek to provide initial insight into conditions under which an unmanipulated neuron can functionally replace a lost input. These insights may inform further investigations of single-neuron recovery mechanisms in larger, more complex, and biologically detailed neuronal models.

Less is more: Data-driven quality evaluation of electron diffraction for intelligent unit cell identification

Emma B. Fan

Mentors: Hosea Nelson and Dmitry Eremin

Recent advances in artificial intelligence and machine learning have enabled scientists to process and rationalize an unprecedented volume of experimental data. However, this surge in data poses significant challenges to data collection practices. The quality of data acquired and processed becomes the priority, paving the road to autonomous and intelligent data acquisition. One field in particular is undergoing this evolution. Microcrystal electron diffraction (MicroED), a method used to determine 3D molecular structures. Not only have numerous structures been solved using microED, but even new chemical matter has been recently discovered. However, the growing volume of the acquired data presents a technical bottleneck.

To address this, the Nelson lab is developing MILEDD (Machine Learning Leveraging Electron Diffraction Database), a platform designed to streamline and accelerate data processing using AI and ML tools.

My SURF project focuses on improving the acquisition pipeline to ensure higher data quality to be deposited to MILEDD. To achieve this goal, I am using computational methods to filter existing microED data and to determine the minimal number of frames and angular range necessary to accurately determine crystal unit cells. These tools will help automate and optimize not just unit cell identification but also pushing MicroED closer to its full scientific potential.

Calcium isotopes in urine and nail as a tracer of bone health

Yunhan Fang

Mentors: François Tissot, Rebecca J. Ryan, and Theo J. Tacail

Over the past two decades, calcium isotopes ($\delta^{44}\text{Ca}$) in human serum and urine have emerged as promising biomarkers for bone mineral balance. Despite substantial inter-individual variability, $\delta^{44}\text{Ca}$ values exhibit relative stability within individuals, supporting their potential for longitudinal monitoring. In this study, we explored the feasibility of using human nails as a long-term baseline for $\delta^{44}\text{Ca}$ analysis, due to their solid phase and chemical stability. We quantified $\delta^{44}\text{Ca}$ in nail samples using Multicollector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS) and compared these values to $\delta^{44}\text{Ca}$ measured in paired urine samples from the same individuals. Our results indicate that $\delta^{44}\text{Ca}$ values in nails provide a robust personal baseline against which changes in urinary $\delta^{44}\text{Ca}$ can be detected with greater sensitivity. Our approach paves the way for developing a practical, non-invasive biomarker system of calcium isotopes for monitoring bone mineral balance and enabling early detection of related bone diseases, a process further simplified by the ease of nail sample collection.

Fault detection in spacecraft navigation environments

Baaqer M. Farhat

Mentors: Soon-Jo Chung and Aaron D. Ames

Visual-inertial odometry (VIO) has emerged as a reliable solution for spacecraft navigation in uncertain environments. However, the VIO's performance is highly sensitive to sensor degradation and estimator inconsistencies. In this work, we evaluate the robustness of a tightly coupled extended Kalman filter (EKF)-based VIO system, ROVIO, using a dual experimental setup. First, the VIO is deployed on the ARCLab spacecraft simulator that is equipped with a monocular camera and an inertial measurement unit (IMU). Second, in order to complement hardware experiments, we develop a high-fidelity simulator in the NVIDIA Isaac Sim environment which models both spacecraft dynamics and the full perception pipeline that provides one with controlled injection of realistic sensor and algorithmic faults. Using this dual testbed, we systematically analyze the effects of IMU bias, dropout, and noise, as well as camera faults such as occlusion, motion blur, and reduced frame rates, on the accuracy and consistency of VIO state estimates.

Developing an image simulator for the Ultraviolet Explorer (UVEX) mission

Kenji P. Farrell

Mentors: Fiona A. Harrison and Soumyadeep Bhattacharjee

UVEX is an upcoming NASA space mission designed to operate in ultraviolet wavelengths. With the capability to observe sources 50 times fainter than previous missions, it will conduct the deepest UV survey of the sky. Equipped with two imaging cameras in the Near-UV (NUV) and Far-UV (FUV) ranges and a low-resolution spectrograph, UVEX will address a broad range of astrophysical questions, including the evolution of low-mass galaxies, early-time UV emission from cosmic explosions, and stellar astrophysics. Currently, UVEX is in its instrument design phase, during which the optics and detector configurations are being finalized. A critical part of this process is developing simulators that generate realistic mock observations. My project this summer is to develop a simulator for both the NUV and FUV imagers using outputs from the ray-tracing software Zemax. We use point spread functions from Zemax to map point sources on the detector and incorporate spatial vignetting profiles to account for flux loss at the field edges. Additionally, we study how the wavelength dependence of optical components, such as the dichroic beam splitter and photometric filters, affects the final image. Our ultimate goal is to create modular code that incorporates these effects, enabling future testing and modifications. This tool will be integral for assessing UVEX's performance and finalizing its design.

Incorporating uncertainty in the radio interferometry measurement equation

Ethan Feng

Mentors: Gregg W. Hallinan and Ruby L. Byrne

Radio interferometry allows astronomers to obtain detailed sky maps by combining signals from an array radio antennas. Currently, there lacks a statistical approach to account for beam model errors in gridding-based imaging. This has led to the reliance of manual tuning of hyper parameters to compensate for variations in the antenna beam. To tackle this problem we developed a principled approach that directly incorporates beam error into the measurement equation. This framework provides quantitative uncertainty measurements and eliminates dependence of hand tuning. Our method enables robust and statistically principled interpretation of radio interferometry data. This will pave the way for high precision image reconstructions, necessary for applications such as 21 cm cosmology which is fundamental for studying the birth of the first luminous objects in the universe.

Design and implementation of a tunable piezoelectric pressure system for layered 2D materials

Richard H. Feng

Mentor: Stevan Nadj-Perge

Moiré materials are systems of layered two-dimensional (2D) materials. Given the freedom of materials to stack, one can compose devices with distinct physical and electronic characteristics. By exploiting the stacking and rotational degrees of freedom, these systems can exhibit novel phenomena such as superconductivity and unconventional magnetism. The application of high pressure to such systems is of recent interest to the 2D materials community, as pressure changes the coupling between the layers and alters the electronic structure. Currently, this pressure is applied using hydrostatic methods or diamond anvil cells, which are powerful but involve significant technological and experimental overhead. In this project, we are developing a new type of pressure cell that uses simple piezoelectric elements to apply tunable, in-situ force directly on the device. Our prototype is compact, compatible with cryogenic environments, and is expected to reach pressures comparable to other high-pressure techniques, with the added advantage of fine, real-time control.

Quantized acceleration using Allo: Systolic tile implementation

Thomas E. Fenton

Mentors: Mircea R. Stan, Glen A. George, and Yimin Gao

The steep energy cost of AI workloads is increasingly drawing attention, motivating research into more efficient execution strategies. Two prominent approaches are quantization, which reduces storage and compute costs by representing model weights in compact formats, and the design of custom hardware architectures tailored to these workloads. Allo, a Pythonic hardware description language (HDL), offers a pathway for compiling high-level models to hardware but currently lacks support for quantization. In this work, we extend Allo by introducing a quantized systolic tile kernel, enabling developers to express quantized computation directly within the language. We demonstrate the feasibility of this extension by mapping the tile to an Alveo U280 FPGA through VitisHLS. This work lowers the barrier to building efficient AI accelerators by combining quantization-aware design with accessible hardware generation.

XSNAP: Streamlining X-ray supernova spectroscopy and circumstellar medium analysis

Ferdinand

Mentors: Mansi M. Kasliwal and Wynn Jacobson-Galan

We present XSNAP (X-ray Supernova Analysis Pipeline), an open-source Python package that automates end-to-end X-ray supernova analysis across Chandra X-ray Observatory (CXO), XMM-Newton, Swift X-Ray Telescope (XRT), and Nuclear Spectroscopic Telescope Array (NuSTAR). XSNAP provides a unified command-line interface (CLI) for instrument-specific reduction and spectral extraction and application programming interface (API) for spectrum modeling through PyXspec, generating fit parameters and light curves. It further derives circumstellar medium (CSM) densities and mass-loss rates from the fitted spectra using a Bayesian Markov chain Monte Carlo framework.

We prototype and validate XSNAP on SN 2024ggi with CXO, XMM-Newton, and XRT data, demonstrating reproducible multi-epoch, multi-instrument spectral extraction and statistically robust inference. In particular, we have successfully constrained the progenitor star mass-loss rate to $(6.2 \pm 0.3) \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ (assuming a 20 km s^{-1} stellar wind velocity), which aligns with previous observations. We will further stress-test the pipeline on SN 2024iss and SN 2025cof to assess its reproducibility and stability. XSNAP is being readied for a stable public release and subsequent publication on the Python Package Index (PyPI); the code is currently available on GitHub with prototype builds on Test PyPI.

Engineering native N-Terminal access to a membrane enzyme: Dual strategies for structural isolation of HyMraY

Camilla Fezzi

Mentors: William M. Clemons, Jr., and Beebee Yusra Kaudeer

The enzyme MraY catalyzes the first membrane-anchored step in bacterial peptidoglycan biosynthesis by attaching UDP-MurNAc-pentapeptide to the C55 lipid carrier to form Lipid I. Despite its crucial role and importance as an antibiotic target, understanding the structure of MraY remains challenging due to difficulties in obtaining the protein with a truly native N-terminus in a detergent-solubilized, folded state. In this project, we explore two complementary strategies to isolate HyMraY with an unmodified N-terminus from *E. coli*: (1) an affinity-based approach using a His-tagged nanobody Nb7 that specifically binds to folded HyMraY, and (2) an intein-mediated trans-splicing system designed to automatically remove purification tags after expression. We engineered two plasmids: one expressing InteinC fused to HyMraY, and another expressing InteinN with a His-tag, allowing the conditional reassembly of the full intein in trans. At the same time, we expressed and purified Nb7 and performed membrane extraction, Ni-NTA pull-down, SDS-PAGE, western blotting, and size-exclusion chromatography (SEC) to assess complex formation with HyMraY. While initial SEC and western blot data indicate some nanobody binding to MraY, further optimization of binding and detergent conditions is in progress. These two approaches aim to create a powerful platform for high-resolution structural and mechanistic studies of transmembrane enzymes with their native terminal features, with potential broader applications in drug discovery and membrane protein biophysics.

The effect of non-instantaneous switching on time-modulated array performance

Nerissa A. Finnen

Mentors: Hua Wang, Ali Hajimiri, and Basem Ali

Time-modulated arrays (TMA) are an emerging subfield of phased array research. Phased arrays are valued for their electronic beam steering. Traditionally, a phase shifter controls the electromagnetic wave's phase to enable constructive interference of individual elements to form the desired beams. Instead, the TMA employs newly developed high-frequency switches that simplify beam steering by selective antenna activation. This ability lends itself to a wide range of applications from communication devices to high-resolution imaging and radar detection systems. This additional modulation period generates multiple beams that are absent in typical phased arrays. To harness this effect engineers develop switching patterns that optimize the lobes for specialized multibeam formations or sidelobe suppression that enhances a main beam. The switching schemes assume that changes between the on and off states occur instantaneously. In practice, switching takes time, introducing timing overlaps between antenna activation intervals that degrade the radiation pattern. This study investigates the effect of a finite switching period on TMA lobe patterns through analytical derivations and simulations. The simulations visualize lobe degradations that arise from the difference between analysis techniques. The results provide insights that can guide the design of future TMAs.

Hardware-efficient generative quantum Eigensolver for ground state energy estimation

Stuart C. Florescu

Mentors: Alan Aspuru-Guzik, R. Michael Alvarez, and Austin Cheng

Accurately determining ground state energies of molecular Hamiltonians lies at the heart of quantum chemistry, condensed matter physics, and optimization, but doing so on today's noisy quantum devices remains a major challenge. Reliable energy estimation not only advances fundamental science but also underpins applications such as material design and drug discovery. Variational approaches such as the VQE offer a path forward but are hindered by barren plateaus and circuit depths that exceed hardware capabilities. Generative methods avoid some of these issues by directly learning to produce low-energy circuits, yet existing models rely on large, composite gate sets that are not suited to near-term devices.

That's why we develop the Hardware-Efficient Generative Quantum Eigensolver (HE-GQE), which generates quantum circuits composed solely of device-native gates. Our approach produces shallow, hardware-executable circuits that maintain competitive accuracy in estimating Hamiltonian ground states. Benchmarks on H_2 demonstrate reliable dissociation curves, and preliminary extensions to BeH_2 , LiH , and N_2 suggest improved scalability over standard VQE baselines. By combining generative modeling with hardware-efficient design, this work establishes a practical framework for ground state estimation on noisy intermediate-scale quantum devices and points toward broader applications in quantum chemistry and combinatorial optimization.

Shadow celestial OPEs in 4D asymptotically flat holography

Ania Freymond

Mentors: Elizabeth Himwich and David Simmons-Duffin

An effort to realise an analogous correspondence to AdS/CFT exploits the isomorphism $SO(3,1) \cong SL(2, \mathcal{C})$ to posit a duality between 4D asymptotically flat spacetime and a 2D Conformal Field Theory (CFT). In this framework, the linearised massless wave equation admits two distinct highest-weight families of solutions under $SL(2, \mathcal{C})$, related through a shadow transformation. The first is built by Mellin-transforming standard momentum eigenstates to yield so-called *celestial primaries* whose operator product expansion (OPE) directly encodes the collinear limits of momentum space amplitudes, giving rise to a local 2D OPE structure similar to conventional CFT correlators. The second is *a priori* non-local and does not bear the fruit of such an OPE on the celestial sphere, due to its mixing with global descendants. We release this tension by providing a general prescription that endows shadow operators with a local OPE. In particular, we derive how OPE coefficients of collinear limits transform under a shadow map for arbitrary n -point functions using OPE blocks, with

applications to $U(1)$ currents and stress tensors discussed therein. Further work includes generalising this construction from $(3,1)$ to $(2,2)$ signature, and more broadly, assembling an algebraic framework that both encodes the bulk RG flow and harnesses the non-locality of shadow operators to probe the UV/IR mixing crucial for any UV completion of gravity in the bulk.

The impact of water activity on the biotic decomposition of biomass

Daniel J. Fried

Mentors: Alex L. Sessions and Madison Dunitz

The long-term storage of grown biomass has been cited in previous literature as a cost-effective means of sequestering atmospheric carbon. For this to be effective, the biomass must be stored in conditions where it will not decompose over a 100+ year timescale. This is because the decomposition of biomass can release greenhouse gases such as CH_4 , CO_2 , and N_2O . This study investigates the use of cost-effective salts to reduce water activity (a_w) in biomass mixtures, thereby inhibiting microbial metabolism under anoxic conditions. Empirical measurements of a_w were obtained using a dewpoint potentiometer across a range of NaCl and MgCl_2 concentrations in multiple biomass mixtures. Methanogen inoculated biomass incubations under N_2 -purged atmospheres were created as a means of studying biotic decomposition under anoxic conditions. In the incubations, CH_4 , CO_2 , and N_2O concentrations were tracked using Gas Chromatography, paired with both Mass Spectrometry and Flame Ionization Detection. Preliminary data demonstrates a monotonic decrease in gas generation with decreasing a_w , yet some emissions persist even at very low water activities. Future work will integrate this data into long-term gas emission models to predict the rate of biotic decomposition of biomass.

Transient detection and classification models for RAPID

Karan S. Gandhi

Mentors: Ashish Mahabal and Jacob Jencson

This project focuses on building two major machine learning models of the RAPID pipeline for the Nancy Grace Roman Space Telescope (Roman). Roman is scheduled to launch by NASA in late 2026, and RAPID, a Project Infrastructure Team for the telescope, is responsible for providing alerts for various transients that will be captured by the telescope.

The first model is a Real-Bogus classifier, which is a machine learning model used to distinguish between genuine alerts and spurious detections. Once the level-2 processed images are made available by Roman, RAPID will run the differencing pipeline to create and difference the reference and science image. Once these difference images have been generated, we run a source extractor on the difference image to generate alerts. To filter out the bogus alerts, cutouts of these images centered about the alerts will be fed into the Real Bogus model to filter out the bogus events. Using this approach, our classifier achieved a precision of 95% in distinguishing real astrophysical transients from artifacts.

The second model focuses on further classifying the alerts. Once the bogus events are filtered out, Light curves of these alerts will be extracted and fed into another model, which will be responsible for further subclassifying them into variables and various subclasses of the transients.

These models will be essential for the survey to begin discovering transients with the start of operations, as soon as repeat observations from Roman are available and will open up numerous scientific applications

Fourier continuation for reliable derivative computation in physics-informed neural operators

Adarsh Ganeshram

Mentors: Anima Anandkumar and Valentin Duruisseaux

The Physics-Informed Neural Operator leverages the Fourier Neural Operator to learn solution operators in function space and includes physics losses to penalize deviations from known physical laws. Spectral differentiation can be used to compute derivatives for the physics loss, but it inherently assumes periodicity. For non-periodic functions, which are common in real-world applications, this assumption can lead to significant errors, including Gibbs phenomena near domain boundaries which degrade the accuracy of both function representations and derivative computations, especially for higher order derivatives. To overcome this limitation, we introduce the FC-PINO (Fourier-Continuation Physics -Informed Neural Operator) architecture designed to extend the accuracy and efficiency of spectral differentiation to non-periodic and nonsmooth PDEs. We propose integrating Fourier continuation (FC) into the PINO framework at various stages using two FC approaches: the newly developed FC-Legendre and the established FC-Gram. By transforming non-periodic signals into periodic functions on extended domains, Fourier continuation enables fast derivative computations without additional memory overhead. We demonstrate that standard PINO fails to solve nonperiodic and nonsmooth PDEs, even when padding is applied, across challenging benchmarks including the self-similar Burgers equation, viscous 2D Burgers equation, and 3D Navier–Stokes equations. In contrast, our proposed FC PINO framework provides accurate, robust, and scalable solutions, substantially outperforming PINO alternatives based on spectral differentiation, demonstrating that Fourier continuation is critical for extending PINO to a wider range of PDE problems.

SCOS-CBO: A miniaturized dual-wavelength device for simultaneous and non-invasive measurements of cerebral blood flow, volume, and oxygenation

Said M. Garcia

Mentors: Changhuei Yang and Simon Mahler

Monitoring cerebral hemodynamics is critical for assessing brain health and detecting neurological conditions such as stroke and brain injury. To this effort, Yang's lab is currently developing a speckle contrast optical spectroscopy (SCOS) device to non-invasively measure cerebral blood dynamics such as blood flow and volume. This project adds a new measurement component to the SCOS device: cerebral blood oxygenation (CBO). We developed a compact, dual-wavelength optical device to measure CBO non-invasively, building on the existing SCOS system for cerebral blood flow and volume. The redesigned system integrates 808 nm and 1064 nm near-infrared laser diodes and dual photodetectors, using near-infrared spectroscopy (NIRS) to obtain the CBO. Signal acquisition was handled through custom-made PCBs featuring adjustable gain amplifiers and Arduino-based analog-to-digital conversion. The optical design of the laser head mount was optimized for precise alignment and user comfort, with all components enclosed in a 3D-printed, battery-powered housing. We tested the device on five human subjects during a breath-holding exercise and observed significant changes in cerebral blood flow, volume, and oxygenation, validating the system's signal fidelity and responsiveness. This work provides a foundation for future non-invasive brain oxygenation studies, with clinical applications such as stroke risk evaluation and neurological disease monitoring.

Stereospecific synthesis of vicinally brominated polycyclooctene (PCOE) and downstream chemistries

Haleigh J. Gardner

Mentors: E. Bryan Coughlin and Gregory C. Fu

Vicinal 1,2-substitution is an underexplored structure in commodity polymers and is thus an interesting route for the chemical up-cycling of polyolefins. A pathway for the postpolymerization modification of double bonds in a polycyclooctene (PCOE) backbone is used to generate a brominated polymer (Br₂-PCOE). Every internal C=C bond is stereospecifically transformed into vicinal dibromide, mapping the 84% trans content of the parent backbone to an 86% erythro product.

Thermogravimetric analysis confirms bromination: a 60% mass loss at 383 °C corresponds to dehydrobromination of a high conversion backbone, and negligible char remains above 700 °C. NMR evidence demonstrates the same with a complete disappearance of the olefin C=C peak. Differential

scanning calorimetry reveals an amorphous material with a glass transition temperature (T_g) between -35 and -25 °C and no crystallinity from -70 to 70 °C, showing the possibly disruptive effect of stereoregular vic-dibromides. Nucleophilic substitution of the bromides with NaN_3 introduces vicinal diazides, evidenced by an azide stretch at 2100 cm^{-1} ; solubility limits prompt a protected-azide route ($\text{Me}_3\text{SiN}_3/\text{TBAF}$) now in progress to enable full spectroscopic verification and downstream click reactions. Future directions include: thiol-bromo click, alkyne-azide click, and Staudinger reduction. These parallel pathways—stereoselective dihalogenation followed by displacement—open access to a family of regio- and stereodefined vicinal polymers, setting the stage for PolyUP's broader objective of converting mixed polyolefin waste into high-value, functionally diverse materials.

Deep learning for Clean Water Act regulation enforcement and compliance quantification

Henry N. Gaston

Mentor: Hannah Druckenmiller

The Clean Water Act (CWA) is the most important piece of legislation protecting United States water quality, but it also serves as a major regulatory barrier. Section 404 of the CWA regulates what areas developers can and cannot build on in relation to the "Waters of the United States" (WOTUS). The interpretation of WOTUS frequently changes under different laws and Supreme Court rulings, altering what areas are regulated. To help quantify the extent of regulatory change under different interpretations of the law, the group previously developed WOTUS-ML, which accurately maps the scope of CWA jurisdiction. However, there is no existing method to consistently monitor and enforce Section 404 compliance, and therefore decision makers do not have a quantitative understanding of the scope of noncompliance. In this work, we design a sequence-to-sequence transformer model that can accurately identify where and when new construction occurs. This model will be paired with the group's previous WOTUS-ML model to predict how frequently construction is occurring on regulated lands. Further, this model will allow the group to quantify changes to construction rates in areas that become deregulated under different interpretations of the law, providing valuable insight for policymakers.

Design and implementation of a drop on demand (DoD) system for automated drop casting of a radiolytic precursor target

Sophia E. Gershaft

Mentors: Nick R. Hutzler and Phelan Yu

The Hutzler lab is presently studying the possibility of using ultracold, radium-containing molecules as a sensitive, next-generation platform for measuring possible time-reversal violating physics in the nuclear sector. The laser fluorescence spectroscopy experiment utilizes a target consisting of radium-226 salt drop cast onto a gold-plated copper substrate. The current manual drop casting technique results in an inhomogeneous target and an inconsistent yield of precursor to the vapor phase during laser ablation. Inconsistent amounts of atoms are introduced into the gas phase, which subsequently translates to fluctuations in spectroscopic intensity peaks. Thus, systematically addressing this problem would improve signal-to-noise ratio and sensitivity of the cryogenic spectrometer. Introducing a drop on demand (DoD) system allows for reproducibility and automation of the target preparation process. The DoD system was constructed, in which individual droplets are dispensed by a PipeJet nanoliter dispenser onto piezoelectric XY stages, allowing for a precise printing-like effect for target preparation. The system is operated by hardware controls using an ADC board and code written in LabVIEW.

Neural operators for wildfire spread in California

Akshay Ghandikota

Mentors: Anima Anandkumar and Jiachen Yao

Wildfire spread in California is a pressing forecasting problem driven by multi-scale interactions among fuels, weather, and terrain. We identify three scales in which wildfire can be modelled through neural operator methods. First, a coarse-grained, pointwise time-series Fourier Neural Operator (FNO) predicts next time-step cell-wise marginal burn probabilities, without explicit spatial dependence, operating at $\sim 9\text{km}$ daily-weekly scales. Second, a more fine-grained spatiotemporal Local Neural

Operator will predict the next-day burn area fraction profile and associated risk from terrain, fuels, and meteorology input on a 375m-500m grid. Third, for our highest resolution model at <100m spatial resolution hourly, the Local Neural Operator will be used to forecast fire perimeter evolution via a level-set signed-distance-function (SDF) formulation. At such resolutions, the fire plume is known to create its own local 'weather', in which the perimeter spread is modelled by a two-way weather-fire coupling. Thus, we also plan to pair our fire perimeter model with an FNO-based fine-tuned weather predictor that co-evolves near-surface winds and plume-driven buoyant updrafts conditioned on fire heat-flux, approximating fire-atmosphere feedbacks. We aim for our neural operator models at different scales to provide fast, data-driven forecasts that preserve underlying physics dynamics while offering practical lead time for planning and response.

Developing and optimizing an acousto-optic deflector (AOD) system for trapped-ion quantum logic operations

Mark A. Gherghetta

Mentors: Crystal Noel, Manuel A. Endres, and Jerry Chen

Trapped-ion quantum computing has proven to be a promising approach in achieving full-scale quantum computers. In this architecture, the qubit state is encoded in the electronic states of the ion. Single and two-qubit gate operations on this platform are realized with individually addressable laser pulses incident on a chain of ions. Multiple beams can be generated by radio-frequency (RF) driven diffraction through an AOD. Due to the small spacing of ions in a chain, any laser beam incident on a single ion will inevitably leak onto neighboring ions. This crosstalk error poses a challenge that hinders further scalability of the platform. Therefore, a method for minimizing crosstalk errors is desired. In this project, an experimental AOD system was developed to study potential error sources. Beam output was analyzed, and AOD RF input was optimized for amplitude configurability and minimization of crosstalk using a gradient-based optimization algorithm. This analysis is crucial for two-qubit entangling gates and multi-qubit gates used in sophisticated quantum simulations, which will be utilized in a future novel trapped-ion system.

Supporting teaching assistants in theoretical computer science courses

Joseph W. Giambrone III

Mentors: Adam Blank, Claire Ralph, and Matthew M. Gherman

Theoretical computer science classes at Caltech, like CS 38 (Algorithms), are notoriously difficult. In particular, there are typically not enough resources to support the teaching assistants ("TAs") for these classes. Additionally, CS 38 does not currently have recitations, leading to a potential disconnect between lecture materials and homework. Bridging this gap would help students take away more concepts from the class. Our objective is to make improvements to CS 38 informed by a literature review of the current research in computer science education. Specifically, we want to focus on what resources are effective for TAs in classes on algorithms and other theoretical computer science classes. Through this project, we have created new rubric items for archetypes of problems, hints for TAs to provide during office hours, new problems and solutions to replace the existing homework sets, and a full set of weekly recitation materials that include example problems and walkthroughs. We hope that as a result of our work, CS 38 will be a more enjoyable and less frustrating experience for students next spring.

Using Raman and optical spectroscopy to isolate the spectroscopic signatures of the rare earth elements

Stephen W. Goehringer

Mentor: George R. Rossman

Many modern technologies require an abundance of rare earth elements, yet few economically viable deposits have been identified. This project aims to improve our ability to discover new rare earth deposits by collecting detailed spectroscopic data on rare earth chemicals, and identifying/quantifying the unique spectroscopic signatures of the rare earth elements. We then analyzed an array of fluoride samples (a mineral prone to rare earth substitutions), and used our spectroscopic signatures to imply the concentrations of rare earth elements in the sample. We confirmed our results with an X-ray Fluorescence machine, demonstrating that this approach is a promising option for field exploration.

Robotic arm for autonomous electrical panel inspection and repairs

Alexander T. Gogola

Mentors: Joel W. Burdick and Yacine Derder

Electrical panels are ubiquitous throughout any industrial plant. The goal of this project is to be able to autonomously inspect and perform repairs on electrical plants. We have designed a robotic arm to be attached to a drone. We have designed it such that it is lightweight and has a high level of precision to perform the desired tasks. Through the use of a compliant mechanism to hold the tool, we can reliably complete tasks. This research provides a general robotic arm and controller which is capable of being implemented on various mobile platforms. We show that common electrical panels tasks can be accomplished using this autonomous system.

Investigating neural and physiological synchronization during cooperative gameplay

Zeynep Goktepe

Mentors: Shinsuke Shimojo and Katelyn Haly

This project explores the connection between team flow and synchronization in brain and body activity. Team flow is a shared state of deep focus that occurs when people work together smoothly. We studied this by recording brain signals (EEG) and heart rate from pairs of players as they played cooperative video games. In the first phase, participants played a rhythm game called ePlegona, but the gameplay was too complex and unfamiliar to reliably trigger flow. To address this, we designed a simpler game, Hop Harmony, inspired by Flappy Bird. This game promotes faster learning and coordinated actions. Using a 37-pin interface, we linked in-game events to external trigger signals for precise alignment with EEG data. We plan to compare the results from both games to test whether higher flow states lead to stronger neural and physiological synchronization between players. Our goal is to understand whether known brain patterns linked to flow extend across different cooperative settings.

Modeling core-collapse supernovae beyond shock breakout

Maria F. Gonzalez

Mentors: David Vartanyan, James W. Fuller, and Daichi Tsuna

Core-collapse supernovae (CCSNe) shape galactic evolution, form neutron stars and black holes, and disperse alpha-capture elements up to, and beyond, the iron peak. Current observations reveal strong asymmetries in supernova morphology whose origins remain unclear. Further investigation requires three-dimensional simulations, which are critical for modeling the chemical and dynamic properties of CCSNe. We conduct a case study using three-dimensional hydrodynamic simulations to examine how parametrically evolved profiles of circumstellar material (CSM)— the host environment of a star— affect late-time observed properties of CCSNe. We model CSM with constant, power-law, and hybrid density profiles and varying masses for a 17- M_{\odot} progenitor. Our simulations begin ~ 1 day post-explosion and follow shock evolution through the CSM over timescales of days to weeks. Increasing the CSM mass by a factor of 10 delays the shock's outward progression by $\sim 3-4$ days. While

differences in morphology are dependent on constant and power-law density profiles, they are not as prominent. This study underscores the impact that the CSM of progenitors may have on CCSNe and their observed asymmetries. Future work may synthesize light curves as the explosion propagates through the CSM.

Reconstructing mammalian traits using carbon stable isotope ratios of amino acids

Mia R. Gonzalgo

Mentors: Julia Tejada and Ricardo M. Baptista

Over 80% of large mammals became extinct in the last Pleistocene Ice Age, leaving most of their biological traits unknown. Reconstructing mammalian diets is particularly crucial for elucidating the vegetation structure, niche partitioning, predator-prey interactions, and paleoclimate of fossil ecosystems. While nitrogen stable isotope ratios of glutamate and phenylalanine have been used to indicate trophic position, carbon stable isotope ratios of amino acids record photosynthetic pathways and can differentiate primary producers. We investigated if combinations of $\delta^{13}\text{C}$ of 11 amino acids (Glx, Ala, Gly, Thr, Ser, Val, Leu, Pro, Asx, Phe, Lys) and $\delta^{15}\text{N}$ of 9 amino acids (Glx, Ala, Gly, Thr, Val, Leu, Pro, Asx, Phe) are informative of mammalian feeding behavior. We analyzed amino acid ratios of mammals with known diets using agglomerative hierarchical clustering to allow for nuanced classifications and observed if individuals with shared feeding behaviors clustered together. We found that $\delta^{13}\text{C}$ of amino acids may elucidate provenance, and combined $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ systems (Gly, Lys; Thr, Val) may predict diet. Further evaluation is warranted to determine if clusters reflect other biological traits, such as body mass, basal metabolic rate, and fermentation type.

Unitary Eichler basis theorems

Samuel P. Goodman

Mentor: Elena Mantovan

The goal of this project is to extend the Eichler basis problem on the level of superspecial points beyond the classical (GL₂) and Hilbert modular surface settings (as considered by Marc-Hubert Nicole, yielding a basis of classical modular forms at level $\Gamma_0(p)$ from series attached to the points of the superspecial locus), specifically to unitary settings. Since unitary settings no longer admit positive definite inner product forms, the classical theta series constructions must be modified, which we do using the Kudla theta lift framework that has become essential in the Kudla Program. We reinterpret the superspecial basis problem, explaining a bridge between superspecial points and automorphic forms in terms of Rapoport-Zink uniformizations. We attach theta series to each superspecial point of the special fiber at p of the Shimura variety over an imaginary quadratic field attached to $U(1,n)$ at Iwahori level and use these theta series to construct a map of modules over the Iwahori-Hecke algebra, which we claim is an isomorphism on the Steinberg parts.

Modeling and inverse design of quantum state evolution under laser-induced transitions

Nivedha Gopinath

Mentors: Anima Anandkumar and Myrl Marmarelis

We investigate the laser-driven population dynamics of CaH^+ co-trapped with Ca^+ in a quantum logic spectroscopy experiment. The system is modeled as a multilevel quantum system with six or more rotational-hyperfine states, coupled to a shared motional mode of the two ions. Transitions between states are driven by externally controlled laser fields, inducing either carrier or sideband processes that evolve both the internal and motional states over time. The primary objectives of this work are twofold: (1) to predict the quantum state evolution under time-dependent laser fields, and (2) to perform inverse design—optimizing laser parameters to achieve target final-state populations, enabling fast and efficient preparation of quantum states in this high-dimensional Hilbert space.

We construct a high-fidelity dataset using quantum dynamics simulations under varying laser frequencies and detunings. Each trajectory spans over 9 seconds, capturing long-duration coherent evolution. A Fourier Neural Operator (FNO) model, augmented with a Softmax output constraint, is trained to map frequency-time inputs to full time-resolved state population dynamics. We then apply

brute-force search in frequency space to identify laser parameters that minimize final-state error, and compare predicted outcomes to solver ground truth.

Preliminary results demonstrate strong predictive performance and successful inverse solutions in several regimes. Ongoing work includes validating inverse-designed solutions with full solvers, exploring gradient-based optimization, and scaling to higher-dimensional control protocols. This framework provides a fast, differentiable surrogate for high-cost quantum simulations, with applications in coherent control and quantum logic operations.

Toward shoreline-aware thermal water segmentation for UAVs in near-shore environments

Agnes M. Göransson

Mentors: Soon-Jo Chung, Anahita Eshghetorki, Joshua Cho, and Matthew Anderson

Autonomous systems must be able to perceive their surroundings reliably, even in visually challenging environments such as low light or fog. While RGB cameras are common, they often fail under these conditions. Thermal cameras provide a more robust signal, but labeled thermal datasets for model training are limited and costly to produce. This work explores how thermal image segmentation for water in near-shore environments can be improved using simplified class mappings and self-supervised pseudolabels, enabling the use of unlabeled data to enhance learning. Additionally, we investigate whether adding an additional label for shoreline is possible without re-annotations, while maintaining high segmentation performance. To further support perception, we explore monocular depth estimation and edge detection to provide geometric context to the segmentation model. Combined, these components create a modular and data-efficient perception pipeline that improves segmentation accuracy and robustness in challenging environments, while remaining practical for deployment in UAV-based autonomous systems.

A quality mesh of the global ocean for simulations of the overturning circulation

Sadik O. Görgü

Mentors: Jörn Callies and Henry Peterson

Overturning circulation helps distribute heat and tracers around the globe, on thousand-year timescales. Recent observations and theory underline the importance of diabatic upwelling over sloping topography in shaping this circulation. Common numerical models use structured grids, which struggle to represent these new physical processes. To better simulate the overturning, an algorithm must be developed to generate a high-quality unstructured tetrahedral mesh of the oceans. In this project, we are building a pipeline for generating such a mesh using real bathymetry data and Gmsh meshing software. We determine closed coastline loops from the bathymetry, ensuring that the node spacing is consistent with the desired mesh resolution. The ocean bottom is then meshed with a varied horizontal resolution based on the local topographic slope. This, with the surface boundary, defines the three-dimensional ocean volume which is then meshed with tetrahedrons. We first applied this method to idealized basins in Cartesian space, verifying their quality using a finite element ocean model. We then extended the process to multiple realistic bodies of water, using the Marmara and the Black Seas as a test case. The next step is to generalize this algorithm to spherical geometry and, ultimately, create a global mesh of the ocean.

Building an in situ ellipsometer with multiwavelength measurement capability for atomic layer deposition/etching

Kavya N. Gotecha

Mentors: Austin J. Minnich and Mariya Ezzy

This project presents the development of an in-situ multi-wavelength ellipsometry system designed for real-time monitoring of thin film growth during Atomic Layer Deposition (ALD) or Atomic Layer Etching (ALE) processes. Ellipsometry is a non-destructive optical technique that determines thin film thickness and optical constants by analyzing the change in polarization of reflected light, quantified by the ellipsometric parameters Psi (ψ) and Delta (Δ). The proposed approach utilizes simulated light intensity data to extract these parameters, applies Fresnel model calculations, and fits the film thickness for each ALD cycle, ultimately enabling the plotting of thickness per cycle (TPC) for detailed

growth analysis. The project aims to overcome the limitations of traditional single-wavelength ellipsometry by extending the capability to multi-wavelength operation, thereby improving the accuracy and reliability of thickness extraction. The software workflow incorporates inverse modeling algorithms, regression techniques, and matrix solutions to process ellipsometric data across several wavelengths. This enables independent determination of film properties without heavy reliance on assumptions, which is crucial for complex multilayer systems. The simulated platform supporting research-driven modifications and integration into ALD environments. The expected outcome is a validated tool for real-time, cycle-by-cycle thin film characterization, with accuracy within 5% of reference values.

A quasi-polynomial-time classical algorithm for Lindbladian evolution

Charvi Goyal

Mentors: John P. Preskill and Thomas Schuster

Most quantum systems in nature are open, meaning they interact with their environments and experience noise. It is unclear whether such systems can be efficiently simulated classically, since the naive description of a quantum system requires classical resources that scale exponentially with respect to system size. We present a quasi-polynomial-time classical algorithm for simulating quantum systems that are affected by continuous-time Lindbladian noise. The algorithm computes the expectation value of any local observable for any local Hamiltonian with a bounded degree of interaction. We show that our algorithm succeeds with a small average error over input states drawn from an ensemble (e.g. the computational basis) for any noise channel in the depolarizing class. Our approach extends existing truncation-based methods for quantum circuits to continuous-time Lindbladian evolution. We do so by evolving our system under an effective truncated Hamiltonian in operator space, leveraging the fact that noise will dampen non-local correlations in the system exponentially more than local correlations. A natural avenue for future research is to explore the extent to which these results extend to other physically relevant noise channels, such as thermal noise.

Commissioning a 100 mK ADR cryostat for CMB and line-intensity mapping applications

Suvinay Goyal

Mentors: James J. Bock and Kenny Lau

The BICEP Array 4 (BA4) receiver, the latest in the BICEP series, is scheduled for deployment in the 2026/27 season to measure the Cosmic Microwave Background (CMB), the oldest detectable light in the Universe. The Tomographic Ionized-carbon Mapping Experiment (TIME), a line intensity mapping experiment observing in the same microwave regime, will probe the star formation rate during the epoch of reionization by measuring the redshifted [C II] 158 μm line. My SURF project supports both experiments through work on the "Pinkie" Cryostat, a testbed equipped with an Adiabatic Demagnetization Refrigerator (ADR) backed by a three-stage He4/He3/He3 sorption cooler. This testbed provides a stable 100 mK bath, enabling performance tests of Transition-Edge Sensor (TES) detectors designed for BA4, and also supports characterization of the newly developed tin-coated readout cables for TIME. Our goals are to commission the cryostat to meet its thermal and readout specifications, and to evaluate whether the new TIME cables can replace the current ones, which have significantly limited observation efficiency.

Designing synthetic microbial communities for sustainable nitrogen delivery in the rhizosphere

Elisa S. Grillo

Mentors: Gözde S. Demirer, Chiara Berruto, and Eugene Li

To reduce reliance on chemical fertilizers a synthetic microbial community capable of converting atmospheric nitrogen to plant available nitrate was developed. The community is composed of both nitrogen-fixing and nitrifying bacteria, including *Azotobacter vinelandii*, *Nitrosomonas europaea*, *Nitrobacter winogradskyi*, and *Nitrobacter hamburgensis*. Growth and nitrogen production were assessed with monoculture and coculture experiments, using colorimetric assays to track nitrogen levels in the form of ammonium, nitrite, and nitrate. Initial results have guided media optimization to

support compatibility between strains. Future directions include implementing these microbial communities in both hydroponic and soil-based plant systems to assess nitrogen delivery, as well as investigating chemotactic behavior of *A. vinelandii* to identify unique attractants that will then be engineered to be secreted by plant roots to improve colonization efficiency. These efforts aim to lay the groundwork for a developed synthetic community capable of targeted nitrogen delivery to plant roots.

Designing mechanophore-containing polymers for targeted release of molecular cargoes

Zoe R. Grogan

Mentors: Maxwell J. Robb and Liam A. Ordner

While typical methods to induce chemical reactions include exposure to heat and light, mechanochemistry provides an alternative pathway by employing mechanical force (primarily introduced via ultrasound) to aid chemical reactions by lowering their activation energy barriers. Molecules known as mechanophores are specifically designed to enable productive covalent transformations in response to the stimulus of mechanical force when incorporated into polymers. This project is dedicated to constructing a mechanophore whose productive chemical response is the release of a small-molecule chemical cargo. Previous studies into these molecules revealed a relationship between cargo release kinetics and mechanophore substitution caused by stabilizing influences of substituent groups. We aim to expand upon these studies by synthesizing a mechanophore containing a methoxy electron donating group and a methyl substituent. This mechanophore will allow for further investigation of the structure-activity relationship for molecular release, as well as provide insight regarding the release mechanism.

Successful synthesis of this molecule has been achieved, and future work includes the incorporation of the cargo-loaded mechanophore into a polymer and subsequent sonication to collect data regarding the release kinetics of this mechanophore.

Exploring synthetic conversational data with LLMs under privacy constraints

Pranit S. Gunjal

Mentors: R. Michael Alvarez and Rafal D. Kocielnik

There is a growing demand for AI solutions, leading companies to develop larger, more powerful models capable of handling complex tasks, from ChatGPT to game-playing bots like DeepBlue and AlphaGo. However, as these models become more complex, they need more data—a major bottleneck since data availability can't keep up. One solution is to generate high-quality synthetic data to train these models. This is in fact being done in order to train the large mainstream LLM models that have become popular [1]. However, the methodology for generating high quality synthetic data is not quite clear as this is a relatively new area in the literature. This study looks to address this question by investigating the generation of synthetic data. A specific context for this exploration will be in looking at video game chat content and seeing if high quality chat content can be generated in this context. These chats present an interesting use case as they lack proper grammar and syntactic flow, as they are often filled with abbreviations, mistypings, and expletives. The chats also present the opportunity to analyze complex scenarios of multi-player interactions influenced by game events. Another use case that this study will look to explore will be the Reddit Emotions dataset. This large public dataset contains reddit user comments and the contrast between these two datasets are vast, as the Reddit comments should provide more coherent and understandable text as compared to the video game chats (also the LLM might be more familiar with the Reddit data as it is known that LLMs have been pre trained on the Reddit dataset). The contrasts between the two will present additional insight in the efficacy of using an LLM for generating text content with different properties and degrees of complexity. Furthermore, this study also aims to create high quality synthetic data while utilizing privacy preserving methods to ensure that sensitive information is not leaked.

Brown dwarfs in eclipse: A nested sampling approach to inferring internal temperature via broadband photometry

Aryan Gupta

Mentors: Andrew W. Howard and Steven Giacalone

Brown dwarfs occupy a curious middle ground in exoplanetary systems. Although they orbit host stars like exoplanets, their atmospheric structures and strong internal heat contributions resemble low-mass stars. Close-in brown dwarfs are especially valuable targets, as measuring their internal temperatures can offer key insights into their formation histories — whether they form through planet-like core accretion or star-like gravitational instability mechanisms. In this work, we extend the HELIOS radiative transfer code to generate a grid of 121 brown dwarf atmospheres of varying internal temperatures and heat redistribution efficiencies. From these models, we compute secondary eclipse depths across multiple observed photometric bandpasses. By comparing simulated and observed eclipse depths, we implement a nested sampling framework using Dynesty to retrieve posterior distributions for internal temperature and the heat redistribution efficiency. We also investigate how the uncertainties on internal temperature depend on the choice of photometric bandpasses used. Ultimately, this approach will enable us to estimate the internal temperatures of five close-in brown dwarfs, combining scheduled observations on Palomar’s WIRC instrument with TESS archival data. These results may shed light on how intrinsic properties, such as mass and energy transport, influence the thermal evolution of brown dwarfs in stellar systems.

Partially observable model-based reinforcement learning in function spaces

Jay Gupta

Mentors: Anima Anandkumar and Myrl Marmarelis

Model-based reinforcement learning (RL) has recently shown improved scalability and data efficiency by using learned world models to predict future states and guide decision-making. In complex physical control tasks like turbulent drag reduction in 3D channel flows, full-state observation during deployment is often infeasible due to practical constraints. Typically, only partial observations—such as pressure readings at boundaries—are available, leading to challenges under partial observability. To address this, we propose a framework consisting of two components: an observer model and a policy model. The observer model predicts the next full state based on the current state and action, serving as a surrogate during training. The policy model, on the other hand, learns to produce actions directly from partial boundary observations and is used during deployment. Both models leverage neural operators, which can learn mappings between functions and generalize across different resolutions—crucial for PDE-governed systems like fluid flows. The observer is a Physics Informed Neural Operator trained using a physics loss to generalize to unseen scenarios better. This setup also allows handling nonstationary environments, such as those with varying Reynolds numbers, without retraining. We validate our approach on computational fluid dynamics (CFD) tasks, showing superior performance and generalization compared to model-free baselines. Our method enables effective control under partial observability, making it suitable for real-world deployment. We are also working on developing a RL environment library based on JAXFLUIDS to deal with more complex fluid control scenarios.

Spectral gap and mixing times in the repeated averages process on graphs

Nikash Gupta

Mentor: Lingfu Zhang

The repeated averages process is a stochastic averaging dynamics on graphs, with mixing times characterized for several structured families such as the complete graph, cycle, hypercube, and binary tree. A general expression applicable to all connected graphs, however, remains unknown. Existing conjectures propose that the mixing time is governed by the spectral gap of the graph Laplacian, but this relationship has not been fully established. We analyze specifically the L2 to L1 mixing time, focusing on graphs constructed by combining cliques and cycles. These constructions maintain rapid local averaging while introducing small spectral gaps, and the results suggest that they may mix faster than predicted, providing evidence that the conjectured dependence on spectral gap does not universally determine mixing behavior.

Physics-based inverse design for electromagnetic structures

Shan R. Gupta

Mentors: Ali Hajimiri and Jatin Mathur

Given the time- and resource-intensive design process for electromagnetic structures, there has been much academic and industrial interest in inverse design, where a computational algorithm takes in a desired device function and outputs a structure that achieves it. Current inverse design techniques rely on neural networks that require large volumes of simulations to train on, gradient-based methods that suffer from both binarization error and convergence to local minima, or heuristic methods that have no measure of global optimality. Here, we derive a physics-based algorithm for inverse design of electromagnetic structures that uses the dyadic Green's function to analytically solve for an optimal spatial conductivity distribution. Using the method of moments, we present a rapid, accurate design process with quantifiable bounds on global optimality. In implementation, we start with toy electrostatic problems and extend the method to more complicated electrodynamic structures.

Observing sleep behavior within zebrafish using clustering

Amudhan S. Gurumoorthy

Mentors: David Prober and Yun Chiu

Sleep is a very important part of everyday life, yet many of the common sleep practices behind humans remain unknown. This research paper attempts to delve further into the processes behind sleep by studying zebrafish, an organism with a sleeping pattern that resembles that of humans. With data obtained through a GCaMP imaging dataset, this study uses permutation tests to identify responsive neurons whose activity increases or decreases upon HCRT activation and factor based clustering to reveal cell populations with similar neural activity patterns. This consequently shows the neurons most correlated with sleep, which we then analyze to determine the activity of specific regions of the brain during changes in sleep. Then, we can compare this activity to behavioral activity within zebrafish, explaining the cause of certain zebrafish behaviors during sleep. By visualizing the spatial distribution of these functional clusters on the registered brain image, we confirmed these functional clusters could be real cell populations since they are spatially located together. Future work involves translating these neuronal effects to the brains of humans, determining whether particular regions of the human brain are heavily affected during sleep.

Algebraic models of Merge and phases for tensor networks

Henry Gustafson

Mentor: Matilde Marcolli

In Chomsky's Minimalist Program, *Merge* is a set-formation operation combining two syntactic objects. The hierarchical structure building process can be described in terms of *phases*, successive complete substructures. Previous research has attempted to relate the Merge operation to physical models such as tensor networks and renormalization. We show that these models, based on matrix representations, are not sensitive to Merge's non-associativity or phase structure. This project develops algebraic structures suitable for tensor networks while preserving the non-associativity and phase structure not captured by naïve matrix models. We show that there exists a faithful representation of syntactic objects in a Jordan operator algebra. By assigning lexical items to polynomial vector fields and recursively mapping rooted trees to differential operators, we can obtain explicit finite matrices for each tree. We then present a concrete tensor network implementation plan, so that a more accurate model of Merge can be developed.

Investigating dust production in two unusual supernovae with JWST

Daria S. Hajimiri

Mentors: Mansi M. Kasliwal and Jacob Jencson

The James Webb Space Telescope (JWST) provides a new opportunity to study the origins of dust in high-redshift galaxies by observing core-collapse supernovae (CCSNe), which are considered strong candidates for major sites of dust production in the Universe. As part of a growing sample of dusty CCSNe observed with JWST/MIRI, we present mid-infrared imaging observations between 7 and 21

micron of AT2016bse and SN2017gkp. These two CCSNe were selected for their unusual optical light curves and late time infrared excess emission seen by NEOWISE. Flux measurements were obtained through manual aperture photometry and automated point-spread-function photometry, allowing for cross-validation and the identification of systematic errors, particularly in background estimation. These calibrated fluxes were used to construct spectral energy distributions and to test single- and multi-component dust models. This work contributes to a broader effort to develop precise photometry methods for CCSNe with JWST, deriving mid-IR fluxes and constraining dust content over time. The upcoming Roman Space Telescope, with its wide field and infrared sensitivity, will be a powerful discovery engine to build larger samples of dusty CCSNe. Leveraging JWST results, this research advances our understanding of astrophysical dust formation in explosive stellar environments.

Multivariate continued fraction regression with target derivatives

Kieran A. Hale

Mentors: Pablo A. Moscato, Adam C. Wierman, and Andreas Heinecke

Continued Fraction Regression (CFR) is a recent method in symbolic multivariate regression that is based on representing the model as a continued fraction. CFR can be implemented with flexible depth naturally limiting the need to impose a structure on the model before training, which symbolic regression methods often do. The appeal of symbolic regression itself over methods like ANNs or SVR lies in the potential simplicity of the resulting model and its amenability to downstream analysis. For univariate problems, it has been shown that supplying both approximate and exact derivative information as part of a memetic algorithm for CFR can improve the performance of the resulting models – this method has been called CFR with target derivatives. This work extends CFR with target derivatives to multivariate regressions.

Mueller polarimetry of experimental interstellar dust analogs

Muhammed Halil

Mentors: Paul M. Bellan and Andre Nicolov

Interstellar asymmetric dust grains aligned with the magnetic field polarize starlight in the optical-to-infrared spectral range along the direction of minimum extinction. (Whittet 2022) Polarization measurements of interstellar dust are commonly used to study the magnetic field in the interstellar medium. (Andersson, Lazarian, and Vaillancourt 2015) Studies of the alignment process and dust polarization have been largely theoretical and simulation-based. This work aims to provide a laboratory foundation for interpreting astrophysical polarization observations. Experimental analogs of interstellar dust are created using the Caltech Ice Dust Plasma experiment. Ice grains are formed in a low-temperature (50–170 K), low-pressure (100–2000 mTorr) weakly ionized plasma, with an ionization factor (~ 10 –6). Ice grains grow to sizes up to 700 μm , exhibit fractal morphology, and are continuously levitated due to plasma confinement forces. (Nicolov, Gudipati, and Bellan 2024) A dual-rotating polarizer Mueller polarimeter is constructed to measure the Mueller matrix of the ice cloud. By measuring the Mueller matrix of the dust cloud, we investigate how grain alignment correlates with spatial distribution, temperature, pressure, and evolution over time.

Finalizing the characterization of Ly α emission from a sample of low luminosity, broad-line QSOs with KCWI

Charis M. Hall

Mentors: Charles C. Steidel and Evan Nuñez

Investigating the circumgalactic medium (CGM) of distant galaxies with actively accreting supermassive black holes (QSOs) is important for understanding the role of extended gas in galaxy evolution. The CGM is very diffuse and therefore intrinsically faint. It is therefore particularly useful to observe bright emission lines such as Lyman-Alpha (Ly α), a recombination line of neutral hydrogen that can be radiated by the CGM. Due to its role as a tracer of both photoionized and neutral Hydrogen, the presence of diffuse Ly α emission can tell us more about the structure of cool gas within the CGM and the sources responsible for ionizing it. Studying Ly α emission from low luminosity, broad-line QSOs will aid in the broader goal of defining exactly what constitutes a faint QSO. In this study, we characterize the spatially extended Ly α emission of a sample of 7 faint, broad-line QSOs at $z = 2.1$ –

2.6. Using integral field unit (IFU) data cubes observed using the Keck Cosmic Webb Imager (KCWI), we make a comprehensive comparison of Ly α emission within the sample, investigating: 1) the kinematics of the extended emission 2) the spatial extent, surface brightness distribution, and asymmetry of the emission, 3) the luminosity of the extended emission compared to that of the central QSO. Additionally, our analysis of these fainter QSOs provides opportunities for definitive comparisons with studies of emission from star-forming galaxies and hyper-luminous QSOs (HLQSOs), obtained from literature.

The broader goals of this work include better defining existing constraints as well as exploring open questions surrounding this fainter, broadline class of QSOs – e.g. investigating why these objects are so intrinsically faint yet still display many characteristics of more luminous QSOs (broad-lines, bright Ly α emission from these broad-line regions, etc.).

A simple and robust mechanical gripping mechanism for in-space assembly of a solar reflector truss structure

Ethan A. Hamel

Mentors: Sergio Pellegrino and Jongeun Suh

In-space assembly systems require reliable robotic grippers to accurately manipulate components of space structures. The current gripper architecture for assembly of a large reflector array involves a problematic shape memory alloy manipulator which suffers from precision requirements and functional fatigue limitations. This project focuses on developing a simple, reliable gripper that can manipulate specialized components of the reflector truss structure utilizing a gecko-inspired dry adhesive (gMDA). We characterized the adhesive's holding strength and loading specifications through mechanical testing and utilized iterative prototyping for design refinement of a flat surface gripper that fits the size requirements of the entire assembly system. The manipulator functions by pulling two pieces of gMDA towards one another in pure shear while on a flat surface, engaging the adhesive properties, and allowing for three-dimensional manipulation. We incorporated a simple hinging release mechanism permitting reliable mechanical engagement and release as well as a set of linear actuators and a depth sensor that allow for autonomous gripper actuation upon surface contact and manual release when necessary. We completed comprehensive gripper testing to determine if the new architecture is a suitable replacement manipulator.

Determining the extent to which the subgroup of computable elements in the Galois group of the algebraic closure of the rationals is elementary

Hypatia C. Hamkins

Mentors: Russell Miller and Matthew M. Gherman

The Galois Group of the Algebraic Closure of the Rationals is regarded as a complex and poorly understood structure. We investigate the extent to which one can compute the square roots of computable automorphisms in this group. Key aspects of this question reduce to the purely group theoretic question of when, given two groups H and N , there exists a group G such that $G/N \cong H$ and distinct square elements of G have distinct square roots in H . We examine subgroups of the wreath product described by the Krasner-Kaloujnine Theorem to understand how and when groups can be constructed with these properties. Answering the question of when square roots of computable automorphisms are computable is a step towards determining the extent to which the subgroup of computable elements is elementary, which will provide insight into the overall structure of the Galois group.

Faster attention for large language models

Kailen A. Hargenrader

Mentors: Yisong Yue and Ivan D. Jimenez Rodriguez

The attention mechanism is the heart of the transformer architecture underpinning Large Language Models (LLMs). Computing attention scales asymptotically as $O(N^2)$, where N is the model's context length, which is notoriously slow. Our paper provides an alternative formulation of attention which improves asymptotics when combined with sampling without making sparse or linear assumptions, as

done in previous works such as Performer or Reformer. We present *TreeAttention*, a version of hierarchical attention using a binary tree. We find that *TreeAttention* is similarly expressive to standard attention on tasks such as image classification using vision transformers and autoregressive sampling with GPT-2. Additionally, sampling methods provide a trade off between accurate attention approximation and computational efficiency.

A data-driven approach towards the electrochemical nickel-catalyzed reductive cross-coupling of piperidines

Ruchira S. Hariharan

Mentor: Sarah E. Reisman

Piperidines are a functional group ubiquitous in medicinal motifs, present in anticancer agents, Alzheimer's medications, antibiotics, analgesics, antipsychotics, and antioxidants. Thus, piperidine functionalization remains desirable, and an electrochemical Nickel-catalyzed reductive cross-coupling offers a mild, user-friendly platform to this transformation. Our optimization takes a data-driven approach to chiral ligand design: in employing multi-variate linear regression models, we elucidate the ligand features integral to the system's success. Our model provides a metric for exploring chemical space undiscovered via traditional empiricism, in addition to guiding our team on the best ligands for synthesis. Via high-throughput electrochemistry, we then screen these ligands and update our model with the results in an active learning fashion.

ContractionPPO: Certified reinforcement learning via differentiable contraction layers

Narek Harutyunyan

Mentors: Soon-Jo Chung and Matthew Anderson

We present a novel framework ContractionPPO for certified robust control of legged robots by augmenting Proximal Policy Optimization (PPO) with a state-dependent contraction metric layer. This approach enables the PPO policy to not only maximize locomotion performance but also produce a contraction metric that certifies incremental exponential stability of the closed-loop system. The metric is parameterized as a Lipschitz neural network trained jointly with the policy, either in parallel or as a final head of the PPO backbone. We derive hinge-type penalty losses from a differential Lyapunov inequality, enforcing contraction constraints during training and yielding provable convergence of trajectories despite policy expressiveness and observation mapping. The overall loss combines the standard PPO objective with contraction-related penalties, positive-definiteness, conditioning, and Lipschitz regularization, leading to explicit stability margins and robustness to disturbances. We provide necessary and sufficient conditions for exponential convergence, derive upper bounds on worst-case contraction residuals, and detail the integration of metric learning into the PPO pipeline. Our hardware experiments on multiple quadruped locomotion tasks demonstrate that contraction augmented PPO enables robust, certifiably stable control, even in the presence of external disturbances.

Probing substituent influence on reactivity and selectivity in Pd-catalyzed Michael spirocyclization

Daood I. Hashmi

Mentors: Brian M. Stoltz and Christian Strong

Spirocyclic compounds bearing vicinal quaternary and tertiary stereocenters are prevalent in natural products and medicinal chemistry, yet remain difficult to access with high selectivity. Building upon recent work from the Stoltz group, this project aims to expand the substrate scope of an enantioselective Pd-catalyzed Michael spirocyclization that forms spirocycles via Pd-enolate intermediates. In particular, we seek to evaluate the feasibility of forming seven-membered rings by modifying the tether length and substitution pattern of β -ketoester substrates. To date, we have synthesized and characterized a substrate bearing a seven-membered ring precursor with methyl-phenyl substitution at the formerly prenyl position. Reactivity studies under established Pd-catalyzed spirocyclization conditions are ongoing. Additional substrates featuring diverse substitution patterns are currently in progress. These efforts will inform future mechanistic studies and help establish design principles for accessing larger spirocyclic systems through Pd-enolates.

Investigating the contribution of the *zfh1* protein to the polarity in the collective cell migration of the caudal visceral mesoderm in *Drosophila*

Olivia M. Hatcher

Mentors: Angelike Stathopoulos and Jingjing Sun

The caudal visceral mesoderm (CVM) cells, specified at the beginning of embryogenesis, undergo collective cell migration and populate the visceral muscle lining of the *Drosophila* midgut. One aspect of the overall research goal of the Stathopoulos lab is to understand how the front-back polarity is established in the migrating CVM cells during organogenesis. Initial data suggests that zinc finger homeodomain 1 (*zfh1*, ortholog of human ZEB1), which is transcribed evenly throughout CVM cells, is post-transcriptionally regulated, and Zfh1 protein localization exhibits front-back polarity. Therefore, it is hypothesized that Zfh1 plays a critical role in breaking the symmetry within the migrating CVM cells. To investigate this further, truncated and full-length forms of the Zfh1 protein were expressed, and the polarized gene expression in CVM cells were examined in developing embryos using in situ hybridization chain reactions.

Tracking the movement of the dust clump in the debris disc of Beta Pictoris

Polaris C. Hayes

Mentors: Konstantin Batygin and Yinuo Han

The Beta Pictoris debris disc system is notable for its extent and features, including its non-axial symmetry in the form of a localized “clump” of excess dust, centered at around 85 au from the star. Previous analysis by Han et al. (2023) using three epochs over 12 years found the clump to be likely stationary, statistically ruling out both Keplerian motion and 2:1 resonant motion with an outward-moving planet. In this study, we incorporate a new epoch of high-resolution observations from 2024, representing a 21-year time baseline to further constrain the clump’s projected motion. Our methodology includes frame centering via 2D Gaussian fitting, mutual point-spread function (PSF) convolution across epochs, Markov Chain Monte Carlo modeling to identify a consistent spatial configuration, and linear displacement fitting to quantify motion. Tighter constraints on the clump’s dynamics could help to inform its origin and provide implications of planetary formation in the disk, as well as provide key insights into the dynamical processes shaping young planetary systems and the frequency of giant impacts in their evolution.

Understanding the computational limits of bipartite graph alignment

Eric M. He

Mentors: Daniel Cullina and Adam C. Wierman

The growing use of anonymized datasets raises concerns about privacy, particularly their susceptibility to de-anonymization attacks via alignment of correlated data. While graph alignment has been studied extensively in the undirected setting, many real-world settings involve bipartite structures with two distinct node sets, such as users and features, that are both independently anonymized and shuffled. We investigate the information-theoretic limits of aligning correlated bipartite graphs. Specifically, we aim to understand the computational boundary of this problem, where statistically correct recovery is possible but no known polynomial-time algorithms succeed, and explore how different alignment algorithms behave in this regime. Using a correlated Erdős–Rényi model as a base, we analyze the relationship between various graph parameters and alignment accuracy, and we propose novel algorithmic approaches informed by such probabilistic analysis. Our work provides a deeper understanding of the computational feasibility of different regimes in bipartite graph alignment for de-anonymization.

Modeling sill deflation and fault slip during caldera collapse at Bárðarbunga, Iceland

Natalia M. Hernandez

Mentors: Elias Heimisson and Gabriele Benedetti

Caldera collapse occurs when magma is withdrawn from a shallow reservoir, resulting in the structural failure of the overlying rock. During the 2014 eruption of Bárðarbunga, magma migrated from beneath the caldera to feed the Holuhraun eruption, which triggered gradual collapse over weeks. This project investigates the mechanical interaction between magma withdrawal and ring fault slip by modeling surface deformation during this collapse. Using a symmetric model consisting of a deflating sill and slipping fault on MATLAB, the study roughly simulates surface displacements recorded by GPS. We estimated caldera geometry by fitting a circle around microearthquake locations along the system and constrained the sill to this boundary. Modeled displacements were compared to observations from GPS stations active during the collapse, proving successful reproduction of vertical and horizontal displacements. These results provide constraints on reservoir and fault parameters and offer insight into the mechanics of caldera collapse driven by distant eruptions. These constraints are then used to calculate the stresses transmitted to the fault from sill deflation to assess its stability and potential feedback between the magma withdrawal and fault slip.

Photoinduced Ag doping for stabilizing mixed-halide perovskites

Hana Hisamune

Mentors: Barry Rand, Harry A. Atwater, Jr., and Julia C. Brubach

Mixed-halide perovskites offer tunable bandgaps for tandem solar cells, which can exceed the maximum efficiency of single-junction solar cells by harnessing a broader range of the solar spectrum. However, their long-term stability is limited by halide oxidation and segregation under operational conditions, which can lead to permanent film degradation and reduced device performance. This project investigates photoinduced silver (Ag^+) doping as a stabilization treatment to suppress halide segregation in mixed-halide perovskite films. Under illumination, Ag is expected to oxidize spontaneously and migrate into the perovskite lattice via iodine interstitial sites, thereby suppressing halide oxidation. Using photoluminescence (PL) spectroscopy, we tracked the spectral evolution of Ag-coated films and observed a clear reduction in redshift associated with iodide-rich phase formation compared to untreated controls. We optimized this treatment by introducing a LiF wetting layer to improve Ag coverage, and systematically investigated different metal cappings and thicknesses to identify the most effective parameters for suppressing halide segregation. Furthermore, we performed X-ray photoelectron spectroscopy (XPS) to probe iodine-metal interactions to confirm the mechanism behind suppressed halide migration and to explain the variations in PL response observed across different metal treatments.

Examining the effect of heterotrophic bacteria and viral lysis on the size and flux of diatom marine snow particles in the biological carbon pump

Elinor J. Holland

Mentors: Victoria J. Orphan and Jeremy E. Schreier

The biological carbon pump, the process by which atmospheric carbon dioxide is sequestered into the deep ocean through sinking marine snow particles, plays a major role in regulating climate on Earth. Diatoms, unicellular photosynthetic algae, account for $\sim 15\%$ of total carbon exported from the surface ocean making them a major component of the biological carbon pump. As these particles are formed and sink, they are colonized by heterotrophic bacteria. The mechanisms controlling the flux of these particles, however, remains unclear. Here, we examined the potential role bacteriophage play in modulating the size and flux of diatom marine snow particles through the lysis of associated bacteria. We generated diatom marine snow particles using model diatoms *Phaeodactylum tricornutum* (Pt) and *Chaetoceros muelleri* (Cm) in the presence or absence of heterotrophic bacteria and/or bacteriophage using natural communities or model isolates. Using the Malvern Mastersizer 3000E, we measured the size distribution of both the suspended planktonic particles and sedimented, dense particles. Preliminary results using natural bacterial and viral communities suggested contrasting results between the two diatoms. In Cm planktonic fractions, the addition of concentrated virus displayed a

shift from small (1-10 μm) to larger (100-1000 μm) sized particles in both the presence or absence of a bacterial community. In Pt planktonic fractions, however, the addition of concentrated virus created >100 μm sized particles that were not seen in any other treatment. These data suggest that diatom marine snow particle size distributions are community specific and can be affected by viruses alone.

Transitioning the high contrast high-resolution spectroscopy for segmented telescopes testbed from FALCO to CATKit2

Jaylen B. Holloway

Mentors: Dimitri P. Mawet and Susan Redmond

The High Contrast High-Resolution Spectroscopy for Segmented Telescopes testbed (HCST) focuses on filling gaps in exoplanet direct imaging technologies by testing key technologies, such as coronagraphs, spectroscopy, and wavefront control, that are essential for the success of future large space telescopes. Previously, HCST operated using MATLAB and the Fast Linearized Coronagraph Optimizer (FALCO) framework, which limited performance due to its slow architecture and difficulty supporting parallel control loops. This project transitions HCST operations to Python using Control and Automation for Testbeds Kit 2 (CATKit2), a real-time control architecture designed for high-contrast imaging testbeds. The controls for each testbed component were implemented in Python, which enables faster execution and improved flexibility. The core functionalities of each component were verified in numerous preliminary tests, including retrieving images from the science camera. Additional safety checks are being implemented to ensure reliability, and a graphical user interface is under development to support ease of use. The new Python-based architecture is expected to exceed the performance of the old system in terms of speed, accuracy, and stability. The system transition creates a dependable foundation for ongoing exoplanet imaging research and future upgrades of the HCST.

Flume experiments on cohesive riverbank width

Natalie R. Homyk

Mentors: Michael P. Lamb, Kimberly L. Miller, and Tingan Li

Understanding river width adjustment is vital for mitigating hazards and informing infrastructure development. We aim to quantify erosion of cohesive mud under controlled conditions to test if the channel reaches equilibrium width when shear stress matches bank material strength. This study presents the initial findings of flume experiments on the self-adjustment of cohesive riverbanks. We conducted flume experiments with a homogeneous mixture of clay, silt, and organic matter to isolate shear stress on muddy banks, allowing precise control and measurement of bank strength and erosion. These conditions offer an ideal platform to test if rivers stabilize at a width where flow forces balance bank resistance. We first calibrated friction and partitioned boundary shear stress using non-eroding gravel runs. In these initial experiments, we adjusted discharge and downstream base level, while taking water-surface scans to map hydraulic response to obtain normal flow conditions and define starting conditions for cohesive-bank runs. Muddy bank experiments combine time-lapse imaging to track erosion rates with scans of the water surface to quantify shear stress, enabling assessment of whether channel width stabilizes when shear stress balances bank strength.

Rainbow on a chip: High-performance visible and short near-infrared laser sources based on germano-silicate ultra-low-loss photonic integrated circuits

Hanfei Hou

Mentors: Kerry J. Vahala and Haojing Chen

High-performance lasers spanning the visible and short near-infrared (NIR) spectrum (380–1100 nm) are essential for emerging quantum technologies, yet their chip-scale integration is hindered by high material loss at shorter wavelengths. Germano-silicate glass has recently emerged as a promising photonic integrated circuit platform with potential for ultra-low loss across this full band. Here, we demonstrated integrated visible and short NIR lasers based on germano-silicate optical microresonators using two complementary approaches. In spectral regions with available semiconductor gain media (infrared, red, green, and blue), single frequency, narrow-linewidth hybrid-integrated lasers are demonstrated using self-injection locking scheme, reaching record-low

fundamental linewidths below 100 Hz. In the spectral 'green gap' (530–600 nm) where no suitable gain media exist, we explore frequency-converted lasers based on third-harmonic generation. Together, these results establish germano-silicate as a versatile platform for visible and short NIR integrated laser sources, with broad potential for quantum information and precision measurement applications.

LeanLibrary: A comprehensive library for AI-assisted theorem proving in Lean 4

Ryan L. Hsiang

Mentors: Anima Anandkumar and Robert Joseph George

Mathematics is experiencing a fundamental transformation through the integration of artificial intelligence and formal verification. Despite the significant advancements in combining large language models with the Lean theorem prover, existing tools are fragmented across different repositories and require considerable programming background to set up and use effectively. This project integrates the various Lean+AI tools into a unified library, providing a consistent API for data extraction, interaction, model training, and theorem proving. The framework offers multiple training methods for fine-tuning large language models on domain-specific Lean codebases. In addition, using the fine-tuned models as tactic generators, we implement a proof search algorithm that constructs a goal-tactic graph with Depth-First Search and extracts the proof using the shortest-path algorithm.

Investigation of the cancer cell resistance mechanisms to p97/VCP ATPase inhibitor via single-cell and bulk phosphoproteomics

Ying-Hsin Hsiao

Mentors: Tsui-Fen Chou and Marion Wan Rion Pang

p97 AAA ATPase is a critical regulator of protein homeostasis and a promising anticancer drug target, with inhibitors such as CB-5083 and CB-5339 advancing to phase I clinical trials. Although p97 inhibitors have demonstrated efficacy in colon cancer xenografts, prolonged exposure results in resistant cell populations acquiring resistance through p97 mutations. To elucidate the mechanisms underlying this drug resistance, we used three CB-5083 resistant HCT116 sublines (CB-R1, CB-R2, CB-R3) and performed integrated bulk and single-cell mass spectrometry-based proteomics. We incorporated phosphoproteomics on both bulk and low-analyte samples, capturing alterations in signaling activity that accompany resistance. Upregulated kinases in CB-R cells were identified through motif-enrichment analysis on phosphoproteomics data. We then performed drug combination experiments between CB-5339 and 20 kinase inhibitors to determine their combined effect with the expectation of potential synergistic cytotoxicity with CB-5339, suggesting specific vulnerabilities in resistant cells. Follow-up single-cell MS profiling after co-treatment revealed pathway reactivation, feedback signaling, and stress responses unique to certain combinations, enabling insight into compensatory survival pathways. Altogether, our study leverages deep proteomic and phosphoproteomic profiling across bulk and single-cell scales to uncover key mediators of resistance and to nominate rational combination strategies that may overcome therapeutic failure in p97-targeted cancer treatment.

The influence of transport on chemistry in the middle atmosphere of Venus

Cheng-an Hsieh

Mentors: Yuk L. Yung and Ting Juan Liao

The atmospheric dynamics of Venus exhibit super-rotation in the troposphere (0 - 60 km), while the mesosphere (60 - 120 km) is characterized by complex dynamics and photochemistry. While the general chemical circulation in this layer presents a long-standing scientific challenge, a recent unexpected discovery of a significant increase in the deuterium-to-hydrogen (D/H) ratio in the mesosphere (~ 60 - 100 km), rising from 162 to 1,519 times Earth's value between 70 and 108 km altitude, suggests the existence of a powerful transport mechanism, possibly an aerosol-driven cycle and a meridional circulation (Mahieux et al., 2024). This study proposes a multi-step model to test and quantify the hypothesis that D/H stratification results from atmospheric transport and chemistry interaction. We utilize wind fields from a Venus General Circulation Model (GCM). By applying Singular Value Decomposition (SVD), we reconstruct the analytical stream function that characterizes the mean

meridional circulation. The derived stream functions are used to drive a 2D Chemical Transport Model (CTM) (Yung et al., 2009). The CTM couples the Prather advection scheme (Prather, 1986) for tracer transport with the KINETIC gas-phase photochemistry model. The primary objective is to simulate the transport and photochemical evolution of the related species to determine if this coupled dynamic-photochemical system can reproduce the observation. This work aims to explain the mechanisms of chemical species in Venus's mesosphere, providing crucial insights into the planet's atmospheric evolution and water loss history (Donahue et al., 1982).

Creating a wearable, non-invasive sebum sensor for solid-state cholesterol detection

Renee C. Hsu

Mentor: Wei Gao

Wearable, non-invasive biosensors are important for easy access continuous health monitoring. We are making a hydrogel sensor that detects solid-state cholesterol levels from sebum on skin. Cholesterol is important for cell membrane structure and production of hormones. It is also an indicator for many health conditions involving hyperlipidemia, an excess of lipids in blood, including type 2 diabetes and peripheral artery disease. The purpose of the hydrogel is to contain cholesterol oxidase while collecting cholesterol molecules from sebum that diffuse through the hydrogel and interact with the enzyme, producing hydrogen peroxide resulting from a reduction reaction. The hydrogel is made with polyvinyl alcohol (PVA) and sits atop an electrode that responds to the reduction reactions of peroxide directly correlating with the concentration of cholesterol, producing electrochemical current correlated with differing concentrations of cholesterol exposed to the PVA hydrogel.

Towards the design of an ultra-high vacuum compatible inductively coupled plasma (ICP) source

Annie M. Hu

Mentors: Austin J. Minnich and Mete Bayrak

Materials research is essential in enabling fabrication of cutting edge semiconductor and quantum devices, especially for nanofabrication of high-quality thin films. Plasmas, with their high density of energetic particles and reactive species, enable faster and more uniform substrate etching and/or thin film deposition. Due to the growing relevance of plasma processing for growing desirable materials in our lab, and our desire to minimize contamination and impurities in our thin films, we hope to build an ultra-high-vacuum (UHV) compatible ICP source for nitrogen plasma. In the future, we hope this technology enables growth of III-V nitrides to test in our lab. In order to create our source, we first tested using a non-UHV-compatible ICP design to see what materials we could use for the dielectric tube, what coil geometries were sufficient to strike plasma, and to observe the behavior and properties of the inductively coupled plasma under different power, pressure, and coil configurations. After understanding what is required to obtain the plasma we want and designing an appropriate grounded aperture to filter out charged species from plasma reaching the substrate, we will assemble the UHV ICP and collect measurements using a Langmuir probe to verify the functionality of the aperture.

Investigating map-free thermal navigation for aerial robots in low-light, over-water environments using imitation learning from traditional planners

Hongyi Hu

Mentors: Soon-Jo Chung, Nikhil Ranganathan, and Xingxing Zuo

This project examines whether a small robot can navigate using only passive thermal imagery when visible light is unreliable and active sensors such as lasers are undesirable. The objective is to learn a controller that converts a thermal image and a goal direction into short motion commands that keep safe clearance from obstacles. To create examples of safe behavior, we have completed an expert pipeline that builds three-dimensional maps with a laser scanner and motion sensors, computes collision-free paths with a classical planner, and time-aligns each path with the thermal video recorded in the same scene. These paired image-action examples will train a compact learning system that imitates the expert's steering and forward motion while using no active sensing at run time and

avoiding reliance on visible-light cameras. Because experiments are not yet complete, the next phase expands the dataset to low-contrast scenes and water surfaces, adds brief memory over recent frames, integrates a simple safety check before each action, and evaluates performance by goal-reach rate, collision rate, and deviation from planned paths in indoor corridors and along waterfronts.

Hard X-ray contribution in AU Mic flares and its minor role in atmospheric escape

Yifan Hu

Mentor: Murray Brightman

Stellar flares significantly impact exoplanetary atmospheres, yet the role of hard X-ray (HXR) emission in flare energetics and atmospheric escape remains poorly constrained. To address this, we coordinated quasi-simultaneous observations of the young M-dwarf star AU Mic using NuSTAR, Swift-XRT, and Einstein Probe-FXT, capturing two distinct flares. Leveraging this multi-instrument data set, we derived an empirical soft-to-hard X-ray (SXR–HXR) scaling relation and combined it with an established extreme ultraviolet (EUV)–SXR relation to quantify the full radiative energy budget (EUV + SXR + HXR). We find the HXR contribution is modest, increasing from 1.7% in quiescence to 3.3% during flare peaks. Even assuming maximal atmospheric escape efficiency, HXR-driven mass loss is only a few percent of the XUV-driven rate. Nonthermal power-law spectral tails are detected in quiescence and during one flare, accompanied by a clear local Neupert effect, signifying impulsive electron acceleration followed by rapid thermalization. Spectral-timing analyses reveal heating is dominated by 3–6 keV photons, with reduced relative contribution from 6–20 keV photons during flares. Thus, AU Mic’s flares remain predominantly thermal events, suggesting that episodic nonthermal processes play a minor role in long-term atmospheric evolution of orbiting planets.

Ultrasonic control of ion channel functions via a sonogenetic redox switch

Noor E. Ibrahim

Mentors: Mikhail G. Shapiro and Hengyu Li

Abstract withheld from publication at mentor's request.

Towards a digital twin: Applying ML methodologies to complete solar event data

Chigozirim N. Ifebi

Mentors: Hillary Mushkin and Ashish Mahabal

This project investigates methods for analyzing and predicting high-latitude particle precipitation using Defense Meteorological Satellite Program (DMSP) data and physics-based and machine learning models. I began by exploring the Ovation Prime model and precipNet framework, developing visualizations of auroral boundaries and electron energy flux in both polar and time-series contexts. To evaluate predictive modeling, I trained machine learning baselines, including random forests, to forecast electron energy flux month-ahead; while initial results highlighted challenges due to the highly variable nature of the flux, they provided a benchmark for comparison. I then implemented the SAITS (Self-Attention-based Imputation for Time Series) architecture to address data gaps and explore sequence-to-sequence forecasting in a multivariate setting that included geomagnetic indices (AE, Bz, SymH). This required restructuring the dataset into sequential formats, masking values for imputation, and adapting GPU-based training in Google Colab. Alongside, I developed interactive visualizations to contextualize model outputs with DMSP observations. The results demonstrate both the promise and challenges of applying advanced sequence models to space physics: while computational resource limitations constrained large-scale experiments, the pipeline establishes a foundation for using attention-based architectures to better capture precipitation variability.

Generalized tube algebras for locally presented quasi-local algebras

Jun Ikeda

Mentors: Corey Jones and Matilde Marcolli

Tube algebras associated with fusion spin chains play a central role in analyzing their categorical structure; in particular, their representation category is canonically equivalent to the Drinfeld center of the underlying fusion category. In this work, we extend that framework by constructing a generalized tube algebra for an abstract quasi-local $*$ -algebra covariant under an isometric group action (for example, translation) on a countable metric space with bounded geometry, assuming local generation and local presentation. We then use this construction to define a fully faithful functor from the category of translation-invariant quasi-local $*$ -algebras over the integers to the category of inverse systems of tube algebras of growing circumference modulo finite differences. Finally, in the case of fusion spin chains, we show that the tube algebra construction intertwines with the DHR functor and we develop a criterion for when a tensor autoequivalence of a DHR category cannot be realized by a quantum cellular automaton on the underlying quasi-local algebra.

On the computational power of nucleation kinetics

Ritali Jain

Mentors: Erik Winfree, Cameron Chalk, and Yancheng Du

Self-assembly is a prevalent molecular phenomenon in the chemical world—from the formation of viral capsids to crystalline structures—with ties to algorithmic behavior arising from programmable local interactions. One particularly interesting kinetic regime is nucleation, a rare event process whose dynamics involve stochastic exploration to overcome an energy barrier and eventually stabilize into an energetically favorable structure. It has been demonstrated that self-assembly under nonequilibrium nucleation kinetics can be programmed to form structures classifying high-dimensional concentration patterns, analogous to neural network-like pattern recognition capabilities. While the previous system responded to given input concentrations by colocalizing particular preferred critical nuclei, in this work, we extend this exploration beyond behaviors reminiscent of associative recall to ask whether nucleation kinetics can support richer forms of computation—specifically, the ability to solve constraint satisfaction problems representative of NP-hard search. To investigate this, we encode constraints of NP-hard problems into DNA-based tile components, coupled with the energetics of tile entropy and bond cooperativity. We formally connect the set of tiles' low-energy configurations to low-barrier growth trajectories, lifting an equilibrium constraint satisfaction problem into nucleation kinetics. Since kinetic behavior is also controlled by the entropic distribution of trajectories, we simulate our tiling systems with forward flux sampling and empirically validate that nucleation kinetics performs combinatorial search by a difference in nucleation rates. Although our constructions illustrate the computational power of nucleation in principle, the tradeoff with nucleation speed is significant, and worst-case behaviors remain slow. Nonetheless, this work lays the theoretical foundation for understanding nucleation kinetics as a medium for constrained combinatorial search and empirically supports the role of energy landscape design in shaping assembly dynamics, at least in the context of nucleation.

Computer-aided diagnosis of breast and lung lesions using medical imaging

Vannsh Jani

Mentors: Ashish Mahabal and David Liu

Breast and lung cancers are among the leading causes of cancer-related mortality worldwide, highlighting the urgent need for improved diagnostic tools. In this project, we focus on computer-aided diagnosis using deep learning techniques applied to medical imaging for lesion detection in breasts and lungs. For breast cancer, we work with 2D mammograms, approaching the task as an image-level classification problem due to the absence of ground truth bounding boxes. We aim to classify masses and suspicious calcifications from mammograms using pre-trained featurizers and MLP classifiers, we fine-tuned the models on a relatively small dataset and achieved an AUC of 0.82. To enhance performance, we are incorporating contrastive language-image pretraining (CLIP) using select clinical attributes as prompts, aiming to provide better context for downstream tasks. For lung cancer, we localized lesions in CT scans by first annotating data in consultation with clinicians. A Faster-RCNN model trained on just 50 samples achieved an AP50 of 0.78. We are now expanding to a

larger dataset and also experimenting with more recent object detection models to improve performance, with the goal of analyzing lesion morphology for improved risk assessment. This work emphasizes the importance of AI-ready data and offers insights into the types of data most useful for deep learning applications.

Sensor-integrated head design for robust perception in humanoid robots

Ana S. Jaramillo

Mentors: Aaron D. Ames, Adrian Boedtker Ghansah, and Sergio A. Esteban

The AMBER Lab at Caltech conducts research on locomotion, control, and human-robot interaction, aiming to build robots that can safely operate in human environments. Recently, the lab has been working with the Unitree Humanoid G1, a humanoid designed for research in robotics and human-robot interaction. Ensuring safety in humanoid operation requires robust perception, as the robot must reliably sense and respond to its environment. This project focuses on enhancing perception of the G1 robot through the development of a new head design that integrates multiple visual sensors. The redesigned head integrates four RGB-D cameras, providing a comprehensive field of view for safer navigation and interaction. Early results show smooth integration of the cameras with ongoing progress in visualization. Future work will refine the head's mechanical design to further improve perception, robustness, and safety.

3D medical imaging with neural operators

Armeet S. Jatyani

Mentors: Anima Anandkumar and Jiayun Wang

We develop 3D neural operator layers with local inductive biases, extending the DISCO framework to three dimensions. The resolution-robust capabilities of neural operators enable us to train 3D MRI reconstruction models with limited 3D data. We train an accelerated MRI reconstruction task on the SKM-TEA MRI dataset, which to our knowledge is the largest 3D volume-scanned MRI dataset. Our 3D DISCO layers are a novel machine learning architecture. They have applications in physical simulation, PDE solvers, and scientific analysis, extending beyond medical imaging.

Simulations of Shor's algorithm with reduced density matrices

Nathan Jay

Mentor: Marco Bernardi

Shor's algorithm is a quantum algorithm that provides superpolynomial speedup in factoring integers. Classical simulations of this algorithm require exponential resources, but using reduced density matrices provides a speedup. This project further explores using reduced density matrices in simulation of the core subroutine in Shor's algorithm—phase estimation. Through simulation of phase estimation circuits, pitfalls of 3-RDM simulations are found at the SWAP gates, as well as when tracing down to 1-RDMs. A more faithful SWAP treatment within the RDM picture is outlined, and efficient tracing procedures are identified as a key direction for improvement.

Optimization of experimental parameters for the production and usage of a muon beam at the Light Dark Matter eXperiment (LDMX)

Thuwaragesh Jayachandran

Mentors: Bertrand Echenard and David G. Hitlin

This project investigates the optimization of muon production from electron-fixed target collisions for use in the Light Dark Matter eXperiment (LDMX), with the goal of enabling a high-quality muon beam to probe dark sector physics. Using the Geant4 simulation framework, we model interactions between an 8 GeV electron beam and a tungsten target to evaluate muon yield and background processes under varying target geometries. We systematically explored the impact of target thickness on both the muon and background yields, finding that increasing thickness and narrowing the angular limits

improves muon-to-background ratios without significantly reducing muon yield. Additionally, we performed spatial and angular analysis of muon emission and background particle fluxes to inform filtering strategies. We also performed numerical calculations based on the characterization of the muon flux to understand the sensitivity of the experiment that can be performed with muons.

Interannual variation of the Earth's brightness observed by DSCOVR

Xun Jian

Mentors: Yuk L. Yung and Siteng Fan

The Earth's energy budget plays a key role in global warming. Anthropogenic activities have significantly altered the climate system, modifying radiative forcings. This affects the amount of solar energy absorbed by Earth as well as the outgoing longwave radiation. However, the assessment of this long-term evolution is challenging due to the limited temporal length and global coverage in space-borne observations. In this work, we leverage the unique orbit of Deep Space Climate Observatory (DSCOVR), which is located at the first Sun-Earth Lagrange (L1) point, whose instruments continuously observe the fully sunlit Earth, providing comprehensive data for energy-budget studies. The spacecraft and instruments onboard have been in operation since 2015, so it becomes possible to investigate the interannual variations using this ten-year data. Leveraging this data, we analyze the Earth's brightness at ten wavelengths from UV to NIR using the narrow-band Earth Polychromatic Imaging Camera (EPIC), as well as the disk-integrated energy flux measured by the NIST Advanced Radiometer (NISTAR). Explainable machine learning techniques are applied to remove and correct geometric effects of Sun-Earth-spacecraft viewing angles. The interannual variation of Earth's bulk spectrum is then investigated and evaluated. This work provides observational constraints on Earth's energy budget changes under a warming climate.

Using an expected volume heuristic to guide adaptive sampling of molecular dynamics simulations of proteins

Gavin N. John

Mentors: Gregory Bowman and Mitchell Guttman

The vast majority of drugs target proteins. As such, identification of protein binding sites and an understanding of protein conformational heterogeneity are important first steps in virtual drug discovery. The Bowman lab specializes in the identification and characterization of cryptic pockets: binding sites normally internal to the protein, but that become exposed as the protein undergoes conformational changes. Due to their nature, these are much harder to identify, but represent a massive number of potential drug targets. The lab has developed several tools to assist in the discovery of cryptic pockets, of which two are particularly important. The first, PocketMiner, is a neural network that can quickly and accurately predict residues that might form part of cryptic pockets. The second, FAST (Fluctuation Amplification of Specific Traits), is a conformational analysis tool that uses adaptive sampling and a customizable geometric component to direct molecular dynamics simulations to conformational spaces of interest. Here, we developed a new geometric component that uses the predictions from PocketMiner to generate an estimate of the pocket volume that was used in a FAST simulation of a candidate protein target, TEM-1 beta-lactamase, which successfully demonstrated pocket opening behavior.

Benchmarking control barrier function methods for real-time resilient UAV swarm coordination

Edward S. Ju

Mentors: Aaron D. Ames, Pio Ong, and Ryan M. Bena

Swarm networks of unmanned aerial vehicles (UAVs) operating in formation often require communication connectivity while avoiding collisions. We present a study on real-time connectivity maintenance using control barrier functions (CBFs) and demonstrate implementation on Crazyflie hardware. We compare three CBF approaches: CBF-QP with naive affine connectivity constraints, CBF-SDP with linear matrix inequality Laplacian constraints, and CBF-QP with local connectivity conditions. Through simulation and hardware experiments, we analyze the trade-offs between computational complexity and task performance for each method. Our scalability tests demonstrate

that our CBF-SDP approach achieves safe, real-time connectivity preservation. We provide quantitative task performance metrics comparing our methods with existing approaches, demonstrating real-time feasibility and scalability for swarm applications.

Evaluating quantum-scale dispersion compensation via pulse compression and Hong-Ou-Mandel interference

Raghava K. Kalidindi

Mentors: Maria Spiropulu and Raju Valivarthi

This work presents a detailed investigation into dispersion compensation for the long-distance transmission of time-bin encoded quantum states using classical light as a substitute. A tunable dispersion compensator (TeraXion TDCMX-SM) was used to counteract chromatic dispersion over 10-100 km of optical fiber. Pulse broadening was quantified using full-width at half maximum (FWHM) measurements derived from photon arrival time histograms acquired via a Time Tagger Ultra. A fiber-based interferometer setup was used to generate early and late time-bin pulses from a single laser source, demonstrating preservation of time-bin structure following propagation and compensation. Using a low-bandwidth gas cell laser eliminated any secondary peaks that form due to the limited bandwidth of the compensators (40-58 GHz), enabling clean pulse compression and effective dispersion compensation over 100 km.

To improve dispersion alignment beyond pulse width metrics, the Hong-Ou-Mandel (HOM) visibility measurements were made. The dispersion compensation setup is being integrated with a polarization control system to enable stable transmission of polarization-encoded quantum states. Entangled photons are being used to make interference and visibility measurements, providing quantum-level validation of the compensation system's performance.

Numerical simulations and data generation for learning closure models

Krishna Kamalakannan

Mentors: Kaushik Bhattacharya, Harkirat Singh, and Lianghao Cao

Closure models are critical in accurately capturing unresolved or subgrid-scale processes in complex physical systems, such as fluid dynamics, climate modeling, and material deformation. Recently, there has been a rise of interest in using high-fidelity simulated data or experimental data to learn closure models using techniques such as operator learning and differential programming. However, there is a lack of standardized and well-documented testing problems and datasets, which makes it challenging to systematically compare the strengths and limitations of different learning methods across various mechanistic systems. We address this issue by designing simple and representative test problems, generating datasets, and evaluating the performance of learning methods. Emphasis was put on reproducibility and accessibility--the designed test problems, code, and datasets will be shared with the broader research community to foster collaboration and further advancements in the field.

Advancing ASTM E659 testing: Investigating and optimization of the current ASTM testing methods and apparatus

Jason M. Kamau

Mentors: Joseph E. Shepherd and Charline Fouchier

The autoignition temperature(AIT), defined as the minimum temperature at which a fuel ignites without an external ignition source, is a crucial parameter in assessing fire hazards across many industries. The most used methodology for determining this temperature is the ASTM-E659 standard in the United States. However, the Explosion Dynamics Laboratory, under Professor Shepherd's supervision, established that the mechanisms governing autoignition remain poorly understood, particularly in complex hydrocarbon fuels. Insights into the dispersion and ignition of such fuels under the ASTM-E659 conditions have been reached thanks to an optically accessible experimental setup. The fuel of study (hexane) was injected inside a heated test cell via a syringe pump system. Flow, concentration, and temperature data were acquired via an IR laser, photodetector, thermocouples, a high-speed camera, and LabVIEW, and analysis was done via MATLAB. The cell design was updated during the project to improve the repeatability of the tests. We evaluated injection repeatability and

convection effects on concentration over a couple of tests. The calculated injected moles of fuel in the cell for all the tests were approximately 91% of the predicted moles. Stronger convection, driven by vertical temperature gradients, showed faster mixing. Finally, ignition was investigated inside the cell.

Designing a digital twin for Brookhaven National Laboratory's Rapid Cycling Synchrotron as part of the Electron-Ion Collider project

Nora K. Kane

Mentors: Vahid Ranjbar and David G. Hitlin

The Electron-Ion Collider (EIC), currently in design at Brookhaven National Laboratory, will be a first-of-its-kind particle accelerator capable of colliding beams of electrons and heavy nuclei to illuminate the answers to central questions in nuclear physics. The EIC will use a Rapid Cycling Synchrotron (RCS) to accelerate electron beams from 750 MeV to 18 GeV; this acceleration is essential to successful experimentation in the EIC. To ensure the stability of beams within the RCS, the effect of quadrupole strength misalignments on beam motion must be rigorously understood. However, quantifying optical response to such deviations is prohibitively slow using standard exhaustive tracking studies. Thus, we present a digital twin of the RCS: a machine-learning surrogate model that maps inputted quadrupole strengths to key twiss parameters at every element within the RCS lattice in real time. The model is trained on MAD-X simulation data and learns directly from the accelerator optics, enabling rapid optics studies, misalignment tolerance evaluations, and magnet setting optimization that would otherwise be computationally expensive. The resulting model augments conventional modeling by providing fast, physics-consistent optics estimates for design exploration and prospective online tuning during commissioning and operations, with the approach generalizing to other accelerators.

OrbNet-Materials: Orbital-based GNN for materials properties prediction

Minhyuk Kang

Mentors: Anima Anandkumar and Beom Seok Kang

Accurate electronic band structures are fundamental to materials discovery, but DFT is computationally expensive and most ML surrogates either rely on geometry-only inputs or predict only scalar properties rather than the full band energy. Our OrbNet-Materials, a periodic extension of orbital-learning GNN can predict full electronic band structures for crystalline materials at a fraction of DFT cost. Building on the success of OrbNet in orbital learning for molecular system, we generate k -dependent atomic-orbital matrices via DFTB+ using low-cost semiempirical quantum mechanical (QM) calculations (GFN1-xTB) and feed them to an SE(3)-equivariant OrbNet framework. A PBC-aware graph links each unit cell to intra-cell and periodic-image neighbors within a cutoff, and per- k inference predicts $e_n(k)$ and derived properties. We train with a dispersion-aware loss: pointwise energy MSE plus finite-difference penalties on band slopes, with optional extra weight at high-symmetry points. Together, these components establish an end-to-end pipeline for orbital learning in periodic materials. OrbNet-Materials has strong potential to serve as a fast, orbital-aware surrogate for DFT in high-throughput discovery, driving inverse design and active-learning loops for photovoltaics, thermoelectrics, and catalysis.

Serotonin dynamics in the VMHvl Esr1 during social interactions

Zara H. Kanold-Tso

Mentors: David J. Anderson, Amit Vinograd, and Takumi Itakura

Serotonin (5-HT) is a neuromodulator which mediates emotional states like fear, safety, and aggression. However the real time dynamics of 5-HT during social behaviors are unknown. Aggression is a highly conserved state that is promoted by estrogen receptor type 1+ (Esr1+) neurons in the ventrolateral part of the ventromedial hypothalamus (VMHvl). Therefore, we did fiber photometry recording of 5-HT dynamics in VMHvl Esr1+ neurons with GRAB_5HT sensor during social interaction under different social experiences. Using Behavior Ensemble and Neural Trajectory Observatory (BENTO) and deep-learning programs like Deep Action, we correlated 5-HT traces with behavioral

data. We found transient and persistent time locked decreases in 5-HT when intruders entered a resident's cage and when resident mice attacked the intruder. These decreases may be related to social fear responses or defensive states in response to the intruder. Further experimentation and social situations are needed to validate these traces and elucidate the meaning of the decreases.

Neural crest cells in jaw regeneration

Peiyu Kao

Mentors: Marianne Bronner and Miyuki Suzuki

Neural crest cells, which give rise to diverse cell types, are essential for craniofacial development and have been shown to contribute to organ regeneration, including the heart and digit tip. However, their contribution to organ regeneration is not well understood. Urodele amphibians exhibit extraordinary regenerative abilities, and recent findings have revealed upregulation of neural crest-related gene during newt limb regeneration, suggesting the critical role of neural crest cells in regeneration. Newt can also regenerate jaw, and since craniofacial tissues are largely neural crest-derived, the role of neural crest cells in regeneration is especially intriguing. Using Iberian ribbed newt (*Pleurodeles waltl*) as a model, we aim to characterize the role of neural crest cells in jaw regeneration. We examine neural crest cells through *in situ* hybridization chain reaction staining with neural crest cell markers such as *Sox10* and *PO*. We found *Sox10* expression throughout the entire jaw post-amputation. We also utilize live imaging in *Sox10*-Cre vector-injected into Cre responder transgenic newts to trace neural crest cells and assess their role in wound healing, dedifferentiation, proliferation, and redifferentiation during jaw regeneration. Our work may provide valuable insight into jaw regeneration, with potential application to improving regeneration methods in mammals and humans.

Learning affine maps for an amortized noise-agnostic filter

Gautham Kappaganthula

Mentors: Andrew M. Stuart and Bohan Chen

Classical data assimilation (DA) methods typically assume access to the observation operator H and the observation-noise covariance Γ . In many practical settings, neither is known: only noisy measurements are available, or H and Γ can be inferred only crudely, which degrades the performance of Kalman-type filters. We propose a learning-based analysis step that learns an affine mean-field map acting on ensemble mean and anomalies, which recovers the Ensemble Kalman Filter and Ensemble Square Root Filter updates under specific parameterizations. However, our method is noise- and operator-agnostic and does not require explicit H or Γ . To amortize across different noise levels, ensemble sizes, or even observation operators, we train with a reweighted loss that balances optimization across noise and ensemble size, and can mix different observation operators during training. Experiments on Lorenz '63, Lorenz '96, and the Kuramoto-Sivashinsky systems show that our learned affine map performs comparably to classical methods with access to true H and Γ and significantly outperforms classical baselines that rely on approximate or unknown noise information.

Searching for pulsation in low mass stars using supervised learning techniques

Waly M Z Karim

Mentors: James W. Fuller and Rocio Kiman

M-dwarfs, the most prevalent stars in our solar neighborhood, remain poorly understood, partly due to persistent discrepancies between theoretical models and observational data concerning their radii and effective temperatures. Asteroseismology—the study of stellar oscillations—offers a promising avenue for resolving these issues. Although detecting pulsations in low-mass stars has historically been challenging, TESS light curves present new opportunities due to their red sensitivity and short-cadence observations. We have developed a supervised algorithm to classify light curves and identify pulsation features in low-mass stars by training a convolutional autoencoder on a labeled catalog of variable stars using TESS 2-minute cadence data. The neural network autonomously extracts features, which are then passed to a classifier head to categorize the stars. Our model achieves 96% accuracy

in detecting solar-like oscillations in variable stars. Since low-mass stars exhibit surface-level convection similar to that of solar-like oscillators—believed to drive pulsations—developing a highly accurate deep learning model for identifying such oscillations represents a significant step toward discovering new low-mass pulsators.

O-GlcNAc transferase activity and protein-protein interactions at synapses

Sigríður Karlsdóttir

Mentors: Linda C. Hsieh-Wilson and Jamison Takashima

O-linked glycosylation of nuclear and cytoplasmic proteins is a covalent post-translational modification catalyzed by O-GlcNAc transferase (OGT). Aberrant OGT activity has been shown to be correlated with cancer, diabetes and Alzheimer's disease (AD) and although OGT is known to localize to synapses, its role in synaptic function is not fully understood. We chemoenzymatically labeled AD brain samples with biotin and blotted the samples with a streptavidin conjugated dye to examine O-GlcNAcylation levels. We observed a decrease in O-GlcNAcylation in the crude synaptosome, compared to age matched control samples, as well as an increase of O-GlcNAcase and decrease in OGT which was in line with expectations and previous data. We then performed co-immunoprecipitation to confirm the interaction of OGT and PSD-95 among other synaptic proteins such as Synapsin 1 and Homer1. Unlike what was expected, the only interaction observed was between OGT and the inhibitory protein gephyrin, contrary to previously acquired results which shown that OGT and PSD-95 interact. Therefore it is likely that these results stem from problems in experimental setup and we are currently optimizing an in vitro pull-down experiment to determine the site on OGT where PSD-95 interacts.

Investigating the role of angiotensinogen (AGT) in oxidative stress and inflammation in retinal pigment epithelium (RPE) cells with high-risk CFH (Y402H)

Isabella G. Kedikian

Mentors: Deborah Ferrington, Dennis A. Dougherty, Johnson Hoang, and Peng Shang

Age-related macular degeneration (AMD), a leading cause of blindness in the elderly, is strongly linked to both cigarette smoke exposure and the Y402H polymorphism in the Complement Factor H (CFH) gene. This project investigates the role of angiotensinogen (AGT) and the renin-angiotensin system (RAS) in driving oxidative stress and inflammation in retinal pigment epithelium (RPE) cells carrying this high-risk (HR) CFH variant. Previous research from induced pluripotent stem cell-derived (IPSC) RPE cells from human donors had shown elevated levels of AGT expression in HR cells, and this was confirmed through ELISA. Experiments exposed cells to varying concentrations of cigarette smoke extract (CSE), angiotensinogen converting enzyme (ACE), and renin to assess RAS activation via AGT and angiotensin II levels, lipid droplet formation, reactive oxygen species (ROS) production, and NFκB signaling. Results revealed increased lipid droplets and mitochondrial ROS in response to CSE, though inconsistencies between time points and limitations in ELISA and Western Blot sensitivity posed as challenges. Future experiments aim to refine treatment timing and explore RAS and CSE interactions more precisely. This work contributes to understanding how the CFH Y402H polymorphism and CSE interact through RAS signaling and converge to drive AMD pathology, offering potential therapeutic targets.

Real-time occupancy map generation from onboard LiDAR data for safety-critical control

Raffi A. Khondaker

Mentors: Aaron D. Ames, Gilbert Bahati, and Ryan M. Bena

Safe navigation in dynamic, cluttered environments demands onboard perception that maintains a timely, reliable model of nearby obstacles. LiDAR (Light Detection and Ranging) is widely used for its accurate range geometry and robustness to lighting, yet it is susceptible to occlusion, measurement noise, and ambiguity from ego-motion. This work presents a real-time occupancy-grid mapping approach from onboard LiDAR for safety-critical control. The method maintains a probabilistic two-dimensional grid and updates it with each scan in real-time. Free space is labeled along each viewing direction up to measured surfaces, which are marked as occupied, while the prior grid is propagated using uncertain robot motion estimates. Mild temporal decay and spatial smoothing limit

overconfidence and reduce isolated false positives. The resulting grid is thresholded to obtain obstacle regions and also defines the domain for a Poisson-based Control Barrier Function, which computes a smooth safety field whose zero level marks obstacles. This mapping integrates into a safe navigation pipeline to adjust control inputs in real time on resource-constrained robots and motivates continued work on handling moving obstacles and adaptive thresholds.

The development of BLE wireless communication between the 65-nm CMOS fluorescence sensor and bacteria cells

Auriyon A. Khosravi

Mentors: Azita Emami and Ting-Yu Cheng

Conventional land management practices often lack the precision required to reliably monitor soil nutrient availability. A critical consequence is the inefficient application of phosphorus fertilizers, with approximately 10% of applied phosphorus entering the water supply annually. This project introduces a wireless sensing system to monitor bioavailable phosphorus using *P. synxantha* bacteria embedded in a 3D hydrogel matrix, referred to as the encapsulate. Under phosphorus-deficient conditions, the bacteria express fluorescent proteins upon excitation, producing optical signals that reflect nutrient stress and cell growth. These signals are detected by a 65-nm CMOS fluorescence sensor and transmitted via a Nordic Bluetooth Low Energy (BLE) chip for wireless communication. To enable accurate data acquisition, the system implements a register-based control protocol over an I2C interface and is coordinated by a finite state machine managing sensor initialization, analog-to-digital conversion, and power regulation. To ensure reliable sensor function, we developed a robust encapsulate package that physically secures the CMOS sensor. Additionally, a PDMS gel layer was applied to the chip to provide electrical insulation and retain the hydrogel matrix containing the bacteria. This integrated biosensor presents a scalable solution for precision agriculture, enabling nutrient monitoring to reduce environmental runoff and ecological degradation.

Sensor fusion system for infrared-based fire detection and localization

Dami Kim

Mentors: Morteza Gharib and Julian Humml

Unmanned Aerial Vehicles (UAVs) offer significant potential for wildfire detection, yet commercial solutions are often cost-prohibitive and limited by environmental conditions. This work presents a low-cost system integrating a radiometric infrared (IR) camera and an Inertial Measurement Unit (IMU) for real-time hotspot detection and 3D localization. The IR camera's intrinsic and extrinsic parameters were calibrated through a checkerboard-based ROS/OpenCV pipeline using a program called Kalibr, with preprocessing steps applied to mitigate low resolution and frame rate limitations of the IR camera. Localization was achieved by transforming detected thermal image pixels into 3D world coordinates, using the pinhole camera model and incorporating IMU orientation. Experimental validation in a controlled scenario demonstrated localization errors as low as 20-30 cm, with results revealing that lower reprojection error does not always correlate with improved localization accuracy due to calibration biases. The proposed system demonstrates the feasibility of low-cost UAV-based thermal hotspot detection, providing a foundation for future integration with GPS, rangefinders, and UAV flight trials for wildfire monitoring.

Design and simulation of an acoustic waveguide for quasi-point source generation in photoacoustic tomography

Jinsung Kim

Mentors: Lihong Wang and Manxiu Cui

Photoacoustic tomography (PAT) benefits from calibration using an ideal ultrasonic point source, but real transducers exhibit directional bias. We propose an acoustic waveguide to transform a 1 MHz transducer output into a quasi-point source. Using 2D axisymmetric k-Wave simulations, the spline-parameterized geometry was optimized via a genetic algorithm with a multi-term loss function. Simulations show improved angular uniformity over the baseline. Fabrication and experimental validation will assess performance for enhancing PAT system calibration.

On-shell constraints and the emergence of supersymmetry

Stavros Klaoudatos

Mentors: Nima Arkani-Hamed and Maria Spiropulu

The traditional formalism of Quantum Field Theory is one plagued by redundancies, non-uniqueness, and heavy algebra, wherein fields and Lagrangians dominate the stage, while also being opaque to the little group representation theory, which classifies particles. By recasting the subject in on-shell terms, spacetime symmetries and unitarity take on the key role of constraining possible theories. In the convenient language of spinor-helicity, three-point amplitudes are fixed completely by little group weights, and when considering amplitudes of massless spin 1 particles, one instantly arrives at the need for a Yang-Mills structure and charge conservation. The analogous analysis on massless spin 2 particles yields the universality and diagonality of gravity. Unitarity, via consistent factorization requirements, constrains charged particles to spin less than $3/2$ and does not allow gravity to couple to particles of spin greater than 2. Extending this analysis to massless Schwinger-Rarita fields, supersymmetry emerges through the need for factorization, and the super-Yang-Mills and supergravity supermultiplets are uniquely determined. Finally, analyticity and positivity requirements on partial-wave expansions impose bounds on high-energy amplitude behavior, strongly constraining the space of UV-completable low-energy amplitudes.

Investigating improvements to sensitivity of next generation gravitational wave detectors with internal squeezing

Umran S. Koca

Mentors: Lee P. McCuller and Sander Vermeulen

Current generation gravitational wave (GW) detectors like LIGO/Virgo use frequency dependent external squeezing incident on the dark port of the interferometer to improve sensitivity to strains. Research has been done on internal squeezing, putting the squeezer within the IFO in the Signal Extraction Cavity (SEC). Internal squeezing can improve detection bandwidth and strain sensitivity at high frequencies while not impacting low frequency sensitivity. However, no previous study has tried to implement directional internal squeezing. My project tests squeezing fields propagating toward the arms while anti squeezing field returning from the arms. I use the GW simulation package Finesse, with realistic loss values for injection and readout losses as well as a squeezer crystal with tunable, directional phases and amplitudes. I demonstrate that while internal squeezing does not provide a sensitivity improvement for Cosmic Explorer unless internal losses are less than 0.01%, this design could improve the sensitivity of LIGO above 1 kHz using internal losses on the order of .1%.

Understanding and quantifying pseudocapacitance through measurements of entropy

Nora K. Kristufek

Mentors: Nicholas P. Stadie and Brent T. Fultz

Fast-charging, energy-dense batteries are crucial to reduce the reliance on fossil fuels and to expand renewable energy use[1]. Faradaic materials have high energy density but charge slowly due to complete ion desolvation and electron transfer[1][2]. On the other hand, capacitive materials charge quickly but have low energy density due to using electrostatic adsorption without desolvation or electron transfer [2]. Pseudocapacitive materials, which exhibit partial desolvation and partial electron transfer, could offer a promising solution to the drawbacks of each—but their behavior is poorly understood, and no standard, quantitative metric exists to define a material as pseudocapacitive[3][4][5]. We propose an entropy-based metric in order to quantitatively distinguish between capacitive, faradaic, and pseudocapacitive mechanisms, measured using two temperature-dependent electrochemical methods [5][6][7]. First, we measure the lithiation entropy as a function of lithiation state for five materials of interest using an isothermal half-cell against lithium metal: zeolite-templated carbon (ZTC) being capacitive, graphite and lithium iron phosphate (LFP) being faradaic, and Nb_2O_5 and p-HBC being considered as pseudocapacitive [3]. Then we examine the desolvation entropy for the electrolyte using a non-isothermal, symmetrical H-cell (lithium metal against lithium metal) [7]. Combining these two metrics across all of the above-mentioned materials (consisting of all three mechanism types), we report the unique desolvation entropy for each, providing a quantitative scale for

Mechanistic insights into the binding of Girdin and Daple to dynein transport machinery

Aurelia H. Kuester

Mentors: Aga Kendrick, Rustem F. Ismagilov, Álvaro de la Gándara, and Delaney Sanders

Cytoplasmic dynein-1 (dynein) is a motor protein that is responsible for retrograde intracellular transport and requires both dynactin and an activating adaptor protein for motility. Girdin and Daple, two signaling proteins linked to cancer progression and cell migration, contain conserved motifs found in dynein activating adaptors, including a Hook domain and Spindly motif. Their oncogenic potential is closely tied to their subcellular localization, a process which may be influenced by dynein-mediated transport. This project investigates how phosphorylation and disease-associated mutations in Girdin and Daple affect their ability to interact with dynein transport machinery. Specifically, we assess whether phospho-mimetic or phospho-deficient mutations at conserved serine residues modulate binding to the dynein-dynactin complex. Preliminary data from biochemical assays suggest that select mutations alters binding of Girdin and Daple to dynein and dynactin, supporting a model in which adaptor autoinhibition and phosphorylation state modulate motor recruitment. These findings support a model in which adaptor phosphorylation and autoinhibition regulates binding with dynein transport machinery.

Disruption of resonant-chain planetary systems

Diya T. Kumar

Mentors: Fei Dai and Lynne Hillenbrand

Type-I disk migration can capture planets into chains of mean-motion resonances (MMRs) at the inner edge of the protoplanetary disk, including higher-order MMRs that have been observed in young planetary systems despite their weaker dynamical strength. Observationally, ~90% of young systems host at least one resonant planet pair, but this fraction declines sharply with age - dropping to ~40% for adolescent systems and ~20% for mature systems - indicating that resonant chains are disrupted over time. Previous work has shown that Type-I migration can produce both first-order and higher-order resonances, with second-order (e.g. 5:3) and third-order (e.g. 5:2) configurations forming through the breaking of pre-existing first-order resonances. In this work, we take these resonant chains from multi-planet migration simulations and evolve them forward through a phase of disk dissipation and ultimately integrate them for 1 GYR to investigate their long-term stability. This work will contribute to characterizing the dynamical pathways and timescales by which resonances break, and to assess how various characteristics of the resonant chain influence its survival. The results will help interpret the observed decline of resonance over time and connect the architectures of young, resonant chain systems to their final configurations in older planetary systems.

Mapping the human speech cortex with a multi-scale foundation model

Shrujana S. Kunnam

Mentors: Edward Chang, Ueli Rutishauser, and Shailee Jain

Understanding how the human brain processes speech is essential for uncovering the neural basis of communication, a cornerstone of social interaction, culture, and cognition. While prior studies have linked specific brain regions to distinct speech features, a large-scale investigation of global brain dynamics and fine-grained spatial organization across many individuals has not yet been conducted. The Chang Lab is building the first large-scale AI-based simulation of the human speech cortex, enabling accurate, high-resolution predictions of population-level electrocorticography (ECoG) responses to naturalistic language. Leveraging over 50,000 ECoG electrodes recorded from more than 180 participants, this model captures shared structure in speech-evoked neural activity across individuals and brain regions. The model's powerful generalization capabilities enables two novel downstream applications. First, we use unsupervised learning techniques to uncover how speech is functionally organized in the brain. By clustering the raw ECoG activity and the model's internal representations, we identify groups of electrodes that respond similarly to different speech features using a hypothesis-free, data-driven approach. Second, we use the learned ECoG model that captures population-level activity to bootstrap the prediction of single-neuron firing in the speech cortex,

recorded using high-density Neuropixels probes. This allows us to link population-level dynamics to single-cell responses, elucidating how speech is encoded across multiple spatial scales. Overall, this work aims to uncover novel insights into the multi-scale neural architecture of speech perception across individuals.

Building cell radios for deep-tissue wireless detection of biochemical factors

Sudarshanagopal Kunnavakkam

Mentors: Mikhail G. Shapiro and William Benman

Abstract withheld from publication at mentor's request.

Cutoff window for the Gibbs sampler process

Colin H. La

Mentor: Lingfu Zhang

Chatterjee, Diaconis, Sly, and Zhang previously proved the precise cutoff time for the repeated average process, which serves as a powerful model for social science and physical phenomena. The Gibbs sampler process generalizes the repeated average process by replacing the fixed average with a random weighted average. This work investigates whether the Gibbs sampler process exhibits cutoff phenomena in terms of total variation distance and establishes bounds for the cutoff window. In this paper, we approximate the Gibbs sampler process with an analogous branching structure and leverage techniques from large deviations theory to approximate tail distributions in the asymptotic regime. Identifying a precise cutoff window lends to a sharper understanding of the convergence behavior of the Gibbs sampler process, which has key implications for models in economic theory and physical systems.

Preparation of the enolate coupling partner towards the total synthesis of sesquiterpenoid dimer natural products

Raquel G. Lample

Mentors: Brian M. Stoltz and Chloe Cerione

Abstract withheld from publication at mentor's request.

Verifiably correct datasets in first-order logic for large language model reasoners

Henry B. Lane

Mentors: Matthew W. Thomson and Tony Yue Yu

Current Large Language Models (LLMs) reasoners achieve impressive results on a wide variety of cognitively demanding benchmarks, yet still display extremely brittle and often formally incorrect reasoning steps on complex tasks, default to heuristic strategies that neglect logical faithfulness, and often collapse under minor adversarial perturbations. A key limitation for current LLMs is the lack of diverse verifiably correct and fine-grained training data sets that contain not only problem statements, but also formal proof steps. Methods which generate synthetic data, such as those that leverage automated theorem provers to mine lemmas, often explore a highly restricted and narrow subset of first-order logic space. In this report, we detail a new approach to address generation of synthetic first-order logic datasets in sequent calculus and natural deduction, called FOLSeqGen that constructs intuitionistic first-order logic sequents by the iterative forward application of Gentzen's G3i rules, a variant of Sequent Calculus. The generator samples uniformly over the rule schema, yielding proofs with a diversity of inference steps. As the system iteratively constructs sequents from a given random axiom set, all derived sequents are guaranteed to be verifiably correct and contain a proof trace, demonstrating the derivability of the sequent.

Discovery and parameter estimation of PDEs using physics-informed neural networks (PINNs)

Edgar A. Larios

Mentors: Franca Hoffmann, Aras Bacho, and Kathrin H. Hellmuth

Jupiter captures high radiation levels and large quantities of radiation, making it very difficult for NASA spacecraft to probe the planet or its surroundings. To better design its missions, NASA relies on models that describe the radiation environment of Jupiter, as well as data collected from previous missions. The radiation environment of Jupiter can be represented by a partial differential equation (PDE) that is structurally similar to the Fokker-Planck equation. A physics-informed neural network (PINN) was used to discover, solve, and invert this PDE. Some of the techniques that were used to create a robust PINN-based pipeline include data normalization and hyperparameter tuning. To verify the reliability of the PINN, it was applied to synthetic benchmark problems. Results show that the PINN was able to solve all the PDEs (including the PDE that describes the radiation environment of Jupiter), but was always unable to properly recover the coefficients of the PDEs. These findings suggest that PINNs can solve forward problems reliably, but it is difficult to make them suitable for inverse problems. I recommend continued testing on synthetic benchmark problems to improve the robustness of the developed PINN-based pipeline before applying it to study Jupiter's radiation environment.

Treasury buybacks to improve liquidity of securities markets

Ryan J. Leal

Mentors: Darrell Duffie and Jaksa Cvitanic

The goal of this ongoing project is to model the US Treasury securities market with a focus on Treasury buybacks, which are a re-purchase of these securities by the Treasury, and reopenings, where the Treasury auctions additional amounts of security it has previously issued. Our model revolves around solutions to dealer's optimal behavior in the auction, buyback, interdealer, and customer interaction settings. These optimal behaviors, and market clearing, determine a solution to the Hamilton Jacobi Bellman equation for dealer's values of their expected future net cash flows. We optimized the model's parameters to exhibit accurate empirical moments using a variety of heuristic and computational techniques and adjusted structural details of the model until the model satisfactorily represents an abstraction from the true US Treasury securities market for a given sector. Fixing the mean path of outstanding debt, we observed a decrease in debt servicing costs and social costs when increasing buyback operations, with this effect diminishing as we increased buybacks. Similarly, introducing more reopening operations decreased debt servicing costs and social costs, with a diminishing effect.

Extreme atmospheric wind sensing and quantification for adaptive control of a fixed-wing UAV

Brandon Lee

Mentors: Morteza Gharib and Xiaozhou Fan

Fixed-wing aircraft operating in turbulent environments face significant control challenges due to sudden wind gusts that exceed conventional control system capabilities. This project aims to develop and validate an experimental apparatus that evaluates an adaptive disturbance rejection control algorithm. A remote-controlled fixed-wing aircraft was modified to fit custom pitot-static probes feeding five differential pressure sensors per wing. Sensor data travels through a Teensy 4.1 microcontroller to an NVIDIA Jetson Orin Nano running Robot Operating System. A neural network model uses filtered pressure inputs to estimate instantaneous wind speed and direction. Initial verification by manual gust tests confirmed proper electronic system functionality and successful real-time data collection from pressure sensors. We will calibrate the system in a controlled wind tunnel, add servo-driven control surfaces, and perform tethered outdoor trials with fan-generated gusts.

Quantifying peak-shift style exaggeration in comic covers and its marketplace signal

Brendan D. Lee

Mentors: Colin F. Camerer and Katelyn Haly

Supernormal stimuli are exaggerated versions of stimuli that organisms have an innate tendency to respond to. Comic books, for instance, often feature hyper-exaggerated heroic physiques, explosive action, and saturated colors to captivate readers. This project investigates whether such visual exaggeration predicts commercial success by developing an automated pipeline to quantify these features and correlate them with sales data. A custom web crawler was built to harvest comic book covers and their metadata, which were then matched to a sales database. To quantify the visual elements, two parallel computer-vision models were employed: an OpenCLIP model measured the semantic similarity between covers and engineered prompts, while a GPT-4o mini vision model assigned discrete scores for the same attributes. These analyses yielded a composite Stimuli Index for each cover. Sales metrics from Comichron were then regressed against this index. A preliminary analysis revealed a modest, positive correlation with revenue, supporting the initial hypothesis. While these early results suggest a link between heightened visual stimuli and commercial performance, a larger sample is required to achieve statistical power. Ongoing work will expand the dataset across more publishers, incorporate validation from human raters, and explore the potential of using these models to predict the success of new cover designs.

On the absolute prismatic cohomology of number rings

Justin D. Lee

Mentor: Matthias Flach

Prismatic cohomology was introduced by Bhatt and Scholze as a new p-adic cohomology theory that admits specializations to well-known cohomology theories, such as crystalline cohomology, Etale cohomology, and de Rham cohomology. Despite having been studied extensively, the absolute prismatic cohomology has not been computed for the simplest cases of p-complete rings. It is known, by the Hodge-Tate comparison theorem, that the cohomology is concentrated in the zeroth and first degrees. In this project, we work towards computing the absolute prismatic cohomology of the ring of integers of local fields. To achieve this, we adapt and improve upon a method of relative to absolute descent developed by Antieau, Krause, and Nikolaus.

Decentralized collaborative learning for fault estimation in multi-spacecraft systems

Taekyung Lee

Mentors: Soon-Jo Chung, Satvik Kumar, and Vrushabh Zinage

Fault detection and isolation are critical challenges in heterogeneous multi-spacecraft systems, where hardware differences, nonlinear interactions, and limited communication make traditional model-based approaches impractical. This project presents a decentralized collaborative learning approach that addresses these challenges through novel integration of causal relationships and distributed consensus mechanisms. The methodology embeds known subsystem-level causal relationships into variational autoencoders for root cause subsystems and conditional variational autoencoders for causally linked subsystems, systematically distinguishing between primary anomalies and propagated effects. Each spacecraft independently encodes nominal subsystem behavior into orthogonal representations, preventing fault masking between subsystems. Spacecraft share encoded data, model parameters, and physical states across time-varying communication networks, achieving distributed consensus through multi-layer graph neural networks that fuse neighbor information. Experimental validation on a multi-spacecraft hardware testbed demonstrated successful fault isolation among sensors and actuators. The approach enables robust fault diagnosis in distributed space systems without requiring centralized coordination or identical spacecraft configurations, advancing autonomous operation capabilities for future multi-spacecraft missions.

Computational framework for predicting acoustic force fields in ultrasound neuromodulation

Andrea H. Li

Mentors: Mikhail G. Shapiro and Alen Pavlic

Abstract withheld from publication at mentor's request.

Universal high-rate quantum fault-tolerance via transversal dimension jumping

Christine Li

Mentors: John P. Preskill and Qian Xu

A major obstacle to practical quantum computing is noise from unwanted interactions between qubits and their environment. To mitigate this, quantum information must be encoded in a quantum error-correcting (QEC) code. Logical operations can be performed fault-tolerantly using transversal gates, which naturally suppress the spread of errors. However, no single QEC code supports a universal set of gates transversally. One possible workaround is code-switching: teleporting logical states between complementary QEC codes, each supporting different transversal gates, to achieve universal fault-tolerant computation. In this work, we introduce a scalable, transversal method for code-switching between arbitrary 2D and 3D balanced product codes—a broad family of quantum low-parity density check (qLDPC) codes with lower overhead than the prevailing surface code. This is the first generalized protocol enabling fault-tolerant logical teleportation between qLDPC codes to achieve universal computation. As a concrete demonstration, we identify and simulate small, high-rate, experimentally feasible 2D-3D qLDPC code pairs that collectively support a universal, fault-tolerant gate set, with parameters such as $([[18, 2, 3]], [[27, 3, 3]])$ and $([[54, 2, 6]], [[81, 3, 5]])$. As an alternative to magic state distillation, our results suggest a potential paradigm shift in how universal fault-tolerant quantum computation can be realized.

Fulton's intersection theory of Matroid

Guanxi Li

Mentor: Paolo Aluffi

A Matroid is a combinatorial abstraction of the notion of linear independence. It has many cryptomorphic definitions and relates to many other combinatorial structures, such as graphs and polytopes, in a natural way. In the past decade, many geometric models of matroids have been understood through algebraic and tropical geometry. One could recover combinatorial information by studying the Chow ring associated to the geometry. Many conjectures regarding the log-concavity of the various polynomials related to matroids have been proven by proving the Kahler package on the Chow ring. In the literature, the Chow ring of a matroid is studied through toric and tropical intersection theory. In this project, we study the intersection theory of matroids through Fulton's perspective. Specifically, we define a notion of Segre classes for matroids.

Synthesizing and examining the novel magnetic topological semimetals properties of TaCoTe₂

Xiang-Yu Li

Mentors: Linda Ye and Tao Lu

Magnetic semimetals are a new class of materials that combine time reversal symmetry breaking and topology. TaCoTe₂, a recently proposed van der Waals material, is a layered antiferromagnetic semimetal with a high Néel temperature (~ 310 K) and has type-II Dirac fermions protected by glide mirror symmetry. Upon the inclusion of SOC, this Dirac point opens a small gap, but a new type-II Dirac point emerges approximately 0.2 eV below the Fermi level. Those makes TaCoTe₂ a candidate system for exploring novel quantum transport phenomena, such as the in-plane anomalous Hall effect arising and investigating quantum geometry. To synthesize single crystals, we first obtained polycrystals by solid-state reaction and subsequently applied a chemical vapor transport (CVT) method using TeCl₄ as a transport agent. We confirmed the polycrystals matched the expected structure by powder X-ray diffraction (XRD), but the single crystals grown by CVT unexpectedly showed a stoichiometry closer to TaCo₂Te₂, as revealed by energy-dispersive X-ray

spectroscopy(EDS). XRD and phase diagram further supported that a more stable phase TaCo₂Te₂ might have formed during transport. To solve this, we attempted growth parameters optimization by adjusting the temperature gradient and transport agent concentration. Additionally, we proposed a tellurium self-flux growth method for better phase selectivity and crystal yield. If successful, we plan to perform transport measurements under rotating magnetic fields to probe the in-plane Hall effect. These measurements will provide insight into the role of magnetic symmetry and quantum geometry in antiferromagnetic topological systems.

Implementation and calibration of an optimality photosynthesis model in ClimaLand

Yuchen Li

Mentors: Tapio Schneider, Julia C. Sloan, and Renato Braghiere

Models of photosynthesis embedded in Earth System Models (ESMs) are important for simulating ecosystem carbon fluxes as well as energy transfer via latent heat. However, their accuracy is limited by the need to prescribe plant type-specific biogeochemical parameters, which are often difficult to constrain. Optimality-based photosynthesis models have shown promise in alleviating this issue by directly predicting optimal photosynthetic parameters via a cost-minimization principle. In this project, we implement one such model, the P-model, within ClimaLand, the land surface component of the ESM being developed by the Climate Modelling Alliance (CliMA). We first validate the model against eddy covariance observations from flux tower sites and show that it consistently outperforms the traditional Farquhar photosynthesis model. Next, using the ensemble-based calibration capabilities of the CliMA software ecosystem, we use Ensemble Kalman Sampling to quantify uncertainty in free parameters in the model. Lastly, we evaluate the calibrated model over the global domain and benchmark its performance against observational products and other established ESMs.

Understanding the mutagenic bypass of HMCES peptide adduct

Yushan Li

Mentor: Daniel R. Semlow

AP-interstrand cross-links (AP-ICLs) are cytotoxic as they covalently link the two strands of the DNA duplex, preventing strand separation and blocking essential cellular processes such as DNA replication and transcription. The repair mechanism for AP-ICLs is coupled to DNA replication and involves generation of an AP site on single-stranded (ss)DNA that will be cross-linked by the 5-hydroxymethylcytosine binding, embryonic stem-cell-specific (HMCES), forming a DNA protein crosslink (DPC). The HMCES-DPC stabilizes AP sites and suppresses double strand breaks (DSBs) during AP-ICL repair. The AP site stabilized by HMCES will later be bypassed by translesion synthesis (TLS) polymerase and the sequencing of AP-ICL repair products indicates that HMCES-DPC also influences the mutagenicity of TLS past an AP site, favoring deoxyguanosine (dG) insertion opposite the AP site. However, the basis of this mutagenic signature remains unclear. To understand what drives this mutagenicity, we will be studying 1) whether the bypass of the AP site by TLS polymerases happens during or after the proteolysis of HMCES-DPC and 2) the specific TLS polymerases that bypass the AP site during the AP-ICL repair. To address these questions, this project involves purifying the TLS polymerase Pol κ and generating a point mutation on the SRAP domain of HMCES to make it self-reversal deficient. We have successfully cloned SRAP E129A and are currently optimizing the purification procedure for Pol κ . Once Pol κ is purified, it will be utilized to observe the replication intermediates in AP-ICL repair reactions involving the HMCES-DPC.

Investigation of the generalisability of reinforcement learning algorithms on mathematical environments by a case study of the Andrews-Curtis conjecture

Zhongyuan Li

Mentors: Sergej G. Gukov and Muhammad A. Shehper

This study aims to investigate the generalisability of some important reinforcement learning(RL) algorithms in mathematical environments. In the study, we use the Andrews-Curtis conjecture as the maths environment for the case study. Standard baseline RL algorithms such as A2C is first implemented to obtain baseline performance on the generalisability in this environment. The algorithm of Phisical Policy Gradient is then implemented and the results are compared with the baselines.

Laser Diode Floating Zone (LDFZ) growth and characterization of ultrahigh-purity crystals for skyrmion qubits

Yingxiao Liao

Mentors: Xuemei Cheng and Stevan Nadj-Perge

A quantum bit, or qubit, is the core entity of quantum computing. Current examples of qubit systems include ultracold atoms, trapped ions, quantum dots, photons, superconducting circuits, and nitrogen-vacancy (NV) centers in diamond. Recently, theorists have proposed magnetic skyrmions, topologically protected swirling spin textures, as a promising candidate for macroscopic qubits due to their topological stability, nanoscale size, and helicity-based characteristics.

Our group plans to apply Laser Diode Floating Zone (LDFZ) technique to grow the bulk single crystals: Gd_2PdSi_3 , GdRu_2Si_2 , $\text{Gd}_3\text{Ru}_4\text{Al}_{12}$, YIG, BiYIG, which are identified by modeling group as hosting nanoskyrmions, to develop potential materials for skyrmion qubits. After crystal growth, X-Ray Diffraction (XRD) method will be used to characterize the crystal's orientation and structure. Additionally, the magnetic and magneto-transport properties of the grown crystals will be investigated using a Physical Property Measurement System (PPMS).

In this summer's research, I will synthesize and characterize the $\text{Gd}_3\text{Ru}_4\text{Al}_{12}$ bulk single crystals. The measured structural and magnetic properties of the grown crystals are expected to contribute to the development of skyrmion-based qubit materials.

Random utility with aggregated alternatives

Yuexin Liao

Mentor: Kota Saito

This paper studies when discrete choice data involving aggregated alternatives such as categorical data or an outside option can be rationalized by a random utility model (RUM). Aggregation introduces ambiguity in composition: the underlying alternatives may differ across individuals and remain unobserved by the analyst. We characterize the observable implications of RUMs under such ambiguity and show that they are surprisingly weak, implying only monotonicity with respect to adding aggregated alternatives and standard RUM consistency on unaggregated menus. These are insufficient to justify the use of an aggregated RUM. We identify two sufficient conditions that restore full rationalizability: non-overlapping preferences and menu-independent aggregation. Simulations show that violations of these conditions generate estimation bias, highlighting the practical importance of how aggregated alternatives are defined.

Biocatalytic synthesis of chiral phosphoramides using engineered heme enzymes

Ethan N. Lin

Mentors: Frances H. Arnold and Hayden Carder

Chiral phosphoramides are valuable phosphorous-containing compounds found in therapeutics and agrochemicals. However, current methods for their synthesis often rely on chiral auxiliaries, and catalytic methods are limited. Here, we present efforts toward development of *Aeropyrum pernix* protoglobin enzyme scaffolds for the enantioselective amination of racemic H-phosphinate substrates. Starting from a protein variant optimized for P-H carbene insertion, error-prone PCR and staggered extension process PCR in conjunction with site-saturation mutagenesis targeting active site residues improved the enzyme's yield (2.5-fold) and selectivity (from ee= +30% to +50%). Based on initial findings that residue 145/149 mutations led to inversion in enantioselectivity, a double-site combinatorial library at those residues was generated, leading to a change in enantioselectivity from ee= +50% to -30%. Substrate-scope analysis indicated initial activity for amination of phosphinates bearing bulky cyclohexyl and homobenzyl substituents as well as phosphine oxides; additional substrates are being explored. These enzymes represent a tunable and cost-economical platform for sustainable synthesis of chiral-at-phosphorus compounds.

Searching for planetary nebulae in CLU PTF H α survey using segmentation and machine learning algorithms

Ryan X. Lin

Mentors: Shrinivas R. Kulkarni and Soumyadeep Bhattacharjee

Planetary nebulae (PNe) are ionized shells of gas ejected by intermediate-mass stars in late stellar evolution, though similar PN-like structures can also arise from binary interactions or unrelated processes such as bow shocks. A major challenge is the gap between the $\sim 4,000$ confirmed and candidate PNe in the HASH catalogue and theoretical estimates of 6,600-60,000, motivating systematic searches in new datasets. Narrow-band H α imaging has been the primary discovery method, but past surveys have focused on the Galactic plane. The Census of the Local Universe (CLU) H α survey, covering 26,470 deg² of the northern sky, offers a largely unexplored high-galactic-latitude search space. Here, we develop segmentation-based and machine learning algorithms to detect compact and extended nebulae, enabling automated, wide-field searches for new PNe and related emission-line sources. In our segmentation-based algorithm, we implement multiprocessing and memory optimisations to enhance algorithmic performance, Bayesian optimisation to find optimal hyperparameters, and temporal crosschecking to reduce the number of false detections. Our segmentation-based algorithm yielded positive results, achieving a recall of 59.8%, resulting in several new planetary nebula candidates. In our machine learning algorithm, we experiment with various convolutional neural network architectures for low-latency and wide-field searches, yielding impressive performance.

Learning physics causality for inverse PDEs in generative neural operators

Thomas Y. Lin

Mentors: Anima Anandkumar and Jiachen Yao

We investigate methods to let generative neural operators learn physics causality for inverse partial differential equation (PDE) problems with sparse observation. Prior work on generative PDE solvers relies on joint embeddings of parameter and solution spaces, learning their correlation rather than their causal relation. Our key idea is to introduce a surrogate operator into both training and inference, thereby formulating a “vertical” physics loss in addition to the conventional “horizontal” data loss. We also provide a training curriculum across loss terms to improve practical efficiency. To keep the pipeline fully data-driven, we approximate the surrogate operator with a pretrained neural operator, enabling end-to-end optimization without hand-crafted solvers.

Modeling and simulation of antennas for absolute flux measurements in early cosmology

Yanfen Lin

Mentors: Gregg W. Hallinan and Nivedita Mahesh

One of the most significant open questions in astrophysics is understanding the Cosmic Dawn—the era approximately 50 million to one billion years after the Big Bang during which the first stars, galaxies, and black holes emerged. The best way to study this period is by detecting the highly redshifted 21-cm signal emitted by neutral hydrogen. This project focuses on modeling and simulating broadband antennas for absolute flux measurements to aid in detecting this faint radio signal. Using CST Studio Suite, we developed and analyzed MANAS (Measuring Antenna Neutral-Hydrogen Signal), a monopole disccone antenna operating from 30–100 MHz. We investigated antenna performance metrics including gain, reflection coefficient (S_{11}), and beam response to identify the optimal design, providing guidance to the team during antenna construction and answering key design questions.

PdCu catalyst engineering for electrochemical transformation of 1-butene to 2-butanone

Alexis N. Lindenfelser

Mentors: Karthish Manthiram and Chenyu Jiang

The oxidation of 1-butene yields 2-butanone, an industrially relevant chemical with applications ranging from pharmaceuticals to plastics. 2-butanone, with its high knock-resistance, octane-like enthalpy of vaporization, and high-octane rating, has the potential to be a greener alternative to traditional fossil fuels if manufactured using energy-efficient methods. Electrochemical synthesis avoids the high pressures, temperatures, and dangerous oxidants traditionally required in thermochemical 2-butanone synthesis. Herein, we reported an electrochemical system using PdCu alloy as an efficient electrocatalyst for ketonization with water as the O-atom source at ambient pressure and temperature. We investigated the effects of Pd:Cu molar ratio on the catalytic performance by systemically synthesizing a variety of PdCu catalysts which were evaluated using x-ray diffraction (XRD). It was found that catalysts with equimolar palladium and copper ratio were the most effective. In addition, the influence of additives, such as sodium bromide, were studied to gain insights into the reaction mechanism.

Lower time complexity of DNA winner take all neural network combining shared fuel amplification and pairwise annihilation

Anthony K. Lindo

Mentors: Lulu Qian and Matthew Plazola

DNA's ability to participate in toe-hold mediated displacement reactions allows the molecule to be programmable and participate in a numerous amount of computer science principles. One of the most promising are DNA neural networks. There are two implementations of a winner take all behavior known as pairwise annihilation and shared fuel amplification. Pairwise annihilation involves weighted sums eliminating each other until there's a single survivor and then later restoring itself to produce a signal of 1 while the losers remain 0. The advantage associated with this system allows it to be robust to changing strand concentrations while the disadvantage is it's $O(n^2)$ time complexity with each increasing input. Shared fuel amplification involves a host of weighted sums competing for a shared fuel strand while surviving sequestration from thresholding strands. The advantage associated with this system allows it to occur at an almost linear time complexity, but it's much less robust and doesn't exhibit true winner take all. The winning strand doesn't compute to 1 but a steady state that requires a look up table. I'm developing a system that allows the system to remain robust while maintaining a linear time complexity. By allowing a fuel strand to remain competitive throughout the system and letting the threshold get the winner to near 0, and having restoration occur afterwards, the winning strand can compute to 1 much quicker than having it compete with other losing strands directly.

Investigating the role of *Esrrb* in nephron development using zebrafish models

Kara Z. Lo

Mentors: Marianne Bronner and Tianli Qin

The nephron is the functional unit of the kidney. It comprises a blood filter and an epithelial tubule with specialized segments that enable essential physiological functions, including metabolic waste excretion, hormone production, and maintenance of plasma homeostasis. Disruptions in nephron development (nephrogenesis) can lead to nephron dysfunction or loss, contributing to renal disease and broader systemic effects. To investigate genetic regulation of nephron segment patterning, we used the zebrafish pronephros, a model that shares cellular and genetic conservation with the mammalian nephron. We identify and focus on the estrogen-related receptor beta (*Esrrb*) as a candidate regulator of cell fate and patterning of distal segments. Mutants from CRISPR/Cas9-mediated knockouts were analyzed using in situ hybridization chain reactions (HCR). Preliminary findings reveal abnormal pronephric tubule morphology, altered expression patterns of segment-specific markers, and the presence of pericardial edema, suggesting compromised osmoregulatory function.

The negligible ideals of some symmetric groups, and its application to the Krull dimension of the integral negligible quotient of any finite group

Vivian Loh

Mentor: Matthew Gherman

For a finite group G and a G -module M , an element $u \in H^d(G, M)$ is negligible over \mathbb{Q} if for every field extension L/\mathbb{Q} and every continuous group homomorphism from $\text{Gal}(L_{\text{sep}}/L)$ to G , u is in the kernel of the induced homomorphism $H^d(G, M) \rightarrow H^d(L, M)$. When a G -module M is a unital ring and has a trivial G -action, the negligible elements form an ideal of the cohomology ring $H^*(G, M)$, denoted $I(G, \mathbb{Z})$. The negligible quotient is $H^*(G, \mathbb{Z})/I(G, \mathbb{Z})$. We compute a strict lower bound on the Krull dimension of the negligible quotient of $H^*(G, \mathbb{Z})$ for even $|G|$, and find that when $|G|$ is the product of distinct odd primes, the Krull dimension is zero. Generalizing a result from Serre, we prove that twice any class is negligible in $H^*(S_n, M)$ for finitely generated M with a trivial G -action. We compute the mod-2 negligible ideal for $S_{3 \leq n \leq 8}$, the mod- p^k negligible ideal for S_n when $p \leq n < 2p$, the integral negligible ideal for S_3 , and the Krull dimension of the integral negligible quotient for S_4 . Analyzing restrictions to and from the alternating group, we compute the mod-2 negligible ideals for $A_{3 \leq n \leq 5}$, the radical of the mod-2 negligible ideals for $A_{6 \leq n \leq 9}$, and the mod- p^k negligible ideals when $p \leq n < 2p$.

Shift invariance in half-space last passage percolation and directed polymers

Yunhao Lou

Mentor: Lingfu Zhang

Last passage percolation is a probabilistic model in which independent random weights are assigned to the vertices of the two-dimensional integer lattice, and one studies the maximum sum of these values along any directed path between two given points. The model is integrable when the weights are geometric or exponential. It has been proved that in those cases the model admits a nontrivial shift invariance in the joint distribution of passage times. We prove a similar invariance in the corresponding half-space models, where the environment is symmetric across the diagonal, and extend this result to a related directed polymer model with inverse-gamma weights.

Engineering cyclotide binders against IL-17A

Matthew H. Luk

Mentors: Karl D. Wittrup and Justin S. Bois

IL-17A is a pro-inflammatory cytokine that plays a major role in chronic inflammatory diseases such as Plaque Psoriasis and Multiple Sclerosis. While there are currently FDA-approved IL-17A inhibitor drugs on the market (Secukinumab and Ixekizumab), they are monoclonal antibodies that require injection administration and have the potential to induce immunogenicity, leading to an anti-drug antibody (ADA) response. In contrast, cyclotide drugs – small, cyclic peptides typically composed of ~ 30 amino acids – can be taken orally and stored at room temperature due to the highly stable nature of their structure. We hypothesize that they will exhibit reduced immunogenicity and increased efficacy, as their small/stable structure lowers the chances of neutralizing antibodies being produced. For this project, we created a library of cyclotides using error-prone PCR and implemented high-throughput screening with the use of Yeast Surface Display (YSD). Our objective is to discover an effective cyclotide binder in our error-prone cyclotide library for further affinity maturation or cyclotide characterization, with the hopes of creating a cyclotide drug that binds against and inhibits IL-17A with our cyclotide binder.

Task-aware mesh decomposition for Sim2Real robotics learning

Justin Luo

Mentors: Hao Su and Gunter Niemeyer

Sim2Real robotics training depends on a realistic and efficient simulation process; however, accurate physical simulation is a major computational bottleneck. As such, mesh decomposition algorithms such as CoACD have emerged, allowing for simulation agents to be simplified into convex meshes for simulation. The goal of this project is task-aware mesh decomposition: for many tasks, certain sections require more detail than others (e.g. when training a robot to pick up a mug, we can apply

greater detail to the handle than the rest of the object). By optimizing our convex meshes to suit our tasks, we can save huge amounts of computational complexity while maintaining a realistic interface between all interacting agents. With fewer meshes to consider training can be accelerated massively, allowing robotics researchers to iterate models at a faster pace.

Exploring and predicting the combinatorial effect of cytokines on downstream signaling

Natalie J. Lytell

Mentors: Michael B. Elowitz and Dayeon J. Shon

The JAK-STAT pathway is a crucial mediator of immune responses, translating extracellular cytokine signals into transcriptional programs that shape immune cell behaviors. Over 50 cytokines act through only four Janus kinases (JAKs) and seven signal transducer and activator of transcription (STAT) proteins, creating a many-to-many network where numerous ligands collaborate to influence a fine-tuned reaction carried out by a limited set of transcription factors. Within this network, STAT monomers compete to form DNA-binding homodimers and heterodimers that drive downstream gene expression programs. This STAT dimerization network thus acts as a key layer of signal integration, but it remains unclear how combinatorial cytokine inputs are encoded into specific STAT dimer distributions and how those distributions impact genome-wide target gene activation. The ability to understand and predict how these signaling molecules implement a precise downstream response is necessary for designing and implementing equally precise therapeutic strategies. To address these questions, we generated and characterized reporter cell lines that measure the activities of specific STAT dimers. By analyzing their responses to cytokine combinations, we aim to gain a clearer picture of how these signals are processed by the STAT dimerization network.

A study on the response mechanisms of solar-induced chlorophyll fluorescence (SIF) to heat stress in global ecosystems based on multi-source satellite data

Wenhao Lyu

Mentors: Yuk L. Yung, Liyin He, and Yuan Wang

Solar-Induced Chlorophyll Fluorescence (SIF) is a key indicator of vegetation photosynthesis and is highly sensitive to environmental stress. This study investigates the dynamic response of SIF to heat stress across global ecosystems. We evaluated the correlation between satellite SIF (TROPOMI/GOSIF) and ERA5-Land air temperature, focusing on identifying regions with negative correlations that signify photosynthetic inhibition. Using auxiliary data such as MODIS NDVI/Land Cover and soil moisture, we analyzed the regulatory effects of water availability and climate zones. Our results demonstrate that drought critically regulates SIF's response to high temperatures. We observed a clear decline in SIF during strong heatwave events in many regions, providing robust evidence of physiological constraints imposed by extreme heat. This study uncovers complex spatial response mechanisms, identifies regions vulnerable to heat stress, and establishes a multi-sensor framework for diagnosing vegetation health, improving ecosystem monitoring under climate change.

Development of mosaic nanoparticle vaccine candidates to protect against diverse sarbecovirus strains

Indeever Madireddy

Mentors: Pamela J. Bjorkman and Alexander Cohen

Global human health is threatened by potential spillovers of zoonotic SARS-like betacoronaviruses (sarbecoviruses). Two well-known sarbecoviruses are SARS-1 and SARS-CoV-2 which were responsible for the 2003 SARS-1 outbreak and the COVID-19 pandemic, respectively. Due to the danger that sarbecoviruses pose to human health, it is pertinent to develop a pan-sarbecovirus vaccine that confers protection against both evolving SARS-CoV-2 variants and any future zoonotic spillovers. Recent work has shown that a mosaic-8 receptor binding domain (RBD) nanoparticle that co-displays 8 distinct RBDs from different viruses can generate cross-reactive and cross-neutralizing antibody responses that target conserved viral epitopes. Mosaic-8 also confers protection against mismatched strains that were not present on the particle suggesting its use as a broadly protective sarbecovirus vaccine.

To improve the responses elicited by mosaic-8, the antibody landscape elicited by a diverse set of sarbecoviruses was used to guide the development of 7 new mosaic RBD nanoparticles. Each displays a different combination of RBDs from different viral clades. The breadth and neutralization potency of the antibodies elicited by these vaccines is currently being characterized. These mosaic vaccine candidates will serve as an updated vaccine against all sarbecoviruses and future emerging variants of concern.

Dissecting zebrafish hunting behavior using deep reinforcement learning-trained recurrent neural networks

Raaghav Malik

Mentors: Kanaka Rajan and Markus Meister

Understanding how neural systems give rise to complex natural behaviors remains a central challenge in neuroscience. Larval zebrafish present a powerful model for addressing this problem, combining rich ethological behaviors such as prey hunting with a compact, transparent brain. While experimental work from groups including Engert, Roy, and others has illuminated key sensorimotor motifs in zebrafish hunting, the computational mechanisms that underlie these behaviors remain poorly understood. In this project, we introduce a complementary modeling approach that leverages deep reinforcement learning (DeepRL) to train recurrent neural networks (RNNs) to perform naturalistic hunting in a simulated zebrafish environment. Our contributions are threefold: (1) we develop a flexible, biologically inspired simulation framework with virtual zebrafish agents that perceive, move, and hunt in an arena consistent with larval behavior; (2) we conduct detailed behavioral analyses that recapitulate key hallmarks of zebrafish ethology, including vergence-linked hunting, speed modulations, and stereotyped approach trajectories; and (3) we extract emergent RNN dynamics to gain insights into possible algorithmic implementations of the hunting program.

We demonstrate that our agents develop a convergence-before-turning hunting strategy, reproduce known statistics of prey capture maneuvers, and exhibit behaviorally distinct explore/hunt regimes. Eye vergence dynamics closely track behavioral state and align with experimental observations. Finally, we explore interpretable alternatives such as probabilistic finite-state programs and compare them to the RNN-based control policies. This work highlights the utility of task-optimized RNNs as mechanistic hypotheses for animal behavior and opens avenues for integrating them with biological data to better understand sensorimotor transformations in the brain.

Developing systems for multi-modal measurements of microbial activity

Maryam Malkosh

Mentors: Sujit Datta and Pablo Bravo

Soil plays a significant role in housing complex interactions between plants, their roots, and microbes. The rhizosphere, the region surrounding plant roots, represents increased microbial activity driven by the secretion of root exudates and their transport through complex media. Avoiding limits due to soil opacity, a transparent soil proxy, cryolite, can be used for direct observation of microbial dynamics alongside different textures and pore sizes. For both growth of microbial samples and non-invasive microscopy capabilities, we designed a custom resin-printed enclosure. It uses suction and reverse osmosis membrane filtration to separate water, exudates, and excess media from soil for later chemical analysis and simulates wetting and drying cycles. Future work will target complementary measurements such as gas sensors for carbon dioxide and oxygen consumption and water potential sensors to fully characterize the microbial metabolism.

Development of an inducible acoustic biosensor for protease activity using Plum Pox Virus protease and engineered gas vesicles

Neev Mangal

Mentors: Mikhail G. Shapiro and Jee Won Yang

Abstract withheld from publication at mentor's request.

Evaluating and characterising the antibody response to mosaic RBD nanoparticles as novel vaccine candidates

Darshana Marathe

Mentors: Pamela J. Bjorkman, Alexander Cohen, and Jennifer R. Keeffe

Two sarbecoviruses (SARS-CoV and SARS-CoV-2) have been responsible for epidemics in humans in recent years, with SARS-CoV-2 causing the COVID-19 pandemic. The surface glycoprotein, Spike, is the most variable between related coronaviruses, undergoing rapid evolution on a comparable timescale as that of transmission events and ecological dynamics. Mutations in the receptor binding domain (RBD) of the spike protein can give rise to Variants of Concern (VOCs) which show increased transmissibility compared to the original strain and the potential to evade immune responses. The new mosaic nanoparticle vaccine candidates developed by the Bjorkman lab involve the display of multiple RBDs from different sarbecoviruses on a single nanoparticle, with the aim of stimulating a broader response than by a monovalent vaccine. These mosaic vaccines can provide protection against more distantly related SARS-CoV-2 VOCs and importantly against a potential zoonotic spillover event for an as-yet-unidentified animal sarbecovirus. My project involves cloning, expressing, and characterising monoclonal antibodies elicited in response to immunisation with such vaccines. This will ultimately ascertain whether the vaccine candidates effectively elicit monoclonal antibodies that exhibit broad binding to SARS-CoV-2 VOCs and animal sarbecoviruses, and retain broad neutralisation capacity, even against sarbecoviruses not represented by antigens on the vaccine.

Neural mechanisms of context-guided goal pursuit in humans

Aleksandar Marinkovic

Mentors: John P. O'Doherty and Sneha Aenugu

Context guides our goals and sculpts the value representations for our actions in the world. In this study, we investigate the neural and computational mechanisms by which context modulates goal selection and subsequent value estimation of the state space. We designed a rich naturalistic navigation paradigm where the goals locations are explicitly modulated by the hidden context. Participants sample visual clues from the environment to accumulate evidence in favor of multiple contexts and selectively pursue goals based on their inference of the hidden context. We use Bayesian reinforcement learning to account for decision-making patterns pertaining to value estimation based on contextual ambiguity. We plan to investigate this computational hypothesis in conjunction with neuroimaging data acquired through fMRI to identify neural mechanisms of computations underlying contextual goal pursuit in humans.

Ester accretion products from RO_2+RO_2 chemistry of methyl vinyl ketone

Priscila Marquez

Mentors: Sarah E. Reisman and Kristen E. Gardner

Volatile compounds are important compounds, because they oxidize to produce organic peroxy radicals in the atmosphere. With accretion products, we focus on the study of RO_2 chemistry, because two peroxy radicals can undergo a reaction to form $ROOR$. The Wennberg group has studied accretion product formation of self-reacting ethene derived hydroxy peroxy radicals. These formations are interesting, because these compounds become lower in volatility and are more likely to partition in the particle phase thus providing new information aerosol formation. The principal focus on ester accretion products is that some RO_2 can react to form esters. They are similar to peroxide products, because they experience an increase mass. Additionally, these esters can be found in different aerosol samples and have the potential for possible gas phase mechanism for their formation. Herein, we focus on a synthetic plan to make potential accretion products derived from methyl vinyl ketone (MVK) to better understand if $RO_2 + RO_2$ chemistry is important for MVK and the substantial impact it can have on our environment. The synthesis plans focus on creating 3,4-dihydroxybutan-2-one, 1-hydroxy-3-oxobutan-2-yl acetate, and 2-hydroxy-3-oxobutyl acetate. Once synthesized, we will test the sensitivity of GC-CIMS of the compounds so we can know in the gas phase what concentration we are forming and if the ester accretions products formed.

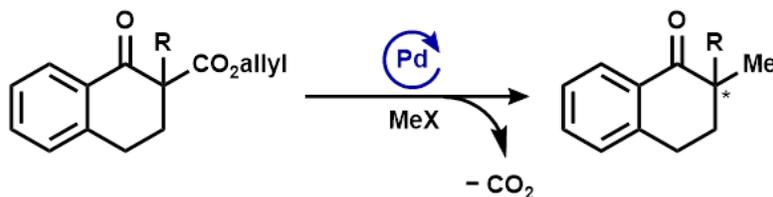
Enantioselective palladium-catalysed methylation of alpha-tetralones

Andrew S. Marriott

Mentors: Brian M. Stoltz and Sara Siddiqui

The construction of enantioenriched all-carbon quaternary stereocentres is a major challenge in synthetic chemistry; the steric bulk of these sites hinders reactivity, leading to very poor yields and limiting available synthetic pathways to complex targets. Successful development of enantioselective alkylation chemistry at tertiary sites would allow for straightforward late-stage modification of synthetic targets, simplifying synthetic routes to a range of natural products and pharmaceuticals.

The Tsuji-Trost allylation has been adapted by the Stoltz Group to give access to enantioenriched protonation and intramolecular alkylation products, but limited success has been had so far with intermolecular reactivity. We present an extension of this work to simple external electrophiles, exploring the methylation of alpha-tetralone derivatives in the presence of a chiral palladium catalyst.

**Multivariable matrix monotone functions**

John G. Mattson, Jr.

Mentor: Otte Heinaevaara

Loewner's theorem characterizes single-variable functions that preserve the Loewner ordering (matrix monotone functions). Dobsch discovered the Dobsch matrices in 1937, and showed that positivity of the Dobsch matrices is a necessary condition for matrix monotonicity in one dimension. Donoghue later showed that this positivity is also sufficient. We study multivariable analogs of matrix monotone functions, as presented and defined in the paper of Agler, McCarthy, and Young (*Ann. Math*, 2013). In particular, we study the locality of multivariable matrix monotonicity, including analogs for the Dobsch matrices that characterize fixed-size matrix monotonicity in the single-variable case. We construct paths of tuples of matrices in order to extract potential Dobsch analogs in the multivariable case. Future work should involve finding a general form of Dobsch analogs for a general setting, and potentially seeing if their positivity is sufficient for local matrix monotonicity in the sense of Agler, McCarthy, and Young.

Early fault-tolerant quantum algorithms for matrix functions via Trotter extrapolation

Arul R. Mazumder

Mentors: John P. Preskill and Samson Wang

In this work we construct algorithms for estimating properties of general matrix functions based on product formulae, with applications to tasks like quantum phase estimation and quantum linear systems. The core innovation combines Trotterization with Richardson extrapolation, enabling exponential improvements in error scaling via classical post-processing compared to product-formulae approaches, without increasing quantum circuit depth. We also extend the method to a partially randomized scheme—mixing deterministic product formulas and randomized unitaries—which improves performance for systems where Hamiltonian decompositions are dominated by a few terms, such as those arising in quantum chemistry. Overall, the algorithm has low circuit depth and only one ancillary qubit potentially making it well-suited for early fault-tolerant quantum devices.

Modeling and shielding of mobile electron beam for increased asphalt durability

Maverick S. McKown

Mentors: Maria Spiropulu, Adi Bornheim, and Christopher J. Edwards

Improving the durability of road infrastructure presents a significant economic and engineering challenge. A novel solution is the use of a mobile 10 MeV, 20kW electron beam to irradiate and strengthen freshly paved asphalt. However, the deployment of such a high-power accelerator in a public environment creates a critical radiation safety hazard, which is a primary barrier to its industrial application. This research addresses this problem by designing and modeling an effective radiation shield for the mobile unit. Using the Monte Carlo code MARS15, complex primary and secondary radiation fields produced when the electron beam interacts with the road surface are simulated. The work involves first creating and validating a baseline simulation of the beam with a simple geometry, which will then be expanded to model the entire truck and road system to determine unshielded dose rates. This analysis will guide the design of a practical shield, evaluating materials such as tungsten composites and layered metals and addressing the engineering challenge of maintaining a shield flush with an uneven road surface. The development of a verified shielding solution is essential for the safe deployment of this technology, enabling its potential to deliver significant improvements to transportation infrastructure.

From black hole seeds to Little Red Dots: Validating progenitors of active galactic nuclei

Jude E. McLean

Mentors: Philip F. Hopkins and Daichi Tsuna

Since it began its mission in 2021, the James Webb Space Telescope has fundamentally changed and challenged our understanding of the universe and our place in it. In the last few years JWST has identified a number of high redshift, dense objects now referred to as Little Red Dots. Their relative abundance and compactness, coupled with their high mass/luminosity, make them good candidates for the early progenitors of current-day Active Galactic Nuclei and the SMBHs that we expect reside at their centers. Speculative work under this "dusty" AGN interpretation of LRDs has yielded interesting insights regarding the life cycle of SMBHs. Principal to our project is the work of a previous graduate student, Yanlong Shi, which suggests that a method of "seed" BH capture followed by a period of Hyper-Eddington accretion may be the mechanism responsible for the birth and growth of these SMBHs. Using a semi-analytical model in conjunction with the assumptions inherent to Shi's work, we study the population dynamics of these objects, further validating this dusty AGN hypothesis and this non-exotic method of SMBH formation.

Development of a microcontroller-based system for molecular beam epitaxy

Asher L. Medina

Mentors: Joseph L. Falson and Veronica Show

Molecular beam epitaxy (MBE) enables the precise growth of high-purity crystalline materials by evaporating source elements onto a substrate in ultra-high vacuum. This project focuses on the development of a compact control system that can monitor and regulate pressure and temperature within the MBE chamber. The system integrates a digital interface, sensor feedback, and logic-based automation to ensure safe operating conditions and maintain reproducibility during material growth. Initial testing has validated the system's ability to interpret pressure signals and respond to simulated environmental changes. While full integration with the MBE system is in progress, this work lays the foundation for more stable and automated synthesis conditions. Future efforts will focus on deploying the system under vacuum and expanding its functionality to support next-generation tools such as thermal laser epitaxy platforms (TLE).

Structural characterization of PER2 nuclear import via the PER2-NLS2–mmKap- α 2 Complex

Philip-David Medows

Mentors: André Hoelz and Chia-Yu Chien

Period Circadian Regulator 2 (PER2) is a key transcriptional regulator in the mammalian circadian rhythm, acting as a transcriptional inhibitor in the nucleus following nuclear import. This nuclear import occurs after the formation of a trimeric complex consisting of PER2, an α -karyopherin protein that binds to one PER2's nuclear localization signals (NLS), and a β -karyopherin protein. This project aims to characterize PER2's nuclear import mechanism by crystallizing one of its two NLS sites in complex with mmKap- α 2, a mouse α -karyopherin. We will use x-ray crystallography to determine the structure of this NLS–mmKap- α 2 complex, thereby enabling the identification of key molecular interactions essential for PER2 nuclear import. These findings will inform future studies of circadian regulation at the molecular level.

Modeling oscillating and rotating locomotion of active nematic droplets

Rohan Mehta

Mentors: Matthew W. Thomson and Fan Yang

Active nematic droplets offer a minimal platform for programmable microscale locomotion, yet existing hydrodynamic models fail to capture the full range of experimentally observed behaviors. We revisit the continuum framework of Giomi *et al.* and systematically vary boundary conditions (homeotropic versus planar anchoring) and initial nematic alignment (uniform versus isotropic). High-resolution pseudo-spectral simulations uncover previously undiscovered modes of locomotion under planar anchoring and isotropic alignment, which qualitatively resemble oscillating and rotating modes seen in experiment. By exploring the dynamics of these modes, we take an important step towards building a more accurate theory of active nematodynamics, which can eventually be applied towards general programming of active droplet locomotion.

Statistical and mechanistic models revealing natural aggression in *Drosophila*

Xinyue Meng

Mentors: David J. Anderson and Udi Binshtok

A fundamental challenge in systems neuroscience is understanding how complex behaviors emerge from external stimuli, especially when identical sensory cues can produce different behavioral outcomes. Traditional linear regression methods struggle to explain such variability. Recent advances have uncovered specific neuronal populations, such as the Anterior Inferior Protocerebrum (AIP) neurons, that regulate aggression in male *Drosophila* (Duistermars *et al.*, 2018). However, the precise neural mechanisms linking sensory inputs directly to aggressive responses remain largely unknown. In this study, we address this gap by introducing latent internal states into our modeling framework, hypothesizing that these hidden states modulate how sensory cues elicit aggression. Using a hybrid Generalized Linear Model–Hidden Markov Model (GLM-HMM), we analyzed behavioral data collected through automated tracking of naturally interacting pairs of male flies. Our results demonstrate the presence of multiple internal states characterized by distinct regression weights, suggesting discrete behavioral strategies that flies alternate between during aggressive interactions. These states are associated with specific sets of sensory cues, revealing a nuanced interplay between external stimuli and internal psychological conditions. This integrative computational approach offers a powerful method to dissect the complexity of aggression in *Drosophila*, highlighting the importance of latent states in behavioral variability and paving the way for mechanistic models linking continuous neural dynamics to discrete behavioral decisions.

Fragmentation is efficiently learnable by quantum neural networks

Mikhail Mints

Mentors: John P. Preskill and Eric R. Anschuetz

Hilbert space fragmentation is a phenomenon in which the Hilbert space of a quantum system is separated into exponentially many dynamically disconnected Krylov subspaces. We can define the *Schur basis* to be a basis labeling these subspaces. Given a set of local operators generating a family of Hamiltonians that exhibit fragmentation, we are interested in constructing a quantum circuit that transforms states in this basis to a bitstring representation of their labels that can be directly measured to classify the input state. In this project, we prove that this transformation can be efficiently *learned* from a set of training data using *quantum neural networks*, provided that the dimension of the bond algebra is polynomial in the system size. To demonstrate this, we analyze the properties of loss landscape distributions in quantum neural networks. We prove that in this setting, it is possible to eliminate barren plateaus and poor local minima, guaranteeing efficient trainability.

Data visualization for an exploratory sun emissions dashboard

Anya B. Mischel

Mentors: Hillary Mushkin, Allan Labrador, Ashish Mahabal, and Santiago V. Lombeyda

Understanding solar flare activity is a critical area of astrophysics due to its potential to disrupt satellites, communication systems, and power grids on Earth. With over 25 years of solar probe data totaling approximately 1 TB, efficient data summarization and visualization are essential for identifying trends in solar activity. We developed an interactive web-based visual analysis interface and dashboard utilizing data from the STEREO and ACE missions. This tool enables researchers to filter solar events by various determinants (including emission strength, classification, etc), examine specific time windows, and sort by various parameters. Researchers can explore relationships between key variables such as event duration, peak emission magnitudes of detected elements, element ratios (e.g., iron-to-oxygen), and overall flare intensity. This tool facilitates deeper insights into the dynamics of solar flare activity and lays the groundwork to integrate additional datasets from other solar probes and add additional features.

Estimating magnetic braking in individual millisecond pulsars to describe local galactic acceleration

Sophie A. Mobley

Mentors: Susan V. Gardner and Nick R. Hutzler

Pulsars are rapidly rotating neutron stars that emit electromagnetic radiation through their magnetic poles. The offset between their spin axis and magnetic axis causes these emissions to be received as pulses by outside observers. Millisecond pulsars (MSPs) are a class of pulsars with a spin period of <10 ms that typically have incredibly stable spin periods. Still, most pulsars are observed to be gradually slowing down. One source of spindown is the loss of energy due to magnetic radiation. This project aims to estimate energy loss due to magnetic braking by using data from MSPs in binary systems, where other spindown effects are well-characterized. If the spindown due to magnetic braking is understood, then the apparent spindown due to galactic acceleration effects can be better estimated in individual MSPs. From these estimates, we hope to be able to better capture the nuances of the local galactic acceleration field. Moreover, this project is part of a larger effort to search for black hole-pulsar binaries. By characterizing the intrinsic spindown due to magnetic braking, extrinsic spindown effects can be isolated and analyzed with more clarity.

Upper bounds on the optimal pebbling number of graphs with high minimum degree

Piash Mondol

Mentor: Matthew M. Gherman

Given a distribution of pebbles on the vertices of a graph G , a pebbling move takes two pebbles from one vertex and puts one on a neighboring vertex. The optimal pebbling number is the least k such that some distribution of k pebbles permits reaching each vertex. It is conjectured that the optimal pebbling number of a graph on n vertices with minimum degree at least 3 is at most the ceiling of $n/2$.

We design a pebbling technique that proves the conjecture for graphs with minimum degree at least 5 and improves the known upper bound on the optimal pebbling number of graphs with minimum degree 3 or 4. Further, we find upper bounds and some lower bounds on the optimal pebbling number of 3-regular circulant graphs and grid graphs.

Groundwork for Hodge-refined Whitehead torsion

Samuel J. Moss

Mentors: Aravind Asok and Tom B. Graber

Given a manifold M of dimension $n \geq 5$, the s -cobordism theorem provides a bijective correspondence between h -cobordisms of M and elements of $\text{Wh}(\pi_1(M)) := K_1(\mathbb{Z}[\pi_1(M)])/\{\pm\pi_1(M)\}$ through a cobordism invariant known as Whitehead torsion. Let X be a smooth projective variety over \mathbb{C} , and let W be an algebraic deformation of X parameterized by the unit interval I such that the fibers of W have isomorphic (mixed) Hodge structures on their cohomology and quotients of $\mathbb{Q}[\pi_1(X)]$ by powers of its augmentation ideal. In this paper we lay some of the groundwork for defining a variation of Whitehead torsion which can detect whether an algebraic deformation of such a variety is trivial. Since we expect this invariant to make use of various Hodge structures present for smooth projective varieties, we refer to this invariant as "Hodge-refined Whitehead torsion." We first provide an explicit computation of the Hodge structures on the cohomology of a class of smooth projective varieties with fundamental group $\mathbb{Z}/5\mathbb{Z}$. In doing so, we develop a spectral sequence for calculating the Hodge structures and numbers of projective hypersurfaces and their quotients by free group actions, and we explore some of its consequences. Finally, we define a notion of "Hodge-refined" rings and modules, and we discuss how we expect these tools to be used in defining a Hodge-refined Whitehead torsion.

Assembly and qualification of the barrel Precision Timing detector for the high luminosity upgrade of CMS at CERN

Nabeeha W. Mubeen

Mentors: Maria Spiropulu and Soham Bhattacharya

The LHC will begin its Long Shutdown 3 (LS3) in 2026 to upgrade the accelerator for CERN's HL-LHC (High Luminosity Large Hadron Collider) era. This era will help improve the sensitivity for standard model physics studies such as the characterization of the Higgs boson and searches for physics beyond the standard model such as exploring dark matter production. This project focuses on precision timing measurement at the Compact Muon Solenoid (CMS) experiment. This will be achieved by working on the assembly of the barrel timing layer (BTL) which is one of the two components of the CMS minimum ionizing particle Timing Detector (MTD). This will be the first detector at collider experiments dedicated to precision timing with a resolution of 30-60 picoseconds. Construction of the BTL consists of assembling sensor modules (SMs) and detector modules (DMs). Rigorous quality assurance and control tests of SMs and DMs are performed to ensure optimal performance. The BTL is segmented into 72 trays where each tray contains 6 readout units (RU). Each RU contains 12 DMs, and a DM includes 2 SMs mounted on a front-end electronic card. This project involves activities in the assembly procedure, from building and testing modules, to constructing trays.

An analytical phase-space approach to Measurement Device Independent Quantum Key Distribution

Ishani Mukherjee

Mentors: Maria Spiropulu and Raju Valivarthi

We develop an analytical model of a Measurement-Device-Independent Quantum Key Distribution (MDI-QKD) protocol using phase-space techniques from quantum optics. Our approach yields closed-form expressions for Hong-Ou-Mandel (HOM) interference visibility, gain, and error rate. We incorporate experimental imperfections such as time-bin bias, channel loss, detector dark counts, and photon distinguishability. Unlike prior work that relies on photon-number approximations, our expressions for gain and error rate are exact. Further, we derive a tight lower bound on the secure key rate from our analytical expressions. Our model predicts improved gain and optimized key rates compared to existing numerical simulations of the same experiment due to the increased accuracy of our phase-space computations.

Engineering hemoproteins for regiodivergent C-H amination towards pyrrolidines and piperidines synthesis

Orna Mukhopadhyay

Mentors: Frances H. Arnold and Ziqi Li

Nitrogen heterocycles (N-heterocycles) are ubiquitous scaffolds featured in biologically active molecules of new pharmaceuticals. Chiral piperidine and pyrrolidine scaffolds constitute a good majority of these N-heterocycles, but using small-molecule catalysis requires complex asymmetric methods to purify and produce the optimal enantiomer. Enzyme-directed enantioselective synthesis of these can minimize off-target effects and maximize therapeutic efficiency. We aim to develop biocatalytic methods toward C-H amination to prepare these scaffolds from simple starting materials via intramolecular reaction that can form both the piperidine and pyrrolidine product. We have used error-prone and site-saturation mutagenesis to evolve the wild type of *Tam* protoglobins such that this synthesis is achieved with regiodivergent scaffold formation. We have concurrently used LevSeq to gain insight into sequence and function data for each round of evolution. We have successfully been able to synthesize the pyrrolidine scaffold with high yield. We have identified an optimal variant for the pyrrolidine scaffold, and we are working to improve the activity and enantioselectivity for the piperidine variant. Afterwards, we will continue with testing the reactions in different conditions and examine the substrate scope of our final pyrrolidine and piperidine variants.

Multi-modal mobility morphobot redesign for fully autonomous payload delivery

James D. Muren, Jr.

Mentors: Reza M. Nemovi and Joshua A. Gurovich

The Stork (M4) platform is a multi-modal morphobot drone that can transform itself from a flight mode with four propellers, to a driving mode repurposing its propeller housings as wheels. This platform is being developed to flexibly tackle the issues of autonomous package delivery in residential areas, while still maintaining the efficiency of flight capabilities.

The goal is autonomous delivery, thus, the package must be deposited from the bottom of the drone and have an opening that allows for autonomous delivery without any human involvement. In addition, the ability to efficiently navigate a short flight of stairs without the use of flight capabilities is ideal. Finally, for the purpose of reducing weight, the target is to use a minimum number of actuator motors for transformation.

This will require making a more robust actuation system that can guarantee proper clearance for the package, in addition to seamless transformation.

The specific focus of this project will be a two stage actuation system. It will use one stage to create vertical motion of the main chassis of the drone, then the second stage will use linear actuators to extend the propellers into flight position. The advantage of this design is that it minimizes friction with the ground as opposed to the current single stage actuator system.

Mapping emission features of the interstellar medium with SPHEREx

Giulia Murgia

Mentors: James J. Bock and Ari J. Cukierman

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) is a NASA mission designed to perform a full-sky near-infrared spectral survey between 0.75 and 5 μm . This work analyzes SPHEREx observations to create line maps of spectral features in the Galactic plane, with particular focus on the 3.3 μm emission feature of polycyclic aromatic hydrocarbons (PAHs). We implemented continuum filtering to isolate line emission and applied source masking, sigma clipping, and auroral contamination removal using template fitting techniques to improve map quality. To reduce the influence of zodiacal light, analyses were restricted to a $\pm 10^\circ$

band around the Galactic plane, where interstellar dust emission dominates. These methods enabled the construction of extended line maps of PAHs and hydrogen recombination features, providing new large-scale views of diffuse structures in the interstellar medium and enabling cross-correlation studies with other surveys of thermal dust emission.

Circular dichroism action spectroscopy for precise enantiomeric excess measurement

Linus Z. Murphy

Mentors: Mitchio Okumura and Leah Stevenson

We developed a novel method of measuring enantiomeric excess in organic samples via a technique known as Circular Dichroism Action Spectroscopy (CDAS). CDAS is a specialized form of Action Spectroscopy, a spectroscopic method that measures the Mass Spectrometric (MS) signal of a sample after the sample is photodissociated at a parametrized wavelength. By circularly polarizing the photodissociation laser pulse, chiral samples will photodissociate more or less depending on if the strongest absorbing bonds are circularly aligned with the laser pulse polarization. By repeatedly performing this technique and averaging the resulting MS signals, a reliable measure of enantiomeric excess can be determined. This technique has potential applications in the search for extraterrestrial biology, as it is largely portable in interplanetary probes and reliable for a variety of chiral chemical systems. We partially constructed a CDAS system with a 266 nm 1kHz pulse diode laser.

Quantum chaos and black holes in $N = 2$ SYK and D1-D5-P

Damian R. Musk

Mentors: Joseph D. Lykken, Maria Spiropulu, and Kyriakos Papadodimas

We explore the emergence of chaotic dynamics within the protected BPS sectors of the D1-D5-P system, with a particular focus on the fate of states with nonzero right-moving R-charge j_R . While the elliptic genus captures an index of BPS states immune to lifting under deformations, the full BPS partition function—refined by j_L and j_R —provides a more granular view of the spectrum and its potential sensitivity to moduli. We investigate whether states with j_R , associated with black hole "hair," survive deformations away from the orbifold point, and whether their degeneracies can grow parametrically to account for black hole entropy.

Analysis of urban seismic signals from the Community Seismic Network (CSN) using K-means clustering

Patricia Anne S. Mutia

Mentor: Monica D. Kohler

The Community Seismic Network (CSN) consists of over 1200 stations with MEMS-based triaxial accelerometers mainly placed across the greater Los Angeles County. Due to the placement in a heavily-populated urban setting, the recorded waveform data includes significant noise from various sources such as population density, seismic site conditions (e.g. sedimentary basins with energy scattering in soft soil), anthropogenic sources (e.g. construction, traffic, and trains), and installation locations (e.g. basement versus upper building levels). To explore whether machine learning can distinguish between seismic and human-generated signals, we applied k-means clustering on pre-processed hourly noise metrics (RMS, L1 norm, and max peak ground acceleration) to assess cluster cohesion and separation across time and space. Overall, cluster separation was low but consistent patterns emerged that aligned with daily human activity cycles and school schedules. These results highlight the potential of unsupervised learning in identifying subtle recurring noise patterns in urban seismic data. Future work will focus on improved preprocessing, cyclical time encoding, and spatiotemporal visualizations to better interpret cluster structure and isolate anthropogenic influences.

A machine learning approach to surveying solar energetic particle time profiles

Kshemaahna Nagi

Mentors: Allan Labrador and Ashish Mahabal

The sun has an 11 year solar cycle. During this cycle, it occasionally ejects high energy particles such as energetic electrons and ions called Solar Energetic Particles (SEP). In order to understand some of the conditions behind these SEP events, such as mean ionic charge states and source temperatures, researchers analyze the decay phases of the SEP event time profiles. This is currently done using manual or semi-automated methods making it a tedious and time-consuming process. The goal of this project is to build and evaluate machine learning models to classify the decay phases of SEP events as exponential, power law or irregular. Events are identified from raw data using the Pruned Exact Linear Time (PELT) algorithm. Using fixed size bins, DMDT histograms of the events extracted are created and the DMDT histograms are fed to CNN-transformer hybrids designed and built for this purpose. Three hybrid architectures were built and evaluated on a small toy dataset including CoAtNet, Convolutional-Enhanced Transformer (CeiT) and Convolutional Vision Transformer (CvT). Preliminary results show that the CoAtNet model has the best performance.

Hydroacoustic analysis of the 2022-2023 Tanaga Island seismic unrest

Neha Narayan

Mentors: Gabrielle Tepp, Robert Dziak, Ross Parnell-Turner, and Vaibhav Ingale

Volcanic monitoring and hazard evaluation is difficult in remote locations like the Aleutian Islands. Tanaga Island, one of the volcanic islands in the Aleutians, experienced a period of seismic unrest, attributed to magmatic transport and recorded by a hydrophone array deployed in the Bering Sea. A preliminary study found that seismic events recorded by the array compared well with a United States Geological Survey seismic event catalog. Another recent study relocated the seismic events with greater accuracy, reducing uncertainty in source characteristics. Comparing the hydroacoustic events to this relocated catalog may help constrain trends in the event source parameters. In this study, we match the hydroacoustic and seismic catalogs by signal arrival time and back-azimuth, and use the ray-tracing based modeling software, Bellhop, to model transmission loss and determine the sound source levels. Assuming conversion points at 2.5 and 3.5 km below sea level, we estimated the transmission loss between the event locations and the hydrophone array as ~96 and 107 dB, respectively. Using the matched events, we reanalyze the relationships between event location, depth, magnitude, and rise time. These findings will characterize the seismicity near Tanaga Island to aid hazard assessment and future studies of the region's seismic activity.

Developing spectral analysis tools for WISER: Spectral angle mapper and spectral feature fitting

Daphne B. Nea

Mentors: Bethany L. Ehlmann, Joshua Garcia-Kimble, and Judy S. Adler

Imaging spectroscopy enables remote identification of materials by capturing their unique spectral signatures across hundreds of wavelength bands, but freely available tools for efficient, large-scale analysis remain limited. To address this limitation, the Ehlmann Research Group at Caltech developed WISER, a free, open-source software to help scientists analyze imaging spectroscopy data. In this project, we integrate two complementary algorithms into WISER: Spectral Angle Mapper (SAM) and Spectral Feature Fitting (SFF). These tools help scientists efficiently detect and identify materials in their images, streamlining data analysis to aid research and discovery. SAM computes angular similarity between a target spectrum, a spectral library, or image cube and a reference library and the SFF module quantifies absorption-band alignment through continuum removal and R^2 goodness-of-fit. Both tools support user-defined wavelength bounds and thresholds, batch processing of hyperspectral cubes, and dynamic result visualization via a PySide2 interface. By vectorizing core computations and enforcing data-quality controls, our plugin accelerates material matching and feature analysis, broadening access to open-source spectral mapping for planetary and geological research.

Restructuring Caltech's CS 2 to support students of all majors

Tobjorn L. Nelson

Mentor: Adam Blank

Caltech's introductory computer science curriculum (consisting of CS 1, 2, 3 and 24) is currently designed with CS 1 to be the only course meant for *all* students at Caltech. The remaining classes are meant primarily for CS majors or students with a generally high interest in the subject. With over half of CS 2's enrollment in the winter term of 2025 consisting of non-CS majors, the overall goal of this research was to make CS 2 a more widely applicable course for students of all majors. As of winter term, 2025, CS 2's curriculum revolved around teaching students how to implement data structures. Projects now instead teach students how to use data structures and various algorithmic techniques through programming real-world applications including, but not limited to, JSON parsers, web crawlers, search engines, navigation apps. By shifting the course's focus away from implementing data structures and towards applying them, we hope that students will learn effective ways to use the tools that computer science offers them, so they can start applying it to their own respective research projects, regardless of the focus.

Hypervelocity impact ionisation of Europa-relevant ice grains for SUDA data interpretation of NASA's Europa Clipper Mission

Holly L. Nerurker Espinoza

Mentors: Paul D. Asimow, Bryana Henderson, and Sankhabrata Chandra

NASA's Europa Clipper mission will investigate the chemical makeup of Europa's surface and plumes to assess the moon's potential habitability. One of the key instruments aboard the spacecraft, the Surface Dust Analyzer (SUDA), is a Time-of-Flight (TOF) impact ionization mass spectrometer that measures the ion fragments produced when micrometer-scale ice grains impact a target-plate at hypervelocity. However, interpreting SUDA's data requires understanding of how variables such as pH, salinity, and impact velocity influence ionization patterns, and to-date no comprehensive laboratory database exists. To address this gap, we are conducting controlled impact experiments with salt solutions, systematically varying pH (2, 5, 8 and 11), salinity (10 mM, 100mM, 500mM, 1M and saturation), and grain velocities (3.0, 3.5, 4.0 km/s) both in cation and anion mode. The selected salts (NaCl, Na₂SO₄ and Na₂CO₃) are thought to be present on Europa's surface based on observations by the Near Infrared Mapping Spectrometer (NIMS) on Galileo spacecraft and Hubble Space Telescope. Preliminary results reveal systematic changes in peak intensity and cluster formation; for example, integrated salt cluster peak areas increase with salinity up to 500 mM. By building a spectral database that captures these trends, this work will enable confident identification of surface composition not only for Europa, but for Enceladus and other icy or ocean worlds.

Probing SmI₂-mediated inner sphere electron transfer to Mo^{IV} imido complexes in an electrocatalytic nitrogen reduction system

Bao T. Nguyen

Mentors: Jonas C. Peters and Hoimin Jung

The reduction of nitrogen to ammonia with well-defined molecular transition metal catalysts is of great interest for opportunities to better understand mechanisms of N₂ reduction and for offering a possible alternative to the energy-intensive Haber-Bosch process. Recent work by our group has demonstrated the electrocatalytic reduction of N₂ with SmI₂ and a molybdenum catalyst with high Faradaic efficiency. A proposed key step of the mechanism is an inner sphere electron transfer (ISET) step between SmI₂ and a protonated Mo^{IV} imido species, which allows for a milder applied potential that mitigates competing acid reduction. Herein, we describe the synthesis of functional analogs of the protonated Mo^{IV} imido species as well as attempts to probe possible interactions between Sm and these complexes to better understand the nature of the proposed ISET step in our reported electrocatalytic system.

Functional flow matching for self-supervised representation learning on time series data

Duy H. Nguyen

Mentors: Anima Anandkumar, Jiachen Yao, and Jiayun Wang

Self-supervised approaches like masked autoencoding have proven effective for learning time series representations. However, their architectures typically yield a single static feature vector, limiting their ability to support downstream tasks that require multi-level classification from the same input signal. We propose a self-supervised learning framework based on Functional Flow Matching (FFM), a continuous-time generative model that operates directly in function spaces. By pretraining an FFM model, we learn rich and label-free representations of time series trajectories. We address the challenge of distribution shift between the noisy inputs seen during pretraining and the clean data samples used for downstream tasks. We hypothesize that because FFM allows for extracting features at any intermediate time step of the generative process, we can access a feature hierarchy corresponding to different levels of abstraction. A key novelty of our approach is exploiting this to perform multi-level feature extraction—capturing everything from low-level patterns to high-level semantic concepts—all from a single pretrained model. We will demonstrate that this approach enables more powerful and versatile representations, and we evaluate our method on downstream tasks, including multi-label classification.

Calibrating land models using FLUXNET observation data: Investigating the variation of vegetation parameters with environmental conditions

Thanhthanh V. Nguyen

Mentors: Tapio Schneider and Julia C. Sloan

Land vegetation greatly affect the atmosphere via the flux of carbon, water, and energy that occurs during photosynthesis. In order to develop a new, state-of-the-art Earth System Model (ESM) that better simulates the biogeochemical and physical interactions on Earth, CliMA (the Climate Modeling Alliance) aims to also develop a novel Land System Model (LSM) that uses the fluxes of vegetation recorded by global FLUXNET site towers to more accurately parameterize plant-photosynthesizing components. For this project, we built the structure for running single-site parameter calibration, where we first simulate a FLUXNET tower with its corresponding information for soil, plant structure, etc. We then pass the outputs through CliMA's [EnsembleKalmanProcesses.jl](#) optimization algorithm to identify which parameters are primarily responsible for the fluxes in the atmosphere attributing to photosynthesis. We also aim to create a process to calibrate all FLUXNET sites simultaneously, allowing us to better isolate and build an accurate set of these parameters.

Improving Higgs boson decay classification into tau leptons via fine tuning of the Particle Transformer

Tuyen T. Nguyen

Mentors: Maria Spiropulu, Jennifer Ngadiuba, and Raghav Kansal

This project aims to develop a machine-learning framework that enhances the identification of Higgs boson decays into tau-lepton pairs in proton-proton collision data. We implement a two-stage pipeline in which a Particle Transformer network is first pretrained on one hundred million jets using constituent-level kinematic and interaction features. The resulting jet embeddings are then combined with high-level jet features and passed to a DeepSet classifier for event-level signal versus background discrimination. Training is conducted on a 45/5/50 split with Lookahead and RAdam optimizers, checkpointing epochs with the best validation accuracy and loss. As model training continues, we will assess the impact of joint optimization, and refine hyperparameters to maximize background rejection at fixed signal efficiency. These investigations will inform subsequent studies on real detector data.

Improving boresight pointing of the BICEP/Keck telescopes with CMB data

Saina Nikmehr

Mentors: James J. Bock and Kenny Lau

The BICEP/Keck (BK) experiment aims to measure B-mode polarization in the Cosmic Microwave Background (CMB) to constrain models of cosmic inflation. Built on the Antarctica ice sheet at the South Pole, the BK telescopes use star cameras to calibrate its pointing trajectory, and a CMB-based boresight tracking method was previously developed to reduce reliance on erroneous star camera results through yearly tracking. In this work, we build upon the existing CMB-based method to enable weekly tracking. By independently extracting mount shifts from the correlation of high-precision BK maps with full-sky Planck reference maps at the same frequency in every round of weekly data reduction, the new method enables timely correction of pointing shifts. As modern ground-based CMB experiments—such as BICEP/Keck, the Simons Observatory (SO), and the South Pole Telescope (SPT)—now feature up to 10^4 detectors, their CMB cameras have surpassed their star cameras in sensitivity. This advancement enables a real-time approach that offers sub-arcminute precision and paves the way for a star camera-independent boresight calibration in the future.

Modeling the chemistry of the RNO 90 and AS 209 protoplanetary disks: A computational approach revealing radial profiles using CO and H₂O spectroscopic data

Alana C. Nisperos

Mentors: Geoffrey A. Blake and Emma Dahl

Protoplanetary disks are differentially rotating structures of gas, dust, and ice that surround young stars. Their inner regions are sites of planetary system formation, as the materials present within are thought to be the building blocks that constitute any resulting planets. However, our understanding of this innermost material is greatly limited. This project combines ground based high-resolution near-infrared spectra acquired with the Keck II telescope with mid-infrared spectroscopy from the James Webb Space Telescope (JWST). Together, these observations are used to determine the physical conditions that arise within two disks: AS 209 and RNO 90. To do this, we ran retrieval models that used Bayesian inference to initially constrain the probable temperature, column density, and emitting area parameters for the CO molecule, via high dispersion rovibrational spectra covering 4.6-5.3 microns. We ultimately mapped the radial column density profiles of the CO disk emission and compared the results to H₂O retrievals generated by JWST. This provides estimates of the C/O ratios in the warm gas near the inner disk surface of AS 209 and RNO 90. Long term, comparing the chemistry of disks to that of exoplanetary atmospheres can provide deeper insight into disk structure and resulting planetary formation.

Investigating thermophoresis and self-thermophoresis of aerosols in microgravity for improved climate modeling

Ama A. Obeng

Mentors: Jeffrey L. Moran, John O. Dabiri, and Jacob Velazquez

Aerosols in Earth's atmosphere influence its climate in several ways, for example by absorbing sunlight, which tends to warm the planet, or reflecting it, which tends to cool the planet. The mechanisms by which aerosols are transported through the atmosphere remain incompletely understood, which limits the accuracy of climate models. This project will test whether thermophoresis (particle migration in response to a temperature gradient) is important in driving atmospheric aerosol transport. Samples will be launched to the International Space Station (ISS), where microgravity eliminates the settling of particles due to gravity. This approach isolates the contribution of thermophoresis to aerosol transport, monitored using optical microscopy. My contributions to this project primarily lie in selection, procurement, and characterization of the aerosols that will be sent to the ISS: these are carbon soot, sodium chloride, and silica. The ISS-based experiments will provide valuable data quantifying their response to known temperature gradients, enabling their thermophoretic mobilities to be characterized as functions of particle material and size. We will also test polystyrene microspheres half-coated in a metal, which we hypothesize will undergo "self-thermophoresis" by asymmetrically absorbing light (and converting it to heat), thus being one of the first examples of particle self-propulsion through air.

Applications of inverse theory to isotopic data in order to elucidate reaction dynamics: Principles and application to simple gas phase systems

Jaden K. Olah

Mentors: John M. Eiler, Amy E. Hofmann, Forrest McCann, and Noam Lotem

The structure and controlling variables (rate constants, etc.) of chemical reaction pathways are recorded in the measurable isotopic abundance ratios of network reactants, intermediates and products. Numerical modeling has shown that the combinatorics of isotopic substitutions in the reactions manifest themselves in distinctive clumped isotope signatures (i.e., proportions of multiply substituted isotopologues). Here we explore whether reaction network pathways can be inferred from measured isotopic abundance ratios by the application of mathematical inverse theory.

The use of inverse theory allows for the prediction of initial or prior conditions of a system from the observations of its output parameters. This application of inverse theory introduces an advance beyond previous, simpler approaches of forward modeling using pre-hypothesized reaction scenarios. However, such applications remain relatively limited. As an initial model system, we used inverse theory to model how all six isotopologues of hydrogen record information about the reaction network in which they participated them and how to access and use such information from experiments. First, we constructed a forward model for the chemical equilibrium and isotopic exchange of isotopologues of H₂ in gas phase, using a test reaction network of 24 reactions (with two different stoichiometries: H-H = H + H and H-H* + H-H = H-H + H-H*) and 9 unique species (H₂, HD, etc., and atomic H, D and T).

Taking advantage of the sparse stoichiometric matrices that describe the dynamics of such reaction systems, we apply several methods from inverse theory such as sparse system identification (SINDy) and inverse Jacobian methods to model different pathways through the reaction phase space corresponding to the addition or removal of certain reactions from the forward model simulating certain environmental conditions. For instance, in our model system described above we might wish to discriminate whether a system undergoes H₂-H₂ exchange, or H₂ dissociation and reformation, or both. Our results demonstrate that inverse methods can identify different reaction pathways through chemical phase space, offering a method for determining possible reaction pathways from measured isotopic abundances of natural hydrogen. We are extending the application of these methods to more complex molecules systems containing H₂, H₂O, CO₂ and/or methane, with the aim of using isotopic abundance ratios to inform the use of inverse theoretic models for predicting probable reaction pathways.

Investigating the mechanisms of *Arabidopsis thaliana* root hydrotropism in the context of osmotic stress

Andrew N. Oldag

Mentors: Trevor M. Nolan and Irene Liao

Increased interest in the dynamics of root growth under drought stress flowed from the general trends of an increase in global drought and uncertainty over agricultural crop production. The process of hydrotropism involves a detection of a difference in surrounding water potentials and a growth of the root towards areas of increased water abundance, thus it represents an interesting issue of root development in both a spatial and temporal context. We are investigating the dynamics of *Arabidopsis* growth in both water limited and hydrotropism inducing conditions to understand the mechanisms of water presence detection by roots and growth under these conditions. In order to identify dynamics of cellular morphology, we use confocal timelapse live imaging. Whereas to develop a broader understanding of root growth dynamics and the rate at which specific parts of the root grow, also known as root growth velocity, we use kinematic imaging and computer vision techniques. Decreased root growth velocity as well as shifts in the primary zones of cellular division and elongation were observed under increasingly severe drought conditions. Additionally, the root bending angle, the main methodology of differential root growth, increased under more severe hydrotropic conditions.

Structural analysis of AgIH as a comparative model for DPAGT1

Grace H. Otos

Mentors: William M. Clemons, Jr., and Jacob Kirsh

N-glycosylation is a post-translational modification where glycans are added to asparagine residues on proteins. In humans these modifications are important for cell adhesion, migration, and signaling. In archaea they are essential for forming a protective proteinaceous layer on the membrane, enabling survival in extreme environments. The initiating proteins for this process in humans, bacteria, and archaea are homologs DPAGT1, MraY, and AgIH respectively. Through preliminary AlphaFold analysis, we find AgIH is more structurally similar to DPAGT1 than MraY. This analysis motivates us to further investigate AgIH as a model system to understand DPAGT1. This project compares the sequence and structure of DPAGT1 and AgIH to identify key similarities and differences. To enable an in-depth comparison we employed a combined computational and experimental approach: AlphaFold to predict structures and investigate features of interest, and CryoEM to obtain high-resolution structural data for both proteins. A structure for DPAGT1 has already been solved by the Clemons lab. Building on this, we focused on analyzing DPAGT1 bound to a truncated muraymycin analog, a potential cancer drug, to characterize its binding interactions. We are continuing to process CryoEM data to determine the structures of both AgIH and DPAGT1 in complex with the drug.

Data-driven prediction of land use change using multi-modal machine learning

Kiran K. Pabla

Mentor: Hannah Druckenmiller

Land-use change plays a central role in shaping both environmental conditions and economic outcomes. Over the past century, large-scale ecosystem conversion has enabled sustained economic growth and facilitated food production to be sufficient enough to support a growing global population. However, at the same time, human well-being depends critically on ecosystem services, such as air and water filtration and natural hazard mitigation, that are rarely priced into markets and therefore often undervalued in land-use decision-making. Determining where land-use change is most likely to occur is essential for guiding conservation strategies, particularly under the ongoing conditions of accelerating urbanization and mounting environmental stressors that we are facing in today's society. Thus, to address this need, we strived to develop a data-driven model to predict land-use transitions over a twenty-year time range. The model is trained on historical data collected from 1996 to 2016 and is designed to be applied toward forecasting future land-use changes. Existing models often struggle to capture the complexities of land conversion across different geographic and socio-economic conditions. Most rely primarily on structured tabular data, making it difficult to generalize across diverse regions. This project seeks to overcome these limitations by integrating high-resolution satellite imagery with datasets consisting of climate records and economic indicators such as property values and land prices through a multi-modal learning framework.

Generating synthetic neural data via conditional diffusion for broader applicability of brain-computer interfaces

Sanvi Pal

Mentors: Nishal Shah, Joel W. Burdick, and Siyuan Tao

A key application of brain-computer interfaces (BCIs) is decoding intracortically recorded neural signals generated during attempted speech, helping restore the ability to communicate for people with speech impairments. A crucial limitation of current speech BCI systems is the large amount of time a participant has to spend in collecting training data for the speech decoder. Generating synthetic data that faithfully models neural dynamics for a target phoneme sequence could potentially accelerate speech decoder training and enhance the generalizability of speech BCIs to new users. Latent Diffusion for Neural Spiking Data (LDNS) is an unconditional diffusion model trained on intracortical spike recordings from a BrainGate2 participant (T12), during attempted speech. We observed that an RNN speech decoder achieving around 25% phoneme prediction error rate on real data performs significantly worse on LDNS-generated neural activity, revealing the limitations of unconditional

generation. We explored conditioning LDNS on phonemes in two ways. First, we used a GRU-embedding of the entire phoneme sequence to condition the LDNS model. Second, we converted the sequence of target phonemes into a sequence of phoneme probabilities at each time point and used an embedding of the instantaneous phoneme probabilities as an input to the LDNS at each time-step.

Deep learning and coarse graining on discrete element simulation data to learn constitutive models for granular flow

Amitesh Anand Pandey

Mentors: Kaushik Bhattacharya, Harkirat Singh, and Lianghao Cao

Discrete Element Method (DEM) simulations are a high-fidelity computational technique used to model granular materials, consisting of discrete particles, to uncover the underlying physics governing various processes. However, DEM scales poorly with system size, making it computationally intractable for simulating real-world systems. Instead, these simulations can be leveraged to inform macro-scale models, which offer a more efficient approach to studying large-scale systems. In this work, we run DEM simulations across a range of cases, varying particle properties, grain-level interactions, flow geometries, and system sizes to explore their effects. We employ advanced tools to extract meaningful coarse-scale properties from grain-scale simulations, enabling the development of accurate macro-scale models and advancing the understanding of granular material behavior.

Characterizing redox dependent structural changes of RuBisCO

Joel Kai Chen Pang

Mentors: Karthish Manthiram and Luis Burgos

Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) is the most abundant soluble carbon-fixing protein found in photosynthetic organisms. Although the enzyme's structure and catalytic activity have been a subject of thorough investigation, limited advances relative to the wild type have been attained. In this work, we posited that a limited understanding of the protein's structural changes as a function of redox potential has hindered efforts in the field. We employed an electrochemical approach to establish fixed solution potentials. Additionally, to predict redox influences in our system, we modelled permeating oxygen via a reaction-diffusion model on COMSOL Multiphysics software. These findings further elucidate an underexplored space in biochemical studies and could provide new foundations for rational protein engineering efforts.

Lambda-Gray Molasses cooling on the Cesium-133 D₁ transition line for enhanced loading of atoms in optical tweezer arrays

Shrishti Pankaj Kulkarni

Mentors: Manuel A. Endres, Hannah Manetsch, and Kon Leung

Neutral atoms in optical tweezer arrays are gaining prominence as qubits for quantum computation due to their highly scalable nature and long coherence times. However, due to the stochastic nature of atom loading processes, atom arrays typically host only 50% of their total atom capacity, which limits their overall scaling and the complexity of the algorithms that can be implemented. Lambda-enhanced Gray Molasses (LGM) is a laser cooling procedure that uses dark states, i.e., states decoupled from light, which has been previously shown to result in enhanced loading on the order of 80% in other alkali atoms, by reducing atom losses and decoherence due to scattering. We present our methodology for implementing LGM on the D₁ transition line ($6^2S_{1/2} \rightarrow 6^2P_{1/2}$) of ^{133}Cs , with enhanced controllability of important scanning parameters necessary for further study of cooling and enhanced loading capabilities in our atom arrays.

Impact of oscillating magnetic fields on skyrmion configurations

Veronica M. Parakhin

Mentors: Gil Refael and Nina Del Ser

Magnetic skyrmions are topologically protected spin textures that offer promise for next-generation data storage and spintronic devices. While the behavior of individual skyrmions under applied fields is well characterized, the collective dynamics of multiple skyrmions remain poorly understood. This project investigates how groups of skyrmions behave when subjected to oscillating magnetic fields, with a focus on their rotational motion, stability, and energy dynamics. To establish a theoretical foundation, we derived the continuous free energy of a chiral magnet from the discrete spin Hamiltonian, including contributions from exchange interactions, the Dzyaloshinskii–Moriya interaction, and external magnetic fields. We then used micromagnetic simulations in MuMax3 to study the driven dynamics of one and two skyrmions under resonant and off-resonant magnetic fields. Simulations show a strong resonance response characterized by periodic breathing behavior. Future work will extend to systems of two or more skyrmions, using stroboscopic sampling to isolate collective motion and determine whether skyrmions rotate with constant radius and linearly increasing angular displacement. These results will inform analytical modeling of skyrmion torque and interaction under weak periodic driving.

Search for Higgs boson pair production in the $b\bar{b}\gamma\gamma$ decay channel at the LHC with the CMS experiment

Nityaansh Parekh

Mentors: Maria Spiropulu and Si Xie

The Higgs self-coupling appears in Higgs boson pair production, a rare process whose measurement probes the shape of the Higgs potential and tests the Standard Model. The $b\bar{b}\gamma\gamma$ final state offers a favorable combination of branching fraction and mass resolution, but demands precise energy calibration and reliable background modeling. This project improves sensitivity to nonresonant HH to $b\bar{b}\gamma\gamma$ by first calibrating electron energy reconstruction through a Z to $e\bar{e}$ study. This involves implementing ZeeAnalyzer, which inverts the electron veto to produce NTuples that contain the dielectron mass distributions. These distributions are fit with a double-sided crystal ball function and a single gaussian (separately) across multiple data and Monte Carlo eras over different detector regions to quantify resolution differences and to gauge any mismodelling which would in turn require smearing corrections. Recent work has verified the centrally used smearing correction including its up and down systematic variations, identified a ParticleNet score selection that increases signal-over-background, and applied cross-section normalizations to stack Monte Carlo samples for constructing a background model for ZZ to $e\bar{e}b\bar{b}$ to compare with data. Together, these efforts tighten the detector resolution modeling, laying groundwork for diphoton mass fits targeting the di-Higgs signal.

Partially observable model-based reinforcement learning for drag reduction in compressible turbulent flows

Taeyang Park

Mentors: Anima Anandkumar and Myrl Marmarelis

Active control of compressible turbulent flows presents significant challenges not found in incompressible regimes, including long-term instabilities such as acoustic waves and local shocklets that destabilize simple control strategies. This work presents a framework for Partially Observable Model-Based Reinforcement Learning to address this challenge, evolving the PINO-PC architecture by leveraging a differentiable CFD solver (JAX-Fluids). We augment the original observer model to function as a multi-step "world model" that is trained on the full state information from the simulation. This augmented observer is designed to perform stable "rollouts", enabling the control policy, which operates on realistic partial observations from wall-mounted sensors, to anticipate and counteract the slow-building instabilities that myopic, single-step predictions would miss. We detail the architectural modifications required for this approach and ensuring the stability of the learned world model in multi-step predictions.

Low-cost multilayer antireflective coating for extra-atmospheric photovoltaics

Carlton G. Passley

Mentors: Harry A. Atwater, Jr., and Susana Torres-Londono

The efficiency of photovoltaic (PV) solar cells, particularly for space applications, is fundamentally limited by light lost due to surface reflection. This project aims to develop a low-cost, multilayer antireflective coating (ARC) optimized for Gallium Arsenide (GaAs) PVs used in the Space Solar Power Project (SSPP), where stringent mass, cost, and durability requirements must be met for extra-atmospheric operation. The approach leverages "wet chemical" spin-coating methods, focusing on sol-gel-derived SiO₂ and TiO₂ layers to reduce reflectance across the 400–900 nm spectrum to below 5%, with a special emphasis on maximizing transmission in the 700–900 nm range crucial for our GaAs cells. The project systematically evaluated nanoparticle and sol-gel methods, iteratively refining synthesis and deposition parameters based on transfer matrix method (TMM) simulations, surface microscopy, and optical measurements. Early experiments highlighted challenges with nanoparticle adhesion and sol-gel film uniformity, leading to improvements in precursor chemistry, spin-coating, and annealing processes. Theoretical modeling and preliminary experimental results indicate that a properly optimized dual-layer SiO₂/TiO₂ ARC can outperform more complex multilayer designs, offering an effective and scalable path to meet SSPP requirements. Future work will focus on achieving reproducible sol-gel recipes and validating performance gains directly on functional PV devices.

Exploring single- and multi-modal embedding spaces through whole-image and component representation analysis

Amrita Pasupathy

Mentors: Matthew W. Thomson and Surya Hari

Images are often represented as high-dimensional vectors within embedding spaces, enabling quantitative similarity assessment based on spatial proximity. While single-modal models can embed only image data, multi-modal models also embed additional input types, such as text captions, within the same space. Our work aims to identify the strengths and limitations of various single- and multi-modal embedding spaces in order to inform improvements in representation quality. Specifically, we analyzed semantic and geometric similarities between neighboring embeddings, examined the influence of individual embedding dimensions on image features, and compared whole-image embeddings with those of their components. The findings will guide the construction of component graphs inspired by Hippocampal Indexing Theory, representing the first step toward advancing existing graph-conditioned diffusion approaches.

Measuring energy usage in research labs towards reducing Caltech's energy consumption

Aarohi R. Patel

Mentors: Julia A. Kornfield, Dennis L. Ko, Maximilian Christman, and Tasha Cammidge

At Caltech, research centers and labs account for as much as 75% of the Institute's total energy costs. A significant amount of energy waste exists due to inefficient equipment management. To find opportunities to save energy, we first need to accurately measure lab equipment energy usage. We conducted lab walkthroughs to build a detailed inventory of over 600 pieces of lab equipment across various labs. From this inventory, we installed 20 energy monitoring sensors onto frequently used equipment to collect real-time energy consumption data. Early findings have revealed discrepancies between estimated and actual energy usage. To address this, we developed a less invasive prototype sensor to measure, analyze, and visualize equipment-level energy consumption. We determined that some ideal targets include freezers and deployed our prototype to estimate potential energy savings. Data collected from these sensors formed the foundation for a targeted education campaign to reduce energy consumption at Caltech.

Implementation of a control algorithm for a tip-tilt mirror for beam jitter correction

Ariana M. Pearson

Mentors: Dimitri P. Mawet and Susan Redmond

The High Contrast High-Resolution Spectroscopy for Segmented Telescopes Testbed (HCST) tests and develops hardware and technology for exoplanet detection using direct imaging techniques. The testbed can currently reach a dark hole contrast of $1E-8$, but beam jitter caused by room vibrations degrades the coronagraph's performance and can diminish the contrast attained. By taking the reflection of the beam off the focal plane mask and redirecting it to a designated camera, a control algorithm loop will be developed for a tip-tilt mirror to correct for beam jitter. The algorithm, written in Python, is service-based and will use a PID controller. This implementation is expected to increase the testbed's run efficiency and will allow for continued technology development.

3D-architected electrodes for zinc-ion batteries

Tosten N. Pearson

Mentors: Julia R. Greer, Kaiyu Zhao, and Yingjin Wang

Novel battery chemistries and designs have been at the forefront of recent energy storage research. However, achieving both high energy and power densities is challenging, particularly due to transport limitations and internal resistance at high electrode mass loadings. Notably, ion mass transport limits and electrical resistance hinder battery performance at higher electrode mass loadings. In response, 3D-architected electrodes offer a promising solution to the limitations of high-capacity, high-rate electrodes due to their high specific surface areas and enhanced ion transport pathways. To overcome these challenges, this project develops a 3D-architected, interpenetrating-electrode system that enhances ion accessibility and structural conductivity. Interdigitated polymer lattices were additively manufactured via 3D printing and subsequently carbonized to produce glassy carbon lattices. Zinc and manganese dioxide will be selectively electrodeposited onto the carbon-based scaffolds in future work, with charge and discharge performed at varying rates to assess suitability for high-rate applications.

The role of DNA2 in the cGAS-STING signalling pathway

Anya J. Peedle

Mentors: Judith L. Campbell and Eunny Bae

DNA2 is a structure specific 5'-3' nuclease/helicase that displays ATPase activity. It has roles in cell cycle regulation, telomere maintenance and mitochondrial replication. DNA2 aids in DNA replication, specifically Okazaki fragment maturation and 5' long flap cleavage. It also repairs DSBs by initiating homologous recombination and re-starting stalled replication forks with WRN or BLM. DNA2 is overexpressed in tumours including breast cancer, ovarian cancer and pancreatic cancer as it mitigates replication stress providing a survival advantage. Therefore DNA2 is a good therapeutic target, where inhibition limits DNA repair and sensitises cells to chemotherapeutics. Here, we are looking at the role of DNA2 in cGAS-STING signalling. This is an innate immune pathway that detects cytosolic DNA and triggers inflammatory responses. DNA2 can also be targeted for degradation by CDK12 phosphorylation, which triggers ubiquitin-proteasomal degradation. We hope to overexpress DNA2 using CDK12 inhibitors, hypothesised to increase cGAS-STING signalling. We also used tamoxifen induced knockout of DNA2 to demonstrate decreased levels of cGAS-STING signalling. Chronic cGAS-STING activation leads to multiple inflammatory diseases including heart failure and liver disease, which can be potentiated by chemotherapies such as doxorubicin. Therefore understanding the role of DNA2 could yield therapeutic benefits for aberrant cGAS-STING signalling.

The fast and the furious: Explosion properties of faint stripped-envelope supernovae from the Zwicky Transient Facility

Nikhita Penugonda

Mentors: Mansi M. Kasliwal and Kaustav Das

Stripped-envelope supernovae (SESNe) are a subclass of core-collapse supernovae characterized by the loss of their outer hydrogen and, in some cases, helium layers prior to explosion. This study investigates the photometric properties of SESNe identified in the Zwicky Transient Facility's Census of the Local Universe (CLU) survey, the largest systematic survey of SESNe to date, with a particular focus on low-luminosity objects. Light curves for over 600 SESNe candidates were modeled using Gaussian Process regression to extract key features, including peak absolute magnitude, explosion epoch, rise and decline timescales, and luminosities in the g - and r -bands. The resulting distributions indicate that these transients exhibit a rise time of $11.26^{+3.28}_{-2.31}$ days, a decline time of $15.68^{+5.53}_{-3.17}$ days, and a peak absolute magnitude of $-17.47^{+0.69}_{-0.50}$ mag in the r -band. These parameters will be used to infer the mass of synthesized Nickel-56, a key driver of luminosity in core-collapse supernovae. This analysis aims to parametrize explosion physics and progenitor characteristics of SESNe, contributing to a deeper understanding of their role in stellar evolution and galactic chemical enrichment.

Constraining the axion-proton coupling with AGN

Dylan Perez

Mentors: Gian F. Giudice, Elias R. Most, and Sokratis Trifinopoulos

The axion is a theorized spin-0 particle which has been studied extensively for its ability to address several longstanding problems in physics. It was first proposed to explain the observed lack of charge-parity symmetry violation in the strong force, but has since become more widely studied for its viability as a dark matter candidate. The axion's couplings to Standard Model (SM) particles can be derived, allowing for predictions of its effect on observed physical phenomena. In this project, we examine axion production in active galactic nuclei (AGN), which exhibit a range of high-energy phenomena. Particularly, axions can be produced via proton-proton interactions in the accretion disk and by protons accelerated in relativistic jets. By modeling axion production in these regions, we can predict axion detection rates at terrestrial detectors as a function of their coupling to protons, which may allow us to derive novel constraints on the coupling. With more detailed modeling, we may also be able to predict and constrain modifications to the electromagnetic emission from AGN induced by the axion-proton interaction.

Understanding the cloud-aerosol interactions in stratocumulus clouds using the EDMF framework

Eric M. Pham

Mentors: Tapio Schneider, Akshay Sridhar, Anna B. Jaruga, Olivia Alcabes, and Sajjad Azimi

Marine stratocumulus clouds play an important role in regulating the Earth's climate because they provide a net cooling effect, but they have proven quite a challenge to represent correctly in climate models. From micron-scale aerosols to macro-scale turbulent and convective motion, they are governed by physics that operates across a broad range of scales. In an attempt to capture this complexity in CliMA's atmosphere model, ClimaAtmos, the 2-moment microphysics model (2M) is coupled with the Eddy Diffusivity Mass Flux (EDMF) scheme. The combined parameterizations should be able to represent the effects of turbulent mixing and transport, as well as the microphysics leading to rain formation. To evaluate the EDMF+2M coupled sub-grid-scale parameterization's ability to produce sensible stratocumulus clouds, the liquid-water-path (LWP) and number concentration (N) time evolution of perturbed stratocumulus-like initial conditions ensembles are compared against those produced by large eddy simulations (LES). The EDMF+2M's ability to replicate the same effects of cloud thinning due to entrainment & precipitation and cloud thickening due to radiative cooling observed in LES outputs will inform us on whether the EDMF+2M bulk scheme can adequately represent the dominant physics in stratocumulus clouds.

Wake dynamics and propulsive efficiency of natural and biohybrid robotic jellyfish

Kyra T. Phaychanpheng

Mentors: John O. Dabiri and Simon Anuszczyk

The ever-changing nature of our oceans demands innovative methods to better understand and monitor their conditions, ecosystems, and dynamics. However, current ocean monitoring tools face the common challenge of propulsive efficiency as a limiting factor, and are limited to fully mechanical underwater autonomous vehicles or purely biological approaches. A biohybrid robot jellyfish—a live *Aurelia aurita* equipped with engineered electronics that electrically stimulates the jellyfish to contract—combines biological efficiency with programmable control. We investigated and compared the wake dynamics of naturally swimming and biohybrid *Aurelia*, the latter being electrically stimulated to pulse at regular two-second intervals. Yet, understanding how engineered stimulation alters their natural propulsion is key to evaluating their efficacy as biohybrid systems. To analyze this, a 3D Particle Image Velocimetry (PIV) scanning system was employed, in which laser sheets repeatedly scanned over the tank to illuminate the pulsing jellyfish and the subsequent motion of suspended micron-size particles in the water. Animal swimming dynamics were captured by a high-speed camera. A custom MATLAB program then identified and reconstructed the 3D volume for each time step and performs the PIV. With this, we constructed velocity vector fields from the data and calculated vorticity in 2D and 3D with original MATLAB scripts. These metrics allow for a comprehensive analysis and modeling of the jellyfish's kinetic energy, wake dynamics and structure evolution. This research not only advances our understanding of jellyfish locomotion and energetics, but moreover, their downstream capability. In future applications, biohybrid jellyfish may serve as live, low metabolic cost and high efficiency sensors capable of detecting climate changes, monitoring ocean conditions, and exploring deep-sea environments.

Substrate-induced nonlinear Hall effect in 2D materials

Sesselja Picchietti

Mentors: Joseph L. Falson and Yann Cho

The nonlinear Hall effect, NLHE, serves as a probe of topological states in materials and their Berry curvature dipoles. Breaking inversion symmetry, a prerequisite for observing a NLHE, is typically achieved by twisting, straining, or applying a large out-of-plane dielectric field. However, these methods do not result in a fixed Berry curvature dipole. In this study, we report a substrate-induced NLHE in graphene stacked on a-plane ZnO. Unlike conventional methods, the observed NLHE exhibits directional dependence, indicating that the Berry curvature dipole orientation is fixed by the presence of a singular mirror axis and in-plane polarization. To further investigate this effect, we employed x- and y-cut LiNbO₃ substrates, which possess the necessary symmetry and flatter surfaces as confirmed by atomic force microscopy. Additionally, we explored 2D superconducting NbSe₂ to observe angle-dependent supercurrents. Introducing a buffer layer between the conductor and substrate may also be used to tune the induced NLHE. Substrate-induced symmetry breaking offers a new avenue for engineering NLHE and exploring topological properties of 2D materials.

Genomic and morphological insights into novel spirochete morphotypes occurring with sulfur-cycling microbial sediment rafts

Anna I. Piland

Mentor: Jared R. Leadbetter

The phylum *Spirochaetota* contains some of the largest and most morphologically unique bacteria known to mankind. These spiral-shaped bacteria move through viscous environments using periplasmic flagella, with some species reaching lengths up to 500 μm . This project aims to uncover more details of spirochete classification and evolutionary relationships by focusing on both marine bacteria and novel freshwater forms. Planned comparative genomic sequencing of aquatic spirochetes will provide the opportunity to update phylogenetic placement and clarify relationships to other spirochetes. Upon the discovery of *Spirochaeta plicatilis*-like organisms, various small spirochetes, and two previously undescribed uniquely shaped spirochetes in sediment rafts from Caltech's Beckman Behavioral Biology pond, community samples enriched with these spirochetes were gathered for DNA extraction and planned metagenomic analysis. Through microscopic analysis, the latter two morphologically conspicuous spirochetes were determined to be of unprecedented dimensions, with

wavelengths of around 1 to 1.2 μm for one type and wavelengths as small as 0.4 to 1 μm in the other, dependent on organism orientation, with both sharing a large amplitude of 0.5 μm . Based on its morphology, spatial relationships, and behavior, the morphotype with the smaller "slinky"-like wavelength is potentially a novel species that remains undocumented in scientific literature.

Investigating the effects of sex variations on trophoctoderm function and embryo fitness using stem cell-based models

Manasvi Pinnaka

Mentors: Magdalena D. Zernicka-Goetz and Sergi Junyent

In vitro fertilization (IVF) has long been associated with a higher male-to-female birth ratio when compared to natural conception, but the mechanisms underlying this phenomenon are still poorly understood. During early development, both mouse and human embryos form the same fundamental structure, the blastocyst, which consists of three main lineages: the epiblast (EPI), the primitive endoderm (PrE), and the trophoctoderm (TE). Mouse embryos, therefore, serve as an ideal model to study the developmental means by which these sex-specific differences arise. Meglicki et al. (unpublished) found that in late preimplantation development, the TE of male mouse embryos develops faster than that of females in high glucose cultures. To further evaluate this connection between sex and TE function, this study utilized blastoids, stem-cell based embryo models developed by the Zernicka-Goetz lab that highly resemble the natural blastocyst. Male and female TSC lines were generated to model the TE and cultured with pre-established male and female ESC lines (to mimic the EPI) and inducible Gata4-expressing cell lines (to mimic the PrE) in low and high glucose environments. To assess the impact of sex variations on early embryo fitness, the composition/proportion of each cell lineage and overall blastoid formation efficiency were compared across conditions.

Rhizosphere engineering of a sucrose-driven metabolic niche to direct plant carbon into microbial storage

Virginia H. Pistilli

Mentors: José Dinneny, Jared R. Leadbetter, and Christopher Dundas

Microbial storage compounds are fundamental to soil carbon cycling, yet the ecological function of these energy-rich polymers - particularly at the plant-microbe interface - remains unclear. Polyhydroxyalkanoates (PHAs) are one such storage compound, and with well-characterized metabolic and nutrient constraints in the context of bioplastic production. Here, we develop a high-throughput microplate assay using Nile Red - a lipophilic and fluorescent dye staining intracellular storage compounds - and corroborate it with confocal microscopy of stained PHA granules to quantify polyhydroxyalkanoate (PHA) accumulation in model *Pseudomonas putida* KT2440 both *in vitro* and on plant roots. Leveraging synthetic biology, we engineer *P. putida* KT2440 strains with modified PHA metabolism to maximize accumulation. In vitro analyses across these mutants and mixtures of plant-relevant carbon sources reveal distinct metabolic interactions between plant exudates profiles and microbial PHA accumulation, highlighting the underexplored role of microbial carbon storage in shaping rhizosphere carbon flux. Additionally, we demonstrate that the introduction of sucrose catabolism to strains grown on *Arabidopsis thaliana* roots exhibiting increased sucrose exudation increases PHA accumulation - a proof-of-concept of how rhizosphere engineering on both plant and microbial sides can be used to construct a metabolic niche that sequesters photosynthetically derived carbon.

Practical spaceplates for ultra-compact optical systems

Alexander P. Plekhanov

Mentors: Andrei Faraon and Phillippe M. Pearson

The miniaturization of optical systems has driven significant interest in flat optical elements that can replace bulky free-space propagation regions. Spaceplate optical metasurfaces offer a promising solution by replicating the phase accumulation of free-space propagation within a significantly thinner structure. However, existing spaceplate designs face significantly limiting trade-offs between compression ratio (R), numerical aperture (NA), bandwidth, and transmission efficiency, restricting

their practical application. In this work, we leverage forward- and inverse-design techniques to engineer, fabricate, and experimentally demonstrate photonic crystal slab spaceplates with high performance across all key metrics. These designs are tailored for the mid-IR, yet readily adaptable to other wavelengths through appropriate material selection.

Initial designs were developed through manual parameter exploration and validated with RCWA and FDTD simulations, yielding practical structures on SiO₂ and sapphire with simulated compression ratios up to $R \approx 70$, an NA of 0.2, and acceptable transmittance over a 50 nm bandwidth. Inverse design techniques were leveraged to further optimize these geometries. The designs are now being fabricated and experimentally characterized. To our knowledge, this work will constitute the first experimental demonstration of a photonic crystal slab spaceplate, paving the way for the development of ultra-compact optical systems in imaging and integrated photonics.

Analytical approaches for multi-modal proteomics for eye disease

Architish B. Prasad

Mentors: Vinit Mahajan and Michael A. Vivic

Previous work in the Mahajan Lab at Stanford has leveraged proteomics based assays to achieve protein expression analyses from both human and mouse eyes for various diseases. This SURF project utilized techniques in bioinformatics and machine learning to gain insights in these data and guide further experimental work. These datasets considered multiple diseases of the eye including retinal detachment, retinitis pigmentosa, age-related macular degeneration (AMD), and eye senescence. Results include analysis that found certain post-translational modifications were over-represented in extracellular matrix proteins with retinal detachment. In AMD, complement proteins were variably expressed for each disease stage, possibly explaining variable patient outcomes in recent clinical trials that target different complement proteins in AMD. Other datasets, including one for eye fluid metabolomics data, were compared with previous work to provide justification for expanding sample set sizes in future validation studies. In new applications for this proteomic data, machine learning studies were initiated to construct models for protein diagnostic biomarkers and proteomic clocks.

YSN-Class (Young SuperNova Classifier)

Oleksandra Pyshna

Mentors: Mansi M. Kasliwal, Ashish Mahabal, and Wynn Jacobson-Galan

We present YSN-Class (Young SuperNova Classifier), a multi-modal supernova classifier with emphasis on early-time observations (e.g., < 1 week post-explosion). Presently, YSN-Class combines two modalities (optical photometry and spectra) with varying representations and features in a fusion architecture. Our classifier is trained and tested on a sample of 2242 supernovae from the Census of the Local Universe (CLU) survey, a volume-limited, spectroscopically-complete Zwicky Transient Facility (ZTF) sample. Currently, in photometric classification mode, YSN-Class scores 85% in the weighted accuracy metric and has an average F-1 score of 72% for three supernova classes (Ia, II, and Ib/c) and with data at <5 days since the estimated explosion date. In addition, YSN-Class can sub-classify type II supernovae into two classes: "flash features" and "no-flash features", which are used to identify observational signatures of interaction between supernova ejecta and confined circumstellar material, getting a 73% average F-1 score based on photometry that covers maximum supernova brightness. YSN-Class is a promising way of classifying supernovae with ZTF, which can be combined with the upcoming Vera C. Rubin Observatory (VRO) transient detection alert stream and existing real-time classification pipelines in order to provide a robust classification within the first ~days since explosion.

An interactive framework for determining hypervelocity star origins in a dynamic galactic potential

Andrew S. Qin

Mentors: Ana Bonaca and Kareem J. El-Badry

Hypervelocity stars (HVSs), ejected from galactic centers via the Hills mechanism, serve as powerful probes of galactic dynamics and the processes occurring near supermassive black holes. While many HVSs have been presumed to originate from the Milky Way (MW), recent evidence suggests a significant fraction may be linked to an intermediate-mass black hole (IMBH) within the Large Magellanic Cloud (LMC). Investigating these origins requires sophisticated numerical simulations, yet current methodologies to enable such analysis are often narrow in scope, as they typically rely on fixed potential models that do not allow for the exploration of uncertainties in the underlying parameter space. Our project addresses this gap by developing a novel, interactive simulation software for the 3D Virtual Reality VizLab at Carnegie Observatories. The software enables users to manually tune key physical parameters of the Milky Way and LMC potentials—such as bulge, nucleus, and dark matter halo masses as well as scales—and immediately visualize the resulting impact on HVS trajectories. Underpinning this visualization is a high-fidelity, time-varying gravitational potential that models the dynamic evolution of the MW-LMC system using interpolated N-body simulation data. If time permits, this software will be used to analyze data from 56 recently surveyed HVS candidates, which were identified using deep u-band photometry from the SMASH survey. This analysis could provide valuable new constraints on the mass of the LMC's central IMBH and its surrounding environment.

Design and fabrication of an EDF-powered drone for emulating flight control systems of self-landing cryogenic rockets

Catherine Qu

Mentors: Morteza Gharib and Jack N. Caldwell

Self-landing rockets rely on a navigation system generally consisting of a thrust vectoring control (TVC) subsystem to mechanically angle the engine to counteract and stabilize the pitch and yaw of the vehicle during flight. The characterization for the software control of a large-scale cryogenic rocket calls for the development of a smaller-scale electric ducted fan (EDF) powered drone to simulate the flight as accurately as possible. We focused on designing a linearly actuated TVC system capable of balancing a maximum tumble in moderate winds, while remaining compact and lightweight. In addition, the integration of a linear rail system to shift weights vertically about the body of the drone allows simulation of fuel consumption, which in turn shifts in the moment of inertia of the cryogenic rocket. To mitigate the rotational inertia caused by the rotation of the EDF, smaller fans are mounted around the top of the drone in the plane containing the central axis of the rocket body. Through controlled flights as well as field-testing, we aim to achieve a stable take-off, extended hover, and landing of the drone before implementing the control system to the larger rocket.

Stress-testing distributional reinforcement learning: Calibrated risk control and out-of-distribution robustness in Atari under a 1M-step budget

Guanni Qu

Mentors: Sergei G. Gukov and Muhammad A. Shehper

Distributional reinforcement learning models full return distributions rather than means, enabling uncertainty awareness and risk-sensitive control. I present a reproducible evaluation of C51 and QR-DQN under realistic stressors and generalization tests. The protocol standardizes compute ($\leq 1M$ environment steps per task), seeds (3), and evaluation, and reports mean \pm sd across seeds. A small-control validation established internal validity and robust defaults (support aligned to return scale; ~ 51 atoms) and showed n-step returns improve sample efficiency over a matched DQN. Building on that baseline, I target visually rich domains (Atari tasks). These results provide actionable guidance on when Distributional RL's distributional heads matter and how to set support/atoms for calibrated, risk-aware decisions that generalize OOD.

Time dependent probabilistic seismic hazard assessment using non-Poissonian distributions

Sohan K. Raghuvanshi

Mentors: Domniki Asimaki and Grigorios Lavrentiadis

Conventionally, the most popular technique to quantify seismic hazard is Probabilistic Seismic Hazard Analysis (*PSHA*) which relies on the Poissonian assumption for recurrence of earthquakes due to model simplifications. However, it fails to capture complex real-world trends and does not fit the empirical data well. The reason lies in the fundamental assumption of the Poissonian process the “Memoryless Property” which assumes the most likely time for a major event is right after the previous; however, in reality large events exhibit periodicity, while small ones clustering and time dependent recurrence interval. To overcome these limitations, we aim to develop a framework for incorporating time dependent behavior in *PSHA* by using non poissonian distributions. To achieve this, we have explored time dependent models like Brownian Passage Time, to account for time since the last major earthquake, and employed Markov chain Monte Carlo to induce time dependency between events. We have successfully prepared a simple composite model, a combination of exponential and BPT, which acts as a framework for incorporating time dependent behaviour. Further efforts will be made to derive analytical expressions for the composite model and move ahead by adding more complex models to improve the fit.

Reducibility and hardness of random quantum stabilizer codes

Akshar D. Ramkumar

Mentors: Vinod Vaikuntanathan and Hsin-Yuan Huang

The task of decoding random linear codes, termed Learning Parity with Noise (LPN), is a computational problem that is widely believed to be hard. It has served as a versatile post- quantum cryptographic assumption—recently, a quantum version of this problem was proposed, called Learning Stabilizers with Noise (LSN). LSN is the algorithmic task of decoding a random quantum stabilizer code. Very little was previously known about LSN, including its relationship to other computational problems like LPN, and whether it shares its nice properties. We show that LSN is harder than a particularly hard case of LPN, for which no subexponential algorithms are known. In doing so, we apply a new technique that relates LPN to a version of the problem for more structured linear codes. Furthermore, we extend the equivalence of LPN's search and decision formulations to LSN, showing that certain reducibility properties of LPN extend to LSN. These results show that generic quantum codes are harder to decode than classical codes— the cryptographic utility of LSN, however, remains open.

Study of erbium doping in germano-silicate photonic integrated circuits

Avani Ranka

Mentors: Kerry J. Vahala and Haojing Chen

Germano-silicate, a mixture of silica (SiO_2) and germania (GeO_2), is a promising substrate for the fabrication of ultra-low-loss optical circuits known as photonic integrated circuits (PICs) due to its ultra-low material loss window extending from the low-visible to near infrared bands (400 nm-2000 nm). The material's ability to host erbium ions, which generate optical gain in the 1550 nm telecommunications band, with excited-state lifetimes consistent with erbium-doped optical fibers makes it a favorable platform for erbium-doped optical devices. These devices have applications ranging from wavelength-division multiplexing (WDM) in data centers to high pulse power mode-locked lasers and frequency combs. We present erbium-doped optical resonators and spiral amplifiers in a novel germano-silicate platform designed to recreate the response of erbium-doped fiber amplifiers (EDFAs) of fiber optic technology on a chip-based scale.

Mathematical modeling through inductive reasoning with LLMs

Sreeyutha Ratala

Mentors: Tanja Kaser, Michael C. Vanier, and Marta Knezevic

Large Language Models (LLMs) have demonstrated remarkable capabilities in data analysis and mathematical modeling through natural language interaction. We explore their potential for mathematical modeling via inductive reasoning, where the model infers underlying mathematical rules solely from numerical data. Specifically, we evaluate whether LLMs can analyze numerical data points and extract symbolic expressions capturing relationships between independent and dependent variables. To isolate inductive reasoning performance, we use a controlled, noise-free dataset that facilitates clear pattern matching and explicit cause-effect identification. Our analysis focuses on in-context learning across subtasks, including numerical reasoning, cause-effect identification, and mathematical expression formation. We further investigate search-based reasoning strategies and backtracking, which expose models to intermediate reasoning and revision steps; these improve accuracy by up to 45% on the full task compared to direct or chain-of-thought prompting. In the cause-effect identification subtask, models achieved correct comparisons in 63% of cases with structured data by only 0.2% when datapoints were permuted, indicating that LLMs encounter challenges in handling order-perturbed inputs. Our findings shed light on the extent to which LLMs can perform interpretable, data-driven reasoning, highlighting their potential to understand and model data and their applicability to tasks in numerical analysis and automated modeling.

Photon pointing at a Muon collider using 3D ECAL segmentation and machine learning

Medha S. Ravi

Mentors: Harvey B. Newman and Kiley E. Kennedy

In high-energy muon colliders, precision reconstruction of final-state particles is essential for disentangling new physics from beam-induced background (BIB). One of the most critical and challenging final-state objects is the photon, especially in the context of precision Higgs boson measurements such as $(H \rightarrow \gamma \gamma)$. Unconverted photons do not leave tracks and must be reconstructed entirely from calorimeter information. In this project, we propose a machine learning-based algorithm to infer the production (z) -vertex of such photons using 3D spatial information from an electromagnetic calorimeter (ECAL). We employ 3D convolutional neural networks (CNNs) to regress the photon's production vertex from segmented calorimeter energy depositions. We demonstrate initial performance on simulated data and validate the approach against a simple analytical method. We also discuss the broader scientific significance of this technique for future colliders and other fields.

The Gaussian curvature of superminimal immersions in the round 4-sphere

Tisya C. Rawat

Mentor: Riccardo Caniato

Through this SURF project in Differential Geometry, we investigated the existence of negatively curved minimal surfaces in spheres, particularly in S^4 . We studied the following problem: Is there a negatively curved, closed, minimal surface in a round sphere? The problem has remained open for decades, since there are serious obstructions, given by the positive curvature of the ambient space, to the existence of negatively curved minimal surfaces in spheres. Bryant and Hano have invented methods to generate minimal surfaces in spheres with semi-explicit twistorial constructions. We studied new methods to understand the Gaussian curvature of Bryant–Hano surfaces. We show that no smooth superminimal immersion in S^4 can have strictly negative Gaussian curvature, as any such immersion of genus $g \geq 2$ must have at least one umbilic point.

Irrationality proofs by arithmetic holonomy bounds

Eduardo H. Rodrigues do Nascimento

Mentor: Vesselin A. Dimitrov

We explore Calegari, Dimitrov and Tang's method of Arithmetic Holonomy Bounds for irrationality proofs, seeking both applications of the method to new irrationality proofs and improvements to the method, which would open the possibility for proofs of new irrationality results. Specifically, we show that 1 , $\log(2)$ and $\pi^2/6 \log^2 2 / 2 + \log^2(3) - 2\text{Li}_2(1/3)$ are \mathbb{Q} -linearly independent, which implies that the latter two numbers are irrational. We also show that if $\varphi = (1 + \sqrt{5})/2$ is the golden ratio, the numbers 1 , $5 \log^2(\varphi)$ and $\sqrt{5}(\pi^2/12 + \log(\varphi)\log(\varphi/5) + \text{Li}_2(-\varphi^{-2}))$ are \mathbb{Q} -linearly independent (and hence, the two last ones are irrational).

Furthermore, we use a related method involving Hermite-Padé approximants and the product formula from algebraic number theory to reprove Mahler's theorem that the p -adic logarithm is transcendental when applied at algebraic numbers. Finally, we generalize a rationality result by Cantor and expand the key idea to generalize multiple other holonomy bounds in the literature.

Visualizing and understanding spatial microbial dynamics of free-living vs. symbiotic nitrogen-fixing bacteria in a novel cryolite soil proxy system

Lila I. Rodriguez-Aceves

Mentors: Sujit Datta and Pablo Bravo

Understanding spatial microbial dynamics in opaque media limits our ability to directly observe and quantify these important metabolic processes including nitrogen fixation. Directly visualizing nitrogen-fixation of free-living and symbiotic bacteria can provide direct optical imaging of microbial activity in three dimensions. Cryolite is a transparent soil proxy with a refractive index similar to water, with the potential of enabling the visualization of microbial dynamics in three dimensions. We have characterized the physical, chemical, and optical properties of various cryolite forms including rocks, powder, and wet-granulated particles through pH testing, optical density measurements, and confocal microscopy and put it in contrast against natural soils. Cryolite demonstrated transparency in water and nutrient media, with cryolite dust maintaining optical clarity even at higher densities. Although attempts to produce soil-like textures via sintering and granulation were unsuccessful due to structural instability and safety concerns, cryolite dust and crushed particles proved most effective for imaging. Initial fluorescence microscopy confirmed imaging depths of up to 2 micrometers, across multiple grains of material. These findings establish cryolite as a viable transparent medium for real-time microbial ecology and lay the groundwork for studying soil-microbe interactions in structured environments.

Analysis of optical timescales based on ultrastable cryogenic silicon resonators referenced by a strontium lattice clock

Hannah J. Rose

Mentors: Jun Ye, Nelson Darkwah Oppong, and Dahyeon Lee

Timescales, such as UTC and its physical realizations, allow for the synchronization and timing of events such as financial transactions and observations for Very-Long-Baseline Interferometry, with modern timescales being measured by counting the period of a stable oscillator referenced to an atomic transition. While current timescales typically utilize the microwave frequency produced by hydrogen masers referenced to the hyperfine transition of Cesium to achieve fractional frequency uncertainties around 10^{-15} or 10^{-16} , cryogenic silicon resonators have demonstrated fractional stability around 10^{-17} and strontium lattice clocks referenced to the $^1S_0 \rightarrow ^3P_0$ transition below 10^{-18} systematic uncertainty at optical frequencies, giving the potential for a substantial improvement in timing accuracy. This work builds on a previous effort by the group demonstrating the feasibility of such an optical timescale over a 34-day campaign and aims to develop a toolchain to produce a continuously generated optically oscillating signal from using a two-cavity ensemble, including a method of analyzing the timescale accuracy from the cavity - Sr clock comparison. This also provides an opportunity to continually track the difference between this timescale and the NIST realization of UTC over a fiber link, with the goal of making optical contributions to official timescales.

Enhancing binary black hole simulations through adaptive mesh refinement

Hannah Röttgen

Mentors: Saul A. Teukolsky, Mark A. Scheel, and Nils Vu

Accurate simulations of binary black hole mergers are crucial for understanding gravitational waves. As detectors become more sensitive, the need for higher-precision numerical relativity simulations grows. My project contributes to the development of such simulations within the SpECTRE code, which uses discontinuous Galerkin methods to achieve high resolution and scalability. A key feature of this method is adaptive mesh refinement (AMR), which adjusts the simulation's resolution based on local accuracy needs. My work focuses on improving the refinement criteria that guide this process and integrate them into binary black hole simulations using the SpECTRE code. I began by analyzing diagnostic tools such as truncation errors and convergence rates in both scalar wave and binary black hole simulations. After identifying limitations in the current refinement approach, I implemented and tested new strategies, starting with simpler scalar wave cases. I will apply these strategies to binary black hole simulations, aiming to improve accuracy and efficiency while maintaining reasonable computational cost. The results will inform future refinement techniques used in high-precision gravitational wave modeling.

Developing stopping criteria for C–H oxidation regioselectivity prediction

Carolyn Ruan

Mentors: Sarah E. Reisman and Anjali Gurajapu

Accurate regioselectivity prediction models for C–H oxidation are crucial towards derisking C–H activation steps in synthetic campaigns and synthesis planning, ultimately reducing reliance on slow, resource-intensive experiments and enabling more efficient drug design and material development. Furthermore, generating the dataset for a successful model may require significant time and laboratory resources for the purification, characterization, and precise assignment of the functionalization site. Recent work in the Reisman Lab has used active learning-based acquisition functions with random forest models to reduce the number of data points needed to perform accurate prediction for C(sp³)–H functionalization. This project aims to develop a stopping criterion for the active learning loop to minimize the number of required experiments for training while maintaining model performance. Various molecular properties, random forest model and acquisition function performance metrics, and sequential machine learning models are investigated as stopping properties.

Integrated distributed Bragg reflector for next-generation chip-scale beam-steering lasers

Brendan J. Rudberg

Mentors: Mo Li, Lihong Wang, and Qixuan Lin

Creating the world's smallest beam-steering laser requires that all components be integrated onto a chip just one square centimeter in size and less than a millimeter in thickness. The laser component of this device will take advantage of a distributed Bragg reflector (DBR), which is a waveguide that uses periodic changes in refractive index to reflect light of a specific wavelength, known as the Bragg wavelength. The DBR serves to restrict the laser to a single mode and a narrow linewidth. In particular, a wavelength of 1550 nm, bandwidth of 3 nm, and a peak reflectance of 90% is desired. We performed several simulations to optimize these values and determine the rough dimensions of the DBR. Next, we designed and fabricated a chip containing several DBRs sweeping several parameters using an electron-beam lithography process on a blank lithium niobate-on-insulator chip. The characteristics of this chip were then measured using a scanning electron microscope and specialized spectroscopy setup. This process was repeated several times with other chips containing DBRs sweeping new parameters. Due to the precision required at this nanometer-scale fabrication, inductively coupled plasma (ICP) etching was inconsistent. However, combining this process with hydrogen silsesquioxane (HSQ) negative resist for silicon dioxide deposition yielded good results. These results represent a critical step toward integrating beam-steering lasers for next-generation LiDAR and optical communication systems.

Investigating the role of cortical structures in spatial learning and navigation using acortical mice

Katelyn A. Sadorf

Mentors: Markus Meister and Jieyu Zheng

This project investigates how mice navigate complex environments in the absence of cortical structures. Acortical mice—genetically engineered to lack neocortex and hippocampus—were trained in the Manhattan Maze, a modular two-layer system requiring goal-directed navigation through masked corridors. Using Bpod behavioral software, we precisely recorded reward acquisition and port entry latencies to assess learning progress. While wild-type mice rapidly learned single-decision paths, acortical mice required extended exposure and sometimes manual intervention. Despite this, they reliably acquired simpler mazes over time. We introduced intermediate-level maps to test for generalization and found limited transfer to more complex configurations, suggesting a lack of flexible learning compared to wild-type mice. However, acortical mice retained maze proficiency after rest periods, indicating durable memory. Ongoing work involves retraining, expanding maze complexity, and comparing behavioral data to wild-type performance. Future analysis will include DeepLabCut-based trajectory modeling to explore subcortical decision-making strategies. These findings contribute to understanding the extent to which spatial learning can occur without cortical input.

Validation of cryolite as a proxy porous media for bacterial models

Amelia Saffron

Mentors: Sujit Datta and Pablo Bravo

Ammonia fertilizer production through the traditional Haber-Bosch process relies on methane combustion, which releases harmful amounts of carbon dioxide into the atmosphere. This motivates the development of alternative methods for efficient and scalable ammonia production based on nitrogen-fixing soil bacteria. However, visualizing bacterial activity to optimize porous media models, including in soil and fixed-bed reactors, presents challenges due to the media's opaque characteristics. To overcome this, we are working to validate the use of cryolite as a proxy porous media for quasi 2D modeling in bacterial systems. Embedding microbial communities in a cryolite-rich environment represents a drastic difference in the physiochemical composition in regard to what the microbes have been subjected to for years of evolution. In particular, we are working on characterizing the spatiotemporal and metabolic activity of bacteria in modified cryolite scaffolds through confocal microscopy. As a first-order approximation, we are characterizing growth differences in two lab-grown strains: *Escherichia coli* and *Bacillus subtilis* in wet environments, as well as quantification of growth in soil-like structures. Future research will include utilizing the pre-existing enzymatic machinery in *Azotobacter vinelandii*, a free-dwelling, methanogenic, and nitrogen-fixing soil bacterium, to develop an ammonia bioreactor model.

Developing a system to optimize microbial carbon fixation

Efe Sakarya

Mentors: Victoria J. Orphan and Madison Dunitz

In order to mitigate the growing climate change problem, current carbon capture and sequestration (CCS) methods are being employed; however, they are not scalable. This project investigates the use of microbial communities collected from Mono Lake, an environment with high salinity and alkalinity, for carbon capturing in an experimental set-up designed to select for the most efficient and resilient strains in terms of carbon fixation. Carbon levels inside the columns that contain water samples with algal-microbe populations were quantified using Total Organic Carbon (TOC) measurements. The additional data from DNA sequencing, as well as temperature and light from HOBO data loggers, were utilized to assess environmental and biological variables. Preliminary results show that columns populated with microbial and algal communities increased their carbon capture efficiency gradually. Correlation analysis is ongoing to identify key factors influencing carbon fixation. These findings demonstrate the viability of biological systems as sustainable carbon capture solutions and offer a starting point for improving the selection of more effective strains in future studies.

Decoding brain activity with structured sparse representations from functional ultrasound imaging

Siddhesh Ashish Salfale

Mentors: Anima Anandkumar and Bahareh Tolooshams

Brain-computer interfaces (BCIs) aim to translate brain activity into actionable commands, with the potential to restore communication and control for individuals with neurological conditions. Functional Ultrasound Imaging (fUSI) is a powerful new neuroimaging method that captures high-resolution brain activity, even in deep regions and during natural behavior. While promising, current fUSI-BCI decoding approaches often rely on black-box models or linear methods like PCA, which fail to offer insight into how decisions are made or which brain patterns contribute—posing a major challenge for interpretability and trust in neuroscience and clinical settings. This project introduces a new decoding framework designed to extract human-interpretable patterns from fUSI data. Inspired by the brain's own principles of efficient coding, we developed a structured sparse autoencoder to learn a small number of meaningful components that reflect distinct brain functions. By encouraging sparsity in both space and across brain regions, our model reveals which areas are most relevant for decoding a particular behavior or intention. Unlike traditional approaches, our method preserves spatial organization and disentangles overlapping neural processes, making it easier to connect computational outputs back to brain function. Ultimately, our work aims to bridge the gap between performance and interpretability in fUSI-based BCIs—enabling scientists to not just decode brain activity, but to make it human interpretable.

Engineering a non-immunogenic drug-inducible vector system for self-replicating RNA vaccine delivery

Ameerah O. Saliu

Mentors: Bruce A. Hay and Thomas A. Adamo-Schmidt

Self-replicating RNA represents a promising platform for the next generation of vaccines. Most currently available mRNA vaccines (such as those used in the SARS-CoV 2 pandemic) utilize an mRNA encoding the target antigen. With these, the lifetime of antigen expression is determined by that of the mRNA. As a result, the dose of antigen may be sub-optimal, representing a limiting factor for inducing a robust immune response. In contrast to simple mRNA vaccines, there has been recent interest in generating self-replicating vaccines, which are able to generate a more significant immune response despite a lower initial titre. Of course, this system carries an obvious drawback, in that it has the potential to allow unregulated replication in host cells, which could have serious health repercussions. To address this, we aim to build a drug inducible, evolutionarily resilient polymerase control switch by which self-amplifying and self-sustaining RNA production can be turned on or off.

In this preliminary investigation, I am using an in vitro assay to assess the safety and efficacy of this novel vector system. Using fluorescence as a marker of replicative activity, I am first testing our ability to achieve replicon amplification only in the presence of an inducer of heterodimerization that brings two otherwise inactive fragments of the RNA-dependent RNA polymerase (RdRp) together. The sensitivity of this system is being assessed through dose-response analysis to identify optimal conditions for replication. In parallel, a second goal I am pursuing is developing a non-immunogenic packaging strategy in which the replicon RNA is linked to immunologically silent membrane proteins to facilitate extracellular vesicle-mediated transfer to neighbouring cells, thereby amplifying antigen production without eliciting anti-vector immunity. Together, these approaches provide the foundations for the use of controllable self-amplifying RNA delivery system to produce more robust vaccine responses and improve patient outcomes.

Turbulence! A multi-scale investigation into the dynamics of the circumgalactic medium around UGC 7342

Maria J. Sanchez Rincon

Mentors: Mandy Chen and Charles C. Steidel

The circumgalactic medium (CGM), the outermost nebulous part of a galaxy, can reveal information about the dynamics and turbulence present in the gases of a galaxy. UGC 7342, a galaxy in the Coma Berenices constellation, has little to no constraints on its dynamics within the circumgalactic medium. Mapping these motions can lead us to information on galaxy growth and evolution. The 2020 Decadal Survey of astronomy called "unveiling the drivers of galaxy growth" a priority area in astrophysical research. For this project, we are focusing on mapping the brightness of [OIII] λ 5008, [NII] λ 6584, H-alpha and H-beta emissions, measuring the velocities of the [OIII]5008 emission, plotting the Baldwin, Phillips Telervich (BPT) Diagram, and probing the gas dynamics with velocity structure functions (VSFs). Through analyzing the velocity structure functions, we can infer and constrain the type of turbulence present, along with the scales at which kinetic energy is injected and dissipated in the form of heat. These results will shed light on how intertwined different areas of various scales in galaxies are, no matter their separation and scale.

Refined characterization of brown dwarf binary Gliese 229B with sika

Sage J. Santomenna

Mentors: Dimitri P. Mawet and Jerry Xuan

Recent research has demonstrated that the brown dwarf system Gliese 229B is an extremely close binary orbiting at a separation of just 0.042 AU, a discovery that gives us an opportunity to study the dynamics of a class of stellar systems that are just beginning to be detectable with high-resolution spectroscopy. In this work we first detail the development of sika, a flexible modeling framework that allows us to efficiently and reproducibly fit complex models to astronomical data. We then use sika to refine our characterization of the Gliese 229B system using new high-resolution spectroscopic observations.

Engineering protoglobins for industrially relevant cyclopropanation reactions

Lana L. Saopraseuth

Mentors: Frances H. Arnold and Martin Power

Abstract withheld from publication at mentor's request.

Post processing modules for high-speed measurement device independent quantum key distribution

Vishruth Satuloori

Mentors: Maria Spiropulu, Prathwiraj Umesh, and Raju Valivarthi

As Quantum Key Distribution (QKD) systems continue to improve on the hardware side, software that can create usable keys from the generated bit strings is necessary to make practical use of QKD systems in commercial and private use. The basic software relies on two steps: an error correction and then a privacy amplification step, with the error correction step using a process called cascade reconciliation and the privacy amplification using a series of fourier transforms, which, when combined, are then used to generate a usable encryption and decryption key that is held by both parties and is practically impossible to be known by an attacker. Using this method, we are able to show a reliable key generation at a rate of 10 megabytes per second.

Distributional exploration bonuses

Toby J. Saunders-A'Court

Mentors: Sergei G. Gukov and Muhammad A. Shehper

We introduce a new exploration bonus for reinforcement learning whose value is proportional to the information gain of a estimate distribution of returns updated with the distributional Bellman operators introduced in (Bellemare, 2016 / C51) and (Bellemare, 2018 / Quantile Regression). This method of combining exploration bonuses and distributional perspectives on reinforcement learning is predicted to generalize well other distributional methods commonly used in modeling partially observable Markov decision processes. We also propose a similar psuedo-count-based method for likewise combining these two aspects of reinforcement learning.

Analysis of cell dynamics within the shoot apical meristem of *Arabidopsis thaliana* using confocal microscopy

Brygid Sawitsky

Mentors: Elliot M. Meyerowitz and Paul T. Tarr

The shoot apical meristem (SAM) is a collection of totipotent cells which generates all above-ground plant organs, making its cell dynamics of significant interest to plant biologists. Understanding the pattern and rate of cell division within this population of stem cells has been a long-standing question in plant developmental biology. Utilizing the model plant *Arabidopsis thaliana*, transgenic plants with markers for different phases of the cell cycle were analyzed using confocal microscopy to produce both long- and short-term images. Confocal microscopy is a technique allowing for high-resolution, 3D imaging of cells and tissues. Traditional point scanning confocal laser scanning microscopy (CLSM) limits the ability to image at short time scales due to the slow scan speeds; therefore, a variation of CLSM that utilizes a resonant scanner was utilized, increasing the scan speed by greater than tenfold. Analysis of the cell dynamics from these 4D time-resolved images provides an insight into how cells within the meristem grow and divide over time.

Kernelized Stable Fluids for simulating physically accurate solutions

Lennart A. Scholz

Mentors: Houman Owhadi and Aras Bacho

Solving the Navier–Stokes equations is of great importance both in physics and applied mathematics. Due to their nonlinearity, most of the established solution algorithms, such as the pseudospectral method, have shortcomings, including stability problems for large timesteps. This problem is addressed by the Stable Fluids method, which solves the Navier–Stokes equations in an unconditionally stable manner. However, the method has a disadvantage: the solution of the advection step is not volume-preserving. The method solves the advection part by tracing each point backwards in time along the divergence-free velocity vector field of the fluid. The flow of a divergence-free velocity vector field is theoretically volume-preserving, but not if we approximate it using the method of characteristics, as proposed by the Stable Fluids method. We propose Kernelized Stable Fluids in order to ensure volume preservation when solving the advection step, thereby making the algorithm suitable for scientific simulations and not just visual effects.

Remote monitoring of inland water systems and their flux and gas transfer velocities in real-time

Luis Y. Serrano Laguna

Mentors: Woodward W. Fischer, Bryn Stewart, John S. Magyar, and Simon Andren

Literature has shown that inland water sources such as rivers tend to be large contributors to CO₂ flux. However, the mechanics behind the gas transfer between inland waters' surface and the atmosphere still remains difficult to monitor; current methods fail to account for the temporal and spatial variability inland water systems tend to experience due to natural processes that occur such as photosynthesis and respiration. This makes it difficult for researchers to obtain measurements representative of the entire system due to time constraints. This project aims to address these issues through the development of a robust sensor probe network for remote monitoring of CO₂

concentrations in water and potentially the gas transfer velocity in real time. The system consists of submerged probes monitoring the water dynamics of CO₂, temperature, and dissolved oxygen. A floating gas chamber will also be deployed for monitoring the flux of the water surface through a mass-transfer model at steady-state equilibrium. The embedded system behind the probes and gas chamber consists of a microcontroller capable of continuous transmission of sensor data through long range communication, allowing for real-time monitoring. A receiving hub will keep track of several deployed probes in different areas of the inland water systems to account for spatial variation and perform flux calculations for real-time gas transfer monitoring. This will improve our understanding of inland water system dynamics and offer a low-cost and scalable solution for large areas compared to other systems such as LI-COR.

Building towards predictive modeling of team flow based on solo flow across cognitive abilities

Ridah S. Shanavas

Mentors: Shinsuke Shimojo and Mohammad Shehata

Team flow is a highly immersive, synchronized collective cognitive state linked to enhanced engagement and group performance but its relationship to the cognitive abilities profiles of team members remains largely unexplored. Towards this, we developed a platform supporting individual and dual-player gameplay with four cognitive card-matching mini-games. Each mini-game is based on the Cattell-Horn-Carroll (CHC) framework and targets a specific ability: visual processing, general knowledge, quantitative reasoning, or lexical knowledge. Each mini-game has a preview phase, when cards are visible but not selectable, followed by an execution phase where participants select cards from memory. This allows separate analysis of planning and decision-making. Eye-tracking measurements, including gaze, pupil size, and saccades, are collected using NeonGlasses by Pupil Labs, with custom calibration steps for accurate mapping. Subjective flow experience is assessed through questionnaires administered during each session. Initial testing has refined the data analysis pipeline processing both game and eye-tracking data. With large-scale participant testing planned for the future, this platform provides the foundation to investigate how cognitive ability profiles shape team flow and inform predictive modeling of team formation. Ultimately, this research aims to guide strategies for maximizing team flow, with applications in education, sports, and collaborative work.

A comparative study of model-based and reinforcement learning control paradigms for planar biped walking

Ritwik Shankar

Mentor: Aaron D. Ames

Choosing between model-based and model-free control strategies for bipedal locomotion is inherently challenging, as each paradigm presents its own set of strengths and limitations. In this work, four distinct strategies are evaluated on a planar biped simulated in NVIDIA's IsaacSim. First, a pure reinforcement-learning baseline is trained to output joint setpoints for a proportional-derivative (PD) controller that tracks the commanded base velocity. Second, a deterministic pipeline employs a reduced-order linear inverted pendulum (LIP) model to generate desired foot trajectories, solves for joint angles via an optimisation-based inverse-kinematics (IK) solver, and applies a PD law to compute joint torques. Third, two hybrid schemes blend learning with physics-based modelling: in the RL-IK-PD approach, a policy proposes foot placements and CusADi (CUDA-accelerated CasADi) with Pinocchio are employed to solve IK using a GPU; in the LIP-RL-PD method, the linear pendulum produces step targets while an RL agent learns to perform the inverse kinematics mapping before PD tracking. The final goal is to present simulation-based ablation of reward components and compare the fully model-free, model-based and the hybrid approaches; forthcoming hardware trials will provide additional insights.

Automating the measurement of high rate entanglement at INQNET

Karen I. Shekyan

Mentors: Maria Spiropulu and Raju Valivarthi

Entanglement is central to quantum information processing, with time-bin entangled photons being one of the primary mediums for protocols such as entanglement distribution and swapping. These methods can be realized for the purpose of quantum key distribution or long-distance communication but suffer from attenuation, causing a significant slowdown in the transmission of data for postprocessing. As such, we work to automate the generation of time-bin entangled photons by developing software to control the necessary laser, interferometers, and SNSPDs (superconducting nanowire single-photon detectors). To further counter the issues present in long-distance communication, we incorporate polarization stabilization, dispersion compensation, and clock synchronization modules. We particularly focus on polarization stabilization and demonstrate the automation of this process over a 150-km fiber, successfully maintaining a fidelity exceeding 96% with a polarization drift of 0.25° per second over 24 hours.

Sparse autoencoder neural operators: Model recovery in function spaces

Ailsa X. Shen

Mentors: Anima Anandkumar and Bahareh Tolooshams

We frame the problem of unifying representations in neural models as one of sparse model recovery and introduce a framework that extends sparse autoencoders (SAEs) to lifted spaces and infinite-dimensional function spaces, enabling mechanistic interpretability of large neural operators (NO). While the Platonic Representation Hypothesis suggests that neural networks converge to similar representations across architectures, the representational properties of neural operators remain underexplored despite their growing importance in scientific computing. We compare the inference and training dynamics of SAEs, lifted-SAE, and SAE neural operators. We highlight how lifting and operator modules introduce beneficial inductive biases, enabling faster recovery, improved recovery of smooth concepts, and robust inference across varying resolutions, a property unique to neural operators. This perspective provides a foundation for interpreting neural operators through the lens of sparse representation learning.

cuEquivariance implementation of OrbNet-Equi for accelerated orbital learning and foundation-scale training

Erh-Wei Sheng

Mentors: Anima Anandkumar and Beom Seok Kang

Quantum mechanics-informed geometric deep learning combines physical priors with symmetry-aware neural networks to predict molecular properties efficiently. OrbNet-Equi is a leading model in this domain, using quantum mechanical matrix features as input to an $SE(3)$ -equivariant message-passing network. This approach, known as orbital learning, enhances data efficiency and accuracy by embedding electronic structure directly into the learning process. However, the original implementation of OrbNet-Equi uses the torch-gauge backend, where Clebsch–Gordan tensor products are computed via separate CUDA kernels. This design limits GPU utilization and scalability.

In this project, we implement a new backend for OrbNet-Equi using NVIDIA's cuEquivariance library, which fuses spherical tensor operations into optimized CUDA kernels. The updated architecture removes Python-level bottlenecks, improves memory efficiency, and modularizes key components such as diagonal reduction and message passing. This enables more effective use of modern hardware for large-scale training. By accelerating core operations in OrbNet-Equi, we establish the computational foundation for future orbital-level foundation models that can generalize across diverse molecular systems while maintaining high efficiency and fidelity.

Phase space formulation of quantum optics for measurement-device-independent quantum key distribution

Ahaan Shetty

Mentors: Maria Spiropulu and Raju Valivarthi

Measurement-device-independent quantum key distribution (MDI-QKD) has proven to be an exciting and groundbreaking approach to develop secure, side-channel attack resistant quantum communication. A novel approach to theoretically modeling time-bin qubits in an experimental MDI-QKD setup is by using the phase space formulation of quantum optics to derive analytic results. In the setup, Alice and Bob's transmission of coherent state pulses to Charlie are modeled, including every physical component realized experimentally via symplectic transformations. Through the representation of a bucket-type photon detection as Gaussian, a two-fold detection probability has been calculated for the purpose of the Bell State Measurement (BSM). This has been used to derive data for key rate, error rate and gain for the generation of a shared secure key. Further, time-bin overlap between qubits, detector dead time and dark count probabilities have all been modeled and included in derivations. The exciting results have been successful and largely in agreement with other theoretical predictions and experimental realization of MDI-QKD setups. In addition, this theory is being extended to a setup with more than two parties involved, and including quantum teleportation using entangled TMSV states for secure long-distance communication.

A DNA-based linear classifier for sequential analog signals

Xiaorui Shi

Mentors: Lulu Qian and Matthew Plazola

Compared to conventional electronic computing, molecular computation offers superior energy efficiency, intrinsic parallelism, and enhanced biocompatibility. Since biomolecules natively exist in living organisms, molecular computing has the potential to enable in vivo intelligent medical diagnosis and therapy. Furthermore, biomolecular concentrations can represent continuous variables, overcoming the inherent binary limitations of electronic computers. In molecular computing, DNA-based neural networks utilize molecular hybridization and strand displacement reactions to emulate neuronal operations, functioning autonomously in bodily fluids or cells without external power sources. This provides inherent advantages for biomolecular diagnostics, such as cancer biomarker classification and concentration analysis.

Most prior DNA computing studies have focused on binary encoding of concentrations (high = logic '1', low = logic '0'), with limited exploration of direct analog signal processing. However, analog signal classification is critical for medical diagnostics. Additionally, the irreversible nature of DNA hybridization and strand displacement reactions typically restricts constructed neural networks to single-use operation. Recent advances include the development of DNA-based variable-gain amplifiers that process concentration-dependent analog signals, and the demonstration of thermal energy as a universal reset mechanism for DNA neural networks. These networks maintain stable performance across multiple cycles, enabling iterative computation and unsupervised learning.

In this project, we designed and experimentally realized a reusable DNA-based analog linear classifier. This system processes DNA concentrations as continuous variables through amplification and summation operations, with thermal resetting (heating/cooling cycles) allowing repeated computations for sequential inputs. Our work establishes a foundational step toward DNA computing systems capable of processing time-varying analog signals and adaptive learning.

New experimental platform for investigating soliton and wave dynamics in 1D and 2D Polycatenated Architected Materials (PAMs)

Kensuke Shimojo

Mentors: Chiara Daraio and Xiaoxiao Xiong

Polycatenated Architected Materials (PAMs) are a new class of metamaterials composed of interlocked ring-like elements, which offer unique, tunable nonlinear dynamics and energy-dissipative behavior under mechanical loading. Compared to conventional architected or granular materials, PAMs exhibit highly customizable resistance to specific deformation modes, due to the high internal degrees of

freedom in their interlocked and per-unit topology. This enables their potential use in advanced shock absorption applications, such as impact-resistant helmets or vehicle protection systems, where tailored mechanical responses are desirable. Because most existing experiments only investigate static properties of PAMs, investigations into the dynamics of PAMs are necessary to fill the knowledge gap for such applications. To this end, we developed an experimental platform to investigate force and soliton propagation in 1D and 2D PAM systems. Using this platform, we obtained high-quality, analyzable data from experiments investigating 1D chains, junctions of chains, and 2D chainmail meshes. These experiments allowed us to compare experimental signatures of nonlinear wave propagation with theory. The setup's modular design allows for various different configurations of PAMs and actuation modes, such as transverse or rotational actuation and the integration of various sensors into the PAM units, yielding great potential for future experimentation.

Evaluating the ecological utility of bulk oxygen isotopes in western Amazonian mammal enamel

Alyssa H. Shin

Mentors: Julia Tejada and Joshua S. Anadu

Oxygen isotopes are often used to understand past climates, but the extent of their value in reconstructing ecological or physiological traits in mammals remains uncertain. This study analyzes bulk $\delta^{18}\text{O}$ in tooth enamel from 143 mammal specimens located in closed-canopy rainforests of western Amazonia. Samples encompass a range of diets and habitats across ten taxonomic orders. $\delta^{18}\text{O}$ values generally align with ecological expectations (e.g., aquatic species often have lower $\delta^{18}\text{O}$ than terrestrial species), but overlap among groups constrains their predictive utility in the absence of complementary data. Clustering analyses incorporating $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ show that $\delta^{18}\text{O}$ contributes meaningfully to ecological grouping. To explore the drivers of $\delta^{18}\text{O}$ variation, a species-specific model was calibrated to Amazonian conditions and closely predicts the observed $\delta^{18}\text{O}$ values. Overall, while $\delta^{18}\text{O}$ holds limited power on its own, it can provide useful ecological insights when combined with additional data.

Modeling methane flux for long-term organic carbon sequestration

Sanskriti Shindadkar

Mentors: Alex L. Sessions and Madison Dunitz

One promising method for scalable carbon sequestration is industrial algal biomass farming in seawater. Evaporation of the sea water media increases the overall salt content for long term storage, reducing degradation and methane production. However, measuring the long-term emissions is a difficult task to do purely experimentally. Building on PFLOTRAN (a massively parallelized reactive-transport program) we model the relevant microbial reactions and molecular transport, to predict the flux of carbon dioxide and methane from the sequestered biomass. By modelling reactions such as acetoclastic methanogenesis, methylotrophic methanogenesis, and hydrogenotrophic methanogenesis, along with fermentation and acetogenesis, the model is able to forecast the net production and concentration of different chemical species on a 100-year timescale, to ultimately predict methane and carbon dioxide flux, beyond what we can experimentally test in a lab. The forecasted gas production from the model will be compared with future experimental data collected on samples on the order of weeks, months, and perhaps years.

Nucleocytoplasmic transport of circadian clock proteins

Talaysha S. Simonds

Mentors: André Hoelz and Sabrina Doerrich

The molecular circadian clock is an important regulator of diurnal physiology and behavior with a rhythm of 24-hours. At the molecular level, it consists of a transcriptional-translational feedback loop (TTFL) in which positive elements CLOCK and BMAL drive the transcription of negative regulators PER and CRY that inhibit their own expression. To block the transcriptional activation of CLOCK-BMAL, the negative regulators PER and CRY have to be translocated into the nucleus. This shuttling of cargos through the nuclear pore complex mediated by transport factors called Karyopherins is known as nucleocytoplasmic transport. While transport of circadian clock proteins is essential to regulate the

circadian oscillations, it has not been studied systematically. Our research project aims to investigate the interactions between circadian clock proteins and Karyopherins. To accomplish this, we recombinantly express and purify the required proteins and ultimately test their interactions through size exclusion chromatography coupled with multi-angle light scattering (SEC-MALS).

Disentangling input-driven and intrinsic mechanisms of line attractors in hypothalamus

Pushkar S. Singh

Mentors: David J. Anderson and Aditya Nair

The ventrolateral ventromedial hypothalamus contains neurons whose activity forms a one-dimensional "line attractor" that integrates signals leading to social behaviors. Whether this integration reflects intrinsic evidence accumulation dynamics or the integration of deterministic external inputs remains unknown. We analyzed calcium imaging data from two social behaviors: aggression in male mice (Nair et al, 2023) and mating in female mice (Liu, Nair et al, 2024) by fitting competing single-dimension dynamical models: one assuming integration dynamics are intrinsic to the neural system itself, and another requiring external behavioral inputs to drive the integration process. Model comparison showed that input-driven formulations consistently provided a superior fit, indicating that ongoing behavioral information, not autonomous drift, better explains the attractor trajectory. These findings argue that hypothalamic integration depends on deterministic external signals and offer testable predictions about the origin and sign of those signals. Current work is extending the analysis to additional datasets to determine the generality of this input dependence and to refine mechanistic hypotheses for future perturbation experiments. This research provides new insights into the computational principles underlying social behavior integration in the hypothalamus.

Dispersion compensation for entanglement distribution in quantum networks

Shreyas Singh

Mentors: Maria Spiropulu, Prathwiraj Umesh, and Raju Valivarthi

Quantum Key Distribution (QKD) is a powerful scheme allowing communicating parties to create an encryption key whose security is guaranteed by the laws of quantum mechanics rather than the assumed difficulty of computational problems. QKD, along with other promising applications of quantum networks, requires the long-distance distribution of entangled qubits, often implemented using time-binned photons sent through optical fibers. However, the accuracy and rate of qubit transmission is hampered by chromatic dispersion (CD), an effect which increases the timing uncertainty of qubit detection and compounds over longer distances and higher photon bandwidths. We seek to experimentally mitigate the effects of CD on entanglement distribution by means of tunable dispersion compensators based on fiber Bragg gratings. We design an algorithmic protocol to minimize the time-spread of photons traveling through fiber spools with length varying up to 100 km, and demonstrate its efficacy using modulated laser pulses detected with SNSPDs. Additionally, we aim to reproduce Hong-Ou-Mandel (HOM) interference between two independent dispersion-compensated photons, demonstrating the viability of various QKD protocols over long distances.

Data-driven interpolation of pressure distributions in soft tissue phantoms via sparse piezoresistive sensing

Ria Sinha

Mentors: Chiara Daraio and Brian Ahn

This project explores a data-driven approach for full-field pressure mapping using sparse sensor input and machine learning. The objective is to reconstruct detailed pressure distributions from a limited number of sensor measurements by combining finite element modeling and experimental calibration. A multilayer physical phantom was fabricated to approximate biological soft tissue, incorporating 16 thin-film pressure sensors arranged in a 4x4 grid. Each sensor was custom-made using layered conductive materials and calibrated using known weights to establish the relationship between electrical output and pressure. Simultaneously, a COMSOL Multiphysics model was developed to simulate pressure distributions across a range of material properties using an 8-parameter sweep. These simulation results, combined with the corresponding sparse sensor values, form the training data for two machine learning models: a simple convolutional neural network (CNN) and a U-Net

masked autoencoder. The CNN provides a baseline, while the U-Net architecture offers a more advanced interpolation method for capturing spatial structure. All data handling, training, and evaluation are performed in Python. This framework sets the foundation for a reliable pressure estimation system that can be applied to medical diagnostics, soft robotics, and structural monitoring, where dense sensing is impractical but high-resolution mapping is still needed.

Energy scale of sphalerons

Pritvik Sinhadc

Mentor: Harvey B. Newman

Sphalerons are unstable, static, finite-energy solutions of classical field equations that facilitate baryon and lepton number-violating transitions, making them essential in the context of electroweak theory, symmetry breaking, and baryogenesis. These non-perturbative topological field configurations, if experimentally confirmed, could provide critical insights into the matter-antimatter asymmetry in the universe and offer direct phenomenological evidence for Beyond Standard Model (BSM) physics. Current estimates place the sphaleron energy barrier height between 9 and 20 TeV, but there remains uncertainty due to higher-order electroweak corrections, the influence of the Higgs potential, and thermal effects. This research refines these theoretical estimates, develops collider-search strategies, and assesses the feasibility of detecting sphalerons at high-energy colliders such as the Large Hadron Collider (LHC), High Luminosity LHC (HL-LHC), and the Future Circular Collider (FCC-hh). The project, therefore, integrates advanced Monte Carlo simulations, Bayesian inference methods, LHC Run 2 and Run 3 datasets to probe potential sphaleron-induced signatures, thereby setting upper limits on their production cross-section. The research also involves event reconstruction techniques using BaryoGEN, HERBVI, HERWIG, and Pythia to differentiate sphaleron-like events from Standard Model backgrounds, applying deep learning classifiers and jet substructure analysis. Further, sensitivity projections for next-generation colliders are generated, evaluating the required energy thresholds and luminosity constraints for sphaleron discovery. A novel aspect of this research is the exploration of sphaleron transitions in modified electroweak scenarios, including their connection to topological defects and gravitational waves from first-order phase transitions, which may be detectable by Laser Interferometer Space Antenna (LISA) and pulsar timing arrays. If sphalerons are confirmed experimentally, this would possibly be a landmark discovery in particle physics, showing evidence for electroweak baryogenesis and potential modifications to the Higgs field dynamics. In the absence of positive detection, the results from this research would still yield crucial constraints on sphaleron physics, shaping future experimental searches and theoretical refinements in high-energy physics. By integrating collider phenomenology with computational modeling as well as early-universe constraints, this research definitely establishes a comprehensive framework for sphaleron detection and characterization, guiding future searches for non-perturbative electroweak processes.

Enzymatic in-situ generation of silylium ions via protodesilylation of allylsilanes

Shreya Sivaramakrishnan

Mentors: Hosea Nelson and Kunal Jha

Protodesilylation of allylsilanes is the cleavage of Silicon – Carbon (σ) bond through the protonation at the allylic γ – carbon centre. However, silicon containing molecules are not native substrates to enzymes due to its low abundance in living organisms, which adds complexity to the presented problem. This project explores a biocatalytic route to generate silylium ions within the enzyme pocket as enzymes are known for its high selectivity and mild reaction conditions. Oleic Acid Hydratase (OAhyd) are flavin dependent enzymes known to catalyse the hydration of non-activated CC double bonds in olefins; and it has been reported to have hydrophobic active site. This makes OAhyd enzyme library ideal for this study as the generated silylium ions are highly electrophilic, which can be stabilised within a hydrophobic active site with relative ease. We have taken a dual approach for this study 1) Enzymatic screening of 12 substrates against the OAhyd enzyme library and 2) Design and synthesis of a “target molecule” mimicking the native substrate of the enzyme and subsequently screen it against the library. Despite the enzyme having a hydrophobic active site, at present, we expect silanol formation due to the possibility of nucleophilic attack by hydroxide (from the buffer environment) on the silylium ion. Thus, we identified Silanol using gas chromatography–mass

spectrometry (GC-MS), to verify the activity of the enzymes and find the most potent enzyme for this reaction. Further exploration of silylium ion stabilization within the enzyme's active site, prior to nucleophilic attack, can open multiple possibilities in organic transformations since silylium ions are known to act as potential reactive lewis acid catalysts.

Estimating stationary distributions of Hopf algebra Markov chains in Merge

David Skigin

Mentor: Matilde Marcolli

After Noam Chomsky proposed his Minimalist thesis on language, Professor Marcolli developed an extensive mathematical treatment of the subject, firmly showing how some of the core computational structures in syntax can be interpreted through algebraic structures: specifically, Marcolli's construction relies on Hopf algebras, which elegantly capture the way sentences are combined and recombined through the Merge operator. An outstanding question in this field is the statistical action of Merge, namely if it is possible to find syntactic structures more favored in stationary distributions. Although this problem remains unsolved, I present a few potential approaches I developed over the summer to tackle this.

Improving the modeling of cement carbonation and carbon uptake

Logan A. Smith-Perkins

Mentors: Melany L. Hunt and Ricardo A. Hernandez

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 CO₂. The current estimate of the mass of CO₂ that can be absorbed by cement is 40-50% of the CO₂ 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 CO₂ concentrations.

By employing a finite element method (FEM) using COMSOL Multiphysics we simulate the CO₂ diffusion throughout a block cement and incorporate the carbonation reactions that are missing in the approximate model. This improved FEM 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.

Designing cryogenic liquid fuel flow and high pressure nitrogen gas pressure control valves for use in rocketry throttling applications

Lucas A. Smith

Mentor: Morteza Gharib

The PARSEC team at Caltech is developing a self-landing rocket system for the intercollegiate Lander Challenge. Thus, we must have precise control over the throttling of the engine's thrust. This project centers around the design and development of two critical throttling systems. The first controls the flow of liquid fuel provided to the engine. This system must be able to withstand volatile conditions such as high vibration and cryogenic temperatures while providing precise and responsive control over the fuel mass flow rate and downstream pressure. The second system is responsible for the pressurization of the fuel tanks via nitrogen gas. It must be capable of maintaining a constant downstream pressure while provided a variable upstream pressure (750-4000 PSI). The valves chosen were a ball valve for the liquid system and needle valve for the gas, both fitted with actuators and microcontrollers for remote, automatic control. After designing and constructing the systems, we collected data such as flow rate, upstream pressure, and downstream pressure of the valves in comparison to their position and in different conditions. Using this data we characterized the valves to predict mass flow rate of fuel and tank pressurization in order to aid tuning of the systems.

Spectral-motivated grid refinement criterion for GRMHD simulations

Sam W. Solod

Mentors: Elias R. Most, Nils Vu, and Yoonsoo Kim

Numerical simulations of astrophysical flows around compact objects such as black holes demand high accuracy in regions of sharp gradients, turbulence, and discontinuities, while also requiring computational efficiency over large domains. Adaptive mesh refinement (AMR) offers a powerful tool to achieve this balance, but the success of AMR hinges on the quality of refinement and de-refinement criteria. In this work, we explore a grid refinement strategy inspired by spectral methods, applying a criterion based on modal coefficients, originally developed for discontinuous Galerkin codes, to a finite volume framework. We implement this method in the GPU-parallelized code AthenaK and evaluate its effectiveness on a number of problems that test the numerical accuracy and efficiency of the method. We find that the criterion can effectively track discontinuities without over refining smooth regions while nicely coarsening grid structure over smooth regions. This approach has promising applications to general relativistic magneto-hydrodynamic (GRMHD) simulations of accretion flows and jet launching, where capturing small scale physics as well as computational efficiency is crucial. This work takes a step towards a physically informed refinement strategy that could enable faster and more accurate simulations of extreme astrophysical phenomena.

Terahertz time-domain investigation of molecular quantum bits

Alan Song

Mentors: Geoffrey A. Blake and Jax Dallas

Molecular quantum bits (qubits) that store quantum information on an $S=1/2$ or $S=1$ metal center are tunable, precise, and customizable (Bayliss et. al. 2020). Extending the spin coherence time (T_m) would therefore increase the utility of the qubit and make applications such as quantum computing more accessible. Near room temperature, T_m is limited by the vibration-mediated spin relaxation time (T_1), a timescale the Hadt group hypothesizes is controlled by the thermal population of totally symmetric vibrational modes (Kazmierczak et. al. 2024).

Terahertz (THz) time-domain spectroscopy provides a direct probe into the dynamics of these vibrational energy states. A qubit's response to a broadband femtosecond pulse in the 0-8THz range can be tracked with an 800nm probe pulse in conjunction with a gallium phosphide (GaP) detector crystal. Cyclic olefin copolymer (TOPAS) and high-density polyethylene (HDPE) have good transparency in this frequency domain and can be used as sample media, either as solid solutions of qubit in polymer or pressed pellet mixes.

With THz scans of the qubit targets $\text{Cu}(\text{acac})_2$, $\text{Cu}(\text{TMHD})_2$, and CuTPP , we hope to demonstrate the population of thermally accessible vibrational modes in these molecules. Computational density functional theory (DFT) calculations indicate which of these vibrational modes are totally symmetric. Correlating the spectroscopic data with the known T_m of these qubits over this temperature range will confirm or deny the Hadt group's hypothesis, allowing for more informed and targeted molecular qubit synthesis in the future.

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Neural cellular automata for pattern generalization and seed-indexed pattern formation

Samuel A. Sosa

Mentors: Erik Winfree and Inhoo Lee

Neural Cellular Automata (NCA) are models that grow complex patterns using local update rules and decentralized computation. I reimplemented a widely used NCA framework (Mordvintsev, 2020) in JAX, building a differentiable training pipeline with custom update loops and randomization handled through JAX's key system. The result is a clean, flexible setup for exploring NCA behavior and modifying the model's core components. I'm investigating whether a single NCA can reproduce multiple patterns using shared weights, either by training sequentially on different targets or by using binary-indexed seeds to grow distinct outputs. Early results are promising, and these experiments highlight how NCAs might simulate features of morphogenesis—the process by which cells self-organize into tissues and organs. Shared-weight models echo how a single genome supports diverse outcomes depending on context, while seed-based switching resembles how specific cues can trigger different developmental paths. This work may inform future tools that let researchers prototype and explore developmental processes *in silico*, offering an interpretable, lightweight framework for studying self-organization in both biological and artificial systems.

Evaluating the feasibility of external tracers of aurora contamination in SPHEREx data

Dallin E. Soukup

Mentors: James J. Bock and Chi Nguyen

The recently launched Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) surveys the entire sky in 0.75-5 micron near-infrared light. While treatments of known foreground contaminations already exist in the science analysis pipeline, aurora is an unexpected source requiring added correction steps. This project aims to find a tracer to accurately validate the aurora brightness measured by the new data reduction. Two potential tracers were considered: 1) high-energy particle flux from the Geostationary Operational Environmental Satellites (GOES) and 2) simulated flux from the Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting Prime (Ovation Prime/OP). These data sets were evaluated against SPHEREx measurement of aurora brightness. First, GOES data was obtained from the National Centers for Environmental Information server. Next, the SPHEREx and GOES data were matched by timestamp and overplotted. Small correlations were found for certain energy channels, but often only after a time delay was applied, suggesting that GOES is not an effective tracer. OP has greater potential because it directly predicts aurora power representing any location at any given timestamp, therefore better matching SPHEREx observations. The OP simulation will be further refined and analyzed as a tracer in future works.

Engineering and analysis of guayule latex-algae biocomposites for sustainable material applications

Emily A. Stanton

Mentors: Chiara Daraio and Siddharth Premnath

To prevent plastic pollution and the waste generated through current biocomposite processing, we have developed a new type of biocomposite out of guayule latex and algae. We hypothesize that increasing guayule-latex volume fraction will enhance cyclic resilience while sacrificing stiffness. We compressed samples containing 0-15 wt% guayule latex with a carver press at 8 tons and tested these samples for cyclic loading and compression modulus. We also designed and manufactured a compression mold to create three-point bend test samples. We have analyzed the effect of volume fraction of latex on the cyclic loading/unloading cyclic behavior of these biocomposites and found that as latex concentrations increase by 5 wt%, the peak stresses of each sample decrease by approximately .5 MPa. The residual strain increases at a faster rate over 9 cycles as the guayule latex increases up to 10%. We will run compression tests to determine the compression modulus, the yield strength, the failure modes, and the strain at those failure modes of the biocomposites. We will also use the samples from the mold we created to perform the 3 point bend test and conduct a systematic comparison of latex-algae composites manufactured by high-pressure compression molding versus 3D printing.

Analyzing pulsar anomalies for compact binary searches

Sage H. Stanton

Mentors: Susan V. Gardner and Nick R. Hutzler

Pulsars are neutron stars where we detect pulses of radiation. These are constantly emitted cones focused by the strong magnetic field caused by the neutron stars' rapid rotation, so that we see them as pulses instead of as constant emissions. While not all pulsars emit regular pulses, those that do can be used to probe new physics theories and facilitate searches for new types of dark matter and investigations into the structure of the pulsar itself. This project aims to determine specific effects on a pulsar from being in a binary with a black hole that might make such a binary more easily discoverable. One particular focus is the determination of the modifications of the orbit from the tidal flexing of a neutron star and other sources of energy loss. Working in conjunction with other parts of the project focusing on the spin down variations in ordinary pulsars and the effects from different black hole environments helps create the larger context for the analysis. We hope to later be able to use these results to facilitate the discovery of a pulsar black hole binary utilizing the data from the upcoming Square Kilometer Array and the Caltech Deep Space Radio Array.

Laboratory characterization of Snowball Earth-analog cryoconites

Elin A. Stenmark

Mentors: Robin Wordsworth, Heather A. Knutson, and Charlotte Minsky

Snowball Earth events were rare globally glaciated states in Earth's climate history. At least two such events – the Sturtian and Marinoan glaciations – occurred during the Neoproterozoic era, after the evolution of eukaryotic diversity. The fossil record shows that microbial diversity survived the Snowballs, while geologic evidence for post-Snowball oxygenation points to sustained primary production. However, explaining how life survived the Snowballs is a challenge: kilometer-thick ice sheets prevented Solar radiation from reaching subglacial habitats and halted the weathering processes that supply essential nutrients to the biosphere. Cryoconites – supraglacial meltwater pools supplied by nutrient-rich dust – may have provided a habitat for survival of photoautotrophs during Snowballs. In this work, we perform the first-ever experimental analog study to physically characterize cryoconite holes under controlled conditions. We establish a protocol for simulating cryoconite formation by using a solar simulator tuned to Neoproterozoic-like solar fluxes to irradiate basalt-covered ice. We use a thermocouple array to measure 3D heat distribution, and record cryoconite depth and diameter, at steady state. Future work includes simulating a 24-hour day-night freezing cycle and introducing biological cultures to assess cryoconite productivity. These experiments lay the groundwork for assessing the potential of cryoconites as viable microbial habitats during Snowball glaciations.

A reaction network for probing strangeness equilibration in neutron star mergers

Melvin Storbacka

Mentors: Elias R. Most and Jiaxi Wu

One of the main goals of gravitational astrophysics is to constrain the equation of state (EoS) of neutron stars. For EoSs including strange matter, the high densities and temperatures during a neutron-star merger are associated with the emergence of large amounts of strange matter. However, depending on the equilibration timescale of strange matter, the merger could drive the system out of equilibrium, which in turn could affect the dynamics of the merger. Therefore, quantifying equilibration timescales is important for determining whether future merger simulations should include strangeness out-of-equilibrium effects.

To this end, we develop a reaction network for solving the time evolution of the number densities of an arbitrary number of included particle species and reactions. The network couples to a chiral mean field EoS and can be used with time-dependent trajectories from astrophysical simulations. This network will enable post-processing of neutron-star merger simulations for analysis of strange equilibration.

Pion form factor from a three-point function in lattice quantum chromodynamics

John M. Sullivan

Mentors: Frank Lee and Mark B. Wise

Quantum chromodynamics (QCD) is the field theory which describes the strong interaction between quarks. Lattice QCD is a method of solving equations in quantum chromodynamics by formulating space and time as a lattice of points. We aim to verify that a three-point function in lattice QCD can be used to calculate the form factor of a pion. The form factor is a function of momentum transfer that describes how the distribution of charge within a particle changes as the energy level of the particle changes. We used the Perlmutter supercomputer at NERSC as the platform for the computation of our three-point function. We will extract the form factor from our data with a covariance fitting function called a jackknife function that accounts for correlation and error propagation. We used Mathematica to perform our data analysis. Previous work in the field has utilized four-point functions to calculate important quantities. Computational evaluation of four-point functions is time- and energy-intensive. By demonstrating that a three-point function can determine the pion form factor, we aim to present a more efficient alternative to the current standard computational method.

***In vitro* translation and aminoacylation of Bpa-tRNA(UAG) for cotranslational incorporation of a site-specific photo-crosslinker**

Marton Szabo

Mentors: Rebecca M. Voorhees and Lena Boegeholz

The quality control of multisubunit membrane protein complexes in the endoplasmic reticulum (ER) requires coordinated folding, membrane insertion, and subunit assembly. In the absence of interaction partners, orphan subunits could be targeted for degradation, a process linked to the ER-located protein TXNDC15, hitherto identified through experiments conducted at the Voorhees group. TXNDC15 was established as a factor interacting with MARCH6 ubiquitin ligase, promoting degradation of certain ER-related membrane proteins, including GET1, a protein responsible for the post-translational delivery of tail-anchored proteins. To validate physical interactions between TXNDC15, MARCH6, and the orphan subunit GET1, a system is being developed for site-specific incorporation of the UV-inducible crosslinker, p-benzoyl-L-phenylalanine (Bpa). This project establishes an optimized *in vitro* transcription system based on purified T7 RNA polymerase for producing full-length Bpa-tRNA(UAG), and an *in vitro* translation platform for the incorporation of the aminoacylated tRNA by the purified Bpa-tRNA synthetase, ultimately incorporating the non-canonical amino acid into the target protein GET1 at multiple probing sites. Preliminary results confirm the success of the IVT platform and the incorporation of Bpa into GET1 constructs at defined sites. This experimental pipeline could support targeted crosslinking experiments to map transient ER protein interactions site specifically during membrane protein quality control.

The neuro-immune axis in the dural meninges and its role in migraine

Amina Tajammal

Mentors: Diane Mathis, William M. Clemons, Jr., and Miguel Marin Rodero

Migraines affect over 12% of the global population and are the most common neurological disorder in humans. Most existing therapies target the symptoms of migraines and focus on prevention; however, the exact mechanism by which they occur and progress is not well-understood. Migraines are strongly linked to the meninges, specifically the dura mater, which hosts diverse immune populations. Mouse models have established that regulatory T (Treg) cells play a crucial role in maintaining meningeal homeostasis; ablating them has been shown to cause neurodegenerative-like effects, including impaired neurogenesis and memory impairment. In terms of treatment, research and subsequent clinical trials have demonstrated that CGRP (calcitonin gene-related peptide) inhibitors are highly effective at treating the immediate symptoms of migraines. CGRP is a neuropeptide released by TRPV1+ (transient receptor potential vanilloid 1) neurons in the meninges and plays a critical role in the progression of migraines. This project will use immunohistochemistry (IHC) to study the neuro-immune axis by staining Tregs, CGRP, and nerves in the meninges. Subsequent quantitative analyses have been performed to investigate possible cross-talk between Tregs and CGRP+ and CGRP- nerves by analyzing the microscopic proximity of Tregs to these nerves. Analyses thus far have revealed greater proximity between Tregs and CGRP+ nerves, as opposed to CGRP- nerves. Further

experiments and data analysis are required to verify this, which will be conducted by staining mouse meninges that have been ablated for Tregs. These will subsequently be compared for differences in innervation, branching, and nerve density. This will provide conclusive evidence on how the neuron-immune axis in the meninges is involved in migraines and help elucidate its mechanism.

Dissecting root thermomemory: Heat stress priming and elongation dynamics in *Arabidopsis* through automated phenotyping

Katherine W. Tam

Mentors: Trevor M. Nolan and Xiaohui Li

With wildfires and increased temperatures damaging natural and agricultural environments, the need to understand and enhance plants' abilities to survive and flourish upon exposure to extreme heat is crucial through the study of root elongation dynamics in *Arabidopsis thaliana* upon heat stress and priming. After the exposure to a single heat event, the plant establishes a thermomemory which allows them to survive a more extreme heat stress event and to recover in the days after. The effects of a variation in temperature and duration of these exposures in the context of root dynamics are quantified and assembled into a phenotype x treatment matrix through automated phenotyping. Automated data gathering is implemented through Smart Plate Imaging Robots (SPIROs); the data analysis pipeline is performed through an independently developed root measurement and graphing model. Preliminary results show favorable root elongation during recovery after priming at 32°C and stressing at 42°C with substantial characterization within this temperature range. Additionally, intriguing yet ambiguous phenotypes have emerged which demonstrate the effects of extreme heat onto root systems and the amazing paths for recovery. This study establishes the experimental methodologies and baseline characterizations for future genetic dissections of root thermomemory.

Adaptive modeling and exogenous Li support for neuromotor-impaired musculoskeletal models

Yingyin Tan

Mentors: Yanan Sui and Gunter Niemeyer

We present an adaptive, simulation-driven framework for designing and optimizing gait-assistive exoskeletons for individuals with neuromotor impairments. Stroke-related gait deficits are modeled in the MS-Human-700 musculoskeletal framework by scaling muscle activations to reflect neural signal degradation and validated against clinical gait data. Four one-dimensional actuators are placed at key body points, and the Dynamical Synergistic Representation with Soft Actor-Critic (DynSyn-SAC) algorithm identifies optimal magnitudes and directions of assistance forces across the gait cycle. The optimized force patterns aid the redesign of the single-motor "Exohip" exoskeleton developed by the Ren Group. Using the MPC² model-based control framework, we test proposed mechanical changes in near real time, ensuring new designs deliver the simulated assistance benefits while respecting mechanical constraints. This approach supports the creation of more efficient and personalized exoskeletons for diverse neuromusculoskeletal impairments without requiring structural redesign.

Integrated entangled photon pair source on thin-film lithium niobate

Adelynn S. Tang

Mentors: Alireza Marandi, Rithvik Ramesh, and Thomas Zacharias

Integrated photonics has become a leading platform for quantum information processing (QIP) systems on a single chip. It provides unique advantages, including room-temperature operation, low loss, scalability, and compatibility with existing nanofabrication techniques. The development of quantum light sources, such as entangled photon pairs, is essential for achieving large-scale quantum networks and applications like quantum sensing, metrology, communication, and computation. While significant progress has been made in developing on-chip entangled photon pair sources, most implementations still rely on bulky, table-top lasers to provide pump, preventing scalability and accessibility of QIP. This project demonstrates a compact, integrated entangled photon pair source pumped by a small diode laser. Utilizing the strong optical nonlinearities of the thin-film lithium niobate (TFLN) platform, biphotons can be generated on-chip from spontaneous parametric down-conversion (SPDC). The diode laser is butt-coupled to a TFLN waveguide-based SPDC source to

produce entangled photon pairs. The biphoton quality was characterized through its coincidence-to-accidental ratio, pair generation rate, and single photon behavior. This demonstration enables a practical path toward scalable QIP.

Developing photon reconstruction algorithm for the muon collider

Alyna X. Tang

Mentors: Harvey B. Newman and Kiley E. Kennedy

The discovery of the Higgs boson in 2012 confirmed the mechanism of spontaneous symmetry breaking in the Standard Model, but the detailed shape of the Higgs potential—particularly near its minimum—remains unknown, motivating the need for a future high-energy collider. One leading candidate is the muon collider, which offers clean collisions at multi-TeV energies. However, muons are unstable and decay into electrons and positrons that initiate electromagnetic showers upon interacting with collider materials, generating severe beam-induced background (BIB) that floods detectors with out-of-time noise. In this challenging environment, precision photon reconstruction is essential for measuring key Higgs decay channels and enabling searches for new physics involving photon-rich final states. Using simulated photon-gun samples with and without BIB, we analyzed energy deposition in the electromagnetic calorimeter by studying the longitudinal and transverse development of electromagnetic showers, as well as hit timing distributions across calorimeter cells from both signal and BIB. Based on these insights, we developed a photon reconstruction algorithm designed for the muon collider environment, combining spatial clustering, timing cuts, and additional mitigation strategies to suppress BIB and enhance reconstruction performance.

Cold gas thruster design, analysis, manufacturing, and testing for roll control of a self landing rocket

Miigwan D. Tanner-Wostrel

Mentors: Morteza Gharib and Jack N. Caldwell

The goal of this project is to build a cold gas roll control thruster for a rocket in development at PARSEC. This is necessary because the gimbaling of the rocket's main engine will control the rocket's attitude, with exception of roll. The propellant in use is nitrogen tapped from the main propellant pressurizing tank. Using isentropic flow equations, nozzle geometry is determined and a minimum length nozzle contour is generated in Matlab using the method of characteristics. Nozzles with JIC connections are 3d-printed from acrylic and a nozzle bench test rig is built to determine nozzle performances. Informed by bench test results, a thruster system is designed for use on the rocket and metal nozzles are 3d-printed. Beyond this project, the final thruster system design will be tested, and if generated torque is too little or system mass is too great, the design will be iterated upon.

Extending frequency-based spatiotemporal reduction techniques to periodic systems

Lindsay N. Taylor

Mentors: Tim E. Colonius and Caroline Cardinale

Model reduction techniques have traditionally focused on spatial representations, but recent advancements have explored the use of spatiotemporal bases to improve the accuracy of reduced-order models. The proper orthogonal decomposition (POD) method, which computes modes of the state matrix in the spatial domain, has been the standard approach. However, it can suffer from reduced accuracy when only a limited number of modes are retained. In contrast, spectral proper orthogonal decomposition (SPOD) offers a more efficient framework by incorporating Fourier-transformed POD modes of each trajectory in the state space, improving the representation of the system's dynamics. This approach involves solving the governing partial differential equation (PDE) algebraically for the linear term, while the nonlinear term is approximated using the discrete empirical interpolation method (DEIM). The reduction process consists of two key phases: an offline stage to approximate the necessary operators, and an online stage that performs the projection. When compared to traditional POD-based methods, SPOD demonstrates superior accuracy with respect to the number of retained modes and computational time. However, a limitation of SPOD is its

assumption of periodicity, which may cause spectral leakage when applied to nonperiodic systems. To assess the technique's performance and limitations, we extend the SPOD framework to the Kuramoto-Sivashinsky equation, a well-known chaotic system that exhibits both periodic and nonperiodic behavior across different bifurcations.

Gibbs conditioning principles for Markovian discrete-time interacting particle systems on regular graphs

Ritvik S. Teegavarapu

Mentors: Kavita Ramanan, Franca Hoffmann, I-Hsun Chen, and Sarath Yasodharan

This project investigates Gibbs conditioning principles for the empirical neighborhood measure of discrete-time Markovian interacting particle systems evolving on regular graphs. The dynamics of each vertex state are governed by local Markov transition kernels acting on the vertex neighborhood, leading to dependence structures that preclude direct application of classical tools. We express the Gibbs conditioning principle dynamic LDP for the sequence of empirical measures, identifying a rate function expressed as a relative entropy correction by the log-likelihood ratio of interacting and non-interacting systems. This rate function characterizes rare fluctuations away from the law of large numbers limit, known as the local field equation (LFE). For the one-step case, we formulate and solve a variational problem subject to co-variation constraints, yielding an explicit form of the Gibbs conditioning principle. The resulting optimizer exhibits a modified Markov kernel with exponential tilts determined by Lagrange multipliers enforcing marginal consistency. We further analyze the case of 2-regular graphs, where the limiting graph is the integer lattice, and the LFE admits tractable structure, providing insights into the most likely system evolution under rare event conditioning.

Precision light control and tracking for high-resolution infrared spectroscopy at the diffraction limit with Keck-HISPEC

Yann C. Terrien

Mentors: Dimitri P. Mawet, Ashley Baker, and Nemanja Jovanovic

The High-resolution Infrared SPectrograph for Exoplanet Characterization (HISPEC) is a future instrument for the Keck II telescope, designed to perform precise observations of exoplanets by capturing infrared light at extremely high spectral resolution. A critical subsystem of this instrument is the front-end instrument, which prepares and stabilizes the incoming starlight before it reaches the spectrographs. The front-end system combines real-time beam alignment, image stabilization, and atmospheric dispersion correction to ensure efficient light transmission. It splits the light into two paths optimized for different infrared bands and actively maintains the alignment using a dedicated tracking camera and fast correction optics. To limit thermal noise and improve sensitivity, the tracking detector and associated optics are cryogenically cooled. Recent work has concentrated on optimizing alignment and validating optical performance.

The design was finalized in 2024, and the instrument is now undergoing full-scale development, with initial operations anticipated in 2026.

Improving EV aggregate flexibility with end-to-end learning

Apoorva V. Thanvantri

Mentors: Adam C. Wierman, Christopher T. Yeh, and Nicolas Christianson

As the population of electric vehicles (EVs) rises, meeting their charging demand efficiently while continuing to ensure reliable power grid operation has become increasingly challenging. To facilitate this, aggregators – entities that pool energy resources into one market participant – are tasked with combining the constraints encoding the charging flexibility of each EV into an aggregate flexibility set. Computing this set exactly is intractable, motivating the use of approximation methods. It is vital that the approximation is reliable, meaning infeasible power schedules must not be included in the approximate set, since this can lead to grid instability. Current approximation methods either do not provide this guarantee, or they come at the cost of overly conservative representations that may neglect regions of the true aggregate set important to downstream performance. To push the reliability vs. performance pareto frontier, we develop a novel approach by learning an inner

approximation of the aggregate flexibility set via Input Convex Neural Networks (ICNNs). We apply this model to a variety of objectives, including electricity cost minimization. We evaluate our method against several other approximations on real-world load data and compare performance on downstream tasks while guaranteeing reliability.

Experimental characterization of ice spheres formed through fluid fragmentation and flash freezing

Jordan L. Threat

Mentors: Xiaojing Fu and Nathan Jones

This project aims to optimize the process for creating ice spheres necessary to assemble laboratory snowpacks used in snow hydrology research. We produce ice spheres between 0.5 and 2 millimeters in diameter by flash freezing liquid droplets. To produce liquid droplets, we leverage the Rayleigh-Plateau instability of a water jet introduced by a syringe, which breaks into droplets in the air due to surface tension. These droplets then fall into a bath of liquid nitrogen below, where they freeze on impact into spherical ice and are later collected for further testing and analysis. The height and flow rate of the water jet, as well as the diameter of the syringe tip, are systematically varied in search of the desired droplet size range, which is determined by sieving the ice particles. The eventual goal of the project is to use the ice beads to perform imbibition experiments to measure the capillary retention curve of an ice bead pack. This will help to determine the hydraulic property of our laboratory snowpacks.

Developing a spike S2 domain-based pan-coronavirus vaccine

Emma L. Titus

Mentors: Pamela J. Bjorkman and Chengcheng Fan

Many SARS-CoV-2 and MERS neutralizing antibodies target the spike protein receptor-binding domain, which is subject to frequent mutations, necessitating continual vaccine updates. To overcome this limitation, we are developing a vaccine designed to elicit antibodies that recognize the more conserved S2 domain of the spike protein thereby achieving broader protection. From mice that were immunized with our vaccine candidate, we isolated sequences for over 200 monoclonal antibodies (mAbs) and cloned 27 into expression plasmids. We first evaluated the binding of these 27 mAbs using transfection supernatants to SARS-CoV-2 and MERS spike proteins and S2 domains using an Enzyme-Linked Immunosorbent Assay (ELISA) and found that 19 mAbs showed binding to one or more of the SARS-CoV-2 or MERS constructs. These 19 mAbs were expressed and purified at a larger scale and tested for binding by ELISA at different concentrations. In this ELISA, 8 mAbs showed strong binding to SARS-CoV-2 spike and S2 domain, 5 mAbs showed strong binding to MERS spike and S2 domain, the remaining mAbs showed weak or no binding. Cross-reactive mAbs with strong binding are promising candidates for neutralization and may also target the conserved regions of the spike protein, which will be further studied.

Analyzing the asymptotic behavior of the integrality gap for the Goemans-Linial SDP relaxation of the Uniform Sparsest Cut

Grace H. To

Mentor: Seung-Yeon Ryoo

The Sparsest Cut Problem is a fundamental graph cut problem that aims to find a cut (a two-part partition) of a graph with uniform demands between pairs of vertices such that the edge capacities per demand cut is minimized. The Goemans-Linial SDP relaxation gives the best known approximation ratio ρ_{IG} for this problem, and its value directly corresponds to how well metric spaces embed into ℓ_1 ; in the special case of uniform demands, ρ_{IGunif} corresponds to average distortions of metric spaces into ℓ_1 . It was recently proven that $\rho_{IG} \asymp \sqrt{\log n}$. However, the behavior of the integrality gap for the uniform case ρ_{IGunif} is still not well understood. Kane and Meka computationally prove a better lower bound for ρ_{IGunif} of $\exp(c\sqrt{\log \log n})$ for some universal constant $c > 0$, and we aim to find an approach using metric embeddings to prove an equivalent lower bound.

Developing a standardized multi-domain multi-modal live-cell imaging dataset and pipeline for building a generalist cell tracking deep learning model

Oyinade O. Togun

Mentor: David A. Van Valen

The dynamic behavior of living cells, revealed through live-cell microscopy, is fundamental to biological discovery. However, extracting quantifiable insights is hampered by the limited generalizability of existing segmentation and tracking models across diverse biological domains and imaging modalities. This work addresses this challenge by establishing a Python-based pipeline and standardizing multi-domain, multi-modal live-cell imaging datasets for building a generalist cell tracking deep learning model.

Our pipeline systematically processes heterogeneous live-cell imaging data, converting it into a uniform 6-dimensional (P, T, H, W, Z, C) Zarr format. The recent proliferation of publicly available live-cell imaging datasets has provided a crucial resource for this work, offering a rich variety of biological domains and imaging modalities. This framework incorporates image denoising and segmentation using the Cellpose deep learning algorithm. Key technical methods include the development of a memory-safe, frame-by-frame processing loop to prevent crashes on large datasets and explicit parameterization to avoid unintended image resizing and preserve data integrity.

This work successfully produced a comprehensive and quality-controlled dataset of cell segmentation of the 22 distinct live-cell imaging sources. Our pipeline consistently generated high-quality segmentation masks for a wide range of cell types and imaging modalities. The resulting dataset is fully processed and ready for the next phase of quantitative analysis, including feature extraction and training a generalist cell tracking model.

The pipeline provides the essential foundational infrastructure to overcome key challenges in multi-modal bioimage analysis. By generating a standardized dataset of segmented and characterized cellular objects, our work serves as a foundation that enables the development of a powerful, generalist deep learning model capable of automatically analyzing cellular dynamics across diverse biological systems. Future work will focus on integrating a tracking module to produce a final, comprehensive dataset of tracked ground truth objects.

Polymer synthesis in *Comamonas testosteroni* KF-1 under nitrogen depletion

Madison Elle C. Tongco

Mentors: Ludmilla Aristilde, Jared R. Leadbetter, and Xinyu Chen

Comamonas testosteroni, a bacterium isolated from wastewater, is known for its ability to degrade plastic-related compounds, as well as its ability to produce polyhydroxyalkanoates (PHAs) as valuable biopolymers with potential applications in plastic waste valorization. We grew *C. testosteroni* on nitrogen-limited media with gluconate as the source of carbon and analyzed PHA production via confocal microscopy and flow cytometry. We found that the stationary phase of nitrogen-limited cultures produced the highest levels of PHAs. We quantified PHA monomers along with possible glycogen synthesis via liquid chromatography-mass spectroscopy (LC-MS). We obtained only medium-chain-length PHAs, with no short-chain-length PHAs and negligible levels of glycogen. Our findings thus illustrate the preferential production of selective polymers in gluconate-grown *C. testosteroni* under nitrogen-limited conditions.

Disorder-induced gapping of the soft electronuclear mode in an Ising magnet

Josephine A. Tsai

Mentors: Thomas F. Rosenbaum and Daniel Silevitch

We characterize the softening of the lowest-energy collective electronuclear mode near the ferromagnetic-paramagnetic quantum phase transition in $\text{LiHo}_{0.99}\text{Y}_{0.01}\text{F}_4$, a weakly disordered dipolar Ising magnet. We aim to understand how disorder affects quantum criticality and the behavior of low-energy collective excitations. A magnetic field transverse to the Ising axis drives the phase transition via quantum tunneling. In order to map the soft mode, we perform microwave spectroscopy in the zero-temperature limit using a loop-gap resonator, and track peaks in the inverse resonator quality factor arising from resonant absorption of the soft mode. In pure LiHoF_4 , the lowest-energy electronuclear mode softens continuously to zero as the critical point is approached from both the ferromagnetic and paramagnetic phases. In strongly disordered $\text{LiHo}_{0.65}\text{Y}_{0.35}\text{F}_4$, the soft mode is broadened and observed only in the paramagnetic regime; in the ferromagnet, domain wall scattering and disorder-induced decoherence suppress the collective excitation. By contrast, in weakly disordered $\text{LiHo}_{0.99}\text{Y}_{0.01}\text{F}_4$, the soft mode is clearly resolved in both the ferromagnetic and paramagnetic phases, and the mode softening exhibits a qualitatively sharper profile around the quantum critical point.

Episomal DNA isolation for oncogenic virus detection and viral vector discovery

Emily Tu

Mentors: Rustem F. Ismagilov, Christopher Neimeth, and Natalie Wu-Woods

Abstract withheld from publication at mentor's request.

Decompression of the bacteriophage MS2's genome utilizing cell-free systems

Grace R. Tuhabonye

Mentors: William M. Clemons, Jr., and Yan Zhang

The motivation of this project comes from the rise of multidrug-resistant bacteria, which can be dangerous when trying to fight bacterial diseases. Bacteriophages, bacterial viruses, can serve as an alternative to antibiotics because they evolve with bacteria and are highly specific. However, most phages have compressed genomes, where many genes overlap, making them difficult to engineer. The objective of this project is to decompress the MS2 genome to enable more efficient genome editing. Decompressed MS2 is synthesized using cell-free TX-TL systems because these reactions maximize product formation without relying on living cells. The synthesized phages are analyzed with plaque assays to visually confirm bacterial lysis and with reverse transcriptase-polymerase chain reaction (RT-PCR) to amplify and sequence MS2 DNA to verify the decompressed genomic structure. Functional phages were observed once in plaque assays using various concentrations of Mg, but no DNA product matched the expected MS2 RNA length. Future steps are to synthesize phages with 4 mM Mg to confirm plaque formation and optimize RT-PCR protocols to successfully amplify MS2 at the correct length.

Enhancing AutoSamp with efficient NUFFT-based joint optimization of k-space sampling and image reconstruction for accelerated MRI

Idil A. Turasi

Mentors: Shreyas S. Vasanawala and Yisong Yue

AutoSamp is a deep learning framework that jointly optimizes k-space sampling and image reconstruction for accelerated MRI. While effective, it suffers from slow convergence under high acceleration rates. In this project, we aimed to enhance AutoSamp by integrating a more efficient Non-Uniform Fast Fourier Transform (NUFFT) pipeline using a fast Jacobian approximation to improve memory usage and gradient stability during sampling optimization. Since the original Jacobian approximation was implemented in PyTorch, a full reimplementation in TensorFlow was required for compatibility with the AutoSamp framework. I reimplemented the NUFFT operators with sensitivity encoding (SENSE) and incorporated Jacobian-based components for backpropagation. The new pipeline is being evaluated on the Stanford 3D FSE Knees dataset. While training runs successfully, the model currently shows overfitting with suboptimal validation and reconstruction performance. This

may be due to the lack of optimized NUFFT support in TensorFlow in the current implementation, unlike the PyTorch-based NuSense module used in the original study. Future work will focus on integrating the TensorFlow MRI library to improve NUFFT performance, enable efficient Jacobian computation, and fine-tune regularization to enhance generalization.

Beyond-Landau phase transitions in D4 non-Abelian topological order

Avinash Vadali

Mentors: Jason F. Alicea and Pablo Sala

Noise is an ever-present factor within all physical systems, yet its effect on the ordering of quantum matter remains poorly understood. In particular, the classification of topological phase transitions induced by Bose condensation remains an open question. This work provides a comprehensive study of the phase diagram of D4 non-Abelian topological order under the proliferation of various species of anyons. We identify quantum phase transitions via classical Monte Carlo simulations and study the resulting phases through effective field theories. Using classical order parameters, we implement a general framework for studying beyond-Landau phase transitions induced by proliferation of anyons with non-trivial mutual statistics. The understanding of phases of D4 developed in this paper can be more generally applied to transitions in numerous 2 + 1D topological orders. Given that D4 is the first non-Abelian topological order to be physically realized, a complete phase diagram for D4 will be instrumental in an accurate assessment of the system's promise as a topological quantum memory.

Anomaly detection in astrophysical time series using recurrence plots

Mariana Vale Taveira

Mentors: Matthew J. Graham and Kira Nolan

Large time-domain surveys, such as the Zwicky Transient Facility (ZTF), produce extensive time series datasets that frequently include rare or unanticipated patterns of variability. Identifying such anomalies can point to new astrophysical phenomena, yet this task is complicated by the irregular sampling that characterizes many observations. In this work, we investigate recurrence plots (RPs) as a framework for representing and quantifying the dynamical structure of astrophysical time series, with the objective of enabling automated anomaly detection. We constructed a processing pipeline to generate high-resolution RPs from both synthetic and real ZTF active galactic nuclei (AGN) light curves. The synthetic set spans a range of stochastic and deterministic signal types, and is used to train a convolutional Siamese network with contrastive loss to learn a similarity metric directly from RP images. Real AGN light curves are regularized and embedded using parameters optimized through data-driven methods before RP computation. The trained network then compares pairs of RPs to build a dissimilarity matrix, from which candidate outliers can be identified. This combination of recurrence analysis and deep metric learning is designed to retain the interpretability of the RP representation while scaling to large datasets. Although developed for AGN light curves, the approach is applicable to other classes of astrophysical time series.

Analysing the contribution of strongly peraluminous granites to the marine Sr isotope record through the in situ Sr isotopic analysis of plagioclase

Georgie M. Van Dyke

Mentors: Claire Bucholz and Paolo Sanchez

This project aims to determine whether positive excursions in the marine strontium isotope record ($^{87}\text{Sr}/^{86}\text{Sr}$) can be linked to increases in weathering rates associated with major continental collisions. Rb is an incompatible element and is therefore enriched in the continental crust and depleted in the mantle, such that crustal weathering results in marine radiogenic Sr influx. Plagioclase is the dominant Sr host in most metamorphic and igneous rocks, but Rb is incompatible in its crystal structure. Continental collisions provide suitable metamorphic conditions in which radiogenic Sr is remobilised from K-rich phases of sedimentary rocks into more labile phases in strongly peraluminous granites (SPGs). One such phase is plagioclase, which is weathered more rapidly, resulting in a strong radiogenic Sr flux.

SPG rock chips from the Neoproterozoic to Mesoproterozoic were mounted and polished. Major element concentrations were determined using electron probe microanalysis (EPMA) and homogeneous grains with minimal inclusions were chosen for subsequent in situ Sr isotopic analysis by laser-ablation multicollector inductively coupled plasma tandem mass spectrometry (LA-MC-ICP-MS/MS). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were obtained from isochron intercepts and from mean data values at very low $^{87}\text{Rb}/^{86}\text{Sr}$. The data was analysed alongside the sample ages and marine $^{87}\text{Sr}/^{86}\text{Sr}$ record.

First light and characterization of the DSA-2000 test array

Shuyu W. van Kerkwijk

Mentor: Vikram Ravi

The 2000-dish Deep Synoptic Array (DSA-2000) will be a large leap forward in radio telescope instrumentation, operating as a "radio camera" that produces reliable, high-resolution images. A two-dish test array has been commissioned at Owens Valley Radio Observatory ahead of construction of the full array in Nevada. Our objective was to characterize the performance of this test array, and use it to make science measurements of dark molecular gas in the outer Galaxy. We built an end-to-end control suite that automates source tracking and data recording through a graphical interface. For tracking, we fit an on-sky-calibrated 11-parameter pointing model to translate celestial targets (right ascension and declination) into local azimuth and elevation commands for the antenna drives. For recording, we convert raw digitizer output into standard measurement sets, correcting for antenna geometry and Earth's rotation to keep signals in phase. Using this system, we successfully obtained first light from the test array. We also identified and resolved several system-level issues that will inform design decisions for the full array.

Time-dependent Schrödinger equation simulations of Floquet-driven exciton dynamics in monolayer WS_2 as a platform for carrier-envelope phase-controlled light-matter interaction

Amith Varambally

Mentors: David Hsieh and Mingyao Guo

We present time-dependent Schrödinger equation (TDSE) simulations of Floquet-driven exciton dynamics in monolayer WS_2 under mid-infrared optical driving. By modeling the optical response in the absence of carrier-envelope phase (CEP) stabilization, we recover key experimental features of the transient absorption spectrum and reveal signatures of strong-field-induced exciton resonances and sideband formation. These results establish a computational framework for probing the interplay between strong periodic driving fields and excitonic wave packet evolution in two-dimensional semiconductors. This platform enables a systematic investigation of CEP-sensitive phenomena, wherein the absolute optical phase of few-cycle pulses can induce subcycle exciton dynamics. Our approach lays the groundwork for exploring a broader class of CEP-governed light-matter interactions in solid-state systems, with potential implications for ultrafast quantum control and optoelectronic applications. Planned experimental upgrades to incorporate a CEP-stable laser will allow for direct validation of these predictions and enable quantitative comparisons between simulation and experiment.

Knowledge graph-informed predictions of multigene transcriptional profiles

Annika S. Viswesh

Mentors: Pradeep Ravikumar, Frederick D. Eberhardt, and Chandler Squires

Predicting how gene perturbations alter cellular transcriptional profiles is fundamental for understanding genetic interactions, designing combinatorial therapies, and engineering new cell states. Recent foundation models incorporate graph-based representations of genes and perturbations to improve prediction for both single and multigene cases. However, these models are limited to narrow knowledge graphs, where gene relationships are largely defined by co-expression rather than functional interactions within transcriptome pathways. Furthermore, genetic perturbations are not treated as probabilistic priors, which limits interpretability into how different perturbations interact to shape transcriptional response. The contributions of our work are threefold. First, to more accurately represent gene interactions within molecular networks, we incorporate biomedical knowledge graphs to extract information on shared reactions, pathway membership, and molecular function, and encode

these relationships through pre-trained language models. Secondly, we use a mixture-of-experts approach combined with permutation-invariant perturbation embeddings to form post-perturbation representations that distinguish between different genetic interaction patterns, making it possible to relate predicted transcriptional changes to the underlying type of interaction. Finally, we introduce a classifier-free guidance diffusion framework in place of linear cross gene decoders, allowing us to obtain predicted transcriptional profiles conditioned on post-perturbation information. We demonstrate that the diffusion component of the framework improves generalizability for both seen and unseen multigene perturbations. Evaluation of the constructed domain knowledge embeddings and mixture-of-experts modules is ongoing.

Efforts toward precise stellar characterization for Keck Planet Finder spectrographs

Veronika C. Voss

Mentors: Andrew W. Howard and Luke Handley

The accurate characterization of stellar properties (such as effective temperature, surface gravity, metallicity, and rotational velocity) is essential for understanding the structure and evolution of planetary systems. These stellar parameters influence key measurements like planetary radius, mass, and orbital dynamics. Traditionally, determining these stellar parameters requires a detailed analysis of the stellar spectrum on a system-by-system basis. The Keck Planet Finder (KPF), with its high-resolution and high signal-to-noise capabilities, presents a powerful opportunity to automate this process. Our research aims to develop an automated algorithm that can estimate stellar properties from KPF spectra by interpolating through a catalog of well-known systems. Inspired by a proven algorithm for an older generation spectrograph, our method is designed to operate efficiently across a broad range of stellar types and spectral features due to the wide bandpass and high resolution of the new instrument. Once complete, the algorithm will enable rapid, reliable characterization of stars observed by KPF. The algorithm is currently under development, and a spectral library is being constructed. We are exploring several new data reduction steps for calibrating the library, which are not yet in the standard instrument pipeline. The algorithm will be deployed on all past and future KPF observations, robustly calculating the spectral properties of thousands of stars and enhancing our understanding of at least that many planets.

x86-64 to ARM assembly language

Robert R. Walker

Mentors: Adam Blank and Ethan Ordentlich

As machine learning has become the skill of any industry applicant, programming languages such as Python, Java, and C++ dominate every computer scientist's resume. While these languages may remain industry standard and more user friendly languages, they can't interface directly with the hardware of the computer, which is a necessity for understanding the inner-workings of the machine. Because of the different way of thinking required to write efficient assembly code and its ability to interact directly with machine hardware, learning assembly can help students understand how their computers work at a much deeper level. While x86-64 has been perfectly adequate to date, its initial release date in the late 1990's brings into question if it's still the right choice. With the vast majority of new processors (including everything Apple produces) using chips that only support a newer assembly language called ARM and the decrease in learning difficulty that would result, the change to teaching ARM assembly must be made, and must be made now. By updating Caltech's Computer Systems course to the new ARM assembly language, we are better preparing our students for the future soon to come.

Multimodal modeling and prediction of neuromuscular fatigue for intelligent control during functional electrical stimulation of a murine hindlimb

Keyu Wan

Mentors: Shriya Srinivasan, John O. Dabiri, and Patrick Pariseau

Functional Electrical Stimulation (FES) has become a crucial method for restoring movement in individuals with neurological impairments. By delivering controlled electrical pulses to muscles, implanted FES systems can produce coordinated movements that mimic voluntary actions. However, the effectiveness of FES is often constrained by the onset of muscle fatigue, a phenomenon in which muscle fibers gradually lose their ability to sustain forceful contractions under repeated stimulation. This gradual decrease in force output occurs much more rapidly during FES than for natural, nerve-mediated muscle activation. The aim of this project is to investigate neuromuscular fatigue dynamics in rat hindlimb by integrating force, electromyography, and muscle length signals under controlled electrical stimulation. Experimental protocol involves implanting recording and stimulation electrodes in anesthetized rats to evoke and monitor leg muscle activity across varied stimulation waveforms and amplitudes. Experimental datasets demonstrate correspondence between physiological responses and stimulation profiles, enabling robust modeling of fatigue progression. Multimodal data were processed for eventual training of deep learning models for predictive fatigue analysis and adaptive control strategies. This work demonstrates the feasibility of integrating physiological sensing and machine learning to achieve fatigue-aware control of muscle stimulation, with potential applications in neuromuscular rehabilitation, wearable exoskeletons and neural prosthetic systems.

Swallow classification and analysis via multichannel sEMG-IMU patch

Chloe Wang

Mentors: Wei Gao and Sijie Ji

Dysphagia is a highly prevalent swallowing disorder affecting 1 in 17 adults and may lead to complications such as malnutrition, aspiration, and respiratory infection. Early detection is critical, as dysfunction may first appear as subtle coordination differences across bolus textures and volumes. We present a custom multichannel sEMG-IMU patch to noninvasively collect electrophysiological and spatial data of swallow activity. To optimize both user comfort and signal quality, the patch incorporates a thin, skin-conformal design; a 4x4 surface EMG array; and an inertial measurement unit. Participants completed a series of swallowing tasks, resulting in 10 texture-based and 5 volume-based classes. Signals were bandpass and notch filtered, and swallow windows were extracted for analysis. Spatio-temporal energy maps were generated for visualization, and thirteen features were extracted per window to train single and multi-output classification models with various base estimators and spatial configurations. Model performance was evaluated on a 80-20 train-test split. Results demonstrate bolus texture and volume can be classified with over 90% accuracy, highlighting the potential of the sEMG-IMU patch for noninvasive swallow classification.

Implementing finite element modeling in the MS-Human-700 musculoskeletal model

Ellie J. Wang

Mentors: Yanan Sui and Joel W. Burdick

The MS-Human-700 is a whole-body musculoskeletal model trained to move with reinforcement learning. This project seeks to increase the anatomical fidelity of the MS-Human-700 by applying finite element modeling (FEM), a modeling technique that simulates objects as collections of small, deformable parts. We adapt soft-body modeling strategies from the Toyota Total Human Model for Safety (a leading FEM model used for injury simulation) into the MS-Human-700 physics engine and training algorithm. This novel implementation enables body components such as extremities to move more realistically under trained muscle control while maintaining computational efficiency. By increasing the realism of movement dynamics, this approach may introduce sensorimotor experience in simulation and provide richer training data for future motor learning research.

Modular motion tokenization for high-dimensional motor control: A case study on MS-Human-700

Erica Wang

Mentors: Yanan Sui and Adam C. Wierman

Tokenization is a foundational tool in natural language and vision, enabling composable representations that scale effectively in large models, such as GPT. In current motion control literature, discrete tokenization remains largely unexplored. In this work, we propose a novel framework for the tokenization of complex motor trajectories in musculoskeletal systems, with a focus on MS-Human-700, a highly-detailed humanoid model featuring over 700 muscle actuators. Our approach leverages vector quantization techniques and byte-pair encoding to form compositional representations of full body motion. These tokenizations capture reusable structure across the control space, allowing for efficient modeling, planning, reinforcement learning in high-dimensional motor tasks.

Rigorous investigation of human baselines towards more comprehensive VQA benchmarks and robust VLMs

Olivia Y. Wang

Mentors: Pietro Perona, Katelyn Haly, and Raphaela H. Kang

The rapid growth of large Vision Language Model (VLM) capacity is largely owed to the practice of benchmarking. Vision Question Answering (VQA) benchmarks are image-text question sets which allow for a controlled environment to assess how well models can understand and reason about images and text together. Despite these intentions, the construction of these benchmarks lacks standardization and these benchmarks are frequently misapplied. Human baseline evaluation across different benchmarks are evaluated in undercontrolled varied settings, making actual human-experienced difficulty on each task unclear. While the benchmarks offer a great way to get a general sense of model performance in VQA, they do not offer any insights into how specific model architectures may be affecting the final performance. In addressing these points, we collect human evaluations on ten VQA benchmarks across 100 subjects. Evaluating the effects of question presentation order, timing, and image resolution on human evaluation compared to model evaluation, we offer a paradigm for vision scientists to follow in the future when creating new benchmarks or model architectures.

Cultivation and analysis of aquatic anaerobic oxalotrophic methanogenic microbial communities

Wendy Wang

Mentors: Jared R. Leadbetter and Yuk L. Yung

Methanogens are obligate anaerobic archaea that produce methane from their metabolism, using various substrates such as H₂ and formate to reduce CO₂ into methane. Here, we investigate the possibility of a single oxalotrophic methanogenic organism, or the characteristics of a methanogenic oxalotrophic community of organisms. Using environmental samples (termite gut and BBB pond) put into defined media, we extracted an oxalate-dependent methanogenic community and characterized its constituents using RNA-iTAG. We obtained the DNA of an unknown environmental methanogen (BPM-1) from campus and compared its growth in coculture with known and unknown methanogens (*M. hungatei* and *M. formicicum*) and oxalate degraders (*O. formigenes*). We investigated the possibility of syntrophic growth between the oxalate degrader and methanogen through OD600 measurements of their respective growth curves and identified whether oxalate is used as an electron source or as a substrate for reduction in community degradation through C13 radiolabeling. To further understand oxalotrophy, we explored novel oxalotrophic pathways such as phototrophy in pond/soil communities. By growing cultures in defined oxalate media under IR light, we identified phototrophic oxalate-dependent communities/organisms.

Blow-up scenarios in the Keller-Segel system

Zirui Wang

Mentors: Thomas Y. Hou and Xiang Qin

Blow-up phenomena are central to the study of nonlinear partial differential equations, capturing finite-time singularity formation and revealing deep links between analytic structure and dynamics. A key question is whether a solution admits a type I or type II blow-up ansatz, as this distinction governs both the qualitative behavior and the analytical approach. In many cases, the absence of an explicit blow-up profile makes determining the rate substantially more challenging.

In this work, we focus on the Keller-Segel system, including both the variant with logistic damping and the high-dimensional case. We investigate the structure of exact self-similar profiles and the possibility of type II blow-up through a combination of asymptotic analysis and high-resolution numerical simulations, providing quantitative blow-up rate estimates and insights into the stability of the underlying profiles.

Nanofabrication of metal-vacuum-metal tunnel junctions via angle deposition

Daniel Q. Wareham

Mentors: Axel Scherer and Geraldine Silva Galindo

Metal-Vacuum-Metal (MVM) diodes and triodes are a promising alternative to silicon-based Field Effect Transistors (FETs) which, for decades, have been the fundamental unit of electronics, but whose continued miniaturization now faces substantial technological hurdles. In MVM diodes (or junctions), electrons flow from an emitter to an anode either after field emission or via direct quantum tunnelling. Nearby third and fourth electrodes can be used to modulate this flow, making a transistor. In this project, we fabricated and characterised a MVM tunnel junction, doing so with a geometry which easily allows for the future creation of MVM triodes. Ytterbium(II) Fluoride, a novel inorganic self-developing e-beam resist allowing for future vacuum-only processing, was deposited on bulk silicon, onto which trenches of less than 10 nm in width were created. We then deposited metal at an angle toward the side of the trenches and stopped right before the two sides contact, leaving a 1-2 nm gap small enough to allow for tunnelling effects. We intend to confirm the success of forming an isolated junction with electron microscope voltage imaging and detect the presence of tunnelling when probing by measuring the linear I-V characteristic expected of MVM tunnel junctions.

Exploring the role of flax fiber on the structural and mechanical behavior of 3D-printed *Chlorella vulgaris* biocomposites

Katelyn S. Waugh

Mentors: Chiara Daraio and Israel Kellersztein

The long-term persistence of petroleum-based plastics in natural ecosystems creates serious environmental concerns, and even many biodegradable alternatives, such as biopolymers or wood, require ideal conditions to break down effectively. Biomass-based composites provide a renewable and biodegradable option that adapts to diverse applications. However, improving their structural reliability and mechanical performance remains an area of active research. In this SURF project, we used flax fibers, extracted from agricultural waste, to investigate their reinforcement effect on *Chlorella vulgaris* microalgae and hydroxyethyl cellulose (HEC) biocomposites. We process our materials via extrusion 3D printing at room temperature and without the use of any petrochemical components, resulting in lightweight materials with tailored properties and geometries. High fiber loadings affect the printability of the structures due to nozzle clogging and irregular extrusion. Dimensional analysis shows reduced shrinkage in the x-y plane, attributed to fiber alignment because of flow during printing. Structural analysis through scanning electron microscopy (SEM) demonstrated that the *Chlorella* cells remained intact after 3D printing processing, showing the microalgae cell resilience to high shear stress. Quasi-static three-point bending shows an improved flexural modulus of 1211 MPa, which is 25 % higher than the reference material (967 MPa), while maintaining comparable bending strength. We identify pull-out phenomena at fracture surfaces as the main mechanism of energy absorption.

These results identify flax fibers as a promising reinforcement of microalgae-based materials, providing a sustainable alternative to wood and plastics, for diverse engineering applications such as packaging, construction, or furniture.

Fourier neural operators for time dynamics of antiferromagnetic Mott insulators

Miles M. Waugh

Mentors: Anima Anandkumar and Chuwei Wang

Mott insulators exhibit complex nonlinear photoexcitation dynamics under intense optical driving, which could enable carrier multiplication beyond the Shockley–Queisser limit, making them promising candidates for next-generation solar cells. However, simulating these strongly correlated quantum systems is computationally expensive because classical integrators require fine temporal discretization to fully resolve the nonlinear dynamics. We address this challenge by employing Fourier Neural Operators (FNOs) as surrogate models to predict the time evolution of momentum distributions in optically driven Mott insulators. Our FNO model, trained using data from a fourth-order Runge-Kutta solver, exhibits an approximately 500-fold speedup while maintaining an average relative L2 test error of 0.0153 in predicting post-pulse momentum distributions over a range of system and driving parameters. These results demonstrate the ability of neural operators to serve as efficient surrogates for modeling nonequilibrium dynamics in strongly correlated systems, which could help advance our understanding and discovery of quantum materials.

Characterization of high-pressure high-temperature synthetic nanodiamond precursors

David V. Welt

Mentors: Jonathan S. Owen, Theodor Agapie, Augustin Braun, Daybis Tencio, and Johnson Dalmieda

High-pressure high-temperature (HPHT) synthesis is a promising method for growing nanodiamonds with good purity and crystallinity. However, in order to improve control over the synthesis process, the mechanism of nanodiamond growth from starting materials must be better understood. This project used mass spectrometry, 1H-NMR and DOSY spectroscopy, powder X-ray diffraction, and UV-visible absorbance and photoluminescence spectroscopy to characterize the mixtures of intermediate compounds from HPHT syntheses. Samples were run at intermediate temperatures and pressures to study the product mixtures close to the decomposition point of the starting material. Adamantane was present in some of the samples, and TiF₃ was present in all samples, supporting the loss of hydrogen fluoride as part of the reaction mechanism. The presence of adamantanol in some samples indicated that the standard sample preparation in air allows for oxygen incorporation that may impact the process of diamond growth or introduce variability between otherwise consistent samples. Additional components corresponding to broad NMR signals and high molecular weight MALDI peaks were further investigated by optical spectroscopy. Improving synthetic control via mechanistic understanding may allow us to better tailor synthetic processes to produce nanodiamonds well-suited to incorporating nitrogen vacancy centers, which are promising for applications in quantum sensing.

Building a brain cellular microscopy data portal for accelerating AI-driven segmentation and analysis in neurodegenerative diseases

Noelle Y. Wilkinson

Mentors: David A. Van Valen and Joud Mari

Understanding how neuronal morphology contributes to cognition and disease requires large-scale, standardized datasets of neuronal images. Traditional tracing methods capture only simplified skeletonized representations of neurons and lack volumetric details that are crucial for advanced analysis. Recent advances in neuronal segmentation have enabled more comprehensive representations, known as volumized masks, which preserve fine structural details of dendrites and axons, as well as their spatial organization and connectivity. These annotations are better suited for AI and machine learning based approaches to studying morphology in neurodegenerative disease contexts. However, current public data repositories remain limited in diversity, annotation type, and imaging modality, restricting reproducibility and scalability in the field. To address this gap, we are developing an open-source, cloud-based data portal of 2D and 3D neuronal microscopy images curated and annotated for segmentation applications. The portal currently includes 9 datasets with

approximately 35,000 raw images and 250,000 cells. It will feature metadata-driven search, filtering, visualization, and download capabilities through a user-friendly web application. By releasing this resource to the neuroscience community, we aim to accelerate AI-driven morphological analysis, establish new benchmarks for segmentation tasks, and promote reproducible, large-scale research at the intersection of neuroscience and machine learning.

Toward contact-aware humanoid locomotion: A modular foot sensing platform

Dylan C. Winer

Mentors: Aaron D. Ames and Adrian Boedtke Ghansah

Stable locomotion in humanoid robots requires accurate knowledge of foot-ground interaction forces, yet existing systems often lack integrated, distributed foot sensing and typically rely on flat, rigid feet that omit the heel-toe rolling found in human gait. To address this, we developed a modular sensing platform with a passive toe mechanism for a new humanoid robot in the AMBER Lab. The system integrates FlexiForce™ force-sensitive resistors (FSRs) amplified through non-inverting op-amp circuits, inertial measurement units (IMUs), and magnetic encoders. Each FSR is individually calibrated to linearly interpolate force from analog voltage output. A custom 4-layer PCB interfaces with a Teensy 4.1 microcontroller, supporting analog readout, 16 status LEDs, dual IMU input, and a PWM-based encoder for passive toe angle measurement. The standalone mechanical design includes toe and midfoot segments, torsional spring toe actuation, a waterjet-cut rubber sole, and helical insert fasteners. All components are mounted to a modular foot structure appended to the Unitree G1 humanoid for initial testing. Final integration will enable measurement of distributed ground reaction forces, segment orientations, and joint angles during walking. This modular platform offers a scalable foundation for contact-aware control to improve future humanoid locomotion and manipulation.

Refinement of cpSRP43 chaperone variants via secondary selection in a yeast model of Parkinson's disease

Callum J. Wolvers

Mentors: Shu-ou Shan and Arpit Gupta

Parkinson's disease is characterised by the pathological aggregation of alpha-synuclein into amyloid fibrils, contributing to degeneration of dopaminergic neurons. Molecular chaperones offer a promising therapeutic avenue by preventing and reversing such misfolding events. One such chaperone, the chloroplast signal recognition particle 43, has been shown to inhibit alpha-synuclein aggregation with sub-stoichiometric efficiency. Nonetheless, its activity is improvable through directed evolution in cellular models of Parkinson's disease. The Shan lab has accomplished this using a novel toxin-antitoxin model in *E. coli*, though this yielded an excessive number of evolved chaperone variants. To refine this, we conducted secondary selection on a library of successful variants using a different, yeast-based model of PD. In doing so, we selected successful variants with greater stringency, allowing more precise biochemical characterisation of increasingly promising chaperone variants.

Framing artificial intelligence in law through science fiction

Elizabeth J. Won

Mentor: Jennifer A. Jahner

Using science fiction narratives and current legal disputes and publications, this project analyzes how AI is alternately conceptualized as an autonomous agent or a mechanical tool, an extension of human intention. Each metaphor carries distinct implications for legal questions of liability and rights. Science fiction works like *Klara and the Sun* by Kazuo Ishiguro, *I, Robot* by Isaac Asimov, and stories by Philip K. Dick exemplify how metaphors can impact legal reasoning. *Klara and the Sun*, *Do Androids Dream of Electric Sheep?* and stories by Asimov foreground AI as a quasi-agent, highlighting issues of empathy and agency, while *Minority Report* and other Asimov works explore how dangers can arise from human misuse of AI tools. This tension becomes evident in *Mobley v. Workday*, a current employment discrimination case in which Workday defends its AI-driven hiring platform as a neutral tool, while plaintiffs argue that its design enables systemic bias. The case highlights the complicated assignment of responsibility. By situating these narratives alongside current legal controversies, the project shows how law's treatment of AI is bound by the language we use to describe it.

Modeling human threat processing using immersive virtual reality and multimodal physiological data integration

Maxwell J. Woodruff Vale

Mentors: Dean Mobbs and Noah S. Okada

Motivation is often downregulated in mental disorders such as depression and anxiety, yet the specific mechanisms driving this dysfunction remain poorly understood. Fear plays a central role in both conditions, but existing research on fear and effort often relies on artificial contexts, limiting understanding of these processes in naturalistic settings. This project addressed this gap by developing a novel, gamified virtual reality (VR) toolkit for studying fear responses in a controlled laboratory environment. The core methodology involved creating a VR foraging task designed to elicit and quantify human defense responses. This toolkit integrates multimodal data streams from a Pupil Labs Neon eye-tracking device for precise gaze and pupil dilation, and an Omni One treadmill for physical effort exertion. This rich, time-series dataset informed a machine-learning model capable of predicting physical effort exertion in response to threat. This work significantly advances VR as a powerful tool for investigating human emotions in ecologically valid scenarios, contributing to the intersection of computational ethology and neuroscience.

Developing an approach to assess early misfolding events in Huntington's Disease

Jaidyn M. Woods

Mentors: Judith Frydman, Rebecca M. Voorhees, Ivana Bukvin, and Korbin Kleczko

Huntington's Disease (HD) is a devastating neurodegenerative disorder characterized by the expansion of a CAG repeat (>35) in exon 1 of the Huntington gene (HTT). Aggregation and misfolding of the mutant protein are hallmarks of the disease, although the precise drivers of cellular pathology are unknown. Here, the role of the N17 domain of HTT in early misfolding was investigated. This domain emerges first during translation and has been suggested to initiate HTT misfolding and early oligomer formation. To explore it, the antibody fragment VL12.3, which selectively recognizes the N17 domain, was purified and expressed, allowing for the selective pull-down and purification of ribosomes translating the HTT protein. Furthermore, to structurally characterize misfolding events, 70S ribosomes with an extended 44 helix in their 16S rRNA were purified, allowing for the hybridization of biotinylated oligonucleotides to immobilize them. These immobilized ribosomes will be used to produce ribosome nascent chain complexes (RNCS), in which the conformations explored by the emerging nascent chain can be mapped using single-molecule Forster Resonance Energy Transfer (smFRET). This will characterize the earliest steps in HTT misfolding, potentially uncovering novel targets for therapeutic intervention in HD.

System identification to improve sim-to-real transfer of reinforcement learning policies for humanoid locomotion

Logan A. Woudstra

Mentors: Aaron D. Ames, Blake Werner, and Lizhi Yang

Reinforcement learning (RL) policies for humanoid locomotion are trained in simulated environments and typically experience performance degradation when transferred to hardware. This decreased performance is due to differences that exist between the simulator and reality, called the sim-to-real gap. One approach to minimize this gap is system identification, which seeks to estimate the physical parameters of the real-world system so that the simulator can better approximate its dynamics. In this work, we perform system identification, utilizing Wasserstein Distance and Maximum Mean Discrepancy to measure the distributional differences between trajectories rolled out in Nvidia IsaacSim and on hardware for the Unitree G1 humanoid robot. To search for the parameters that optimize these similarity measures, we employ the Covariance Matrix Adaptation Evolutionary Strategy, enhanced with parallelized generation evaluations for increased efficiency. With the development of our end-to-end system identification pipeline, we perform both sim-to-sim and sim-to-real alignment to demonstrate the effectiveness of our approach to learn parameters that enhance the transferability of RL policies between training and deployment environments.

Constraining properties of dust formed in Wolf-Rayet binary WR 112 using mid-infrared and millimeter observations

Donglin Wu

Mentors: Konstantin Batygin and Yinuo Han

Dust, tiny solid particles in interstellar space, plays an important role in the formation of stars and planets. Binaries that host a carbon-rich Wolf-Rayet (WC) star, the late stages of some of the most massive stars, have been theorized to be major dust producers. The dust production rate of WR112, a single WC binary system, is comparable to the total dust production rate of all asymptotic giant branch stars in the Small Magellanic Cloud; these stars are known to be important dust producers. While previous studies have found dust in these systems are in expanding spiral shells, there lacks accurate characterization of the properties of dust in these shells. We combined mid-infrared observations by the James Webb Space Telescope (JWST) and millimeter-wavelength observations by the Atacama Large Millimeter Array telescope (ALMA) to derive the spectral energy distribution (SED) of the dust. By fitting dust emission models to the SED, we were able to constrain the grain properties of dust in the WC binary system. We found that the SED is consistent with emission from carbonaceous dust and the dust grains have to be smaller than half a micron in size. This study leads to a better understanding of the type of dust produced by WR systems and the sources of carbonaceous dust in the interstellar medium. The constraint on grain sizes may inform future models of dust formation in WR systems and their influence on the galactic environment.

Coarse-to-fine diffusion language models

Frank Y. Xiao

Mentors: Pietro Perona and Rogerio Aristida Guimaraes

Diffusion Language Models (DLMS) have recently emerged as an exciting potential alternative to autoregressive models. However, the current masked diffusion paradigm does not take advantage of the intermediate computations done during the diffusion reverse process, instead collapsing every masked token to a single generic mask during every intermediate step. We propose a coarse-to-fine diffusion process that introduces semantically meaningful intermediate tokens that allow DLMS to pass tokens through a hierarchy of masks before settling on their final lexical values. We (i) define a new discrete forward noising process that respects arbitrary mask hierarchies, (ii) generalize the Rao-Blackwellised ELBO to multi-transition chains, yielding a low-variance training objective, and (iii) design an efficient ancestral sampler that exploits the hierarchy for faster decoding. We benchmark our methods on generative perplexity tasks on LM1B and explore the viability of coarse-to-fine DLMS.

Investigating and improving Z-boson mass resolution for Higgs decay to dimuon searches

Jiahui Xie

Mentors: Maria Spiropulu, Christina Wang, Cristian Peña, and Si Xie

The Higgs boson decaying to a dimuon pair is a rare Standard Model process with a branching ratio of $\sim 0.02\%$. Detecting it with high statistical significance (5σ) requires precise mass resolution to distinguish the narrow Higgs peak from large Drell-Yan and Z-boson's decay to dimuon backgrounds. Because the same reconstruction pipeline simulation is used for both Z and Higgs events, improving Z-boson mass resolution, which is a well-established standard candle, would directly enhance Higgs sensitivity. Here, we evaluated the effect of Beam Spot Constrained (BSC) reconstruction on Z-boson and Higgs mass resolution in 2022–2024 CMS Monte Carlo simulations and collision data, across different production modes (ggH, VBF, ttH). Gaussian fits to invariant mass spectra were used to quantify resolution changes, revealing a consistent improvement after BSC, with the ttH category showing an improvement of up to $\sim 10\%$ in σ . To investigate the origin resolution differences between production modes, we examined the pseudorapidity distributions and muon momentum residuals of the Monte Carlo results, but the observed patterns were never fully explained. These results confirm that BSC improves resolution and provide the basis for future smearing algorithms to align simulation with data, supporting higher-precision H to $\mu\mu$ searches.

Uncovering prospective planning and subgoal representation in human neurons

Samuel W. Xie

Mentors: John P. O'Doherty and Cooper Grossman

To understand how the human brain plans multiple steps ahead, this project investigates model-based hierarchical reinforcement learning (MB-HRL) using high-resolution intracranial recordings during epilepsy patients' performance of the Space Taxi task. Unlike fMRI, intracranial recordings provide sub-millisecond temporal resolution of single-neuron activity, enabling the study of how neurons encode intermediate subgoals during decision-making. Because information in the brain is often represented in a distributed fashion across neural populations, decoding analyses are a powerful tool for probing these representations. In certain regions, we are able to decode subjects' upcoming choices *before* they occur, and this accuracy improves with increased neural dimensionality—particularly in regions such as ACC and PRV. The project focuses on decoding plans for sequential choice during the early stages of the task to uncover prospective planning. Additional analyses explore cross-condition generalization and the geometric structure of neuron population activity using metrics such as parallelism scores. Challenges include dataset limitations that necessitate aggressive trial subsampling, potentially reducing classifier performance. Nevertheless, decoding analyses and population correlations offer promising insight into how neurons encode subgoals and value information. This work builds on prior studies of MB-HRL by applying decoding and representational geometry techniques to human electrophysiological data, providing new insight into how the brain structures future-directed planning.

Modeling incumbency effects and defeat probabilities in US Congressional elections

Allison Xin

Mentors: Jonathan N. Katz and Daniel Ebanks

This project investigates the role of incumbency and district-specific effects in predicting electoral outcomes for U.S. Congressional elections. The principal objective is to quantify incumbency advantage and estimate defeat probabilities for individual candidates using a Bayesian hierarchical model. The analysis incorporates historical election data, district characteristics, and candidate-specific indicators to evaluate how incumbency interacts with factors such as redistricting regimes and regional trends. We employ the ElectIt modeling framework, which integrates logistic regression with hierarchical random effects to account for temporal, geographic, and district-level variation. Posterior predictive simulations are used to compute defeat probabilities and decompose candidate performance into district-level (g) and individual effects. Preliminary results show significant variability in incumbency advantage across time, with stronger effects in earlier decades and attenuation in recent cycles. Candidate-specific defeat probabilities align closely with observed outcomes, validating the model's calibration. These findings offer new insight into how incumbency interacts with structural political changes and provide a framework for forward-looking electoral forecasting. Future work will extend this analysis to explore how candidate effects and district-level uniqueness shape electoral risks.

Investigating methods for constraining cosmological parameters in the Pantheon+ analysis

Zilan Xiong

Mentors: Charles L. Steinhardt and Philip F. Hopkins

The Pantheon+ analysis constrained cosmological parameters from light curves of Type Ia (SNe Ia) supernovae from a variety of surveys spanning a wide range of redshifts (from $z = 0.001$ to 2.26). SNe Ia are imperfect standard candles, necessitating a standardization process. To determine cosmological parameters, the Pantheon+ analysis uses a general analysis package for supernova light curves called SNANA. SNANA is a complex software comprised of multiple independent pieces written in at least four different languages (Fortran, Python, C, and C++) that form a pipeline that has been in development for upwards of the past 25 years. The Pantheon+ analysis determined a dark energy equation of state parameter $w = -1$ and cosmological parameters that closely align with a Λ CDM model. In this project, we recreate the Pantheon+ analysis using SNANA, and we show that the cosmological parameters determined by SNANA are sensitive to an assumed cosmology used in its

standardization pipeline. Different cosmologies are found during cosmological analysis when different assumptions are provided to SNANA. This renders SNANA unfit for constraining cosmological parameters and points toward a need to rewrite its codes such that a cosmological model is not imposed.

Elucidating the mechanism of nitrogenase model compound-catalyzed carbon-sulfur bond cleavage

Alex S. Xu

Mentors: Jonas C. Peters and John Ovian

Recent reports of carbon-sulfur bond cleavage in nitrogenase-related enzymes have spurred an ongoing effort to better understand inorganic cofactor-catalyzed carbon-sulfur bond cleavage. One way in which the reaction can be better understood is through the use of model compounds such as the tris-phosphineborane iron ($B(C_6H_4PiPr_2)_3Fe$, denoted here as "TPBFe") platform developed by the Peters group. This complex was designed to mimic the $[Fe_8S_9C]$ cluster, the same cluster found in both nitrogenases and their related enzymes. In this study, we elucidate the mechanism of the TPBFe-catalyzed carbon-sulfur cleavage reaction through a kinetic Hammett study *via* NMR spectroscopy. We find the mechanism to most closely resemble...*[as the study has not yet been completed, this is as far as I can go in my abstract]*. Future areas for inquiry include developing a viable catalytic cycle for the reaction followed by condition screening for optimal turnover.

Adaptive throttle control for autonomous race cars using meta-learning

Emily Y. Xu

Mentors: Soon-Jo Chung and Thomas A. Berrueta

Autonomous motorsports demand precise, responsive vehicle control under rapidly changing and unpredictable track and environment conditions. In the Indy Autonomous Challenge (IAC), time-varying factors such as tire and track temperature or wind create discrepancies between predicted and actual vehicle behavior. These discrepancies act as disturbances, introducing residual dynamics that impact the vehicle's ability to maintain a desired speed and trajectory. Traditional physics-based methods often fail to capture these time-varying effects accurately. We introduce an adaptive throttle controller capable of modeling and compensating for these forces to better capture the relationship between throttle input, drivetrain response, tire forces, and acceleration. A neural network is trained offline to construct a set of basis functions that capture invariant features of the vehicles dynamics, and online adaption continuously updates corresponding coefficient weights to estimate residual forces using vehicle data in real time. The neural network is embedded within the C++ IAC vehicle codebase to allow for adaptive control on the race car while driving, estimating time-varying residual forces to optimize vehicle performance. The system is evaluated through simulation testing, measuring improvements in lap time consistency and reduced residual force magnitude, measured as the difference between expected and expected longitudinal acceleration, compared to current baseline controllers.

Closed-loop soft bioelectronic device integrating multimodal sensing and vagus nerve stimulation for stress management

Isabel Xu

Mentors: Wei Gao and Dickson Yao

Stress is a pervasive condition linked to impaired cognition, poor decision-making, and serious health risks, underscoring the need for improved monitoring and intervention strategies. This project aims to develop a closed-loop soft bioelectronic platform that integrates multimodal sensing and vagus nerve stimulation (VNS) for stress management. The system combines sensors for cardiovascular and glucose monitoring with stimulation electrodes for selective vagus nerve activation on a soft stretchable electronics platform that incorporates a water-responsive shape morphing actuator and bioadhesive. The sensors are fabricated through laser cutting, electrochemical deposition, and spray coating and validated through mechanical and chemical testing. Behavioral experiments and physiological monitoring in rodent models confirmed expected stress-induced biomarkers and

behavioral changes, establishing a reliable experimental framework. In the future, by integrating these components into a cohesive platform and implementing machine learning models for real-time stress classification, this device has the potential to drive the development of more personalized and responsive therapeutic approaches to stress-related conditions.

Optimizing machine learning-enabled spatial barcodes for pooled optical screens

Benjamin Y. Yang

Mentors: David A. Van Valen and Sam Holtzen

In order to probe cellular dynamics of multiple pathways, a pooled screen subjects cells with several simultaneously expressed biosensors to a given treatment. However, pooled screens are currently limited by the availability of reliable and fast barcoding methods to identify each expressed construct in a given cell. Therefore, we are developing a barcoding method where guide RNAs (gRNAs) generate spatially-resolved barcode patterns to enable multiplexed phenotypic screens. In this method, an enzymatically-deactivated Cas9 (dCas9) and the gRNAs bind to genomic repeat regions. The subsequent nuclear patterns are visualized by fluorescent in-situ hybridization and classified by a machine learning model. Here, we make several improvements to this method. We have collected new training data for the machine learning model to improve the signal-to-noise ratio. We show that a tetracycline-inducible gRNA plasmid design can be used to prevent epigenetic silencing of the gRNA system. Lastly, we aim to demonstrate the utility of spatial barcodes using a model system of nuclear-translocating biosensors to concurrently probe the activation of three mitogen-activated protein kinases: ERK, p38, and JNK.

Investigating orbital angular momentum light-induced excitonic states in MoS₂ on periodic strained SiO₂ nanoarray via scanning tunneling microscopy and photoluminescence

Cheng-Hsun Yang

Mentors: Nai-Chang Yeh and Jen-Te Chang

We investigate the interplay between nanoscale strain engineering and orbital angular momentum (OAM) light in controlling excitonic states in monolayer MoS₂. Periodic SiO₂ nanopillar arrays are used to induce localized strain fields that funnel excitons, while OAM light excitation provides an additional degree of freedom to manipulate higher-order (Rydberg) excitons. The research combines experimental and computational approaches: photoluminescence (PL) and scanning tunneling microscopy/spectroscopy (STM/STS) under OAM illumination probe the strain–OAM–exciton coupling. At the same time, molecular dynamics (MD) simulations model the strain field distribution and *ab initio* tight-binding (TB) calculations evaluate the resulting modifications to excitonic properties.

To enable high-fidelity measurements, we developed an ice-aided transfer (IAT) method for residue-free placement of monolayer MoS₂ onto nanopatterned, conductive substrates, achieving sub-millimeter-scale coverage with excellent PL uniformity (± 2 meV). Optical measurements on wet-transferred samples reveal systematic strain-induced PL redshifts —most significant for smaller and denser nanopillar arrays— consistent with bandgap renormalization. As for twisted light-assisted STS experiments, we observe a pronounced increase in the conduction-band density of states in strained regions, indicative of electron redistribution from the K valley to the Q valley.

These results establish the experimental and theoretical foundation for direct nanoscale studies of strain–OAM–exciton coupling, paving the way for controlled manipulation of excitonic states in 2D materials for solid-state quantum simulation.

Function conditioned enzyme generation with masked diffusion language models

Kerui Yang

Mentors: Frances H. Arnold and Jason Yang

Enzymes, proteins that catalyze chemical reactions, are difficult to engineer due to their complex relationships between their sequence, structure, and function. To generate enzymes with prespecified functions, we developed an approach using Masked Diffusion Language Models (MDLM) which have emerged as a new paradigm for data-efficient, scalable and steerable text generation. We adapted these models to condition amino acid sequence generation on enzymatic function, using classifier-free guidance. To enhance controllability and diversity, we further evaluated the effect of guidance techniques, as well as improved sampling strategies. *In silico*, we found that the proposed method can generate enzyme candidates that are diverse, realistic and designable, offering a promising direction for steerable enzyme generation with potential applications in biotechnology and synthetic biology.

Distinguishing dark matter substructure from the stochastic gravitational wave background in pulsar timing correlations

Yi Wei Yang

Mentors: Kathryn M. Zurek and Kim V. Berghaus

Pulsar timing arrays (PTAs) present an especially powerful probe into dark matter (DM) substructure at extremely low densities and masses (down to $\sim 10^{-13} M_{\odot}$). Transiting DM subhalos can induce correlated Doppler and Shapiro delays within pulsar phases, enabling PTAs to place fundamental bounds on small-scale structure. We show that the Doppler-stochastic signal previously modelled as a non-stationary random walk becomes equivalent to a stationary process with a $1/k^4$ power spectrum after polynomial subtraction of the pulsar timing model, allowing existing stochastic search pipelines (e.g., `exttt-enterprise`) to be easily adapted to DM searches. We then construct a more complete picture of noise and find that the DM-induced covariance is suppressed by $\sim 10^3$ relative to leakages of intrinsic monopolar pulsar noise and quadrupolar gravitational-wave background (GWB) power into the dipolar mode. Nonetheless, under optimistic PTA parameters ($\sigma_{\text{rms}} \sim 10$ ns, $\Delta t \sim 1$ week, $N_p \sim 1000$, $T = 30$ yr), the aggregated signal could still produce $O(10^{-1})$ constraints on the DM fraction at $M \sim 10^{-10} - 10^{-9} M_{\odot}$ for PBHs. We finally explore correlations between Doppler, Shapiro, and Einstein effects to construct a gauge invariant framework for probing DM substructure with PTAs.

Forecasting Alzheimer's disease progression using brain-age slopes and longitudinal MRI

Dean Yao

Mentors: Pratik Chaudhari and Elena Mantovan

Early detection of accelerated neurodegeneration is essential for timely intervention in Alzheimer's disease. Leveraging longitudinal MRI data from the Alzheimer's Disease Neuroimaging Initiative (ADNI) – 10,755 scans from 2391 participants – I trained an AutoGluon ensemble model to estimate "brain age", achieving a root mean squared error of ~ 30 months on a held out test set. For each longitudinal subject, the slope of brain age and biological age was calculated and slopes greater than 1 indicated accelerated aging. A polynomial regression that combines the slope of a patient's progression with their respective MRI scan and demographic factors was used to predict the slope of their next progression. These findings show that a patient's historical progression and MRI data can forecast disease progression and provide an interpretable metric for monitoring neurodegenerative risk.

Expanding the CRISPR-based toolkit for *in vivo* gene editing in mammalian systems

Wenting Ye

Mentor: David J. Anderson

Adaptation to changing environments is vital for survival. In mammals, reproductive behaviors (e.g. mating and aggression) are modulated by neuromodulators, e.g. neuropeptides. Gene editing approaches using SpCas9 have revealed the importance of Neuropeptides modulating neural activity in brain regions such as ventromedial hypothalamus (VMHvl) via G-protein-coupled receptors (GPCRs). Oxytocin receptor (Oxtr) and the arginine vasopressin receptor-1A (Avpr1A) in the VMHvl during

aggression. Yet the large size of *spcas9* requires a two-virus system one for enzyme and one for the gRNAs that guide the Cas9 protein to the specific genomic loci. To overcome this, we aimed to expand the CRISPR-based toolkit for in vivo gene editing in mammalian systems. A major limitation of the use of SpCas9, requires a two-virus system due to its large size. We evaluated the smaller *Staphylococcus aureus* Cas9 (SaCas9), which can be efficiently packaged into a single AAV vector and allows efficient viral delivery. From biochemical approach, we validate gRNAs targeting *Oxtr* and *Avpr1a* using N2a cells. We also did functional imaging using hypothalamic-derived cell lines (GT1-7 and mHypoA1-2) expressing endogenous receptors to monitor calcium responses after peptide stimulation. We successfully cloned gRNAs, confirmed viral SaCas9 expression, and observed potential calcium activity, suggesting SaCas9-based in vitro platform may support functional interrogation of neuropeptidergic signaling.

Ultraviolet spectroscopy of infant type II supernovae

Rujula J. Yete

Mentors: Mansi M. Kasliwal and Wynn Jacobson-Galan

Ultraviolet spectroscopy of type II supernovae at early times is rare, but provides key insights into the circumstellar environment before explosion. We present ultraviolet spectra obtained from the Hubble Space Telescope of 8 supernovae within the first week of explosion. We also present a full analysis of the type IIb supernova SN2024iss, which is one of the closest type IIb supernovae ever detected. We extracted UV, optical, and near infrared spectra of the young supernovae with software provided from the Hubble STIS team. For SN2024iss, we compared its HST spectrum (taken 7 days after explosion) with other similar early-time type II supernova spectra, analyzed the evolution of its spectrum over time, and derived its bolometric luminosity, temperature, radius, and blackbody spectra over time from photometric observations. Additionally, we compared its evolution to models for binary progenitor systems and shock breakout/cooling in order to constrain progenitor characteristics. From this analysis, we present an estimate of the supernova's progenitor radius and stellar type. These results help us better understand the characteristics of type II supernovae, massive star death, and help shape science goals for the upcoming Ultraviolet Explorer (UVEX) space mission.

The thermoelectric measurements of ferromagnetic quantum materials

Kenneth J. Yi

Mentors: Linda Ye and Takashi Kurumaji

The thermoelectric effect is a phenomenon in which a temperature gradient generates an electric current within the material without the presence of an external electric field. Through this mechanism, heat can be directly converted into electricity. The Seebeck effect is the classic thermoelectric property described by the production of an electric field or voltage difference in the direction of the temperature gradient. This phenomenon is obtained by the equation $S_{xx} = -E_x / |\nabla T_x| = \Delta V_x / \Delta T_x$. The Nernst signal is given similarly by $S_{xy} = E_y / |\nabla T_x| = \Delta V_y / \Delta T_x$, transverse to the gradient, with an external magnetic field in the z direction. Additionally, the anomalous Nernst effect (ANE) is related to the Nernst effect but is dependent on magnetization of the material as opposed to the external magnetic field. Various ferromagnetic materials are known to have large Berry curvatures which arise from the specific electronic arrangements and states of the atoms. An internal field allows for the conduction electrons to give rise to a large anomalous Nernst signal. Initial Seebeck measurements of Fe_4GeTe_2 yielded a clear signal with parabolic temperature dependence and symmetric magnetic field dependence, while Cr_3Te_4 showed a clear Nernst signal with an antisymmetric magnetic field dependence. This allows for the future steps of precisely characterizing the thermoelectric properties along with the ANE of these ferromagnets.

Simultaneous mapping of multiway interactions: Understanding the mechanisms of enhancer-promoter interactions through SPRITE data

Maya C. Yie

Mentors: Mitchell Guttman, Allen W. Chen, and Isabel N. Goronzy

DNA, along with RNA and protein, is organized into complex three-dimensional (3D) structures in the nucleus of eukaryotic cells. In particular, enhancer-promoter (E-P) interactions, the contact between the region of a gene where transcription initiates (P, promoter) and a cis-acting region of DNA (E, enhancer), have been shown to be important in regulating gene expression. However, much is still unknown about E-P interactions. Current methods, such as Hi-C, can only map pairwise interactions. To observe whether multiple enhancers and promoters interact simultaneously and in what combinations, we used RNA and DNA Split-Pool Recognition of Interactions by Tag Extension (RD-SPRITE), a method recently developed in the lab that can track genome-wide multiway, long-distance interactions between RNA/RNA, RNA/DNA, and DNA/DNA. We developed an analysis pipeline that identifies enhancers and promoters and determines multiway E-P interactions within the SPRITE dataset. Our results show that simultaneous E-P hubs appear to exist across the genome, with the majority of the multiway interactions being hubs containing one promoter and multiple enhancers. Understanding how enhancers and promoters interact provides valuable insight into gene regulation and its impact on critical cellular processes, including cell fate and other factors in disease.

Interpretable deep learning for functional fine-mapping of chromatin QTLs in Alzheimer's Disease

Clara Yu

Mentors: David Knowles and Shinsuke Shimojo

Chromatin quantitative trait loci (caQTLs) link genetic variation to changes in chromatin accessibility and transcription factor (TF) binding, offering insight into the regulatory basis of disease risk. This project aims to develop an interpretable deep learning pipeline to fine-map caQTL variants in Alzheimer's Disease by identifying disrupted TF binding motifs across relevant cell types. Using pre-trained ChromBPNet models, base-pair resolution attributions were generated for caQTL variants in microglia, applying DeepLIFT/SHAP to quantify sequence contributions. These attributions were integrated with Tangermeme for motif discovery and annotation using the HOCOMOCO v11 and JASPAR databases. Variant-level analyses revealed that 60.8% of variant-fold pairs showed motif changes, with agreement between predicted motifs and ChromBPNet consensus TFs increasing from 2.6% to 53.7% when grouping motifs by families. These results highlight the value of motif family aggregation for capturing shared TF sequence preferences. Future work will extend this pipeline to additional brain cell types (neurons, astrocytes, oligodendrocytes) and refine TF annotations by reconciling discrepancies between model-predicted motifs and consensus TFs. This approach demonstrates how interpretable deep learning can bridge variant-level predictions and regulatory mechanisms, advancing our ability to pinpoint functional loci underlying disease-associated noncoding variation.

Constraining the organic carbon properties of subsurface sediment in the Yukon Delta

Emily Q. Yu

Mentors: Michael P. Lamb and Yutian Ke

Arctic deltas function as major carbon sinks. A vast reservoir of organic carbon (OC) is stored within Arctic and sub-Arctic permafrost, which is increasingly vulnerable to release as rising temperatures and higher rainfall accelerate the thawing process. We analyzed 48 bank-sediment samples collected along a source-to-sink trajectory in the Yukon River Delta, encompassing diverse terrains of varying depositional ages. Samples were freeze-dried, decarbonated, and analyzed for grain-size distribution with laser diffraction; OC content was determined by elemental analysis of homogenized aliquots. We synthesize grain-size distributions and OC measurements to understand sedimentological controls on carbon content in the delta, thereby clarifying its role in regulating regional and global carbon cycles.

Rationalizing specific ion effects in electrochemical nitrate reduction using machine learning potential simulations

Ryan D. Yu

Mentors: Kara D. Fong and Madeline Murphy

Ammonia serves as a key component in fertilizers that help address the issue of world hunger. However, these ammonia-based fertilizers have increased nitrate water pollution by disrupting the natural nitrogen cycle. Electrochemical nitrate reduction to ammonia presents a promising way to both produce ammonia and help close the nitrogen cycle by consuming nitrates. In this process, though, the effect of pH and specific cations on nitrate density and distribution near the electrode is not well understood. Unfortunately, studying this with density functional theory is very computationally expensive, and traditional MD has accuracy limitations and restrictions. As such, we trained a machine learning potential to bridge the gap of accuracy and computational cost to give an atomistic view and study the properties of nitrate near a TiH_2 electrode interface.

Strain engineering of monolayer-MoS₂ transistors by substrate engineering

Yi-an Yu

Mentors: Nai-Chang Yeh and Wen-Hao Chang

Transition metal dichalcogenides (TMDCs) are a family of two-dimensional (2D) materials that are considered one of the most promising candidates for extending Moore's law, due to its atomically thin nature and excellent electrical properties under thin-body. Among various kinds of TMDCs, MoS₂ is the most popular one. However, field effect transistors (FETs) made from TMDCs materials often faced with several obstacles such as low carrier mobility. These problems hinder the performance of TMDCs-FETs significantly, and numerous efforts have been devoted to resolving these issues. Nonetheless, there is no universal method to improve carrier mobility. Although there are several proposed methods to enhance the carrier mobility, we believe that strain engineering is the most promising method to achieve this goal. Thus, in this research project, we aim to improve the carrier mobility of TMDCs-FETs by strain engineering. In particular, we fabricate substrate with pre-patterned nanostructures to apply strain to the MoS₂. After transferring monolayer (1L)- MoS₂ on to the substrate, we will perform optical material characterization including Raman spectroscopy and Photoluminescence to characterize the effect of strain. Then, we will fabricate 1L-MoS₂ transistors to investigate effect of pre-patterned substrate strain on the transport properties of 1L-MoS₂ transistors.

Single-shot passive ultrafast all-optical replicated Kerr imaging (SPUARK)

Daopeng Yuan

Mentors: Lihong Wang and Junfu Zheng

Ultrafast imaging is essential for capturing transient phenomena that occur on femtosecond to picosecond timescales, yet existing single-shot techniques are limited by frame rate, spatial resolution, and reliance on compressed sensing. This project develops a single-shot passive ultrafast all-optical imaging approach, SPUARK, that uses a two-dimensional Kerr gating matrix to directly record ultrafast dynamics without solving an inverse problem. By splitting the event beam into multiple replicas and sequentially overlapping them with time-delayed pump pulses in a CS₂ nonlinear medium, the system achieves direct single-shot femtography with enhanced fidelity and resolution. By integrating diffractive optics and interferometric modules with comprehensive strategies for pulse management, beam shaping, and spatial control, we demonstrated high-fidelity, high-resolution Optical Kerr Effect (OKE) and Dual-Optical Kerr Effect (DOKE) imaging of ultrafast events, including plasma generation, pulse-front tilt, orbital angular momentum (OAM) beams, and light propagation in multimode fibers and optical diffusers. Challenges such as dispersion-induced attenuation, optical aberrations, limited Kerr-medium response, and nonlinear fiber effects were mitigated through precise optical redesign, advanced system optimization, and refined experimental strategies.

Development of a second-harmonic generation autocorrelator for measuring femtosecond laser pulse duration

John L. Zambrano

Mentors: Scott K. Cushing and Jocelyn Mendes

This project focuses on the design and construction of a custom intensity autocorrelator to measure the temporal width of femtosecond laser pulses using second-harmonic generation (SHG). Accurate pulse duration characterization is essential in applications such as ultrafast spectroscopy and nonlinear optics, where timing precision impacts experimental outcomes. The autocorrelator system was developed to offer a low-cost, flexible diagnostic alternative to commercial instruments and manufacturer specifications. The experimental setup included alignment of an infrared beam through a nonlinear crystal, with SHG detection via an IR-sensitive card and photodetector. Although a measurable SHG signal has not yet been achieved, the optical system has been fully constructed and aligned. Troubleshooting procedures involved verifying beam height, spatial overlap, and crystal orientation. Future modifications include the integration of iris diaphragms and a focusing lens to enhance spatial beam overlap and SHG efficiency. The completed setup provides a foundation for further optimization and testing in ongoing work.

A live modern interactive dashboard to display KOA's metrics at scale

Min Phone Myat Zaw

Mentors: Graham Berriman and Judy S. Adler

Since 2004, the Keck Observatory Archive (KOA) has operated as a NASA-funded collaboration between the NASA Exoplanet Science Institute (NExScI) and the W.M. Keck Observatory. It ingests, curates and serves all data acquired by the twin 10m Keck telescopes on Mauna Kea, Hawaii. In the past three years, KOA has begun a modernization program that will replace the architecture and systems, used since the archive opened, with a new infrastructure. This infrastructure will position KOA to respond to the rapid growth of new and complex data sets that will be acquired by new instruments now in development. And to respond to the rapid follow-up needed to identify the deluge of alerts of transient sources expected by new survey telescopes such as the Rubin Observatory. Since 2002, KOA has ingested new data in near-real time, generally within one minute of creation, and makes them immediately accessible to observers through a dedicated web interface. The archive is now deploying a new scalable Python-based, VO-compliant query infrastructure built with the Plotly-Dash framework and R-tree indices to improve performance (x20).

This project will exploit the new query infrastructure to develop a dashboard that will return, in near real-time, metrics on the performance and growth of the archive (growth in size, monitor growth in the number of users, ...). These metrics assess the current health of the archive, and guide planning future hardware and software upgrades. This single dashboard will enable, for example, monitoring of real-time ingestion, as well as studying the long-term growth of the archive. Such a metrics dashboard is an essential part of the new architecture. Current methods of gathering metrics are inadequate to support the archive as it scales going forward. These methods suffer from high latency, are not optimized for on-demand metrics, and are scattered among various tools.

A synthetic cell platform: Development of protein expressive and payload releasing vesicles and their encapsulation in hydrogels

Pierre A. Zeineddin

Mentor: Matthew W. Thomson

During the 2025 SURF program, we have continued designing and constructing a synthetic cell platform that produces clinically relevant proteins, releases its payload into a liquid or gel environment. Concretely, we have

a) shown that our synthetic cells (Giant Lamellar vesicles, GUVS) can be stored in hydrogels (prolonging their lifespan on the order of days),

b) tested a **pore forming protein that can release clinically relevant proteins**, as well as

c) collected preliminary results on said pore forming expression alongside fluorescent proteins.

With the pore protein Listerolysin O releasing large cargo (75 kDa) from our synthetic cells, we see a very near future where the synthetic cell platform can produce proteins expressible in cell free expression media. This is grounded in an advantage of the easy to form, inducible pore forming proteins.

Continuing our work on gathering cargo expression and release data, we plan to perform flow cytometry assays with immune cell populations, producing and releasing those critically important proteins used in fighting cancers and immune system activation. Success in showing activation will show the power of a simple synthetic system. It is our hope that this design platform will enable researchers, engineers to design experiments that delve deeper into therapeutic studies, regrow damaged or previously irreparable tissues--with cartilage, even one day brain tissue being regrown.

Integrating and characterizing the Unitree D1 robotic arm for whole-body control research

Eloise Zeng

Mentors: Aaron D. Ames and Zachary Olkin

This project focuses on integrating the Unitree D1 robotic arm into the Caltech AMBER Lab's robotics research interface, Obelisk, with the goals of enabling whole-body control experiments on the Unitree Go2 quadruped-armed system and improving the alignment between simulated and real-world robot behavior. After extensive debugging of the Unitree D1 SDK and Obelisk, I developed a teleoperation system consisting of a controller, state estimator, and hardware interface. The controller leverages the Pinocchio Python library to perform inverse kinematics on the gripper, and I implemented a joystick-based interface for intuitive user control. Despite these efforts, the D1 arm consistently failed to follow commands reliably, even after extensive troubleshooting and communication with Unitree support, ultimately leading to the conclusion that the hardware is defective. The project has since pivoted toward preparing for future research in model predictive control and reinforcement learning.

AI-driven mathematical discovery for the Andrews–Curtis conjecture

Caroline Zhang

Mentors: Anima Anandkumar and Robert Joseph George

Automated theorem proving (ATP) with large language models (LLMs) has demonstrated impressive progress on undergraduate and olympiad mathematics. However, these problems are distant from the forefront of open mathematical research. In this work, we make the push beyond competition benchmarks and investigate the unsolved Andrews–Curtis (AC) conjecture in group theory. We benchmarked state-of-the-art LLM theorem provers on AC-related tasks, revealing a substantial performance gap: models that perform well on competition-level benchmarks fail in research-level reasoning. To bridge this gap, we formalized the AC conjecture in Lean. We introduce a deterministic autoformalizer, ACC, that rigorously verifies AC trivialization paths and produces the corresponding Lean proof. Building on this, we leveraged LLMs for theorem discovery, synthesizing patterns from autoformalized proofs as general, reusable theorem statements. Finally, we incorporated these theorems into reinforcement learning (RL) agent training. Across all runs, we solved 753 presentations belonging to the Miller–Schupp (MS) family, disproving them as potential counterexamples to the AC conjecture. Our results lay the foundation and spearhead the shift towards AI-driven mathematical discovery for research-level problems.

Sulfoxonium ylides as a carbene precursor in biocatalysis

Chaoyi T. Zhang

Mentors: Frances H. Arnold, Chenghao Liu, and Theophile Lambert

Abstract withheld from publication at mentor's request.

Design of synthetic caspase-based circuits for programmable cancer therapy

Evan Z. Zhang

Mentors: Michael B. Elowitz, Andrew Lu, and Lukas Moeller

Therapeutic circuits represent a new potential cancer treatment modality that uses engineered proteins, delivered into cells as mRNA via lipid nanoparticles, to detect if a cell is cancerous and trigger programmed cell death in response. Recent work has shown that engineered protein circuits targeting oncogenic Ras mutants can potently kill Ras mutant cancer cells, with little off-target effect on Ras wild-type cells. However, the current generation of these circuits contain a viral protease-based sensor module, which may raise the risk of a host immune response against the viral components of the circuit itself. Here, we present a remodeled version of the circuit that uses a single human caspase-based module as both a sensor and cell death effector. We demonstrate that the new design maintains potent and specific killing of HEK293 cells with ectopically overexpressed mutant Ras. Overall, these results provide the groundwork for re-engineered circuit designs that preserve the advantages of therapeutic circuits while potentially minimizing immunogenicity.

MRI in-bore microwave link fidelity investigation for a wireless coil array

Ruijia Zhang

Mentors: Shreyas S. Vasanawala and Steven H. Low

To overcome the limitations of cabled RF coil systems in Magnetic Resonance Imaging (MRI), this project evaluates the performance of a 200 Mbps wireless communication prototype inside an MRI bore. The study tested various transmitter (Tx) and receiver (Rx) antenna configurations, including patch and horn antennas, across three environments: a test bench, a mock-up bore, and a head-only gradient bore. Performance was quantified using the Signal Fidelity Factor (SFF) and real-time eye diagrams. While the link achieved near-perfect fidelity (SFF > 0.99) on the test bench, performance within the bores was highly dependent on antenna placement and orientation due to the complex electromagnetic environment. The results identified specific spatial "sweet spots" where certain configurations achieved excellent signal integrity (SFF up to 0.97), while others suffered complete signal degradation (SFF as low as 0.69). This work demonstrates the feasibility of high-speed wireless data transmission in-bore but confirms that its success is critically dependent on optimizing antenna selection and positioning to mitigate multipath interference.

Inverse scattering solution for kidney stone detection

Weihan Zhang

Mentors: Tim E. Colonius and Chris Zhang

This project develops a computational framework for the non-invasive detection of kidney stones using inverse acoustic wave scattering. A Gaussian pulse is propagated through body fluids, and the pressure field of the scattered wave is recorded by probes positioned around the domain. By formulating the problem as an inverse optimization task, we infer the stone's size and location from the measured pressure data. The methodology integrates forward modeling with inverse problem-solving techniques, examining the effectiveness of local methods such as the Gauss-Newton and Levenberg-Marquardt algorithms, full waveform inversion, global methods such as the particle swarm optimization, and hybrid global-local approaches, ensuring robust convergence with limited prior knowledge. Extensions to two-dimensional and potentially three-dimensional reconstructions further enhance accuracy, enabling a viable framework for kidney stone imaging, optimizing accuracy and computational cost.

Towards building a "toolbox" for the synthesis of bicyclo[3.2.1]octanes

Zhehao Zhang

Mentors: Sarah E. Reisman and Kala Youngblood

The Grayanane diterpenoids possess diverse bioactivities such as analgesic, antifeedant, anti-inflammatory, antinociceptive, and cAMP and ion channel inhibitory effects. The bicyclo[3.2.1]octane ring system found in the Grayananes remains a challenging project in natural product total syntheses, and existing methods are often hindered by racemic synthesis, limited access to oxidation patterns, or minimal synthetic divergence. Here, we report progress towards developing strategies for synthesizing bicyclo[3.2.1]octane systems with oxidation patterns found in complex grayananes with accessible cross-coupling handles. We can also envision access to a diverse set of bioactive grayananes through synthesizing differently functionalized bicyclo[3.2.1]octanes followed by coupling to a more conserved west-side fragment.

Constraining grain size dependent dynamics in AU Mic's debris disk: A joint JWST and ALMA study of the vertical structure

Junyi Zhao

Mentors: Konstantin Batygin and Yinuo Han

We present a joint modeling of JWST NIRCам F444W coronagraphic images and ALMA Band 6 visibilities of the debris disk around AU Mic, viewed edge on. Though using a unified Bayesian MCMC framework implemented in emcee combined with parametric disk models, we derive the vertical scale height h at infrared and millimeter wavelengths under the same disk inclination and position angle. This analysis provides the first direct measurement of grain size dependent vertical stirring in AU Mic by combining high contrast scattered-light imaging and interferometric data. By quantifying how scale height differs between infrared-emitting and millimeter-emitting grains we can constrain collisional damping rates and turbulence levels, providing evidence on planetesimal assembly and the physical processes that govern disk evolution around young stars. Our unified Bayesian framework can be readily applied to other systems, offering a powerful pathway to test theories of disk dynamics and the early stages of planet formation across diverse stellar environments.

Realistic baryon-ejection from the recoil of magnetar giant flares

Ruimian Zheng

Mentors: Elias R. Most and Yuan Feng

Giant Flares (GFs) are the most energetic transient outbursts from Magnetars. Recent models predict baryon-ejection from the "recoil force" of the GFs to explain the GF radio rebrightening and identify the potential for r -process. We performed GRMHD simulations using AthenaK to localize the shock and observe the ablation of the crust at various initial conditions. By varying the equation of state, we probe different regimes of the neutron star crust. We systematically quantify the mass ejection and its nuclear composition.

Fourier neural operator ansatz for scalable variational Monte Carlo of strongly correlated quantum systems

Shizhao Zheng

Mentors: Anima Anandkumar and Chuwei Wang

Accurate simulation of strongly correlated quantum systems remains a central challenge in condensed matter physics. Variational Monte Carlo (VMC) with neural quantum states (NQS) has become a strong approach. While neural backflow architectures such as neural network backflow have shown strong performance, they often face challenges in scaling to larger lattices and in efficiently capturing long-range correlations. In contrast, our Fourier Neural Operator (FNO) ansatz leverages Fourier modes to capture both short- and long-range correlations. This design makes optimization more stable and helps the wavefunction adapt quickly when applied to different system sizes. Here, we introduce an FNO-based variational wavefunction (FNO-NQS) and show that it can model quantum many-body states efficiently and transfer across system sizes with little additional cost. Our approach achieves stable optimization when applied to the Hubbard model. More importantly, although the FNO ansatz

does not directly yield the exact ground state when transferred across system sizes, it provides highly effective initializations that enable rapid convergence. This characteristic demonstrates its prospects as a scale-aware approach for speeding up variational studies of many-body physics. Together, these findings highlight that FNO-NQS can effectively link the strengths of spectral machine learning methods with the demands of quantum many-body physics, providing a scalable path for future investigations.

Shape optimization with neural operators

Jiayi Zhou

Mentors: Anima Anandkumar and Valentin Duruisseaux

Shape optimization is central to modern engineering design. A typical pipeline involves shape parameterization, PDE-based evaluation of performance metrics, and iterative optimization. In this work, we propose a fully differentiable shape optimization framework that leverages neural networks (NNs) for shape representation and neural operators (NOs) for efficient PDE approximation. Unlike traditional approaches such as control nodes, which require extensive manual setup and offer limited flexibility, our NN-based parameterization supports complex geometries and enables gradient-based optimization. We also aim to address the incorporation of geometric constraints. Another key focus of our work is numerical robustness and convergence behavior during optimization. We investigate the distribution-invariance property of neural operators, ensuring consistent performance across varying discretizations and point cloud samplings.

A critical review on variation of sweat composition and how sweat calcium affects bone health

Wenjing Zhou

Mentors: François Tissot and Theo J. Tacail

Isotopic composition of Ca in urine can reflect the bone mass change. However, significantly lower $\delta^{44/42}\text{Ca}_{\text{urine}}$ was observed after exercise. This research aims to conduct a review about how sweat calcium potentially affect bone health and discuss the variation of sweat composition due to different ages, genders, diets, exercise and diseases. Different methods on sweat collection and analysis will also be compared in terms of accuracy. Database of sweat composition and concentration was compiled from different literatures, and a synthetic sweat composition table was developed based on a critical review. A plan was made to carry out tests for wipe contamination, size of wipe to choose and Ca recovery from wipe. The synthetic sweat was also planned to be used to determine the method for analyzing sweat samples and the minimum volume of sweat needed to be collected for iCAP and MC-ICP-MS.

Long-range simultaneous two-qubit gates using dual-rail transmons with in situ erasure detection

Alan Zhu

Mentors: Oskar J. Painter and Gihwan Kim

Current super-conducting qubit implementations typically struggle to perform long-range two-qubit gates, instead necessitating chains of nearest-neighbor interactions. This restriction has prevented the use of more efficient quantum error correction codes requiring long-range interactions. To address this, we present a novel platform built on dual-rail transmons coupled to a long-range metamaterial bus. Utilizing cross-cross resonance interactions and multiple modes of the bus, long-range Controlled-Z (CZ) gates can be simultaneously applied to pairs of qubits with minimal leakage into non-participating qubits. Moreover, the dual-rail allows for in situ erasure detection with ancillary qubits, which increases post-selected fidelities and can further improve the efficiency of quantum error correction codes. To quantitatively characterize our device's performance, we will perform two-qubit Clifford randomized benchmarking of the CZ gate. Thus far, we have simulated the performance of randomized benchmarking with our native gate set. However, further work is required to experimentally realize and characterize these gates on the device.

Spin-dynamics of coupled electrons and nuclei at the classical and quantum interface

Mark Zhu

Mentor: Lihong Wang

This project is aimed at examining the energy and dynamics of atoms in external magnetic fields at the classical and quantum interface, which are determined by the Bloch equation and the von Neumann equation respectively. We specifically study the hyperfine interaction between the electron and nuclear spins, comparing a classically-inspired mean field treatment to the quantum mechanical Breit-Rabi formula. We investigate the role of quantum entanglement as a form of statistical correlation which produces differences between the two models, and present a derivation of the von Neumann equation from the Bloch equation as a way to bridge the quantum and classical paradigms. From this we can better characterize the physical nature of magneto-atomic processes and technologies, such as magnetic resonance imaging, atomic clocks, and spin-based quantum computers.

Optoelectronic mode-locked laser via regenerative RF feedback in thin-film lithium niobate

Oluwaseun N. Adeyeye

Mentors: Alireza Marandi and Rithvik Ramesh

Mode-locked lasers (MLLs) are essential tools in modern photonics, enabling high-impact applications in frequency metrology, ultrafast spectroscopy, biomedical sensing, and photonic computing. However, traditional MLL systems remain bulky, expensive, and power-intensive—factors that limit their deployment beyond controlled laboratory environments. This project aims to develop a compact, integrated mode-locked laser using thin-film lithium niobate (TFLN), a second-order nonlinear material known for its strong electro-optic response and compatibility with nanophotonic fabrication. My research focuses on characterizing picosecond pulse generation and evaluating key performance metrics such as output power and frequency comb bandwidth. Through hands-on photonic integration and optical measurements, this research advances the goal of a scalable, energy-efficient ultrafast laser platform suitable for real-world applications.

Structure and composition optimization of FeWO₄ photoanodes enhance photoresponse in PLD grown thin films

Ann E. Alekseenko

Mentors: Harry A. Atwater, Jr., and John Hylak

FeWO₄ holds promise as a photoanode based on its 1.9 eV band gap, n-type electrical conductivity, and Pourbaix stability in bulk aqueous electrolyte. We investigate the relationships between crystal structure, composition, and opto-electronic properties of epitaxial FeWO₄ (100) thin films grown on sapphire (001) using pulsed laser deposition (PLD). Additionally, we investigate photoanode device performance metrics using FeWO₄(100)/Pt(111) PLD grown heterostructures. We utilize PLD process variables, namely substrate temperatures from 500-800°C and target compositions of Fe³⁺ containing Fe₂O₃/WO₃ and Fe²⁺ containing FeWO₄, to induce structural and compositional variations in FeWO₄ thin films. $\omega/2\theta$ scans confirm FeWO₄ (100) out-of-plane crystal orientation, while Φ and ω scans characterize the in-plane epitaxial alignment and coherence, respectively. Additional structural characteristics are analyzed from transmission electron microscopy (TEM) of the FeWO₄ thin films on sapphire, and X-ray Photoelectron Spectroscopy spectra assess Fe²⁺:Fe³⁺ ion ratios. Preliminary chopped light linear sweep voltammetry and chronoamperometric analysis measurements performed on FeWO₄(100)/Pt(111) heterostructures with 100 mW/cm² sunlight intensity in a SO₃ bulk liquid electrolyte (pH=9) show photocurrent and stability characteristics comparable to published FeWO₄ work. Successful synthesis of FeWO₄(100)/Pt(111) photoanodes from PLD is a major step towards understanding the compositional aspects of metal oxide absorber layers underpinning ideal photoanode performance.

Measuring MTCH2-dependent protein insertion into the outer mitochondrial membrane using a split-luciferase system and targeted AAVS1 integration

Diego Alfaro Carcoba

Mentor: Rebecca M. Voorhees

Proper localization of proteins to the outer mitochondrial membrane (OMM) is essential for maintaining mitochondrial integrity and function. MTCH2, an OMM insertase, mediates the insertion of a subset of mitochondrial membrane proteins. This project develops a reporter system to measure the efficiency of MTCH2-dependent protein insertion. Using a split-luciferase reporter system, one half is fused to Metaxin2, an OMM protein independent of MTCH2, while the other half is fused to test certain proteins, such as CYB5B, that are known to rely on MTCH2 for insertion. These constructs are integrated into the AAVS1 safe harbor locus via transfection into both wild-type and Metaxin2-knockout HEK293T cells. Genomic DNA extraction and PCR confirmed genomic integration, and luminescence assays show CYB5B properly inserts into the OMM and reconstitutes the reporter, resulting in luminescence. Ongoing work expands the system to include more MTCH2-interacting proteins and introduces MTCH2 knockout via lentiviral transduction to further validate its role by comparing luminescence before and after knockout.

Investigating hierarchical value construction using human single-neuron recordings

Etienne A. Atangana

Mentors: John P. O'Doherty and Ueli Rutishauser

Humans make decisions by evaluating the expected value of potential outcomes and selecting the option with the highest perceived reward. Understanding the neural mechanisms underlying the construction of value is essential for elucidating how the brain makes decisions across different domains. To investigate this, we collected single-neuron recordings from four epilepsy patients with clinically implanted electrodes as they simultaneously rated the value of food images. We ran Poisson generalized linear models for each patient separately and focused on neurons that significantly encoded the full model, which included both food features and subjective value ratings as predictors. Partial R-squared values from reduced models containing only features or only value ratings were compared to assess their relative contributions to neural activity. We found preliminary evidence that neurons in the amygdala are more feature dominant, while medial orbitofrontal cortex and supplementary motor area neurons are swayed towards encoding value. This supports the idea that food stimuli are decomposed into individual features that guide the construction of value within a hierarchical brain network. Future directions include expanding the dataset as more patients complete the study and conducting a group-level analysis by pooling all available data.

Investigating *Bacillus subtilis* as a microbial delivery system for sustained plant peptide hormone release in soil

Hannah R. Bachmann

Mentors: Gözde S. Demirer and Carl McCombe

Fertilizers enhance plant growth by enriching soils with essential nutrients. However, their overuse is environmentally damaging and unsustainable, prompting the need for alternative practices that reduce fertilizer dependence. One promising solution is the use of plant-associated microbial communities, which can naturally increase nutrient availability, yet our ability to engineer these interactions is limited by an incomplete understanding of how plants influence root microbiomes. Among the signaling molecules plants use to shape microbial interactions are peptide hormones, small, secreted proteins that regulate development and stress responses. This project aims to optimize a microbial delivery system for sustained peptide hormone release in the root environment, enabling investigation of their roles in microbiome modulation and potential in engineering beneficial interactions. We are using *Bacillus subtilis*, a natural soil-dwelling microbe with a well-characterised capacity for protein secretion. To optimize the *B. subtilis* system for peptide delivery, we have screened multiple gene promoters to drive peptide production and compared strains for their ability to colonize and persist on *Arabidopsis* roots. Peptide secretion was quantified using a high-throughput luminescence assay, while hormone function was assessed by monitoring changes in plant gene expression. These findings contribute to the advancement of microbial tools for improving sustainability in agriculture.

Designing CMOS fabricated microrobotic actuators with origami folding motion

Henrik N. Barck

Mentors: Chiara Daraio and Xiaoxiao Xiong

The introduction of CMOS fabrication to the field of microscopic robots brings mass scalability and integration with a variety of sensor and actuator technologies. Combining integrated circuits with CMOS fabricated actuators can lead to new biomedical and environmental applications, but most work is still in a proof of concept stage. Surface electrochemical actuators have demonstrated high curvature at low voltages and shape morphing capability, but has only been used for locomotion with microrobotic chips. We introduce a simulation method to test origami patterns of actuators that morph between planar and 3D shapes. These simulations motivate designs to be fabricated and tested experimentally. We began the fabrication process of lattice designs, but didn't finish due to time constraints. This work pushes the integration of CMOS circuits and microactuators along the path to addressing biomedical and environmental challenges like microsurgery and pollutant collection.

Theoretical ellipsometer for thin films of silicon and aluminum and related compounds

Michael K. Battiest

Mentors: Austin J. Minnich and Finley Donachie

To overcome limited access to ellipsometer, we implemented a Python-based simulation spectroscopic ellipsometry for thin films. The simulator primarily uses the transfer matrix method to model ellipsometry outputs, specifically the amplitude ratio (XXXXX) and phase difference (XXXXX). The simulation outputs reveal how optical properties evolve with film thickness, including the presence of tunable XXXXX minima across different materials and layer configurations. The benefit of the model is that the theoretical experiment avoids costly fabrication and makes it possible to evaluate different films without a physical experiment. This approach allows preliminary optical screening of materials prior to fabrication which bypasses intermediate steps that require plasma ALE development workflows. This research provides insight into thin film selection for semiconductor applications that require precise control of reflectance, and it enables comparison between future experimental and theoretical ellipsometry data.

Preparation of cyclopentane fragment en route to Hypatulone A

Aniya M. Buckland

Mentors: Brian M. Stoltz and Kim R. Sharp

Abstract withheld from publication at mentor's request.

Investigating the optical variability in BAL and non-BAL quasars as a parametrizing factor for BAL classification

Josie C. Carrillo

Mentor: Matthew J. Graham

Broad Absorption Line (BAL) Quasars or Quasi-Stellar Objects (QSOs) are a subclass of active galactic nuclei (AGN) distinguished by high-velocity outflows observable through blueshifted absorption features in their spectra. While these objects are spectroscopically well-studied, their optical variability characteristics remain mostly unexplored. There have been individual examples of BAL Quasars showing extreme variability (Stern 2017). This project presents an initial investigation into the variability of BAL quasars compared to a matched sample of non-BAL quasars. We plan to apply a range of statistical variability metrics to quantify and compare across both populations. We also explore the potential of using machine learning models to classify BAL quasars based on their variability. This work aims to assess whether BAL quasars exhibit unique variability signatures that could create a new identification method in future large-scale surveys. These results will contribute valuable insight into the behavior of AGNs and inform the development of a variability-based classification system.

Searching for changing-look active galactic nuclei via multi-epoch X-ray variability and optical spectral follow-up

Vincent Caudillo

Mentors: Fiona A. Harrison and Elias Kammoun

Active Galactic Nuclei (AGNs), powered by gas accretion onto supermassive black holes, rank among the most luminous and variable objects in the universe. Recently, some AGNs have been observed to go between an unobscured (Type 1) and obscured (Type 2) spectral states on human timescales as opposed to 10^4 - 10^7 years – a contradiction to the standard unification model. These AGNs, now classified as “changing-look AGNs,” (CLAGNs) offer a unique window into accretion physics – making them important to identify. Yet with only a few hundred confirmed cases, we lack statistical and physical insight into these phenomena. Taking advantage of AGNs’ strong presence in the X-ray band, we identify possible candidates by cross-matching a catalog of 133,414 X-ray selected AGNs from the Chandra Source Catalog with Swift, XMM-Newton, and eROSITA – applying filters on galactic latitude, detection significance, redshift availability, and instrumental biases. We then statistically flagged the most variable sources – those with flux swings $\geq 6x$ and hardness-ratio differences ≥ 0.8 . This selection yields 1,439 new high-variability AGNs, which are then followed up by optical, infrared, and

X-ray light curves and optical spectral analysis. This is one of the largest samples of CLAGN candidates to date, with dozens expected to be confirmed, which will help us understand how intrinsic accretion rate fluctuations and variable line-of-sight obscuration may drive these state changes. This sample will not only improve models of supermassive black hole growth and feedback but also guide future multi-wavelength time-domain surveys and contribute to theoretical frameworks for AGN unification.

Multimetallic complexes for small molecule reactivity: Expanding dinuclear nickel systems through third-metal variation

Sherlyn Cazares

Mentors: Theodor Agapie and Matt R. Espinosa

Multimetallic complexes represent a new direction in inorganic chemistry, offering novel approaches to small molecule activation and catalytic transformations by mimicking nature's metalloenzymes. Bimetallic systems, particularly those involving nickel and cobalt centers, have demonstrated enhanced reactivity and selectivity compared to their monometallic analogues by stabilizing reactive intermediates. Recent advances suggest that introducing a third metal can further expand the scope of reactivity and modulate electronic environments.

Trimetallic systems are yet to be fully explored in current literature. However, those that do appear in literature have shown unique capabilities in redox chemistry and C-H bond activation, highlighting the potential of such complexes to surpass the limits of mono- and bimetallic systems.

This project proposes the synthesis of novel bimetallic nickel complexes with a tetrapyridine ligand designed to support the strategic placement of a third metal (scheme 1). The objective of this project is to systematically evaluate how the identity of a third metal influences small molecule activation. This work aims to develop new structure-function relationships in multimetallic catalysis by leveraging geometric adaptability and electronic modulation, untimely advancing the design of catalysts capable of complex and selective chemical transformation.

Enhancing intergroup contact through collaborative team flow using an online geolocation game

Nandi V. Chase

Mentors: Colin F. Camerer and Katelyn Haly

Established in his text *The Nature of Prejudice* (1954), American psychologist Gordon Allport's Contact hypothesis proposes that contact between members of different or opposing groups can reduce prejudice and promote tolerance under the right conditions: equal status, common goals, intergroup cooperation, and institutional support. Contact hypothesis research provides evidence suggesting that contact typically reduces prejudice, yet reveals gaps including the dearth of longitudinal research on prejudice reduction. In this study, we assess, in the long-term, the hypothesis using an online game interface to facilitate intergroup contact. Our gaming interface of choice was Geoguessr— an online geolocation game that tasks players with identifying a location using context clues from Google Street View imagery. As participants— many being of different cultural and racial backgrounds— played the game, we collected and transcribed recordings of their conversation to classify changes in their attitudes toward one another, leveraging natural language processing techniques and sentiment analysis. We also determined whether team flow— a shared state of immersion, focus, and enjoyment—during the game predicts improvements in intergroup attitudes. Thus far, preliminary findings suggest that gaming interventions provide viable contexts in which to facilitate intergroup collaboration, though information about their potential to reduce the behavioral aspect of prejudice has not been deduced. This study has important practical implications including, for example, reformed public policy and community building.

Low-cost spalled GaAs (110) thin film solar cells

Bonnie Chen

Mentors: Harry A. Atwater, Jr., and Andy Nyholm

The Caltech Space Solar Power Project (SSPP) strives to harvest solar energy from space and wirelessly transmit it back to Earth using microwaves. To fulfill this goal, it is necessary to create low areal weight, high efficiency, radiation-hard, and low-cost solar cells, with costs at least similar to those of terrestrial solar cells, in order for space solar to be desirable. The vast majority of terrestrial solar cells are bulk solar cells. However, bulk solar cells exceed the efficiency to areal weight ratio required to launch solar cells into space economically. Moreover, thin-film semiconductors have been traditionally produced using epitaxy, which significantly increases manufacturing costs due to requirements for high quality substrates, high vacuum processes, and specialized equipment. In this project, we explore different configurations of GaAs thin film solar cells. We design and fabricate thin-film solar cells with EL2-annealed and diffusion-doped (110) GaAs using the method of spalling. A GaAs (110) wafer is first electroplated with a stressed nickel layer, then spalled into a thin film. Contacts are deposited using photolithography and electron-beam deposition. We investigate experimental methods to reliably produce these spalled cells, including etch rates of various GaAs substrates, adhesive removal, and nickel etching, as well as efficiency of differently sized cells (from .25mm² to 1cm²). Through electromagnetic field simulations and finite element multiphysics simulations with Ansys Lumerical, we also examine the specific power of spalled GaAs (110) to spalled GaAs (100), which is a more readily available substrate material, and has a corrugated surface that may exhibit light trapping mechanisms. With these experimental and computational methods, we advance the development of low cost space solar cells.

Studies in calcium isotope speciation in urine

Margo T. Crothers

Mentors: John M. Eiler, François Tissot, Rebecca J. Ryan, and Theo J. Tacail

Background: It has been proposed that calcium (Ca) complexation with organic ligands found in urine favor the heavy isotopic species, providing a mechanistic explanation for isotopically heavy urine relative to other Ca reservoirs in the body. **Aims and Methods:** Here, we conduct a study of isotopic fractionation among Ca species in urine. First, we study the effects of solid phase precipitation on the bulk Ca isotopic composition of natural urine samples. Second, we begin development of a method with ESI Orbitrap IRMS that discretely measures isotopic composition of multiple aqueous Ca-ligand species in a single sample. **Conclusions:** Solid compositional analyses reveal variable solid phases in urine with similarly varying effects on isotopic composition. Analysis of Ca-complexes on ESI Orbitrap can produce consistent precision in simple mixtures, but the full effects of a more complex matrix on measurement precision and accuracy are yet to be rigorously tested. **Implications:** Precipitation has variable effects on calcium fractionation, depending on precipitate composition and quantity, which varies even among demographically similar individuals. ESI Orbitrap IRMS has the potential to measure complex-specific Ca isotopes, but a greater understanding of sample matrix effects is needed before measurements can be performed on natural samples on a large scale.

Investigating the role of S503 phosphorylation in PAX3-FOXO1-mediated protein interactions

Mykenzi C. Davis-Cowart

Mentors: Shasha Chong and Michael Di Martino

PAX3-FOXO1 is a fusion protein that drives a rare and aggressive childhood cancer known as alveolar rhabdomyosarcoma. We believe it does so by forming pathological condensates in the nucleus. These condensates depend on interactions that are mediated by disordered regions of the protein. One specific site of interest is serine 503 (S503), which lies in a portion of the disordered region that is important for its protein-protein interactions. S503 is a known phosphorylation site of P3F. Since phosphorylation changes the local charge properties, and charge properties are known mediators of protein-protein interactions at disordered regions, we think that phosphorylation at S503 affects how strongly PAX3-FOXO1 interacts with itself and with other interaction partners. Stronger or weaker interactions may influence condensate formation and transcriptional control.

We hypothesize that phosphorylation of S503 changes the interaction strength between PAX3-FOXO1 molecules and other interaction partners. If this is true, then phosphomutants should have significantly different interaction strengths. To test this, we mutated S503 to A503, which is non-phosphorylatable, and to D503, which mimics phosphorylation. We are measuring the coefficient of variation (CV) in puncta formation assays to compare how easily the mutants form condensates compared to the non-mutant. If interaction strength is affected, this may reduce PAX3-FOXO1's ability to regulate gene expression, which could help block cancer-driving activity.

Using vibrational imaging to understand huntingtin aggregation and its role in Huntington's disease

Helen J. Fenske

Mentors: Lu Wei, Adrian Colazo, and Berea Suen

Huntington's disease is a fatal neurodegenerative disease that occurs when the Huntingtin gene carries a mutation causing 36-250 CAG repeats, overexpressing mutant Huntingtin (mHTT) with corresponding polyglutamine (polyQ) expansion regions which form neuronal aggregates. Current research demonstrates that the formation of these polyQ aggregates lead to inflammation and neuron death, and that the number of polyQ repeats impacts age of onset and symptom severity, but it is currently unclear why this change has such a dramatic effect on disease progression. Additionally, current analytical methods used often involve bulky labels that may perturb mHTT's native behavior. Our study focused on bioimaging huntingtin aggregates in live and fixed rat neurons to better understand disease behavior. To accomplish this, we conducted imaging studies on 46Q and 97Q mHTT constructs. Our work primarily looked at analytes labeled with deuterated glutamine for SRS imaging, but we also looked at constructs labeled with deuterated valine and GFP. Our analysis looked for differences in aggregate localization trends, aggregate development, and label-attributed size and density changes.

Investigation of in-situ iron doping and ferromagnetism in 2-dimensional MoS₂

Jackson C. Glass

Mentors: Nai-Chang Yeh and Daniel Anderson

Semiconducting two dimensional transition metal dichalcogenides (TMDs) are of interest for their applications in semiconducting electronics and valleytronics. We investigate the in-situ substitutional doping of iron atoms in the TMD molybdenum disulfide (MoS₂), grown using chemical vapor deposition. Such doping can be performed to synthesize two dimensional dilute magnetic semiconductors. The elemental composition is studied through x-ray photoelectron spectroscopy. The magnetic and optical properties of Fe:MoS₂ samples are studied using temperature-dependent Raman and photoluminescence spectroscopy. We observe below room temperature ferromagnetic effects, and evidence of iron incorporation. We additionally consider CMOS temperature compatible synthesis of amorphous boron nitride monolayers to preserve electrical properties.

Oxygen generating smart bandage for wound management

Sofia H. Granieri

Mentors: Wei Gao and Kexin Fan

Chronic wounds such as diabetic ulcers are often oxygen-deficient, which impedes healing and increases risk of infection. To address this issue, a smart bandage device is being developed that supplies oxygen and hypochlorous acid to promote wound healing, while simultaneously monitoring wound conditions to ensure an optimal healing environment. In this study we started developing several components of this device, including hypochlorous acid sensors, hydrogels for oxygen generation, and membranes for oxygen and fluid transport. The primary focus has been on optimizing a wear resistant hydrophobic coating for a Janus membrane to facilitate oxygen delivery to the wound and fluid transport into the hydrogel. Here we present preliminary findings, with the aim of integrating these components into a functional device in the future.

High-throughput, high-strain-rate material testing and characterization via Automated Rapid Direct Impact Tester (ARDIT) for predictive modeling

Mason M. Holmes

Mentors: Guruswami Ravichandran and Aditya B. Shedge

For fiber-reinforced composites tested at strain rates above 10^2 s^{-1} , constitutive data is relatively sparse, limiting the fidelity of impact constitutive design models. This is largely due to the two conventional testing methods: Split-Hopkinson (Kolsky) bar and laser-shock having individual limiting drawbacks. Split-Hopkinson bars have lower-throughput data collection, and laser-shock methods struggle with boundary condition control. In an effort to obtain such data, and build similar constitutive design models, we have completed the construction of the Automated Rapid Direct Impact Tester (ARDIT). ARDIT is an automated gas gun capable of performing controlled planar impacts at strain rates from $10^2 - 10^4 \text{ s}^{-1}$, while keeping track of data such as impact velocity, surface velocity, and images for Digital Image Correlation (DIC). DIC allows for a full-field measurement approach to assess deformation resulting from ARDIT impacts.

Post-completion of ARDIT, the main focus has been calibrating ARDIT's mechanical and optical systems using an isotropic, well-documented material: copper. Future phases of the project will extend testing to carbon fiber and other composites, collecting large data sets needed for machine learning. ARDIT is the fundamental experimental component for high-throughput, high-strain-rate characterization needed to feed prediction models.

SFB power spectrum emulator: Spherical Fourier-Bessel power spectrum emulation to constrain fundamental cosmology

Elizabeth Huber

Mentors: James J. Bock and James Cheshire IV

The SFB power spectrum emulator is a spherical Fourier-Bessel (SFB) emulator which enables inference of cosmological parameters, motivated by SPHEREx's (Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer) goal to constrain primordial non-Gaussianity and model time evolving dark energy. Given a set of cosmological parameters, the SFB power spectrum emulator emulates a corresponding SFB power spectrum. The emulator is a neural network which was trained on a Latin Hypercube sampling of cosmological parameters, used to generate Cartesian matter power spectra, then subsequently transformed to SFB power spectra with primordial non-Gaussianity, f_{NL} , and bias parameter modeling. After completion, this software will provide a widely accessible rapidly iterable surrogate for classical Boltzmann solvers, and will provide increased accuracy in constraining cosmological parameters by enabling improved data isolation and mode cuts. Future applications include applying our SFB power spectrum emulator to eBOSS cosmological surveys, and applications to SPHEREx to forecast their sensitivity to dark energy parameters, namely w_0 and w_a .

LIP-guided reinforcement learning for robust and efficient bipedal locomotion

Timothy Kennedy

Mentors: Aaron D. Ames and Kejun Li

State-of-the-art locomotion controllers for bipedal robots often fall into one of two categories: model-free reinforcement learning (RL) controllers and model-based feedback controllers. Both of these options come with downsides, where RL controllers can be computationally expensive and have a high sim-to-real gap, whereas model-based controllers often lack robustness to unmodelled dynamics and terrain variations. We propose a hybrid framework that embeds a reduced-order linear inverted pendulum (LIP) model into the RL reward through a control-Lyapunov-function (CLF) term. The CLF steers learning towards LIP-consistent trajectories while preserving RL's flexibility. On the Unitree G1 humanoid, our method reduces cost of transport by 34% and position error by 75% relative to pure RL, outperforming both baselines in robustness, accuracy, and energy efficiency.

Investigating localization using wavepacket dynamics on quantum computers

Melody Lee

Mentors: John P. Preskill and Roland Farrell

While the dynamics of single particles are simulatable on classical computers, these simulations become exponentially complex when scaled to include many interacting particles. The nature of quantum computers, however, makes them ideal for tackling such problems. In particular, we study disorder-induced localization, which lends insight into key phenomena such as thermalization. In this project, we introduce a novel approach to probing localization as a function of energy by studying the time evolution of energy-dependent wavepackets. First, we compare several wavepacket preparation methods with a tradeoff between circuit depth and number of mid-circuit measurements. Using the 56-qubit H2-2 Quantinuum device, we prepare and time evolve wavepackets on an 8 by 7 lattice. We present a new bit flip error mitigation method that leverages maximum likelihood estimation. From the mitigated results, we observe a clear distinction between high and low energy wavepacket dynamics that is due to disorder. By fine-tuning the disorder with a quasiperiodic function, we study the single-particle mobility edge (SPME) in one dimension on a 120-qubit IBM device. We extend this to the many-particle system at half-filling, which provides insight into the stability of the SPME with interactions. This shows a promising new direction for modeling complex transport dynamics.

Connecting the dots: Searching for Little Red Dot analogs in nearby bright compact galaxies

Robert J. Mailliard

Mentors: Fiona A. Harrison and Peter Boorman

The *James Webb Space Telescope (JWST)* has revealed an unexpected abundance of extremely bright compact red galaxies, named Little Red Dots, in the early universe. Little Red Dots are a new class of galaxies that no other telescope has detected previously. Thus, not much is known about how Little Red Dots fit into the evolution and creation of galaxies we know today as well as the growth of supermassive black holes. Less sensitive telescopes than *JWST* would stand a better chance of detecting Little Red Dots nearby, but so far Little Red Dots seem to be nonexistent in the nearby universe. Therefore, we ask if Little Red Dots are hiding among archival datasets of nearby bright compact galaxies. Luckily, Little Red Dots have a unique photometric property of being very blue in the ultraviolet and very red in the optical, which allows us to identify candidates within other bright compact galaxies. We have thus extracted multiple archival samples of bright compact galaxies and created an algorithm to statistically compare each with the typical photometric properties of Little Red Dots. By combining our method with the largest sample of bright compact galaxies known to date, we aim to create the first statistical basis for connecting Little Red Dots to the nearby universe.

Investigating the non-canonical binding interface between NEIL3 glycosylase and PCNA

Sophia R. Martinez-Whitman

Mentors: Daniel R. Semlow and Richa Nigam

DNA interstrand cross-links (ICLs) are highly toxic lesions that stall DNA replication and must be resolved to preserve genome integrity. NEIL3, a DNA glycosylase, initiates the repair of certain ICLs by cleaving glycosidic bond without disrupting the DNA backbone. This summer, I am investigating how NEIL3 interacts with the replication processivity factor PCNA, which is known to bind at a non-canonical interface within NEIL3's glycosylase domain. Using pre-constructed NEIL3 plasmids containing alanine substitutions in this domain, I am expressing and purifying wild-type and mutant NEIL3 proteins in *E. coli*. After optimizing induction and purification conditions, I successfully purified wild-type NEIL3 and several individual mutants using nickel affinity chromatography. *In vitro* pull-down assays will compare the ability of wild-type and mutant NEIL3 to bind PCNA. Loss of binding in specific mutants will help identify residues critical for this interaction. These studies aim to define the non-canonical NEIL3-PCNA binding interface and provide insight into how NEIL3 is regulated during ICL repair.

Lab-based growth and spectroscopic analysis of temperate seagrass and macroalgae

Maricellyn L. McDonald

Mentors: Victoria J. Orphan, Daniel Utter, John S. Magyar, and Kelly Luis

Submerged aquatic vegetation serves a key role in coastal ecosystems as an element of the habitat and a food source for many marine organisms. Additionally, seagrasses, like *Zostera marina*, are known to play a key role in carbon sequestering. Despite the known ecological services of seagrass and other aquatic vegetation, current monitoring approaches present challenges in consistency, standardization, and efficiency. A promising alternative to traditional methods is the use of spectroscopic instruments which can both map the presence of aquatic vegetation and provide insight to its health. This project examines the visible to near-infrared spectra of seagrass and macroalgae grown in lab-based tanks, addressing two key problems: how do the spectra of varying aquatic vegetation differ and what is the best approach to perform lab-based visible to near infrared spectroscopy on live marine samples? This is addressed in two concurrent phases; the growth and monitoring of macroalgae and seagrass in the lab setting and the assembly of an imaging box for the collection of spectral data. Ultimately the project aims to create an ongoing catalog of lab-based spectral data to inform the interpretation of spectral data collected in the field.

Type II AGN at $z \sim 2-3$

Ricardo J. Mendez

Mentor: Charles C. Steidel

The discovery of ubiquitous Ly α emission around quasars (QSOs) at redshifts (z) $\sim 2-3$ has allowed for direct probes of the Circumgalactic medium (CGM). This project aims to characterize ultraviolet (UV) emission at CGM-scales around Type II active galactic nuclei (AGN). The role of AGN feedback in regulating galaxy evolution is still largely misunderstood, and this project aims to improve our understanding of AGN at peak star-formation. We primarily use Keck Cosmic Web Imager (KCWI) integral field unit (IFU) observations in the UV rest frame we are able to characterize both the spatial and spectral dimensions of the Ly α nebulae. In addition to KCWI, ancillary optical spectroscopy and imaging from Keck/MOSFIRE and *Hubble Space Telescope* Wide Field Camera 3, are utilized in order to better constrain the kinematics and physical properties of the CGM around these objects. These observations will then be compared against the nebulae of Type I AGN in the sample. Comparisons of kinematics, linewidths, and spatial extent will be made. The strength and shape of the emission at radial distances will also illuminate clues about the ionization sources and physical morphology of the host galaxies.

Investigating the substrate specificity of O-GlcNAc transferase (OGT)

Jesus E. Mendoza

Mentors: Linda C. Hsieh-Wilson and Maia Helderbrand

The addition of O-linked β -*N*-acetylglucosamine (O-GlcNAcylation) to serine or threonine residue in proteins is involved in a variety of cellular processes, with its dysregulation being linked to the onset of various neurodegenerative diseases. The addition of this sugar is catalyzed solely by the enzyme, O-GlcNAc transferase (OGT), which poses the question of how OGT can selectively glycosylate many different substrates. The adaptor protein hypothesis proposes that OGT can interact with specific interactors or "adaptor proteins" which guide OGT to specific locations and substrates. We focused on two putative adaptor protein candidates, DDX6 and ATXN2, which were identified through our lab's previously generated NOTISE proteomics networks. We then generated DDX6 knockout (KO) and ATXN2 KO HEK293T cell lines through CRISPR/Cas9 and fluorescence-activated cell sorting (FACS). These cell lines were then validated via western blotting and lysed for downstream chemoenzymatic labeling and enrichment for mass spectrometry-based proteomic analyses. If DDX6 or ATXN2 are adaptor proteins, we expect to observe changes to O-GlcNAcylation on specific substrates in the KO lines compared to the control. Deeper investigation into this mechanism can guide new interventions that selectively modify O-GlcNAcylation events by targeting OGT to specific substrates, especially in pathways that are implicated in neurodegenerative diseases.

Mechanical characterization and eutectic impact on additively manufactured ceramic composites for space exploration

Fernando Milach Teixeira

Mentors: Katherine T. Faber and Zachary Chase

Space exploration poses many challenges for material performance. Materials expected to endure these challenges require extreme thermal, radiation, and corrosion resistance. A novel, hybrid process combines laser-powder bed fusion and reaction bonding manufacturing techniques, creating advanced ceramic composites comprised of alumina and yttria-stabilized zirconia. Mechanical characteristics of the material produced via this route are unknown, particularly with the addition of an indium-gallium eutectic to the material during the sintering process to enhance the wetting of alumina and reduce porosity. I aim to characterize the mechanical properties of the composite and the impact of the eutectic on such properties: specifically, the material's flexure strength, hardness, and elastic moduli using testing methods such as equibiaxial flexure, Vickers hardness, and impulse excitation of vibration testing in conjunction with eutectic diffusion experiments. Initial eutectic diffusion experiments show no gravitational influence on the diffusion of the eutectic but reveal unexpected cracking, linked to inconsistencies with the laser-powder bed fusion process. Preliminary mechanical tests indicate a low flexural strength due to porosity, cracking, and challenges with sample preparation of the material. Despite complications, this research lays the groundwork for optimizing ceramic composites manufactured for extreme environments and drives innovation for novel fabrication strategies for aerospace-grade materials.

Biochemical characterization of UFD-3/PLAA intrinsically disordered regions and their role in neurodegenerative pathogenesis

Marc Moroz

Mentors: Tsui-Fen Chou and Yanping Qiu

Phospholipase A2 Activating protein (PLAA) is a co-factor of Valosin-Containing protein (VCP), a protein that is necessary for the function of the Endoplasmic Reticulum-Associated Degradation (ERAD) pathway. Through this relationship, mutations in PLAA are known to play a role in the pathogenesis of Degradation-Associated Neurodegenerative Disorders (DAND). However, *Caenorhabditis elegans* (*C. elegans*) with mutations in the intrinsically disordered region (IDR) of Ubiquitin Fusion Degradation protein 3 (UFD-3), the *C. elegans* homolog of PLAA, demonstrated inhibited formation of p-bodies—a symptom of DAND—and a direct interaction with mRNA Decapping enzyme 1 (DCAP-1) seemingly independently of Cell Division Cycle protein 48 (CDC-48.2), the VCP *C. elegans* ortholog. Investigating this mechanism may reveal a neurodegenerative role for UFD-3 independent of CDC-48.2. As a result, this study seeks to learn more about the UFD-3 recruitment of DCAP-1 by characterizing UFD-3 *in vitro*. Protein expression of UFD-3 is in progress for *in vitro* characterization—in the presence of CDC-48.2, which may potentially act as a stabilizing and solubilizing agent. This study will contribute to our knowledge about UFD-3 and hopefully increase our understanding of neurodegenerative diseases.

Interrogating the AtGet3a-AtGet4 interaction in the *Arabidopsis thaliana* guided entry of tail-anchored proteins (GET) pathway

Stanley A. Muñoz

Mentors: William M. Clemons, Jr., and Conner W. Wells

Tail-anchored (TA) proteins are a topologically distinct class of integral membrane proteins that require post-translational targeting by the Guided Entry Tail-anchored (GET) pathway. While this process is well characterized in fungi and metazoans, its mechanism in plants remains poorly understood. In the model organism, *Arabidopsis thaliana*, AtGet3a and AtGet4 are predicted homologs of cytosolic GET pathway components. This project investigates how AtGet4 regulates the ATPase activity of AtGet3a and which conserved residues mediate their interactions. Conserved residues in AtGet3a and AtGet4 were identified through multiple sequence alignment. Mutations were introduced by site-directed mutagenesis, constructs were expressed in *E. coli*, and purified using Ni-NTA affinity chromatography as well as size exclusion chromatography. ATPase and qualitative chromatographic

studies will be performed to assess the significance of these interactions. Understanding the molecular mechanisms between AtGet3a and AtGet4 will provide insight into the evolutionary conservation and divergence of the GET pathway and provide the basis for future structural and functional studies in plants.

ULX marks the spot: Searching for bright UV emission around ultraluminous X-ray sources

Sophia C. Nicolella

Mentors: Fiona A. Harrison and Hannah Earnshaw

Ultraluminous X-Ray Sources (ULXs) are binary star systems exhibiting super-Eddington luminosities and are thought to be candidates for intermediate-mass black holes or magnetized neutron stars accreting matter at super-Eddington rates. However, the process that causes their ultraluminosity is not well-understood, and ULXs are not well studied in the ultraviolet regime, which may be able to tell us about the surrounding environments, formation channels, and life cycles of these types of systems. We created a catalog of bright UV sources corresponding to known ULXs. Using observational data from the Swift UVOT instrument, we analyzed their UV emission to investigate the conditions in which they reside and whether the accreting source itself is UV-bright. Since UV variability and super-Eddington UV luminosities are likely indicative of a ULUV, we generate UV light curves in order to compare them to the X-ray output, identify the best ULUV candidates in the sample, and report on their properties.

Wireless power transfer system for low power, millimeter scale implantable biomedical sensors

John I. Ogbu

Mentors: Azita Emami and Shengsheng Wang

Biomedical sensors are a vital part of many of the high-impact implantable medical devices (IMDs) used in modern healthcare to provide continuous, functional support, early disease diagnosis, and/or drug delivery in targeted tissue or organs. Recently, the Mixed-Mode Integrated Circuits and Systems (MICS) Lab demonstrated an implantable, 3D alternating current (AC) magnetic sensor design that used a magnetic gradient technique to achieve high-resolution sensing in a 65-nm CMOS process. The MICS sensor requires 14.8 μ W of power to operate and common powering solutions, such as discrete batteries or various energy harvesting systems, are unideal due to their ineffectiveness within the intended use cases of the MICS sensor. Here, we present a wireless power transfer (WPT) system that meets the power, size, and longevity demands of the MICS sensor. The system consists of one receiver (RX) coil fabricated in the 65-nm mode on the sensing chip and three external, orthogonal printed circuit board (PCB) spiral transmitter (TX) coils to provide 3D power transfer capabilities. A 13.56MHz AC current is passed through the TX coil(s), which allows us to model the TX coils as RLC resonator tanks using a lumped circuit model. The RX and TX coils are inductively coupled; according to Ampère's Law, the AC current in the TX coil(s) produces a time-varying magnetic field. This field produces time-dependent variations in the magnetic flux of the RX coil. By Faraday's Law, the changing magnetic flux induces a time-varying voltage across the RX coil. This induced voltage produces a current that flows in a direction that, according to Lenz's law, opposes changes in the magnetic flux produced by the TX coil(s), resulting in wireless power transfer via an AC current. The efficiency of this process is heavily dependent on the geometry of the RX and TX coils and determining the ideal geometry of the coils requires solving a multivariate optimization problem. The peripheral power electronics for the system consists of impedance matching networks on both the TX and RX sides of the system, a preamplifier on the TX side, and a rectifier and DC-DC converter on the RX side for signal shaping. The on-chip electronics use a supply voltage of 1.2V to match the constraint given by the MICS sensor.

A geologic map of Isla Tortuga: A contribution to the volcanic history of the Guaymas Basin, Gulf of California (México)

Emilia R. Pelegano-Titmuss

Mentors: Joann M. Stock and Adriana Piña-Paez

Isla Tortuga is a young, basaltic volcanic island located in the Guaymas Basin (GB), which is a pull-apart basin in the Gulf of California (GOC) oblique rift system. The GOC is located at the boundary of the Pacific and North America plates and occupies part of an oblique divergent plate boundary. The International Ocean Discovery Program Expedition 385 drilled sediments in the GB and found that sills are intruding into the Quaternary sediments. After fieldwork was done by Caltech on Tortuga, petrographic comparison showed that the sills and samples collected from Tortuga have similar crystal sizes, textures, mineral compositions, and geochemistry. Thus, it was concluded that Tortuga and the sills are part of the same magmatic plumbing system in the GB. Therefore, Isla Tortuga is a key component of the volcanic and tectonic history of the GB. A geologic map of Isla Tortuga has been produced using Quantum Geographic Information System (QGIS). There is no other significant documentation for the geologic units on Isla Tortuga. There are a total of twenty one units on Isla Tortuga, and the geochemical composition of these units provides evidence for the magma recharge event that was proposed to have occurred before the last eruption.

Optimal experimental design for Jupiter's radiation belt

Cristian D. Peña

Mentors: Franca Hoffmann, Aras Bacho, and Kathrin H. Hellmuth

Understanding Jupiter's radiation environment is critical for designing safe and effective spacecraft missions, yet the limited availability of observational data makes their dynamics mostly unknown. This project investigates how mathematical tools can improve the scientific return of spacecraft missions aimed at studying Jupiter's radiation belt. We first model Jupiter's radiation belts using a partial differential equation, the Fokker-Planck equation, whose coefficients must be estimated from sparse data. To estimate these coefficients, we pose a Bayesian inverse problem that incorporates prior knowledge and quantifies uncertainty while inferring model inputs from data. By parameterizing candidate paths and maximizing the determinant of the Fisher Information Matrix, which quantifies trajectory informativeness, we then identify spacecraft paths that offer the greatest potential for reducing model uncertainty. These efforts are supported by the adjoint method, which enables efficient computation of how changes in the model's coefficients influence both its predictions and the informativeness of different designs.

Analysis of the dimethylallyl radical using pulse laser photolysis cavity ring-down spectroscopy

Keaton A. Raney

Mentors: Mitchio Okumura and Kristen Roehling

Polyaromatic hydrocarbons are crucial in processes like combustion and soot formation, and small hydrocarbon radicals are thought to be their precursors. Therefore, species like the three-carbon allyl radical have been the subject of much research. However, the electronically excited *A* state of the allyl radical remains uncharacterized due to its short lifetime. Therefore, looking at similar species could elucidate further understanding of the proposed *A* state. In this work, spectra of dimethylallyl were recorded with a pulse laser photolysis cavity ring-down spectrometer from 410–418 nm. The experiments took place in a flow reactor at 50 torr and 293K. The influence of the two methyl groups on the excited states of the radical were studied. Complete characterization of the electronically excited *A* state of the dimethylallyl radical requires further work.

Bird's eye multi-sensor fusion adaptation for the Indy Autonomous Challenge

Carlos A. Rivas

Mentors: Soon-Jo Chung and Haeyoon Han

One of the primary roadblocks facing large-scale deployment of autonomous vehicles is the varying levels of perception robustness and adaptability to unknown environments. Using the Indy Autonomous Challenge (IAC) as a platform for innovation, this work develops a learning-based perception algorithm for the Indy Autonomous car, which utilizes a LiDAR and cameras via sensor fusion. We first evaluate the baseline LiDAR-based and bounding box approaches, which have limitations in long range situations. To improve the long-range performance, BEVFusion, a learning-based sensor-fusion method, is considered, and we conduct the preliminary evaluation with the pre-trained model. Adjustment of the algorithm specifically for the car will be performed in the future.

Development of a microfluidic platform for uniform cell-laden hydrogel spheres

Ian E. Rocha

Mentors: Julia A. Kornfield, Raj S. Mukkamala, and Rohit Srikanth

The purpose of this research is to develop a microfluidic platform which can consistently create spherical alginate gel droplets with diameters under 300 μm and encapsulated bacterial cells for environmental sensing applications. Early designs were simulated in ANSYS Fluent fluid dynamic software and prototyped using dissolvable 3D printed microfluidic scaffolds embedded in polydimethylsiloxane (PDMS). A fabrication method to create microfluidic devices was developed using 3D printed positive channel molds and curing PDMS layers together, avoiding the usage of soft-lithography or plasma treatment. Thus far, alginate droplets with diameters less than 300 μm have been successfully created using the fabricated chips with either ethyl acetate or mineral oil as the continuous phase. Future work will focus on gelling created droplets, analyzing their physical shape and characteristics, and encapsulating bacteria into droplets.

Health-aware optimal power flow

Elizabeth L. Rogers

Mentors: Adam C. Wierman and Nicolas Christianson

Electric grid operators rely on optimal power flow (OPF) models to manage the power grid. Typical OPF models aim to minimize the economic cost of grid operation, subject to the physical power flow constraints. In this work, we are interested in extending OPF to account for negative externalities imposed by electricity generation. Whereas recent work has extended OPF to account for carbon emissions, we focus on the health effects associated with power generation, specifically those caused by ambient fine particulate matter and ozone air pollution concentrations. Thus, we introduce a Health-Aware Optimal Power Flow (H-OPF) model, which aims to minimize the combined economic cost of grid operation and public health impact. An adaptation of the Carbon-Aware OPF model, our H-OPF model proposes generalized emission flow equations and constraints, allowing for flexibility in application-specific implementation. Finally, we examine a synthesized power grid managed using the H-OPF, Carbon-Aware OPF, and DC-OPF schemes, respectively, and provide a comparison of their load management decisions and overall health impacts.

Numerical simulation and analysis of homogenized material properties arising from random microstructures

Rodolfo A. Ruiz

Mentors: Kaushik Bhattacharya and Harkirat Singh

Numerical simulation of material response to external stimulation (e.g., loading and heating) can be expensive because a numerical solver must resolve details on the scale of the material's microstructure when solving a problem that typically deals with much larger scales. A process called homogenization lets us estimate the solution to a differential equation of interest at a much lower computational cost by eliminating the scale of the microstructure and approximating the multi-phase system with one homogenized material property. In this project, random microstructures that consist of circles of one phase embedded in a different phase will be generated, and their homogenized

properties will be solved numerically. By varying characteristics of the microstructure, such as volume fraction, number of circles, and material property contrast, we aim to identify conditions under which a limited number of statistical properties of randomly generated microstructures are sufficient to predict the statistics of the homogenized material properties accurately.

Mode-resolved study of electron-phonon interactions in monolayer and bilayer MoS₂

Siam Sarower

Mentors: Marco Bernardi and David Abramovitch

MoS₂ is a two-dimensional (2D) direct band gap semi-conductor from the transition metal dichalcogenide (TMD) family, and it can be arranged into a bilayer to provide a transition to an indirect band gap semi-conductor. Recently, we found that electron-phonon (e-ph) interactions in MoS₂ at the valence band maxima is primarily mediated by longitudinal-acoustic (LA) and z-optical (ZO) modes for intervalley scattering, while intravalley scattering is dominated only by the ZO mode. However, a detailed understanding of which phonon modes control electron-phonon scattering and pairing interactions is lacking for both monolayer and bilayer structures. This motivated us to explore the role of mode-dependent e-ph interactions on scattering and coupling strengths in monolayer and bilayer MoS₂ via first-principles calculations. Here, we investigate which phonon modes contribute significantly to intra and intervalley coupling at the valence and conduction band extrema. Moreover, we provide what phonon modes contribute to intra and interlayer coupling in AA and AB stacked bilayer MoS₂.

Effects of oxytocin receptor knockdown in cholecystinin A receptor-expressing neurons in the ventromedial ventrolateral hypothalamus on female sexual learning and motivation in female mice

Raquel S. Schlichting

Mentors: David J. Anderson and Emma Boxer

Female sexual learning and motivation are regulated by complex interactions between neuropeptide and neurotransmitter signaling, yet the specific contributions of oxytocin remain unclear. To investigate this, we performed a targeted knockdown of the oxytocin receptor (OxTR-KD) in the ventrolateral subdivision of the ventromedial hypothalamus (VMHvl), focusing on neurons expressing the cholecystinin A receptor (CCKar), which have been implicated in female sexual behavior. Using an adeno-associated virus (AAV) delivering CRISPR-Cas9, we bilaterally targeted VMHvl CCKar-expressing neurons in sexually naïve female mice (n = 8). Each of the experimental (n=4) and control (n=4) mice underwent two mating assays during proestrus, followed by a week of co-housing with males to increase sexual experience, then were reassessed. Behavioral interactions were annotated using Bento, a MATLAB-based analysis platform, and subsequently quantified. Preliminary data indicate that sexual receptivity was reduced in the OxTR-KD animals, as evidenced by higher rejection rates compared to controls. This suggests that oxytocin signaling in VMHvl CCKar neurons play a role in sexual behavior in female mice. Ongoing experiments will test these findings further by administering an oxytocin injection to wild-type females and performing additional mating assays.

Engineering a tunable American flag pattern using a reaction diffusion model

Eric F. Segrest

Mentors: Erik Winfree and Daichi Hayakawa

Reaction diffusion systems are a crucial biochemical mechanism used for encoding information without explicit genetic instruction. These systems are a set of chemical reactions that occur between slowly diffusing chemicals, allowing for local behavior and pattern formation. The ability to engineer reaction-diffusion systems to match a target spatial pattern demonstrates a high-level understanding of how these systems function. This study will demonstrate the design and theoretical physical implementation of an American flag reaction diffusion pattern while minimizing the information required to describe the system. The caveat to reducing information allows the system to be physically feasible by allowing some finite error rather than infinite theoretical precision. The tools used in this analysis include the icrn Python package as well as VisualPDE. This study describes an American Flag bound by a circle rather than a rectangle, with a scale defined by the reaction diffusion system. This system is well understood, and various specifications may be fine-tuned. By modifying the diffusion

constants and reaction rates, the scale of the large circle, small spots, thickness, and repelling properties of the stripes, and more, may be easily controlled. These findings may support future research in understanding biological applications of reaction diffusion systems, as well as implementing reaction diffusion systems in non-biological systems for efficient information encoding.

Investigating the origin of radio emission in SN 2021bmf: Off-axis GRB or circumstellar interaction?

Grace Showerman

Mentors: Gregg W. Hallinan and Jessie M. Miller

We present a multi-wavelength analysis of the broad-lined Type Ic supernova (SN Ic-BL) SN 2021bmf aimed at determining the origin of its bright radio emission. Using observations from the Karl G. Jansky Very Large Array (VLA) in L, S, C, and X bands, we construct a broadband radio spectrum from twelve sub-bands after careful flagging and calibration. The spectrum is well described by a synchrotron self-absorption model, with a peak flux density of $S_{\max} = 14.6 \pm 0.2$ mJy at 6.5 GHz. Parameter estimation using nested sampling with dynesty constrains both the spectral indices and peak properties, confirming that the observed emission is inconsistent with expectations for an off-axis gamma-ray burst (GRB) jet. Instead, the data is best explained by strong interaction between the SN ejecta and a dense circumstellar medium (CSM). This conclusion is supported by Keck LRIS spectroscopy, which reveals emission line evolution that is consistent with ongoing CSM interaction. Taken together, our results demonstrate that the luminous radio emission in SN 2021bmf likely arises from a dense CSM environment rather than a hidden GRB.

Selectivity in palladium-catalyzed CDC of substituted pyrroles for (+)-cyanocycline A synthesis

Neiman C. Sneed

Mentors: Brian M. Stoltz and Bryce E. Gaskins

Cyanocycline A is a complex natural product with notable anticancer and antitumor activity. Its total synthesis presents multiple challenges due to its densely substituted ring system. A key step in the synthetic plan involves forming a Carbon–Carbon bond between a pyrrole and a pyridine N-oxide via a palladium-catalyzed cross-dehydrogenative coupling (CDC) which enables direct C–H activation without pre-functionalization. This project examined how changes in reaction order and catalytic conditions influence the regioselectivity of the CDC step. Reactions were carried out under inert atmosphere using various oxidant ligand combinations, and products were monitored and analyzed by TLC, flash chromatography, and ^1H NMR. These efforts aim to identify conditions that favor selective arylation at the desired position on the pyrrole, contributing to broader advances in C–H functionalization and highlighting the impact of electronic and steric effects on catalyst-controlled site selectivity.

Methane mosaics: Architecture of ANME-SRB mat aggregates

Lily P. Strange

Mentors: Victoria J. Orphan and Daniel Utter

Anaerobic oxidation of methane (AOM) occurs in microbial communities composed of anaerobic methanotrophic archaea (ANME) and their sulfur reducing bacterial partners (SRB) that together form syntrophic aggregates. These consortia are incredibly diverse in phylogenetic distribution and spatial structure, even forming 1-5 cm microbial mats, an invaluable structure to study the physiology and ecology of ANME. Recently, ANME-SRB mats were discovered and sampled at a methane seep off the coast of Santa Monica. However, the spatial and phylogenetic organization of these mats has remained largely uncharacterized. Therefore, we employed fluorescent in situ hybridization (FISH) and microscopy to visualize the spatial distribution of different ANME clades (e.g. ANME-2b, ANME-2c), SRB bacteria, and aggregates throughout the mat. We also used fluorescent stains targeting DNA, lipids, and glycoproteins to identify compositions of the extracellular matrices organizing individual

aggregates into larger mat structures. Preliminary investigation revealed complexity and diversity of taxon arrangements and matrix materials beyond expectations of an organized structure. Image statistics and aggregate classification are expected to reveal distinct patterns that may inform future studies on these samples.

Fabrication of helical trilayer graphene, a two-dimensional material with exotic electronic and topological properties

Jamie Talmor

Mentor: Stevan Nadj-Perge

Helical trilayer graphene (HTG) is a two-dimensional material formed by stacking three layers of graphene, with a twist angle between each layer. The rotational misalignment between layers results in moiré patterns; with lattice relaxation, the moiré patterns form a supermoiré lattice and intrinsically break C_{2z} symmetry at the moiré scale. L. Xia *et al.* showed that, at a magic angle of 1.8° , HTG forms topological flat bands, leading to exotic electronic and topological properties such as the anomalous Hall effect and correlated states at multiple integer and fractional fillings. This makes HTG a promising platform in the study of strongly correlated electronic systems in quantum materials. Here, we demonstrate the experimental realization of HTG devices. Graphite is exfoliated to obtain atomically thin graphene flakes, which are stacked using a stacking stage to form HTG. Additional graphite flakes and hexagonal boron nitride layers form the bottom gate, which dopes electrons and induces a displacement field into the device. Future work will use scanning tunneling microscopy to directly image the supermoiré lattice and measure the density of states in HTG.

Carbon-carbon bond formation from unactivated sp^3 C-H bonds via samarium(II)

Athena Thai

Mentors: Sarah E. Reisman and Nathan C. Friede

Catalytic samarium(II) chemistry offers a promising pathway for carbon-carbon bond formation under mild and sustainable conditions, but practical implementation is limited by poor catalyst turnover and extreme sensitivity to coordination effects. This project investigates a dual catalytic system that combines visible-light photoredox activation with samarium(II)-mediated radical capture to achieve C-C bond formation from unactivated sp^3 C-H nucleophiles and ketone electrophiles. Using benzylacetone and tetrahydrofuran (THF) as model substrates, a systematic reaction screening approach was used to optimize photocatalyst loading, hydrogen atom transfer (HAT) catalyst structure, substrate stoichiometry, and additive compatibility. Quinuclidinyl benzenesulfonate at 1.0 equivalent was found to balance radical generation while minimizing catalyst inhibition from over-coordination. Optimal reactivity was observed using samarium triflate (1.0 equiv), a tertiary amine HAT catalyst (1.0 equiv), an iridium-based photocatalyst (2 mol%), and 5 equivalents of THF under strictly moisture-free conditions in acetonitrile, irradiated at 450 nm for 2 hours, achieving yields up to 45%. Coordination effects, including those from additives, HAT catalysts, and THF concentration, strongly influenced samarium solubility and reactivity. These findings define key parameters for improving reactivity, radical capture, and catalyst turnover, laying the foundation for future development of chiral or asymmetric systems.

A survey of data-driven techniques for network inference

Owen M. Tolbert

Mentors: Andrew M. Stuart and George Stepaniants

Networks are a crucial component of research across various scientific disciplines, and inferring the connectivity of those networks with sparse observational data is a pertinent challenge. Here we explore methods from causal inference and machine learning to solve this problem. We begin by studying the Synergistic, Unique, Redundant, Decomposition (SURD) framework to causally infer the connections between nodes in a networked dynamical system. In this direction, our results are inconclusive as the SURD framework does not infer unique dependencies between nodes and does not

scale to larger network sizes. Next we explore the use of neural network architectures, specifically variational autoencoders, to recover network connectivity from time series data. Our preliminary experiments apply these methods to networks of mass-spring and Kuramoto oscillators, showing how they infer the structure of linear as well as nonlinear dynamical systems.

Optimizing electrode and cladding design for high-efficiency lithium niobate electro-optic modulators

Deven K. Tseng

Mentors: Alireza Marandi and Benjamin Gutierrez

Electro-optic modulators (EOMs) leverage the Pockels effect in materials such as lithium niobate to modulate the refractive index under an applied electric field. These high speed, efficient EOMs enable precise optical phase control which has led to many applications such as integrated mode-locked lasers. Prior work by Guo et al. demonstrated an on-chip actively mode locked laser using EOMs with simulated modulation efficiency of $V_{\pi}L = 1.1 \text{ V cm}$. To advance towards more robust and efficient mode-locked lasers, EOMs must achieve a low $V_{\pi}L$ while maintaining low optical loss. In this work, the dependence of $V_{\pi}L$ and loss on electrode spacing and oxide cladding thickness is explored through simulation in Lumerical CHARGE and FEEM solvers. EOMs with varying device geometries were fabricated, and ongoing work focuses on characterizing these devices and comparing experimental results with simulation to inform future designs of high performance modulators and mode-locked lasers.

Expanding the scope of C(sp²)-F bond activation processes facilitated by light-absorbing Ni-based complexes

Annalissa Valdez

Mentors: Ryan G. Hadt, Jacob O. Rothbaum, and Maria Blankemeyer

Photocatalysis has gained significant attention as a useful tool for aiding the development of new reactivities in organic synthesis. Moreover, merging thermal catalysis with photochemistry has had a profound impact in facilitating challenging sp²-sp² and sp³-sp³ C-C or C-X coupling reactions. The Hadt group synthesized (t-Bubpy)Ni(II)(p-tetrafluoropyridyl)₂ and characterized the complex using single-crystal X-ray diffraction, NMR, and mass spectrometry. Preliminary mechanistic studies suggest its formation via multimolecular, para-selective C(sp²)-F activation of pentafluoropyridine. The complex is air- and moisture-stable under ambient conditions and undergoes a clean C-C bond-forming transformation upon visible light irradiation at room temperature. Furthermore, Ni(p-PyF₄)₂(t-Bubpy) activates stronger C(sp²)-F bonds, thus broadening the substrate scope of Ni-mediated C(sp²)-F activation. Fluorimeter and UV-Vis spectroscopy was utilized to analyze photophysical properties. Absorbance spectra show charge transfer bands and a λ_{max} at 370nm, consistent with a metal-to-ligand charge transfer (MLCT) transition. Emissions observed between 450-550 nm indicate the formation of an emissive species.

Towards a mechanistic characterization of type II single gene lysis proteins via *in vivo* and *in silico* approaches

Diego Antonio Velazquez Vargas

Mentors: William M. Clemons, Jr., and Roujon Nowzari

Single stranded RNA (ssRNA) bacteriophages are viruses that exert bacterial autolysis by the expression of a single protein, referred to as Single Gene Lysis proteins (SGLs). These proteins can be categorized based on their mode of action: while type I SGL disrupt the synthesis of bacterial cell wall, type II induce host lysis without affecting the net production of peptidoglycan. Although Type II SGLs have been extensively studied since the discovery of the lysis protein L from ssRNA phage MS2 (almost 50 years ago), their lytic mechanism remains a long-standing unresolved question, whether it involves enzyme inhibition, pore-like structure formation, or entirely novel interactions. To clarify these possibilities, we aim to apply a dual *in vivo* and *in silico* approach. The first approach involves fusing the lysis proteins to MiniTurboID, an enzyme that labels proteins in a $\sim 10 \text{ nm}$ radius, which may identify possible targets of type II SGLs. In parallel, we conducted molecular dynamics simulations using GROMACS to model L oligomerization within a lipid bilayer, aiming to show its

impact on membrane stability. These experiments may help clarify the lytic mechanism of L, contribute to the characterization of other type II SGLs, and ultimately support combating multidrug-resistant bacteria.

Grand canonical quantum mechanics study for CO₂RR on PcFe MOF catalyst

Samhitha Venkat

Mentors: William A. Goddard III and Sejun Kim

As reducing CO₂ levels becomes increasingly important to curbing greenhouse gas emissions, the electrochemical reduction of CO₂ to form hydrocarbon products offers a promising route to achieving this goal. While Cu-based catalysts are able to produce significant quantities of methane and ethylene, catalysts that operate at lower overpotentials and achieve greater product selectivity are required for electrochemical reduction to become industrially viable. This study investigates the effectiveness of a phthalocyanine based two-dimensional metal-organic framework with Fe active sites in catalyzing methane and ethylene products using the grand canonical DFT method. We have thus far obtained intermediates for the proposed reaction pathway for methane formation. Further calculations are required to obtain a complete energy profile for the methane and ethylene formation pathways.

Investigating the regenerative capacity of the craniofacial neural crest

Azucena K. Virgen

Mentors: Marianne Bronner and Tatiana Solovieva

The neural crest (NC) is a highly migratory and multipotent embryonic stem cell lineage that contributes to the development of the heart, craniofacial structures, peripheral nervous system, and more. NC disruptions in the chick embryo model can result in defects comparable to human developmental defects, like Treacher Collins and DiGeorge syndrome. Despite the prevalence of congenital craniofacial defects, previous literature suggests that surgically ablated NC populations can regenerate, depending on the timing and extent of surgical ablation. We aim to resolve the spatial and temporal regenerative capacity of the craniofacial NC to further investigate the cellular origin and mechanism of regeneration. We will use the chicken embryo as a model due to its similarity to early human embryonic development and its accessibility to experimental perturbations. We hypothesize that craniofacial NC has a higher regenerative potential in earlier developmental stages, before migration into surrounding tissues. To test this, we will perform varying surgical ablations of cranial NC at different developmental stages. After ablation, we will use NC-specific antibodies to visualize any NC regeneration 3 to 18 hours post ablation. These findings will inform future studies to identify the cellular mechanism involved in NC regeneration and craniofacial development.

Examining the $\delta^{15}\text{N}$ composition of fungi and lichen amino acids

Claire Xu

Mentors: Julia Tejada and Mattia Tagliavento

Establishing the trophic positions of organisms is crucial for understanding ecosystem structure and species interactions. Recently, amino acid stable isotope analysis has emerged as a method for determining trophic position through comparing the isotopic value of "source" amino acids—those that experience little or no trophic fractionation and thus provide an internally referenced nitrogen baseline (e.g., phenylalanine)—to "trophic" amino acids—those that do fractionate when moving between trophic levels (e.g., glutamic acid). While some primary dietary sources, such as plants and algae, are isotopically well-characterized, others, namely fungi and lichens, remain understudied despite serving as key food sources and nutrient cyclers. Constraining their isotopic value is critical for accurate interpretations of the isotopic signals of their consumers and establishing a modern baseline for interpreting ancient ecosystems.

Here, we present $\delta^{15}\text{N}$ measurements of amino acids of mushrooms and lichen from Southern California. In addition to applying classic linear regressions, we performed unsupervised cluster analyses on our data, as well as our data in combination with published isotopic values for primary producers and consumers. We aim to get insights into trophic dynamics, nitrogen uptake, and metabolism among mushroom and lichen species.

Constraining the lithification conditions for Martian regolith breccia using shock recovery experiments

Audrey Yin

Mentors: Paul D. Asimow and Jinping Hu

The meteorite Northwest Africa (NWA) 7034 and its paired stones are the only samples on Earth representative of the near-surface martian crust and are classified as a polymict breccia. Due to the variety of clast types and partial/full resetting of chronometric systems, the history of the meteorite is complicated, making it difficult to pinpoint a time and the conditions for lithification. Uniquely, NWA 7034 contains only crystalline plagioclase, rather than maskelynite, which defines a firm upper bound of < 20 GPa for the stone's shock pressure. We performed shock recovery experiments on martian regolith analog in order to constrain the pressure-temperature conditions for lithification without maskelynite formation. Analysis of recovered samples demonstrate that powdered basaltic analog can be lithified at a pressure of $6 \pm 1/-3$ GPa. The samples record partial preservation of plagioclase crystallinity and a transition from more crystalline plagioclase closer to the impact crater to increased maskelynite formation closer to the back wall of the recovery chamber, due to the reflected shock off the back wall to a higher pressure. We also tested a novel recovery chamber design with in situ pressure gauges, and additional test shot(s) will be carried out before use with another powdered rock sample. This work contributes to the overall understanding of NWA 7034's lithification timeline, broader impact processes, and the history of the martian near-surface environment.

Behavioral and immunological consequences of excessive sugar intake

Barbara I. Ayala

Mentors: Yuki Oka and Yameng Zhang

Sugar is an essential dietary carbohydrate, fundamental for living organisms, but its overconsumption has become a major contributor to global health deterioration. Currently, the typical American adult exceeds the recommended daily sugar intake by 50%. This excess disrupts systems involved in maintaining homeostasis, such as the immune system or neural circuits. Recent studies have associated sugar-rich diets with the development of a systemic proinflammatory state and immunocompromised conditions. For this reason, this project aims to create a mouse model that mimics long-term excessive intake of three common sources of sweetness in the American diet: glucose, sucrose, and acesulfame potassium (AceK), an artificial non-caloric sweetener. Using a standardized paradigm, we trained mice with sweet solutions under deprived conditions to model sugar overconsumption. Preliminary preference results suggest that, after restriction, mice exhibit ingestive behavior that exceeds their energy needs, showing a clear bias toward higher-caloric solutions such as glucose over water or non-caloric sweeteners. To assess the long-term effects of this behavior, we will evaluate systemic inflammation and neuronal activity in satiety-related brain regions following chronic sugar exposure. Molecular analyses such as qPCR and ELISA will be used to link consumption patterns with pathological mechanisms associated with chronic disease risk.

Expanding in-situ capabilities of a table-top soft X-Ray absorption spectrometer for probing electrocatalyst electronic structure

Jacob A. Cho

Mentors: Scott K. Cushing and Alejandro Arellano

Soft X-ray absorption spectroscopy (SXAS) is an element-specific technique for probing the local electronic and geometric structure of materials, making it ideal for studying catalytic systems under operating conditions. *In-situ* and *operando* SXAS further improves the versatility of the technique by revealing changes in oxidation state, bonding environment, and active-site structure during electrochemical reactions, providing critical insight into catalytic mechanisms. This project aims to expand the *in-situ* capabilities of the Cushing Lab's table-top SXAS system through the design and implementation of a vacuum-compatible adapter that integrates both a commercial liquid electrochemical TEM holder and a static TEM holder with the beamline. In parallel, static SXAS measurements of nitrogen-substituted pyridinium (NsP) films electrodeposited on silver electrodes were conducted to establish baseline spectra of the C K-edge, N K-edge, and Ag M_{4,5}-edges. These systems are of interest because NsP films have been shown to suppress the hydrogen evolution reaction during CO₂ reduction, enabling highly selective CO production, and is a viable candidate for *in-situ* SXAS on the table-top. The adapter will ultimately enable *in-situ* and *operando* gas- and liquid-phase SXAS measurements, allowing real-time tracking of electronic structure changes during catalysis. By improving the flexibility and accessibility of *in-situ* SXAS in a lab-scale setting, this work aims to accelerate the study of catalytic materials and inform the design of more efficient systems for CO₂ conversion and other energy-relevant reactions.

Using eye-tracking to investigate social attention in autism

Nishimwe Joise

Mentors: Ralph Adolphs and Brenna Outten

Atypical eye gaze behavior is one of the earliest signs of autism spectrum disorder (ASD), and yet most research on social attention in ASD is conducted in laboratory settings that lack external validity. This project utilizes eye-tracking technology and face-based stimuli that become increasingly naturalistic, from static images to real-world face-to-face interactions, to explore how individuals with ASD attend to social cues. To establish a reproducible experimental set-up, we piloted our experimental procedure with neurotypical and ASD participants using the Pupil Labs Neon Eye-Tracking glasses. Piloting aids in the methodological refinements that will inform areas of adjustment for the upcoming study and ensure a reliable experimental setup that can influence future research on how individuals with ASD engage with social stimuli. More broadly, this work may have implications for ASD diagnosis and intervention that leverage eye-tracking technology.

Characterizing sacral-derived progenitors of the developing enteric nervous system

Mandoline H. Nguyen

Mentors: Marianne Bronner and Jessica Jacobs-Li

Commonly referred to as the “second brain”, the enteric nervous system (ENS) consists of neurons and glia which regulate gastrointestinal function. The ENS is derived from two distinct subpopulations of the neural crest, the vagal and sacral. While both populations contribute to the ENS of the post-umbilical intestine, their differences remain poorly characterized. Our lab’s single-cell RNA sequencing of post-umbilical sacral neural crest-derived cells revealed an absence of a progenitor cluster in contrast to vagal-derived populations. Despite lacking this progenitor pool, the sacral crest still gives rise to neurons and glia indicating differences in developmental trajectory and timing. These findings, along with prior studies showing that mature enteric glia can revert to a progenitor state, suggest that sacral-derived glia may serve as a neuronal progenitor pool. We hypothesize that sacral-derived progenitors exhibit a non-canonical state where neuronal, glial, and neural crest markers are co-expressed. To test our hypothesis, we performed indirect antibody staining on transverse sections of the chicken gastrointestinal tract across developmental stages. Additionally, we utilized DiI-mediated lineage labeling of the premigratory sacral neural crest to identify primitive sacral structures and assess co-localization of progenitor and glial markers at earlier stages of development.

Radical-based deoxygenation of alcohols via visible-light irradiation of a titanium-porphyrin complex

Sophia Razavi

Mentors: Brian M. Stoltz and Benjamin Gross

The deoxygenation of alcohols is a fundamental transformation in organic synthesis that enables the selective removal of oxygen groups to yield hydrocarbons. Inspired by the oxygen transport and activating functions of iron-containing porphyrins such as heme, we are developing a titanium-porphyrin complex that performs the reverse process: radical-mediated deoxygenation. Our method centers around radical-based deoxygenation of alcohols and homolytic cleavage, initiated by visible light irradiation of a Ti(IV)-porphyrin complex. Upon photoexcitation with purple LEDs in the presence of an electron and proton donor, the reduced Ti(III) complex serves as the active species for substrate activation, and the alcohols coordinate with the Ti(III)-porphyrin complex enabling homolytic cleavage of the C-O bond.

Elucidation of cpSRP43-GUN4 protein dynamics through proximity-based biophysical techniques

Dennis Rui

Mentors: Shu-ou Shan, Alex R. Siegel, and Yelim Yi

Photosynthetic organisms rely on properly functioning light harvesting complexes (LHCPs) which serve as antennas for photosynthetic complexes to mediate carbon fixation for 99% of the biological energy expenditure on Earth. The proper biogenesis of this pathway is in part mediated by cpSRP43, a conserved molecular chaperone in chloroplasts. It has been shown that cpSRP43 harbors two distinct conformational states: a *closed*, structured state dedicated to the *de novo* biogenesis of LHCPs, and an *open*, disordered conformation, which protects tetrapyrrole biosynthesis (TBS) enzymes that mediate chlorophyll synthesis from heat-induced destabilization. However, the mechanism behind the client recognition of cpSRP43 is not well understood. A combination of biophysical approaches, namely XL-MS, NMR, and fluorescence (specifically FRET) spectroscopies, will be used to provide the first molecular model of how the conformation-dependent chaperone activities of cpSRP43 can recognize and remodel mature TBS enzymes to reshape their aggregation behavior during heat stress. Specifically, we aim to identify the molecular interactions between the disordered *open* conformation of cpSRP43 and GUN4, a well-characterized TBS client that serves as an accessible model system. Elucidating these molecular mechanisms will provide insight into the design of engineered proteins with switchable functions and therapeutic strategies targeting protein control pathways.

Synthesis of multimechanophore polymers for the controlled release of COS with a fluorescent reporter and for separate luminescent systems

Hanna P. Shan

Mentors: Maxwell J. Robb and Yu Ling Tseng

Polymer mechanochemistry utilizes mechanical force to drive productive chemical transformations in stress-sensitive molecules called mechanophores. The Robb group has designed a mechanophore that leverages a furan-maleimide Diels-Alder adduct. Upon activation, the mechanophore undergoes a retro-[4+2] cycloaddition, resulting in a reactive furan intermediate that decomposes in polar protic solvents to release a covalently bound cargo. Multimechanophore polymers (MMP) are especially attractive since we can trigger multi-mechanophore activation from a single polymer chain to achieve enhanced functional response. The group has developed a modular MMP platform, allowing for swapping attached cargo for diverse responses. I am leveraging this modularity to achieve two distinct functionalities, luminescence and COS release.

Mechanoluminescence is the emission of light from materials in response to force, which has potential applications such as bioimaging. A successful model reaction using pentafluorophenol as a leaving group has resulted in a viable method for attaching the chemiluminescence to the mechanophore. For the other project, COS is rapidly converted to H₂S in cellular environments and has potential therapeutic effects. Release of aminocoumarin as a fluorescent receptor with COS will provide an effective and nondestructive method of monitoring H₂S release. The synthesis of the mechanophore for COS release is underway.

Optimizing the gas diffusion electrode for lithium mediated nitrogen reduction

Anupama Subramanian

Mentors: Karthish Manthiram and Gangsan Lee

The current industry standard for producing ammonia, an essential component of fertilizers, is the Haber Bosch process. This reaction operates at extremely high temperatures (400-500 °C) and pressures (150-250 bar). This results in heavy costs and high carbon emissions, consuming 1% of global energy. The electrochemical synthesis of ammonia through lithium mediated nitrogen reduction (LiNRR) provides a promising alternative that allows for production at near-ambient conditions. This project utilizes a gas diffusion electrode (GDE) which greatly improves nitrogen gas availability for lithium plated at the electrode. This project evaluates the implications of modulating pressure gradients and electrode surface areas to optimize ammonia production. By electrochemically plating porous copper onto stainless steel electrodes, the pore size and mesh surface area can be manipulated. The goal is to build a platform for modulating pressure to facilitate nitrogen reduction while gaining a fundamental understanding of electrode surface architecture. A greater understanding of the diffusion pathway and surface chemistry is integral for improving the Faradaic Efficiency of this system.

Understanding contributions of mitochondrial translocase of the outer membrane (TOM) to the integrated stress response under iron deficient conditions

Adeline L. Sun

Mentors: David C. Chan and Yogaditya Chakrabarty

Mitochondria play a dual role in maintaining cellular homeostasis. In response to stress, damaged mitochondria are removed through mitophagy, the selective degradation of damaged mitochondria by lysosome recruitment. In addition, mitochondria also activate global stress responses such as the integrated stress response (ISR). Activation of ISR leads to reduced protein synthesis and increased translation of transcription factors that aid cell survival and recovery. Recent findings suggest that the translocase of the outer mitochondrial membrane (TOM), best known for importing nuclear-encoded mitochondrial proteins, may also stabilize molecules that initiate mitophagy during stress conditions that activate the ISR. We aim to investigate whether TOM-associated proteins contribute to ISR activation. We are generating CRISPR-Cas9 interference knockdowns of TOM20, TOM22, and SAM50 in

mammalian cells, treating these cells with stress-inducing agents such as the iron chelator DFP and the mitochondrial membrane depolarizer CCCP, and assessing ISR activation by measuring expression of canonical ISR markers ATF4 and phosphorylated-eIF2 α . These experiments will help define the role of TOM in ISR under different stress conditions and offer insights into how mitochondria coordinate both internal quality control via mitophagy and cytosolic stress signaling.

Engineering single-chain AMP-activated protein kinase complexes to investigate metabolic regulation and hearing loss

Isabella H. Yang

Mentors: André Hoelz and Michael S. Gruhne

In cells, chemical energy is consumed and produced to propel key metabolic processes. Cells must quickly sense the energy needs of the organism, utilizing or producing ATP in response. Chiefly, AMP-activated protein kinase (AMPK), a cellular energy sensor, recognizes and maintains the ratio of ATP to AMP. In the cochlea, metabolic activity of inner hair cells (IHCs) is necessary for the conversion of auditory stimuli into neural signals. Loss of IHC activity, caused by noise overexposure, aging, or ototoxic drug treatments, results in permanent hearing loss. AMPK inactivation has been heavily implicated in IHC death and resulting ear damage, suggesting that overexpression of certain AMPK isoforms may protect against auditory impairment. However, overexpression of individual AMPK subunit isoforms can broadly alter the expression of other subunits, preventing high-confidence overexpression of specific complexes. To remedy this, individual human AMPK subunit isoforms were linked together to produce single-chain AMPK (scAMPK) complexes. scAMPK complexes were expressed in *E. coli*, purified via column chromatography, and compared to their respective heterotrimeric forms through folding pattern and activity. Such development of scAMPK proteins allows complexes with designated isoforms to be expressed with increased reliability, optimizing AMPK overexpression for widespread clinical applications, particularly therapies for hearing loss.

Cavity enhanced sum frequency generation for indirect detection of 2 micron photons

Amarnath

Mentors: Rana X. Adhikari and Francisco Salces Carcoba

The next-generation gravitational wave detectors aim to surpass current sensitivity limits by reducing thermal noise through operating in longer wavelength, cryogenic cooled temperatures and the use of crystalline silicon optics. This requires transitioning from 1064 nm lasers, as used in the current LIGO detectors, to longer wavelengths around 2 μm , where silicon exhibits low optical absorption. However one of the challenges at 2 μm is the lack of high quantum-efficiency (Q.E) photo detectors. We explore to set up a cavity enhanced Sum frequency generation (SFG) configuration for the indirect detection of 2 μm signal. This involves 2 micron signal combined with 1064 nm pump to yield 700 nm up-converted photons which can then be detected by the high Q.E detectors. For SFG, We set up a mode-matched, pump resonant, bowtie cavity with PPLN crystal as nonlinear material inside cavity for high power build up to achieve higher Up-conversion efficiency.

Toward a scalable framework for evaluation of potential Cosmic Explorer sites

Tooba Ansar

Mentors: Robert Schofield and Michael R. Landry

Cosmic Explorer is a third-generation gravitational-wave observatory concept that will offer an order-of-magnitude improvement in broadband sensitivity over current gravitational-wave observatories. This leap in sensitivity results from Cosmic Explorer's expansive 40-km arms, allowing it to detect gravitational wave sources across the universe that remain unresolved by existing detectors. In developing Cosmic Explorer, it is important to identify sources of ambient noise near potential sites that could limit its high sensitivity, as well as ensure sufficient land clearance for its extensive arm length. In this paper, we propose a method for identifying noise sources and surveying land availability around candidate sites using geographic information systems. With hundreds of suitable locations, we aim to develop a scalable approach for remote evaluation of Cosmic Explorer sites to hone in on those most promising for eventual on-ground testing.

Filter cavity angular control system for green auxiliary beam

Tomris I. Dogan

Mentors: Adam J. Mullavey and Begum Kabagoz

Frequency dependent squeezing has played a key role in improving the sensitivity of the LIGO detectors since the beginning of the O4 observation run. This improvement has been made possible by the newly installed filter cavity, which enables the required frequency-dependent behavior and has been in operation for nearly two years. To support the locking of this cavity, an auxiliary green beam is used to pre-lock its length, allowing fine tuning to the infrared (IR) resonance frequency. However, if the green beam loses lock at any point during this process, it can prevent successful IR locking. To address this issue, we implemented an automatic alignment scheme for the green beam to improve locking reliability and minimize the need for manual alignment adjustments.

The alignment control scheme is based on dither modulation and demodulation of the transmitted green beam power, with feedback applied to the alignment mirrors via a multi-stage suspension system. Preliminary tests demonstrate meaningful progress and provide a promising basis for continued development of a fully automated alignment system.

PPLN crystal nonlinear gain measurements for tabletop waveguided optical parametric amplification

Nora Dreslin

Mentors: Peter Carney, Rana X. Adhikari, and Shruti Maliakal

LIGO (Laser Interferometer Gravitational-Wave Observatory) uses frequency-dependent quantum squeezing to increase sensitivity to gravitational waves from astrophysical phenomena like black hole mergers and neutron star mergers. At high frequencies ($>1\text{kHz}$), gravitational wave signals are obscured by the shot noise of the laser due to uncertainty in the phase of the wave. At low

frequencies ($<100\text{Hz}$), radiation pressure noise from uncertainty in the amplitude of the laser's photons masks gravitational wave signals as it causes the interferometer mirrors to rumble at low, unpredictable frequencies. Quantum squeezing decreases uncertainty in one quadrature of light, phase or amplitude, while increasing uncertainty in the other. The current squeezing method uses an optical parametric oscillator (OPO) to generate squeezed light and then squeeze the LIGO signal in whichever quadrature necessary for the frequency of the gravitational wave being detected. Waveguided optical parametric amplification (WOPA) aims to simplify the current method of squeezing by eliminating the cavity within OPO and generating squeezed light in a single pass through a nonlinear crystal waveguide, periodically-poled Lithium Niobate (PPLN). This project measures the nonlinear gain of WOPA to identify loss and tune the setup to improve our measured squeezing levels to approach those currently seen in OPO in LIGO.

Inferring inspiral properties of binary black-hole mergers from the ringdown

Serena R. Fink

Mentors: Eliot Finch and Simona J. Miller

The effect of progenitor masses and spins on the inspiral phase of a gravitational-wave signal from binary black hole coalescence is relatively well understood for the case where spins are aligned with the orbital angular momentum. Less is known about how progenitor properties—especially misaligned spins—impact the ringdown. The accuracy and precision with which inspiral parameters (component masses and spins) can be inferred from the ringdown alone remains an open question. As several high-mass (most ringdown-dominated) systems observed by LIGO have misaligned spins, the ability to predict inspiral properties from the ringdown would improve existing measurements, and potentially give new insight into this portion of the binary black hole population. We introduce a least-squares fitting method for inverting ringdown surrogate models, allowing us to map from measured quasinormal modes back to inspiral parameters. This method varies in quality depending on the amplitude surrogate. The surrogate that has been explored the most in this project, NRSur3dq8_RD, reasonably estimates parameters for systems with near-equal masses and smaller spin magnitudes, but provides less accurate estimates in systems with highly unequal masses and larger spins. To better assess the uncertainty and correlational structure in our parameter-space, we additionally perform parameter estimation using ringdown surrogate models.

Magneto-optical trap assembly for cold rubidium quantum filtering applications

Talia E. Glinberg

Mentors: Lee P. McCuller and Daniel Grass

An innate filtering problem in GQuEST (Gravity from the Quantum Entanglement of Space Time) arises from shot noise in the projective readout of weak, high-frequency, stochastic space-time fluctuations that lie beyond LIGO's current sensitivity range. To address this, the RbQ project is developing a system that uses a 2D- and 3D-magneto-optical trap (MOT) setup to cool and trap rubidium atoms into atomic clouds that can be transported and used as tunable optical filters for enhanced signal detection. To drive the desired atomic transition in rubidium, 780 nm light was produced via second-harmonic generation in a waveguide, followed by alignment through a free-space and fiber-based optical setup. Laser frequency stabilization was achieved using the Pound-Drever-Hall locking technique, using a rubidium vapor cell as a frequency reference. This work advances the use of cold atom-based quantum filters in next generation gravitational wave detectors, enabling improved projective readout and more sensitive detection of low SNR, high-frequency, signals beyond LIGO's current range.

Investigations of binary neutron star range oscillations at LIGO Livingston

Gabriel D. Grant

Mentor: Jane Glanzer

The Laser Interferometer Gravitational Wave Observatory (LIGO) is composed of two interferometers that detect gravitational waves from coalescing black hole and binary neutron star mergers. The binary neutron star inspiral range (BNS) is a metric used to monitor detector sensitivity. Due to the extreme precision of the LIGO detectors, the BNS range must be carefully supervised for potential

noise. This project focused on identifying and characterizing the source of unusual noise that has been occurring since the start of the fourth observing run (O4). In particular, the BNS range at the LIGO Livingston (LLO) detector frequently oscillates with a 30-minute period that produces increased noise in the main gravitational wave data channel from 30 to 50 Hz. Many auxiliary sensors have also been exhibiting oscillations, making it difficult to understand the behavior and source of this noise. By generating band-limited root mean square plots, spectrograms, and using cross-correlation analysis for many days across O4, we have seen that select temperature sensors, accelerometers, seismometers, and microphones are highly correlated with the gravitational wave strain. This suggests that the source of these oscillations could be physically located near one of these sensors.

Investigating the co-precessing frame approximation for binaries on eccentric orbits

Sam Johar

Mentors: Lucy M. Thomas and Taylor Knapp

Quasi-circularity has historically been assumed for detected gravitational waves from black hole compact binary coalescences (CBCs). As detector low-frequency sensitivity improves, we expect to detect CBCs from farther before merger, before eccentricity has been radiated away. To analyze these signals, we will need well developed and robust eccentric models. Few existing models incorporate precession and eccentricity together as waveforms resulting from this combination of effects are complex and difficult to model. The co-precessing frame is one tool that simplifies precessing waveforms by creating a reference frame in which the z-axis is always aligned with orbital angular momentum, a transformation that is well-studied for quasi-circular systems and often used to create precessing waveform models. Here we evaluate the co-precessing frame approximation for eccentric and precessing systems using numerical relativity simulations. We find that, while shifting to the co-precessing frame counteracts amplitude modulation in the waveform envelope, mode asymmetries caused by precession remain in the untwisted waveform. The determination of which precession features are not affected by the co-precessing frame transformation will aid in future efforts to construct a robust waveform model that includes the effects of both eccentricity and precession.

Investigating the source of inferred parameters' discrepancies between LIGO detectors in GW231123

Krzysztof Król

Mentor: Sophie Bini

GW231123 is a short duration gravitational wave (GW) signal, consistent with a binary black hole merger with a total mass of 190-265 M_{\odot} . It is the most massive binary black hole confidently observed to date. Both components are highly spinning and likely have masses in the mass gap caused by pair-instability supernova processes. The event is challenging to analyze because of its very short duration and limited accuracy of waveform models for such an extreme system. Additionally, significant differences between inferred posteriors for total mass and spins arise when parameter estimation is performed using LIGO Hanford-only and LIGO Livingston-only data, raising concerns about the presence of spurious transient noise overlapping with the GW signal. In this project, we quantify these differences and investigate their causes through simulated signals similar to GW231123.

Numerical simulation of quantum enhanced interferometer readout

Reilly H. Loughman

Mentors: Lee P. McCuller, Jeffrey D. Wack, and Sander Vermeulen

The Rubidium Quantum sensing (RbQ) experiment uses a quantum enhanced measurement system to increase the sensitivity of the GQuEST experiment, which aims to detect quantum gravitational effects through phase shifts in a tabletop interferometer. To support the development of RBQ, I constructed quantum-optical simulations to explore atom-light interactions in cavity systems. The simulation framework I explore how control pulse timing, frequency, and amplitude affect signal detection, and calculates the Quantum Fisher Information (QFI) to identify which experimental parameters, such as cavity loss or coupling strength, most impact sensitivity. An application is a Λ -type rubidium atom transition between three hyperfine states - the maximum expectation value in the final state is found

to be 0.866 where the frequency of the two transitions are optimal at 1.616 GHz and 0.970 GHz with a timing difference of 0.389 ms. These results inform the design of RbQ and provide a foundation for optimizing quantum sensing in future gravitational wave detectors, where simulation-driven tuning can improve precision and mitigate the effects of noise.

Noise characterizations in tabletop waveguided optical parametric amplification experiment

Tanisha Ray

Mentors: Rana X. Adhikari, Peter Carney, and Shruti Maliakal

Gravitational wave detectors such as Advanced LIGO rely on exquisite sensitivity to detect minuscule spacetime perturbations, making them susceptible to a variety of noise sources. Among the most fundamental is quantum noise, which arises from vacuum fluctuations entering the interferometer's antisymmetric port. To mitigate this limitation, frequency dependent squeezed vacuum states—quantum states with reduced uncertainty in one quadrature—are injected to suppress the quantum noise. Currently, squeezing at LIGO is achieved via optical parametric oscillators (OPOs) using resonant cavities. This project explores Waveguided Optical Parametric Amplification (WOPA) as a cavity-free alternative that offers architectural simplicity and potential robustness against alignment instabilities. WOPA utilizes a single-pass configuration through a periodically poled lithium niobate (PPLN) waveguide, pumped with 532 nm light, to generate broadband squeezed vacuum states at 1064nm. This work aims to develop a detailed noise and loss budget for the WOPA-based squeezing source. The analysis includes contributions from laser frequency and intensity noise, phase noise, polarization mismatch, propagation and coupling losses in the waveguide, imperfect mode matching, and gain imbalance at the balanced homodyne detector (BHD). The ultimate goal is to identify and limit these noise sources, thereby increasing the achievable level of squeezing.

Robust optics simulation for mode-mismatch reduction at LIGO Hanford

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The Laser Interferometer Gravitational-wave Observatory (LIGO) Hanford site employs quantum squeezing to increase effective observational range by approximately 30 Mpc — a significant portion of LIGO's total 150 Mpc range. However, the quantum squeezing process may induce substantial mode-mismatch losses upon injection into the main interferometer beam. To combat this, two piezo-actuated curved mirrors exist near the squeezer output path to allow for precise control of beam propagation. In this work, we characterize the squeezed beam propagation along these actuated curved mirrors, creating a comprehensive model for extracting optimal voltage supply to each mirror for mode-mismatch minimization. Using experimental data from a diverted squeezer beam, we construct a macro-level model for beam parameter computation by supplied mirror voltage alone. Our model approach then yields both mode-mismatch quantification (by forward propagation) as well as mirror curvature estimations (by back propagation), ultimately establishing global characteristics for the beam and associated optics.

Mapping and Correcting the Surface of the GQuEST End Mirrors

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The GQuEST (Gravity from the Quantum Entanglement of Space-Time) end mirrors are susceptible to surface deformations which can cause incomplete interference at the differential output. I used an optical profiler to image the surface of these end mirrors and calculated the coupling coefficients to higher order modes. Using a custom adjustable mirror mount, I was able to actuate on the end mirrors and correct for these deformations. We expect to need to correct 2.6×10^{-4} diopters of focusing power and I have been able to correct 9.4×10^{-2} diopters, thus enabling GQuEST to lower the classical noise floor by minimizing the mirror thickness while minimally increasing the contrast defect. This correction involved a mixture of the HG_{02} , HG_{11} , and HG_{20} modes. I expect to improve the precision and purity of my corrections with a more direct mounting system I recently installed.