Caltech Student-Faculty Programs

Session U Abstracts

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 $LiHo_{0.99}Y_{0.01}F_4$, 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 $LiHo_{0.65}Y_{0.35}F_4$, 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 $LiHo_{0.99}Y_{0.01}F_4$, 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.

Monte Carlo simulation of the $LiHo_xY_{1-x}F_4$ quantum Ising magnet
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Mentors: Daniel Silevitch and Thomas F. Rosenbaum

This project investigates the quantum dynamics of the disordered Ising magnet $LiHo_xY_{1-x}F_4$, 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 $LiHo_xY_{1-x}F_4$, 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.

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.

Investigating orbital angular momentum light-induced excitonic states in MoS_2 on periodic strained SiO_2 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 MoS_2. Periodic SiO_2 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 MoS_2 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 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 simulation.

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.

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 relaltive to those off the track in the HID while the source was in the hard state.

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.

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 $\geq$ 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.

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.

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.