Caltech Student-Faculty Programs

Session V Abstracts

Evaluating quantum-scale dispersion compensation via pulse compression and Hong-Ou-Mandel interference
Raghava K. Kalidindi
Mentors: Maria Spiropulu and Venkata (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.

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.

An analytical phase-space approach to measurement device independent quantum key distribution
Ishani Mukherjee
Mentors: Maria Spiropulu and Venkata (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.

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 ($\sigma_{rms} \sim 10$ 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.

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.