NEXT-GENERATION QUANTUM SENSING FOR HIGH ENERGY PHYSICS

Lead Laboratory: Argonne National Laboratory

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Abstract

This project will develop a set of next-generation quantum sensing paradigms with sensitivity and other capability enhancements derived from quantum coherence and/or entanglement. The overall goal of the program will be to develop a small set of experiments that demonstrate the technologies, their advantages, and explore new spaces in HEP science. The overall theme here is a search for new interactions (e.g., condensate dark matter, directional dark matter detection, new constraints on the time variation of fundamental constants) using precision quantum measurement tools. Topical coverage includes optical clocks and semiconductor detectors. A theory and modeling effort exploiting leading-edge high-performance computing will form part of this activity. Initial scientific results are expected within the first two years of the project.

This effort grows out of an earlier set of individual QuantISED pilot projects: 1) A DOE/NIST collaboration (Argonne HEP and the Ion Storage Group, NIST Boulder, co-led by Salman Habib and David Hume), 2) a theoretical project on lattice computations with quantum computers led by James Osborn (Argonne), and 3) an effort to develop directional dark matter detectors using nitrogen-vacancy (NV) centers in diamond led by Ron Walsworth (Maryland).

This project directly leverages Argonne capabilities in materials science and micro-fabrication, materials and device characterization, theory and modeling, quantum networks, and advanced computing. Work on atomic clocks will be a close collaboration with NIST Boulder involving Argonne staff, postdocs, and students. The semiconductor-based effort with NV-diamond technology will be led by the precision measurement and quantum technologies group at the University of Maryland. The proposed plan is consistent with the long-term aims of the Argonne Quantum Initiative, which is designed to support the scientific goals of the DOE/SC offices, including DOE HEP, in quantum science and technology.

Overview

This project brings together a three-institution collaboration (Argonne National Laboratory, NIST Boulder, and the University of Maryland) to develop new directions in quantum sensing targeted to high energy physics (HEP) applications. Advances from this work are also expected to have broader significance for next-generation quantum technologies on a wider scientific front. The roots of quantum sensing have historically been in precision metrology and in areas such as gravitational wave detection, where one is hunting for extremely weak signals. The techniques used in these areas are fundamentally different from those so successfully employed in traditional high energy physics to discover and explore the particle physics Standard Model (SM).

It is clear for a number of reasons, both theoretical and observational, that, as a description of nature, the SM is incomplete. Dark energy and dark matter (DM) are obvious examples of fundamental physics that the SM does not address. Many searches for Beyond Standard Model (BSM) physics will of course rely on experiments with next-generation accelerator experiments. At the same time, however, a number of exciting possibilities exist for BSM studies using quantum sensing techniques. These include time variation of fundamental constants, dark matter searches, and weak violations of fundamental symmetries. Since the mid-1990's, the development of quantum techniques has been significantly accelerated by the emphasis on quantum information processing and quantum communication focusing on the role played by entanglement and quantum coherence.

An important aspect in building a HEP-oriented quantum sensing program at Argonne is to develop collaborations with world-leading partners for mutual benefit, and for helping to build new capabilities. This aspect of the project is reflected in 1) the connection to NIST (David Hume), with their world-leading effort in atomic, molecular, and optical (AMO) physics and technology, specifically in the area of atomic clocks, and 2) the collaboration with the Quantum Technology Center at the University of Maryland (Ron Walsworth) with their powerful sensing technology based on nitrogen-vacancy (NV) centers in diamond.

The project focuses on the use of novel quantum sensing techniques to explore BSM physics. The methods cover a wide range of applications, including ultra-low mass dark matter searches (quantum condensates), WIMPs, and time variation of fundamental constants. Success in this research program will result not only in the phased development of individual technologies but will also open the door to new combinations (e.g., use of single photon detection in atomic clocks). The team includes a strong theoretical and modeling component to support the experimental effort.

Quantum Sensing with Atomic Clocks

The remarkable progress of atomic clocks over the last 20 years, particularly with the advent of optical clocks, has cemented their status as the most precise and accurate measurement devices ever built. In terms of measurement limits, this technology is relatively mature, having realized quantum-limited precision decades ago and now pushing through those boundaries towards quantum-enhanced measurements. At the same time the scientific reach of atomic clocks continues to broaden. Early on they were recognized as near-ideal tools to test predictions of relativity theory, which was demonstrated dramatically in experiments that put atomic clocks aboard aircraft and a sounding rocket. More recent work has shown that comparing clocks based on different atomic species provides the most stringent tests for variation in fundamental constants, which is predicted in BSM theories including string theories and models of ultralight dark matter. As these devices are further developed to be more sensitive and robust by novel application of quantum metrology protocols, they will be able to cover a larger range of parameter space for BSM physics (Figure 1). We can envision vast networks of optical clocks operating in labs, mobile platforms, field stations, observatories and even in spacecraft, all with sensitivities beyond what we have achieved so far and connected via ultrastable optical links to provide a new window into fundamental processes that drive the universe. Applications span the full range from basic tools to enable science like very-long baseline interferometry, relativistic geodesy and gravitational wave detection, to direct quantum sensors to test the fundamental symmetries of physics and search for weakly interacting particles beyond the standard model.

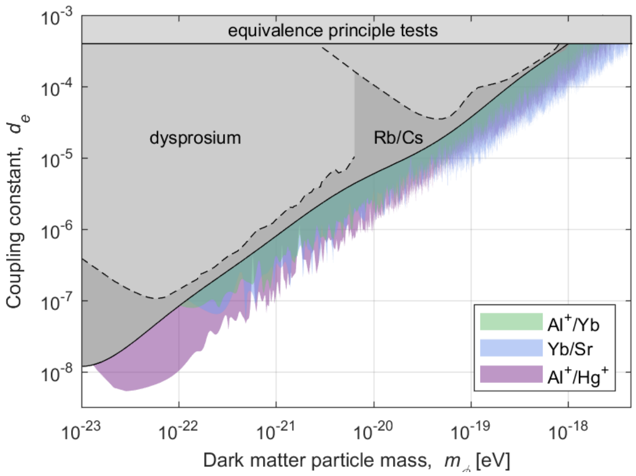


Figure 1. ***Constraints derived from optical clock data on the coupling constant*** d_e ***for ultralight dark matter [Beloy et al, Nature 2021].***

We aim to extend the sensitivity and bandwidth of optical-clock-based probes of new physics. This includes BSM physics such as drifts of fundamental constants, which rely primarily on long-term stability of the clock, as well as the search for ultralight bosonic dark matter, for which the mass range can be broadened by increasing the measurement bandwidth. In both cases, we will aim at new direct constraints using comparisons between the Al^+ quantum logic clock to the Yb optical lattice clock. In addition, we will pursue a second type of measurement which compares the Al^+ resonance frequency to the resonance frequency of a cryogenic optical cavity. Atom/cavity measurements rely on the differential sensitivity of the atomic clock frequency and the cavity length to variation in the fine structure constant. In addition to providing more stringent tests, this effort will explore quantum techniques that can be applied to future searches for BSM physics using other atomic systems, such as the ^{229}Th nuclear transition, which is expected to exhibit vastly increased sensitivity to these effects and is currently under development in the NIST group.

The theoretical program associated with this work will focus on modeling entanglement-enhanced protocols as well as simulations of quantum condensate dark matter for detailed predictions of the behavior to be expected on small spatial scales. This work will be based on a new variant of the Argonne HACC (Hardware/Hybrid Accelerated Cosmology Code) developed in the first round of QuantISED support. This code will provide the highest resolution simulations carried out to date using exascale supercomputers; these systems are expected to make their first appearance in 2022/2023 at the Argonne and Oak Ridge Leadership Computing Facilities.

Directional WIMP Detection Below the Neutrino Floor using Diamond

WIMPs remain one of the most compelling DM candidates, despite decades of searches without discovery. They occur naturally in many BSM theories; and are predicted to arise, via thermal freeze-out in the early universe, with an abundance consistent with the observed dark matter density. WIMP direct detection is a long-term effort, with exclusion bounds on masses and WIMP-nucleon cross-sections shrinking by several orders of magnitude each over the past three decades. Upcoming WIMP detectors will also be sensitive to solar neutrinos. Coherent neutrino scattering induces single nuclear recoils, frustrating standard background discrimination. Solar neutrinos thus constitute an irreducible background for future detectors – the "neutrino floor." Discovering WIMPs with conventional detectors requires identifying annual modulation of the signal as the Earth's velocity changes relative to a putative WIMP "wind" induced by solar system motion through the galaxy. To do so on top of the neutrino background could require an impractically large number of events. Alternatively, *WIMP searches can probe below the neutrino floor with directional detection*. Determining the particle's incoming direction enables rejection of solar neutrino events, allowing a low-background search for cosmological WIMPs.

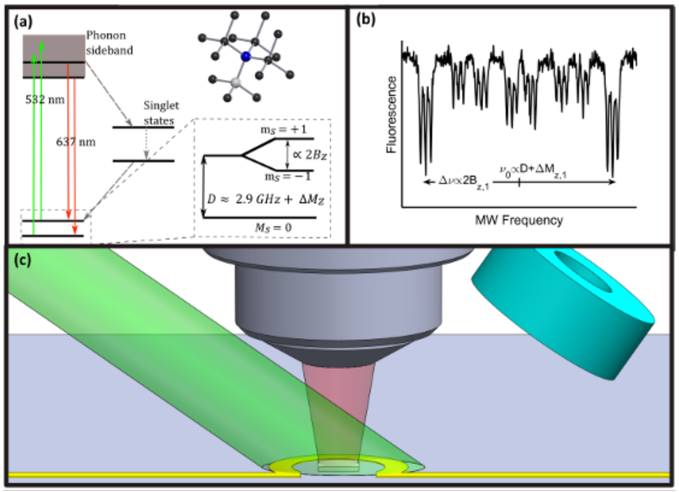


Figure 2. ***(a) NV energy levels and crystal structure: carbon atoms (black spheres); substitutional nitrogen (white sphere) and lattice vacancy (blue sphere). (b) Example NV optically detected spectrum as a microwave (MW) drive is scanned in a bias magnetic field. Strain yields a common-mode shift in transition frequencies. (c) Quantum diamond microscope (QDM) schematic: green excitation light, yellow MW antenna, bias field provided by a teal ring magnet. NVs emit spin-dependent red fluorescence under optical and MW excitation, detected with a microscope objective and camera.***

The proposed diamond-based detector finds candidate events using well-developed HEP instrumentation and background-discrimination methods including charge, phonon, or scintillation collection. Directional discrimination will be performed via precision measurement of damage tracks resulting from rare WIMP or neutrino scattering within the diamond crystal, using precision quantum defect spectroscopy and/or x-ray microscopy. When a WIMP or neutrino scatters in diamond, it imparts substantial kinetic energy to a single carbon atom, which initiates multiple secondary recoils. These recoils leave lattice vacancies, interstitial atoms, and distorted bonds, causing a characteristic track of stable crystal damage originating at the site of the interaction and extending $\sim$ 100nm in the diamond. For recoil energies above 3keV corresponding to a $>$ 2GeV WIMP mass scattering from a carbon nucleus, the damage tracks are predicted to exhibit measurable head-tail asymmetry, and to be oriented near the direction of the incoming particle.

The basic principle of directional detection in diamond can be summarized in the following three key steps: 1) An event is registered and triangulated on a mm-scale segment of a large total quantity of diamond ($\sim$ 1m^3) by photon, phonon, or charge-carrier collection, using established semiconductor detection techniques. The time stamp of the event determines the orientation of the laboratory and detector relative to potential sources such as the Sun (for solar neutrinos) and the galactic center (for WIMP-wind particles). 2) Using diffraction-limited optics and quantum defect spectroscopy, the event's damage track is localized to a $\sim \mu$m voxel within the mm-scale diamond segment. 3) Superresolution optical methods or high-resolution x-rays map the damage track at the nanoscale, yielding the required directional information to discriminate, statistically, WIMPs from solar neutrinos (Figure 2). Steps 2 and 3 are performed on a timescale that is short relative to the time for other events to occur, given all backgrounds (estimated ~week).

In the three-year project, we will demonstrate the three steps of the detection method for small numbers of mm-scale diamond segments, building on our promising results to date supported by the initial two-year QuantISED program. The three-year goal is to have reduced technical risk such that a cm-scale prototype detector could then be developed, with both WIMP candidate event detection and damage track directional detection. Subsequently, the technique would be ready for scale-up to a large-volume ($\sim$ 1m^3) detector, likely to be operated in rejection of solar neutrino events, allowing a low-background search for cosmological WIMPs in an underground facility to reduce backgrounds other than neutrinos. Discussions with commercial diamond fabricators (e.g., Element Six) indicate that such a quantity of high-quality synthetic diamond can be produced at costs competitive to conventional WIMP detectors. Note that in addition to our effort on directional DM detection, diamond is also the focus of active study by HEP groups for next-generation, non-directional detectors of lower mass DM ($\sim$ 10eV to sub-GeV), as 1) it offers excellent semiconductor properties; and 2) the relatively light carbon nucleus provides an improved sensitivity profile for low-mass DM candidates compared to xenon or other heavy target materials.

The BNL QuantISED Program

POC: Andrei Nomerotski (anomerotski@bnl.gov)

Advances in modern quantum sensing and quantum computing are expected to provide excellent opportunities for high energy physics. We describe below BNL QuantISED program, which started in 2019 and has been renewed in 2021. The topics are listed below along with their BNL POCs.

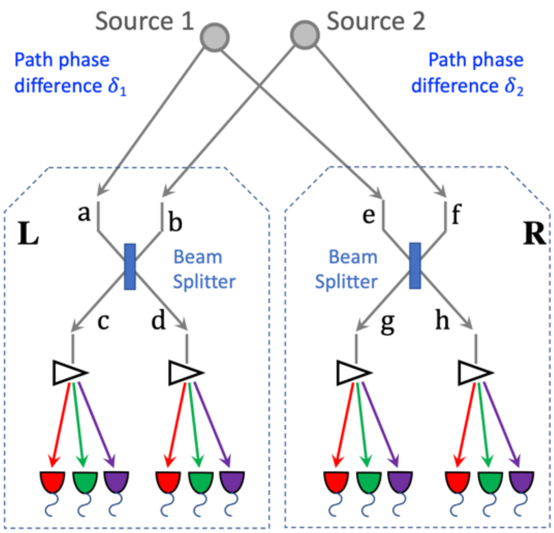
Quantum-assisted optical interferometers: *PI Andrei Nomerotski (BNL), co-PIs: Paul Stankus (BNL), Ning Bao (BNL)*

This QuantISED project is expected to provide major improvements in astrometric precision of optical telescopes. Photon phase difference in two locations is measured employing sources of entangled photons and teleportation techniques. This enables long baselines and improves astrometric precision by few orders of magnitude with major impact on several Cosmic Frontier research areas. The approach can be generalized from the entanglement of photon pairs to multipartite entanglement in multiple stations to explore different configurations and to guide future experimental developments. In addition to the capability to generate and distribute entangled photons over long distances, practical schemes under investigation require photon detectors with excellent temporal and spectral resolutions. Our goal is to develop a small-scale on-sky experiment with HEP scope by 2024. This project leverages BNL efforts in quantum networking research and would be one of its first science applications. The project web site with first results and publications can be accessed at https://www.quantastro.bnl.gov .

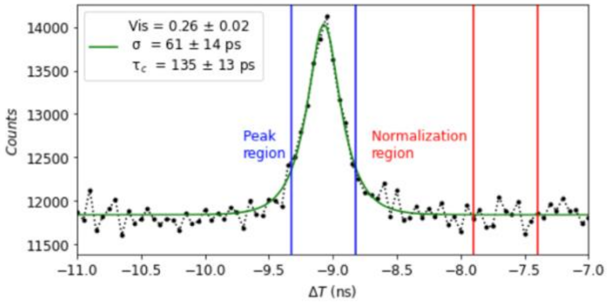
Quantum-accelerated artificial intelligence: *PI Shinjae Yoo (BNL), co-PIs Chao Zhang (BNL), Yen-Chi (Sam) Chen (BNL), Tzu-Chieh Wei (Stony Brook University), Sau Lan Wu (University of Wisconsin)*

This QuantISED project is investigating the advantages of using Quantum Machine Learning for data-intensive HEP applications, where we are developing new quantum-enhanced deep learning methods. The project is targeting the future long baseline neutrino oscillation experiment DUNE data and also the LHC data for the quantum-accelerated event classification and particles trajectories fitting. Early results, which employ the quantum convolutional neural network (QCNN), quantum graph convolutional neural network (QGCNN), and quantum long short-term memory (QLSTM), have shown a similar performance or quantum advantage in terms of convergence speed and accuracy for key tasks, in comparison to current solutions using classical computing methods. Specifically, we plan to apply hybrid quantum-classical approach to demonstrate quantum generative adversarial network and quantum autoencoder on both DUNE and LHC applications. To further improve our representation, we plan to investigate quantum tensor network and quantum metric learning. Our metaQuantum software framework for quantum machine learning significantly improved our productivities in simulation and real quantum computer experiment and we plan to improve further by enabling AutoML capabilities (automatic hyperparameter tuning and automated quantum architecture search).

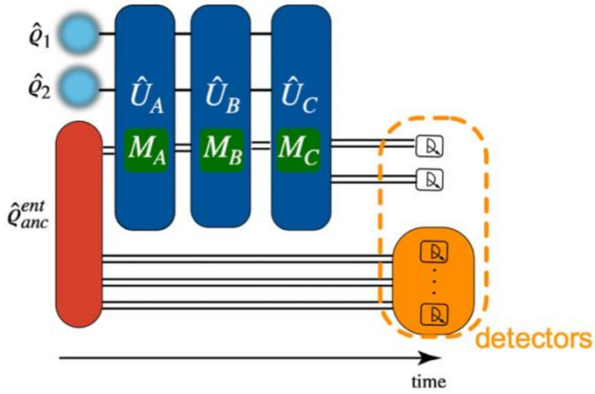
Supporting materials for **Quantum-assisted optical interferometers**



Basic arrangement of the novel interferometer is the following: the photon modes a and b at station L are brought to the inputs of a symmetric beam splitter, with output modes labelled c and d; and the same for input modes e and f split onto output modes g and h at station R. The four outputs are then each viewed by a fast, single-photon sensitive detector. If the two photons are close enough together in both time and frequency, then due to quantum mechanical interference the pattern of coincidences between measurements at "c" and "d" in L and "g" and "h" in R will be sensitive to the difference in phase differences $(\delta_1 - \delta_2)$; and this in turn will be sensitive to the opening angle between the two sources.



We started bench-top experiments of two-photon interferometry employing thermal 794 nm photons emitted by a narrow spectral line of argon vapor. The photons are registered with superconducting nanowire single-photon detectors and single-photon avalanche detectors. See example of the Henry Brown – Twiss peak fit with a Lorentzian function with decay time of 135 ps convoluted with experimental resolution of 61 ps.

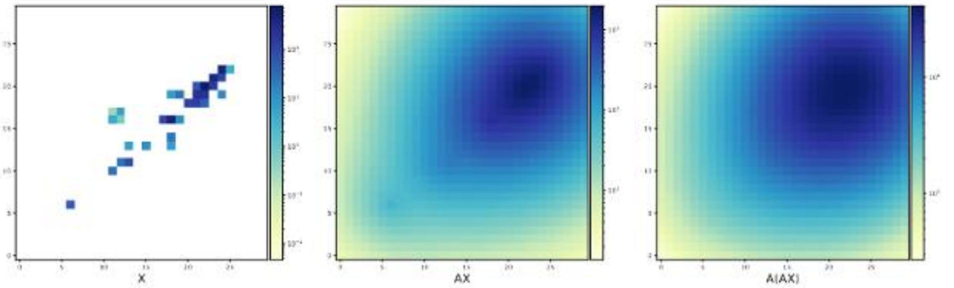


We are developing new theoretical schemes for the proposed interferometer which use multi-partite entanglement (ex W or GHZ states) distributed between multiple stations, and quantum protocols to process information in noisy environment for evaluation of experimental observables. The shown quantum circuit illustrates density operators ρ with multi-partite entanglement distributed over three stations (A, B, C) and states registered by single-photon detectors.

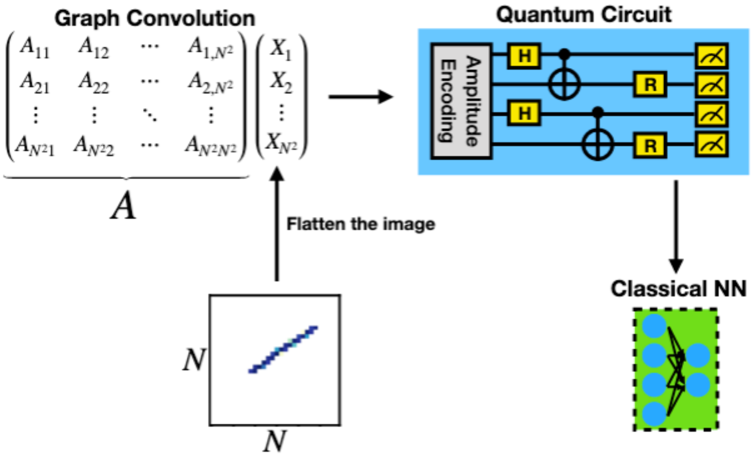
Publications:

1. P.Stankus et al, arxiv:2010.09100, in review.
2. A.Nomerotski et al, arxiv:2012.02812, SPIE Proceedings.
3. Y Zhang et al, Phys Rev A 101 (5), 053808 (2020).
4. P Svihra et al, Appl. Phys. Lett. 117, 044001 (2020).
5. A.Nomerotski et al, arxiv: 2107.09229, TIPP Proceedings.

Supporting materials for **Quantum-accelerated artificial intelligence**

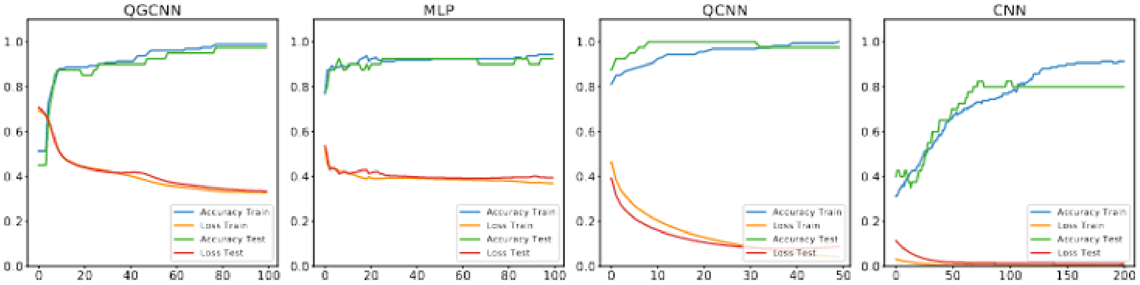


The original DUNE input data, **X**, is rather sparse, making it difficult for QML models to classify. The situation worsens when encoding the image with amplitude encoding (AE) as the vector normalization procedure causes significant information loss. The input X is multiplied by the adjacency matrix **A**. The results of AX and A^2X shows much more smooth results for better AE.



We developed hybrid quantum-classical graph convolution (shown left). The proposed hybrid quantum-classical graph CNN contains three major components: 1) graph convolution 2) VQC, and 3) classical post-processing.

We compared the performance between different architectures in the task of muon versus proton binary classification. QGCNN and QCNN demonstrates superior performance (higher accuracy and converge faster) than classical MLP and CNN models (shown below). QGCNN is much faster than GCNN on the quantum simulation.



Publications:

1. QCNN: Chen, S.Y.C.; Wei, T.C.; Zhang, C.; Yu, H.; Yoo, S. Quantum Convolutional Neural Networks for High Energy Physics Data Analysis. arXiv 2020, arXiv:2012.12177.
2. QGCNN: Chen, S.Y.C.; Wei, T.C.; Zhang, C.; Yu, H.; Yoo, S. Hybrid Quantum-Classical Graph Convolutional Network. arXiv 2021, arXiv:2101.06189
3. QLSTM: Chen, S.Y.C.; Yoo, S.; Fang, Y.L.L. Quantum Long Short-Term Memory. arXiv 2020, arXiv:2009.01783.

Quantum enhanced detection of quantum fields and charged particles

Oak Ridge National Laboratory

Research Area: Quantum Information Science Enabled Discovery (QuantISEd) for High Energy Physics

Principal Investigator: Raphael Pooser

Partner university: Purdue University, coPIs: Rafael Lang, Sunil Bhave

Partner university: University of Maryland, coPI: Jacob Taylor

Partner Laboratory: Lawrence Berkeley National Laboratory, coPI: Daniel Carney

Motivation

This project focuses on exploiting the potential of quantum sensing technologies to enable extreme sensitivities to measure ultra-rare events and ultra-weak fields and interactions following the recent QuantISED (Quantum Information Science Enabled Discovery) community report. Towards this goal, three specific lines of inquiry are followed: [A] Can novel transducers be developed to be sensitive to BSM particles, interactions, and fields? [B] Can multiple quantum approaches be combined to improve their sensitivity? and [C] Can quantum systems be designed to work for multiple BSM searches? These lines of inquiry provide a complementary approach to developing quantum sensing technologies for BSM physics, which directly address the needs and goals of the QuantISED program. Specifically: we develop novel transducers, including accelerometers and magnetometers to enable the detection of ultra-light and ultra-heavy DM; by combining quantum approaches such as squeezing and back-action evasion, we can reach the sensitivities needed to detect such rare events; and by developing a novel quantum sensing platform that accommodates multiple transduction mechanisms joined to a state-of-the-art, quantum-entangled back-end, we can speed up future advances in detector technologies to reach increased sensitivities when scaled to a fully-entangled detector array. The primary deliverable is the development of the foundation for a quantum enhanced, multi-modal probe of BSM physics.

Despite the incredible successes of the Standard Models of particle physics and cosmology, the nature of dark matter (DM) and dark energy (DE) and their interactions with normal matter are among the biggest gaps in our understanding of the Universe, and arguably the most pressing and exciting physics problems today. A recent report from the QuantISED community of principle investigators noted that physics beyond the standard model will likely “be accessed by experiments that offer unprecedented sensitivity.” In particular, the QuantISED program seeks to leverage “quantum 2.0” experiments and sensors, where “quantum 2.0” refers to the second quantum revolution that has brought about exquisite control of fragile quantum systems to access sensitivities impossible with classical devices. Quantum 2.0 devices, combined with HEP science goals, present a unique opportunity to develop new research rooted in quantum physics that is distinct and independent of the HEP cosmic, energy, and intensity frontiers. The QuantISED program can advance quantum research for HEP by advancing sensors to new regimes of sensitivity; using integration to enable scalability for HEP sensors; and building next-generation HEP experiments with novel materials and advanced quantum techniques.

Our project focuses on fulfilling these goals by exploiting the potential of quantum sensing technologies to advance the energy and mass frontiers in searches for particles, interactions, and quantum fields beyond the standard model. The use of quantum approaches -squeezing and back action evasion- to reach sensitivities beyond the standard quantum limit (SQL), or the minimum noise a classical sensor can obtain, is at the forefront of HEP detector R&D, because of the extreme sensitivities it will bring to measuring ultra-rare events and ultra-weak fields and interactions. The program aims to produce both accelerometers and magnetometers to detect impulses via interactions with particles through gravitational and electromagnetic forces. The readout of these sensors will be quantum-enhanced with squeezed light, while the signal-to-noise ratio will be optimized variationally using machine learning techniques by adjusting the experimental apparatus to maximize quantum noise reduction (see Fig. 1).

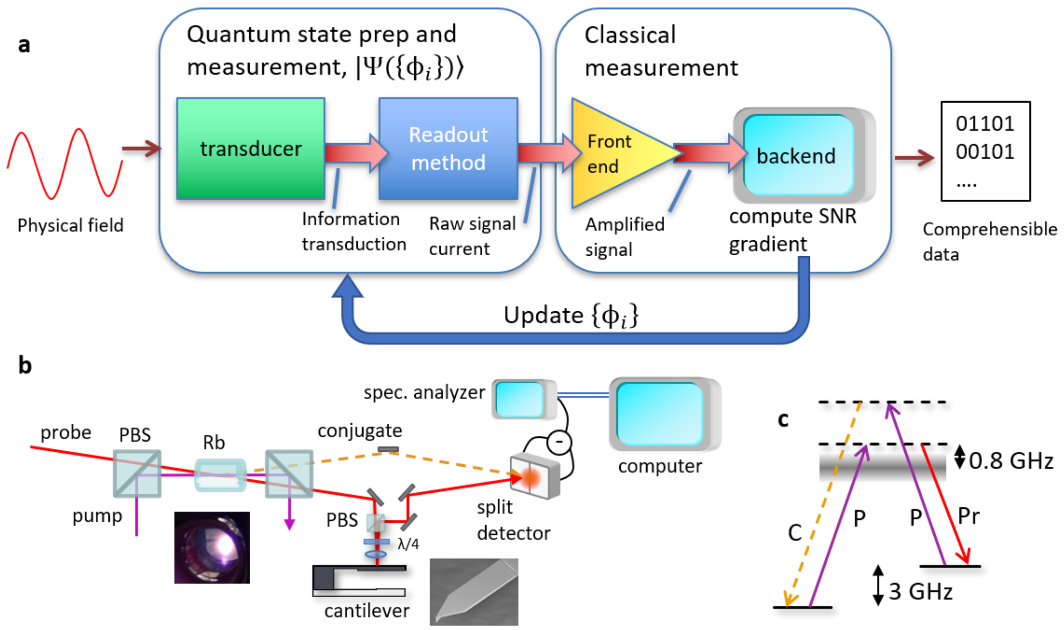


Figure 1: **a:** Our sensing paradigm places a transduction mechanism, a readout method, or both, into a quantum state for use in transduction of a physical quantity. The red arrows trace the path of a signal through the platform. Classical measurements amplify signal currents to enable computation of the SNR. A back-end interprets the signal and acquires it as data. In a feedback loop, the back-end can determine a new parameter set and instruct the state preparation mechanism to prepare a new quantum state, transduce a new signal, and acquire new data, iterating this operation until the SNR is maximized. **b:** An example quantum state preparation and measurement apparatus, used in the present project to provide a source of squeezed light and signal transduction in the optical domain. A weak probe field and a strong pump interact near the D1 line (795nm) and stimulate the emission of photons into two modes: the probe and a third field called the conjugate. These quantum-correlated fields exhibit quantum noise reduction. One acts as a transduction for reading displacement from a micro-electrical-mechanical device while the other acts as a quantum noise reference. **c:** The energy levels in Rb at the D1 line associated with four wave mixing, which amplifies the fields at the probe and conjugate frequencies.

Prior work within QuantISED

The Quantum Information Science (QIS) program at ORNL has continued to grow and change as part of QuantISED throughout 2020 and 2021. A key shift has included the move from quantum simulation on near term quantum computers into the domain of quantum sensing. ORNL's long term goal is to contribute to the discovery of physics beyond the standard model via new detection paradigms enabled by quantum information science techniques. In particular, contributing to sensing platforms and networks to place new limits on the existence of dark matter or dark energy using quantum noise reduction would satisfy this goal. Quantum sensing also overlaps very well with ORNL's core expertise while remaining highly relevant to ORNL's long term goals for HEP research.

Prior quantum simulation results demonstrated new algorithms of interest to HEP for detector design, scattering problems, and neutrino oscillations [1]–[3] (two published and the third accepted into Quantum Information Processing). These simulations were executed on noisy intermediate scale quantum computers such as IBM-Q. The primary focus was on WIMP detection via scattering and collision. These publications demonstrated the ability to simulate phenomenological versions of these scattering problems on quantum computers, but they illuminated that digital quantum simulation has a long way to go before it contributes key information to detector designs. Other projects related to detection include quantum machine learning for particle tracking and exploring magnetic tunnel junctions as a potential dark matter detector. These have been sunsetted to provide room to focus on developing quantum sensing for detector development as a key capability.

Current Progress

The program aims to produce both accelerometers and magnetometers to detect impulses via interactions with particles through gravitational and electromagnetic forces. To this end, in the first quarter the project commenced building magnetometer apparati and squeezed light sources for use in the devices. The project also sourced optomechanical devices from Purdue for use in accelerometers. Theoretical work at Purdue, LBNL, and UMD resulted in predictions for dark matter limits as well as potential applications of squeezed light to networked accelerometers.

Magnetometry

Progress on the magnetometry-based quantum sensing platform has moved from detailed CAD designs to components being assembled on the bench. Figure 2 shows the conceptual CAD design for the magnetometry-based quantum sensing platform with the squeezed optical source on the left and magnetic shield on the right. For the choice of the magnetic shield, a four layer, commercially available shield from Twinleaf known as the MS-2 was chosen. The MS-2 provides an ultra-low magnetic field environment for evaluating new quantum sensing technologies with built in multi-axis magnetic field coils and a background magnetic noise of 10 fT/Hz$^{1/2}$.

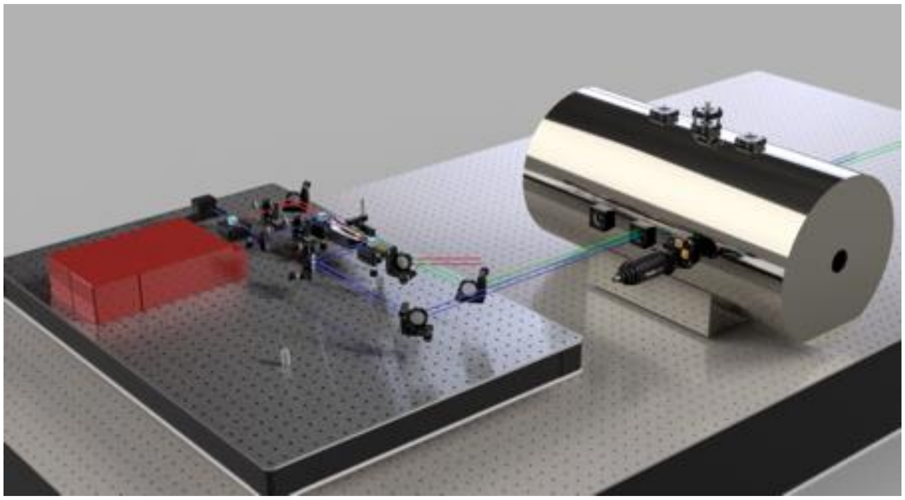


Figure 2 – A conceptual CAD model of the magnetometry-based quantum sensing platform with squeezed optical source on the left and magnetic shield on the right.

Research towards a magnetic transducer has yielded an exciting new concept based on the use of a magnetostrictive MEMS (Mag-MEMS) device. The idea behind Mag-MEMS is that a conventional MEMS acceleometry sensor is coated with a thin film of a magnetostrictive material. Under displacement by an external force, such as that imparted by gravitational interaction of a massive dark matter particle, the displacement-induced strain leads to stress in the magnetostrictive thin-film. This stress alters the magnetic permittivity which is observed as a changing magnetic field. When operated in a low magnetic field background environment, this stress-induced magnetic field can be detected using a vapor-cell based atomic magnetometer. The benefit of such an approach is that the sensor does not suffer from unwanted feedback or back-action caused by reading out the vapor-cell based atomic magnetometer. Thus, this technique is inherently back-action evading readout modality.

The Mag-MEMS is an entirely new concept and its fabrication will require depositing a thin film of a magnetostrictive material on a MEMS acceleometry sensor. To do this, a DC magnetron sputtering system is being constructed for deposition of magnetostrictive thin films on silicon substrates. Figure 3 shows progress on the thin-film deposition system.

Figure 3 – A DC magnetron sputtering system for depositing thin film coatings. This system will be used to prepare magnetostrictive thin films on silicon substrates needed to test the Mag-MEMS concept.

Squeezed light sources

The squeezed light source layout is complete and alignment for nonlinear amplification is complete (Fig. 4 shows a closeup of some of the critical components). Measuring intensity difference quantum noise reduction is the next step. Once this is completed, we will integrate the squeezed light source with the magnetometer to perform magnetometry with reduced noise floor. The same squeezed light source will be used as the source for accelerometry by reflecting the light from the front face of a MEMS device and measuring phase shift as a function of local strain.

The optical components of the source have been placed on a “bread board”, and the input laser is fiber-coupled to the set up. This enables the setup to be moved between experiments. The project’s experiments are currently divided between two lab spaces at the moment, with accelerometry in one space and magnetometry in the other. The portable nature of the squeezed light source means that it can be moved from one experiment to another. An additional source will be built in the future to enable the magnetometry and accelerometry experiments to function simultaneously.

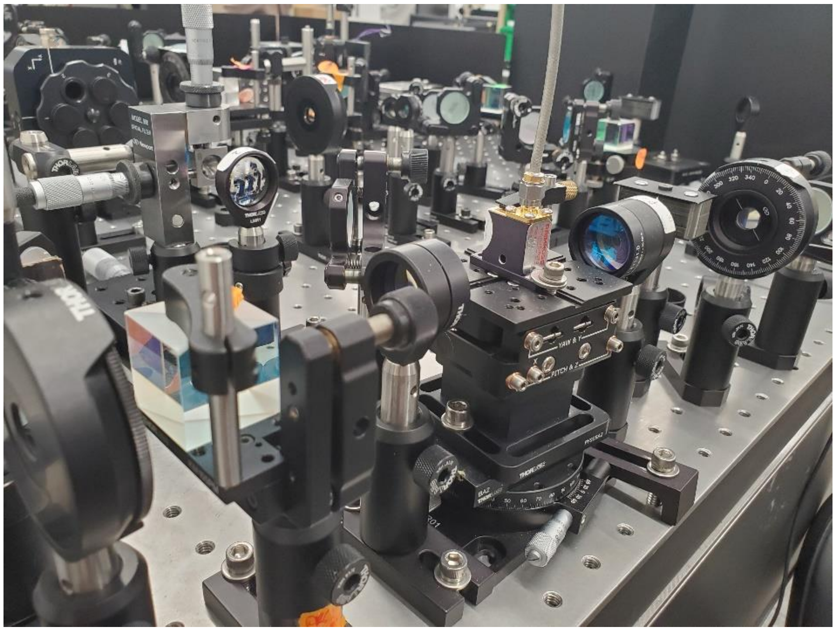


Figure 4: Optical components of the squeezed light source placed on a portable breadboard. In the foreground an acousto-optic modulator is shown in a double-pass configuration. The double-pass diffraction efficiency was tuned to 3% for about half of the nominal input RF drive power capacity, providing ample headroom of hundreds of microwatts available in probe power. The device provide a probe field by frequency-downshifting a field by 1.5GHz into the first order output, twice, for an effective downshift of 3GHz, obtaining the needed energy separation shown in Fig. 1c. The resultant fields are then sent to the rest of the optical train shown in the background, leading the Rb vapor cell.

In addition, the project performed theoretical calculations to predict the effects of using two-mode squeezed states of light on multiple accelerometers simultaneously. We found that for coherent, collective measurements, the SNR is enhanced by the squeezing amount, just as in single-sensor configurations. However, to obtain a larger 1/N scaling for N-mode squeezed states, we find that fully entangled sensors are required. That is, the entanglement amongst the optical modes must be transduced onto the sensors before readout. Nonetheless, for joint measurements over distributed signals, quantum noise reduction still provides a net improvement over classical-networked sensors.

Outlook

In the next few years, the program will continue building quantum sensors that use quantum noise reduction and back action evasion for use in table top experiments that will demonstrate the potential of our approach to detect exotic fields and charged particles. In particular, we will develop optical-domain quantum noise reduction (at near IR wavelengths) for enhancing the readout of both accelerometers and magnetometers. These platforms will allow us to probe the sensor's coupling to dark matter both gravitationally and electromagnetically. Because we focus on quantum sensors at optical wavelengths, our approach is very complementary to the existing portfolio of HEP detector research, especially as pertains to the search for physics beyond the standard model. Quantum sensing platforms which operate at microwave frequencies are under construction within the HEP lab complex. Therefore, our devices probe dark matter mass and energy limits in complementary regions of the spectrum: at the ultralight and heavy (>WIMP mass) scales. The addition of this quantum sensing capability thus adds a powerful capability to the HEP office's expanding portfolio.

Publications (prior work)

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Development and Characterization of Superconducting Quasiparticle-Sensitive Sensors and Qubits

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Abstract

Our QuantISED research program was born from the recognition that there are several physical analogues in design between cryogenic detectors used in High Energy Physics (HEP) science missions (as in the SuperCDMS dark matter experiment) and superconducting devices used for Quantum Information Science (QIS). In both cases, single-crystal semiconductor substrates are patterned with thin films of superconducting materials, albeit with very different goals. In the HEP case, superconducting sensors detect energy deposited by particle interactions. A primary design driver is to optimize the coupling of energy into the sensors, in order to detect very small amounts of energy in the substrate (such as could potentially be deposited by dark matter). On the QIS side of things, specially designed circuits containing Josephson junctions form superconducting qubits which can be used to perform quantum computations. In this case, a primary design driver is to minimize coupling of energy into the thin films so as to minimize disruption of the state of the qubit. We realized that there is a common need in both cases to improve understanding of how energy in the substrate (in the form of phonons) couples into the superconducting thin films to create excitations called quasiparticles. For HEP devices, the goal is to improve the sensitivity of superconducting sensors by encouraging production of quasiparticles; whereas for the QIS qubit devices, the goal is to better isolate the superconducting circuits and thus to mitigate production of quasiparticles.

We propose to build upon our established collaboration of HEP and QIS experts to develop advanced methods for measuring and modeling energy transport in cryogenic devices, leveraging specific HEP and QIS technologies to improve understanding and performance of devices instrumented with superconducting, quasiparticle-sensitive sensors and qubits. Our research program relies on the QIS expertise in fabrication and operation of qubit devices at MIT Lincoln Laboratory and Massachusetts Institute of Technology (MIT) to conduct measurements with novel devices specifically designed to explore phonon coupling and superconducting behaviors. HEP expertise with cryogenic detectors at Pacific Northwest National Laboratory and Texas A&M University provides the knowledge and experience to develop an empirical basis for modeling the coupling of superconducting circuits to the cryogenic environment and energy sources. Through comparison of device data to phonon-transport simulations, we propose to advance our phonon-coupling research by exploring a broader range of superconducting materials (and thus dependence on phonon frequency) and by studying the effects of quasiparticle diffusion and recombination on device performance. Further, we will test and characterize a new high-sensitivity sensor concept and explore non-BCS superconducting behavior in transmon qubits. We will leverage the outcomes of our research to develop applications to HEP science missions, by using our simulation framework to explore novel designs and (more generally) to advance detector-response modeling for cryogenic detectors instrumented with superconducting sensors.

Complex quantum systems and the quantum universe

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Abstract

Quantum field theory and quantum gravity are fundamentally theories of information, a fact that has led to foundational new insights at the interface of high energy physics, quantum information, and quantum computing. The goal of this consortium is to combine expertise in high energy theory and quantum information science, to address the most pressing theoretical questions in these fields. We will build new tools for the study of entanglement in quantum field theories and quantum gravity, especially in cases in which field theory and gravity are equivalent (or dual) to each other. The consortium will study an interlocking set of fundamental questions (see Objectives above) that will drive the next wave of progress in both fields. We aim to make foundational advances in both Quantum Information Science (QIS) and High Energy Physics (HEP). In QIS, the consortium will seek to produce: (a) progress in characterizing the possible distributed patterns of entanglement between many parties that can be naturally induced by the dynamics of physical theories, and that will be robust to noise in quantum computation; (b) progress in understanding whether and when the dynamics of a physical system can be "fast-forwarded" on a quantum computer, and what sorts of dynamics produce pseudo-random states that are relevant for problems like the black hole information paradox; (c) a classification and characterization of the kinds of novel open-system dynamics that can be driven by entanglement with other systems; and (d) new classes of tractable models that can be used as examples by theorists and/or simulated on quantum computers. In HET, the consortium will study: (a) the emergence of spacetime from entanglement in holographic theories, and the use of entanglement to extract information from behind horizons; (b) the role of baby universes and spacetime wormholes in quantum gravity, especially with regard to whether they lead to large quantum effects that require the cosmos to be treated as a disordered statistical ensemble; and (c) non-spatially organized entanglement, e.g. in matrix theories, and the role of such entanglement in the holographic emergence of flat space.

OBJECTIVES

Our broad goals are twofold. We will (1) develop techniques to study the organization and dynamics of quantum information in complex systems; and (2) use quantum information techniques to study fundamental problems in gravity, including the physics of black holes and cosmology. We will achieve these goals by pursuing seven specific objectives as described below. Some of these objectives (such as 1 and 2) concern the general study of quantum information in complex systems, while others (such as 5 and 6) focus on certain types of physical systems; but all seven make connections between quantum information science and the physics of complex systems. We describe these objectives briefly here, and in detail in section.

Objective 1 -- Multi-party entanglement

A quantum system with many parts can have a dizzying array of different kinds of correlations that can be of deep physical significance. While the theory of two-party entanglement is well-developed --- albeit still fairly complicated --- our current understanding of multi-party entanglement is less clear. We will elucidate the role of multi-party quantum correlations in quantum field theory and in gravity, including in the context of holographic dualities. Specific challenges include understanding which sorts of multi-party entanglement arise holographically, and which entanglement measures are most appropriate to detect them. More broadly, the possible patterns of multi-party entanglement that are achievable in quantum theories have not been classified. Multi-party entanglement plays a potentially important role in problems ranging from robust quantum computation and communication to compressive sensing of quantum information. Likewise, it is implicated in problems in theoretical physics ranging from chaos, to the emergence of classicality, to the recovery of information from black holes.

Objective 2 -- Computational complexity

We will study the evolution of complexity and the complexity of evolution in quantum theories. Complexity is an important notion in quantum computation because it determines how hard it is to build a computing device or algorithm to carry out a given task. In quantum gravity, the notion of complexity of time evolution has become important because complexity of the underlying state appears to be related to the volume of spacetime regions. Complexity also plays an increasingly important role in our understanding of quantum chaos. We aim to shed light on complexity in quantum dynamical systems and in their gravitational realizations.

Objective 3 -- Open quantum systems

The study of such open systems, in particular the characterization of non-Markovian dynamics with quantum memory, is an important and still developing subject. We propose a suite of projects aimed at developing this subject and applying it to problems in quantum gravity and cosmology. We will provide a classification of non-Markovian dynamics based on different properties of the environment. We will work out examples of non-Markovian evolution of local probe systems in field theories and their spacetime duals, in order to develop non-Markovianity as a diagnostic and computational tool. We will extend current results on low-entropy/high-free energy configurations in few-qubit systems to explore why it appears necessary to postulate a low-entropy initial state of the universe. We will also further develop the effective field theory of open quantum systems, using strongly coupled quantum theories with holographic duals as an environment. We will extend ongoing work on entanglement timescales in bipartite oscillator systems to more complex systems, and attempt to synthesize holographic analyses to construct non-Markovian effective field theories.

Objective 4 -- Non-spatial entanglement

Entanglement between spatial regions of quantum field theories has yielded great insight into holography and quantum gravity. Understanding entanglement based on other means of organizing the Hilbert space --- in field space, or by spatial scales --- is of urgent importance. In the context of holography, there are holographic dualities to theories of matrix quantum mechanics with no spatial directions. There are good arguments that local physics on scales below the radius of curvature of anti-de Sitter space are encoded in matrix degrees of freedom of the holographic dual theory, and the bulk spacetime includes a radial direction that encodes the spatiotemporal scales of dual quantum phenomena, while the organization of quantum field theories by wavenumber is also important in inflationary cosmology. We will examine the open-system dynamics of subsets of degrees of freedom in gauged matrix models. We will also study the dynamics of mode entanglement and time-dependent decoupling for interacting field theories in de Sitter space. And we will develop time-dependent perturbative diagonalization techniques for Markovian master equations to study decoupling in open quantum systems.

Objective 5 -- Black holes and the emergence of spacetime

We will develop recent insights related to the black hole information problem in AdS/CFT and beyond. It has now been understood that the semiclassical gravitational path integral is powerful enough to capture many deep properties of the dynamics of black holes, including the Page curve and the Hayden-Preskill protocol. There are however several mysterious aspects of this formalism, including the apparent use of an incorrect description of the Hawking radiation, and the role of unusual Euclidean configurations called replica wormholes. We will develop a deeper information-theoretic understanding of these calculations, which we expect to involve a fusion of ideas from the theories of coarse-graining, complexity, and quantum error correction.

Objective 6 -- The cosmos

We will study the organization and evolution of quantum information in cosmology, using techniques from both holographic duality and the theory of open quantum systems. During the period of inflation in the very early universe, and in the late universe as it transitions to an epoch of accelerating expansion driven by dark energy, spacetime is approximately described by de Sitter space. De Sitter space shares some features with anti-de Sitter, but the theory of quantum gravity in de Sitter remains poorly understood. We will approach this problem using recent insights in black hole physics, including the importance of higher topologies and baby universes in the gravitational path integral, and their role in encoding quantum information behind a horizon. Cosmological spacetimes share many features with black hole interiors, including horizons and spacetime singularities, which will motivate our approach to quantum gravity in the early universe. We will also study inflationary perturbations from the point of view of quantum information, using an open quantum system approach. In particular, we will study the non-Markovian evolution of quantum coherences in primordial perturbations, and their imprints in late-time cosmological observables.

Objective 7 -- Tractable models of computation and information

We will tackle hard information-theoretic and complexity-theoretic problems using inspiration and ideas from high energy physics. We will develop increasingly accurate toy models of AdS/CFT and study holography-inspired constructions of pseudorandom states and their connections to post-quantum cryptography. We will study the suitability of near-term quantum computers for simulating SYK and related models. We will develop the set of holographic states as a natural set of ``exactly solvable'' models, whose entanglement structure is nontrivial but sufficiently simple to admit tractable answers to information-theoretic questions (e.g.,computable distillable entanglement). Finally, we will seek to import ideas from high energy physics into quantum computing by using exact answers to the geodesic equations in the unitary group to improve variational quantum algorithms.