High Energy Physics
Quantum Information Science Awards Abstracts
Cosmos and Qubits

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PI: Nishant Agarwal, University of Massachusetts-Lowell,
Co-PIs: Adolfo del Campo, Archana Kamal (Massachusetts-Lowell); Sarah Shandera (Penn State)

The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology
PI: Raphael Bousso, University of California- Berkeley
Co-PIs: Ehud Altman, Ning Bao (UC Berkeley); Patrick Hayden (Stanford); Christopher Monroe (Maryland); Yasunori Nomura (UC Berkeley); Xiao-Liang Qi, Monika Schleier-Smith (Stanford); Irfan Siddiqi (LBNL); Brian Swingle (Maryland); Norman Yao, Michael Zaletel (UC Berkeley)

Algebraic approach towards quantum information in quantum field theory and holography
PI: Daniel Harlow, Massachusetts Institute of Technology
Co-PIs: Aram Harrow and Hong Liu (MIT)

Entanglement in string theory and the emergence of geometry
PI: Veronika Hubeny, QMAP, University of Califonia-Davis
Co-PIs: Mukund Rangamani, QMAP (UC Davis)

Quantum Information in a strongly interacting quantum simulator: from gauge/string theory duality to analogue black holes
PI: Martin Kruczenski, Purdue University
Co-PIs: Chen-Lung Hung, Sergei Khlebnikov, Qi Zhou (Purdue)

Entanglement in Gravity and Quantum Field Theory
PI: Robert G. Leigh, Ph.D., University of Illinois
Co-PI: Thomas Faulkner, Ph.D., University of Illinois

Quantum error correction and spactime geometry
PI: John Preskill, Caltech
Co-PI: Patrick Hayden (Stanford)

Holographic Quantum Simulation with Atomic Spins and Photons
PI: Monika Schleier-Smith
Co-PIs: Gregory Bentsen, Emily Davis, Avikar Periwal, Eric Cooper, Patrick Hayden

Quantum Communication Channels for Fundamental Physics (QCCFP)
PI: Maria Spiropulu, California Institute of Technology
Co-PIs: C. Peña (Fermilab), D. Jafferis (Harvard)

Quantum simulation: From spin models to gauge-gravity correspondence
PI: Vladan Vuletic, MIT
Co-PI: Mikhail Lukin (Harvard)

Probing information scrambling via quantum teleportation
Norman Y. Yao, Lawrence Berkeley National Laboratory/University of California-Berkeley

Interplay of Quantum Information, Thermodynamics, and Gravity in the Early Universe

Nishant Agarwal, University of Massachusetts Lowell
Adolfo del Campo, University of Massachusetts Boston, Archana Kamal, University of Massachusetts Lowell, Sarah Shandera, The Pennsylvania State University

The early Universe is a rich testbed of quantum gravity and out-of-equilibrium quantum physics in general. The goal of this proposal is to explore fundamental questions in both domains: quantum origins of the early Universe and strongly-interacting quantum matter.

Under the first direction we will develop a fully quantum mechanical framework for the early Universe using an open system approach. In particular, we will focus on the non-Markovian vs. Markovian evolution of system modes, quantum correlations, and signatures in late-time observables. Further, we will use tools from quantum resource theory and thermodynamics to explore why it appears to be imperative to postulate a low entropy initial state of the Universe.

Under the second direction we will investigate open quantum system dynamics in strongly-coupled qubit and oscillator systems. We will specifically focus on detailed studies of non-Markovian evolution, entanglement dynamics, and quantum backaction evasion in these systems, including experimental realizations and implications for gravity. Further, we will establish thermodynamics for chaotic quantum systems, with emphasis on the dynamics of information scrambling, and implications for black hole solutions in AdS/CFT and quantum gravity.

The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology

Raphael Bousso, UC Berkeley (Principal Investigator)

Ehud Altman, UC Berkeley; Ning Bao, UC Berkeley; Patrick Hayden, Stanford; Christopher Monroe, U. Maryland; Yasunori Nomura, UC Berkeley; Xiao-Liang Qi, Stanford; Monika Schleier-Smith, Stanford; Irfan Siddiqi, LBNL; Brian Swingle, U. Maryland; Norman Yao, UC Berkeley; Michael Zaletel, UC Berkeley (Co-Investigators)

Research in quantum gravity has been accelerating thanks to powerful tools and insights from quantum information theory. At the same time, developments in quantum gravity are feeding back into quantum information science, leading to a rich interplay between these two fields. This collaboration aims to identify and develop nascent connections in key areas, including the black hole information problem and quantum information scrambling; the emergence of spacetime from entanglement via quantum error correcting codes; low energy applications and information theoretic interpretations of energy conditions originally derived in a quantum-gravitational context; and the dynamics of wormholes and its relation to quantum teleportation.

A key feature of our collaboration is a focus on near term quantum devices: what are the quantum technologies that might arise from quantum gravity? Which puzzles about quantum gravity might be addressed with such quantum devices? A central organizing principle is the use of tensor networks, which were originally developed for understanding the structure of low-energy quantum states in nonrelativistic many-body systems. Quantum gravity research has shown that tensor networks can be used to model the emergence of spacetime geometry from an underlying quantum theory. At the same time, the appropriation of tensor networks for the study of quantum gravity and black holes has inspired novel applications elsewhere. Tensor networks can be calculational tools, useful not only for describing ground states, but also for elucidating the dynamics of quantum information in strongly coupled systems.

As such, our collaborations is comprised of several distinct components. First, we have three distinct quantum device platforms, each with its unique advantages in probing quantum physics as inspired by holography and quantum gravity. Second, we have a team of high energy and quantum information theorists that are well-versed in (and in some cases, discovered) the emerging connections between quantum information and quantum gravity. Finally, we also have several experts in condensed matter/AMO physics to help translate these questions into a form that can be implemented by the experimental component of the collaboration. Examples of specific current projects include the study of scrambling, probing quantum energy conditions, studying the dynamics of quantum chaos, and benchmarking quantum error correcting codes inspired by holography.

Algebraic approach towards quantum information in quantum field theory and holography

PI: Daniel Harlow

Co-PIs: Aram Harrow and Hong Liu

This is a proposal for a two-year research grant from the DOE Office of Science to study connections between algebraic quantum field theory, holographic quantum codes, and approximate Markov states. These subjects have all been of much recent interest: the algebraic approach to quantum field theory has recently been used to prove remarkable general results such as the quantum null energy condition, and holographic quantum codes have given us a new perspective on classic problems in quantum gravity. In both cases the technical tools which lead to the new results can be understood as using the special properties of ``quantum Markov states''; states which saturate strong subadditivity. These states are also very interesting in quantum computing, with applications to quantum error-correction, efficient preparation of Gibbs states on quantum computers, efficient compression with side information, and many other areas.

Our proposal is to do a combined study of these three issues, seeking to systematically understand the connections between them. We are optimistic that this will lead to many new insights about quantum field theory, quantum gravity, and quantum information.

Entanglement in string theory and the emergence of geometry

Veronika Hubeny, QMAP, UC Davis, (Principal Investigator)
Mukund Rangamani, QMAP, UC Davis, (Co-Investigator)

The proposed project seeks to elucidate the fundamental nature of spacetime by utilizing recently-gained insights from the AdS/CFT correspondence – a ‘holographic’ duality which relates a gravitational theory in asymptotically Anti-de Sitter (AdS) spacetime to a lower-dimensional conformal field theory (CFT), effectively living on the boundary of AdS. Since the CFT is a quantum field theory without gravity, in this context the primary aim translates to one of understanding how the bulk spacetime geometry actually emerges from the boundary CFT.

Remarkably, progress over the past few years hints at profound relations to entanglement, a quintessentially quantum quantity. The key elements facilitating this connection are the Ryu- Takayanagi (RT), and its covariant generalization, the Hubeny-Rangamani-Takayanagi (HRT) prescription, for computing entanglement entropy for spatially organized degrees of freedom in the field theory in terms of areas of extremal surfaces in the bulk geometry. These prescriptions in fact capture the leading semi-classical answer for the entanglement entropy for a spatial region in a strongly coupled CFT. It is also known that the next sub-leading correction involves the entanglement between the gravitational degrees of freedom in the bulk geometry. These ideas have led to the important conceptual paradigm that entanglement is the underlying glue that binds together the geometric structure of the spacetime, codified in the “ER=EPR” paradigm.

To understand how entanglement is responsible for building geometry from scratch, one needs to elucidate the holographic map at a deeper level. For one, the current discussion is rooted in the strong coupling regime of the field theory, where the bulk dual is a classical gravitational field theory. Given that the full extent of the AdS/CFT duality maps the CFT Hilbert space onto the Hilbert space of the quantum string theory in the asymptotically AdS spacetime, one should be able to understand how to extend the RT-HRT prescriptions to be valid at the full quantum level (and for any value of the coupling). This is the overarching goal of the current program.

Hubeny & Rangamani aim to undertake a research program which primarily transcends current investigations in the subject, and provides a platform for formulating the correspondence between entanglement and geometry directly at the level of the full string theory Hilbert space. Some of the directions the Investigators propose to explore are to understand how entanglement structures get repackaged across dualities (be they field theory dualities or more general open-closed string dualities), and to develop tools inspired by operator algebras to understand the emergence of locality in string theory. These investigations will draw from developments in general relativity, quantum field theory, string theory, and quantum information and will provide a concrete framework to further the connections between entanglement and geometry.

Quantum Information in a strongly interacting quantum simulator: from gauge/string theory duality to analogue black holes

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Dep. of Energy Quantum Information Science (QIS) Kick Off Principal Investigators' Meeting, Jan 31-Feb 1, 2019, Bethesda, MD.

The AdS/CFT correspondence implies that, in the strongly interacting regime where quantum effects are large, systems encode and transmit information in a very different way than they do at weak coupling. In particular, from the quantum mechanics of a field theory emerges a higher dimensional space time with non-trivial metric and gravity. Important as they are for the theory of quantum information, wider applicability of these ideas to Quantum Information Science (QIS) requires controllable experimental systems where similar ideas apply. Inspired by this far reaching ideas, we consider an experimental setup where an atomic quantum gas in an optical lattice is driven into a strongly coupled quantum critical regime. The system can be described by the Bose-Hubbard model and the critical region of interest by the O(2) three dimensional Wilson-Fisher fixed point. Theoretically this system is studied with a combination of techniques valid in various regimes, including, mean-field theory, 4-e expansion, conformal bootstrap, numerical simulations and qualitative ideas from AdS/CFT. Experimentally a 2D quantum gas is formed by evaporative-cooled cesium atoms trapped in an oblate optical potential to ensure a large surface area (> 400μm) occupying > 50x50 lattice sites.

The main objective is to create and study the time evolution of entanglement between separated regions of space. As a result, we will get a new understanding into the encoding and transmission of quantum information in this and possible other strongly interacting systems.

Entanglement will be measured using Renyi entropy following recent ideas in the literature. Our immediate goals are to (1) use existing and newly developed theoretical tools to study the creation and evolution of entanglement in strongly coupled systems, and design experimental tests that can be carried out in the systems to which we already have experimental access, (2) develop new experimental techniques for synthesizing highly controllable strongly coupled quantum gases, and (3) perform the experimental tests and compare the results with the theory.

Further goals include the manipulation of the local sound speed to create far from equilibrium states such as shock-waves and sonic black holes that should create large amounts of entanglement and lead to new quantum phenomena in strongly coupled systems.

Entanglement in Gravity and Quantum Field Theory

The Board of Trustees of the University of Illinois
Robert G. Leigh, Ph.D., University of Illinois (Principal Investigator)
Thomas Faulkner, Ph.D., University of Illinois (Co-Investigator)

It is becoming increasingly clear that ideas from quantum information theory, particularly the notion of quantum entanglement, play a fundamental role in some of the deepest aspects of our modern theories of quantum fields and gravity. The aim of this research is to explore the role that quantum entanglement plays in quantum field theories and in the nature of space-time and gravity. Building on a variety of new results obtained in these regards at the University of Illinois, we plan to explore the constraints on the dynamical content of quantum field theories that follow from their entanglement properties. Topological field theories are important examples of particularly simple quantum field theories whose patterns of entanglement make connections between high energy physics, condensed matter physics and mathematics. These theories are directly relevant to low energy properties of certain materials. The study of such theories will allow us to investigate ideas that are relevant to quantum information research, such as new notions of entanglement between multiple parties and the quantum properties of interfaces between different phases of such materials.

In addition, we will employ new results in mathematics which strengthen monotonicity constraints on relative entropy to study their ramifications in quantum field theories, and we will use quantum information methods to study the emergence of quantum gravity and string theory in holographic quantum field theories. The project investigators are in an ideal position to make important contributions to these exciting areas, contributing both to the evolution of the application of quantum information concepts in high energy physics and to the further development of general quantum informational ideas.

Quantum error correction and spactime geometry

John Preskill (Caltech), Patrick Hayden (Stanford)

Quantum error correction and the holographic principle are two of the most far-reaching ideas in contemporary physics. Quantum error correction is the basis of our belief that scalable quantum computers can be built and operated in the foreseeable future. The AdS/CFT holographic correspondence is currently our best tool for understanding nonperturbative quantum gravity. Remarkably, recent advances indicate that these two deep ideas are closely related. Specifically, AdS/CFT posits a dictionary in which the observables of a bulk spacetime are mapped to the observables of a quantum field theory living at the boundary of the spacetime, and this dictionary can be interpreted as the encoding map of a quantum error-correcting code.

In this project we are developing this connection further, in multiple directions, by advancing the theory of quantum error correction and by clarifying how this theory can be used to build more general and powerful approaches for probing spacetime physics. In particular, we will extend the formalism of operator algebra quantum error correction with the goal of clarifying how emergent gauge symmetry arises in the bulk spacetime, and develop the theory of approximate error correction with the goal of quantifying the robustness of bulk quantum geometry with respect to errors in the boundary theory. We anticipate that our work will illuminate how quantum information is encoded and processed by black holes, and the role of quantum entanglement in the very early history of the universe.

Currently we are studying the properties of approximate quantum error-correcting codes that admit continuous symmetries. In particular, we have derived bounds on the fidelity that can be achieved by a recovery map for a code which admits continuous time evolution. The fidelity becomes perfect in two interesting limits --- when the length (number of physical subsystems) of the code diverges with the local subsystem dimension fixed, and when the local dimension diverges with the length fixed. Both limits are relevant for investigations of the AdS/CFT dictionary which we are continuing to pursue.

In addition, we have applied the recently developed theory of universal subspace quantum error correction to the reconstruction of black hole microstates in AdS/CFT duality. This work explains how the approximate error-correcting code underlying the bulk-to-boundary dictionary becomes exact in the semiclassical limit.

Holographic Quantum Simulation with Atomic Spins and Photons

Gregory Bentsen, Emily Davis, Avikar Periwal, Eric Cooper, Patrick Hayden (co-PI), Monika Schleier-Smith (PI), SLAC/Stanford

The theories of quantum mechanics and gravity were developed to describe such opposite extremes of the physical world that the connections between them were long deemed out of reach of experiments. Advances in engineering controllable quantum systems, coupled with profound theoretical developments, offer the new opportunity of probing concepts of quantum gravity in the laboratory. The unifying theoretical framework is the holographic principle, under which spacetime geometry emerges from quantum entanglement. An extreme limit of this duality are strongly interacting quantum systems that can equivalently be viewed as black holes, yielding a simple gravitational description. A characteristic feature of black-hole duals is that they rapidly scramble quantum information—at a rate conjectured to be the fastest possible in nature.

A requirement for fast scrambling is a non-local graph of interactions in the quantum system, epitomized by the paradigmatic Sachdev-Ye-Kitaev model featuring non-local hopping of fermions. We engineer a related class of bosonic models in a quantum simulator composed of laser-cooled atoms. By using light to induce spin-exchange interactions among atoms trapped in an optical resonator, we simulate long-range hopping of interacting bosons (spin excitations). A key goal is to image how the influence of a localized perturbation spreads on a variety of coupling graphs. Toward this end, a valuable tool is the ability to effectively reverse the flow of time by switching the sign of interactions, a capability realized in our experiment. We furthermore present progress in controlling the structure of non-local interactions to build toy models of holographic duality conducive to fast scrambling. Such models will offer a starting point for exploring how measurements performed on a quantum system can reveal the holographic geometry.

Quantum Communication Channels for Fundamental Physics (QCCFP)

PUBLIC ABSTRACT

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Quantum channels are fundamental to Quantum Information Science since they allow the communication of quantum information without the loss of quantum coherence. The most familiar example of a quantum channel is the “Alice-Bob” quantum teleportation, which exploits the fact that Alice and Bob share a pair of entangled states, known as an Einstein Podolosky Rosen (EPR) pair. In the consortium research program we propose, we explore deep connections between entanglement distribution protocols and the nature of gravity both theoretically and experimentally. The theoretical activity will be assisted by quantum simulators realized on near-term gate-programmable quantum computers. We will also define how such quantum channels and protocols can be realized using photonic qubits and fiber-based quantum networks and prototype the technology enhancements required to realize these protocols. This experimental activity will take advantage of the FQNET quantum network that was build in 2017-2018 and commissioned in the fall of 2018 at Fermilab.

Quantum simulation: From spin models to gauge-gravity correspondence

Vladan Vuletic (MIT) and Mikhail Lukin (Harvard University)

Quantum many-body systems with coherent and controllable interactions will enable the realization of novel quantum materials, the quantum simulation of problems that cannot be simulated on classical computers, computational systems that are exponentially faster than existing classical algorithms, and the direct investigation of the conjectured duality between gravitational theories and quantum field theories. This pilot project will focus on the gauge-gravity correspondence, and use a controllable quantum many-body system close to a critical point to experimentally test the gauge-gravity duality and related concepts. The dynamics of a large quantum system containing more than 50 qubits will be investigated in various critical regimes, bounds on the maximum speed of quantum scrambling will be determined that are relevant to the scrambling of information by black holes, and the relation between scrambling, quantum scars, and gravitational theories will be investigated.

This work at the interface of high-energy physics, gravity, and quantum many-body physics is performed in collaboration between the groups of Mikhail Lukin at Harvard, and the group of Vladan Vuletic at MIT. The experimental part of the work will be performed on an existing apparatus that can deterministically prepare reconfigurable arrays of individually trapped and detected cold atoms. The atoms are coupled to each other via strong, coherent interactions induced by excitation to atomic Rydberg states. In this system, the collaboration has recently realized a programmable Ising-type quantum spin model with tunable interactions for a system size of up to 51 qubits. The setup features fast control compared to the sub-microsecond characteristic evolution time of the system, so that controlled quench can be performed, and the subsequent dynamical evolution observed with single-qubit resolution.

In particular, the team will attempt to create highly entangled states that are superpositions of maximally separated areas in phase space, and explore the measurement of out-of-order time correlation functions that are relevant, e.g., to the question how and how fast information becomes dissipated when ordered systems disappear into a black hole (quantum scrambling). Entanglement in a variety of quantum phase transitions will be probed, and ideas originating from the gauge-gravity duality will be explored in this system.

Recently we have used the quantum simulator system to study the quantum critical dynamics of several quantum phase transitions. By studying the growth of spatial correlations while crossing the Ising-type quantum phase transition, we experimentally verify the quantum Kibble-Zurek mechanism, explore scaling universality, and observe corrections beyond the Kibble-Zurek predictions. This approach is subsequently used to measure the critical exponents associated with chiral clock models, providing new insights into exotic systems that have not been understood previously, and opening the door for precision studies of critical phenomena, simulations of lattice gauge theories, and applications to quantum optimization.

HEP Pilot: Probing information scrambling via quantum teleportation

PI: Norman Y. Yao (LBNL & UC Berkeley)

The black-hole information paradox represents one of the central open questions at the interface of modern high energy physics and quantum information science. While general relativity predicts that the information is lost forever, the evolution according to quantum mechanics is unitary, hence reversible, suggesting that there may in principle be a way to recover the information. The classic thought experiments for the black hole information paradox is the following: suppose that Alice throws a secret quantum state into a black hole -- is it then possible for an outside observer, Bob, to reconstruct it by collecting the Hawking radiation emitted at a later time. Over two decades ago, seminal work by Page demonstrated that if the dynamics of the black hole could be approximated as a random unitary, then Bob would need to wait at least half the lifetime of the black hole. Recently, Hayden and Preskill added an interesting twist to this classic setup by considering a black hole, which is entangled with a quantum memory that Bob possesses. There, it was shown that the decoding of Alice's quantum state could be performed with an exponential speedup.

However, there is a subtlety in this argument. While it was shown that such a decoding is information-theoretically possible (i.e. that there exists a unitary operator which reconstructs the state by acting only on the Hawking radiation and quantum memory), it remains unclear if such a unitary is actually physically implementable and what form the quantum circuit might take.

In this pilot, we propose to explore a novel probabilistic decoding protocol (building upon recent work by Yoshida and Kitaev) for reconstructing a quantum state from the Hawking radiation in the Hayden-Preskill black hole thought experiment. The protocol attempts to teleports a quantum state thrown into a black hole to an outside observer by projecting pairs of outgoing Hawking radiation from two sides of an entangled black hole into EPR pairs. The chaotic dynamics of the black-hole is simulated by performing unitary operations to implement an effective "scrambling" operation.

One of the main focal points of the pilot is to explore whether such a protocol can effectively distinguish between chaotic scrambling dynamics and decoherence. This represents a particularly challenging question for typical correlation-function-based measurements (e.g. out-of-time-order correlators). To this end, we will investigate the behavior of the decoding protocol in the presence of multiple different forms of "noise", including both extrinsic depolarization/dephasing and intrinsic imperfections in quantum control. Moreover, we will attempt to bound the amount of scrambling in a many-body quantum circuit by using the teleportation fidelity associated with the protocol. In particular, by extracting a "noise" parameter from our protocol, we will quantify the non-scrambling induced decay of out-of-time-order correlators. Our results open the door to experimentally measuring quantum scrambling with built-in verifiability.

High Energy Physics
Quantum Information Science Awards Abstracts
Foundational QIS- Theory and Simulations

Quantum Simulation of Quantum Field Theories
PI: Tanmoy Bhattacharya, LANL
Co-PIs: Shailesh Chandrasekharan (Duke University), Rajan Gupta (LANL), Hersh Singh (Duke University), Rolando Somma (LANL)

Quantum Information Science for Applied Quantum Field Theory
PI: Marcela Carena, Fermilab
Co-PIs: J. Amundson, R. Harnik, A. Kronfeld, A. Macridin, P. Spenzouris, Fermilab,
D. Kaplan, M. Savage, University of Washington, John Preskill, CalTech

Dipolar molecule emulator of lattice gauge theories
PI: Bryce Gadway, University of Illinois Urbana-Champaign
Co-PIs: J. Shen, D. Luo, M. Highman, B. Clark, B. DeMarco, A. X. El-Khadra, University of Illinois at Urbana-Champaign

Foundations of Quantum Computing for Gauge Theories and Quantum Gravity
PI: Yannick Meurice, University of Iowa
Co-PIs: M. McGuigan (BNL), R. Brower (BU), S. Lloyd (MIT), (MSU) A. Bazavov (MSU), S. Catterall, (Syracuse), S. Jordan (Maryland), D. Berenstein and X. Dong (UCSB)

Variational Consistent Histories: A Hybrid Quantum-Classical Algorithm for Quantum Foundations
DOE HEP QuantISED Grant: Disentangling Quantum Entanglement:
PI: Andrew Sornborger, LANL
Co-PI: Andreas Albrecht (UC Davis)

Quantum Simulation of Quantum Field Theories

Tanmoy Bhattacharya (LANL), Shailesh Chandrasekharan (Duke University), Rajan Gupta (LANL),
Hersh Singh (Duke University), Rolando Somma (LANL)

The efficient simulation of quantum field theories is one of the main challenges in high energy physics. The only first-principles method when perturbation theory fails involves taking the limit of a discretized path integral evaluated by importance sampling. Often, however, the relevant measure is not positive when the paths are expressed in any known set of classical variables, and the integral becomes exponentially hard to compute. Hence novel computational paradigms are highly desirable. Here, we explore possible gains in using quantum computers to solve quantum field theories. In this, our goal is both to formulate the problem in a language expressible on a finite quantum computer and to develop efficient quantum algorithms for computing the quantities of interest. In particular, we will focus on expectation values of physical observables and correlations in thermal equilibrium as well as on time-dependent properties of QFTs such as scattering amplitudes and response functions.

We shall begin by understanding how to map any desired continuum field theory onto a discrete space-time lattice with a small finite Hilbert space at each lattice site. The idea is that if we can discretize the problem preserving its symmetries, then renormalization group flow can help in the construction of the continuum field theory. As the first example in this direction, we explore if the physics of the O(3) sigma model can be obtained from an O(3)-symmetric two-qubit Hamiltonian on each lattice site. As a first project, we shall explore if we can reproduce the physics of the Wilson-Fisher fixed point in 2+1-dimensions using such a qubit Hamiltonian. As a second project, we explore if we can obtain the asymptotic freedom of the O(3) sigma model in 1+1-dimensions via the qubit system. We will also explore how the approach to the continuum limit depends on the number of qubits used per site.

Simultaneously, we shall develop algorithms for simulating these systems on a quantum computer. Our current work in this direction uses a coupled system of naïvely discretized quantum oscillators as a discrete realization of the free scalar field theory and constructs a quantum algorithm to prepare the vacuum state of this Hamiltonian. The main feature of our algorithm is that the time taken to prepare this state scales almost linearly in the number N of space discretization points. This is an improvement over other known quantum algorithms, where the time scales quadratically or worse with N. The core of our algorithm is a new factorization of the discrete Fourier transform that relates the field variables to the canonically conjugate momenta, and is inspired by the well-known quantum Fourier transform. We also make use of a recent procedure to prepare quantum states with Gaussian amplitudes developed by one of us [1], which was successfully implemented to simulate a simple QFT associated with a quantum harmonic oscillator. We also plan to study this free scalar field theory to find new algorithms for time dependent problems like scattering amplitudes.

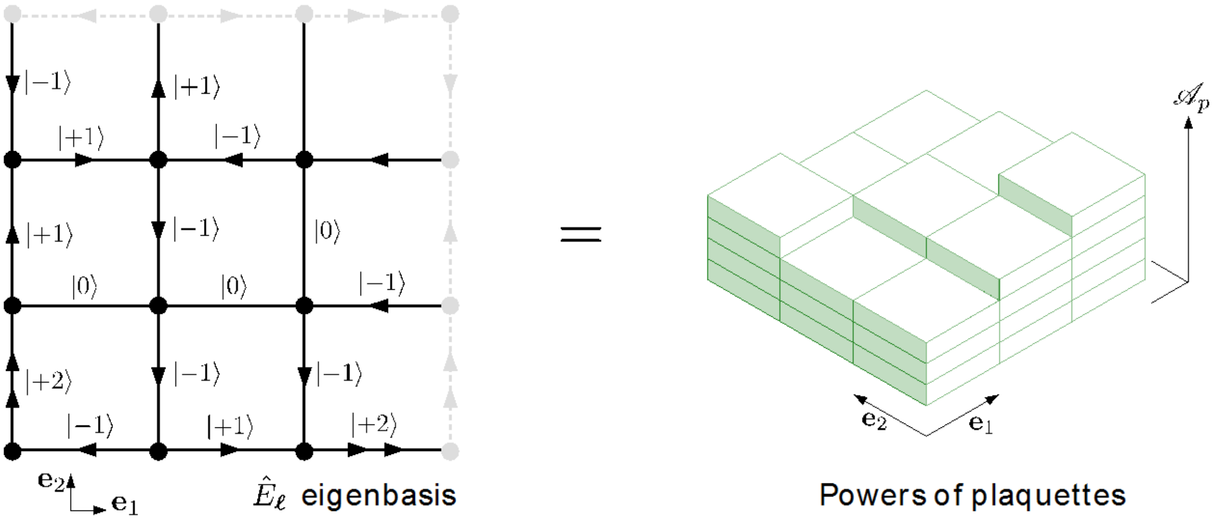
[1] R.D. Somma, “Quantum simulations of one-dimensional quantum systems”, *Quant. Inf. Comp.* **16** 1125–1168 (2016).

Quantum Information Science for Applied Quantum Field Theory

John Preskill, CalTech
J. Amundson, M. Carena (PI), R. Harnik, A. Kronfeld, A. Macridin, P. Spenzouris, Fermilab,
D. Kaplan, M. Savage, University of Washington.

Quantum computer seems to be the right abstract model for capturing all information processing that Nature allows, including that being performed by the most fundamental processes. The aim of this project is to explore and further develop connections between quantum information science (QIS) and quantum field theories (QFTs) in high energy physics. QFTs provide the foundation of high energy physics, from QED and low energy effective field theories of the strong and weak interactions, to the gauge theories of the Standard Model (SM) of particle physics, and to possible extensions beyond the SM. Applied QFT, i.e., QFT-based calculation, is a critical part of the analysis and interpretation of high energy physics experiments.

QFT and its applications present us with a variety of challenges, both computational and conceptual. In our work we identify several specific QFT challenges that may be fruitfully attacked with the tools of QIS. We are exploring new approaches to simulations of the Standard Model of particle physics. In particular, we are investigating approaches to reducing error in quantum simulation of QFTs utilizing the techniques of effective field theories. We also employ QIS techniques to develop new tools for high energy physics experiments, such as simulation of models for hadronization at the LHC, as well as new approaches to Feynman integral reduction. In addition, we explore ways in which the tools and language of QIS can shed new light on models for physics beyond the SM. Our work will help harness the power of quantum information science into applications that will advance the field of high energy physics.



Foundations of Quantum Computing for Gauge Theories and Quantum Gravity

BNL (M. McGuigan), BU (R. Brower), MIT (S. Lloyd), MSU (A. Bazavov), Syracuse (S. Catterall), U. of Iowa (Y. Meurice, PI), U. Md. (S. Jordan), UCSB (D. Berenstein and X. Dong)

Goals. Developing the fundamental building blocks of quantum computing for problems in High Energy Physics that are beyond classical computing. This includes real time evolution and calculations with sign problems encountered in lattice gauge theory and holographic approaches to strongly coupled systems. The long-term goals are to provide scalable quantum codes to describe the evolution of hadrons in collider experiments (jet physics), the early universe and the exploration of new models in quantum gravity and conformal field theory (CFT).

Work in progress. The ongoing research combines overlapping expertise in quantum computing, gauge-gravity duality and lattice gauge theory. This includes:

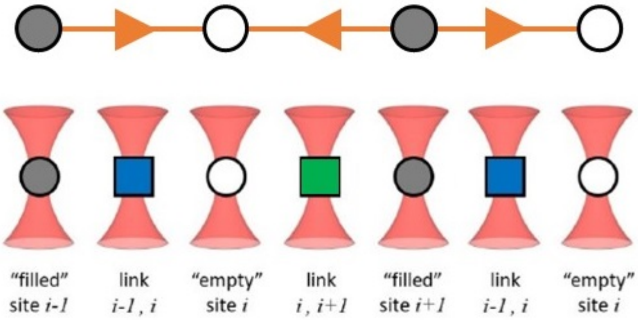
- Preparation of vacuum states of lattice field theories on universal quantum computers using the “jagged adiabatic path” method. MERA-based variational algorithms for simulating CFTs. Trapped ion implementations.
- Toolkit to translate tensor networks or quantum links formulations of lattice models into circuits implementable on quantum computers with polynomial time scaling.
- Benchmarks for real time scattering allowing comparison among quantum computers. Use of clock-shift, position, and harmonic oscillator basis for discrete quantum mechanics.
- Tensor network calculations for the non-abelian Higgs model and Euclidean de Sitter gravity. Discrete formulation of quantum algorithms in tessellations of AdS Space. Use of Rényi entropies of subregions (arXiv:1811.04081) to distinguish microcanonical from canonical features in theories holographically dual to gravity. Applications for evolution after quantum quenches.

Connection with quantum simulation experiments. Some of the procedures proposed can also be implemented using cold neutral atoms in optical lattices or trapped ions. Experimental implementations of variational procedures are being considered in collaboration with Guido Pagano from Chris Monroe’s ion trap group. Our recent experimental proposal (PRL 121 22320) for the Abelian Higgs model could be implemented in cold atom facilities. This is an unexplored direction for high-energy physics models and there is a niche that could be filled in our National Laboratories.

Dipolar molecule emulator of lattice gauge theories

J. Shen, D. Luo, M. Highman, B. Clark, B. DeMarco, A. X. El-Khadra, B. Gadway
University of Illinois at Urbana-Champaign

The quantum many-body problem is a great unsolved, cross-cutting challenge in physics that is of fundamental importance. Our understanding of phenomena related to dense quark matter, in particular, is challenged by this practical intractability of classical simulations. Because of the sheer cost and challenge of performing experiments that probe the length and energy scales relevant to such physics, there are practical motivations for finding theoretical methods to address the many-body problem. One promising approach, first proposed by Richard Feynman in the 1980s [1], is based on the use of a programmable and controllable analog quantum system to emulate the physics of a many-body problem of interest. This idea has been greatly extended over the interceding decades. We now, for instance, have formalized protocols for how computers based on quantum logic and bits (*i.e.*, qubits) could improve performance for many computational tasks, including simulations of particle physics problems [2,3]. While there are currently worldwide efforts to develop mid- to large-scale quantum computers, we are still likely many years away from such devices outperforming classical supercomputers. Even though digital quantum computers are still at a stage too premature for such tasks, an approach more directly along the lines envisioned by Feynman based on analog quantum simulators has advanced rapidly over the past two decades and can now treat many-body problems on par with or beyond the capabilities of modern supercomputers [4]. There has already been a great deal of theoretical work in considering analog quantum simulation approaches to problems with HEP relevance [5,6].



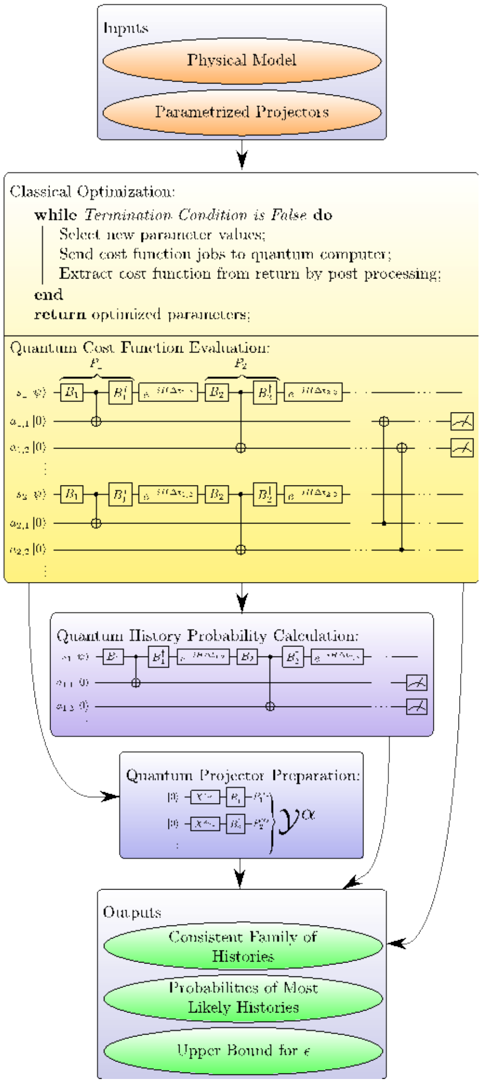
We describe how ultracold polar molecules—reproducible, controllable, scalable, and highly coherent quantum particles—can be used for the analog emulation of dynamical phenomena central to our understanding of particle physics, such as string-breaking and confinement. Specifically, we discuss how Abelian quantum link models in (1+1)d can be constructed based on arrays of polar molecules that are fixed in space but support direct dipolar exchange interactions between different rotational states. We describe how Gauss' law is imposed in such a system, through control of the internal state-dependent energy landscape of the molecules. We also discuss the possibilities for extending to higher-dimensional and non-Abelian quantum link models, by harnessing the naturally large internal state space of polar molecules and their ability to be trapped in tunable geometries.

[1] R. P. Feynman. Simulating physics with computers. *Int. J. Theor. Phys.* **21**, 467 (1982).
[2] S. Lloyd. Universal quantum simulators. *Science* **273**, 1073 (1996).
[3] S. P. Jordan, K. S. M. Lee, and J. Preskill. Quantum algorithms for quantum field theories. *Science* **336**, 1130 (2012).
[4] A. Mazurenko, C. S. Chiu, G. Ji, M. F. Parsons, M. Kanász-Nagy, R. Schmidt, F. Grusdt, E. Demler, D. Greif, and M. Greiner. A cold-atom Fermi-Hubbard antiferromagnet. *Nature* **545**, 462 (2017).
[5] U.-J. Wiese. Ultracold quantum gases and lattice systems: Quantum simulation of lattice gauge theories. *Annalen der Physik* **525**, 777 (2013).
[6] E. Zohar, J. I. Cirac, and B. Reznik. Quantum simulations of lattice gauge theories using ultracold atoms in optical lattices. *Rep. Prog. Phys.* **79**, 014401 (2016).
[7] A. V. Gorshkov, S. R. Manmana, G. Chen, E. Demler, M. D. Lukin, and A. M. Rey. Quantum magnetism with polar alkali-metal dimers. *Phys. Rev. A* **84**, 033619 (2011).

Title: Variational Consistent Histories: A Hybrid Quantum-Classical Algorithm for Quantum Foundations

DOE HEP QuantISED Grant: Disentangling Quantum Entanglement:

PI – Sornborger (LANL), Co-PI Albrecht (UC Davis)



```
while Termination Condition is False do
    Select new parameter values;
    Send cost function jobs to quantum computer;
    Extract cost function from return by post processing;
end
return optimized parameters;
```

The foundations of quantum mechanics have been debated for much of the past century. Of crucial importance to the understanding of the world we experience is the quantum-to-classical transition, i.e., the emergence of classical behavior from quantum laws. The Consistent Histories (CH) formalism was introduced by Gell-Mann, Hartle, Griffiths, and Omnès to address some of these fundamental issues. The inventors considered CH to be "the Copenhagen interpretation done right", as it resolves some of the paradoxes of quantum mechanics by enforcing strict rules for logical reasoning with quantum systems.

In this formalism, the Copenhagen interpretation's focus on measurements as the origin of probabilities is replaced by probabilities for sequences of events (histories) to occur. Hence, by avoiding measurements it avoids the measurement problem. The sets of histories whose probabilities are additive (as the histories do not interfere with each other) are considered to be consistent and are thus the only ones able to be reasoned about in terms of classical probability and logic. Regardless of one's opinion of the philosophical interpretation (on which we are agnostic), this computational framework has proven useful in applications such as investigating whether or not quantum cosmological theories are singular, understanding quantum jumps, and evaluating the arrival time for photons at a detector.

One of the main reasons that this framework has not received more attention and been more widely applied is that carrying out the calculations for non-trivial cases can be difficult. While numerical approaches have been attempted, they require exponentially more resources as either the number of times considered or the system size grow. This makes these approaches unusable for any but the simplest cases.

Here we present a scalable, variational hybrid quantum-classical algorithm (VHQCA) for the CH formalism, which achieves an exponential speedup over classical methods both in terms of the system size and the number of times considered. It will allow exploration beyond toy models, such as the quantum-to-classical transition in mesoscopic quantum systems. We expect this to revitalize interest in the CH approach to quantum mechanics, by increasing its practical utility.

With the impending arrival of the first useful noisy quantum computers, the field of VHQCAs, which make the most of short quantum circuits combined with classical optimizers, has been taking off. VHQCAs have now been demonstrated for myriad tasks ranging from finding the ground states of quantum systems to quantum factoring. The VHQCA framework potentially brings the practical applications of quantum computers years closer to fruition. Hence, practical implementations of our algorithm will be feasible on near-term quantum devices.

High Energy Physics
Quantum Information Science Awards Abstracts
Tools for QIST Research

NECQST: Novel Electronics for Cryogenic Quantum Sensors Technology
D. Braga, FNAL, J. D. Cressler, GeorgiaTech, M. Shaw, JPL, M. Spiropulu, Caltech

Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit
Skipper-CCD: new single photon sensor for quantum imaging
PI: Juan Estrada, Fermilab

Coherence Times and Dark Sector Searches
Lead PI: Dr. Alexander Romanenko, Fermilab
Co-PI: Prof. Robert McDermott, Univ. of Wisconsin-Madison
Co-PI: Dr. David Pappas, NIST/Univ. of Colorado-Boulder

FPGA-Based Quantum Control for HEP Simulations with Qutrits
Irfan Siddiqi, Gang Huang, and Lawrence Doolittle, Lawrence Berkeley National Laboratory (LBNL)

NECQST: Novel Electronics for Cryogenic Quantum Sensors Technology

FNAL (D. Braga), GeorgiaTech (J. D. Cressler), JPL (M. Shaw), Caltech (M. Spiropulu)

Superconducting nanowire single photon detectors (SNSPDs) are the highest performing detectors available for time-correlated single photon counting from the deep UV to the mid-infrared. SNSPDs have been widely adopted within the quantum information science (QIS) community to enable, among others, fundamental tests of quantum physics, long-distance quantum communication, and quantum computing with trapped ions.

It is only within the past year, however, that state-of-the-art low-noise cryogenic amplifier technology has been used to improve the timing resolution of SNSPDs. By incorporating a cryogenic amplifier designed for radio astronomy, researchers at JPL were able to successfully reduce the timing jitter in SNSPDs from 12 ps FWHM to a record 2.7 ps FWHM. By leveraging recent advances in cryogenic transistor technology and the expertise in high-speed detector readout circuits available in the high-energy physics community, there is significant potential to improve the timing jitter, maximum count rate, and scalability of SNSPDs to enable significant new advances in QIS technology.

NECQST is a two-year technology development effort that focuses on the development of low-noise cryogenic amplifiers specifically designed for use with SNSPDs, based on state-of-the-art, commercially available SiGe heterojunction bipolar transistors (HBTs), operating at a range of 1-4 Kelvin. When cooled, SiGe HBTs naturally exhibit improved frequency response, current gain, noise, bandwidth, and output conductance. They exist in a BiCMOS implementation (SiGe HBT + Si CMOS), which are fabricated on large wafers at high yield and low cost using conventional silicon processing techniques and silicon economy-of-scale.

In this collaboration, the ASIC Development Group at Fermi National Accelerator Laboratory (FNAL) will develop crucial device models to predict the shift of transistor design parameters at deep cryogenic temperatures, while Cressler Group at the Georgia Institute of Technology (GT) will design the readout circuits with input from the Superconducting Devices Group at the Jet Propulsion Laboratory (JPL) and FNAL. JPL will finally integrate the devices with state-of-the-art SNSPDs and benchmark their performance.

Expected major outcomes are a reduction of the timing jitter of SNSPDs from the current record of 2.7 ps toward 1 ps and below, by reducing the noise of the readout amplifier chain, and a drastic reduction in the power dissipation associated with the use of low-noise cryogenic amplifiers.

Improving the timing jitter, maximum count rate, and pixel count of SNSPDs by developing improved cryogenic readout circuits, will ultimately enable transformative new capabilities in ultra-high-rate quantum communication, such as the transfer of quantum information between remote quantum information processing systems, the secure transfer of classical data over fiber at multi-Gbps speeds, and free-space communication with space-based quantum assets. Such performance advances will directly benefit the Caltech Intelligent Quantum Networks & Technologies (INQNET) program, and specifically the Fermilab Quantum Network program (FQNET) which aims to demonstrate high-rate quantum communication at Fermilab.

Skipper-CCD: new single photon sensor for quantum imaging

PI: Juan Estrada – Fermilab
Co-PI: S. Holland, LBNL

Quantum imaging addresses the possibility of beating the limits of classical imaging by exploiting the peculiar properties of quantum optical states, such as entanglement. In the past few years sub-shot-noise imaging was demonstrated and sub-diffraction-limited quantum imaging was realized. A typical experimental setup for quantum imaging is shown in Fig. 1, where a pixelated photon detector is used to image the fields of idle and signal entangled photons produced by a non-linear optical element (BBO). The requirements in quantum imaging experiments include counting individual photons and measuring their correlations. The work proposed here is focused on introducing the newly developed skipper-CCD into the field of quantum imaging as a way to significantly improve signal to noise ratio (SNR) in these applications. This new sensor has photon counting capabilities in a very wide dynamic range, as shown in Fig. 1.

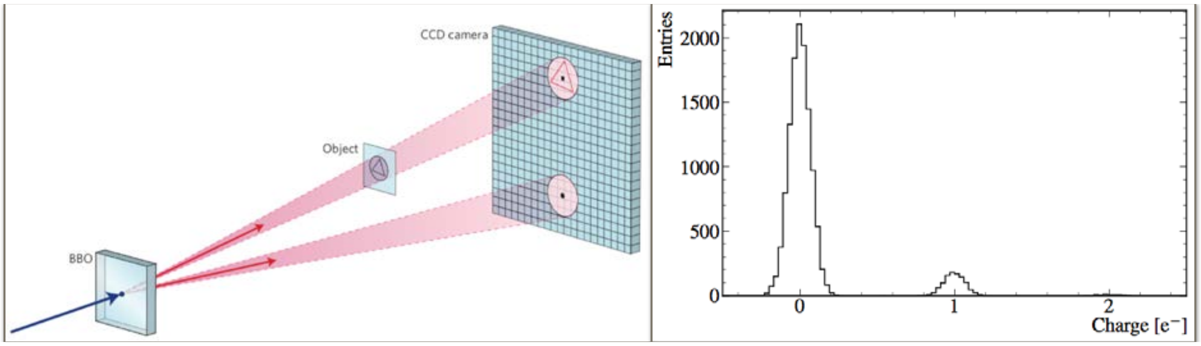


Figure 1. Left) The differential quantum imaging experiment. The β-barium borate (BBO) crystal produced an entangled pair which is then imaged with a CCD camera. Non-classical correlations are used for the improved differential imaging of a weakly absorbing object. [Figure from Nature Photonics] Right) Photon counting capabilities of the skipper-CCD, showing the signal for zero and 1 photo-electrons.

The project has three main thrusts. First, demonstrate sub-shot-noise quantum imaging with existing skipper-CCD. Second, design a new faster skipper-CCD optimized for quantum imaging applications. Finally, explore the potential of quantum imaging as a search for the entangled production of dark photons.

Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence Times and Dark Sector Searches

Lead PI: Dr. Alexander Romanenko (Fermilab)
Co-PI: Prof. Robert McDermott (Univ. of Wisconsin-Madison)
Co-PI: Dr. David Pappas (NIST/Univ. of Colorado-Boulder)

3D superconducting cavities are key elements of the superconducting quantum computing architectures. They can both serve as qubits in alternative logical state encodings such as “cat” states, or as a means to manipulate the transmon quantum states or as a quantum memory. The project combines complementary strengths of collaborating institutions – unique HEP SRF cavity technology and science (Fermilab) and QIS expertise (Univ. of Wisconsin-Madison and NIST) – for a potential thousand-fold increase in the coherence of the 3D superconducting qubits and memory. The same devices can be used as an enabling platform for the next generation of dark photon searches and exploring the proposed microwave communication concept, which is the secondary direction of the proposal.

Fermilab is the world leader in science and technology of superconducting radio frequency (SRF) cavities for accelerators and holds the capabilities to manufacture and surface-engineer niobium SRF cavities of record intrinsic quality factors $Q > 2x10^{11}$ at $T \sim 1.4$ K [3], and recently has demonstrated the full quantum regime $Q \sim 2x10^{10}$ corresponding to photon lifetimes up to **2 seconds**. In addition, Fermilab possesses broad expertise in successful large-scale integration of high Q cavities. The most recent example is manufacturing ~20 cryomodules for LCLS-II at SLAC each containing eight 9-cell 1.3 GHz cavities with $Q > 2.7x10^{10}$ operating at 2 K.

In addition to the core SRF infrastructure, Fermilab has established a brand new ultralow temperature (down to < 10 mK) and quantum measurements SRF lab with a dilution refrigerator, magnetic shielding, and RF equipment for the full SRF cavity and qubit characterization.

University of Wisconsin, Madison is among the experienced QIS institutions with capabilities to design, manufacture, and characterize the transmon-type Josephson-junction-based qubits.

NIST has the unique strength in developing kinetic inductance traveling wave quantum limited amplifiers enabled by the extensive lithographic and surface characterization capabilities.

Combined, a high-quality transmon integrated into a high-quality-factor SRF cavity, and a quantum limited amplifier used for the state readout would allow to realize the potentially *record high coherence* (several orders of magnitude improvement) *superconducting 3D qubits and memory*. The same devices offer unique opportunities in experiments on quantum microwave communication, and in fundamental physics (dark photon searches).

FPGA-BASED QUANTUM CONTROL FOR HEP SIMULATIONS WITH QUTRITS

Irfan Siddiqi, Gang Huang, and Lawrence Doolittle

Lawrence Berkeley National Laboratory (LBNL)

Our objective is to develop a broadly applicable, portable tool set within the framework of superconducting-circuit-based quantum information systems that (i) leverages specialized technical expertise developed for accelerator controls and (ii) is optimized for executing quantum simulation experiments focused on HEP relevant phenomena requiring the use of ternary quantum logic. We propose to develop optically interconnected field programmable gate array (FPGA) modules for extensible control systems suitable for operating multiple quantum circuits with low latency and timing imprecision. Using this hardware, we will implement logical gate operations in ternary quantum logic and employ fast feedback routines to minimize fidelity losses due to stochastic noise processes.

The eight transmon ring quantum processors developed at UC Berkeley have demonstrated lifetimes that bring qutrit control within reach. We will use a high-bandwidth FPGA quantum control module to fully characterize the performance of an eight qutrit device, and implement novel computation and sensing protocols tailored for future HEP applications. Further, we will realize two, optically interconnected FPGA based interface modules with 14 bit resolution, < 3 ps timing jitter, single FGPA latency < 300 ns, and interconnect delays < 1 μs.

We will develop and publish a design repository of the complete system (hardware, firmware and software) used to drive, read out, and rapidly reset multi-qudit processors. Our work will also pave the way for the future development of dedicated Application Specific Integrated Circuit (ASIC) devices, possibly operating in a cryogenic environment.

High Energy Physics

Quantum Information Science-based Quantum Sensors

Nanowire Detection of Photons from the Dark Side
PI: Karl K. Berggren, MIT
Co-PIs: Asimina Arvanitaki (Perimeter), Masha Baryakhtar (NYU), Junwu Huang (Perimeter), Ilya Charaev (MIT), Jeffrey Chiles (NIST), Andrew E. Dane (MIT), Robert Lasenby (Stanford), Sae Woo Nam (NIST), Ken Van Tilburg (NYU/IAS)

Quantum Simulation and Optimization of Dark Matter Detectors
PI: A.B. Balantekin, University of Wisconsin- Madison
Co-PIs: S. Coppersmith (UW), C. Johnson (San Diego State), P.J. Love (Tufts), K. J. Palladino (UW), R.C. Pooser (ORNL), and M. Saffman (UW)

Microwave Single-Photon Sensors for Dark Matter Searches
PI: Daniel Bowring, Fermi National Accelerator Laboratory

Quantum Metrology for Axion Dark Matter Detection
PI: Aaron S. Chou, Fermilab
Co-PIs: Konrad Lehnert (Colorado/JILA/NIST), Reina Maruyama (Yale), David Schuster (Chicago)

Search for Bosonic Dark Matter Using Magnetic Tunnel Junction Arrays
PIs: Marcel Demarteau, Argonne National Laboratory & Vesna Mitrovic, Brown University
Co-PIs: Ulrich Heintz, John B. Marston, Meenakshi Narain, Gang Xiao (Brown)

Quantum Sensors HEP-QIS Consortium
Maurice Garcia-Sciveres, Lawrence Berkeley National Laboratory

Quantum-Enhanced Metrology with Trapped Ions for Fundamental Physics
PIs: Salman Habib, Argonne National Laboratory & David B. Hume, NIST
Co-PIs: John J. Bollinger & David R. Leibrandt (NIST)

The Dark Matter Radio: A Quantum-Enhanced Dark Matter Search
PI: Kent Irwin, Stanford/SLAC
Co-PI: Peter Graham (Stanford)

Quantum Sensors for Light-field Dark Matter Searches
PI: Kent Irwin, Stanford/SLAC
Co-PIs: Peter Graham (Stanford), Alexander Sushkov (Boston), Dmitry Budker (Mainz, Berkeley), Derek Kimball (Cal State East Bay)

Quantum system engineering for a next-generation search for axion dark matter
PI: Alex Sushkov, Boston University
Co-PIs: Dmitry Budker (UC Berkeley & Mainz), Peter Graham (Stanford), Surjeet Rajendran (UC Berkeley), Derek Jackson Kimball (Cal State East Bay), Kent Irwin (Stanford/SLAC)

Towards Directional Detection of WIMP Dark Matter using Spectroscopy of Quantum Defects in Diamond
PI: Ronald Walsworth, Harvard-Smithsonian Center for Astrophysics
Co-PIs: David Phillips (Harvard) and Alexander Sushkov (Boston University)

Nanowire Detection of Photons from the Dark Side

Asimina Arvanitaki (Perimeter), Masha Baryakhtar (NYU), Karl K. Berggren
(MIT), Junwu Huang (Perimeter), Ilya Charaev (MIT), Jeffrey Chiles
(NIST), Andrew E. Dane (MIT), Robert Lasenby (Stanford), Sae Woo Nam
(NIST), Ken Van Tilburg (NYU/IAS)

Existing searches for dark matter have so far covered only a small fraction of the 90 orders of magnitude of potential mass-parameter space in which it could exist. If dark matter is to be eventually discovered, we must vastly broaden the range of our search space. However, attempts to detect the infrequent excitations of photons caused by dark matter are greatly hampered by the presence of non-negligible background signals. Examples of confounding signals can be found from blackbody radiation, radioactive decay, and cosmic radiation. These challenges are particularly frustrating in the 10 meV to 10 eV mass range, where thermal background radiation plays a significant role, and where low-dark-count detectors are difficult to develop. As a result, the search for dark matter in the ≈ 1 eV range is proving to be slow to get going. However, recent developments have changed this landscape. In recent years, the development of fast and low-dark-count single-photon detectors for photonic quantum information applications promise a radical improvement in our capacity to search for dark matter. The advent of superconducting nanowire detectors, which have fewer than 10 dark counts per day and have demonstrated sensitivity from the mid-infrared to the ultraviolet wavelength band, provides an opportunity to search for bosonic dark matter in the neighborhood of 1 eV. These detectors are simple to fabricate and operate, and can be combined with gas cells, dielectric stacks, or combinations of these structures in cryogenic targets, optimized for dark matter absorption. We will develop a new paradigm in dark matter detection. The new detector architecture will be based on the combination of a resonant absorber target (designed to enhance dark photon dark matter to photon conversion by use of coherent quantum superposition of absorption processes) with a superconducting nanowire detector (designed to detect the resulting coherently emitted photon).

Once demonstrated in a search for dark photon dark matter, the architecture we will design can be adapted to suit detection of other forms of bosonic dark matter, including axions, dilatons and moduli. Searches for these dark matter candidates will require improved detector sensitivity, scaled up volumes of the targets, as well as specific materials and molecules and application of magnetic fields.

The key outcome of this work will be the development of a new understanding of the issues to be faced in building a scalable, tunable, and robust bosonic dark matter detector that takes advantage of superconducting nanowire detectors and optimized resonant nanofabricated targets. The optimization of the system detection rate, false-event vetoing capability, cost, experimental duration, and analytic methods will be described. As a consequence, a new era of dark matter searches based(DM) on small, affordable, and scalable quantum-information technologies and methods will be ushered into existence.

QUANTUM SIMULATION AND OPTIMIZATION OF DARK MATTER DETECTORS

A.B. Balantekin (University of Wisconsin- Madison (UW)), S. Coppersmith (UW), C. Johnson (San Diego State U.), P.J. Love (Tufts U.), K. J. Palladino (UW), R.C. Pooser (ORNL), and M. Saffman (UW)

Observations of the Cosmic Frontier have demonstrated that most of the matter in the Universe is dark matter. Experiments such as LZ aim to reveal the nature of particle dark matter. Quantum simulation has the potential to enhance greatly the capabilities of dark matter experiments because it could enable the determination of the detailed many-body wavefunctions of the relevant targets with much more precision than is possible with current classical computations. Knowing the properties of these wavefunctions in detail enables the extraction of more information about the properties of the dark matter than would be possible otherwise.

In this project, we will exploit the power of quantum computation to understand the response of various possible dark matter detectors via improved understanding of the interactions between dark matter particles and noble gas targets. We have put together an interdisciplinary team of theoretical and experimental physicists at the University of Wisconsin-Madison, computational physicists at San Diego State University, as well as quantum computational scientists at Tufts University and Oak Ridge National Laboratory. The goal is to use a quantum simulator to calculate the detector response to dark matter particles. The simulator to be used is an array of neutral atom qubits that is being developed at UW-Madison. We are also exploring the use of noise-resilient hybrid quantum-classical algorithms such as the Variational Quantum Eigensolver.

Recent work based on effective field theories has demonstrated that symmetry constraints on the interactions between dark matter and detectors allow more than two interaction channels previously considered, and it is of great interest and importance to understand the response of different targets to all possible effective operators governing these interactions.

A major component of the research plan is to understand and mitigate the behavior of the neutral atom array so that high accuracy and precision calculations can be performed. In other contexts it has been shown that correction and mitigation schemes that are tailored to the physics of the system have the potential to greatly enhance the ability to overcome errors and decoherence.

The project leverages expertise in high energy theory and experiment, traditional numerical techniques, quantum information theory, nuclear and atomic physics, and quantum error correction in the context of quantum algorithms. This project couples closely with two of the science drivers for particle physics outlined in the recent strategic plan presented in the Report of the Particle Physics Prioritization Panel.

Microwave Single-Photon Sensors for Dark Matter Searches

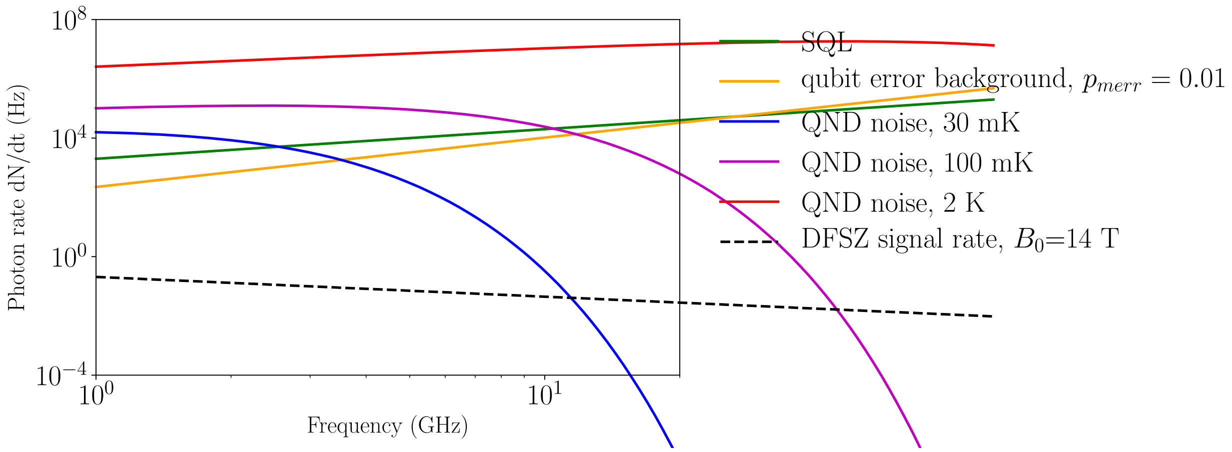
Daniel Bowring
Fermi National Accelerator Laboratory

The axion is a pseudoscalar boson whose existence would help solve several profound, open problems in modern physics. One such problem is the existence of dark matter; the axion is a promising explanation for this phenomenon. Another is the so-called “strong CP problem”, which addresses CP violation in the strong nuclear force. The axion was first proposed as a consequence of spontaneous “Peccei-Quinn” symmetry breaking, which breaking would explain the neutron’s anomalous electric dipole moment.

Theorists expect that the axion should couple weakly to electromagnetism. Many axion search experiments exploit this coupling by using a strong magnetic field to induce axion-to-photon conversion, and then looking for the microwave-frequency photons that would result from such a process. However, for practically achievable laboratory conditions and an axion mass on the order of 10 GHz, the signal power from axion-to-photon conversion is expected to be less than 1e-22 watts. At that level, even amplifiers operating at the quantum limit, such as DC SQUIDs, can be too noisy for efficient axion detection. This noise is a consequence of the Heisenberg uncertainty principle. Phase-preserving linear amplifiers simultaneously measure the occupation number and phase of a system, and these parameters have a nonzero commutator; they cannot be measured simultaneously to arbitrary precision.

The focus of my 2018 DOE Early Career Award is to develop quantum bits (qubits) for use in particle detection experiments, specifically in the context of axion searches. For the detection of single microwave photons, superconducting “transmon” qubits offer a significant advantage over standard linear amplifiers. These devices enable quantum nondemolition (QND) measurements, which may be thought of as an extreme case of state-squeezing. In a QND experiment, the phase of a photon state is randomized at every measurement so that amplitude (i.e. photon number) can be measured repeatedly and with high precision. QND measurements are compared with standard, quantum-limited amplifier measurements in Figure 1.

This measurement technique, enabled via qubits provided to us by partners at the University of Chicago, represents a novel application of quantum information technology to the field of particle physics. It has the potential to enhance axion search speeds by four orders of magnitude while enabling sensitivity to weak axion-photon coupling models. The goal of this research program is to adapt quantum nondemolition measurement techniques for use in an axion search. It would form the basis for the technical design of a next-generation axion experiment.



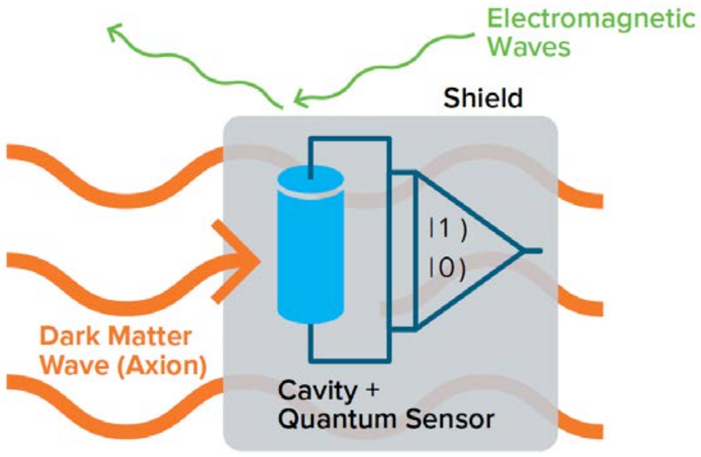
Quantum Metrology for Axion Dark Matter Detection

Aaron S. Chou (Fermilab), Konrad Lehnert (U.Colorado/JILA/NIST), Reina Maruyama (Yale), David Schuster (U.Chicago)

This consortium seeks to develop quantum-enhanced techniques to enable the detection of dark matter waves composed of axions – a new particle hypothesized to solve the 70-year mystery of the vanishing neutron electric dipole moment.

While current axion experiments are already operating near the standard quantum limit of phase-preserving amplifiers, the next-generation technology being developed will avoid the quantum zero-point noise by measuring only the signal photon amplitude while ignoring the conjugate phase observable. For example, qubit-based artificial atoms can be used to nondestructively sense the electric field signal of individual signal photons generated by the axion dark matter. This sensor can output yes/no (1 or 0) answers for whether it sees a signal, and achieve readout noise levels far below the standard quantum limit.

Another related technique prepares the initial cavity state with a large amplitude wave in all phases of its oscillation in order to stimulate the emission of photons from the dark matter wave while simultaneously evading shot noise. High-Q photonic bandgap cavities and Rydberg atom-based sensors are also being developed to target higher mass axions. Together these innovative technologies will enable future experiments to reach sensitivity to the long sought-after QCD axion and probe new physics from atomic to cosmological scales.



An oscillator prepared in a quantum superposition of all possible phases of its oscillation has enhanced sensitivity to the dark matter waves in its environment.

Search for Bosonic Dark Matter Using Magnetic Tunnel Junction Arrays

PIs: Marcel Demarteau (Argonne National Laboratory), Vesna Mitrovic (Brown University)
Co-PIs: Ulrich Heintz (Brown University), John B. Marston (Brown University), Meenakshi Narain (Brown University), Gang Xiao (Brown University)

Abstract: The existence of Dark matter has been established by a variety of astrophysical observations, such as galaxy rotation curves, the dynamics of galaxies within galaxy clusters, and the temperature fluctuations in the cosmic microwave background radiation. Dark matter constitutes the vast majority of the matter content of the universe. The nature of the dark matter remains unknown and is among the most prominent outstanding questions of modern science. Dark matter particles are believed to be weakly interacting, stable, and cold. The currently known particles within the standard model of particle physics cannot account for dark matter. Axions are a good candidate for dark matter and are believed to couple to the electromagnetic field generating short-ranged spin-dependent interactions in matter. The strength of such interaction and what physical observables it would affect are unknown. An example of an open question is whether axion interactions could induce physical flux, i.e. a "real" magnetic field detectable by magnetically sensitive probes, or just "fictitious" fields, possibly only observable through measurements of quantum correlations. Thus, the key to detecting axions is to attain spin sensitive, intrinsically quantum, and spatially resolved probes. The main objective of our proposed work is to develop such probes. NMR techniques are used to detect such fields, whereas the sensing of local precession fields is done by Magnetic Tunneling Junction Arrays to assure spatial resolution.

Based on the spin-dependent coherent quantum tunneling effect, magnetic tunneling junctions (MTJs) have been developed into a high performance solid-state magnetic sensor for their superior properties, including high sensitivity, low power consumption, miniaturized size, thermal stability and broad frequency response. The high magnetoresistance ratio (MR) is a particularly valuable property which allows MgO-based MTJs to generate large signals in response to weak, pico-Tesla, external magnetic fields. This proposal aims to establish MTJs as a proof of principle as a novel probe of light dark matter detection, based on the NMR technique. The MTJs will be used as a direct detector of field modulation patterns induced by either nuclear or electronic spins. This will be used as a direct probe of spin-dependent interactions generated by axions and quantum correlations induced by axion fields. The oscillating axion fields of unknown frequencies requires that all the measurements will have to be performed by stepping the field and tuning the RF resonance circuit, for NMR, in small overlapping steps. Since in a conventional NMR experiment the signal is detected inductively, sensitivity is severely limited. MTJs provide a clear advantage and their ultrafast response offers the possibility to explore frequency or energy dependent interactions not accessible in SQUID-based approaches. The ultrafast response allows to precisely measure spin decoherence times. Time varying fields, such as those proposed to arise from axions make MTJs an ideal candidate detector.

Quantum Sensors HEP-QIS Consortium

Lawrence Berkeley National Lab., UC Berkeley, U. Mass. Amherst
PI: Maurice Garcia-Sciveres

We will apply advances in QIS technology and precision measurement to the search for low mass particle dark matter (DM). Elucidating the nature of DM is one or the most compelling problems of high energy physics. Interest in searching for particles of much lower mass than atomic nuclei and even electrons has been fueled by recent theoretical developments. Some promising theoretical directions, such as Asymmetric Dark Matter and Hidden Valleys, which predict low mass DM particles, were developed by one of the PIs on this consortium.

The search for low mass DM particles is mainly limited by our ability to detect very small signals with high fidelity and little or no background. In this regard, QIS developments related to much lower noise detectors are a very promising avenue. While ultra low noise sensing of single quanta is a problem common to QIS and low mass DM detection, the detailed requirements are different. Therefore, to fully take advantage of QIS technology, a multidisciplinary effort is needed, one involving particle physics experiment and theory, materials science, and QIS. This consortium brings together expertise in all of these disciplines.

We will instrument two different dark matter detection targets with a variety of sensors, with a sensitivity goal to reach unexplored parameter space. This concrete goal drives the sensor and readout development, and provides a basis for sensor comparisons. The initial target materials are superfluid He and GaAs crystals at cryogenic temperature. These materials are complementary in their predicted sensitivity to dark matter particle interactions, yet they can be instrumented with the same type of sensors. We will explore system aspects and readout of sensors on these platforms, which are critical elements for deployment of new technologies. GaAs also produces IR scintillation light that we would like to detect with high quantum efficiency and single photon sensitivity. We are additionally exploring new potential target materials and have already theoretically discovered three ultra low bandgap materials.

Through a significant theoretical effort we aim to single out the materials with enhanced coupling to DM, for example by coherent effects, and to understand how to maximize coupling of signals to different sensor types. We are finally trying to make use of decoherence in ensembles of quantum states as a tool for DM detection, initially through calculation of possible sensitivity to DM models.

Quantum-Enhanced Metrology with Trapped Ions for Fundamental Physics

Salman Habib[1], David B. Hume[2] (Principal Investigators),
John J. Bollinger[2], **David R. Leibrandt[2]** (Co-Investigators)
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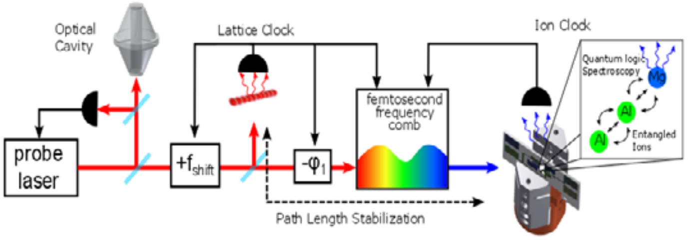
9700 S. Cass Ave, Lemont, IL 60439
[2]National Institute of Standards and Technology, Time and Frequency Division
325 Broadway, Boulder, Colorado

We plan to use quantum information techniques for precision measurements with trapped laser-cooled ions. These measurements will test the foundations of the standard model in two ways:

1) Measuring possible drifts in the fundamental constants

2) Searching for dark matter as an ultralight particle

We will focus on the two separate experimental systems in the NIST group, an optical atomic clock based on $^{27}Al^+$ and a Penning trap experiment with 100s or 1000s of $^9Be^+$ ions. In both these systems there is a clear application to these goals in high energy physics and a role for quantum-enhanced metrology. In the Al^+ optical clock we will develop and implement frequency metrology at the Heisenberg limit with maximally entangled states of ions. With this quantum-enhanced sensitivity, comparisons between the Al^+ optical clock and other atomic clocks at NIST will be the most sensitive measurements ever performed for testing the variation of the fine structure constant. In the Penning trap experiment, we will develop new techniques for sensing ion motion and weak forces below the zero-point fluctuations. This will enable a new range of sensitivities for electric field detection that can be applied to searches for hidden-photon dark matter. Since we have existing experimental systems with many of the capabilities already in place, in the duration of this pilot program, we will perform experiments to test our protocols and confirm their performance. If successful, these measurements will be among the first applications of quantum-enhanced metrology in atomic systems. By demonstrating the conditions under which quantum metrology is useful in precision measurements, our results should be relevant for a much broader range of atomic and molecular systems. In addition to the search for drifting fundamental constants and ultralight dark matter, applications of these systems in high energy physics includes measuring the electric-dipole moment of the electron and precision tests of quantum electrodynamics. With the convergence of progress both in terms of quantum control and precision measurement, we anticipate broad discovery potential in the coming years.



Sketch of the setup for Heisenberg-limited measurements between a lattice clock and an ion clock

The Dark Matter Radio: A Quantum-Enhanced Dark Matter Search

PI: Kent Irwin (Stanford, SLAC), Co-PI: Peter Graham (Stanford)

Advances in quantum sensors have opened a pathway to identify the new physics of dark matter. The nature of dark matter is one of the most important fundamental questions in modern physics. It has been highlighted in the P5 report as a science driver for the U.S HEP program. Quantum sensors are poised to accelerate dark-matter science by measuring the coupling of dark matter to the standard model better than the standard quantum limit (SQL), greatly increasing science reach. The Dark-Matter Radio (DM Radio) is a detector designed from the beginning to be a near-optimal experiment that takes advantage of quantum sensors to search for both axions and hidden photons.

The full DM Radio experiment will probe the QCD axion between 4 neV and 1 μeV mass. The DM Radio Pathfinder, which we are developing here, will probe new parameter space for hidden-photon dark matter between 500 peV and 50 neV. We have shown that the DM Radio single-pole resonant design nearly saturates the SQL on the sensitivity of searches for dark matter [See Chaudhuri, Irwin, Graham, and Mardon, J. arXiv:1803.01627 (2018)]. The DM Radio Pilot is thus a useful testbed for quantum sensors designed to perform better than the SQL. We have now cooled down the Pathfinder resonator (see Fig. 1) and demonstrated an initial resonance with Q=148,000 (see fig. 1). This cooldown uses a dc SQUID amplifier designed by our team (see Fig. 1b). The DM Radio Pathfinder is being used to elucidate the resonator physics and data analysis procedures needed to successfully utilize a quantum sensor, making it an ideal testbed for quantum sensors. We will use it to test quantum sensors based on photon upconverters that convert photons in the DM Radio Pathfinder signal band to microwave frequencies, where they are processed with coherent superconducting quantum devices. The photon upconverter can evade the SQL on dark matter detection through backaction evasion, squeezing, and entanglement.

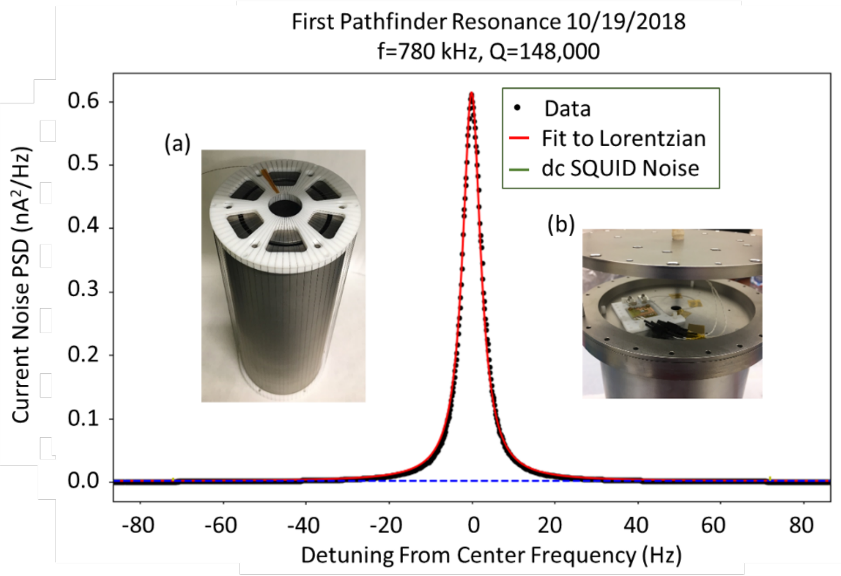


Fig. 1. The first cooldown of the DM Radio Pathfinder. Successful resonant operation is demonstrated with a lumped-element inductor (shown in subfigure (a)) and a tunable capacitor (not shown). The detector response is measured by with a dc SQUID designed by the proposal team (show in the quantum-sensor annex in subfigure (b)). A resonance with Q=148,000 is shown in the first Pathfinder run. This Q is limited by calibration circuitry, which is now being removed post calibration of the experiment.

Quantum Sensors for Light-field Dark Matter Searches

PI: Kent Irwin (Stanford, SLAC), Co-PIs: Peter Graham (Stanford), Alexander Sushkov (Boston University), Dmitry Budker (Mainz, Berkeley), Derek Kimball (Cal State East Bay)

Non-classical techniques that exploit quantum correlations can enable searches for ultralight dark-matter waves. These techniques include squeezing, back-action evasion, and entanglement. Measurements below the Standard Quantum Limit (SQL) are more efficient and sensitive, opening opportunities to reveal new fundamental physics. We are developing quantum sensors for the detection of ultralight dark-matter waves, including the QCD axion. The detection of the QCD axion would both solve the Strong CP problem and identify the nature of the dark-matter in our galaxy. These quantum sensors, which are based on photon upconverters, greatly accelerate searches for QCD axions below 1 micro eV.

The DM Radio and CASPEr axion haloscopes search for the flux of dark matter caused by the motion of Earth through the galactic dark matter halo. They are sensitive to the axion's couplings to electromagnetism (DM Radio), gluons (CASPEr-Electric), or nuclear spin (CASPEr-Wind). DM Radio uses resonant electromagnetic modes, while the CASPEr experiments search for the influence of the axion field on highly coherent samples of nuclear spins.

Superconducting photon upconverters controllably couple a low-frequency signal (at the dark-matter Compton frequency) to a superconducting resonator, upconverting the signal to microwave frequencies, where it is processed with coherent superconducting quantum techniques. The sensors are illustrated in Fig. 1. Fig. 1(a) shows a schematic of the 3D cavity containing the sensor. A prototype of this cavity is shown in Fig. 1(b). The coupling to the cavity mode is mediated by a “Zappe interferometer” consisting of 3 Josephson junctions, shown in schematic in Fig. 1(a), and in prototype in Fig. 1(c). The Optomechanical Hamiltonian that describes these devices is mathematically equivalent to the Hamiltonian that describes LIGO, enabling the implementation of quantum protocols originally developed for gravitational wave experiments, including squeezing, entanglement, backaction evasion, and backaction cooling. The Zappe Photon Upconverter (ZPU) will enhance both DM Radio and CASPEr, enabling the QCD axion band to be fully probed over about 60% of its allowed mass range, including all masses below 1 micro eV (down to the Planck-scale cutoff below 1 pico eV).

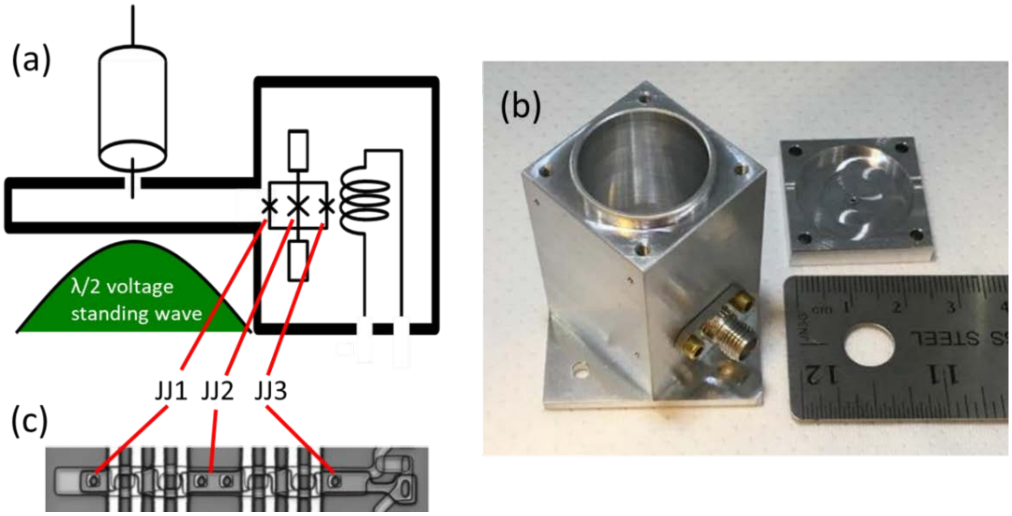


Fig. 1. The Zappe photon upconverter. (a) A schematic of the 3D microwave cavity and the Zappe interferometer coupling to the Compton frequency signal flowing through the inductor. The 3 Josephson junctions in the Zappe interferometer are labeled JJ1, JJ2, and JJ3. (b) A photograph of a prototype microwave cavity. (c) A prototype of the Zappe interferometer, with the 3 JJs labeled.

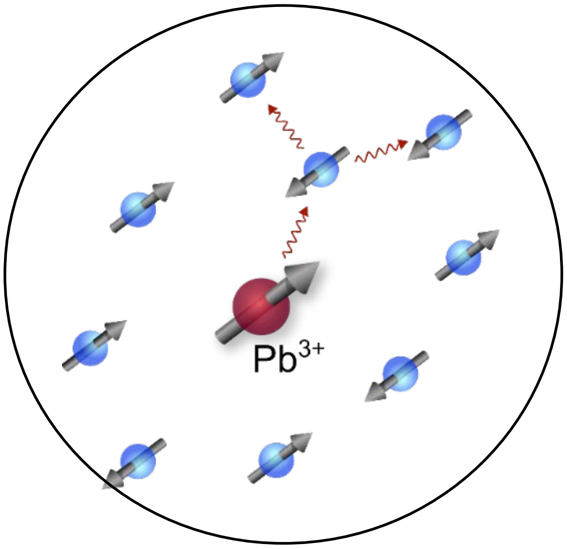
Quantum system engineering for a next-generation search for axion dark matter

PI: Alex Sushkov, Boston University

Co-PIs: Dmitry Budker, UC Berkeley & Mainz
Peter Graham, Stanford University
Surjeet Rajendran, UC Berkeley
Derek Jackson Kimball, Cal State East Bay
Kent Irwin, Stanford University and SLAC

Advances in quantum science and engineering enable new directions in the search for physics beyond the Standard Model. We focus on developing the quantum technology necessary to pursue one such promising direction: the search for ultra-light dark matter, using ensembles of spin qubits as quantum sensors of new physics. The proposed work addresses the challenges of optimizing control over macroscopic ensembles of spin qubits. Achieving robust control is needed for the searches to reach their full potential science reach, which includes, for example, achieving the sensitivity needed to discover a QCD axion over a multi-decade mass range. We will explore two specific experimental approaches: improving the fidelity of initial state preparation for macroscopic ensembles of spin qubits sensitive to new physics, and improving the coherence properties of these ensembles. Achieving these goals has the potential to enable significant improvements in the reach of spin-based searches for ultra-light dark matter.

Figure 1 (color): Expected signal rate (photons per second) for the DFSZ family of axion models (black dashed line), compared with noise/error rates for phase-preserving linear amplifiers operating at the standard quantum limit (SQL, green), and for quantum nondemolition (QND, blue/purple/red) measurements at various temperatures. The industry-typical qubit false-positive error rate of 1% is shown in yellow.



Towards Directional Detection of WIMP Dark Matter using Spectroscopy of Quantum Defects in Diamond

Ronald Walsworth, Harvard-Smithsonian Center for Astrophysics (Principal Investigator)

David Phillips, Harvard-Smithsonian Center for Astrophysics (Senior Investigator)
Alexander Sushkov, Boston University (Senior Investigator)

The next generation of dark matter experiments searching for weakly interacting massive particles (WIMPs) are expected to encounter a confounding background from coherent neutrino-nucleus scattering — a limit called the neutrino floor. We propose a proof-of-principle laboratory-scale demonstration of a new approach to discriminate WIMPs from the neutrino floor by using optical measurements of quantum defects in diamond that act as local sensors of strain within the diamond. When a WIMP scatters in diamond, the induced nuclear recoil is expected to create a tell-tale damage cluster, with an orientation to the damage track that correlates well with the direction of the recoil and hence the incoming WIMP. This damage cluster induces strain in the diamond, shifting the energy levels of nearby quantum defects — nitrogen vacancy (NV) or silicon vacancy (SiV) color centers). The level shifts can be measured optically, making it potentially possible to map the strain environment around the defect in a solid sample, and thereby identify the incoming WIMP direction with high efficiency. The angular distributions of WIMP- and neutrino-sources are expected to differ substantially, potentially allowing effective WIMP signal discrimination from the neutrino floor background.

In our two-year pilot project supported by the DOE QuantISED program, we will address key enabling technical challenges (questions): (i) can NV and/or SiV optical measurements accurately characterize damage tracks analogous to those expected to be induced by WIMPs; and (ii) can diamond samples be fabricated with sufficient strain uniformity to allow efficient damage track identification? Affirmative answers to these questions would set the stage for later studies of the effect of realistic backgrounds; and then possible scale up of this new experimental modality to high densities of quantum defects and large total volumes of diamond, which will be required for practical directional detection of WIMP dark matter.

The proposed project is aligned with the U.S. particle physics community's current vision for the future as embodied in the 2014 report from the Particle Physics Project Prioritization Panel (P5), which advocated path-finding R&D to "develop techniques that can indicate the direction of incoming dark matter particles". The project will also advance the state-of-the-art in quantum information science (QIS) by furthering knowledge of the strain environment that limits the performance of quantum defects in diamond — one of the most promising and broadly applicable QIS sensing platforms for both the physical and life sciences.

High Energy Physics

Quantum Computing

Quantum Information Science in High Energy Physics at the Large Hadron Collider
PI: O.K. Baker, Yale University

Unraveling the quantum structure of QCD in parton shower Monte Carlo generators
PI: Christian Bauer, Lawrence Berkeley National Laboratory
Co-PIs: Wibe de Jong and Ben Nachman (LBNL)

The HEP.QPR Project: Quantum Pattern Recognition for Charged Particle Tracking
PI: Heather Gray, Lawrence Berkeley National Laboratory
Co-PIs: Wahid Bhimji, Paolo Calafiura, Steve Farrell, Wim Lavrijsen, Lucy Linder, Illya Shapoval (LBNL)

Neutrino-Nucleus Scattering on a Quantum Computer
PI: Rajan Gupta, Los Alamos National Laboratory
Co-PIs: Joseph Carlson (LANL); Alessandro Roggero (UW), Gabriel Purdue (FNAL)

Particle Track Pattern Recognition via Content-Addressable Memory and Adiabatic Quantum Optimization
PI: Lauren Ice, Johns Hopkins University
Co-PIs: Gregory Quiroz (Johns Hopkins); Travis Humble (Oak Ridge National Laboratory)

Towards practical quantum simulation for High Energy Physics
PI: Peter Love, Tufts University
Co-PIs: Gary Goldstein, Hugo Beauchemin (Tufts)

High Energy Physics (HEP) ML and Optimization Go Quantum
PI: Gabriel Perdue, Fermilab
Co-PIs: Jim Kowalkowski, Stephen Mrenna, Brian Nord, Aris Tsaris (Fermilab); Travis Humble, Alex McCaskey (Oak Ridge National Lab)

Quantum Machine Learning and Quantum Computation Frameworks for HEP (QMLQCF)
PI: M. Spiropulu, California Institute of Technology
Co-PIs: Panagiotis Spentzouris (Fermilab), Daniel Lidar (USC), Seth Lloyd (MIT)

Quantum Algorithms for Collider Physics
PI: Jesse Thaler, Massachusetts Institute of Technology
Co-PI: Aram Harrow, Massachusetts Institute of Technology

Quantum Machine Learning for Lattice QCD
PI: Boram Yoon, Los Alamos National Laboratory
Co-PIs: Nga T. T. Nguyen, Garrett Kenyon, Tanmoy Bhattacharya and Rajan Gupta (LANL)

Quantum Information Science in High Energy Physics at the Large Hadron Collider

O.K. Baker, Yale University

We pursue scientific research at the interface of High Energy Physics and Quantum Information Science. This includes studies of thermal radiation and quantum entanglement in high-energy collisions at the Large Hadron Collider (LHC), with special emphasis on entanglement entropy and the Higgs boson.

Collider experiments such as proton-proton collisions at the LHC yield hadrons that exhibit an exponential behavior at low transverse momenta, P_T. Transverse momentum distributions in proton-proton scattering processes have been studied in both the ATLAS and CMS collaborations and show evidence for this exponential dependence on P_T (see Figure below for one example). This dependence can be attributed to thermal radiation that is akin to Hawking radiation or Unruh radiation that should exist at the event horizon of astrophysical black holes and neutron stars. This phenomena should not be surprising since at LHC center of mass energies, the proton-proton scattering is effectively parton-parton scattering (partons being quarks and gluons in this case). Because the scattering involves the strong nuclear force, the strongest of all of the fundamental forces in nature, the resulting deceleration gradients are so large that, in magnitude, they are comparable to the acceleration gradients that give rise to Hawking or Unruh radiation in astrophysical systems. The Principal Investigator, in collaboration with a theoretical physicist at Stony Brook University and Brookhaven National Laboratory, have shown evidence for this thermal radiation in several production and decay processes in the ATLAS and CMS data (O.K. Baker and D.E Kharzeev, Phys. Rev. D 98, 054007 (2018)). These studies and findings suggest a deep connection between quantum entanglement (entanglement entropy) and thermalization in high-energy hadron collisions that has to be investigated further as will be done during this funding period. The origin of the apparent thermalization in high-energy collisions at LHC energies will be investigated using the data of the ATLAS, CMS, and other LHC collaborations.

We will confirm or refute the proposed relation between the effective temperature and the hard scattering scale observed at lower energies, and show that it extends even to the Higgs boson production process. This research tests the hypothesis about the link between quantum entanglement and thermalization in high-energy collisions.

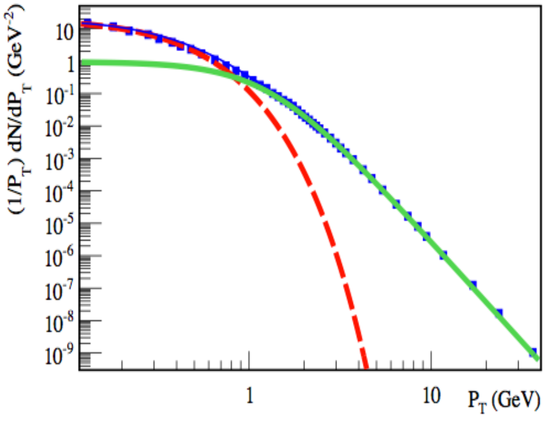


Figure: Charged hadron transverse momentum distribution; thermal (exponential) behavior in red, hard scattering (power law) behavior in green, data in blue squares.

Unraveling the quantum structure of QCD in parton shower Monte Carlo generators

Christian Bauer (PI) (LBNL), Wibe de Jong (LBNL), Ben Nachman (LBNL)

The goal of high-energy physics is to test our understanding of nature at the most fundamental level. Our current understanding is captured by the standard model of particle physics, which is currently being tested at the Large Hadron Collider (LHC) in Geneva, Switzerland. To compare events produced at the LHC against our expectations from the standard model, one uses so-called event generators, which simulate events very similar to those observed at the LHC, but purely from theoretical calculations in the standard model. A clear deviation between data and simulation would indicate physics not described by our current understanding of nature.

A key challenge is that such simulations need to represent a complex quantum process, but are currently limited to using inherently classical algorithms. As a result, the standard event generators are limited in their precision for describing crucial entanglement phenomena observed in the data. We propose to investigate modeling the quantum nature of a event generators with an inherently quantum algorithm, exploiting the recent exciting progress in quantum computation.

The goal of the project is to develop quantum algorithms that allow for event simulation in theories resembling the standard model. This will allow to ultimately test the standard model at currently unattainable precision, deepening our fundamental understanding of nature at the smallest scales. We will build collaborations between High Energy Physics and Quantum Information Science experts developing quantum hardware, software and algorithmic approaches to deliver innovative solutions required to enable such algorithms to run effectively on near-term quantum computers.

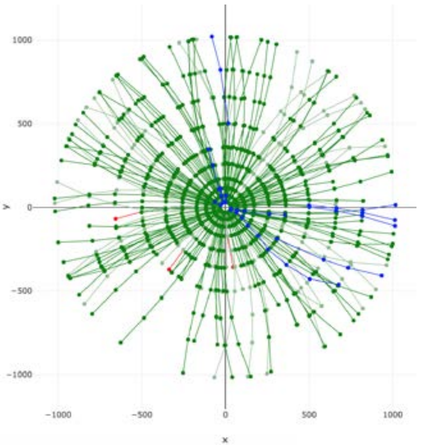
The HEP.QPR Project: Quantum Pattern Recognition for Charged Particle Tracking

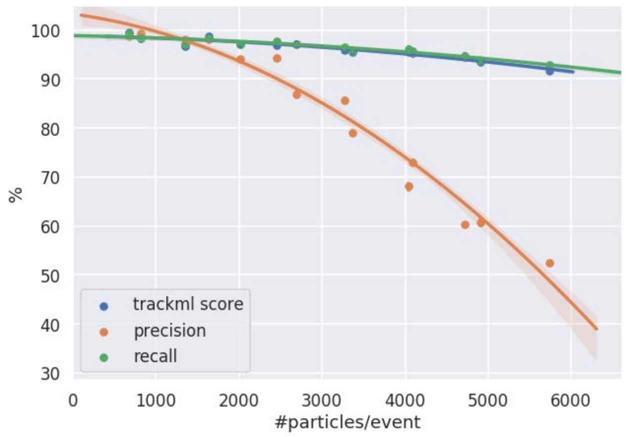
Authors: Wahid Bhimji, Paolo Calafiura, Steve Farrell, Heather Gray, Wim Lavrijsen, Lucy Linder, Illya Shapoval (LBNL)

The era of Universal Quantum Computing may still be a few years away, but we have already entered into the Noisy Intermediate-Scale Quantum era. This ranges from D-Wave commercial Quantum Annealers to a wide selection of gate-based quantum processor prototypes. This hardware provides us with the opportunity to evaluate the potential of the Quantum Computing paradigm for HEP applications. We will present early results from the DOE HEP.QPR project on the impact of Quantum Computing on charged particle tracking.

Due to increasing data rates and event complexities, tracking has become one of the most pressing computational problems facing the HEP community. In HEP.QPR, we are studying the potential of the Quantum Associative Memory (QuAM) and Quantum Annealing (QA) algorithms. QuAM provides in principle an exponential increase in storage capacity compared to classical Associative Memory used in the context of LHC data triggering. We examine the practical limits of storage capacity, as well as store and recall errorless efficiency, from the viewpoints of the state-of-the-art IBM quantum processors and LHC real-time charged track pattern recognition requirements. We present a software prototype implementation of the QuAM protocols and analyze the topological limitations for porting the simplest QuAM instances to the public IBM 5Q and 14Q cloud-based superconducting chips.

We will also present some promising results we achieved expressing the LHC track finding problem as a Quadratic Unconstrained Binary Optimization (QUBO), that can be solved using a D-Wave Quantum Annealer. We generated QUBOs that encode the pattern recognition problem at the LHC using the TrackML dataset and solved them using D-Wave qbsolv and its Leap Cloud Service. Those early experiments achieved a performance exceeding 99% purity, efficiency, and TrackML score at low track densities. We plan to extend the performance of such algorithms at higher track densities by improving seeding algorithms, geographic partitioning, and our QUBO models. We plan to evaluate if the combined classical/quantum annealing approach used by qbsolv provides performance improvements compared to classical QUBO solvers.





Neutrino-Nucleus Scattering on a Quantum Computer

Rajan Gupta, Joseph Carlson (LANL), Alessandro Roggero (UW), Gabriel Purdue (FNAL)

Neutrinos are fascinating elusive particles that interact very weakly with normal matter. Determining the mass hierarchy of the three flavors of neutrinos and studying CP violation in their interactions is a very important part of the DOE HEP program. Neutrino properties are and will be inferred by detecting how neutrinos interact with complex nuclei like Argon in the short-baseline and DUNE experimental neutrino programs at Fermilab. An accurate understanding of the quantum dynamics of a struck Argon nucleus with 18 protons and 22 neutrons is very challenging but crucial to extract detailed information on the subtle nature of the neutrino and its interactions. Quantum computers can, in principle, provide an exponential increase in our capabilities of simulating neutrino-nucleus dynamics and more generally linear response in quantum systems[1].

We are developing algorithms for quantum computers to study linear response in quantum systems. In particular we have developed simplified lattice models to implement on present-day quantum computers, models that can later be extended to more realistic treatments as their capabilities increase. Studying high energy and momentum neutrino scattering on present day quantum computers is interesting because the high energy and momentum scales correspond to short-time (requiring smaller circuits) and small spatial lattices.

In a simple model we have designed circuits to (1) accurately reproduce the ground state, (2) simulate the coupling of neutrinos to the nucleons, and (3) propagate the nucleons for short times to gain information about the energy dependence of the cross section. These are the three key ingredients in simulating neutrinos interacting with nuclei. We are running these algorithms on classical computers and quantum simulators, with the goal of running on actual quantum devices in the near future. We will present our results for the ground state, for the time correlation function and how it can be used to reconstruct the energy dependence of the cross section.

We are also simulating larger systems on classical computers to understand how we can best simulate neutrino-nucleus dynamics using a combination of quantum computer algorithms and the traditional classical event generators. Even in the short-term we should be able to gain fascinating information about this transition from quantum to classical dynamics.

[1] A. Roggero and J. Carlson, ‘Linear Response on a Quantum Computer’, arXiv:1804.01505

Particle Track Pattern Recognition via Content-Addressable Memory and Adiabatic Quantum Optimization

Lauren Ice[1], Gregory Quiroz[1], and Travis Humble[2]

This project will evaluate employing content-addressable memory (CAM) recall in combination with adiabatic quantum optimization (AQO) to improve the pattern matching algorithm for particle track pattern recognition in high energy physics (HEP) detection systems. Track recognition and reconstruction is a challenging and necessary part of most high energy physics (HEP) experiments. To simplify track reconstruction, pattern matching algorithms are commonly employed to prune data of random noise and to help discriminate signals that potentially correspond to particle tracks of interest from background events. Pattern matching quickly identifies potential track candidates by comparing the pattern of detector signals to a library of patterns known to be from events of interest. The time to search the library is decreased by organizing the library patterns into a tree structure however, the speed and effectiveness of the tree search algorithm is sensitive to the amount of random detector noise, background processes, and the spatial resolution of the detector. For this project, the quantum CAM (QCAM) approach will be compared to the tree search method by examining the quality of track reconstruction and computational speed.

CAM represents an associative memory structure in which key-value data is recalled based on its value as opposed to its key. Incorporating AQO, an approach designed to exploit quantum phenomena to find the global minimum of an objective function, CAM recall is cast as a problem of finding the energetic minimum of an Ising model constructed from a database of known key-value pairs. The track recognition problem will be cast as a CAM recall problem and study the performance of AQO via the D-Wave Systems, Inc. 2000Q quantum processing unit (QPU), the newest generation 2048 quantum bit QPU.

The effort will focus on data collected from the OLYMPUS experiment, an experiment designed to measure the two-photon exchange contribution to lepton-proton elastic scattering. This effort will be the first of its kind, in which QCAM is applied to a practical application. The objectives of this study will be to characterize and optimize QCAM performance for a practical application and to compare QCAM to classical methods (here, the tree search method used for the OLYMPUS dataset) commonly used in HEP experiments with respect to the quality of track reconstruction, rejection of noise, and computational speed.

Ultimately, observed improvements provided by QCAM will give insight into the potential advantages of future track reconstruction algorithms that incorporate quantum hardware. The team will begin by applying QCAM to pattern matching in a simulated toy dataset and then will apply the methods to Monte Carlo and experimental data from the OLYMPUS experiment. QCAM performance will be evaluated and optimized with respect to recall accuracy, while exploring bounds on recall capacity. Ultimately, QCAM will be compared to the tree search method by examining the quality of track reconstruction and computational speed.

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[1] The Johns Hopkins University Applied Physics Laboratory

[2] Oak Ridge National Laboratory

Towards practical quantum simulation for High Energy Physics.

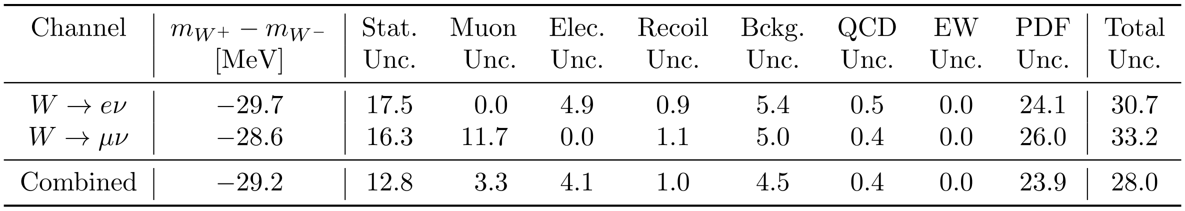
Peter Love, Gary Goldstein, Hugo Beauchemin, Tufts University

Over the last decade quantum algorithms for quantum simulation of electronic structure have become accepted as the most promising early application of quantum computing. They form a major focus of both Google and IBMs commercial efforts to construct a medium-scale quantum computer. The refinement of these algorithms has involved the development of numerous new quantum algorithmic techniques and small-scale experimental demonstrations in various quantum computing hardware platforms.

Quantum algorithms for HEP problems, including algorithms for the simulation of quantum field theory, remain in a more nascent state. Several important results have recently been established but the algorithms proposed to date require many more qubits than are likely to be available in the next five to ten years. We will therefore use the results and techniques developed for quantum chemistry over the course of the last decade to improve the practicality of simulation algorithms for quantum field theories with application to specific HEP questions.

The LHC has entered into a precision era where many of the LHC flagship measurements have systematic uncertainties dominated by theoretical sources, among which the uncertainty in the proton parton distribution functions (PDF). is often the largest. We choose the computation of the proton PDF as a high-impact long-range target for quantum computation applied to HEP.

For example, the W mass measurement (https://arxiv.org/abs/1701.07240) has reached a precision of ~0.02%. As can be seen in the table below (Table 13 from (https://arxiv.org/abs/1701.07240), the largest uncertainty is clearly from the pdf. This is a particularly notable example as the difference in W+ and W- mass is obtained as 29.2 +/- 28 MeV, with the pdf uncertainty accounting for 23.9 MeV, or 85% of this uncertainty.



Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

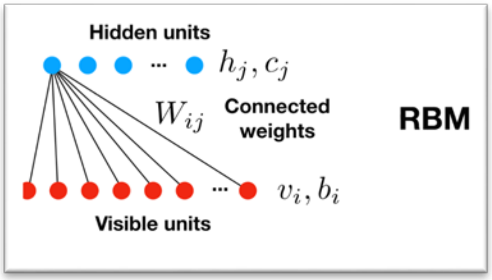
Table 13 from (https://arxiv.org/abs/1701.07240). The uncertainty in the W mass is dominated by the theoretical uncertainty in the proton pdf.

These theoretical errors arise due to limitations of current classical approaches for which the errors are on the order of 5%. Determining the quantum computational requirements to compute the proton PDF's to better accuracy than this, and ultimately to reduce the theoretical error below the experimental error, would significantly improve the sensitivity of many LHC measurements to new physics searches. We therefore focus on the proton pdf and the proton-proton multiply differential cross section as targets for quantum computation, with examples of those target impacts on HEP that set energy ranges and precision requirements for the computation.

High Energy Physics (HEP) ML and Optimization Go Quantum

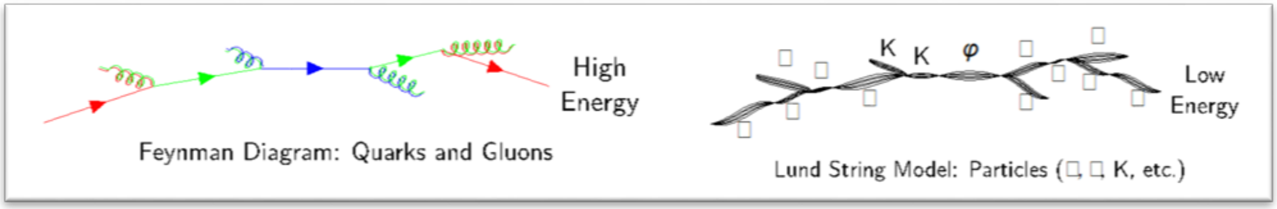
Gabriel Perdue (PI), Jim Kowalkowski, Stephen Mrenna, Brian Nord, Aris Tsaris – Fermilab
Travis Humble (Co-PI), Alex McCaskey – Oak Ridge National Lab

We will explore machine learning (ML) and optimization problems from HEP that can be formulated using Restricted Boltzmann Machines (RBMs) or as Binary Constraint Satisfaction Problems (CSPs). Solutions to these types of problems are feasible with existing quantum annealers, simulators, and gate-based hardware. This project forms a collaboration between HEP and QIS domain scientists from FNAL and ORNL, bringing together the resources necessary to construct and run successful HEP ML and optimization quantum workflows using existing QC systems.

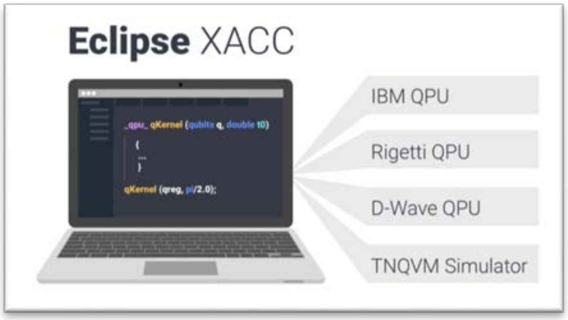


We will study two classification problems from the Energy and Cosmic Frontiers using ML and optimization techniques within the ORNL quantum development and execution environment. For ML, studies include: (1) multi-object detection used in classifying supernova and separating galaxies from stars, (2) compressing and generating simulations to accelerate analyses, and (3) unsupervised learning to detect anomalous objects. The goal is to demonstrate solving an ML problem with scientific data using a quantum annealer.

For optimization, we will study the color reconnections (CR) phenomenon at particle colliders, which involves a minimization of the lengths of QCD strings. This involves: (1) formulation of the string minimization problem as a binary CSP, (2) solution of this problem for realistic partonic configurations, and (3) determination of the phenomenological impact of global solutions and identification of deficiencies in the underlying models. The goal is to reduce the uncertainty on the top quark mass as extracted from HEP data.



The ML and the optimization components will be implemented as classical/quantum hybrid applications. A challenge is to determine the number of states required to solve physics problems given the available QC space. Simplifications necessary to fit within current constraints will be studied. The structure of these problems is well suited to ORNL's XACC (https://ornl-qci.github.io/xacc/) quantum programming framework. The structure also provides a setting for Fermilab HEPCloud (http://hepcloud.fnal.gov) integration. We will develop realizations of the above-described applications using mixed-language programs, targeting D-Wave and Google's quantum hardware, with C++ and Python to classical processing, while offloading of optimization to quantum hardware.



```
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{
...
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qKernel (qreg, pi/2.0);
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Quantum Machine Learning and Quantum Computation Frameworks for HEP (QMLQCF)

PUBLIC ABSTRACT

Several technologies for building quantum computing systems and devices have made considerable progress over the past few of years. Photonic gates can be imprinted in devices to form quantum circuits, microwave cavities are becoming more performant, ion traps are getting more reliable, and the number of qubits in quantum annealing systems has grown to the thousands. It is thus becoming practical to realize quantum algorithms on hardware testbeds, rather than simulators, to perform algorithmic validation and benchmarking experiments. We propose a multi-prong program of research for the investigation of applications of quantum algorithms, technologies, and simulations on challenging areas in High Energy Physics and an associated program of benchmarking and validation. Specifically within this project we target to explore quantum-assisted tracking, vertexing, and particle-based reconstruction algorithms and methods , real-time decision making and inference algorithms with various time and flow constraints, data anomaly detection, rapid data access & indexing schemes and hybrid computation architectures. We also target to investigate possible deep connections between deep learning networks and renormalization group flow. These studies could lead to new physical insights about both. The project proposed is designed to impact High Energy Physics while developing quantum methodologies that can be used in other computation and data intensive sciences.

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(Co-Investigator) Panagiotis Spentzouris, Fermilab
(Co-Investigator) Daniel Lidar, USC
(Co-Investigator) Seth Lloyd, MIT

Quantum Algorithms for Collider Physics

Prof. Jesse Thaler and Prof. Aram Harrow
Massachusetts Institute of Technology

The goal of our research is to unite powerful analysis techniques in high energy physics with cutting-edge advances in quantum computation. Broadly speaking, Thaler's research is aimed at discovering new physics at the Large Hadron Collider (LHC) and Harrow's research is aimed at unlocking the capabilities of quantum computers. Through this innovative work at the interface of high energy physics and quantum information science, we aim to maximize the discovery potential of the LHC and future colliders by demonstrating how quantum algorithms can expose important features in collision events that would otherwise be intractable with classical methods.

To search for new physics at colliders like the LHC, one relies on a series of algorithms to enhance signals of interest and mitigate backgrounds. Many of these algorithms are related to identifying and classifying jets—collimated sprays of particles that are copiously produced in high-energy collision events. Almost every LHC collision involves jets in some way, but the algorithms that are currently used to identify and classify jets are constrained by the limits of classical computation. Quantum algorithms could fundamentally change the way that collider data is analyzed, either by speeding up existing classical algorithms or by enabling quantum representations of the collision debris.

We are currently exploring two directions where quantum computation could have a direct impact on collider physics. The first direction is to use quantum machine learning algorithms to classify jets. The detailed pattern of particles within a jet (i.e. its substructure) contains valuable information about its origin, and classical machine learning algorithms have already seen numerous applications in jet classification. This research will address situations where efficiently finding the optimal classifier requires quantum manipulations, either through quantum annealing or through quantum superposition. The second direction is to use quantum clustering algorithms to identify jets. Jet clustering can be viewed as a kind of optimization problem, though most classical algorithms in use at the LHC only find approximate solutions. This research will develop quantum jet clustering algorithms that can efficiently find optimal jet configurations, as relevant for new physics searches involving multiple overlapping jets.

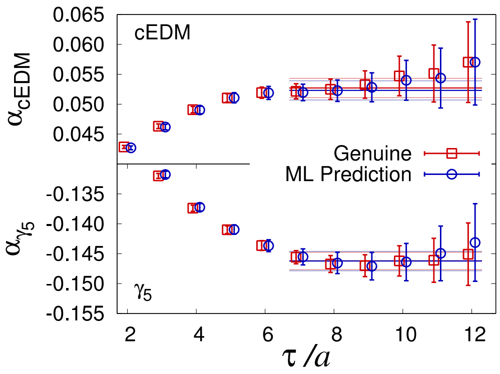
By exploiting the capabilities of quantum computation, this research confronts the challenge of data analysis in collider physics. Moreover, the work described above may pave the way for future applications of quantum machine learning beyond high energy physics, in particular clustering problems in other application domains.

Quantum Machine Learning for Lattice QCD

Boram Yoon (PI), Nga T. T. Nguyen, Garrett Kenyon, Tanmoy Bhattacharya and *Rajan Gupta*
Los Alamos National Laboratory

Lattice QCD is a non-perturbative formulation of QCD, the theory of strongly interacting quarks and gluons. It is solved using Monte Carlo simulations by first discretizing the theory on a hypercubic Euclidean space-time grid. In the lattice QCD Monte Carlo simulations, multiple observables are simultaneously measured on a series of Monte-Carlo samples of gluon fields as calculate expectation value, and the fluctuations of these observables over the Monte-Carlo samples are correlated. By exploiting these correlations between observables, one can build a machine learning (ML) algorithm that predicts values of a set of observables using the information on other observables. Such algorithm allows us to measure only partial of the observables, and to reduce the computational cost for the measurement. The right-hand side plot shows the ML prediction on the lattice QCD calculation of the CP Violating (CPV) phase. After trained on 30% of total simulation data, a boosted decision tree classical ML regression algorithm was able to predict the CPV phase for the remaining 70% of data only using the two-point correlation functions calculated without any CPV interactions.

Prediction of CPV Phase using Classical ML



Recently, sparse coding algorithm has been implemented on the DWave quantum annealing system by our team members. Sparse coding is a representation learning algorithm, which builds a dictionary inferred from the input data and finds a sparse representation, the linear coefficients of the dictionary elements reconstructing the input data. The representation is sparse as the algorithm enforces it to use minimal set of dictionary elements for the reconstruction of a given input data. Because the representation is sparse, the reconstruction picks up only the key features of the data, wiping out unseen fluctuations, and reconstructs input data in a way that can be explained by the dictionary elements. Therefore, by taking array of observables as an input data and setting the target observable to an arbitrary value, the reconstruction fills up the target observable with its prediction value based on the dictionary obtained from a training data set, so it can be used as a regression algorithm. The left-hand side plot shows a preliminary study of the sparse coding regression performed using DWave quantum annealer. Narrower spread of the prediction error than the distribution of original data indicates that the prediction algorithm is working as expected.

Distribution of CPV correlators and ML predictions