The Fermilab QuantISED Program

POCs: Panagiotis Spentzouris (spentz@fnal.gov), Farah Fahim (farah@fnal.gov)

Fermilab has a QuantISED program (https://quantum.fnal.gov) that includes activity areas on quantum computing, quantum sensor-based pathfinder experiments, supporting quantum technology, quantum communications, and intersections of QIS and theoretical particle physics. Most of these activities have multiple university and DOE lab-based collaborators as well as coordinated research with other agencies. The topics are listed below along with their FNAL POCs.

1. Quantum Computing - Machine Learning and Optimization, PI Gabriel Perdue

Develop Quantum Machine Learning and Optimization algorithms for HEP applications ranging from Monte Carlo event generators, to event reconstruction, to data analysis and object classification. Deploy on different platforms of today's NISQ hardware to evaluate and develop the necessary know-how.
Selected highlights: Quantum kernel paper utilizing the highest qubit count to date, on the highest dimensional data to date (https://arxiv.org/abs/2101.09581); Extension of the famous quantum amplitude amplification algorithm to non-Boolean oracles with application to quantum machine learning (https://arxiv.org/abs/2102.04975)

2. Quantum Sensors for Dark Matter, PI Aaron Chou

Develop a variety of complementary quantum sensors to close the gap in existing detector technology between 10^{-5} eV quantum-limited receivers used by axion experiments and eV threshold sensors used by WIMP detectors. Demonstrate viability of new single photon detection technologies in prototype dark matter experiments.
Selected Highlights: Demonstrated qubit-based quantum non-demolition readout of microwave cavity photons with noise 40x below the quantum limit, thus enabling 1300x speed-up of dark matter searches. Results from prototype experiment demonstrating world-leading sensitivity to 10 GHz dark photon dark matter (submitted to PRL. arXiv:2008.12231); Developed concept for broadband dark photon search via spontaneous parametric down-conversion, imaged by Skipper CCDs. Experimental pathfinder results submitted for publication (arXiv:2012.04707)

3. MAGIS-100, PI Robert Plunket

Bring precision atom interferometry to the 100 m scale at Fermilab. Applications include ultra-light dark matter searches, gravitational wave searches at 1 Hz frequency range, and extreme quantum science of wave packet separation (10 m) and superposition. Fermilab is the host laboratory, with responsibilities on delivering the shaft and laser lab, physical and power infrastructure, as well as engineering, assembly and integration, computing and monitoring.
Selected Highlights: Stanford achieves record for laser momentum transfer to Strontium atoms (Phys. Rev. Lett. 124, 083604 (2020)); Science sensitivities and Technical Review paper in submission process "Matter Wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)", P. Adamson et. al. (2021).

4. Quantum Technology - Portable Optical Atomic Clocks, PI Farah Fahim

Advance integrated electronics for chip-based trapped ion chips suitable for supporting a range of different approaches to optical atomic clocks and atomic sensors and will demonstrate this technology in the context of an optical atomic clock based on individually trapped Sr+ ions.

5. Quantum Communications, PI Panagiotis Spentzouris

Advance system development and integration, to achieve operational robustness, high-fidelity, and, eventually, high-rates for quantum teleportation utilizing time-bin photonic qubits at the telecommunication wavelength of 1.5 microns, over the same type of optical fibers used by the telecommunication industry. This is achieved through operating and advancing two pilot testbeds: the **C**altech **Q**uantum **NET**work and the **F**ermilab **Q**uantum **NET**work (https://inqnet.caltech.edu/fqnet/, https://inqnet.caltech.edu/cqnet/).
Selected Highlights: Achieved sustained record high-fidelity teleportation, https://doi.org/10.1103/PRXQuantum.1.020317.

6. Intersections of QIS and Theoretical Particle Physics, PI Marcela Carena

The Quantum Information for Theoretical Particle Physics consortium is led by the Fermilab Theoretical physics department and includes University partners, Caltech, U. of Washington, UIUC, MIT, and Purdue. The consortium conducts research in the areas of Quantum Simulation of QFT, Quantum algorithms for HEP analysis, and Quantum sensors for particle physics exploration and discovery. The consortium aims at unleashing the QIS potential to explore new frontiers and enable new directions of science in HEP.
Selected Highlights: Lamm (Fermilab) and collaborators have systematized the use of discrete subgroups to simulate gauge theories with quantum computers, allowing to estimate the discretization errors reliably (Phys.Rev.D 102 (2020), 114513); Harnik (Fermilab) and collaborators have proposed a novel method to search for new light particles, such as axions and dark photons, using nonlinear optics, a central tool in quantum communication (arXiv: 2012.04707); Savage (UW) and Klco (Caltech) analyzed an approach to simulating SU(3) gauge theories using a local multiplet basis, addressing the redundancy of the description of Hilbert space (arXiv: 2101.10227); Preskil (Caltech) and collaborators have analyzed the simulation of the collision of two bubble walls in 1+1 dimensions, and the production of particles using a spin chain (arXiv: 2012.07243); Unmuth-Jockey (Fermilab) has written a comprehensive review of tensor field theory and its applications in quantum computing (arXiv: 2010.06539); Carena, Lamm, Li and Liu (Fermilab) are studying how trotterization that can be related to an approximate analytic continuation of anisotropic Euclidean lattice calculations. This is being demonstrated in a non-abelian theory in a small lattice with a quantum simulator.

Research at the intersection of Quantum Information Sciences and High Energy Physics at LANL

PI: Rajan Gupta (LANL, rajan@lanl.gov, (505)667-7664);
Co-PI: Andrew Sornborger (LANL, sornborg@lanl.gov, (505) 667-3813);

The four tasks described here investigate areas of high energy physics where the tools of quantum information sciences and simulations performed on quantum computers have the potential to provide very significant results and a deeper understanding of quantum theories.

Task A: Quantum Field Theories as Spin Models on Quantum Computers
PI – Tanmoy Bhattacharya (LANL)
T. Bhattacharya and R. Gupta (LANL), S. Chandrasekharan and students (Duke U.), graduate student A.J. Buser (Caltech) and postdoc H. Singh (U. Washington)
Develop techniques for quantum simulations of interesting quantum field theories using only a few quantum degrees of freedom on each site that interact with neighbors on a finite discrete lattice. Asymptotically free theories, traditionally considered difficult, were analyzed using short-depth quantum circuits in (**R2**) for the O(3) model. They are now working on developing such techniques for other field theories and their properties of interest.

R1: "State preparation and measurement in a quantum simulation of the O(3) sigma model", Alexander J. Buser (Caltech), Tanmoy Bhattacharya, Lukasz Cincio, and Rajan Gupta (LANL), *Phys. Rev*. **D102** (2020) 114514

R2: "Qubit regularization of asymptotic freedom", Tanmoy Bhattacharya, Alexander J. Buser, Shailesh Chandrasekharan, Rajan Gupta, and Hersh Singh, arXiv:2012.02153, under review at *Phys. Rev. Lett.*

Task B: Quantum Computing for Neutrino-Nucleus Dynamics
PI – Rajan Gupta (LANL)
A. Roggero (UW), A. Baroni, J Carlson, R. Gupta (LANL), Andy C.Y. Li, G. Purdue (FNAL)
Neutrino-nucleus cross sections are a dominant systematic in oscillation experiments designed to probe neutrino properties including masses, mixings, hierarchy and CP violation in the neutrino sector. Inclusive neutrino-nucleus scattering is directly given by the real-time two-point correlation functions of current operators acting on the nuclear ground state. This is an ideal application for NISQ-era devices as only a comparatively short time evolution is required.

R3: "Quantum Computing for neutrino-nucleus scattering", A. Roggero, Andy C.Y. Li, Joseph Carlson, Rajan Gupta, and Gabriel Purdue, *Phys. Rev.* **D101** (2020) 074038.

R4: "Two point response functions for neutrino-nucleus scattering on a quantum computer", A. Roggero, Andy C.Y. Li, A. Baroni, Joseph Carlson, Rajan Gupta, and Gabriel Purdue, (in preparation)

Task C: Quantum Foundations on Quantum Computers

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

The availability of an advanced quantum laboratory "in the Cloud" is leading to advances in our understanding of the foundations of quantum mechanics. In this project, we are exploring the utility of QCs and quantum machine learning (QML) methods for studying the emergence of subsystems, einselection, and the role of factorization in particle scattering. Our research is strengthening ties between high-energy physics and quantum information science by funding a consortium of experts from two institutions (LANL, UC Davis).

R5: "Barren plateaus preclude learning scramblers", Zoe Holmes, Andrew Arrasmith, Bin Yan, Patrick J. Coles, Andreas Albrecht, and Andrew T. Sornborger, arXiv:2009.14808 [quant-ph].

Task D: Quantum Machine Learning for Lattice QCD
PI – Boram Yoon, Co-PI – N. Nguyen (LANL)
Aim to develop quantum machine learning (ML) algorithms enhancing analysis of physics data. The correlation of the data generated from physics simulations and experiments encodes physics rules. The study of such correlations is well suited for ML algorithms, with quantum annealers used as an efficient solver of a discrete optimization problem to improve the speed and quality of the ML algorithms. One of the ML algorithms used is sparse coding, which refers to a class of unsupervised ML algorithms for finding an optimized set of basis vectors and the fewest number of non-zero coefficients to accurately reconstruct inputs vectors. The algorithm provides an interpretable feature extraction algorithm of physics data based on their correlation pattern. The mapping of the sparse coding to a quadratic unconstrained binary optimization (QUBO) allows solving sparse coding problems on quantum annealers. Good utilization of the quantum annealing features of the D-Wave system are shown.

R6: "A regression algorithm for accelerated lattice QCD that exploits sparse inference on the D-Wave quantum annealer", N. Nguyen, G. Kenyon, B. Yoon, Sci.Rep. 10, 10915 (2020)

Highlights of the work and plans for the future

Task A: T. Bhattacharya and R. Gupta (LANL), S. Chandrasekharan and students (Duke U.), A.J. Buser (Caltech), H. Singh (U. Washington)

Because of the well understood principles of universality, we expect the long-distance physics of discrete models even with small number of degrees of freedom per site to be described by field theories at the critical points. Even though these field theories, when bosonic, have an infinite number of degrees of freedom per point, the infinity is built up dynamically by accumulating the finite number of degrees of freedom over a volume of size given by the divergent correlation length at criticality. The finiteness of the discrete model, however, makes it amenable to quantum simulations. We had published (*Phys. Rev.* **D100** (2019) 054505) this approach to simulating the O(3) sigma model in 2+1- and 3+1-dimensions, and followed up with the evaluation (**R1**) of the complexity of simulating time evolution and measuring observables in this approach.
What remains unclear is whether all field theories, especially those of interest to high energy physics, can be realized by such construction. In recent work (**R2**), we showed that the critical two-qubits-per-site Heisenberg-comb model in 1+1-dimension is described by the asymptotically-free O(3) sigma model, the first example of this kind. Since the development of classical algorithms for simulating some aspects of O(N) sigma models in (arXiv:1911.12353 [hep-lat]), we plan to extend this work and look for qubit regularization of the O(4) model, the CP^N model, and the Gaussian fixed point in 2+1-dimensions. This will prepare us to handle more complicated models such as $SU_L(N)\times SU_R(N)$ matrix model, models of chiral fermions, field theories that show topological phenomena similar to the θ-vacua of QCD, and gauge theories.
In parallel, our approach is opening up possibilities of using of matrix-product-state algorithms to study ground states of field theories classically, and to apply ideas from entanglement renormalization theory. In addition, we are developing methods to study particle scattering in these theories as well as the entanglement structure of the vacuum. A particularly interesting direction we are currently pursuing are to develop schemes for entanglement harvesting from the vacuum that can be implemented with limited quantum computational resources.

Task B: A. Roggero (UW), A. Baroni, J Carlson, R. Gupta (LANL), Andy C.Y. Li, Gabriel Purdue (FNAL)
In the first paper (**R3**) we used variational methods to prepare the ground state of a three-nucleon system and implemented the relevant time evolution. In addition, we determined the quantum resources required for a realistic calculation. In a second paper (**R3**) we are calculating the two-point correlation function on quantum hardware including methods to mitigate noise on NISQ devices. We are simultaneously investigating different approaches to the real-time correlation function and its inversion to obtain the energy response.

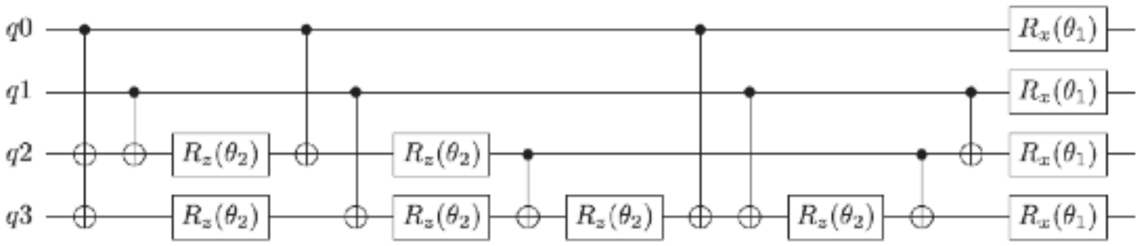


Figure 1) Time evolution circuit for the problem created in Ref **R3**. Actual circuit used depends upon the hardware of the specific machine used.

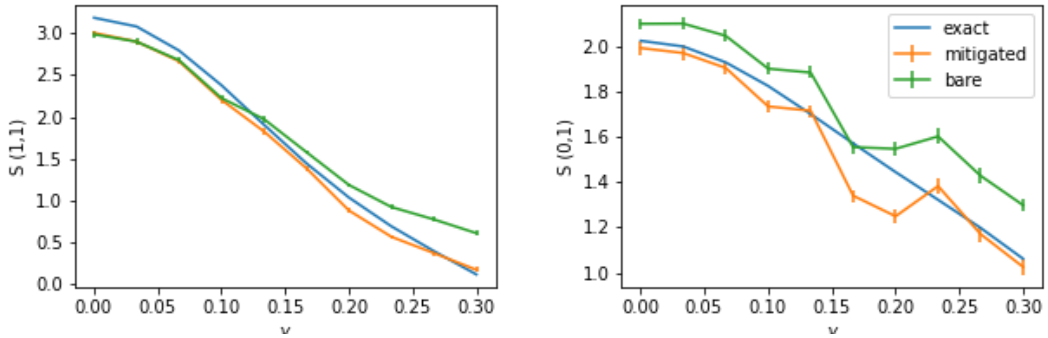


Figure 2) Two components of the two-point response functions on IBM quantum hardware. The blue line is exact, the green lines are bare results on the IBM vigo machine, and the orange lines are results with errors mitigation.

Task C: Highlights - In a paper recently posted on the arXiv (**R5**), we have made progress understanding the limits of learnability of quantum systems. Scrambling, the rapid spread of entanglement and information through many-body quantum systems, is of fundamental importance to thermalization and quantum chaos but can be challenging to investigate using standard techniques. Recently, QML has emerged as a promising platform to study complex quantum processes. This prompts the question of whether QML could be used to investigate scrambling. In this work, we prove a no-go theorem constraining the use of QML to learn an unknown scrambling process. Specifically, we show that employing QML to learn an unknown scrambling unitary, for any choice of variational ansatz, will with high probability lead to a barren plateau landscape, i.e., where the cost gradient vanishes exponentially in the system size. We provide numerical evidence extending our results to approximate scramblers. More broadly, our no-go theorem implies that there are fundamental limits to learning complex physical systems and thus places limits on the learnability of quantum processes.

Ongoing work in this thrust is aimed at constructing a quantum algorithm to identify classical subsystems within larger quantum systems. This work involves PI Sornborger, Co-PI Albrecht, Patrick Coles, and three LANL postdocs, Zoe Holmes, Andrew Arrasmith, and Bin Yan. Additional ongoing work is aimed at studying out-of-time-order correlators with quantum computers. This work involves PI Sornborger, Co-PI Albrecht, Patrick Coles, LANL postdocs Zoe Holmes, Andrew Arrasmith, Bin Yan, and University of Georgia collaborator, Michael Geller.

Clarification of distinction of scope with NQI centers and other federal/SC activities - The work for this task is orthogonal to work being performed by the PI who is also a member of the Quantum Science Center (QSC), one of the five NQI Centers funded recently by the DOE. For the QSC, the PI of this task manages a research thrust (Quantum Algorithms and Simulation) and also participates in work developing quantum sensing algorithms. Additionally, Patrick Coles is project PI of an error mitigation for quantum computing project. This QSC project does not overlap with our QuantISED work scope.

Task D: B. Yoon (PI) and N. Nguyen (Co-PI)
We developed an ML approach replacing part of computationally expensive lattice QCD calculations with computationally cheap ML predictions (Yoon, et al., *Phys. Rev.* **D100** (2019) 014504). We also developed a new ML regression algorithm on D-Wave quantum annealer based on the sparse coding and showed its prediction ability of lattice QCD observables (**R6**). Our team is investigating efficient data compression and feature extraction algorithms based on the sparse coding on quantum annealers.

LBNL QuantISED Quest Program

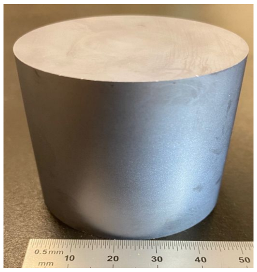
Physics – C.Bauer, D.Carney, M.Garcia-Sciveres (PI), B.Nachman, A. Suzuki
Acc. Tech. & Appl. Phys. – T. Schenkel, G. Huang
Computer Research Division – W. de Jong
Molecular Foundry & Mat. Sci. – S. Griffin, S. Lubner
Bio Imaging – S. Derenzo

Caltech – K. Zurek
JPL – M. Shaw
Princeton – S. Lyon
U. Mass Amherst – S. Hertel
UC Berkeley – J. Analytis, D. McKinsey, M. Pyle, N. Yao
Yale – J. Harris

The QuantISED Quest program brings together the following interconnected goals:

- Use QIS advances to develop next generation sensor technology to eventually reach meV or lower threshold with zero dark counts for Dark Matter (DM) detection
- Produce and try out new quantum materials as DM targets
- Advance the theory of DM coupling mechanisms to coherent modes and quantum states in materials, and calculate the propagation of quasiparticles.
- Develop targeted supporting technology for quantum device readout
- Develop a toolkit for high energy physics field theory calculations and simulations on quantum computers. Demonstrations on NISQ hardware.
- Investigate the flow of information in quantum systems as it relates to physical phenomena, such as black holes.

While further details are given in the remainder of this abstract, the following featured recent publications provide a snapshot of our exciting research:



Many-Body Chaos in the Sachdev-Ye-Kitaev Model
Bryce Kobrin, Zhenbin Yang, Gregory D. Kahanamoku-Meyer, C. T. Olund,
Joel E. Moore, Douglas Stanford, and Norman Y. Yao
Phys. Rev. Lett. **126**, 030602 (2021)

Editors' Suggestion

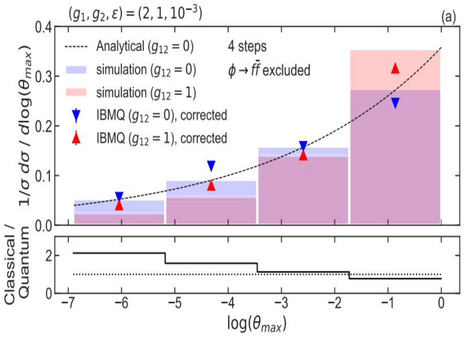
How silicon and boron dopants govern the cryogenic scintillation properties of N-type GaAs
S. Derenzo, E. Bourret, C. Frank-Rotsch, S. Hanrahan, M. Garcia-Sciveres
Nuclear Inst. and Meth. in Phys., A 989 (2021)

Multichannel direct detection of light dark matter: Target comparison
S. M. Griffin, K. Inzani, T. Trickle, Z. Zhang, and K. M. Zurek
Phys. Rev. D **101**, 055004 (2020)

Editors' Suggestion

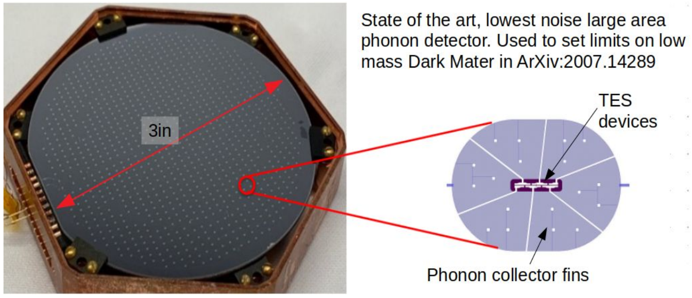
Detecting Light Dark Matter with Magnons
T. Trickle, Z. Zhang, and K. M. Zurek
Phys. Rev. Lett. **124**, 201801 (2020)

Quantum algorithm for high energy physics simulations
Benjamin Nachman, Davide Provasoli,
Wibe A. de Jong, and Christian W. Bauer
Phys. Rev. Lett. Accepted17 December 2020



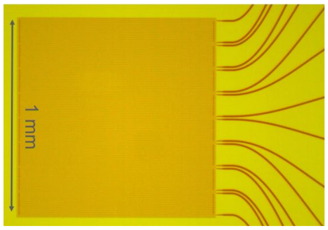
Using QIS advances to develop sensors with meV threshold and zero dark counts

Transition Edge Sensor based Athermal Phonon Detectors are the present low noise workhorse, reaching <10eV threshold. We explore the low noise limit of this technology. As sensor noise is reduced new noise sources must be understood. Environmental noise will affect all sensor technologies as well as superconducting qubit systems (Pyle)



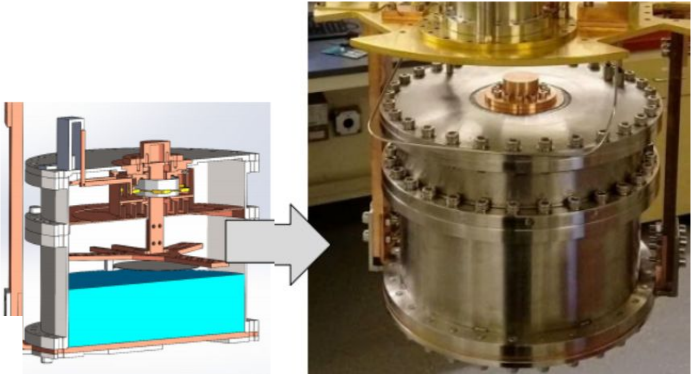
State of the art, lowest noise large area phonon detector. Used to set limits on low mass Dark Mater in ArXiv:2007.14289

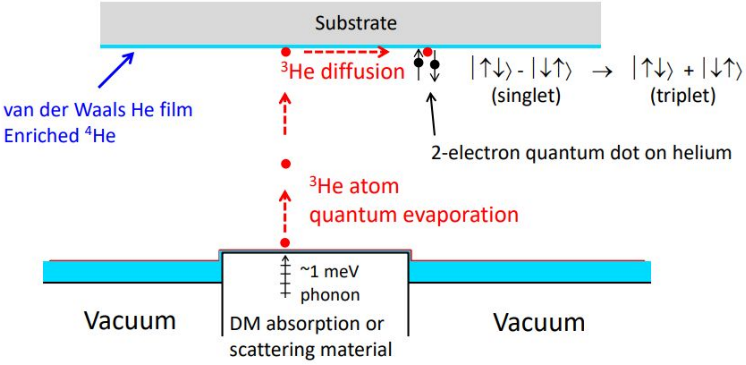
Testing of RF phonon sensors (Kinetic Inductance Detectors). KIDs have not yet achieved as low a noise level as TES's, but have the promist of squeezed vacuum readout. We will test squeezed readout using parametric amplifiers (Suzuki)



Superconducting Nanowire Single Photon Detectors are the third sensor of interest. We are developing large area SNSPDs to couple to GaAs scintillators, and working on lower noise SNSPDs that could be used for He quantum evaporation readout (Shaw)

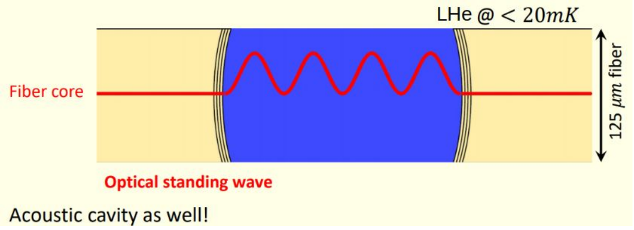
Superfluid He can amplify phonon signals through the process of quantum evaporation. We are developing ^{4}He QE setups to couple to above sensors (Hertel, McKinsey)





Electrons and ^{3}He QE can be detected with coherent spin systems, which have been developed so far as spin qubits, but not as sensors. We are adapting spin qubit devices for use as electron and He QE sensors, and preparing an experiment on phonon assisted (field)-emission of electrons from He (Lyon, Schenkel).

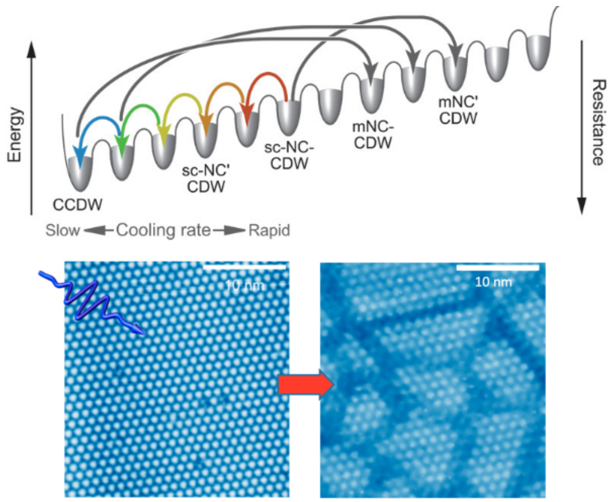
What is the ultimate low threshold of phonon detection possible? Optomechanical cavities will couple phonons in superfluid He to phonons, enabling detection of ueV phonons. We are scaling this technology to volumes relevant for DM detection (Harris).



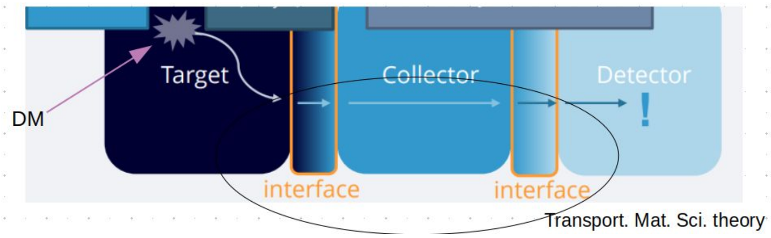
Acoustic cavity as well!

New quantum materials as DM targets

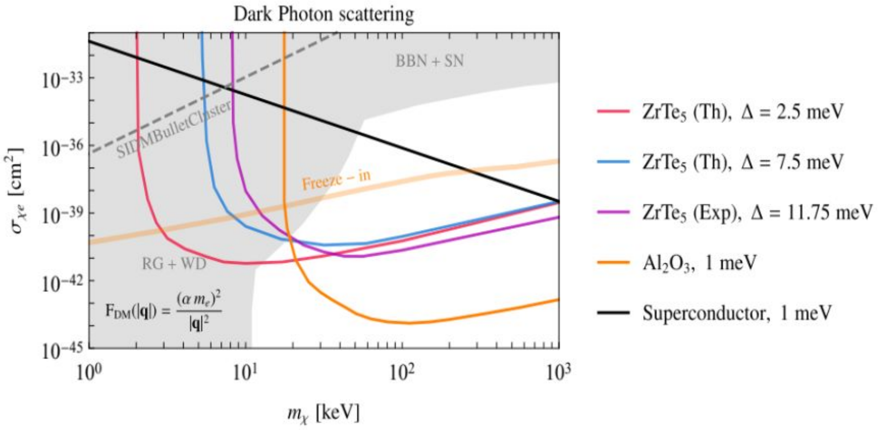
Quantum materials research provides databases on candidate materials that can be exploited for DM detection. The figure shows an example of a correlated system with metastable states that could introduce sensitivity to DM models. Such topological transitions could also be used for new kind of phonon sensors analogous to the superconducting transition sensors (Analytis, Griffin, Lubner)



DM coupling mechanisms to coherent modes and quantum states in materials, and propagation of quasiparticles

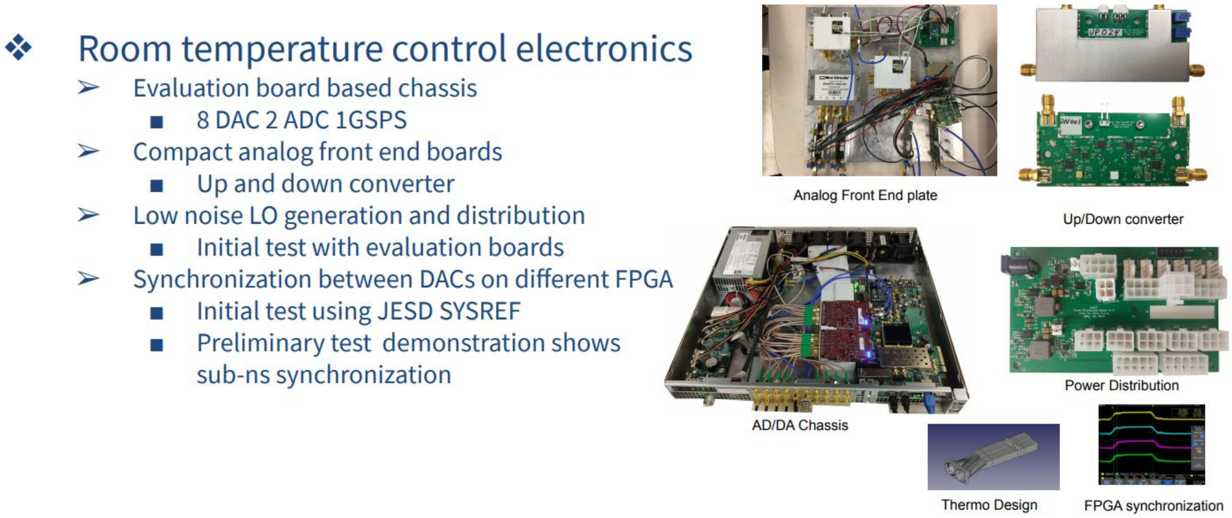


Sufficiently low mass DM particles cannot transfer energy to individual nuclei or electrons. Instead they can only couple to collective modes: quasi-particles. Our theory efforts aim to quantify how DM models couple to different collective modes in a wide range of materials and meta-materials, as well as how excitations propage in bulk, across interfaces, and ultimately to sensors. These activities make use of materials science techniques such a numerical solving of density functional theory on high performance computing at LBNL (Zurek, Griffin)



Phys. Rev. D **101**, 055004

Supporting technology for quantum device control and readout

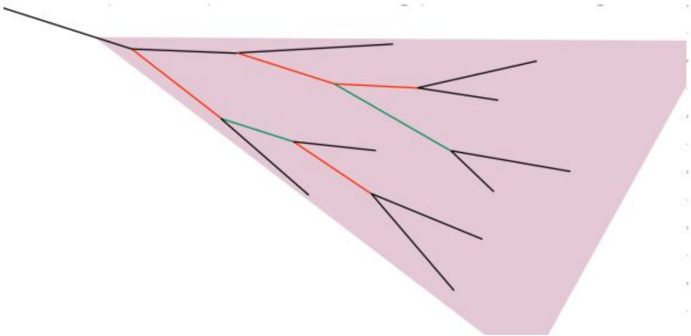


- Room temperature control electronics
  - Evaluation board based chassis
    - 8 DAC 2 ADC 1GSPS
  - Compact analog front end boards
    - Up and down converter
  - Low noise LO generation and distribution
    - Initial test with evaluation boards
  - Synchronization between DACs on different FPGA
    - Initial test using JESD SYSREF
    - Preliminary test demonstration shows sub-ns synchronization

Field theory calculations and simulations on quantum computers

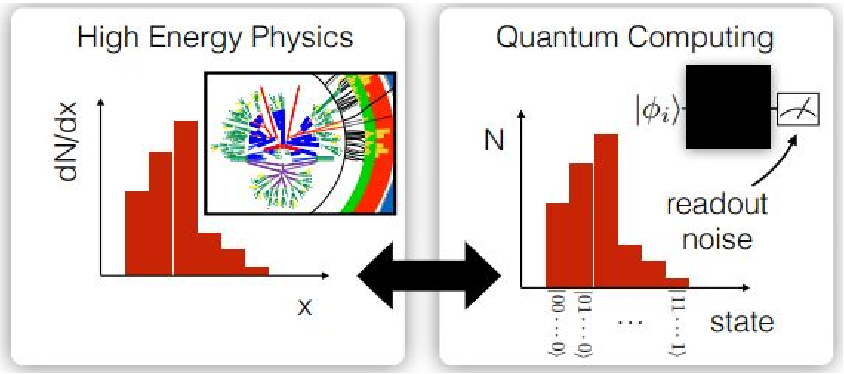
Parton shower algorithms calculate colinear and soft emissions probabilistically. But the number of amplitudes grows exponentially with the number of intermediate particles.

A quantum computer can instead calculate the result of 2^n amplitudes with polynomial growth in n.



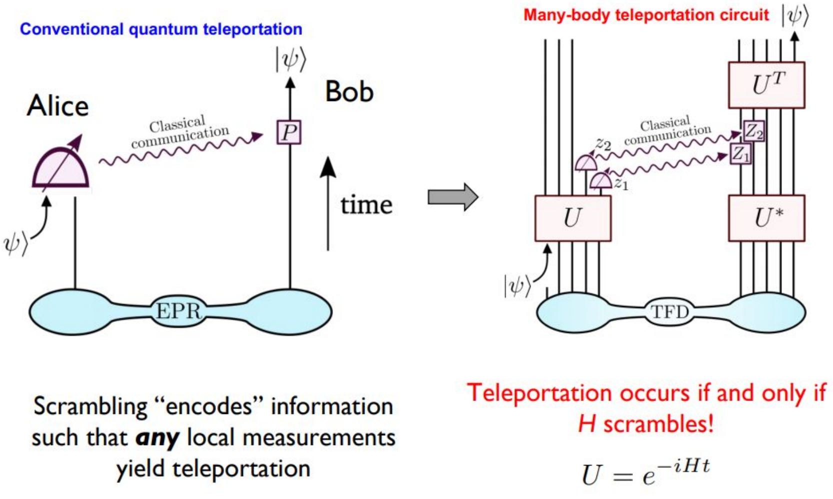
NISQ computers require error correction methods. We apply HEP data unfolding techniques to develop new qubit error correction methods (Bauer, De Jong, Nachman)

ArXiv:1910.01969

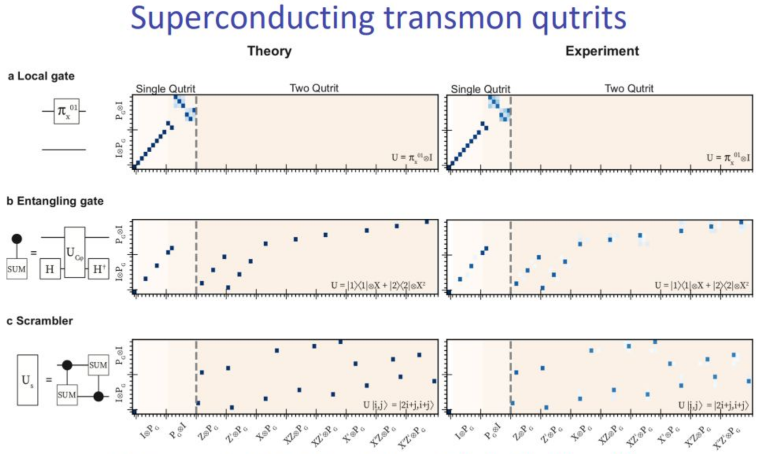


The flow of information in quantum systems as it relates to physical phenomena

Focuses on the study of information scrambling, as happens in black holes, and how scrambling can be measured in laboratory physical quantum systems, such as qubits and qutrits (Yao)



Hayden, Preskill; Gao, Jafferis, Wall; Maldacena, Stanford, Yang (2017)



*** These experiments check to see if U scrambles but not how it scrambles

e.g. fast vs generic scrambling

B. Yoshida, NYY, PRX **9**, 011006 (2019); M. Blok...NYY, Siddiqi arXiv:2003.03307 (2020)

New Directions

The breadth of our program and frequent interaction between the program members are incubators for new concepts. How can sensing and quantum computing be directly combined to give rise to new detection capabilities? How can new ideas in impulse and gravitational sensing (Carney) be combined with collective mode DM coupling? How can decoherence of quantum systems be used for sensing? How can topological transitions be used to make new types of sensor? Ultimately, how else can we look for Dark Matter leveraging emerging QIS technology.

QuantISED Program at SLAC
Quantum Sensing and Simulation for Fundamental Discovery

Lead POC: Kent Irwin irwin@stanford.edu

SLAC has a QIS-based sensing, simulation and discovery program spread across several tasks:

Task A: **Holographic Quantum Simulation**

Lead: Monika Schleier-Smith (Stanford University)

co-PIs: Patrick Hayden (Stanford University), Emilio Nanni (SLAC)

Publication: E. J. Davis, A. Periwal, E. S. Cooper, G. Bentsen, S. J. Evered, K. Van Kirk, and M. Schleier-Smith, "Protecting Spin Coherence in a Tunable Heisenberg Model," *Phys. Rev. Lett.* **125**, 060402 (2020).

Task B: **RF Quantum Upconverters as Quantum Sensors**

Lead: Kent Irwin (SLAC/Stanford University)

co-PIs: Hsiao-Mei Cho (SLAC), Peter Graham (Stanford University), Dale Li (SLAC), Alex Sushkov (Boston University) and Dmitry Budker (Uni Mainz).

Task C: **Fundamental discovery with quantum sensing of LC resonators**

Lead: Kent Irwin (SLAC/Stanford University)

co-PIs: Dale Li (SLAC), Peter Graham (Stanford University).

Publication: A. Phipps et al., "Exclusion limits on hidden-photon dark matter near 2 meV", Microwave Cavities and Detectors for Axion Research. Springer, Cham, 2020. 139-145.

Task D: **Fundamental Discovery with Magnetic Resonance and Spin Ensembles**

Lead: Alexander Sushkov (Boston University)

Pre-print: D. Aybas et. al, "Search for axion-like dark matter using solid-state nuclear magnetic resonance", (2021).

Related Task: **Transduction for New Regimes in Quantum Sensing**

Lead: Emilio Nanni (SLAC)

co-PIs: Paul Welander, Tony Heinz (SLAC) and Amir Safavi-Naeini (Stanford University)

Task A: Holographic Quantum Simulation focuses on realizing and probing quantum spin models with non-local interactions. Such interactions are a characteristic feature of toy models for information scrambling in black holes under the framework of AdS/CFT duality. In our simulation platform [1,2], the spins are encoded in internal states of cold atoms, and their interactions are mediated by photons in an optical resonator. In the pilot phase of the project, we imaged the dynamics induced by all-to-all interactions [1] and, as a byproduct, showed that the interactions can be designed to protect quantum coherence [2]. Complementing these experimental results, we examined theoretically how the connectivity of interactions affects the rate at which quantum information is scrambled [3,4].

Building on these developments, we have recently demonstrated a versatile scheme for programming the graph of non-local interactions in a one-dimensional array of atomic ensembles (**Fig. 1A**). We program the dependence of the couplings $J(r)$ on distance r by tailoring the frequency spectrum of a control field driving the optical resonator. We verify this ability by probing spin correlations in a system of spin-1 atoms, where the cavity-mediated interactions produce correlated atom pairs in states $m = +/- 1$. In the simplest case of a bichromatic drive field, we observe correlations at a distance specified by the frequency spacing in the drive spectrum (**Fig. 1B**), as well as the spreading of these correlations to multiples of the designated distance with increasing time (**Fig. 1C**).

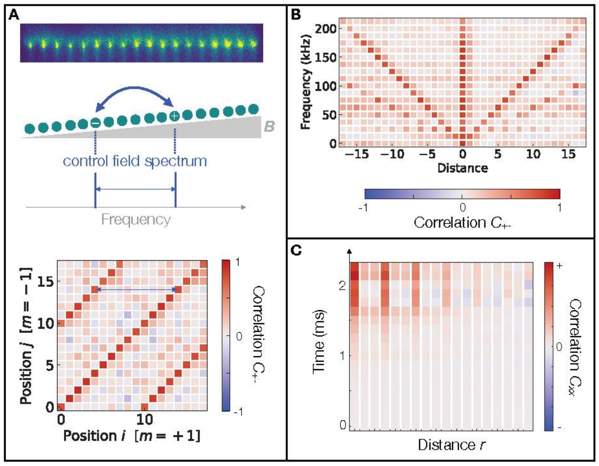


Fig. 1. Programmable non-local interactions.

We have applied these programmable interactions to access emergent geometries that differ from the physical geometry of the atoms in the experiment. For a given set of measured spin correlations, we reconstruct the best-fit embedding of the atomic sites in a Euclidean 2D- or 3D space based on an ansatz of exponentially decaying correlations. Two illustrative examples are shown in **Fig. 2**. In the simple case **(A)** where we turn on interactions at a single distance $r = 3$, the reconstructed geometry is a set of three decoupled chains. A richer geometry **(B)** is obtained by turning on interactions at two distances $(r_1, r_2) = (1, 9)$, and additionally engineering periodic boundary conditions: here, the reconstruction reveals a Möbius strip. For future work exploring toy models of quantum gravity [4], an intriguing question is whether and how our approach might be extended to reveal the holographic bulk geometry.

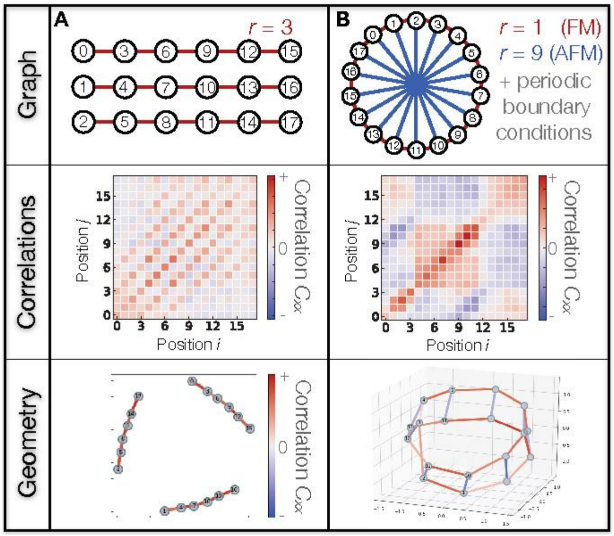


Fig. 2. Emergent geometry from correlations.

We have additionally initiated the design and prototyping of a millimeter-wave cavity that will provide orders-of-magnitude stronger atom-photon coupling, to enable quantum simulations in a strongly interacting regime intractable to classical simulations in a next-generation apparatus.

[1] E. J. Davis, G. Bentsen, L. Homeier, T. Li, and M. H. Schleier-Smith, *Photon-Mediated Spin-Exchange Dynamics of Spin-1 Atoms*, Phys. Rev. Lett. **122**, 010405 (2019).
[2] E. J. Davis, A. Periwal, E. S. Cooper, G. Bentsen, S. J. Evered, K. Van Kirk, and M. H. Schleier-

Smith, *Protecting Spin Coherence in a Tunable Heisenberg Model*, Phys. Rev. Lett. **125**, 060402 (2020).

[3] G. Bentsen, I.-D. Potirniche, V. B. Bulchandani, T. Scaffidi, X. Cao, X.-L. Qi, M. Schleier-Smith, and E. Altman, *Integrable and Chaotic Dynamics of Spins Coupled to an Optical Cavity*, Phys. Rev. X **9**, 041011 (2019).

[4] G. Bentsen, T. Hashizume, A. S. Buyskikh, E. J. Davis, A. J. Daley, S. S. Gubser, and M. Schleier-Smith, *Treelike Interactions and Fast Scrambling with Cold Atoms*, Phys. Rev. Lett. **123**, 130601 (2019).

Task B: RF Quantum Upconverters as Quantum Sensors

In this task, we develop sensors for quantum metrology of electromagnetic signals at frequencies from ~1 kHz to 300 MHz, a region of the electromagnetic spectrum that is much less well developed for quantum metrology than GHz frequencies. The sensor we have developed is referred to as an RF Quantum Upconverter (RQU), which upconverts low-frequency electromagnetic signals into the GHz range, where superconducting quantum technology is mature [1]. The most immediate science motivation is a search for interactions of axion dark matter at masses below 1 μeV, through the direct probe of coupling to electromagnetism (which is further developed in Task C), and to probe spin-coupling to axions (which is further developed in Task D). The sensors (Fig. 1a-b) will also be used in broader application of precision NMR and quantum spin metrology. In the initial phase of the project, we demonstrated quantum upconversion from signals at tens of kHz to 5.5 GHz (Fig.1c-d).

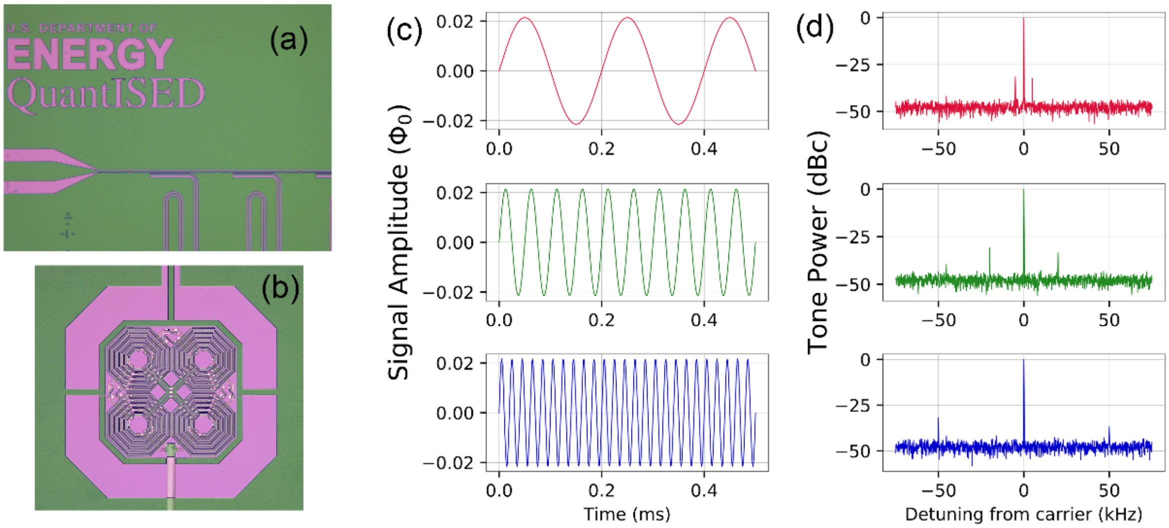


Fig. 1. (a-b) Photographs of a first-generation Radio-Frequency RF Upconverter lithographic design. (c) Oscilloscope time traces of input signals at 5 kHz (top), 20 kHz (middle), and 50 kHz (bottom). (d) Measurements of the power spectrum of the microwave output, showing the strong microwave carrier tone and the upconverted sidebands carrying the signal information.

In an important milestone towards the implementation of quantum backaction evasion, we have recently achieved phase-sensitive gain in upconversion with 29.6 dB of quadrature contrast (Fig. 2). We have developed infrastructure for RQUs based on both lithographic resonators and 3D cavities, and more advanced upconverter designs with 3 and 9 Josephson junctions for improved quantum performance.

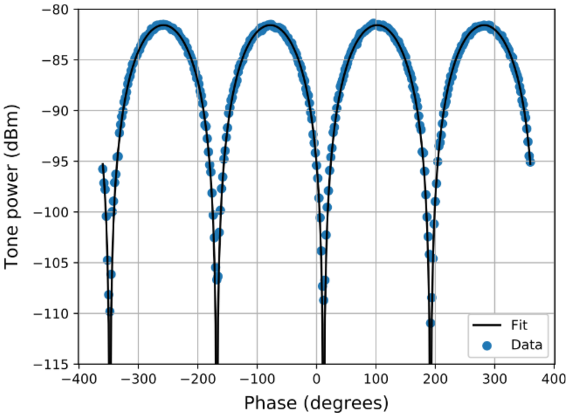


Fig. 2. Data showing phase sensitive gain at 50 kHz input. The maximum observed contrast between the gain for the X and Y quadratures is 29.6dB.

[1] Chaudhuri, Saptarshi. The Dark Matter Radio: A Quantum-enhanced Search for QCD Axion Dark Matter. Thesis, Stanford University, 2019.

[2] Rapidis, Nicholas, et al. "Electromagnetic sensing below the Standard Quantum Limit: 3 kHz to 300 MHz." Bulletin of the American Physical Society, 2021.

Task C: Fundamental discovery with quantum sensing of LC resonators

In Task C we develop, characterize, and implement a testbed for quantum measurement of high-Q LC resonators. This work will make use of quantum sensors including the RQUs developed in Task B. This testbed provides a test of these quantum sensors coupled to LC resonators at full size scales, with realistic inputs, in a context where quantum acceleration can be validated. This testbed will also be used as a platform to search for axions in the sub-μeV mass range, which can naturally be produced at the observed abundance of dark matter [1]. This mass range is particularly interesting because it covers all Peccei-Quinn breaking scales within a few orders of magnitude of the 'GUT' scale 10^{16} GeV.

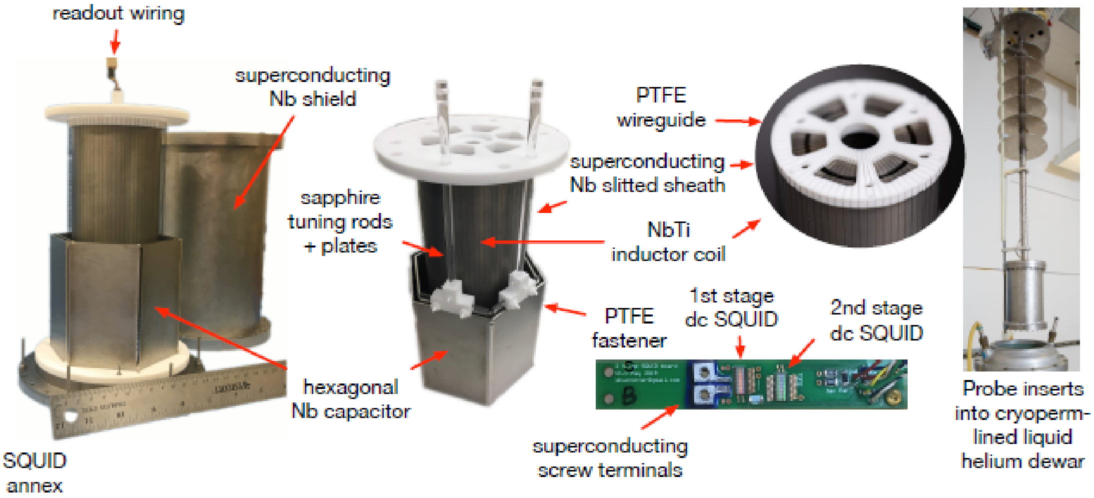


Fig. 1. The DM Radio Pathfinder detector. All components for the tuning assembly have been fabricated. Insertion of the sapphire dielectrics shifts the resonant frequency to within a few percent of the predicted value. Development of software to control the tuning system is mature and is currently being integrated into the complete data acquisition system. Implementation of automated scanning is proceeding.

The DM Radio Pathfinder detector (Fig. 1), which was developed in the Pilot phase of this project, has progressed to operational status. Over the period of the program we have increased the resonator Q from ~1,000 to 150,000. However, we have found that Q is now strongly determined by the bias point of the dc SQUID that we have used for DM Radio Pathfinder, indicating that we are limited by loss in the dissipative dc SQUID. We are now developing a larger quantum testbed at dilution refrigerator temperatures (see Fig. 2) that will achieve higher Q and greater sensitivity with the RQUs developed in Task B.

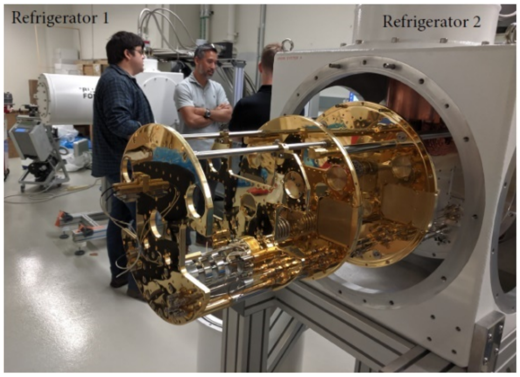


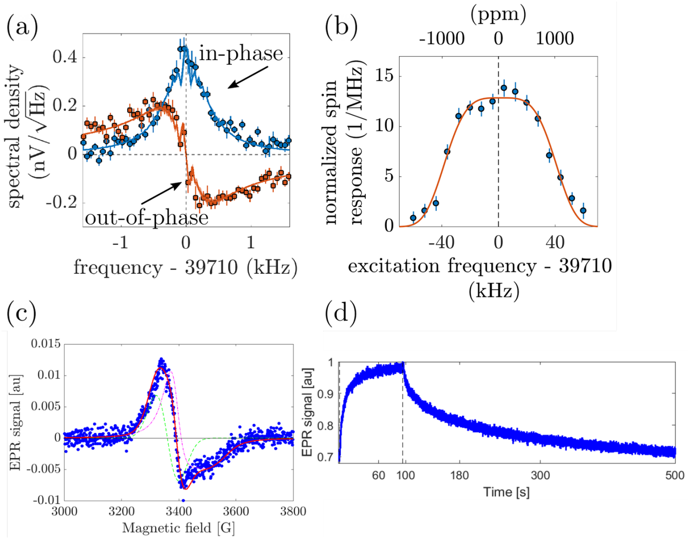
Fig. 2. The quantum testbed for Task C, operated in a BluFors dilution refrigerator.

[1] P.W. Graham and A. Scherlis. Stochastic axion scenario. Physical Review D, 98(3):035017, 2018.
[2] A. Phipps et al. *Exclusion limits on hidden-photon dark matter near 2 neV*. Microwave Cavities and Detectors for Axion Research. Springer, Cham, 2020. 139-145.

Task D: Fundamental Discovery with Magnetic Resonance and Spin Ensembles.

In this task we will focus on development of a diverse toolset for effective use of spin qubit ensembles for fundamental discovery research. The most immediate science motivation is a search for interactions of axion-like ultra-light dark matter with nuclear spins, using the technique of nuclear magnetic resonance (NMR) - an especially promising approach to searching for QCD axion dark matter in the kilohertz to megahertz frequency range [1,2,3]. More broadly, our work may find applications in the fields of precision NMR, quantum sensing, quantum information science, and quantum simulation.

In the pilot phase of the project we performed solid-state NMR measurements on solid ferroelectric PMN-PT and measured the NMR parameters of the ^{207}Pb nuclear spin ensemble, demonstrating spin ensemble coherence times of $T_2 = 17$ ms [4]. In addition, we have studied light-induced transient paramagnetic centers in this material, achieving number densities on the order of 10^{17} cm^{-3}. These achievements form the foundation for leveraging macroscopic ensembles of solid-state spin qubits for fundamental discovery.



(a) ^{207}Pb spin ensemble in PMN-PT: free induction decay frequency spectrum after a 20 ms excitation pulse at 39.71 MHz; both in-phase and out-of-phase quadratures are shown. (b) ^{207}Pb excitation spectrum. (c) EPR detection of light-induced paramagnetic centers in PMN-PT at 10 K. (d) Evolution of paramagnetic centers during and after light excitation at 405 nm.

We will optimize the sensing scheme used to detect the spin ensemble evolution, integrating DC SQUIDs and the SLAC-developed RQU sensors into our experiments and quantifying their noise performance. We will study the sensitivity scaling with spin ensemble size and investigate different materials and spin species, aiming to optimize sensitivity to new fundamental physics. In parallel, we will continue our spin ensemble engineering efforts, using the light-induced paramagnetic centers. Our ultimate goal is to reach the quantum sensitivity limits set by spin projection noise and investigate schemes that can potentially surpass these limits.

[1] M. Battaglieri, A. Belloni, A. Chou, et al. Us cosmic visions: New ideas in dark matter 2017: Community report. arXiv:1707.04591, 2017.

[2] Z. Ahmed, Y. Alexeev, G. Apollinari, et al. Quantum sensing for high energy physics. arXiv:1803.11306, 2018.

[3] Basic Research Needs for Dark-Matter Small Projects New Initiatives. https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf.

[4] Deniz Aybas, et al., “Search for axion-like dark matter using solid-state nuclear magnetic resonance”. arXiv:2101.01241 (2021).

Related Task: Emilio Nanni

Quantum transduction is the coherent manipulation of quantum states at the boundaries of quantum systems, and it lies at the heart of engineering these "systems" into networks, sensors or computers. Coherent transduction of quantum states between two different frequencies is an essential component of many emerging quantum information science (QIS) applications, as it provides an effective way for linking the classical and quantum world. The implementation of quantum sensing systems requires transduction from within microwave to optical wavelengths. In particular, a significant portion of the candidate dark matter spectrum spanning the μeV-eV range lacks techniques for processing or transducing quantum states, thereby greatly limiting the possible reach of quantum sensors.

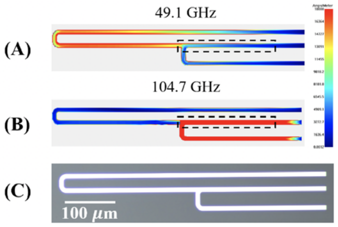


Fig. 1A, B. Normalized current density distribution for the 50 GHz mode (A) and 105 GHz mode (B), respectively. The color bar represents the magnitude of normalized current density: dark blue is 0, bright yellow is 1. The red features are simulation artefacts. **C.** Optical microscope image of the device. The bright areas are 200 nm thick Niobium film and the dark areas are C-plane Sapphire.

Driven by a kinetic inductance nonlinearity, we aim to use four-wave mixing to perform the transduction between one microwave photon and one mm-wave photon, by using two pump photons with frequency: $\omega_p = (\omega_{mm} - \omega_{\mu m})/2$. Our work showed a device that supports the millimeter-wave mode, and now we are developing devices that support resonances at multiple frequency. The first ones support the millimeter-wave mode (~105 GHz) and the pump-mode (~50 GHz).

The two-mode resonator design builds on our previous work, where we consider a thin-film Niobium superconducting device with a single resonance. We designed various geometries with a selection criteria among the geometries to maximize the normalized current distribution overlap normalized to total current. Figure 1 shows an example of a geometry with large overlap. Our next step was to characterize these devices in a 4 K cryostat. Figure 2 shows the experimental results from this structure showing a clear resonance at both frequencies. From these results we are redesigning both the measurement setup and the devices for improved performance as well as beginning to design the incorporation of the microwave resonator, Figure 3. Utilizing local fabrication facilities, we have developed fabrication processes for producing capacitors, inductors and resonators that are needed for our transducers.

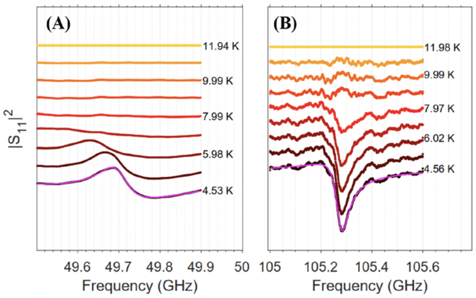


Fig. 2. Change in transmission normalized to 10 K, as a function of temperature (4.3 K – 10 K, bottom to top) for the low-frequency resonance (A) and the high frequency resonance (B).

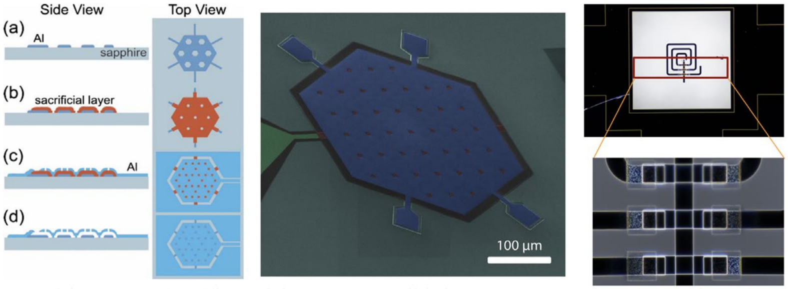


Figure 3: (left) Process and (middle) result for producing parallel-plate vacuum gap capacitor. (Right) Also applied to spiral inductors. These devices are optimized to make resonators at 5 GHz.

FY2021

1. Das, Debadri, et al. "Fabricating low loss, lumped element niobium resonators." Bulletin of the American Physical Society (2021).

FY2020

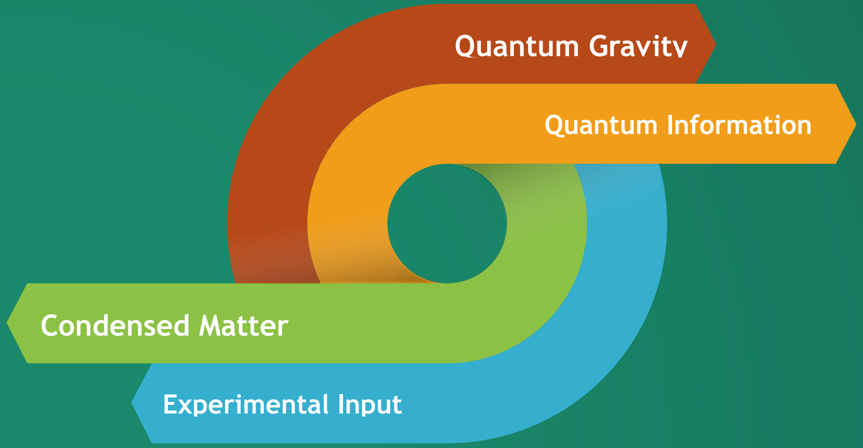
1. K. Multani, H. Stokowski, J. Witmer, W. Jiang, R. Patel, N. Lee, M. Pechal, E. Snively, P. B. Welander, E. A. Nanni, A. Safavi-Naeini, “Progress in Millimeter-Wave Based Quantum Networks,” IRMMW 2020
2. B. Kuchhal, E. Snively, K. Multani, H. Stokowski, D. Das, A. Safavi-Naeni, P. Welander, and E. A. Nanni, “Low-Loss THz Sommerfeld Mode on a Superconducting Niobium Wire for Millimeter-Wave Interconnects,” Accepted IRMMW 2020
3. Multani, K., Stokowski, H., Witmer, J., Jiang, W., Patel, R., Lee, N., Pechal, M., Snively, E., Welander, P., Nanni, E. A. and Safavi-Naeini, A., 2020. Towards the development of a microwave to millimeter-wave quantum frequency converter. Bulletin of the American Physical Society. M07.00012 2020
4. Kuchhal, B., Snively, E., Multani, K., Stokowski, H., Safavi-Naeini, A., Welander, P. and Nanni, E. A., “THz Sommerfeld Wave Propagation on Superconducting Niobium Wire for Millimeter-Wave Interconnects.” Bulletin of the American Physical Society C71.00278 2020

FY2019

1. Stokowski, Hubert, et al. "Towards Millimeter-Wave Based Quantum Networks." 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz). IEEE, 2019.

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

The GeoFlow Consortium has brought together a multidisciplinary, multi-institutional group of theorists and experimentalists to identify and develop emerging connections between key areas of quantum gravity and quantum information science. In particular, it investigates connections between the black hole information problem and quantum information scrambling, the emergence of spacetime from entanglement via quantum error correction codes and tensor networks, and the dynamics of wormholes as related to quantum teleportation. The consortium focuses on theoretical efforts that can be mapped onto new and available quantum machines for tests and benchmarking. It aims to qualitatively advance our understanding of quantum gravity and quantum information, to the point where the connections between the two can be probed experimentally, making use of existing experimental systems at Duke, Stanford, and LBNL.



Quarterly gatherings foster discussion and generate the seed of ideas for many projects. For summaries of previous meetings, check out https://sites.google.com/view/geoflow/home

Principal Investigators: Ehud Altman, Raphael Bousso (lead PI), Yasunori Nomura, Geoff Penington, Norman Yao, Mike Zaletel [UC Berkeley], Brian Swingle [Brandeis University], Chris Monroe [Duke University], Patrick Hayden, Monika Schleier-Smith, Xiao-Liang Qi [Stanford University]

Collaborators: Irfan Siddiqi [LBNL], Machiel Blok [University of Rochester], Ning Bao [Brookhaven]

Accomplishments

🟥 QG 🟧 QI 🟩 CM 🟦 EI

🟧🟩🟦	**Quantum Information Scrambling in a Qutrit Processor**	Observation of scrambling dynamics, relevant for studying the relation between chaos and black holes, in a qutrit processor.	M. S. Blok, V. V. Ramasesh, T. Schuster, K. O'Brien, J. M. Kreikebaum, D. Dahlen, A. Morvan, B. Yoshida, N. Y. Yao, and I. Siddiqi http://arxiv.org/abs/2003.03307 Published in PRX
🟥🟧🟩	**Many-Body Chaos in the Sachdev-Ye-Kitaev Model**	Numerical studies of a quantum mechanical system which exhibits quantum gravitational behavior at large system sizes.	B. Kobrin, Z, Yang, G. D. Kahanamoku-Meyer, C. T. Olund, J. E. Moore, D. Stanford, and N Y. Yao https://arxiv.org/abs/2002.05725, Published in PRL
🟥🟦	**Variational Preparation of SYK Thermofield Doubles**	Using variational methods on near term circuits to prepare states of interest for studying the AdS/CFT correspondence.	V.P. Su https://arxiv.org/abs/2009.04488, Submitted to PRX Quantum
🟩🟦	**Quantum Simulation of Confinement**	Realization of quantum simulation of confinement, a key phenomenon in nuclear and high energy physics.	W. L. Tan, P. Becker, F. Liu, G. Pagano, K. S. Collins, A. De, L. Feng, H. B. Kaplan, A. Kyprianidis, R. Lundgren, W. Morong, S. Whitsitt, A. V. Gorshkov, C. Monroe, https://arxiv.org/abs/1912.11117, Published in PRX
🟩🟦	**Integrable and Chaotic Dynamics of Spins Coupled to an Optical Cavity**	Investigated rich structure in experimental systems of atoms coupled to an optical cavity, which can realize all-to-all spin models, can be tuned to exhibit classical to quantum and from integrable and non-integrable behavior.	G. Bentsen, I. Potirniche, V. Bulchandani, T. Scaffidi, X. Cao, X. Qi, M. Schleier-Smith, E. Altman https://arxiv.org/abs/1904.10966, To appear in Nature Physics
🟥🟦	**Protocol for Measuring Operator Scrambling**	Found a new method to quantify operator scrambling, which can be implemented easily in generic quantum quench experiments.	XL Qi, E.J. Davis, A.Periwal, M.Schleier-Smith https://arxiv.org/pdf/1906.00524.pdf

Accomplishments

QG QI CM EI

🟥🟧	**Beyond toy models: distilling tensor networks in full AdS/CFT**	Invented a tensor network model for holography that reproduces well the boundary CFT state and showed how gravitational local physics in the bulk emerges from an information theoretic perspective.	N. Bao, G. Penington, J. Sorce, A. Wall https://arxiv.org/abs/1812.01171, Published in JHEP
🟥🟩	**Universal tripartite entanglement in one-dimensional many-body systems**	Obtained rigorous and numerical results on tripartite entanglement in many body systems, inspired by holography. These quantities may have implications on simulating 2+1D quantum systems with tensor networks.	Y. Zou, K. Siva, T. Soejima, R. Mong, M. Zaletel https://arxiv.org/abs/2011.11864, To appear in PRL
🟥🟧 🟦	**Quantum Gravity in the Lab: Teleportation by Size and Traversable wormholes**	Quantum gravity inspired experiments and new insights into boundary manifestations of traversable wormholes.	A. R. Brown, H. Gharibyan, S. Leichenauer, H. W. Lin, S. Nezami, G. Salton, L. Susskind, B. Swingle, M. Walter https://arxiv.org/abs/1911.06314, https://arxiv.org/abs/2102.01064
🟥🟧 🟩	**Many-body quantum teleportation via operator spreading in the traversable wormhole protocol**	Characterized the quantum mechanical mechanism for teleportation based on quantum gravitational protocols.	T. Schuster, B. Kobrin, P. Gao, I. Cong, E. T. Khabiboulline, N. M. Linke, M. D. Lukin, C. Monroe, B. Yoshida, N. Y. Yao https://arxiv.org/abs/2102.00010
🟥🟧 🟩	**Quantum Error Correction in Scrambling Dynamics and Measurement-Induced Phase Transition**	Identified the mechanism of the measurement induced entanglement transition in random unitary circuits.	S. Choi, Y. Bao, X. Qi, E. Altman https://arxiv.org/abs/1903.05124 Published in PRL

DOE QuantISED Consortium QCCFP-QMLQC

P.I.: Spiropulu, Maria
California Institute of Technology, Pasadena, California

Co-PI Daniel Jafferis Harvard University

Co-PI Daniel Lidar University of Southern California

Abstract

The proposed program has two major thrusts:
A. Quantum Communication Channels for Fundamental Physics (QCCFP)

We characterize, in quantum information theoretic terms, the distinctly gravitational features of teleportation through a wormhole and finding concrete quantum circuits that realize Hamiltonian systems known to exhibit wormhole teleportation, such as the SYK model. We benchmark quantum circuits in multiple platforms by checking success of teleportation protocols inspired by traversable wormholes involving circuits that result in effectively fully scrambled unitarities on small numbers of qubits. The work is in collaboration with Harvard University and with FNAL. Prior work in this area have yielded important advances for quantum teleportation https://doi.org/10.1103/PRXQuantum.1.020317

B. Quantum Machine Learning and Quantum Computing (QMLQC)

We develop and adapt quantum machine learning algorithms targeting quantum annealers and near-future NISQ-era quantum computers. We apply the developed algorithms to HEP science challenges and benchmark their performance. Important prior work in this are was published in Nature https://doi.org/10.1038/nature24047 and current improvements are published in https://doi.org/10.1103/PhysRevA.102.062405. We further develop and implement online tool suites for the study and application of algorithms utilizing near-term quantum devices as well as conceptual designs and architectures of such workflows and frameworks for use in HEP.

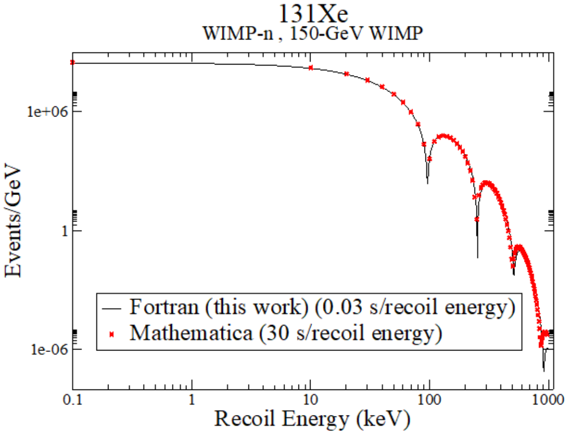
Detection of dark matter and neutrinos enhanced through quantum information

A.B. Balantekin[1](P.I.), S.N. Coppersmith[1,4], C. Johnson[2], P. Love[3], K. Palladino[5], and M. Saffman[1]

[1] University of Wisconsin, Madison
[2] San Diego State University
[3] Tufts University
[4] University of New South Wales
[5] Oxford University

The aim of this interdisciplinary project is to use a quantum simulator to calculate the detector response to dark matter particles and neutrinos. The simulator to be used is an array of 121 neutral atom qubits that is being developed at UW-Madison. This project requires a breadth of expertise, so the team brings together experts on 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. One of the goals is to understand and mitigate errors in the behavior of the quantum simulator so that high accuracy and precision calculations can be performed. Although the primary goal of this project is to apply lessons from the quantum information theory in high energy physics, a secondary goal is to contribute to the development of quantum information theory itself.

We have made significant progress since last summer. To address when quantum computers can outperform classical computers for target characterization, it is critical to perform uncertainty quantification. To start addressing this key task for quantum computation of models relevant to nuclear targets, we explored a simplified model of the many-body targets, calculating its ground state using variational quantum algorithm (VQE) on the International Business Machines Corporation (IBM) Quantum Experience, a publicly available quantum computer, and identifying main sources of computational errors. Energy of variational state as a function of the VQE trial parameter θ is shown in Figure 1 where the results obtained using the IBM Melbourne processor are compared to the exact result as well as to the results of classical simulations of the quantum processor that incorporate several error mechanisms.[1]



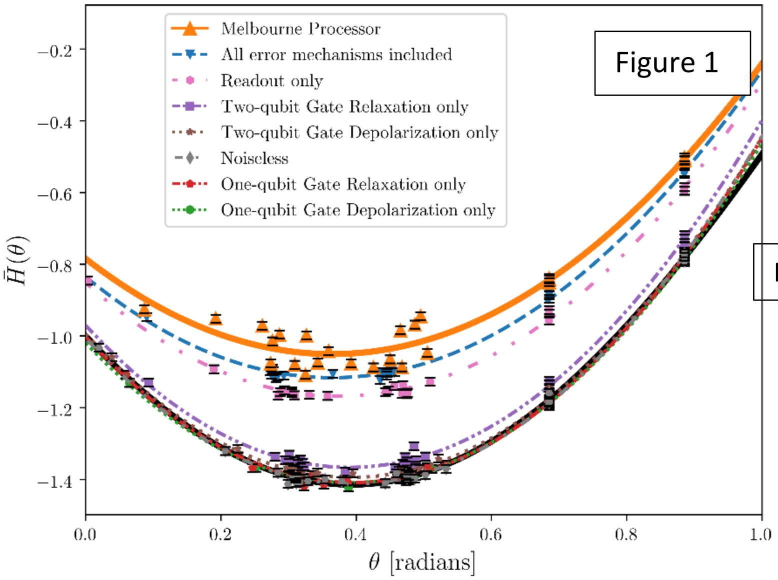


Figure 1

Figure 2

Of course our goal is to use the neutral atom quantum processor at Madison. Work continues to develop the neutral atom system. Laser focusing limits to Rydberg gate fidelity were explored.[2] The current hardware has gate times much shorter than coherence times, but is performance limited by the two-qubit gate error. Figure 2 shows results for a 3-qubit VQE circuit at the Madison processor that ideally prepares the exact ground state of the simplified model of the many-body targets used in the above analysis.

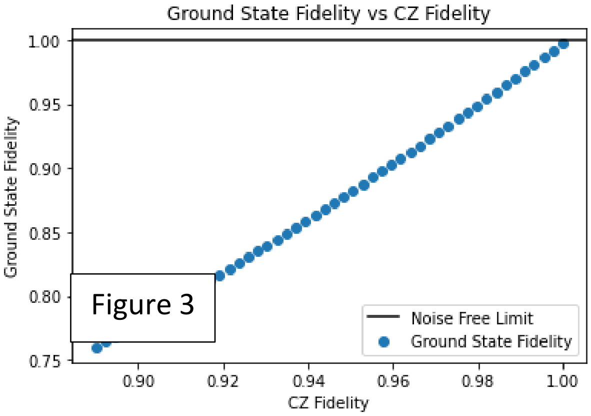


Figure 3

We have also written a fast Fortran code to read in density matrices from nuclear structure calculations, such as a shell-model code, and compute the dark-matter scattering cross-section. This Fortran code runs hundreds of times faster than typically used Mathematica script as illustrated in Figure 3 and comes with Python wrappers to allow for ease of use. This software package will allow researchers to efficiently scan through the space of dark matter coupling constants and, importantly, allow one to do careful uncertainty quantification. This software will be released as free and open source, and we will soon submit the code, a manual, and an accompanying paper for publication.[3] We believe this software package will be of use and interest to the broader dark matter community, both theorists and experimentalists, and as part of our development we have consulted with experimentalists to make sure our product is both useful and relatively easy to use. We plan to carry out our own uncertainty quantification studies using results from classical computers, in preparation for later simulations with quantum circuits.

1. M.J. Cervia, A.B. Balantekin, S.N. Coppersmith, C.W. Johnson, P.J. Love, C. Poole, K. Robbins, M. Saffman, arXiv: 2011.04097 [hep-th].
2. F. Robicheaux, T.M. Graham, and M. Saffman, arXiv:2011.09639 [quant-ph].
3. O.C. Gorton, C. Jiao, and C. W. Johnson, in preparation.

Programmable quantum simulators for lattice gauge theories and gauge-gravity correspondence

P.I.: Lukin, Mikhail Co-PI: Daniel Jafferis

Institution: President and Fellows of Harvard College, Cambridge, Massachusetts

After decades of experimental and theoretical efforts, the field of quantum information science is now at an important junction: quantum computers and simulators are beginning to reach a scale where simulation by classical devices is no longer possible. While these quantum devices are still too noisy to beat classical supercomputers at tasks like prime number factorization, quantum simulations with neutral atoms are reaching domains in which they are believed to have a useful "quantum advantage" over simulations on classical devices. We propose to use a Rydberg quantum simulator to gain critical insights into outstanding problems at the interface of many-body quantum physics and high energy physics.

The focus of the proposed work involves quantum simulation of Lattice Gauge Theories (LGT) and quantum scrambling in quantum gravity models. Specifically, we will use the platform of programmable quantum simulators based on Rydberg atoms in configurable tweezer arrays to carry out quantum simulations of LGTs in one and two spatial dimensions and to perform first quantum simulation of the quantum many-body analog of a traversable wormhole. Our goal is to use large-scale atom-based quantum systems to experimentally create complex models of various forms, study their quantum dynamics and to use advanced quantum information and hybrid quantum/classical concepts to directly probe the entanglement defining such many-body states. This way we should be able to uncover the nature of quantum effects in regimes that are not computationally accessible on classical computers, and with quantum information tools, such as atom-by-atom access and control. Solving these currently intractable problems is the focus of the proposed work. Finally, we will to use these new insights from gauge-gravity correspondence to devise theoretically and test experimentally novel approaches to robust quantum information encoding and protection.

Foundations of Quantum Computing for Gauge Theories and Quantum Gravity

Award Number: DE-SC0019139

PI: Y. Meurice, U. Iowa; Co-PI's: A. Bazavov, MSU; D. Berenstein UCSB; R. Brower, BU;
S. Catterall, Syracuse U.; X. Dong, UCSB; S. Jordan, U. Maryland/Microsoft

The collaboration develops step by step the building blocks of quantum computing for problems in high energy physics that are beyond the reach of classical computing:

- real time evolution and calculations with sign problems in lattice gauge theory,
- holographic approaches to strongly coupled systems.

The scientists involved come from three different communities (see Subtasks below)

- lattice gauge theory (U. Iowa, MSU, Syracuse U., BU)
- quantum gravity (UCSB, Syracuse U., BU)
- quantum information (U. Maryland)

The collaboration designs algorithms which scale efficiently with the size of the system starting with models in low dimensions and moving up in dimensions and symmetries as we progress. The long term goal is the development of scalable quantum codes in four space-time dimensions relevant to the real-time evolution of hadrons in collider experiments (jet physics), and new models in quantum gravity. The methods involve tensorial and quantum link formulations of lattice field theory models relevant to high energy physics.

Part of the research is conducted with cold atoms and trapped ion experimentalists from Harvard, U. Maryland and the MPQ in Garching to setup quantum simulations experiments focused on the real-time evolution, critical and out-of-equilibrium behaviors of lattice gauge theory models. The collaboration uses and benchmarks current NISQ machines involving IBM, Rigetti and Honeywell.

Subtasks:

U. Iowa (Y. Meurice): Real time evolution with NISQ machines and Rydberg atoms, benchmarking, phase shifts, tensor methods, truncations effects, noise robust implementation of Gauss's law, and state preparation with projective methods.

U. Maryland (S. Jordan): State preparation algorithms for NISQ machines and fault tolerant quantum computers. Error-resilient variational methods for preparing ground states of conformal field theories.

Syracuse U. (S. Catterall): New formulations of lattice field theories suitable for quantum computation and exploration of quantum information theoretic aspects of theories with relativistic fermions and gravity.

UCSB (D. Berenstein, X. Dong): Entanglement entropy and equilibration in model systems such as CNOT gate lattices from various initial conditions. Set up for gauged quantum dynamic codes for Yang Mills on systems on qubits (with BU).
BU (R. Brower): Development of quantum link fermionic to Qubit algebras for flat, deSitter and Anti-de-Sitter manifolds, focusing on unitary fields for matrix models, spin chains and gauge theories. Efficiency of alternative Qubit representations (with UCSB).
MSU (A. Bazavov): Effects of truncations, study of clock models with fractional number of states and their possible relation to analog quantum simulations with Rydberg atoms (with U. Iowa).

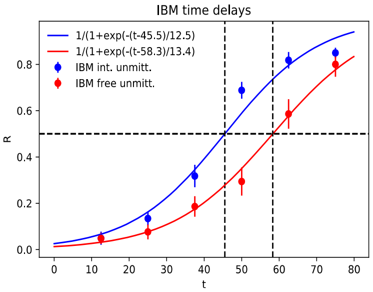
Recent accomplishments:
In 2020, the collaboration has completed work on state preparation by projective methods, the quantum joule expansion, the tensor formulations of the Schwinger model and two-dimensional gravity, boundary correlation functions on MERA-like networks corresponding to tessellations of hyperbolic space, site-by-site quantum state preparation algorithm for fermionic lattice field theories, benchmarking of IBMQ computers for real-time evolution, lattice setup for quantum field theory in AdS2, chiral fermions and equilibration dynamics on a 1-D quantum CNOT gate lattice. This resulted in preprints which have been published or are under review as listed below. A book on quantum field theory and quantum computation has been published as well as a large review article on tensor field theory for quantum computing submitted to Reviews of Modern Physics. Work close to be completed is listed at the end.
As a general trend, the collaboration is transitioning from 1+1 dimensions to 2+1 dimensions.

E. Gustafson, Projective cooling for the transverse Ising model, Phys. Rev. D 101, 071504 (2020).
Jin Zhang, Y. Meurice, and S. -W. Tsai, Quantum Joule Expansion of One-Dimensional Systems, Phys. Rev. A 101, 033608 (2020).
N. Butt, S. Catterall, Y. Meurice, Ryo Sakai, J. Unmuth-Yockey, Tensor network formulation of the massless Schwinger model with staggered fermions, Phys. Rev. D 101, 094509 (2020).
Y. Meurice, Discrete aspects of continuous symmetries in the tensorial formulation of Abelian gauge theories, Phys. Rev. D 102, 014506 (2020).
M. Asaduzzaman, S. Catterall, J. Hubisz, R. Nelson, and J. Unmuth-Yockey, Holography on tessellations of hyperbolic space, Phys. Rev. D.102, 034511 (2020).
M. Asaduzzaman, S. Catterall, and J. Unmuth-Yockey, Tensor network formulation of two dimensional gravity, Phys. Rev. D 102, 054510 (2020).
Y. Meurice, Quantum field theory: a quantum computation approach, 248 pages, Institute of Physics Publishing, Bristol, book in press.
Y. Meurice, Ryo Sakai, and J. Unmuth-Yockey, Tensor field theory with applications to quantum computing, 69 pages, arXiv: 2010.06539, submitted to "Reviews of Modern Physics", under revision.
E. Gustafson, P. Dreher, Zheyue Hang, and Y. Meurice, Benchmarking quantum computers for real-time evolution of a (1+1) field theory with error mitigation, arXiv:1910.09478, under revision.
A. Moosavian, J. Garrison, and S. Jordan, Site-by-site quantum state preparation algorithm for preparing vacua of fermionic lattice field theories, arXiv:1911.03505.

R. Brower, C. Cogburn, A. Fitzpatrick, D. Howarth, C.-I Tan, Lattice Setup for Quantum Field Theory in AdS2, arXiv:1912.07606.
S. Catterall, Chiral Lattice Theories From Staggered Fermions, arXiv:2010.02290.
E. Gustafson and H. Lamm, Toward Quantum Simulations of Z_2 Gauge Theory Without State Preparation, arXiv:2011.11677.
David Berenstein, Jiayao Zhao, Exotic equilibration dynamics on a 1-D quantum CNOT gate lattice, arXiv:2102.05745.

Work close to completion: measurements of phase shifts with IBM and trapped ion machines (U. Iowa); runs on Honeywell H0 quantum computer to evaluate MERA-based quantum algorithms for conformal field theories vacuum preparation (U. Maryland); preparation of vacuum states of more general quantum field theories on fault-tolerant machines by adding lattice sites one by one (U. Maryland); error mitigation methods for U(1) gauge theory with IBM Q (BU); continuum limit of U(1) Quibits (BU and UCSB); unitary matrix quantum mechanics from gauged fermions (BU and UCSB); extending Hyperbolic 2d Lattice to AdS3 for a Quantum Evolution Gravity to CFT dynamics (BU); critical properties of the clock models with fractional number of states (MSU and U. Iowa); effects of truncations on phase transitions (U. Iowa).

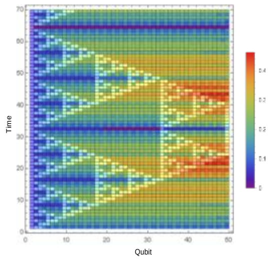
Picture Gallery:



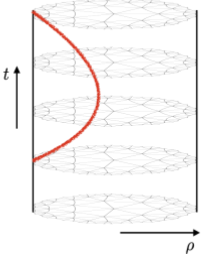
Phase shifts from time delay with IBMQ (U. Iowa)

Overlap after adding one site (U. Md.)

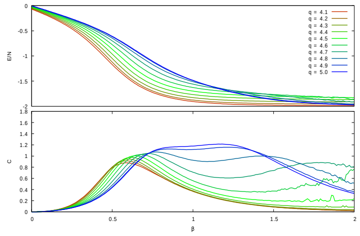
Cubes in the {4, 3, 5} honeycomb PhysRevD.102.034511 (Syr. U.)



Entanglement entropy for a quantum circuit of CNOT gates (UCSB) https://arxiv.org/abs/2102.05745



Temporal propagator for the AdS3 Hamiltonian (BU)



E and C_V for fractional clock models between 4 and 5. (MSU)