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
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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
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Quantum Sensors for Light-field Dark Matter Searches
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Quantum system engineering for a next-generation search for axion dark matter
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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

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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

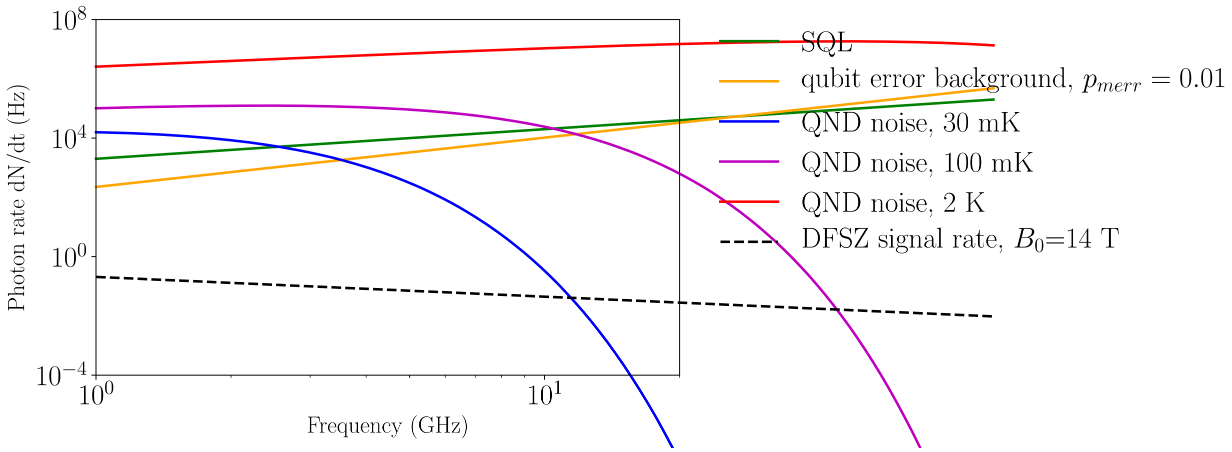
Daniel Bowring
Fermi National Accelerator Laboratory

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.



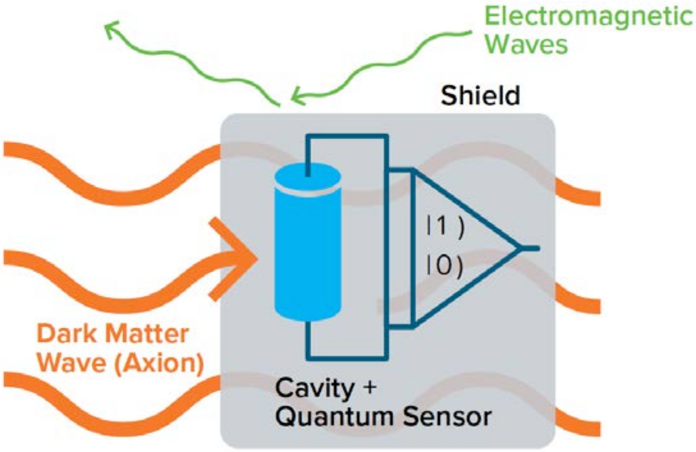
Quantum Metrology for Axion Dark Matter Detection

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

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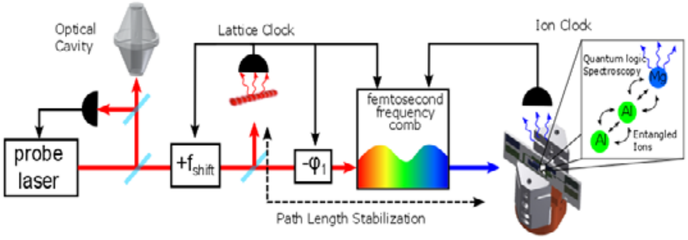
We plan to use quantum information techniques for precision measurements with trapped laser-cooled ions. These measurements will test the foundations of the standard model in two ways:

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 ^{9}Be^{+} 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.

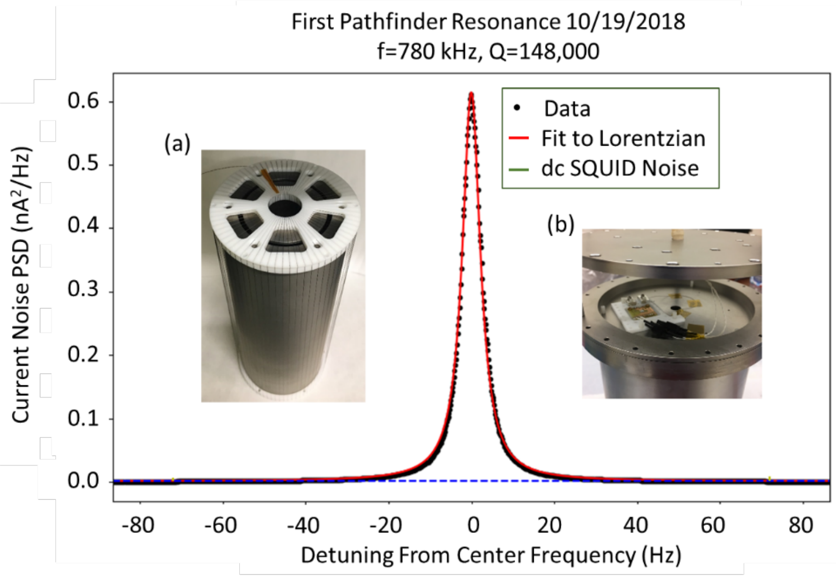


Fig. 1. The first cooldown of the DM Radio Pathfinder. Successful resonant operation is demonstrated with a lumped-element inductor (shown in subfigure (a)) and a tunable capacitor (not shown). The detector response is measured by with a dc SQUID designed by the proposal team (show in the quantum-sensor 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).

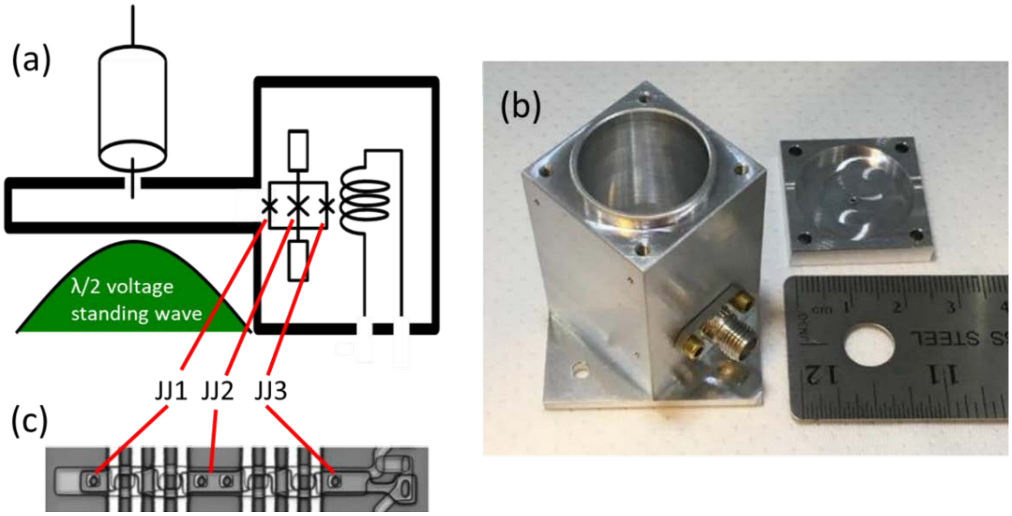


Fig. 1. The Zappe photon upconverter. (a) A schematic of the 3D microwave cavity and the Zappe interferometer coupling to the Compton frequency signal flowing through the inductor. The 3 Josephson junctions in the Zappe interferometer are labeled JJ1, JJ2, and JJ3. (b) A photograph of a prototype microwave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

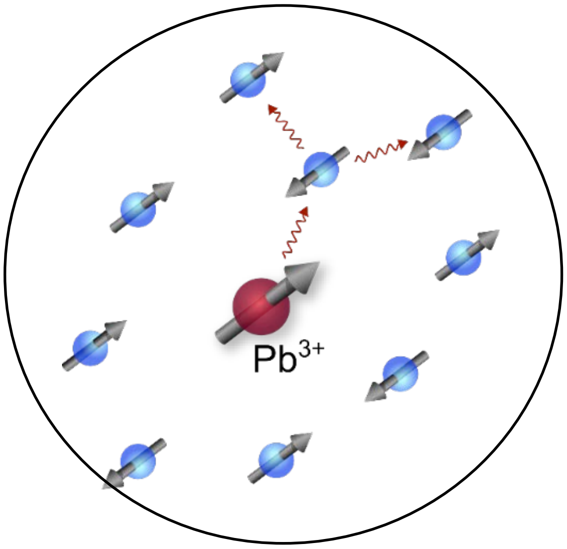


Figure 1 (color): Expected signal rate (photons per second) for the DFSZ family of axion models (black dashed line), compared with noise/error rates for phase-preserving linear amplifiers operating at the standard quantum limit (SQL, green), and for quantum nondemolition (QND, blue/purple/red) measurements 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.