Quantum Sensors Informational Session

IF1: Quantum Sensors
8/19/20

https://indico.fnal.gov/event/44940/

Who we are

- Tom Cecil
    - Argonne National Laboratory
    - SPT, CMB S4
- Kent Irwin
    - Stanford University/SLAC
    - Axions / DM Radio, CMB-S4, legacy in SuperCDMS, x-ray spectroscopy, submm imaging
- Reina Maruyama
    - Yale University
    - Axions, double beta decay, WIMPs (HAYSTAC, CUORE, COSINE-100)
- Matt Pyle
    - UC Berkeley
    - 100meV-10GeV Dark Matter Direct Detection: (SPICE, HERALD, SuperCDMS)

Quantum Sensors in Context

Quantum sensors instrumentation has close connection with:

- IF2: Instrumentation Frontier, photon detectors
- IF7: Electronics/ASICs subgroup
- CF1: Cosmic Frontier, Dark Matter particle-like
- CF2: Cosmic Frontier, Dark Matter wave-like
- AF5: Accelerator for PBC and Rare Processes

Important to make sure that interfaces are well defined, and nothing is “dropped in the cracks.” Submit creative LOIs, even if they don’t fit neat categories.

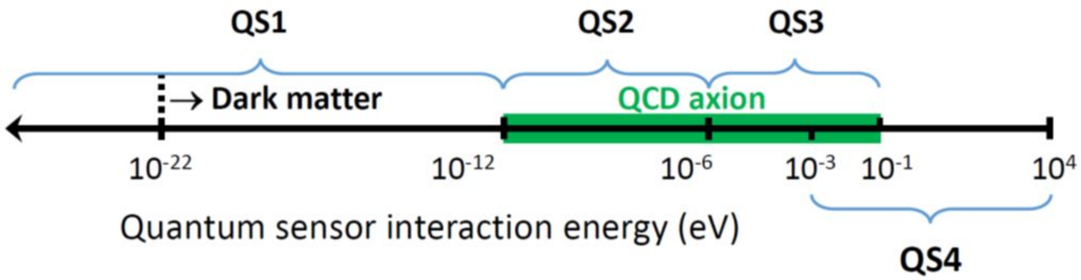
This is an emerging technology area - and connections to other frontiers will emerge.

Liaison with Cosmic Frontier: Kent Irwin, Hugh Lippincott

Quantum Sensors and Snowmass Science

- Ultralight wavelike dark matter (generalized axions, hidden photons, scalars)
- Scattering / absorption of dark matter particles
- Electric dipole moment measurements (electron, nuclear, neutron)
- Gravitational waves
- Dark energy
- Violations of fundamental symmetries
- New forces and particles

Quantum Sensors by Interaction Energy

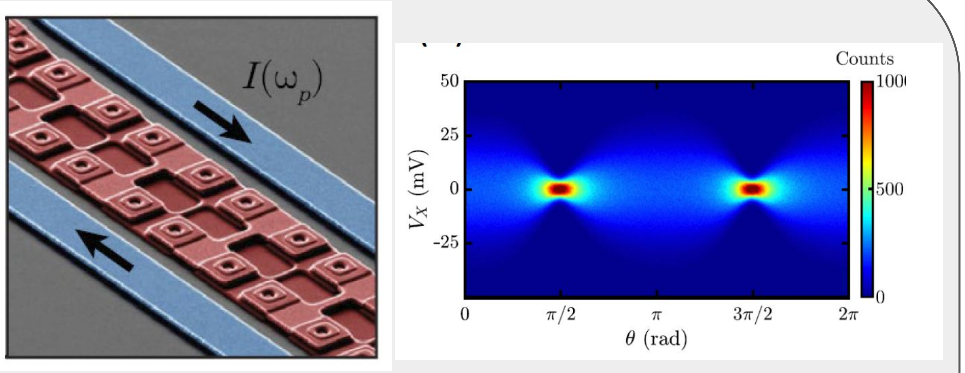


- QS1 (0 eV - 1 peV) - wavelike interactions
  - Atomic & molecular spectroscopy, atom interferometers and mechanical sensors, clocks, atomic magnetometers, spins, quantum defects in solids
- QS2 (1 peV - 1 microeV) - wavelike interactions
  - Nuclear, electronic, and other spins, electromagnetic quantum sensors, optical cavities, quantum defects in solids
- QS3 (1 microeV - 0.1 eV) - wavelike interactions
  - Superconducting qubits / sensors, spins, Rydberg atoms, quantum defects in solids
- QS4 (1 meV - 10 keV) - particle-like interactions
  - Low threshhold phonon and charge detectors, quantum defects in solids, single-photon counters (SNSPD, APD, ...) - interface to IF2: Photon detectors, depending on application

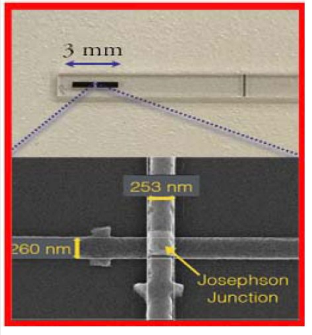
Quantum Sensors by Technology

- Superconducting sensors
  - Operation above and below the Standard Quantum Limit: squeezing, backaction evasion, entanglement, superposition, QND photon counting
  - Qubit-based, quantum upconverters, parametric amplifiers, pair-breaking photon counters
- Quantum ensembles
  - Operation above and below the SQL: superposition, entanglement, squeezing
  - NMR of spin-based sensors, atomic clocks and interferometers, electric dipole moment searches, Rydberg atoms
- Low threshhold quantum calorimeters
  - Detection of low-energy scattering events in ionization, phonons, scintillation
  - Transition-edge sensors, MKIDs, liquid helium, quantum defects
- Related technology, facilities, infrastructure
  - High-Q cavities, magnets, cryogenics, electronics, computing

Superconducting Quantum Sensors



Example 1: Josephson Parametric Amplifier for the HAYSTAC axion search (left). Squeezing achieved in the HAYSTAC experiment (right) (Malnou et al., DOI:10.1103/PhysRevX.9.021023)

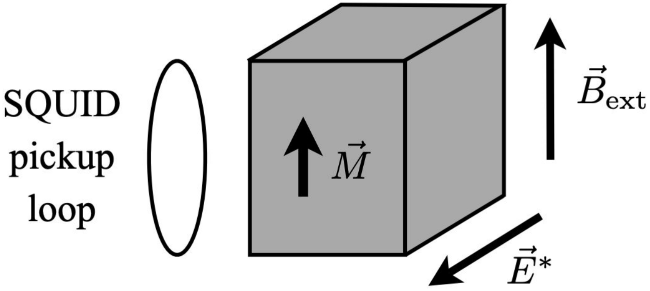


Example 2: Superconducting qubit used as a single microwave photon detector.
Figure credit: D.Schuster, UChicago

- Amplification of coherent signals at the Standard Quantum Limit
- SQL evasion with squeezing, backaction evasion, QND photon counting, and entanglement
- Qubits, quantum upconverters, parametric amplifiers, pair-breaking detectors, ...

Quantum ensembles

- Sensor Examples
  - Solid state spins - Quantum defects, NMR and NV center ensembles
  - Atomic and molecular spectroscopy
  - Atomic vapors - optical magnetometers, clocks, neutral atom interferometers
- Application examples
  - Search for axion dark matter via nucleon EDM using solid-state NMR (1306.6089)
  - Spin coupling to axion-like fields using optical magnetometers (1303.5524)
  - Light-pulse atom interferometry to search for dark matter and gravitational waves (1812.00482)

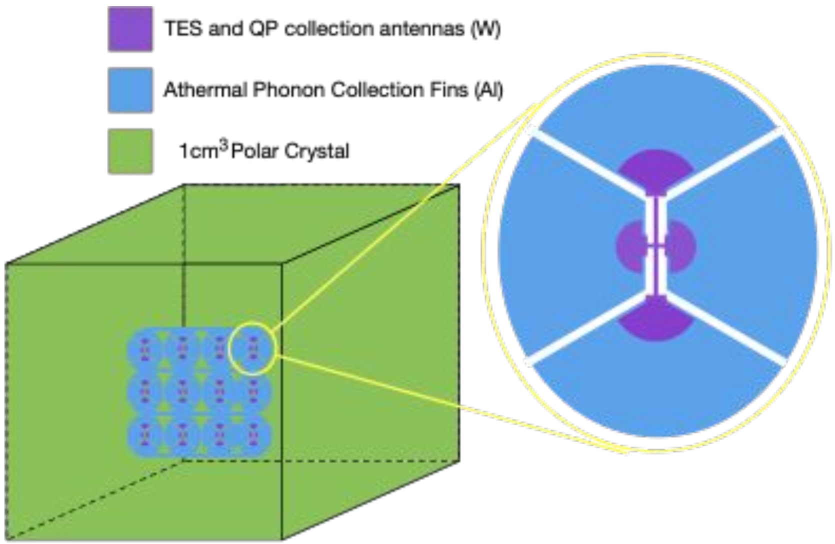


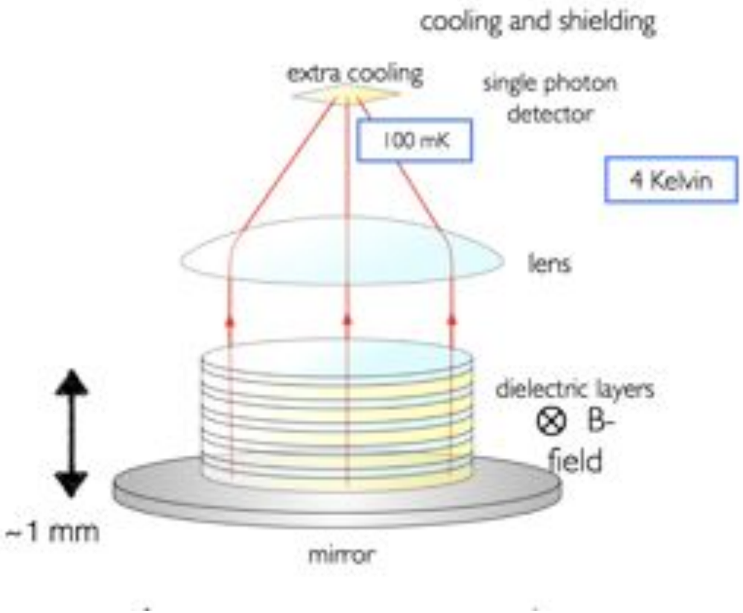
CASPEr: 1306.6089

Particle Interaction with meV-eV energy depositions

Example #1: keV-100MeV Dark Matter interacting with a crystal producing a single optical phonon of O(100meV) 1712.06598

TES, MKIDs, quantum capacitance detector





Example #2: 1meV - 1eV Dark Photon search with optical haloscope 1803.11455

SNSPDs, TES, MKIDs, quantum capacitance detector

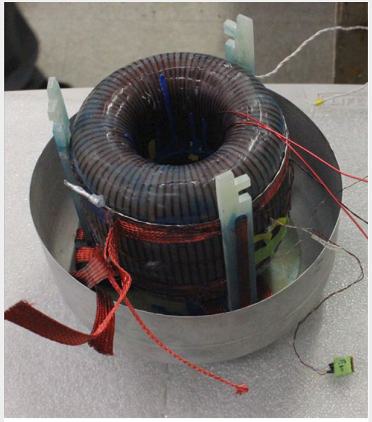
Related Technology, Infrastructure, Facilities

We also need to capture investments needed in related areas. Examples:

High-Q cavities

Figure: Dark SRF Nb cavity

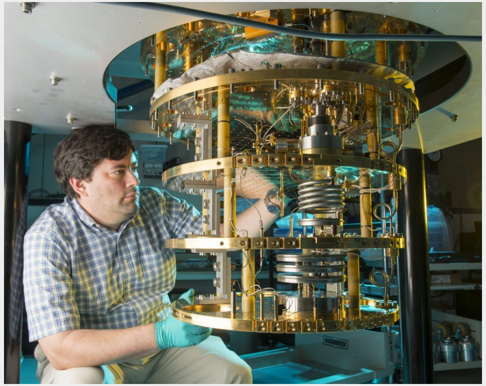
Image credit: A. Grasselino, FNAL



Magnets

Figure: ABRA-10cm magnet

Image credit: L. Winslow, MIT



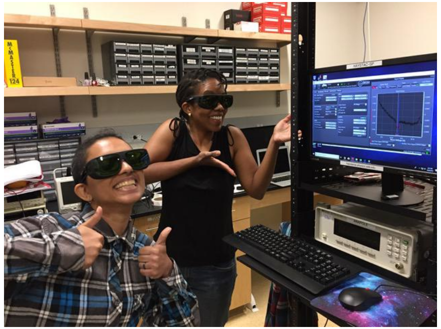
Cryogenics

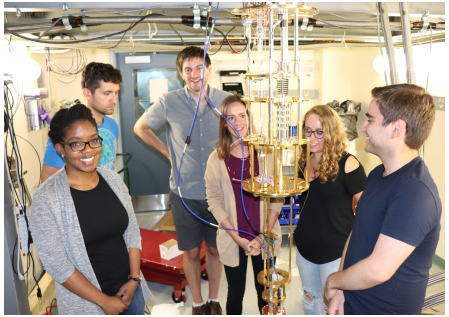
Figure: SuperCDMS refrigerator

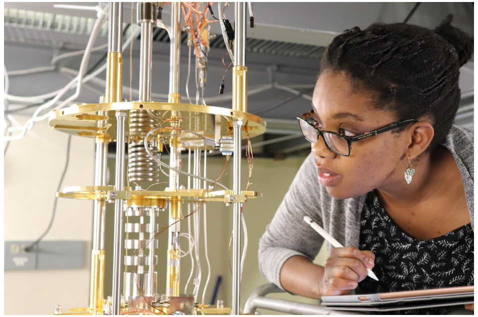
Image credit: Reidar Hahn, FNAL

Training the Quantum Workforce

- Fundamental to the success of the field
- Build on current success
  - 2019 Tanaka Dissertation Award (Ben Brubaker)
  - Student and postdoc placement and retention
  - Investment for University, National Lab, and Industry workforce







Related Studies

- Jan 2015: ASCR-HEP Study Group on “Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing”
- Feb 2015: BES-HEP Round Table Discussion on “Common Problems in Condensed Matter and High Energy Physics”
- Feb 2016: HEP-ASCR Roundtable on “Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science and Computing”
  - https://science.osti.gov/-/media/hep/pdf/Reports/DOE_Quantum_Sensors_Report.pdf?la=en&hash=B2378FA2253DF340A218D6B37C44293403389C59
- Dec 2017: First Workshop on Quantum Sensing for High Energy Physics
  - https://arxiv.org/abs/1803.11306
- Dec 2018: CPAD Report - New Technologies for Discovery
  - https://arxiv.org/abs/1908.00194
- Coming soon: Basic Research Needs - HEP Detectors

Related Investments

National Quantum Initiative

- Will “establish the goals, priorities, and metrics for a 10- year plan to accelerate development of quantum information science and technology applications in the United States”
- Establish 2 to 5 Quantum Centers (up to $10M/NSF center and $25M/DOE center)
- Coordinate research efforts funded through existing programs

DOE HEP-QIS Program QuantISED (Quantum Information Science Enabled Discovery)

- Part of national QIS effort
- HEP Awards of ~ $30M (over 3 years)

Similar efforts from NSF

Conclusions

Submit your LOIs - including those that are “out of the box.” This is a new field.

Contact Information:

- Mailing list: SNOWMASS-IF-01-QUANTUM-SENSORS@FNAL.GOV
- Slack channel: #if01-quantum_sensors
- Webpage: https://snowmass21.org/instrumentation/quantum_sensors