IF1: Quantum Sensors

Instrumentation Frontier White Paper Meeting
11/19/21

IF01 Convenors

- 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 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 in Context

Quantum sensors instrumentation has close connection with:

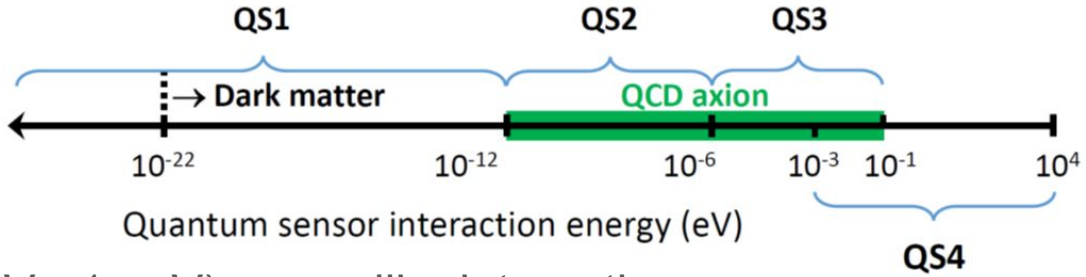
- IF2: Instrumentation Frontier, photon detectors
- IF7: Electronics/ASICs subgroup
- CF1: Cosmic Frontier, Dark Matter particle-like
- CF2: Cosmic Frontier, Dark Matter wave-like
- AF5: Accelerator for PBC and Rare Processes

Important to make sure that interfaces are well defined, and nothing is “dropped in the cracks.”

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

Liaison with Cosmic Frontier: Kent Irwin, Hugh Lippincott

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
- See Basic Research Needs for HEP Detectors report for more details

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

IF01 Community White Papers

- Received 74 LOIs tagged with IF01
- Grouped LOIs into 4 groups
  - Superconducting Sensors
  - Quantum Calorimeters
  - AMO: Spins, NMR, and Defects
  - Interferometers, Clocks, and Traps
- Each community white paper will be guided by a writing committee
  - All are invited and encouraged to contribute

Superconducting sensors

- Convenor: Kent Irwin
- Writing committee:
- LOIs
  - Nr 25: Direct Deflection of Dark Matter (CF/SNOWMASS21-CF1_CF2-TF9_TF10-IF1_IF0_Asher_Berlin-049.pdf)
  - Nr 29: UP-conversion Loop Oscillator Axion Detectors (UPLOAD) (CF/SNOWMASS21-CF2_CF0-IF0_IF1_UPLOAD-067.pdf)
  - Nr 32: Probing the QCD Axion with DMRadio-m3 (CF/SNOWMASS21-CF2_CF0-IF1_IF0_Ouellet-217.pdf)
  - Nr 33: HAYSTAC – Pioneering the Quantum Frontier (CF/SNOWMASS21-CF2_CF0-IF1_IF0_Reina_Maruyama-068.pdf)
  - Nr 34: DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter (CF/SNOWMASS21-CF2_CF0-IF1_IF0_Saptarshi_Chaudhuri-219.pdf)
  - Nr 38: The Oscillating Resonant Group AxioN (ORGAN) Experiment (CF/SNOWMASS21-CF2_CF0-IF1_IF2_ORGAN-095.pdf)
  - Nr 39: Frequency Multiplexed Dark Matter Axion Searches (CF/SNOWMASS21-CF2_CF0-IF1_IF9_Gianpaolo_Carosi-252.pdf)
  - Nr 43: Augmenting Axion Haloscopes With 3 Light-Shining-Through-Walls Experiments (CF/SNOWMASS21-CF2_CF0-RF3_RF0-IF1_IF0_Woollett-220.pdf)
  - Nr 103: Radio Frequency Quantum Upconverters:Precision Metrology for Fundamental Physics (IF/SNOWMASS21-IF1_IF0-CF2_CF0-193.pdf)
  - Nr 105: Tunable Quality Factor Resonators for High Energy Applications (IF/SNOWMASS21-IF1_IF0-CF3_CF0_Rosen-167.pdf)
  - Nr 113: Improved DC SQUIDs (IF/SNOWMASS21-IF1_IF0_Terrano-088.pdf)
  - Nr 116: Transduction for New Regimes in Quantum Sensing (IF/SNOWMASS21-IF1_IF2-AF5_AF7_Nanni-162.pdf)

Superconducting sensors cont.

- Convenor: Kent Irwin
- Writing committee:
- LOIs
  - Nr 121: Superconducting Qubit Advantage for Dark Matter (IF/SNOWMASS21-IF1_IF2-CF2_CF0_Ankur_Agrawal-149.pdf)
  - Nr 124: Coupling Experiment and Simulation to Model (IF/SNOWMASS21-IF1_IF9-CF1_CF2-UF2_UF5-124.pdf)
  - Nr 125: Topological Microwave Circulators for HEP (IF/SNOWMASS21-IF1_IF9-CF2_CF0_Gianpaolo_Carosi-137.pdf)
  - Nr 31: Resonant vs. Broadband Axion Dark Matter Searches in the Background-free Limit – an amicus brief for Snowmass CF2 - IF1 (CF/SNOWMASS21-CF2_CF0-IF1_IF0_Aaron_Chou-175.pdf)
  - Nr 110: Operational definition of quantum sensors (IF/SNOWMASS21-IF1_IF0_Garcia-Sciveres-014.pdf)

Quantum Calorimeters

- Convenor: Matt Pyle
- Writing committee:
- LOIs
  - Nr 20: The TESSERACT Dark Matter Project (CF/SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf)
  - Nr 23: A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS Snolab Facility (CF/SNOWMASS21-CF1_CF2-NF3_NF10-IF1_IF0-UF3_UF2_SuperCDMS-077.pdf)
  - Nr 44: Hidden Orders in Quantum Matter and Dark Matter Detection (CF/SNOWMASS21-CF2_CF0-TF10_TF0-IF1_IF0_Balatsky-170.pdf)
  - Nr 107: Athermal phonon collection / concentration pieces go here: Phonon-Mediated KID-Based Detectors for Low-Mass Dark Matter Detection and Coherent Elastic Neutrino-Nucleus Scattering (IF/SNOWMASS21-IF1_IF0-NF10_NF0-CF1_CF2_Golwala-080.pdf)
  - Nr 109: Search for Light Dark Matter with Vertically Aligned Carbon Nanotubes (IF/SNOWMASS21-IF1_IF0_Francesco_Pandolfi-076.pdf
  - Nr 177: Superconducting Detector Facility for HEP Science (IF/SNOWMASS21-IF1_IF2-177.pdf)
  - Nr 118: Improving the Sensitivity of Athermal Phonon Sensors for Light Mass Dark Matter (IF/SNOWMASS21-IF1_IF2-CF1_CF0-182.pdf)
  - Nr 122: Effects of energy accumulation and avalanche like releases in materials and low energy threshold detectors (IF/SNOWMASS21-IF1_IF2_Gianpaolo_Carosi-179.pdf)

Quantum Calorimeters cont.

- Convenor: Matt Pyle
- Writing committee:
- LOIs
  - Nr 123: Calorimetric readout of a superfluid 4He target mass (IF/SNOWMASS21-IF1_IF8-CF1_CF0_Hertel-158.pdf)
  - Nr 286: BULLKID Low-threshold Kinetic Inductance Detectors (NF/SNOWMASS21-NF10_NF0-CF1_CF0-IF1_IF0_Marco_Vignati-061.pdf)
  - Nr 304: Laboratory-Based keV-Scale Sterile Neutrino Searches (NF/SNOWMASS21-NF3_NF2-RF3_RF0-IF1_IF0_Kyle_Leach-055.pdf)
  - Nr 308: Neutrino Mass Measurements using TES Detectors to Cover the Inverted Hierarchy (NF/SNOWMASS21-NF5_NF0-IF1_IF6_Brian_Mong-113.pdf)
  - Nr 19: Low-gap charge detection for fundamental physics searches (CF/SNOWMASS21-CF1_CF2-IF1_IF2_Kurinsky-029.pdf

AMO: Spins, NMR, and Defects

- Convenor: Reina Maruyama
- Writing committee: Derek Kimball, Shimon Kolkowitz, and Surjeet Rajendran
- LOIs
  - Nr 36: Cosmic Axion Spin Precession Experiment (CASPEr-e) (CF/SNOWMASS21-CF2_CF0-IF1_IF0_Sushkov-100.pdf)
  - Nr 37: Exploring Axion Dark Matter with Ultrasensitive Optical Quantum Sensors (CF/SNOWMASS21-CF2_CF0-IF1_IF0_Young_Jin_Kim-006.pdf)
  - Nr 42: Global Network of Optical Magnetometers to search for Exotic physics (GNOME) (CF/SNOWMASS21-CF2_CF0-RF3_RF0-IF1_IF0_Derek_F_Jackson_Kimball-103.pdf)
  - Nr 108: Quantum Sensing of 3He for Low-Mass Dark Matter Detection (IF/SNOWMASS21-IF1_IF0-RF3_RF0-CF1_CF2_Steve_Lyon-055.pdf)
  - Nr 333: Searches for new sources of CP violation using molecules as quantum sensors (RF/SNOWMASS21-RF3_RF0-TF10_TF0-IF1_IF0_Nick_Hutzler-093.pdf)
  - Nr 332: Doped Cryocrystals for Ultrasensitive EDM Measurements (RF/SNOWMASS21-RF3_RF0-IF1_IF0_Andrew_Geraci-072.pdf)
  - Nr 99: Solid-state directional detection of massive dark matter particle via spectroscopy of quantum defects (IF/SNOWMASS21-IF1_IF0-CF1_CF0_Marshall-110.pdf)
  - Nr 30: Rydberg Atoms as Quantum Sensors for New Physics (CF/SNOWMASS21-CF2_CF0-IF1_IF0-259.pdf)

Interferometers, Clocks, and Traps

- Convenor: Tom Cecil
- Writing committee: Dan Carney, Andy Geraci, Jason Hogan, and Maria Safronova
- LOIs
  - Nr 48: Extreme Precision Astrometry using Two-Photon Amplitude Interferometry (CF/SNOWMASS21-CF3_CF7-IF1_IF2-124.pdf)
  - Nr 111: Ground-Based Gravitational-Wave Detectors as Advanced Quantum Sensors (IF/SNOWMASS21-IF1_IF0_McCuller-138.pdf)
  - Nr 100: Mechanical sensors as particle detectors: SNOWMASS LOI (IF/SNOWMASS21-IF1_IF0-CF1_CF2-TF10_TF0-013.pdf
  - Nr 112: Opportunities for Optical Quantum Noise Reduction (IF/SNOWMASS21-IF1_IF0_Raphael_Pooser-174.pdf)
  - Nr 330: Optically levitated sensors for precision tests of fundamental physics (RF/SNOWMASS21-RF3_RF0-IF1_IF0_Andrew_Geraci-076.pdf) (wrong link)
  - Nr 46: The Atom Interferometric Observatory and Network (AION) for Dark Matter and Gravity Exploration (CF/SNOWMASS21-CF2_CF7-IF1_IF0_Oliver_Buchmueller-018.pdf)
  - Nr 59: Long-baseline Atomic Sensors for Fundamental Physics (CF/SNOWMASS21-CF7_CF2-TF10_TF0-IF1_IF0_Jason_Hogan-164.pdf)
  - Nr 104: The Matter wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) Experiment (IF/SNOWMASS21-IF1_IF0-CF2_CF7-TF10_TF0_Swapan_Chattopadhyay-136.pdf)

Meetings / Timeline

- IF01 White paper workshop in mid December (Date TBD)
- Each white paper writing committee will host its own meetings - watch email list for announcements

Conclusions

- 4 community white papers - writing process is just beginning
- Everyone is invited to contribute to white papers
  - Please get involved early and actively
- Look to mailing list and slack channel for future updates

Contact Information:

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