Quantum Sensors

Superconducting sensors

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Main references

- **A Berlin, et al, Searches for new particles, dark matter, and gravitational waves with SRF cavities, arXiv:2203.12714**
- **CB Adams, et al Axion dark matter, arXiv:2203.14923**
- A Armatol, et al., Toward cupid-1t. arXiv:2203.08386
- A Derevianko, et al., Quantum Networks for High Energy Physics, arXiv:2203.16979
- R Pooser, Opportunities for optical quantum noise reduction. Snowmass2021 - Letter of Interest
- T Heinz, et al., Transduction for new regimes in quantum sensing. Snowmass2021 - Letter of Interest
- A Agrawal, et al., Superconducting Qubit Advantage for Dark Matter (SQuAD), Snowmass2021 - Letter of Interest

Superconducting Sensors

- Superconducting radiofrequency (SRF) Cavities
- Qubit-based single photon counting
- Other SRF and cryogenic technology relevant for IF1
  - Networks and transductions
  - Cryogenic Platform for Scaled-up Sensing Experiments
  - Superconducting-nanowire single-photon detectors (SNSPD)
  - SQUID
  - MKID

Superconducting Radio Frequency (SRF) Cavities

- Very **high-Q resonators** and critical components in particle accelerators
- **Strong active interest for quantum information science (QIS)**, with demonstrated record-high photon lifetime $Q>10^{11}$ also in the quantum regime.
- **Opportunities to search for new particles with SRF cavities at SQMS**
- **Dark photons and axion** (or axion-like particles), either as new particles or dark matter, as well as on **gravitational waves**.
  - SRF cavities can be used for GW: the search for gravity waves across the full spectrum of frequencies, particularly since their discovery by LIGO is very well motivated

Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714

Proposals for axion searches using SRF cavities

- **Two cavities with Static Field:** High-Q SRF cavities and large magnetic fields for a LSW axion search is to sequester the required magnetic fields away from the production and detection cavities. With this approach neither SRF cavity is subject to large magnetic fields and neither suffers a degradation of Q-factor.
- **Two Cavities with a pump mode**: An alternative approach is to replace the static B-field with an oscillatory B-field, which can then be directly run inside the receiver cavity.
- **Single-Cavity Axion Search and Euler-Heisenberg**: Search for both the axion-induced and EH nonlinearities using high-Q SRF cavities. This two-cavity scheme is less sensitive to noise sources which generate nonlinearities in the pump region.

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Qubit-based single photon counting

- Several ongoing or proposed experiments utilizes **SRF resonators coupled to superconducting qubits to detect bosonic dark matter candidates below the SQL.**
    - Photon counting non-demolition measurement for DM searches.
    - For certain DM search schemes, it would also be beneficial to have qubits that can operate successfully **even in high magnetic fields**.
- Two experiments for sub-SQL detection: **HAYSTAC, SQuAD** by implementing qubit-based photon counting
- SQMS also plans to combine SRF cavity technology and **qubit-based photon counting to increase the DM search rate by several order of magnitudes.**
- The Superconducting Qubit Advantage for Dark Matter (**SQuAD**): perform resonant searches for dark matter axions in a broad range from 10-30 GHz using high quality factor dielectric cavities and qubit-based photon counting

- Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714
- Axion Dark Matter, arXiv:2203.14923
- Superconducting Qubit Advantage for Dark Matter (SQuAD), Snowmass2021 - LOI

Other SRF and cryogenic technology relevant for IF1 (1)

Networks and Transduction

- **Networks of quantum sensors for enhanced sensitivity to further improve axion DM searchers**
- **Microwave-optical transduction based on 3D SRF cavities to enhance the conversion efficiency** at the quantum threshold, and below the SQL and enable haloscope searches in the THz regime
- **mm-wave regime** in LOI. Low-loss mm-wave photonics could allow preservation of quantum information at room temperature for a simpler network at laboratory scales, frequency range for axions **above ~10 GHz** (~40 μeV)

Cryogenic Platform for Scaled-up Sensing Experiments

- There is growing demand of large dilution cryogenic platforms capable of reaching milli-kelvin temperatures for quantum computing and quantum sensing. **SQMS center at Fermilab is developing a platform in an experimental volume of 2 meters diameter by 1.5 meters in height.**

- Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714
- Transduction for New Regimes in Quantum Sensing, Snowmass2021 LOI
- Opportunities for optical quantum noise reduction. Snowmass2021 LOI
- Quantum Networks for High Energy Physics, arXiv:2203.16979

Other SRF and cryogenic technology relevant for IF1 (2)

Superconducting-nanowire single-photon detectors (SNSPD) or sensing low count-rate signals due to their high internal efficiency and low dark-count rates.

- Recent proposals for axion search either require SNSPDs that can operate in the presence of **large magnetic fields** or require some means of carrying the light generated by the haloscope from the high-field region to a low-field region where the detectors can operate.
- The suitability of SNSPDs to applications requiring low dark-count rates is illustrated by recent progress in the **LAMPOST** prototype search for dark photon dark-matter using these devices

- Axion Dark Matter, arXiv:2203.14923

Other SRF and cryogenic technology relevant for IF1 (3)

- Read out multiple detectors on a single wire with cryogenic multiplexing technologies with minimal readout noise penalty is to scale experiments to larger detector counts.
- Microwave SQUID multiplexer (µmux): multiplexing factors up to two orders of magnitude larger than conventional cryogenic multiplexing schemes.
- Allow for cryogenic particle detection, such as low-mass threshold dark matter searches, beta decay end point measurements to determine the lightest neutrino mass,
- The CUPID collaboration presents a series of projects underway that will provide advancements in background reduction, cryogenic readout, and physics searches
- CUPID-1T: Microwave Kinetic Inductance Detectors (MKIDs) Metallic Magnetic Calorimeters (MMCs), and high- and low-impedance Transition Edge Sensors (TESes).

- Axion Dark Matter, arXiv:2203.14923
- A Armatol, et al., Toward cupid-1T. arXiv:2203.08386

Conclusions (1)

From the executive summary

- This growth extends far beyond high energy physics (HEP) impacting many areas of science from communications to cryptography to computing.
- Much of the early work in quantum sensors came from outside of ‘traditional’ HEP but is now poised to make significant contributions to the most fundamental questions in physics.
- Technology advances in quantum information science (QIS) provide exceptional theoretical and experimental resources to advance quantum sensing, with promising ideas and arising research projects that could provide mutual benefits in several areas such as materials, detectors, and devices.

Common areas of development

- Back action evading schemes
- Supporting technology: high-Q SRF cavities, mitigate TLS losses, enhance operation under multi-Tesla magnetic field, strength the link with QIST and leverage quantum computing technology
- Small grants and interaction with industries, e.g. SBIR programs
- Develop infrastructures, underground, magnetic, and large cryogenic facilities

Conclusions (2)

- Feedback and comments are welcome
- Please let us know if there are whitepapers, LOI, technology, technique that should be included in the report

- From Jinlong Zhang: “A strong need for much increased **technology development**, in preparation for the next big step in facilities and experiments while we exploit the ones we are currently developing/building”