

Snowmass2021 IF01: Topical Group Report

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1 Executive Summary

The use of quantum sensors in high energy physics has seen explosive growth since the previous Snowmass Community Study. This growth extends far beyond high energy physics (HEP) impacting many areas of science from communications to cryptography to computing. Quantum sensors have been used in searches for dark matter - particle and wave, fifth forces, dark photons, the EDM, variations in fundamental constants, and gravitational waves, among others. These sensors come in a wide range of technologies: atom interferometers and atomic clocks, magnetometers, quantum calorimeters and superconducting sensors to name a few. Early work with quantum sensors was often focused in the cosmic and rare and precision frontiers, but recent concepts seek to expand the use of quantum sensors to the energy and neutrino frontiers solidifying them as fundamental technologies for the future of experimental HEP. Much of the early work in quantum sensors came from outside of 'traditional' HEP - for example development of atomic clocks for precision timing - 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. There are numerous 'table-top' scale experiments underway or ready to start that will explore parameter spaces not previously achievable. These experiments provide the community large 'bang-for-buck' while exploring a wide range of sensing techniques. As these experiments mature, concepts for larger experiments - in terms of the scale of the sensors and number of sensors networked together - are being developed. Future advanced of quantum sensors will require supporting small and larger scale experiments along with an in-demand workforce that stretches beyond field of HEP.

2 Overview

2.1 Introduction

In this report we provide an overview of recent development in quantum sensors and their scientific impact to the high energy physics community as presented in the many LOIs and white papers submitted during the Snowmass 2021 process. We focus on sensors in which the quantum state of the sensor can be measured and manipulated. Also included are quantum calorimeters, which seek to measure individual quanta of energy deposited in the sensor. As a group, quantum sensors are extremely sensitive devices used to explore new physics. The goal is to use hardware and manipulation techniques developed in quantum information science and technology to reach sensitivities better than the standard quantum limit (SQL) over as broad a bandwidth as possible. Many of the most promising quantum sensors for HEP science have been developing for the past decade or more in areas outside of the traditional HEP science and funding sphere. For example, atomic clocks developed over many decades as a source of precision timing standards are now stable enough they can be used in the search for variations of fundamental constants and gravitational waves. At the same time, the field of quantum computing is experiencing multiple breakthroughs. We point the reader to the report from the Quantum Computing topical group in the Computational Frontier for more details, but highlight that many of the technological developments needed to improve quantum computers are also needed to improve quantum sensors: longer coherence times, increases numbers of quantum states, isolation from environmental noise, etc. Quantum sensing and computing also both require a highly skilled workforce. With the arrival of several major tech companies in the field of quantum computing there is fierce competition for workers. The HEP community will need to invest now in order to train the next generation of quantum scientist.

Much of the growth in quantum sensors over the past decade has occurred in small, laboratory based experiments. These small experiments have allowed the broader community to try out many different varieties of sensors (see 3 for examples) aimed at a broad range of scientific targets. The extreme sensitivity of quantum sensors often enables these experiments to make significant gains in unexplored parameter spaces at minimal cost while also advancing the sensor technology. Continued support of these 'table top' experiments serves as a way to rapidly develop sensor technology and help determine those areas where quantum sensors can have the greatest impact. As the fast-paced small experiments mature, those with the significant discover potential begin to emerge along with areas of commonality between the experiments (e.g. the need for advanced high field magnets for axion dark matter experiments or ultra-stable lasers for atom interferometers and clocks). They have reached the point at which plans for larger-scale, longer-term experiments are being developed. These concepts can evaluate the potential reach that can be achieved in a larger effort and the scale of require technological development.

75 2.2 Science

76 *Note : Would like to reference as many white papers as possible that use/discuss*
77 *quantum sensors.*

78 Quantum sensors encompasses a broad spectrum of technologies (as de-
79 scribed in 3 below) and has the potential to impact a wide range of core HEP
80 science. This can seen in the white papers submitted to this community study
81 that make use of these sensors: dark matter - ([1; 2], fifth forces, dark photons,
82 EDM, variations in fundamental constants, and gravitational waves, among oth-
83 ers.

84 3 Technologies

85 3.1 Interferometers, Optomechanics, and Clocks

86 *Note : The contents of this section are in part taken and modified from: Snow-*
87 *mass 2021: Quantum Sensors for HEP Science – Interferometers, Mechanics,*
88 *Traps, and Clocks [3]*

89 Atom Interferometers

90 Atom interferometry is a growing field with a variety of fundamental physics ap-
91 plications including gravitational wave detection, searches for ultralight (wave-
92 like) dark matter candidates and for dark energy, tests of gravity and searches
93 for new fundamental interactions (“fifth forces”), precise tests of the Standard
94 Model (e.g. fine structure constant), and tests of quantum mechanics. In light-
95 pulse atom interferometry, laser pulses are used to coherently split, redirect,
96 and recombine matter waves. Conventional atom interferometry makes use of a
97 pair of counter-propagating laser beams to drive two-photon Raman or Bragg
98 transitions while a new variation takes advantage of long-lived excited states in
99 alkaline-earth-like atoms that can be resonantly driven by a single laser beam.
100 In a gradiometer configuration, two identical atom interferometers are run si-
101 multaneously on opposite ends of a baseline, using the same laser sources. A
102 comparison of the individual atom interferometer signals yields a differential
103 measurement that enables the cancellation of noise common to both interfer-
104 ometers. This in principle enables superior common-mode rejection of noise,
105 allowing for the possibility of, for example, gravitational wave detection using
106 a single baseline. A passing gravitational wave would modulate the baseline
107 length, while coupling to an ultralight dark matter field can cause a modula-
108 tion in the energy levels. This combines the prospects for both gravitational
109 wave detection and dark matter searches into a single detector design, and both
110 science signals are measured concurrently.

111 The MAGIS concept takes advantage of features of both clocks and atom in-
112 terferometers to allow for a single-baseline gravitational wave detector. MAGIS-
113 100 is the first detector facility in a family of proposed experiments based on
114 the MAGIS concept. The instrument features a 100-meter vertical baseline and

is now under construction at the Fermi National Accelerator Laboratory (Fermilab). State-of-the-art atom interferometers are currently operating at the 10-meter scale, while a kilometer-scale detector is likely required to detect gravitational waves from known sources. The Atom Interferometric Observatory and Network (AION) project envisages a staged Atom Interferometry program, starting with a 10 m device and progressing via a 100 m experiment to a 1 km instrument. AION will enable exploration of the properties of ultra-light dark matter (DM) and gravitational waves (GWs) from the very early Universe and astrophysical sources in the mid-frequency band ranging from several mHz to a few Hz, intermediate between the sensitive ranges of LIGO/Virgo/KAGRA and LISA. The ultimate sensitivity of the AION program will be reached by inter-operating and networking with other instruments around the world, similar to the existing LIGO-Virgo network, which will provide science opportunities not accessible to single detectors.

Optomechanical Sensors

Mechanical sensors that can be read out optically (frequencies range from microwave to visible) have advanced rapidly and are now commonly operated in a regime where their sensitivity becomes dominated by quantum noise in the mechanics or readout system. A wide variety of sensors is available, ranging from single ions to kilograms-scale elements. The sensors are uniquely suited to coherent signals with a scale comparable to the size of the mechanical sensor since the signal is coherently integrated into a small number of degrees of freedom (e.g. center of mass motion). A key example of the capabilities of optomechanical sensors is LIGO. Other examples include mechanically suspended reflective pendula; optically levitated dielectrics, cold atoms, and ions; clamped nanomechanical membranes; magnetically levitated systems; and can also include collectively quantized degrees of freedom like phonons.

In addition to their use in gravitational wave detection and precision measurements in metrology, optomechanical devices are rapidly being incorporated into the portfolio of detector systems useful for a number of high energy and particle physics targets. Building on classical proposals for neutrino and dark matter detection with nanoscale targets, proposals now exist to use optomechanical sensors for detection of ultra-light, MeV-to-TeV scale, and ultra-heavy dark matter [4]; neutrinos; high-frequency gravitational waves; fifth-force modifications to Newton's law at tabletop scales; deviations from standard quantum mechanics (including ideas about gravitational breakdown of quantum mechanics); and tests of quantum properties of the gravitational interaction.

Moving forward, a number of key opportunities exist to increase the utility of these devices in the search for new physics. A critical one is the need for new theoretical ideas about potential new signals! At the level of the detector technologies, an important frontier is in advanced quantum techniques to get sensitivities at and beyond the so-called Standard Quantum Limit (SQL). The most common, well-demonstrated method to go beyond the SQL is the use of squeezed light while a less-studied, but enticing option is the use of backaction

159 evasion techniques. Further theoretical development and implementation of
 160 these techniques in disparate situations and physical architectures, especially in
 161 broadband sensing problems, will be of crucial importance in the next decade.
 162 Leveraging multiple sensors (“networks”) and entanglement between them can
 163 similarly enable detection beyond the SQL; using these ideas in searches for new
 164 physics would be extremely interesting.

165 **Clocks and Precision Spectroscopy**

166 Optical clock precision has improved by more than three orders of magnitude in
 167 the past fifteen years, enabling tests of the constancy of the fundamental con-
 168 stants and local position invariance, dark matter searches, tests of the Lorentz
 169 invariance, and tests of general relativity. All current atomic clocks are based
 170 on (1) transitions between the hyperfine substates of the atomic ground state
 171 (microwave clocks) or (2) transitions between different electronic levels (optical
 172 clocks). The frequency ratio of two optical clock frequency is only sensitive
 173 to the variation of the fine structure constant α and optical atomic clocks can
 174 probe the standard matter - dark matter coupling. Promising searches for ul-
 175 tralight particles are feasible through isotope-shift atomic spectroscopy, which
 176 is sensitive to a hypothetical fifth force between the neutrons of the nucleus
 177 and the electrons of the shell. The analysis of precision isotope shift (IS) spec-
 178 troscopy sets limits on spin-independent interactions that could be mediated
 179 by a new particle which could be associated with dark matter. Deployment of
 180 high-precision clocks in space could open the door to new applications, including
 181 precision tests of gravity and relativity, searches for a dark-matter halo bound to
 182 the Sun, and gravitational wave detection in wavelength ranges inaccessible on
 183 Earth. Space-based optical lattice atomic clocks could potentially include the
 184 possibility of a tunable, narrowband GW detector that could lock onto and track
 185 specific GW signals provide a compliment to other experiments (e.g. LISA and
 186 LIGO). Radioactive atoms and molecules offer extreme nuclear nuclear charge,
 187 mass, and deformations, and may be worked with efficiently with the advanced
 188 quantum control toolset of AMO. These rare systems offer an unprecedented
 189 amplification of both parity- and time-reversal violating properties.

190 Several potential pathways existing for improving clock performance: devel-
 191 oping new clocks with much larger sensitivity factors; development of large and
 192 more integrated clock networks; making clocks more portable (critical for space
 193 applications); and improving local oscillator technology as it limits coherent in-
 194 tegration times. Additionally it is possible to probe multiple clocks with the
 195 same laser to cancel out local oscillator noise (similar to using single laser with
 196 atom interferometer). This pushes to near SQL. Pushing beyond the SQL can
 197 be achieved by using entangled states, such as spin-squeezed states. Gains can
 198 also be made by moving to clocks using highly charged ions (also a promising
 199 avenue for isotope shift spectroscopy) or nuclear clocks which have much higher
 200 sensitivities to the variation of α , up to 4 orders of magnitude for nuclear
 201 clocks. Nuclear clocks are highly sensitive to the hadronic sector and could offer
 202 improvements in sensing of DM coupling by 5-6 orders of magnitude. Use of

203 molecular clocks provide direct sensitivity to determining the ratio of the proton
204 mass to electron mass and its variation.

205 **3.2 Spin Dependent Sensors**

206 *Note : The contents of this section are in part taken and modified from: Quantum*
207 *Sensors for High Precision Measurements of Spin-dependent Interactions.*
208 *Arxiv (2022). [5]*

209 Experimental techniques for precision measurement of spin-dependent in-
210 teractions have substantially advanced over recent decades, in no small part
211 because control and measurement of spins, spin ensembles, and quantum materi-
212 als is at the heart of QIS and quantum computing and they share a common
213 foundation with the robust program of research on spin-based quantum sensors
214 for measurement of magnetic fields, magnetic resonance phenomena, and related
215 phenomena. There are three main ways measurements of spins can probe for
216 new physics: new physics can break symmetries of the Standard Model giving
217 rise to novel responses of spins to other fields (e.g. searching for EDM); the new
218 physics can directly affect the spin for example via an interaction with a new
219 field and the spin (e.g. searches for axions and axion-like particles); and new
220 physics can affect the environment of the spin which the spin can sense (e.g.
221 damage to crystals containing defects centers following interaction new physics
222 such as dark matter particles).

223 **EDM**

224 The general approach of EDM experiments is to search for the combined effect
225 of a P- and T-odd Hamiltonian and an applied electric field E , which results in
226 an energy shift for a given quantum state of the atom or molecule. Typically
227 the system is spin polarized via optical pumping or some other hyperpolariza-
228 tion technique such that the system is in a superposition of quantum states
229 with opposite EDM-induced energy shifts. Thus a nonzero EDM will cause
230 the polarized spins to precess in the presence of E . There are several general
231 areas of technology development that can advance the fundamental sensitivity
232 of EDM searches: increase the energy shift by finding system with maximum
233 enhancement factors; improve control techniques to increase the total number
234 of polarized atoms/molecules, and achieving longer spin-coherence times.

235 **Magnetometers**

236 Many theories predict the existence of new force-mediating bosons that couple
237 to the spins of Standard Model particles. One of the primary experimental
238 strategies is to employ a sensitive detector of torques on spins and then bring
239 that spin-based torque sensor within a Compton wavelength of an object that
240 acts as a local source of an exotic field (e.g., a large mass or highly polarized spin
241 sample). Since the observable in these experiments is a spin-dependent energy

shift a sensor employing N independent spins with coherence time τ has a shot-noise-limited sensitivity. Common sensors include NV centers, optical atomic magnetometers and Bose-Einstein condensates (BEC). One promising technology is the development of levitated ferromagnetic torque sensors (LeFTS). The active sensing element consists of a hard ferromagnet, well isolated from the environment by, for example, levitation over a superconductor via the Meissner effect. The mechanical response of the levitated ferromagnet to an exotic spin-dependent interaction can be precisely measured using a superconducting quantum interference device (SQUID). Similar to the LeFTS concept, ultracold twobody interactions in the BEC create a fully coherent, single-domain state of the atomic spins that enables the system to evade the sensitivity limits of traditional spin-based sensors.

Beyond the intrinsic sensitivity, the principal challenge in experiments searching for exotic spin-dependent interactions is understanding and eliminating systematic errors: clearly distinguishing exotic spin-dependent interactions from mundane effects due to, for example, magnetic interactions. By comparing the response of two different systems, effects from magnetic fields can be distinguished from effects due to exotic spin-dependent interactions. This is the essence of comagnetometry, where the same field is simultaneously measured using two different ensembles of atomic or nuclear spins. This effort can be extended to searching for transient interactions through the use of networks of geographically distributed spin-dependent sensors. For example the GNOME network will search for transient and stochastic effects that could arise from ALP fields of astronomical origin passing through the Earth.

Magnetic Resonance

One possible manifestation of ultralight bosonic dark matter is as classical fields oscillating at the Compton frequency. The bosonic dark matter field can cause spin precession via couplings to nuclear and electron spins which can be detected using the broad and versatile tools of magnetic resonance. In a dark matter haloscope experiments, the oscillating field is assumed to always be present, corresponding to case of continuous-wave NMR. The magnetic field is scanned, and if the Larmor frequency matches the Compton frequency, a resonance occurs generating a time-dependent magnetization that can be measured, for example, by induction through a pick-up loop or with a SQUID. This is the method used in the CASPER experiment. A key to CASPER's sensitivity is the coherent "amplification" of the effects of the axion dark matter field through a large number of polarized nuclear spins. Therefore an important technological development is the ability to carry out NMR on the largest possible number of spins.

The QUAX (QUaerere AXion) experiment searches for axion dark matter in a manner similar to CASPER but by exploiting the interaction of axions with electron spins. Ten spherical yttrium iron garnet (YIG) samples are coupled to a cylindrical copper cavity by means of an applied static magnetic field, and the resulting photon-magnon hybrid system acts as an axion-to-electromagnetic field transducer. The QUAX experiment is one of the most sensitive rf spin

286 magnetometers ever realized, able to measure fields as small as 5.5×10^{19} T
 287 with nine hours of integration time.

288 The ARIADNE experiment employs an unpolarized source mass and a spin-
 289 polarized ^3He low-temperature gas to search for a QCD-axion-mediated spin-
 290 dependent interaction: the monopole-dipole coupling. In contrast to dark mat-
 291 ter haloscopes like CASPEr and QUAX, whose signals depend on the local dark
 292 matter density at the Earth, the signal in the ARIADNE experiment does not
 293 require axions to constitute dark matter and can be modulated in a controlled
 294 way.

295 Defects

296 Searches for dark matter via scattering in crystals will soon run into the neutrino
 297 floor - the background of neutrinos from the sun. One path for getting beyond
 298 the neutrino floor is to develop directional detectors. Since the direction of the
 299 sun is known, the detectors can veto signals coming from the direction of the sun;
 300 dark matter interactions by contrast will result in isotropic scattering signals.
 301 One proposal for achieving this directional detection is to monitor damage tracks
 302 in crystals that occur as the scattering dark matter displaces atoms from their
 303 lattice location. These damage tracks can be measured using techniques from
 304 quantum sensing such as NV center spin spectroscopy in noncrystalline diamond.
 305 The NV center spin state is highly sensitive to the local strain in the crystal.
 306 These detectors will require a combination of imaging methods to locate and
 307 determine the direction of the damage tracks as described in [1] but provide a
 308 pathway towards WIMP sensitivity below the neutrino limit.

309 3.3 Quantum Calorimeters

310 *Note : Work in progress. Contact Matt Pyle for details: mpyle1[at]berkeley.edu*

311 3.4 Superconducting Sensors

312 *Note : Contents of this section are in part taken and modified from Snowmass*
 313 *2021 White Papers: Axion Dark Matter [6], and Searches for New Particles,*
 314 *Dark Matter, and Gravitational Waves with SRF cavities [7].*

315 SRF Cavities

316 Superconducting radio-frequency (SRF) cavities are critical components in par-
 317 ticle accelerators. Advances in cavity performance are the results of an improved
 318 understanding of RF superconductivity and materials. In the past 50 years, new
 319 cavity processing techniques were developed to overcome limiting phenomena,
 320 such as field emission, and enhance the superconductivity.

321 SRF cavities are, in their essence, extremely high quality electromagnetic
 322 resonators, devices that are now of strong active interest for quantum infor-
 323 mation science (QIS), with demonstrated record-high photon lifetime $\tau \sim 2s$

($Q > 10^{11}$) also in the quantum regime. For quantum computing, quantum states can be stored and manipulated in electromagnetic resonators, and superconductors at milli-Kelvin temperatures are employed to sustain the coherence of the quantum states for long enough to perform complex computations. For quantum sensing, SRF cavities can furnish a large volume where very weak signals of radio-frequency photons can be collected, with only a small fraction of photons being lost to heat at the cavity walls.

The main focus on the Superconducting Quantum Materials and Systems (SQMS) National QIS Research Center is to advance QIS through the understanding and mitigation of coherence mechanisms in 2D and 3D quantum systems, i.e. planar and cavity based, tackling the decoherence time as a primary limiting mechanisms. This SRF cavity effort is utilized also to pursue fundamental physics questions and pushing the detection sensitivity with SRF cavities. The Snowmass whitepaper [7] summarizes opportunities to search for new particles with SRF cavities at SQMS. The focus is on dark photons and axion (or axion-like particles), either as new particles or dark matter, as well as on gravitational waves. The search for gravity waves across the full spectrum of frequencies, particularly since their discovery by LIGO [8], is very well motivated, potentially opening a new window onto the early Universe or new physics. In this context SRF cavities can be used to search for GW's [9].

It is possible to explore dark photon scenarios using SRF cavities light-shining-through-wall setup. The conversion of some of the photons to dark photons before the wall and conversion back to regular photons past the wall makes such a detection possible, if dark photons exist at a hypothesized mass and coupling. Resonant cavities can be used on both sides of the wall to increase the number of photons on the emitting side and to enhance the probability of conversion of dark photons to visible ones on the receiver side. In particular, in an RF cavity the system can be designed to search for the parametrically enhanced longitudinal coupling of the dark photon. The Dark SRF experiment at Fermilab plans to conduct such a search with ultra-high quality cavities [10–13].

The following materials science and R&D efforts are highlighted to expand current physics searches: enhance the efficiency; mitigate nonlinearities in superconducting cavities due to TLS; reaching high-Q with the cavity in a multi-Tesla field; improving methods for frequency stability and tuning in SRF cavities. New schemes include searches with multiple cavity modes for axions or gravitational waves, nonlinear effects within the cavity walls that can mimic such a signal in particular if the signal mode is near a harmonic; networks of SRF cavities; quantum nondemolition (QND) measurements with superconducting qubits coupled to SRF cavities.

Proposals for axion searches using SRF cavities

The Axions and axion-like particles (ALPs) is a generalization of the QCD axion which does not couple to QCD, but does couple to photons or SM fermions. ALPs are well motivated in their own right in top-down constructions [14;

15]. Like the dark photon case, Light-shining-through-wall (LSW) -type axion searches can benefit from high quality factors, which warrants the harnessing of advances in SRF technology. The necessity for a background magnetic field, however presents a challenge, as high-quality superconductivity does not survive large fields. Novel approaches to allow large magnetic fields with no degradation of Q-factor in SRF cavities are posed.

Two cavities with Static Field: One technique to utilize both 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 [16]. With this approach neither SRF cavity is subject to large magnetic fields and neither suffers a degradation of Q-factor. However, losses in the walls of the conversion region can result in a decrease of the effective Q of the entire system.

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. Sources of noise due to the multi-mode setup can be mitigated by using a pump with high-Q and with the pump frequency well separated from the signal mode frequency. In addition, such noise sources can be further suppressed by optimizing the cavity geometry and material science techniques to reduce nonlinearities [17; 18].

Single-Cavity Axion Search and Euler-Heisenberg: The EH Lagrangian makes a prediction for light-by-light scattering within the SM, which has never been observed at photon frequencies below the electron mass $m_e = 511$ keV because the effect is highly suppressed at low energies. The operating system of a proposed experiment to search for both the axion-induced and EH nonlinearities using high-Q SRF cavities is described in [19–22]. This two-cavity scheme is less sensitive to noise sources which generate nonlinearities in the pump region.

Qubit-based single photon counting

The integration of a qubit into an ultra high cavity may enable new schemes for quantum computing and synergetically allow for employing a 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 [23].

Cavity haloscopes have traditionally extracted the DM signal via an antenna connected to a linear amplifier, such as a Josephson Parametric Amplifier (JPA). Unfortunately, linear amplifiers contribute to their own noise power, and their minimum contribution is the standard quantum limit (SQL). SQL noise increases linearly with frequency, and thus it is necessary to subvert the SQL to make higher-mass searches feasible.

Several ongoing or proposed experiments utilizes SRF resonators coupled to superconducting qubits to detect bosonic dark matter candidates below the

SQL. Two experiments have demonstrated sub-SQL detection: HAYSTAC by implementing vacuum squeezing [24] and SQuAD by implementing qubit-based photon counting [23]. 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) experiment plans to perform resonant searches for dark matter axions with DFSZ sensitivity in a broad range from 10-30 GHz using high quality factor dielectric cavities combined with qubit-based single photon detectors which evade the quantum zero-point noise. R&D is ongoing on developing an analogous photon counting readout based on Rydberg atoms which can be operated at the higher frequencies where qubit devices become more difficult to design and fabricate.

Networks and transduction

Recently, it was shown that the performance of a quantum network could be utilized further to improve axion DM searches [25]. However, the noise in the network will be incoherent among the network nodes. One can make use of distributed squeezed states to exploit the coherent nature of the DM signal. Combining quantum resources (squeezing) in a distributed-network setting can allow for a scan that is faster by a factor of the square number of network nodes in the ideal case. The improvement is enabled by adding the signal at the amplitude level rather than adding powers in the classical network case.

A quantum transduction project at Fermilab is exploring hybrid coherent resonance systems and bi-directional quantum transduction schemes to up/down-convert the microwave information to/from the optical regime and enhance the conversion efficiency at the quantum threshold, and below the SQL. Up/down photon conversion may also enable highly sensitive axion and dark photon halo-scope searches in the THz regime, or microwave single photon counting in optical systems, taking advantage of optical sensing techniques, e.g. high precision counting in interferometry and reduced noise floor [26], also in the Snowmass LOI *Opportunities for Optical Quantum Noise Reduction* [27].

Transduction in the mm-wave regime is also proposed in the LOI *Transduction for new Regimes in quantum sensing* [28] as an effective way for linking the classical and quantum world, and for transporting quantum information on macroscopic scales. Low-loss mm-wave photonics could allow preservation of quantum information at room temperature for a simpler network at laboratory scales, as well as reaching out the frequency range for axions above 10 GHz (40 μ eV) is beyond the reach of current experiments (ADMX).

Cryogenic Platform for Scaled-up Sensing Experiments

The SQMS center at Fermilab is developing a cryogenic platform capable of reaching millikelvin temperatures in an experimental volume of 2 meters diam-

eter by 1.5 meters in height [29]. The platform is designed to host a three-dimensional qubit architecture based on SRF technology, as well as sensing experiments.

SNSPD

Superconducting-nanowire single-photon detectors (SNSPD) are ideally suited for sensing lowcount- 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 recently established robustness of SNSPDs to operation in high fields and their ability to operate at elevated temperatures (relative to alternative superconducting detector technologies) make them well-suited for photon detection in the mid-infrared (meV) to visible (eV) energy range. 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 [30].

Other superconducting and cryogenic sensors

Cryogenic sensors have found a large range of applications for astroparticle detection. Due to integration complexity and thermal loading from cryogenic wiring, the ability to read out multiple detectors on a single wire with cryogenic multiplexing technologies with minimal readout noise penalty is of utmost importance as experiments are scaled to ever larger detector counts. The microwave SQUID multiplexer (μ mux) couples an incoming detector signal to a unique GHz-frequency resonance, thus combining the multiplexability of MKIDs with the clean separation of detection and readout interfaces. This enables multiplexing factors up to two orders of magnitude larger than conventional cryogenic multiplexing schemes.

The wide frequency operation span enables large detector counts for low-bandwidth bolometric applications such as CMB cosmology while maintaining clean interfaces between the detection and readout schemes. Additionally, the large frequency bandwidth and fast resonator response allow for cryogenic particle detection, such as low-mass threshold dark matter searches, beta decay end point measurements to determine the lightest neutrino mass, and coherent elastic neutrino-nucleon scattering.

The CUPID collaboration in the snowmass whitepaper *Toward CUPID-1T* [31] presents a series of projects underway that will provide advancements in background reduction, cryogenic readout, and physics searches, all moving toward the next-to-next generation CUPID-1T detector. Neutron-transmutation doped thermistors (NTDs) are expected as part of the baseline design for CUPID. Multiple modes of superconducting sensors are under development as we look toward CUPID-1T: Microwave Kinetic Inductance Detectors (MKIDs),

493 Metallic Magnetic Calorimeters (MMCs), and high- and low-impedance Tran-
494 sition Edge Sensors (TESes).

495 4 Common Areas for Development

- 496 • back action evasion: Back action evading schemes and squeezing tech-
497 niques can enhance the sensitivity measurement of quantum sensors down
498 to the SQL. Many experiments (for example NMR experiments to axion
499 dark matter) will have their sensitivity limited by quantum back action
500 and techniques will need to be developed for experiments approaching fun-
501 damental projection noise sensitivity limits. One of the purposes of new
502 transduction projects is to leverage both microwave and optical sensing
503 techniques as a way means to implement back action evasion.
- 504 • supporting technologies (laser, cavities, magnets, etc.): Several sensing
505 experiments are enabled by SRF cavities with high-Q. Material studies,
506 effort to mitigate limiting TLS losses, enhancing operation under multi-
507 Tesla magnetic field can provide new resources for quantum sensors. Sim-
508 ilarly, many experiments rely on the use of high-field magnets. Efforts to
509 increase the magnitude, uniformity and scale (larger magnet bores) can
510 result in direct improvements to the experimentally reachable parameter
511 space.
- 512 • Infrastructures: The same characteristics that allow quantum sensors to
513 probe new parameter space allows them to be sensitive to a wide range
514 of noise sources. In some case, experiments may need to be placed in
515 underground labs to avoid noise sources such as cosmic rays or maintain
516 radio purity of sensor materials. Development of shared infrastructure,
517 e.g. underground facilities with cryogenic and or magnetic capabilities
518 could enable the advancement of multiple experimental techniques in a
519 single facility.
- 520 • SBIR program, interaction with companies: DOE programs for commer-
521 cialization and technology transfer programs, such as SBIR/STTR, pro-
522 vides platforms and resources to develop technology for quantum sensors
523 and HEP. With the rapid rise of commercial sector quantum computing
524 and associated technologies, new opportunities are emerging for interac-
525 tions between government sponsored researchers and the commercial sec-
526 tor.

527 5 Summary

528 References

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