Quantum Sensors

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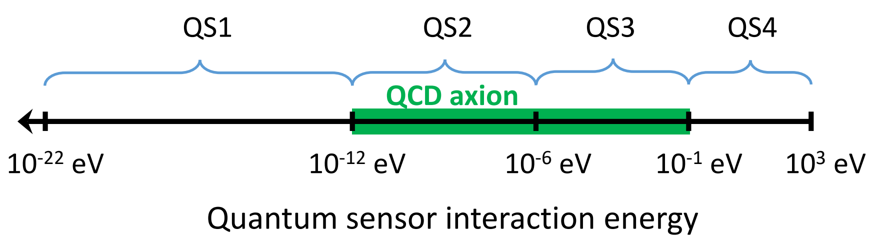
1 Key Technologies and Science Drivers

Quantum sensors are poised to dramatically impact precision measurements for HEP, and they are a game changer for important applications beyond the fundamental sciences. The connections to P5 science drivers include dark matter and dark sectors, inflation, exploring the unknown, and fundamental tests of quantum mechanics. A related field that will also be impacted is gravitational wave astrophysics.

Here we present a table describing a natural way to organize quantum sensor technologies for HEP quantum sensors research. It organizes into four distinct quantum sensor energy ranges (either the energy of an absorbed quantum, or typical scattering energy). These four energy ranges form natural breakpoints in HEP science, quantum sensor technology, and useful quantum protocols.



More specifics of each energy range, including HEP science and sensor technology, are shown in Table 1. There is value in identifying priority research directions (PRDs), with high leverage and potential payoff for investment. PRDs and their associated timelines are derived from both the science needs and the needed sensor technologies tabulated in Table 1,

PRD #1: Develop the quantum sensor technology needed to probe the entire QCD axion band. A natural initial priority for HEP quantum sensor development is the detection of the QCD axion. The QCD axion is a strongly motivated

	Quantum Sensor Energy Range	HEP Science	Quantum Sensor Technology	Quantum Protocols
QS1	$< 10^{-12}$ eV	Ultralight dark matter (generalized axions, hidden photons, scalars), Electric dipole moment, Gravitational waves, Dark energy	Atomic and molecular spectroscopy, atom interferometers and mechanical sensors, clocks, atomic magnetometers, nuclear spins	Superposition, entanglement, squeezing
QS2	10^{-12} –10^{-6} eV	QCD axion Ultralight dark matter (generalized axions, hidden photons) New forces & particles	Nuclear spins, electromagnetic quantum sensors, optical cavities	Superposition, entanglement, backaction evasion, squeezing
QS3	10^{-6} –10^{-1} eV	QCD axion Ultralight dark matter (generalized axions, hidden photons) New forces & particles	Qubits, Nuclear spins, rydberg atoms	Parametric amplifiers, superposition, entanglement, Squeezing, QND photon counting
QS4	10^{-1} –10^{3} eV	Scattering / absorption of dark matter New forces & particles	Single-photon counters (superconducting, APD), Low-threshold phonon and charge detectors	Non-QND photon counting

Table 1: Quantum-sensors organized by interaction energy range and HEP science. HEP-relevant sensors naturally organize into four distinct quantum-sensor energy ranges (either the energy of an absorbed quantum, or typical scattering energy). The HEP science is described for each research priority. Each energy range has its own characteristic quantum sensor technologies and quantum protocols.

Dark Matter candidate that can also solve one of greatest puzzles in high energy physics: the strong CP problem. The search for QCD-axion dark matter thus addresses two of the most important indicators for physics beyond the standard model. It is hard to overstate the importance of this search, which will require both new quantum sensing modalities, and sensitivity beyond the standard quantum limit.

Searches for the QCD axion have historically been limited to a narrow range of axion mass (and frequency). One of the highest impact outcomes from the development of novel Quantum Sensors for HEP Science is the potential to search for the QCD axion over its entire allowed mass range. Without new quantum sensor breakthroughs, a comprehensive search for QCD axions is not possible.

Key quantum-sensing breakthroughs to make this comprehensive search possible include the development of back-action evasion, squeezing, and qubit-based photon counting to improve sensitivity beyond the standard quantum limit for electromagnetic-coupling to QCD axions with mass between $\sim$ neV and $\sim 100\mu$eV. New photon counting techniques are needed to detect electromagnetic coupling to QCD axions above $\sim 100\mu$eV. New quantum protocols are necessary to beat quantum projection noise with spin squeezing in nuclear magnetic resonance based detectors for QCD axion coupling to the strong force below $\sim 1\mu$eV, and for the detection of short-range spin-dependent interactions above $\sim 1\mu$eV. When combined, these breakthroughs would allow complete coverage of the QCD axion band from $\sim p$eV to $\sim$ 10meV.

PRD #2: Develop Quantum Sensor Technology able to expand the frequency-range of searches for Gravitational Waves. Much like the invention of the telescope did for viewing the universe in the optical frequency range of the electromagnetic (EM) spectrum, the kilometer-scale LIGO interferometers have enabled viewing the universe in the domain of gravitational radiation, with remarkable sensitivity at frequencies ranging from 10s of Hz to a few kHz. In this nascent field it is imperative to extend the search to other frequencies, just as x-ray- and radio-astronomy have done for the EM spectrum. Gravitational waves have a variety of predicted sources, ranging from early universe cosmology to binary mergers and insprials of compact objects, to dark matter candidates such as axions and axion-like particles. Quantum-based sensors such as atomic interferometers and atomic clocks are able to detect the resulting space-time strain at frequencies below those studied at Advanced LIGO, and extending above those predicted to be readily accessible in future spaced-based interferometers such as LISA. This mid-band frequency range is ideal for providing advance notice of the timing and location on the sky of upcoming merger events, which would be enabling for multi-messenger astronomy by providing the forewarning needed for electromagnetic telescopes to repoint in order to observe the run-up to coalescence. A somewhat analogous strain can result from oscillating wave-like dark matter. Quantum optomechanical systems represent a promising avenue for higher frequency gravitational wave detection, above the LIGO band.

PRD #3: Searches for electric dipole moments (EDMs) and other precision tests of the Standard Model. Precision measurements with quantum sensors are at the forefront of searches for violation of time-reversal (T) symmetry. T-violation generically manifests as the existence of a permanent electric dipole moment (EDM) along the spin of fundamental and composite particles. Sources of T-violation beyond those in the standard model are required to generate the observed cosmological matter-antimatter asymmetry. Thus standard model extensions, such as supersymmetry, typically predict EDMs near the limits set by current experiments: in fact, EDM experiments probe new physics at higher energy scales than those accessible with the LHC. New quantum sensor technology enabling more precise measurements of nuclear- and electron-spin-dependent interactions can extend the reach of EDM searches to even higher energy scales.

Precision measurements with quantum sensors can also probe energy scales far beyond the LHC frontier in other ways. A number of theories aiming to unify gravity with other fundamental interactions suggest tiny violations of cornerstones of modern physics such as Lorentz symmetry and combined charge conjugation (C), parity (P), and time-reversal (CPT) invariance and imply spatio-temporal variation of fundamental constants. Precision quantum sensors can probe the low-energy consequences of such effects originating at the GUT and Planck scales. Related precision experiments, such as $g - 2$ and fine-structure constant measurements, provide the best tests of QED and are powerful windows into beyond-standard-model physics possibilities.

PRD #4: Technology for large entangled sensor networks Entanglement is a key resource available for improving the sensitivity of quantum sensors. Squeezed light and squeezed spin states have been critical tools for achieving modest improvements in noise floors and sensitivities of detectors. Basic research into the generation and utilization of such entanglement based resources will continue to advance quantum sensors in a variety of applications. Beyond squeezing and laboratory scale non-classical states, large scale entangled sensor networks, where entanglement over long distances is harnessed for dramatic improvements in sensitivity will lead to profound improvements in astronomical interferometers and other sensors. Accelerated research and development into techniques for upconversion and transduction will be critical in realizing such distributed entanglement sensors. Arrays of quantum sensors will also be a resource for background rejection and even track-like signals in certain scenarios.

PRD#5: Develop quantum sensor technology to search for general wave-like dark matter Discovering the nature of dark matter is one of the most important problems in modern physics, and the challenge extends beyond just the search for QCD axions. Recent theoretical progress has revealed that a broader range of very light particles, which naturally arise in unification theories such as string theory, can be excellent dark matter candidates. For dark matter (DM) particle masses below the eV energy scale, in order to achieve the expected average energy density ρ_{DM}, DM must consist of a bosonic field with a macroscopic occupation number, i.e. it must be wave-like. Dark matter this light cannot be fermionic since the Fermi velocity would exceed the escape velocity of the galaxy. Bosonic light DM fields can be as light as 10^{-22} eV (the inverse size of dwarf galaxies). Many of the production mechanisms for wave-like dark matter rely upon cosmic inflation. Therefore, searches for wave-like dark matter provide a new avenue through which to study cosmology. In addition, an intriguing possibility is that dark energy undergoes evolution in time as opposed to being a cosmological constant, which would imply that dark energy involves a very light particle that might interact with Standard Model particles non-gravitationally. A new generation of quantum sensors developed to probe wave-like dark matter would also provide a set of optimal platforms to search for such dark-energy-induced interactions.

Wave-like dark matter can take the form of a scalar, vector (i.e. Dark Photon), pseudoscalar, or axial vector. Generally, the dark matter field oscillates at its Compton frequency determined by the mass of the constituent particles. This oscillating field can produce a variety of physical effects in precision experiments. For scalar DM these include variations of fundamental constants such as the electron mass, proton mass, or fine structure constant, as well as oscillating, composition-dependent accelerations of massive objects. For pseudoscalars these include time-varying nucleon EDMs, spin-torques, and EMFs along magnetic fields. For vector DM one can obtain accelerations, EMFs in vacuum, and spin torques (also a possible signal for axial vector DM). Quantum sensors capable of detecting variations in energy levels of quantum systems, strains on material objects, differential accelerations, spin torques, and small electromagnetic fields are thus well suited to contribute to the search for wave-like dark matter. Examples include atomic clocks, atomic interferometers, magnetic-resonance-based sensors, optical cavities, resonant mass detectors, microwave cavities, LC circuits, single-photon detectors, superconducting resonators, and optomechanical sensors. In order to realize the full discovery potential of these sensors, improvements in the ability to exploit quantum resources–in particular, superposition extending over macroscopic distance scales and/or long times, entanglement, and squeezing–will be essential. Enhanced experimental control over these quantum resources will naturally lead to fundamental tests of quantum mechanics in previously unexplored regimes.

PRD#6: Low-threshhold detection of individual dark-matter interactions Dark matter candidates with mass greater than $\sim$10 eV, but less than 1 MeV, can also benefit from new advances in quantum sensor technology. New quantum sensors have the potential to, for the first time, allow us to detect individual dark-matter particles in this mass range through their interactions with electrons and nucleons in advanced sensors. These include ultrasensitive alternatives to existing bolometers and superconducting detectors for the detection of athermal phonons produced by a particle interaction within a gram-to-kilogram scale mass detector, or the detection of the production of phonons or rotons or in superfluid helium. New quantum sensor modalities have the potential to enable optical readout to detect single GHz scale (μeV) phonons provided energy from a particle interaction could be coupled into the modes of interest. Such detectors might be sensitive to interactions with electrons or nuclei in materials below the threshold for ionization and scintillation in existing detectors.

PRD #7: Quantum sensor technology development for precision searches for exotic interactions. Theoretical extensions of the standard model commonly predict the existence of new light bosons whose corresponding fields can mediate exotic interactions between particles. Examples include pseudoscalar fields (such as the axion) which naturally emerge from theories with spontaneously broken symmetries, scalar fields (such as the dilaton), a common feature of string theories, and vector fields (such as the hidden photon and extra Z' boson), which appear in new gauge theories. These new bosons, as noted above, are candidates to explain, for example, dark matter, dark energy, mysteries surrounding CP violation, and the hierarchy problem. If exotic fields mediated by such bosons exist, they would generate subtle energy perturbations that could be detected with precision quantum sensors such as atomic clocks, atomic interferometers, atomic magnetometers, micro- and nano-resonators, high-Q cavities, etc. To search for such exotic interactions, it is necessary to push the precision frontier of quantum sensors to maximize the sensitivity to energy perturbations. Of course, there is considerable synergy between these pursuits and the goals of the other PRDs discussed above, as well as numerous applications of more precise quantum sensors in other areas of physics.

A revolution in the theory and tools of quantum information sciences has produced new sensitive measurement techniques that can help the High-Energy Physics community to achieve its science objectives. New quantum sensors, for the first time, allow measurements to be made near the intrinsic noise limits imposed by the Heisenberg uncertainty principle, thus accelerating searches for new physics through the detection of dark matter, gravitational waves, and physics beyond the standard model. This leverage works both ways: bringing the unique resources and expertise of the HEP community to bear on the development of quantum sensors will lead to rapid advances in this technology, which will also benefit the quantum information science community.