Opportunities for New Quantum Sensor Technologies for HEP Science

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Summary

- Overview of how quantum sensors can advance HEP science

- Summary of 7 candidate priority research directions (PRDs) identified by BRN team

- Still a work in progress, and BRN team is still seeking input from the community

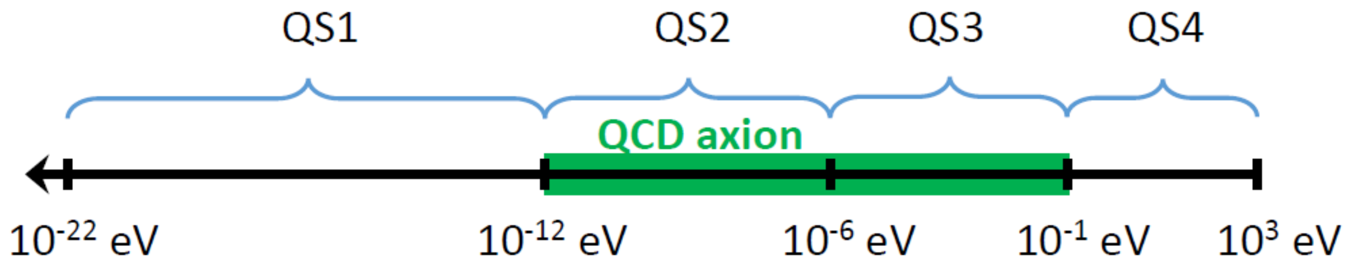
Science Drivers for Quantum Sensors

- Connections to P5 science drivers include:
  - Dark matter and dark sectors
  - Inflation
  - Exploring the unknown
  - Fundamental tests of quantum mechanics

- Related field that will be impacted by quantum sensors is gravitational wave astrophysics

- Fundamental tests of quantum mechanics naturally arise as enhanced experimental control is gained over quantum resources (e.g., entanglement or superposition involving increasingly large distance/time/mass scales)

HEP Science in Various Quantum Sensor Energy Ranges



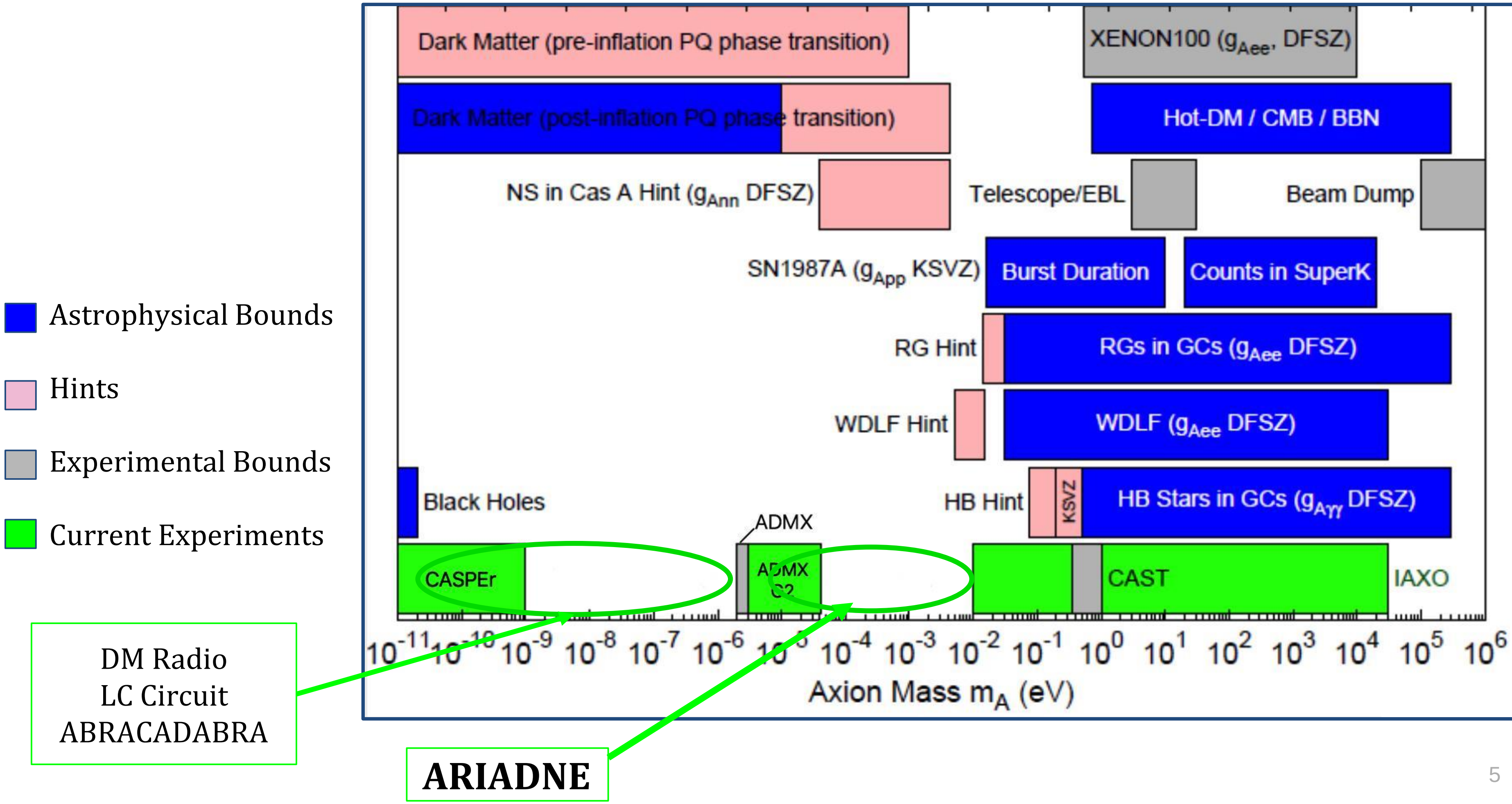
	Quantum Sensor Energy Range	HEP Science	Quantum Sensor Technology	Quantum Protocols
QS1	$< 10^{-12}$ eV	Ultralight dark matter (generalized axions, hidden photons, scalars), Electric dipole moment, Gravitational waves, Dark energy	Atomic and molecular spectroscopy, atom interferometers and mechanical 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

Candidate PRD #1: Develop the quantum sensor technology needed to probe the entire QCD axion band

- Very strong physics motivation
  - Strong CP problem
  - Excellent dark matter candidate

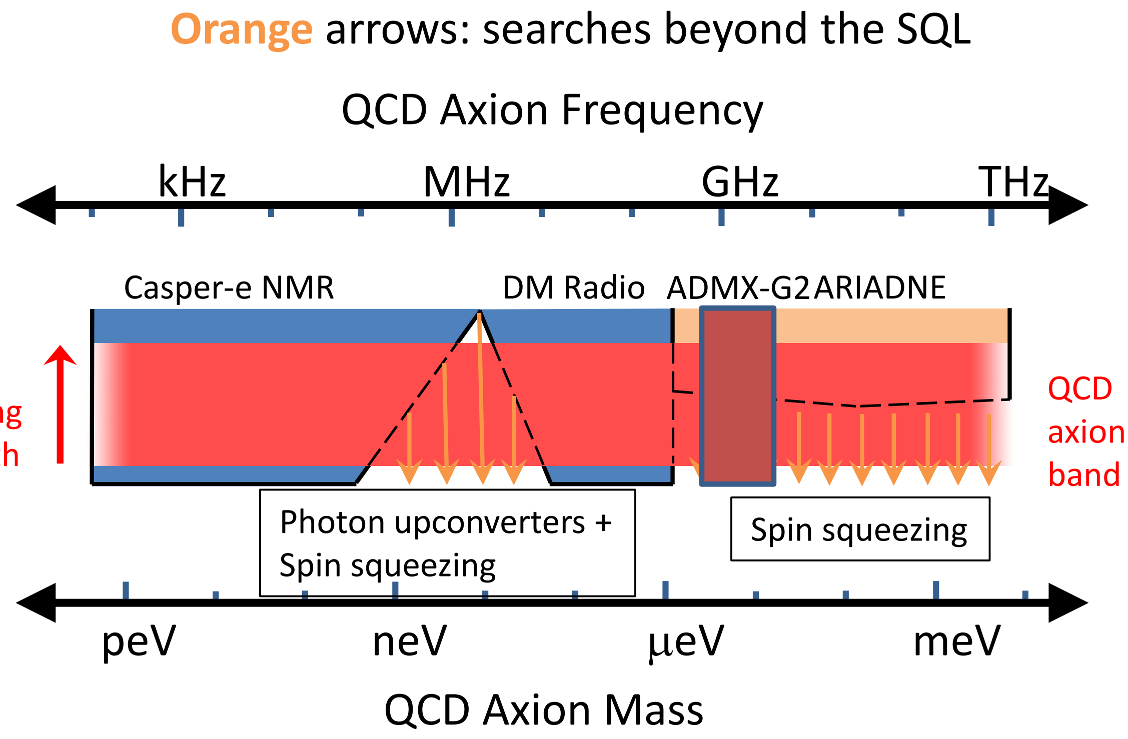
- Quantum sensor technologies
  - Nuclear spins
  - Electromagnetic quantum sensors
  - Optical cavities
  - Qubits
  - Rydberg atoms

Overview of QCD Axion Parameter Space



Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion searches at the Standard quantum limit



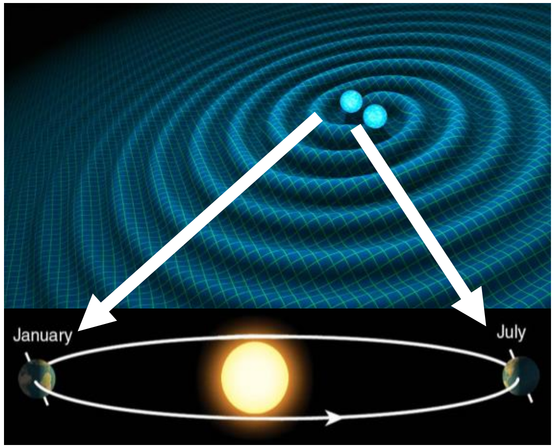
Adapted from: K. Irwin

Candidate PRD #2: Develop quantum sensor technology able to expand the frequency range of searches for gravitational waves

- Science opportunities in mid-band (0.1 -10 Hz) and high frequency >10 kHz ranges
  - Complementary to LIGO and LISA

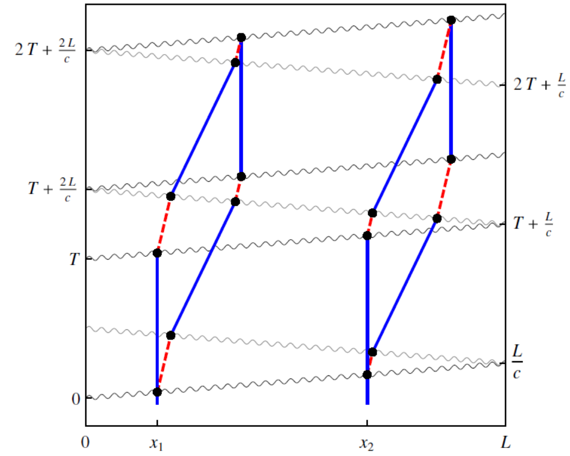
- Mid-band science
  - Search for early universe stochastic sources, e.g., from inflation (mid-band may be advantageous as compared to lower frequencies by avoiding background noise from white dwarf sources)
  - Type IA supernovae
  - Sky localization for multi-messenger astronomy

- High frequency science
  - Primordial black holes
  - QCD axion



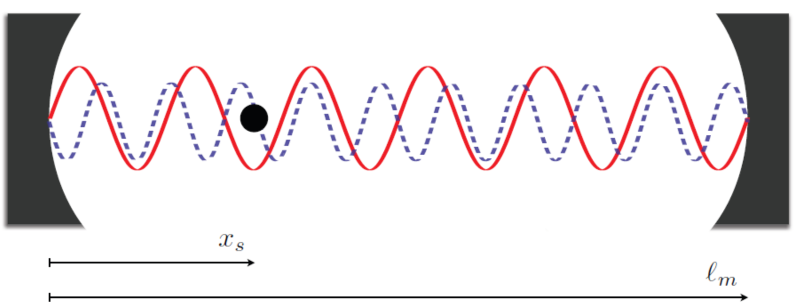
Candidate PRD #2: Develop quantum sensor technology able to expand the frequency range of searches for gravitational waves

- Mid-band quantum technologies
  - Atom interferometers and atomic clocks
  - Leverage macroscopically delocalized quantum states (for interferometers) and long coherence times
  - Leverage squeezed atomic states



Graham et al., PRL 2013

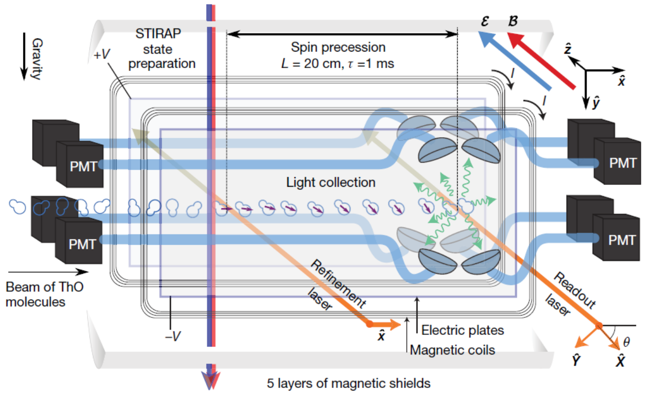
- High-frequency band quantum technologies
  - Improved control of quantum optomechanical systems



Arvanitaki and Geraci, PRL 2013

Candidate PRD #3: Searches for electric dipole moments (EDMs) and other precision tests of the Standard Model

- EDM searches
  - Provide a precise probe of time-reversal (T) symmetry
  - Sources of T-violation beyond those in the standard model required to generate the observed cosmological matter-antimatter asymmetry
  - Standard model extensions (e.g., supersymmetry) typically predict EDMs near limits from current experiments
  - Can improve with new quantum sensor technology: e.g., improved quantum control of molecules, entanglement and spin squeezing



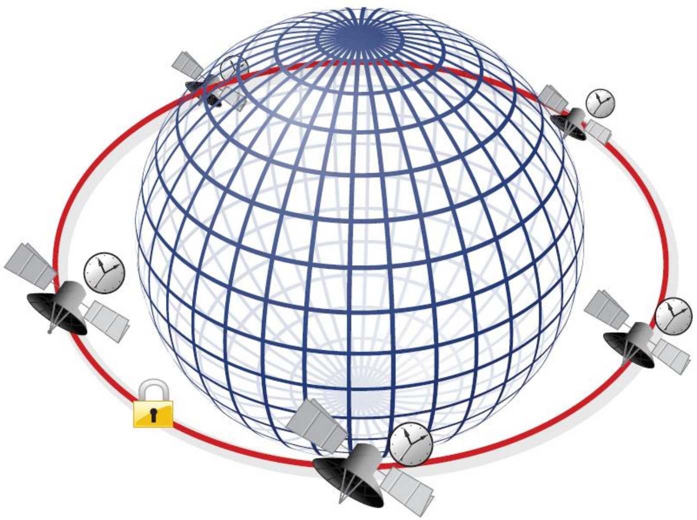
ACME Collaboration, Nature 2018

- Other tests of the Standard Model that can benefit from quantum sensors
  - Searches for spatiotemporal variation of fundamental constants
  - g-2 measurements and measurements of the fine structure constant

Candidate PRD #4: Technology for large entangled sensor networks

- Distributed arrays of quantum sensors can greatly benefit from entanglement between the different sensor nodes
  - Entanglement over long distances
  - Need for research and development into improved techniques for upconversion and transduction

- Wide range of applications
  - Improved global time standards via entangled network of atomic clocks
  - Enhanced astronomical interferometers for higher resolution images
  - Precise navigation
  - Improved geodesy



Komar et al., Nature Physics 2014

Candidate PRD #5: Develop quantum sensor technology to search for general wave-like dark matter

- Beyond just the search for the QCD axion, a broader range of very light particles can be excellent dark matter candidates (also dark energy candidates)
  - Naturally arise in unification theories such as string theory
  - In order to achieve expected average dark matter energy density, must consist of bosonic field with macroscopic occupation number—i.e., must be wave-like (if fermionic, Fermi velocity would exceed escape velocity of the galaxy)
  - Mass scale $>10^{-22}$ eV (limit set by size of dwarf galaxies)
  - Many of production mechanisms rely upon cosmic inflation—provides new probe of cosmology

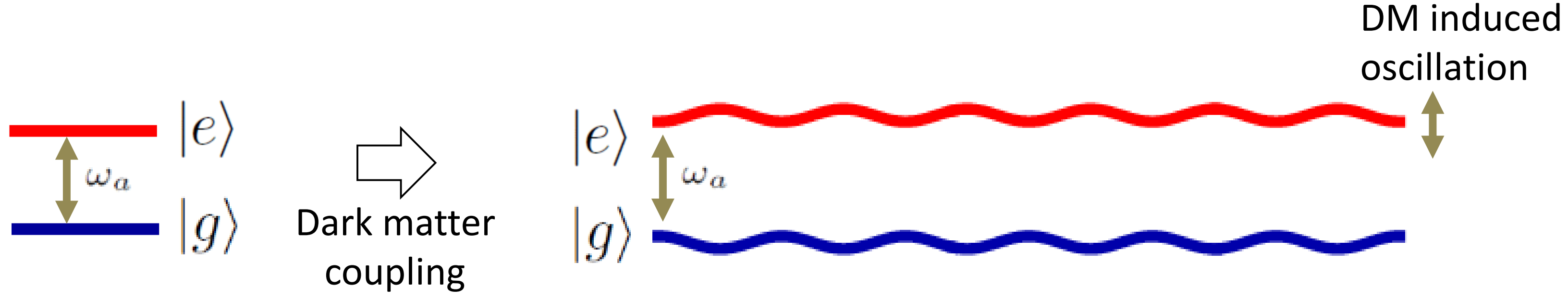
- Dark matter field oscillates at Compton frequency corresponding to mass of constituent particle

$$\phi(\boldsymbol{r},t) = \phi_0 \cos\left(\omega_\phi t - \boldsymbol{k}_\phi \cdot \boldsymbol{r} + \ldots\right).$$

$$\phi_0 = \hbar\sqrt{2\rho_{\mathrm{DM}}}/(m_\phi c)$$

Candidate PRD #5: Develop quantum sensor technology to search for general wave-like dark matter

- Variety of physical effects in precision quantum sensors
  - Oscillation of fundamental constants, which can lead to oscillating transition frequencies (see example below)
  - Oscillating, composition-dependent accelerations
  - Time-varying nucleon EDMS, spin torques, and EMFs along magnetic fields
  - EMFS in vacuum



Candidate PRD #5: Develop quantum sensor technology to search for general wave-like dark matter

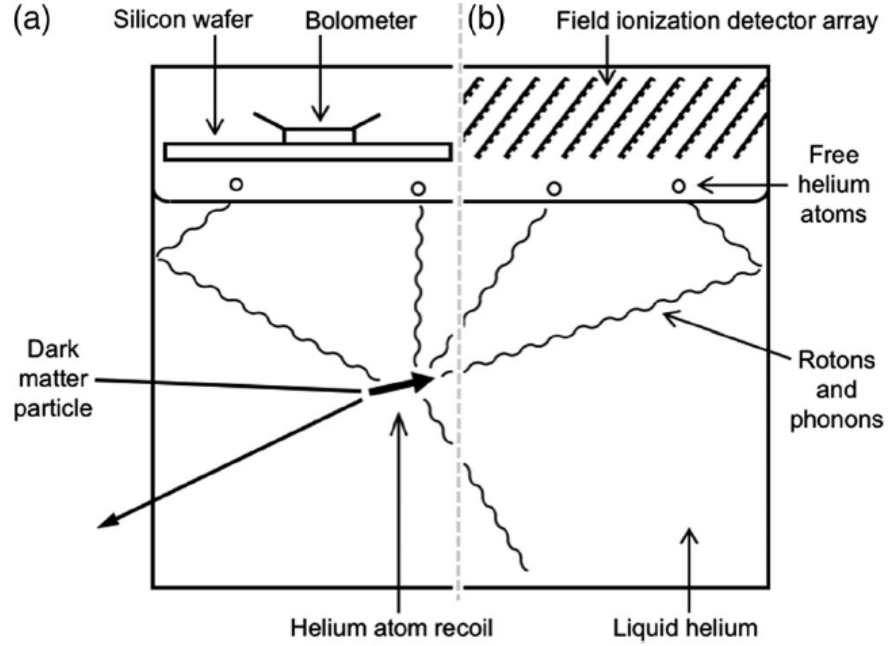
- Relevant quantum sensor technologies include the following
  - Atomic clocks
  - Atom interferometers
  - Magnetic-resonance-based sensors
  - Optical and microwave cavities
  - LC circuits
  - Single-photon detectors
  - Superconducting resonators
  - Optomechanical sensors

- Would leverage a broad range of quantum resources (research and development required to optimally make use of these resources)
  - Superposition involving macroscopic distances and long times
  - Entanglement and squeezing
  - Backaction evasion
  - Parametric amplifiers
  - QND photon counting

Candidate PRD #6: Low-threshold detection of individual dark-matter interactions

- Detect individual dark matter particles with mass in the range ~10 eV – 1 MeV (significant expansion of mass range of dark matter searches)

- Enabled by quantum sensor technologies
  - Ultrasensitive alternatives to existing bolometers and superconducting devices for detection of phonons from dark matter interaction in gram-to-kilogram scale mass detector
  - Ultrasensitive detection of phonons and rotons in superfluid He
  - Optical detection of single phonons

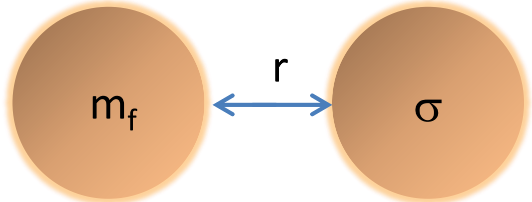


Maris et al., PRL 2017

Candidate PRD #7: Quantum sensor technology development for precision searches for exotic interactions

- Extensions of standard model commonly predict new light bosons that can mediate new interactions between particles
  - Pseudoscalar fields, such as axion (naturally emerge from theories with spontaneously broken symmetries)
  - Scalar fields such as dilaton (common feature of string theories)
  - Vector fields, such as hidden photon (appear in new gauge theories)
  - Candidates to explain dark matter, dark energy, CP violation mysteries, hierarchy problem

New physical effects:



e.g. Monopole-Dipole axion or ALP exchange

- New forces with macroscopic ranges

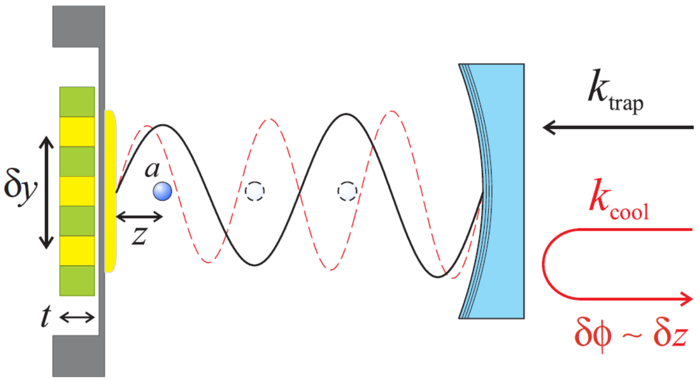
$$U(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right) e^{-r/\lambda_a} (\hat{\sigma}\cdot\hat{r}) \equiv \mu \cdot B_{\mathrm{eff}}$$

Fictitious magnetic field

- Oscillations of fundamental constants

Candidate PRD #7: Quantum sensor technology development for precision searches for exotic interactions

- Effects from such new interactions (e.g., energy perturbations or accelerations) could be searched for with quantum sensors
  - Single particles (electrons, ions) in traps
  - Laser-cooled and quantum-degenerate clouds of atoms
  - Matter wave interferometers (atoms, neutrons molecules) and atomic clocks
  - Magnetometry with polarized atoms in vapor cells or laser-polarized nuclei
  - Nano and micro-scale oscillators and resonators
  - Optically levitated micro-spheres
  - Superfluid helium
  - **Quantum technologies have significant synergy with many of the other PRDs**



Geraci et al., PRL 2010

Conclusion

- Exciting scientific opportunities will be opened by improved quantum sensors
- Identified 7 candidate priority research directions
  - 1. Develop the quantum sensor technology needed to probe the entire QCD axion band
  - 2. Develop quantum sensor technology able to expand the frequency range of searches for gravitational waves
  - 3. Searches for EDMs and other precision tests of the Standard Model
  - 4. Technology for large entangled sensor networks
  - 5. Develop quantum sensor technology to search for general wave-like dark matter
  - 6. Low-threshold detection of individual dark-matter interactions
  - 7. Quantum sensor technology development for precision searches for exotic interactions
- Still collecting input from community