Quantum Sensors for Particle Physics

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Perspectives on Quantum Sensing and Computation for Particle Physics

Overview

Overview — Quantum Sensor Regimes

- Through the dark matter lens
- More generally

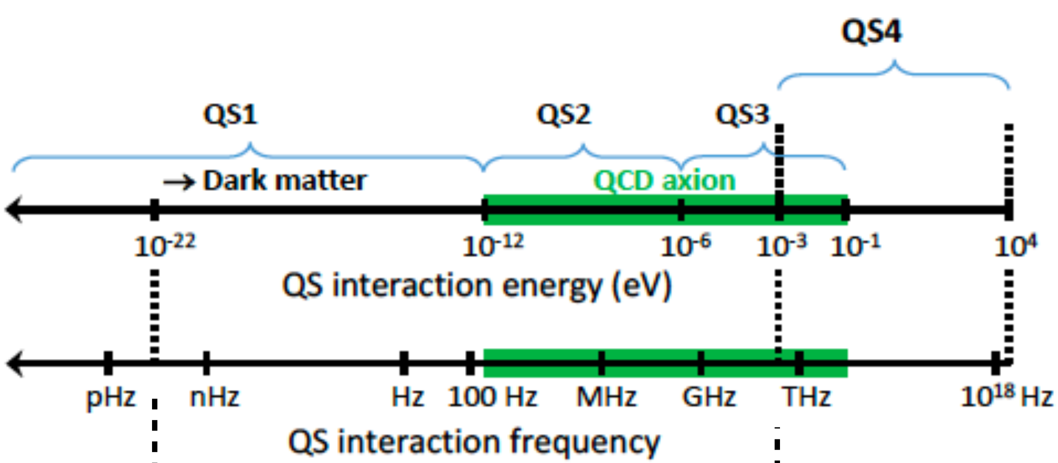
Quantum Calorimetry

Sub-meV Quantum Sensors: the truly quantum regime

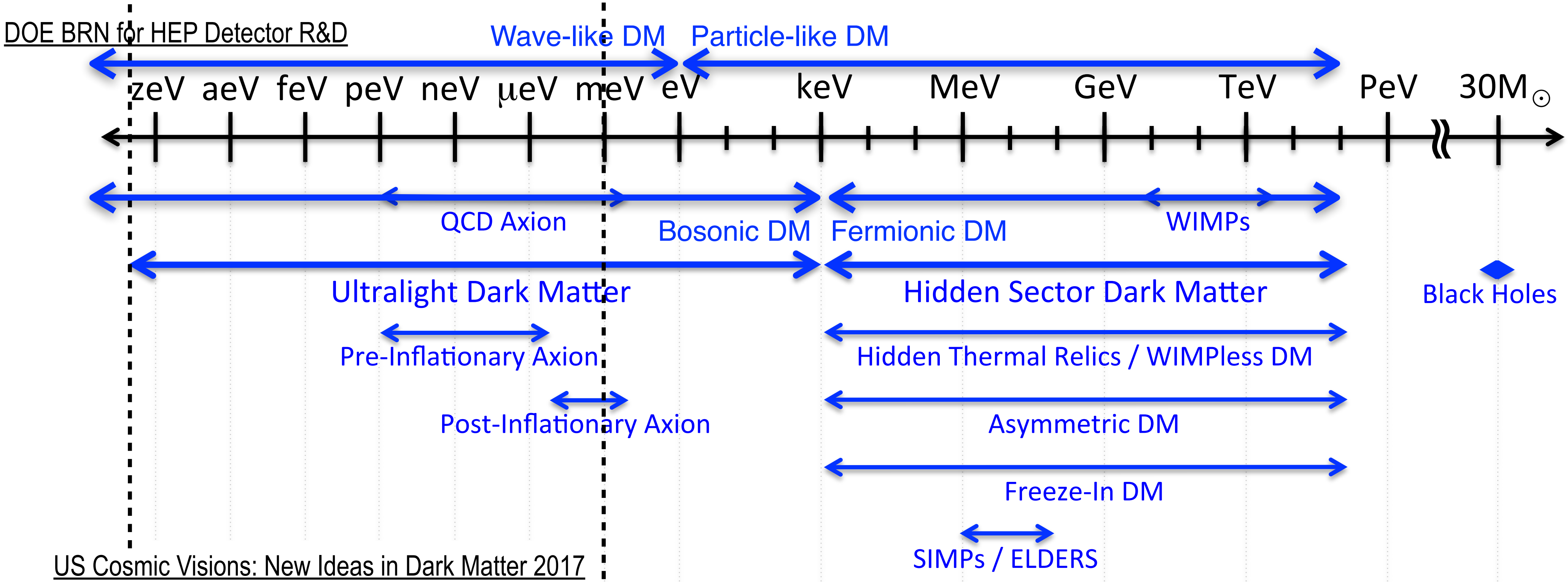
Caveats:

- DM motivates much of the quantum sensing universe
- My own expertise is primarily in quantum calorimetry and dark matter
- Much of the remainder drawn from DOE reports:
  - Basic Research Needs for Dark Matter Small Projects New Initiatives (2019)
  - Basic Research Needs for High Energy Physics Detector Research & Development (2020)

Dark Matter → Quantum Sensors

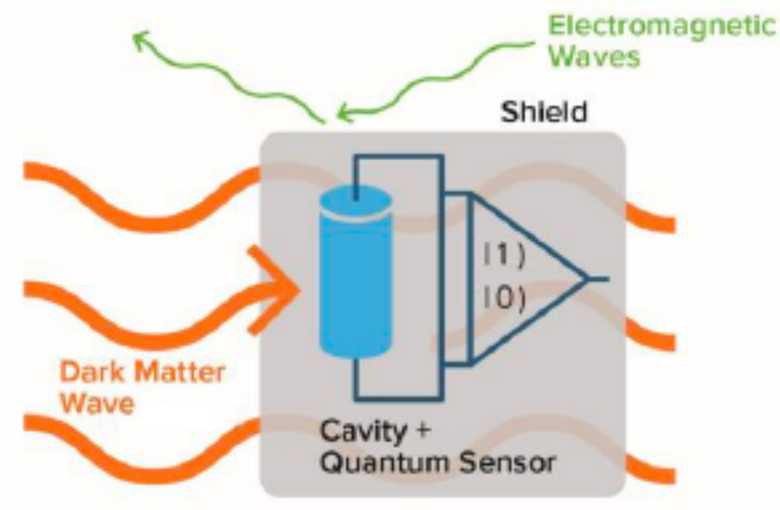


- QS for particle physics driven in large part by 2017 US Cosmic Visions *New Ideas in DM* white paper
- Seeking to cover $E_{dep} \lesssim$ keV inaccessible to classic particle DM searches
- QS regime includes both wave-like (~classical field) and particle-like DM



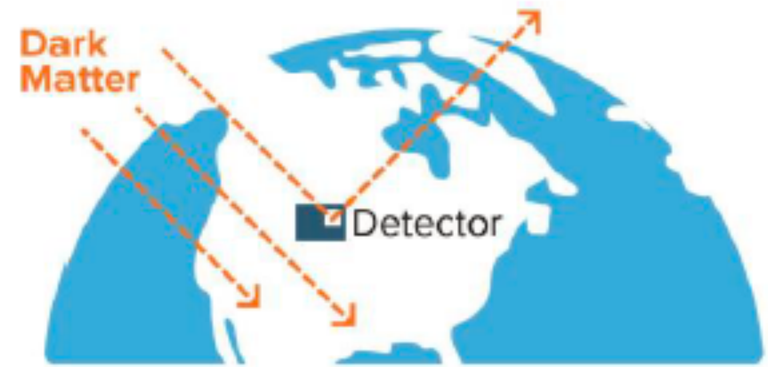
Dark Matter → Quantum Sensors

Wave-like Dark Matter



- Occupation number ≫ 1: cannot identify individual DM particles, sense "Collective force from macroscopic numbers of particles"
- New light scalar (axion-like particle (ALP) or vector (dark photon (DP))
- Quantum zero-point fluctuations are the primary obstacle: a quantum problem
  - Fundamentally quantum approaches needed to circumvent

Particle-like Dark Matter



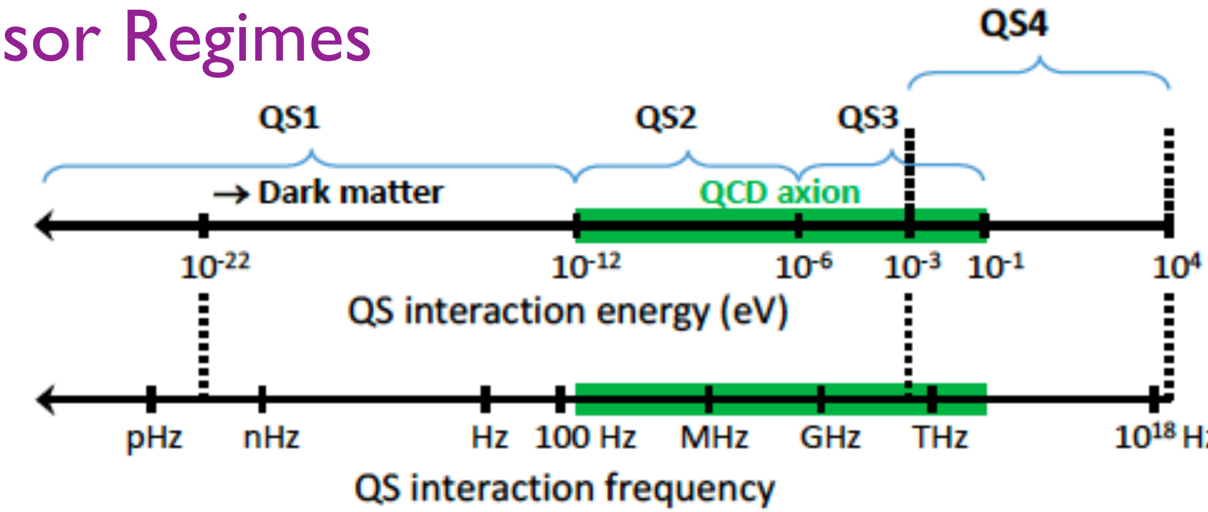
- Occupation number ≪ 1: individual particles can be seen*
- Scattering of fermionic DM, absorption of heavier ALPs, DPs, and
- "Quantum" effects:
  - <u>*Direct*</u> creation of single quantum (not via identifiable particle recoil)
  - Use of quantum sensors to see the very small energy depositions
    - eV → meV → μeV?

*Occupation number > 1 for bosonic DM does not imply particle-like absorption is not possible, but it makes classical field detection possible.

Cartoons from <u>DOE BRN for Dark Matter Small Projects New Initiatives</u>

Beyond DM: Quantum Sensor Regimes

ULDM = ultralight dark matter
EDM = electric dipole moment
GW = gravitational waves
DE = dark energy
FSV = fund. symmetry violations
QND = quantum non-demolition



Regime/ Mass	Science Target		Quantum Sensor Technology	Quantum Protocol
QS1 < 10^{-12} eV	ULDM, EDMs, GW, DE, FSV	wave-like	Atomic and molecular spectroscopy, atom interferometers, mechanical sensors, clocks, atomic magnetometers, nuclear, electronic, and other spins, quantum defects in solids	Superposition, entanglement, squeezing, coherence
QS2 10^{-12} to 10^{-6} eV	ULDM incl. axions, FSV, new forces/ particles		Nuclear, electronic, and other spins, electromagnetic quantum sensors, optical cavities, quantum defects in solids	Superposition, entanglement, backaction evasion, squeezing, coherence
QS3 10^{-6} to 10^{-1} eV			Superconducting and other qubits, nuclear, electronic, and other spins, Rydberg atoms, quantum defects in solids	Parametric amplifiers, superposition, entanglement, squeezing, coherence, QND photon counting
QS4 10^{-3} to 10^{4} eV	ULDM scattering/ absorption, FSV, new forces/particles	particle-like	Single-photon counters, low-threshold phonon and charge detectors, quantum defects in solids	Non-QND photon counting, high spatial resolution measurements of particle tracks

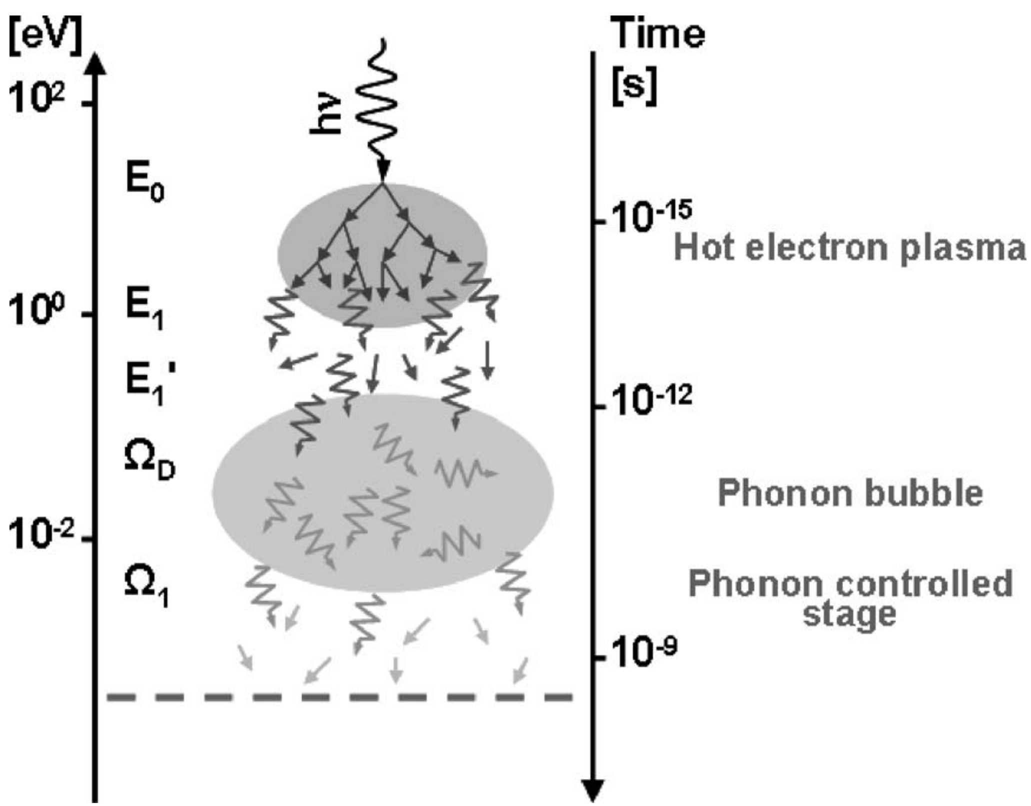
DOE BRN for HEP Detector R&D

Quantum Calorimeters

"Logical conclusion" of existing solid-state modalities for sensing phonons, ionization, and scintillation

Semi-classical picture

- Enough quanta produced to treat as continuous variable
  - Quantization not apparent in $E_{observed}$.



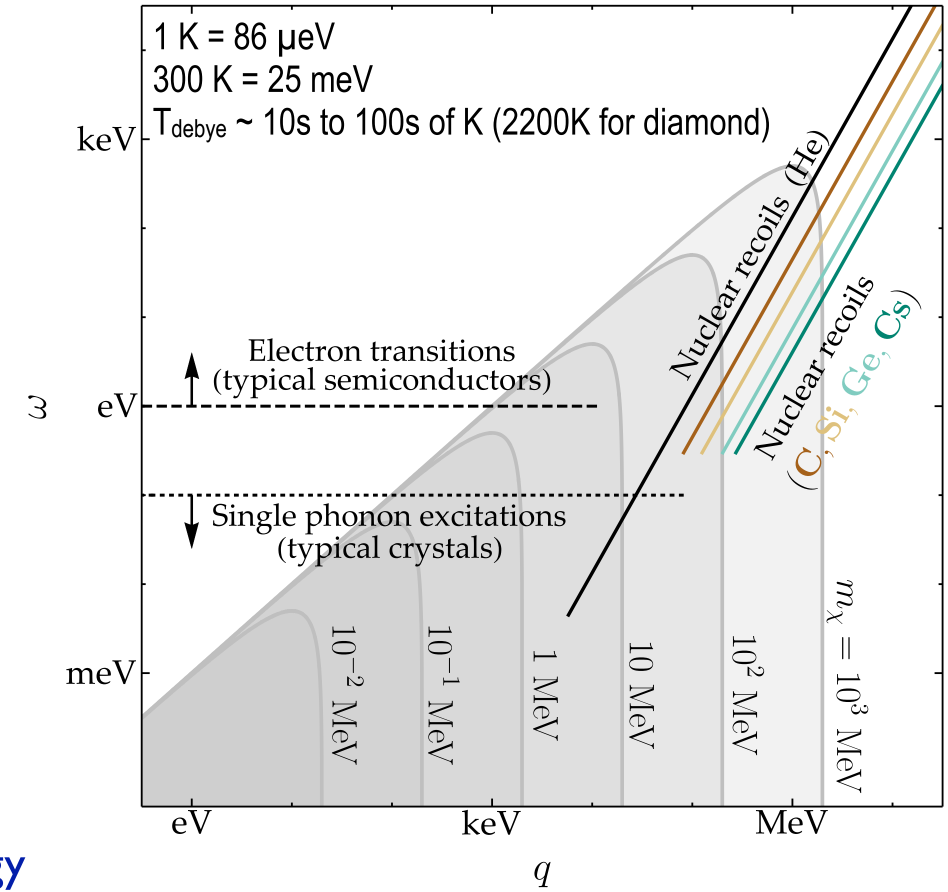
Kozorezov et al PRB: 75, 094513 (2007)

Quantum picture

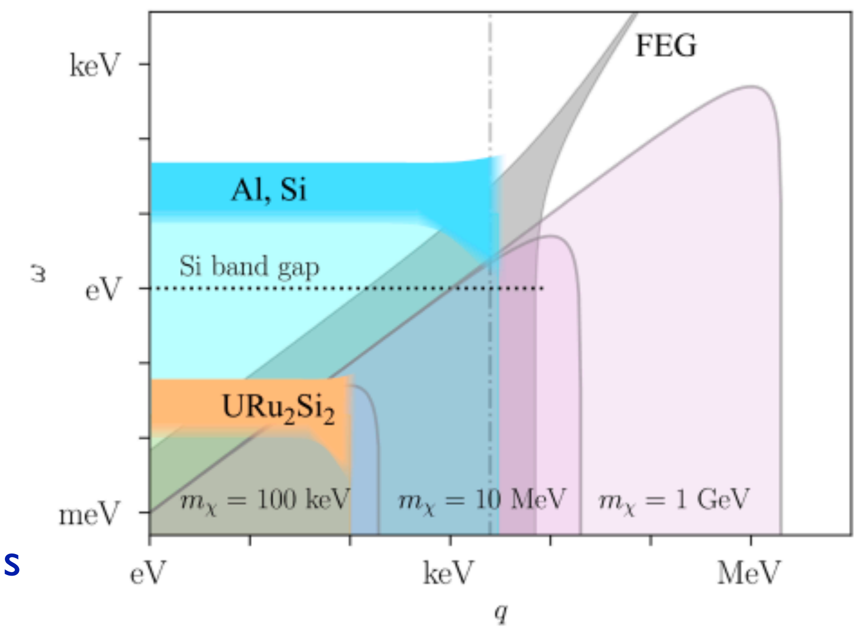
- Production of single charges or scintillation photons (eV quantization)
  - Arguable whether sensing single charges or photons is really "quantum" (e.g., PMTs)
- Innovations that lead to "quantum" regime:
  - SNSPDs that detect single photons with near 100% efficiency
  - Reaching the regime of detection of 1-few athermal phonons (meV) or 1-few thermal phonons (μeV)
  - Energy depositions so small that "quantum" techniques must be used to detect

Quantum Calorimeters: Kinematics and Scattering Modes

- Energy-momentum transfer of galactic DM scattering kinematically limited by max v_{DM}
- Nuclear recoils follow lines
  - Truncated where scattering with single nucleus invalid, q < (lattice constant)$^{-1}$
  - Direct single phonon creation via coherent multi-site interaction valid for lower q
  - Also: coherent photon scattering w/nucleus
- Electron recoils
  - FEG = free electron gas, valid for E > binding energy
    - superconductor gap, semiconductor/insulator bandgap
  - Band gap (e.g. Si) shows energies accessible by e-h pair creation in semiconductors/insulators
    - Suppressed for high q because wavefunction too large
  - Blue shaded region: plasmons
    - Mostly outside allowed region except for heavy f materials (e.g. URu_2Si_2)
- Light/Dark Photon absorption
  - Coupling to unit cell dipole moment in polar materials



Trickle et al, JHEP 3:36 (2020)



Hochberg et al, arXiv:2101.08263

Quantum Calorimeters: Interaction vs. Creation vs. Sensing

Interaction modalities

DM

Nucleus scattering

single-site

multi-site

Electron scattering

single-site

multi-site
(dielectric absorption function)

Neutrinos

Nucleus scattering

single-site

multi-site

Photons

Electron scattering

single-site

multi-site
(dielectric absorption function)

Cavity or antenna mode creation

Creation modalities

Single e-h pair creation

Single scintillation photon creation

Single optical phonon creation

Single acoustic phonon creation

Single Cooper pair breaking

Single plasmon creation

Exotic quanta

Dirac materials, magnons, …

Single conversion photon creation

Sensing Modalities: mostly cryogenic

Transition-Edge Sensors (TESs)

Kinetic Inductance Detectors (KIDs)

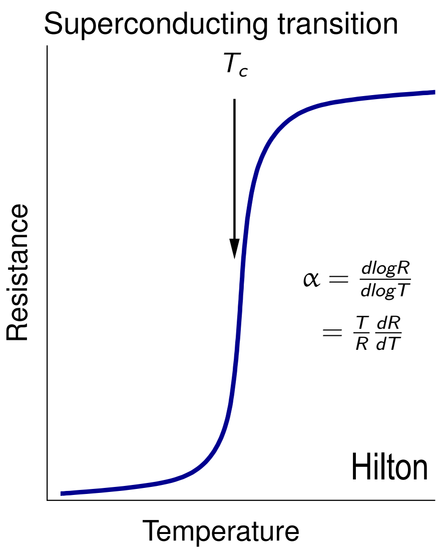
Skipper CCDs

Superconducting Nanowire Single Photon Detectors (SNSPDs)

Parametric amplifiers for squeezing

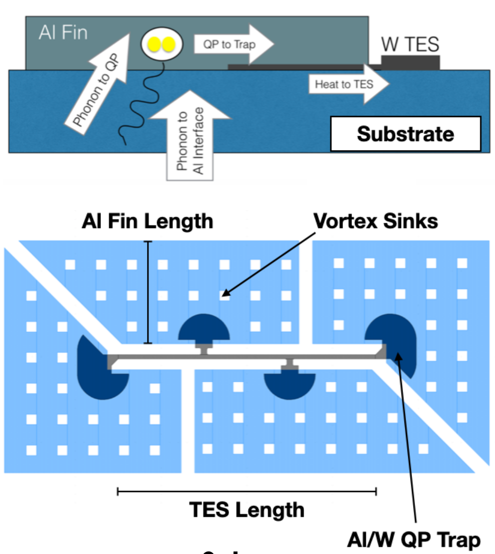
Quantum non-demolition (QND) photon detectors

Quantum Calorimeters Today

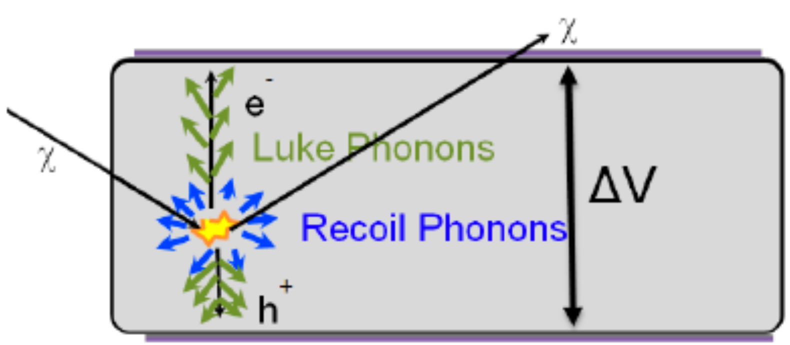


Calorimeters based on Transition-Edge Sensors

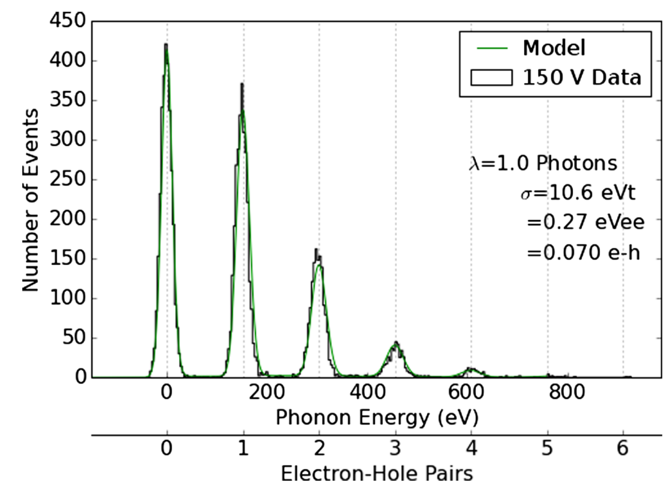
- TESs provide very sharp resistance vs. T curve
  - Electothermal feedback can be used to stabilize
  - Electrical signal measures received energy
- Coupled to calorimetric substrate via athermal phonon collectors
- Now approaching the quantum regime
  - Large bias voltage provides amplification via Neganov-Trofimov-Luke phonons: enables single e-h pair detection
    - But subject to significant leakage currents: single eh pair detection unreliable
  - Native resolution ~ 3 eV achieved
  - Reduced T_c, improved design expected to yield sub-eV resolutions, eventually approaching 10 meV
    - Single eh pair detection without leakage
    - Single phonon detection



~0.1 mm



1-10 cm



PRL 121: 0513401 (2018)

Quantum Calorimeters Today

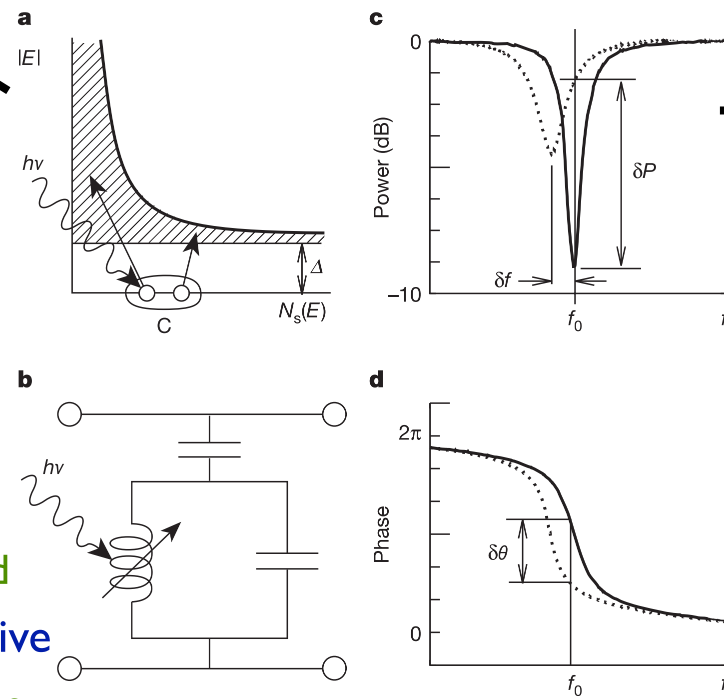
Kinetic Inductance Detectors (KIDs)

Superconductors have an AC inductance due to inertia of Cooper pairs

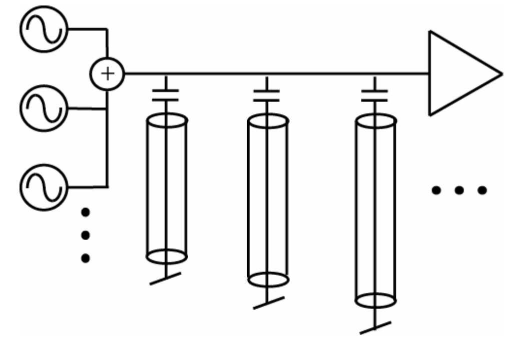
KID = superconducting film incorporated into LC resonator to sense change in L

Energy resolution:
sub-eV → meV
thresholds w/o HV

- Direct sensitivity to pair-breaking phonons
  - Large resonators obviate phonon collectors
- Gapped density of states
  - Thermal quasiparticles exponentially suppressed
- Fundamentally non-dissipative
  - Amenable to QIS techniques (e.g. squeezing, QND)
- Noise is limited by
  - quasiparticle population fluctuations
  - amplifier noise



Day



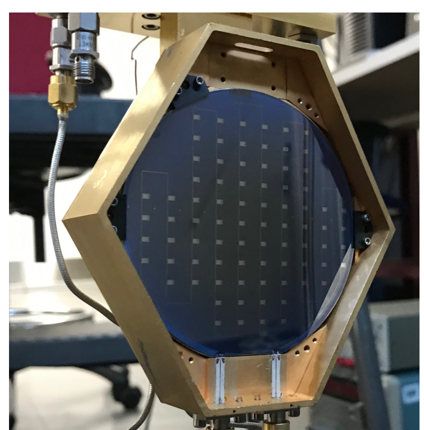
Multiplexing:

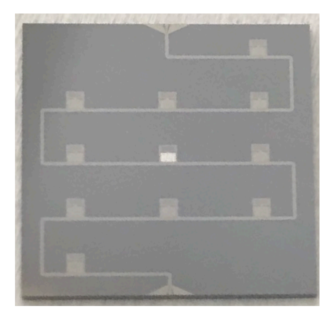
KIDs are Q>10^5 resonators

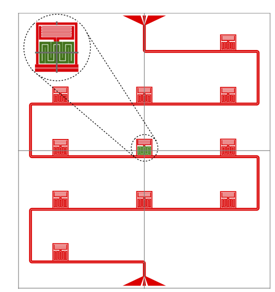
→ Readout many with one cryo line/amplifier; most electronics at 300K

→ Highly position-resolved phonon detection

75 mm
x 1 mm

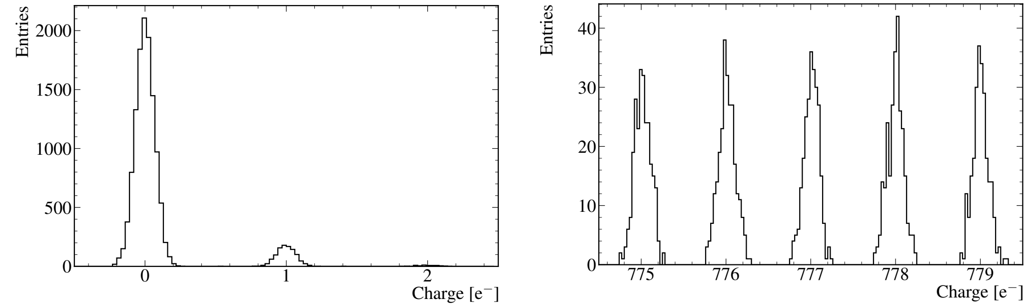






22 mm
x 1 mm

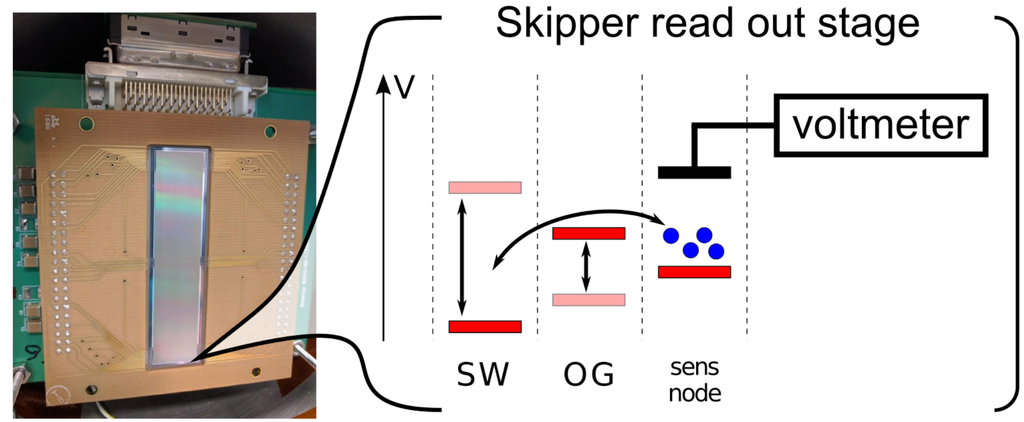
Quantum Calorimeters Today



PRL 119: 131802 (2017)

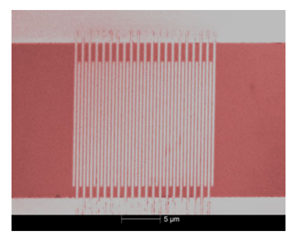
Skipper CCDs

- CCD with two readout innovations
  - High-frequency differencing to reduce impact of 1/f amplifier noise
  - Non-destructive multiple read cycles to reduce electronics noise by √N
- Provides similar single-eh pair sensitivity
- Currently being applied for DM searches, low-light-level astronomy

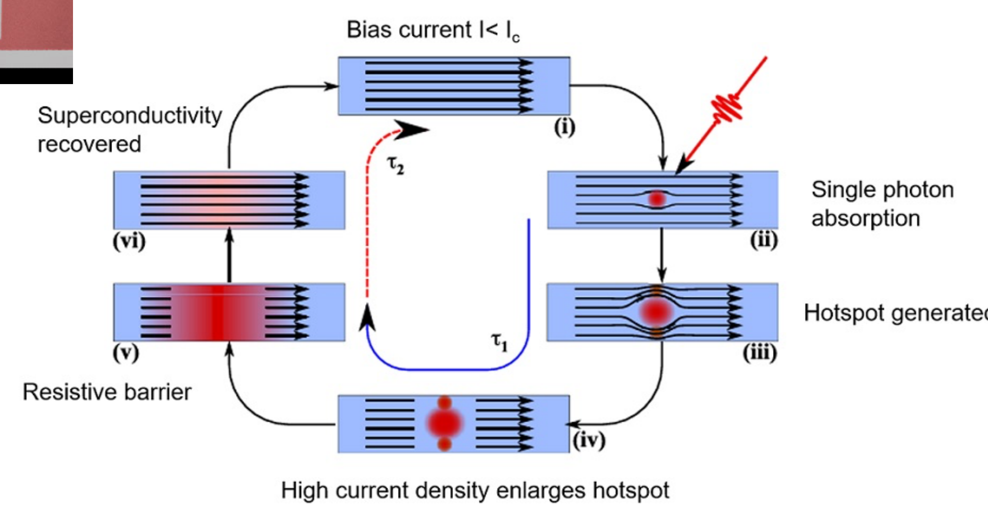


https://sensei-skipper.github.io/#SkipperCCD

Superconducting Nanowire Single Photon Detectors (SNSPDs)



- Threshold detector for single photons
  - Very narrow (~100 nm) superconducting meander biased close to transition
  - Absorption of photon drives normal
- ps timing resolution
- Provides high-efficiency, high-fidelity photon counter for QIS applications
- WSi demonstrated with 100 meV threshold
- Very low dark count rate demonstrated, applicable for DM searches
  - But very small volume



https://singlequantum.com/technology/snspd/

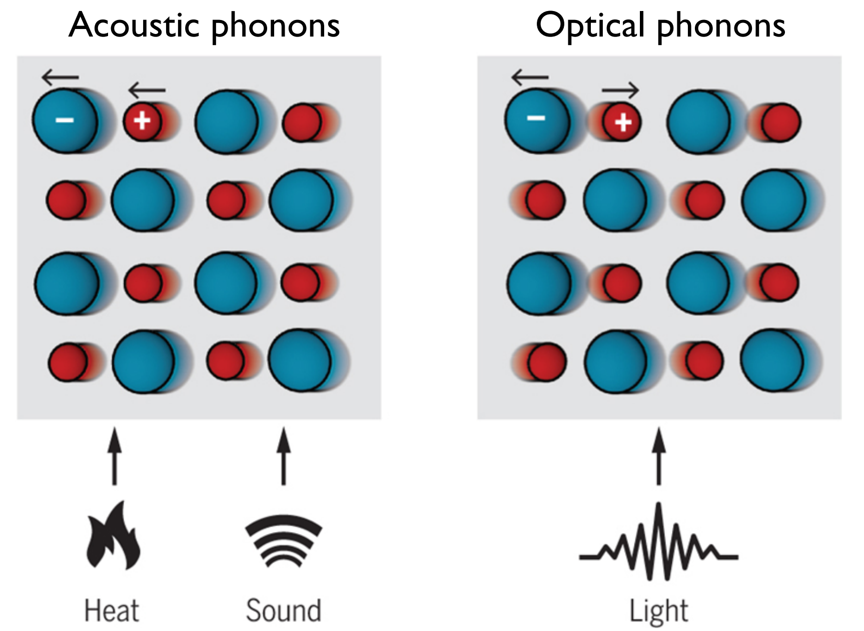
Quantum Calorimeters in the Future

Single optical phonon creation/detection

- Polar materials:
  - > 1 atom/unit cell → optical phonons (10s of meV)
  - polar → unit cell EDM can couple to dark photons
- Optical phonon creation provides access to electron scattering down to few keV m_{DM}

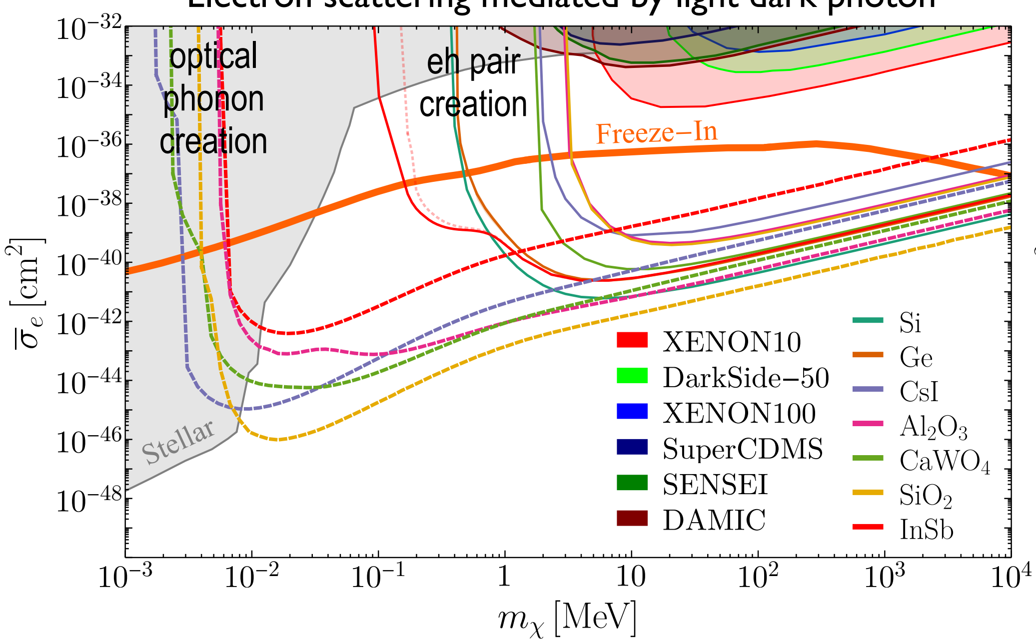
Single acoustic phonon creation/detection

- DM interacting with many nuclei coherently
- Requires meV-100 meV thresholds
- Eventual reach down to few keV m_{DM}

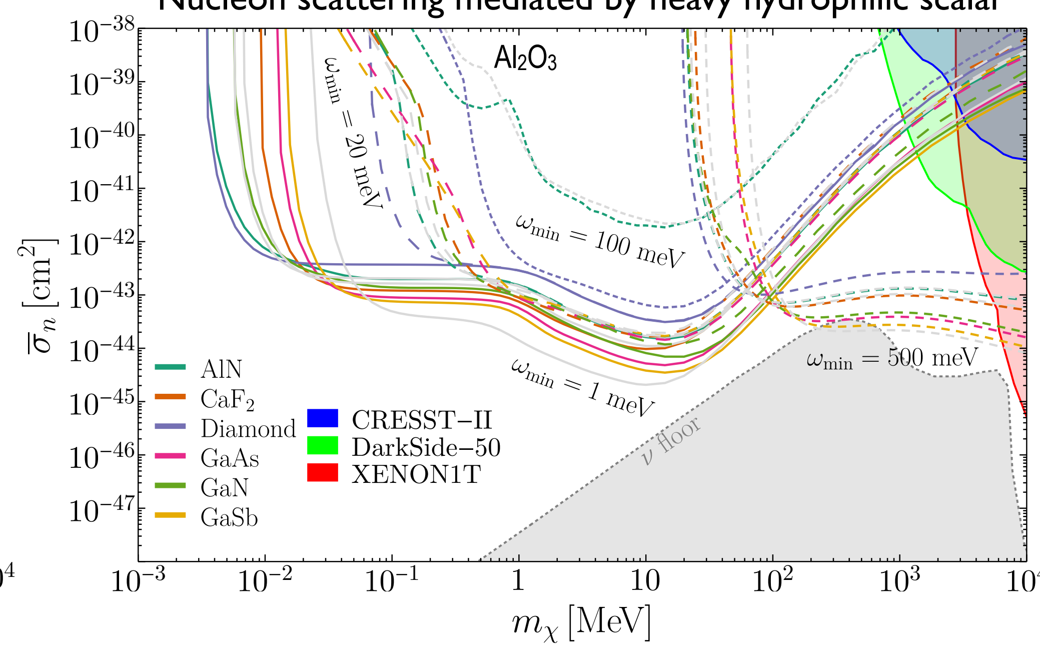


https://images.app.goo.gl/vvBWneR6noCnseCXA

Electron scattering mediated by light dark photon



Nucleon scattering mediated by heavy hydrophilic scalar

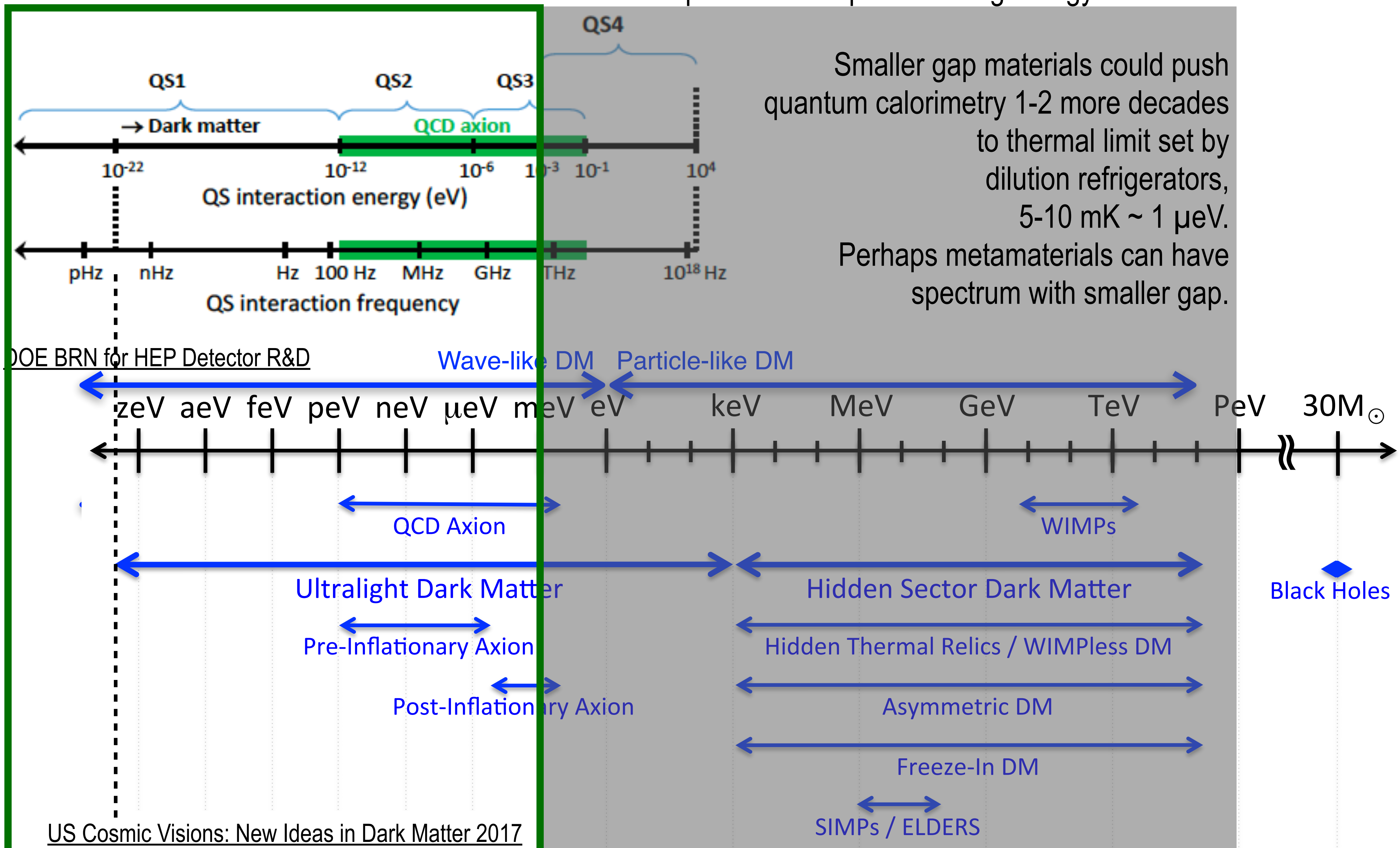


Griffin et al. arXiv:1910.10716

Sub-meV Quantum Sensors (→ Wave-like DM)

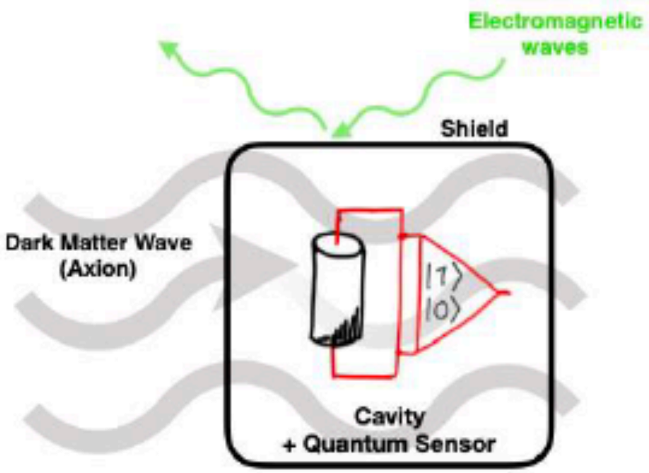
Natural limit for quantum calorimeters
set by smallest available gapped excitation:
superconductor pair-breaking energy ~ 0.1 meV.

Smaller gap materials could push
quantum calorimetry 1-2 more decades
to thermal limit set by
dilution refrigerators,
5-10 mK ~ 1 μeV.
Perhaps metamaterials can have
spectrum with smaller gap.

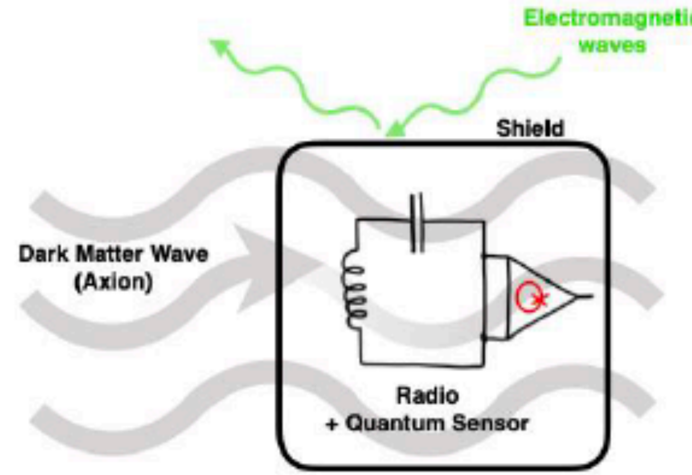


Sub-meV Quantum Sensors (→ Wave-like DM)

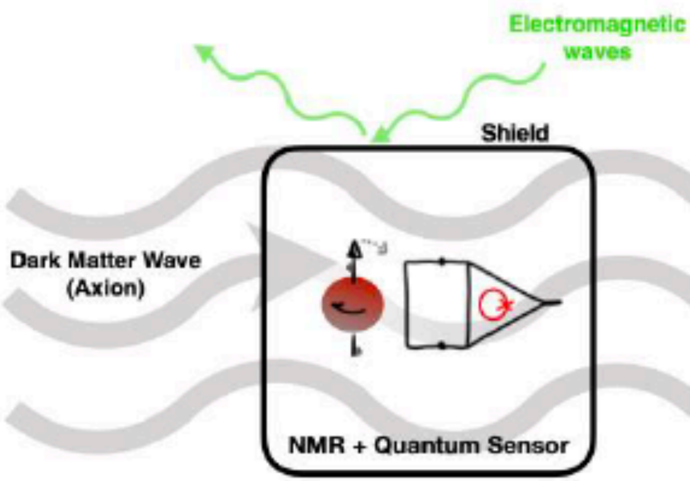
Wide range of techniques depending on coupling and mass: EM, QCD, spin, other



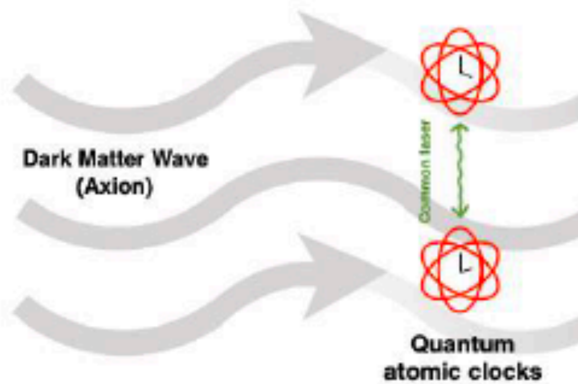
Microwave Cavity



Lumped Element



Magnetic Resonance

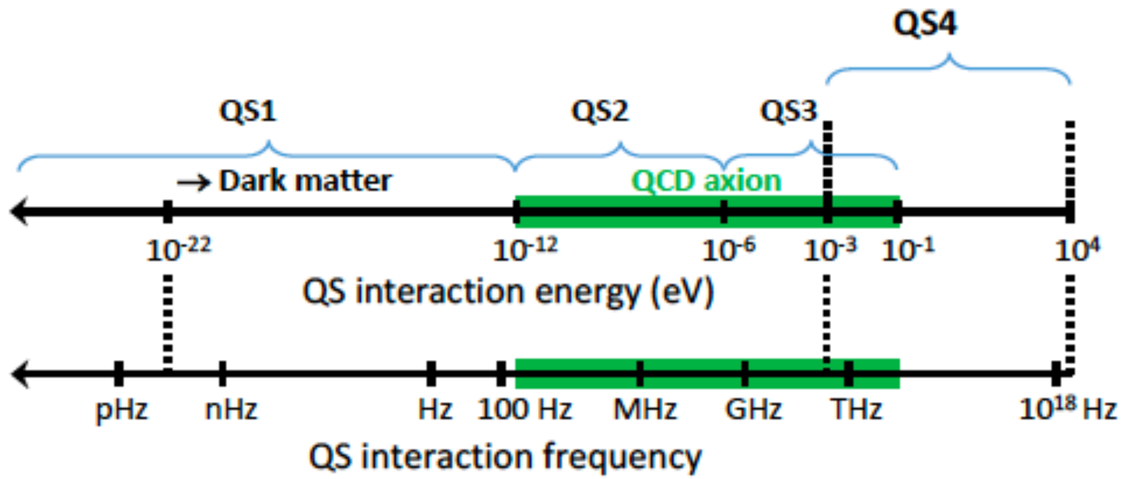


Atom Interferometry

Same approaches amenable to fifth-force/light-shining-through-walls experiments

Cartoons from DOE BRN for Dark Matter Small Projects New Initiatives

Sub-meV Quantum Sensors: ULDM via EM Coupling



DOE BRN for HEP Detector R&D

> 1 μeV (240 Hz) mass range

- < 240 Hz impractical for photon conversion given EM-saturated environment

Classic quantum-limited photon detection problem

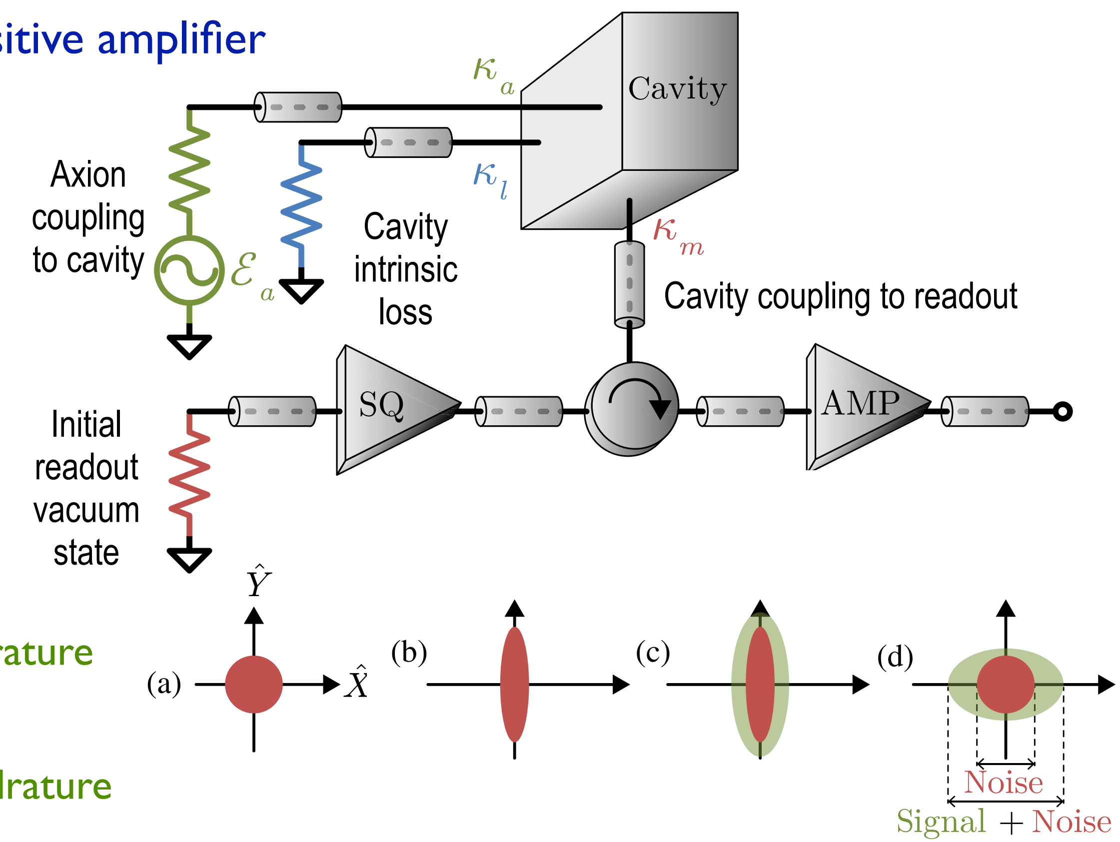
practical limit of commercial dilution refrigerators ≈ 5-10 mK

- → Smallest thermal energy per mode accessible ~ 1 μeV ~ 240 MHz
- → Two regimes:
- 1 μeV to 100 meV (240 MHz to 24 THz, QS3)
  - Detection modality can be placed in quantum ground state
  - e.g., resonant cavity with no thermally generated photons, only 1/2 photon vacuum fluctuation
- 1 peV to 1 μeV (240 Hz to 240 MHz, QS2)
  - Thermal state for detection modality unavoidable
  - Upconvert to GHz for readout to make use of established techniques for sub-SQL amplification

Sub-meV Quantum Sensors: ULDM via EM Coupling

1 μeV to 100 meV (240 MHz to 24 THz, QS3) example: HAYSTAC axion search ($g_{a\gamma\gamma}$)

- Classical amplifier approach:
  - Standard quantum limit (SQL): a phase-insensitive amplifier adds 1/2 photon noise in each quadrature
    - due to internal modes that enable gain in both quadratures
- Quantum sensing approach:
  - Phase-sensitive amplification (Caves, 1982) circumvents this
    - Attenuate one quadrature while amplifying the other, preserving uncertainty area in quadrature phase space.
    - No fundamental limit to noise in amplified quadrature; practical limit set by parasitic losses, 0.01-0.1xSQL achievable
  - Phase-sensitive amplification applied to vacuum can attenuate vacuum fluctuations in one quadrature
- SQ = vacuum squeezer, AMP = phase-sensitive amplifier
- a) vacuum state before SQ
- (b)-(d) w/SQ and AMP:
  - b) vacuum state after SQ: noise squeezed in X quadrature, amplified in Y
  - c) state after addition of signal from cavity
  - d) state after phase-sensitive amplifier: amplify in X, attenuate in Y, without adding significant noise
- w/o SQ:
  - Add 1/2 photon vacuum noise in each quadrature
- w/o AMP (i.e., a standard amplifier)
  - Add 1/2 photon amplifier noise in each quadrature



Sub-meV Quantum Sensors: ULDM via EM Coupling

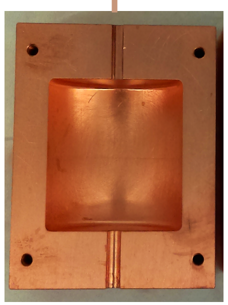
1 μeV to 100 meV (240 MHz to 24 THz, QS3) example: QND photon counting ($g_{a\gamma\gamma}$)

Logical limit of squeezing:

- photon counting senses only the amplitude quadrature
- insensitive to vacuum fluctuations
- quantum non-demolition approach ensures high fidelity to eliminate false positives

e.g., Couple a transmon qubit to axion conversion cavity (Dixit et al 2021)

$$\mathcal{H} = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$



g: cavity-qubit coupling

$\Delta = \omega_q - \omega_c$ detuning

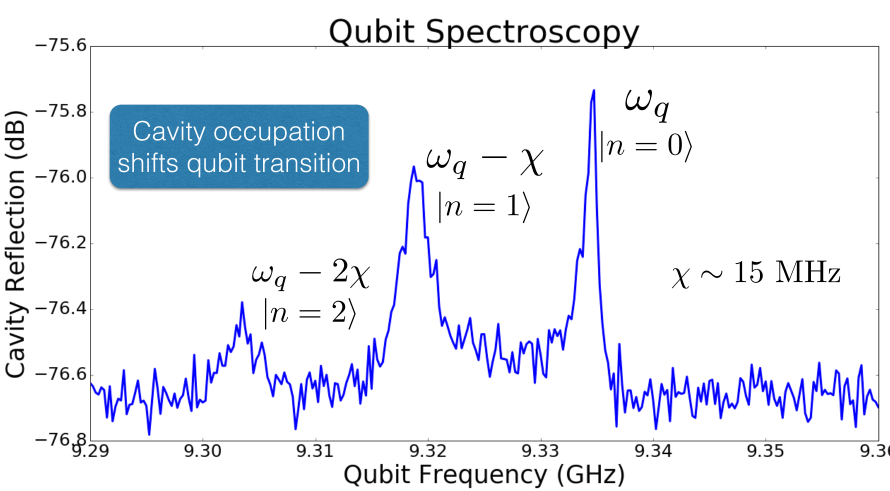
$\chi = \frac{g^2}{\Delta}$ Stark Shift

Axion induced current pumps cavity with photon → Cavity occupation shifts qubit transition

$$\mathcal{H} = \omega_c a^\dagger a + (\omega_q + 2\frac{g^2}{\Delta} a^\dagger a)\sigma_z$$

→ Excite qubit at shifted frequency → Measure flipped qubit by monitoring cavity line shift

$$\mathcal{H} = (\omega_c + 2\frac{g^2}{\Delta}\sigma_z) a^\dagger a + \omega_q \sigma_z$$



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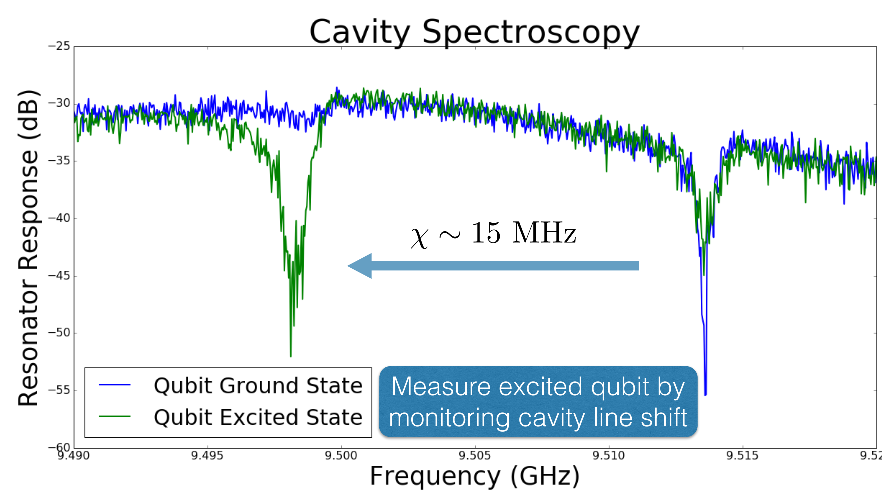

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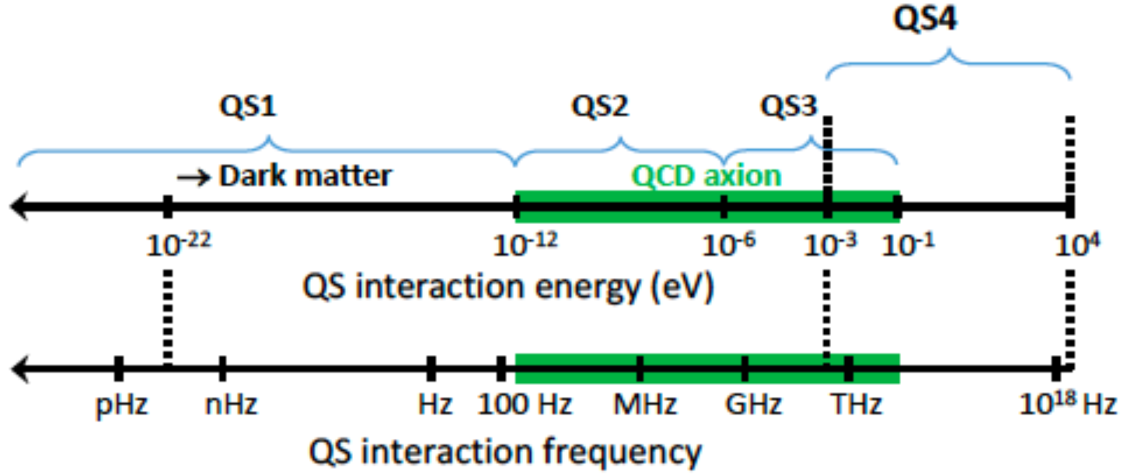
Sub-meV Quantum Sensors: ULDM via QCD & Spin Couplings



DOE BRN for HEP Detector R&D

Exploit the weak coupling between ULDM and nuclear strong charge and/or spin

Axions:

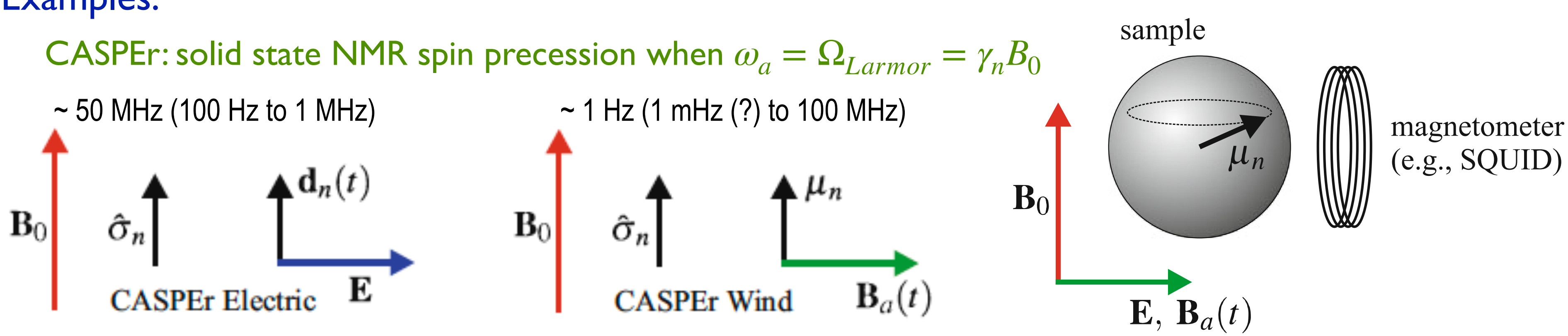
g_d axion-gluon coupling yields a time-varying nuclear EDM along spin axis

g_{aNN} axion-nuclear-spin coupling causes interaction of nuclear spin with gradient of axion field (axion wind)

In both cases, consider axion to be a classical time-varying field $a(\vec{r}, t) = \left(\hbar\sqrt{2\,\rho_{DM}}/m_a\,c\right)\cos\omega_a t$

Examples:

CASPEr: solid state NMR spin precession when $\omega_a = \Omega_{Larmor} = \gamma_n B_0$



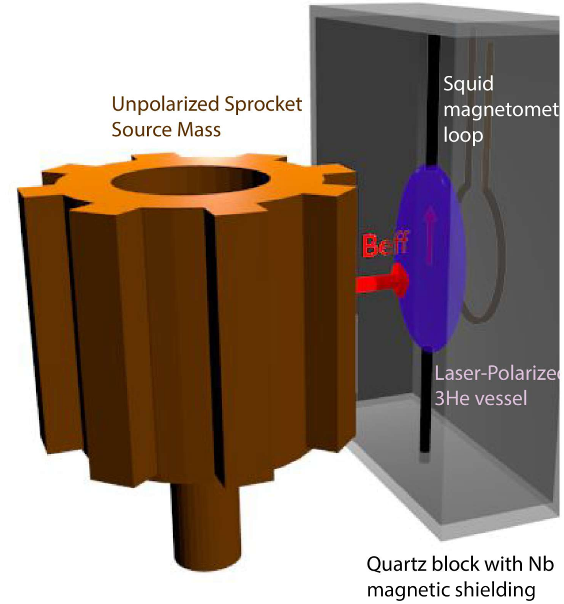
Diagrams from Kimball et al 2020

Atomic magnetometers, spin-polarized torsion balances suitable for lower frequencies (10^{-8} to 100 Hz)

Sub-meV Quantum Sensors: Other Ideas

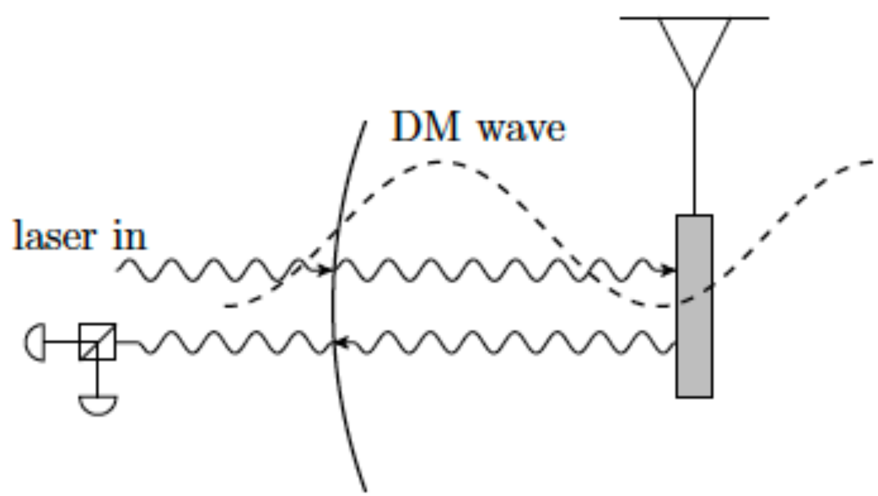
Fifth Forces: Replace time-varying cosmological DM axion-like particle or dark photon field with one created in the lab

- e.g. ARIADNE
  - Apply time-varying ALP fifth force to laser-polarized 3He cell via rotating sprocket source mass
  - NMR measurement of 3He (a la CASPEr)
  - SQUID magnetometer pickup



Opto-Mechanical Approaches for ULDM

- Use laser-interferometric techniques to measure position difference between fixed and suspended masses composed of different materials
  - e.g., g_{aNN} axion-nuclear-spin coupling would result in different DM forces on materials of same mass
- Can benefit from vacuum squeezing/squeeze amplification techniques as used in LIGO (and HAYSTAC)



Carney et al, arXiv:1908.04797

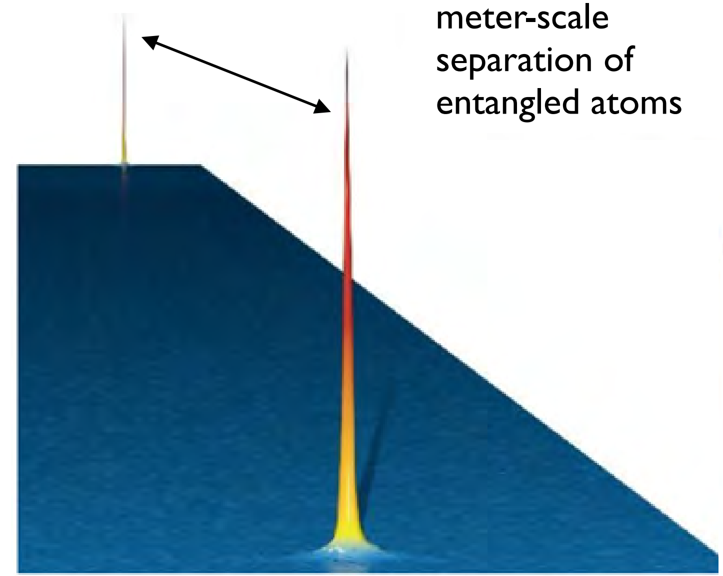
Sub-meV Quantum Sensors: Atomic Clocks, Atom Interferometers, Entanglement, etc.

Signatures of new physics:
DM and symmetry violation

- time-dependent, equivalence-principle-violating accelerations
  - different DM couplings for different types of atoms (e.g., g_{aNN})
  - symmetry violations yielding different forces on different kinds of atoms
- time variation of effective fundamental constants
  - e.g., time-varying atomic transition frequencies
- nuclear spin precession

Technical advances in atom interferometers

- macroscopic delocalization (~1 m scale)
- gradiometer configurations to cancel environmental systematics
- single-photon atom interferometry
- sub-nK cooling
- dual species



Entanglement as a tool

- Squeezing is one type of entanglement: preparation of a specific type of quantum state
- Generically, entanglement provides robustness against random noise processes, decoherence, etc.
- Entanglement of distant sensors may provide ways to search for dark matter, better understand dark energy, and/or do new types of astronomical observations

Conclusions

The field of quantum sensors is very broad-ranging, employing a wide range of techniques from condensed matter physics, atomic/molecular/ optical physics, and quantum information science

The interaction between particle physicists and these other fields has been intellectual exciting and very fruitful

Quantum Sensors are opening up significant new parameter space for precision measurement searches for new particle physics, resulting in the initiation of a wide range of new experiments