Low-Threshold Detectors for Neutrinos: The Long View

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Neutrino Physics Frontier

Blue Sky/Very Long Term Ideas Session

Overview

Low-Threshold Detectors = detectors with meV to eV scale thresholds for scattering of weakly interacting particles (neutrinos, DM)

Outline

DM motivation for low-threshold detectors ("quantum calorimeters")

Potential science interest of low-threshold detectors for neutrino physics

Backups: Quick summary of architectures under development

Caveat

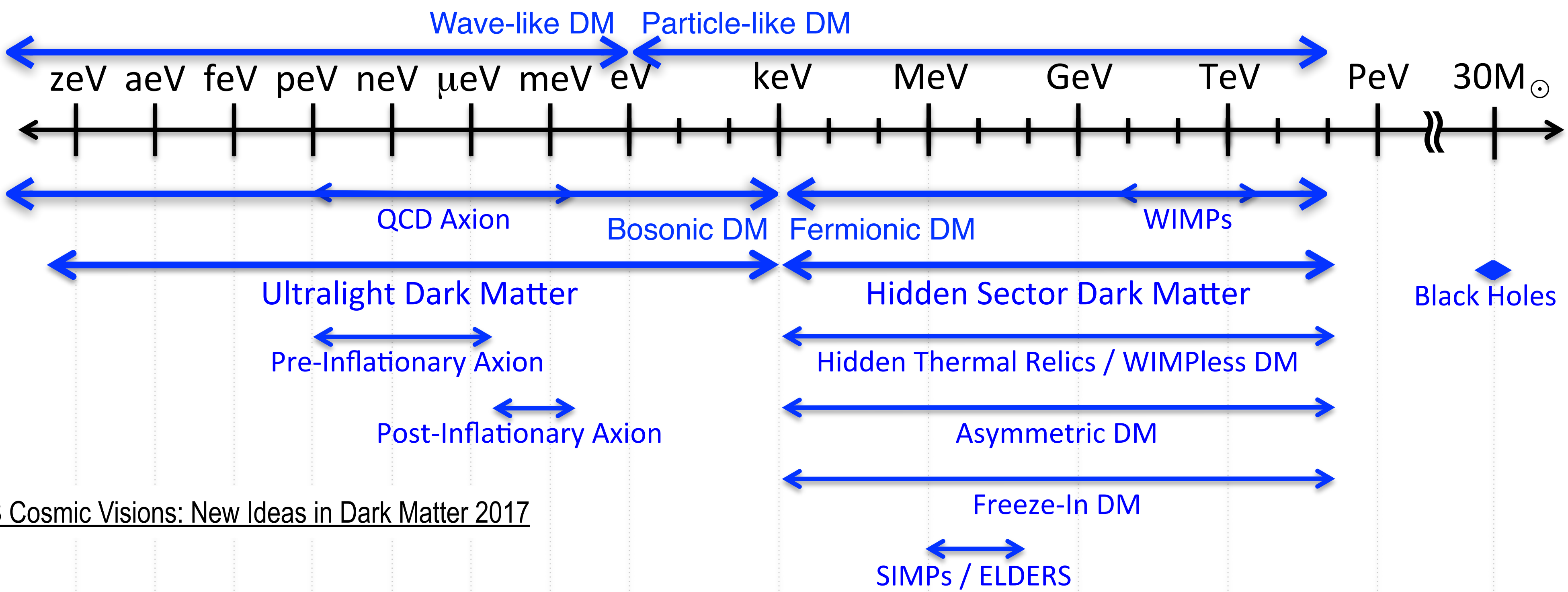
I'm not a neutrino physicist!

But hopefully some developments in DM detection could impact neutrino studies on the 1-2 decade timescale.

For more detail, see Golwala and Figueroa-Feliciano, *Ann Rev Nucl Part Sci*, in press.

DM Motivation for Low-Threshold Detectors

A new picture for DM:



US Cosmic Visions: New Ideas in Dark Matter 2017

Why?

No DM in spite of 30 years of dedicated searches in labs, the sky, and accelerators

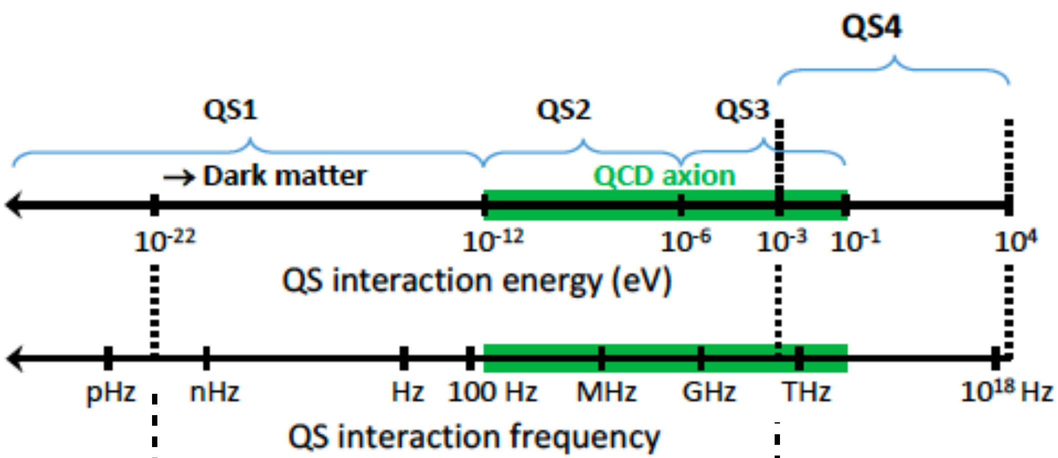
⇒ reconsideration of:

theoretical bias in favor of axions and WIMPs

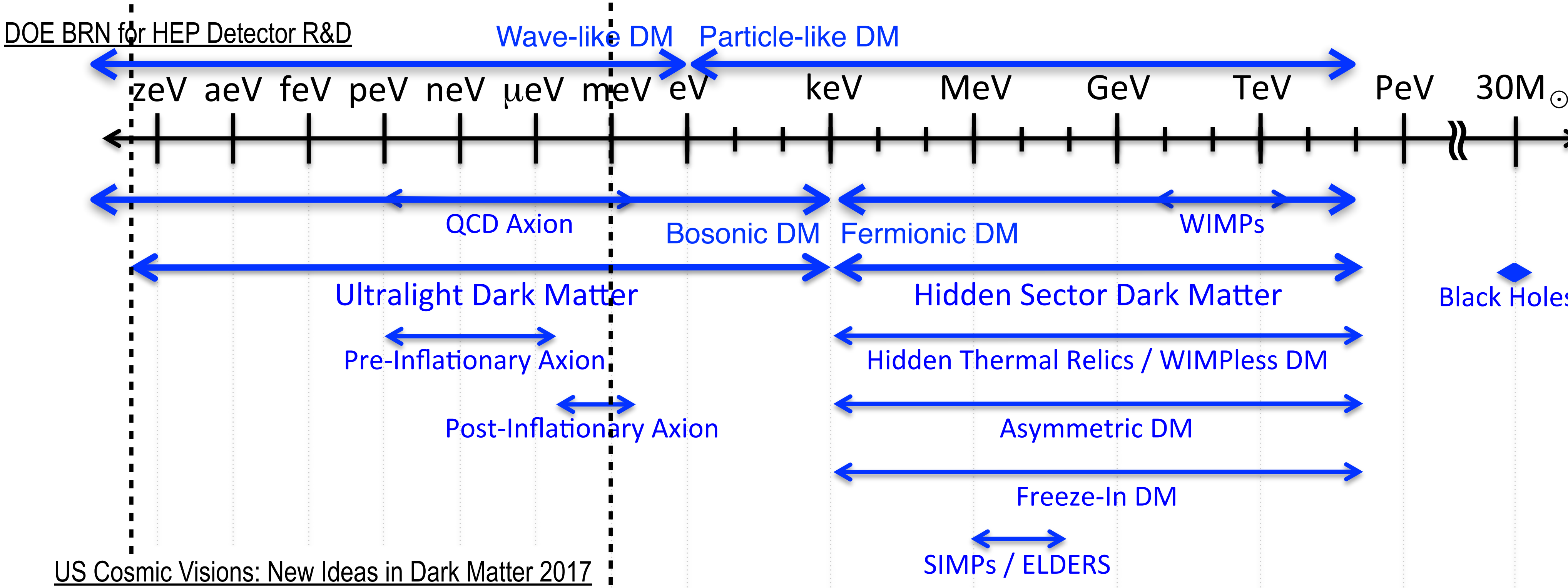
production mechanisms

cosmological constraints

Dark Matter → Quantum Sensors



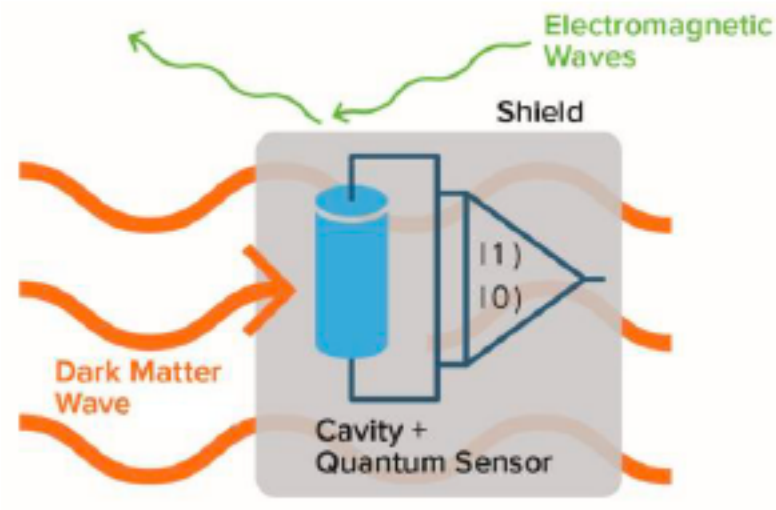
- QS for particle physics driven in large part by 2017 US Cosmic Visions *New Ideas in DM* white paper
- Seeking to cover $E_{dep} \lesssim$ keV inaccessible to classic particle DM searches
- QS regime includes both wave-like (~classical field) and particle-like DM



Dark Matter → Quantum Sensors

Cartoons from DOE BRN for Dark Matter Small Projects New Initiatives

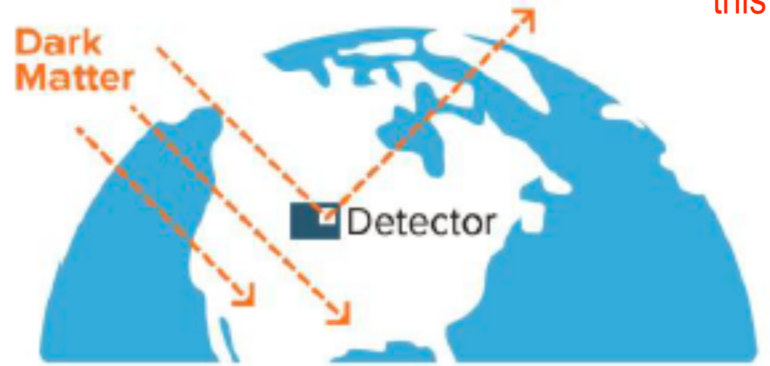
Wave-like Dark Matter



- Occupation number ≫ 1: difficult to 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

relevant for this talk



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

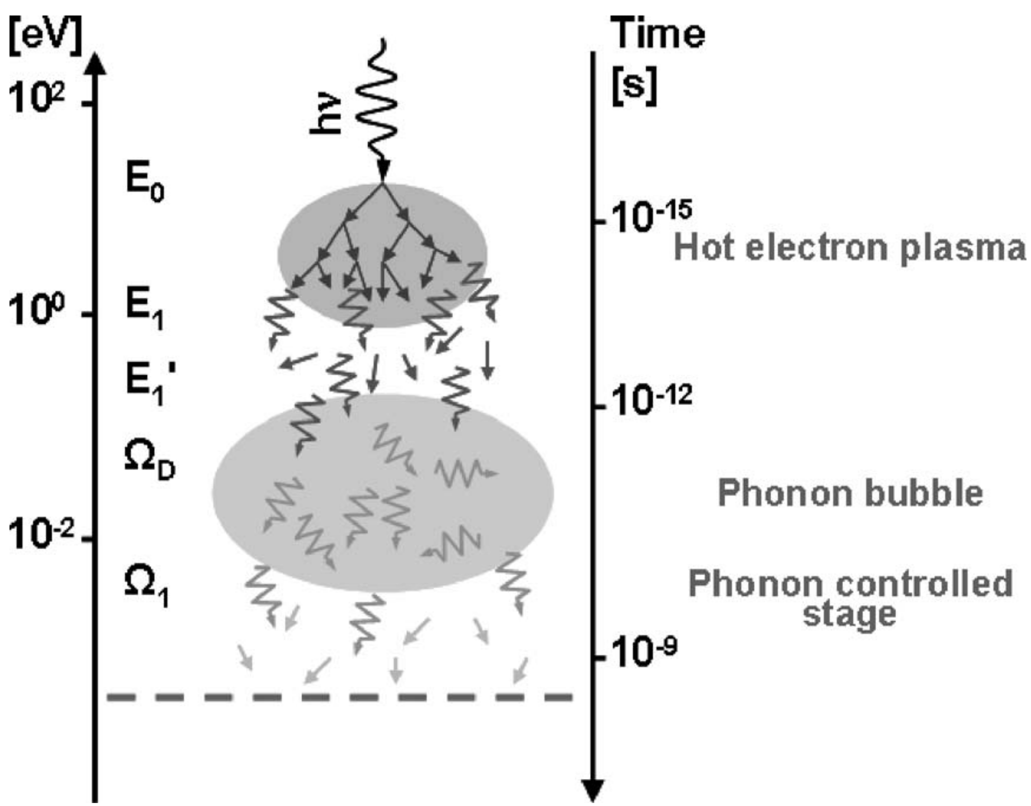
*Occupation number > 1 for bosonic DM does not imply particle-like absorption is not possible, but it makes classical field detection possible.

Quantum Calorimeters for Particle-Like DM

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

Semi-classical picture

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

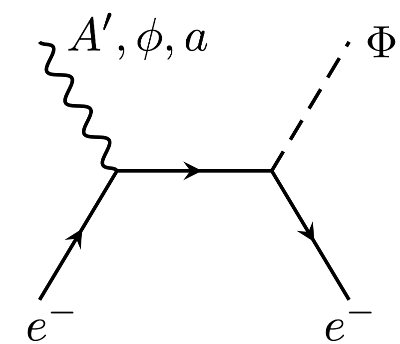


Kozorezov et al PRB: 75, 094513 (2007)

Quantum picture

- Production of single charges or scintillation photons (eV quantization)
  - Arguable whether sensing single charges or photons is "quantum" (e.g., PMTs, SiPMs)
- Innovations considered "quantum":
  - Detection of single photons with nearly 100% efficiency and very low dark count rates
    - vs. PMT, SiPMs
  - Direct production of single condensed-matter quanta like phonons, plasmons, etc.
  - Energy depositions so small that "quantum" techniques must be used to detect

e.g. direct optical phonon production mediated by DM-e coupling



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, phonon detectors

Quantum Calorimeters: DM Kinematics and Scattering Modes

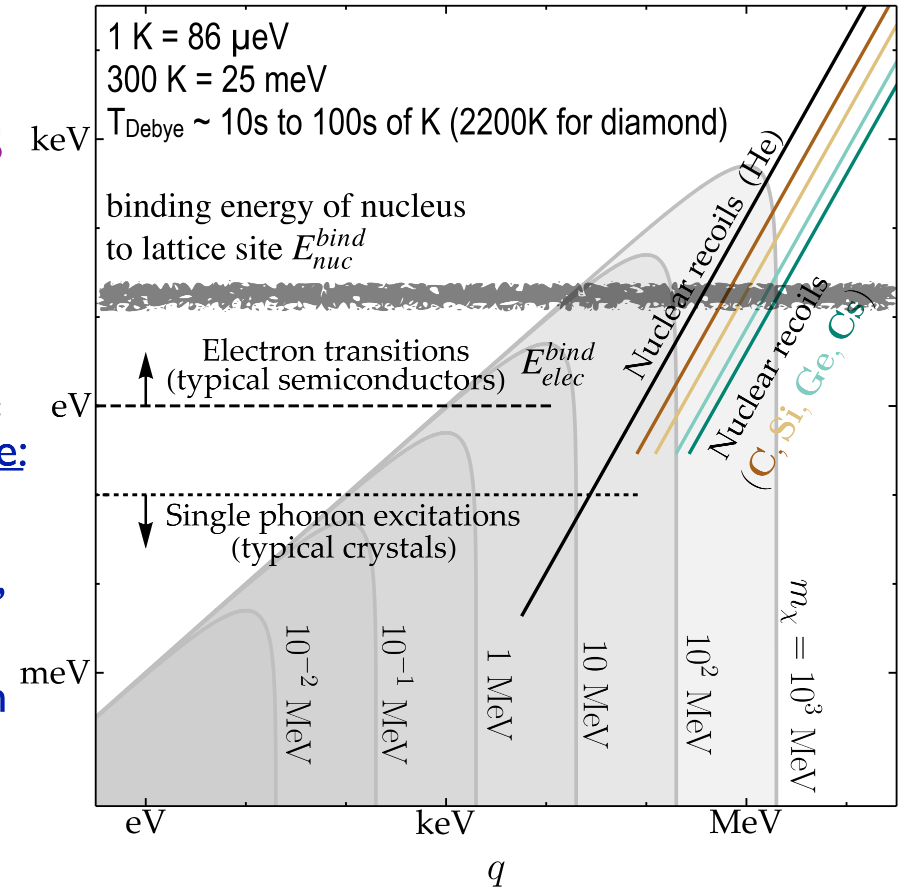
Energy-momentum transfer of galactic DM scattering kinematically limited by max v_{DM}

Interactions with nuclei (~ CEνNS)

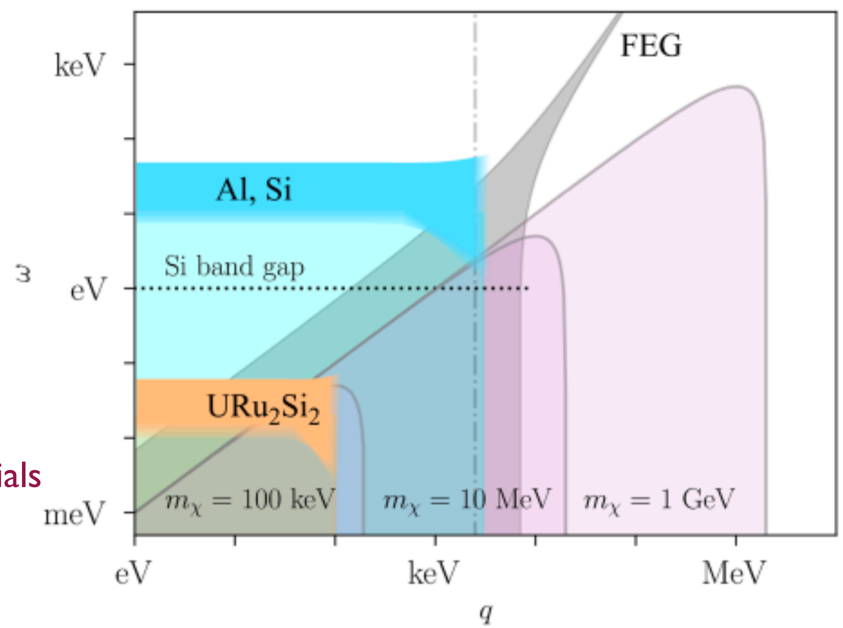
- Up to E_{nuc}^{bind} ~ 10-20 eV, nucleus cannot leave ionic site: direct production of multiple phonons
- Lines truncated when single nucleus scattering invalid, q < (lattice constant)$^{-1}$. Instead, direct single phonon creation via coherent multi-site interaction

Interactions with electrons (EC, NC e^- detection)

- FEG = free electron gas, valid for $E > E_{elec}^{bind}$
  - $E_{elec}^{bind} = 0$ for metals, superconductor (SC) in transition
    - $\sigma_E \propto T^\alpha \sqrt{M}$ because fermionic excitations with no gap
    - $\Rightarrow$ poor σ_E for large target mass for DM
  - E_{elec}^{bind} ~ eV for semiconductor/insulator, meV for SC
    - Gapped excitation spectrum suppresses σ_E
- No electronic excitations for $E < E_{elec}^{bind}$; instead:
  - Blue shaded region: plasmons
    - Most phase space inaccessible except for heavy fermion materials
  - Optical phonon creation by 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

What about neutrinos?

eV-scale thresholds interesting for CEνNS:
not quite quantum, but benefits from QS efforts

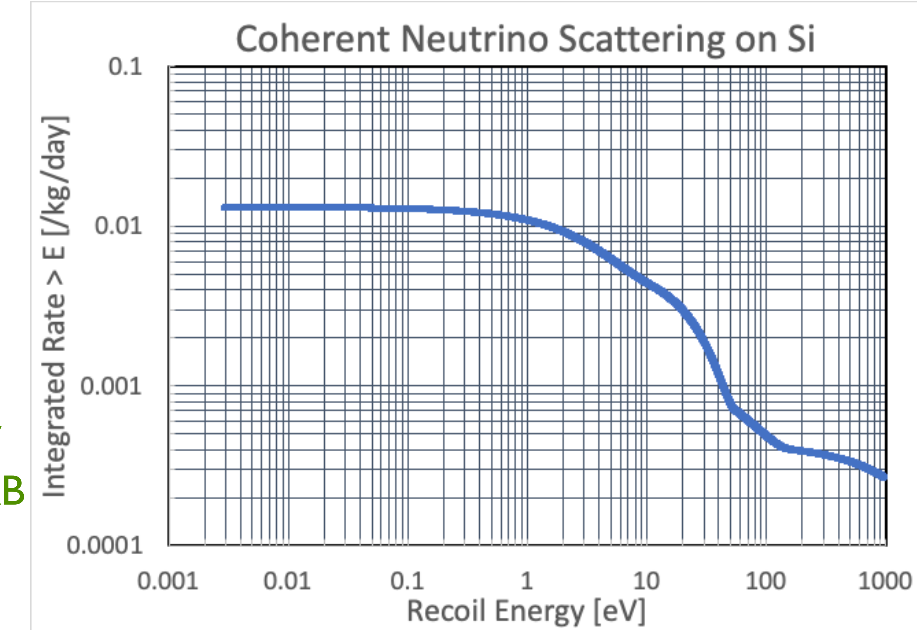
Solar neutrinos: good potential

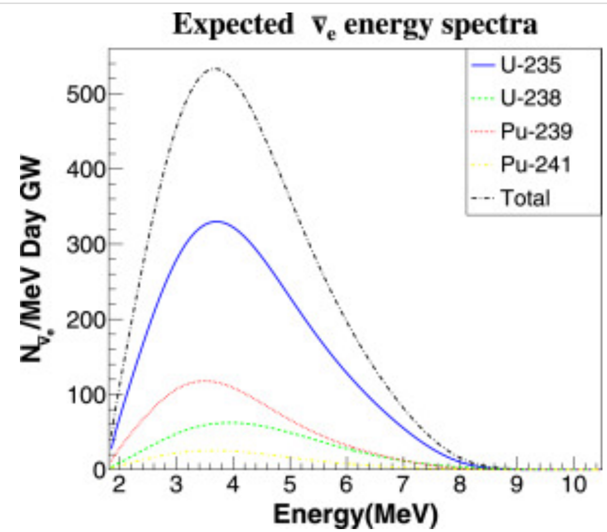
- e.g. SuperCDMS long-term future:
  - 0.5 eV threshold requires 25 gm/Si detector operating at 0V (phonons-only), can deploy 72 kg in SuperCDMS SNOLAB (N ~ 3000 detectors)
  - Expect about 250 pp neutrinos per year
- Sub-10% *statistical* precision on *pp* flux
- Or search for deviations from SM with sub-10% *statistical* precision if LXe measures *pp* flux via ν-e scattering
  - Requires good control of ^{136}Xe background

Reactor neutrinos: much better potential for studying CEνNS

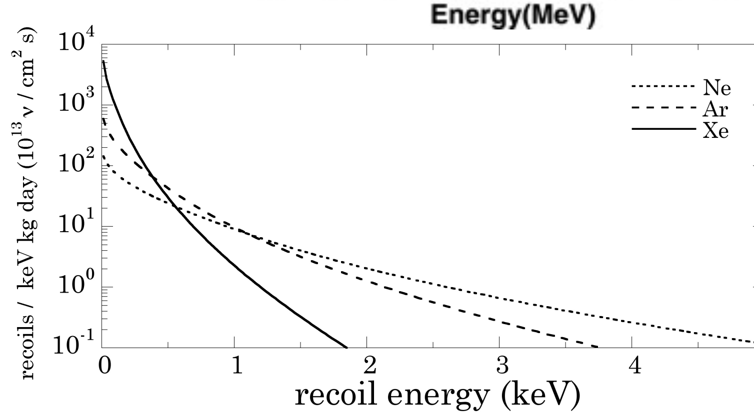
- MeV antineutrino energies $\Rightarrow \langle E \rangle \approx 100$ eV CEνNS in Si: eV threshold captures full spectrum @ ~ 50 events/kg-d
- Large event rates!
  - comparable statistical precision to *pp* neutrinos with 5000x smaller exposure (N ~ 10 detectors for 100 days)
  - 1% *statistical* precision with intermediate mass (N ~ 100 detectors for 100 days)

Both require control of 10-100 eV scale low-energy backgrounds now becoming visible in DM expts





https://doi.org/10.1016/j.nima.2019.163251



Collar

What about neutrinos?

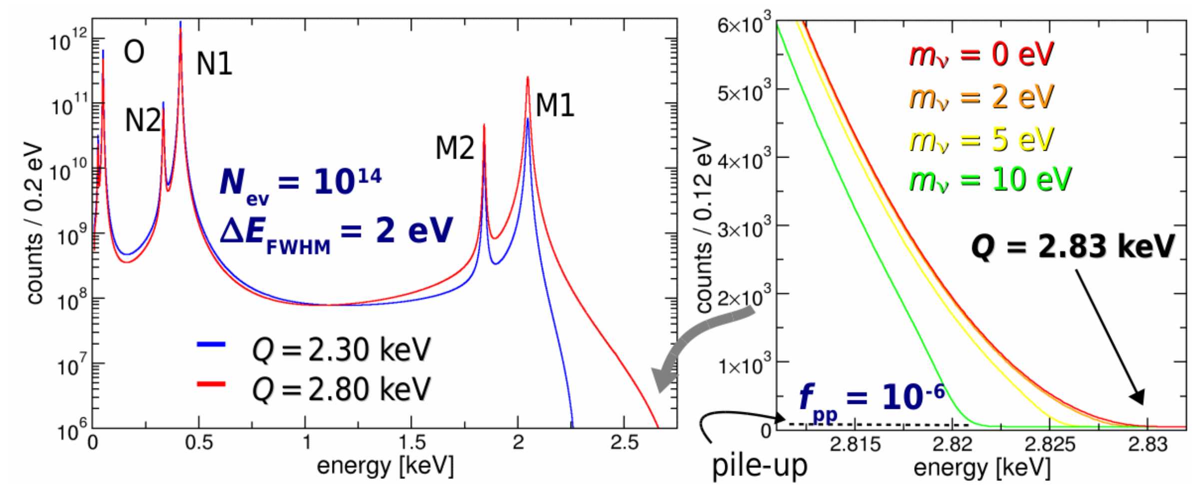
$\mathcal{O}(10)$ meV resolution on electron detection possible with quantum calorimeters

Relic cosmic neutrino background

- PTOLEMY would use neutrino capture (IBD) on tritium producing 1-10 eV electrons
- Requires $\sigma_E < 0.05$ eV
- Small mass (can focus electrons on detector) permits "semi-classical" sensor, $E_{elec}^{bind} = 0$
  - Deposit electron energy in free-electron gas directly
  - Still, benefits from low-threshold/high-resolution goals for sensing modalities (TESs)
- See following talk by A. Tan

Neutrino mass via electron capture endpoint in ^{163}Ho (2.828 keV)

- HOLMES embeds isotope in a calorimeter with high resolution (~low threshold)
- Requires:
  - $\lesssim$ eV resolution to compete with tritium endpoint measurements
  - Characterization of nonlinearity at $E \approx 10^4 \sigma_E$
- Requires "semi-classical" sensor, $E_{elec}^{bind} = 0$, to avoid being limited by counting statistics
  - $E/\sigma_E \gtrsim 10^4$ needed $\Rightarrow N_{quanta} \gtrsim 10^8$
  - Again, benefits from low threshold goals for sensing modalities (TESs)



https://holmes0.mib.infn.it/holmes/

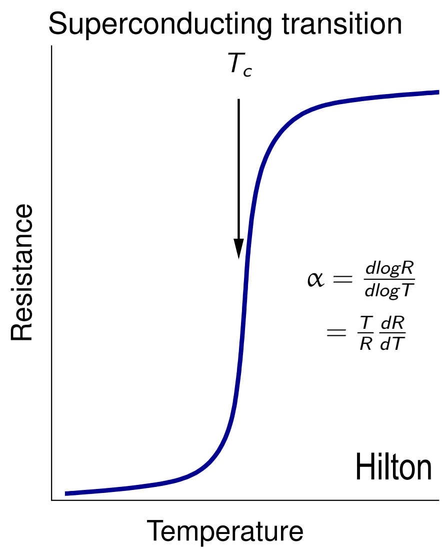
Conclusions

- An expansion in the mass range of interest for DM has led to the development of low-threshold detectors based on quantum sensors
  - Today: eV in single detectors, 10 eV in full experimental deployment
  - Long-term goal: meV thresholds

- Large payloads of such detectors could be useful for neutrino physics in the longer-term:
  - Low-threshold detectors with 1-100 kg target mass
    - Measurements of *pp* neutrinos or using them to look for non-SM CEνNS
    - Search for non-SM CEνNS at reactors
  - High-resolution detectors
    - Detection of low-energy electrons to measure the CνB via neutrino capture
    - EC spectrum endpoint measurements for neutrino mass

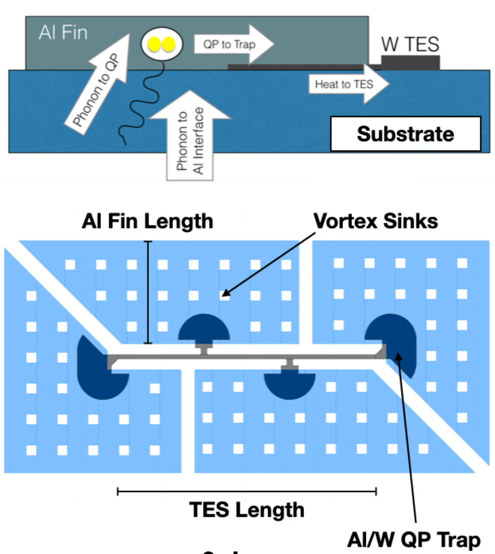
Backups:
Architectures Under Development

Quantum Calorimeters Today

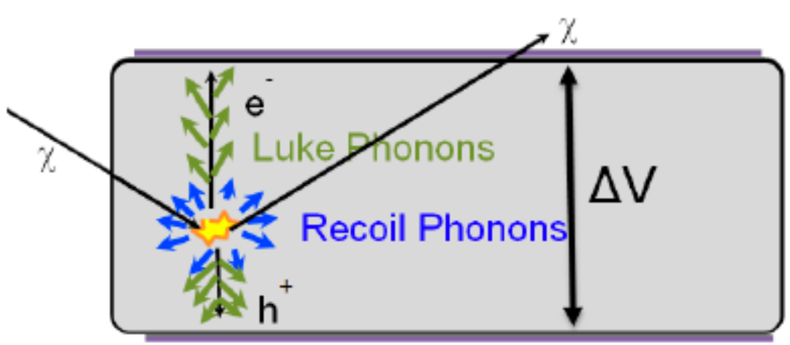


Calorimeters based on Transition-Edge Sensors

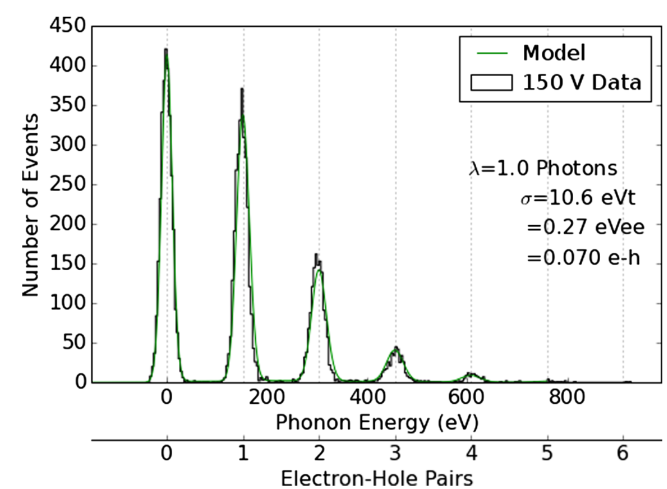
- TESs provide very sharp resistance vs. T curve
  - Electothermal feedback can be used to stabilize
  - Electrical signal measures received energy
- Coupled to calorimetric substrate via athermal phonon collectors
- Now approaching the quantum regime
  - Large bias voltage provides amplification via 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

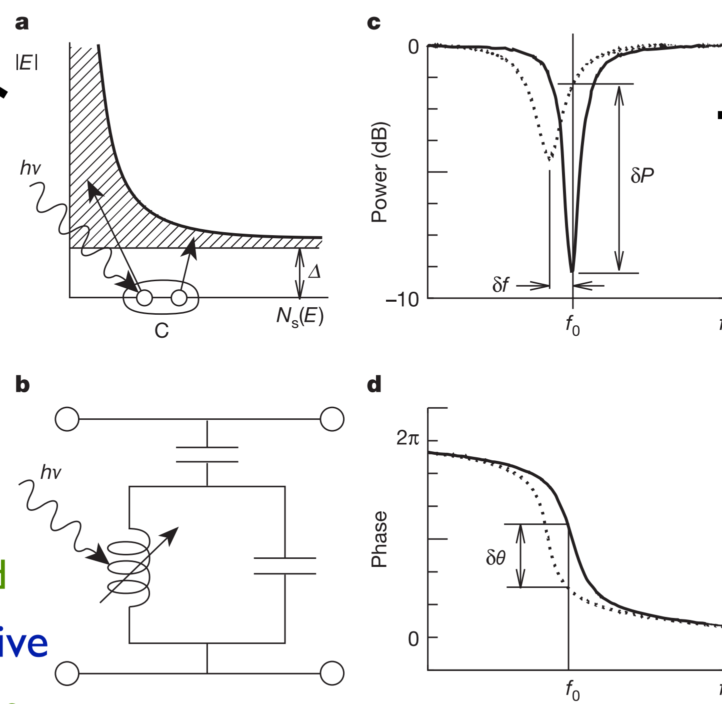
Kinetic Inductance Detectors (KIDs)

Superconductors have an AC inductance due to inertia of Cooper pairs

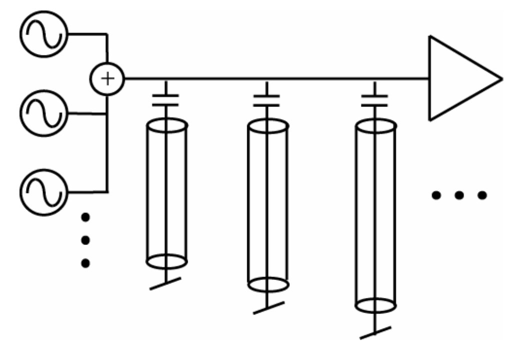
KID = superconducting film incorporated into LC resonator to sense change in L

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



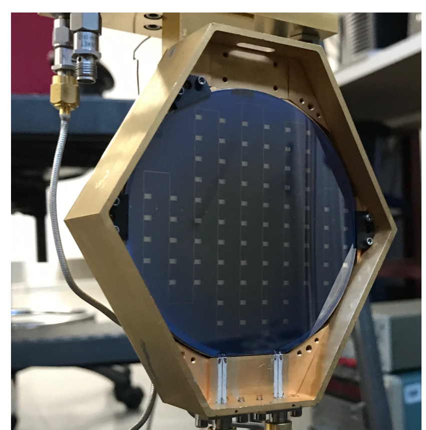
Multiplexing:

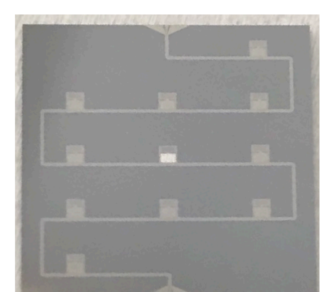
KIDs are Q>10^5 resonators

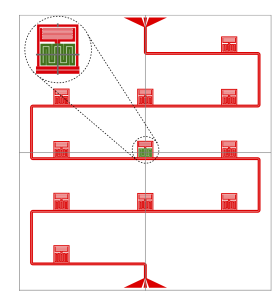
→ Readout many with one cryo line/amplifier; most electronics at 300K

→ Highly position-resolved phonon detection

75 mm x 1 mm





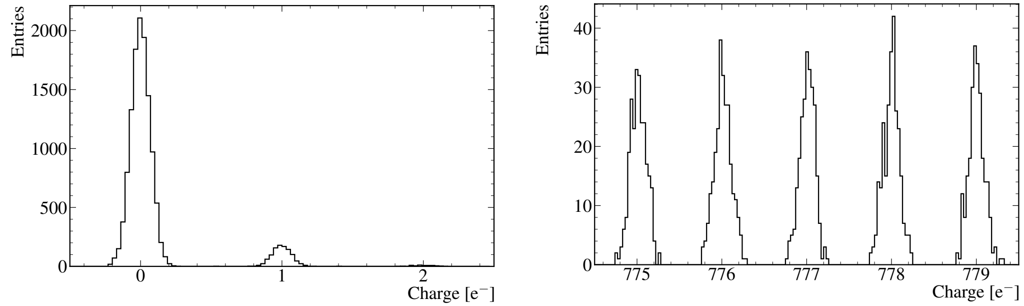


22 mm x 1 mm

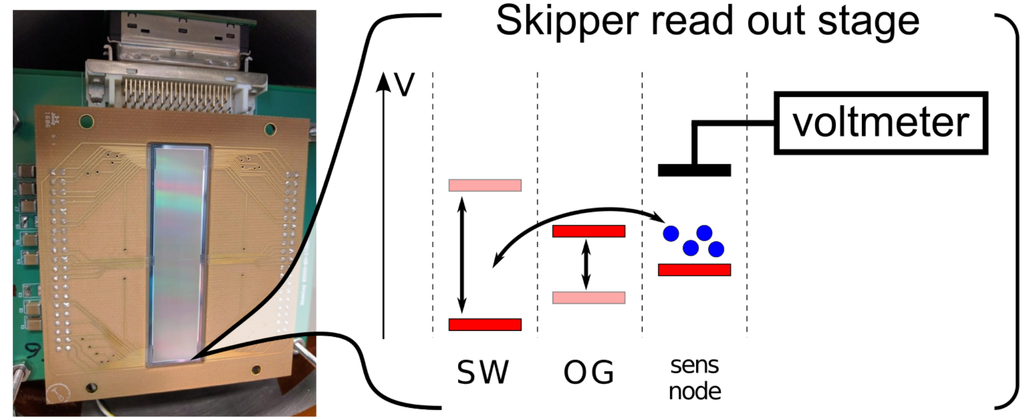
Quantum Calorimeters Today

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



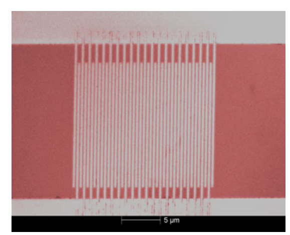
PRL 119: 131802 (2017)

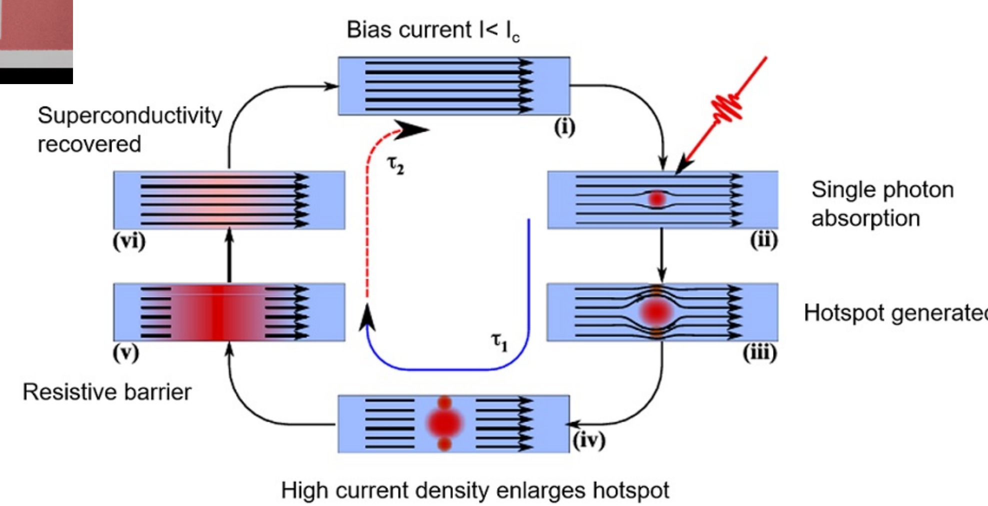


https://sensei-skipper.github.io/#SkipperCCD

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/

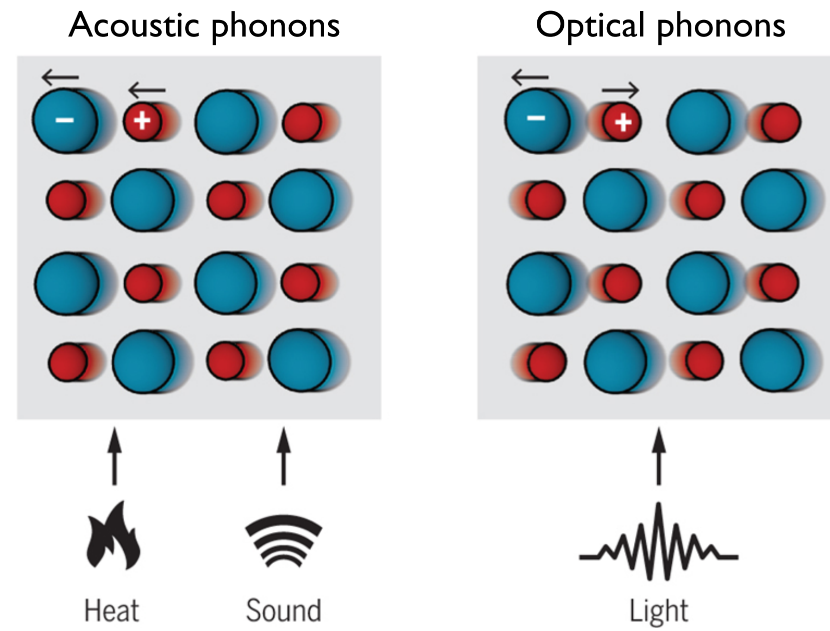
Quantum Calorimeters in the Future

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}

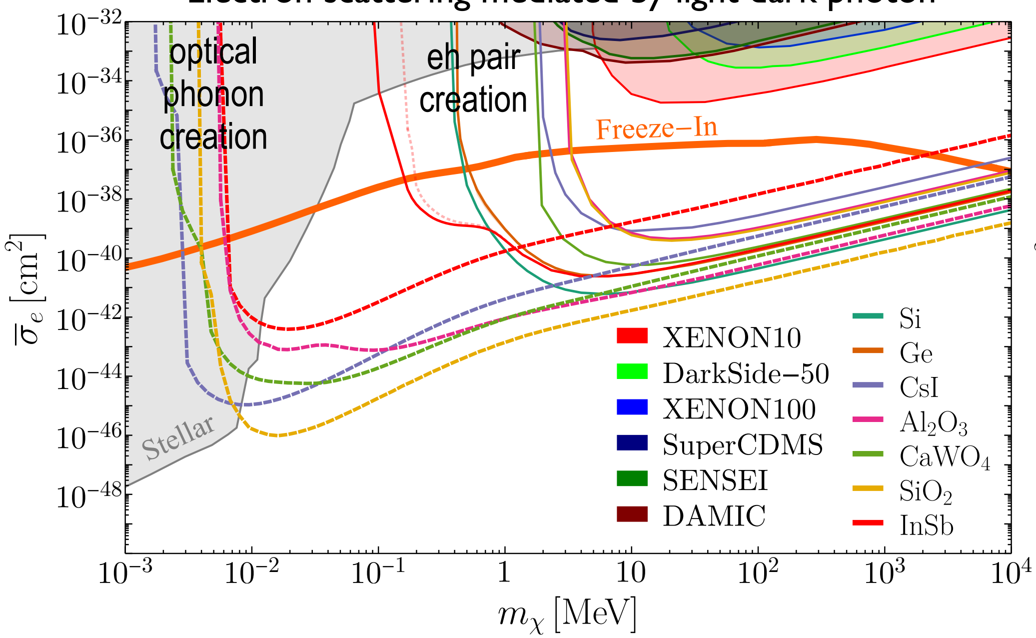
Single acoustic phonon creation/detection

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

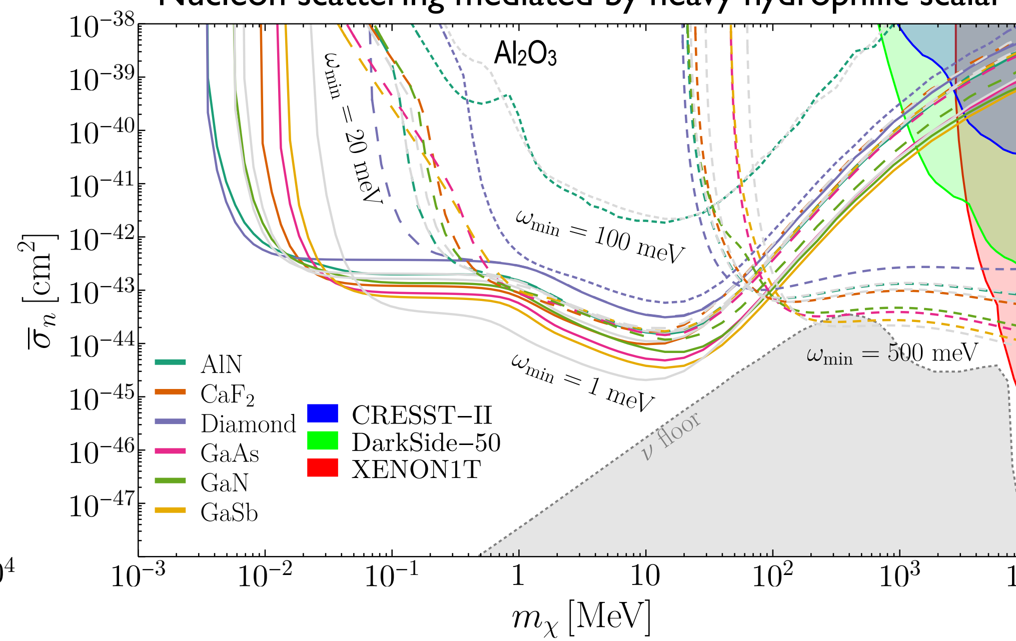


https://images.app.goo.gl/vvBWneR6noCnseCXA

Electron scattering mediated by light dark photon



Nucleon scattering mediated by heavy hydrophilic scalar



Griffin et al. arXiv:1910.10716