Dark Matter Ripples: High-Mass Axions and Low-Mass Fermions

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TeVPA 2024, University of Chicago
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U.S. DEPARTMENT OF ENERGY Stanford University SLAC NATIONAL ACCELERATOR LABORATORY

Low Mass (< GeV) Dark Matter

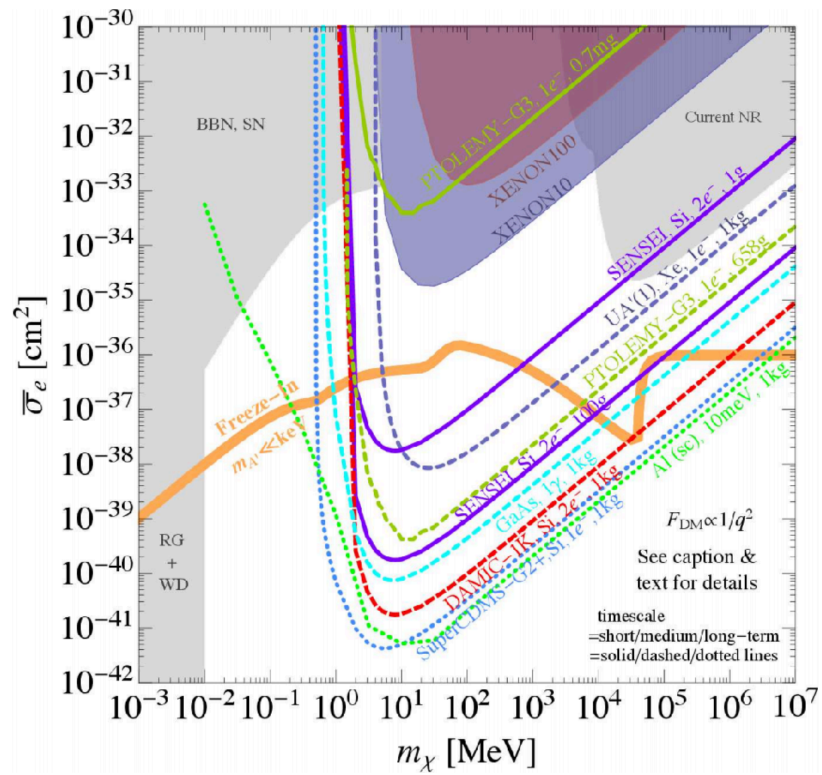
Dark matter in the keV-GeV mass range can produce the correct DM relic density if we introduce a new mediator between the DM and SM

Consider a massive 'dark photon' mediator coupled to a heavy particle which does not interact with SM as the only particles in a new 'dark sector'

- If the mediator is heavier, dark matter can freeze out for the right coupling strengths in the same way as WIMP DM
- If the dark photon is the lighter particle, it can 'freeze in' as the 'heavy' DM decays into dark photons and SM particles

Much of the simplest parameter space completely unconstrained in the freeze-in scenario due to the momentum suppression

Lots of theory work done on these models in the last few years and multiple workshop reports



$$\langle \sigma_A v \rangle \propto \frac{g_D^4}{m_\chi^2}$$

Secluded

$$\langle \sigma_A v \rangle \propto \frac{g_D^2 g_{SM}^2 m_\chi^2}{m_{med}^4}$$

Direct

Low Mass (< GeV) Dark Matter

Dark matter in the keV-GeV mass range can produce the correct DM relic density if we introduce a new mediator between the DM and SM

$$R \sim \frac{1\text{Hz}}{\text{kg}} \left(\frac{\sigma_{e,p}}{10^{-36} cm^2}\right) \left(\frac{30\text{MeV}}{m_\chi}\right)$$

Relic density cross-sections for MeV DM correspond to Hz/kg event rates!

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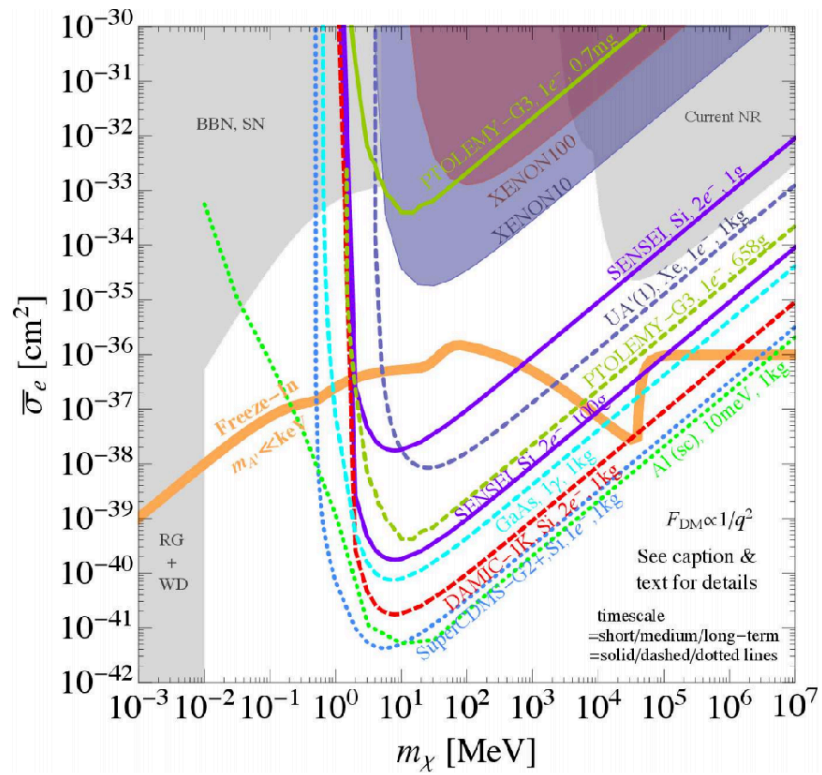

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Direct

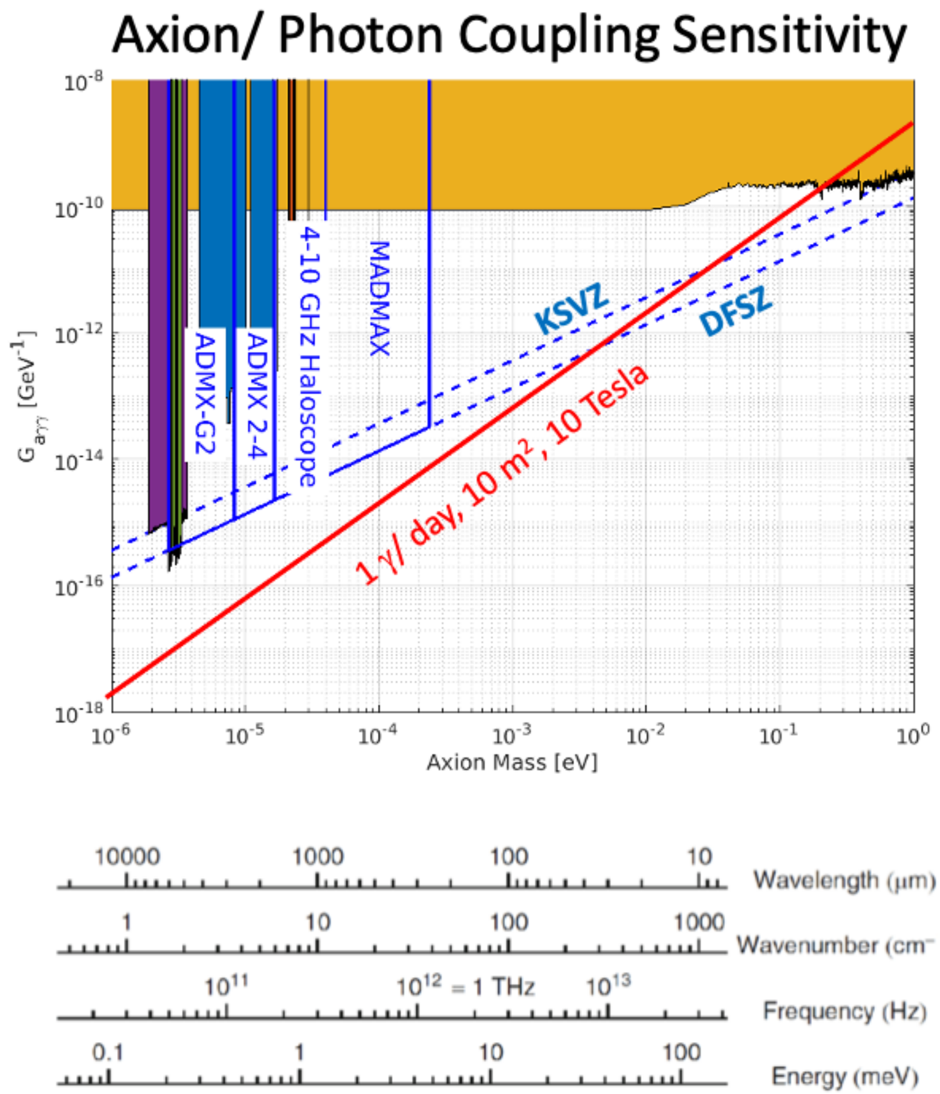
Wide-Band Axion Searches

Current gap in the ~meV-eV absorption regime limited by transition from resonant technologies

We can do wide-band axion searches with meV-threshold sensors! They need to couple to photons rather than phonons, which is accomplished via a waveguide

All technologies useful for phonon sensing are also useful for dark photon and axion searches in this mass range

- These are THz photons, which are technologically hard to probe and are in themselves an interesting field



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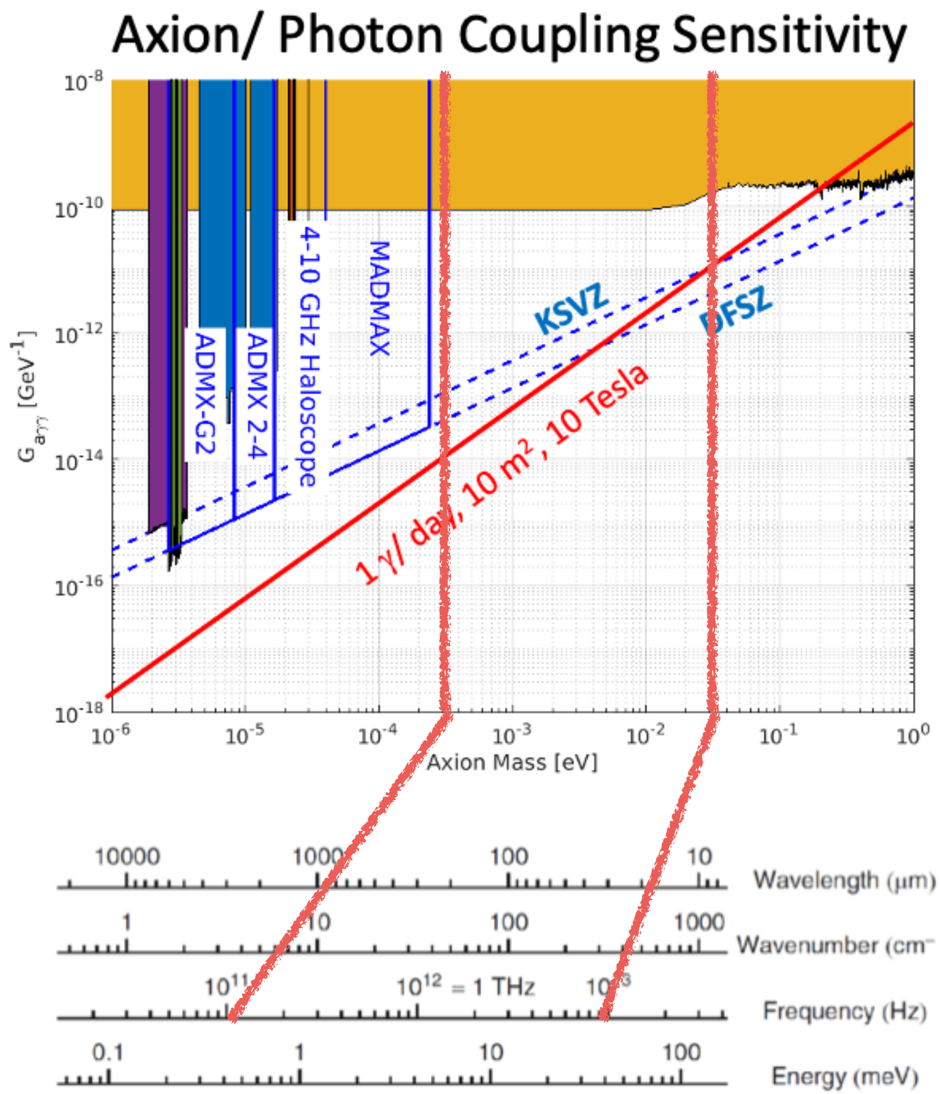
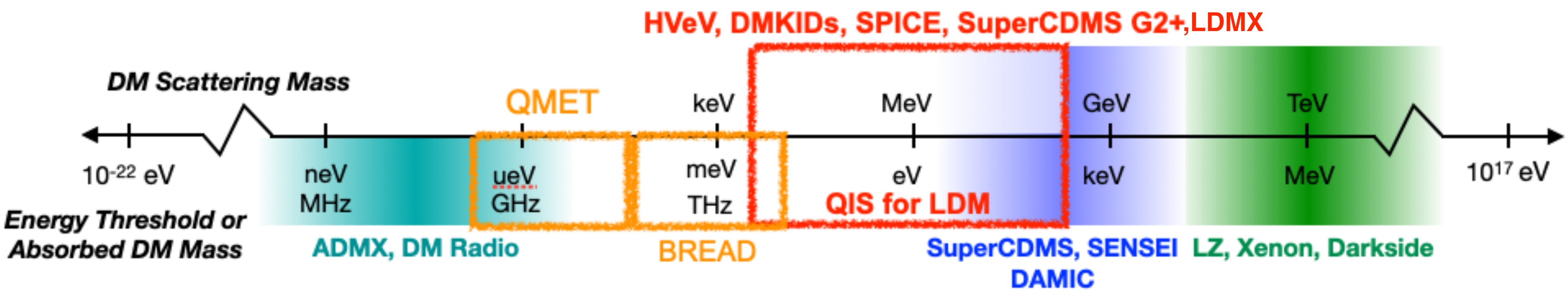


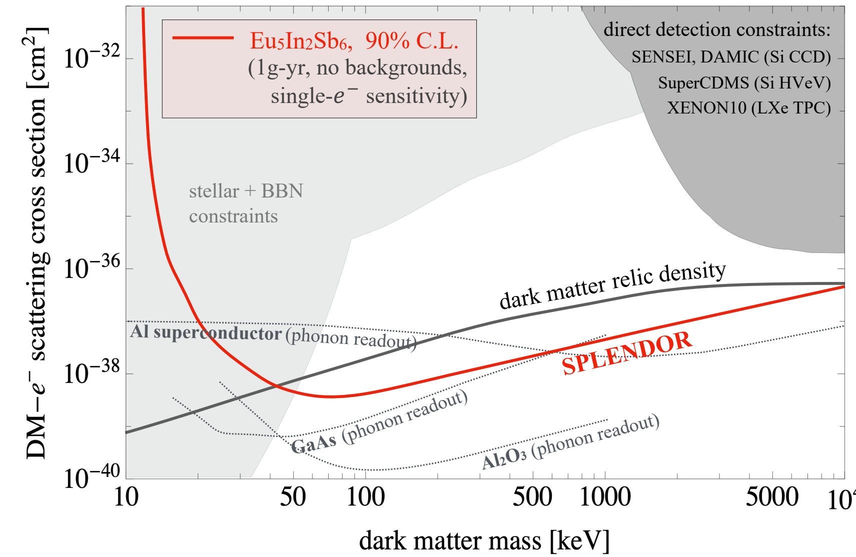
Motivation: Closing the DM Gap

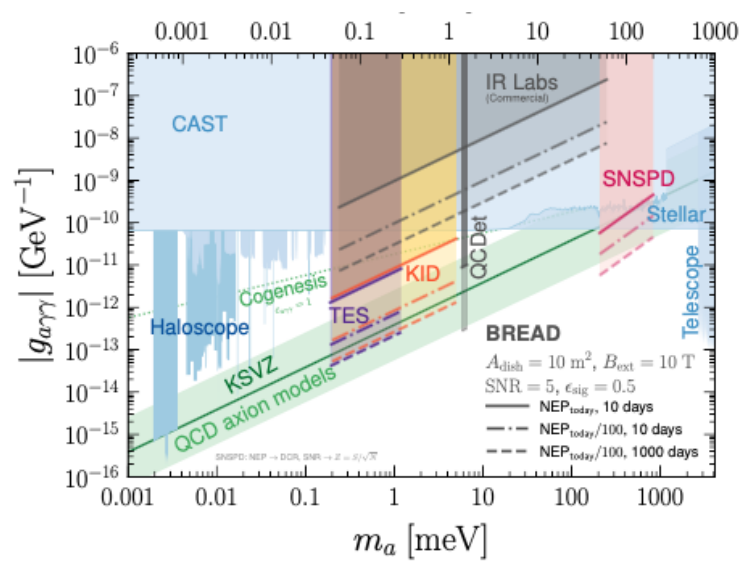


- Existing DM experiments are opening an ever larger window onto axion detection (at low mass) and heavy dark matter (>1 MeV)
- There's a gap of 6 orders of magnitude limited by the challenges of detecting single events at the meV energy scale
- My group at SLAC (DMQIS) focused on applying quantum measurement techniques at the meV scale to HEP problems, with a focus on direct detection of dark matter and single photon sensing

Motivation: Closing the DM Gap (Continued)

- Axion searches and DM scattering experiments can both benefit from reducing detection thresholds!
- **SPLENDOR**, a scattering/absorption search, requires single-charge detection in meV-gap materials to extend semiconductor-style radiation detectors to the quantum energy regime
- **SuperCDMS** can extend its reach below MeV masses by lower phonon energy thresholds - advances in either photon or charge sensing will enable these improvements
- **BREAD**, a wideband axion search concept, will require single photon detection down to THz frequencies (meV energies), above the reach of cavity-style searches.

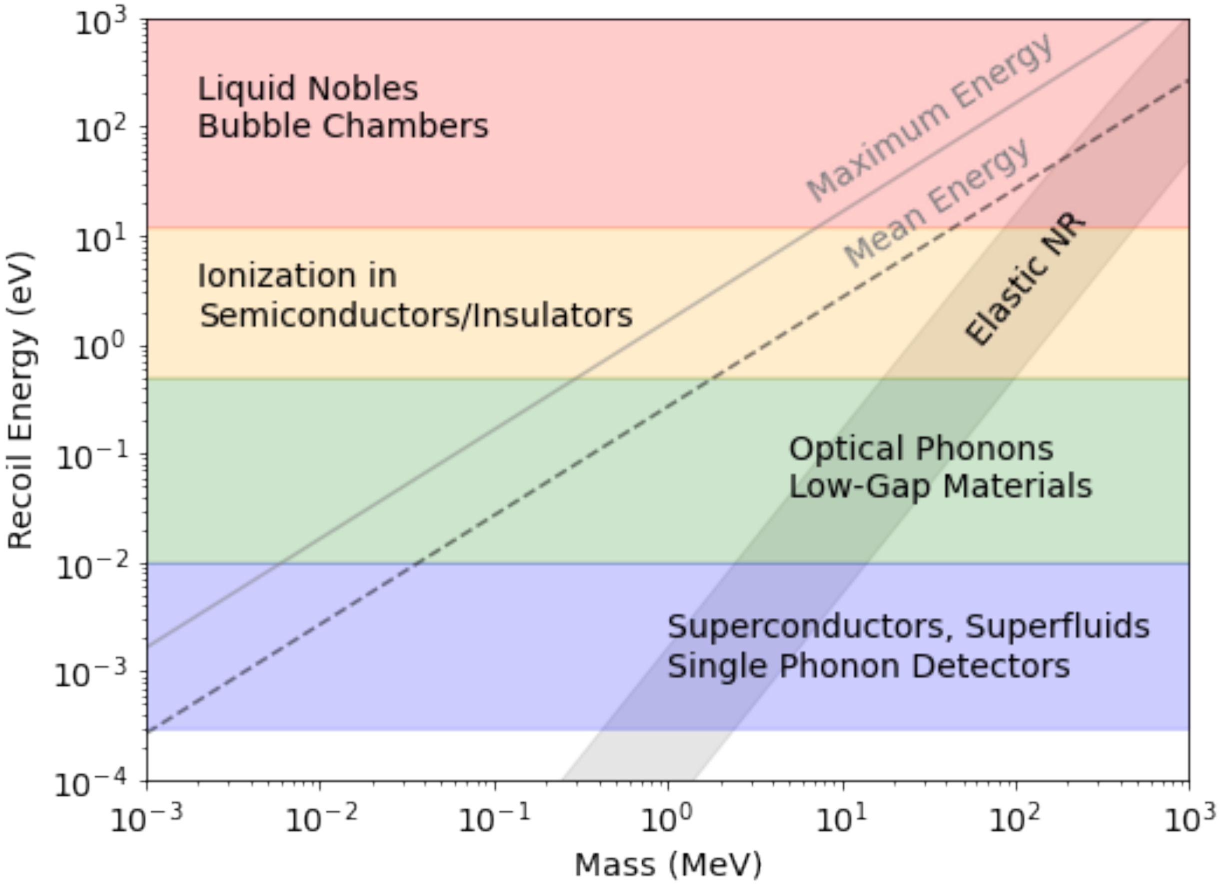




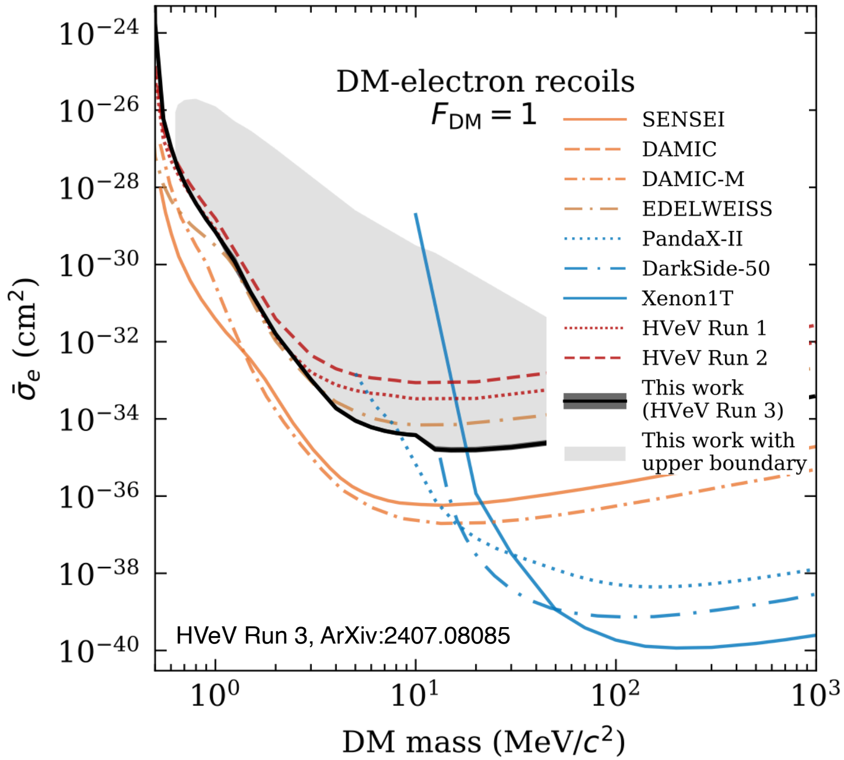
Quantum Sensing R&D For Dark Matter: meV Thresholds

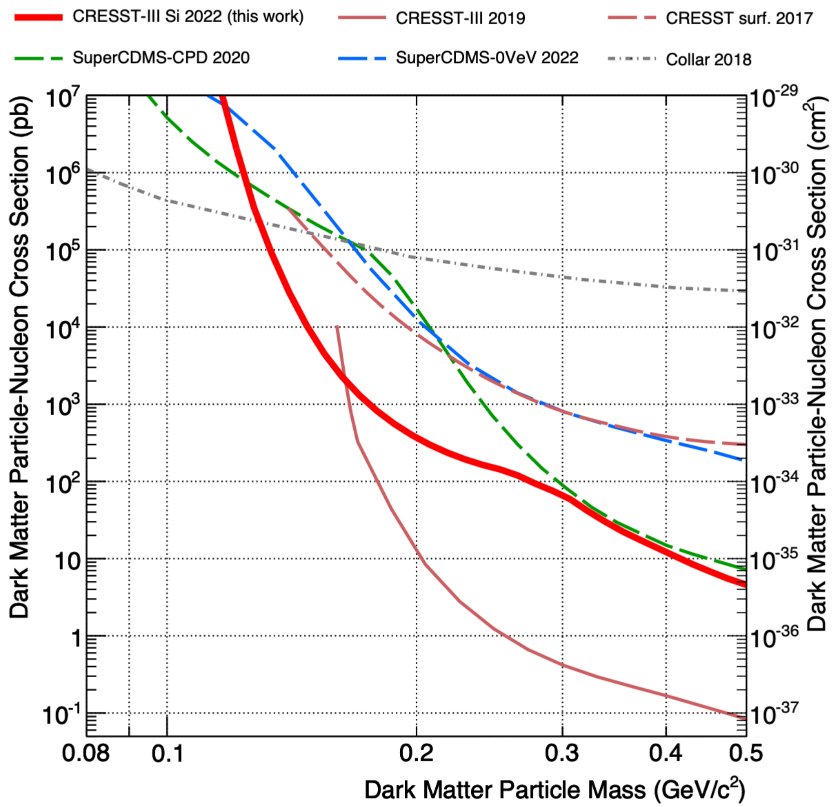
Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade https://arxiv.org/abs/2203.08297

Rouven Essig, Graham K. Giovanetti, Noah Kurinsky, Dan McKinsey, Karthik Ramanathan, Kelly Stifter, Tien-Tien Yu



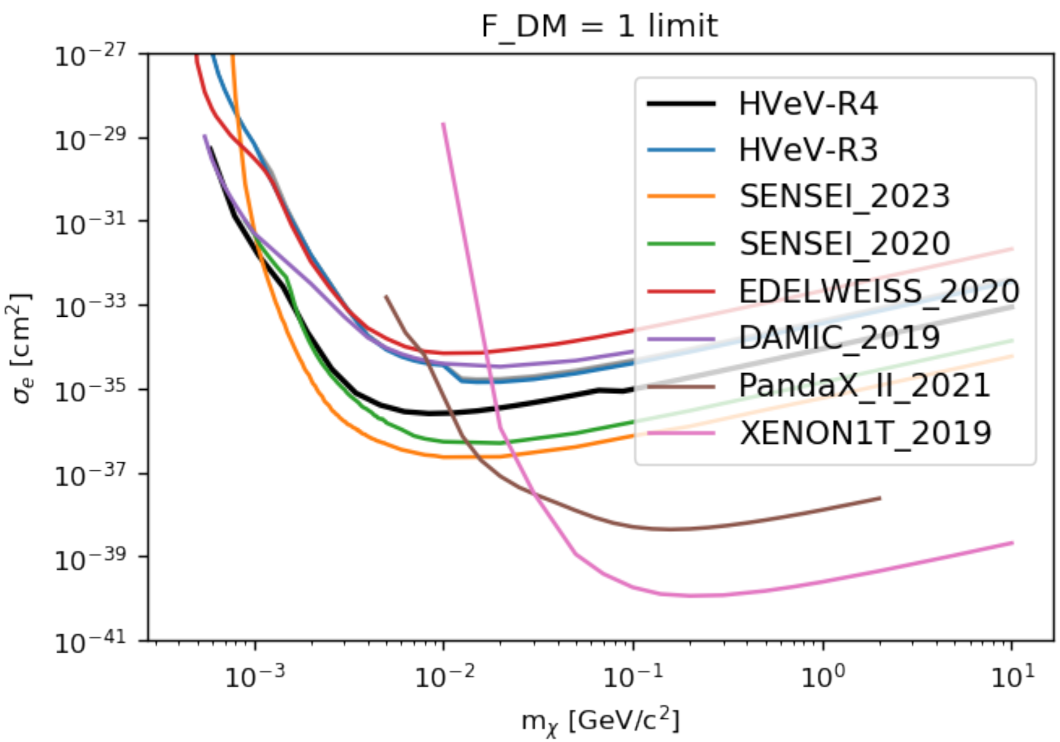
Current Status: DM Scattering

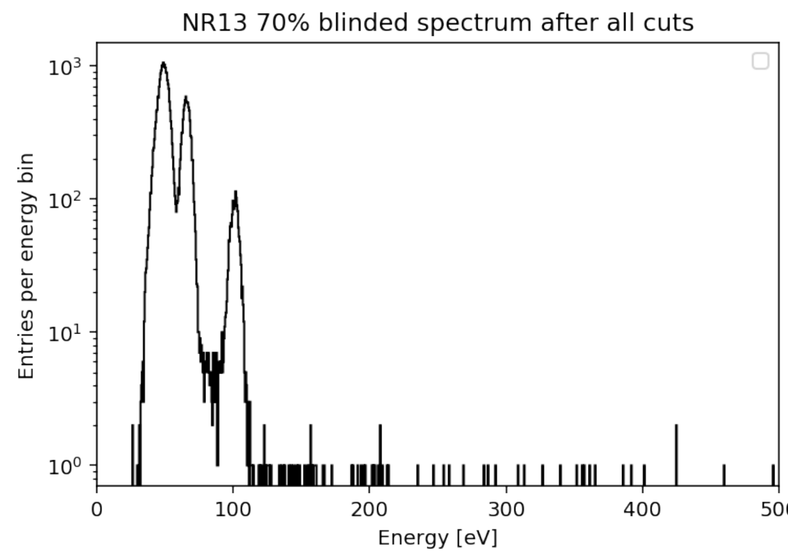




- ERDM currently limited by backgrounds (low energy), exposure (high energy) and ionization thresholds
- NRDM limited largely by backgrounds above threshold (so called low-energy excess) and by energy resolution

SuperCDMS HVeV Run 4





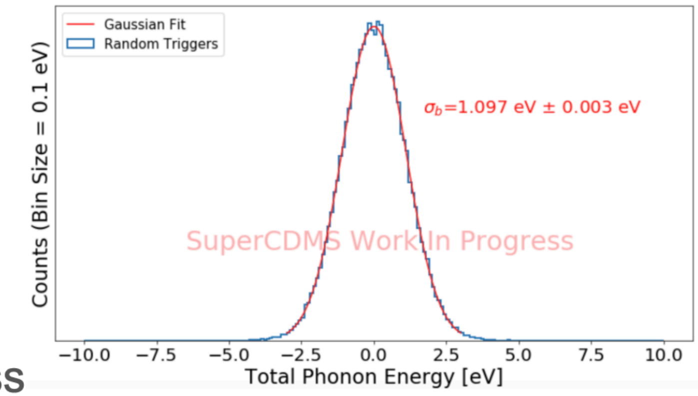
Run 4 (NEXUS@FNAL) in copper-only enclosure drops leakage rate to 3 mHz/g with a single detector (two TES channels)

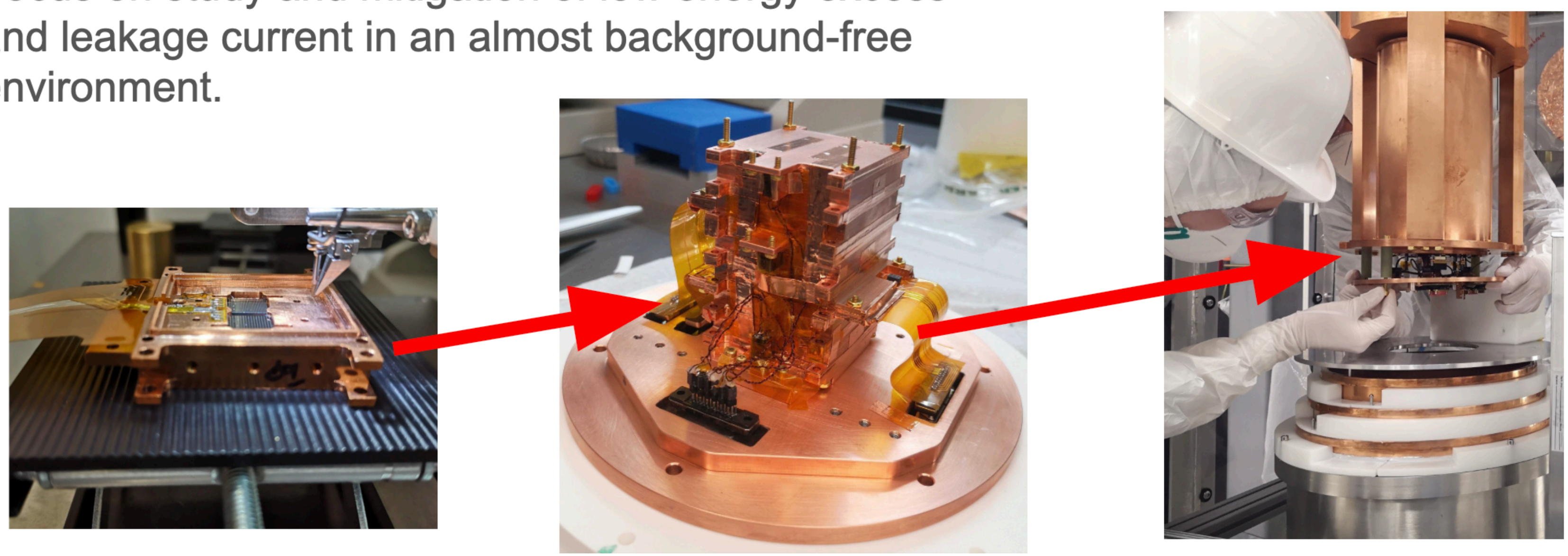
Teaser: HVeV Run 5, SuperCDMS in CUTE

HVeV at CUTE

Currently running 6 HVeV detectors deep UG at SNOLAB in the CUTE facility. Two detectors with sub-eV energy resolution thanks to lower Tc.

Focus on study and mitigation of low energy excess and leakage current in an almost background-free environment.





Also Forthcoming: SuperCDMS Tower Run at CUTE

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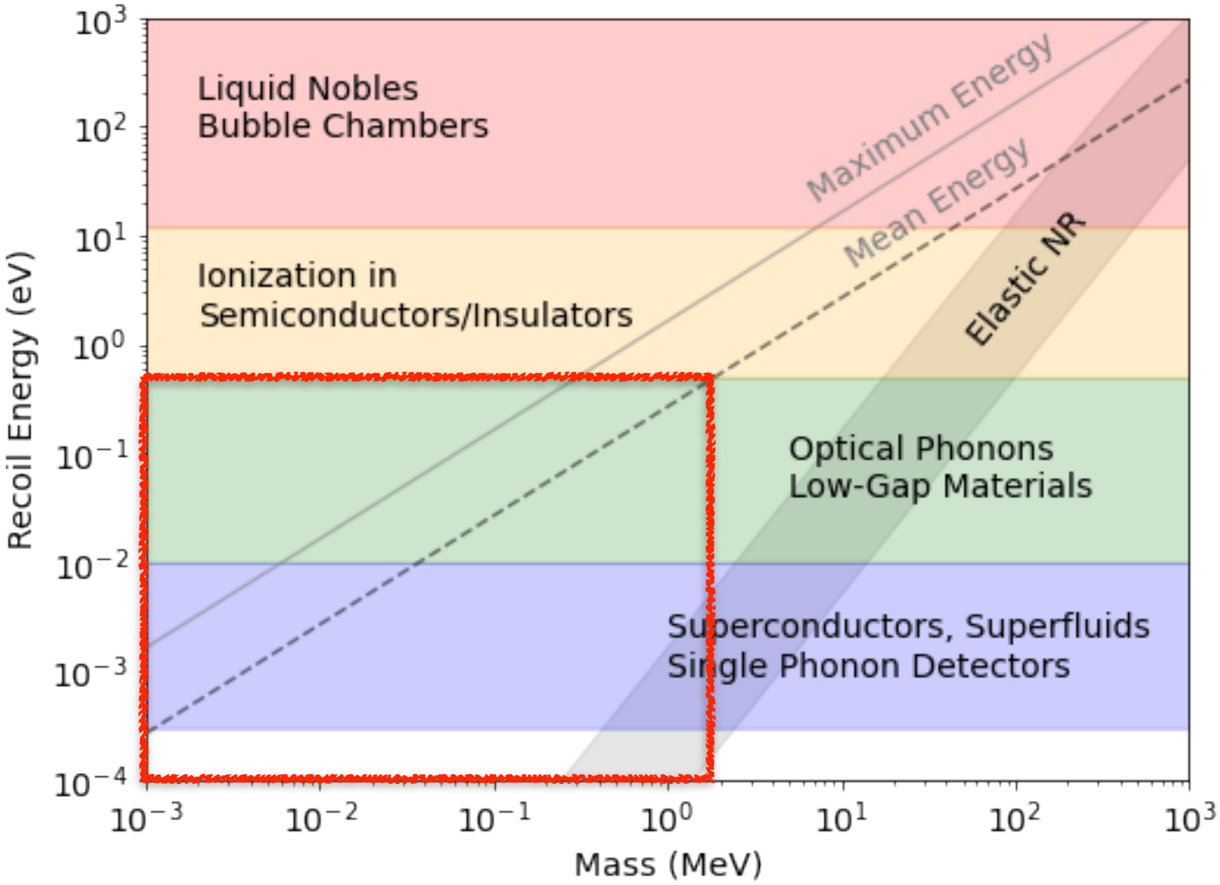
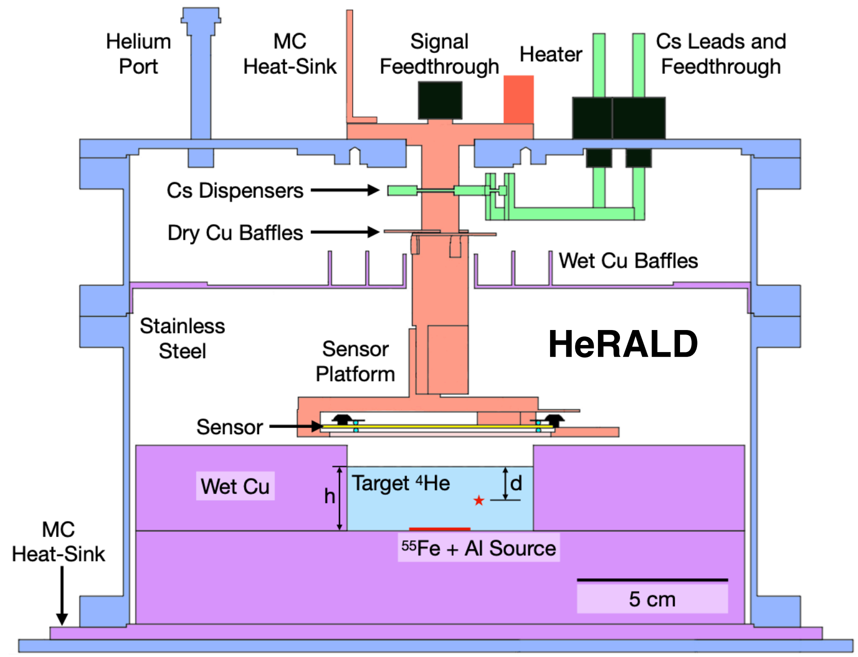
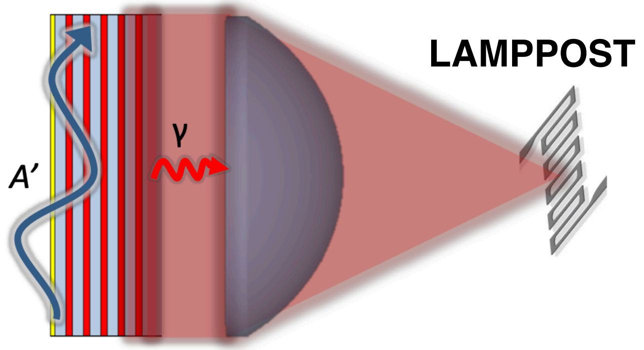


Aside: Photon or Roton Detection

- Many experiments searching for axion dark matter or keV-scale DM produce photons or quasiparticles as their primary excitation

- All of these experiments utilize solid-state readout and require sub-eV resolution to achieve their science goals - we thus focus on readout of excitations in these detectors to understand sensing limitations

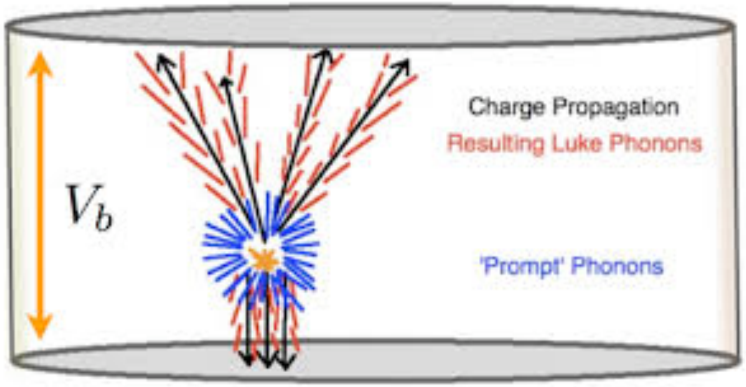




https://arxiv.org/pdf/2110.01582.pdf

Multiple Paths to meV-Scale Energy Sensitivity

Interaction Produces Charge and Phonons in Solid State Target



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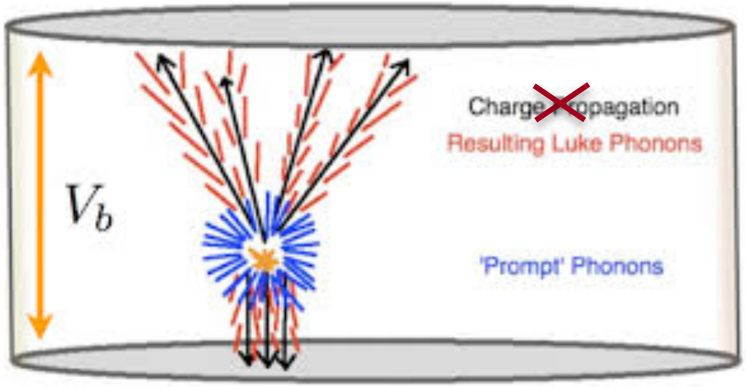

Multiple Paths to meV-Scale Energy Sensitivity

SLAC

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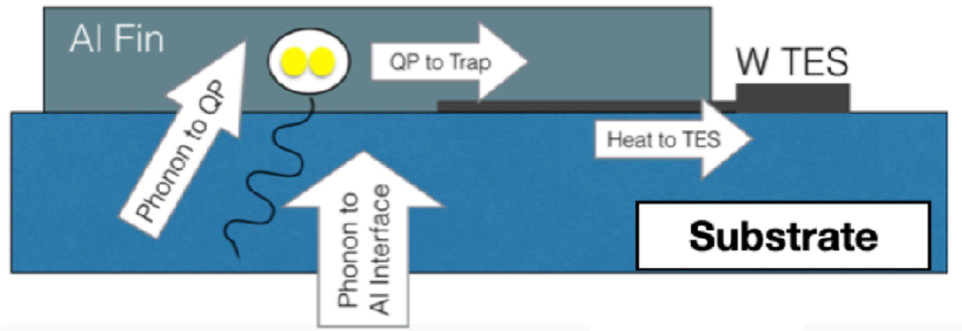
Phonons Captured in Small
Volume of Superconductor



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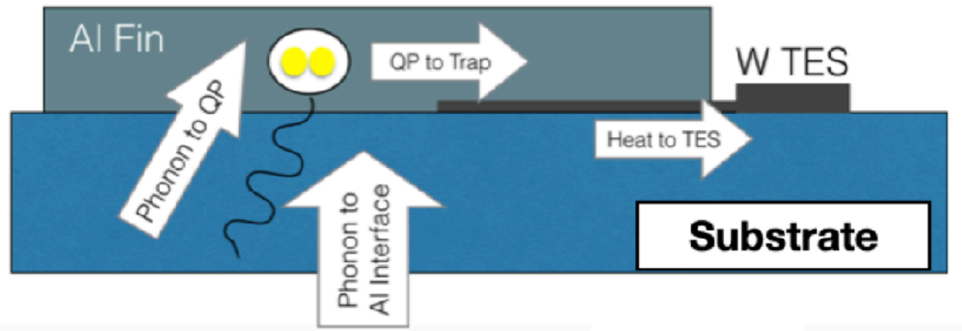

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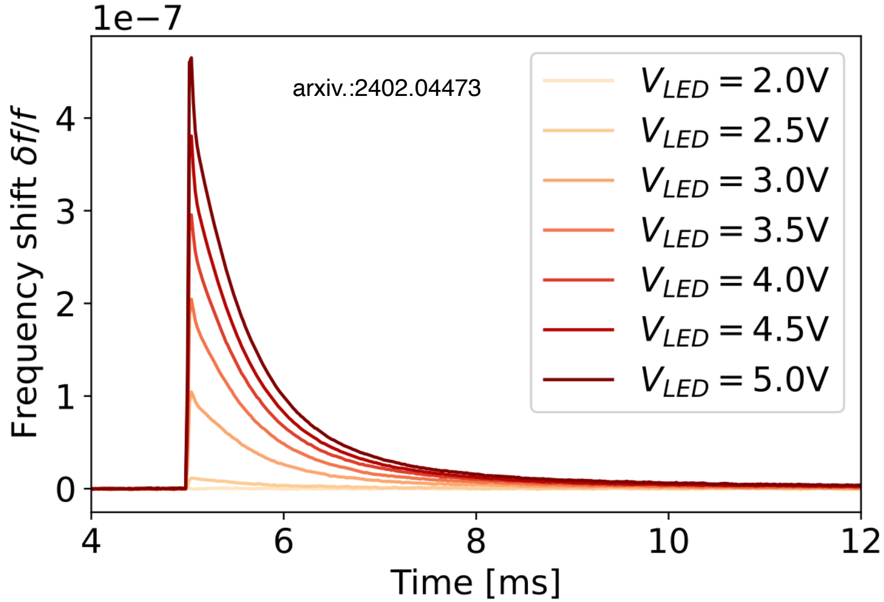

Sensor tracks
quasiparticle density
MKID, TES, SNSPD

Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit

Multiple Paths to meV-Scale Energy Sensitivity

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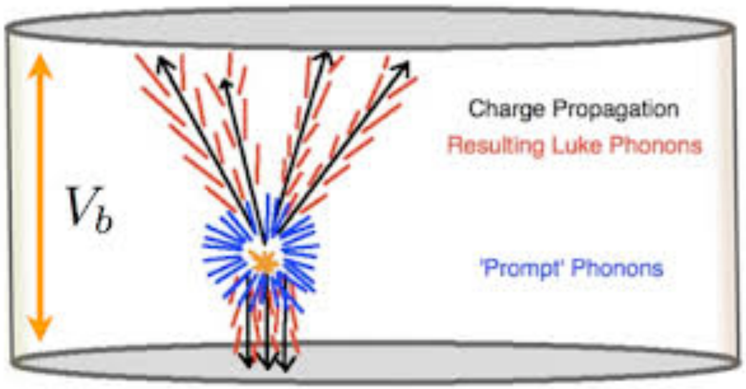
Charge and Phonons Share
Energy, Easily Collected



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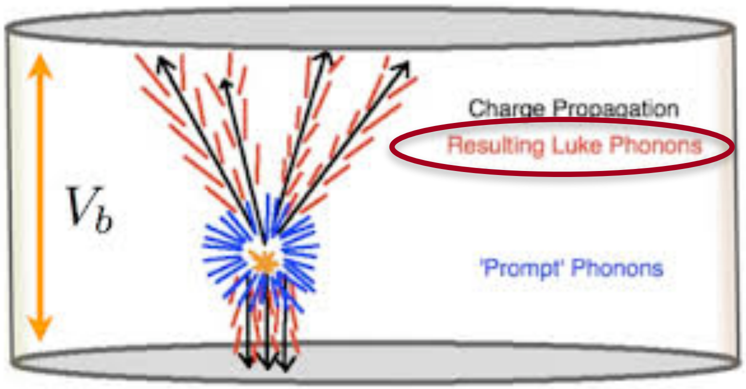

Charge drift produces
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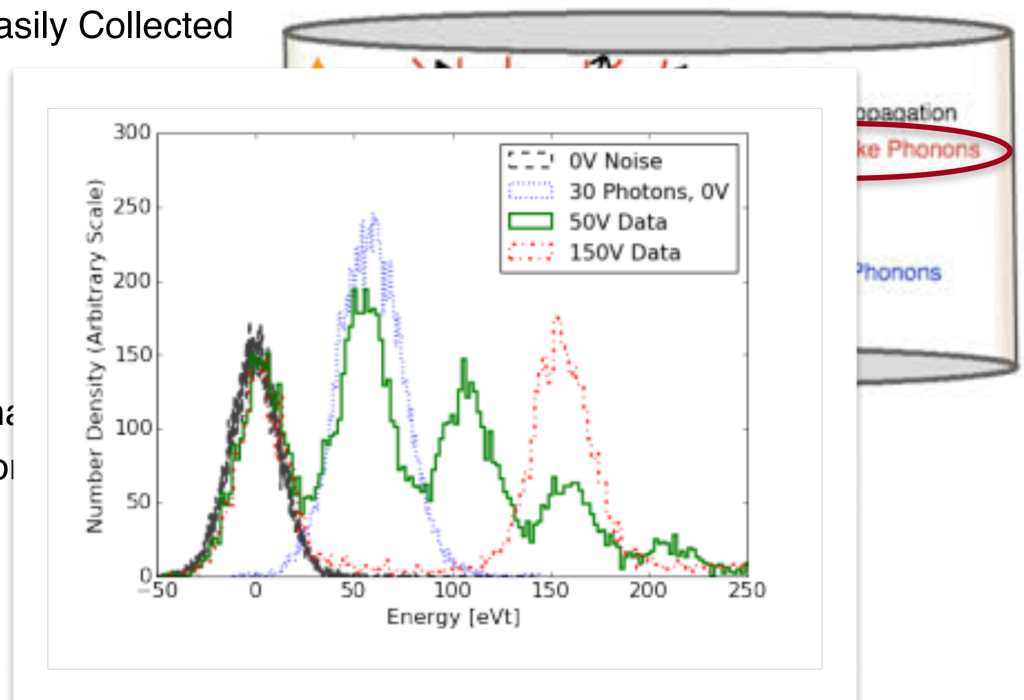

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Charge drifted to concentrated region of crystal or charge gate

Phonons
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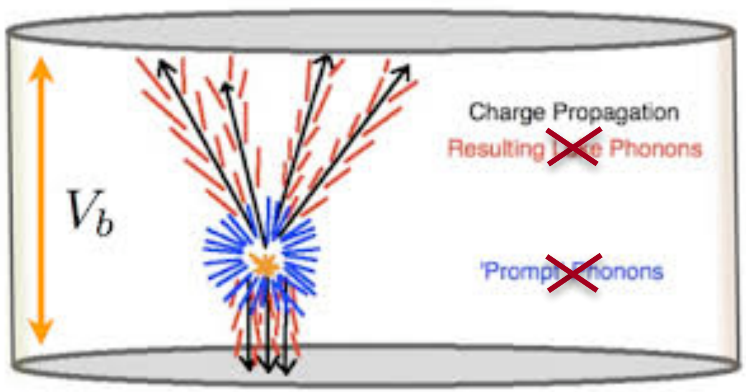

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Wilen et. al, Nature 594, 369-373

Multiple Paths to meV-Scale Energy Sensitivity

SLAC

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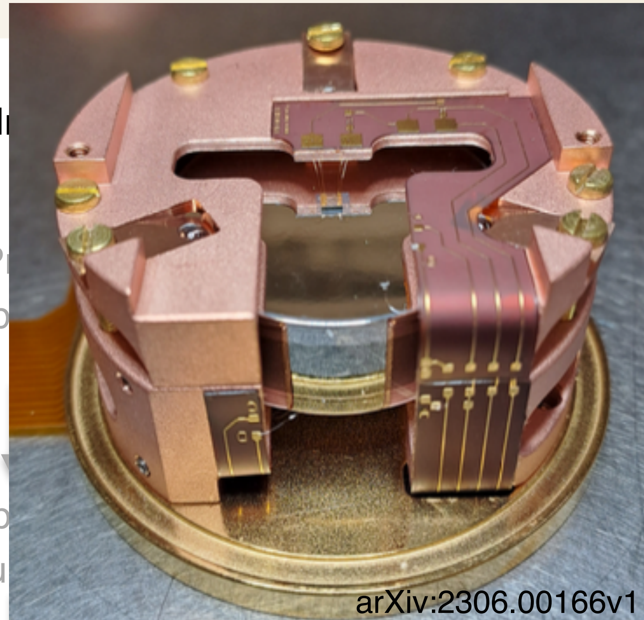

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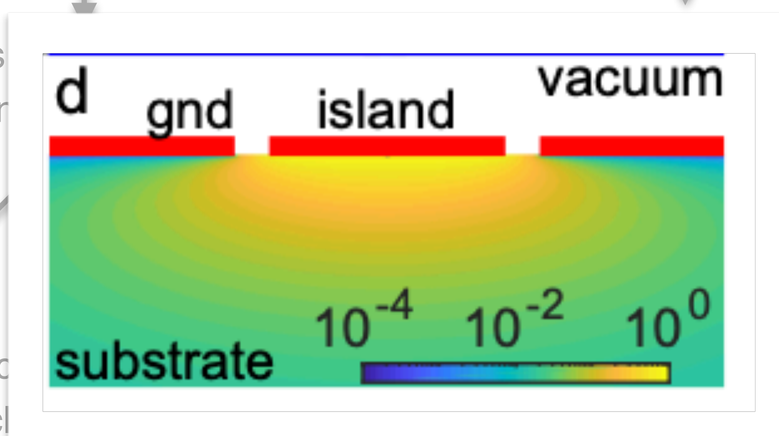

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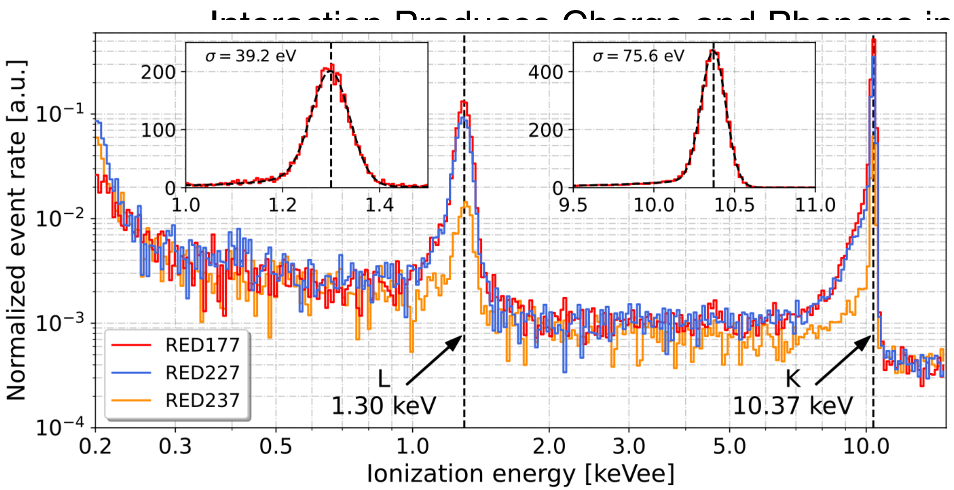
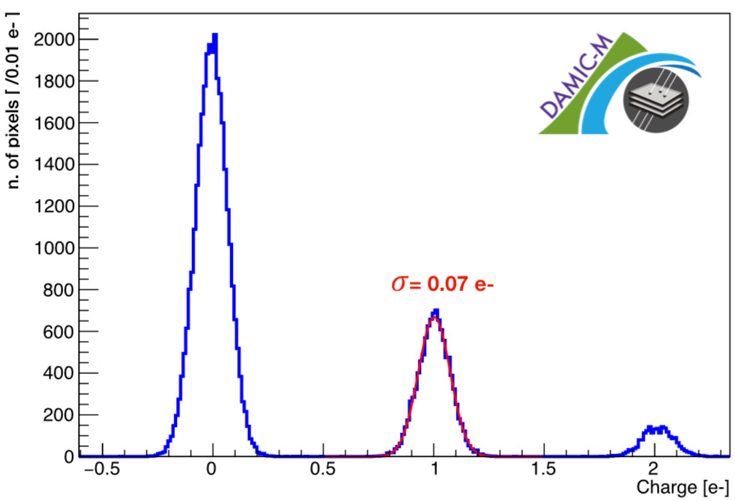
Solid State Target



More Charge Produced, Phonons Cannot be Collected

Charge drifted to concentrated region of crystal or charge gate



Charge induces offset voltage on sensor

Sensor tracks integrated image charge
HEMT, CPB (Charge Qubit)

Multiple Paths to meV-Scale Energy Sensitivity

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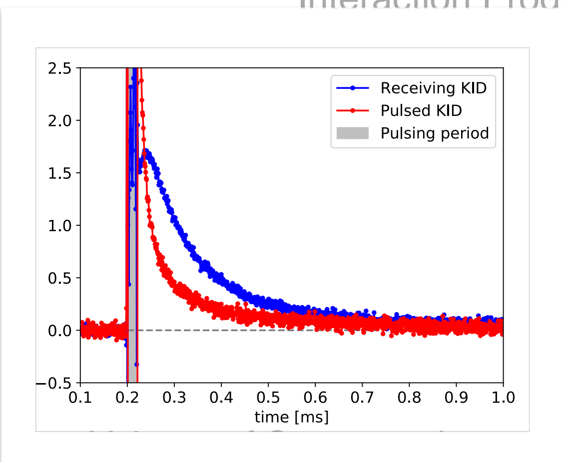
Interaction Produces Charge and Phonons in Solid State Target



Charge and Phonons Share Energy, Easily Collected

More Charge Produced, Phonons Cannot be Collected

Charge drifted to concentrated region of crystal or charge gate

Phonons increase quasiparticle

$$\sigma_e = \sigma_{N_{qp}}(2\Delta) = \sigma_{n_{qp}} V(2\Delta)$$

Charge drift produces more phonons

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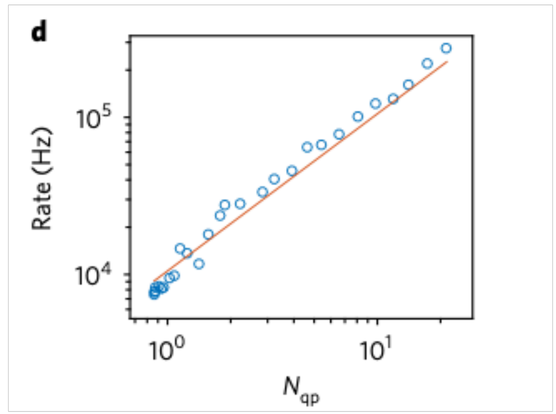

$$E = N_{qp}(2\Delta)$$
$$= \epsilon_{capture}\left[\int_0^{\tau_{pulse}} (\Gamma_{tunnel}(t) - \Gamma_0)dt\right](2\Delta)$$

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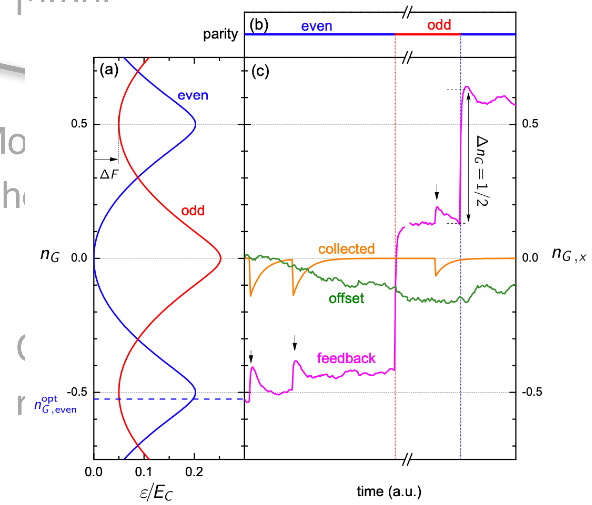

Charge induces offset voltage on

$$\sigma_E = \sigma_q E_{gap}$$
$$\approx (C_{det} + C_g)\sigma_V E_{gap}$$

ArXiv:1711.08758

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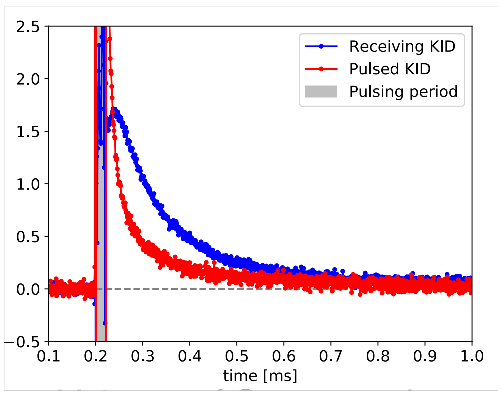

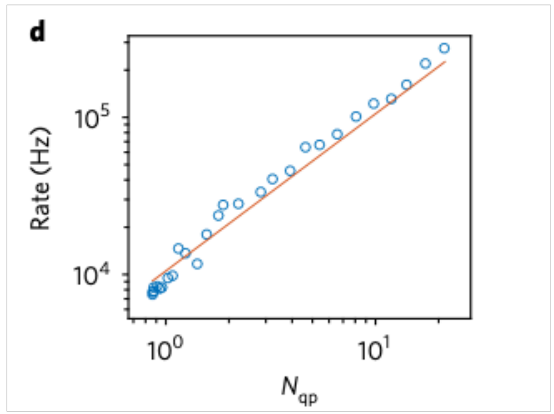

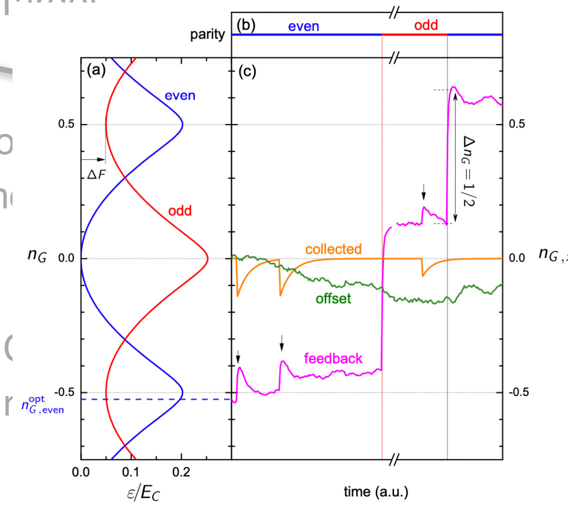

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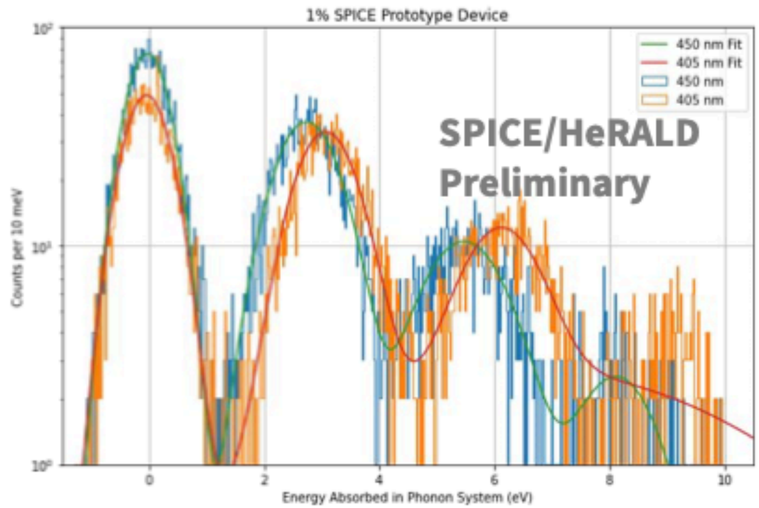
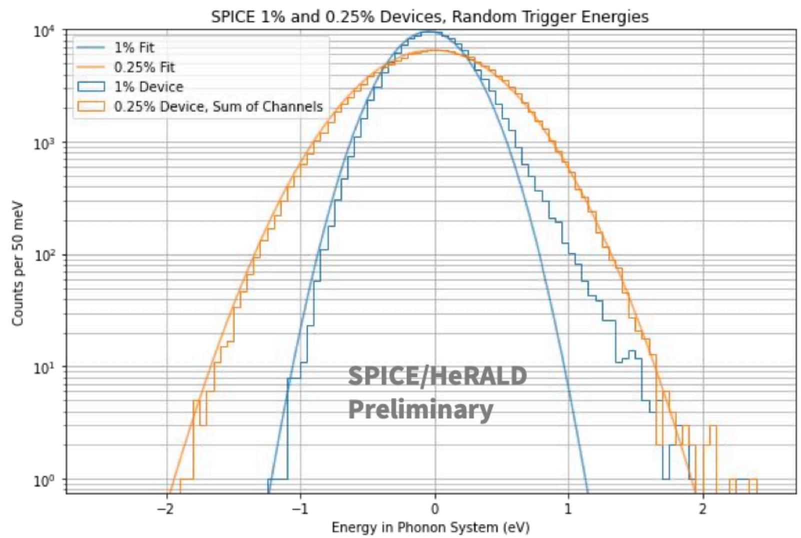
Recent SPICE Results

SPICE detectors (very low sensor volume) starting to approach the 100 meV resolution milestone

Gram-scale single photon detectors with sub-photon resolution



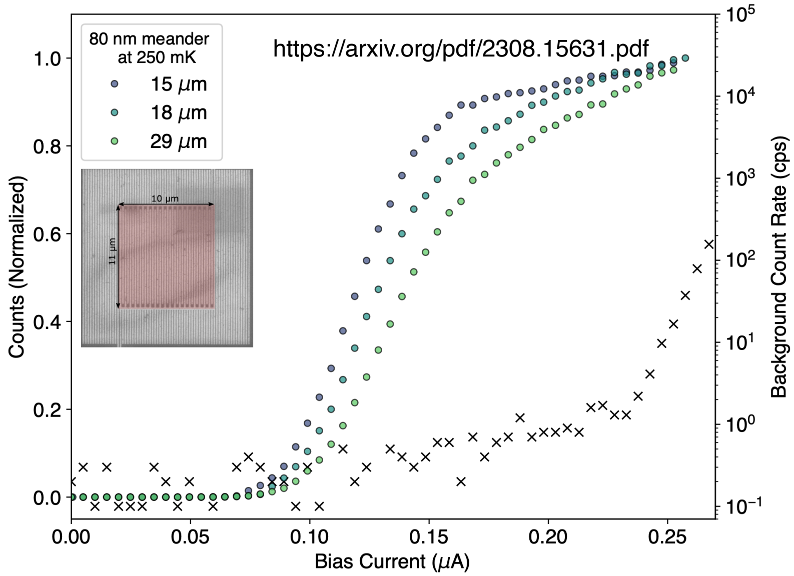
- SPICE 1%: ~273 meV (sigma) energy resolution in phonon system
- SPICE 0.25%: ~460 meV (sigma) energy resolution in phonon system

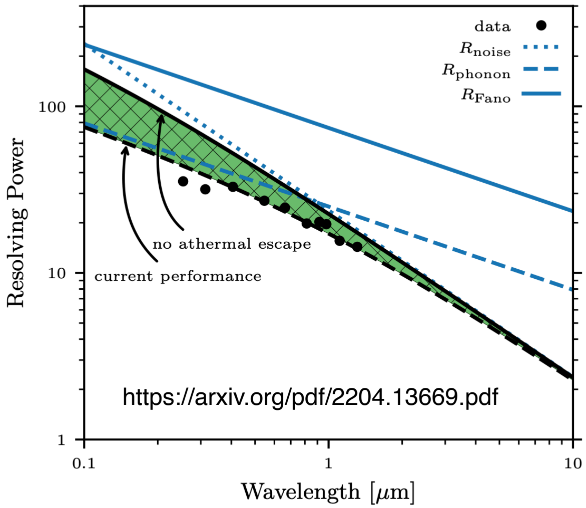


R. K. Romani

Photon Sensing: Rapidly Advancing

- SNSPDs (nanowires) can now reach ~30 microns (40 meV)
  - Not intrinsically spectroscopic, so unlikely to present real discovery potential, but our best bet for quick exclusion
- MKIDs coming close to achieving Fano-limited performance (limited by fluctuation statistics in conversion to quasiparticles)
  - Not as low in energy as nanowires, but with the ability to reconstruct event energy - roughly 100 meV thresholds
  - Significant enhancement likely with new quantum-limited amplification
- QCDs (Quantum Capacitance Detectors) - related to next topic





Energy Sensing with Qubits

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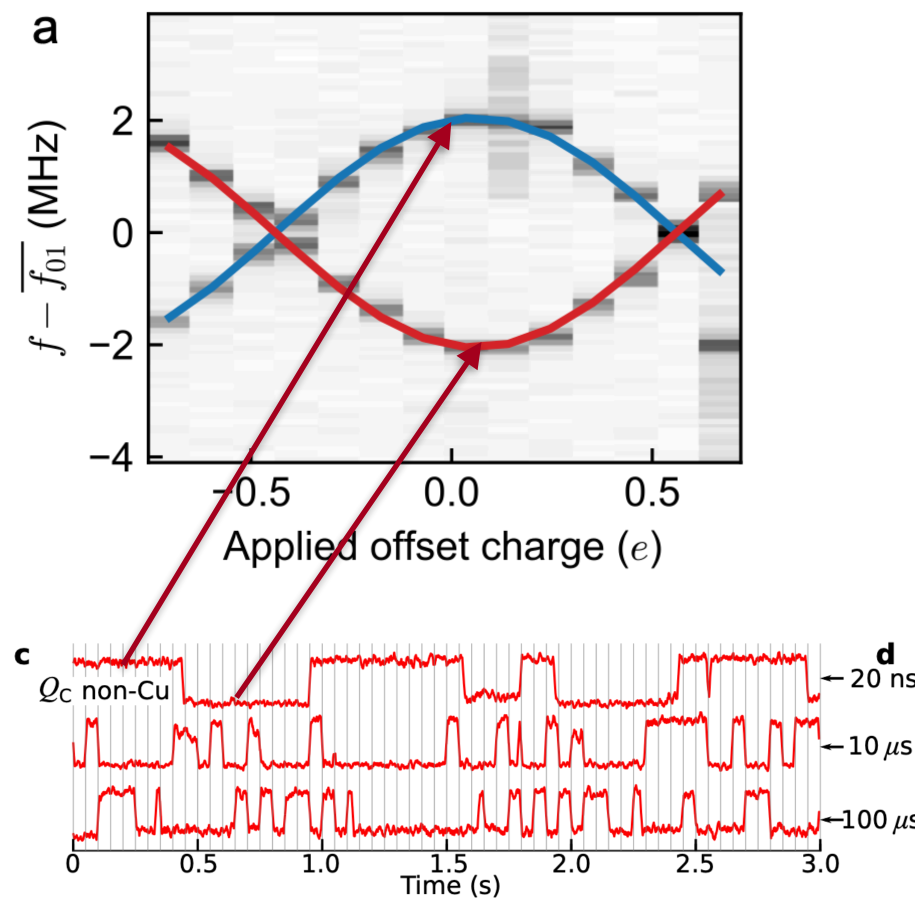
- Qubit-based sensing relies on weakly charge-sensitive qubits, which have ‘even’ and ‘odd’ parity states
- The transition between these states is mediated by quasiparticle transitions
- The rate of these transitions depends on the ambient quasiparticle density near the junctions, created by pair-breaking radiation



$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos(\phi)$$

Proof of Concept: Quantum Capacitance Detector

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- This detector employs a cooper pair box (charge qubit) coupled to a resonator to probe tunneling probability

- The transition frequency depends on steady-state power absorption by the small island between the capacitor and junction

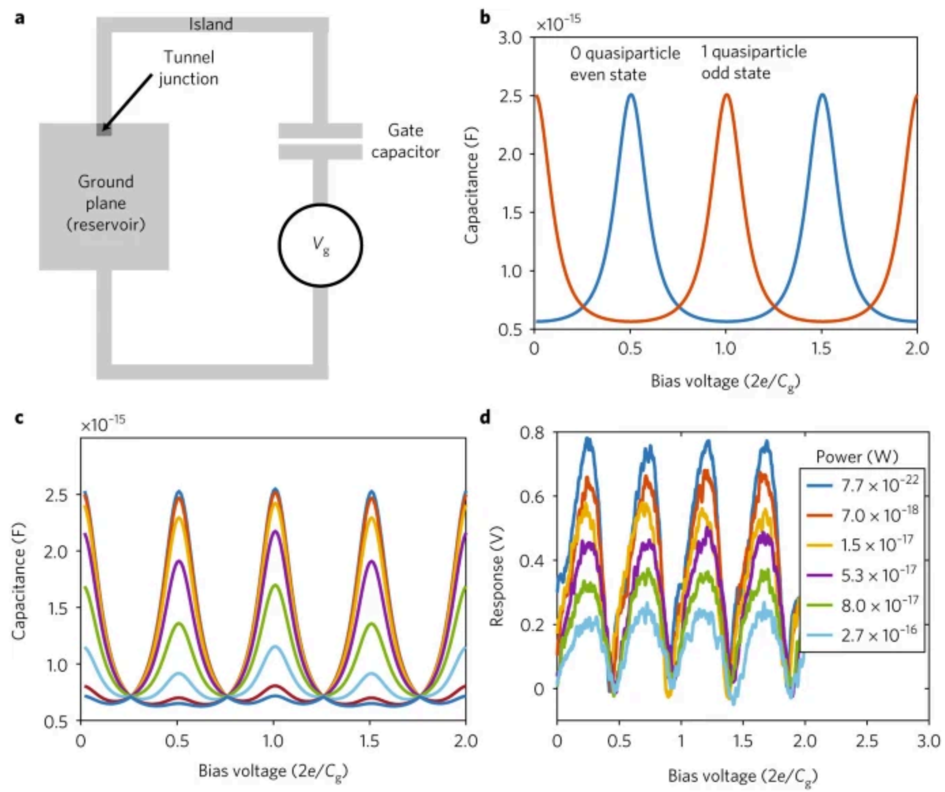
- This detector has the lowest ever achieved noise equivalent power - simply because it is sensitive to individual quasiparticle tunneling events

- We need a strategy to extend the frequency range of these devices

Single photon detection of 1.5 THz radiation with the quantum capacitance detector

P. M. Echternach, B. J. Pepper, T. Reck & C. M. Bradford

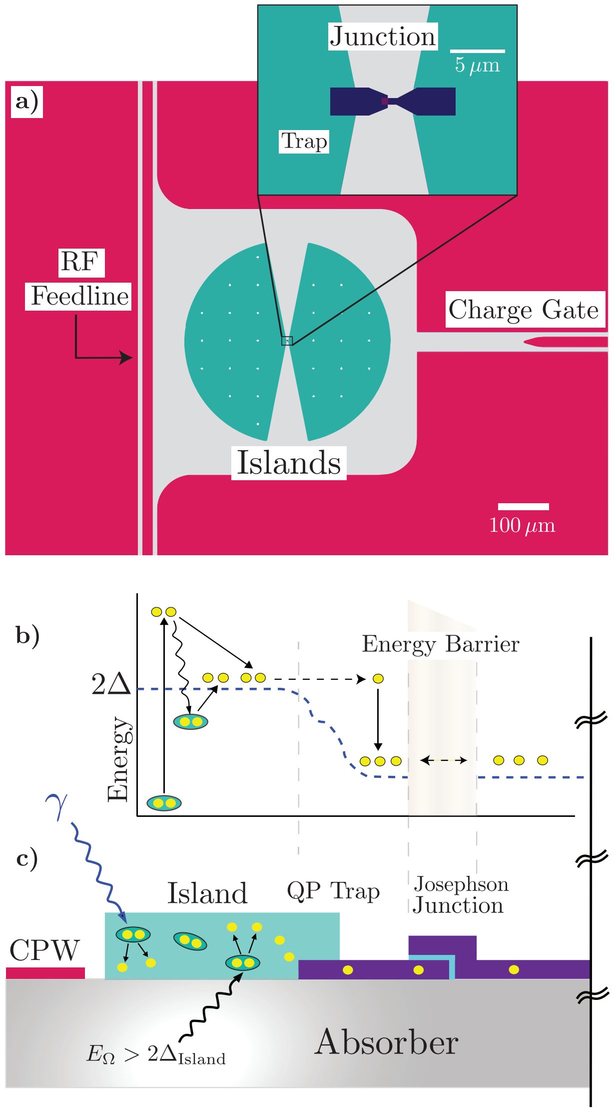
Nature Astronomy **2**, 90–97 (2018) | Cite this article



Superconducting Quasiparticle-Amplifying Transmon

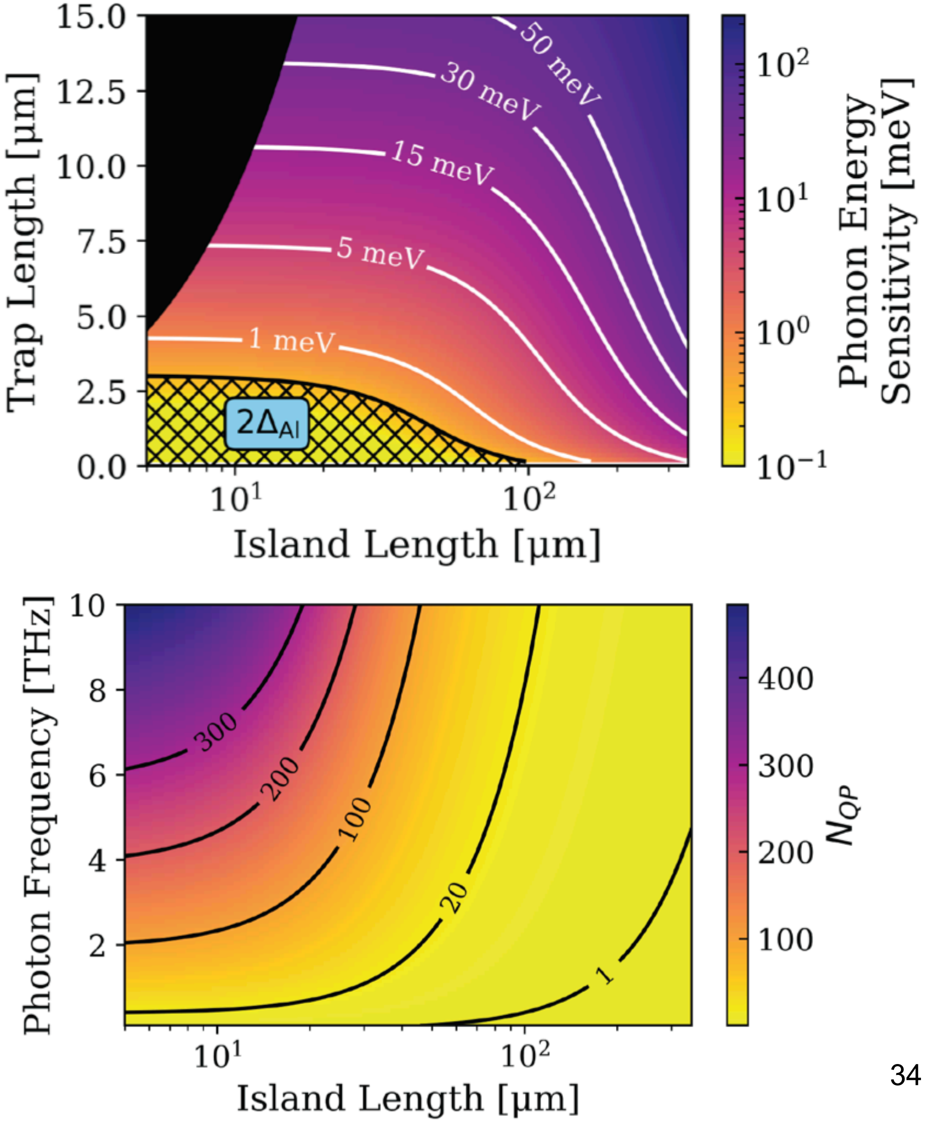
- The SQUAT combines the phonon diffusion modeling of the QET with the quasiparticle counting ability of a weakly charge-sensitive transmon to count phonon-produced quasiparticles.

- Energy detection occurs through a cascade process:
    - Phonon breaks cooper pairs
    - Quasiparticles are trapped in junction leads, leading to addition QP production
    - Tunneling occurs at elevated rate due to enhanced, concentrated qp density, with a timescale defined by the qp lifetime



Projected Sensitivity

- Small trapping regions enable high tunneling efficiency and gap-limited performance
  - Performance will vary based on trapping and tunneling efficiency - all designs are sub-eV for this range of parameters
  - First devices will help benchmark these design parameters
- Single photon detection achievable with a wide range of designs down to 1 Thz - more on this at the end of the talk



DM Induced QP Poisoning

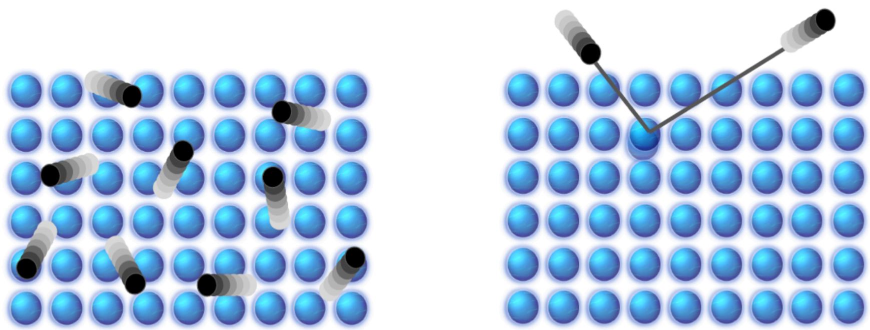
Dark Matter Induced Power in Quantum Devices

Anirban Das,[1,*] Noah Kurinsky,[1,2,†] and Rebecca K. Leane[1,2,‡]

[1] *SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA*

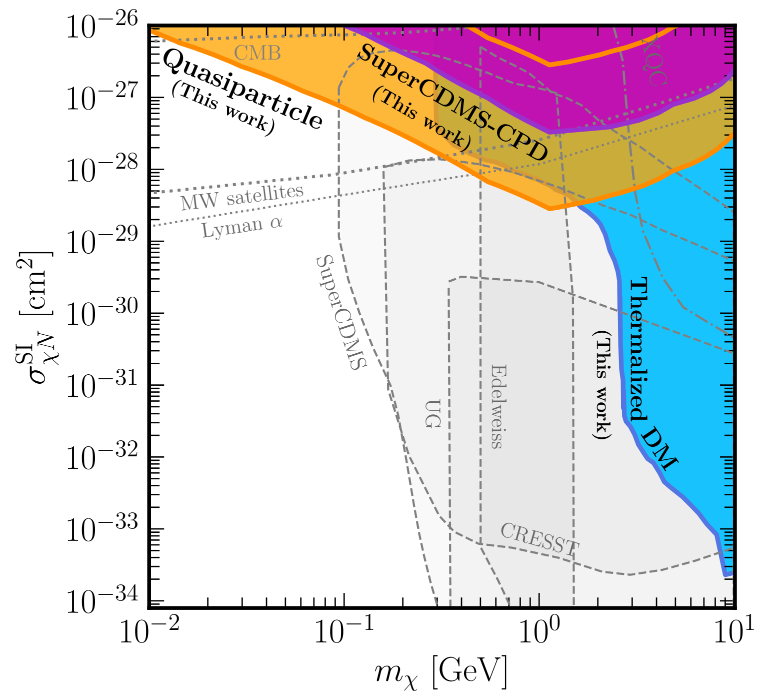
[2] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94035, USA*

(Dated: October 17, 2022)



Noise from DM

Recoil from DM



Limits on DM can be set just from looking at existing quasiparticle poisoning in single-quasiparticle devices!

$$x_{\rm qp} \approx \left(\frac{P_{\rm DM}}{3.6 \times 10^{-21}\,{\rm W}} \right)^{1/2}$$

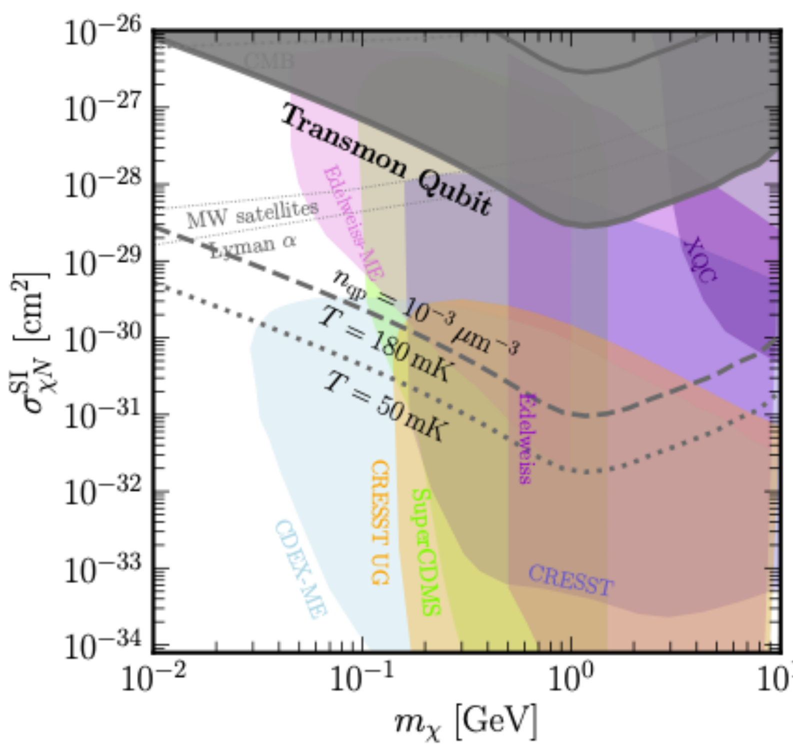
Phys. Rev. Lett. 132, 121801 (2024)

Connecting Parity Switching to Energy Injection

SLAC

- Das et. al. needs to make a number of conservative assumptions that limit the constraining power of this technique
  - We don't have a validated model for equilibrium QP density from rare events - assume mean-field solution
  - The tunneling probability across a junction is not well modeled, and relies on a non-local approximation that has not been verified - sensitivity could be enhanced if multiple tunneling events occur
  - Other mechanisms for producing non-equilbrium QPs are not accounted for

- All of these move the QP limit into new parameter space - sensor R&D can turn this into a true discovery experiment if spectroscopic readout can be demonstrated



$$R_{qp} = \frac{\epsilon_{qp}}{\Delta} \int d\omega\, \omega \frac{d\Gamma}{d\omega}$$

$$\approx \left(\frac{P_{DM}}{9 \times 10^{-23}\ \mathrm{W}\mu\mathrm{m}^{-3}} \right) \mathrm{Hz}\ \mu\mathrm{m}^{-3}$$

https://arxiv.org/pdf/2405.00112

Connecting Parity Switching to Energy Injection

- Das et. al
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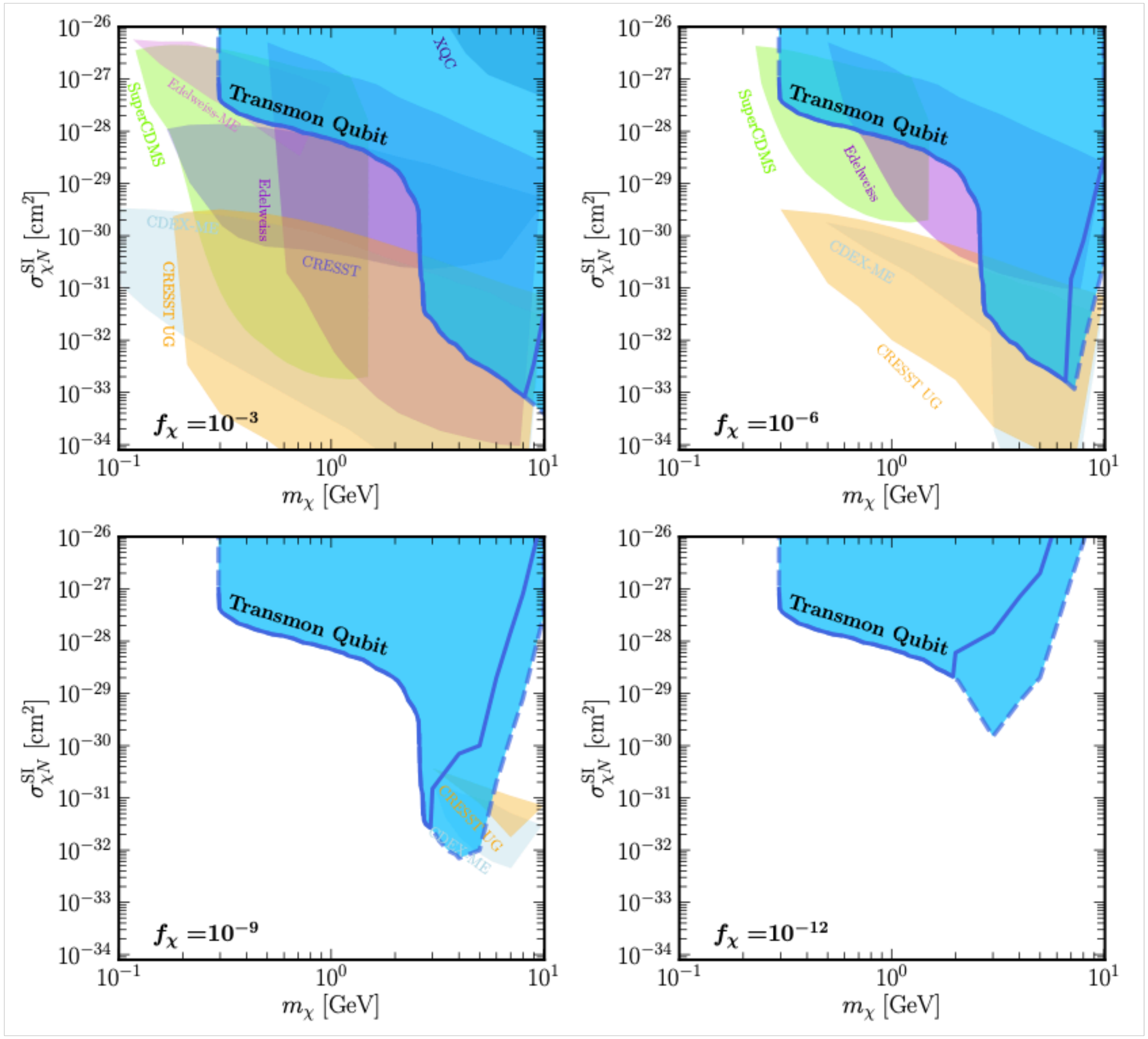
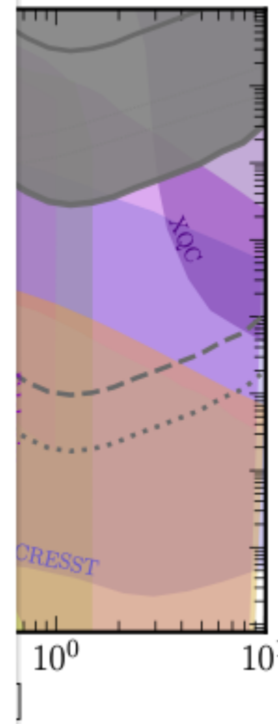


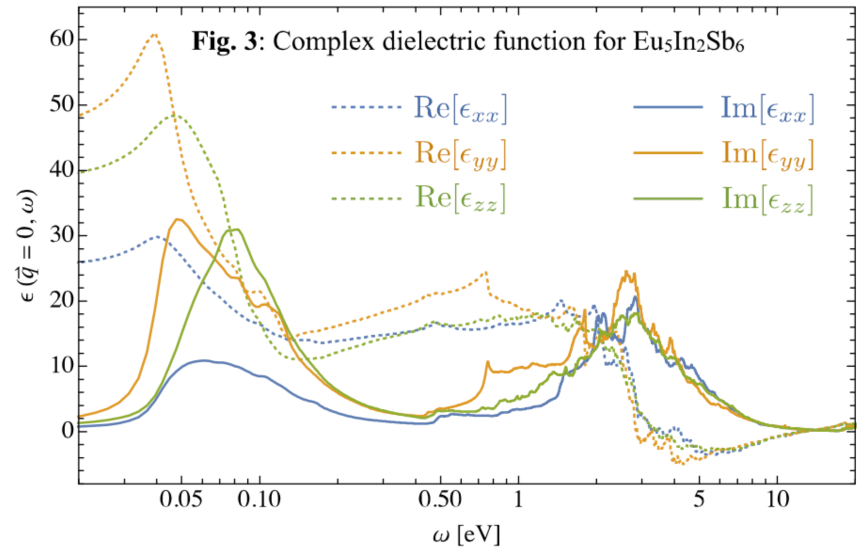


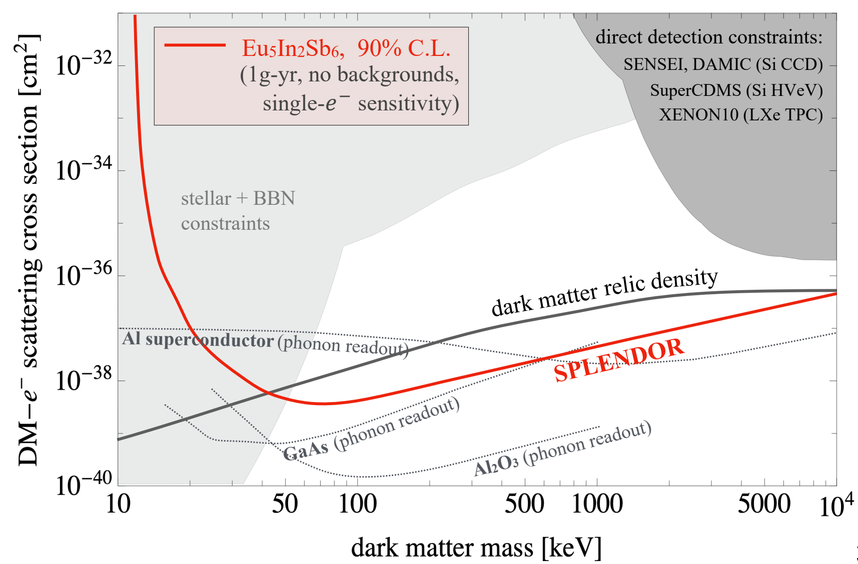
Hz μm^{-3}

Designer Materials for Light DM (SPLENDOR)

SLAC

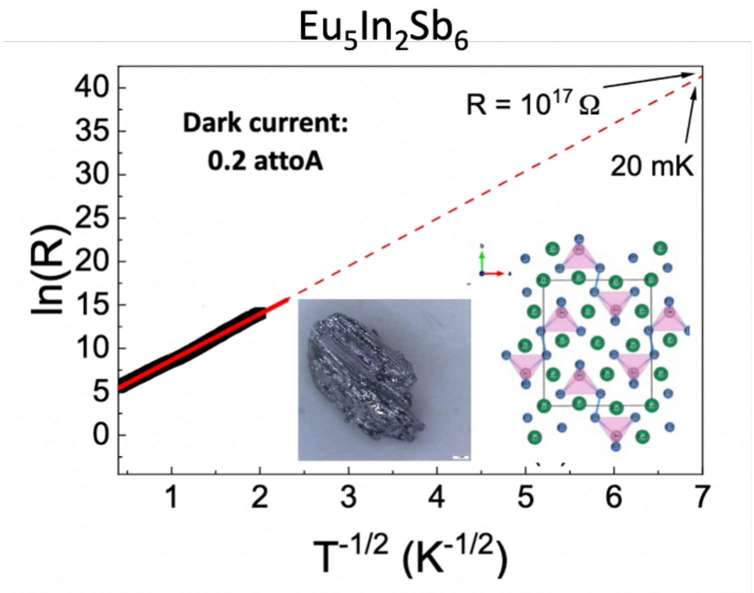
- Materials with high loss in the sub-eV regime (which are well matched to DM) are needed to efficiently probe low-mass DM
- Designer materials with magnetic ordering have tunable bandgaps and high density of states in the sub-eV regime
  - 526 Compound has a gap of 10 meV
- g-day exposures can yield impressive science reach
- Single electron sensitivity is needed for greatest sensitivity
- Sensitivity paper in preparation with results from initial LDRD project - will be out early fall!

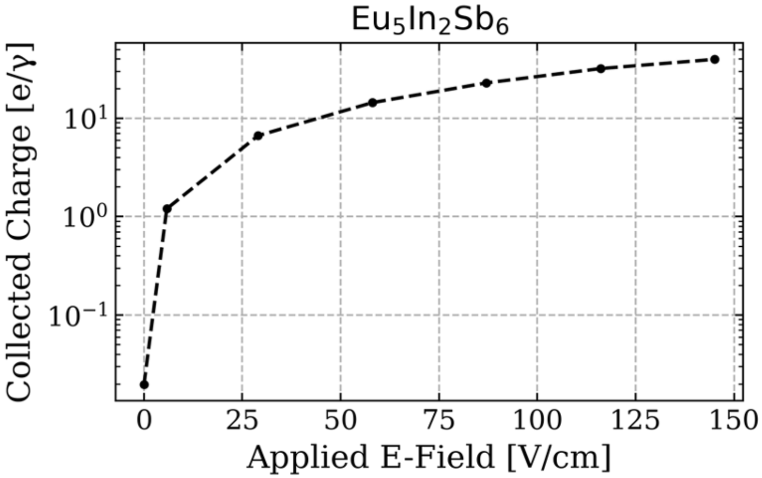




Steady-State Photoresponse - $Eu_5In_2Sb_6$

- Low dark currents observed - further work will determine whether this trend continues to the count/second level at 10 mK
    - Predicted by DFT to lower than ~100 meV
    - Our measurements at 10 mK will establish the first experimental gap measurement
- Charge collection well over 1 electron/eV observed
    - Full collection would be ~30 - 100 e/photon - currently seeing >10% collection. Studies underway at higher bias voltage to measure full collection.
- This is one of a set of 5-6 promising new materials for far-IR photon detection

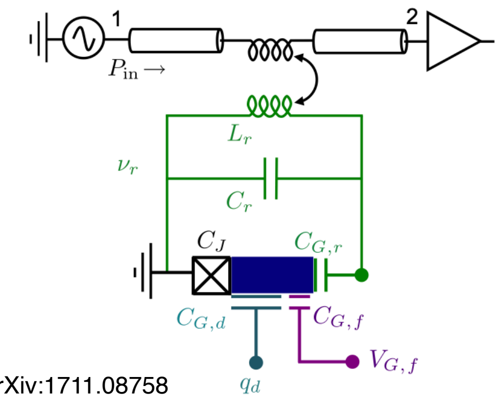




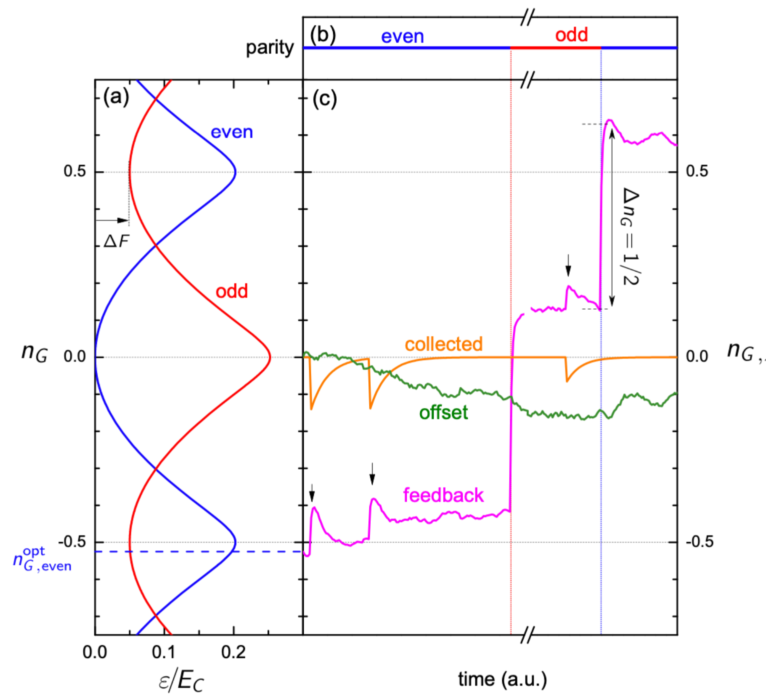
Qubit-Based Electrometers for Quantum Materials

SLAC

- HEMT-based amplifiers likely limited to ~2-5 electrons
- Use extreme charge sensitivity of charge qubits to create single-charge electrometers
  - Generate charge spectrum with flux or gate feedback by nulling feedback signal!
  - Similar to a closed-loop SQUID readout.
- Combine with meV-scale gapped materials for meV-resolution sensors
- Not a new idea! Work is ongoing and picking up steam, riding the momentum from other QIS work.



ArXiv:1711.08758



Qubit-Based Electrometers for Quantum Materials

SLAC

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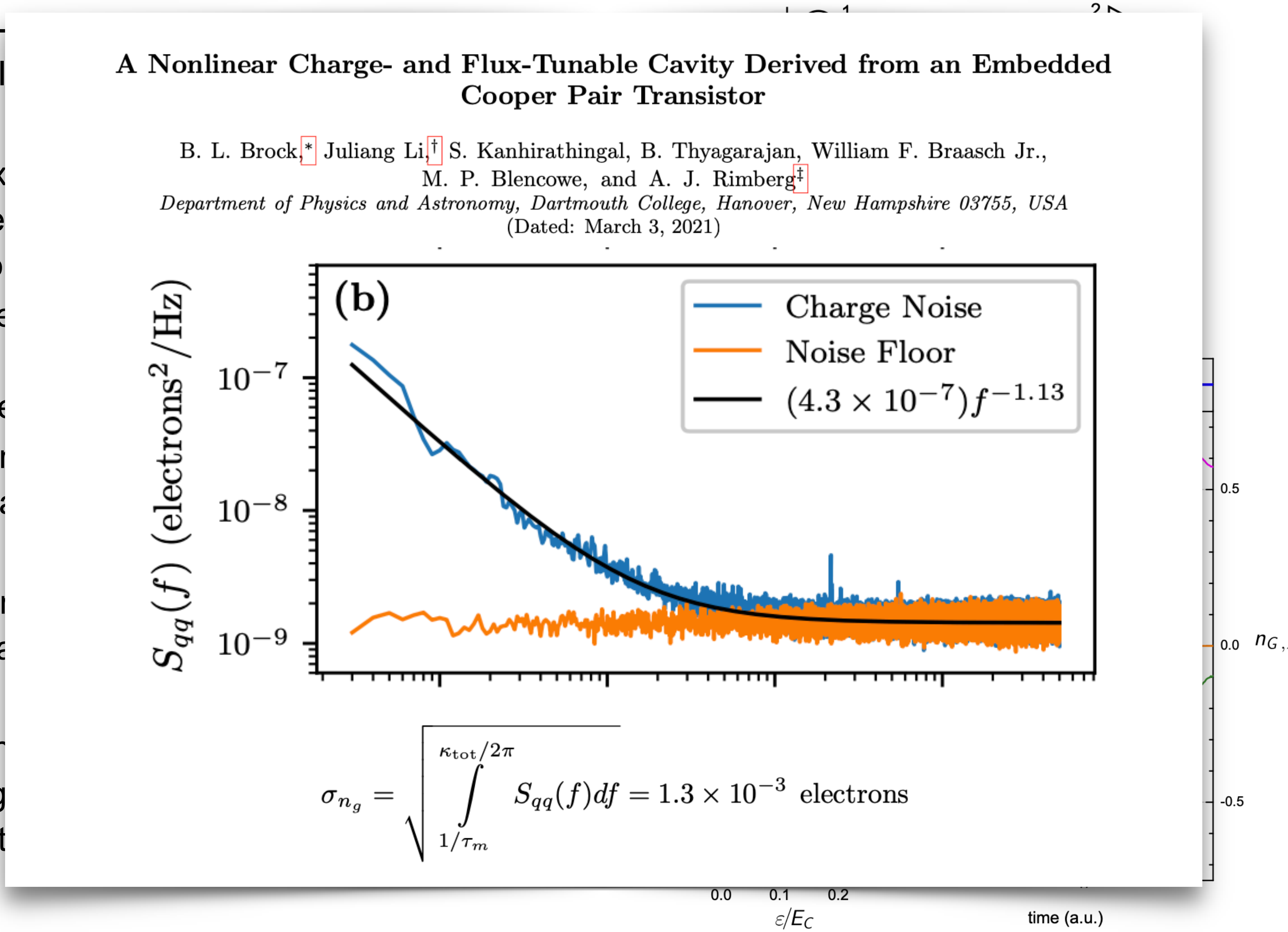


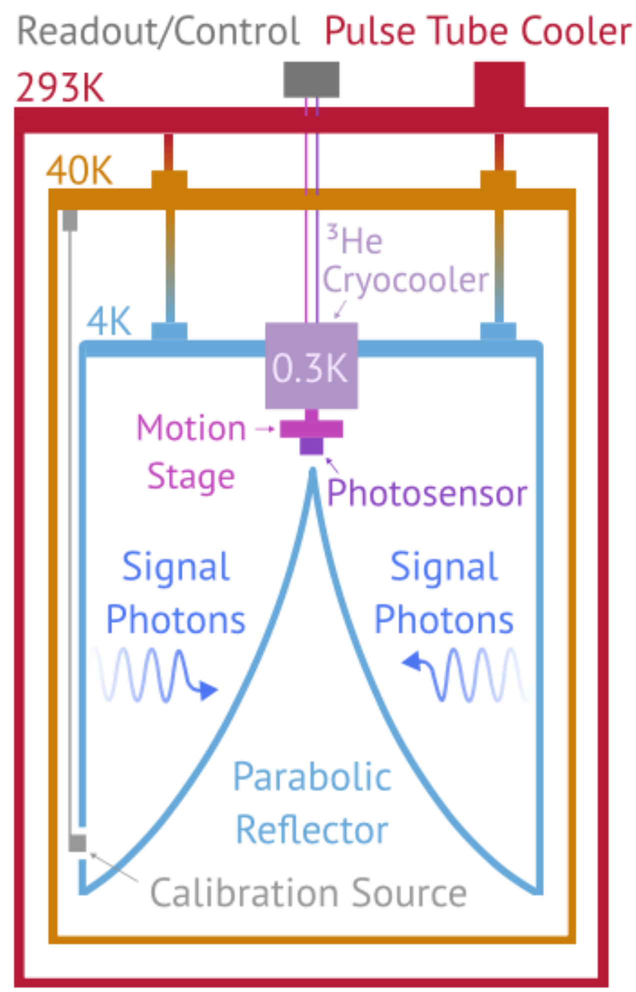
Wide-Band Axion Searches (BREAD)

Initial experiment will couple a 350 mK dish antenna to an existing quantum sensor (either SNSPD or MKID) to do a dark photon search

Many interesting technical challenges

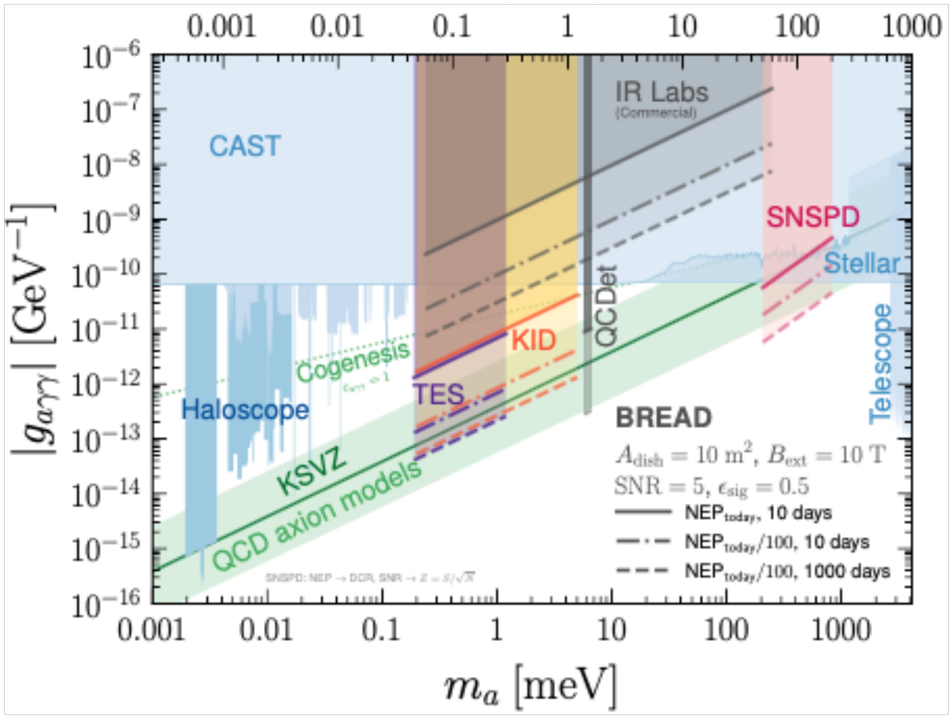
- Sub-Kelvin feedhorn design and characterization
- Development of THz optical paths
- Ability to calibrate wide-band sensors in the meV-eV regime
- Measurement of quantum efficiency in-situ

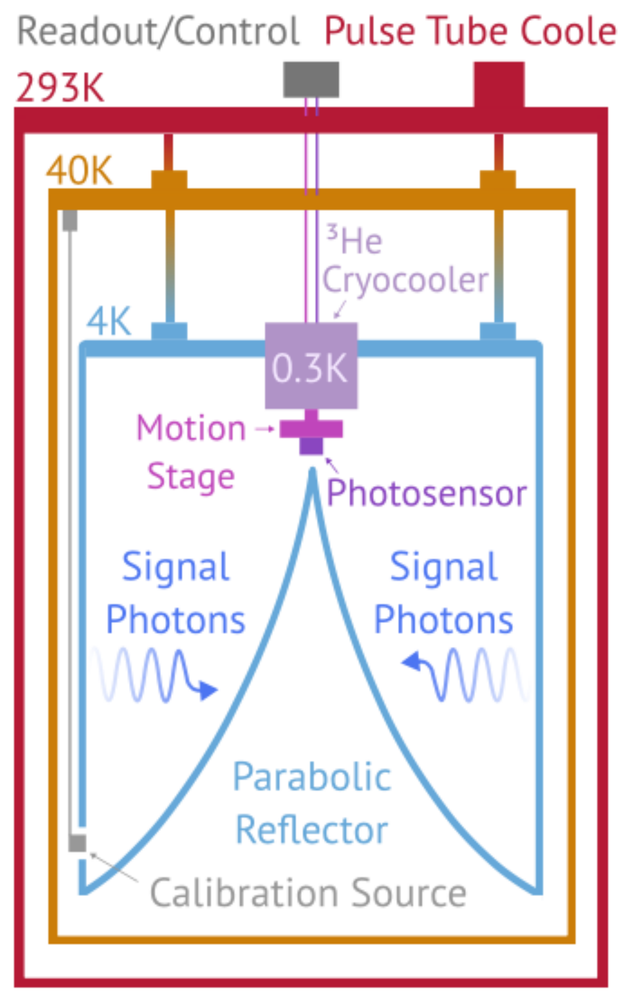
Initial prototype will run at FNAL in the next 1-2 years, ultimate experiment realized in 5-10 years alongside developments in quantum sensing



Liu et. al. (BREAD Collaboration), ArXiv.:2111.12103

Wide-Band Axion Searches (BREAD cont'd)





Change mass sensitivity by swapping photosensor; variety of stages planned with different detector technologies.

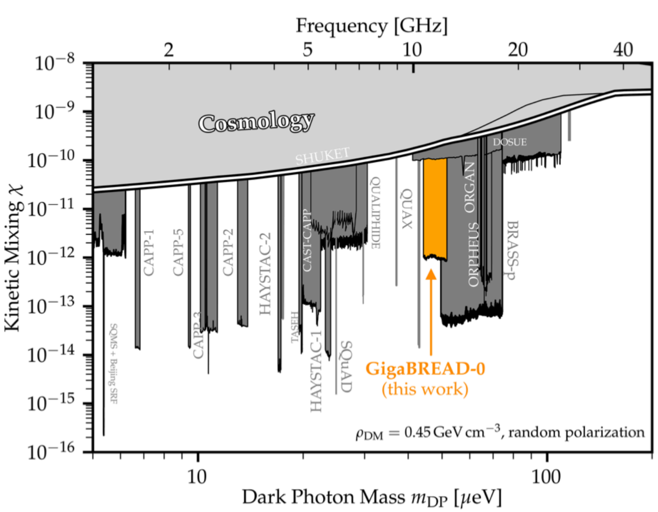
True THz sensitivity requires power noise only achieved in qubit-derived structures (e.g. quantum capacitance detector)

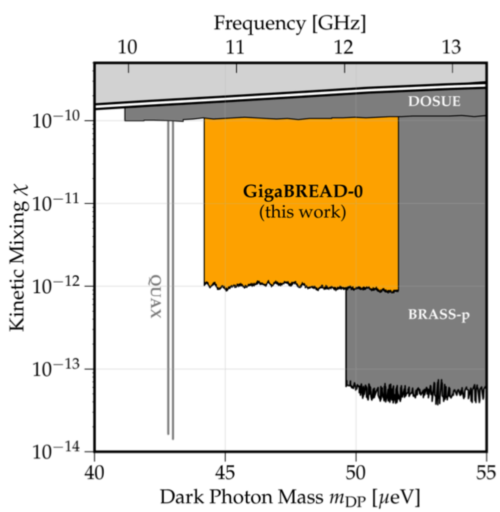
Liu et. al. (BREAD Collaboration), ArXiv.:2111.12103

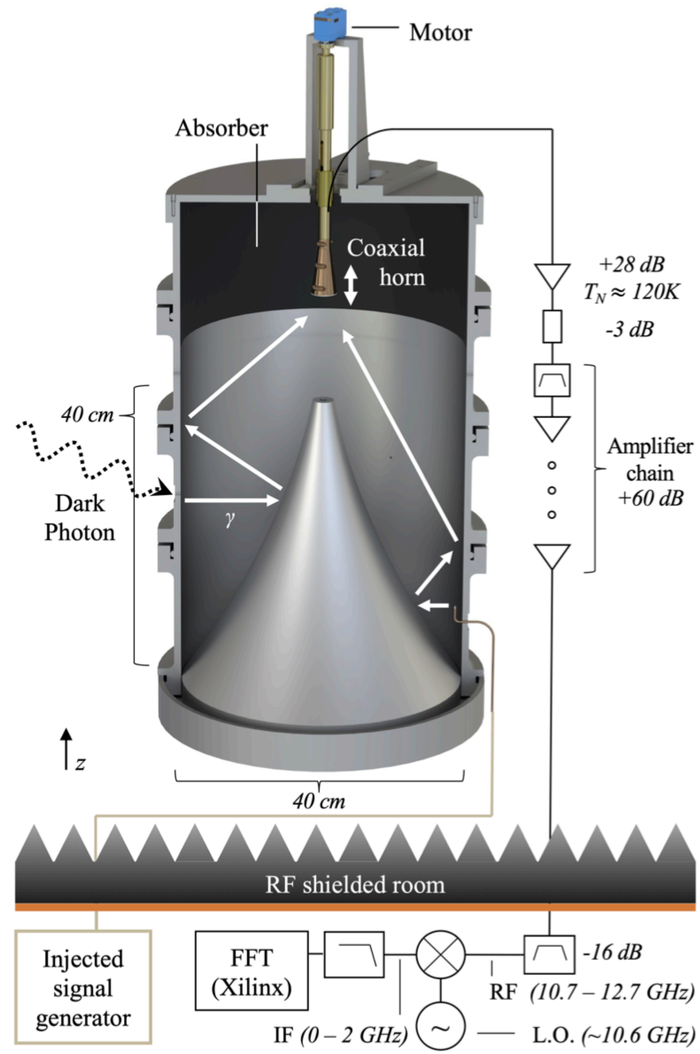
Pathfinder Detector: GigaBREAD

Pathfinder GHz, room-temperature experiment ran a dark photon search at UChicago/Fermilab earlier this year!

Calibration/tuning demonstrated with custom RF-SOC based spectrum analyzer; 2 GHz of bandwidth measured simultaneously







https://arxiv.org/pdf/2310.13891.pdf

Pathfinder Detector: GigaBREAD

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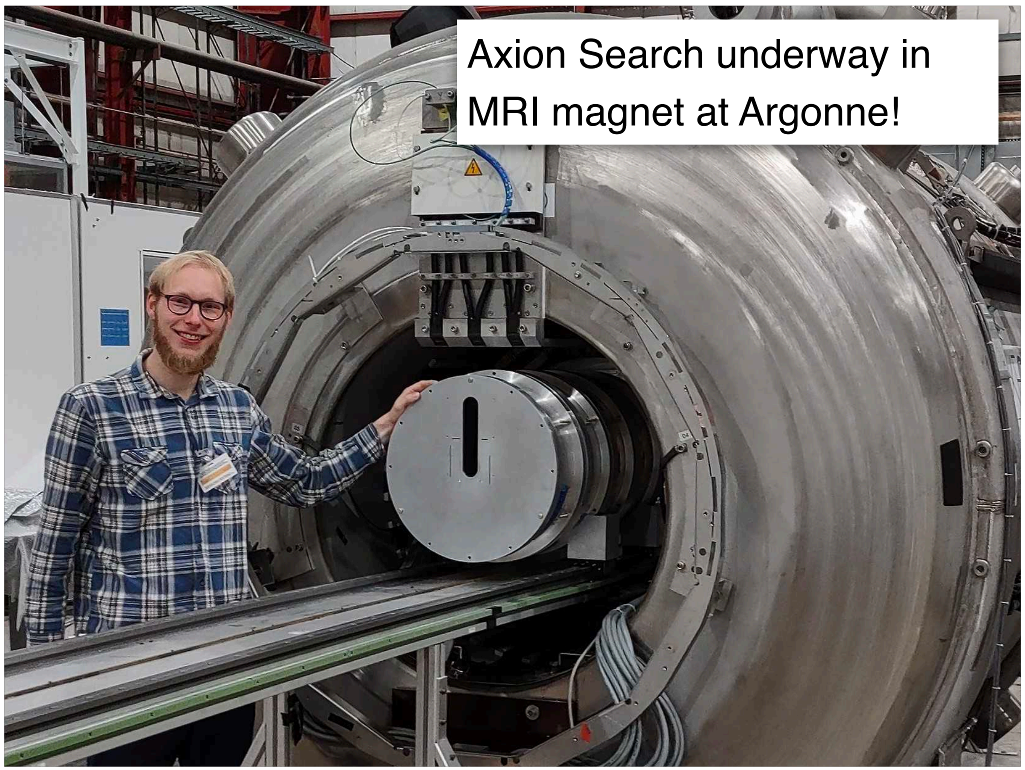
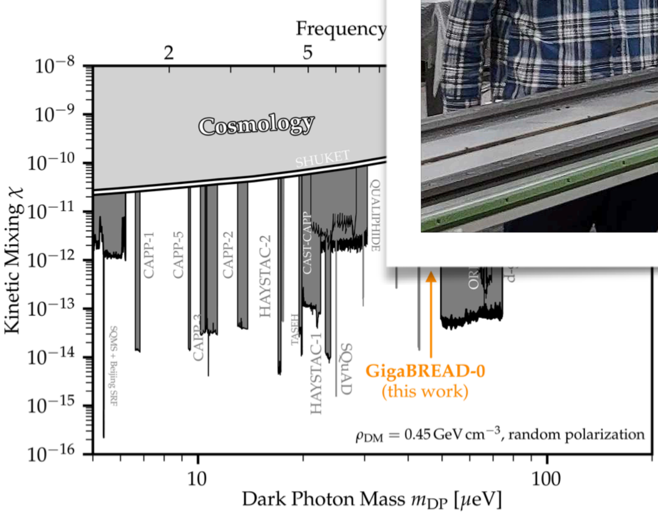
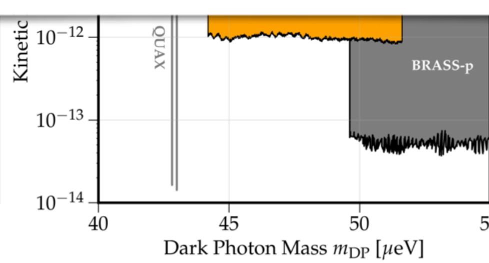
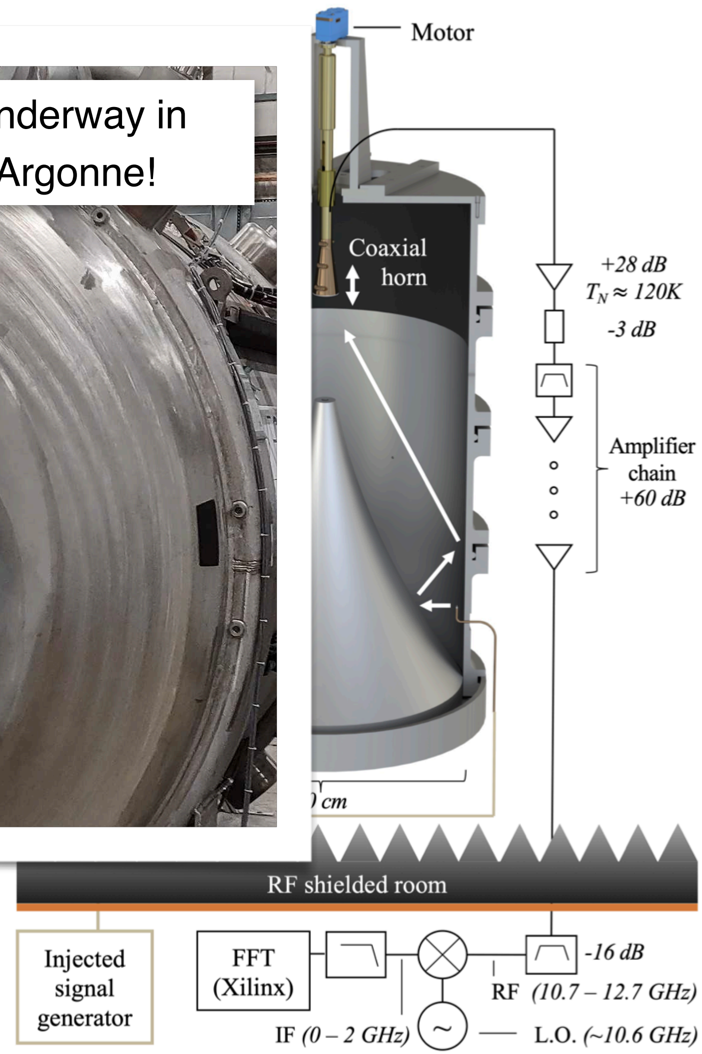




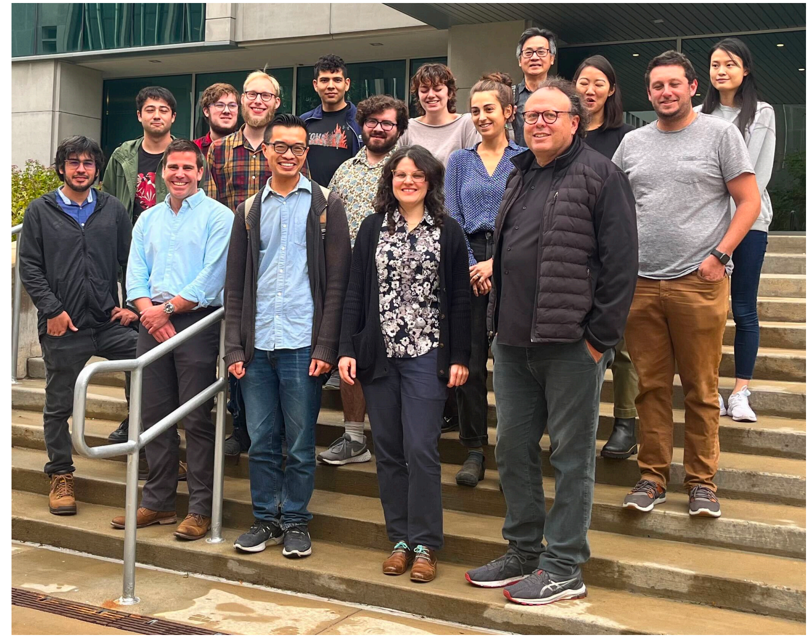


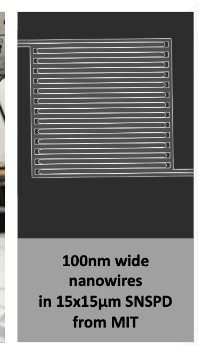


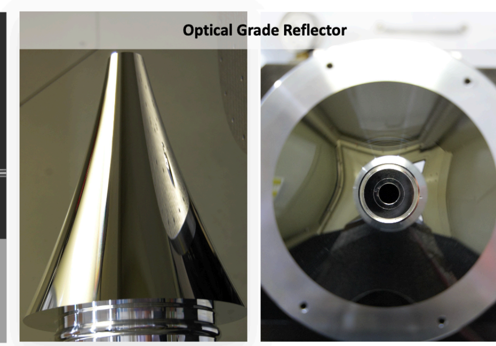
BREAD Collaboration Work in Progress

Multi-tiered development plans to solve individual issues and produce science results on the way to the ultimate high-frequency axion searches:

- UChicago/FNAL - GigaBREAD (10-15 GHz) and QualityBREAD (~100 GHz)
- FNAL/Caltech/JPL/MIT - InfraBREAD (<20 microns), utilizing high-polish reflector with SNSPDs
- SLAC/JPL - TeraBREAD pathfinder
    - THz calibration source
    - Optics design
    - SQUAT or QCD-based readout







Conclusions

SLAC

- Low mass DM searches (meV - MeV) require new detector technologies which are necessarily cryogenic due to the low photon backgrounds required
- Qubits and related devices already show promise for low occupancy in these energy ranges
- Combining the cryogenic expertise from low-background DM experiments with the hardware expertise of QIS is already bearing fruit
- Many different channels and experiments springing up; it is likely to be an interesting few years as new experiments come online.