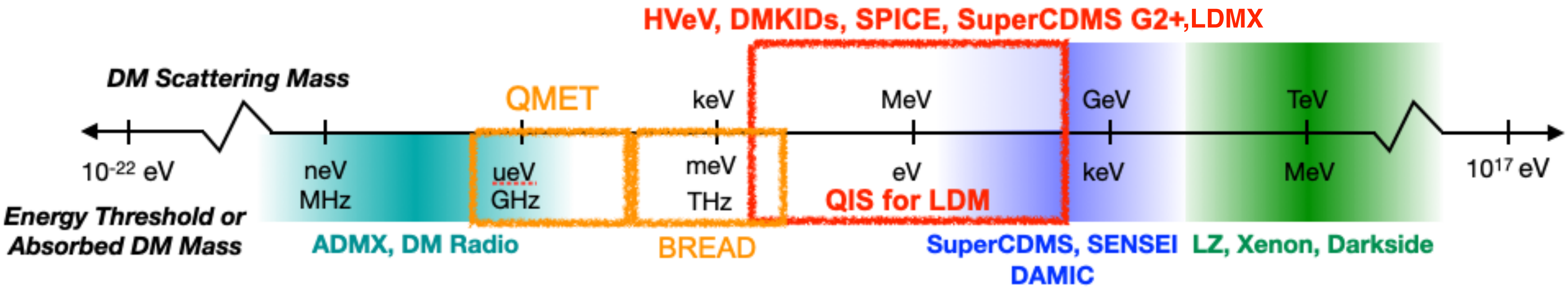
Light/Ultra-Light DM Searches: Reaching the meV Scale

Noah Kurinsky
Staff Scientist, SLAC
The Future of High Energy Physics: A New Generation, A New Vision
Aspen Center for Physics
March 26, 2024

BOLD PEOPLE. VISIONARY SCIENCE. REAL IMPACT.

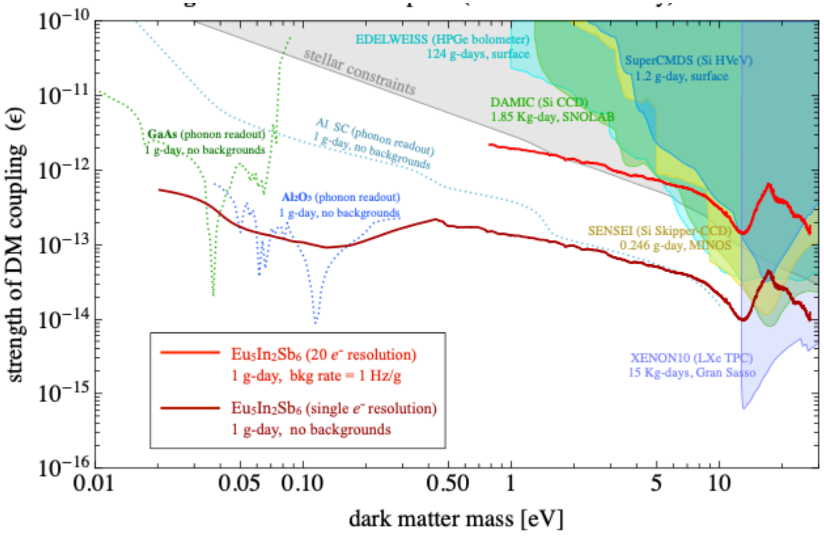
Motivation: Closing the DM Gap

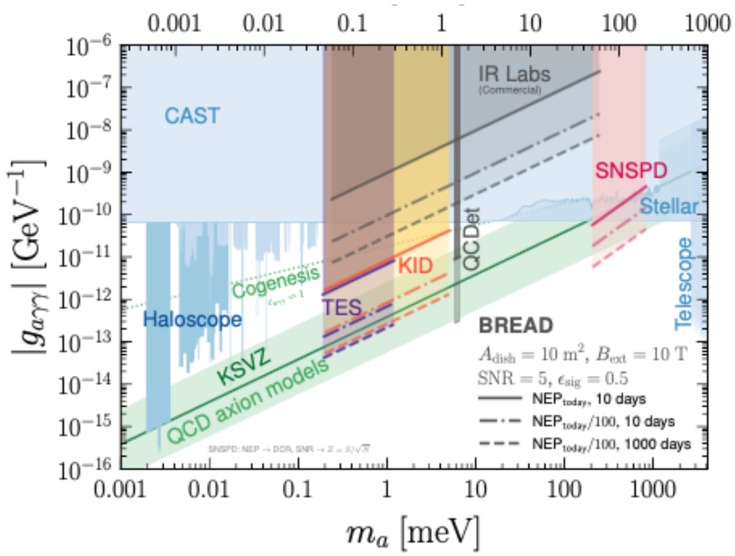


- Existing DM experiments are opening an ever larger window onto axion detection (at low mass) and heavy dark matter (>1 MeV)
- There’s a gap of 6 orders of magnitude limited by the challenges of detecting single events at the meV energy scale
- Our group at SLAC (DMQIS) focused on applying quantum measurement 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.

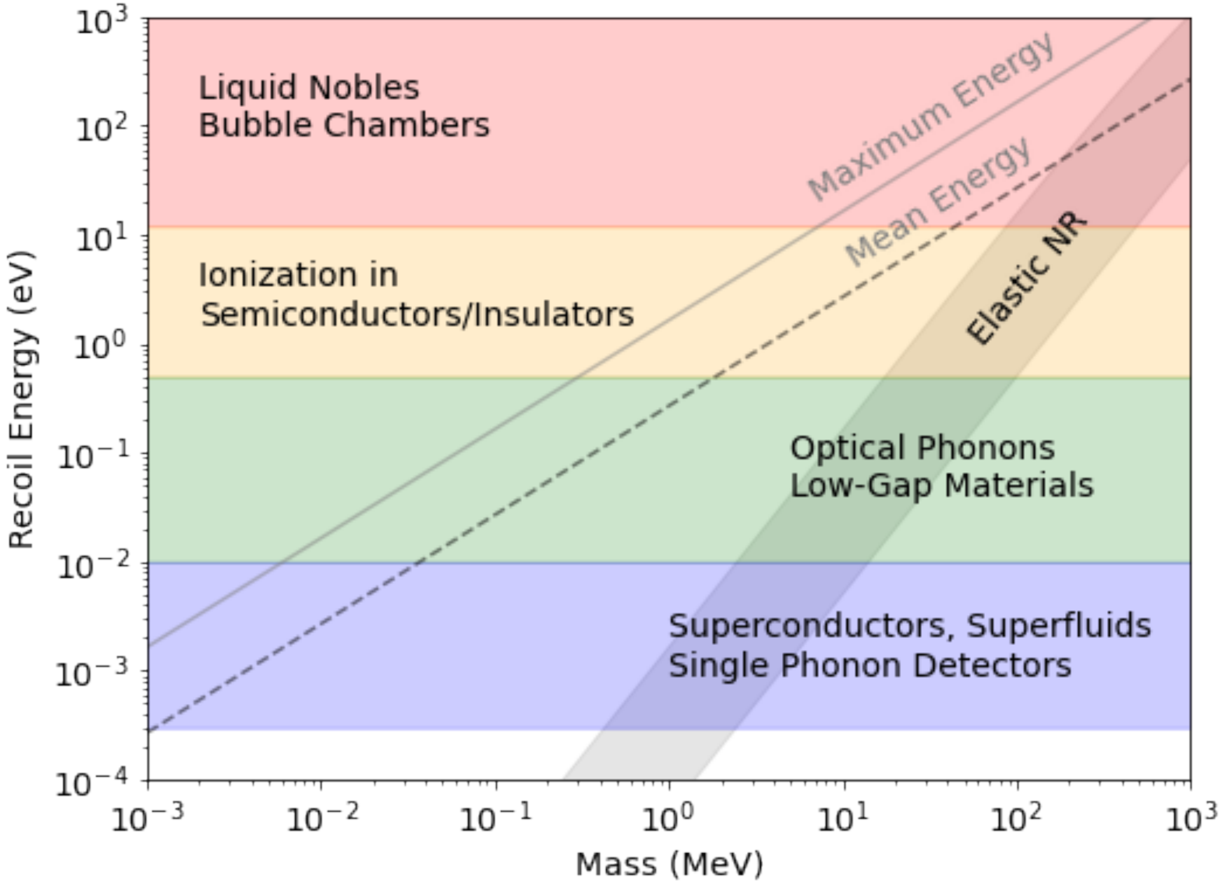




Quantum Sensing R&D For Dark Matter: meV Thresholds

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



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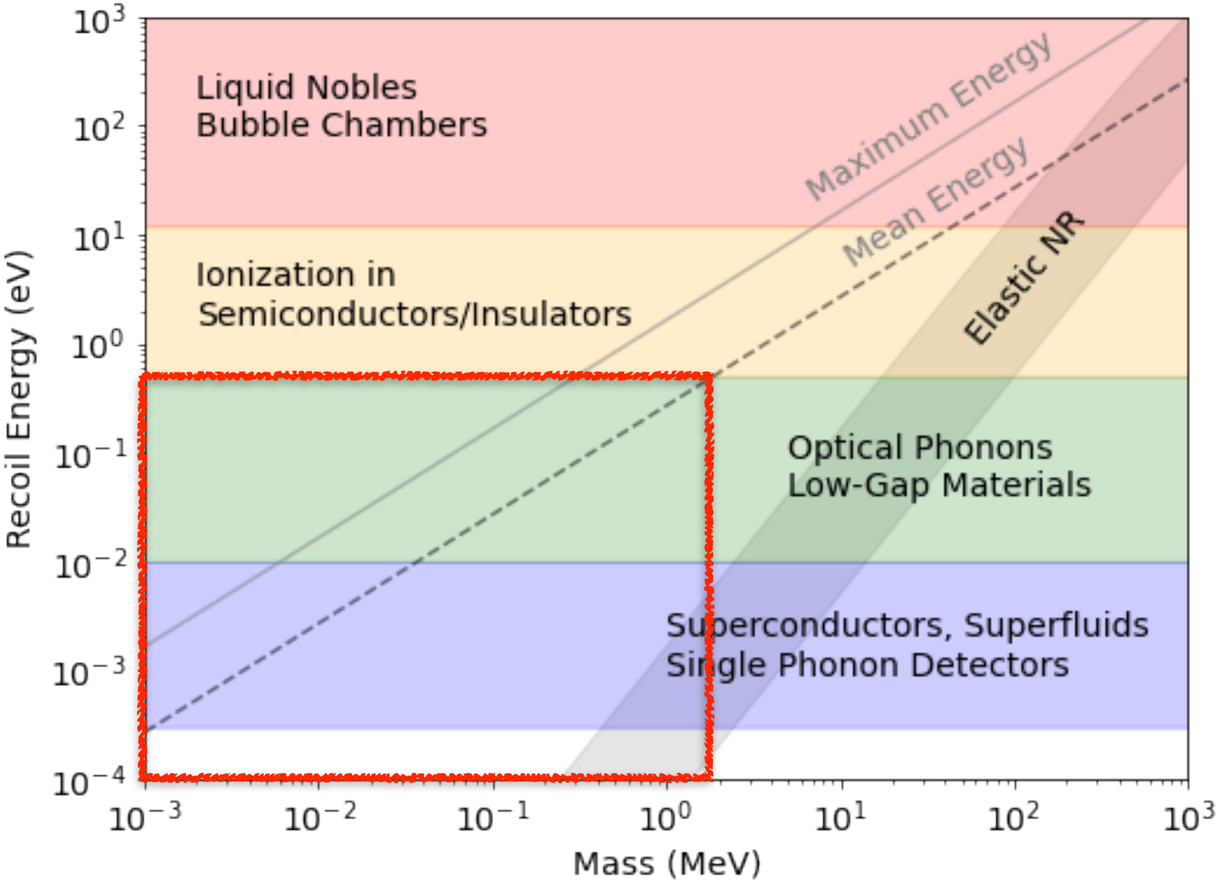
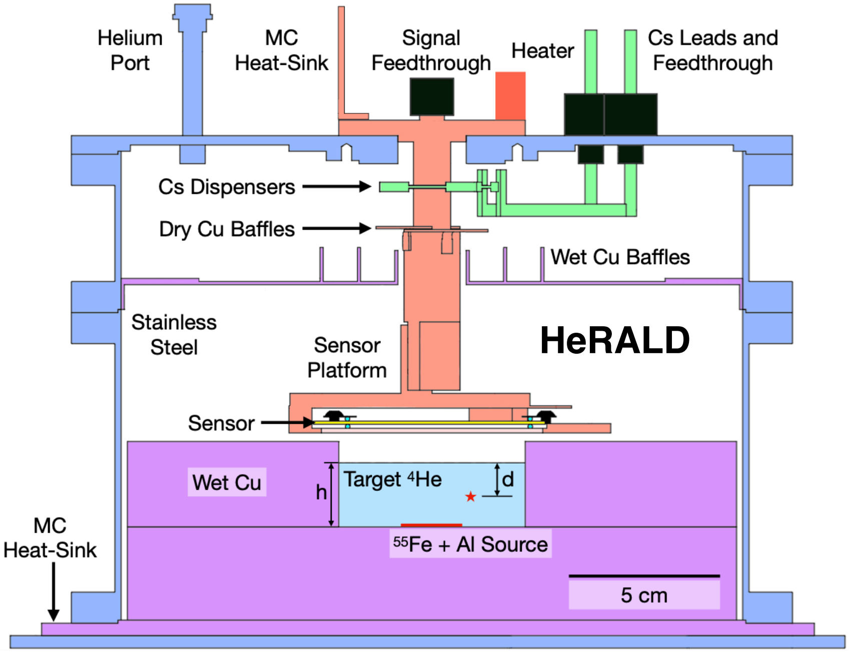
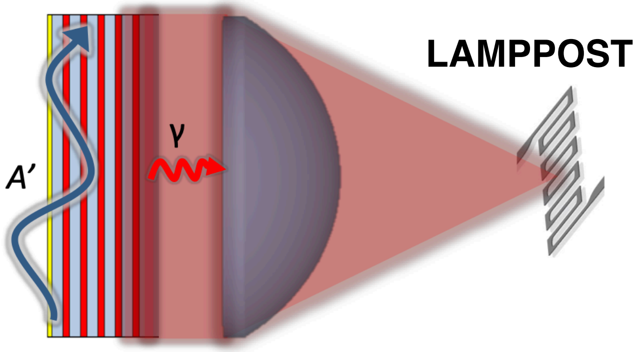


Aside: Photon or Roton Detection

- 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

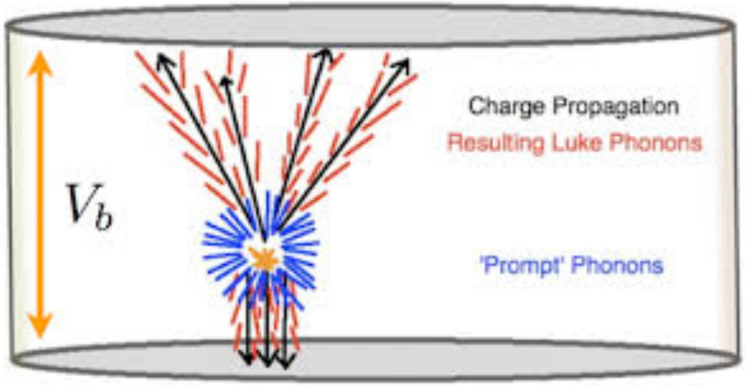




https://arxiv.org/pdf/2110.01582.pdf

Multiple Paths to meV-Scale Energy Sensitivity

Interaction Produces Charge and Phonons in Solid State Target



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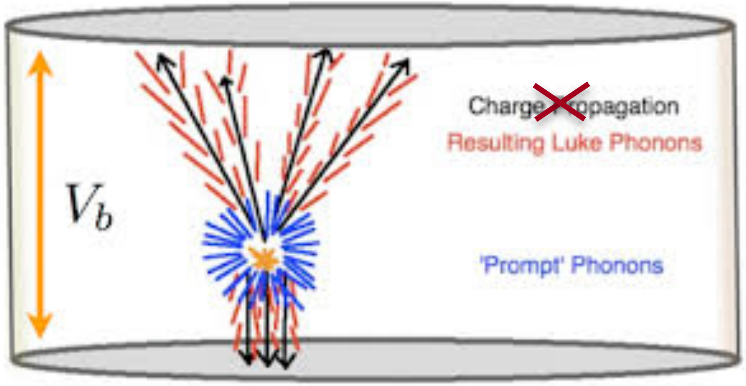

Ren et al, Phys. Rev. D 104, 032010 (2021)

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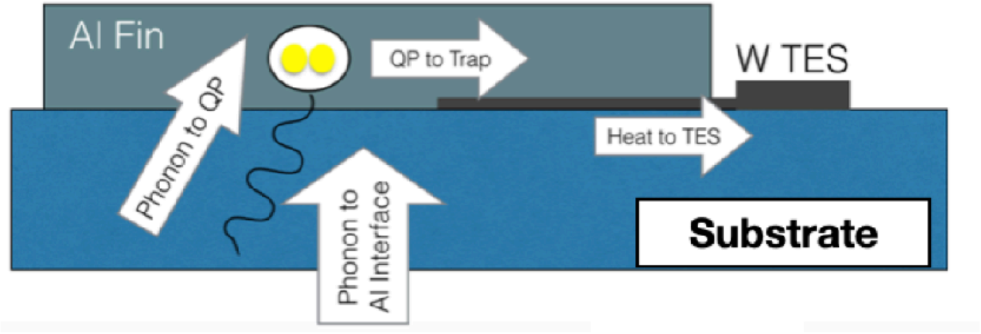
Phonons Captured in Small
Volume of Superconductor



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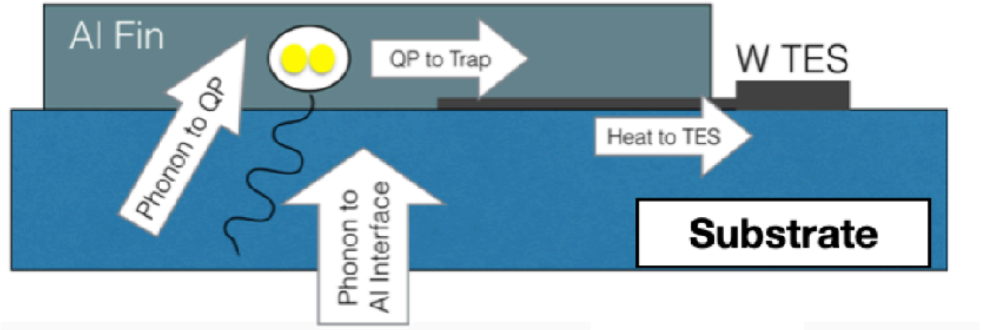

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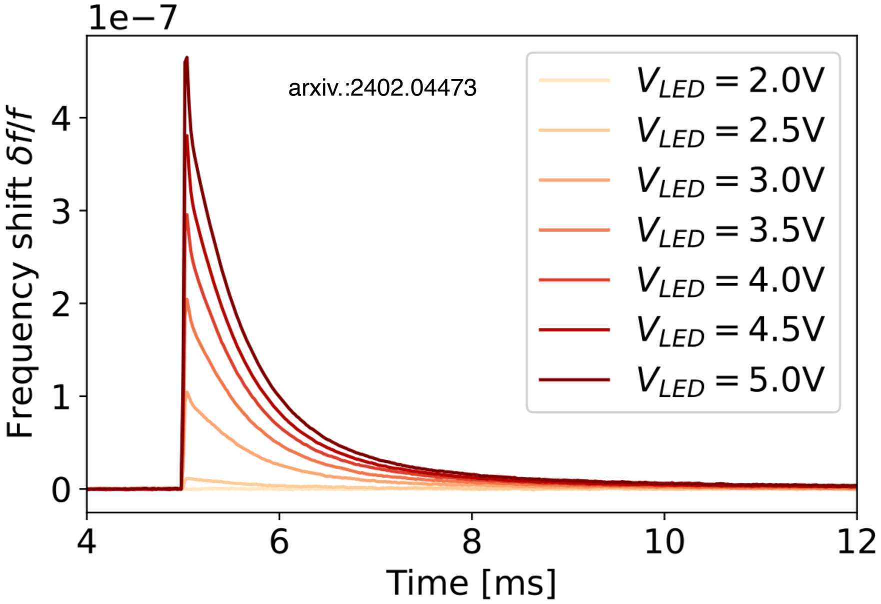
MKID, TES, SNSPD

Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit



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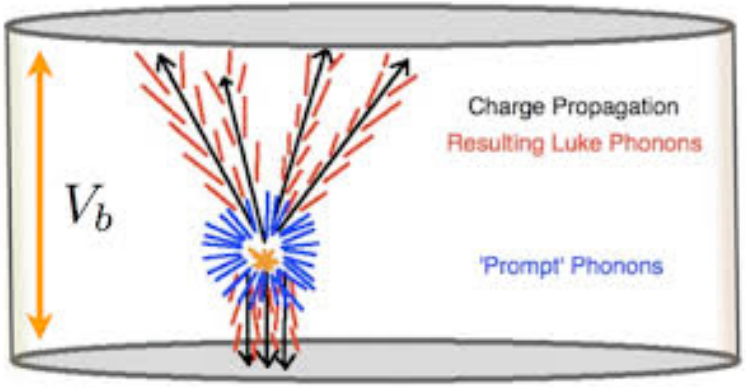

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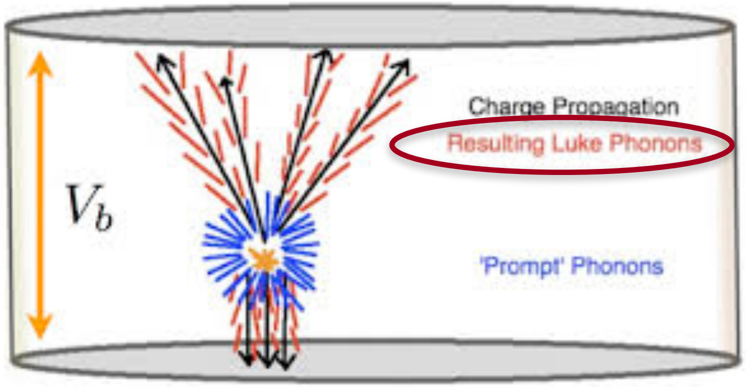

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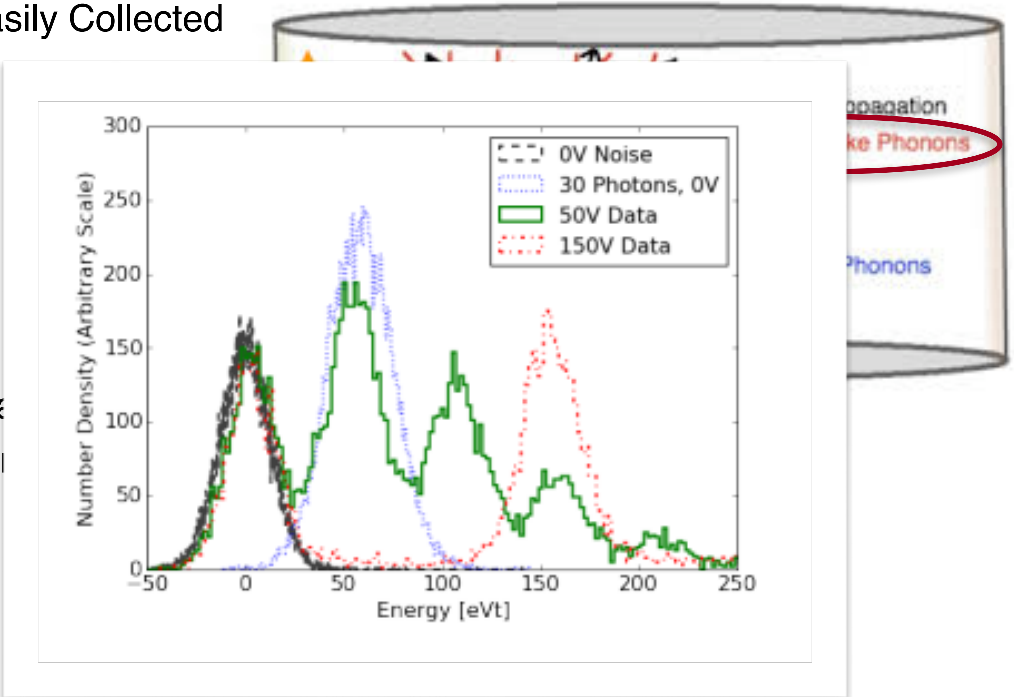

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More Charge Produced,
Phonons Cannot be Collected

Charge drifted to concentrated
region of crystal or charge gate

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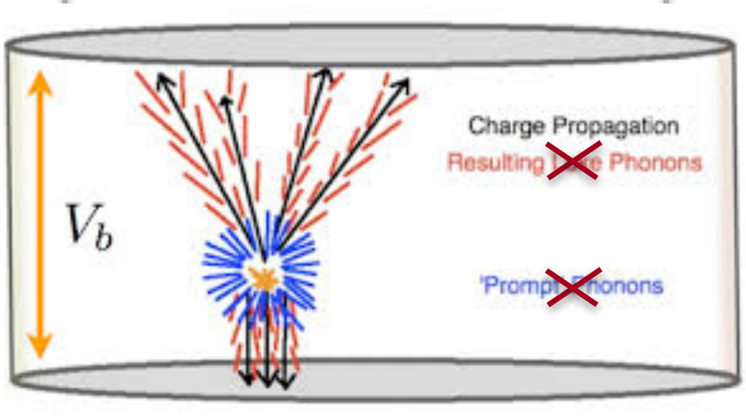

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Wilen et. al, Nature 594, 369-373

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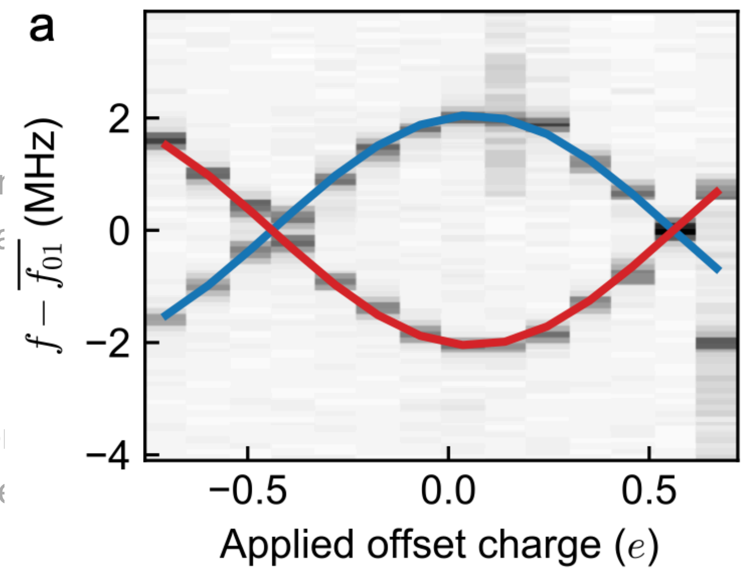

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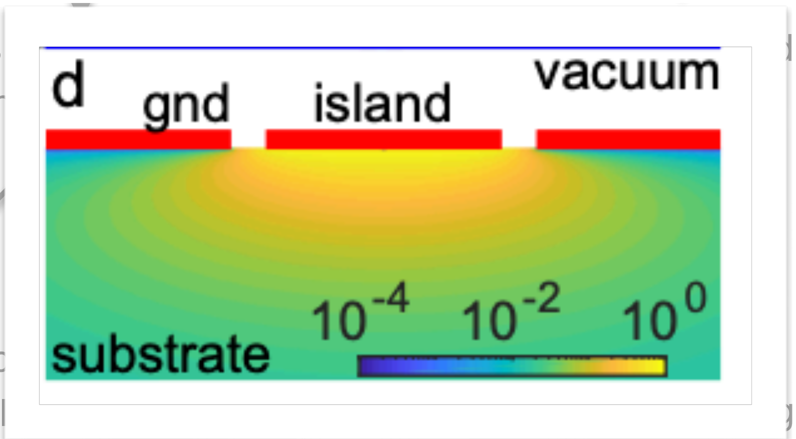

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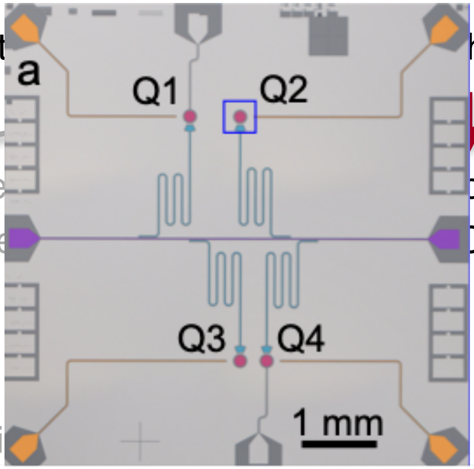

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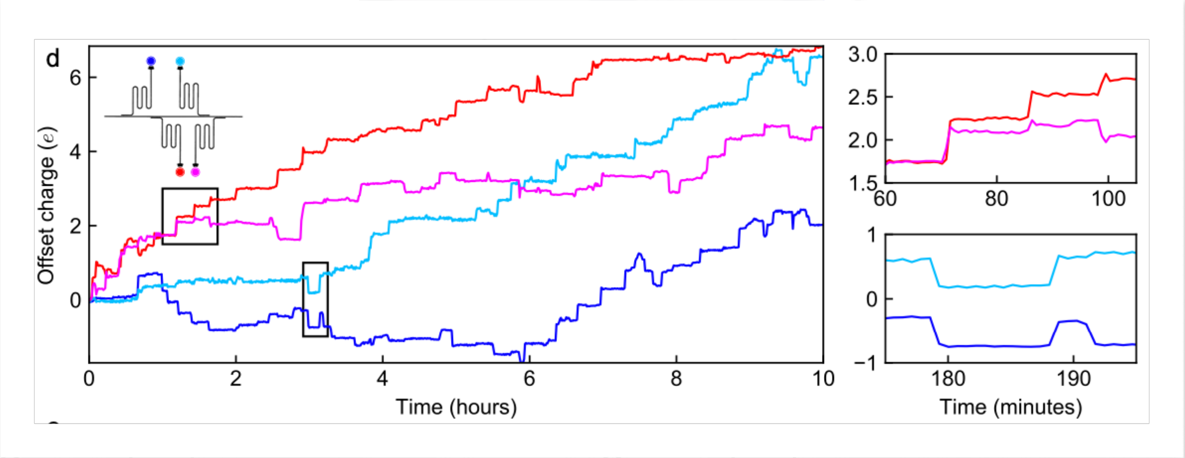

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Sensor tracks integrated
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HEMT, CPB (Charge Qubit)

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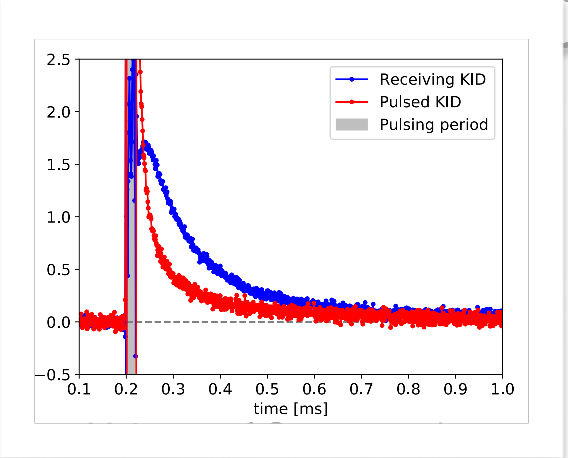

Charge and Phonons Share Energy, Easily Collected

More Charge Produced, Phonons Cannot be Collected

Charge drifted to concentrated region of crystal or charge gate

Phonons increase quasiparticle

or

$$\begin{aligned}\sigma_e &= \sigma_{N_{qp}}(2\Delta) \\ &= \sigma_{n_{qp}} V(2\Delta)\end{aligned}$$

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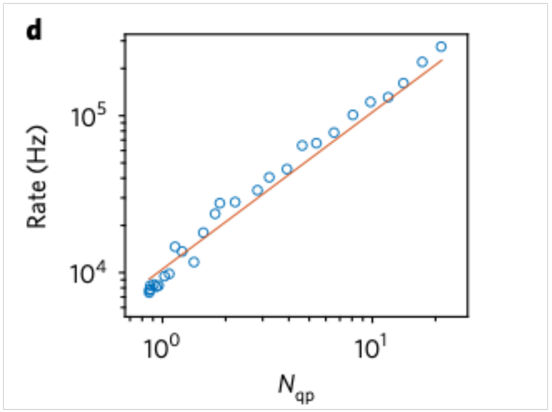

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$$E = N_{qp}(2\Delta)$$

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

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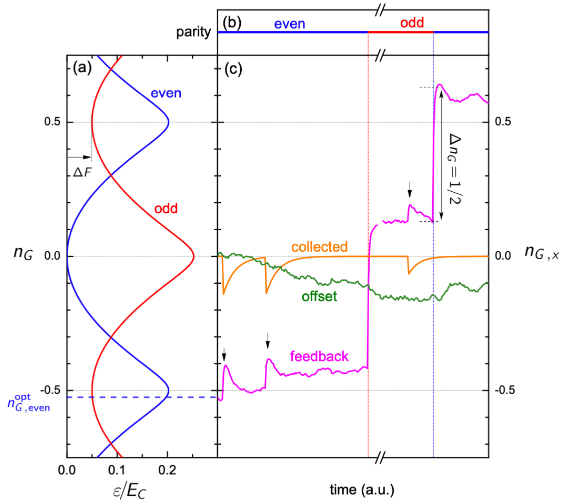

Charge induces offset voltage on

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

ArXiv:1711.08758

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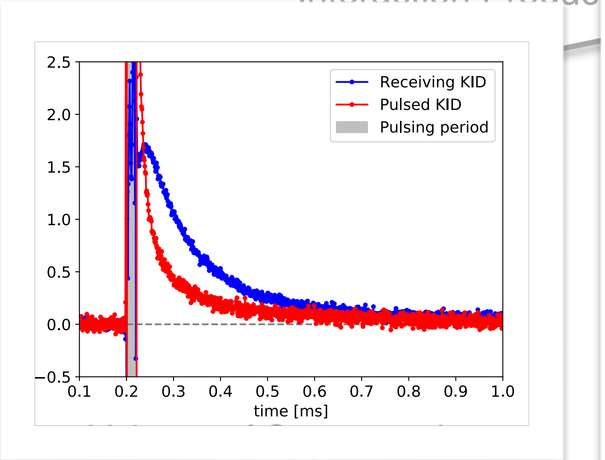

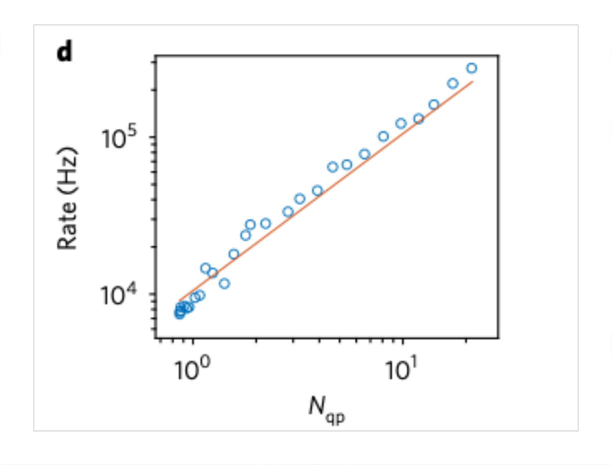

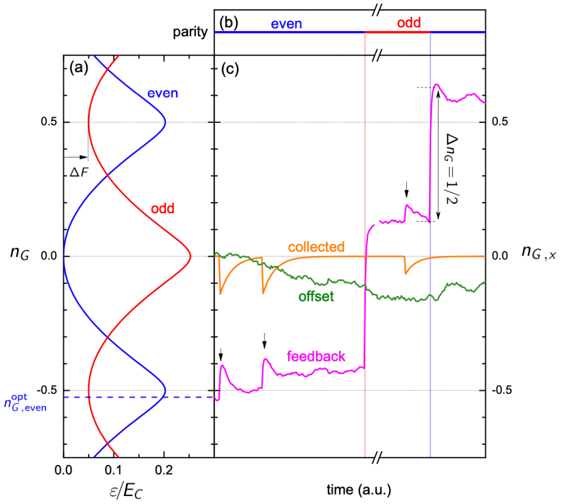

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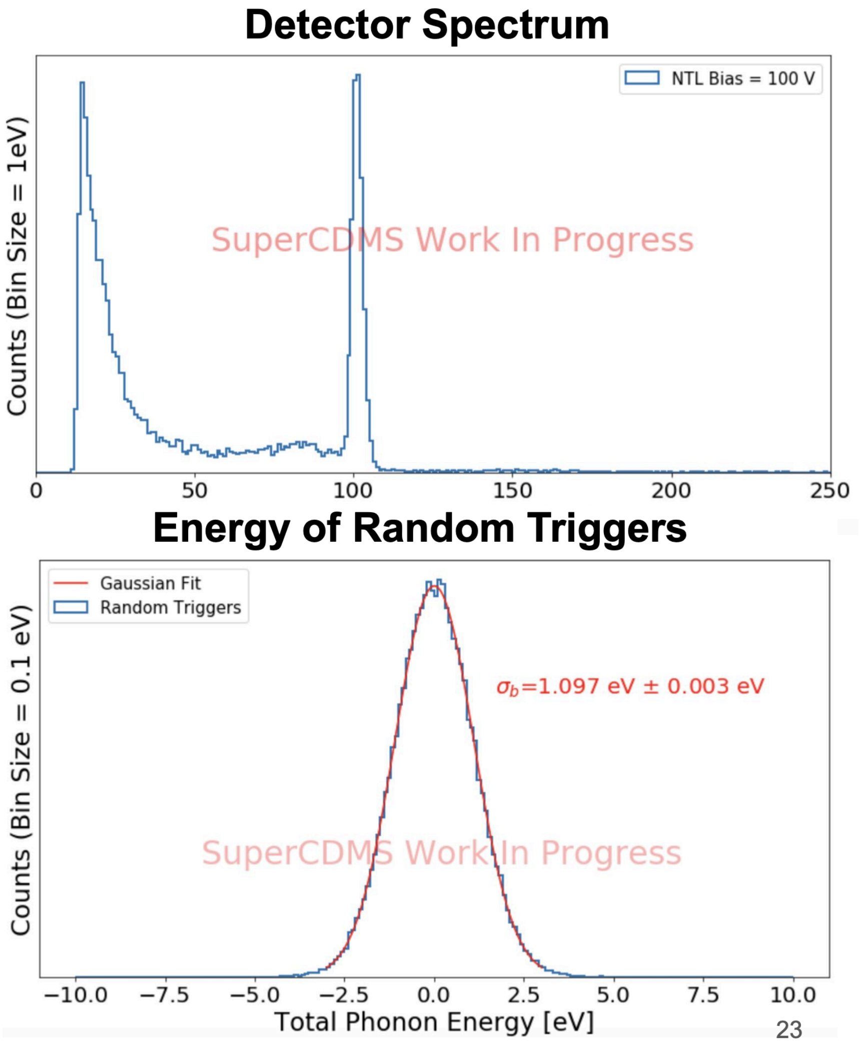
Phonon Sensing: State of the Art

- SuperCDMS HVeV on the cusp of sub-eV resolution with low-Tc, gram-scale detectors
    - Upcoming results from SPICE demonstrated ~200 meV phonon resolution

- Charge resolution at or better than 1%

- Challenges for these sensors are driven by understanding non-ideal effects and eV-scale backgrounds

- Mapping this technology onto new substrates can get us factors of 2-3 without solving fundamental issues, but what else can we try?



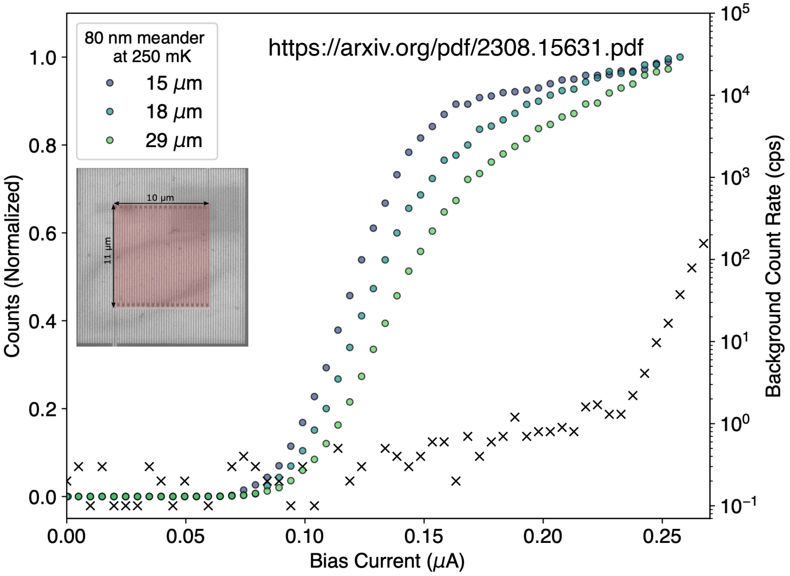
Detector Spectrum

Energy of Random Triggers

https://meetings.triumf.ca/event/348/timetable/#20230712

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, but see Rakshya’s talk for more details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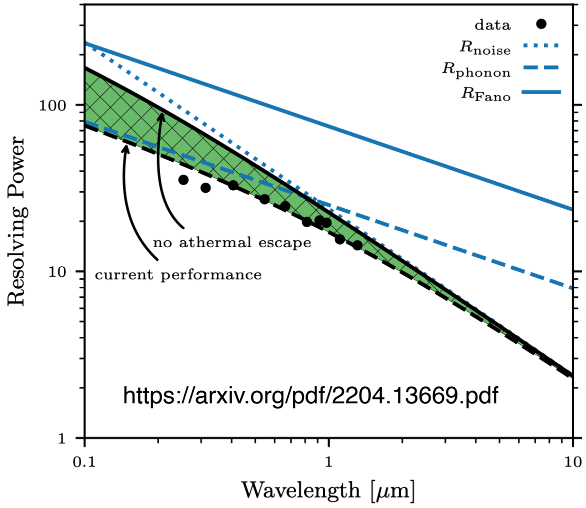
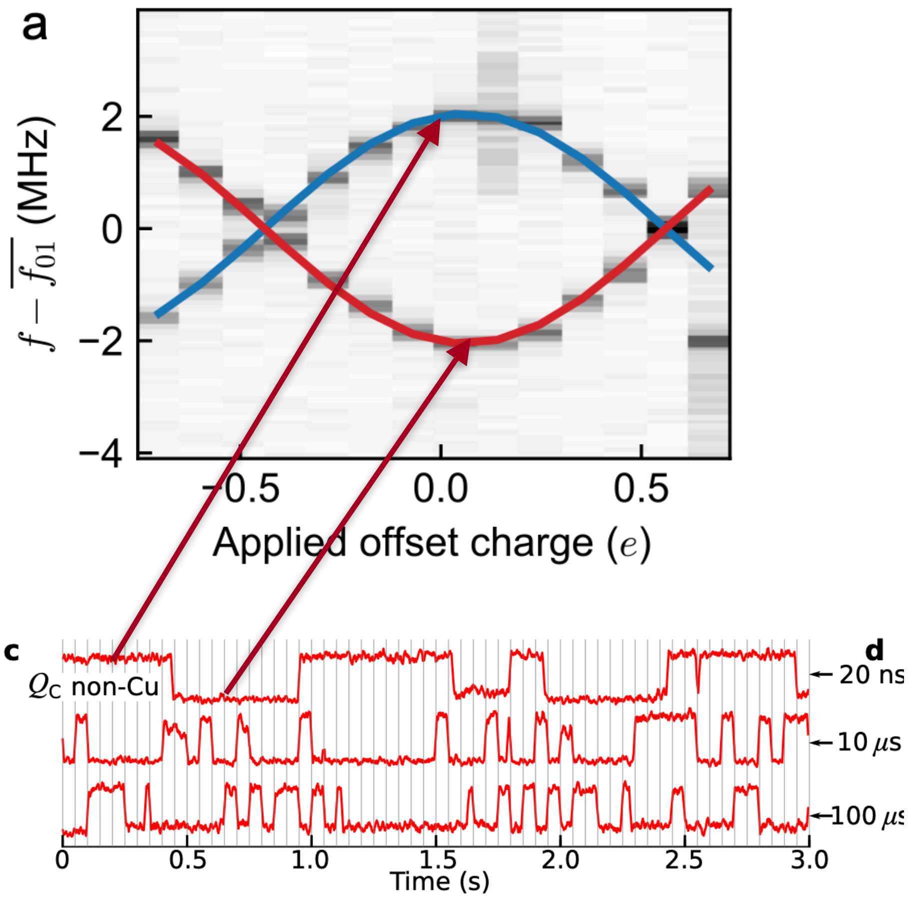

https://arxiv.org/pdf/2204.13669.pdf

Energy Sensing with Qubits

- 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



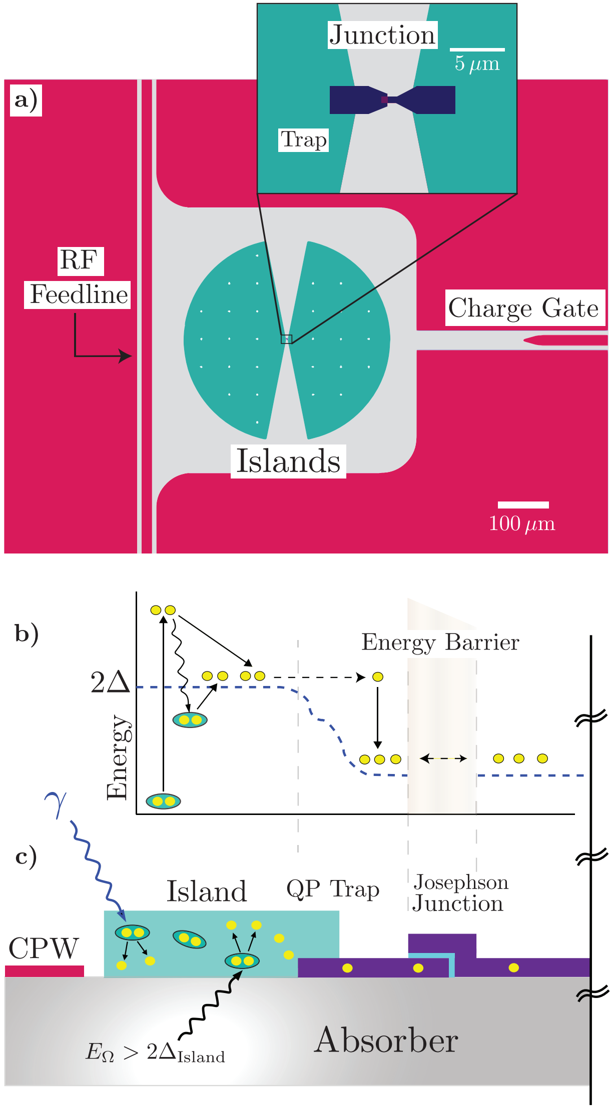
$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J\cos(\phi)$$

ArXiv:2310.01345

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

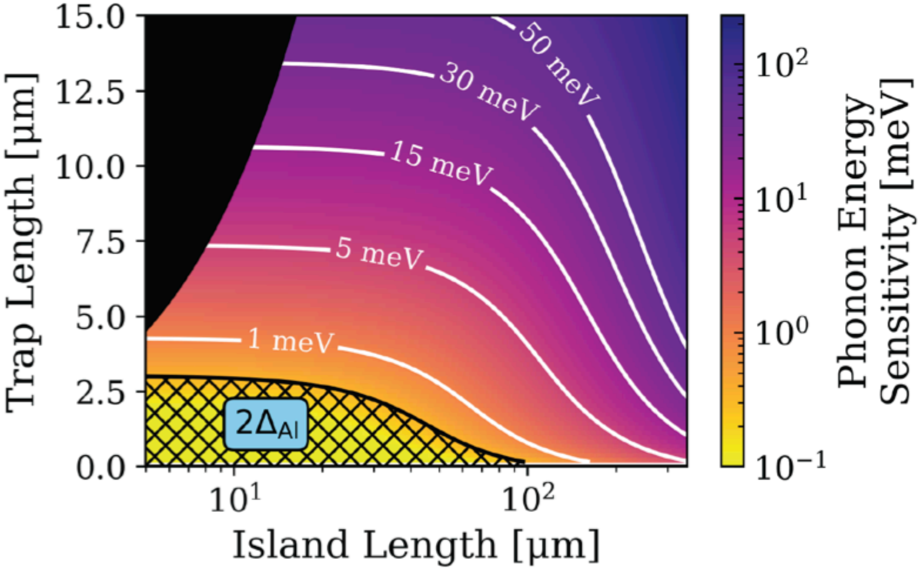


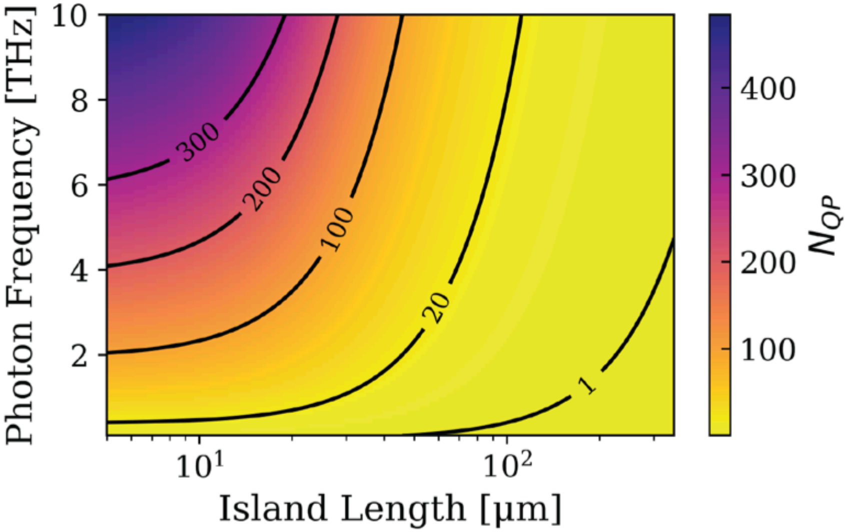
ArXiv:2310.01345

Projected Sensitivity

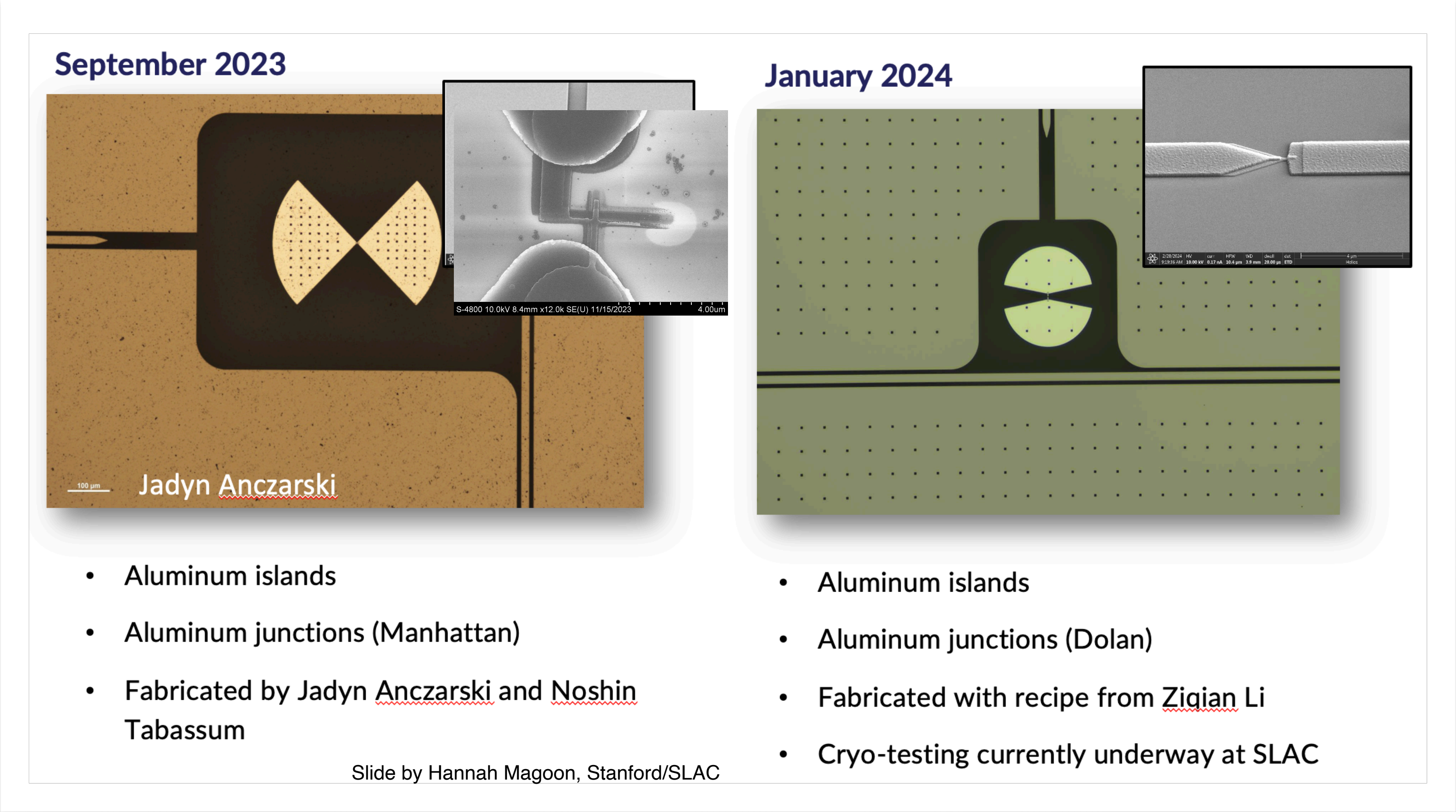
- Small trapping regions enable high tunneling efficiency and gap-limited performance
  - Performance will vary based on trapping and tunneling efficiency - all designs are sub-eV for this range of parameters
  - First devices will help benchmark these design parameters

- Single photon detection achievable with a wide range of designs down to 1 Thz - more on this at the end of the talk





SQUAT Current Status



September 2023

- Aluminum islands
- Aluminum junctions (Manhattan)
- Fabricated by Jadyn Anczarski and Noshin Tabassum

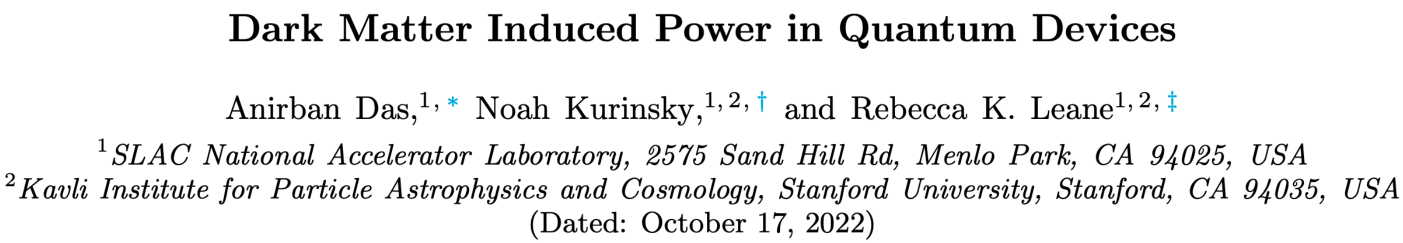
January 2024

- Aluminum islands
- Aluminum junctions (Dolan)
- Fabricated with recipe from Ziqian Li
- Cryo-testing currently underway at SLAC

Slide by Hannah Magoon, Stanford/SLAC

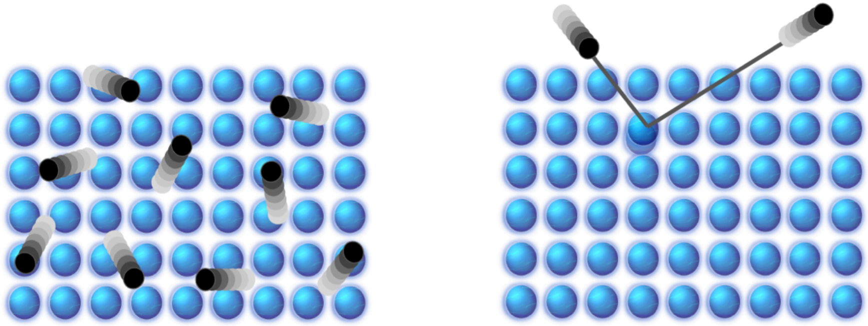
Initial results coming Spring 2024

DM Induced QP Poisoning

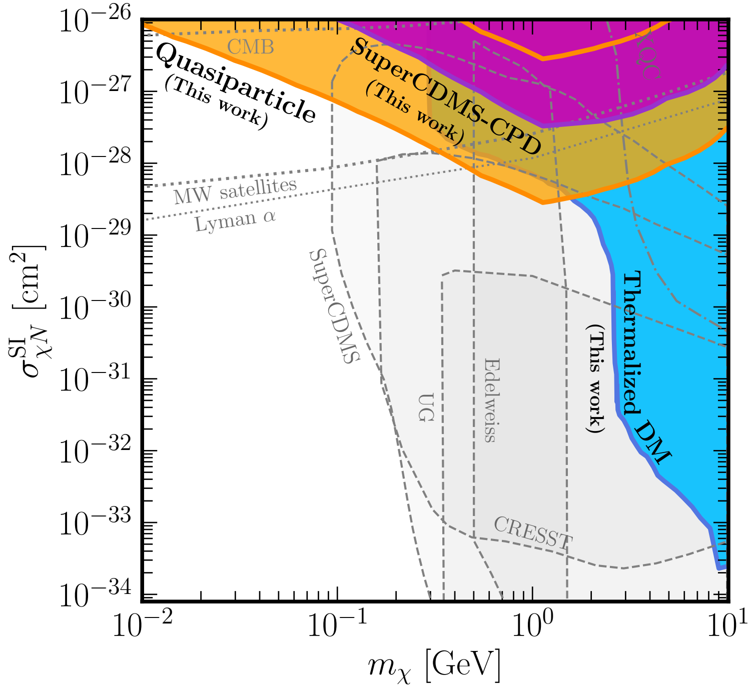


Dark Matter Induced Power in Quantum Devices

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!

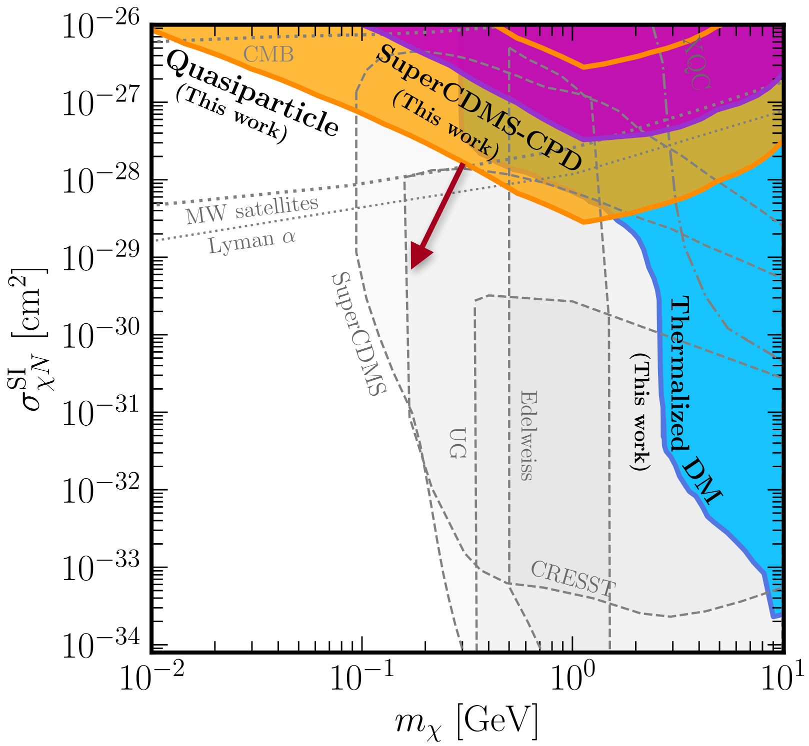
$$x_{\mathrm{qp}} \approx \left(\frac{P_{\mathrm{DM}}}{3.6 \times 10^{-21}\,\mathrm{W}}\right)^{1/2}$$

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

Connecting Parity Switching to Energy Injection

- 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



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

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

Rosa et. al. 2020, https://arxiv.org/abs/2007.06556

Designer Materials for Light DM (SPLENDOR)

- 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 this summer!

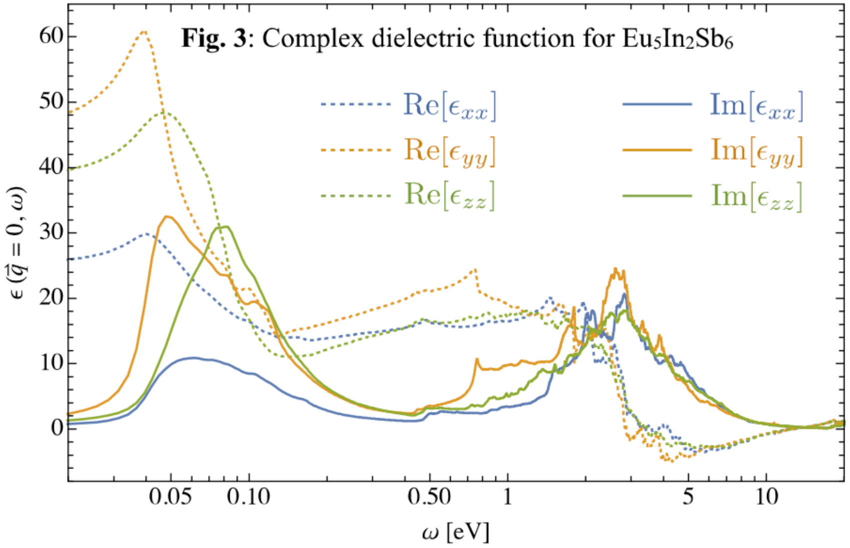
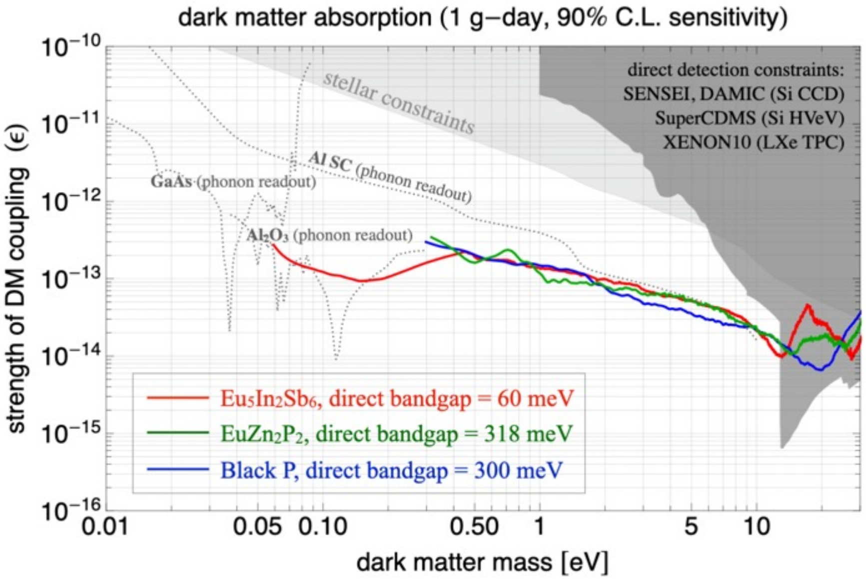
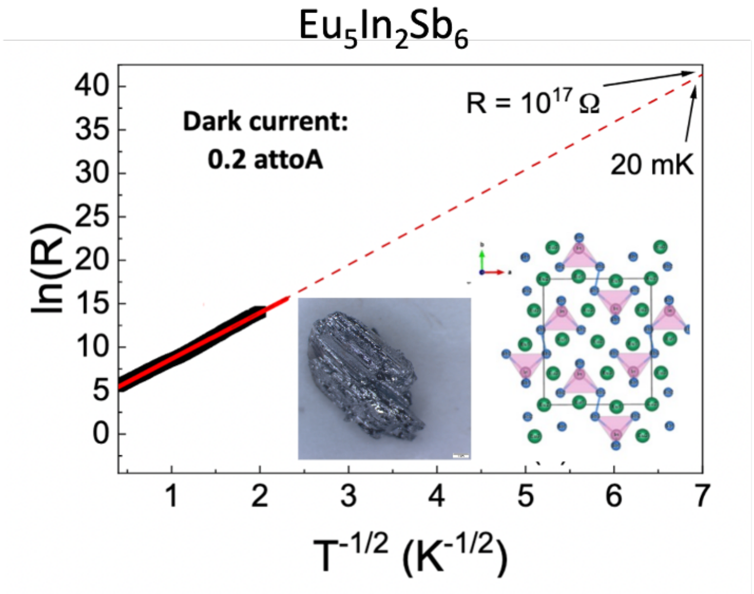


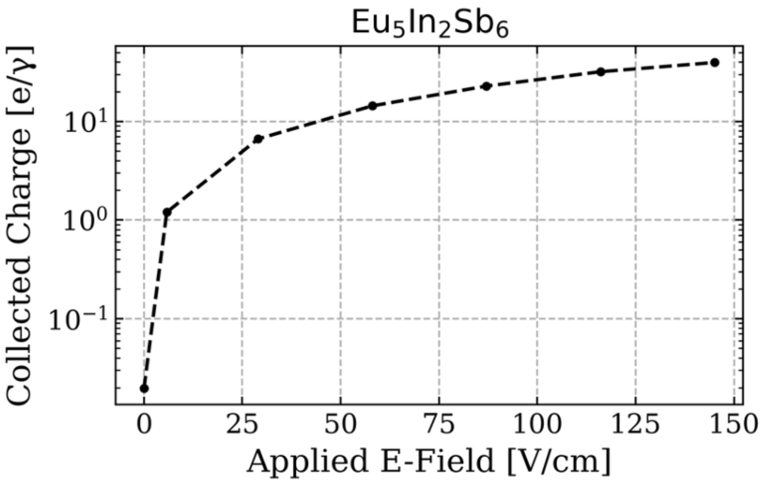
Fig. 3: Complex dielectric function for $Eu_5In_2Sb_6$



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





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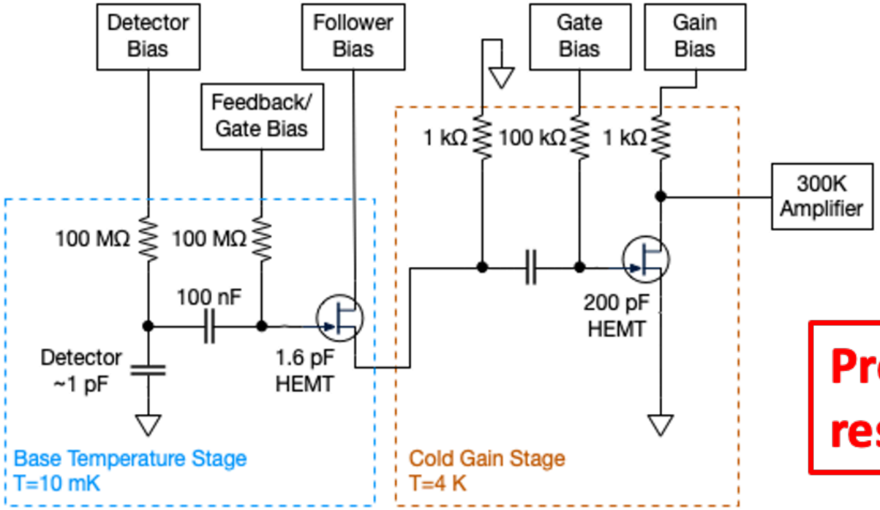
Designing a 10mK Charge Amplifier



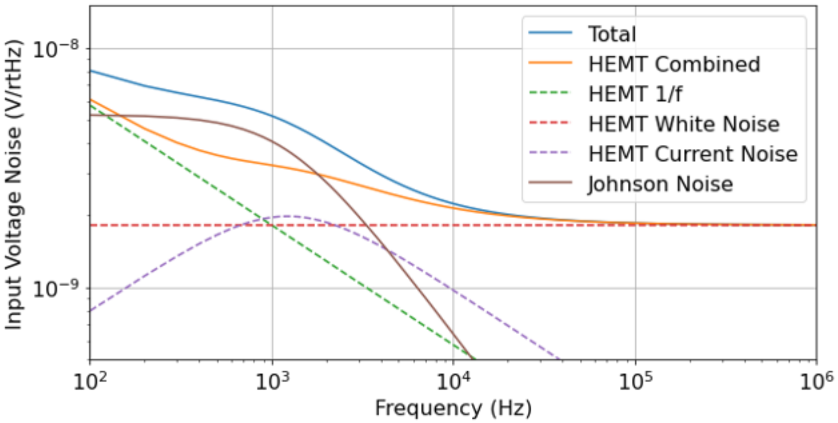
$$
\begin{aligned}
\sigma_E &= \sigma_q E_{gap} \\
&\approx (C_{det} + C_g)\sigma_V E_{gap}
\end{aligned}
$$

Predicted 1-sigma optimal filter resolution: 5.35 electrons

HEMT parameters:
1.6 pF Transconductance: 15 mS
200 pF Transconductance: 50 mS

Amplifier parameters:
Bandwidth: 100 Hz – 1 MHz
Cold gain: 30

~20 uW dissipation at 10 mK
~2.1 mW dissipation at 4 K



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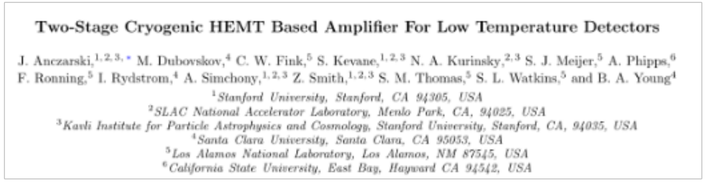
SPLENDOR Two-Stage Amplifier Performance

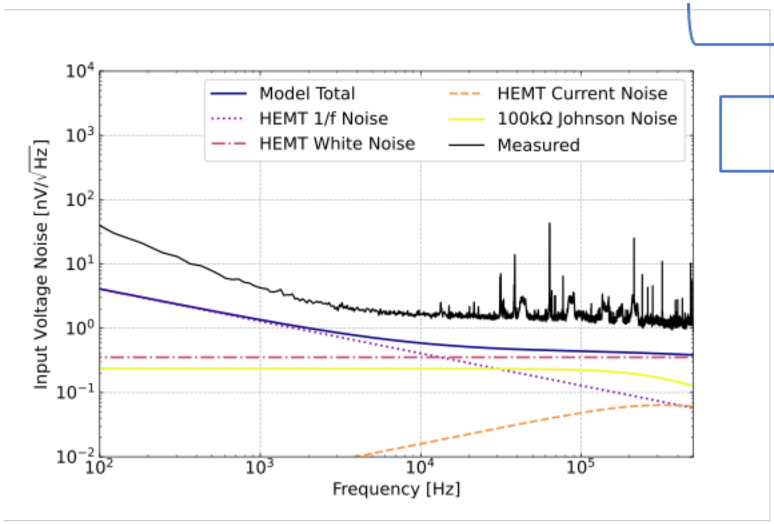
- Novel low-capacitance input-stage allows for <10 electron resolution
- Further optimization expected to achieve <5 electron performance - this should be fully HEMT limited
- Detector housing can be used to screen a broad class of novel quantum materials!

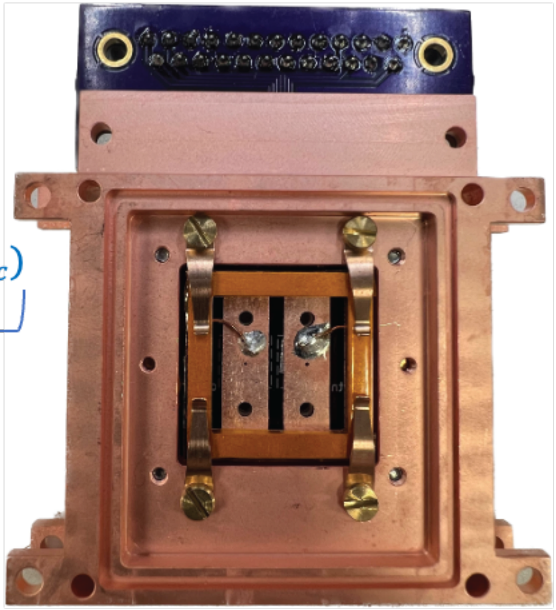


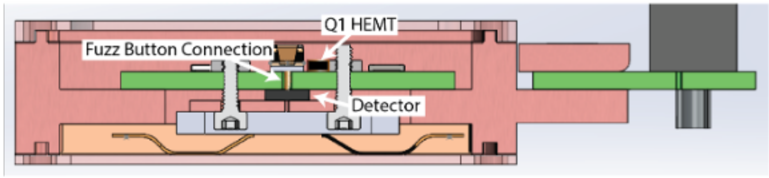
Two-Stage Cryogenic HEMT Based Amplifier For Low Temperature Detectors

J. Anczarski,[1,2,3,*] M. Dubovskov,[4] C. W. Fink,[5] S. Kevane,[1,2,3] N. A. Kurinsky,[2,3] S. J. Meijer,[5] A. Phipps,[6]
F. Ronning,[5] I. Rydstrom,[4] A. Simchony,[1,2,3] Z. Smith,[1,2,3] S. M. Thomas,[5] S. L. Watkins,[5] and B. A. Young[4]
[1]*Stanford University, Stanford, CA 94305, USA*
[2]*SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA, 94035, USA*
[4]*Santa Clara University, Santa Clara, CA 95053, USA*
[5]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[6]*California State University, East Bay, Hayward CA 94542, USA*

$$\sigma_E \sim E_{gap}\ \underbrace{\sigma_V\ (C_{detector} + C_{input} + C_{parasitic})}_{\boxed{\sigma_{charge} \approx 7\ e}}$$

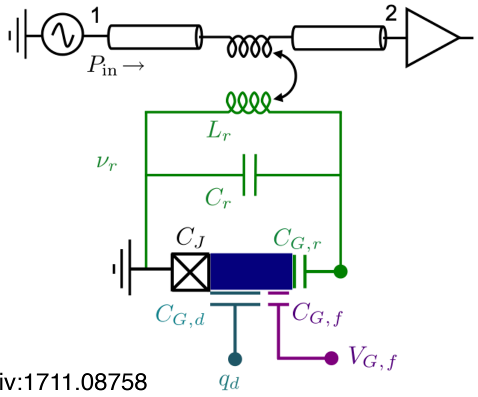




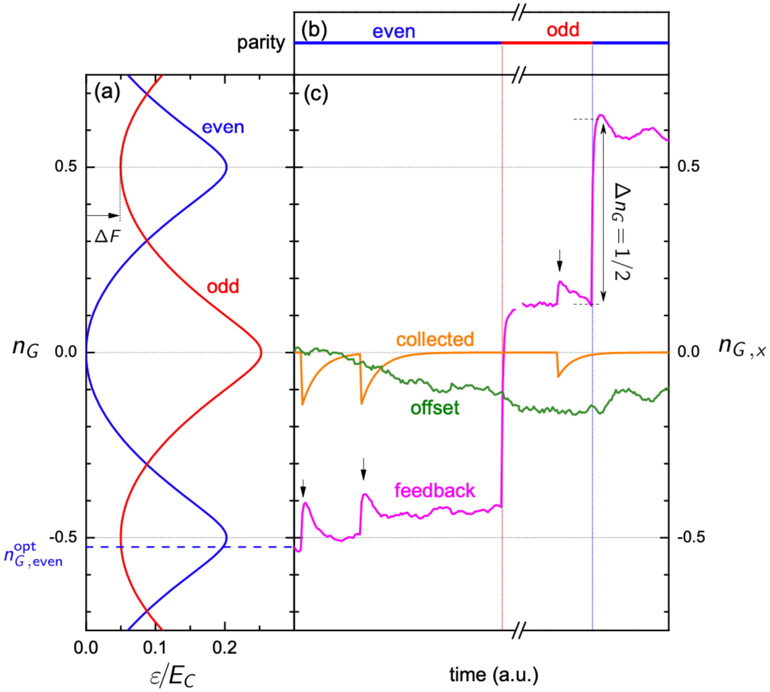


Qubit-Based Electrometers for Quantum Materials

- 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.

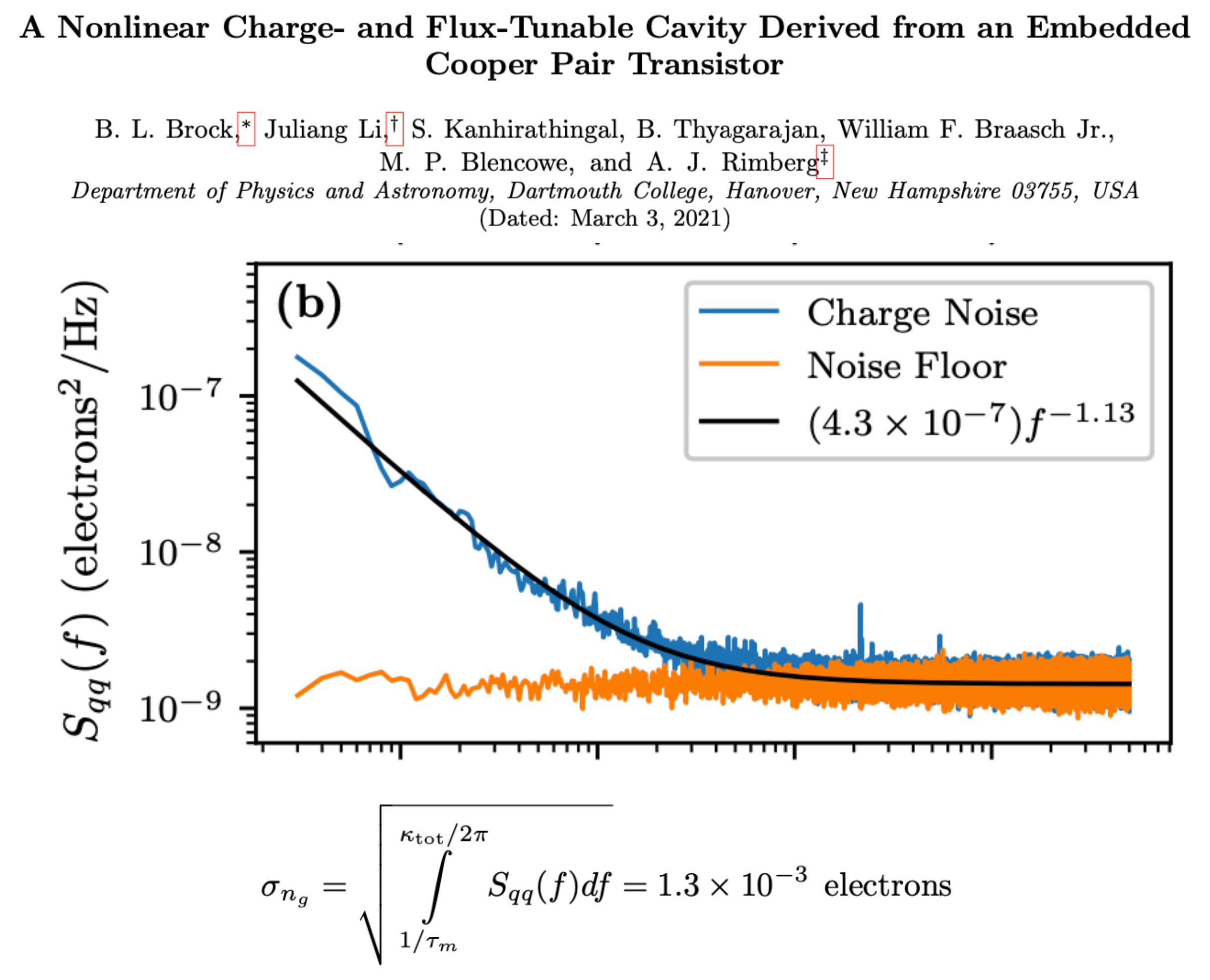


ArXiv:1711.08758



Qubit-Based Electrometers for Quantum Materials

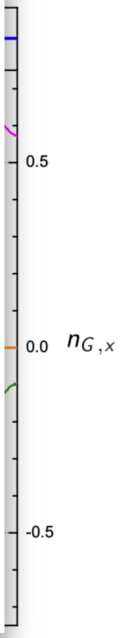
- HEMT-
  ~2-5 el
- Use ex
  charge
  electro
  - Ge
    or
    fee
  - Si
    rea
- Combi
  materia
- Not a r
  picking
  from ot



A Nonlinear Charge- and Flux-Tunable Cavity Derived from an Embedded Cooper Pair Transistor

B. L. Brock,[*] Juliang Li,[†] S. Kanhirathingal, B. Thyagarajan, William F. Braasch Jr.,
M. P. Blencowe, and A. J. Rimberg[‡]
Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire 03755, USA
(Dated: March 3, 2021)

$$\sigma_{n_g} = \sqrt{\int_{1/\tau_m}^{\kappa_{\mathrm{tot}}/2\pi} S_{qq}(f)df} = 1.3 \times 10^{-3} \ \text{electrons}$$



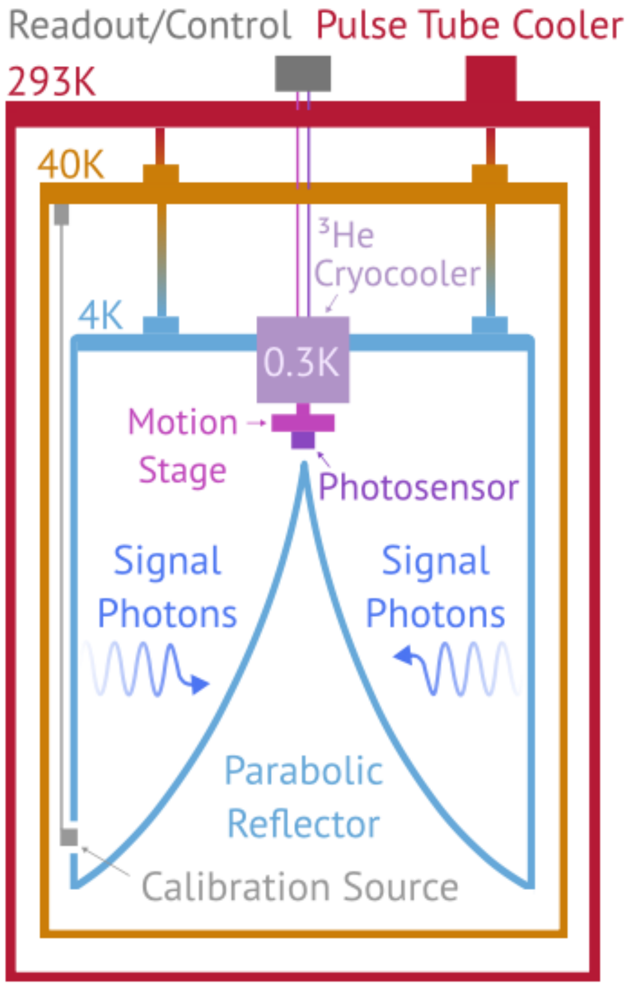
Wide-Band Axion Searches (BREAD)

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

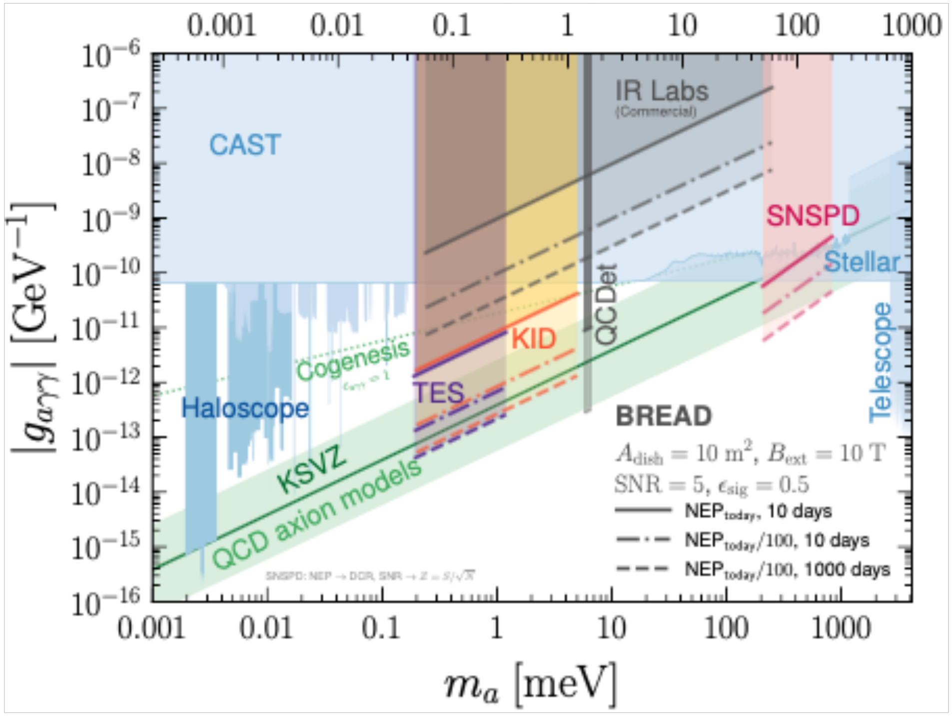
- Sub-Kelvin feedhorn design and characterization
- Development of THz optical paths
- Ability to calibrate wide-band sensors in the meV-eV regime
- Measurement of quantum efficiency in-situ

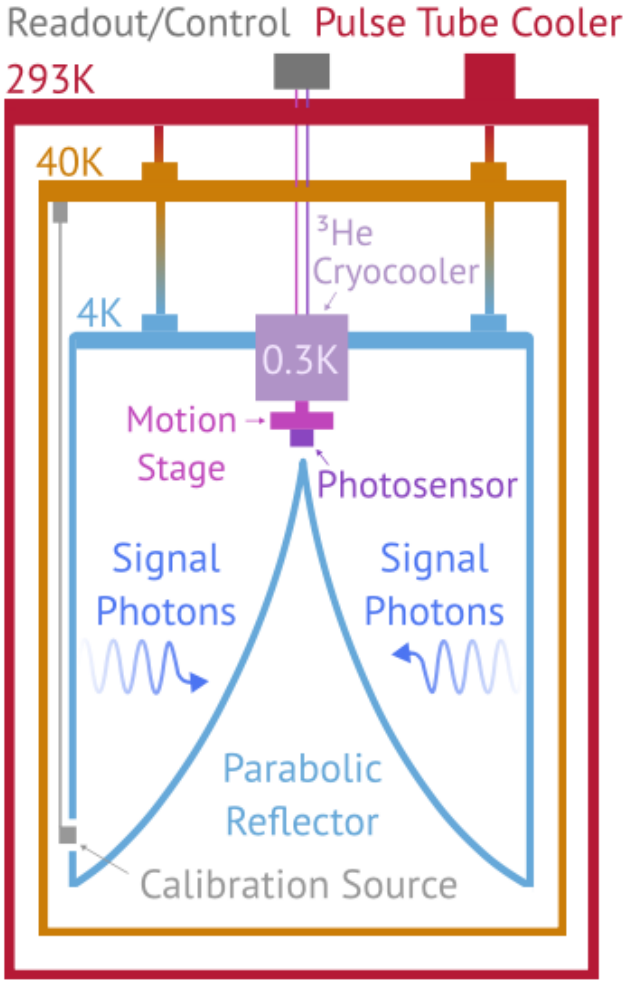
Initial prototype will run at FNAL in the next 1-2 years, ultimate experiment realized in 5-10 years alongside developments in quantum sensing



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)

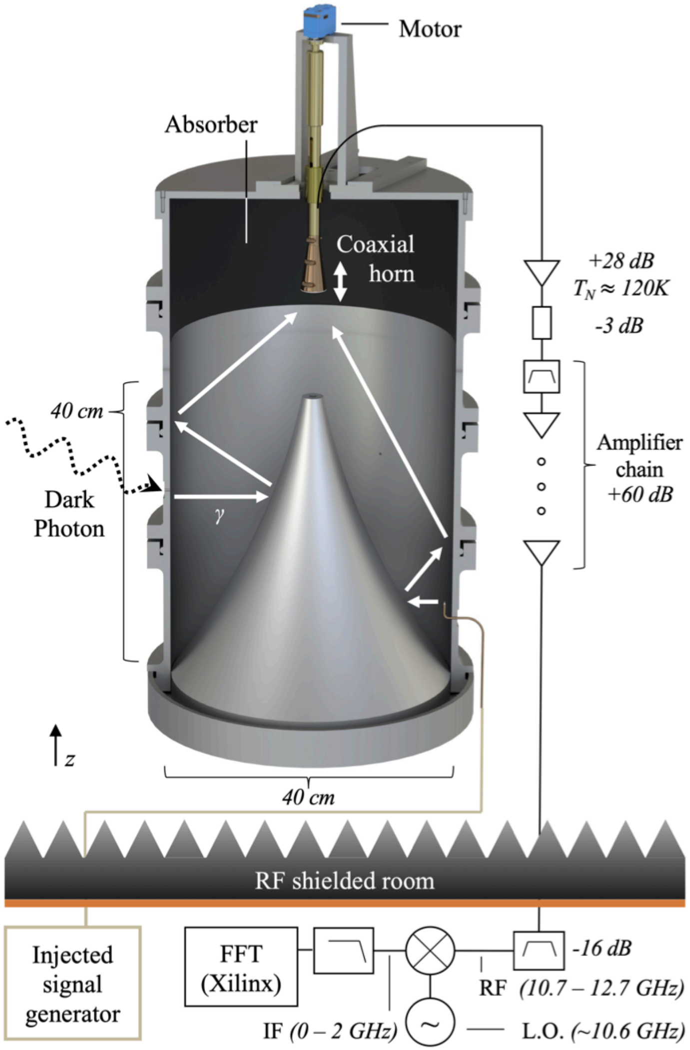
Liu et. al. (BREAD Collaboration), ArXiv.:2111.12103

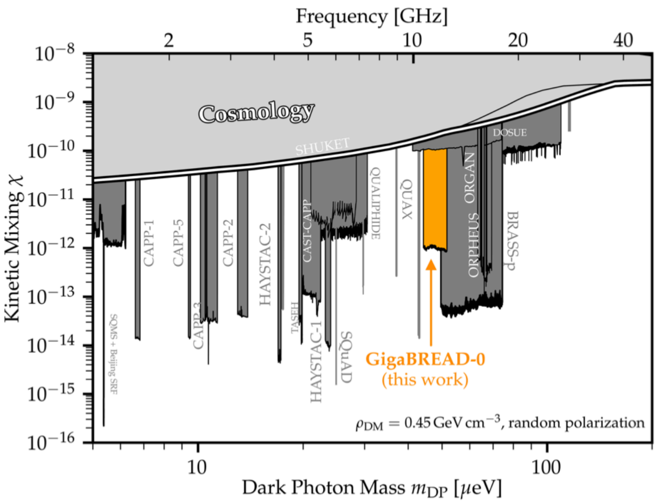
https://arxiv.org/pdf/2310.13891.pdf

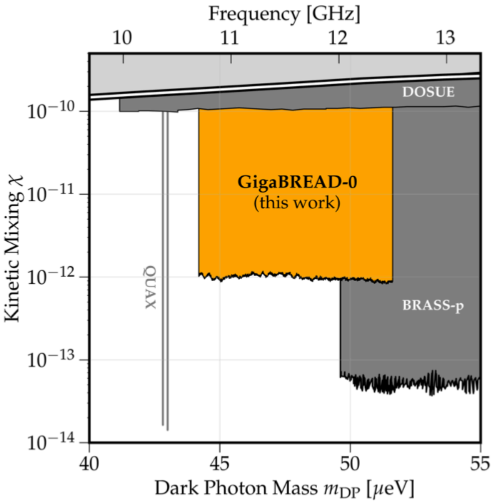
Pathfinder Detector: GigaBREAD

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





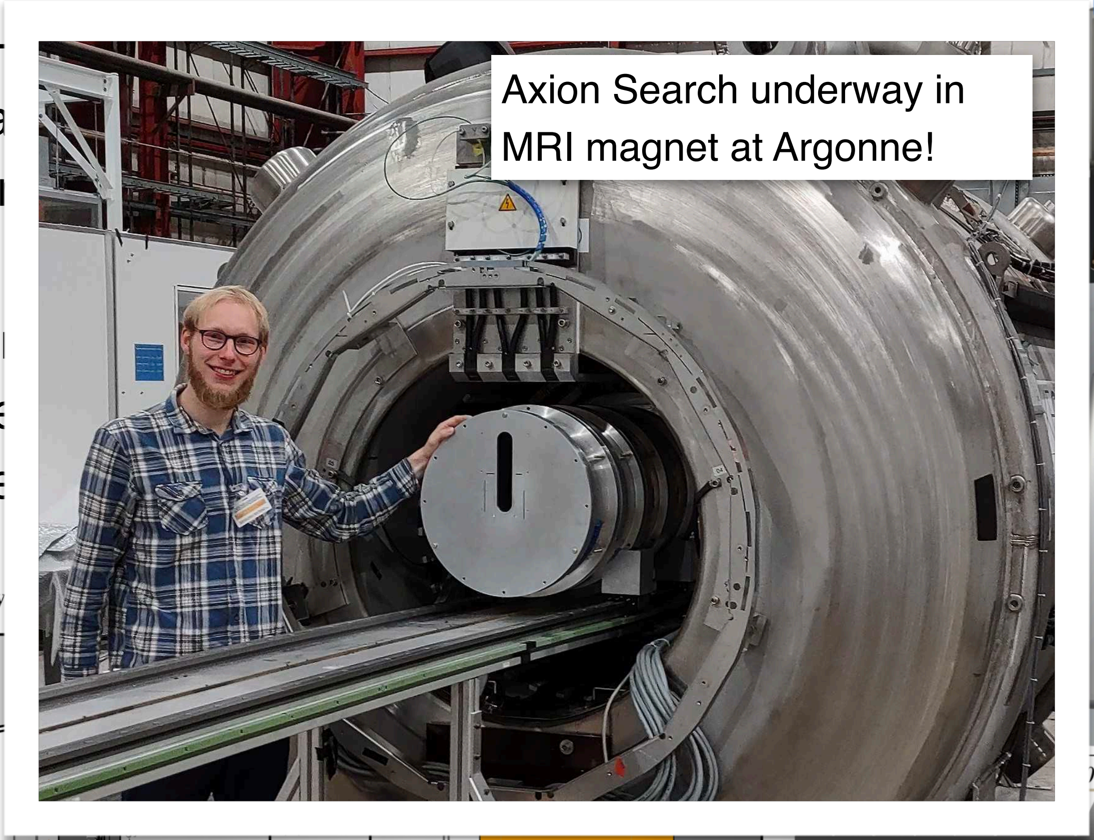


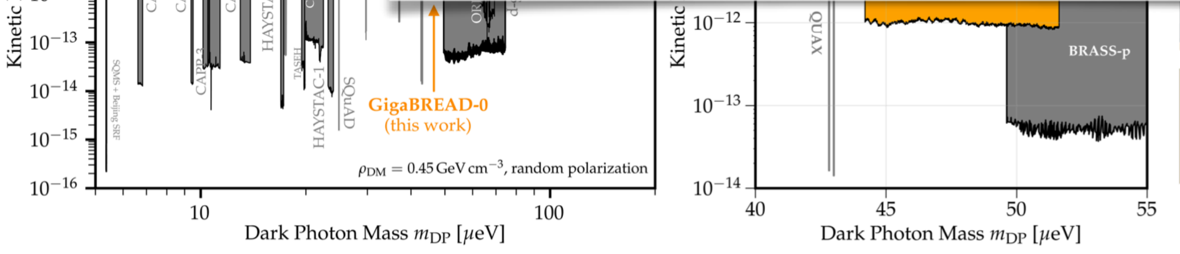
https://arxiv.org/pdf/2310.13891.pdf

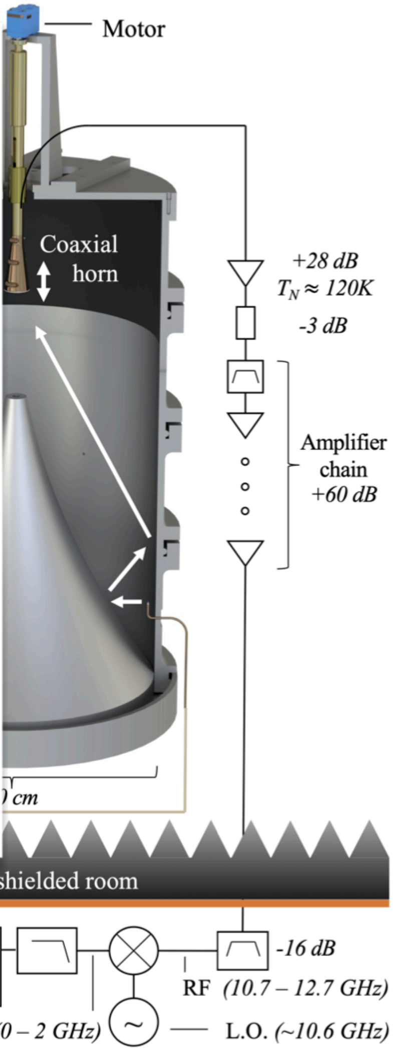
Pathfinder Detector: GigaBREAD

Pathfinder GH
experiment ra
UChicago/Fe

Calibration/tu
RF-SOC base
bandwidth me


Axion Search underway in MRI magnet at Argonne!





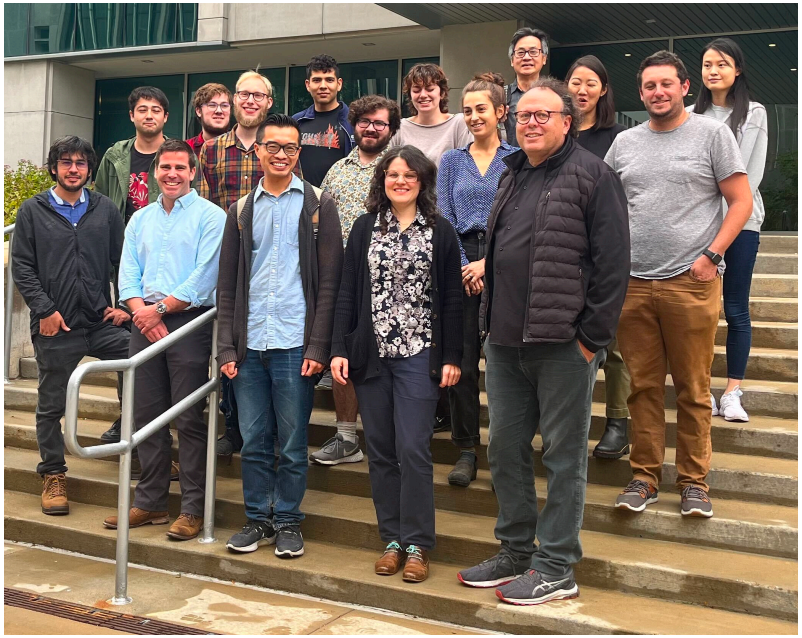
BREAD Collaboration Work in Progress

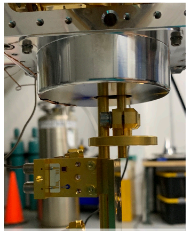
Multi-tiered development plans to solve individual issues and produce science results on the way to the ultimate high-frequency axion searches:

- UChicago/FNAL - GigaBREAD (10-15 GHz) and QualityBREAD (~100 GHz)

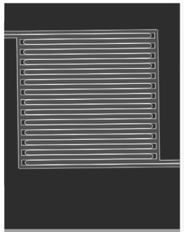
- FNAL/Caltech/JPL/MIT - InfraBREAD (<20 microns), utilizing high-polish reflector with SNSPDs

- SLAC/JPL - TeraBREAD pathfinder
  - THz calibration source
  - Optics design
  - SQUAT or QCD-based readout



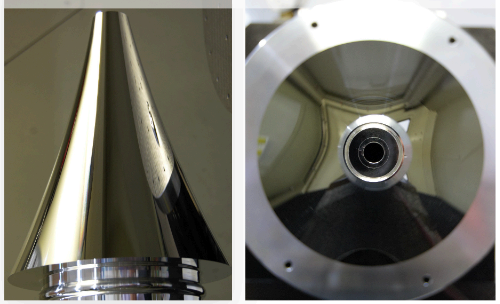


Superconducting Nanowire Single Photon Detector (SNSPD) from JPL



100nm wide nanowires in 15x15μm SNSPD from MIT

Optical Grade Reflector



Conclusions

- 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.