meV-scale Rare Event Detection with Quantum Sensors

Noah Kurinsky
Staff Scientist, SLAC

Prospecting for New Physics through Flavor, Dark Matter, and Machine Learning
March 29, 2023

Motivation: Closing the DM Gap

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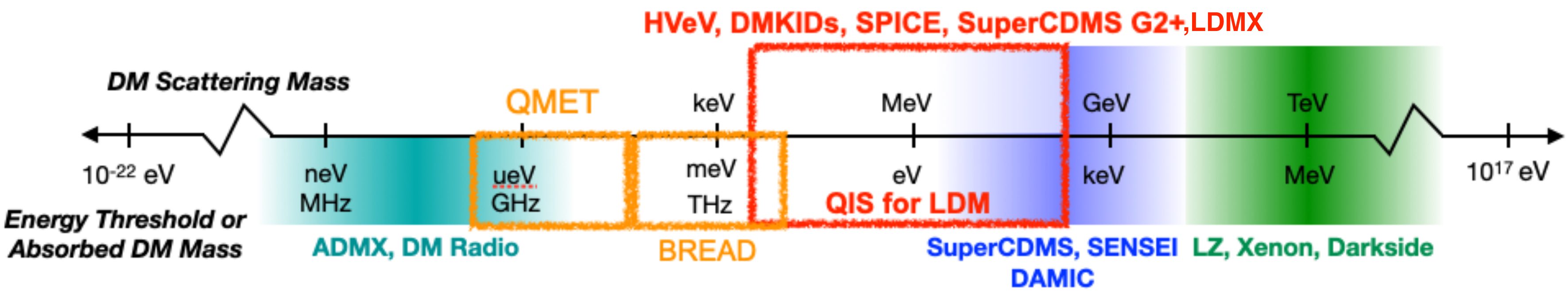
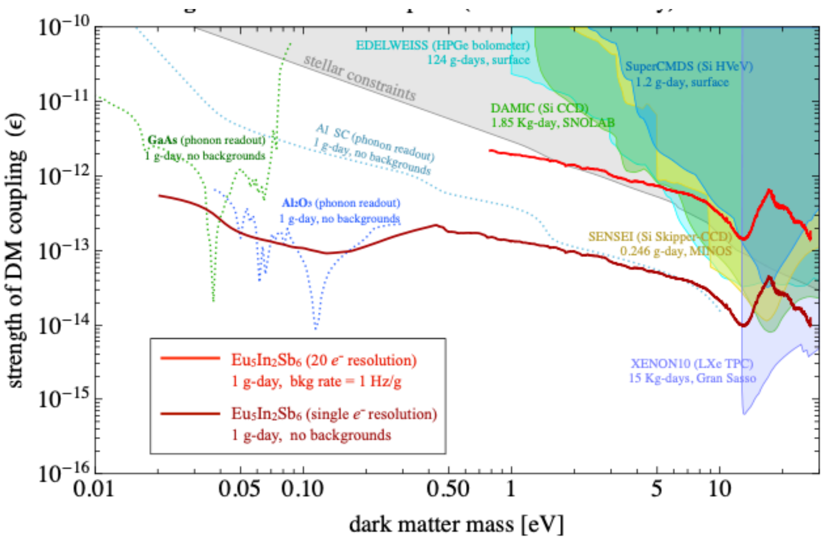
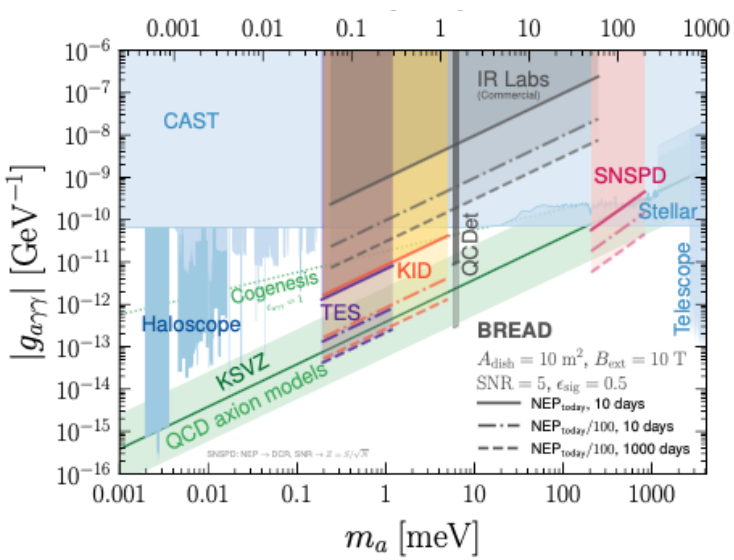


- Existing DOE experiments are opening an ever larger window onto axion detection (at low mass) and heavy dark matter (>1 MeV)
- There's a gap of 6 orders of magnitude limited by the challenges of detecting single events at the meV energy scale
- Our group at SLAC (DMQIS) focused on applying quantum 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!
- **BREAD**, a wideband axion search concept, will require single photon detection down to THz frequencies (meV energies), above the reach of cavity-style searches.
- **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





Quantum Sensing R&D For Dark Matter: meV Thresholds

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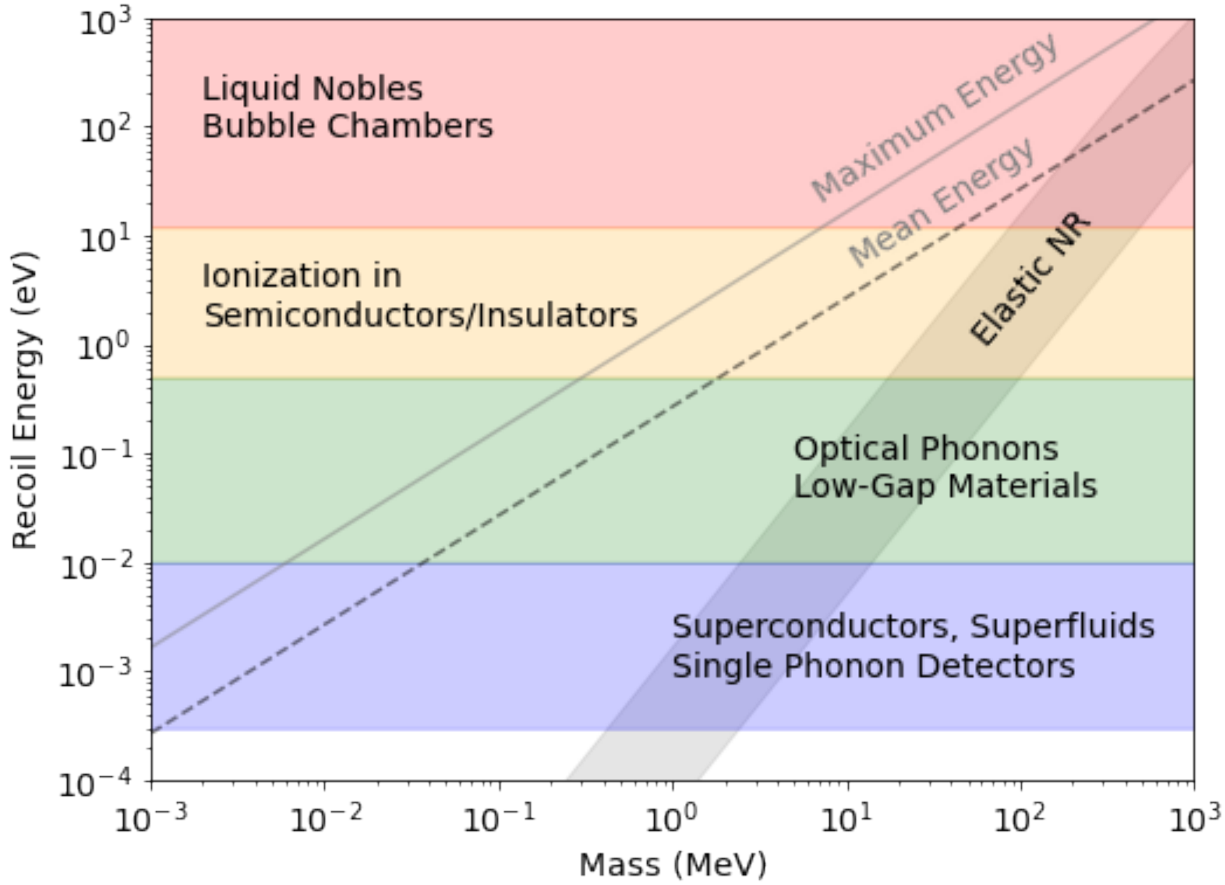
Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade https://arxiv.org/abs/2203.08297

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



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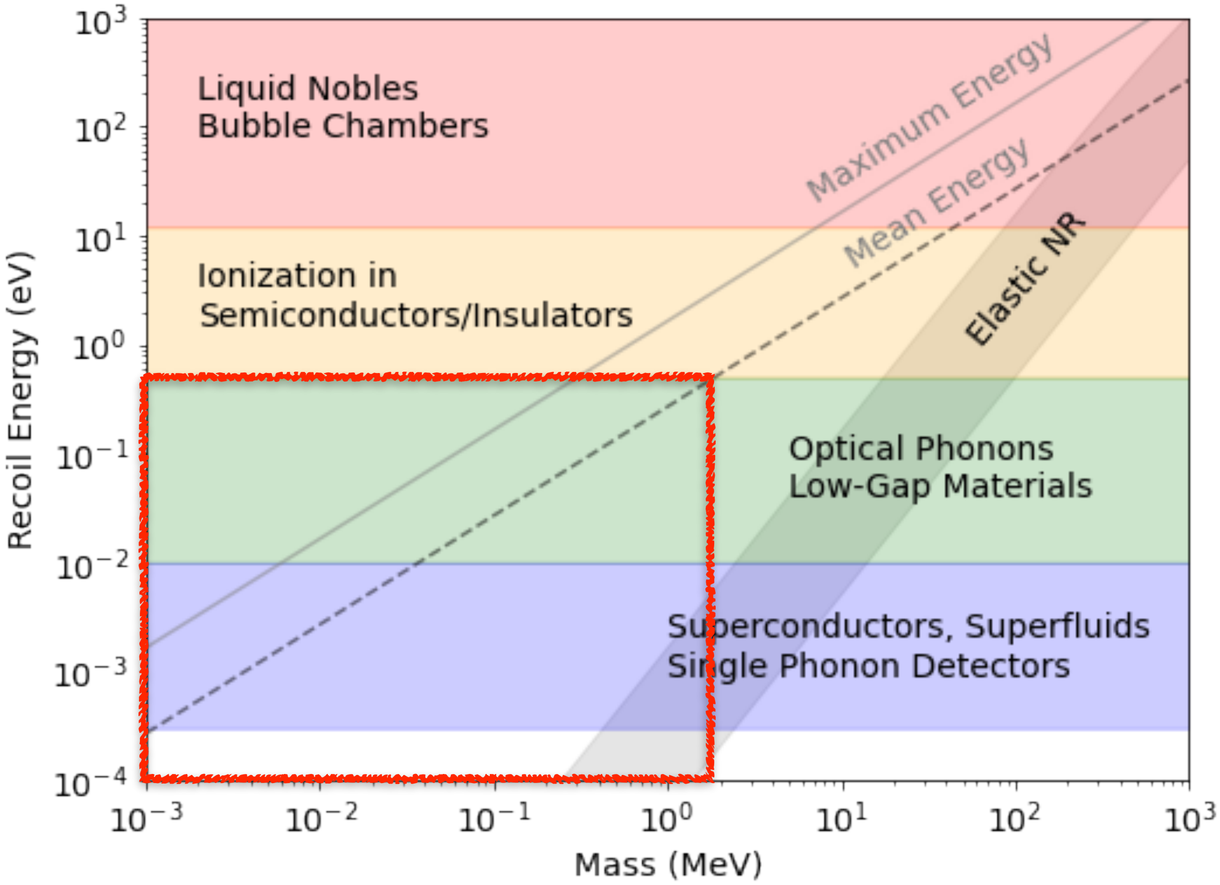
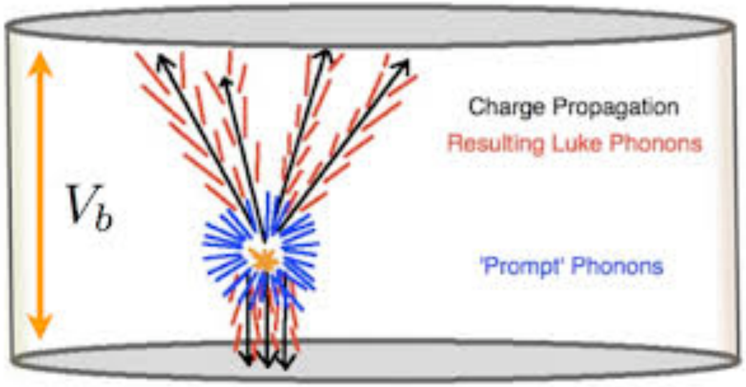


Multiple Paths to meV-Scale Energy Sensitivity

Interaction Produces Charge and Phonons in Solid State Target



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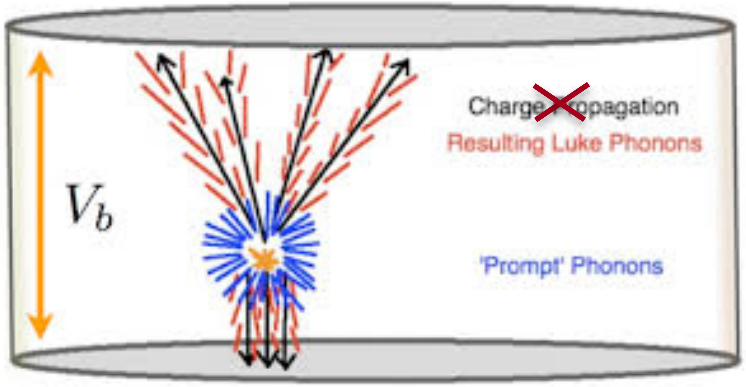

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Phonons Captured in Small
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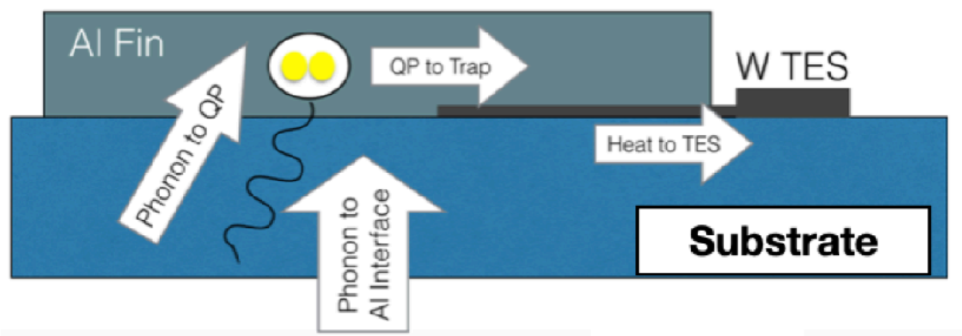

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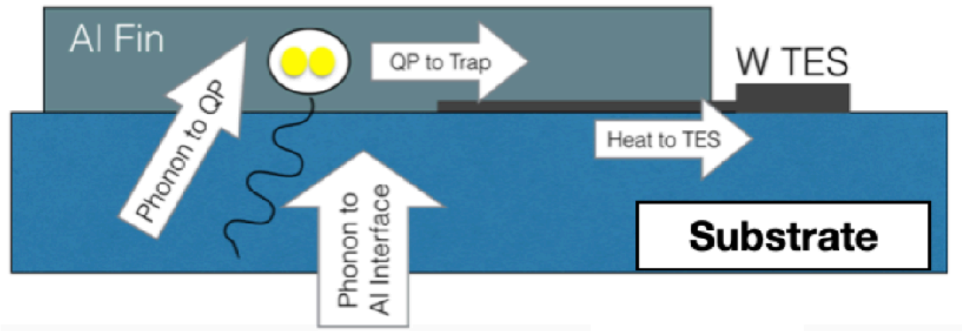

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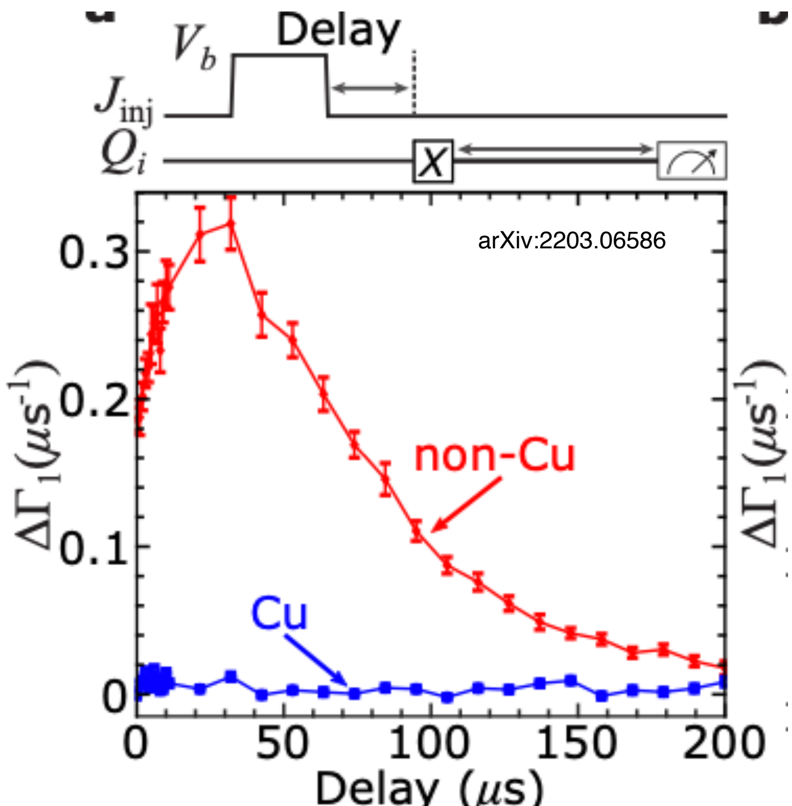

Sensor tracks
quasiparticle density
MKID, TES

Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit

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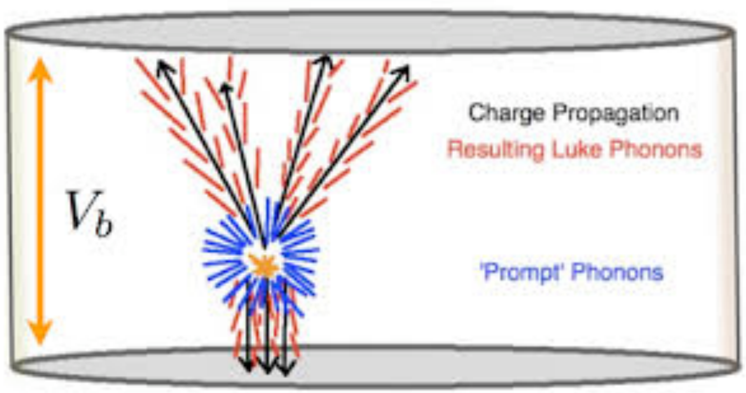

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Ren et al, Phys. Rev. D 104, 032010 (2021)

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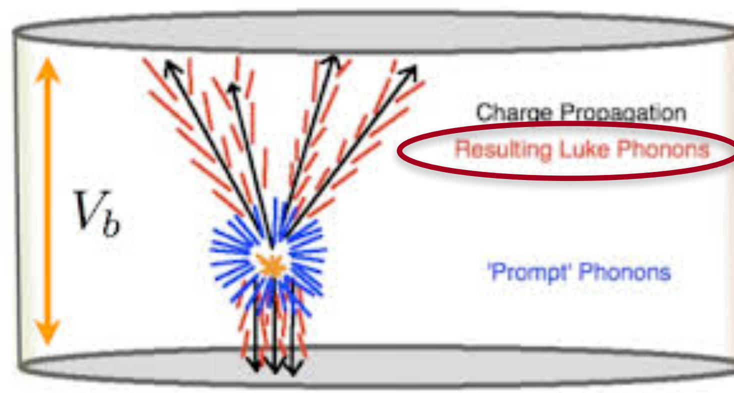

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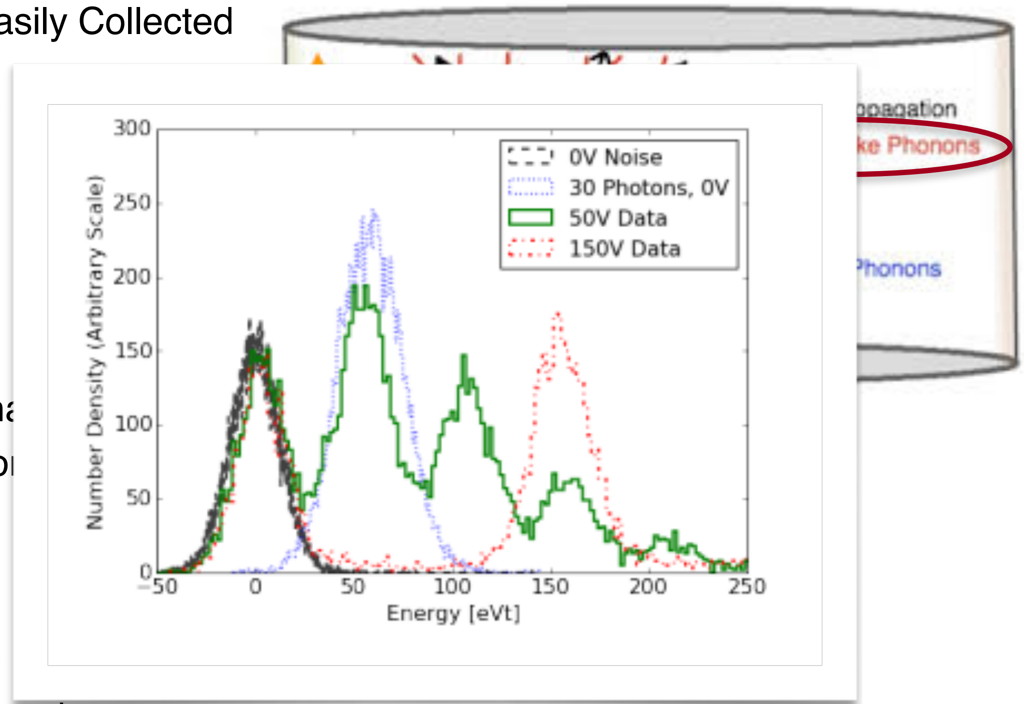

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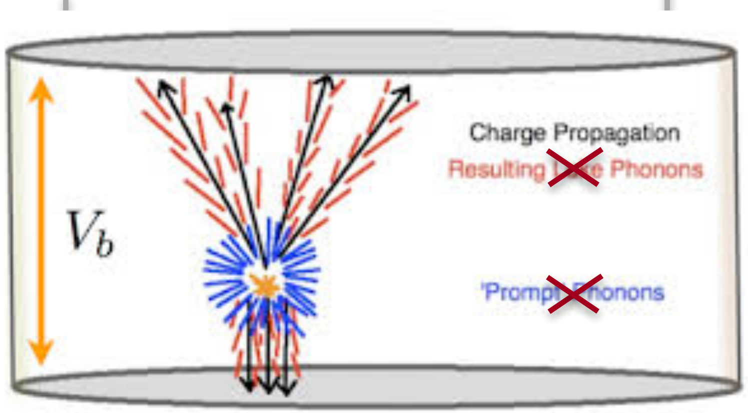

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Wilen et. al, Nature 594, 369-373

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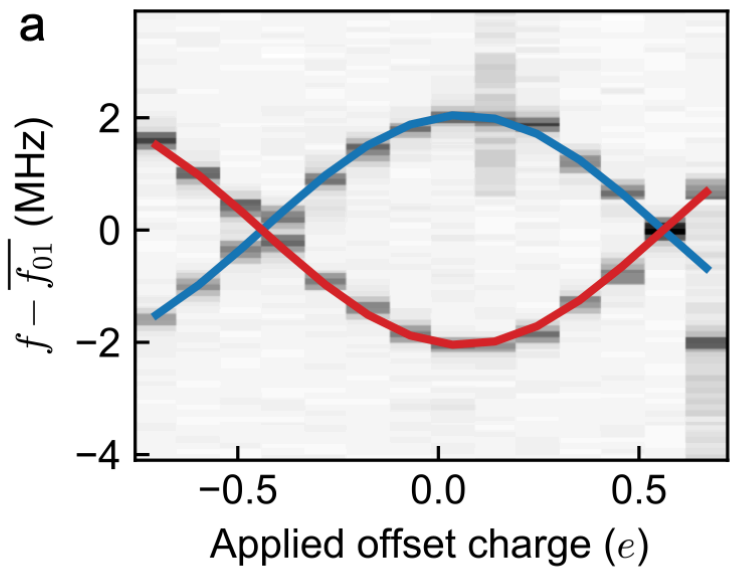

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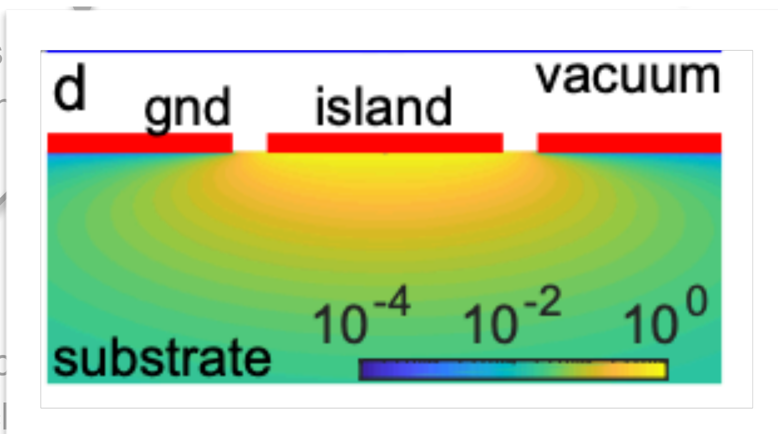

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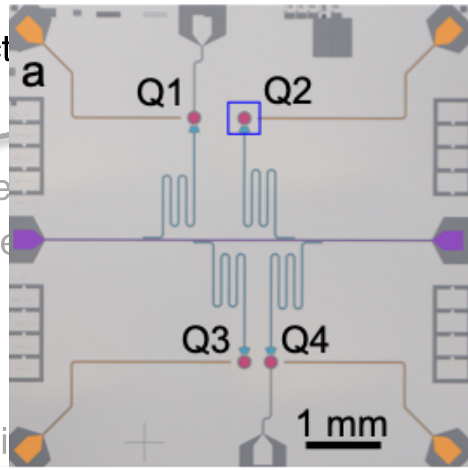

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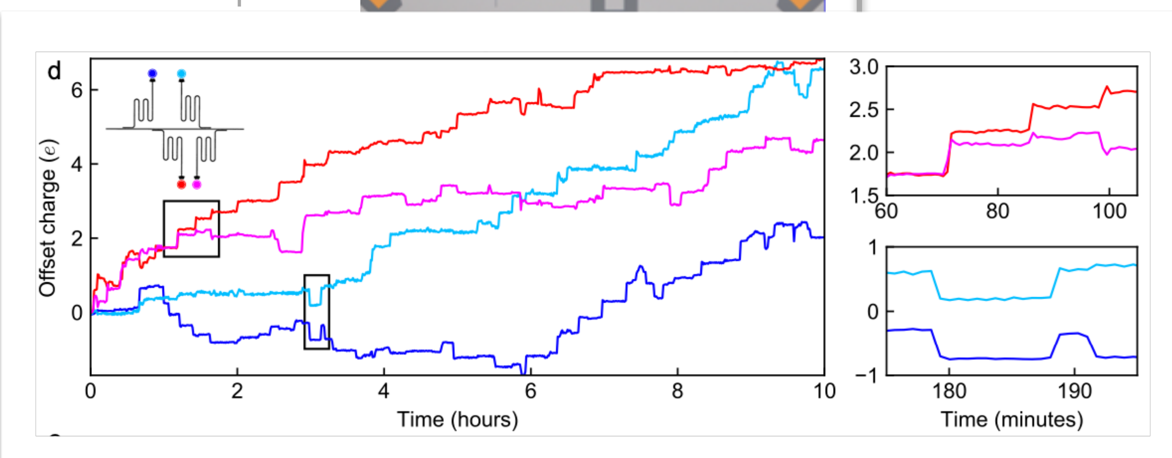

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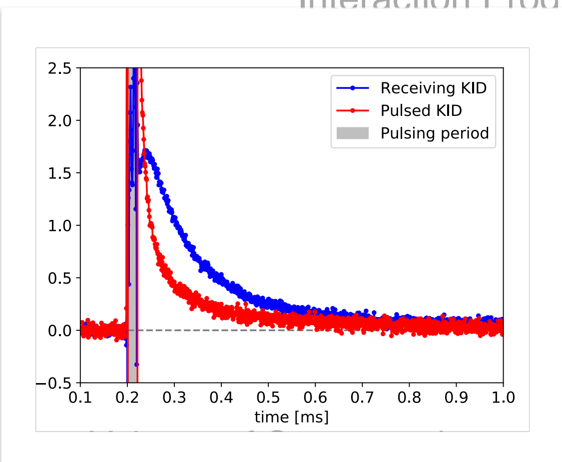

Charge and Phonons Share Energy, Easily Collected

More Charge Produced, Phonons Cannot be Collected

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Phonons increase quasiparticle ... or

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

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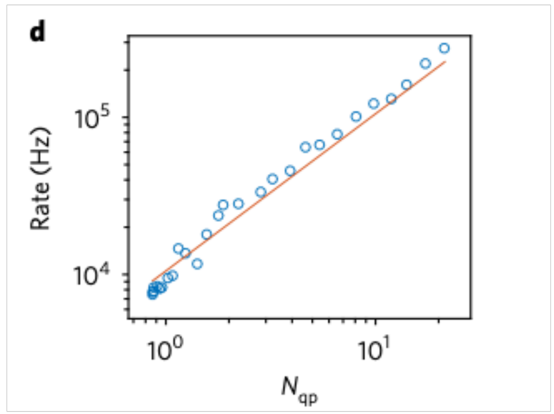

$$E = N_{qp}(2\Delta)$$
$$= \epsilon_{capture}\left[\int_0^{\tau_{pulse}} (\Gamma_{tunnel}(t) - \Gamma_0)dt\right](2\Delta)$$

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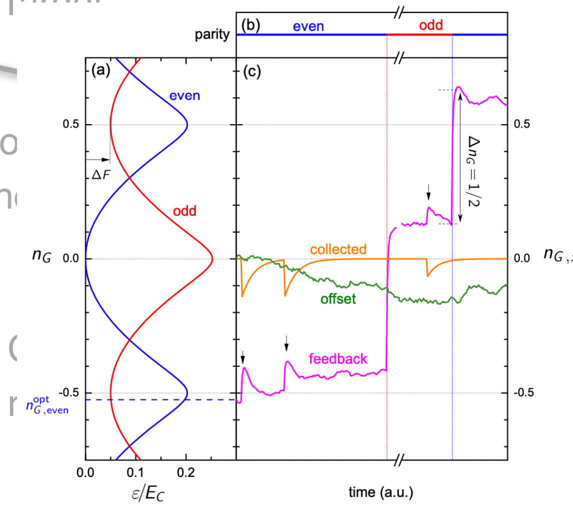

Charge induces offset voltage on

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

ArXiv:1711.08758

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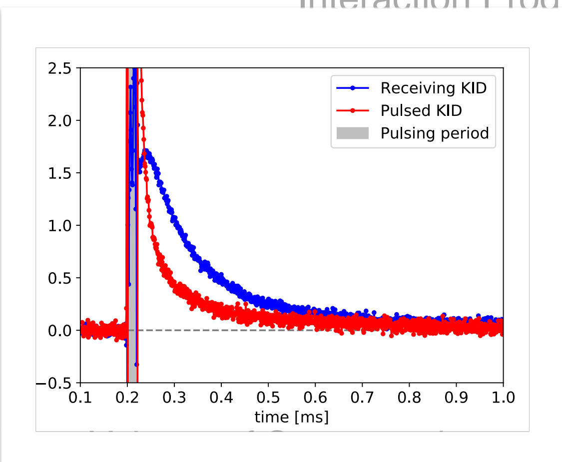

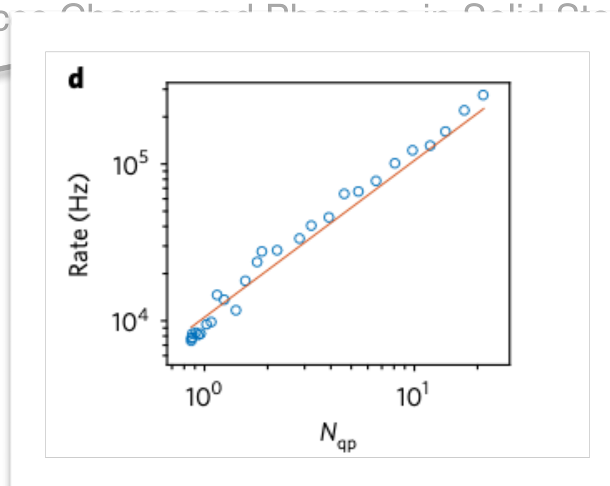

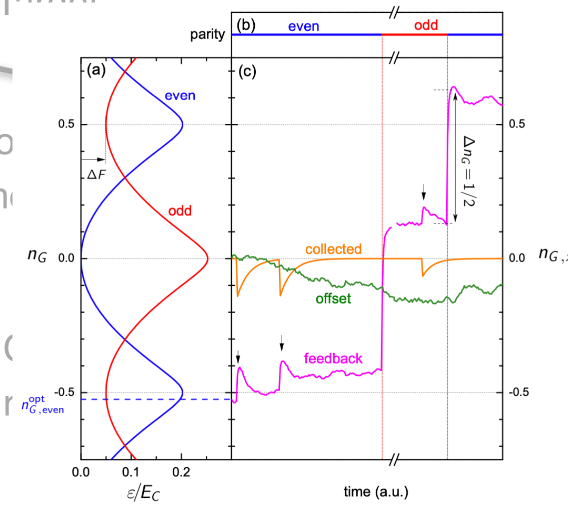

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Energy Sensing with Qubits

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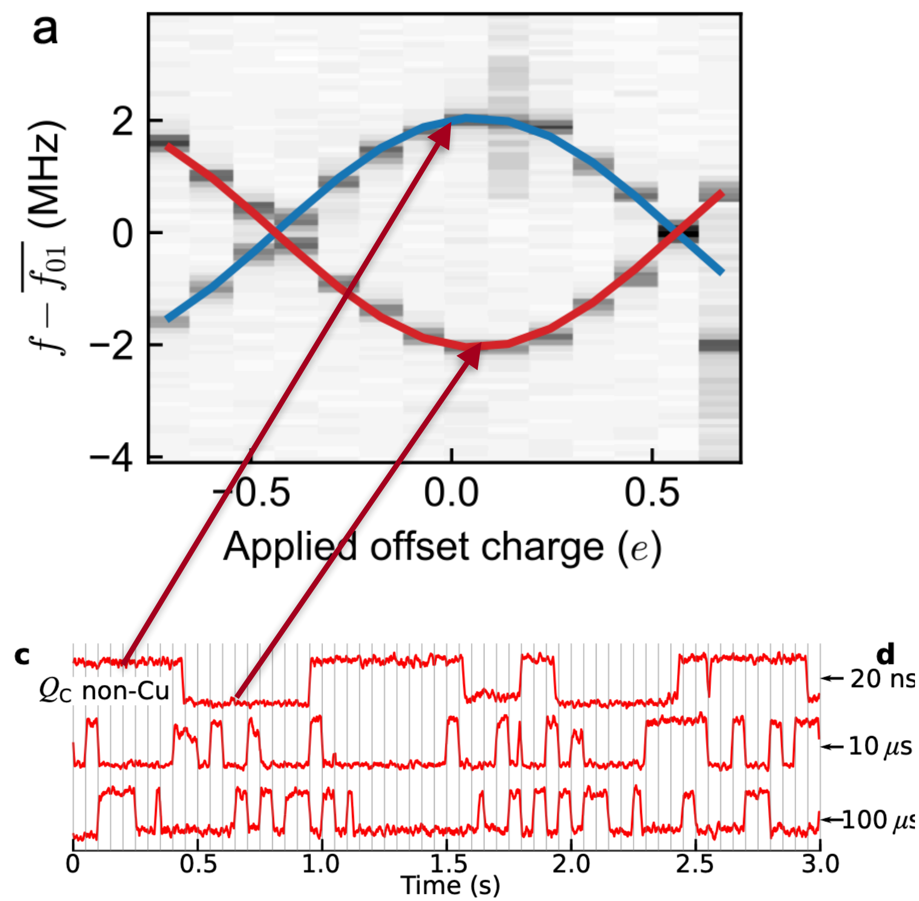
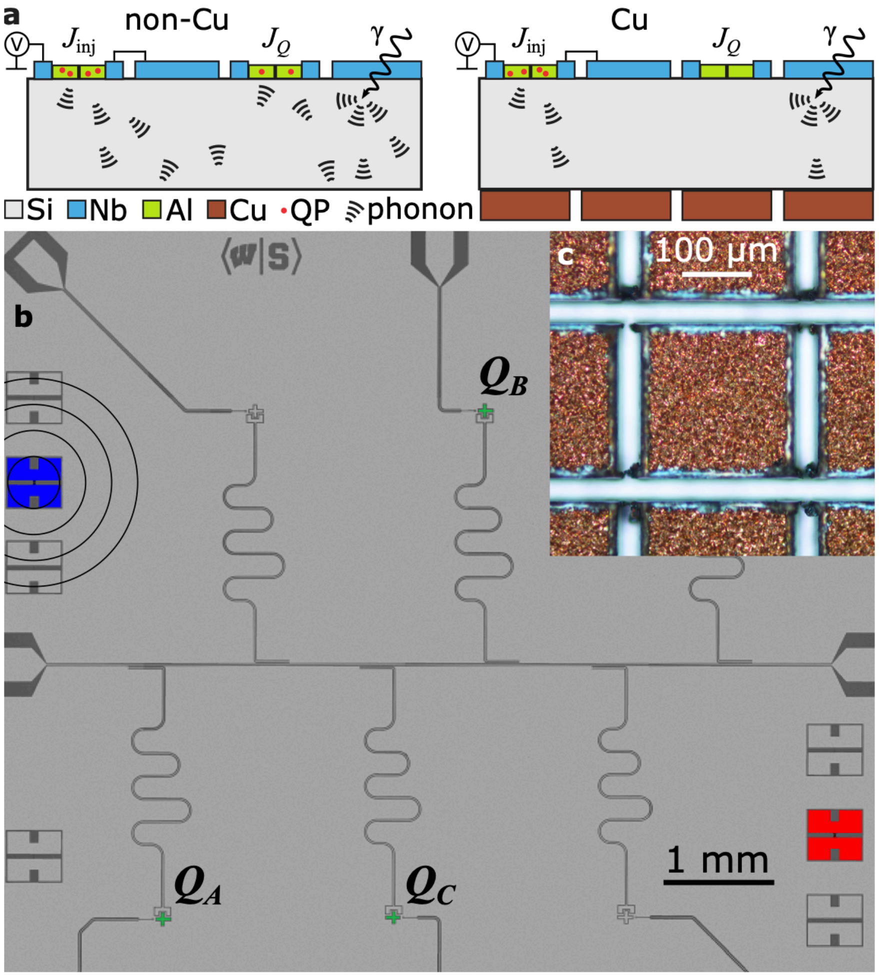
- Qubit-based sensing relies on weakly charge-sensitive qubits, which have ‘even’ and ‘odd’ parity states
- The transition between these states is mediated by quasiparticle transitions
- The rate of these transitions depends on the ambient quasiparticle density near the junctions, created by pair-breaking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



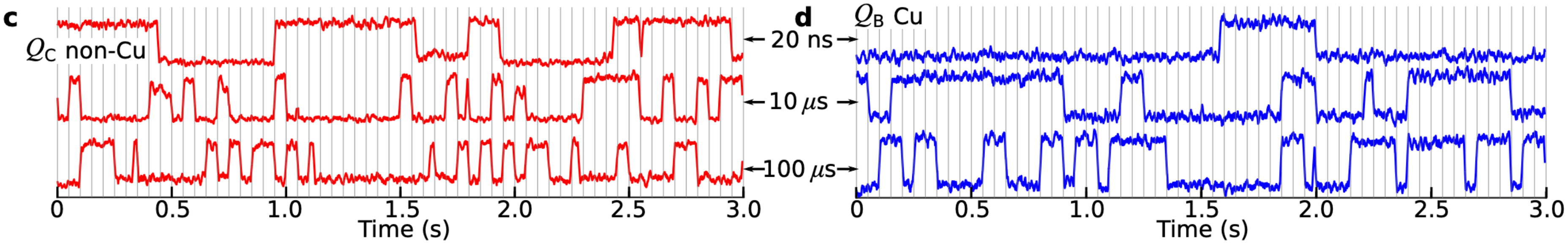
$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos(\phi)$$

Evidence of Phonon Signals

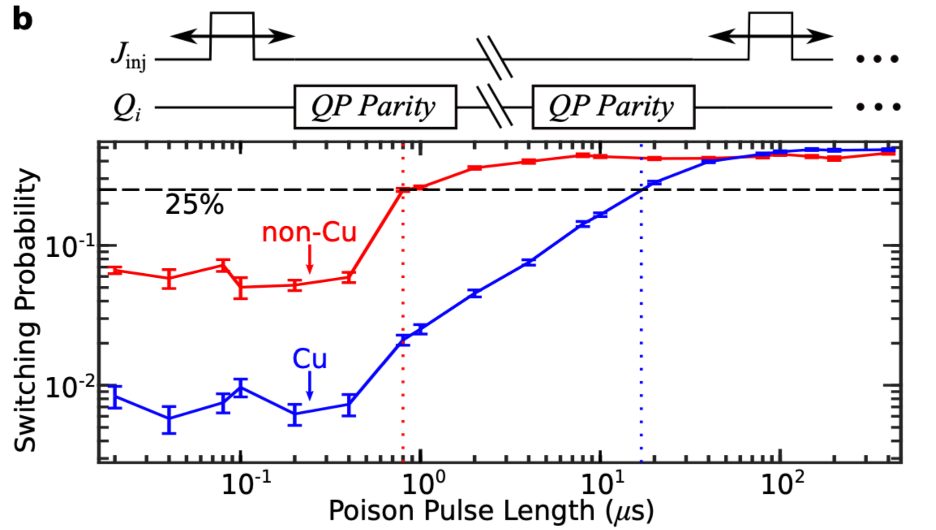
- We can see the effect of phonon-mediating quasiparticle generation by comparing crystals with and without a copper phonon sink
    - In the non-copper case, we expect longer-lived phonons and more effects from athermal events
    - In the copper case, we expect much less phonon propagation
- This demonstration comes form a recent paper out of the Syracuse and Wisconsin groups (see arxiv link)



Evidence of Phonon Signals (cont'd)



- Time-streams of parity switching above show that, at a fixed time after a poisoning event, switching rates differ between chips
- For a known energy injection, this can be used to back out the effective quantum efficiency of the tunneling process
  - Current designs are not optimized for this - this is just a background for conventional qubits



Evidence of Phonon Signals (cont'd)

arXiv:2203.06586

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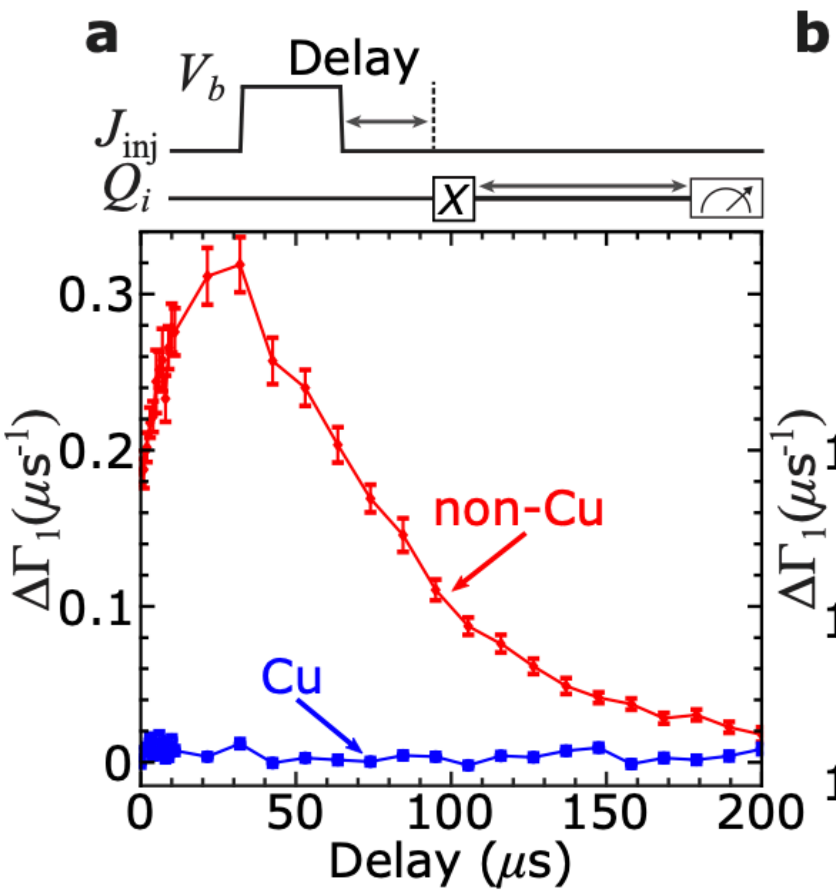
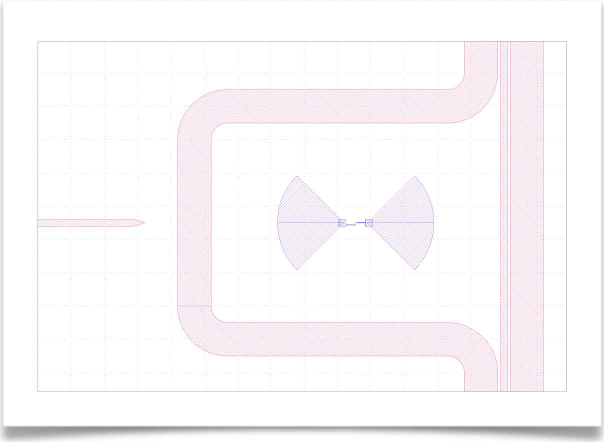
- When run in a different mode, we can see the characteristic time-dependence in the tunneling rate we'd expect from a phonon event!
- The challenge now is to be able to do this in real time - this was done in the current paper using pump-probe techniques to average down noise, with thousands of trials per delay time.
- We also need to optimize the qubits to be *more* sensitive to these events



Qubit-Based Sensor R&D

- Utilize phonon collection modeling from TES-based sensors
- Measure discrete tunneling events across junction as proxy for event energy
- Major R&D task for initial devices is to understand the efficiency of quasiparticle tunneling during thermal events
    - sofa
- Design problem involves producing qubits that are more strongly coupled to the readout line to optimize for sensing
    - Our initial devices aim to develop an architecture useful for both phonon and photon sensing
- Charge tunability also allows us to play with alternative readout schemes sensitive to image charge collected on the qubit island



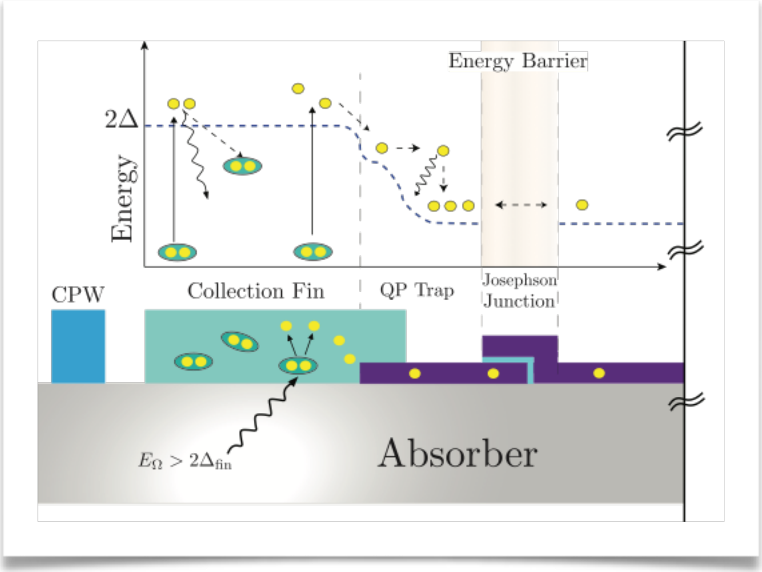


Figure by Caleb Fink, Mask Design by Chiara Salemi

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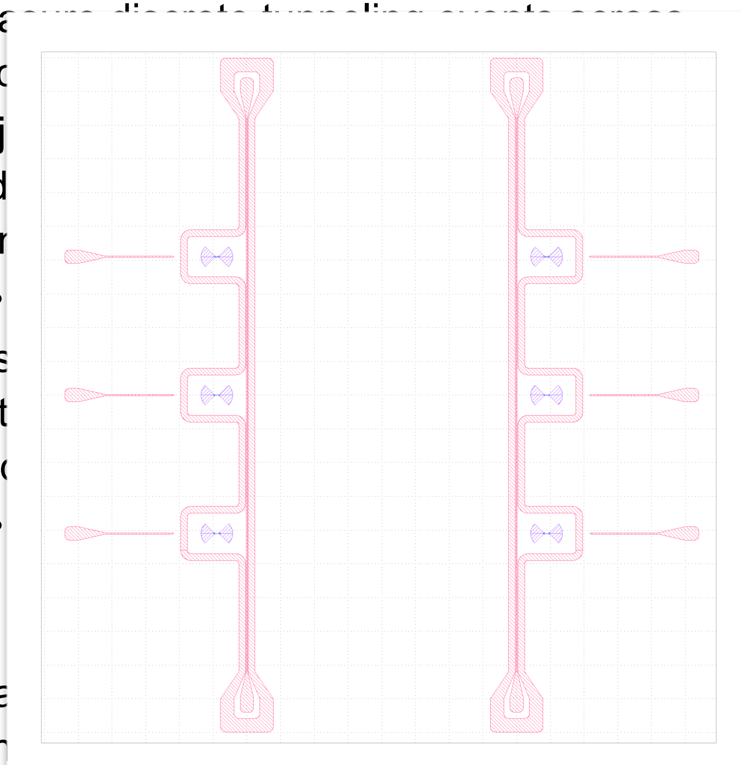

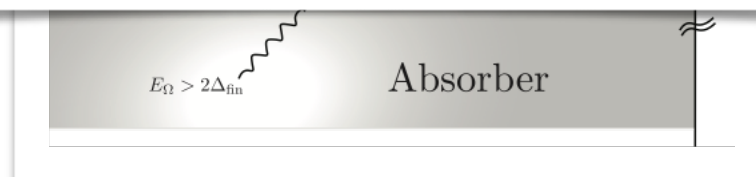

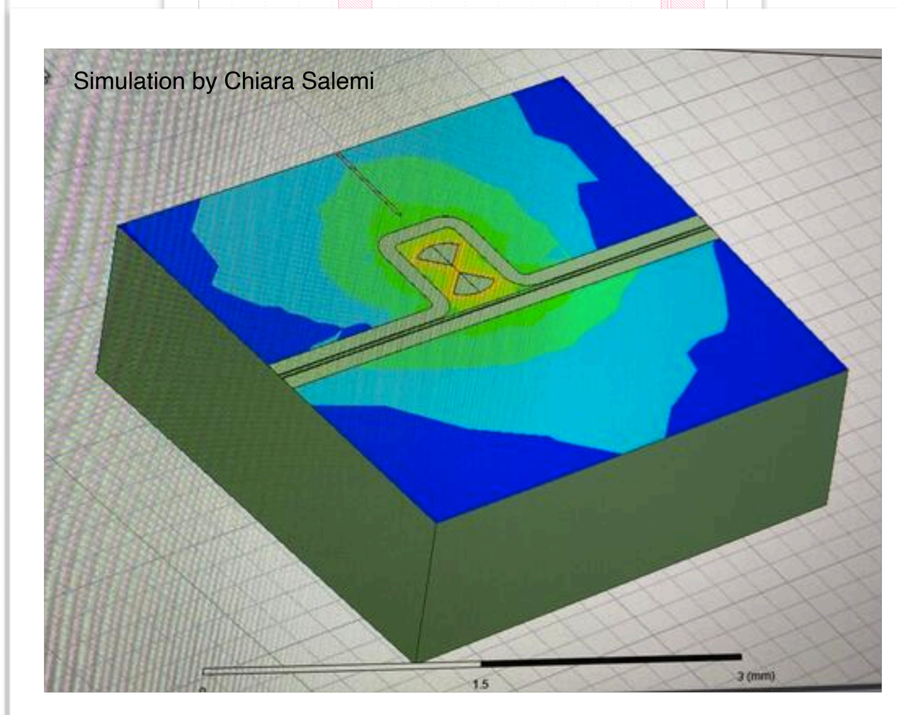

Figure by Caleb Fink, Mask Design by Chiara Salemi

DM Induced QP Poisoning

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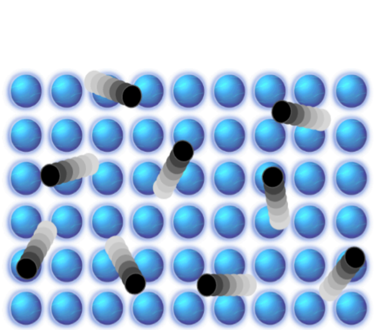
Dark Matter Induced Power in Quantum Devices

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

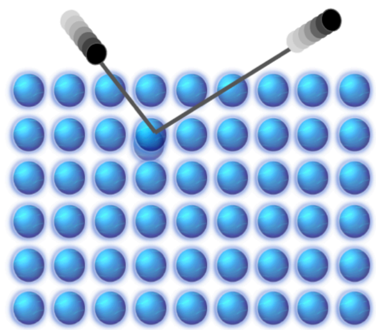
[1] *SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA*

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

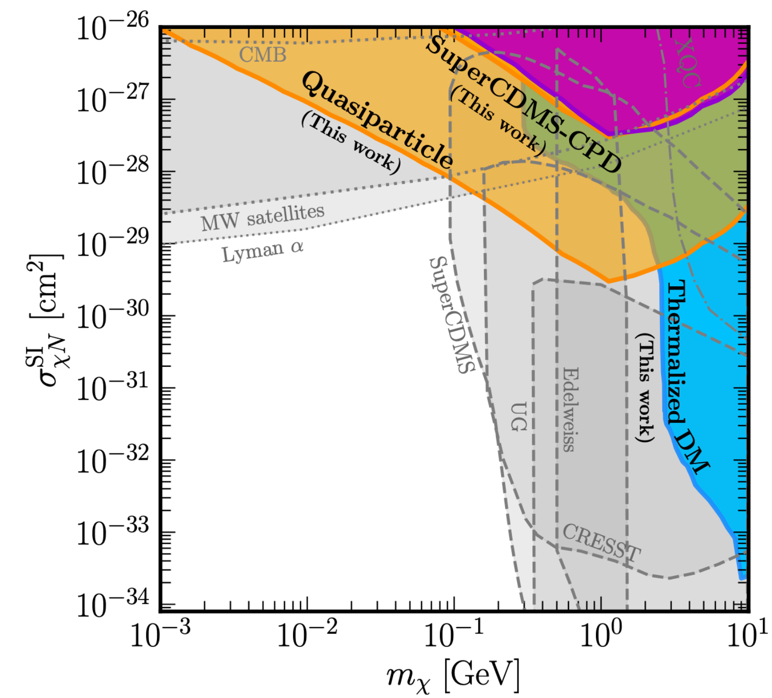
(Dated: October 17, 2022)



Noise from DM



Recoil from DM



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

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

https://arxiv.org/pdf/2210.09313.pdf

Connecting Parity Switching to Energy Injection

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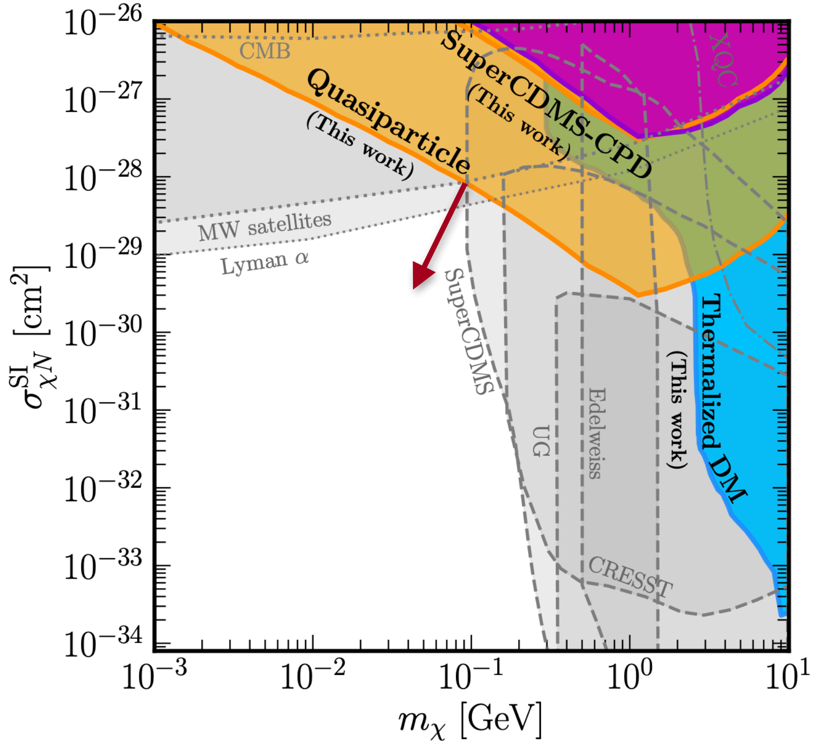
- Das et. al. needs to make a number of conservative assumptions that limit the constraining power of this technique
  - We don't have a validated model for equilibrium QP density from rare events - assume mean-field solution
  - The tunneling probability across a junction is not well modeled, and relies 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

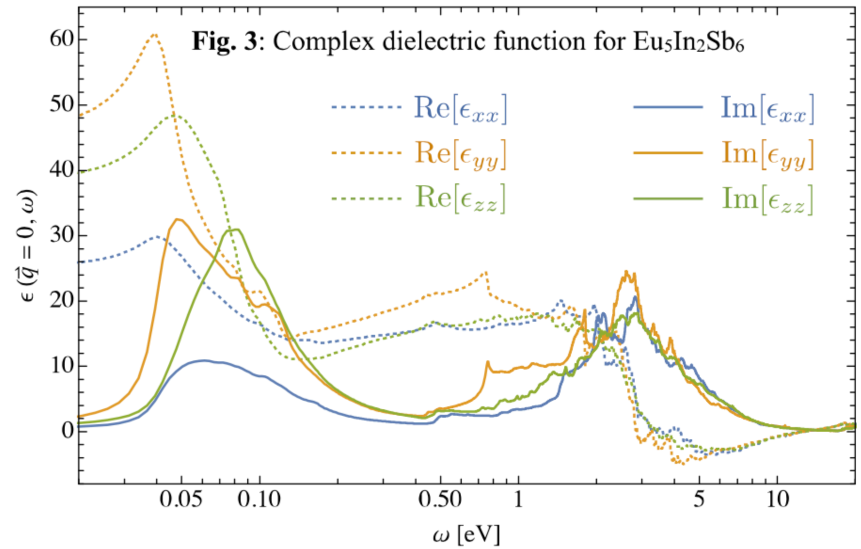
- All of these move the QP limit into new parameter space - sensor R&D can turn this into a true discovery experiment if spectroscopic readout can be demonstrated

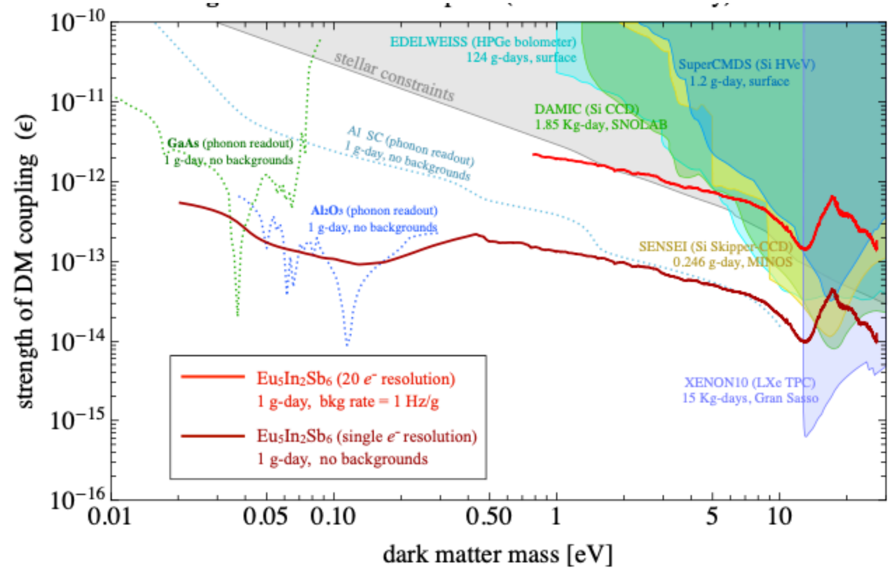


Rosa et. al. 2020, https://arxiv.org/abs/2007.06556

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





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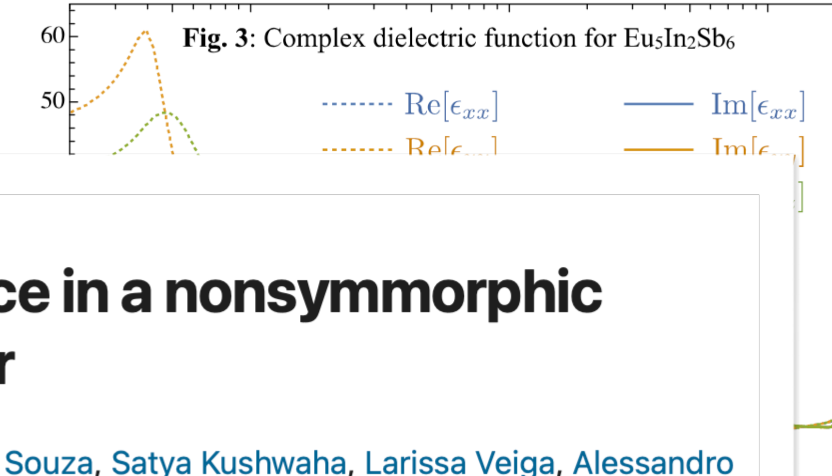
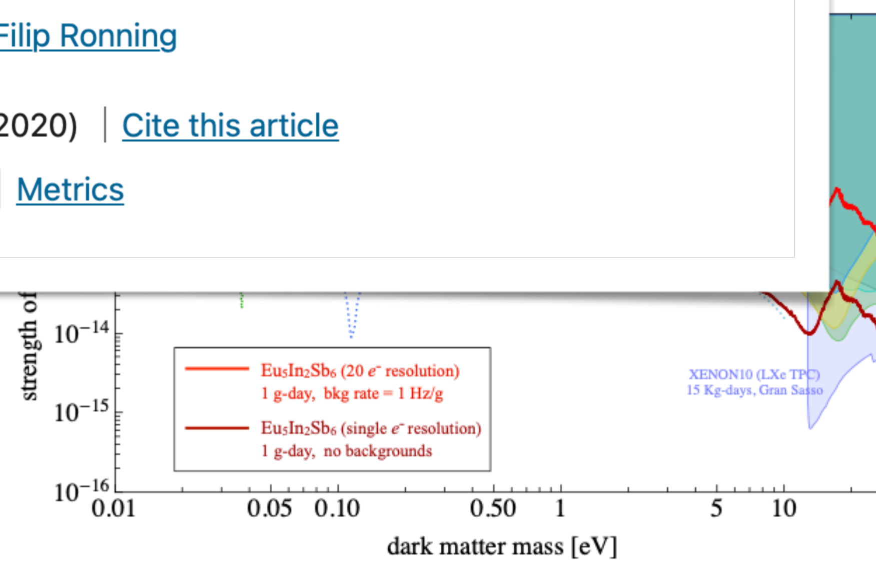


Article | Open Access | Published: 24 July 2020

Colossal magnetoresistance in a nonsymmorphic antiferromagnetic insulator

Priscila Rosa, Yuanfeng Xu, Marein Rahn, Jean Souza, Satya Kushwaha, Larissa Veiga, Alessandro Bombardi, Sean Thomas, Marc Janoschek, Eric Bauer, Mun Chan, Zhijun Wang, Joe Thompson, Neil Harrison, Pascoal Pagliuso, Andrei Bernevig & Filip Ronning

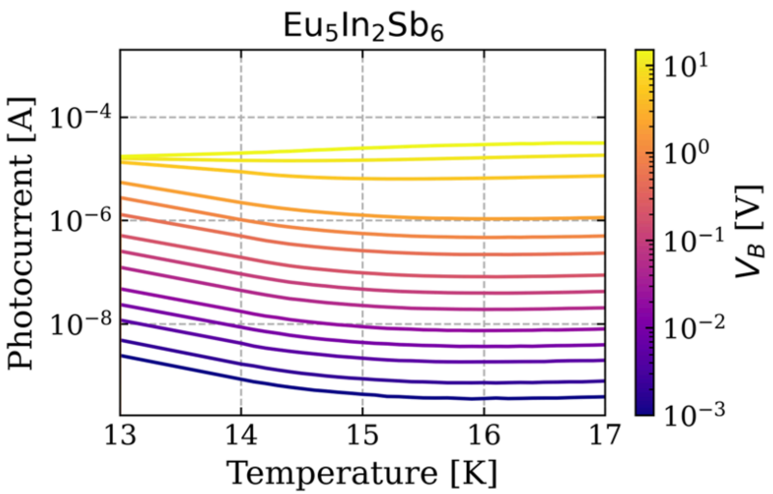
npj Quantum Materials **5**, Article number: 52 (2020) | Cite this article

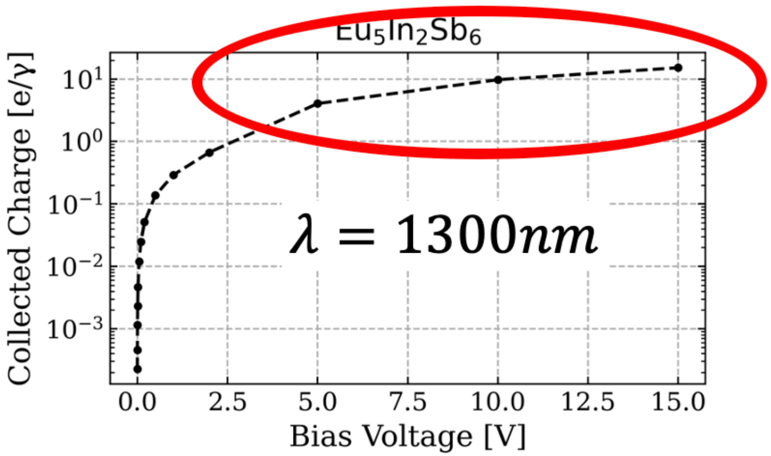


Steady-State Photoresponse - $Eu_5In_2Sb_6$

- Measure photocurrent as function of temperature
- Calculate charge collection (collected charge per photon) from known irradiance and sample size
- At temperature of resistance peak → <u>beginning to see full charge collection!</u>

Full collection would be ~30 - 100 e/photon
- currently seeing >10% collection.
Studies underway at higher bias voltage to measure full collection.

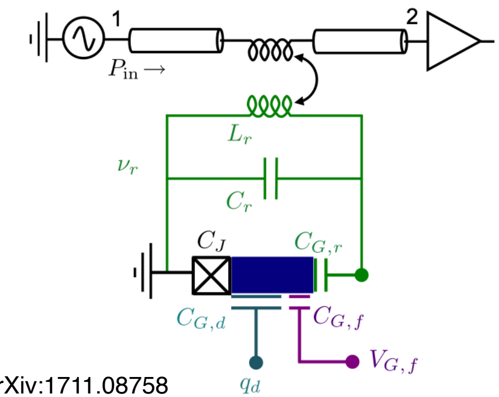




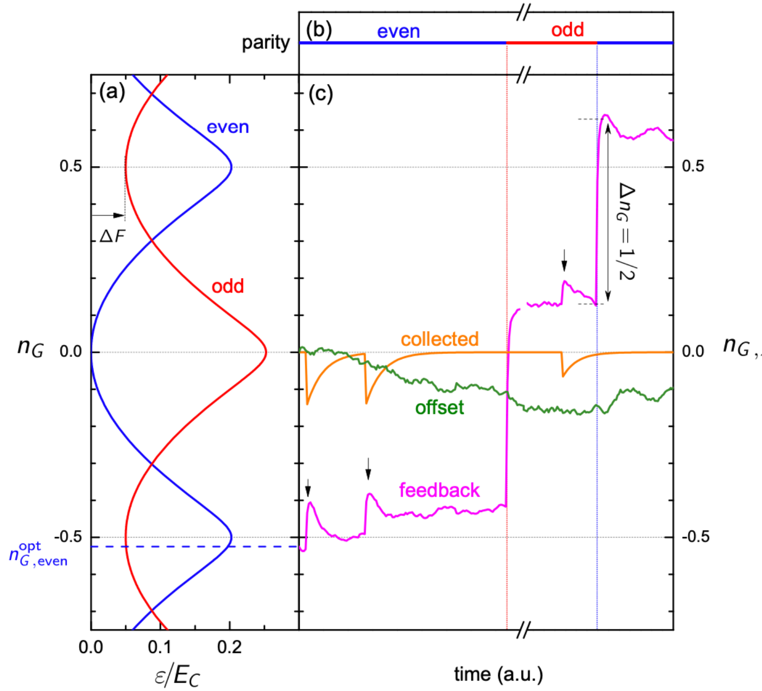
Qubit-Based Electrometers for Quantum Materials

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



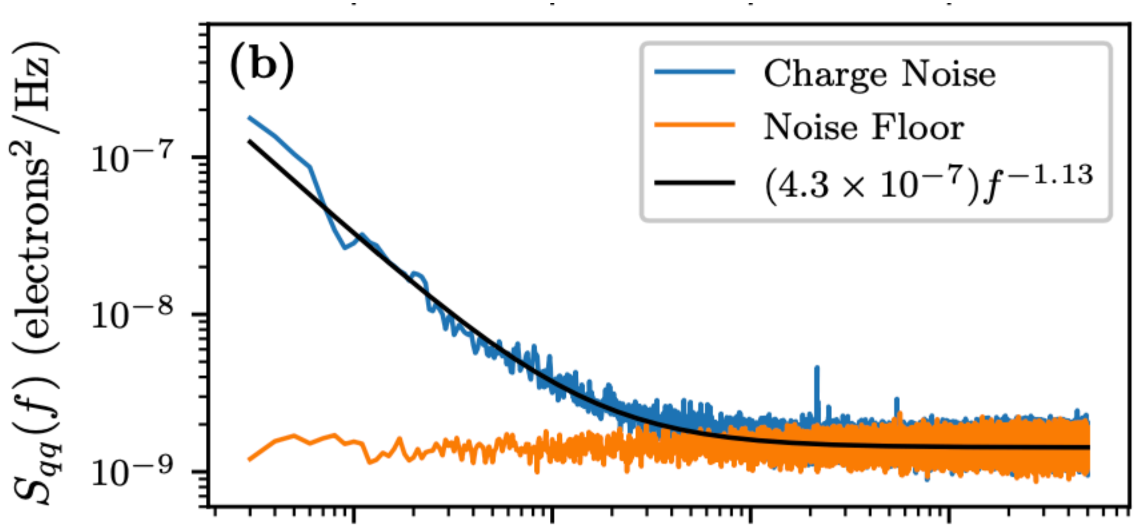
Qubit-Based Electrometers for Quantum Materials

SLAC

- 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)



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

0.5
0.0 $n_{G,x}$
-0.5
0.0 0.1 0.2
ε/E_C
time (a.u.)

Another Application: Wide-Band Axion Searches

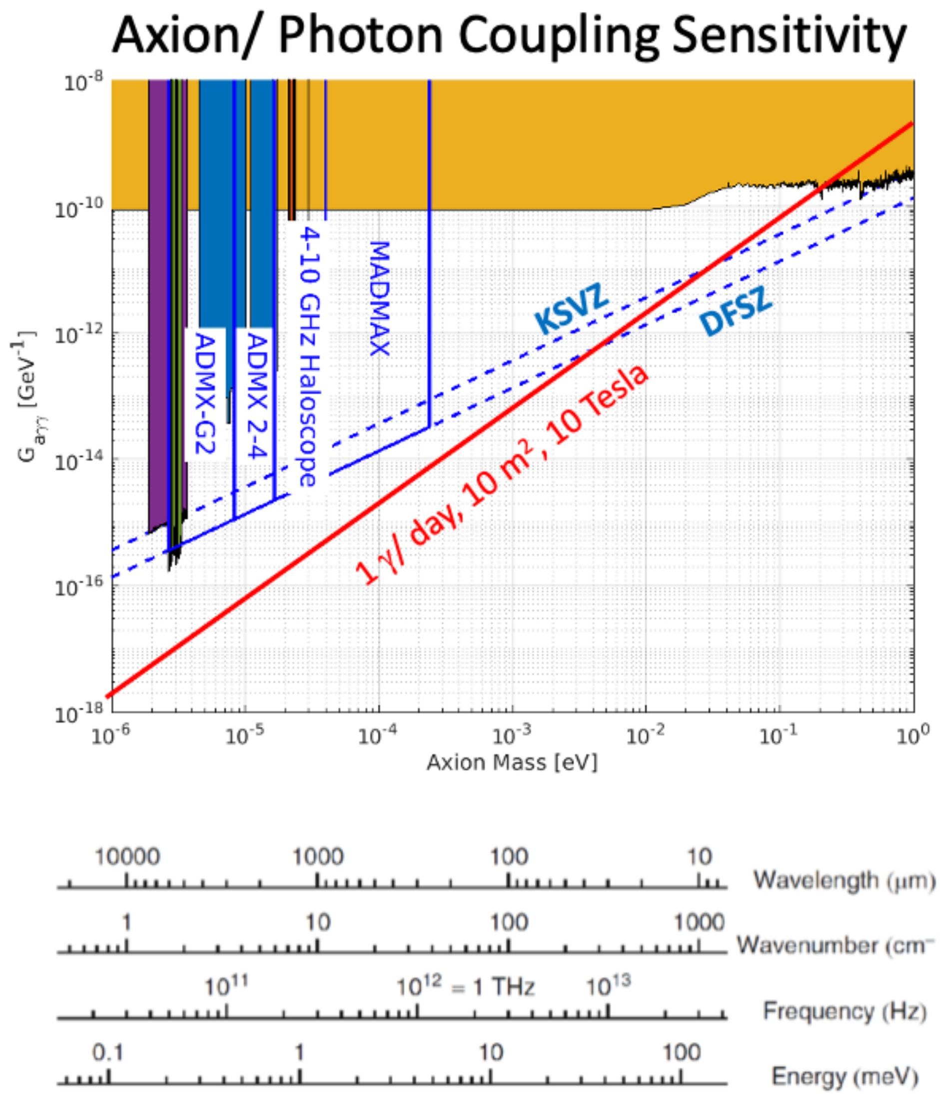
SLAC

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



Another Application: Wide-Band Axion Searches

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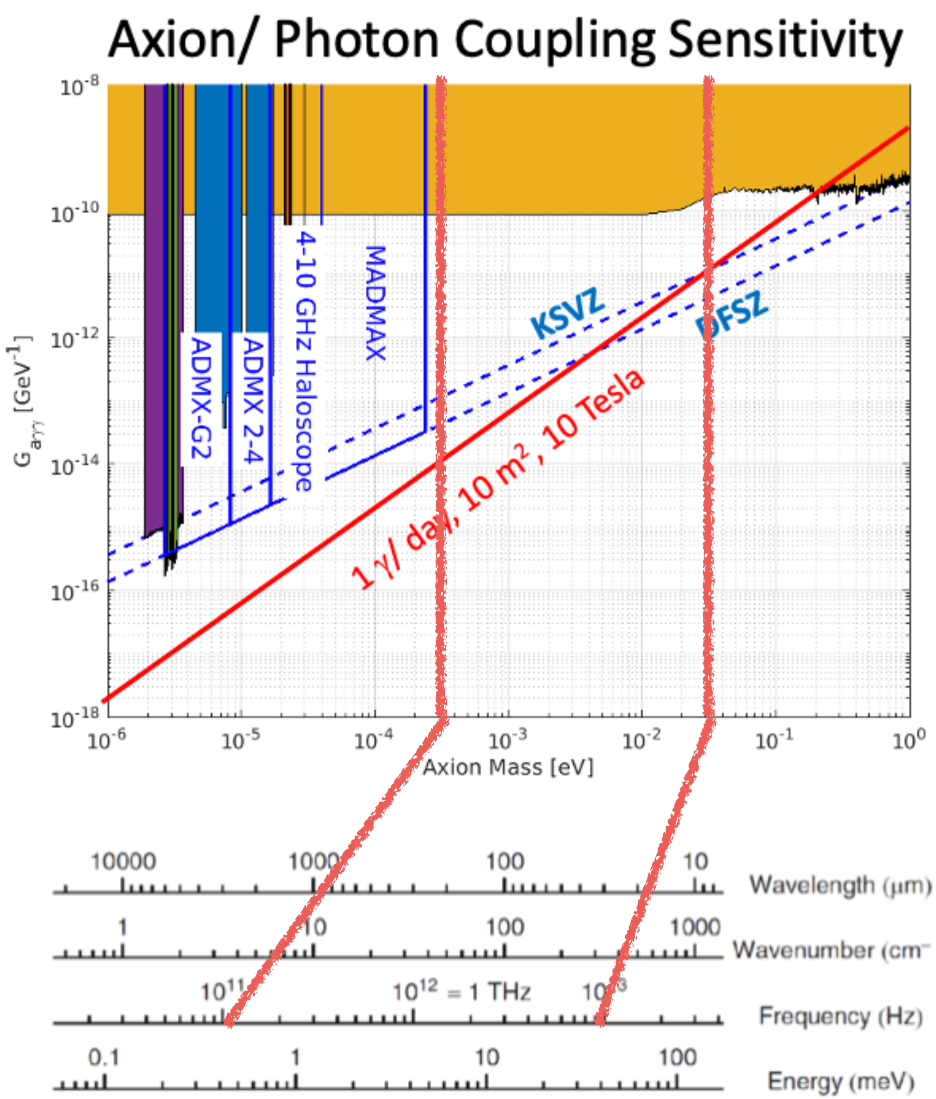


Wide-Band Axion Searches (BREAD)

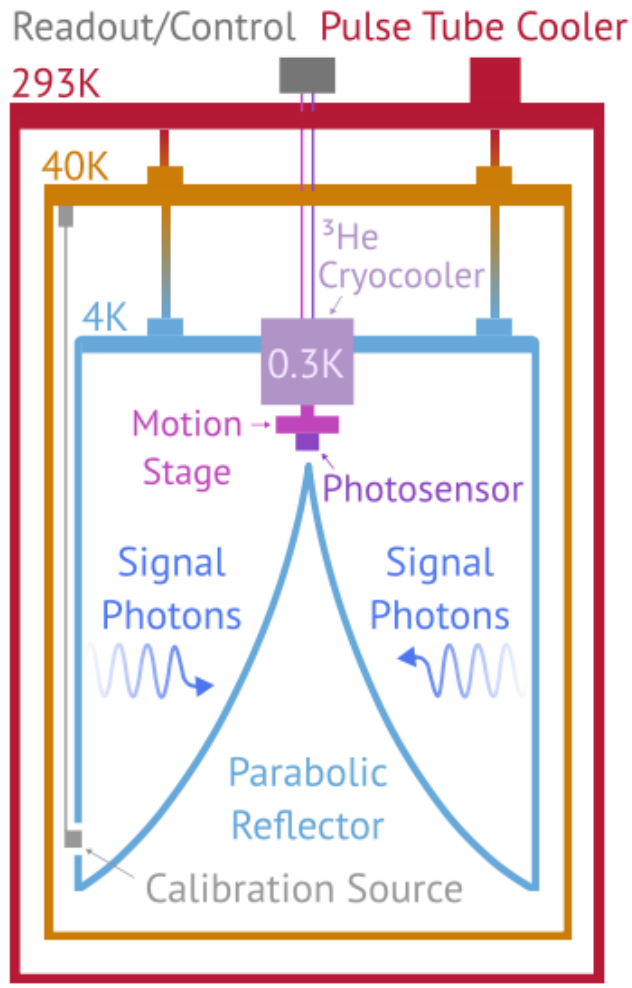
SLAC

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

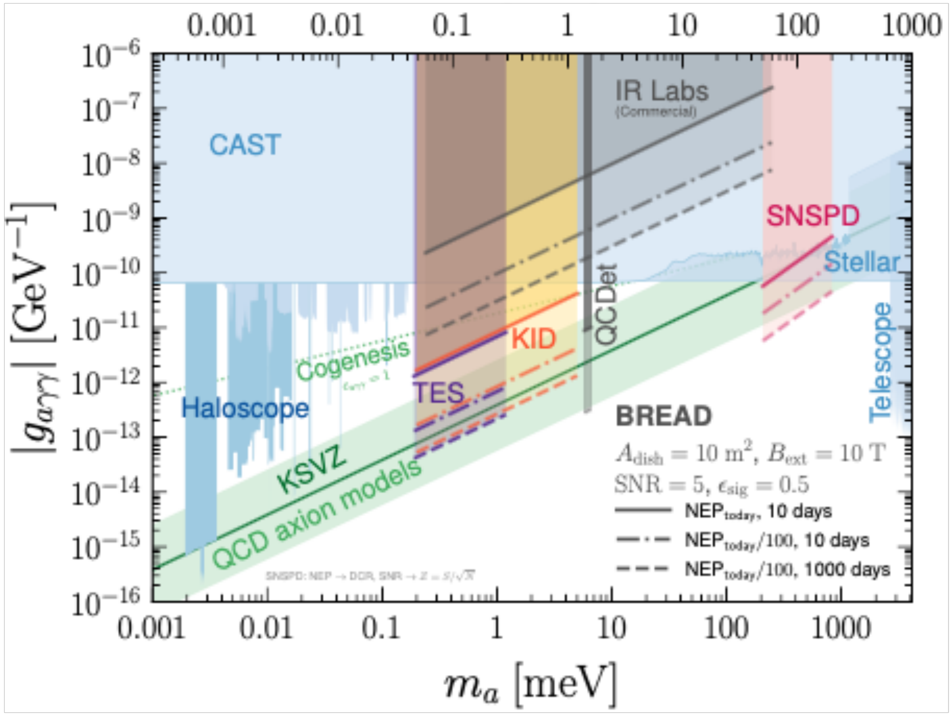
- Sub-Kelvin feedhorn design and characterization
- Development of THz optical paths
- Ability to calibrate wide-band sensors in the meV-eV regime
- Measurement of quantum efficiency in-situ

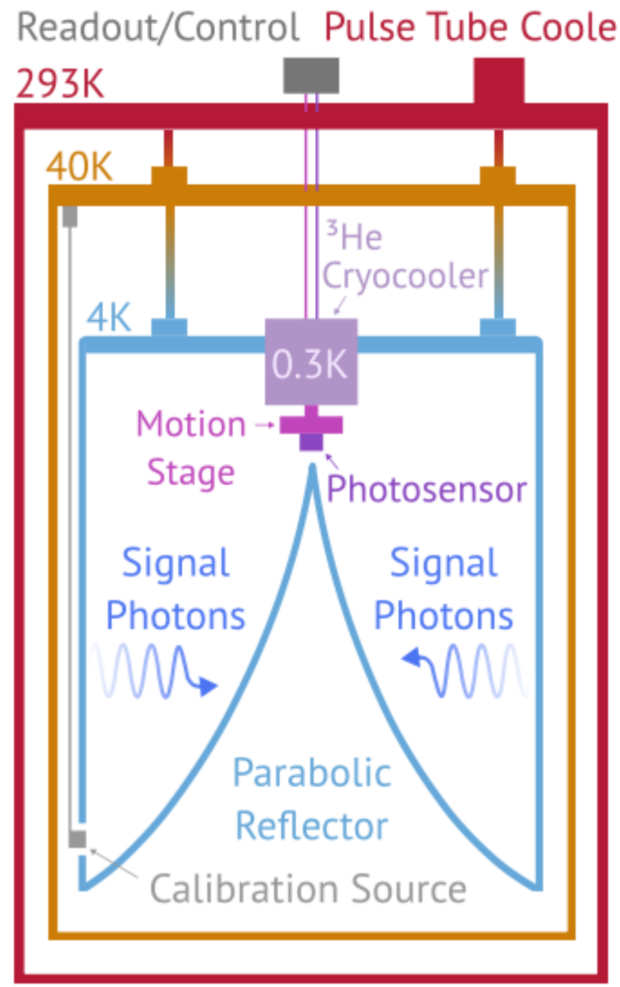
Initial prototype will run at FNAL in the next 1-2 years, ultimate experiment realized in 5-10 years alongside developments in quantum sensing



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

Wide-Band Axion Searches (BREAD cont'd)





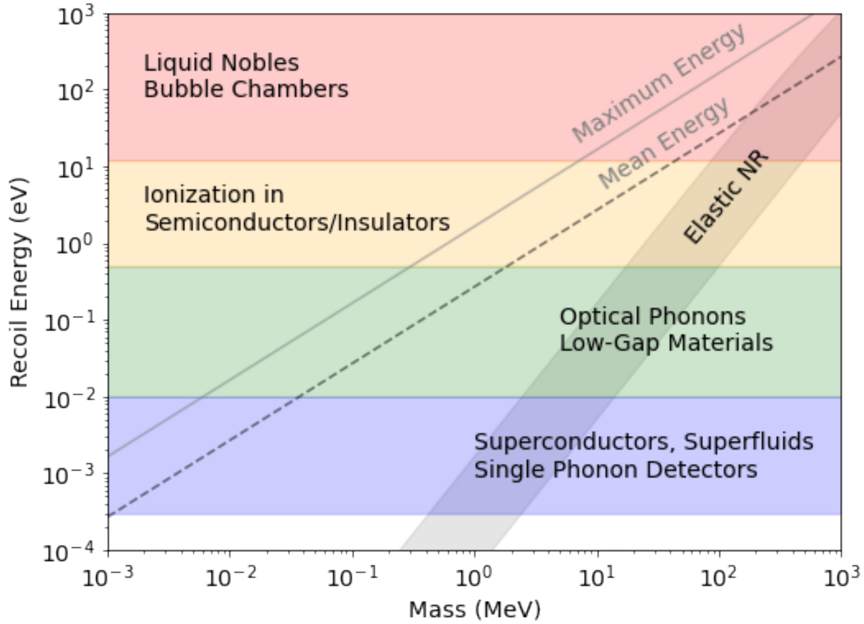
Change mass sensitivity by swapping photosensor; variety of stages planned with different detector technologies.

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

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.



Backup

New Initiatives at SLAC

- Fabrication of superconducting qubits and quantum sensors
  - New R&D program being established with involvement from Kent Irwin (DMRadio), David Schuster (Circuit QED), and Zeesh Ahmed's group (CMB S4) in conjunction with new DMQIS group
  - The Detector Microfabrication Facility (DMF) will enable scale-up of the small devices developed initially on Stanford campus

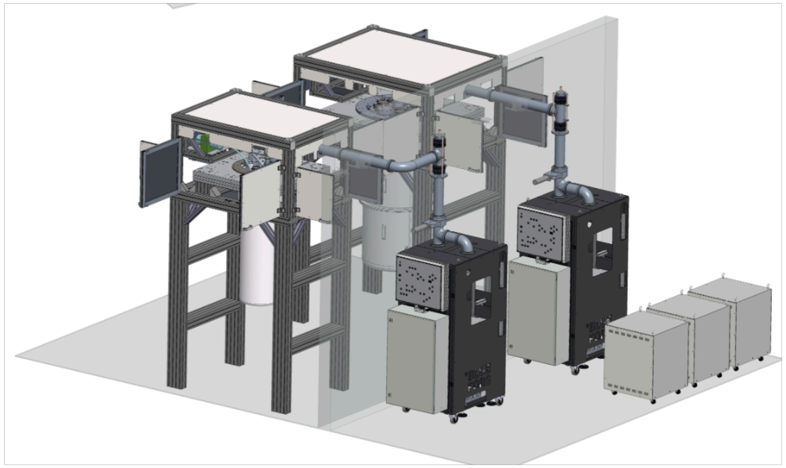
- Establishment of new cryogenic detector testing facility at SLAC
  - By June 2023, there will be 3 new DRs operating in B33 (5 total) dedicated to qubit and sensor testing at SLAC. One is commissioned and the other is being constructed, with a third to be delivered in March

- Development of RF Readout for Quantum Sensors
  - Working with CMB S4 and QNEXT groups to develop robust RF readout platforms capable of feedback and feedforward of resonator arrays
  - Building on the success of Zeesh Ahmed's SMURF system for tone-tracking of microwave resonators

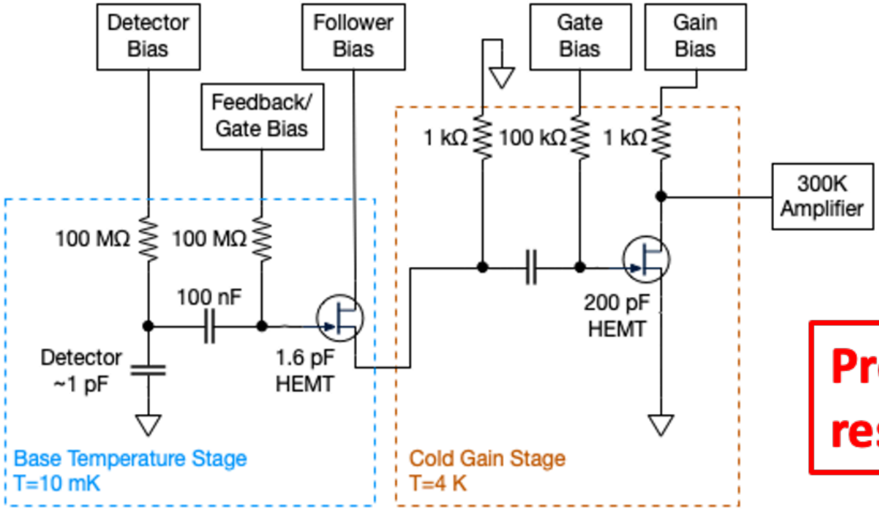
- SLAC is an amazing place to work on quantum sensors for fundamental physics!

New Initiatives at SLAC

- Fabrica … ens
  - Ne … m … uster (n … onj … o
  - Th … ena … ces de
- Establi … y a
  - By … ati … qubit and se
- Developme
  - Workin … elo capabl … or a
  - Buildin … RF microw
- SLAC is an … ors



Designing a 10mK Charge Amplifier



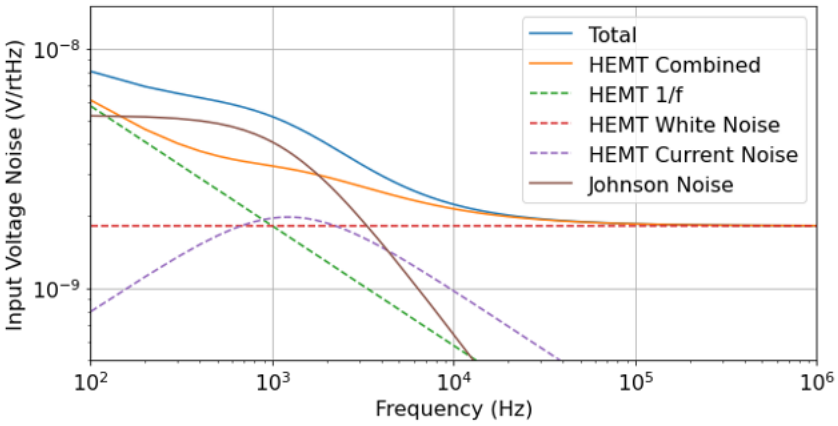
$$\sigma_E = \sigma_q E_{gap}$$
$$\approx (C_{det} + C_g)\sigma_V E_{gap}$$

Predicted 1-sigma optimal filter resolution: 5.35 electrons

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

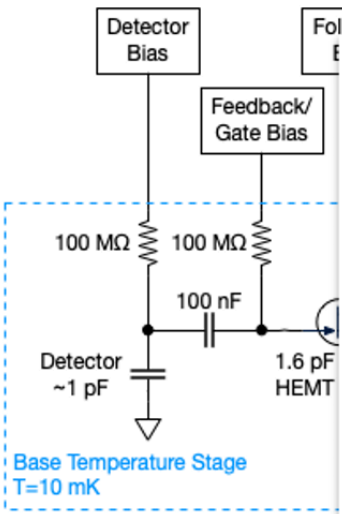
Amplifier parameters:
Bandwidth: 100 Hz – 1 MHz
Cold gain: 30

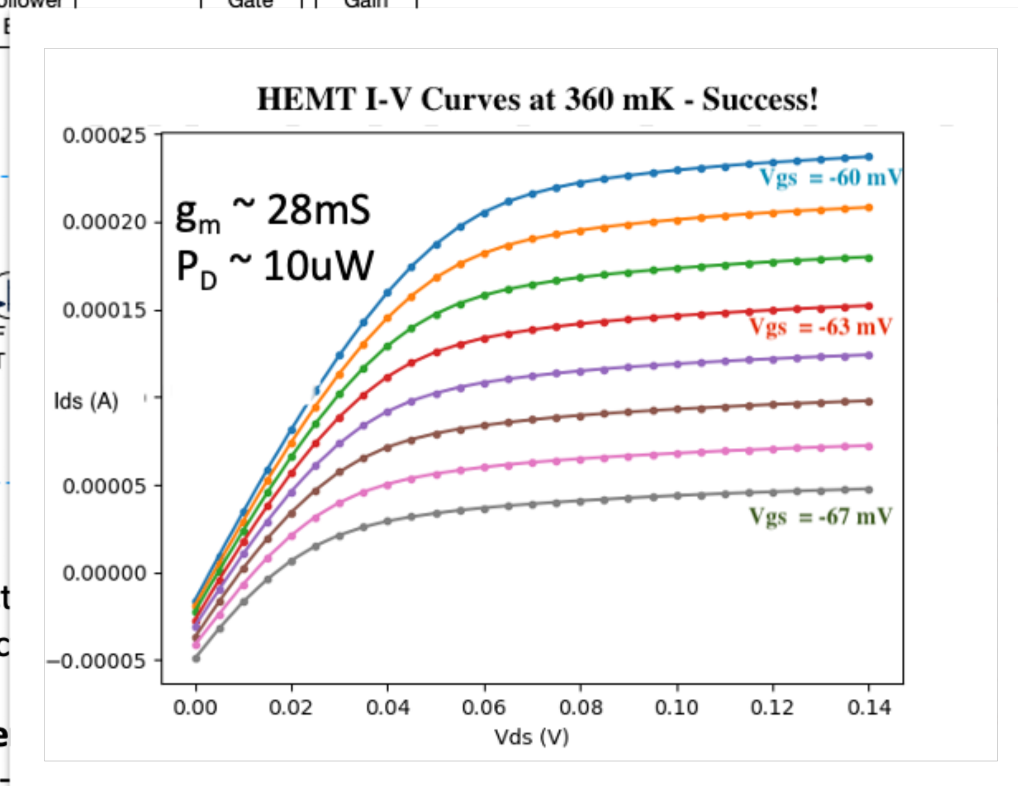
~20 uW dissipation at 10 mK
~2.1 mW dissipation at 4 K



Slides from Caleb Fink, LANL

Designing a 10mK Charge Amplifier



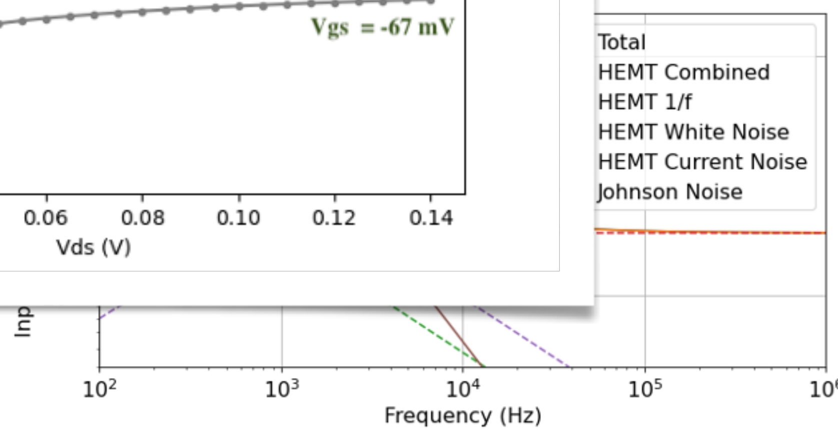


$_{q}E_{gap}$

$_{g})\sigma_V E_{gap}$

al filter

ns



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~2.1 mW dissipation at 4 K

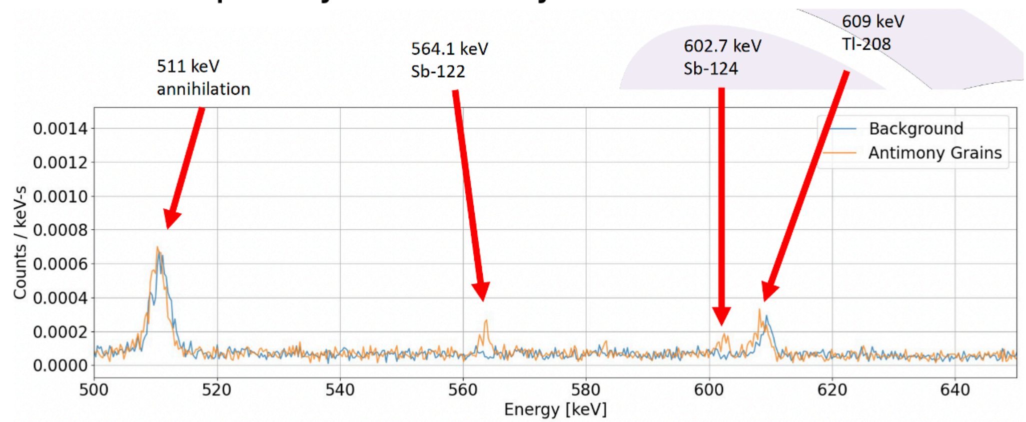
Slides from Caleb Fink, LANL

Radioassay of Eu5In2Sb6 at LANL

SLAC

- Motivation: trace radioactive impurities and radioactivity of the “stable” isotopes
- High-purity Ge detector (gamma/X-ray only)
- Simulations correct for geometry- and energy-dependent effects

Sb has 2 natural isotopes, Sb-121 (57%) and Sb-123 (43%):
69.12 counts per day – low activity
In has 2 natural isotopes, In-113 (4.3%) and In-115 (95.7%)”
129.6 counts per day – low activity

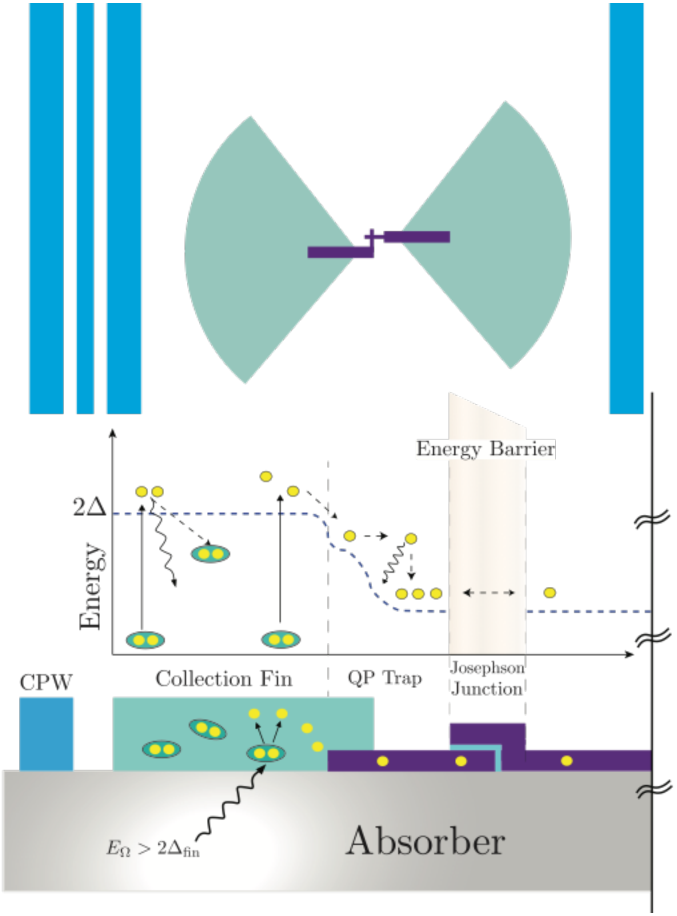


Slides from Caleb Fink, LANL

Qubit-Based Sensor R&D

Slide by Caleb Fink

- Enhance QP signal in transmon by using athermal phonon collection fins
- Collect athermal phonon energy into 'high-T_c' fins
  - Phonons break cooper pairs to SC quasiparticles
  - QP's diffuse until trapped by lower bandgap 'low-T_c' material
  - Trapped QP's tunnel across JJ in qubit until recombination
- Signal enhancement given by ratio of T_c's of two materials
- Couple each sensor to coplanar waveguide and readout in dispersive limit
- Combines two proven technologies – QP trapping and SC qubit readout



meV-Scale Resolution Development Paths

SLAC

Multiple ways to achieve eV-scale or single quantum resolution with carbon-based crystals (large optical phonon energies); these are already substrates used in QIS

Charge readout

- Contact-free cryogenic charge readout (SLAC, CNRS) - limited to 5 electrons, 1 pF
- Charge-sensitive qubits (SLAC, JPL) - in development, sub-electron demonstrated

Athermal Phonon Readout

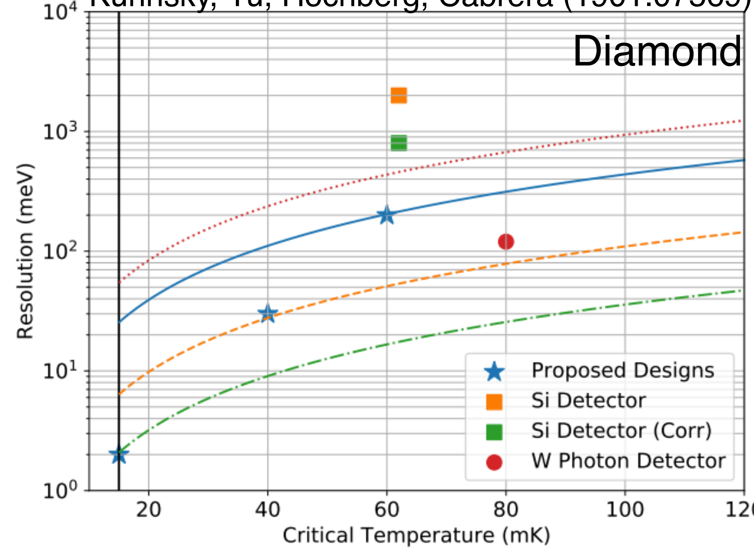
- TES (SuperCDMS + others) - 3 eV phonon, ~100 meV photon
- MKIDs (Caltech/FNAL/SLAC/LBL) - 20 eV phonon, ~100 meV photon
- Nanowires/QCDs - single THz photons (QCD), single IR photons (nanowires)
- Qubit-based readout - single tunneling events detectable, collection efficiency not characterized

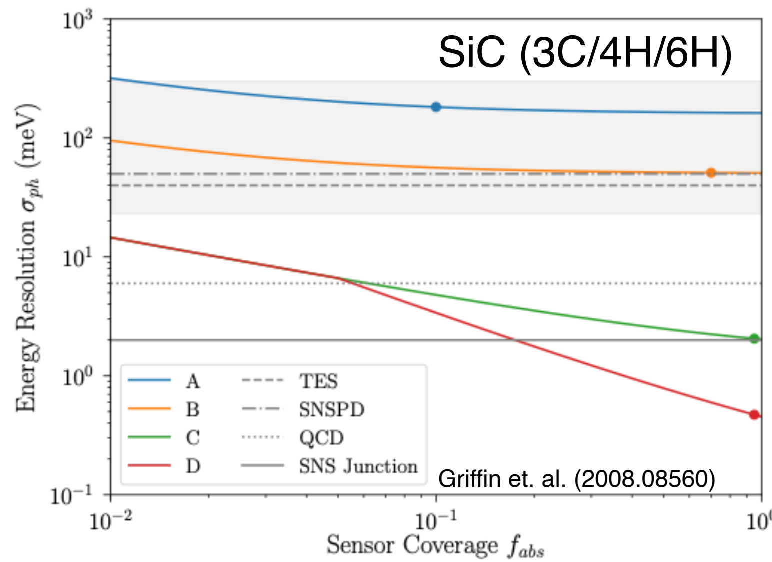
Thermal Phonon Readout

- TES thermometry— CRESST/MPI
- Ricochet-style readout - MIT/NW/others

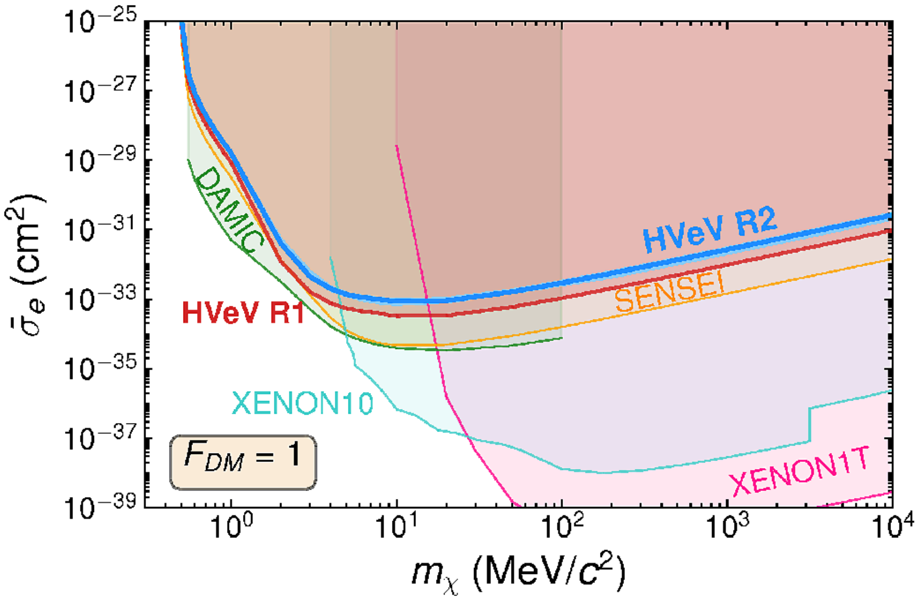
Qubits as drop-in replacements for existing sensors are way ahead!

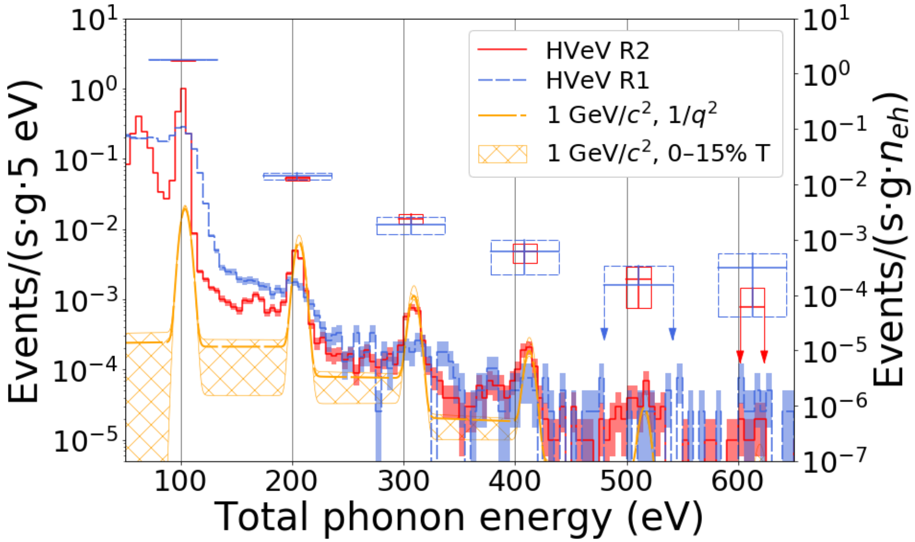
Kurinsky, Yu, Hochberg, Cabrera (1901.07569)





HVeV Run 2



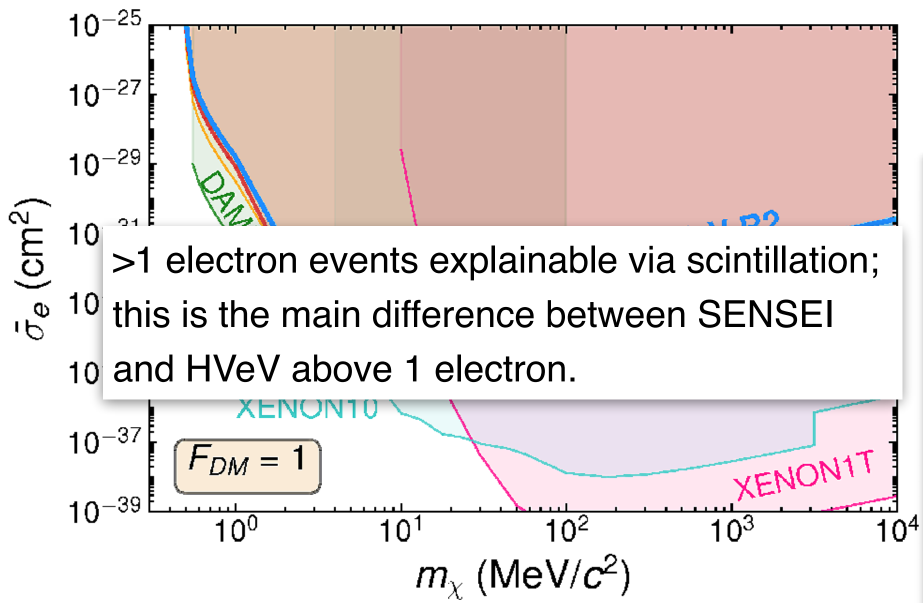


HVeV second run taken with 3 eV resolution detector over the course of 3 weeks:

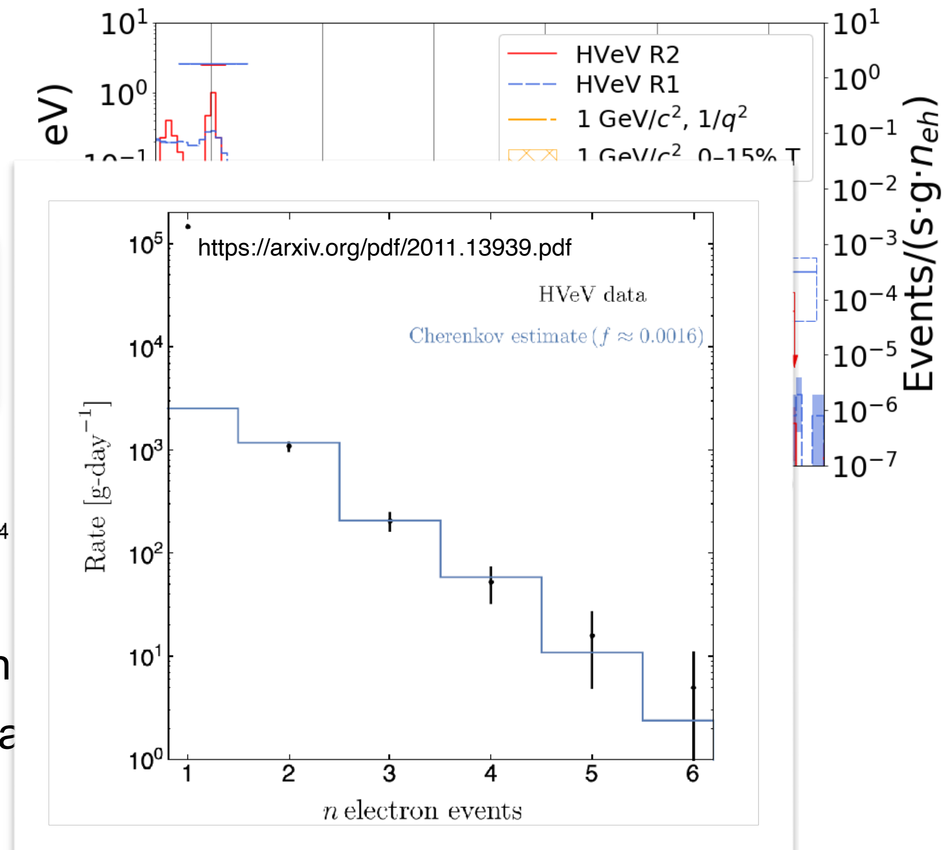
- 60V and 100V spectra show identical backgrounds; signal seen not voltage dependent
- Different prototype, run in a different lab, in a different state
- 0V data acquired with ~10 eV threshold, results still being analyzed
- Rates in *every charge bin* consistent with Run 1…that was completely unexpected

HVeV Run 2

SLAC



>1 electron events explainable via scintillation; this is the main difference between SENSEI and HVeV above 1 electron.



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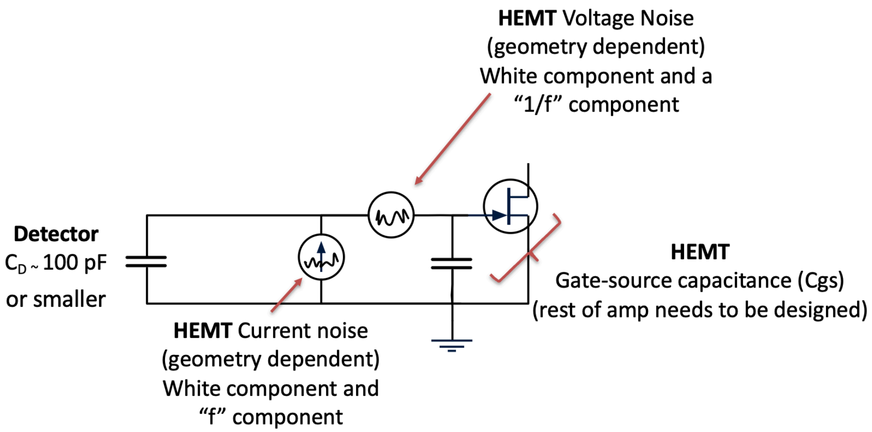
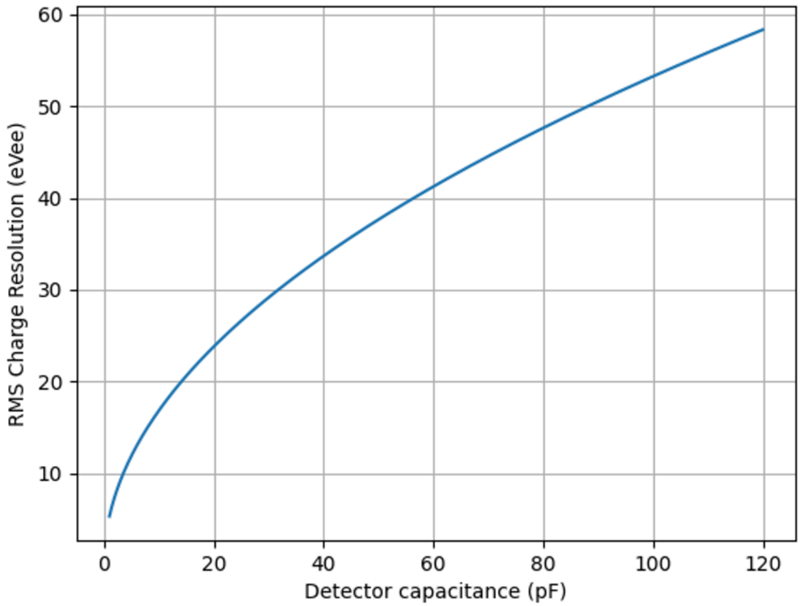
Cryogenic HEMT Charge Amplifier

- Low-gap materials need to operate below 4K to become insulating
  - Need cryogenic charge amplifiers!
- We can improve on SuperCDMS cryogenic charge amplifiers by moving to smaller detector capacitance
  - This pretty much requires moving to low capacitance - we're limited by the voltage noise on the HEMTs, which are process-determined
- We're developing a source-follower scheme which will allow the first-stage amplifier to operate down to 10 mK with the second-stage at 4K, where most of the power will be dissipated



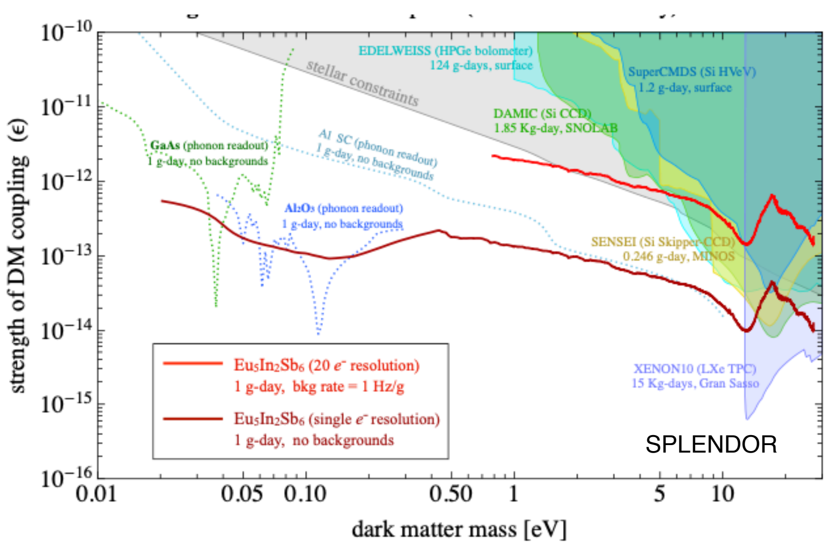


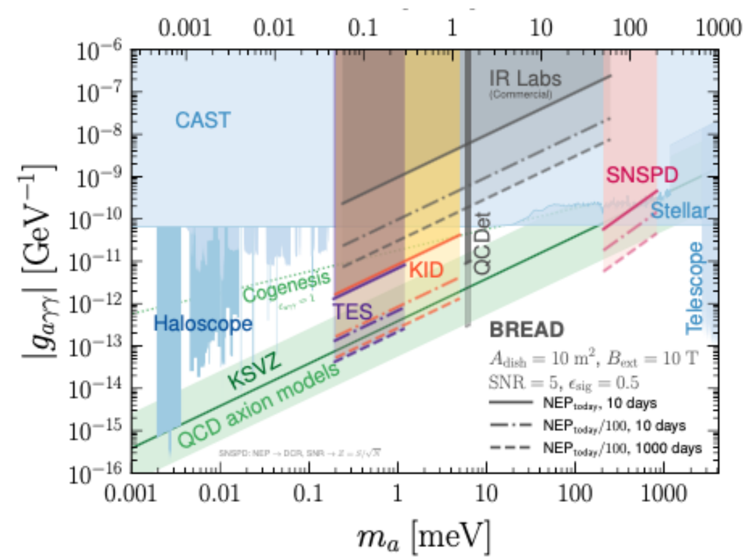
Motivation: Quantum Sensing for Dark Matter Searches

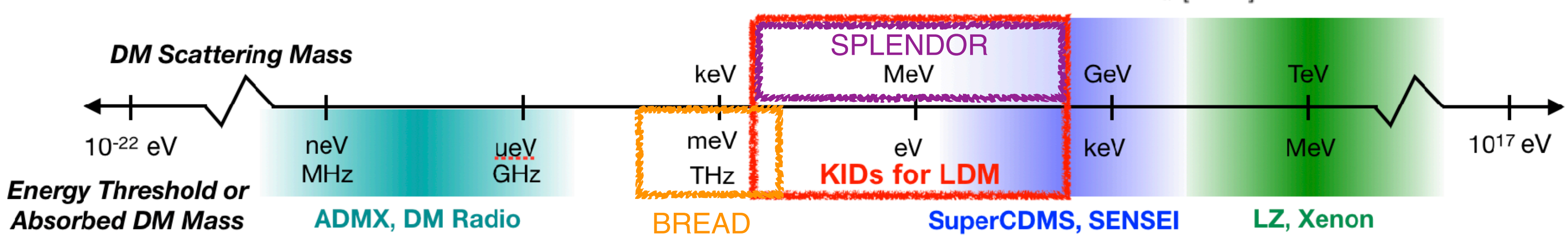
SLAC

Utilize superconducting sensors to search for dark matter in the meV-MeV regime, currently not probed by existing experiments

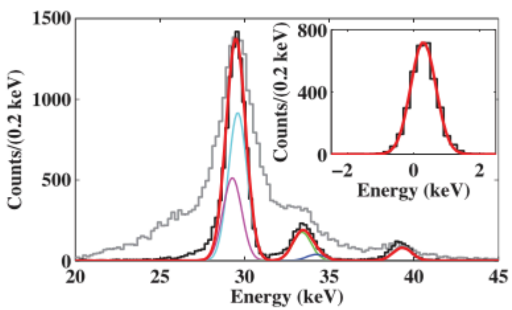
- Sensors derived from qubit co-design work; heavy overlap with QIS - *new DOE ECA*
- KIDs for phonon sensing (SuperCDMS)
- meV-gap materials with single charge readout (SPLENDOR)
- Single THz and IR photon sensors for wide-band axion searches (BREAD)

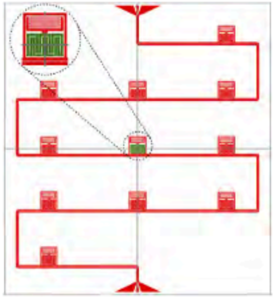


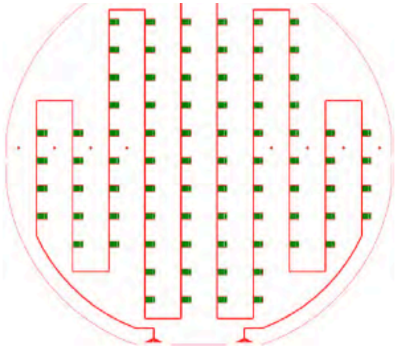




KID Performance To Date (S. Golwala)







Proof of principle: Moore+ APL 2012,
σ_E = 380 eV baseline w/20 KIDs
on 22 mm (small architecture) substrate

Small architecture, Al + Nb cap

σ_E^{KID} = 6 eV (Nb TLS-limited) on energy received in KID,
$\sigma_E^{sub} = (6\text{ eV})/\eta_{ph} \approx 20$ eV on energy deposited in substrate for $\eta_{ph} \approx 0.3$

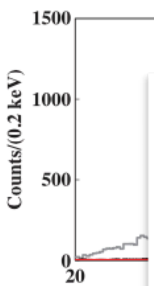
High-Δ, low TLS cap layer ($NbTiN_x$) → σ_E^{KID} = 1.5 eV, σ_E^{sub} = 5 eV

Large architecture, Al only

σ_E^{KID} = 5.3 eV for KID w/optimal Q_c and w/fixable EMI (60 Hz),
$\sigma_E^{sub} = (5.3\text{ eV})\sqrt{320}/\eta_{ph} \approx 300$ eV for 320 KIDs (4% surface coverage)

EMI removed, Q_c solved ⟶ $\sigma_E^{sub} \approx (1.3\text{ eV})\sqrt{320}/\eta_{ph} \approx 80$ eV

KID Performance To Date (S. Golwala)



stage	phonon energy rms small	phonon energy rms large
current (estimated, to be checked with fiber optic data)	20 eV	300 eV
immediate fixes (Q_c, TLS, EMI)	1-7 eV	80 eV
increase τ_{qp} to 1 ms via better BB shielding (free-space and in coaxes)	0.3-2 eV	25 eV
quantum-limited amplifier	50-350 meV	4 eV
T_c = 0.1 K	5-35 meV	400 meV
QIS-based amplifier (guess) (squeezing or qubit QND)	0.5-7 meV	80 meV

NR/ER discr. down to ~0.5 GeV! (increase τ_{qp} to 1 ms; quantum-limited amplifier)

NR/ER discr. down to 1 eh pair (E_R ~ 10 eV) (T_c = 0.1 K; QIS-based amplifier)

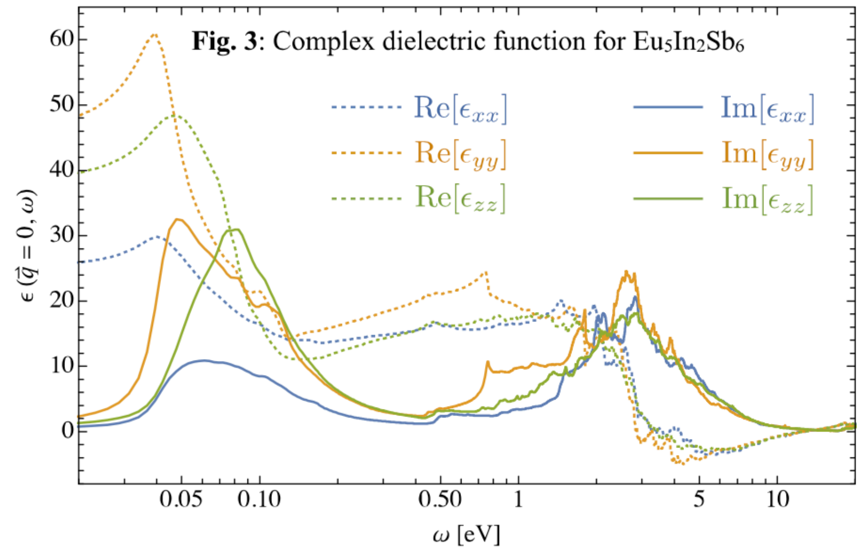
0.1 GeV reach for NRs w/o discr. (0.3-2 eV)

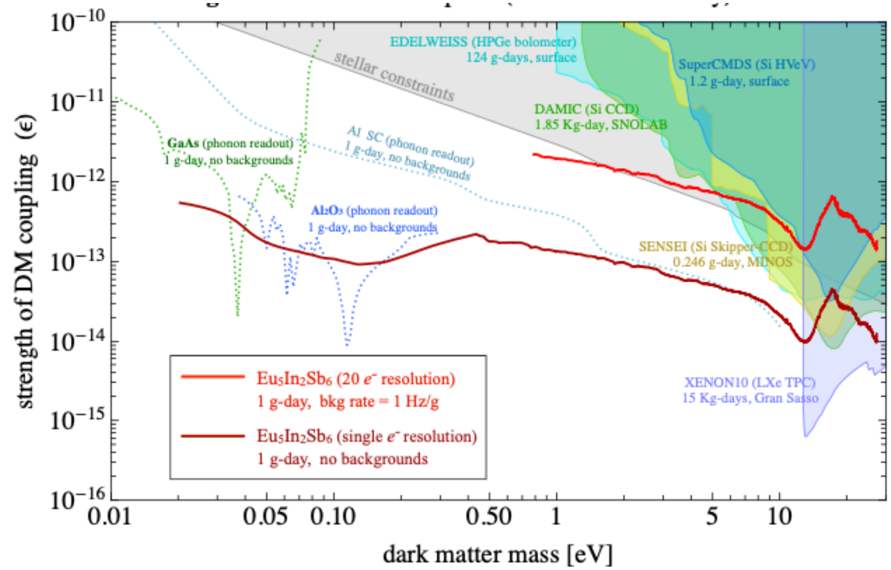
0.03 GeV reach for NRs w/o discr. (50-350 meV)

EMI removed, Q_c solved $\longrightarrow \sigma_E^{sub} \approx (1.3\ \text{eV})\sqrt{320/\eta_{ph}} \approx 80$ eV

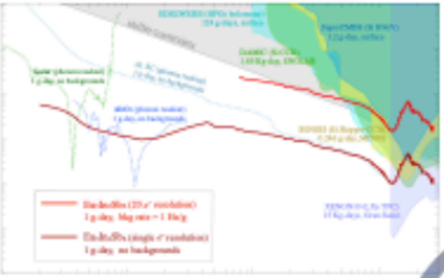
Designer Materials for Light DM (SPLENDOR)

- 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
- g-day exposures can yield impressive science reach
- Single electron sensitivity is needed for greatest sensitivity



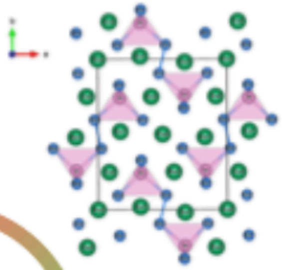


SPLENDOR: DM Detection w/ Quantum Materials



Materials Synthesis

High-quality single crystals with low noise response



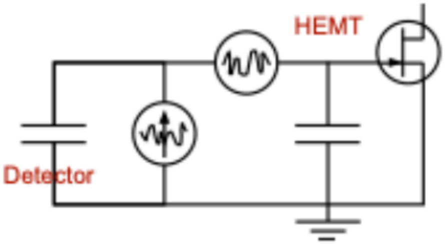
Theory

Dark matter scattering and absorption rates, daily modulation of signal, many-body methods

Dark Matter Detection With Quantum Materials

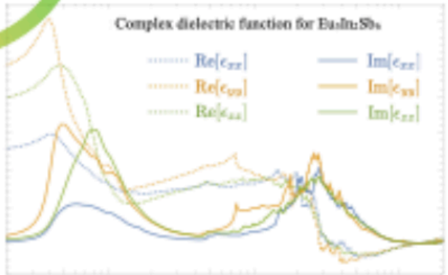
Characterization

M-EELS (dielectric loss function) ARPES (band structure), charge transport



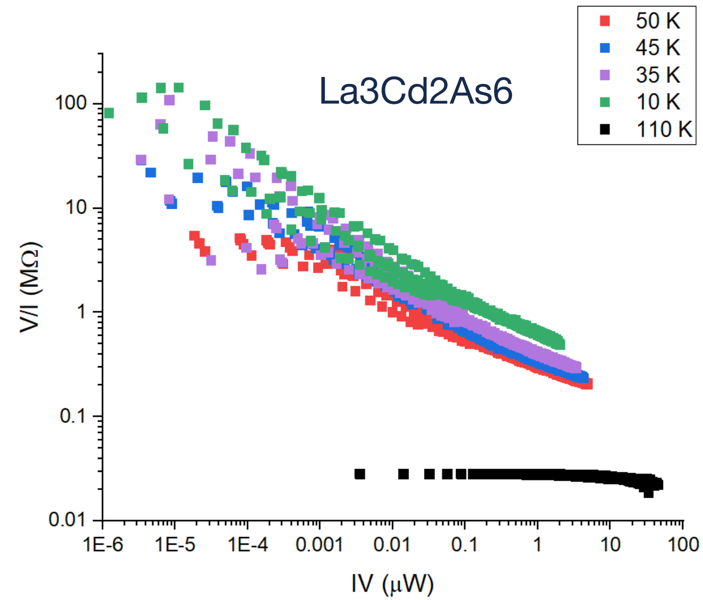
Detection

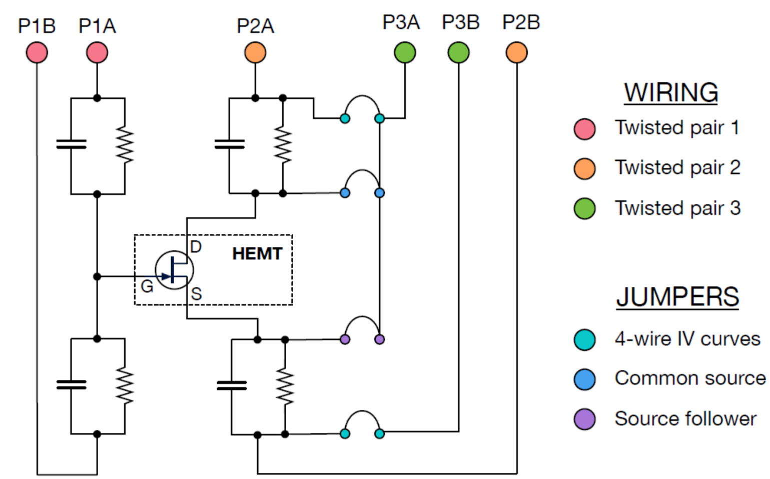
cryogenic charge amplifiers, single e^- resolution



SPLENDOR Detector R&D

- First low-gap samples being tested in dewar at LANL -
  - clear evidence of increased resistance with lower temperature
  - Source-measure unit not sensitive enough for testing below 10K; porting to DR
- HEMTs purchased for first amplifier prototype and testing beginning at CSU East Bay (Arran Phipps)
  - Stanford undergrads helping with HEMT characterization
- Expecting rapid progress over the summer and first charge measurements to be conducted on Si and diamond for comparison to known charge transport performance
  - Low barrier to converting that readout to low-gap materials
  - Challenge is in developing a low-capacitance coupling scheme, likely based on point-contact readout





Qubits as Sensors

Article | Published: 16 June 2021

Correlated charge noise and relaxation errors in superconducting qubits

C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Stanford, L. Cardani, G. D'Imperio, C. Tomei, L. Faoro, L. B. Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen, J. L. DuBois & R. McDermott

Nature **594**, 369–373 (2021) | Cite this article

- Qubits, built on the 'cooper pair box' paradigm, are already intrinsically sensitive to energy differences of Delta (half the cooper pair binding energy)
- Studies of qubit chips have shown sensitivity to single charges in the substrate and to pair breaking from phonons (see Nature paper)
- The 'readout' part of the qubit is a solved problem; the remaining challenges are efficient collection of energy quanta and reduction of environmental noise
    - Both problems are important for achieving a scalable quantum computer!