Detecting Sub-GeV Dark Matter with Quantum Sensors

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LRT 2022
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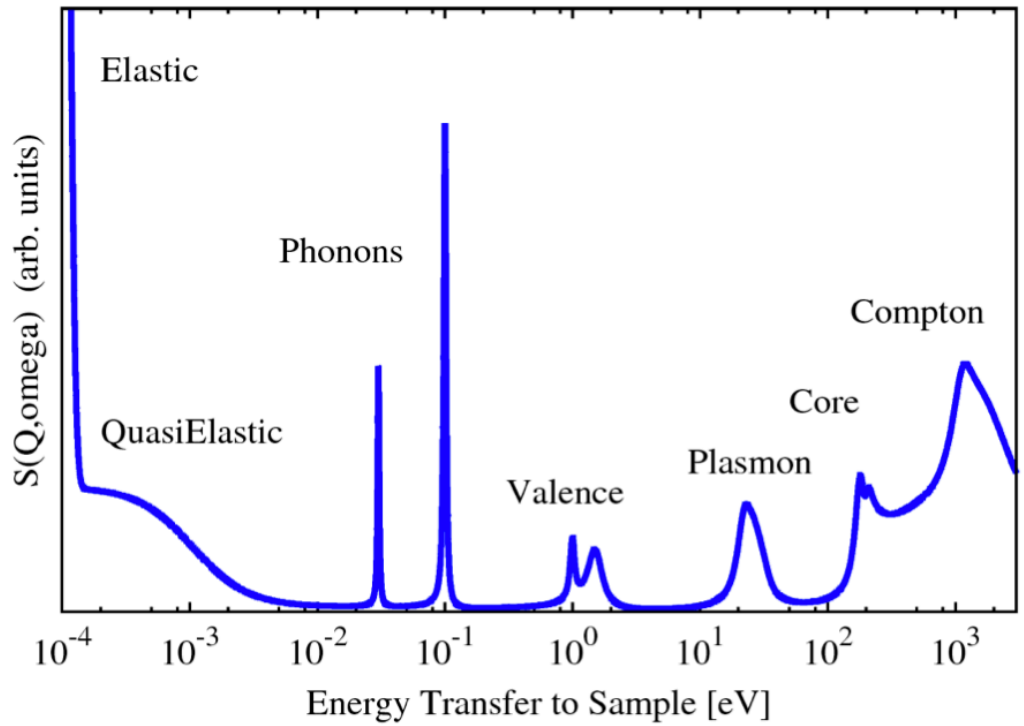
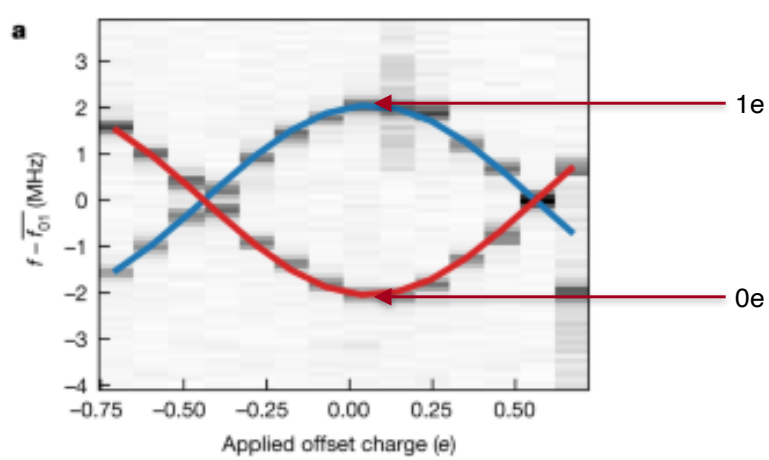
BOLD PEOPLE. VISIONARY SCIENCE. REAL IMPACT.

Outline

- Next-generation DM search prospects
- Progress at eV scales
  - TES readout
  - High phonon efficiency
  - Novel backgrounds
- Progress at meV Scales
  - Roadmap
  - Qubit-based charge readout
  - KID phonon readout
  - Quantum materials
- Conclusions/Path Forward

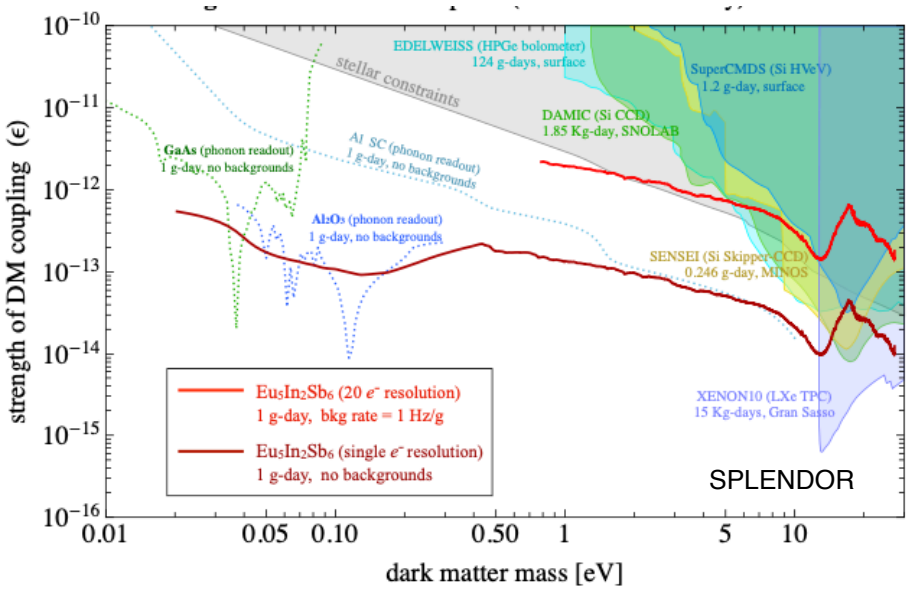


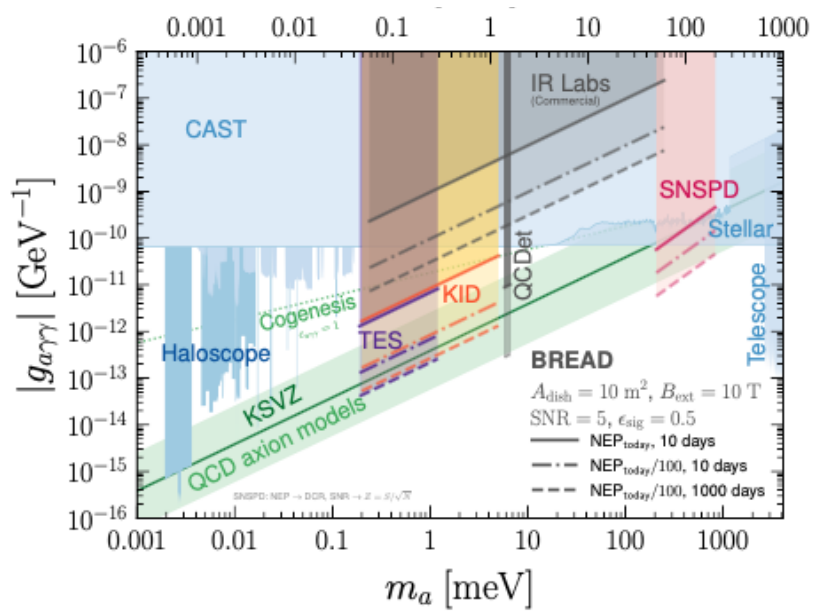


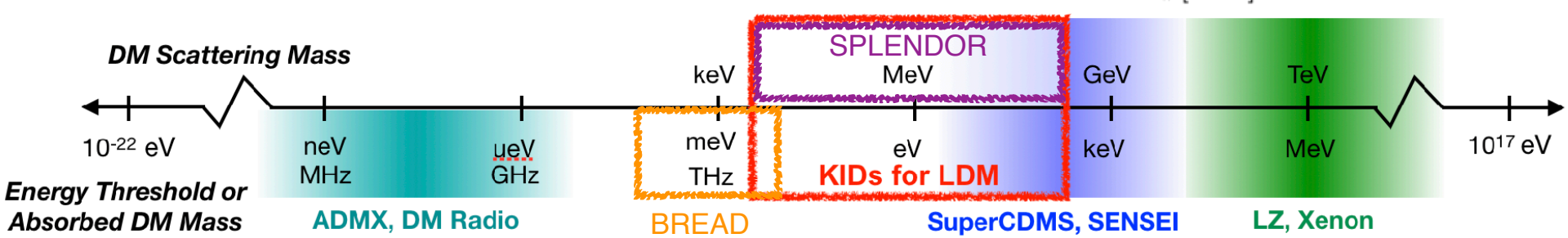
Motivation: Quantum Sensing for Dark Matter Searches

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

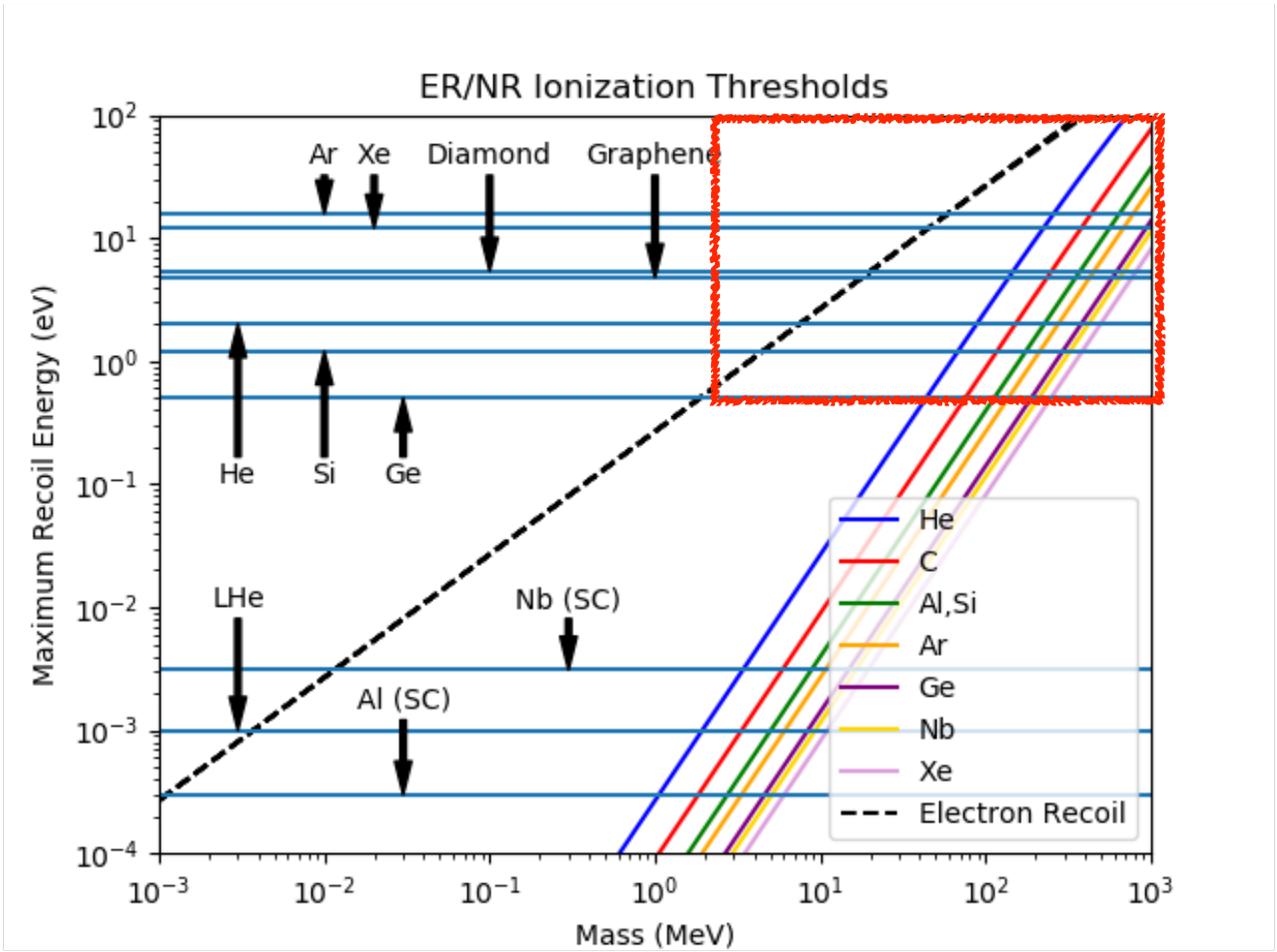
- Sensors derived from qubit co-design work; heavy overlap with QIS - *new DOE ECA*
- KIDs for phonon sensing (SuperCDMS)
- meV-gap materials with single charge readout (SPLENDOR)
- Single THz and IR photon sensors for wide-band axion searches (BREAD)



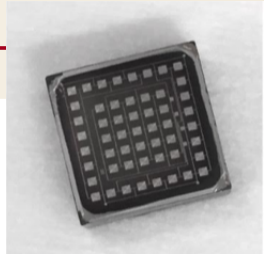




Searching for MeV-Scale DM: eV-Scale Thresholds



Athermal Phonon Sensors (SuperCDMS HVeV)



In any recoil event, all energy eventually returns to the phonon system

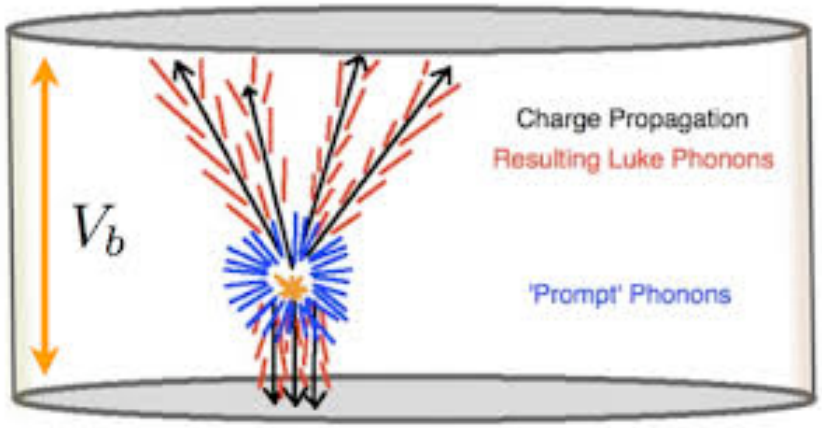
- Prompt phonons produced by interaction with nuclei
- Indirect-gap phonons produced by charge carriers reaching band minima
- Recombination phonons produced when charge carriers drop back below the band-gap

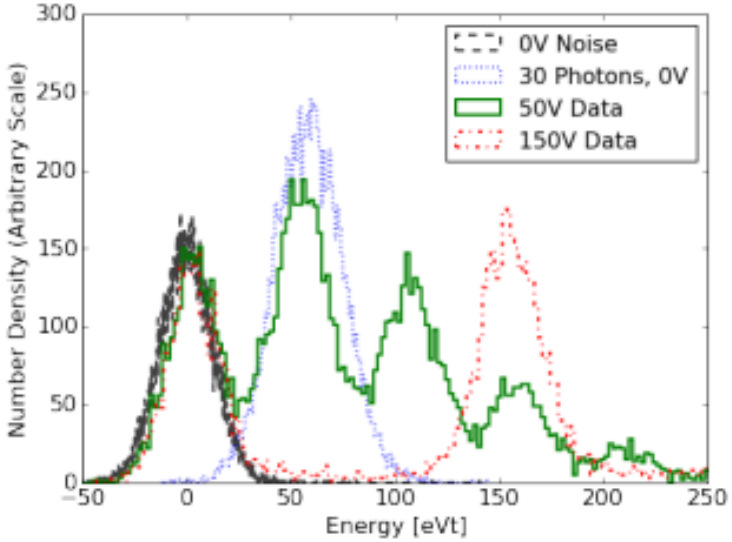
Phonons are also produced when charges are drifted in an electric field; makes sense by energy conservation alone

Total phonon energy is initial recoil energy plus Luke phonon energy, as shown at right

$$E_{phonon} = E_{recoil} + V * n_{eh}$$
$$= E_{recoil}\left[1 + V * \left(\frac{y(E_{recoil})}{\varepsilon_{eh}}\right)\right]$$

Athermal phonons collected in superconducting aluminum fins and channeled into Tungsten TES, effectively decoupling crystal heat capacity from calorimeter (TES) heat capacity





Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Optimal Readout and Triggering

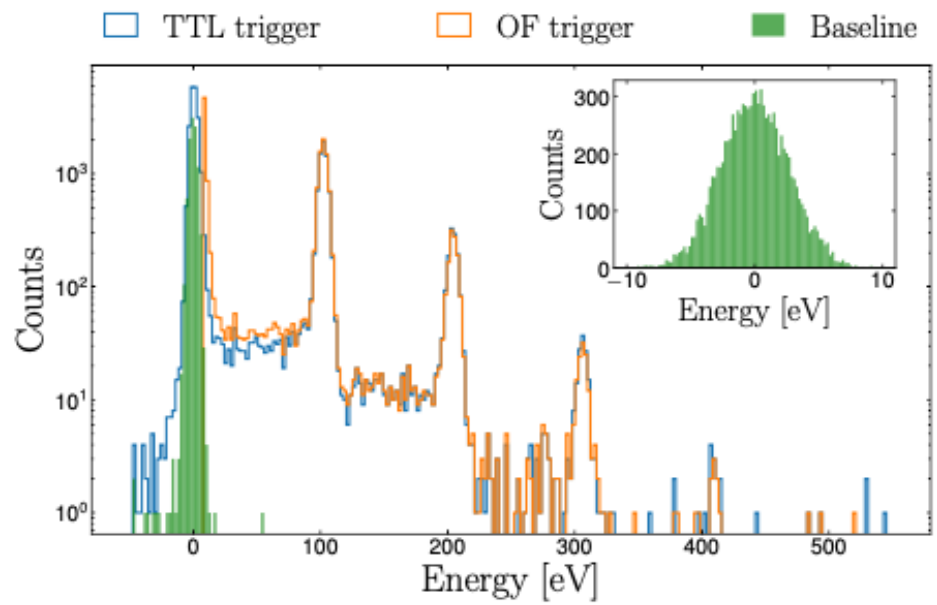
Best performance is by HVeV (gram-scale Si) detector; has repeatedly achieved 2.5 eV resolution, and <10 eV threshold, with the TES-based SuperCDMS sensors.

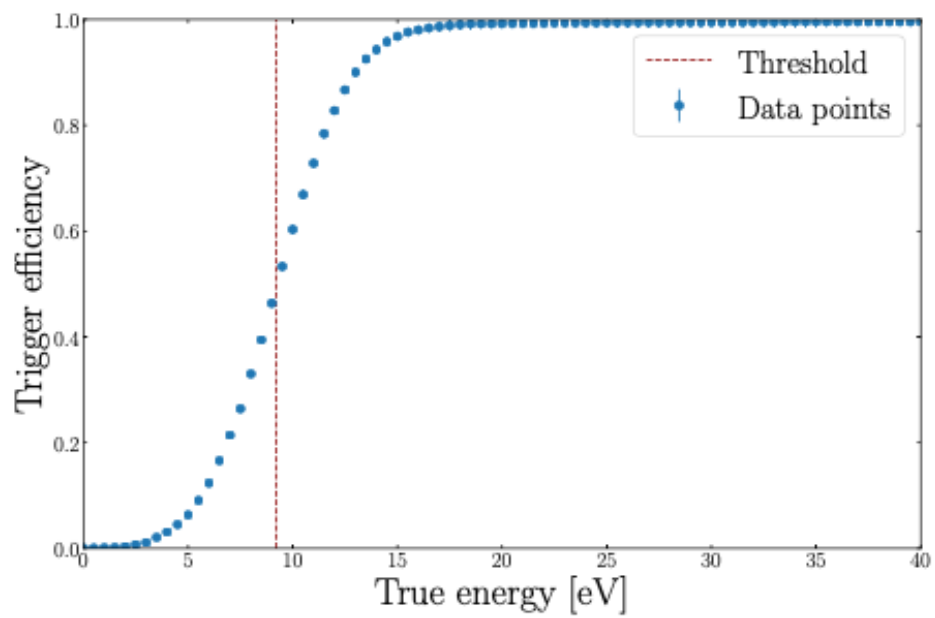
- This detector was run as a DM detector at Northwestern and NEXUS, and in the TUNL neutron beam

Run in continuous readout mode for trigger-free operation, triggering done offline

- Optimal filter trigger and processing with time-shifting and pileup rejection

Achieves >30% energy efficiency, implying that the intrinsic resolution of the TES arrays are less than 1eV



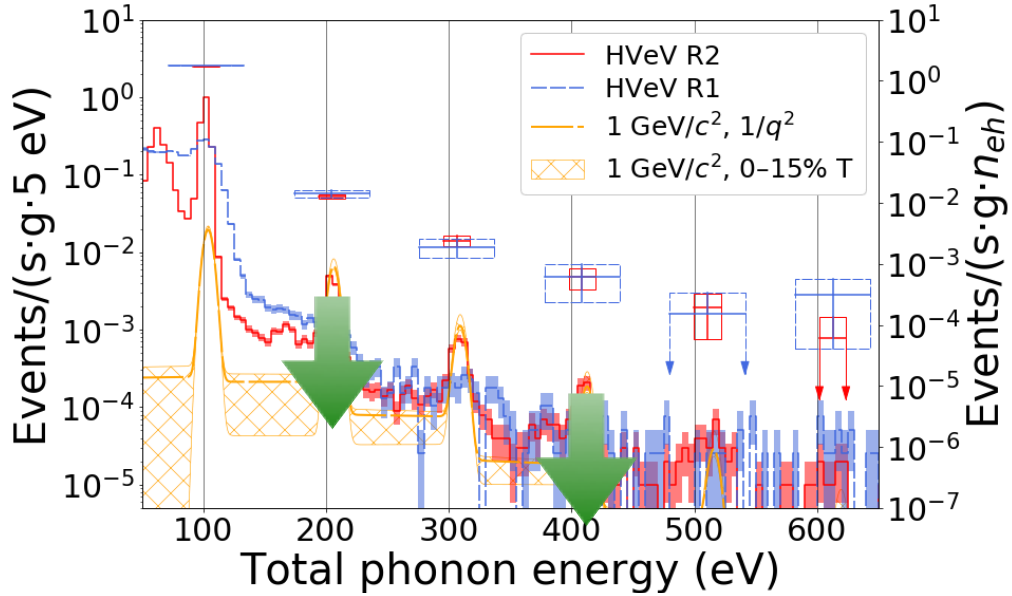


Ren et al (ArXiv:2012.12430)

HVeV Run 3 Status

Science run finished mid-2021 with 3 detectors (including detectors used for Runs 1-2, and a third new design)

- Using coincidence in time to reject bursts of Cherenkov photons
- Building model of leakage pileup to project component of single charge leakage in second electron-hole pair bin
- Still expect single-electron bin is instrumental

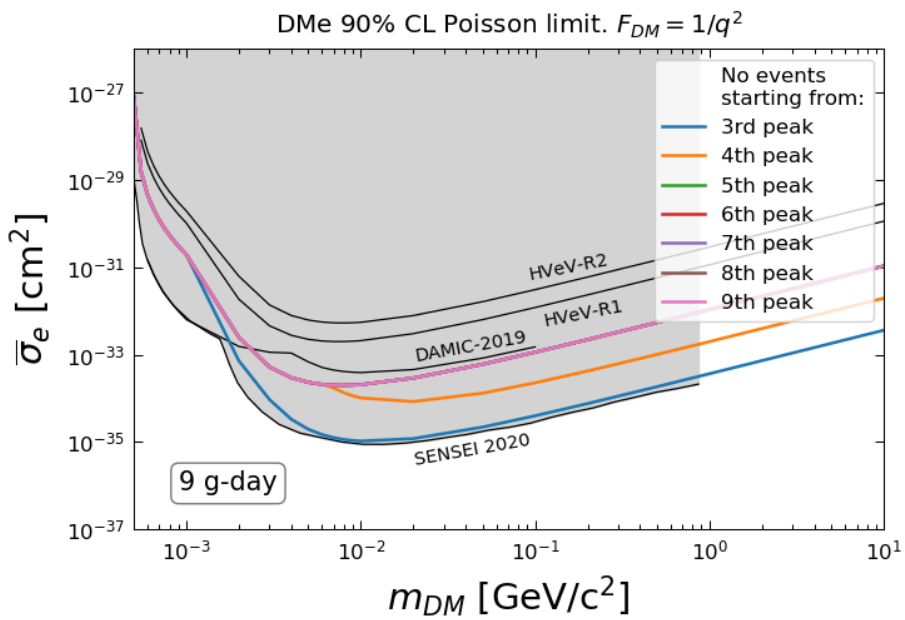


Run started 12/23, officially ended 2/9

- Accumulated ~1 g-days per calendar day
- ~40 g-days of exposure total

Quick turn around expected on analysis, new results by Early 2022

- *Many* auxiliary science results to follow on 0V-HV correlations



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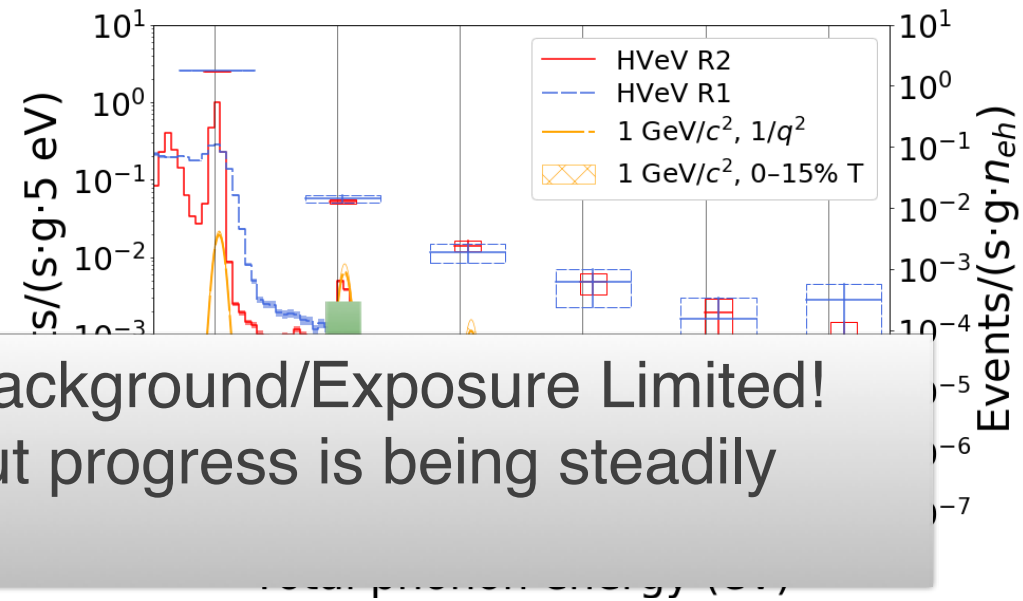

ERDM Above ~2 MeV Now Background/Exposure Limited!
Leakage R&D is important, but progress is being steadily made

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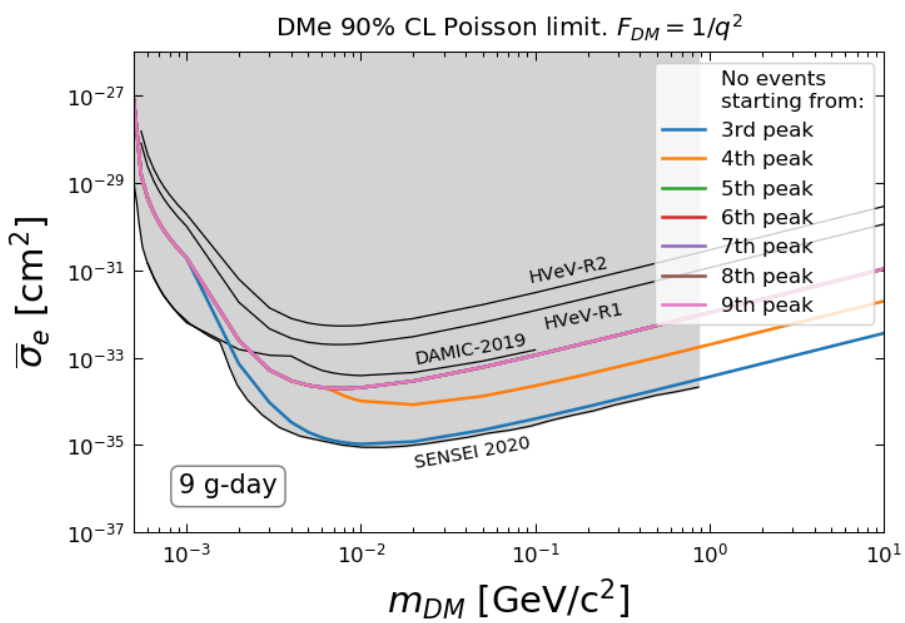
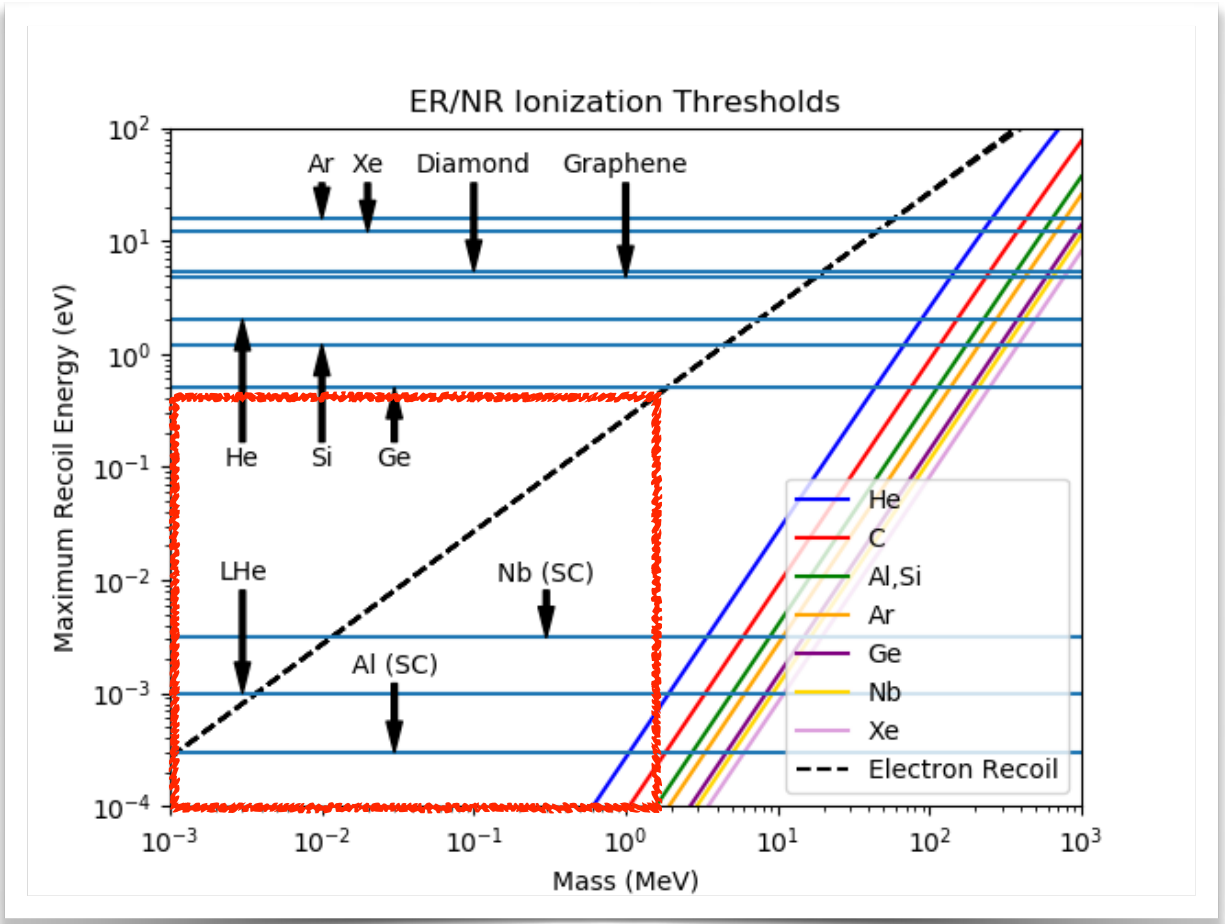
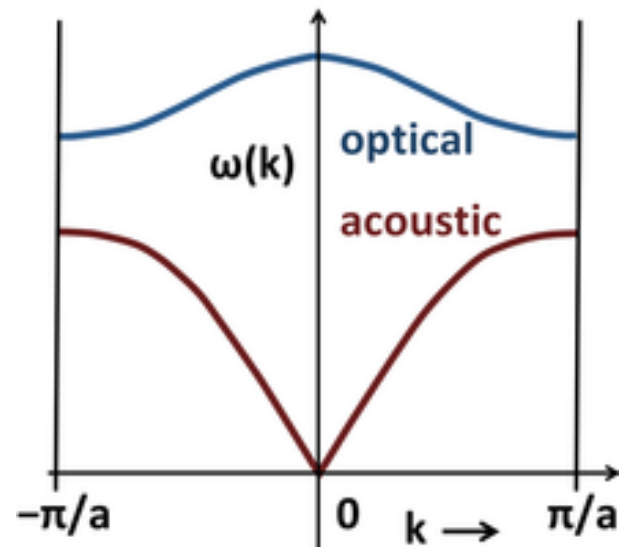


Quantum Sensing R&D For Dark Matter: meV Thresholds

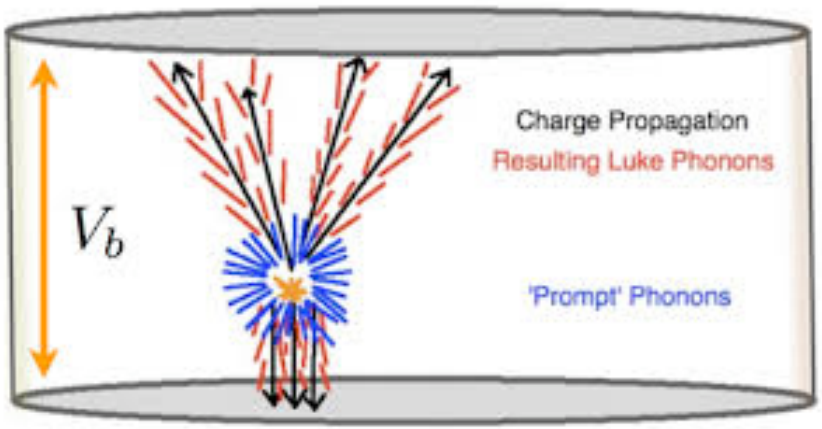




+ Phonons

Multiple Paths to meV-Scale Energy Sensitivity

Interaction Produces Charge and Phonons in Solid State Target



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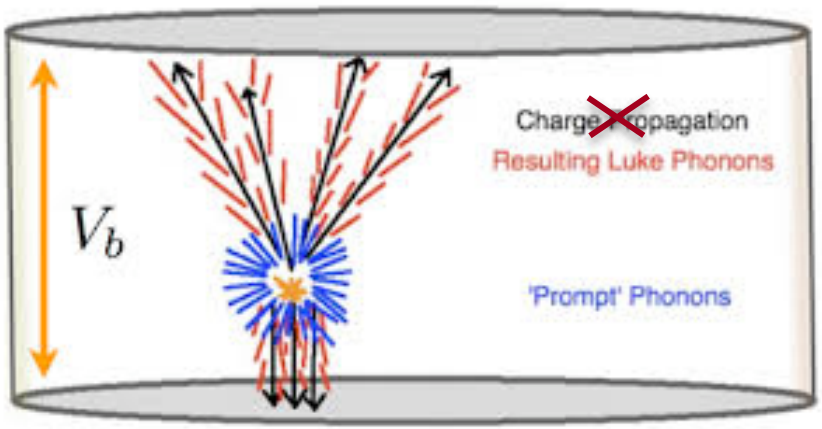

Ren et al, Phys. Rev. D 104, 032010 (2021)

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Phonons Captured in Small
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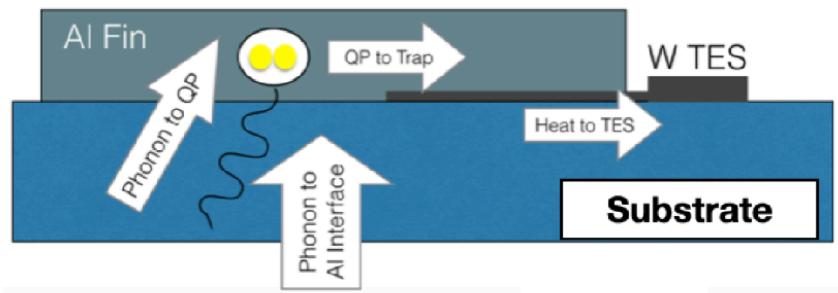

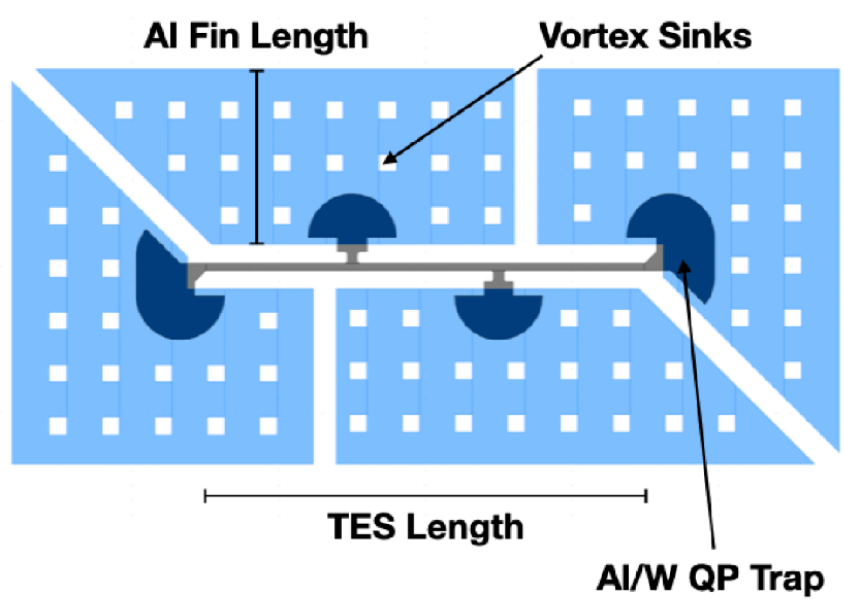

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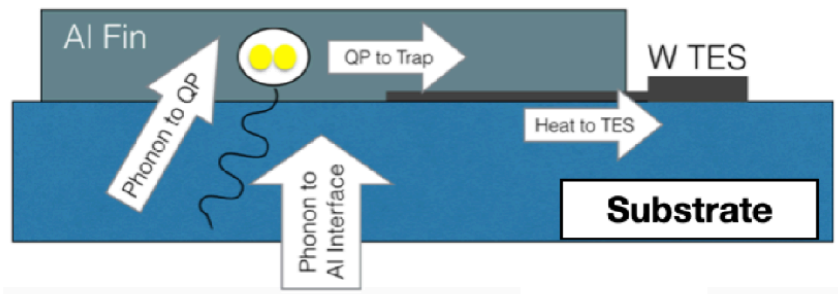

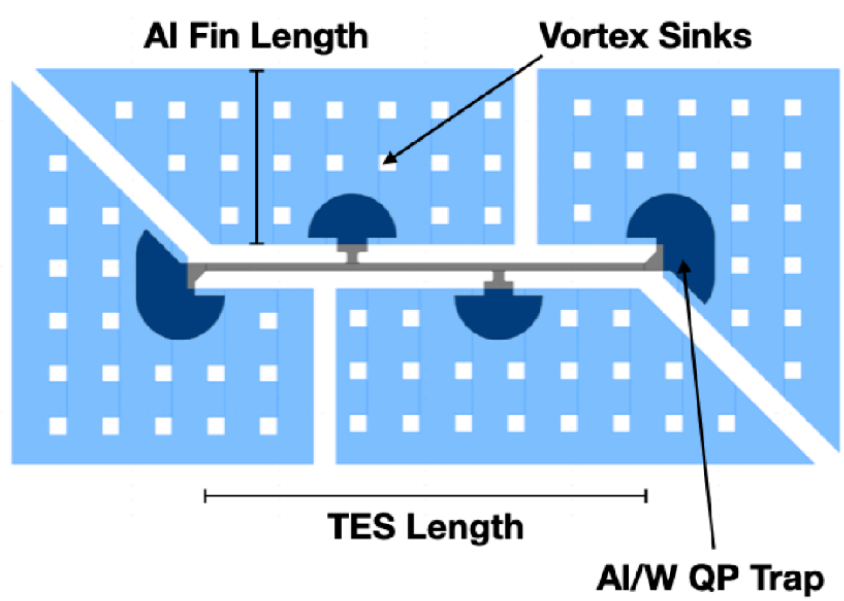

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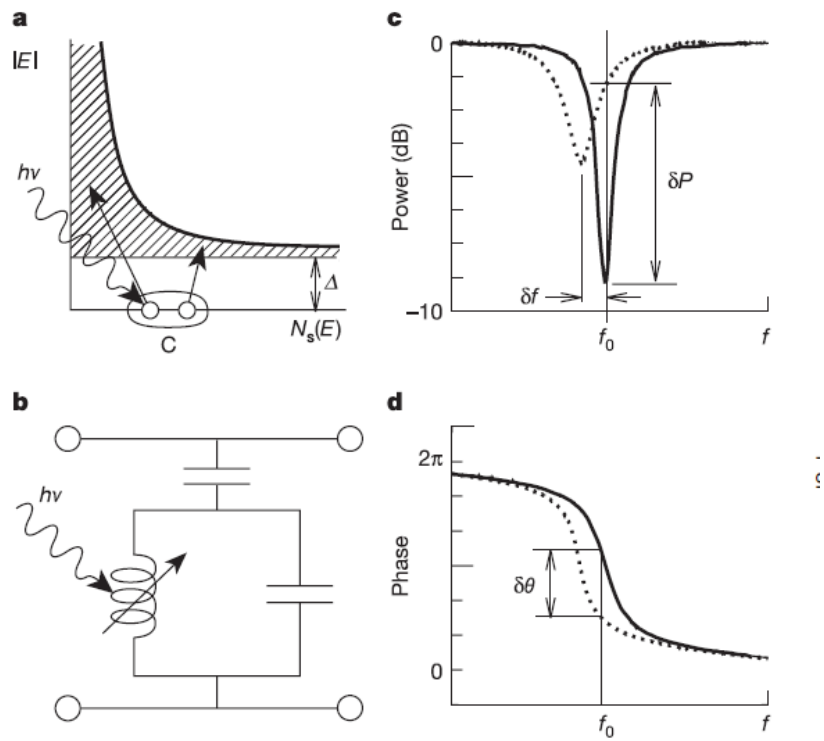

Sensor tracks
quasiparticle density
MKID, TES

Sensor tracks
quasiparticle tunneling rate
QCD, Transmon Qubit

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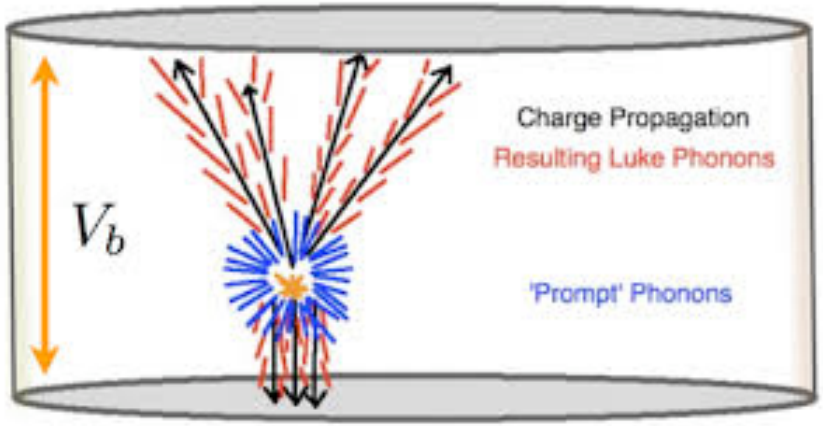
Charge and Phonons Share Energy, Easily Collected



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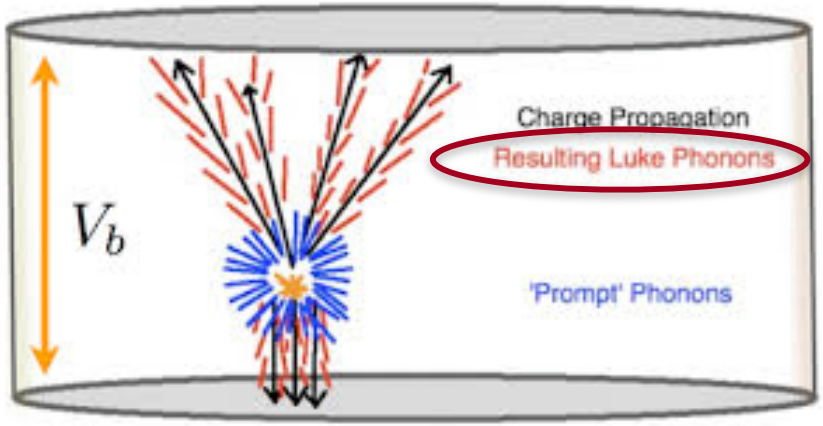

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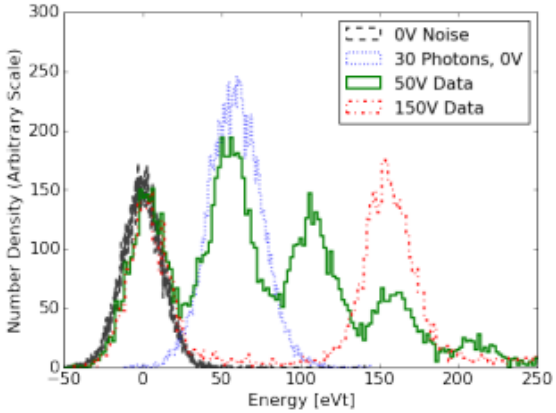
Charge drift produces more phonons



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Charge drifted to concentrated
region of crystal or charge gate

Phonons
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Phonons
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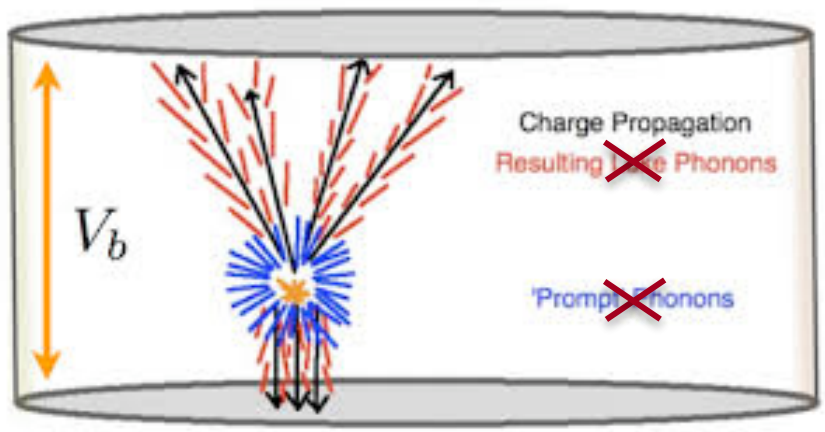

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Wilen et. al, Nature 594, 369-373

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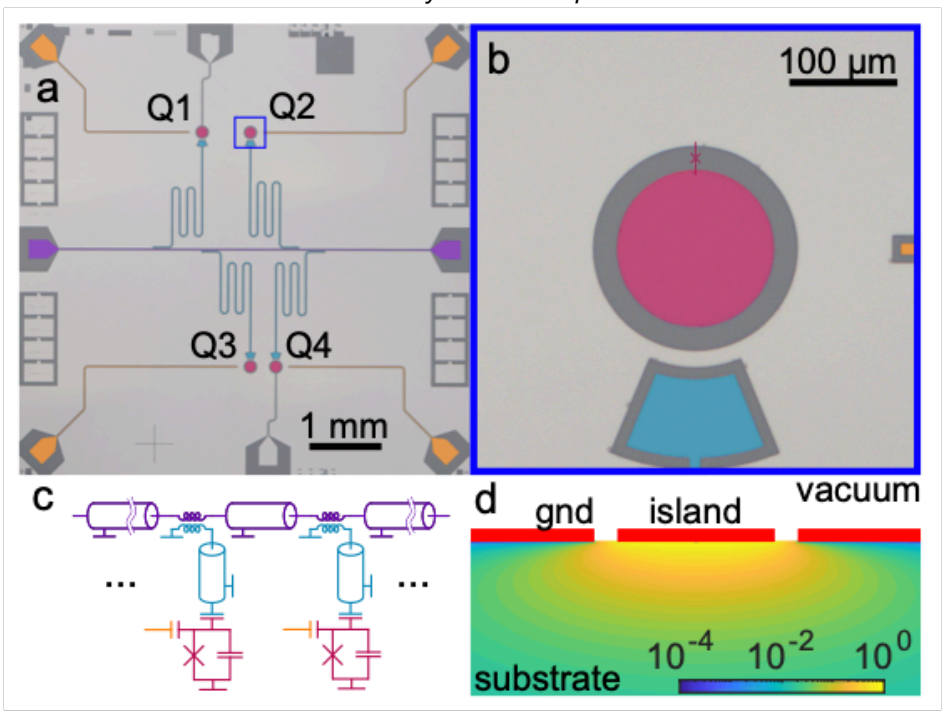
See talk by Giulia D'Imperio



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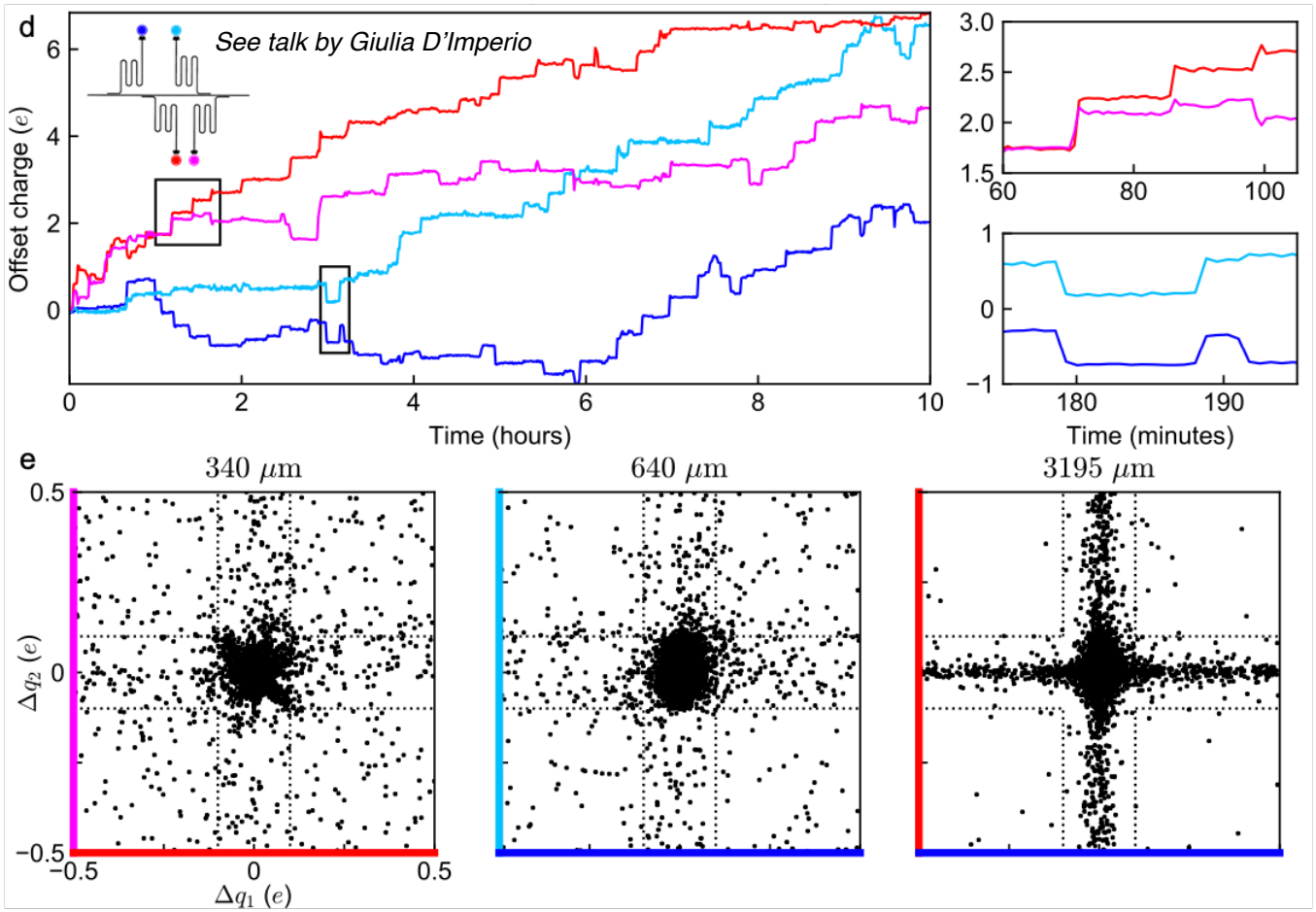

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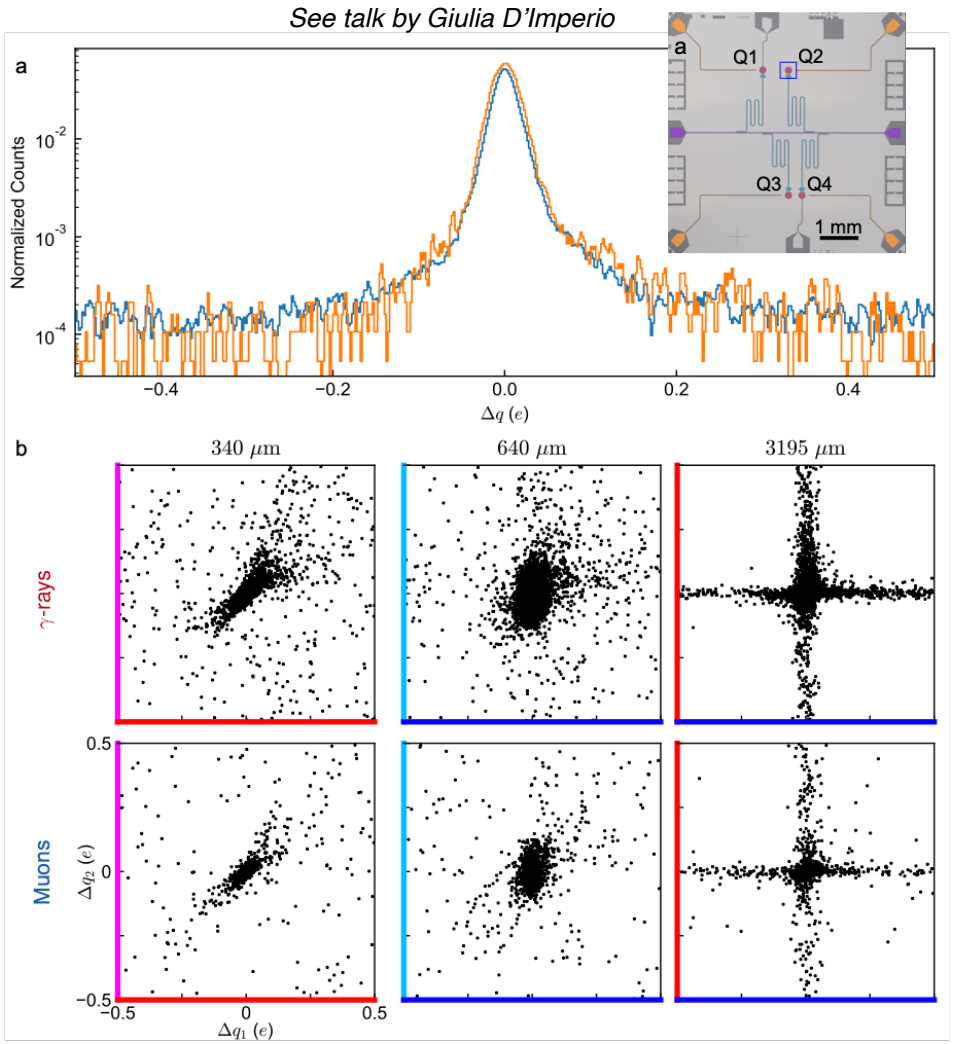

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Sensor tracks integrated image charge
HEMT, CPB (Charge Qubit)

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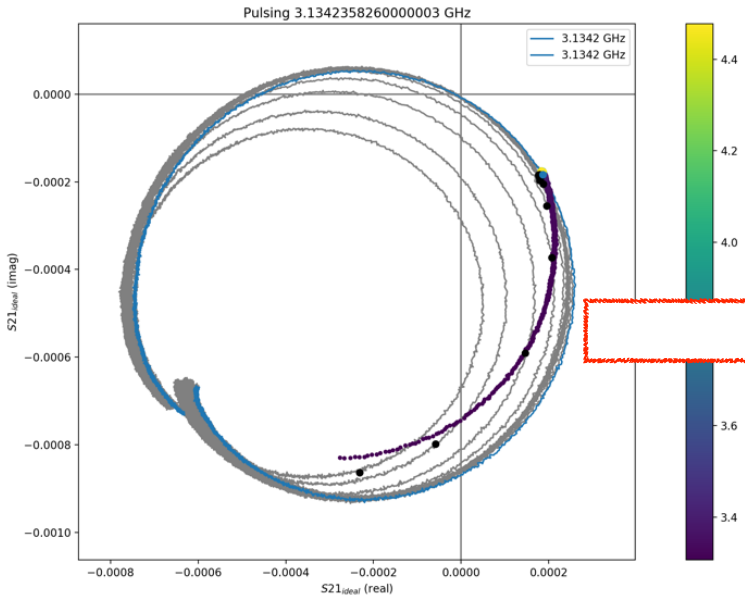

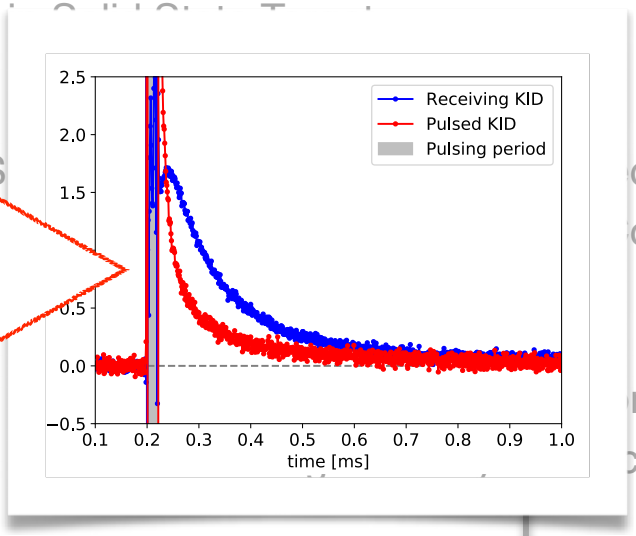

Phonons increase quasiparticle

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

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Echternach et al ,Nature Astronomy Vol. 2, pages 90–97 (2018)

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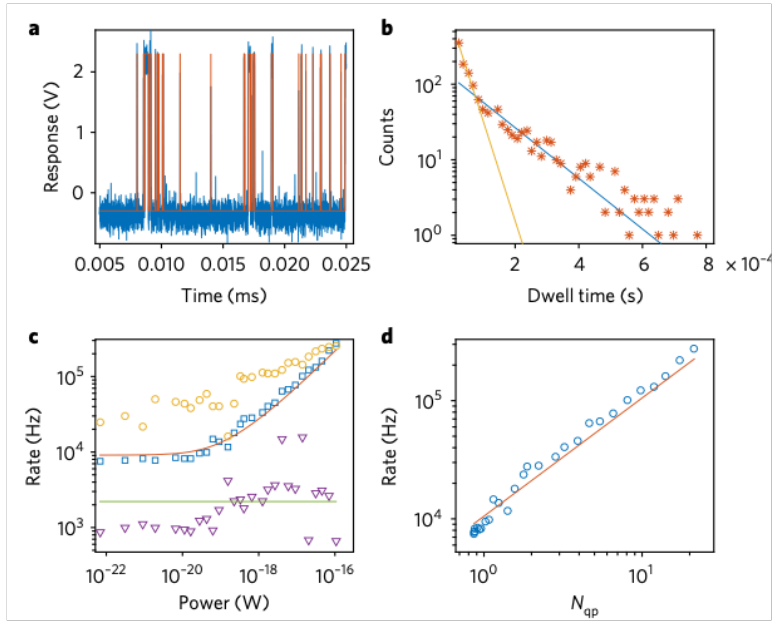

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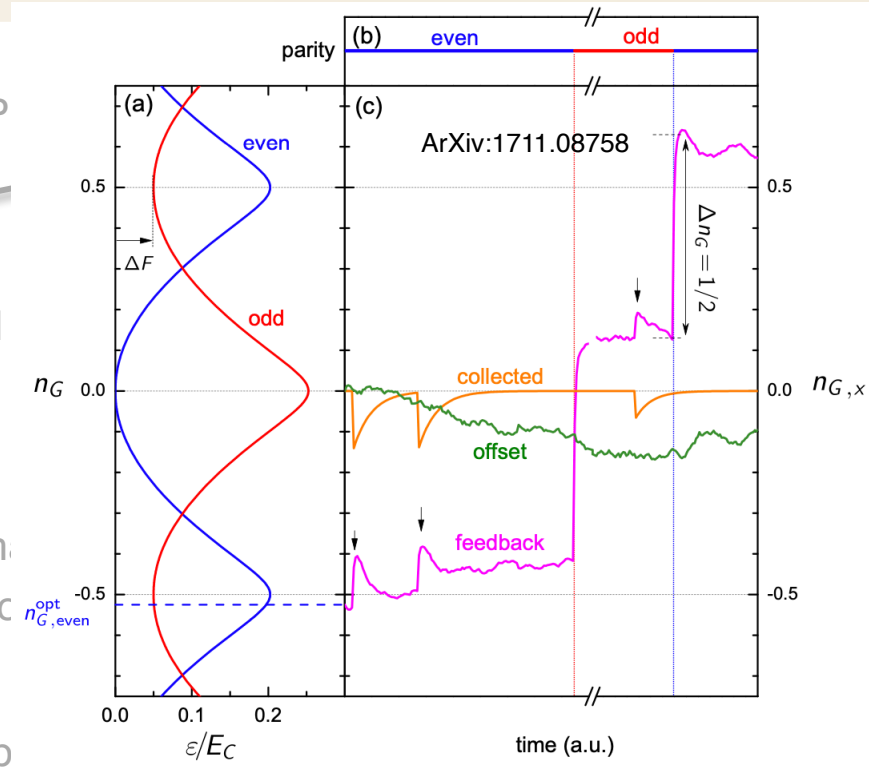

$$\sigma_E = \sigma_q E_{gap}$$
$$\approx (C_{det} + C_g)\sigma_V E_{gap}$$

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ArXiv:1711.03758

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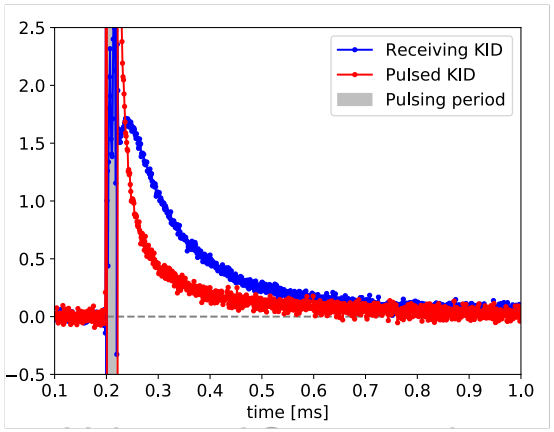

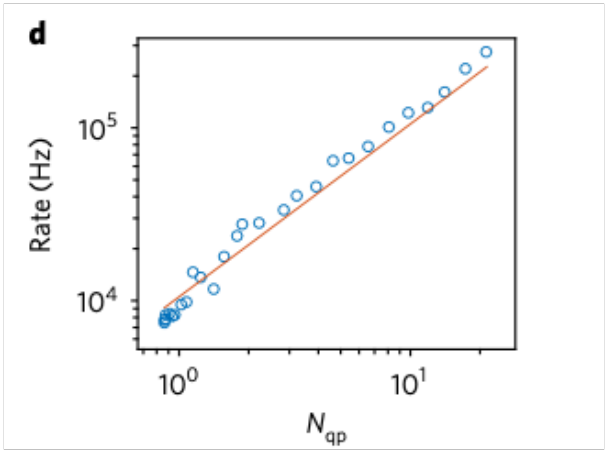

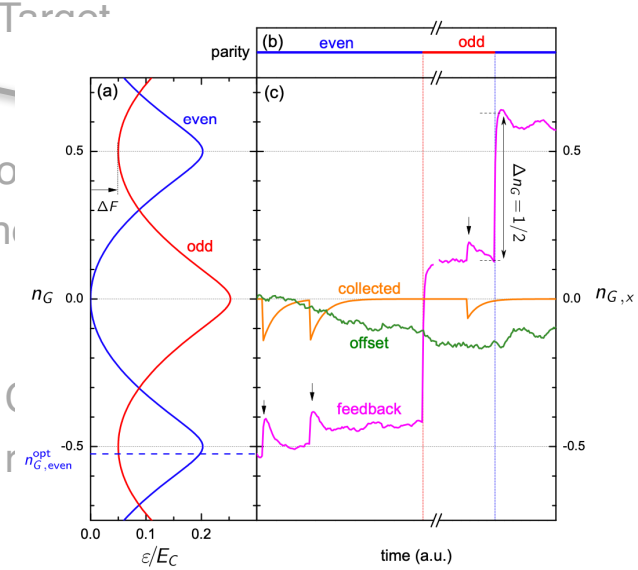

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meV-Scale Resolution Development Paths

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

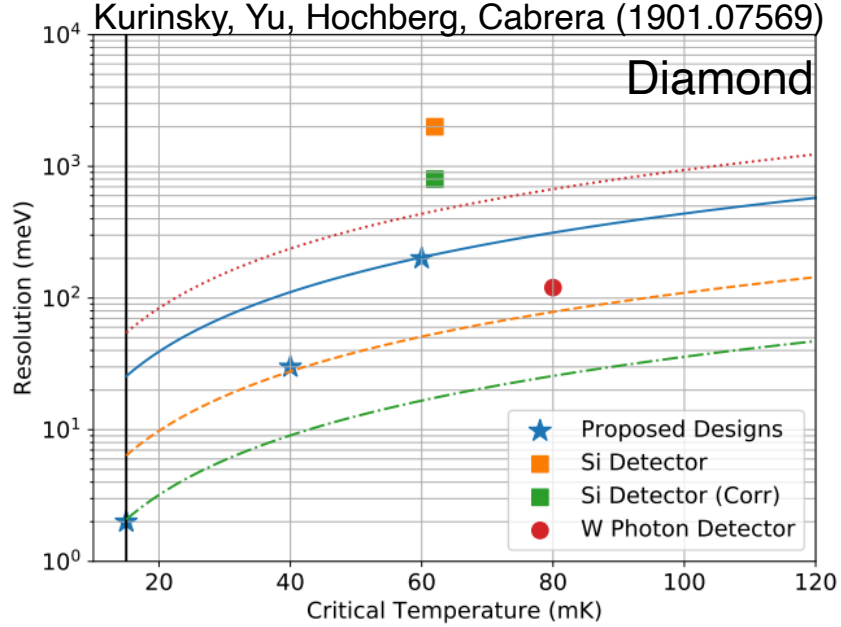
- TES (SuperCDMS + others) - 3 eV phonon, ~100 meV photon (*see talk by R. Romani*)
- MKIDs (Caltech/FNAL/SLAC/LBL) - 20 eV phonon, ~100 meV photon
- Nanowires/QCDs - single THz photons (QCD), single IR photons (nanowires)
- Qubit-based readout - single tunneling events detectable, collection efficiency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

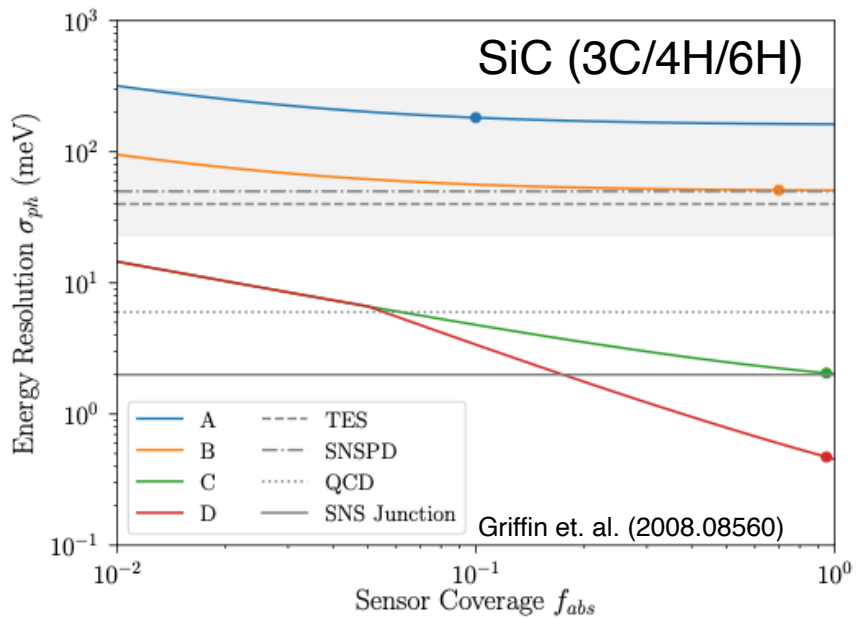
Thermal Phonon Readout

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

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

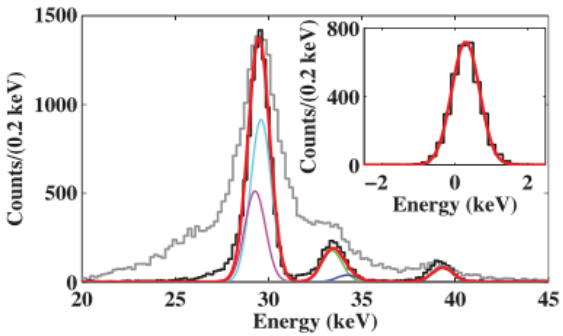
Kurinsky, Yu, Hochberg, Cabrera (1901.07569)

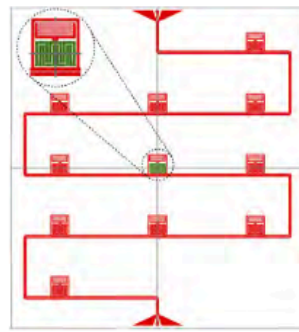


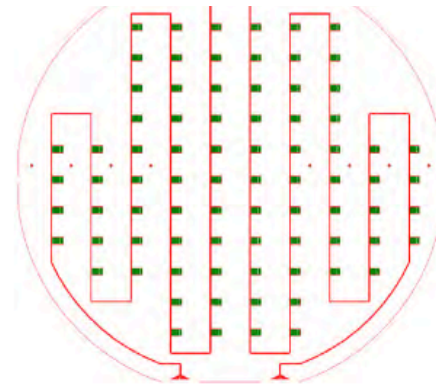


Griffin et. al. (2008.08560)

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 $\eta_{ph} \approx 0.3$

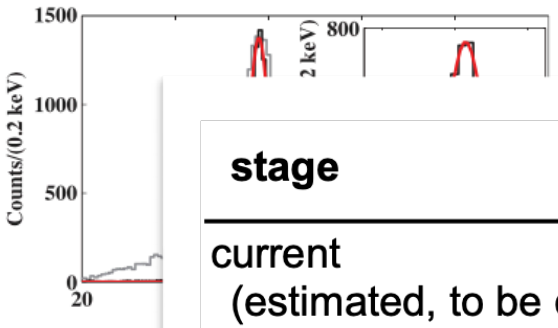
High-Δ, low TLS cap layer ($NbTiN_x$) → σ_E^{KID} = 1.5 eV, σ_E^{sub} = 5 eV

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 $\longrightarrow \sigma_E^{sub} \approx (1.3\text{ eV})\sqrt{320}/\eta_{ph} \approx 80$ 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!

NR/ER discr. down to 1 eh pair (E_R ~ 10 eV)

0.1 GeV reach for NRs w/o discr.

0.03 GeV reach for NRs w/o discr.

Pro

σ_I

o

Sma

σ_I

H

Larg

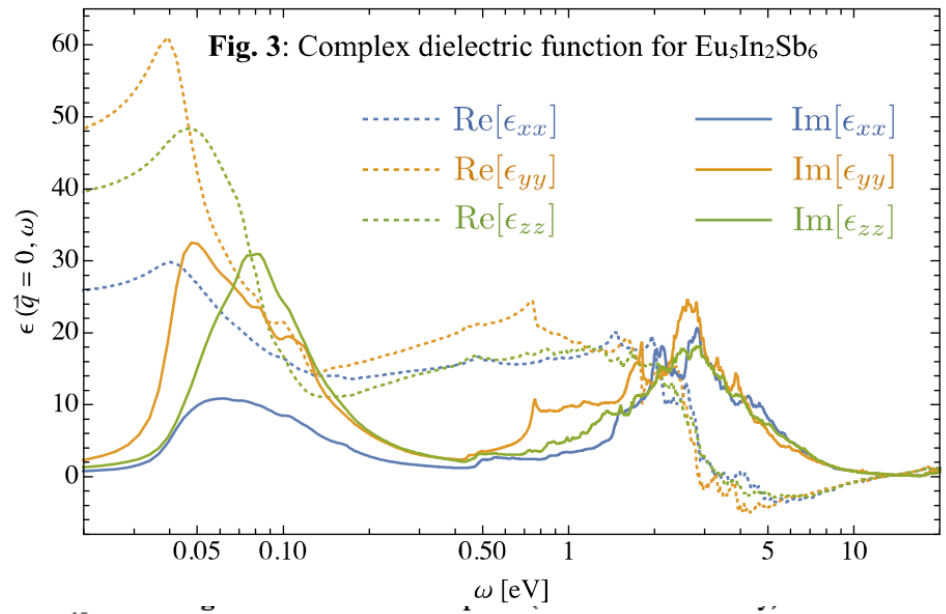
σ_I

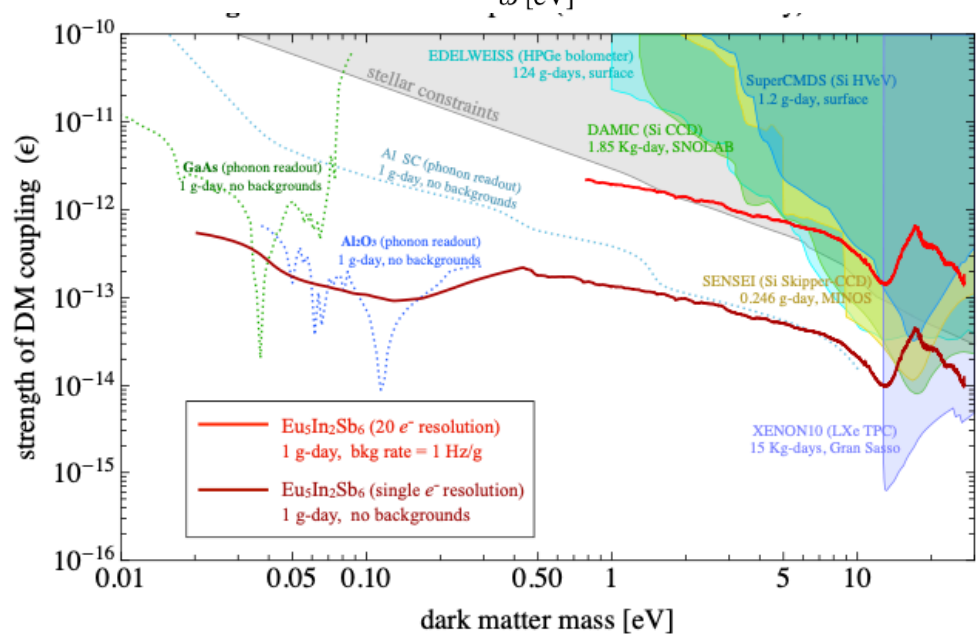
$\sigma_E = (5.5\ \text{eV})\sqrt{320/\eta_{ph}} \approx 300\ \text{eV}$ for 320 KIDs (4% surface coverage)

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

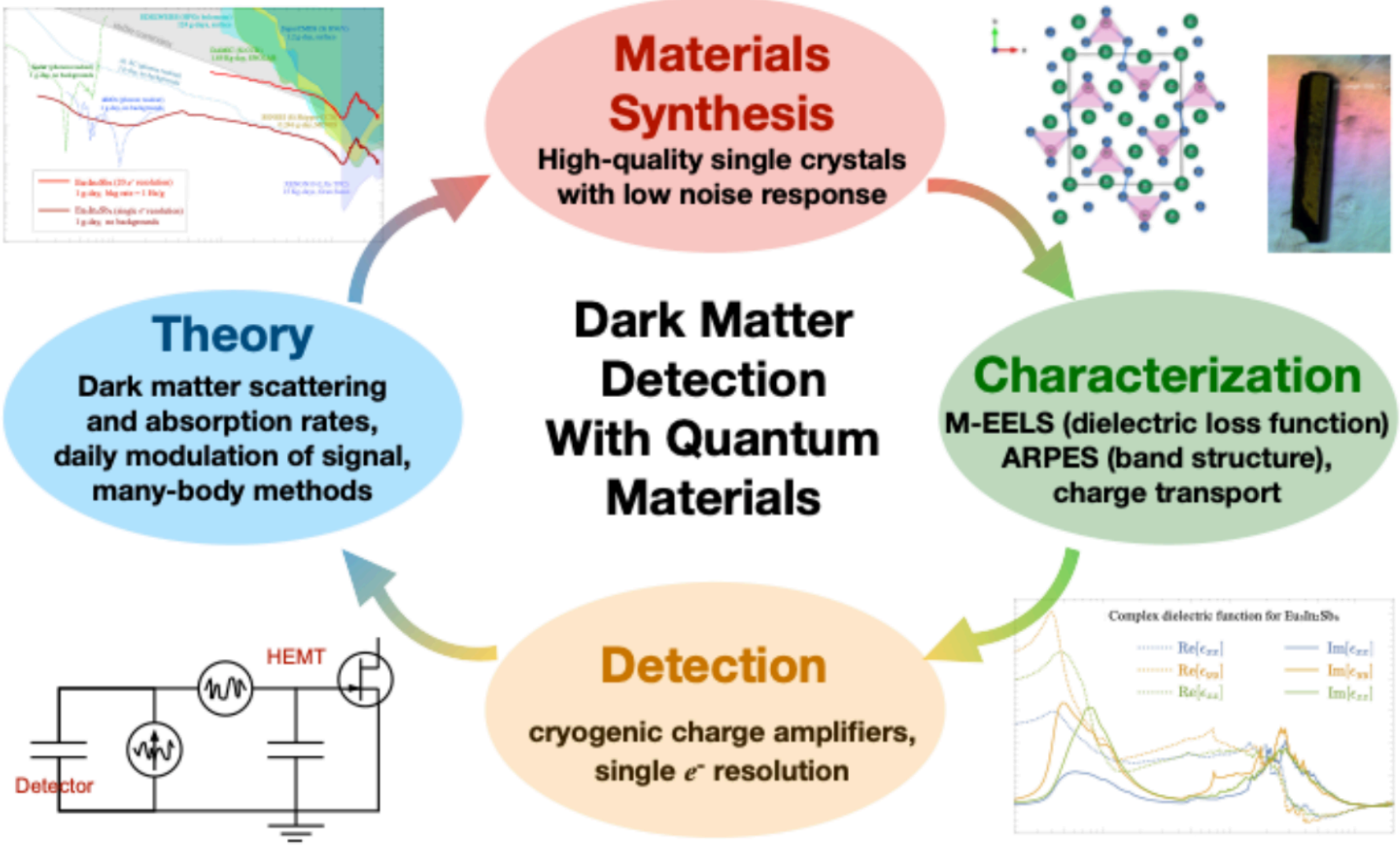
Designer Materials for Light DM (SPLENDOR)

- 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



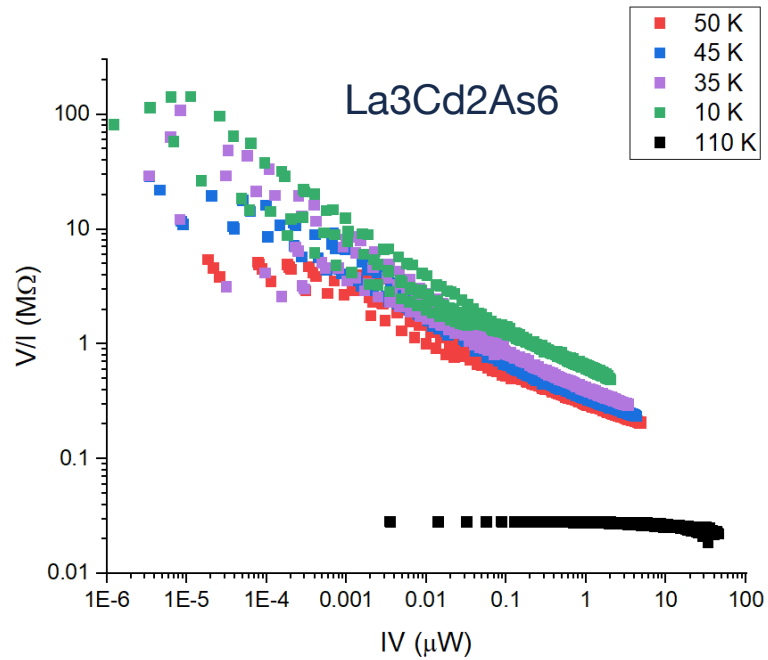


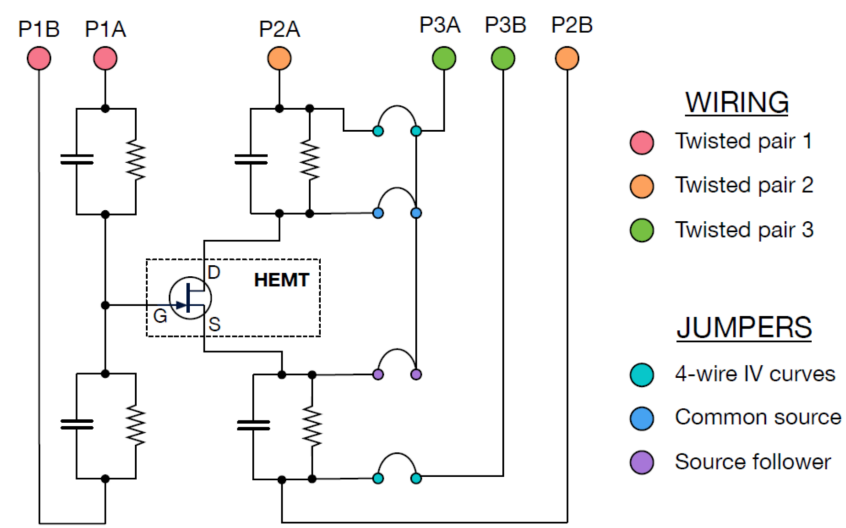
SPLENDOR: DM Detection w/ Quantum Materials



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

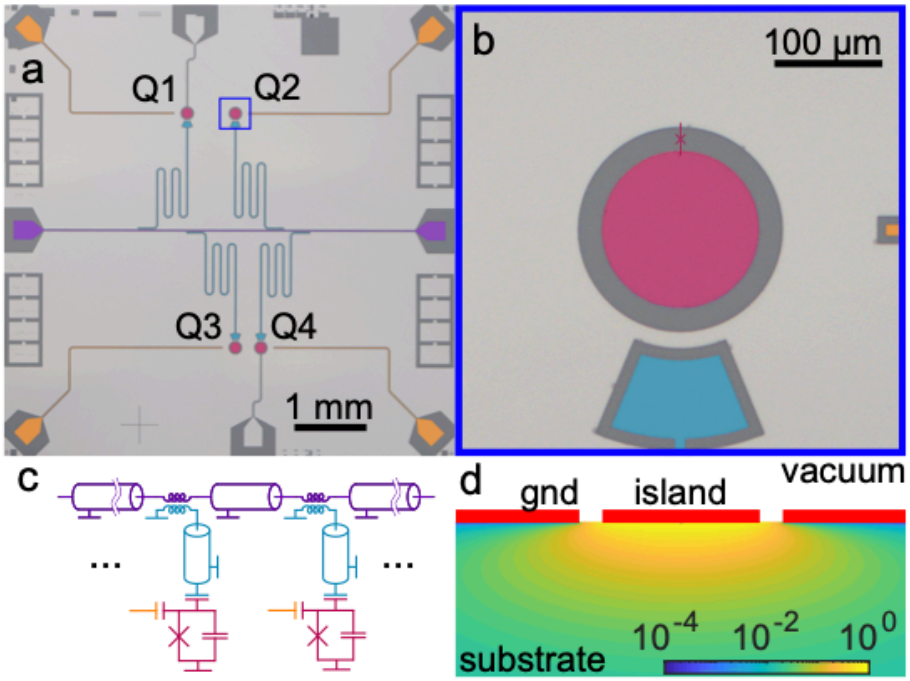
Article | Published: 16 June 2021

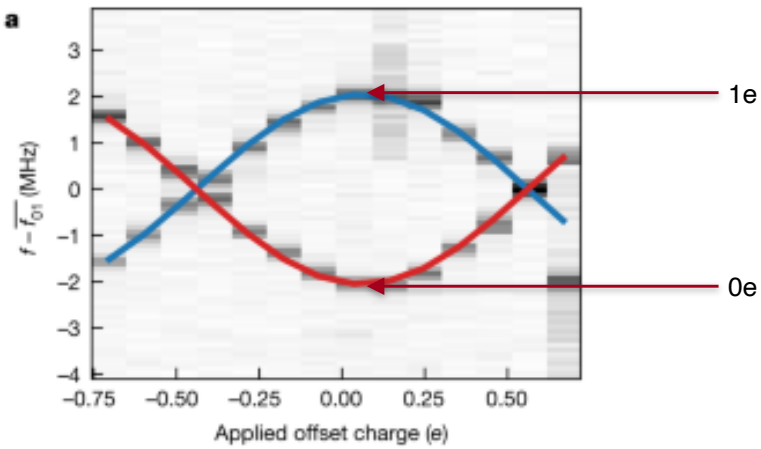
Correlated charge noise and relaxation errors in superconducting qubits

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

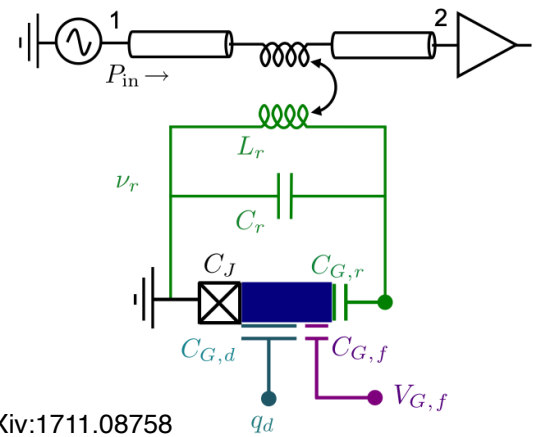
- Qubits, built on the 'cooper pair box' paradigm, are already intrinsically sensitive to energy differences of Delta (half the cooper pair binding energy)
- Studies of qubit chips have shown sensitivity to single charges in the substrate and to pair breaking from phonons (see Nature paper)
- The 'readout' 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!



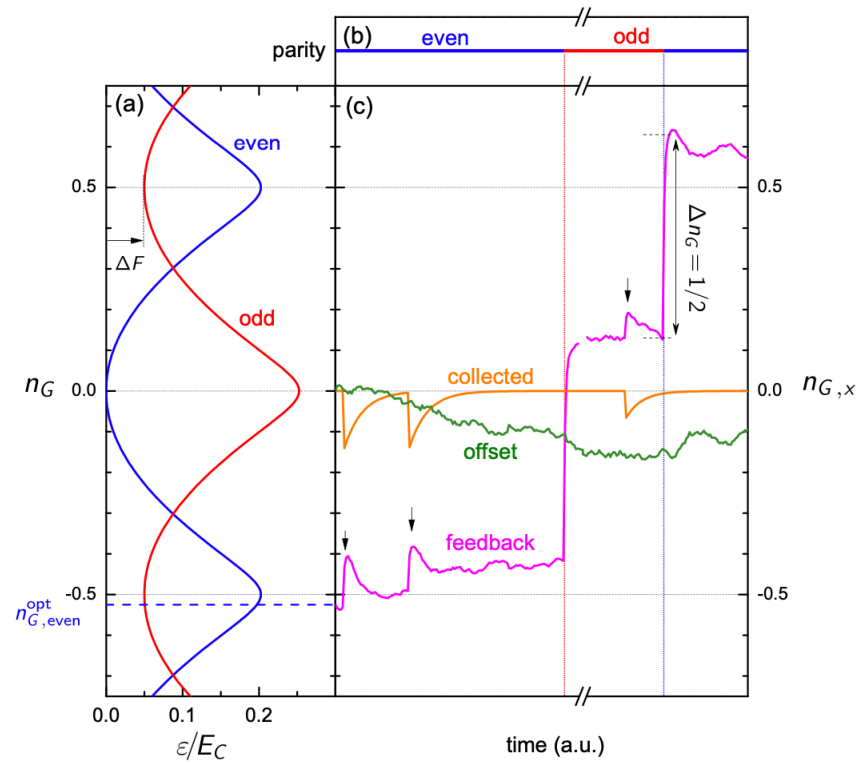


Qubit-Based Electrometers for Quantum Materials

- 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

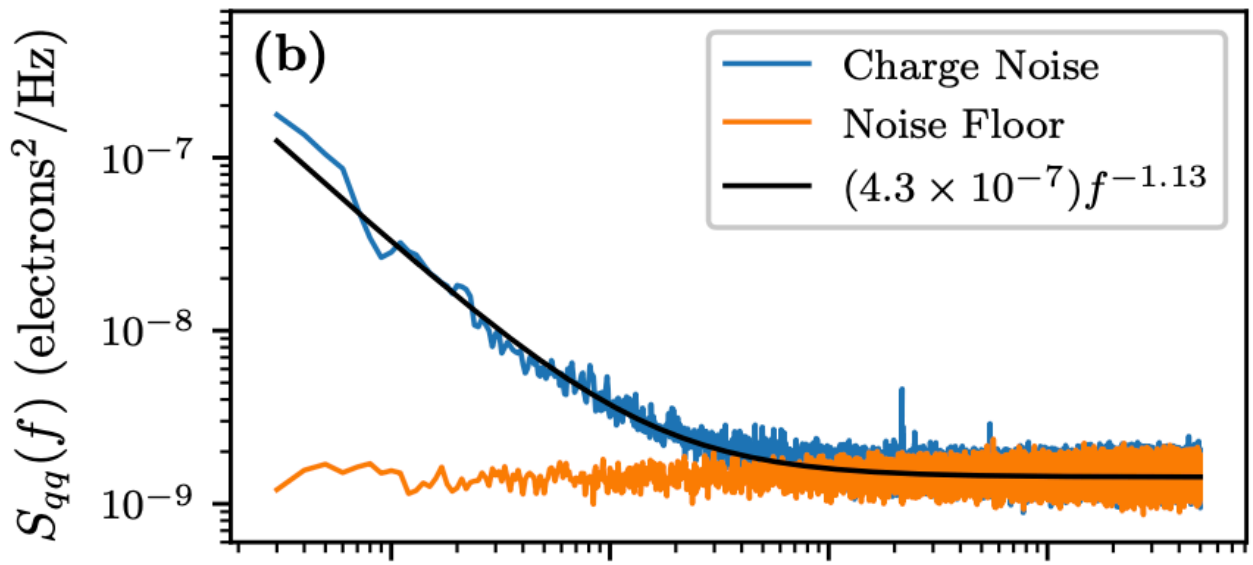


Qubit-Based Electrometers for Quantum Materials

- 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)



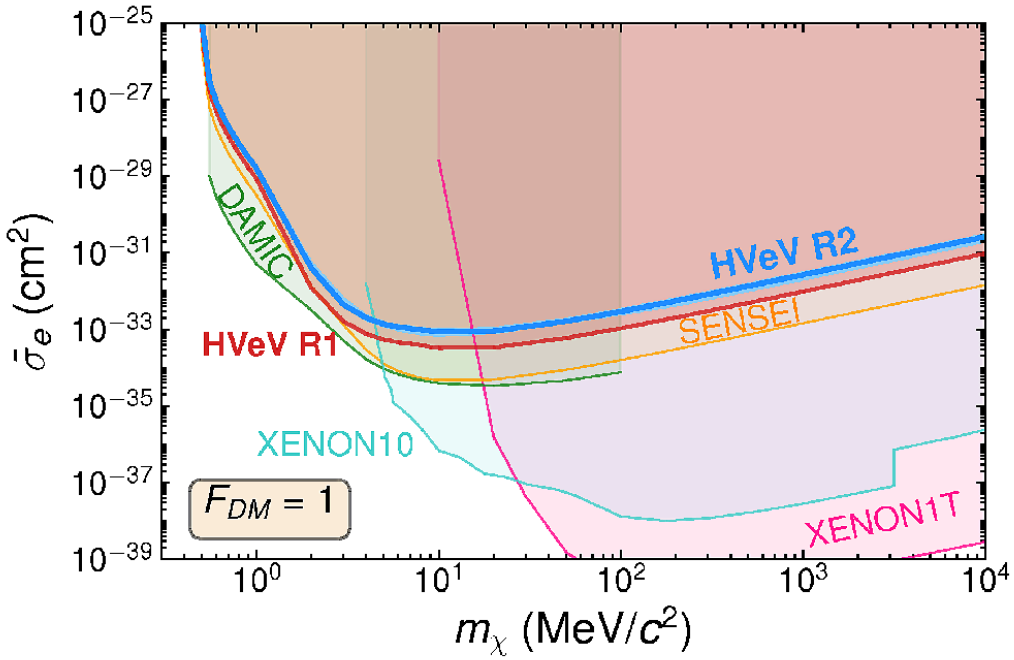
$$\sigma_{n_g} = \sqrt{\int_{1/\tau_m}^{\kappa_{\rm tot}/2\pi} S_{qq}(f)df} = 1.3 \times 10^{-3} \text{ electrons}$$

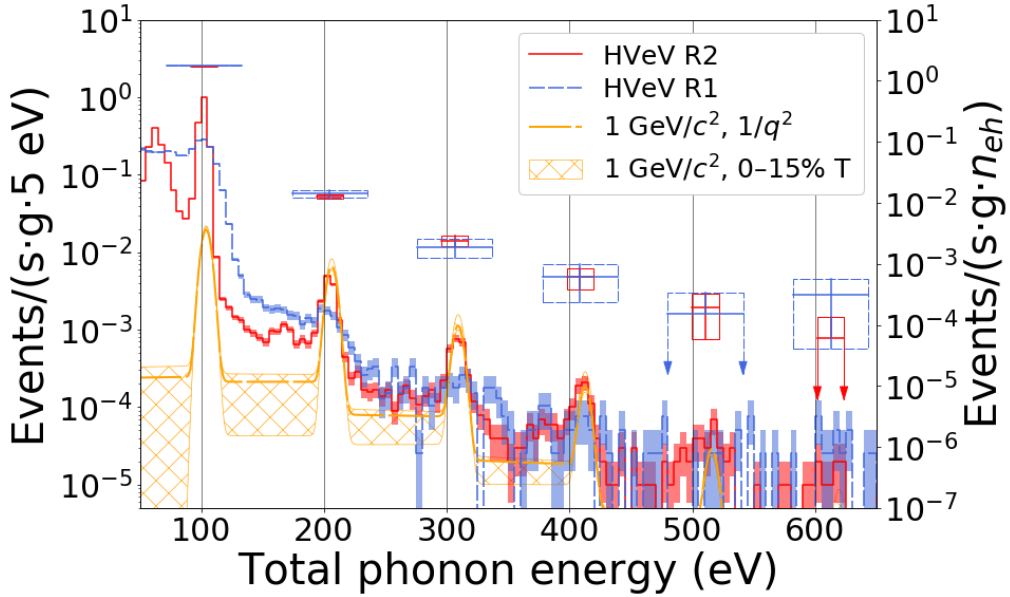
Conclusions

- 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.
- eV-scale searches are maturing and showing us new backgrounds as we try to realize meV-scale searches

Backup

HVeV Run 2

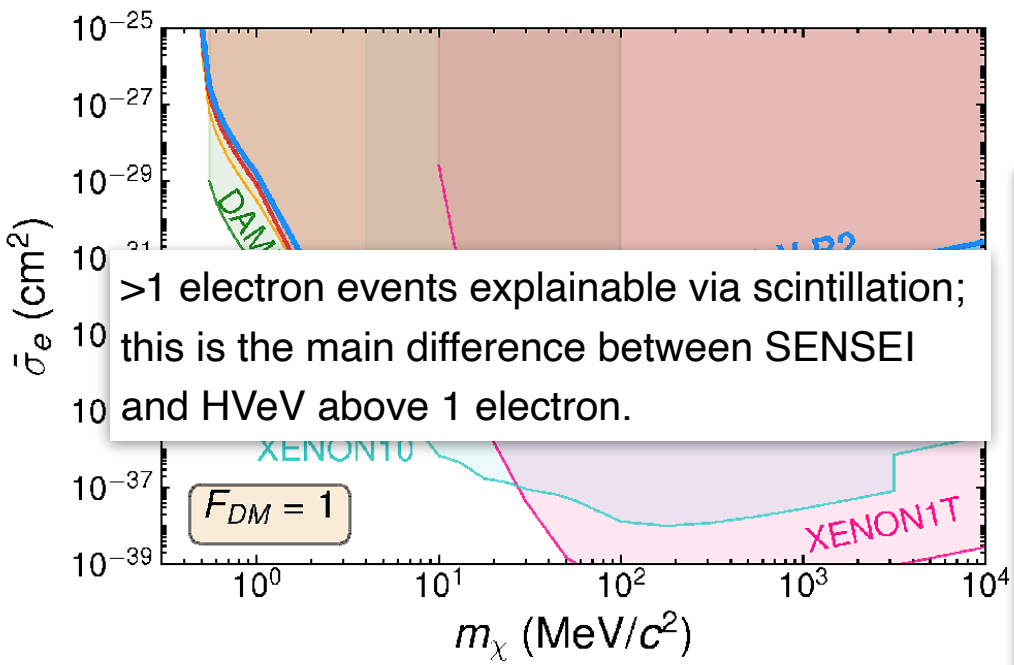




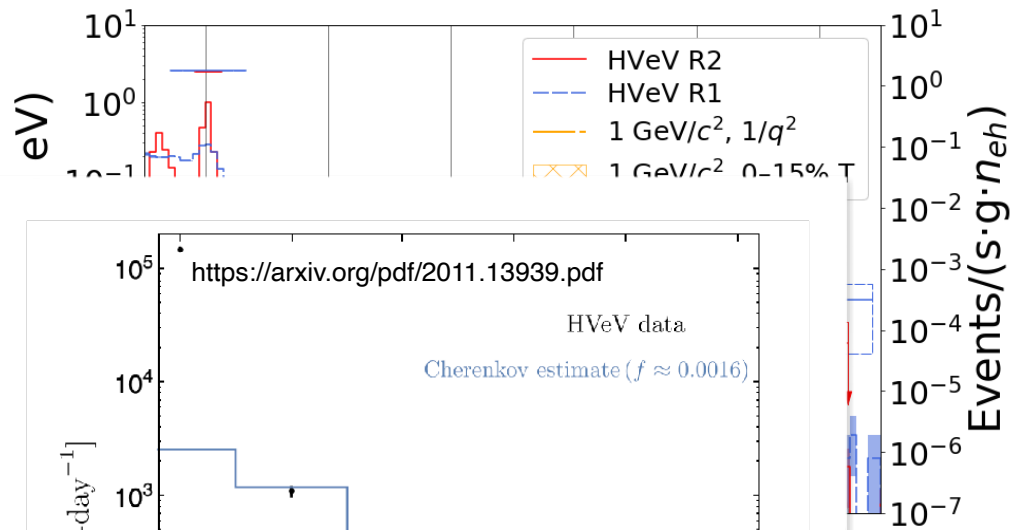
HVeV second run taken with 3 eV resolution detector over the course of 3 weeks:

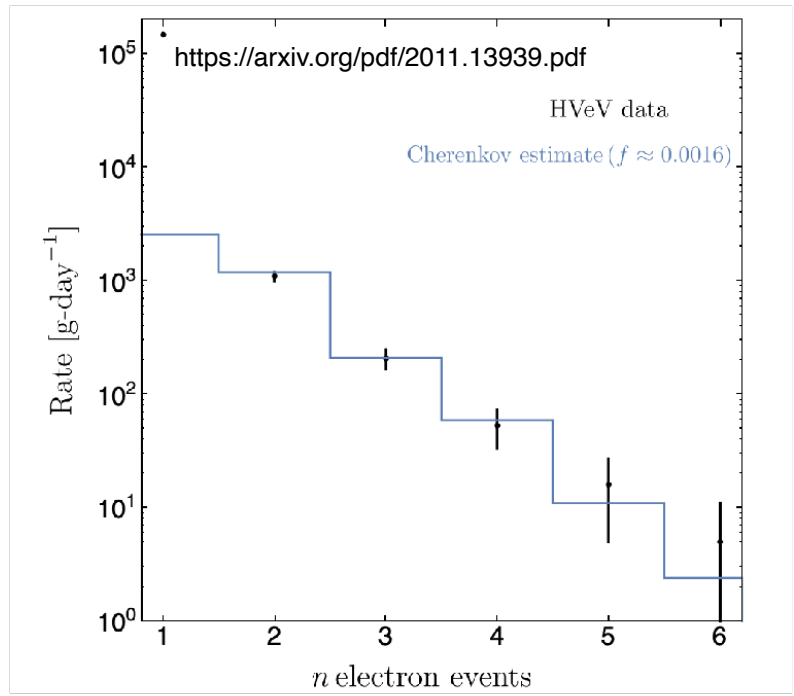
- 60V and 100V spectra show identical backgrounds; signal seen not voltage dependent
- Different prototype, run in a different lab, in a different state
- 0V data acquired with ~10 eV threshold, results still being analyzed
- Rates in *every charge bin* consistent with Run 1…that was completely unexpected

HVeV Run 2



>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