Novel Materials and Qubit Sensors for Probes of Beyond Standard Model Physics

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QMUL SNOLAB Workshop

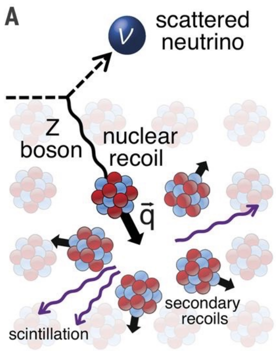
New Physics at the milli-eV Scale

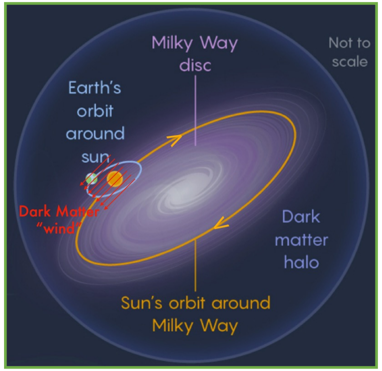
- Light dark matter detection
  - Low mass WIMP-like
  - Dark photon mediated DM
- Low energy CEvNS measurements
  - Exotic weak currents
  - Neutrino magnetic moment
  - Recoil spectrum with neutron number
  - Nuclear fuel and reactor monitoring

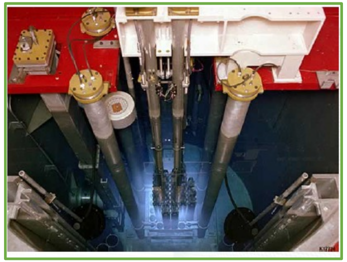
Probes of Beyond Standard Model physics

Precision test of SM

Nuclear Safeguards







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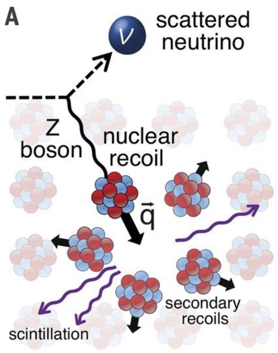
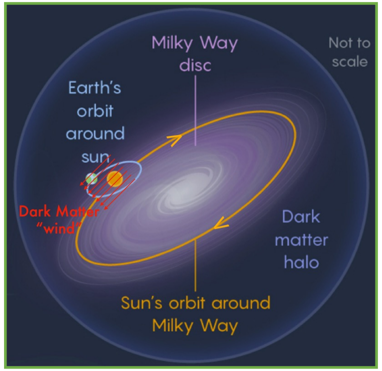
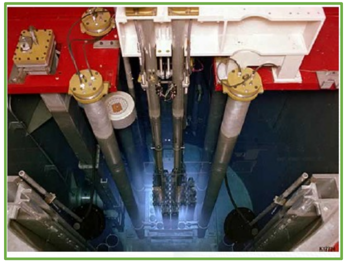
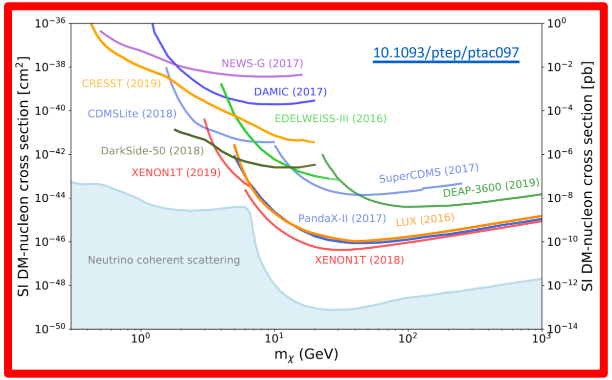


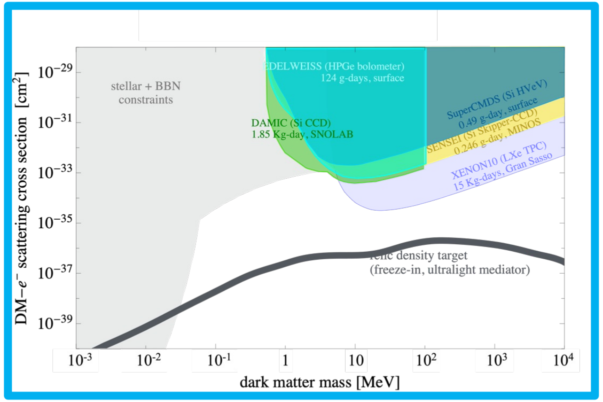


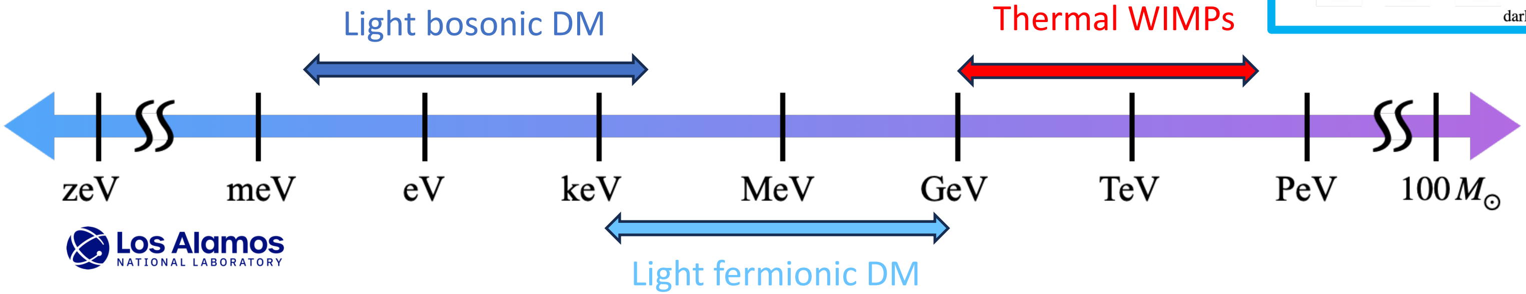


Dark Matter Detection – Past 10 Years

- The parameter space of the ‘classic’ thermal WIMP has been highly constrained
- Many well motivated theories for `low mass dark matter’ – Sub GeV masses
  - Typically require the introduction of a ‘dark sector’ – *allows for electronic interactions*
- Lots of focus over past 10 years on electronically recoiling DM







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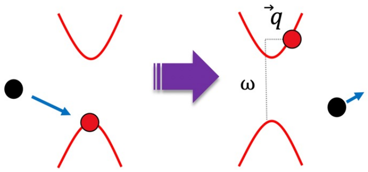
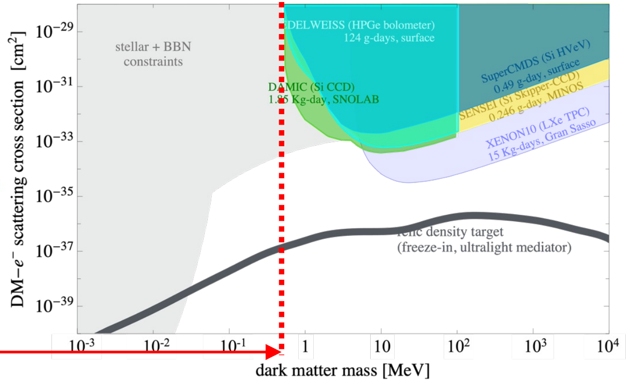
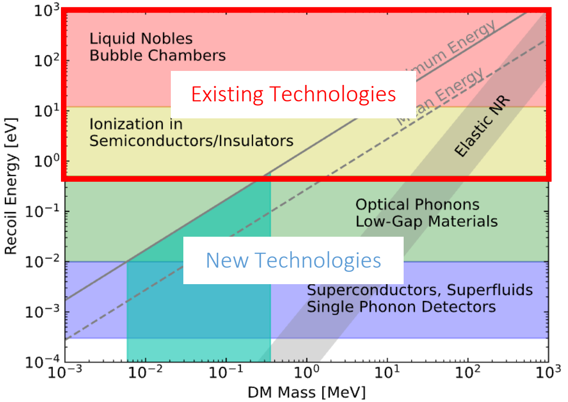
Searching for Dark Matter Below the MeV Scale

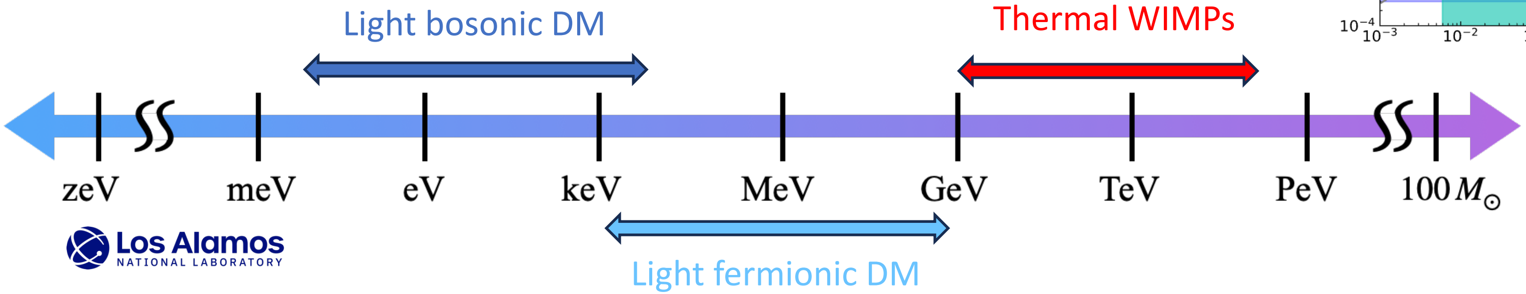
- Many experiments probing DM masses in the MeV-GeV range
- Existing detection technologies (Si, Ge) have O(eV) energy thresholds
- Energy imparted in detector system strongly scales with DM mass
- Probing fermionic DM masses below MeV requires new detection techniques



Mass reach is limited by O(eV) band gaps of Si/Ge





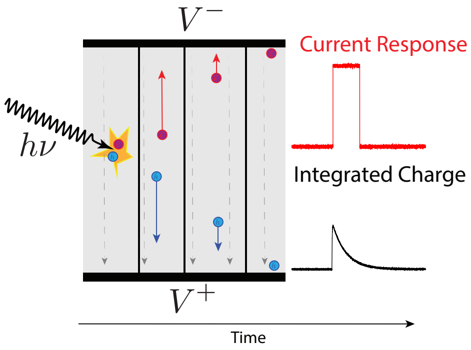


How do we measure milli-eV energy deposits?

(Some) Detector Concepts

Ionization:

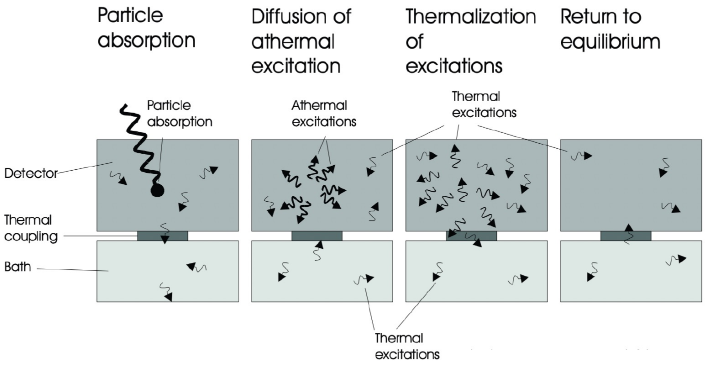
Apply E-Field to collect excited e/h pairs



Sensitivity limited by electronic bandgap and amplifier noise

Thermal Calorimetry:

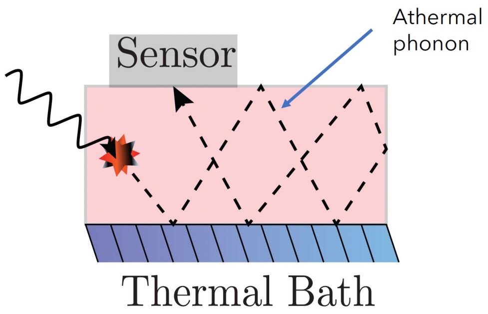
Measure total deposited energy as it relaxes into the thermal system



$$\sigma_E^2 \propto C_{absorber} T^2$$

Athermal Calorimetry:

Measure non-equilibrium phonon energy before thermalization



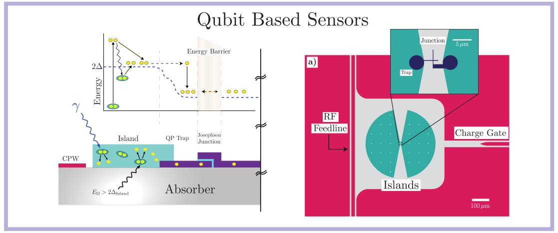
$$\sigma_E^2 \propto \frac{C_{sensor} T^2}{\alpha}$$

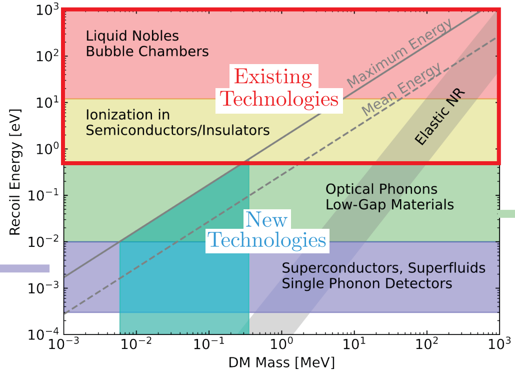
Energy sensitivity is determined by target material and sensing mechanism

Next Generation Detector Requirements

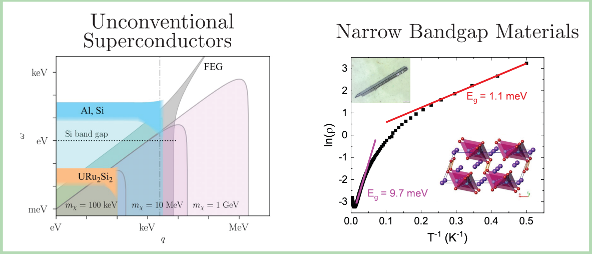
- Lots of interesting physics at milli-eV scale energies
  - Both nuclear and electronic recoils (phonons and electrons)
- Both dark matter and neutrinos have low kinetic energy:
  - These particles impart very little energy into detector
- Next generation of detectors needs sensitivities to milli-eV scale energies
- This requires:
  - New detector targets
  - Sensors to measure meV scale energy depositions

Novel Superconducting Sensors





novel topological materials



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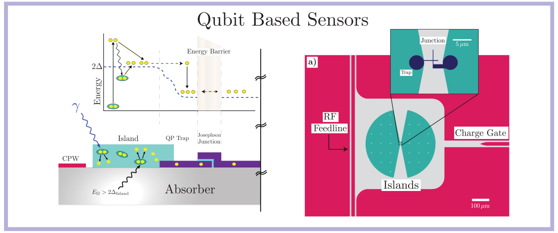

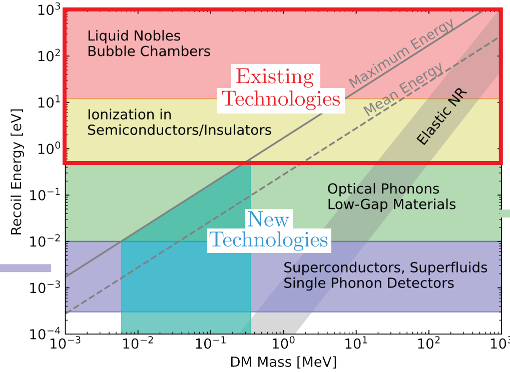

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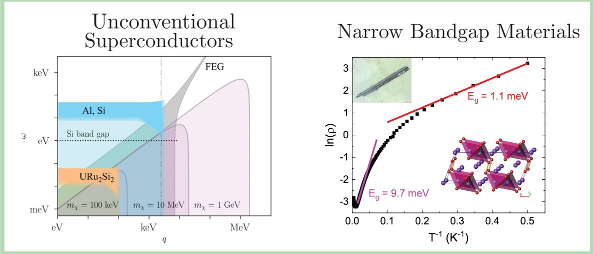
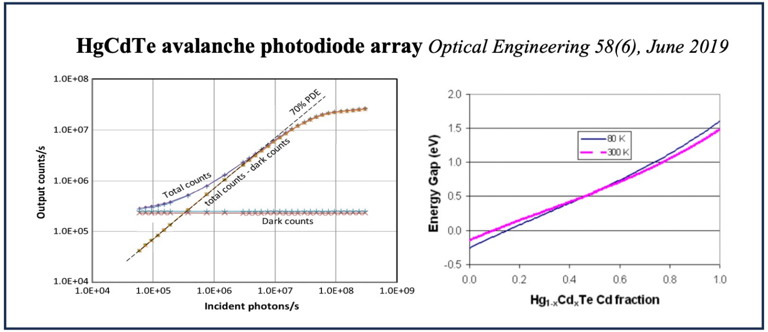
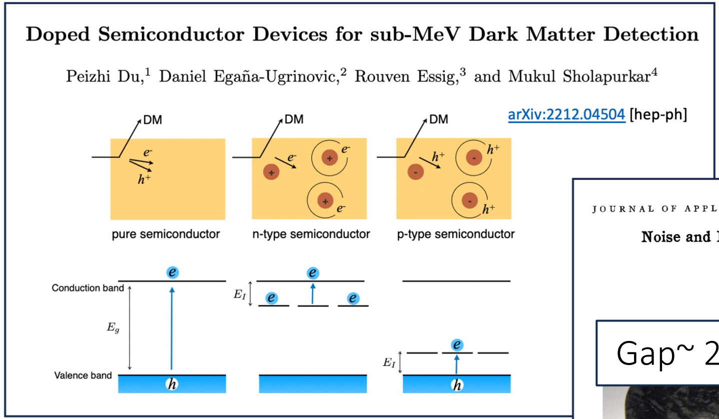
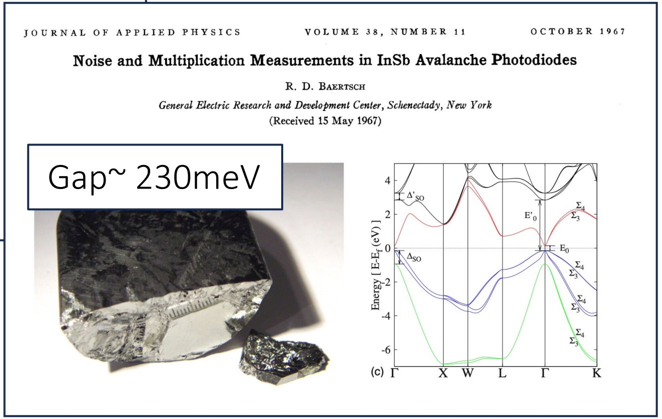


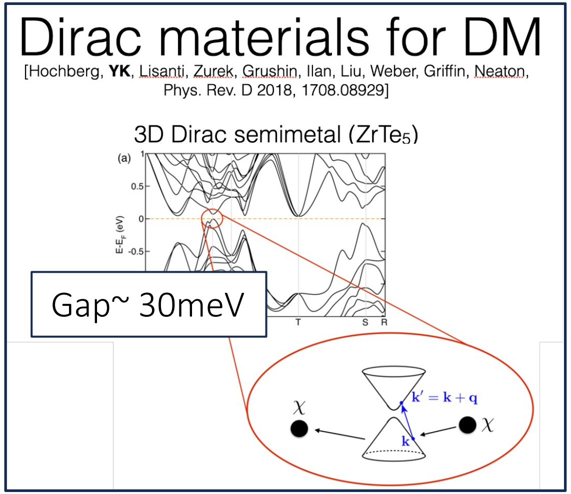
Landscape of Low Bandgap Semiconductors

- Many ideas in recent years for DM detection with narrow bandgap semiconductors
- Existing low bandgap semiconductors either have many impurity states or disorder from high doping
  - Both result is large dark rates



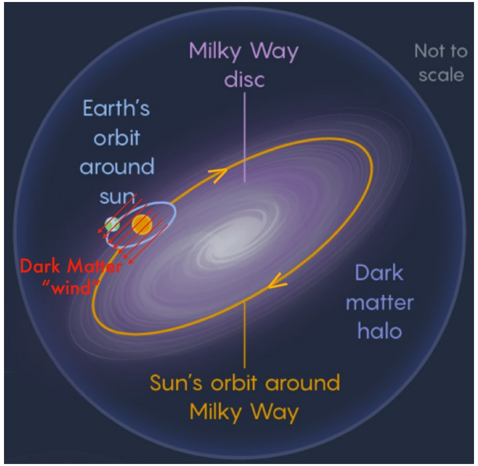


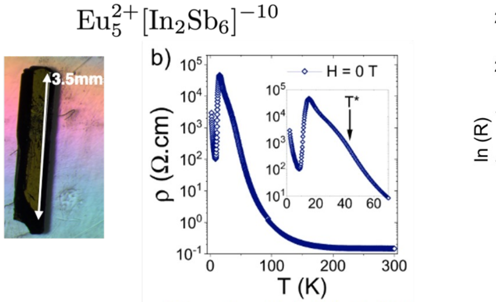




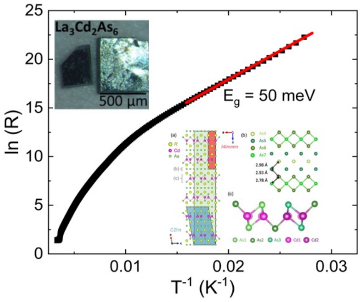
Novel Narrow Bandgap Semiconductors for SPLENDOR

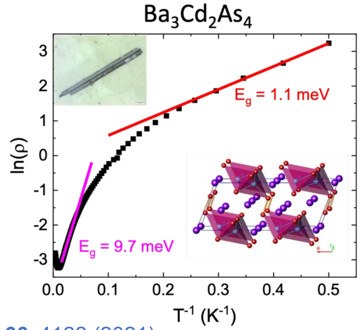
- Search for particles of Light dark matter with narrow-gap semiconductors - SPLENDOR
- Los Alamos funded project developing single-crystal narrow bandgap semiconductors
- Candidate materials have bandgaps in the range of 1-100meV
- Anisotropic bandgaps – sensitive to daily modulation signal



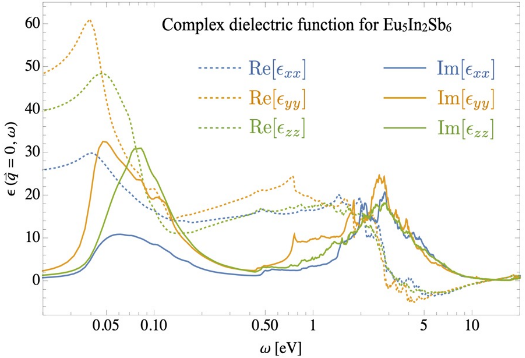


PFS Rosa *et al*, *npj Quantum Materials* **5**, 52 (2020).





MM Piva *et al*, *Chem. Mater.* **33**, 4122 (2021).



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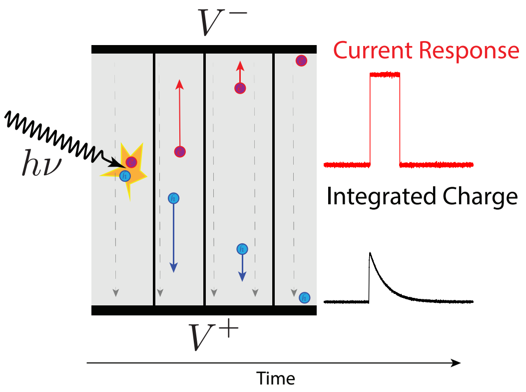
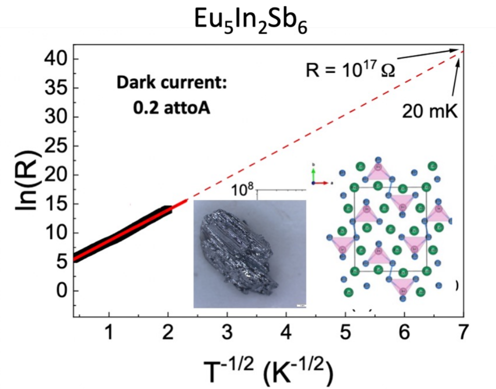
SPLENDOR Material Response

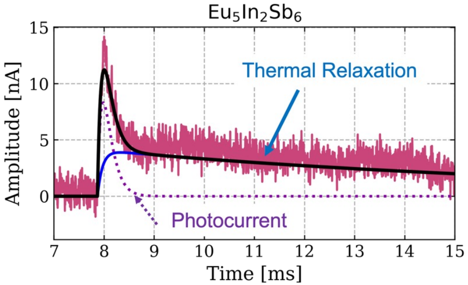


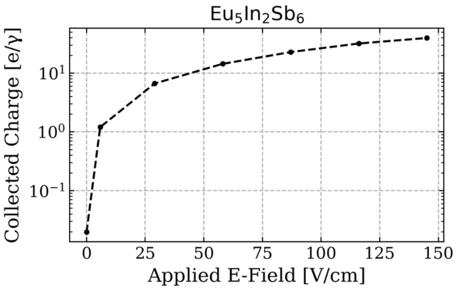
Materials used as point contact ionization detectors – resolution scales as bandgap and amplifier noise



Single crystal synthesis allows for very pure samples - low dark counts over large crystal volumes

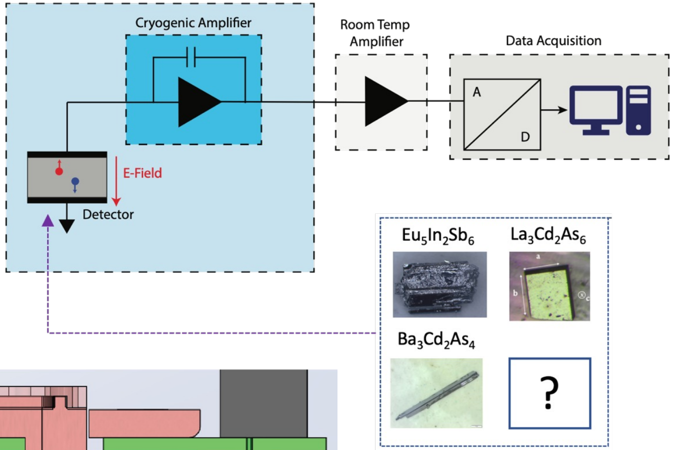
Candidate materials showing photo response to IR light – beginning to reach full charge collection

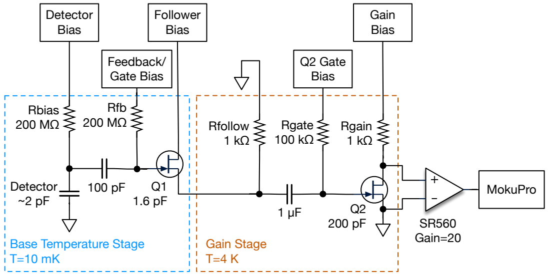




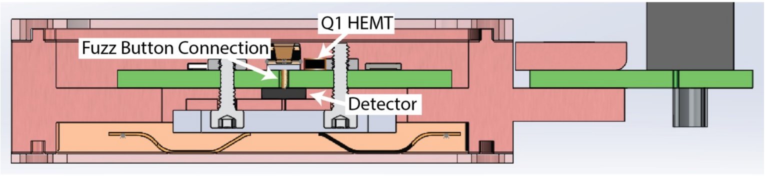
Material Independent Charge Readout

- SPLENDOR is developing a *material independent* cryogenic HEMT based charge readout
- Two stage amplifier using low capacitance CryoHEMTs
- Will allow for the rapid prototyping of any insulating material

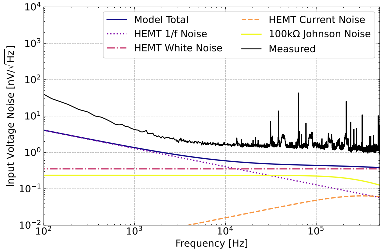




arXiv:2311.02229 [physics.ins-det]



Detector housing and amp topology keep total capacitance at O(1 pF)



$$\sigma_E \sim E_{gap}\ \sigma_V\ (C_{detector} + C_{input} + C_{parasitic})$$

Prototype amp integrated voltage noise: $\sigma_{charge} \approx 7\ e$

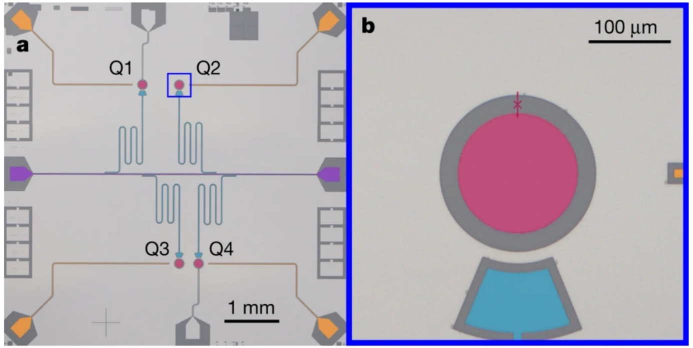
Qubit based charge Amplifier

- Ultimate utility of materials can only be achieved with single charge sensitivity
- Recently given KA25 funding to develop a qubit-based charge amplifier to replace HEMT readout
- Plan to fabricate cooper-pair box based structures on silicon substrate – externally couple detector contact to charge gate of qubit

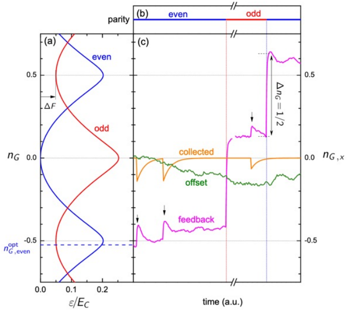
Exploring two low capacitance connections:

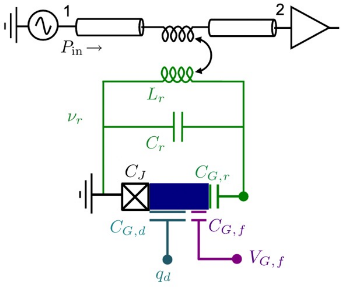
1. Wirebonding sample to qubit gate
2. Modifying SPLENDOR HEMT housing

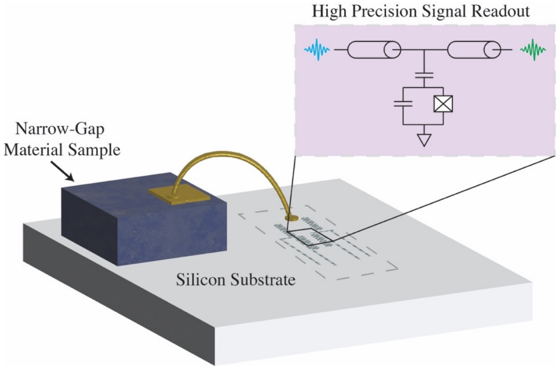
Nature **volume 594**, pages 369–373 (2021)

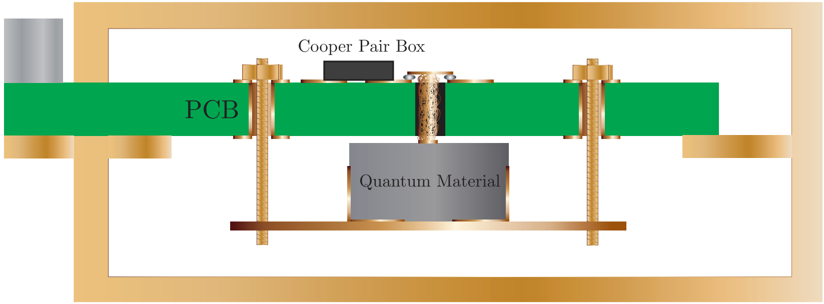


Phys. Rev. Applied 11, 054072









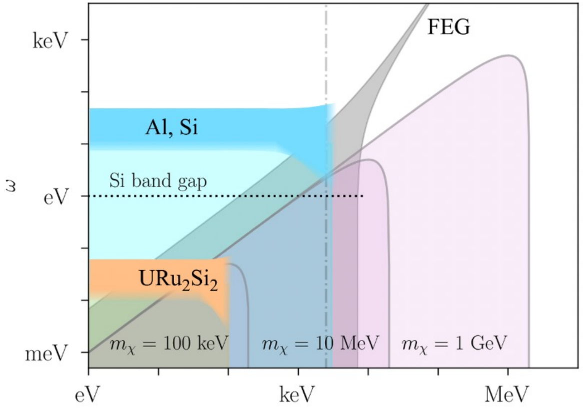
Heavy Fermion Superconductors for Dark Matter

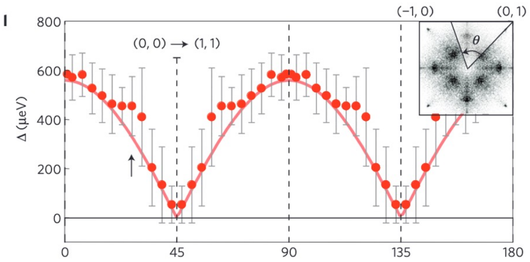
- Class of novel materials with strong light dark matter coupling
- f-electrons hybridize with conduction elections
  - results in quasiparticles with enhanced effective mass (10-1000 m_e)
- Nodal gapped superconductor
- Fermi velocity is reduced by large effective quasiparticle mass
- **Light Dark Matter can easily excite plasmon mode in heavy-f systems since $v_F < v_\chi$**

Potential Materials: URu_2Si_2, $CeCoIn_5$

Determining Dark-Matter–Electron Scattering Rates from the Dielectric Function

Yonit Hochberg, Yonatan Kahn, Noah Kurinsky, Benjamin V. Lehmann, To Chin Yu, and Karl K. Berggren
Phys. Rev. Lett. **127**, 151802 – Published 6 October 2021





Imaging Cooper pairing of heavy fermions in $CeCoIn_5$

M. P. Allan, F. Massee, D. K. Morr, J. Van Dyke, A. W. Rost, A. P. Mackenzie, C. Petrovic & J. C. Davis

Nature Physics **9**, 468–473 (2013) | Cite this article

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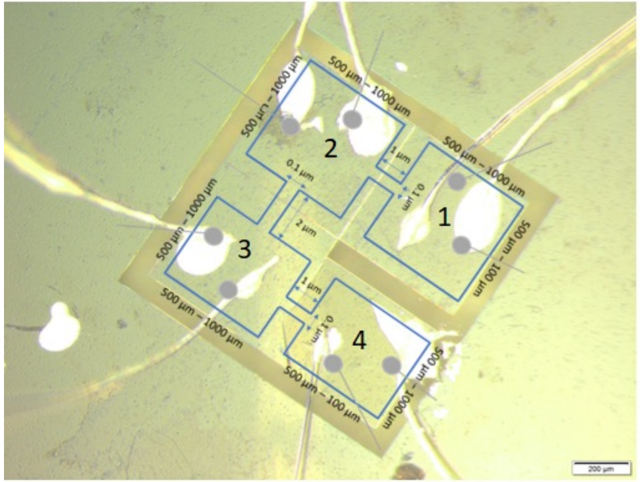
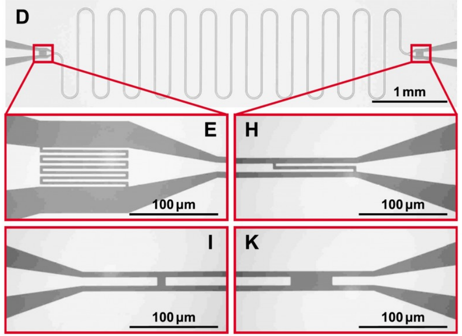
Sensor Development of Unconventional Superconductors

- Kinetic inductance scales with effective QP mass

Large DM coupling
Large Kinetic inductance
} Goal: make MKID out of unconventional SC



- Collaborators at Cornell have developed thin film growth of heavy-f superconductor $CeCoIn_5$
- Can create microstructures down to 100nm using reactive ion etch
- Basic QP transport studies happening at LANL
- Submitting LDRD proposal to study films as potential sensors – etching into mKID and TES structures



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Cornell University

New Physics at the meV Scale

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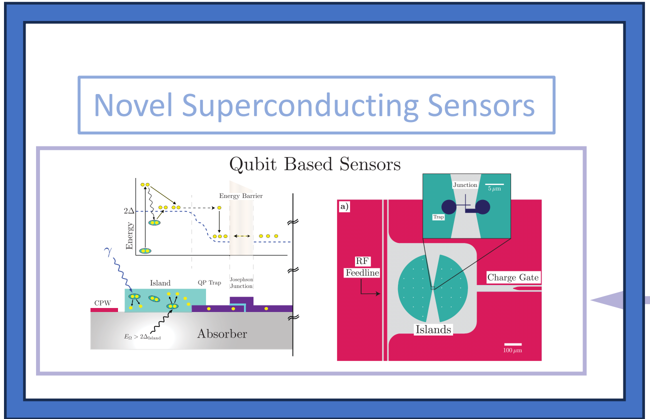
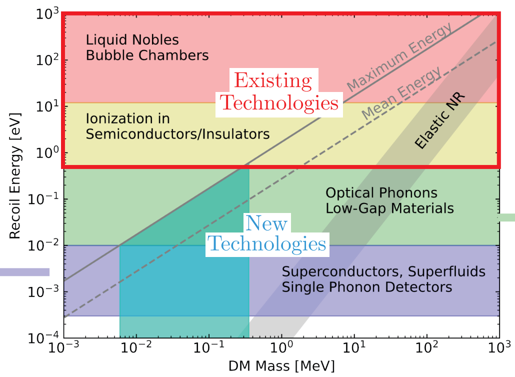
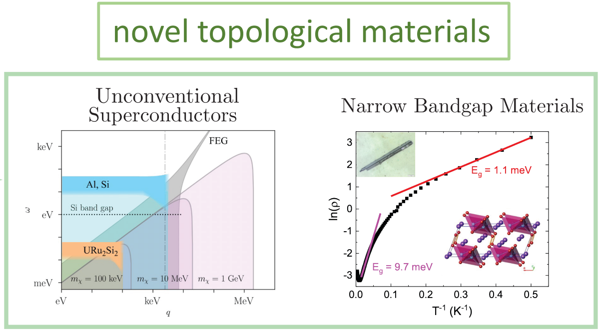
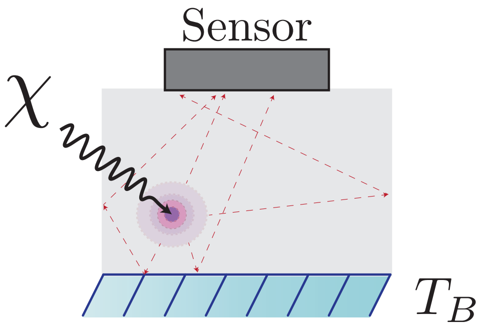


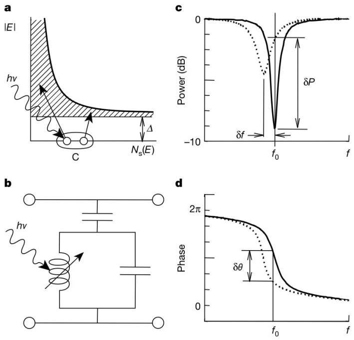


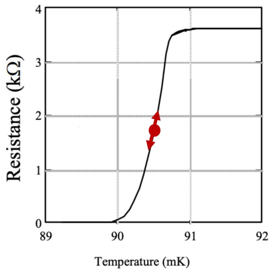


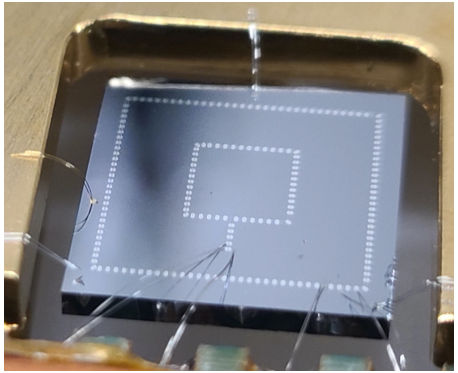
Calorimetry with Superconducting Sensors

- Rare event searches require large exposure
  - SC Sensors typically coupled to much larger absorbers
- Many detectors use sensors patterned on absorber as phonon sensors
- Sensors are typically TESs, MKIDs, or NTDs
  - Use fluctuations in phonon or quasiparticle *densities* to measure energy depositions
- State of the art detectors have achieved O(100 meV) resolutions









Microcalorimetry beyond the Transition Edge Sensor

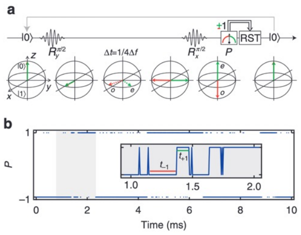
- Multiple experiments have observed correlated errors across qubits originating from phonons in the device substrate
- Groups have demonstrated that single quasiparticle tunneling events can be resolved in transmon qubits via parity flips

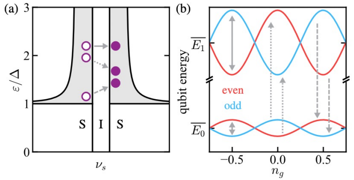
Goal: exploit single QP sensitivity of qubits to make meV scale phonon sensors

Millisecond charge-parity fluctuations and induced decoherence in a superconducting transmon qubit

D. Ristè, C. C. Bultink, M. J. Tiggelman, R. N. Schouten, K. W. Lehnert & L. DiCarlo

Nature Communications 4, Article number: 1913 (2013) | Cite this article

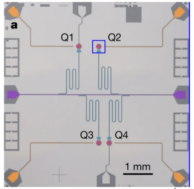




Hot Nonequilibrium Quasiparticles in Transmon Qubits

K. Serniak, M. Hays, G. de Lange, S. Diamond, S. Shankar, L. D. Burkhart, L. Frunzio, M. Houzet, and M. H. Devoret

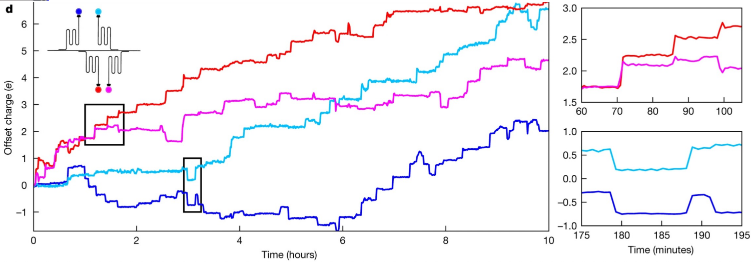
Phys. Rev. Lett. **121**, 157701 – Published 10 October 2018



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



The Superconducting Quasiparticle-Amplifying Transmon

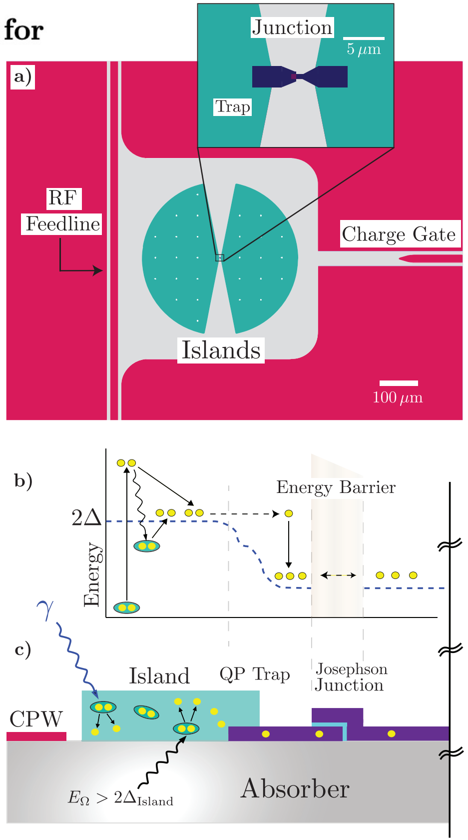
The Superconducting Quasiparticle-Amplifying Transmon: A Qubit-Based Sensor for meV Scale Phonons and Single THz Photons

C.W. Fink,[1,*] C. Salemi,[2,3,†] B.A. Young,[4] D.I. Schuster,[5] and N.A. Kurinsky[2,3,‡]

arXiv:2310.01345 [physics.ins-det]

- A sensor based on the weakly charge-coupled transmon architecture
- Charge dispersion allows for sensitivity to parity flip from single quasiparticle tunneling event
- Leverages quasiparticle trapping and amplifying techniques pioneered by SuperCDMS
- Will be sensitive single meV phonons in substrate with measurement times of $1\mu s$

* *Work funded by DOE HEP Early Career Award, KA25, and Los Alamos National Lab LDRD*



Quasiparticle Trapping

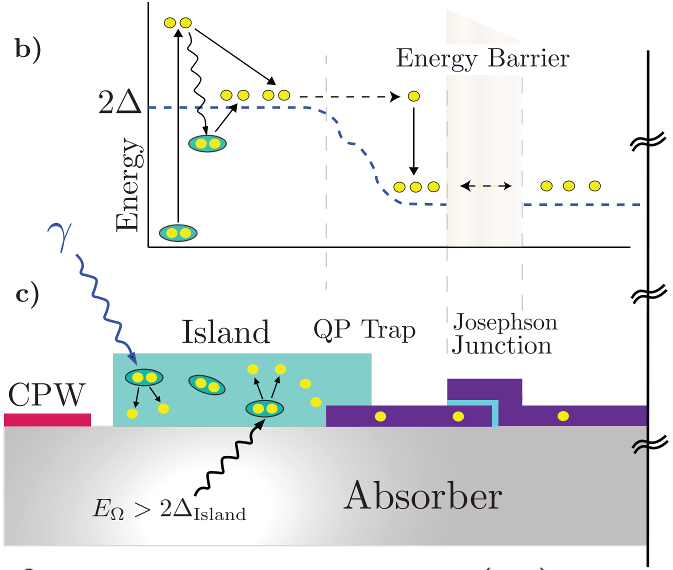
Qubit fabricated from two materials such that

- Islands: Al
- Junctions: AlMn

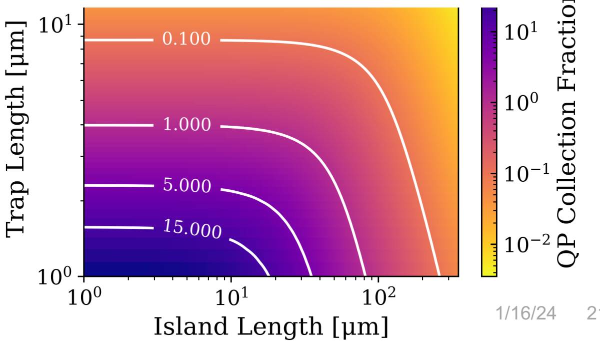
$$\Delta_{junction} \ll \Delta_{island}$$

1. Phonons (photons) with energy greater than $2\Delta_{island}$ break Cooper-pairs in islands
2. Quasiparticles diffuse in island until becoming trapped in lower gap material
3. QP's undergo multiplication process in lower gap material
4. QP's tunnel across junction in low gap material until recombination

Steps 2 & 3 can result in collection efficiencies of greater than unity

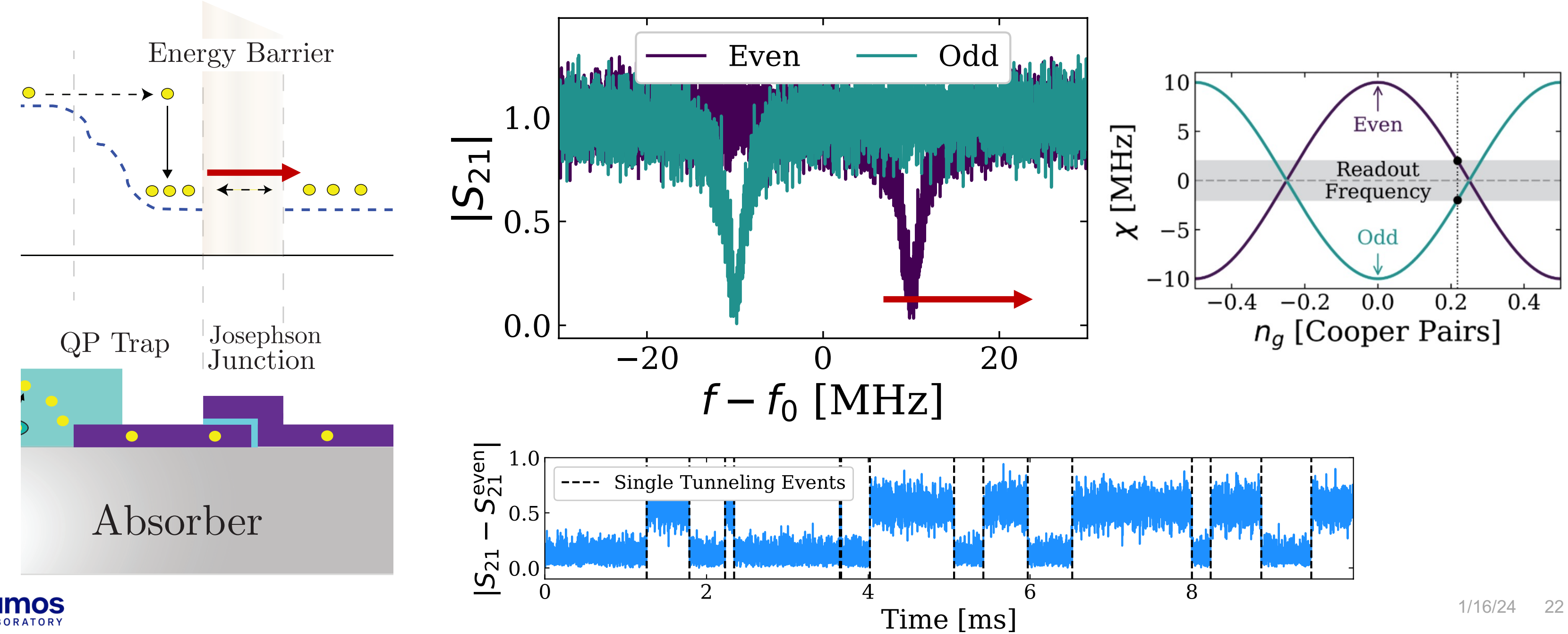


$$\frac{\partial}{\partial t} n(\mathbf{x},t) = D_{\mathrm{island}} \nabla^2 n(\mathbf{x},t) - \frac{n(\mathbf{x},t)}{\tau_{\mathrm{island}}} + s$$



Signal Pathway

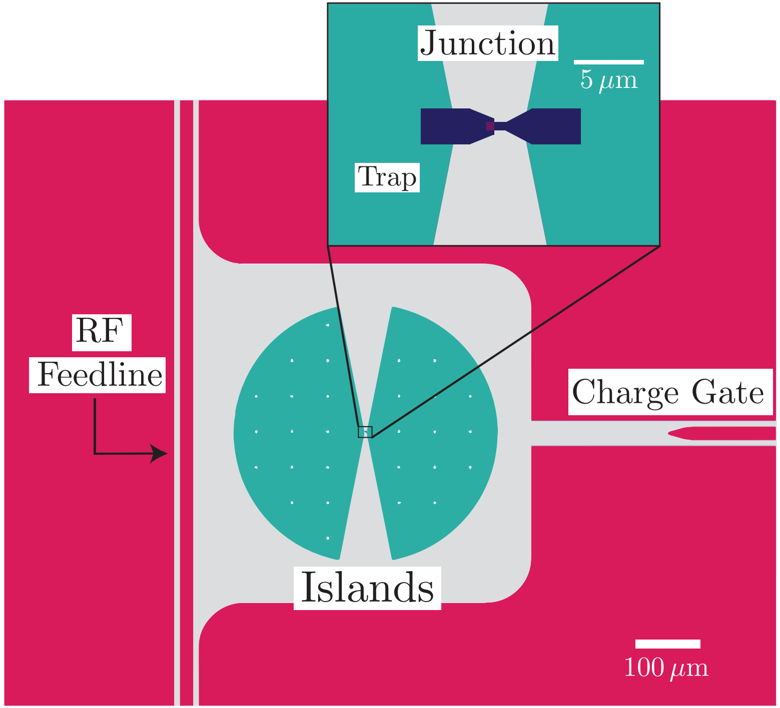
- Quasiparticles in the trapped region of sensor will diffuse until tunneling across junction
- Each tunneling event changes parity state – observable as small frequency shift



Sensor Readout

- Unlike traditional qubit readout, readout resonator is removed
- Resonance determined by qubit transition directly, not by coupled resonator
- Removing resonator couples the qubit much stronger to the environment

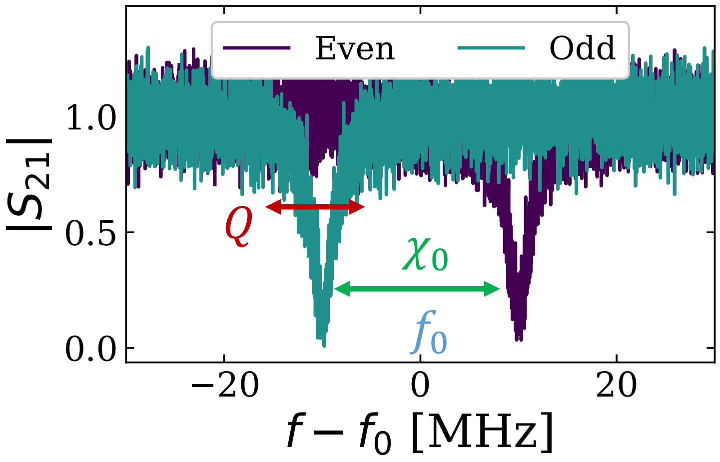
- This change allows unit cell to be decreased
    - Increased pixel density
    - Reduction of two-level system noise
    - Increased detection efficiency



Qubit Tuning

Three parameters to tune:

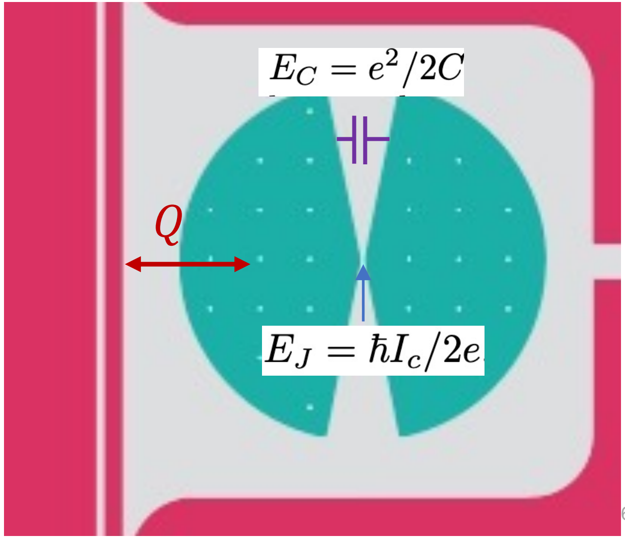
1. Undressed resonance frequency, f_0
2. Frequency separation of parity states, χ_0
3. Total quality factor, Q



f_0 and χ_0 are determined by the charging energy E_C and the Josephson energy E_J

- Determined by Island capacitance and junction parameters

Q is determined by capacitance between qubit and RF feedline



$$\hbar\omega_0 \approx \sqrt{8E_C E_J} - E_C \qquad \frac{2\chi_0}{\omega_0} \approx e^{-\sqrt{8\xi}}\left[A\xi^{3/4} + B\xi^{1/4}\right]$$

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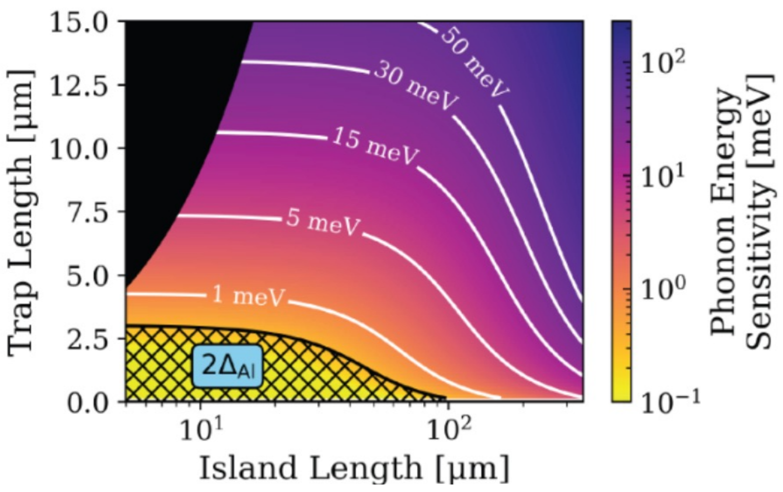
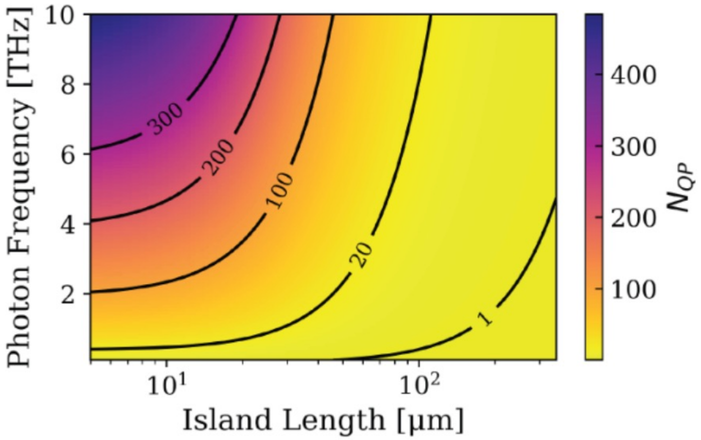
Energy Sensitivity

- Sensor is measuring quasiparticle number
  - Signal enhancement of ratio of energy in QP system to island gap!

$$N_{QP} \approx \frac{\eta_{QP}}{\Delta_{island}}$$

- Readout scheme with sensitivity of parity flip from single QP events allows for sensor geometries sensitive to single meV phonons and photons





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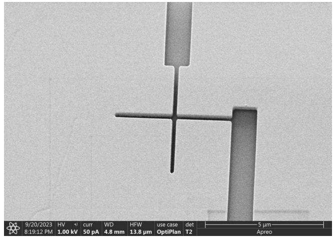
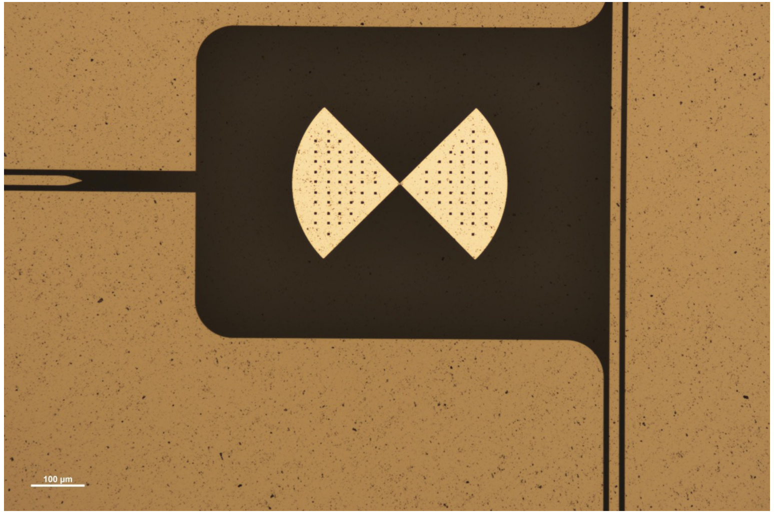
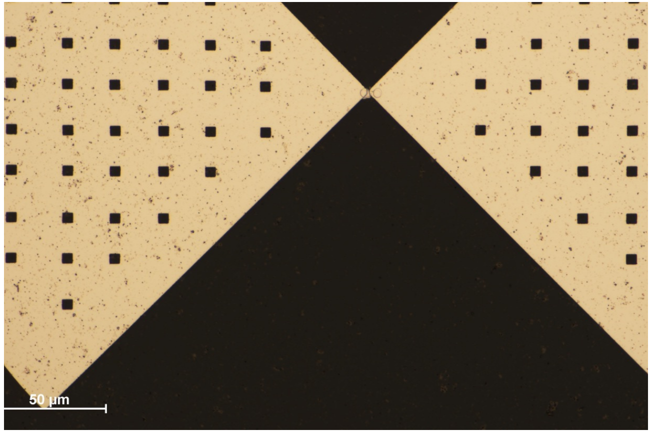
First R&D Prototype Devices



- First prototype devices have been fabricated at SLAC
- Initial device have Al islands and Al junctions (no QP trapping)
- Devices meant to test understanding of qubit parameters and test single QP readout
- Using Manhattan style junctions, next iteration will move to Dolan junctions





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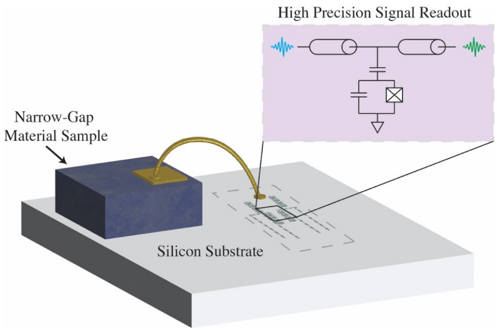
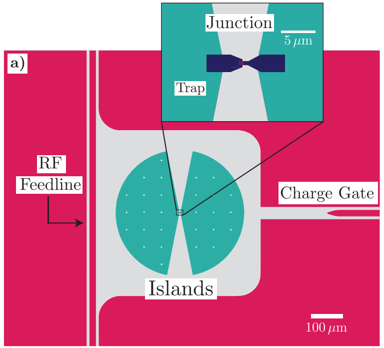
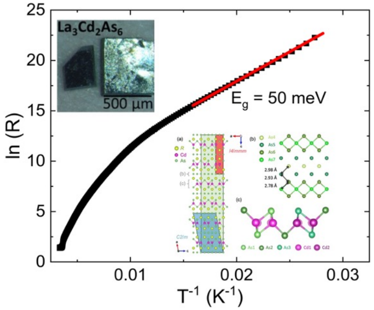
Conclusions

- Wide range of compelling physics at the meV scale – both from HEP and NP.
- To reach these thresholds, advancements in both detector materials and sensor thresholds needs to be made.
- We have made progress on both these fronts - through both the development of **novel quantum materials** and **qubit-based** sensors for both charge and phonons.
- There are many exciting directions to take this work in – always open to new collaborators!







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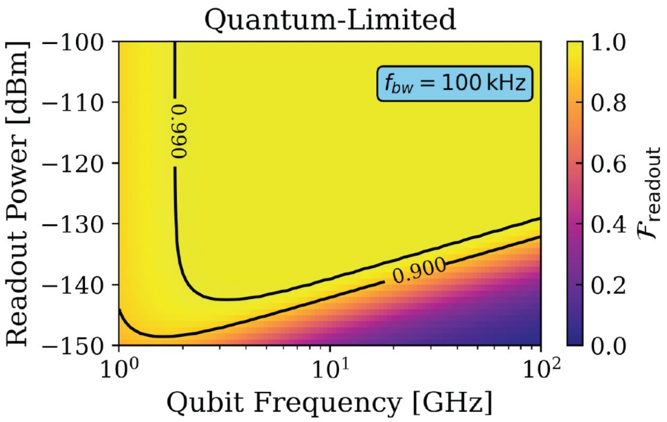
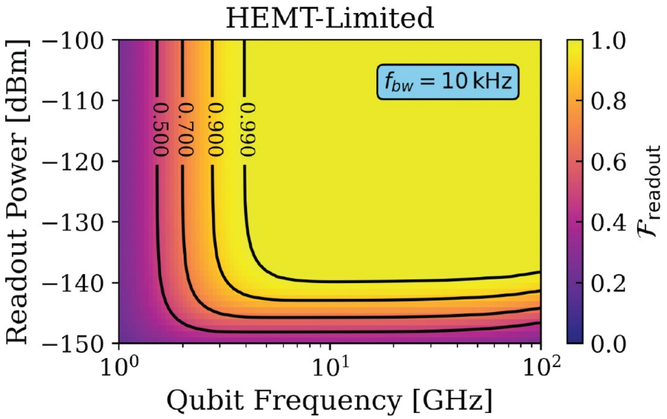
Backup Slides

Signal Efficiency from Readout Fidelity

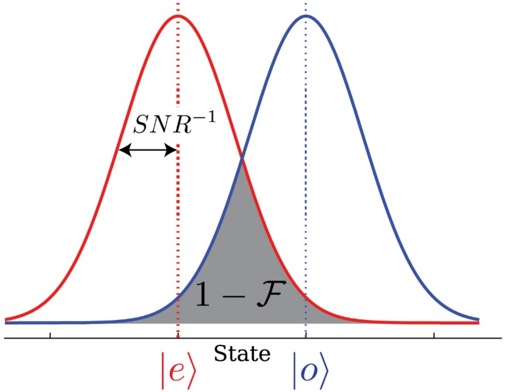
- For a given undressed qubit frequency, the readout bandwidth will be be limited by the readout fidelity
- For quantum-limited readout, perfect fidelity can be achieved with O(GHz) qubits
- HEMT-limited readout requires either BW to be lowered or qubit frequency to be raised





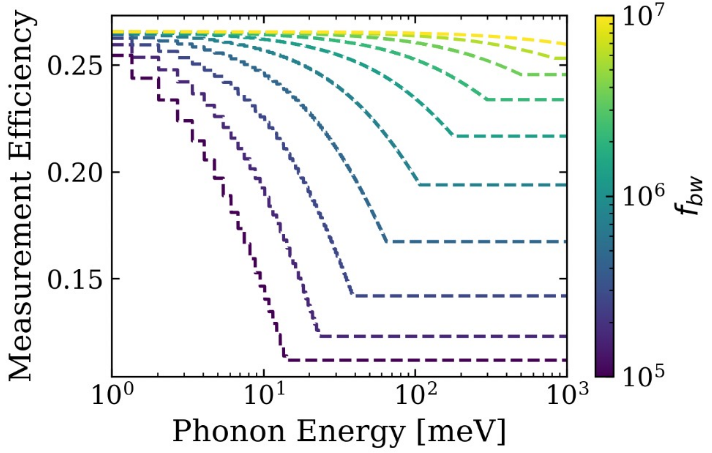
$$\mathcal{F} = 1 - \exp\left(-\frac{SNR}{4}\right)$$

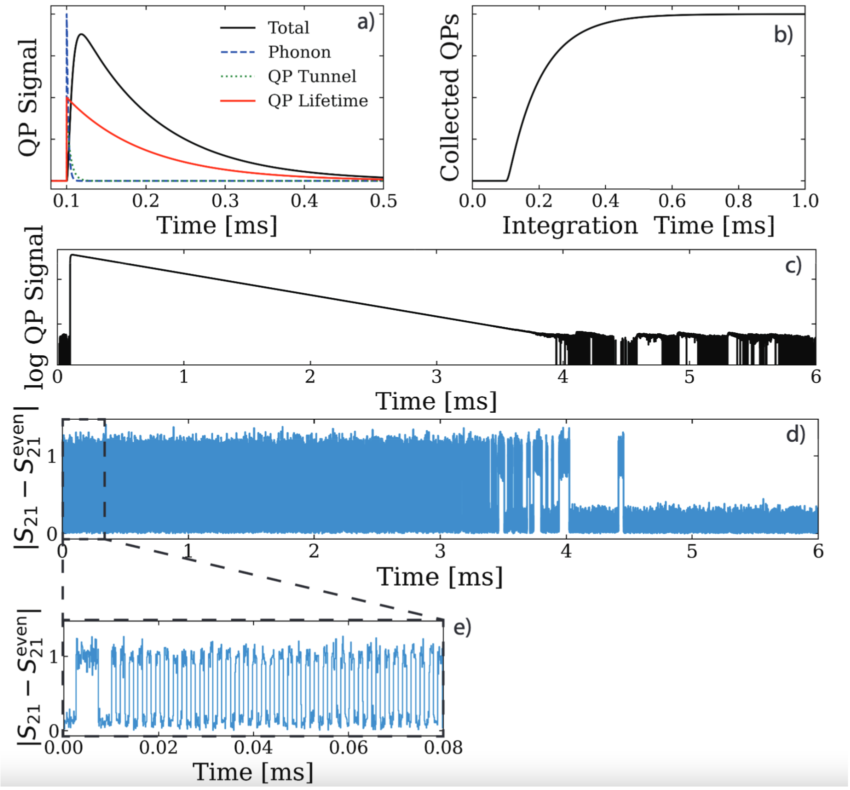
$$SNR^{-1} = \sigma^2 = \frac{2P_n}{\epsilon_r P_r} = \frac{2k_B T f_{bw}\eta\left(\frac{hf}{k_B T}\right)}{P_r\left[1 - \exp\left(-\frac{\hbar f_0^2}{Q_c P_r}\right)\right]}.$$



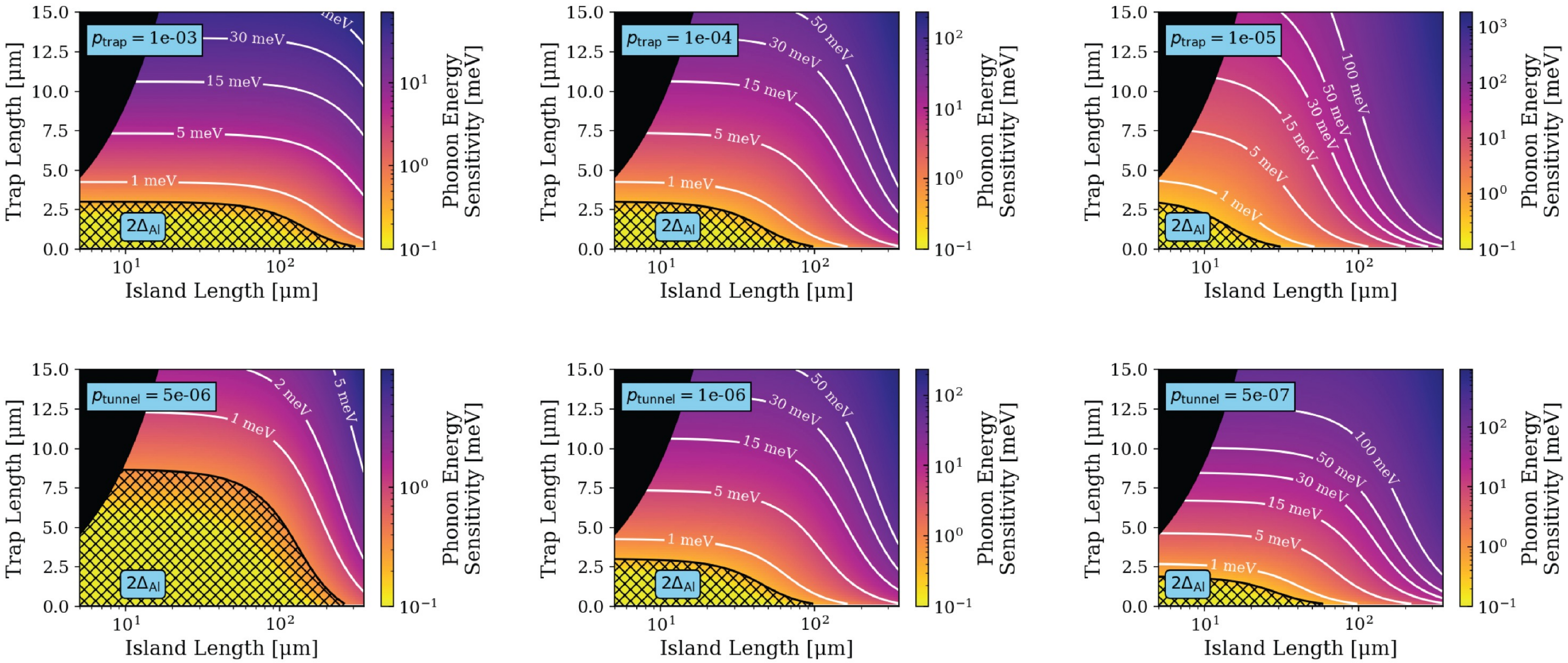
Signal Efficiency from Readout Bandwidth

- Expected signal pulse is convolution of phonon signal, QP tunneling rate, and QP lifetime
- Finite readout bandwidth sets limit on observable parity switching rate
- Bandwidth decreases energy efficiency for events eV and above

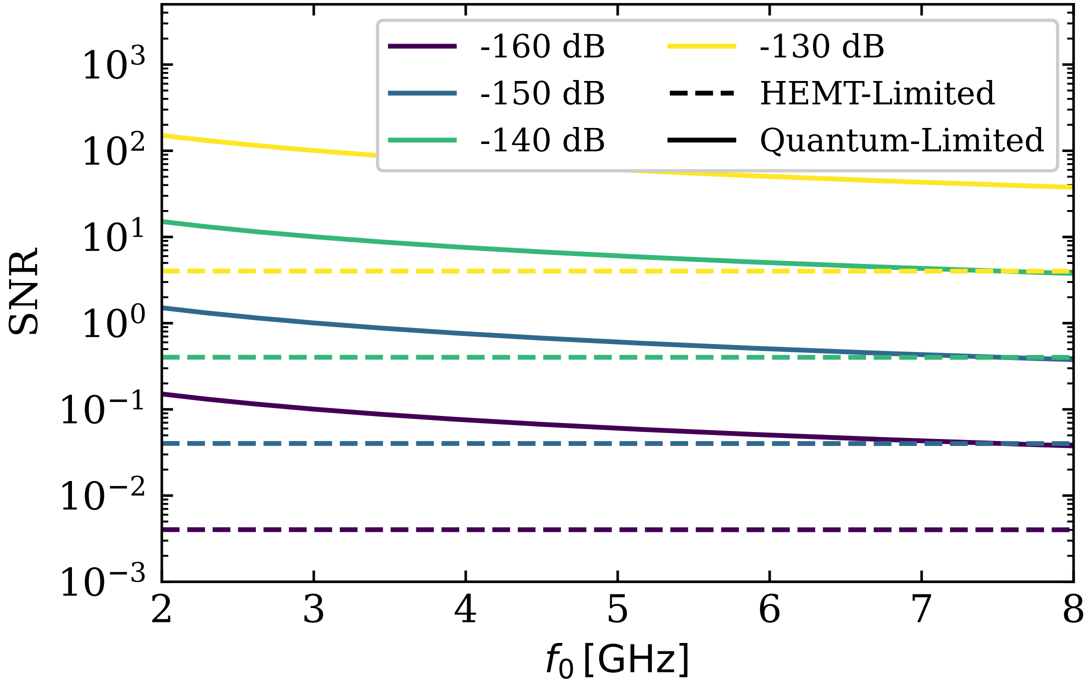




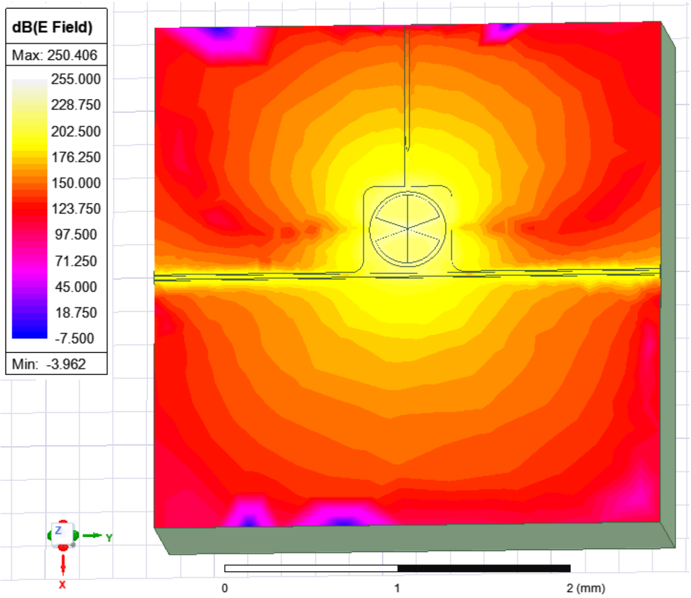
Effect of Tunneling and Trapping

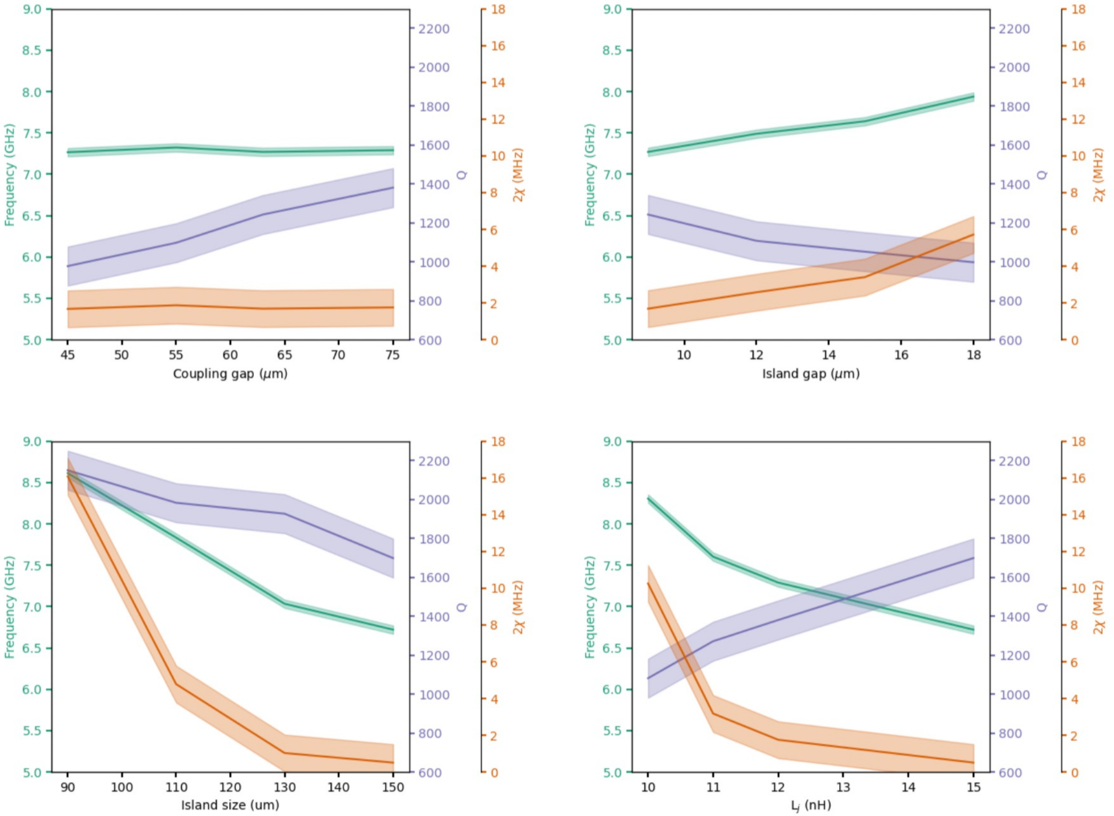


Signal to Noise



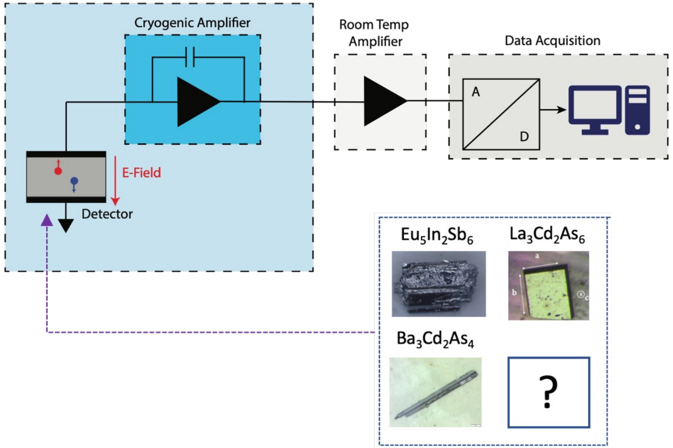
Qubit Simulations

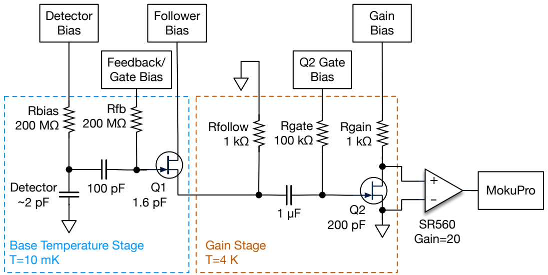




Material Independent Charge Readout

- SPLENDOR is developing a *material independent* cryogenic HEMT based charge readout
- Two stage amplifier using low capacitance CryoHEMTs
- Will allow for the rapid prototyping of any insulating material





arXiv:2311.02229 [physics.ins-det]

Detector housing and amp topology keep total capacitance at O(1 pF)

$$\sigma_E \sim E_{gap}\ \sigma_V\ \underbrace{(C_{detector} + C_{input} + C_{parasitic})}$$

Path to Single-Charge Sensitive Amplifier

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]
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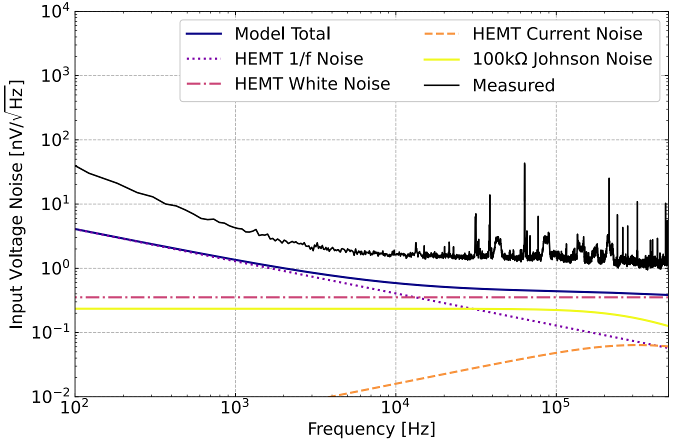
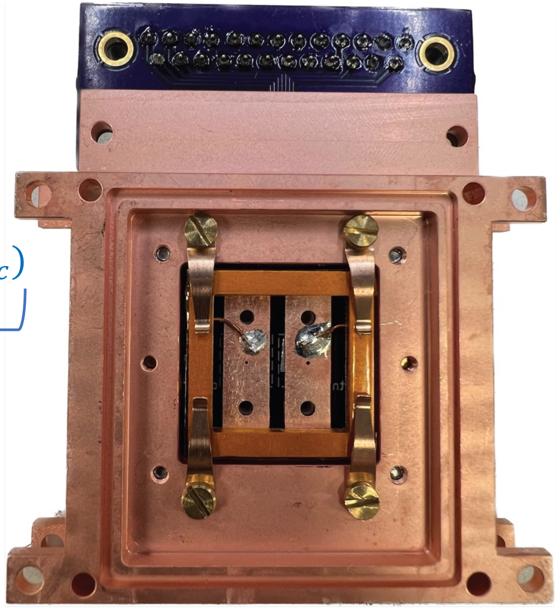
[2] SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA
[3] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA, 94035, USA
[4] Santa Clara University, Santa Clara, CA 95053, USA
[5] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[6] California State University, East Bay, Hayward CA 94542, USA

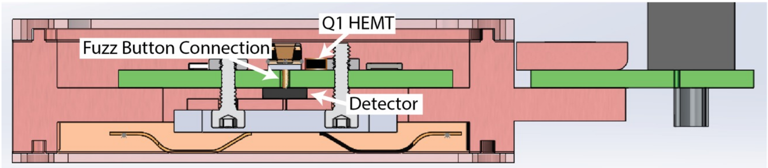
- Prototype amplifier has has an integrated noise of 7 electrons
- Fully optimized version of the amplifier should reach 2-3 electron resolution

$$\sigma_E \sim E_{gap}\ \sigma_V\ (C_{detector} + C_{input} + C_{parasitic})$$

$$\sigma_{charge} \approx 7\ e$$







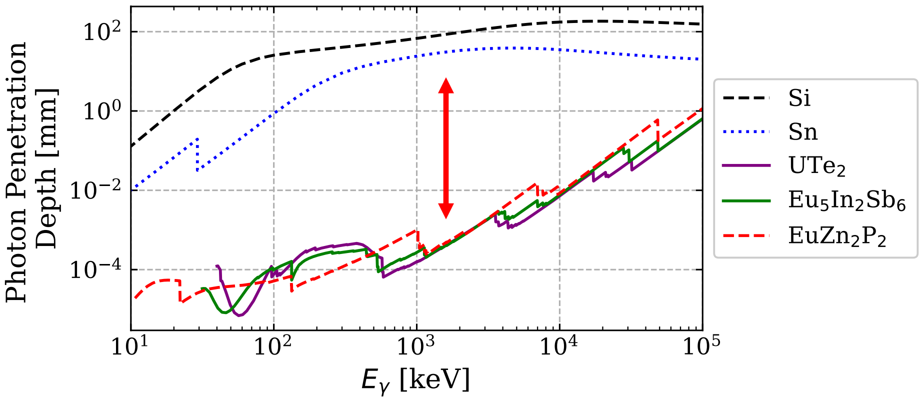
- <u>Relevant physics at the milli-eV scale</u>
  - Dark mater
  - Coherent elastic neutrino nucleon scattering (CEνNS)
  - Nuclear non-proliferation
- <u>Exploration of novel detector targets</u>
  - Novel narrow bandgap semi-conductors for dark matter
    - Ionization readout with HEMTS
    - Ionization readout with qubits
  - Heavy-fermion materials for dark matter
  - <u>Lanthanide, and actinide materials for high efficiency gamma counting</u>
- <u>Novel sensor development</u>
  - Existing superconducting technologies
  - Transmon based athermal phonon sensors

High Efficiency Gamma Detection

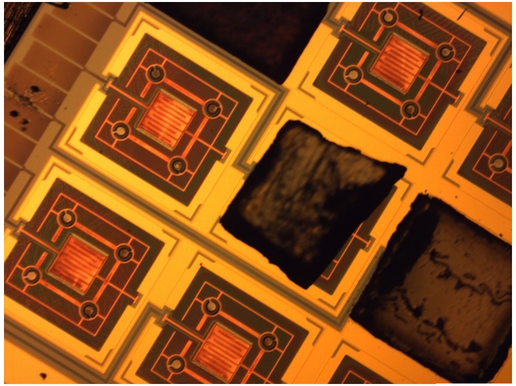
- Superconductor based X-ray spectrometers have been very successful
  - Efficiency drops for high energy gammas

- Large volume HPGe detectors have been used with good efficiency but poor energy resolution

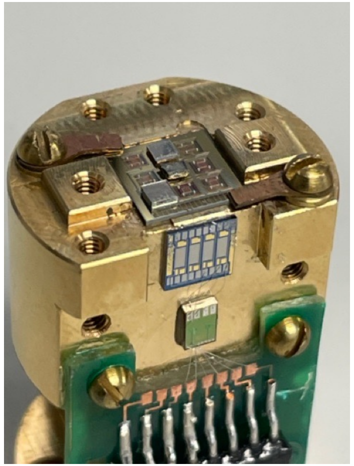
- **Lanthanide, and actinide based materials are typically high-Z and dense giving them many orders of magnitude more stopping power than traditional detector materials**



Quantum Materials as Calorimeters using TESs

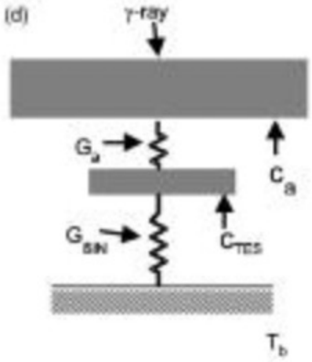


- Currently studying several novel materials as calorimeters with Transition Edge Sensors
- Repurposing gamma TESs made by NIST
- Currently studying LANL grown:
    - narrow bandgap semiconductors: $Eu_5In_2Sb_6$, and $EuZn_2P_2$
    - Topological Insulator SmB_6,



Array-compatible transition-edge sensor microcalorimeter γ-ray detector with $42\ \mathrm{eV}$ energy resolution at $103\ \mathrm{keV}$

B. L. Zink; J. N. Ullom; J. A. Beall; K. D. Irwin; W. B. Doriese; W. D. Duncan; L. Ferreira; G. C. Hilton; R. D. Horansky; C. D. Reintsema; L. R. Vale



- First probe of the non-equilibrium phonon dynamics of many of these materials
- Results expected in early 2024

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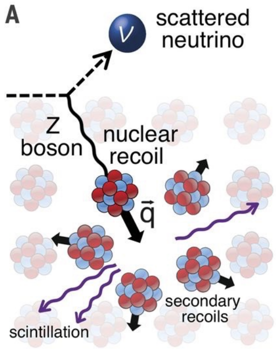
NIST

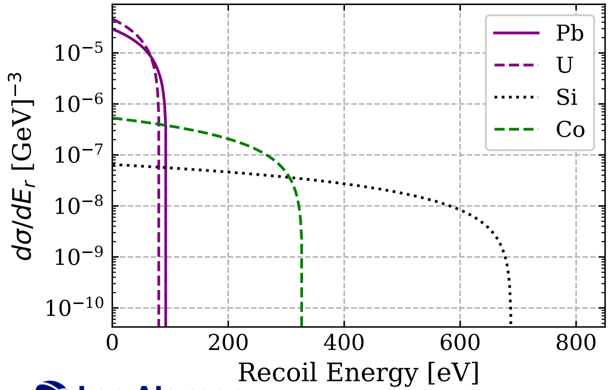
Low Energy Neutrino Physics

- Neutrinos of energy $E_\nu < 50$ MeV will scatter coherently with the entire nucleus
  - CEνNS
- Differential rate depends strongly on Z
  - Threshold scales inversely with nucleon mass
- Lower threshold detectors offer access to large rate enhancement.

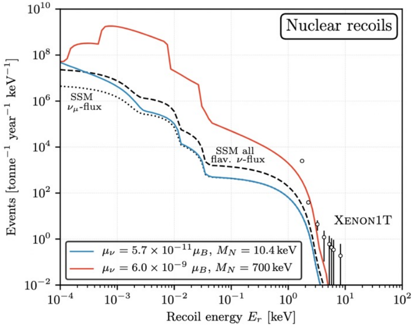


$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{4\pi} \cdot (N - Z \cdot (1 - 4\sin^2\theta_W))^2 \cdot (1 - \frac{E_R}{E_R^{max}}) \cdot F^2(q^2)$$

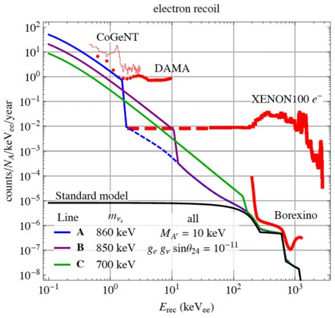
$$E_R^{max} = 2E_\nu^2/(M + 2E_\nu)$$



BSM Neutrino Physics: Neutrino Magnetic moment



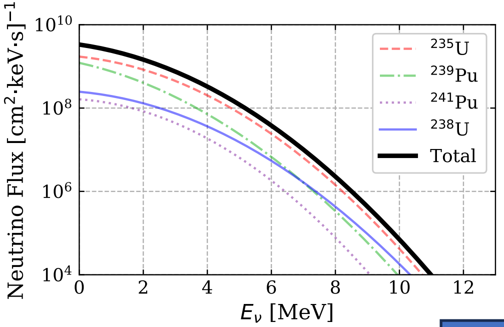
Vedran Brdar *et al* JCAP01(2021)039



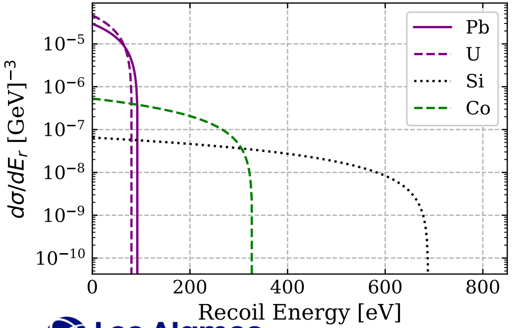
Roni Harnik *et al* JCAP07(2012)026

Nuclear Reactor Neutrinos with Novel Materials

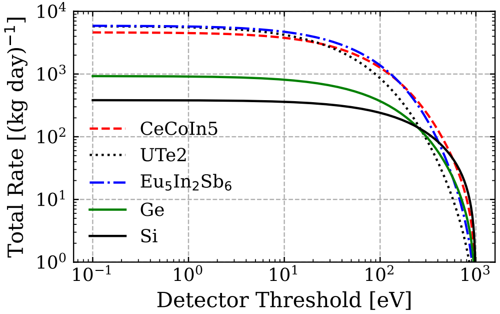
Reactor neutrino spectrum



Differential Rate



Lanthanide, and actinide based materials offer an order of magnitude of rate enhancement over traditional detector materials



Powerful probe of the standard model as well as nuclear safeguard applications

Spent Fuel monitoring

Power Monitoring