Novel Quantum Material Based Detectors for Probes of Beyond the Standard Model Physics

Caleb Fink
Directors Postdoc Fellow - LANL

LA-UR-23-32612

Novel Quantum Materials as Probes of BSM Physics

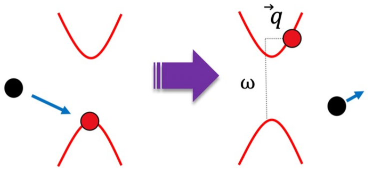
- Light Dark Matter Detection – Electronic Recoils
  - Novel narrow bandgap Semiconductors with the SPLENDOR experiment
    - Development of low noise charge sensitive devices
  - Leveraging unconventional superconductors as sensors

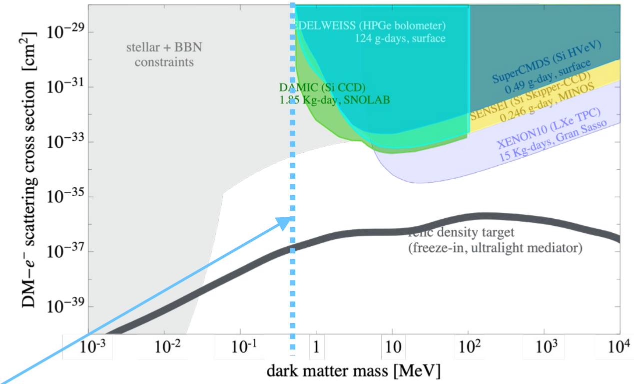
- Nuclear Recoils on the meV scale
  - CEVNS detection with novel materials
  - Qubit based athermal phonon sensors

- High Efficiency Gamma Ray detection with High-Z dense materials

Searching for Dark Matter Below the MeV Scale

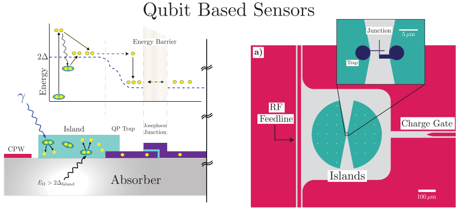
- Low kinetic energy of dark matter requires targets sensitive to very small energy depositions
- Existing detection technologies (Si, Ge) have O(eV) energy thresholds
- Probing fermionic DM masses below MeV requires new detection techniques

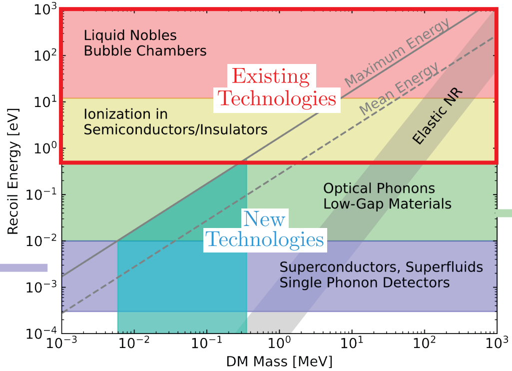




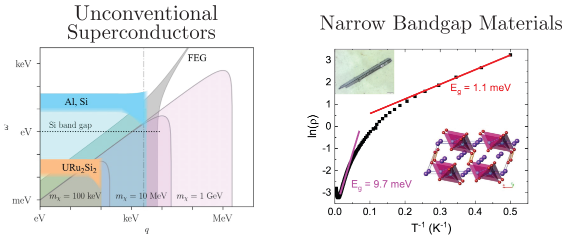
Mass reach is limited by O(eV) band gaps of Si/Ge

Novel Superconducting Sensors





novel topological materials



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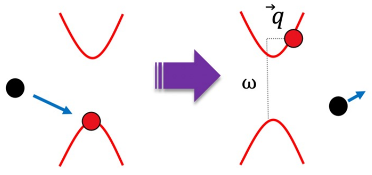

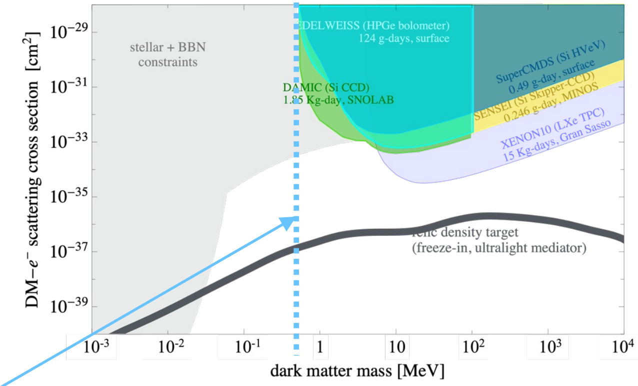

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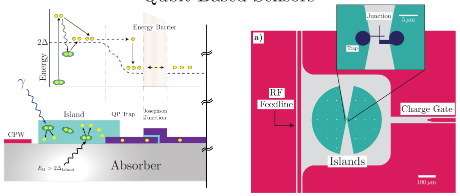
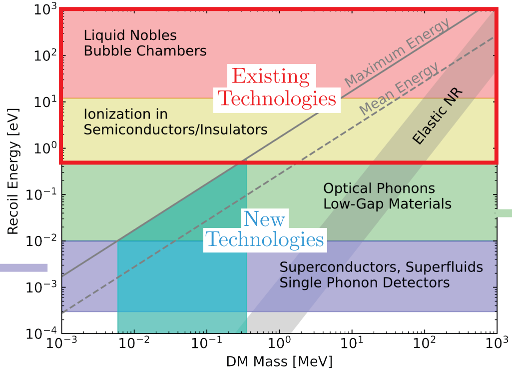
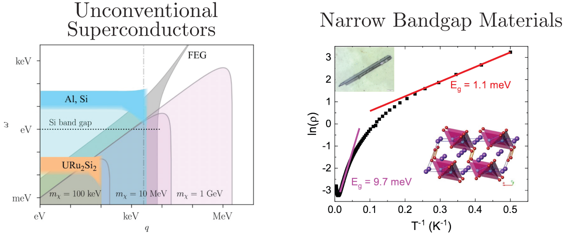
Novel Superconducting Sensors


Qubit Based Sensors



novel topological materials

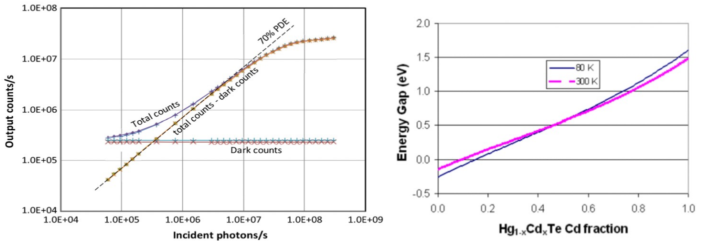

Unconventional Superconductors

Narrow Bandgap Materials

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

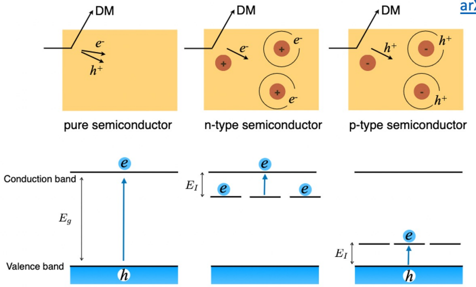
HgCdTe avalanche photodiode array *Optical Engineering 58(6), June 2019*



Doped Semiconductor Devices for sub-MeV Dark Matter Detection

Peizhi Du,[1] Daniel Egaña-Ugrinovic,[2] Rouven Essig,[3] and Mukul Sholapurkar[4]

arXiv:2212.04504 [hep-ph]



JOURNAL OF APPLIED PHYSICS VOLUME 38, NUMBER 11 OCTOBER 1967

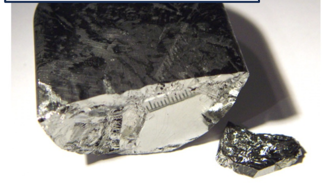
Noise and Multiplication Measurements in InSb Avalanche Photodiodes

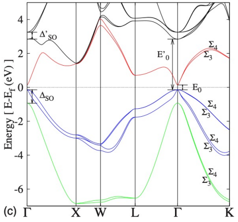
R. D. BAERTSCH

General Electric Research and Development Center, Schenectady, New York

(Received 15 May 1967)

Gap~ 230meV



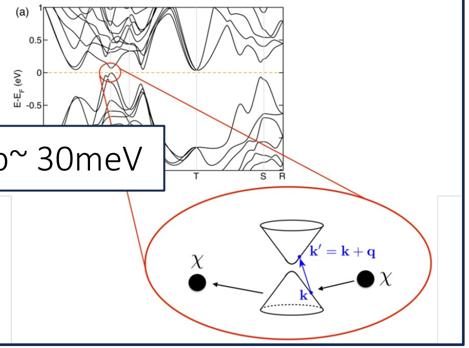


Dirac materials for DM

[Hochberg, **YK**, Lisanti, Zurek, Grushin, Ilan, Liu, Weber, Griffin, Neaton, Phys. Rev. D 2018, 1708.08929]

3D Dirac semimetal ($ZrTe_5$)

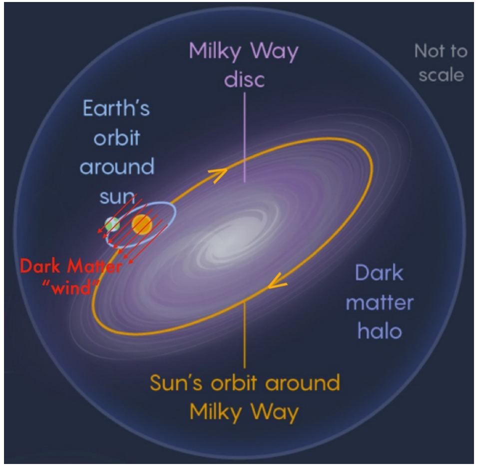
Gap~ 30meV



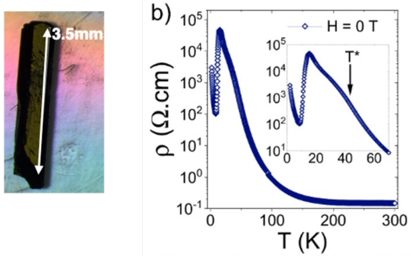
Los Alamos NATIONAL LABORATORY

Novel Narrow Bandgap Semiconductors for SPLENDOR

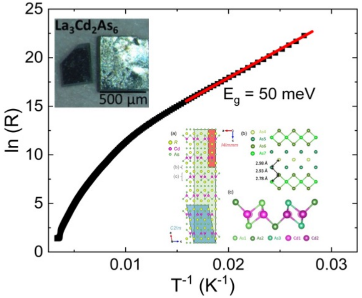
- Search for particles of Light dark matter with narrow-gap semiconductors - SPLENDOR
- Los Alamos funded project developing single-crystal narrow bandgap semiconductors
- Candidate materials have bandgaps in the range of 1-100meV
- Anisotropic bandgaps – sensitive to daily modulation signal

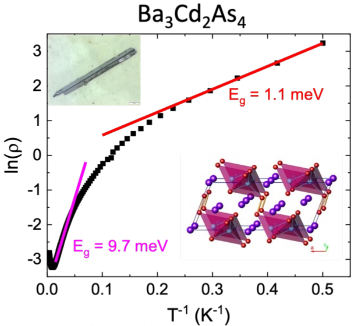


$Eu_5^{2+}[In_2Sb_6]^{-10}$

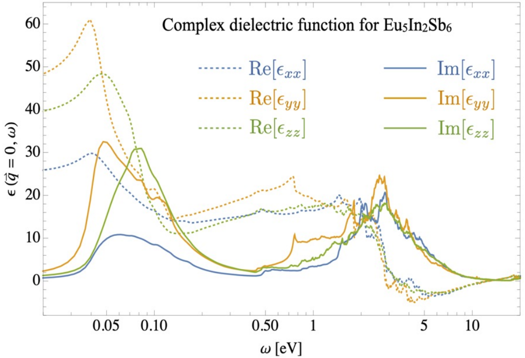


PFS Rosa *et al*, *npj Quantum Materials* **5**, 52 (2020).





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



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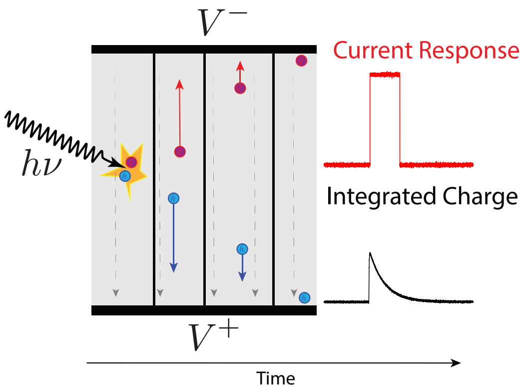
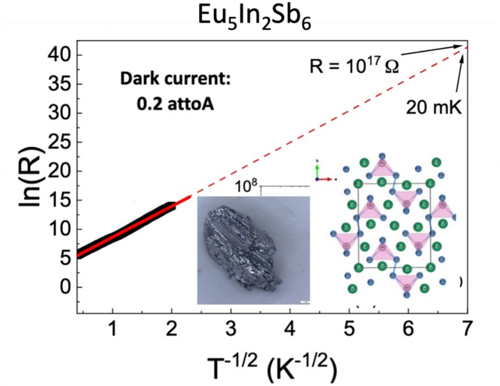
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
CAL STATE EAST BAY
SLAC NATIONAL ACCELERATOR LABORATORY
Santa Clara University

SPLENDOR Material Response

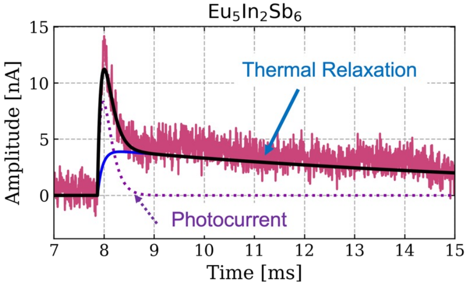
Materials used as point contact ionization detectors – resolution scales as bandgap and amplifier noise

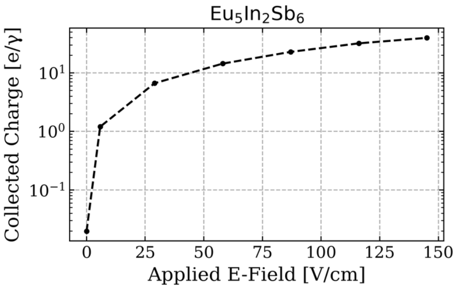




Single crystal synthesis allows for very pure samples - low dark counts over large crystal volumes

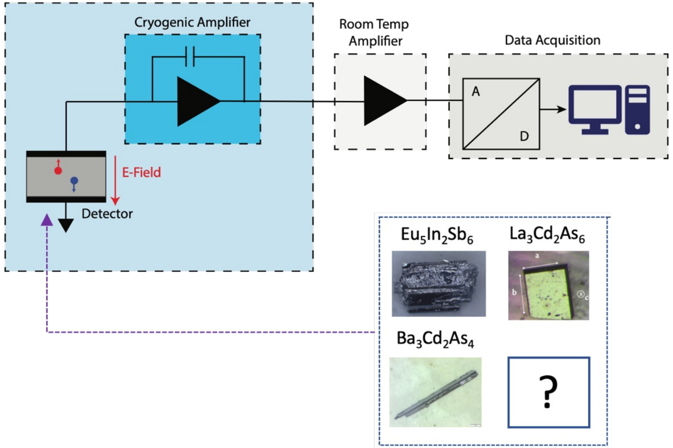
Candidate materials showing photo response to IR light – beginning to reach full charge collection

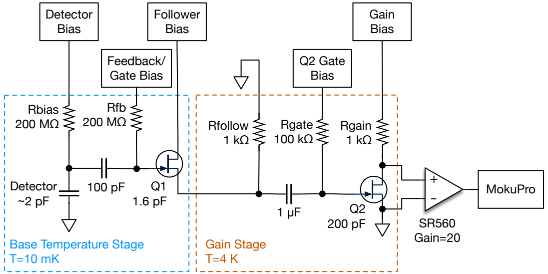




Material Independent Charge Readout

- 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





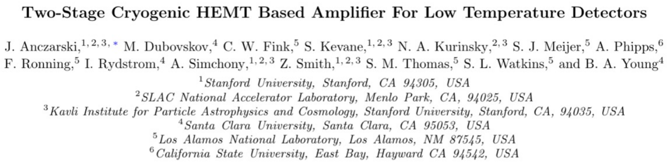
arXiv:2311.02229 [physics.ins-det]

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

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

A. Phipps RDC4 poster session

Path to Single-Charge Sensitive Amplifier



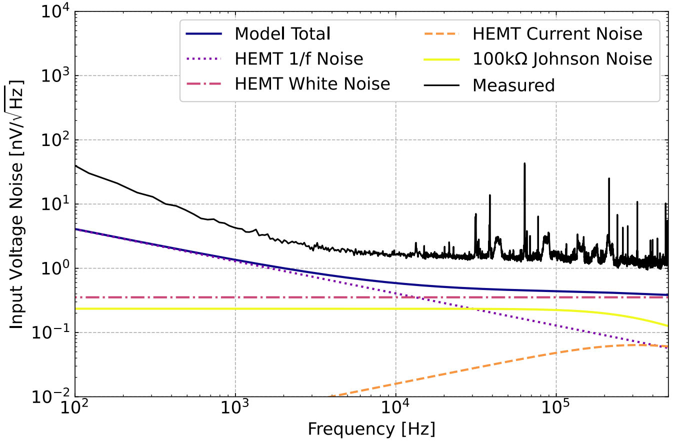
Two-Stage Cryogenic HEMT Based Amplifier For Low Temperature Detectors

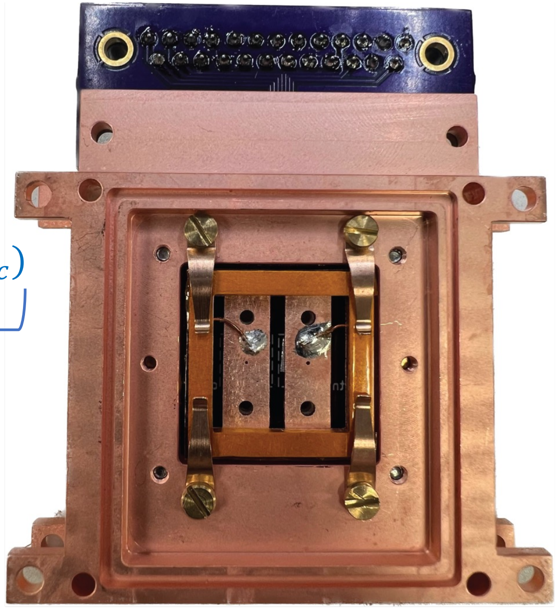
J. Anczarski,[1,2,3,*] M. Dubovskov,[4] C. W. Fink,[5] S. Kevane,[1,2,3] N. A. Kurinsky,[2,3] S. J. Meijer,[5] A. Phipps,[6] F. Ronning,[5] I. Rydstrom,[4] A. Simchony,[1,2,3] Z. Smith,[1,2,3] S. M. Thomas,[5] S. L. Watkins,[5] and B. A. Young[4]

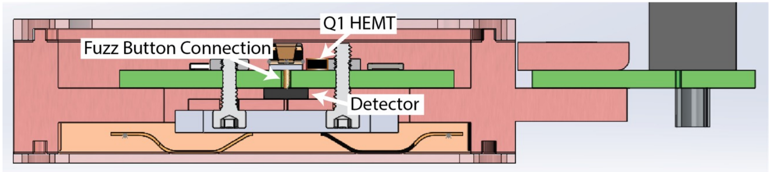
[1] *Stanford University, Stanford, CA 94305, USA*
[2] *SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA*
[3] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA, 94035, USA*
[4] *Santa Clara University, Santa Clara, CA 95053, USA*
[5] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[6] *California State University, East Bay, Hayward CA 94542, USA*

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

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







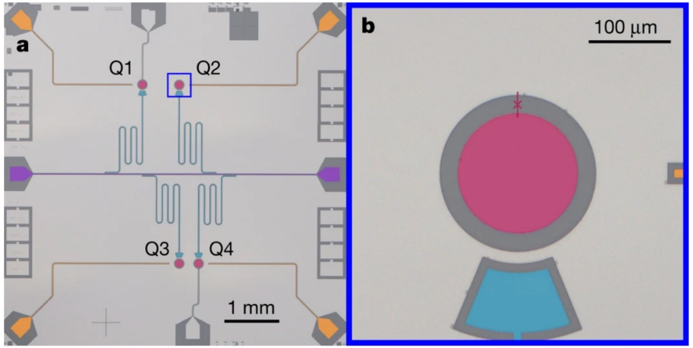
Qubit based charge Amplifier

- 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

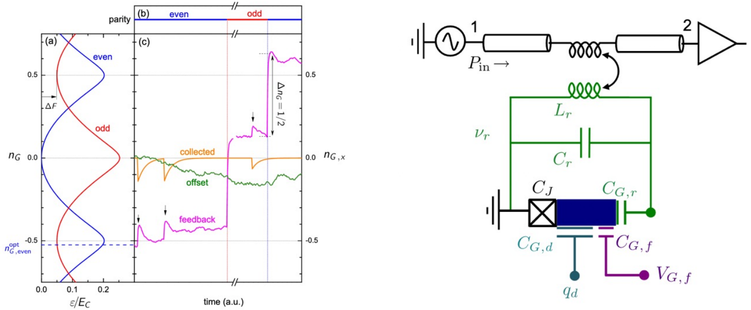
Exploring two low capacitance connections:

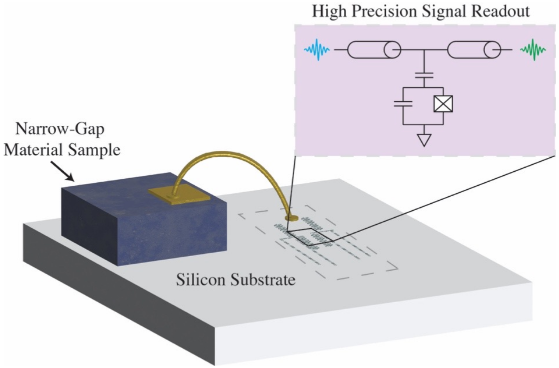
1. Wirebonding sample to qubit gate
2. Modifying SPLENDOR HEMT housing

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



Phys. Rev. Applied 11, 054072





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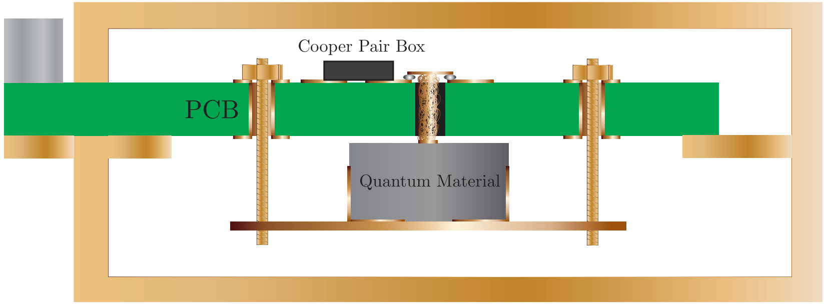

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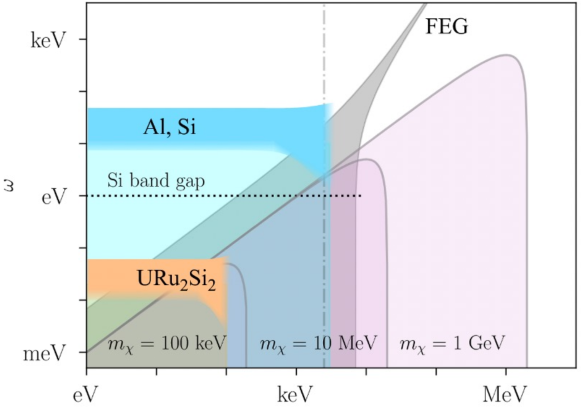
Heavy Fermion Superconductors for Dark Matter

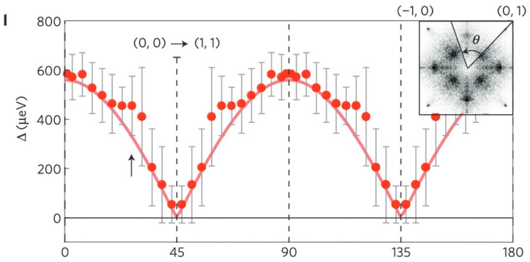
- Class of novel materials with strong light dark matter coupling
- f-electrons hybridize with conduction elections
  - results in quasiparticles with enhanced effective mass (10-1000 m_e)
- Nodal gapped superconductor
- Fermi velocity is reduced by large effective quasiparticle mass
- **Light Dark Matter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

Potential Materials: $URh_2Si_{2,}$ $CeCoIn_5$

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

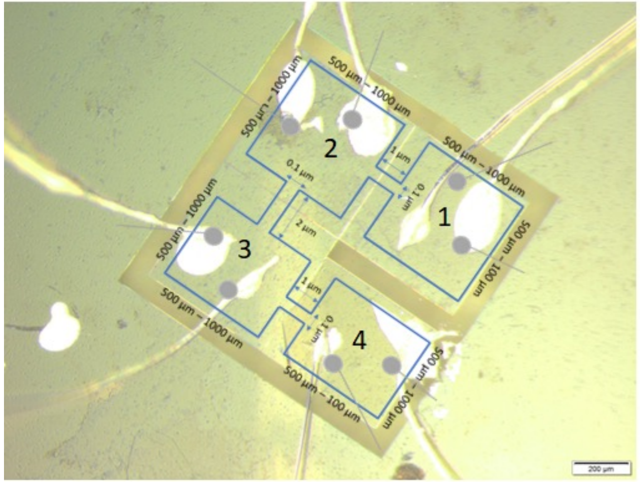
Sensor Development of Unconventional Superconductors

- Kinetic inductance scales with effective QP mass

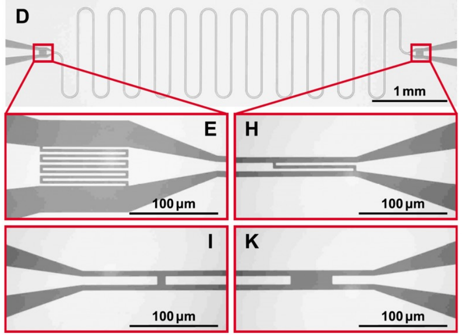
Large DM coupling

Large Kinetic inductance

} Goal: make MKID out of unconventional SC



- Collaborators at Cornell have developed thin film growth of heavy-f superconductor $CeCoIn_5$
- Create microstructures down to 100nm using reactive ion etch
- Basic QP transport studies happening at LANL
- Designing coplanar waveguide structures to measure kinetic inductance of films



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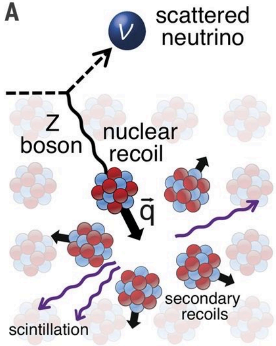
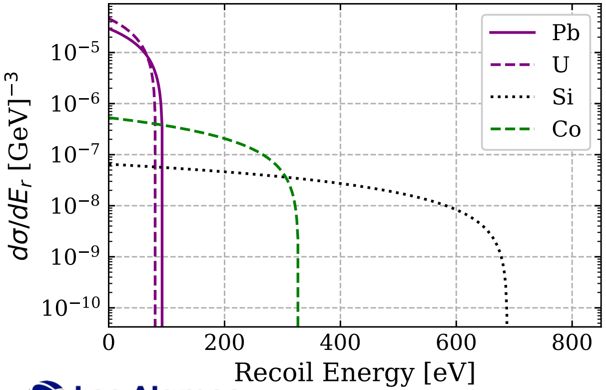
Low Energy Neutrino Physics



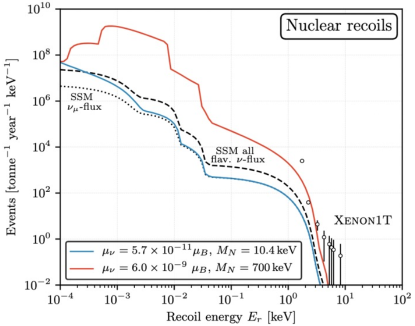
- Neutrinos of energy $E_\nu < 50$ MeV will scatter coherently with the entire nucleus
  - CEνNS
- Differential rate depends strongly on Z
  - Threshold scales inversely with nucleon mass
- Lower threshold detectors offer access to large rate enhancement.

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

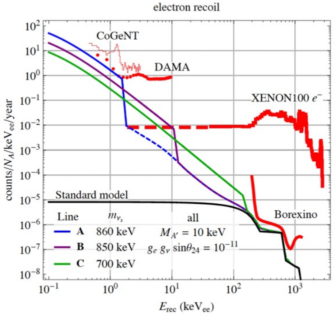
$$E_R^{\max} = 2E_\nu^2/(M + 2E_\nu)$$



BSM Neutrino Physics: Neutrino Magnetic moment



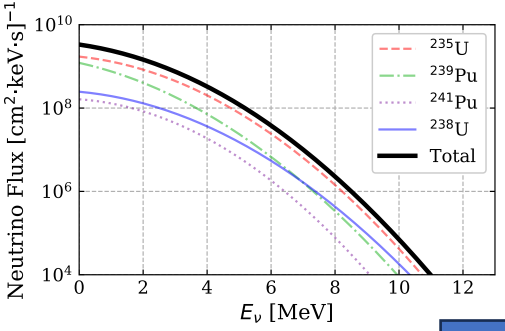
Vedran Brdar *et al* JCAP01(2021)039



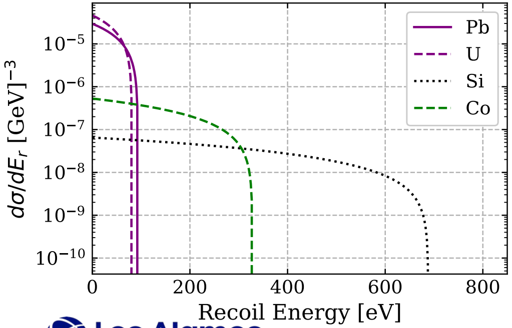
Roni Harnik *et al* JCAP07(2012)026

Nuclear Reactor Neutrinos with Novel Materials

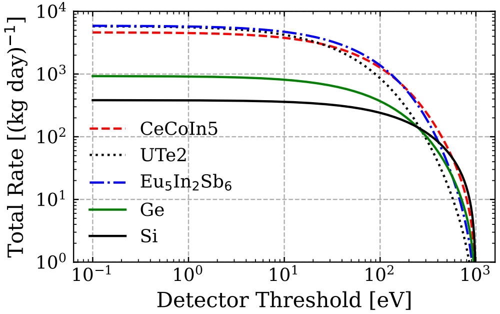
Reactor neutrino spectrum



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

Power Monitoring

Spent Fuel monitoring

The SPLENDOR amplifier development offers way to read charge signal from a variety of these materials – still need way to read out meV scale nuclear recoils

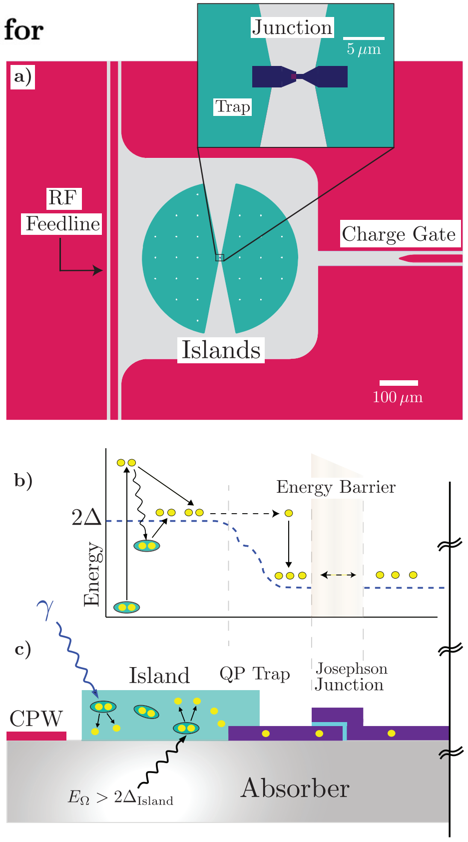
The Superconducting Quasiparticle-Amplifying Transmon

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,‡]

- 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 $1\mu s$

RDC8: session #3



arXiv:2310.01345 [physics.ins-det]

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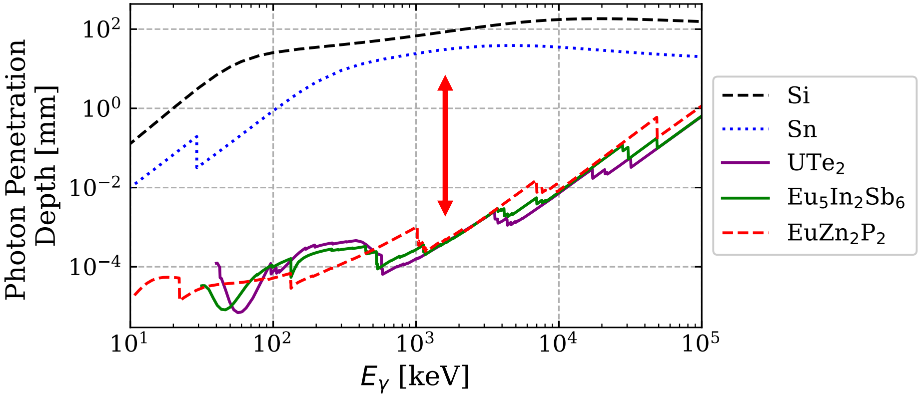
High Efficiency Gamma Detection

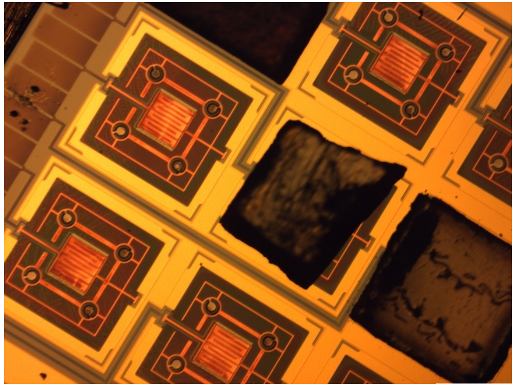
- Superconductor based X-ray spectrometers have been very successful
    - Efficiency drops for high energy gammas

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

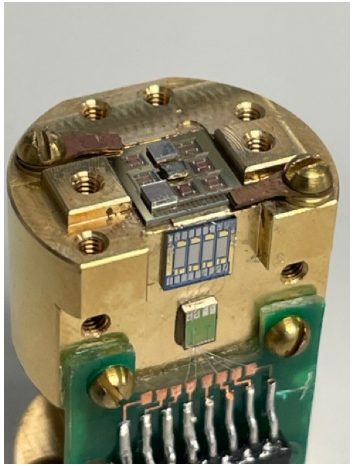
- **Lanthanide, and actinide based materials are typically high-Z and dense giving them many orders of magnitude more stopping power than traditional detector materials**

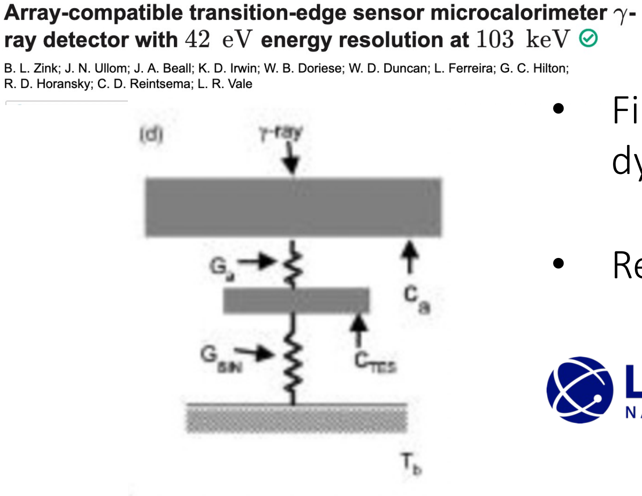


Quantum Materials as Calorimeters using TESs



- 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 late 2023/early 2024

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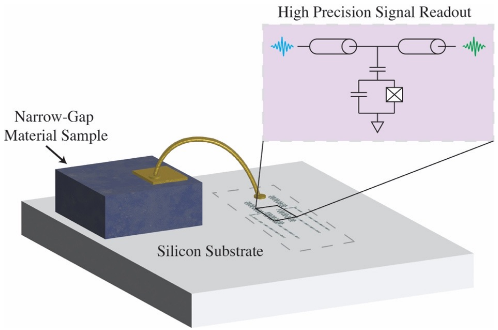
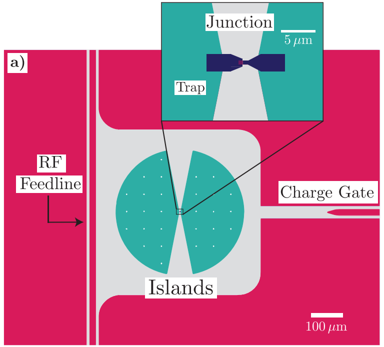
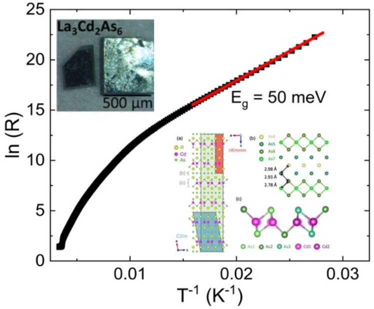
Conclusions

- 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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