



Searching for Light Dark Matter with Narrow-Gap Semiconductors: The SPLENDOR Experiment

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On behalf of the SPLENDOR collaboration

TAUP 2023

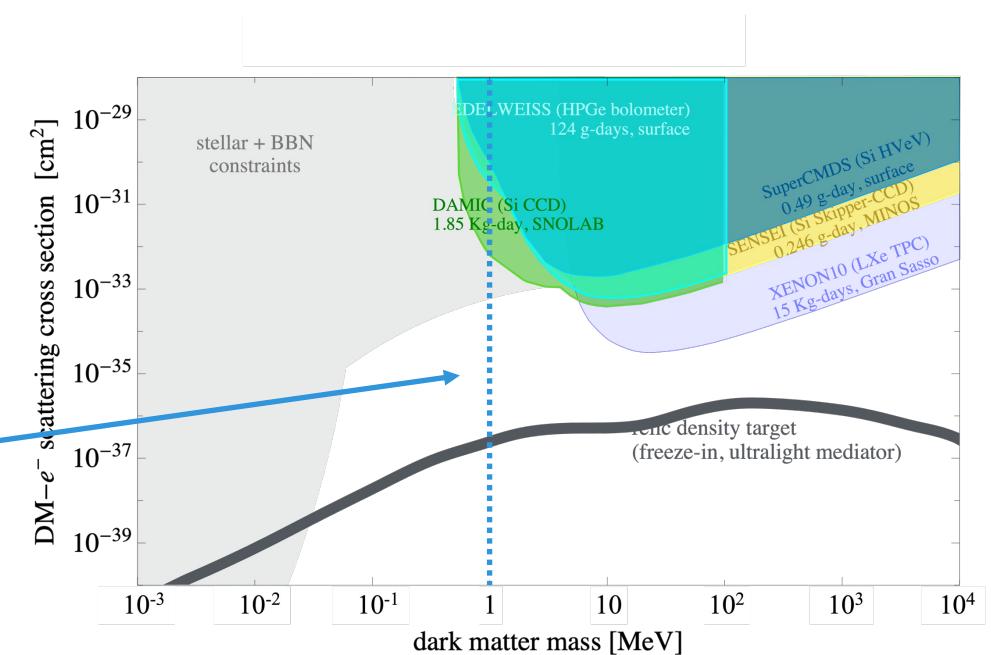
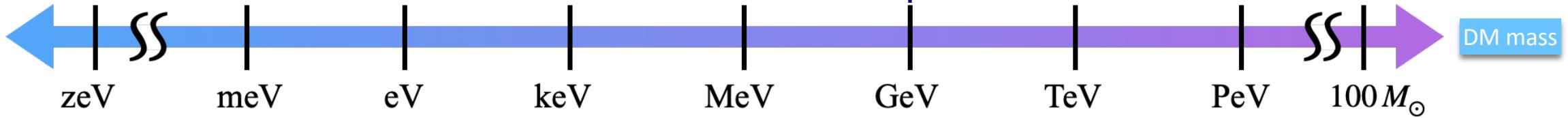
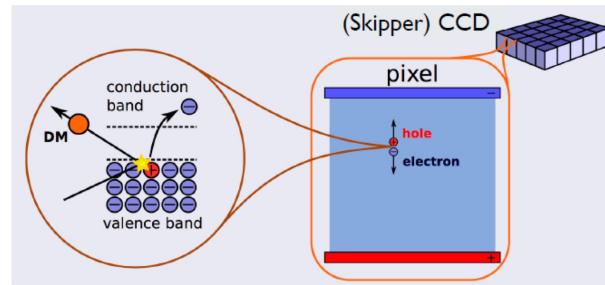
August 28, 2023

LA-UR-23-29709

Dark Matter Detection: Last 10 Years

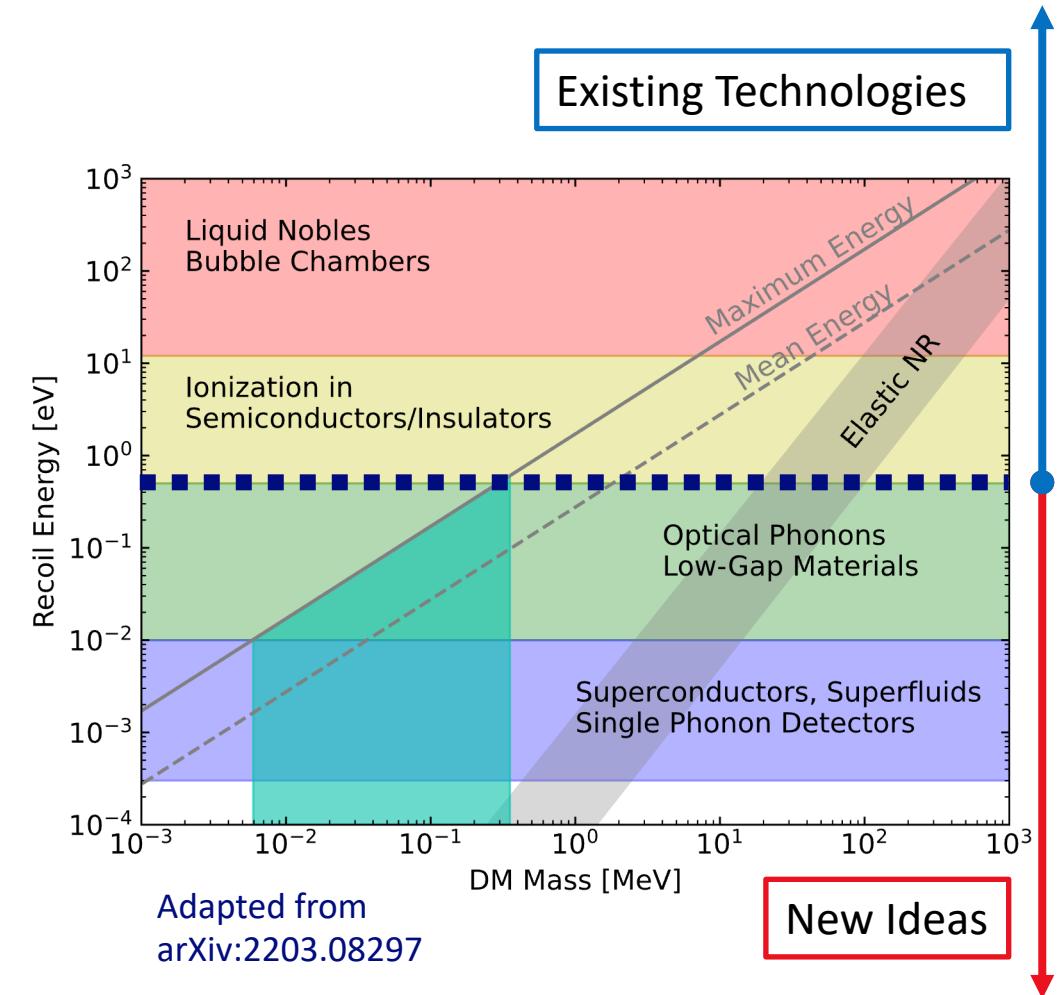
- Lots of focus on DM-electron interactions
- Many experiments probing DM masses in the MeV-GeV range

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

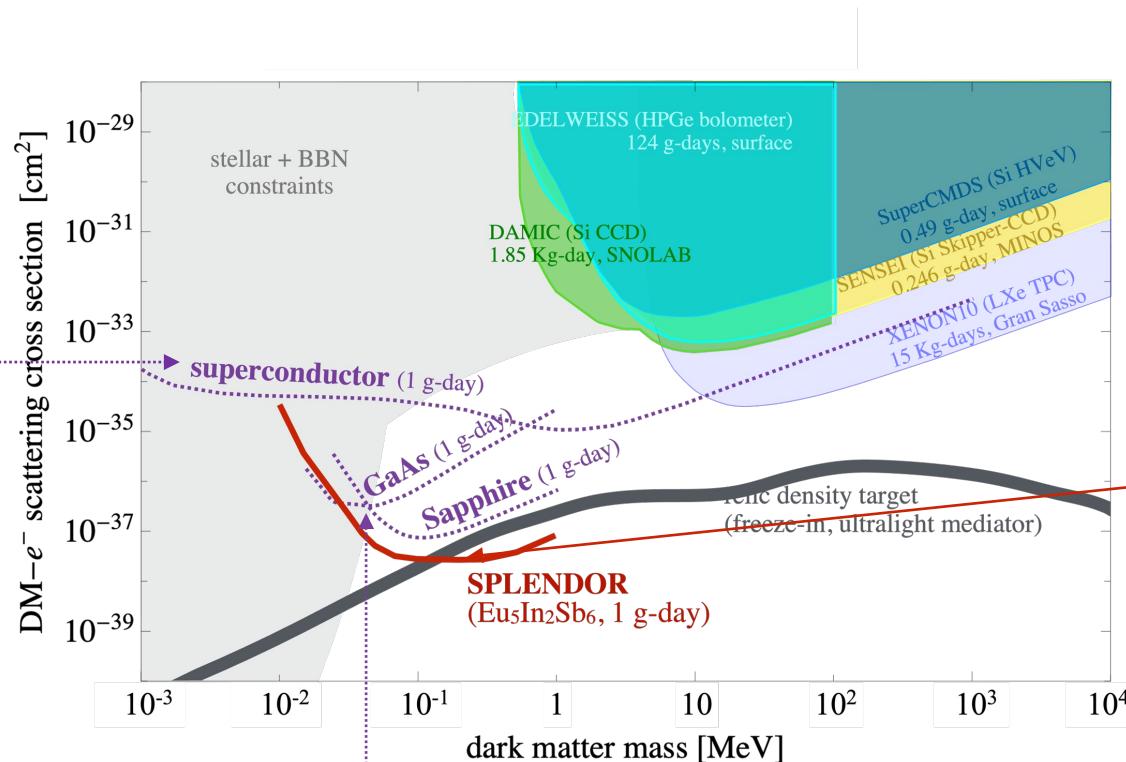
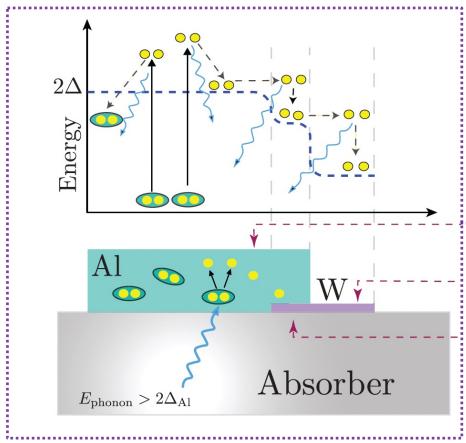


Searching Below the MeV Scale

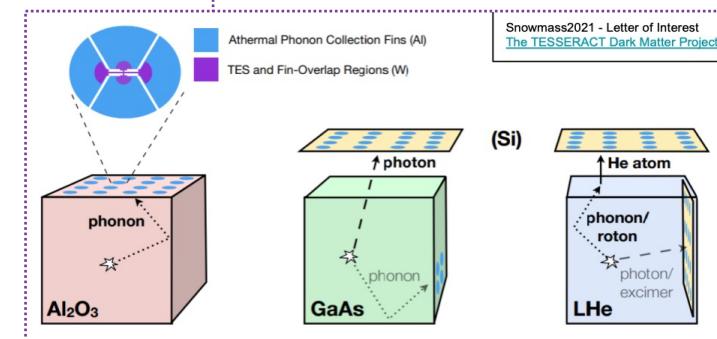
- Low kinetic energy of DM requires targets sensitive to very small energy depositions
- Existing detection technologies have $O(eV)$ thresholds
- Probing fermionic DM with masses below $O(MeV)$ requires new detection techniques



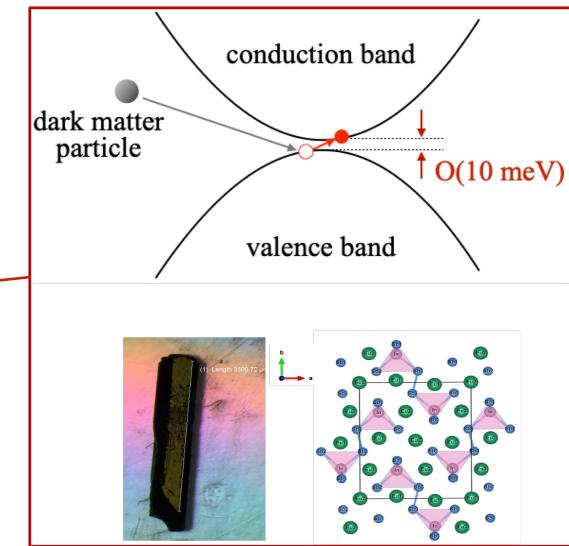
Next-Generation Experiments



Dirac materials and superconductors



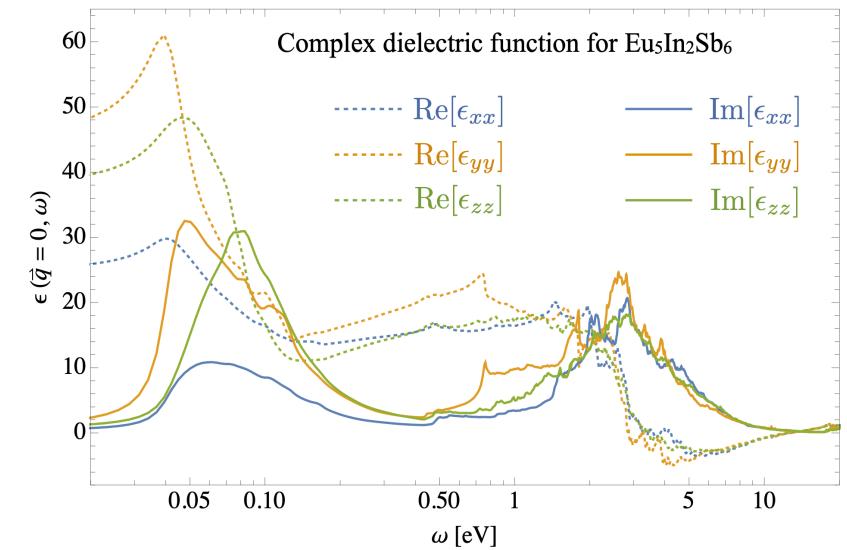
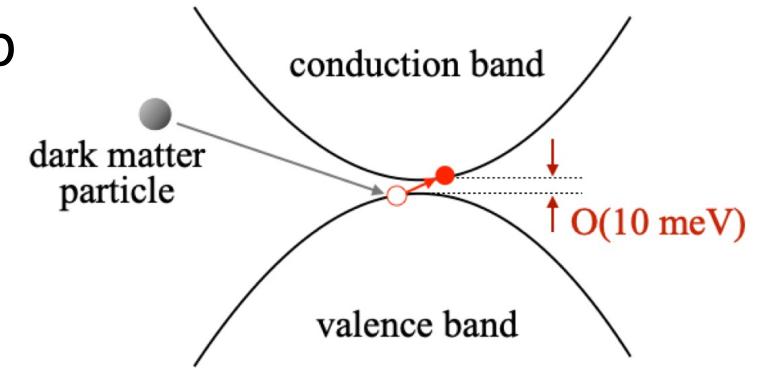
Novel narrow bandgap semiconductors



Optical phonons in polar crystals

The SPLENDOR Experiment

- **Search for Particles of Light Dark Matter with Narrow-Gap Semiconductors**
- SPLENDOR is developing novel single crystal semiconductors with bandgaps of $O(1\text{-}100 \text{ meV})$
- Single crystal synthesis allows for scalable substrates with lower dark rates than existing heavily-doped IR-sensitive photodiodes
- Materials have highly-anisotropic band structures
 - Providing sensitivity to daily DM modulation effects



Dark Matter-Electron Scattering in Semiconductors

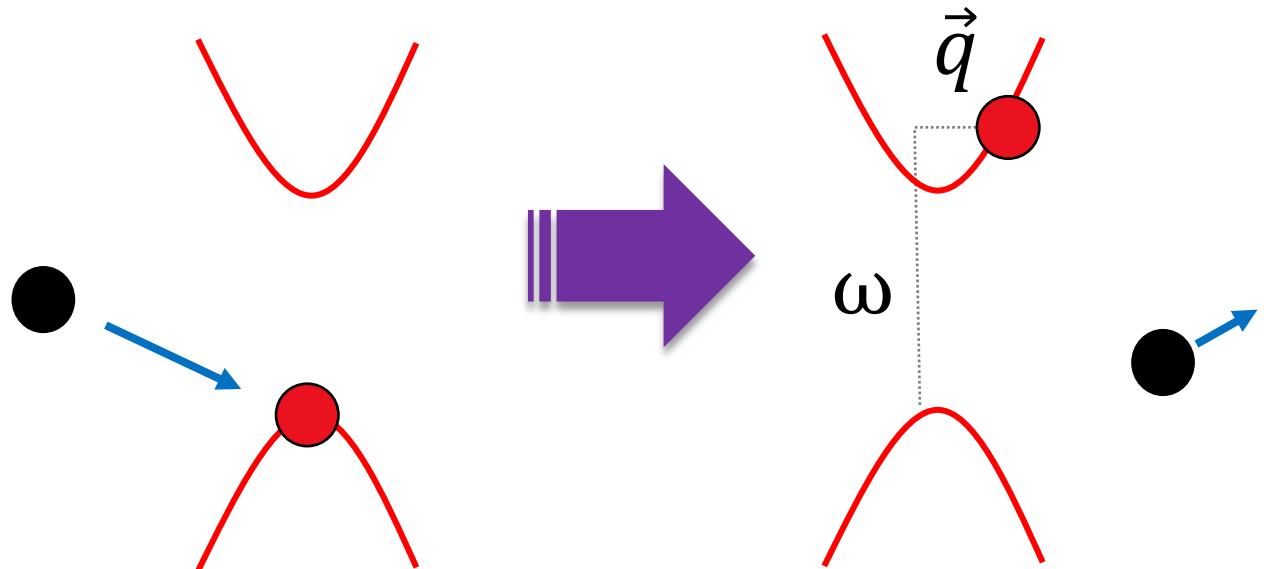
- Inelastic scattering process
- Can formulate in terms of the **Loss Function**
 - Experimentally measurable and theoretically calculable

$$\Gamma(\mathbf{v}_\chi) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[2 \frac{q^2}{e^2} \text{Im} \left(-\frac{1}{\varepsilon(\mathbf{q}, \omega_\mathbf{q})} \right) \right]$$

$$\mathcal{W}(\mathbf{q}, \omega) \equiv \text{Im} \left(-\frac{1}{\varepsilon(\mathbf{q}, \omega)} \right)$$

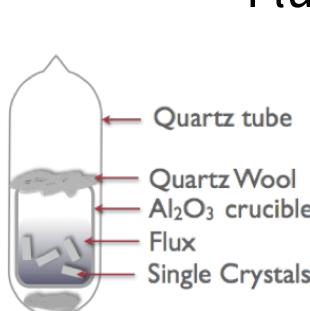
Y Hochberg *et al*, *Phys. Rev. Lett.* **127**, 151802 (2021).

- What materials can we use?

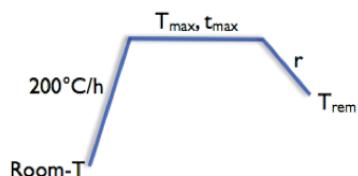


In-House Materials Discovery

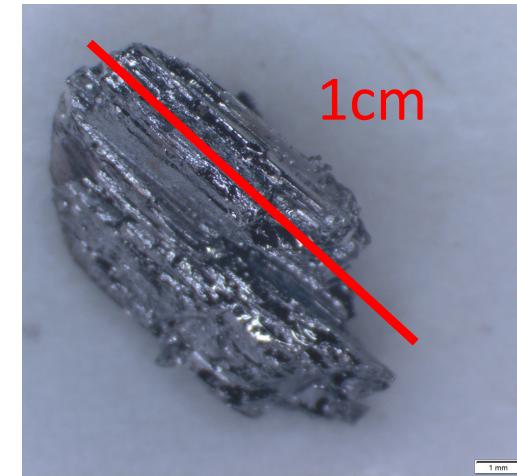
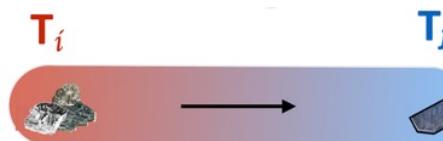
- LANL has the in-house capability to synthesize new single-crystal materials
 - Using flux growth and chemical vapor transport techniques
- Many small bandgap candidate materials grown and characterized



Flux Growth



Chemical Vapor Transport



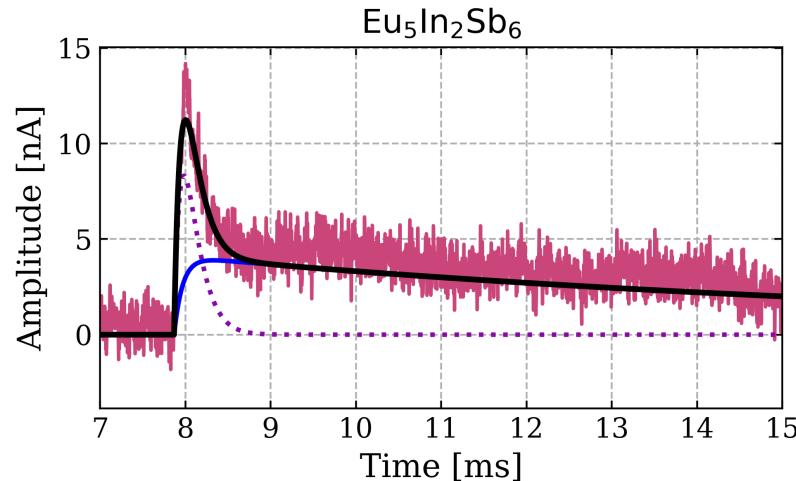
Eu₅In₂Sb₆



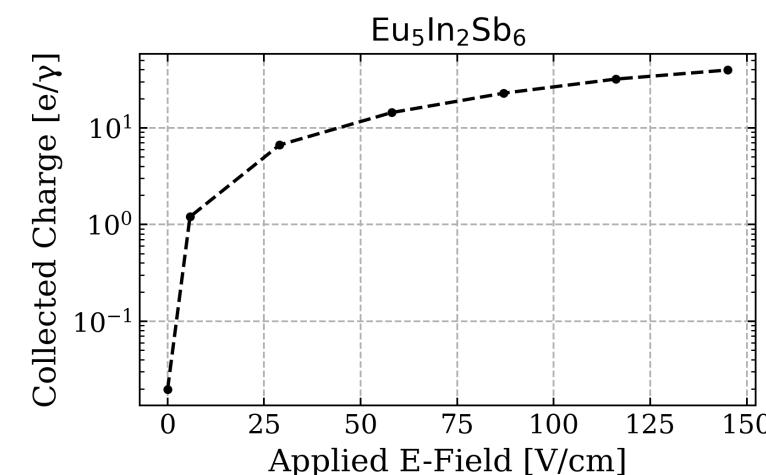
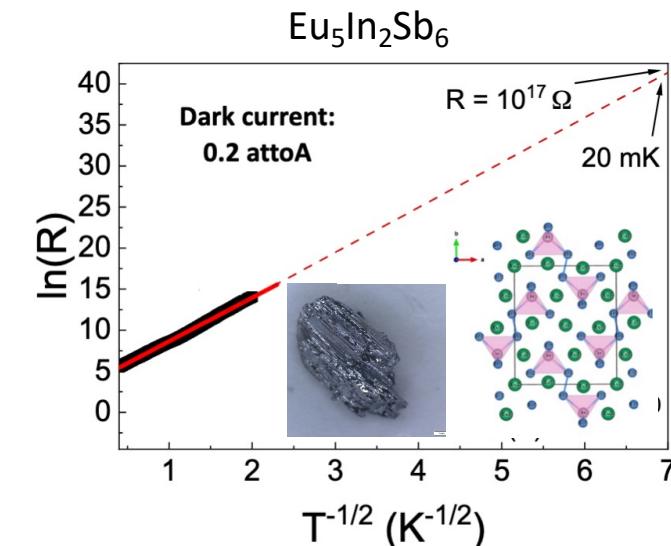
EuZn₂P₂

Materials Characterization

- Initial resistivity measurements indicate activated behavior with band gaps of O(1-100 meV)
 - Indicates sub attoAmps dark rates at mK temperatures
- Materials have photoresponse to IR light
- Beginning to show signs of full charge collection
 - Ongoing studies at lower temperatures



$$\rho(T) = A \exp[(T_0/T)^\beta]$$

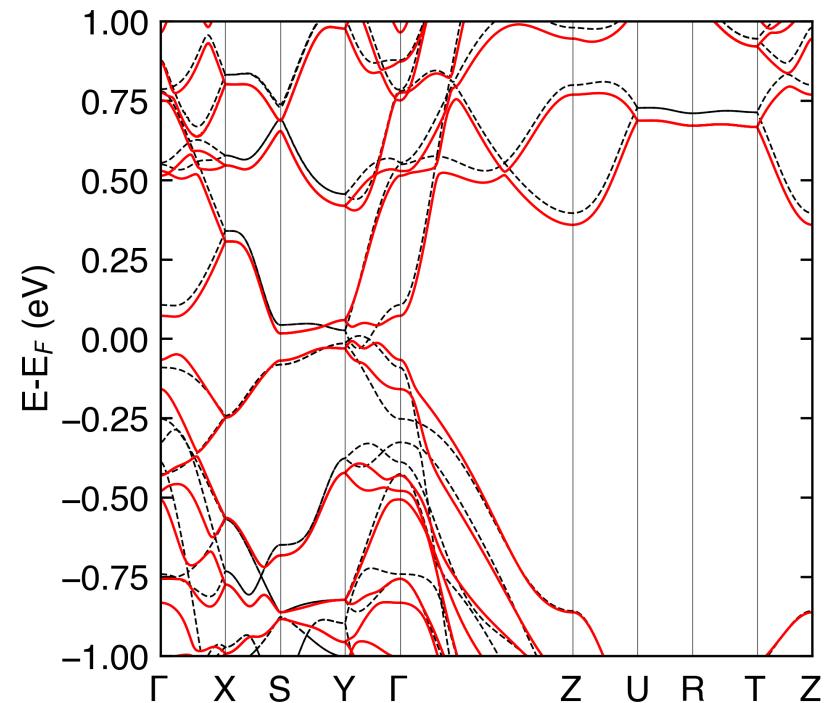


Materials Theory

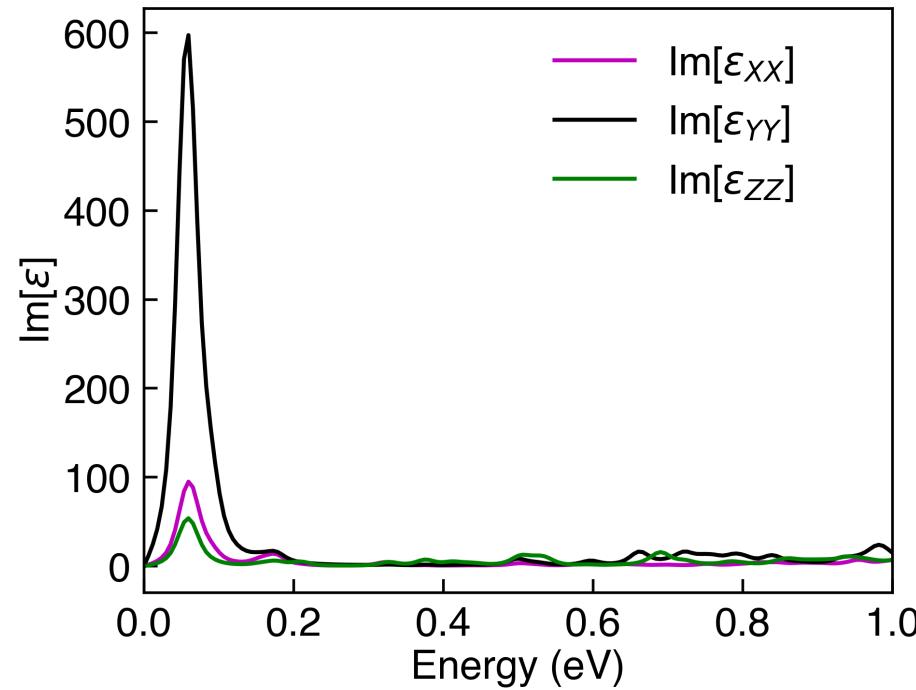
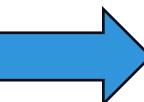
- Use many-body perturbation theory to calculate loss function from first principles

$$\Gamma(\mathbf{v}_\chi) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[2 \frac{q^2}{e^2} \text{Im} \left(-\frac{1}{\varepsilon(\mathbf{q}, \omega_\mathbf{q})} \right) \right]$$

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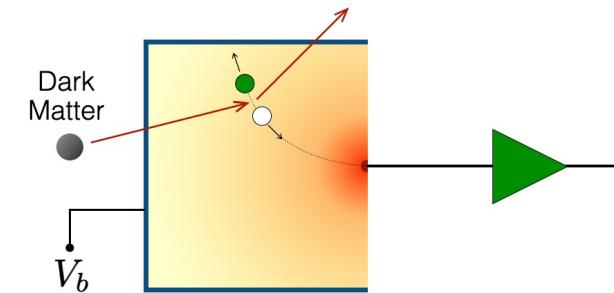
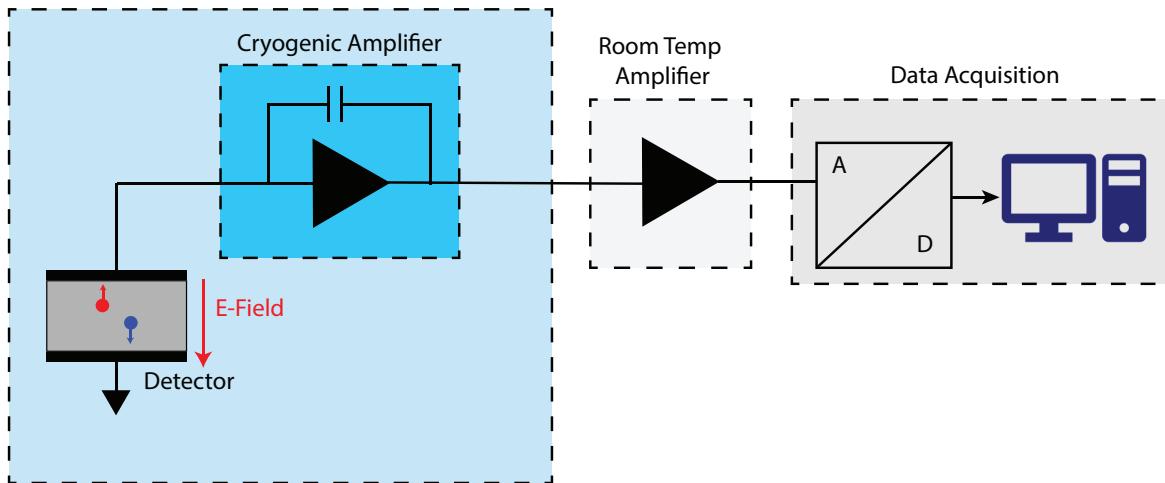
Band structure of Eu₅In₂Sb₆



Dielectric function via
DFT at zero momentum

Detection Scheme

- Use well-known point-contact style detector design
- Design goal: minimize total capacitance

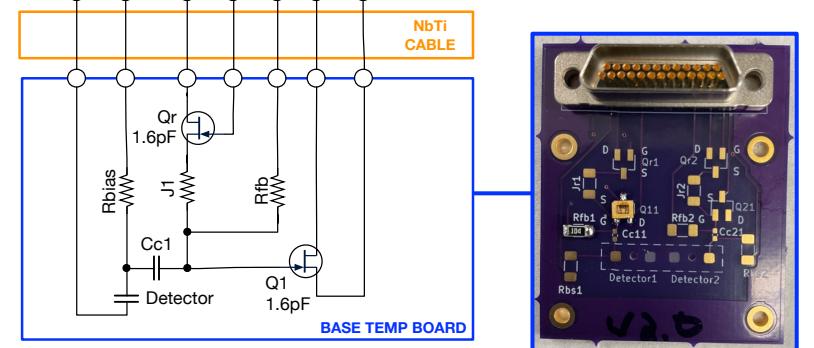
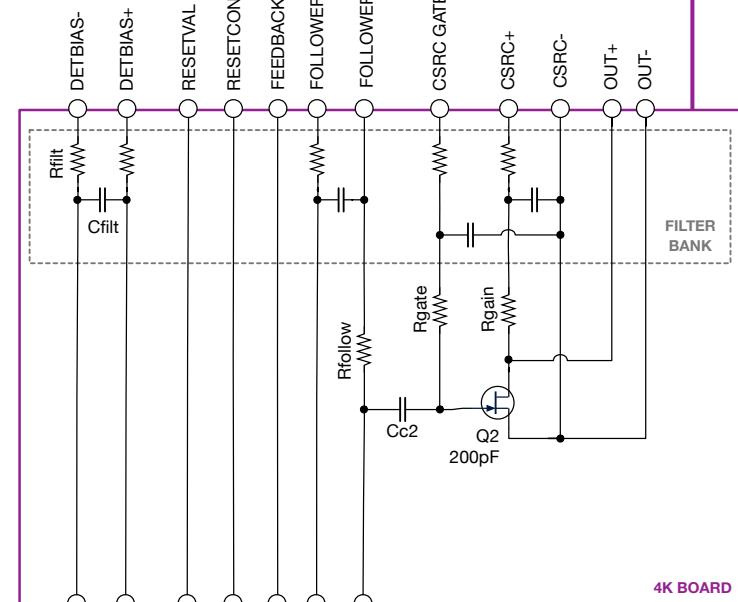
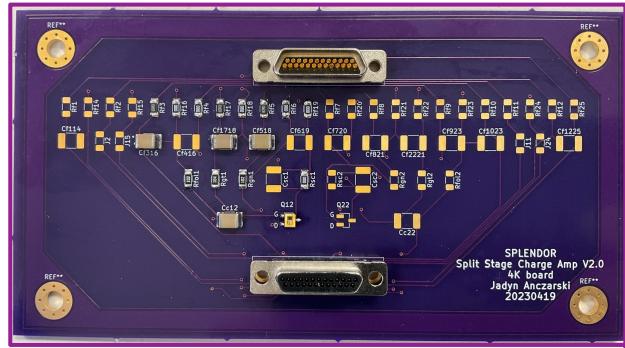
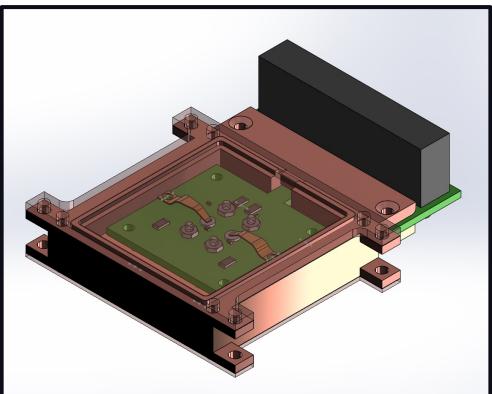


$$\sigma_E \sim E_{gap} \times \sigma_V \times (C_{detector} + C_{input} + C_{parasitic})$$

charge resolution (goal: $\sigma_{e^-} \sim O(1) e^-$)

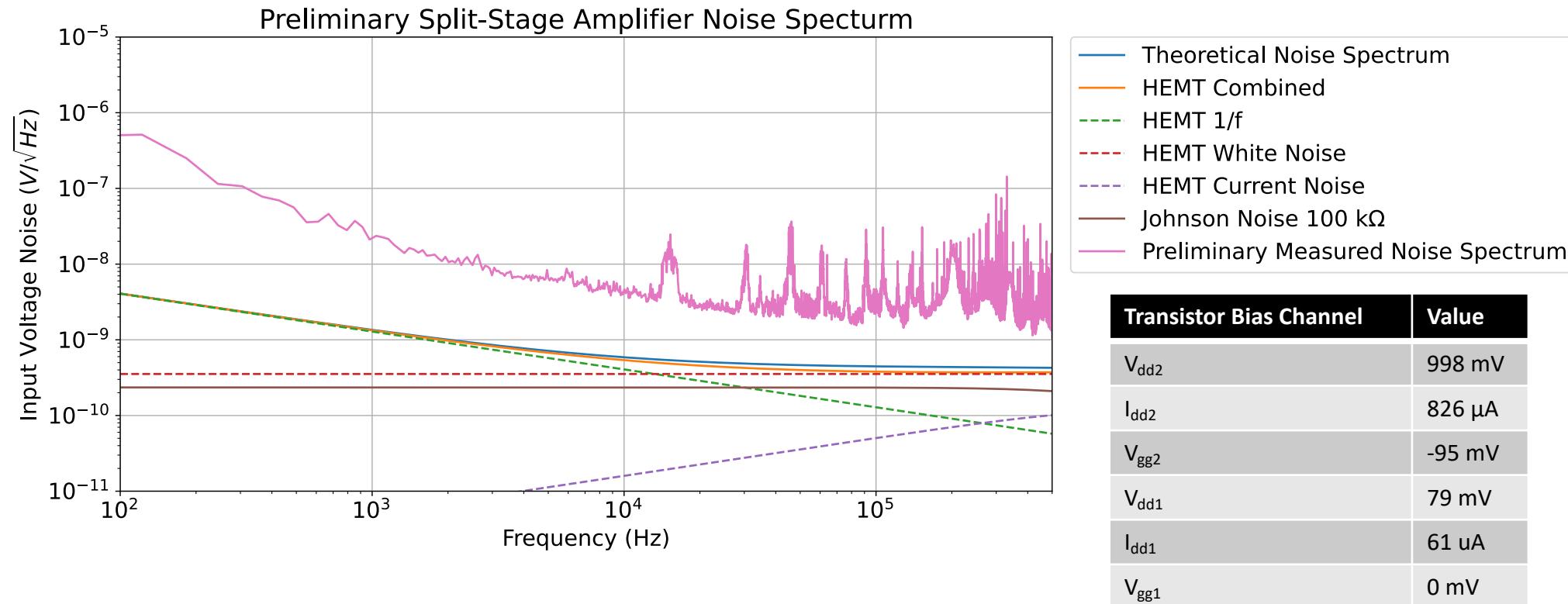
Charge Amplifier Design

- Split-stage cryogenic HEMT-based amplifier
 - 4 K gain stage with 200 pF HEMT
 - 10 mK buffer stage with 1.6 pF HEMT (buffers the upstream capacitance)
- Detector housing
 - Minimize capacitance by placing detector material as close to 10 mK board as possible
- Currently testing in a BlueFors dilution refrigerator!



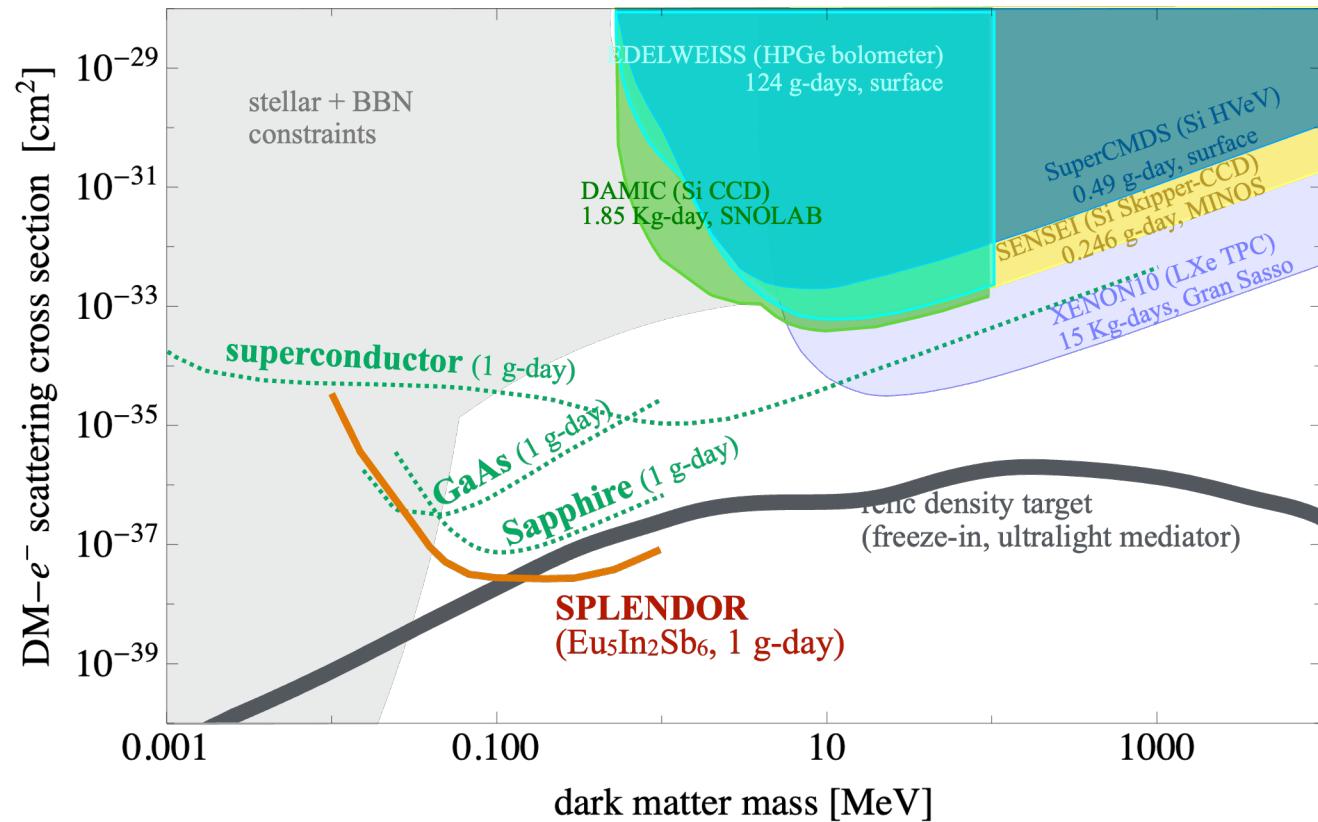
Preliminary Performance of Amplifier

- First input noise measurements in non-optimized setup
 - Indicates a charge resolution of $22e^-$!



Summary and Outlook

- Narrow bandgap materials can significantly expand our low-mass DM reach
 - Using tried-and-true detection techniques
- Near-term goals of SPLENDOR:
 - Optimization of HEMT operating conditions
 - Hunting noise sources
 - Surface DM search dataset expected later this year with prototype detector

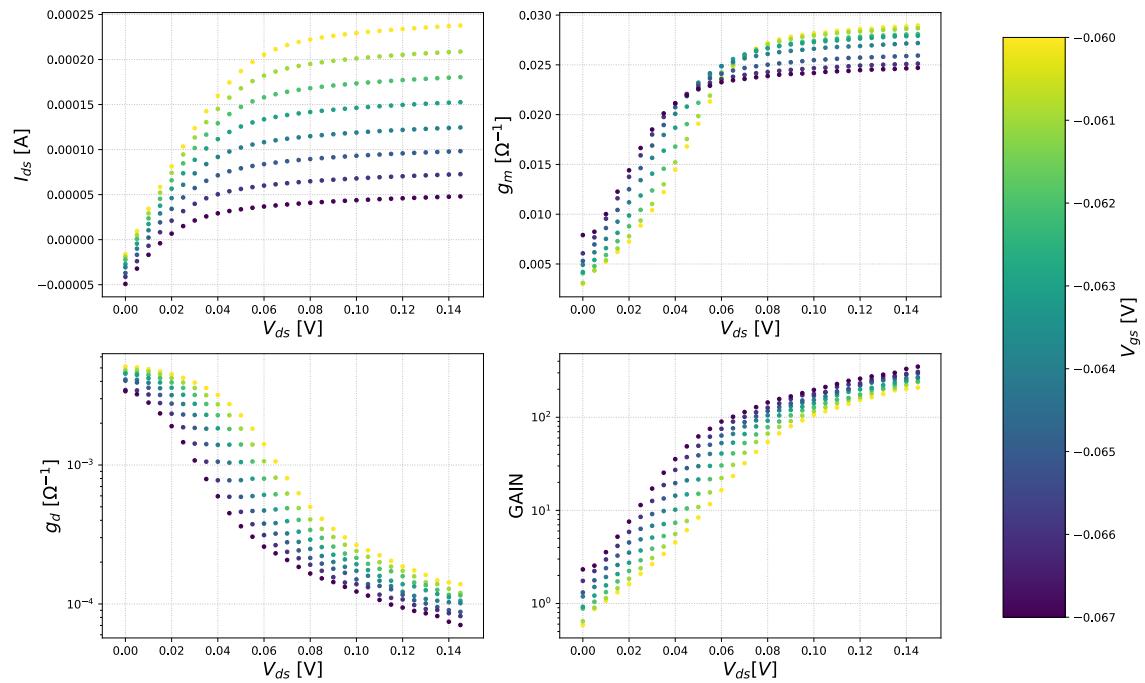


Thank you!

Backup

HEMT IV Curves

200 pF HEMT B1I3 at 4K



1.6 pF HEMT B2A5 at 380mK

