Los Alamos
NATIONAL LABORATORY

Search for Particles of Light Dark Matter with Narrow Gap Semiconductors – The SPLENDOR Project

CPAD Workshop 2022, WG1

Caleb Fink – LANL

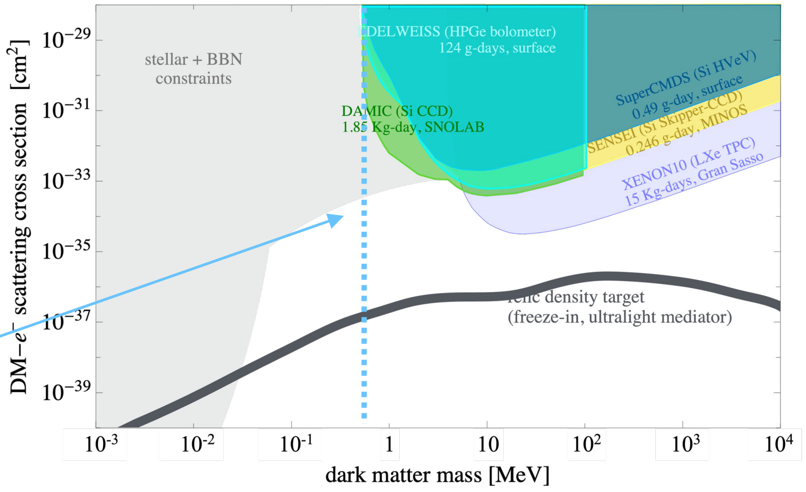
Postdoc MPA-Q

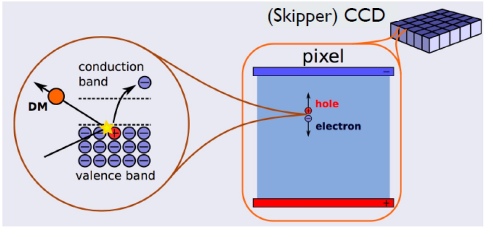
LDRD

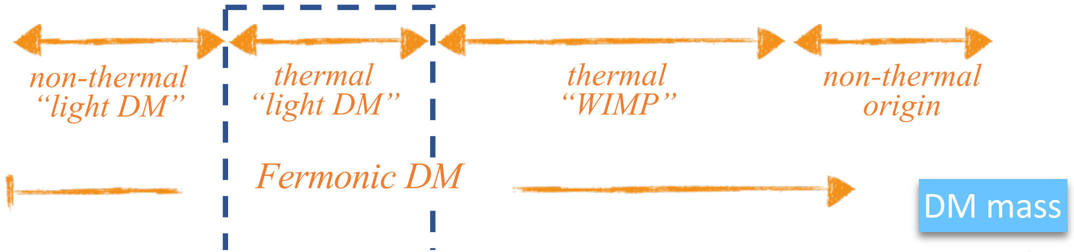
Dark Matter Detection – Past 10 years

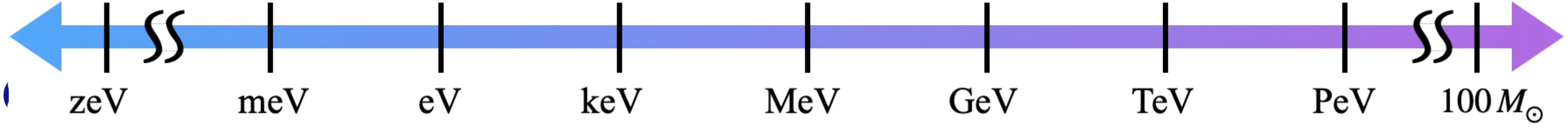
- Lots of focus on DM-electron interactions
- Many experiments probing DM masses in the MeV-GeV range

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



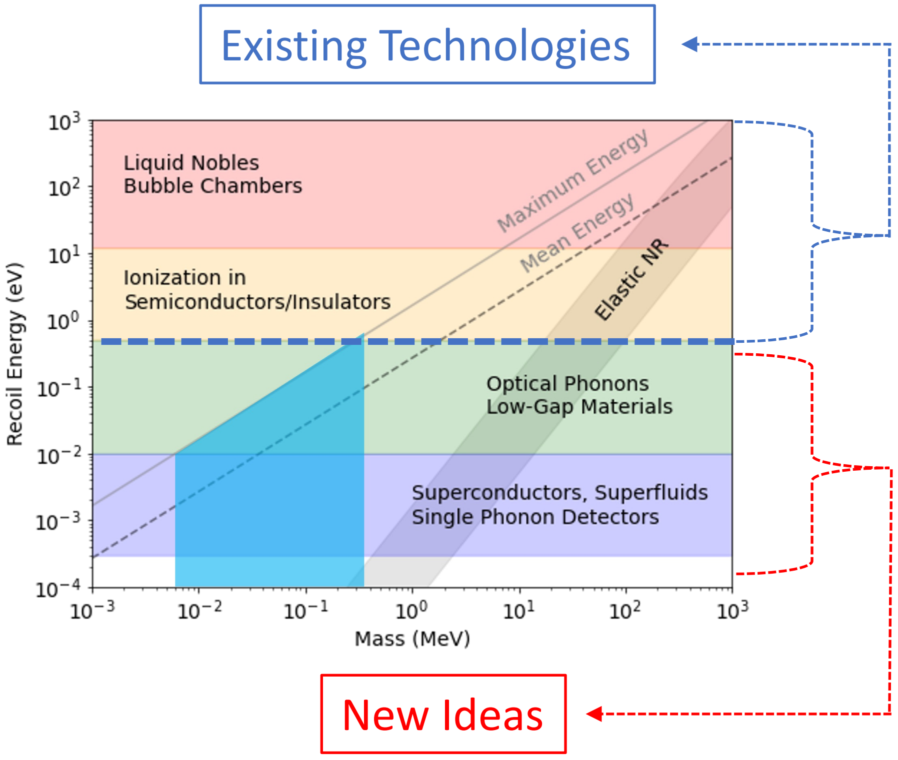






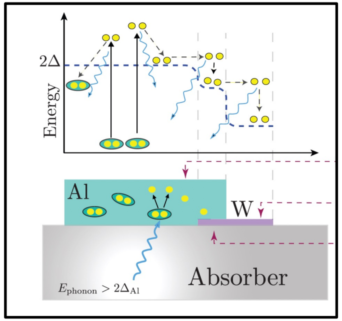
Searching Below the MeV Scale

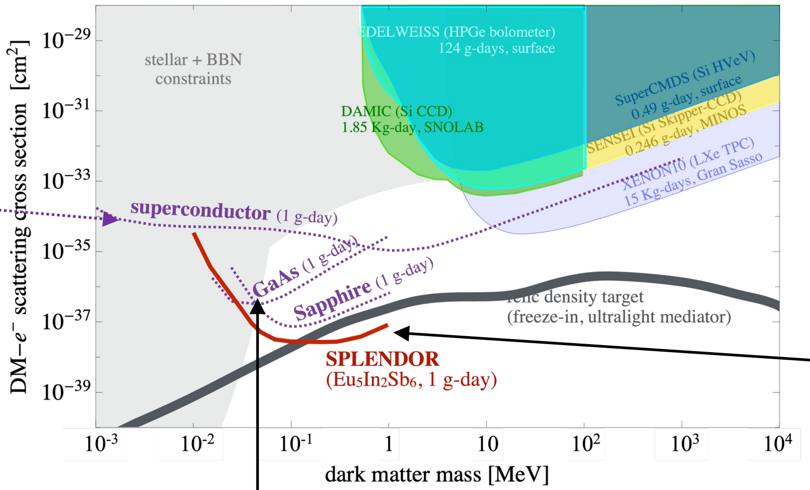
- Low kinetic energy of DM requires target sensitive to very small energy depositions
- Existing detection technologies have O(eV) energy thresholds
- Probing fermionic DM masses below MeV requires new detection techniques

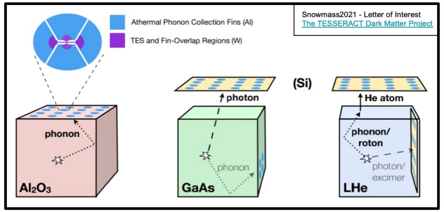


Next Generation Experiments

Dirac Materials and Superconductors

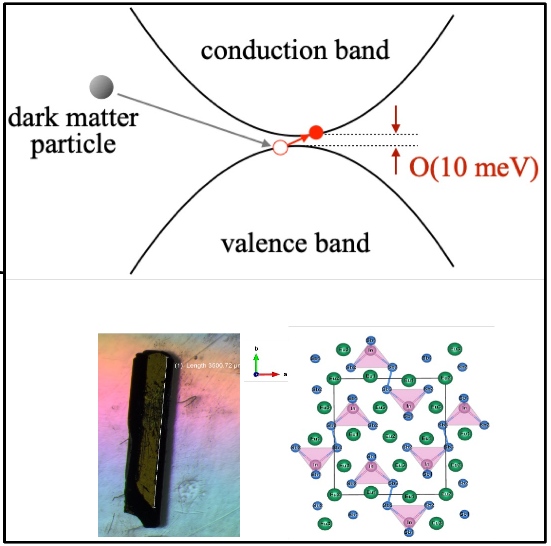






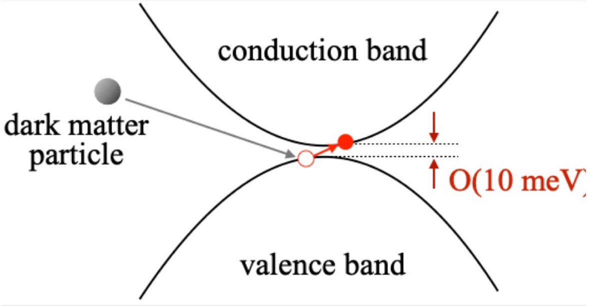
Optical phonons in polar crystals

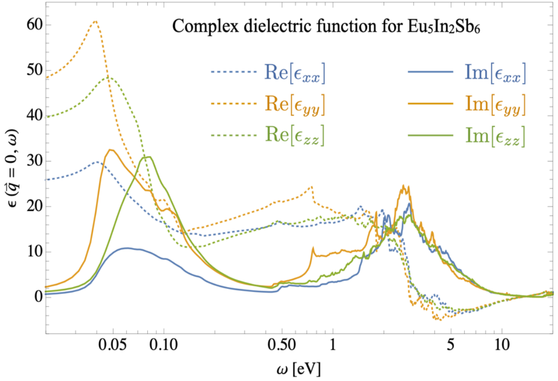
Novel narrow bandgap semiconductors



Search for Particles of Light dark MattEr with Narrowgap semiconDuctORs

- The SPLENDOR project is developing novel single crystal semiconductors with bandgaps of O(1-100 meV)
- Single crystal synthesis allows for scalable substrates with lower dark rates than existing heavily doped IR sensitive photodiodes
- Materials have anisotropic band structures to give sensitivity to daily DM modulation effects





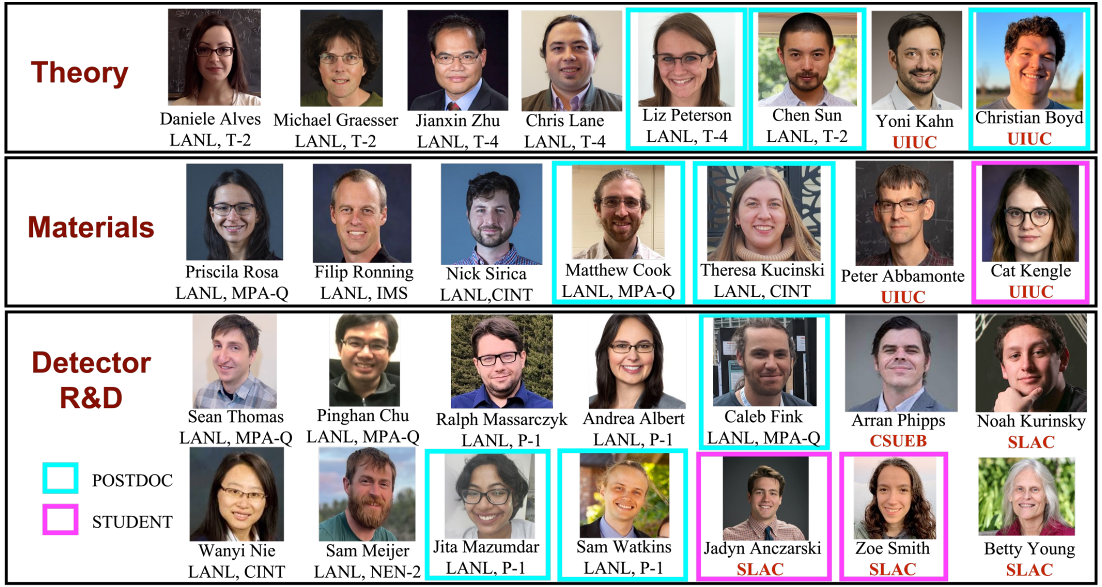
Splendor

Search for Particles of Light Dark Matter with Narrow-Gap Semiconductors

LDRD

SPLENDID Team

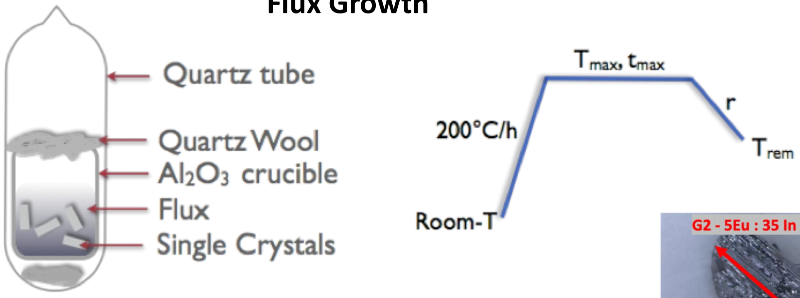
- Relatively small collaboration of 29 members across 4 institutions
- Expertise in:
  - Material synthesis, theory, and characterization
  - Dark matter theory and detection
  - Quantum Sensing

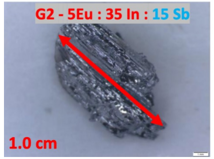


SPLENDOR – Materials Approach

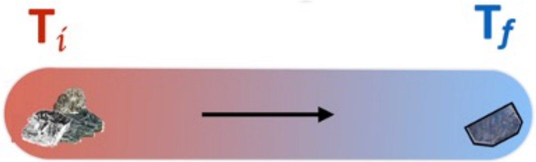
Use Zintl phase and charge density wave principles to synthesize new single crystal materials using flux growth and chemical vapor transport

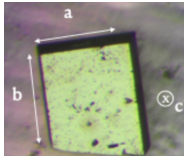
Flux Growth





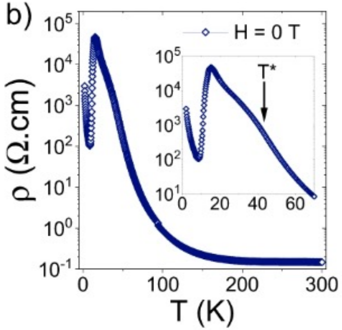
Chemical Vapor Transport





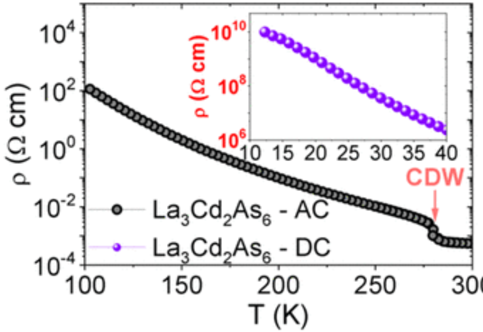
I. Electron count/Zintl phases

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



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

II. Charge density wave



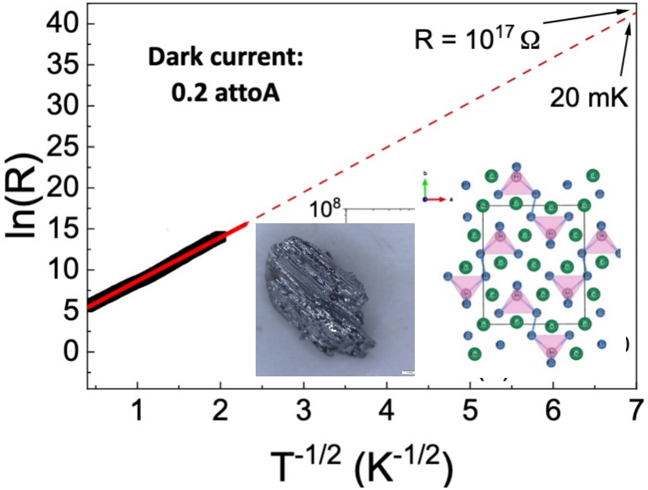
MM Piva *et al*, *Chem. Mater.* ***33***, 4122 (2021).

Materials – Clean Bandgaps

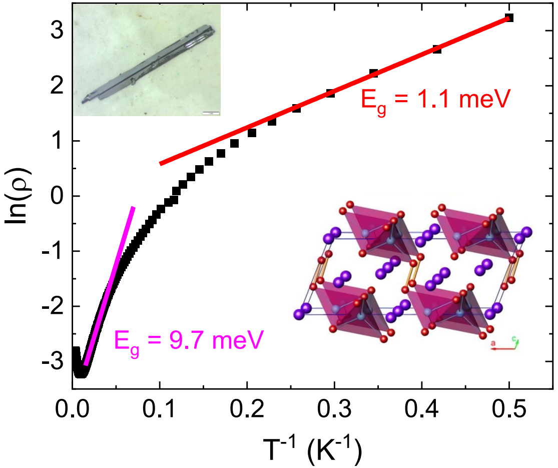
- Initial resistivity measurements of candidate materials show activated behavior with bandgaps of O(1-100meV)
- Indicate a dark rate of sub atto-amps at mK temperatures

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

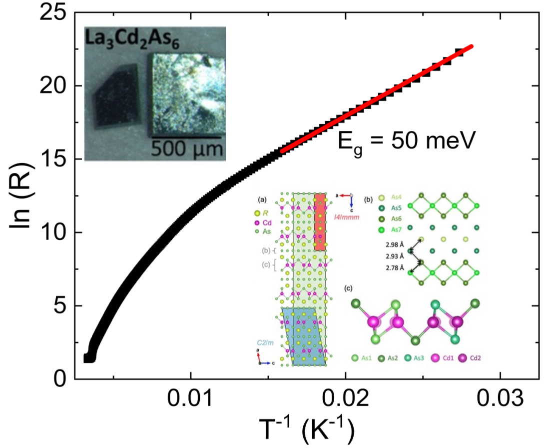
$Eu_5In_2Sb_6$



$Ba_3Cd_2As_4$



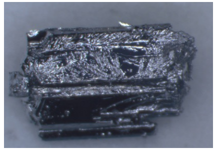
$La_3Cd_2As_6$



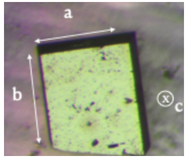
Detector Signal Chain

Develop novel semiconductors with point contact charge collection geometries

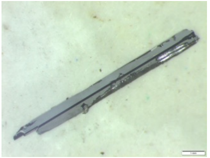
$Eu_5In_2Sb_6$



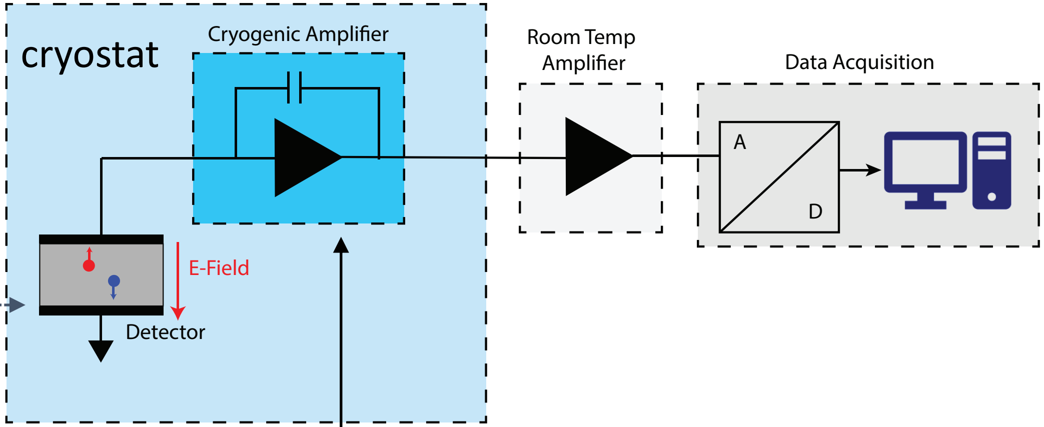
$La_3Cd_2As_6$



$Ba_3Cd_2As_4$



?



Create charge readout scheme with O(1) electron resolution that is <u>device independent</u>

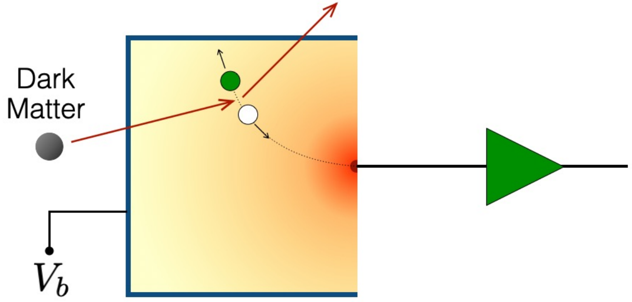
→ Easily portable to different crystals/geometries

SPLENDOR Readout Scheme

Plan to achieve best possible charge, energy resolution (σ_{e^-}, σ_E)

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

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

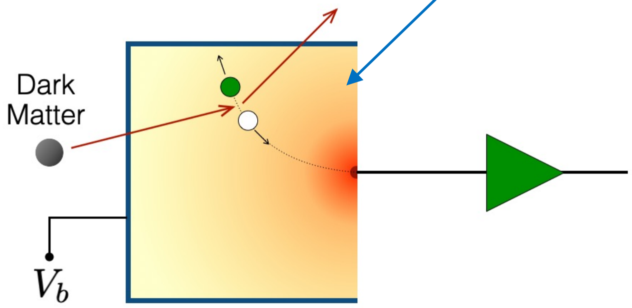


SPLENDOR Readout Scheme

Plan to achieve best possible charge, energy resolution (σ_{e^-}, σ_E)

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

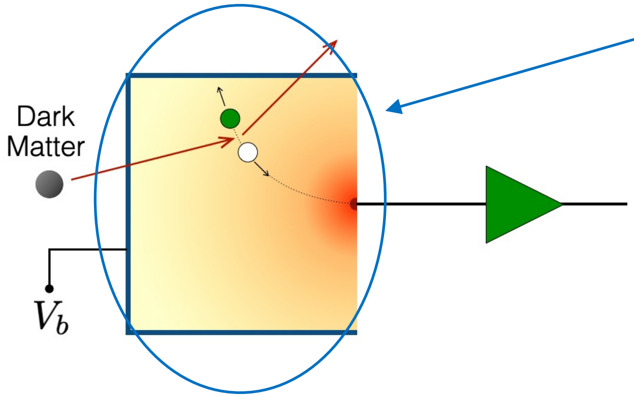
narrowgap materials



SPLENDOR Readout Scheme

Plan to achieve best possible charge, energy resolution (σ_{e^-}, σ_E)

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



Point-contact detector with O(pF) capacitance

(design plating scheme to maximize target volume while minimizing capacitance)

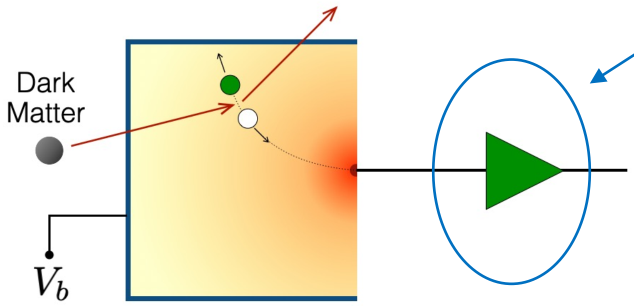
SPLENDOR Readout Scheme

Plan to achieve best possible charge, energy resolution (σ_{e^-}, σ_E)

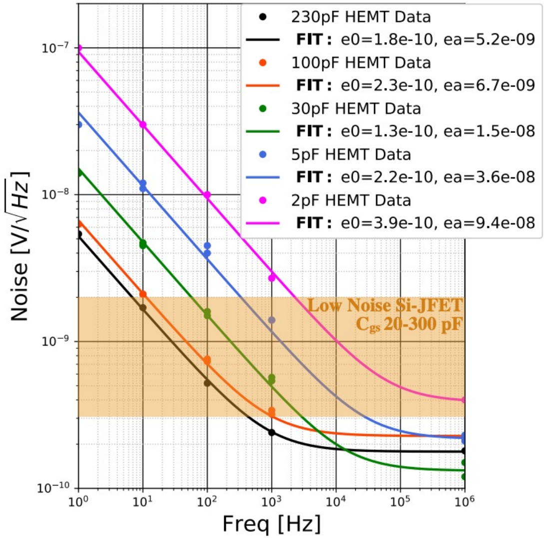
$$\sigma_E \sim E_{gap} \times \sigma_V \times (C_{detector} + C_{input} + C_{parasitic})$$

Low voltage noise HEMTs

(a type of field effect transistor that works at cryogenic temperatures)



Juillard *et al.*, *J. Low Temp. Phys.* **199**, 2020



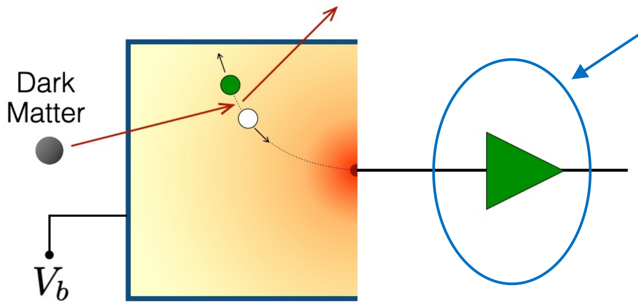
SPLENDOR Readout Scheme

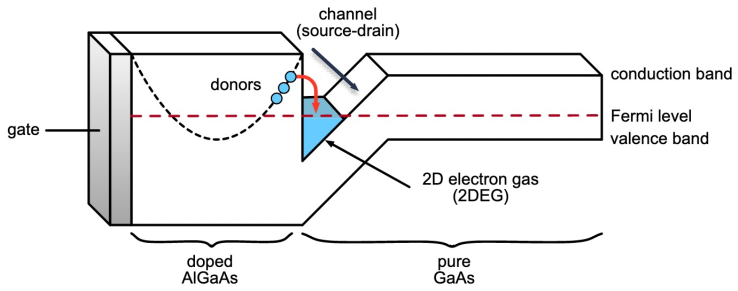
Plan to achieve best possible charge, energy resolution (σ_{e^-}, σ_E)

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

Input capacitance of HEMT

(chosen by setting gate geometry; scale CDMS-style charge readout to small capacitances)



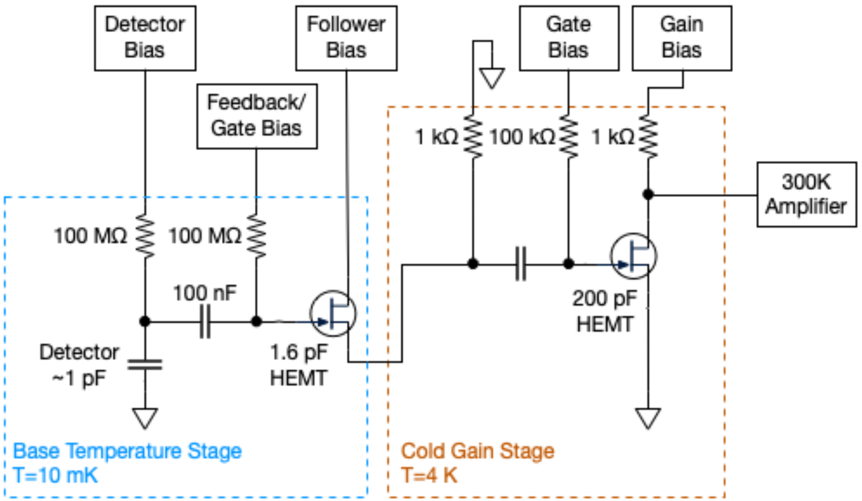


SPLENDOR Readout Scheme

Plan to achieve best possible charge, energy resolution (σ_{e^-}, σ_E)

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

Challenge: minimization of parasitic capacitance in wiring at cryogenic temperatures

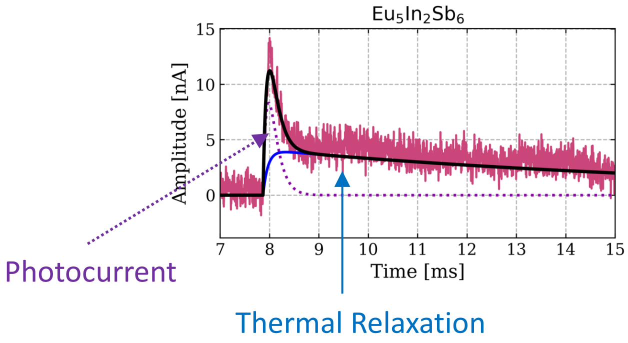


- Design two stage charge amp
- Gain will come from portion at 4K
- Use low capacitance front end HEMT on detector board as a buffer – none of the cabling capacitance will be seen by the detector
- Requires input HEMT with small capacitance
- Needs to operate at 10mK

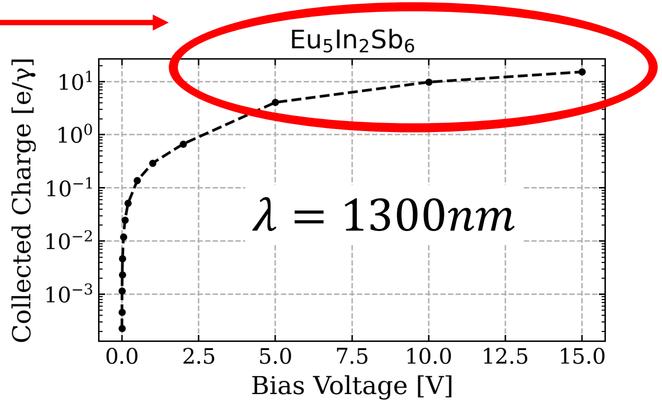
$Eu_5In_2Sb_6$ - Photoresponse

Material photo-response has been measured as function of

- Wavelength
- Temperature
- Applied voltage bias

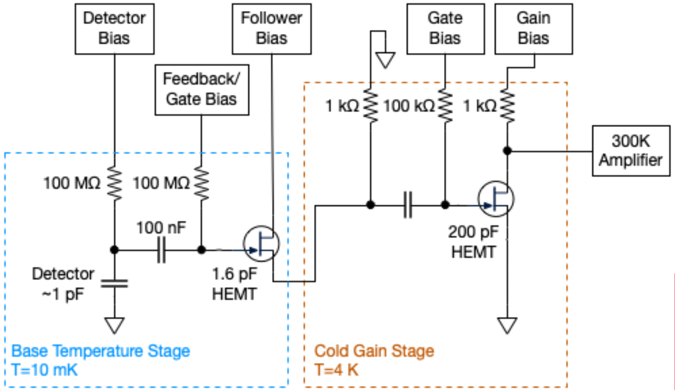


Beginning to see full charge collection with a candidate material!

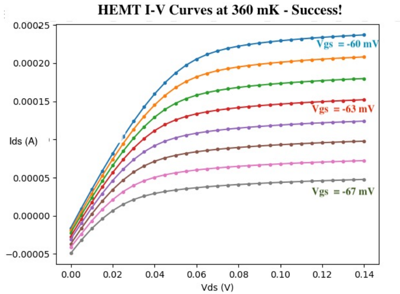


Studies currently underway to measure higher fields at colder temperatures

Expected Performance Based on Initial Screening



Have studied our low capacitance HEMTs down to 300mK

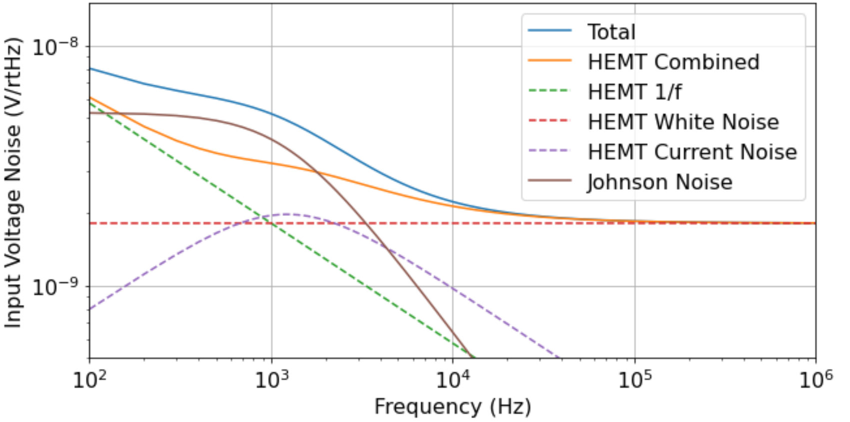


Predicted 1-sigma optimal filter resolution:
5.35 electrons

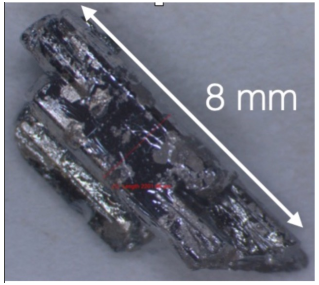
HEMT parameters:
1.6 pF Transconductance: 15 mS
200 pF Transconductance: 50 mS

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

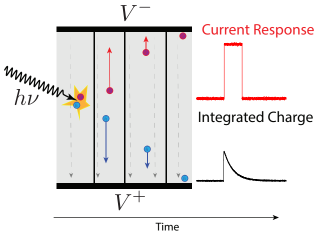
~20 uW dissipation at 10 mK
~2.1 mW dissipation at 4 K

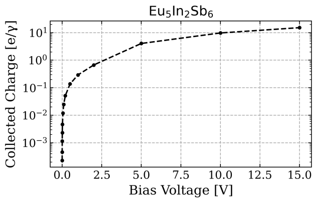


Summary and Ongoing R&D

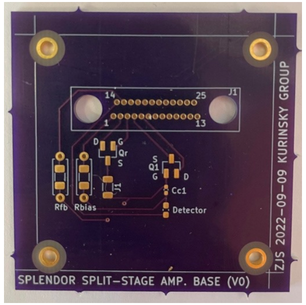


- Materials
  - Close to achieving gram scale crystals
  - Continuing to optimize crystal growth process





- Detector
  - Shown that full charge collection is possible
  - Need to optimize contact geometry



- Cryogenic Amplifier
  - Low Capacitance HEMTs characterized at sub-K temperatures
  - V1 two-stage amplifier is designed and fabricated

Expected Sensitivity

- Full test of prototype detector and amplifier to take place early 2023
- Initial DM science run to take place in 2023
- Follow-up DM search in shallow underground site in 2024
- Expected to probe DM down to O(10 keV) fermion masses and O(10 meV) bosonic masses

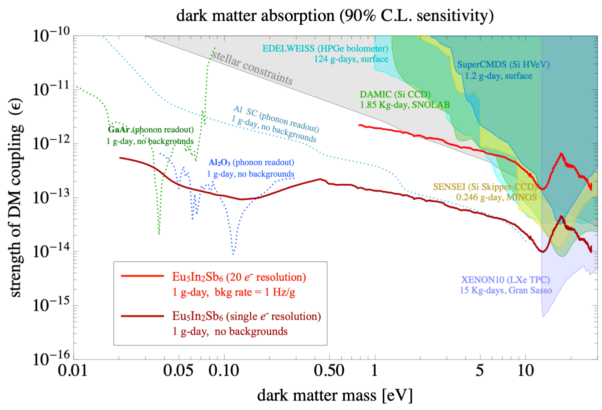


Fig: Reach projections for SPLENDOR ($Eu_5In_2Sb_6$ target) assuming 1 g-day of exposure and zero backgrounds (brownish-red line), or irreducible background rate of 1 Hz/g (bright red line).

25

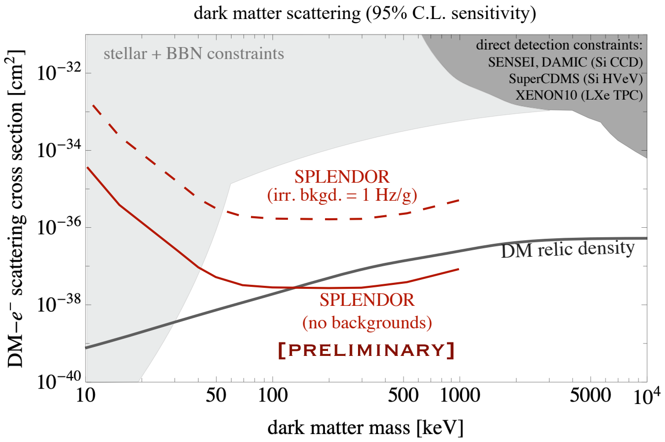
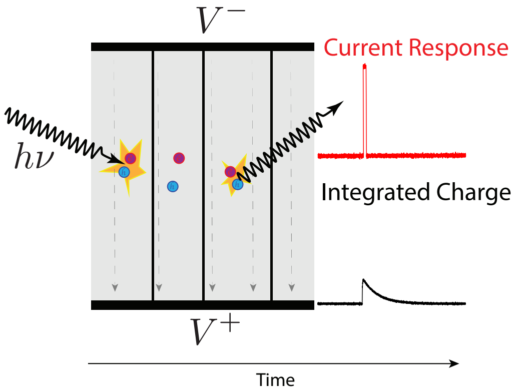


Fig: Reach projections for SPLENDOR ($Eu_5In_2Sb_6$ target) assuming 1 g-day of exposure and either zero backgrounds (solid line), or irreducible background rate of 1 Hz/g (dashed line).

24

Backup Slides

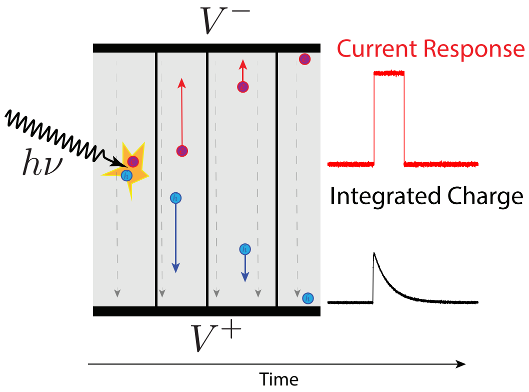
Detector – Charge Collection



<u>Low E-Field</u>

- Field too low to separate electron-hole pair excitons
- Small to no signal response

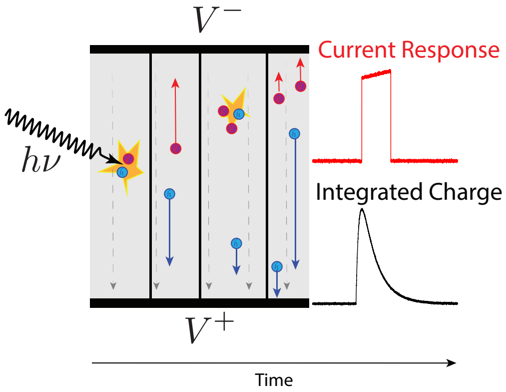
<u>Incomplete Collection</u>



<u>Intermediate E-Field</u>

- Field strong enough to separate excitons
- Drift charges full length of detector

<u>Full Collection</u>



<u>High E-Field</u>

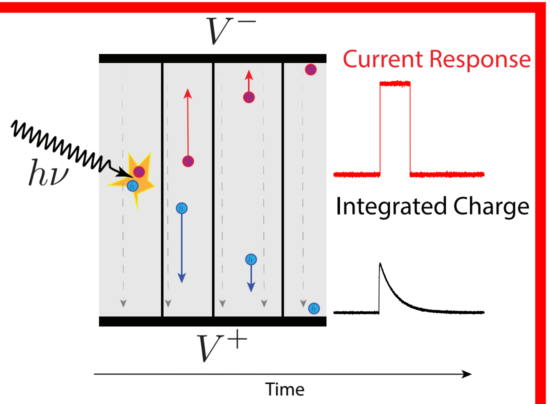
- Drifted charges have enough kinetic energy to create new excitons – "impact ionization"
- Can create chain reaction of charges

<u>Avalanche mode</u>

Detector – Charge Collection

Dark current should scale with voltage bias

Operating in the ‘full collection’ regime is the most conservative way to optimize the charge collection and minimize dark current



Intermediate E-Field

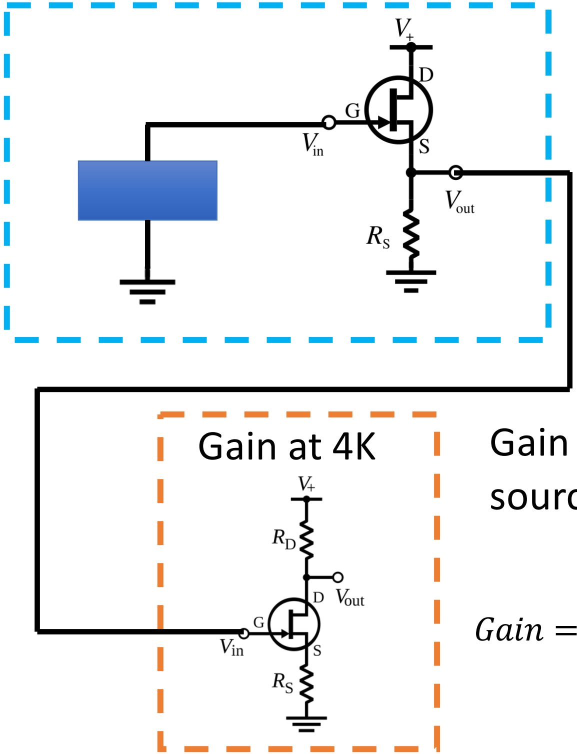
- Field strong enough to separate excitons
- Drift charges full length of detector

Full Collection

- Avalanche mode could potentially create a large increase in dark current
- Reconstruction of event energy is sacrificed

HEMT Amp Topology

Detector Card at 10mK



Use 'common-drain' follower on detector stage

- Unity gain
- Acts as buffer to downstream parasitic capacitance

$$Gain = \frac{g_m R_s}{g_m R_s + 1} \approx 1$$

Gain from common-source stage at 4K

$$Gain = g_m \frac{\left(\frac{1}{g_d}\right) R_D}{\left(\frac{1}{g_d}\right) R_D + 1} \leq \frac{g_m}{g_d}$$

Need to measure HEMT parameters to inform design model:

Transconductance: $g_m = \left.\frac{\partial I_{ds}}{\partial V_{gs}}\right|_{V_{ds}}$

Output Conductance: $g_d = \left.\frac{\partial I_{ds}}{\partial V_{ds}}\right|_{V_{gs}}$

HEMTs at 4K

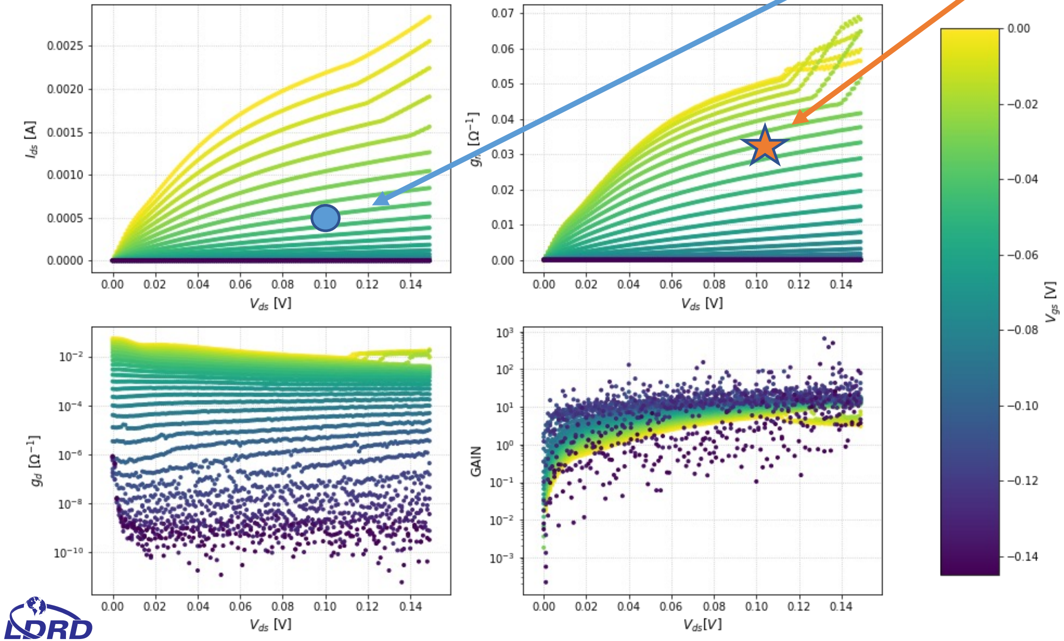
- 1.6 pF, 5 pF, and 200 pF input capacitance HEMTs have been studied at He4 temperatures
- Our measurements agree with characteristics provided by fabricator

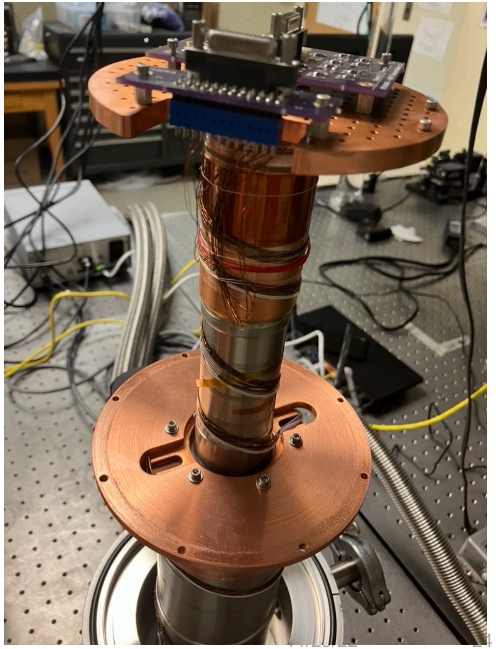
For 1.6 pF:

Power dissipation: 50 μW

Transconductance: 30 mS

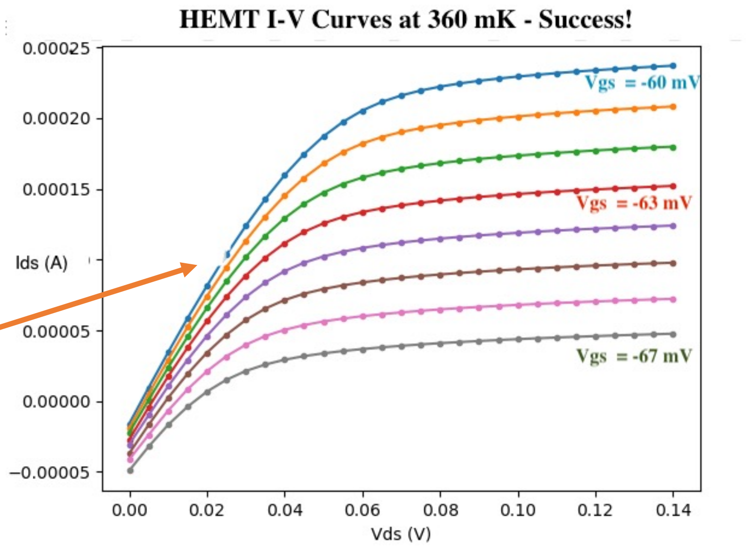
(100 mV Vds w/ 0.5 mA Ids)





HEMTs at 300mK

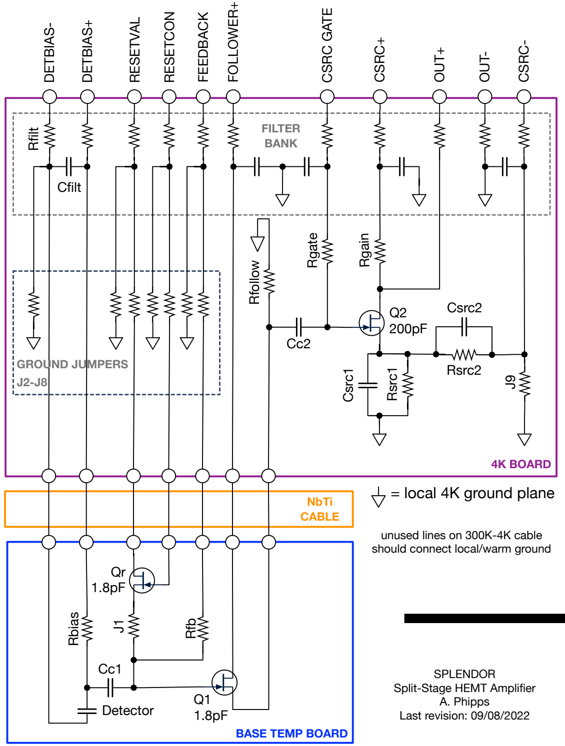
- HEMTs were studied in He3 fridge
  - Do the HEMTs behave as expected below 4K? Yes!
  - Will we be able to handle the heat loads of a HEMT at base temperature? Yes!
- 5 pF and 200 pF HEMTs studied
- 1.6 pF HEMT to be characterized in next few weeks

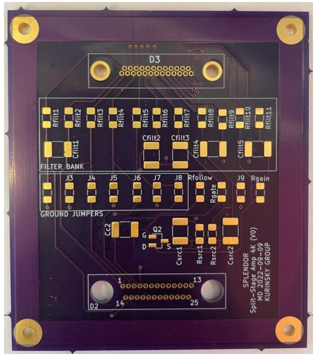


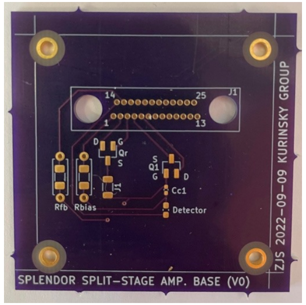
Expected saturation of 200 pF HEMT observed at 360 mK!

HEMT Amp V0 Progress

$$G_{OL} = \frac{V_{out}}{V_{in}} = \left(\frac{g_{m1}R_{follow}}{1 + g_{m1}R_{follow}}\right)(-g_{m2}R_{gain})$$





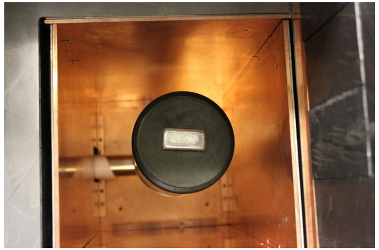


- Prototype V0 of two-stage amp has been designed and fabricated
- Gain comes from 4K board
- Follower HEMT and detector sit on same base temp board – *minimized parasitic capacitance*

Testing of two stage amp to begin next month!

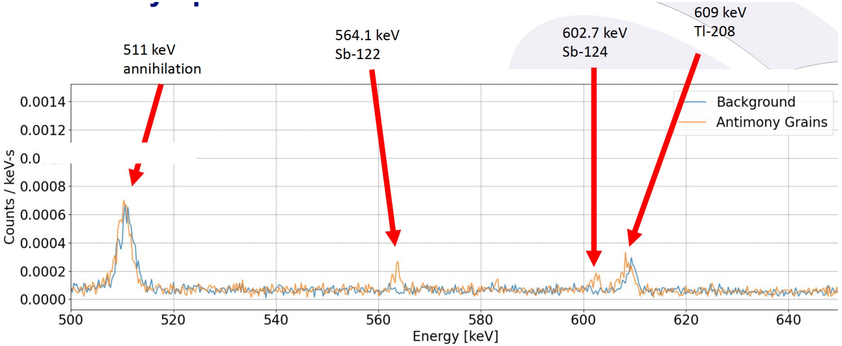
Radioassay of $Eu_5In_2Sb_6$ at LANL

- <u>Motivation: trace radioactive impurities and radioactivity of the "stable" isotopes</u>
- Individual elements studied with High-purity Ge detector (<u>gamma/X-ray only)</u>



In-115 is a known beta emitter

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

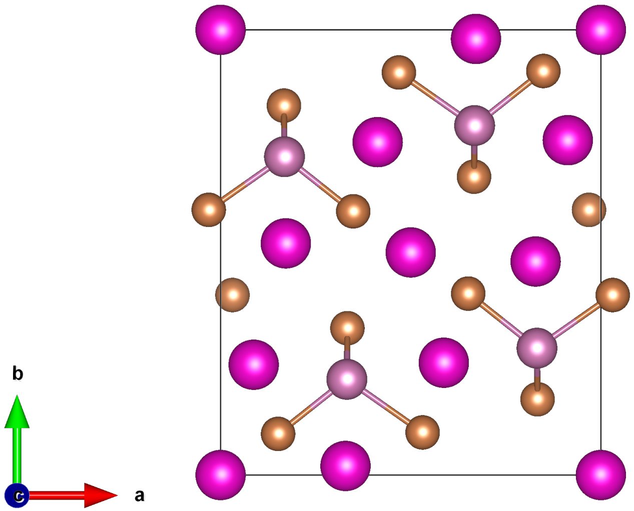


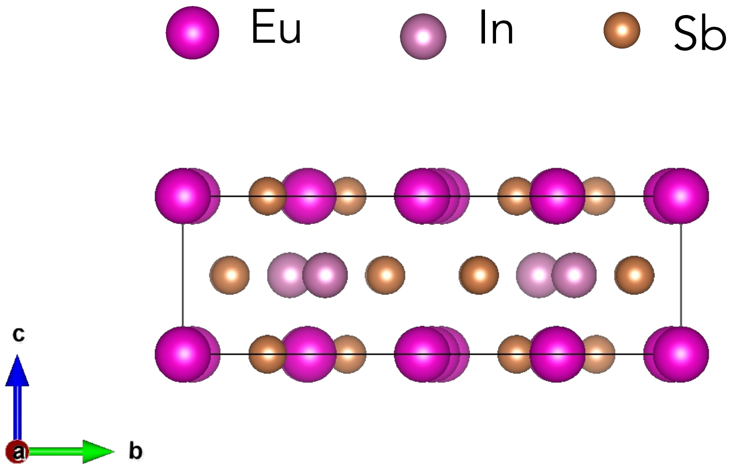
↓

Materials fine for R&D – Low activity isotopically enriched Indium available to be purchased if backgrounds become a problem

<u>Studies of full $Eu_5In_2Sb_6$ sample currently being done</u>

Candidate narrow band gap material: $Eu_5In_2Sb_6$

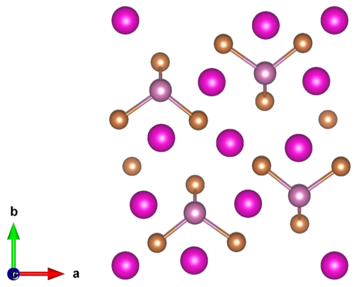




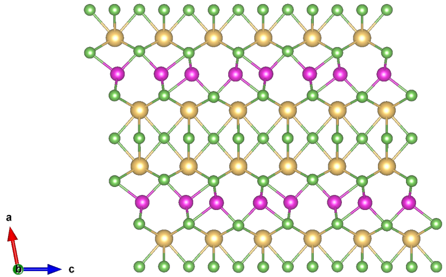
Orthorhombic

a = 12.5535 Å   b = 14.6032 Å   c = 4.6351 Å

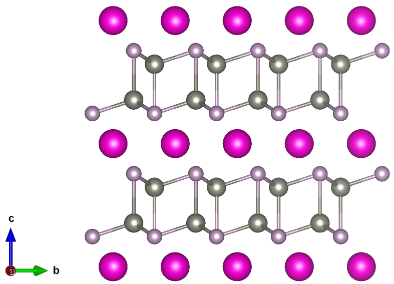
Novel detectors: Narrow band gap materials



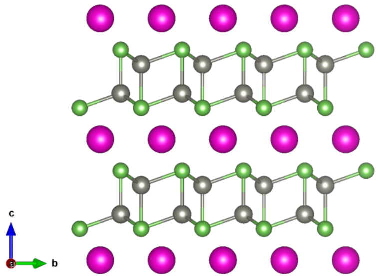
$Eu_5In_2Sb_6$



$La_3Cd_2As_6$



$EuZn_2P_2$



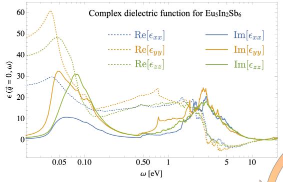
$EuZn_2As_2$

The SPLENDOR Project

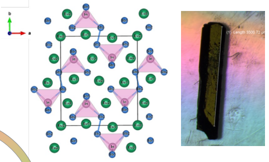
The SPENDOR project is developing novel narrow bandgap semiconductors to be used to search for light dark matter

Developing O(1) electron resolution readout scheme that can be quickly ported to new samples with different form factors

Search for **P**articles of **L**ight dark Matt**e**r with **N**arrowgap semicon**d**uct**or**s



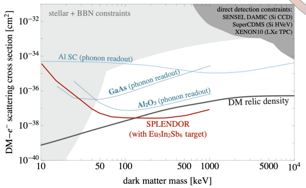
Materials Synthesis
high-quality single crystals
clean narrow bandgaps



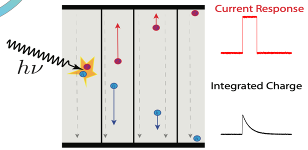
Theory
dark matter scattering and absorption rates, daily modulation of signal, many-body methods

Integrated SPLENDOR effort

Characterization
crystal structure, M-EELS, ARPES, FTIR, charge transport



Detector R&D
cryogenic charge amplifiers, single e^- resolution



UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

CAL STATE EAST BAY

LDRD

Los Alamos NATIONAL LABORATORY

SLAC NATIONAL ACCELERATOR LABORATORY