Cryogenic solid state detectors: SuperCDMS and beyond

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2025 SNOLAB Future Project Workshop

The **S**uper **C**ryogenic **D**ark **M**atter **S**earch

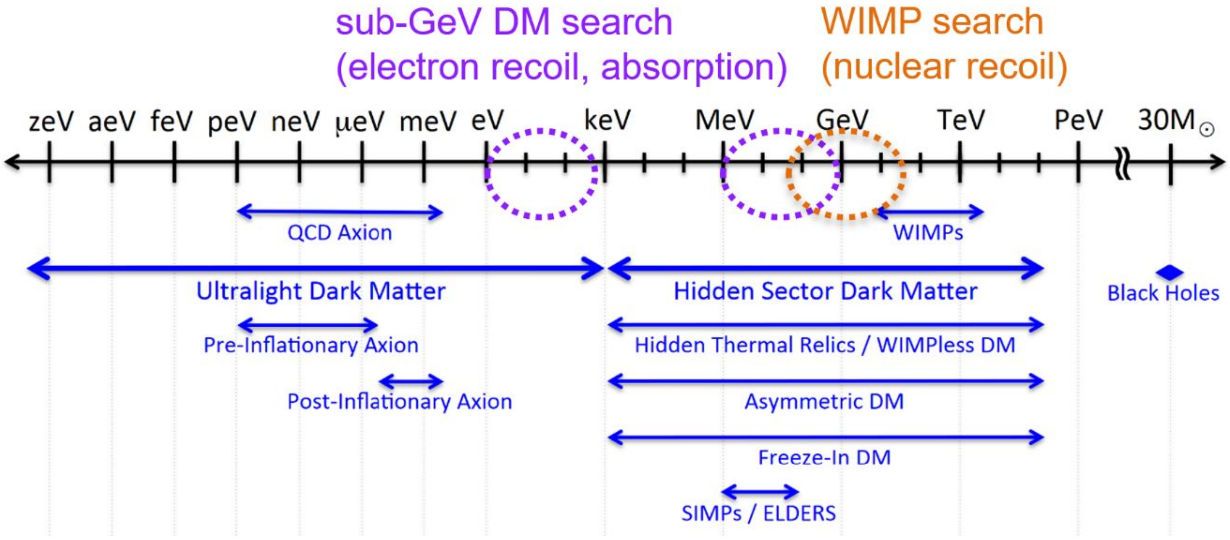
A direct detection search experiment which employs an array of ultra-pure silicon and germanium detectors to search for low-mass (< 10 GeV/c^2) dark matter candidates.

~ 100 researchers at 28 institutes across 6 countries.

Dark Matter Candidates

Looking for a wide range of DM candidates

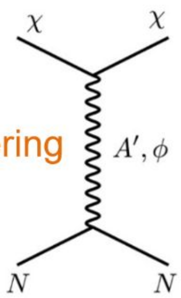
- Dark matter masses from ~5 GeV down to eV



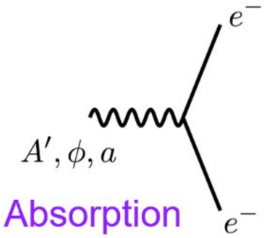
US Cosmic vision ArXiv:1707.04591

Nuclear interaction processes:

Nucleus-recoil scattering

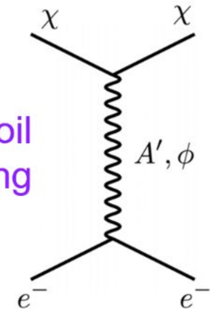


Electronic interaction processes:

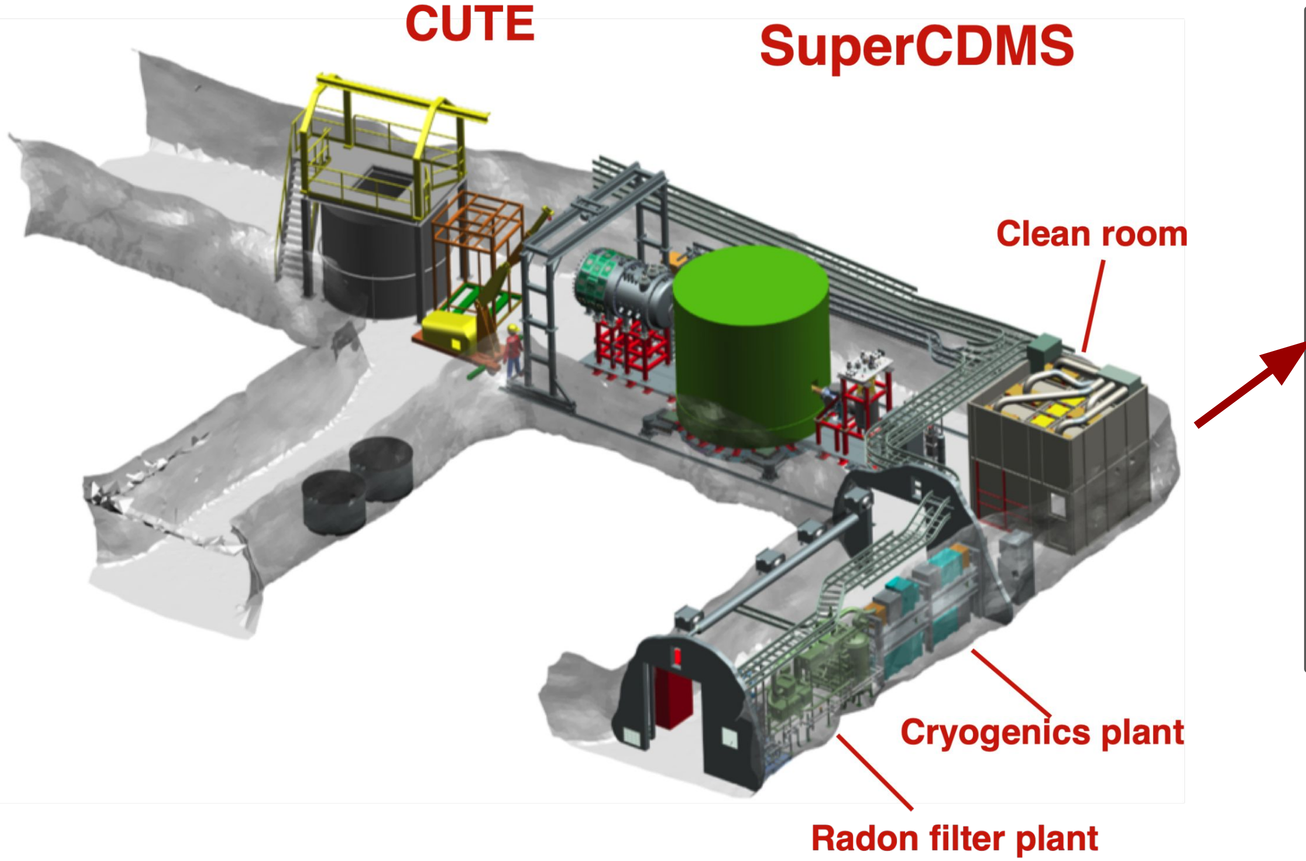


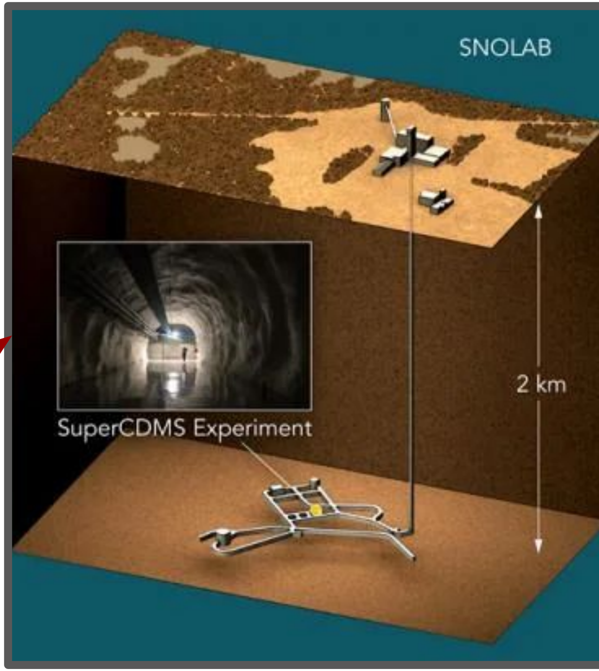
Absorption

Electron-recoil scattering

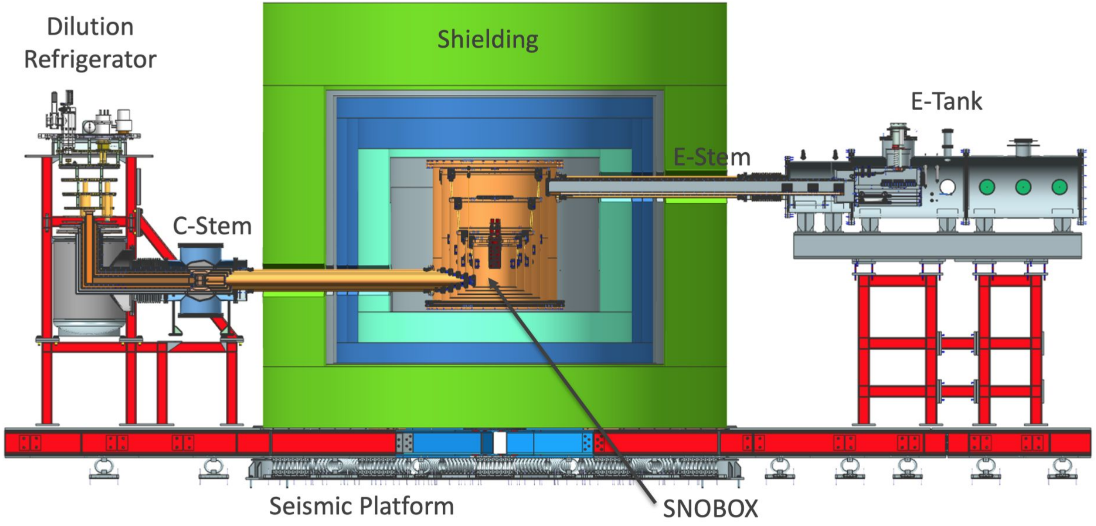


SuperCDMS @ SNOLAB





The SuperCDMS SNOLAB Experiment



Facility:

- 6000 m.w.e. overburden
- 15 mK base temperature
- Initial Payload: ~30 kg total
  - 4 stacks of six detectors (“towers”)
  - 2 iZIP: 10 Ge / 2 Si
  - 2 HV: 8 Ge / 4 Si

Electron Recoil Backgrounds:

- External and facility: O(0.1 /keV/kg/d)
- Det. setup: O(0.1(Ge)-1(Si) /keV/kg/d)
- Total: O(0.1-1 /keV/kg/d)

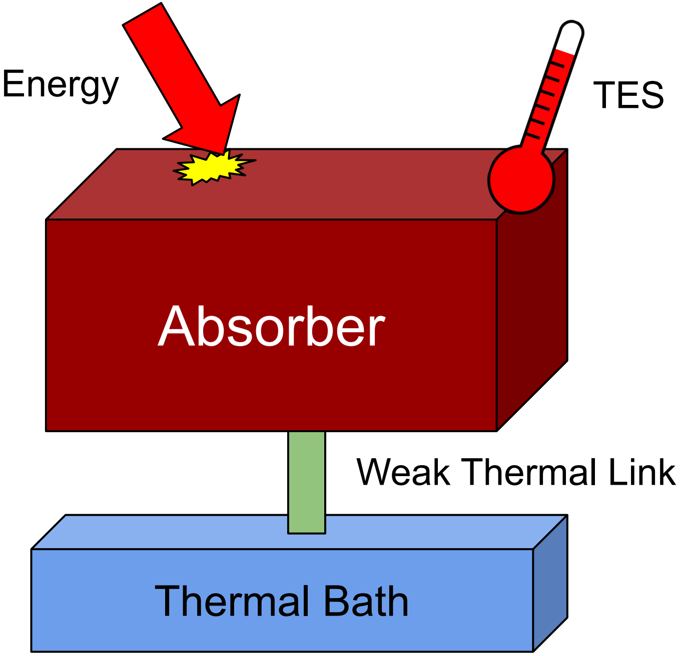
Facility designed to be dominated by solar neutrinos in NR background

Vibration isolation:

- Seismic: spring loaded platform
- Fridge on active vibration damper
- Cryo coolers: soft couplings
  - Braids, bellows
- Copper cans: hanging on Kevlar ropes

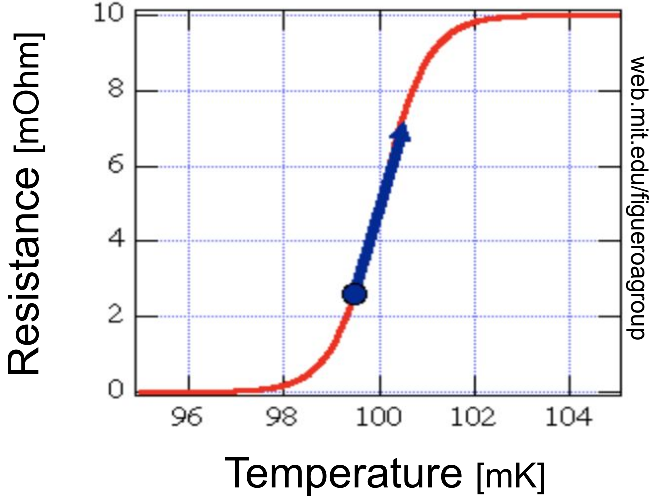
Detector Schematic

Cryogenic Calorimeter



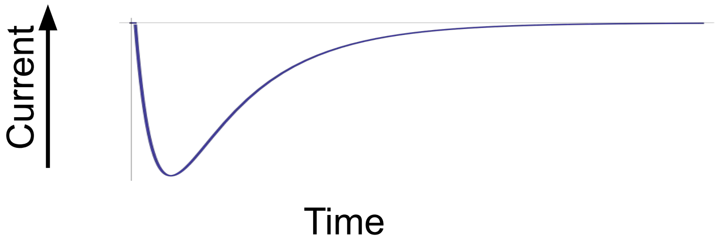
Cryogenically cooled in dilution fridge

Transition-Edge Sensor (TES)



web.mit.edu/figueroagroup

Response of TES



SuperCDMS Detector Technology

Discriminating

~~iZIP~~ Detector:

- Prompt phonon and ionization signals allow for discrimination between nuclear and electron recoil events

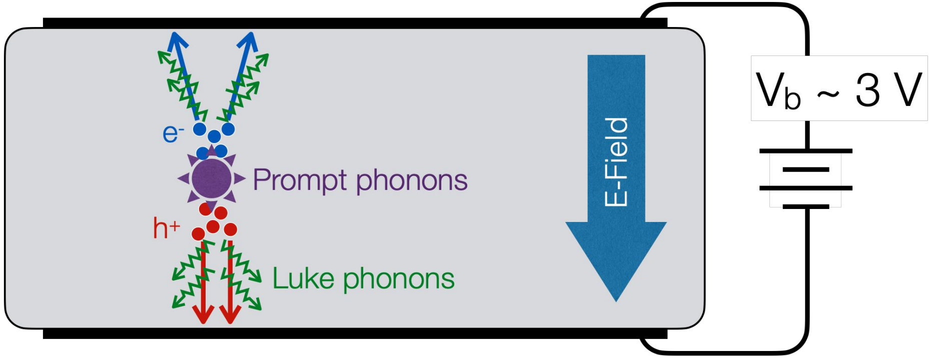
Low Threshold

~~HV~~ detector:

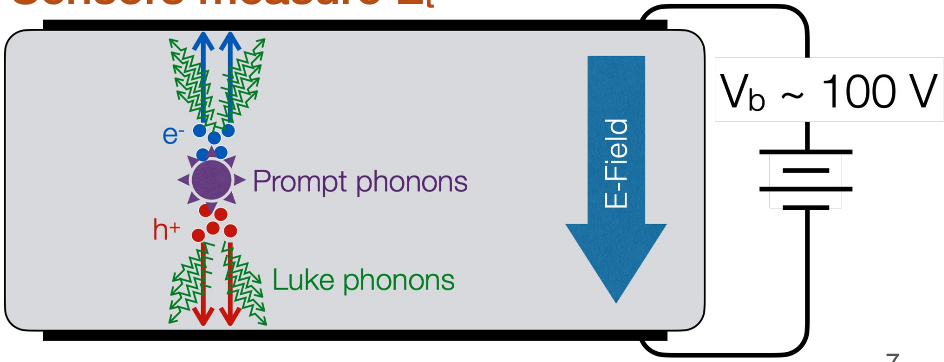
- Drifting electrons/holes across a potential (V_b) generates a large number of phonons (Luke phonons).
  - Enables very low thresholds!
  - Trade-off: No event-by-event NR/ER discrimination

$$\underset{\text{total phonon energy}}{E_t} = \underset{\text{primary recoil energy}}{E_r} + \underset{\text{Luke phonon energy}}{N_{eh} e V_b}$$

Sensors measure E_t, and n_{eh}

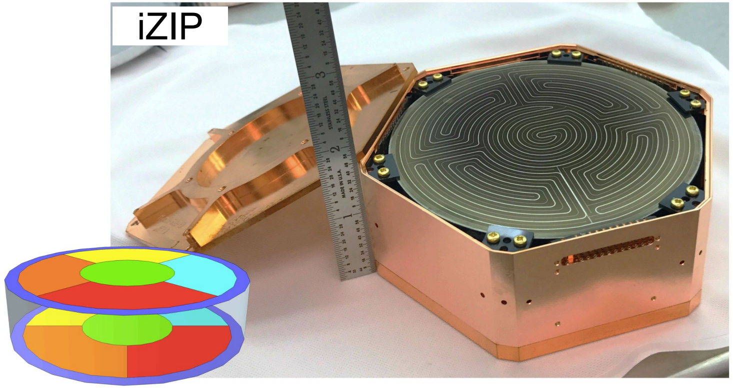


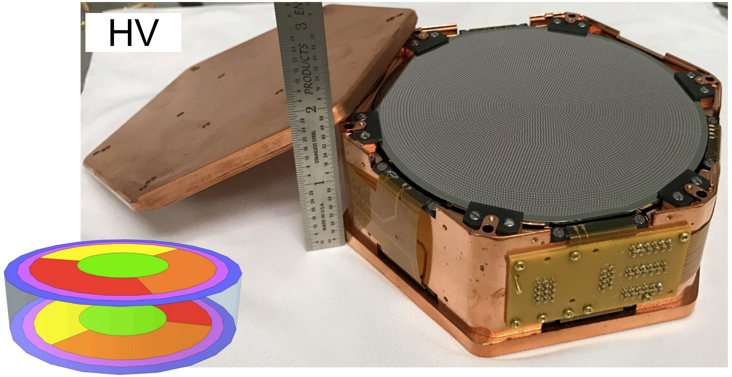
Sensors measure E_t



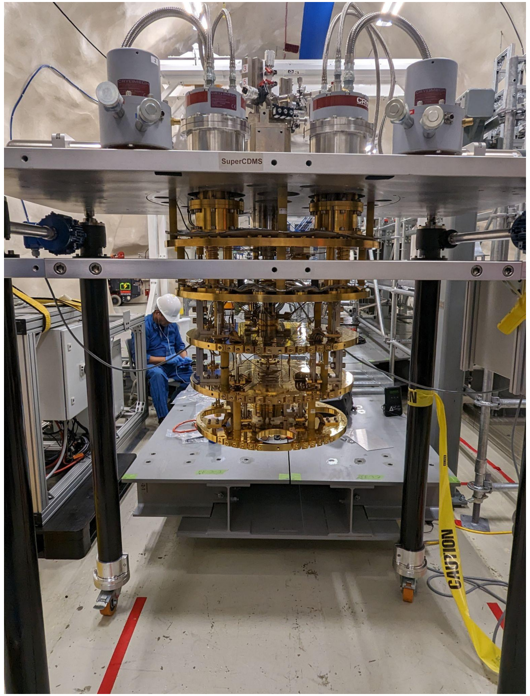
SuperCDMS Detectors: Posing for the Cameras

- Detectors made of high-purity Ge and Si Crystals
  - Si (0.6 kg each) provides sensitivity to lower dark matter masses
  - Ge (1.4 kg each) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
  - Athermal phonon measurement with **TESs**
  - Ionization measurement (iZIP) with **HEMTs**
- Multiple channels per detector to identify event position
- Initial payload will consist of 4 stacks of six detectors (“towers”)
  - 2 iZIP: 10 Ge / 2 Si
  - 2 HV: 8 Ge / 4 Si



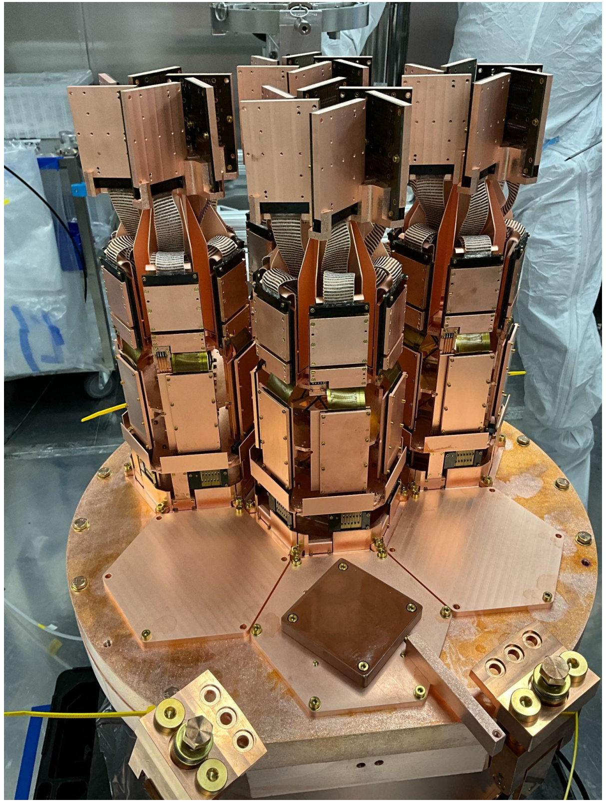


SuperCDMS Installation Status



Dilution refrigerator near C-stem

Shield assembly ⅔ complete
E-tank assembling in progress

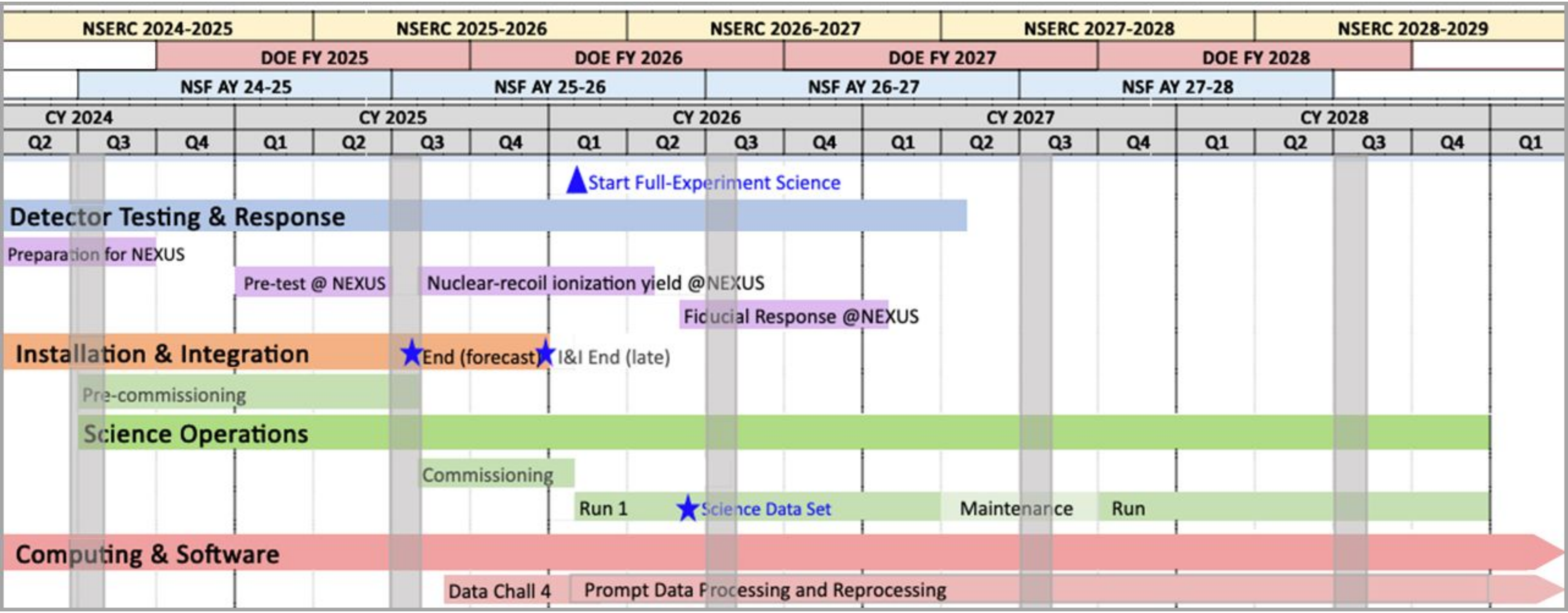


Detector towers installed in SNOBOX

Background control: large scale copper etching

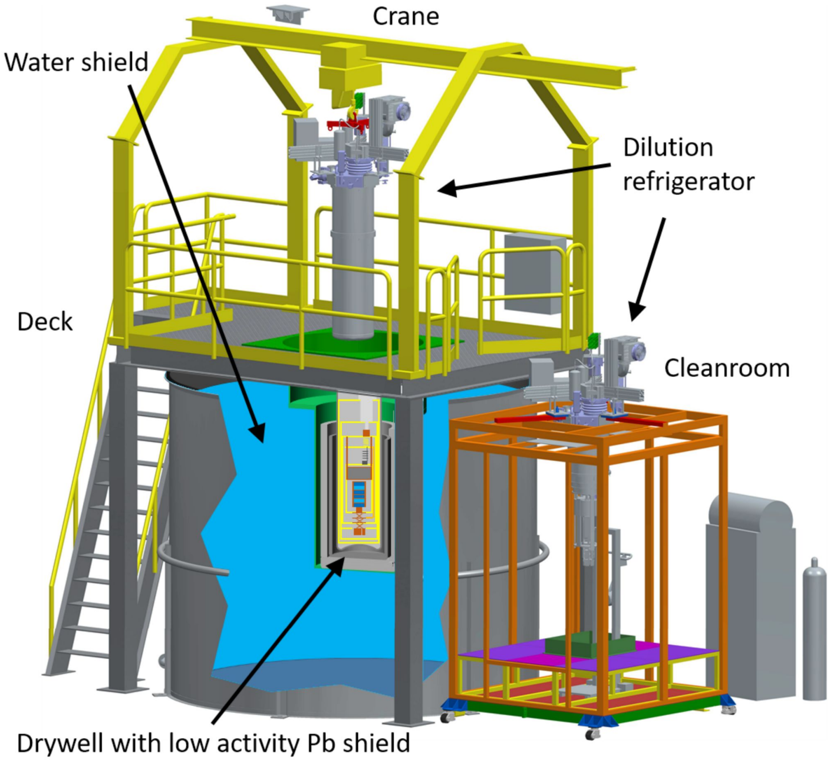
Gingerbread credit: Deena, Stephanie, Sharayah & Sahima

SuperCDMS Schedule

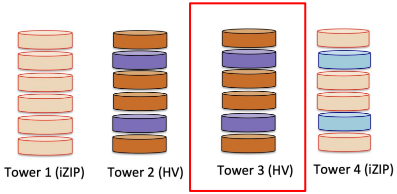


Cryogenic Underground TEst facility (CUTE)

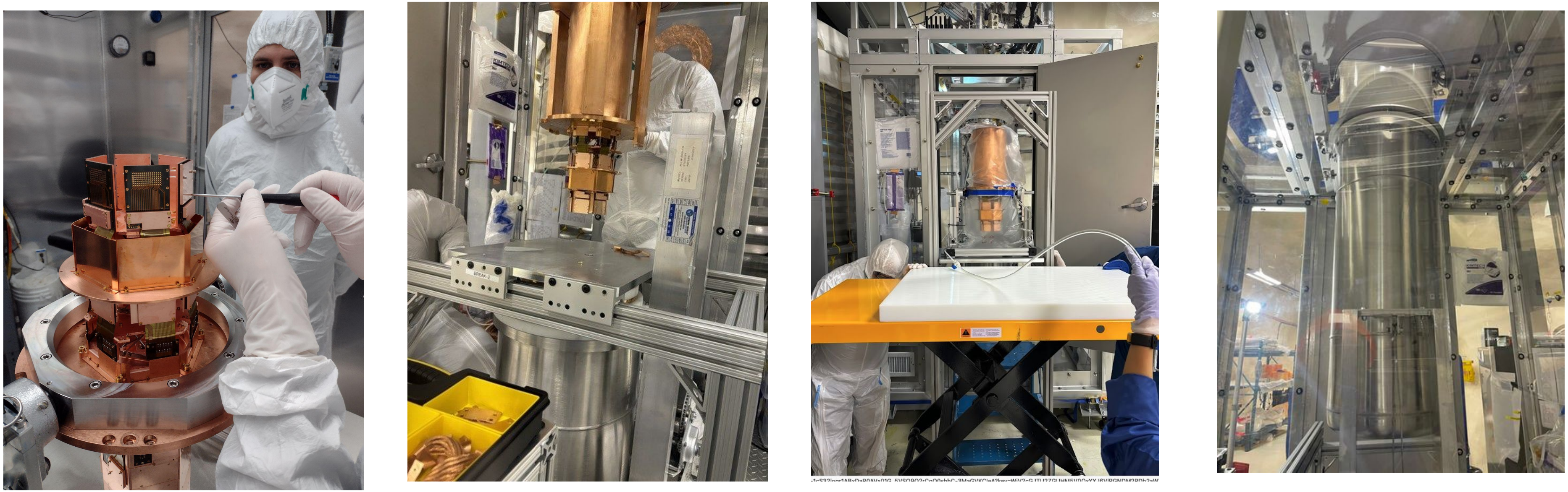
- Friendly neighbour
- Taking on critical mission of detector testing
    - Exercise and debug detectors before SuperCDMS cryostat is in place
- Same environment, same electronics → similar challenges expected
- A small science exposure, mostly to exercise the analysis tools



Tower 3 installation into CUTE



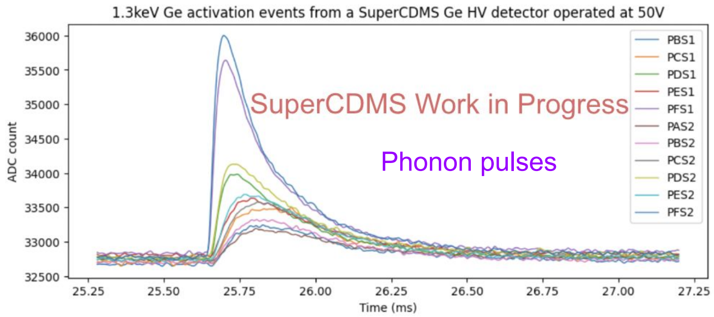
Tower-3 (HV detectors) was installed and operated at CUTE from Oct ‘23 to March ‘24.



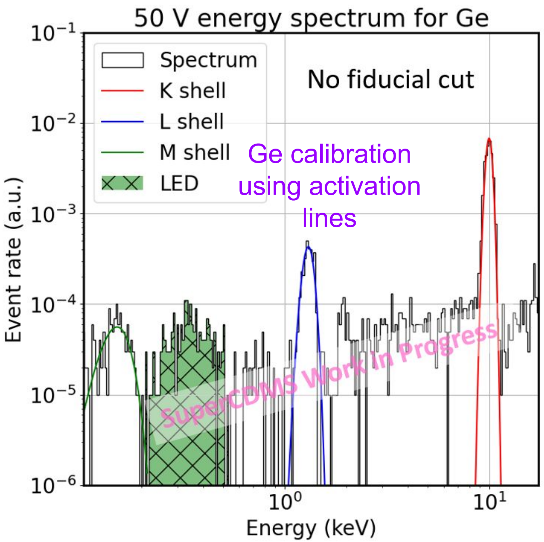
First time operating HV detectors in deep underground low-background facility.

SuperCDMS tower testing at CUTE

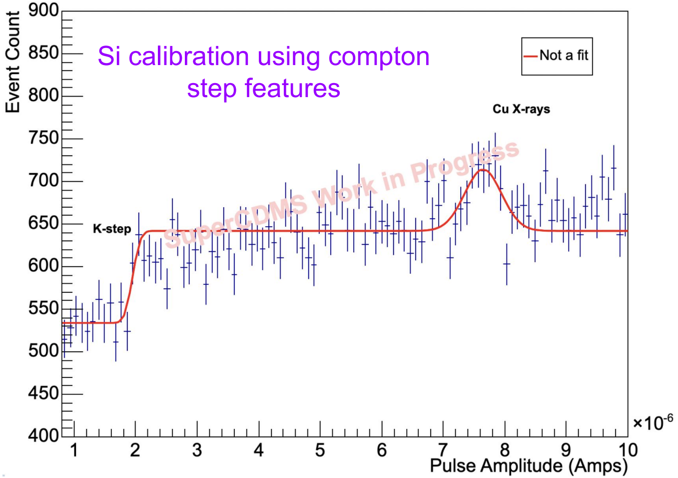
- 151 days of operation:
  - ~ 2 months of calibration data
  - ~ 2 months of low background data
  - Several weeks dedicated for detector characterization such as noise performance, HV testing

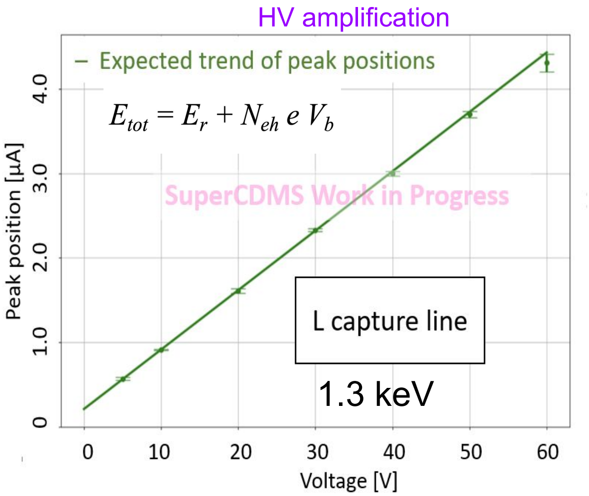

1.3keV Ge activation events from a SuperCDMS Ge HV detector operated at 50V

Phonon pulses


50 V energy spectrum for Ge

Ge calibration using activation lines


Si calibration using compton step features


HV amplification

$$E_{tot} = E_r + N_{eh}\, e\, V_b$$

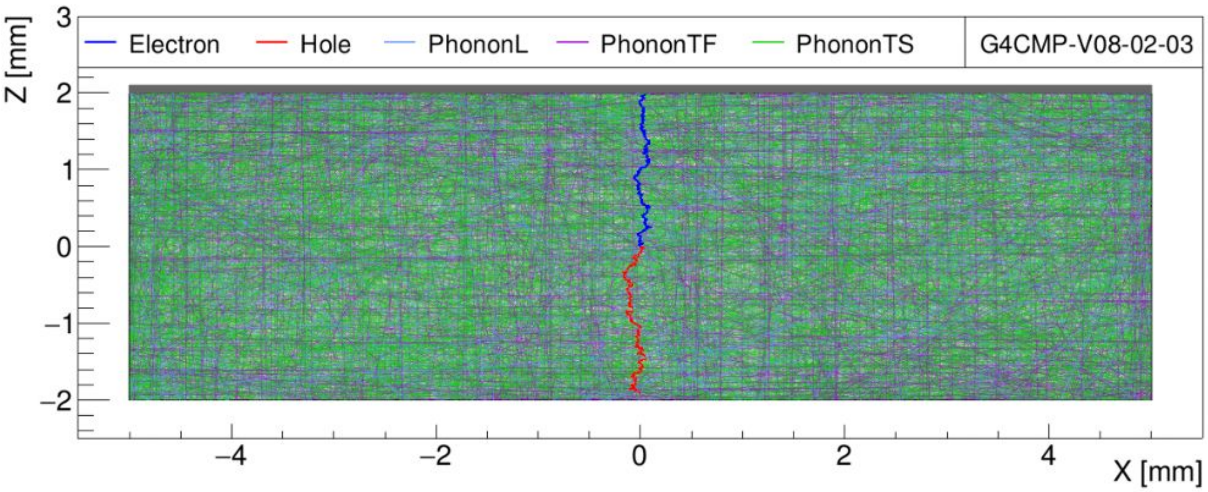
L capture line

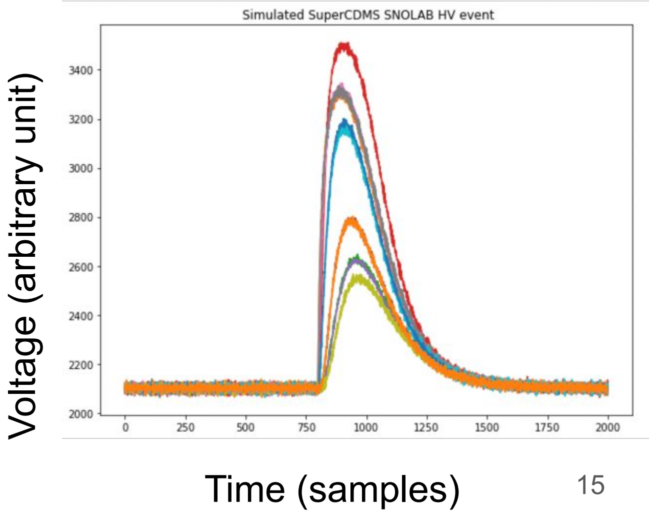
1.3 keV

Stay tuned for more results!

Understanding the detectors: Simulation

- GEANT4 + G4CMP based simulation
  - GEANT4 for energy depositions
  - G4CMP for charge and phonon propagations in crystals (NIM A 1055 168473 (2023))
- Deriving detector response modeling from first principle
- Validation with existing calibration data ongoing

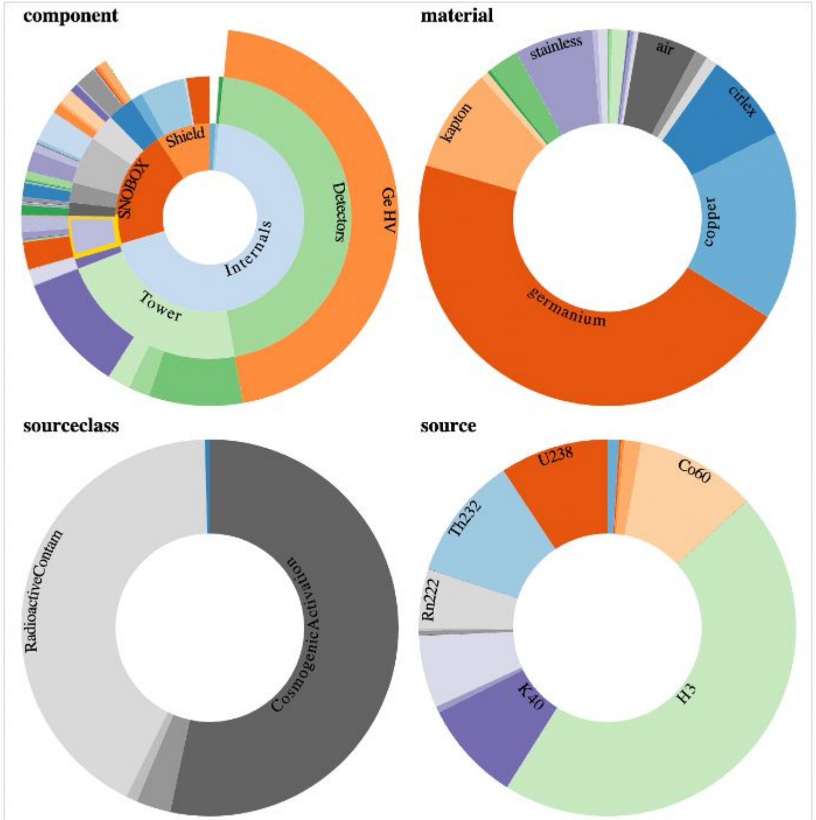




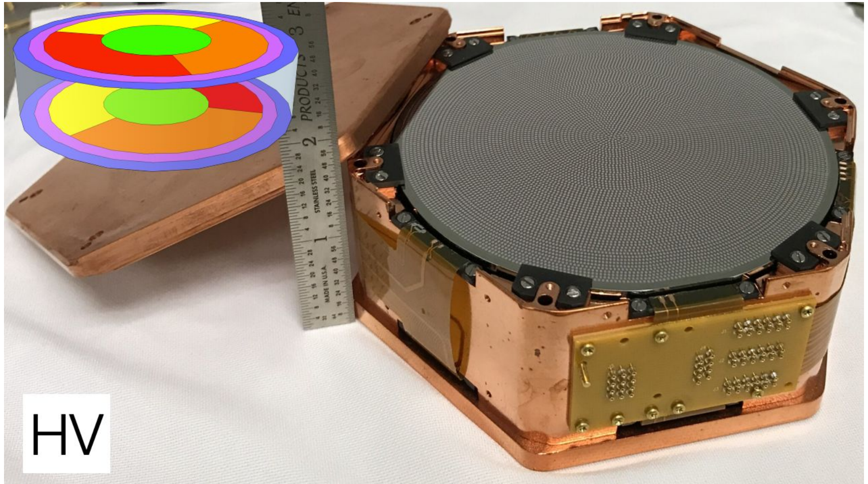
Background modeling

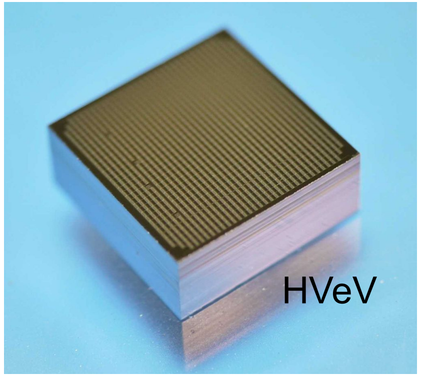
- Background: extensive material cleaning, tracking and screening
- eTraveller: Bookkeeping tool to keep track of material movement
    - Precision accounting for cosmogenic activations
- BGExplorer: Background estimate based on material assay results

βαckγroμnd
EXplorer



Exploring the sensor limit:
HV → HVeV Detectors





HVeV: Prototype HV detector

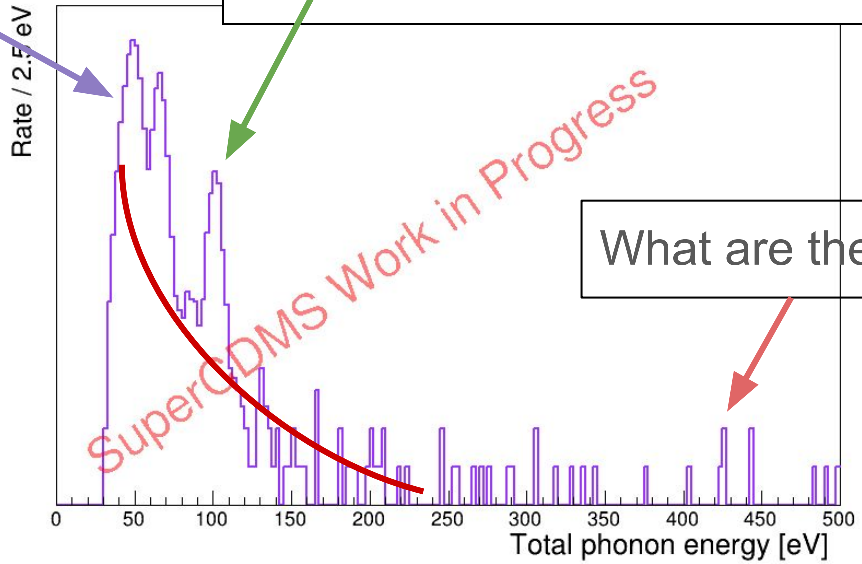
- Gram scale
- eV level resolution

Low mass dark matter search background challenges

- Sub 1-eh peaks
- Hypothesized from unpolished sidewalls
- Will attempt sidewall etching/polishing

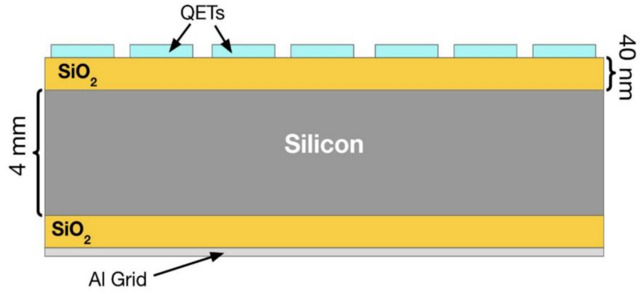
- 1-eh peak
- Could be from electrode leakage, light leakage, etc.
- Attempting electrode blocking materials for mitigation
- Also building better light tight enclosures

- Low energy excess
- Evidence hints different ionization from ER and NR
  - “Heat only”
- Unpacking ER/NR/Heat Only components by operating with different NTL gains

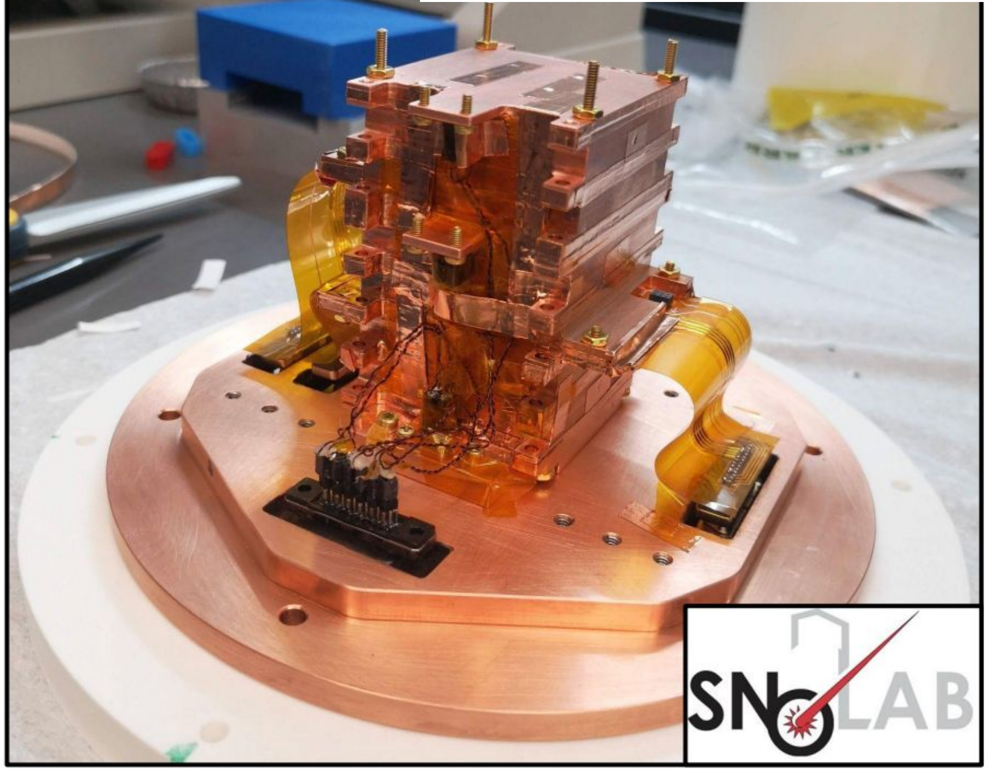


What are these?

Latest attempt: HVeV @ CUTE



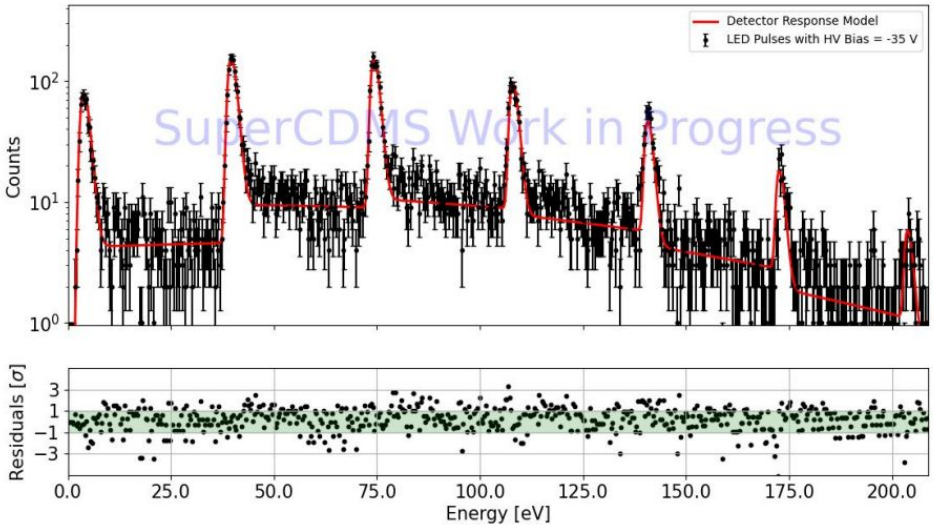
- New light tightness standard
- More sensitive TES sensors
  - Lower Tc, requires lower noise
- Quieter electronics
- SiO_2 insulating layer for charge injection
- Lower background
- Operating detector at multiple voltages to model non-ionizing backgrounds



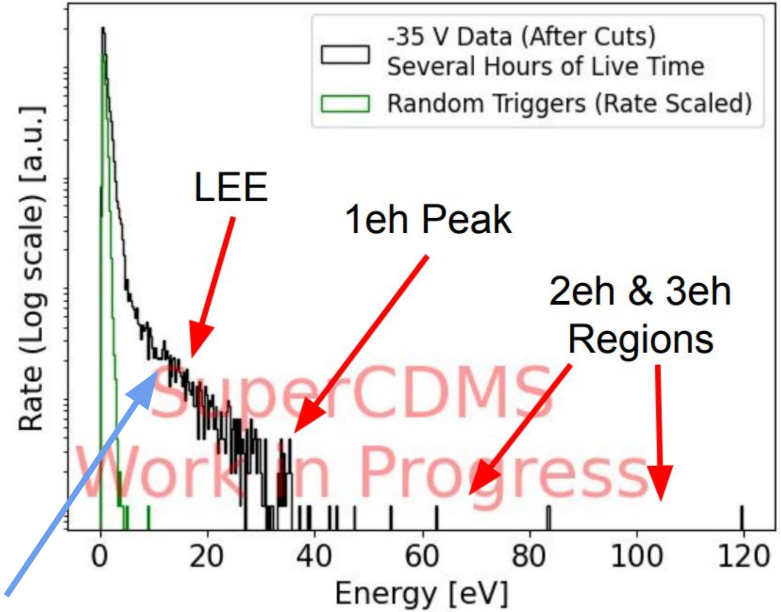
SiO$_2$ HVeV achieved **0.573 eV baseline resolution!**

BEST IN CLASS

Detector response model fit to LED calibration data



Sample Spectrum from Unblinded DM Search Data



LEE

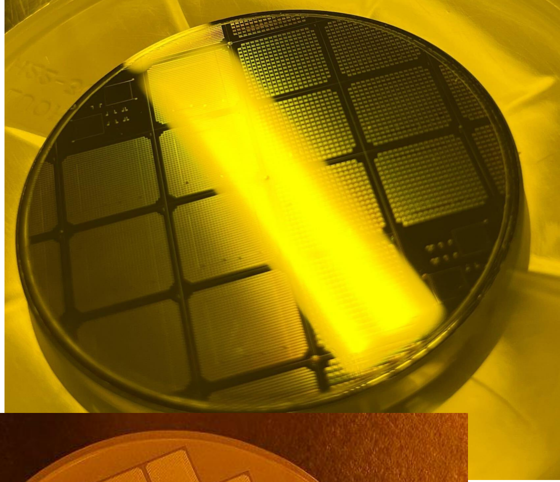
1eh Peak

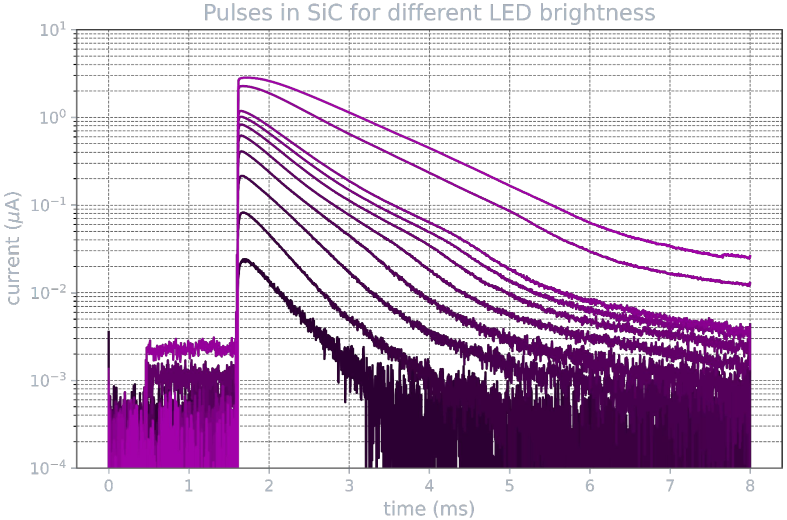
2eh & 3eh Regions

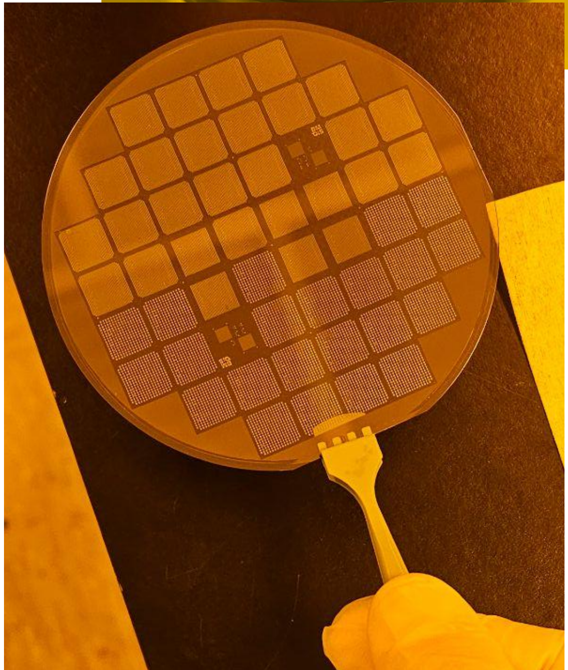
0V data in hand to help model this

HVeV with more targets

- HVeV now comes with different targets
- Germanium, SiC, Diamond, maybe others
- Better low-mass WIMP sensitivity with **Carbon**
- Exploring arts of fabrication
- Coming to SNOLAB soon!

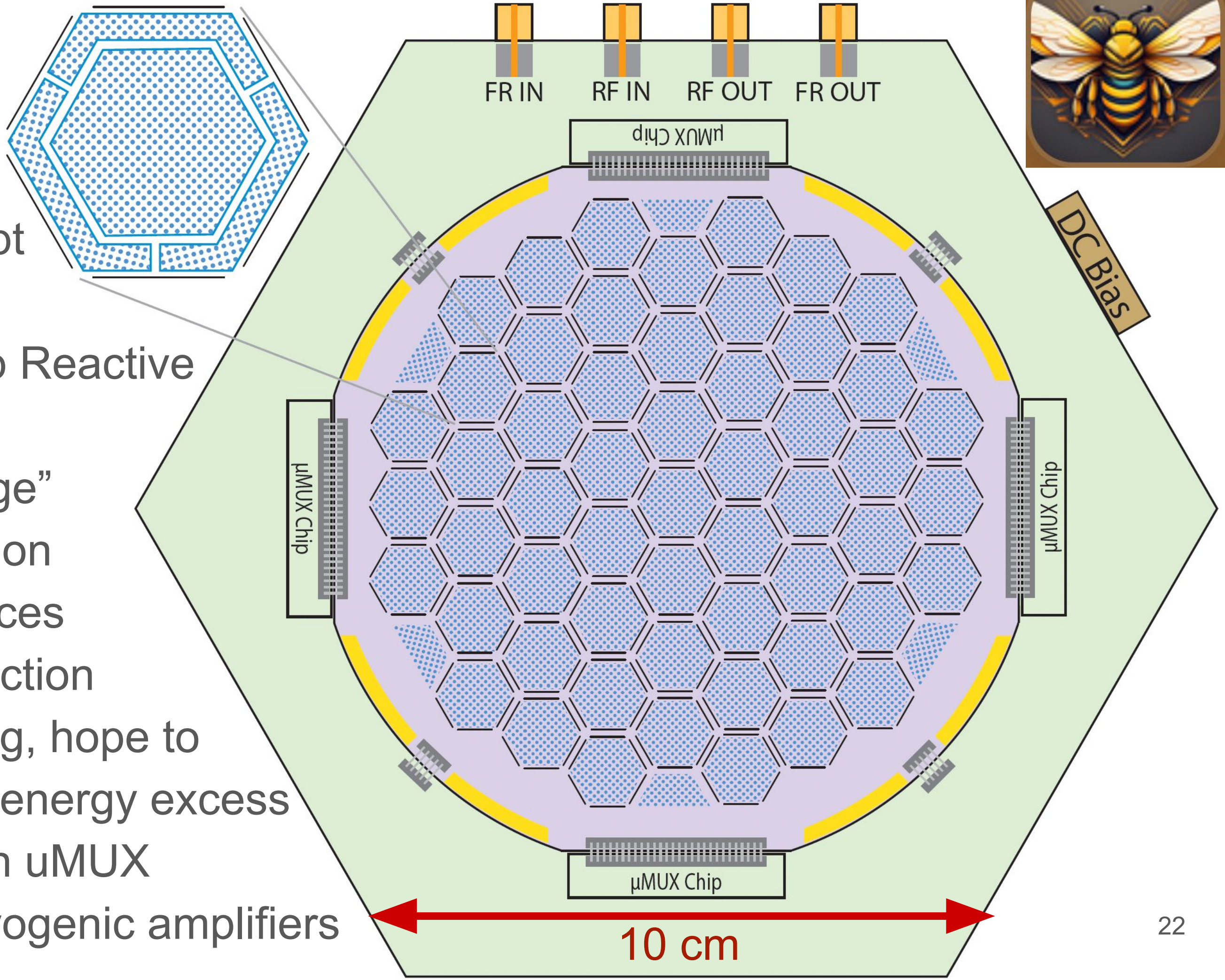






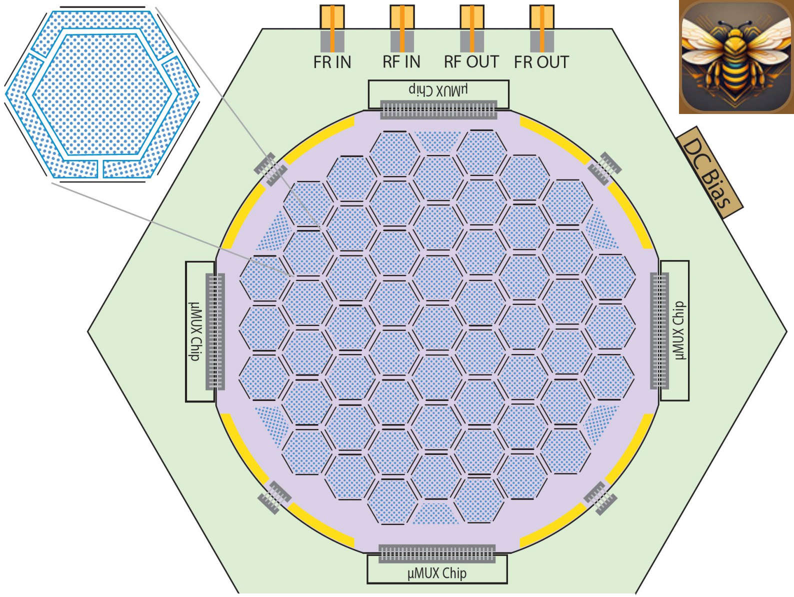
HONEYCOMB

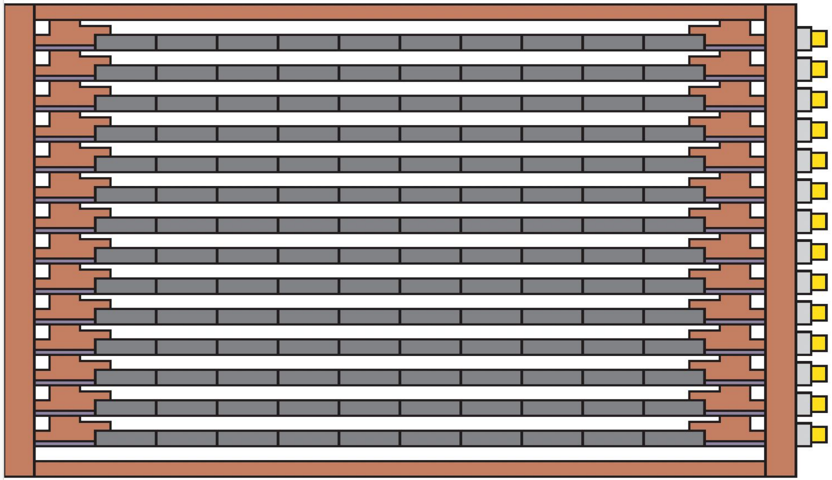
- Scaling up HVeV concept
- A few grams each
- “Dicing” wafer with Deep Reactive Ion Etching trenches
  - Leave a small “bridge” for thermal conduction
  - Smooth dicing reduces sidewall charge injection
  - Stress-free mounting, hope to reduce/remove low energy excess
- Multiplexing readout with uMUX
  - With multi-stage cryogenic amplifiers



HONEYCOMB

- Stacking multiple wafers for O(10 kg) payload
- Aiming for eV level threshold
- Multiple chips serve as active veto for each other
- Perfect match for recent RF readout upgrades for the CUTE facility





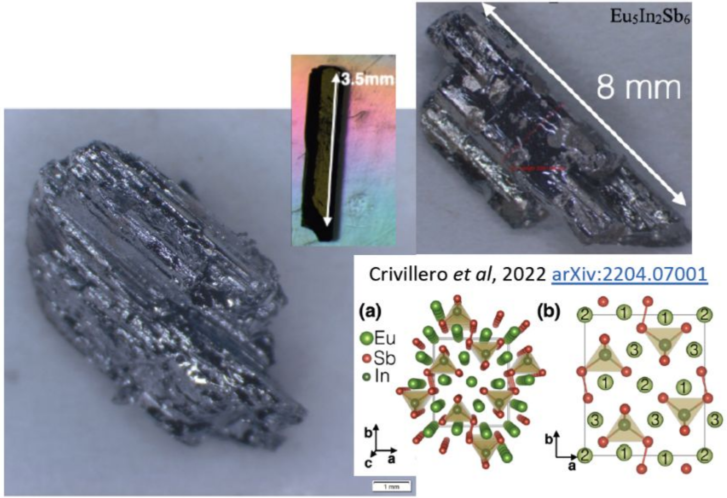
Slides from Taylor Aralis
Questions should be directed to Yoni

Splendor: narrow bandgap materials

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

$Eu_5In_2Sb_6$

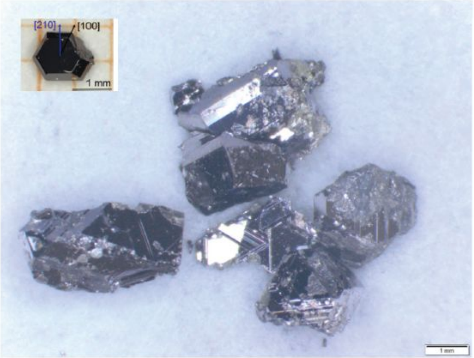
- ~40 meV indirect band gap



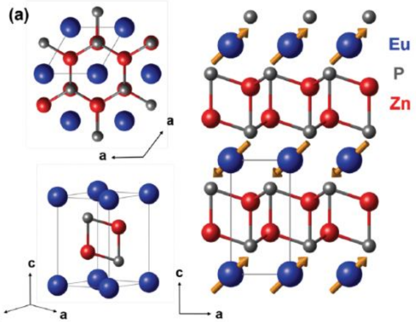
Crivillero *et al*, 2022 arXiv:2204.07001

$EuZn_2P_2$

- ~10-100 meV indirect band gap



Krebber *et al*, 2023 arXiv:2302.14539

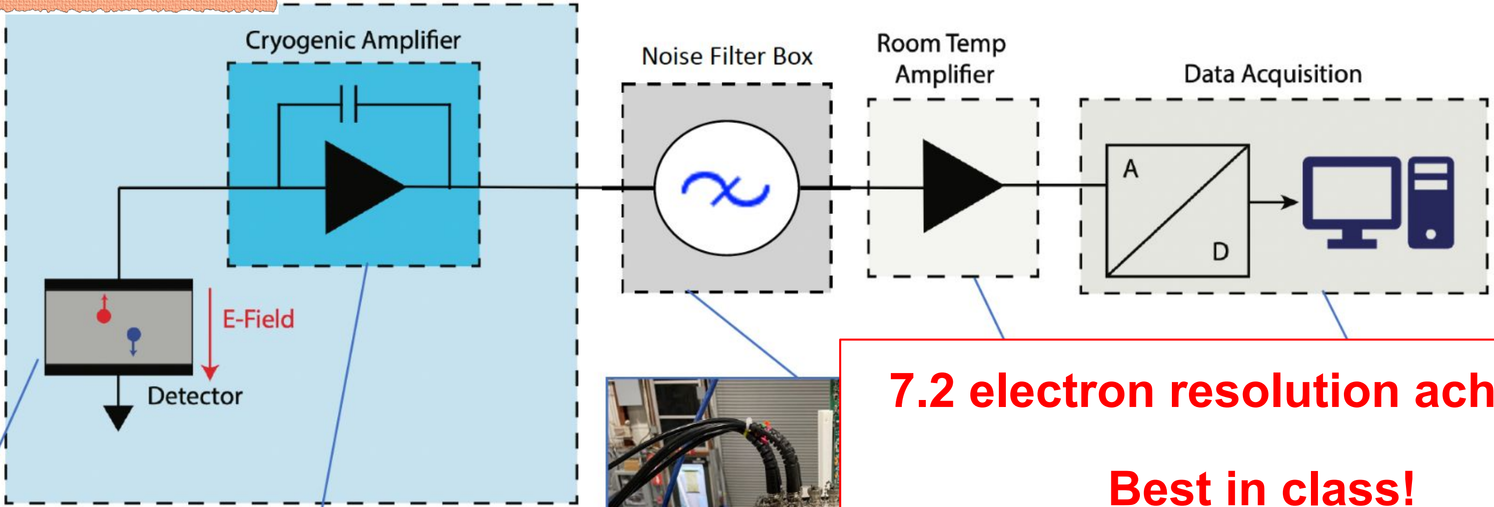


- Both have anisotropic crystal structures, making directional discrimination possible
- Both have low dark current, which is pure background for an ionization detector
- Both grown by SPLENDOR collaboration for this purpose

Slides from Taylor Aralis
Questions should be directed to Yoni

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

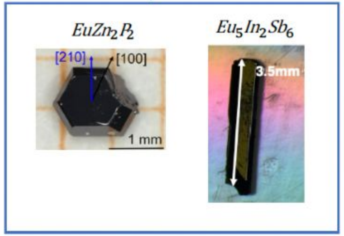
Two-stage charge readout

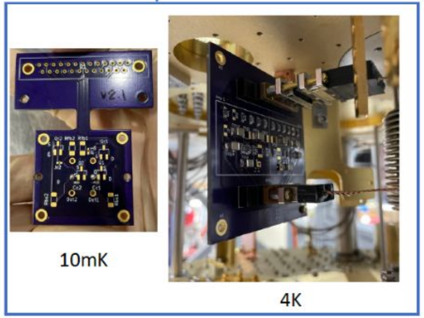


7.2 electron resolution achieved!

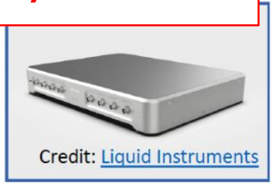
Best in class!

(arXiv:2311.02229)

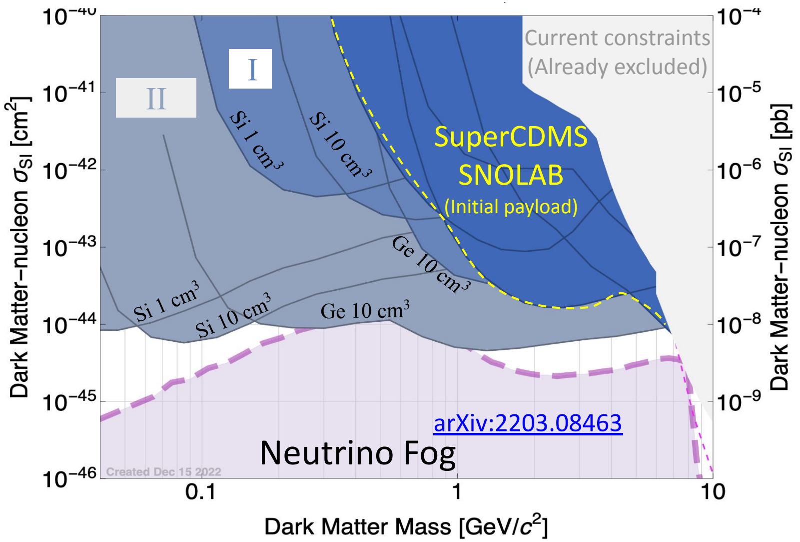


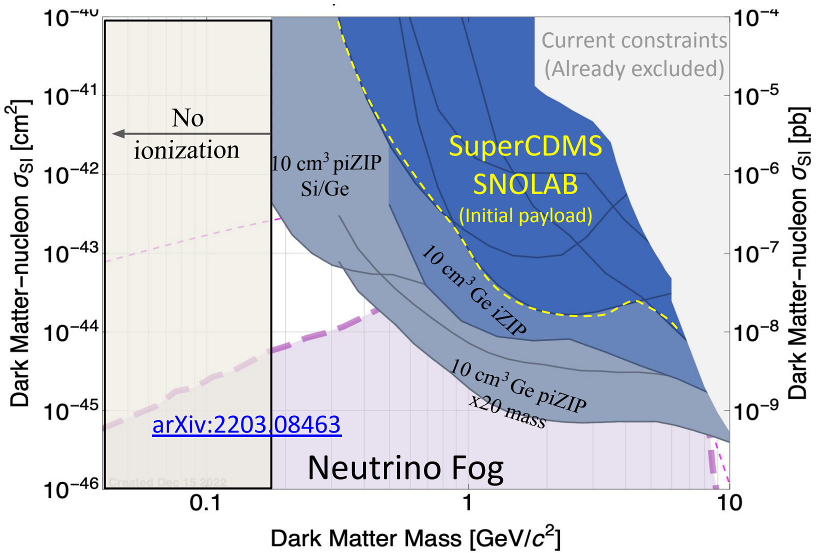



Credit: SRS


Credit: Liquid Instruments

SuperCDMS sensitivity projection : NRDM





Pushing the sensitivity to lower DM mass

- ➢ Future Improvement in phonon resolution: 0V Si/Ge 1 cm^3, 10 cm^3
- ➢ At lower DM masses, DM spectrum steeply rises whereas ER bkg is flat
  - ○ Improved σ_{phonon} allows bkg subtraction statistically with PLR
  - ○ NB: LEE not taken into consideration

Upgrade scenario

I : with in-hand detector technology upgrade

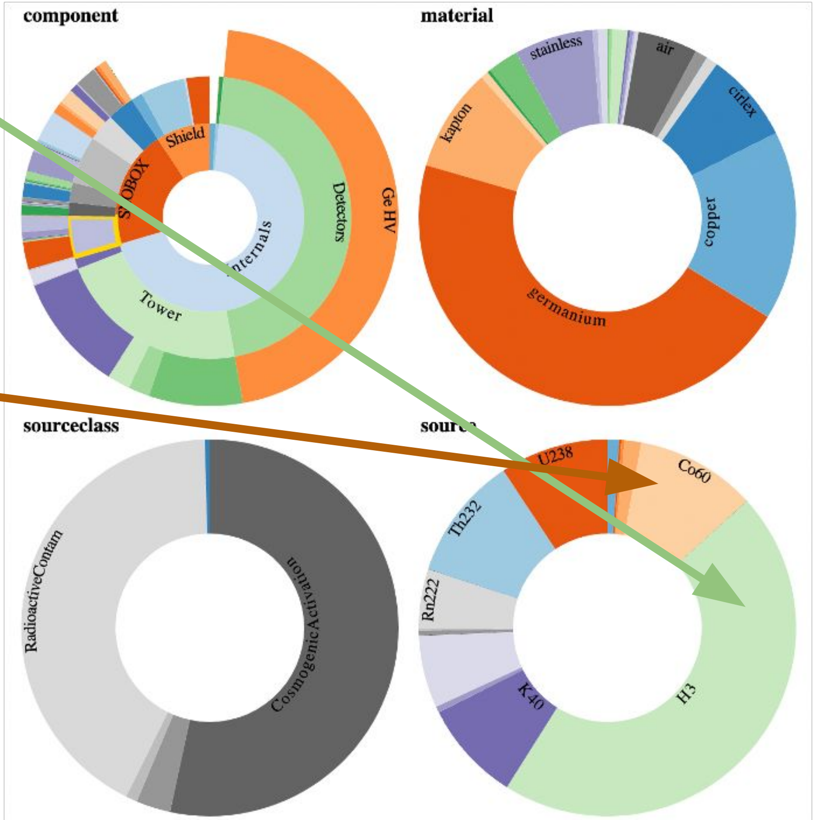
II : with significant technology upgrade & x20 mass

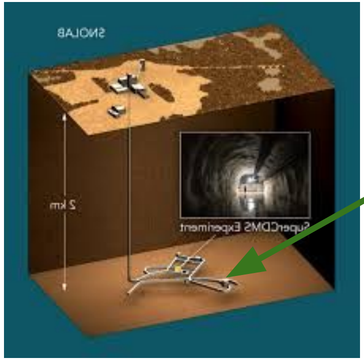
Pushing the sensitivity into the neutrino-fog : three avenues

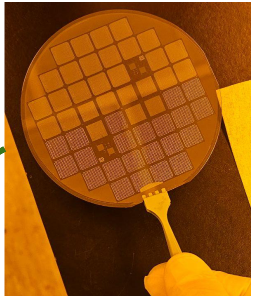
- ➢ HV-SNOLAB-sized detectors : improved σ_{phonon} → spectral discrimination
- ➢ 10 cm^3 iZIP detectors: improved $\sigma_{\text{ionization}}$ → better ER/NR discrimination
- ➢ 10 cm^3 piZIP detectors: measure phonons from E_R and N_{eh} separately → ionization-yield discrimination

Far future: underground detector fabrication

- With all detectors/technology under control, circle back to backgrounds
- Background budget dominated by Tritium, caused by cosmogenic activation
- Solution: Keep the whole detector fabrication cycle underground!
- Also benefit from electroformed copper underground

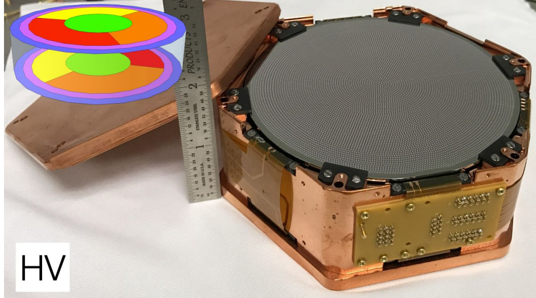


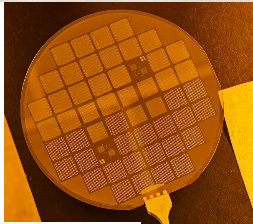


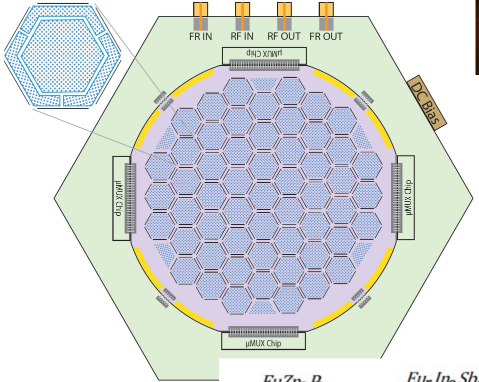


Conclusions

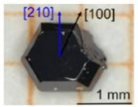
- SuperCDMS is well suited for low mass DM searches
- Low threshold enables low mass NR searches
  - iZIP provides background rejection
  - HV pushes down threshold further
- SNOLAB commissioning well underway
  - Lab provides critical resources for all aspects of the experiment
- HVeV detectors achieve sub-1 eV resolution
  - More variety of HVeV coming soon!
- Two more future experiments on the horizon
  - HONEYCOMB -- extreme phonon sensor
  - SPLENDOR -- charge readout with nano-gap materials







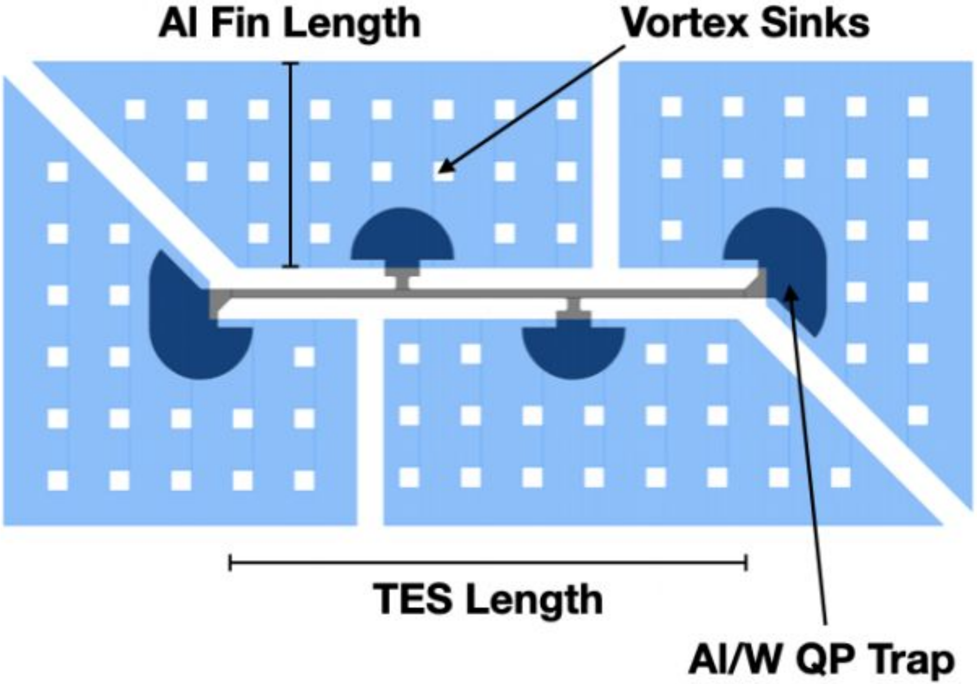
$EuZn_2P_2$

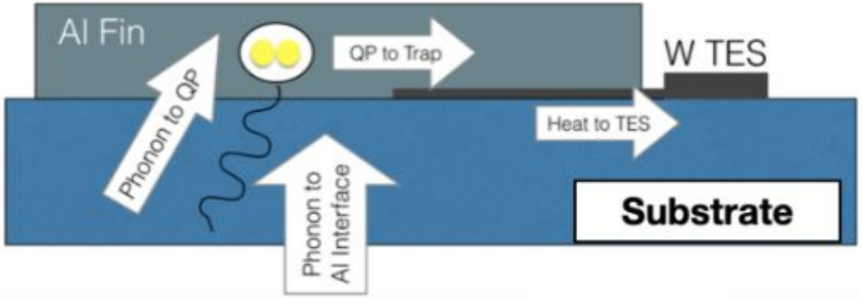


$Eu_5In_2Sb_6$

Bonus Slides

QET Design and Transport





SuperCDMS Detectors & Dark Matter Mass Scales

- Dark Matter Mass Ranges
    - "Traditional" Nuclear Recoil: Full discrimination, ≳ 5 GeV
    - Low Threshold NR: Limited discrimination, ≳ 1 GeV
    - HV Detector: HV, no discrimination, ~0.3 – 10 GeV
    - Migdal & Bremsstrahlung: no discrimination, ~0.01 – 10 GeV
    - Electron recoil: HV, no discrimination, ~0.5 MeV – 10 GeV
    - Absorption (Dark Photons, ALPs): HV, no discrimination, ~1 eV – 500 keV (“peak search”)