SuperCDMS Update

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On behalf of the SuperCDMS Collaboration

2023 Canadian Astroparticle Physics Community Meeting

@SuperCDMS

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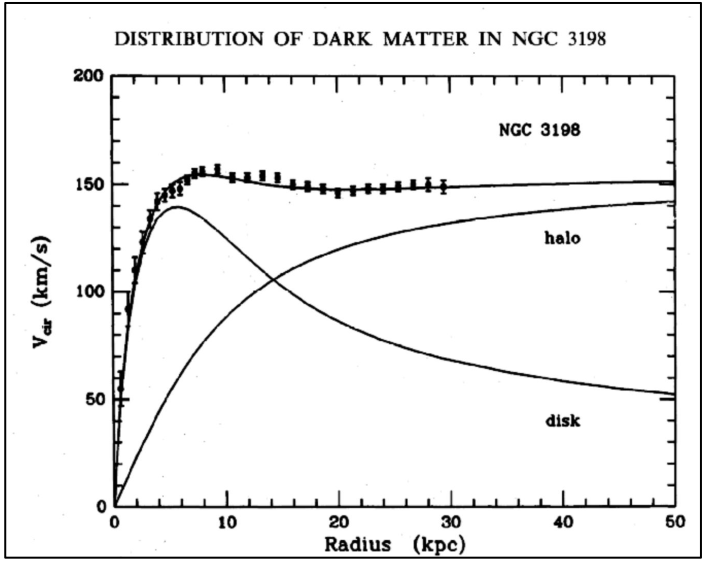
SUPER CDMS
Cryogenic Dark Matter Search

The Evidence for Dark Matter

Gravitational Lensing

smithsonianmag.com

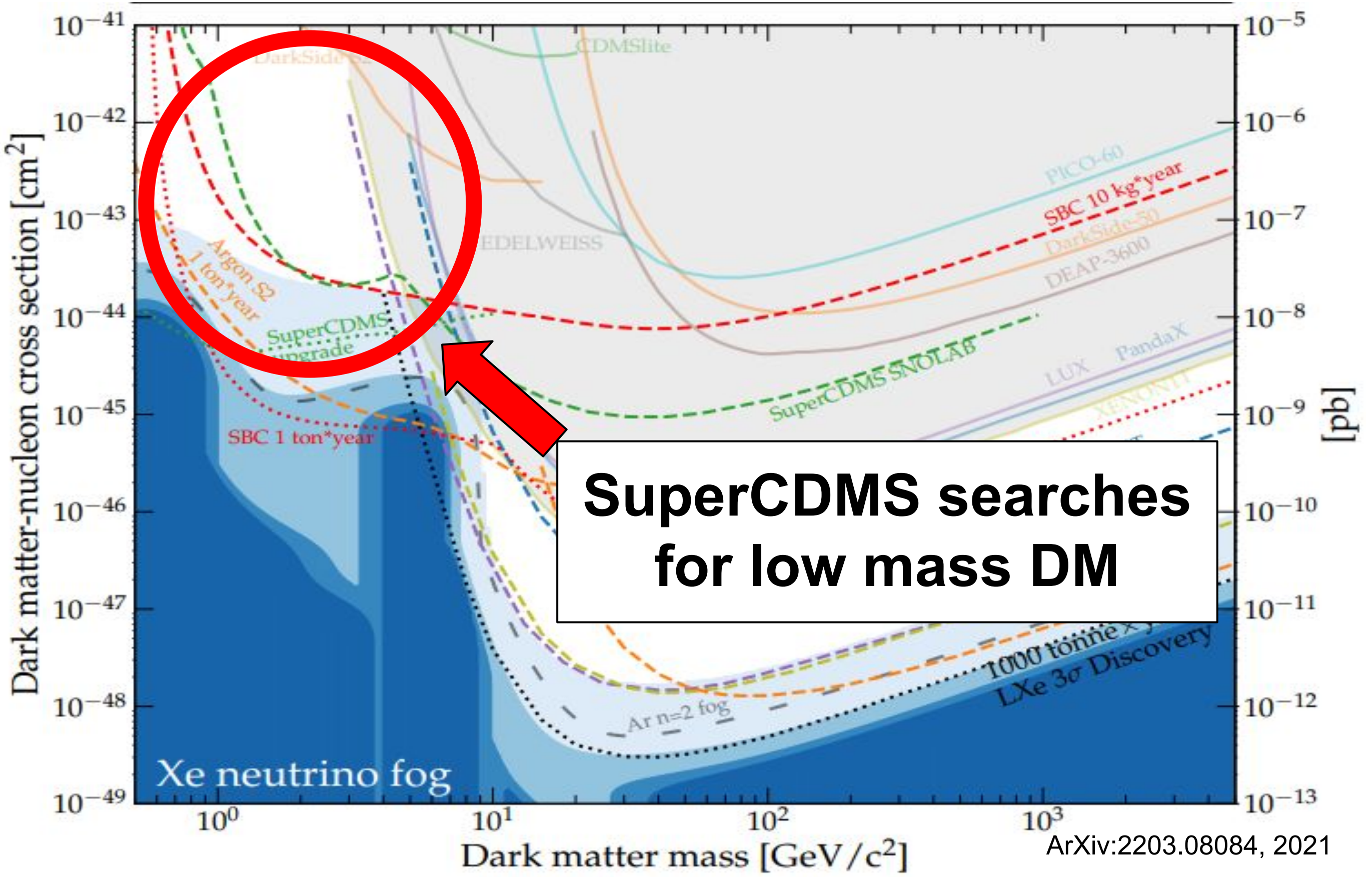
Galactic Rotation Curves



physicsanduniverse.com

~5 times as much dark matter in the universe as regular matter

Dark Matter Searches



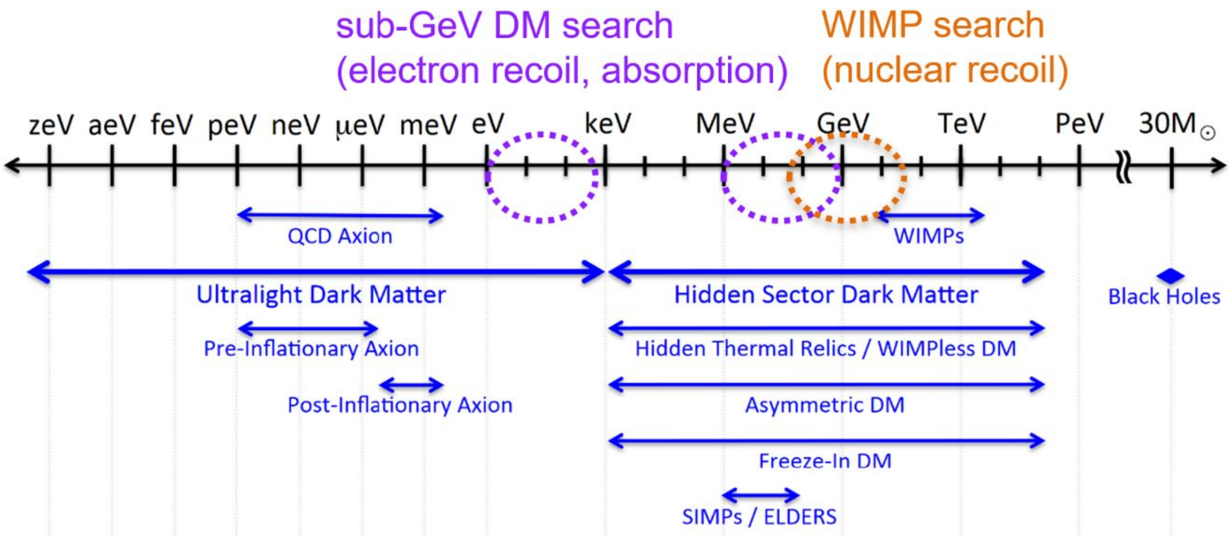
SuperCDMS searches for low mass DM

ArXiv:2203.08084, 2021

Dark Matter Candidates

Looking for a wide range of DM candidates

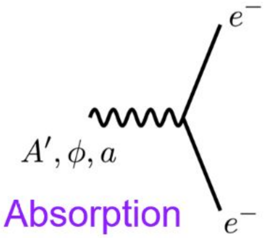
- Dark matter masses from ~5 GeV down to eV



Nuclear interaction processes:

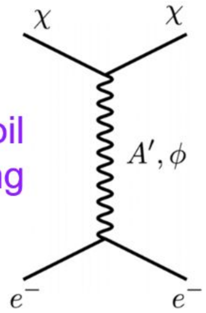
Nucleus-recoil scattering

Electronic interaction processes:



Absorption

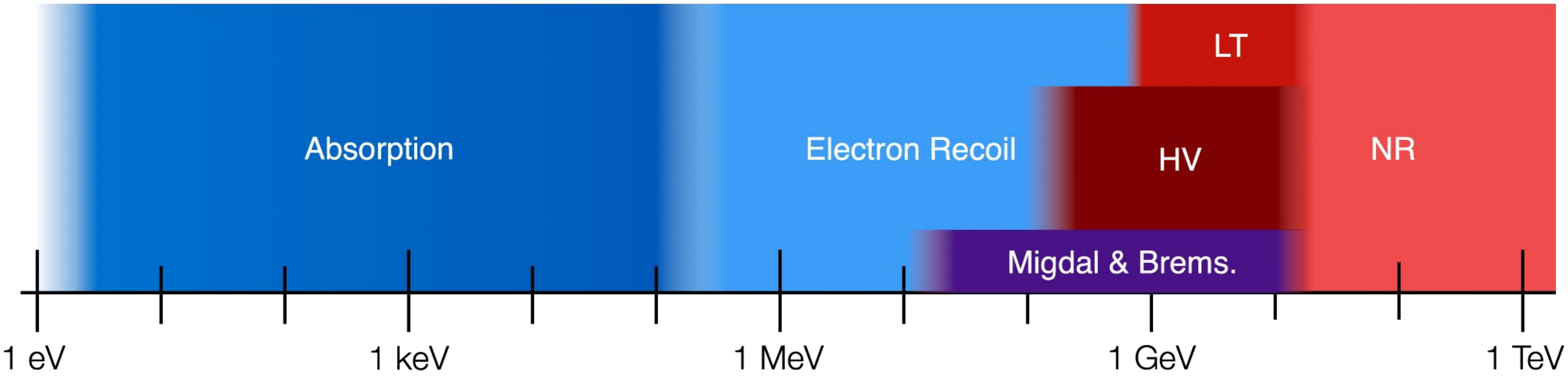
Electron-recoil scattering



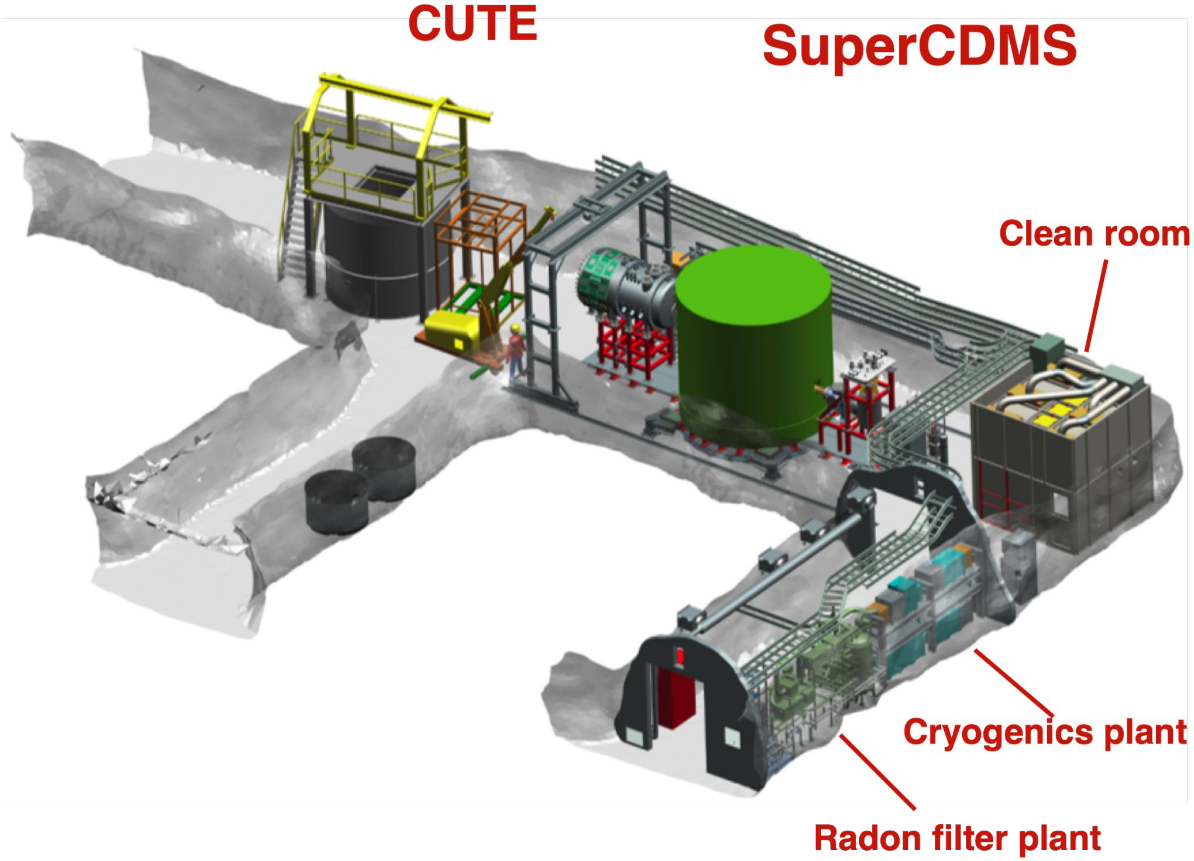
US Cosmic vision ArXiv:1707.04591

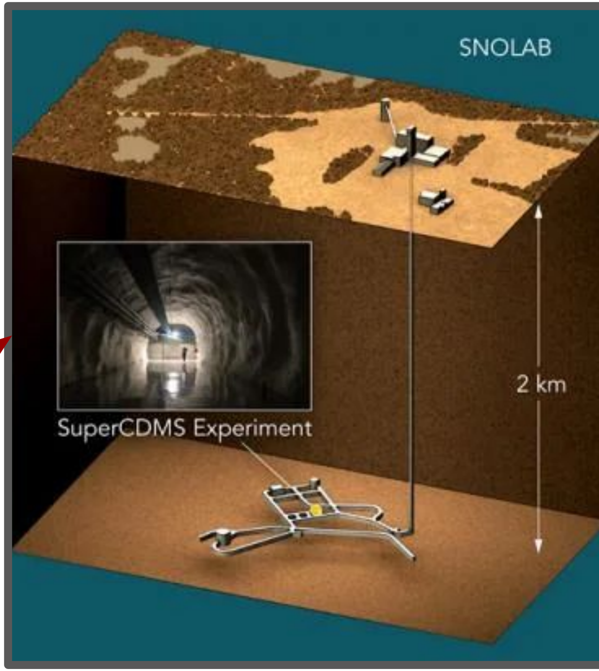
SuperCDMS Detectors & Dark Matter Mass Scales

- 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”)

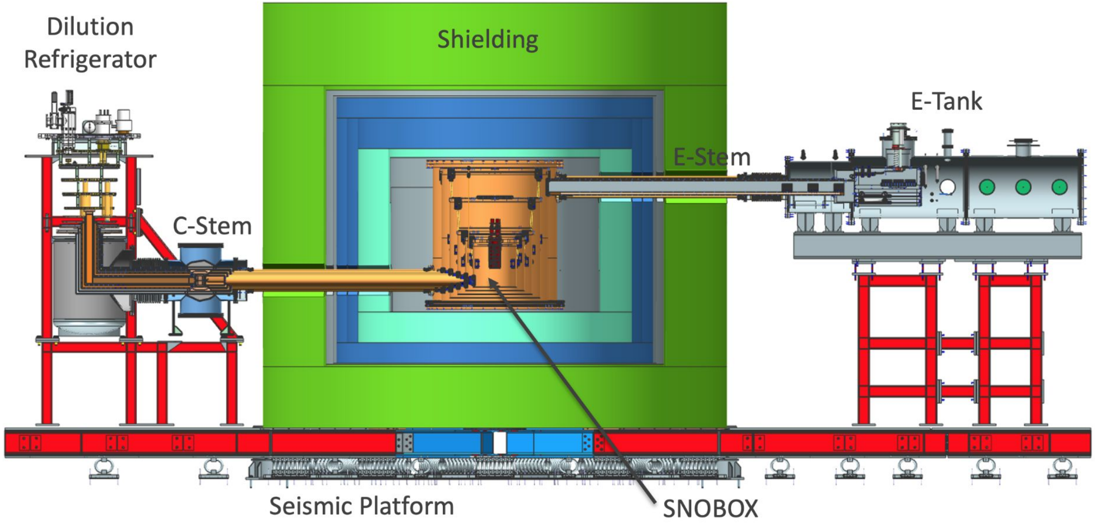


SuperCDMS @ SNOLAB





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)

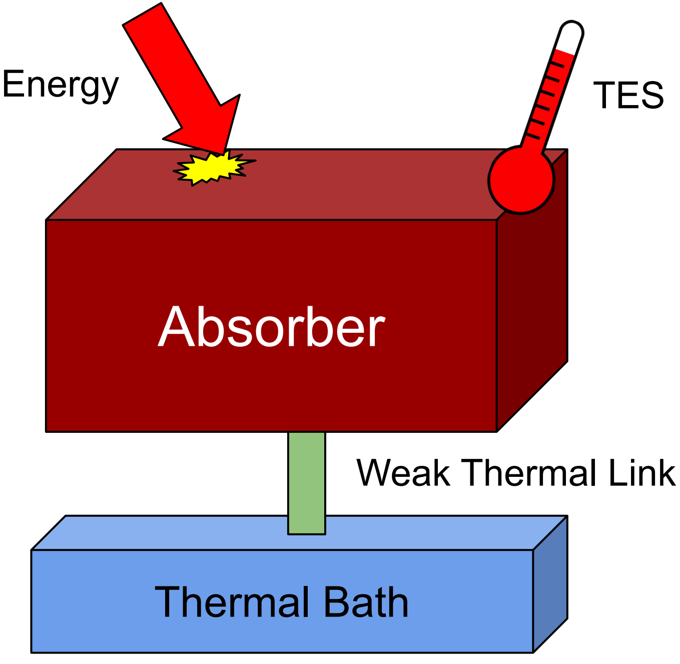
Facility designed to be dominated by solar neutrinos in NR background

Vibration isolation:

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

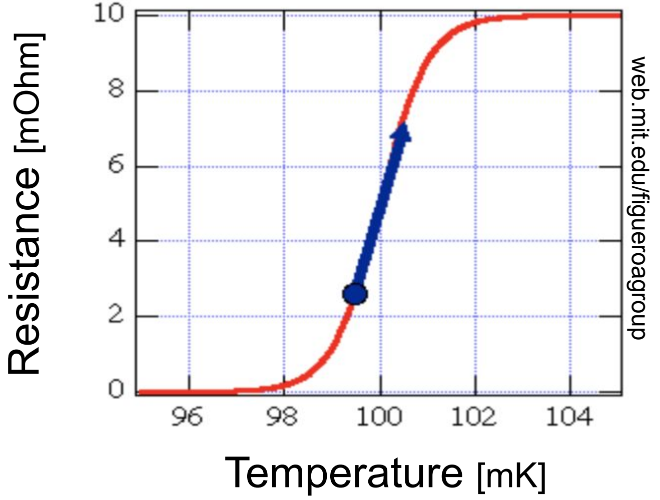
Detector Schematic

Cryogenic Calorimeter



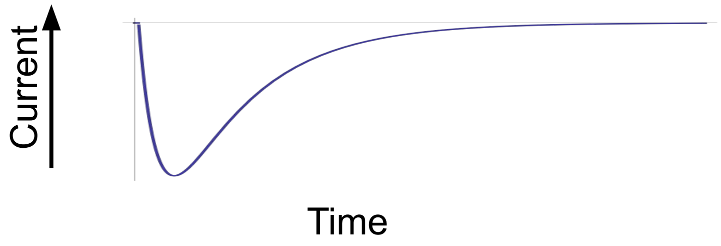
Cryogenically cooled in dilution fridge

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

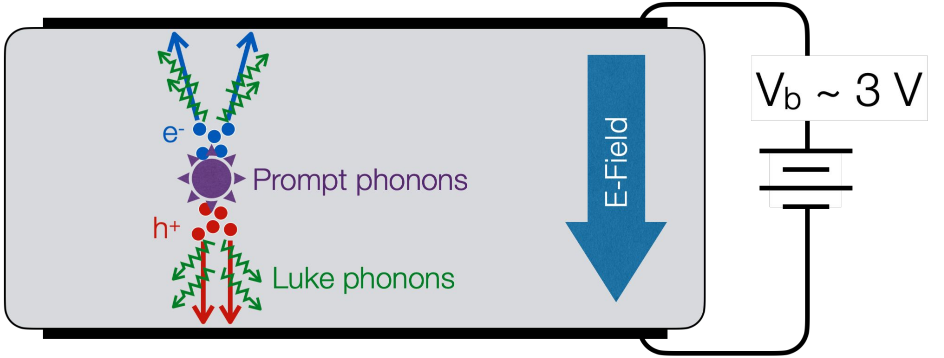
Low Threshold

~~HV~~ detector:

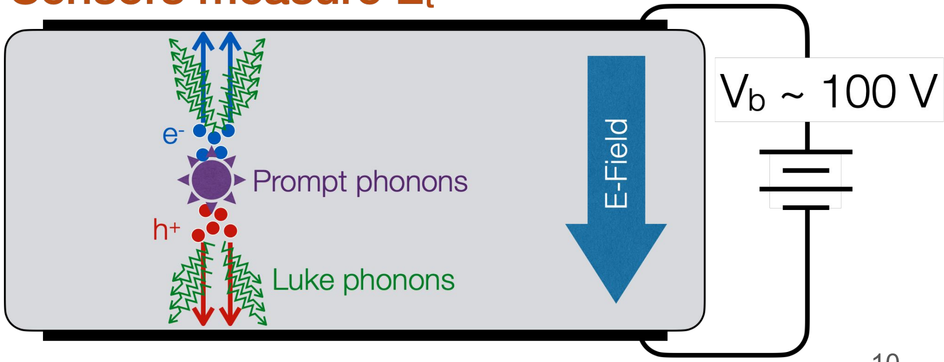
- Drifting electrons/holes across a potential (V_b) generates a large number of phonons (Luke phonons).
  - Enables very low thresholds!
  - Trade-off: No event-by-event NR/ER discrimination

$$\underset{\uparrow\ \text{total phonon energy}}{E_t} = \underset{\uparrow\ \text{primary recoil energy}}{E_r} + \underset{\nwarrow\ \text{Luke phonon energy}}{N_{eh}eV_b}$$

Sensors measure E_t, and n_{eh}

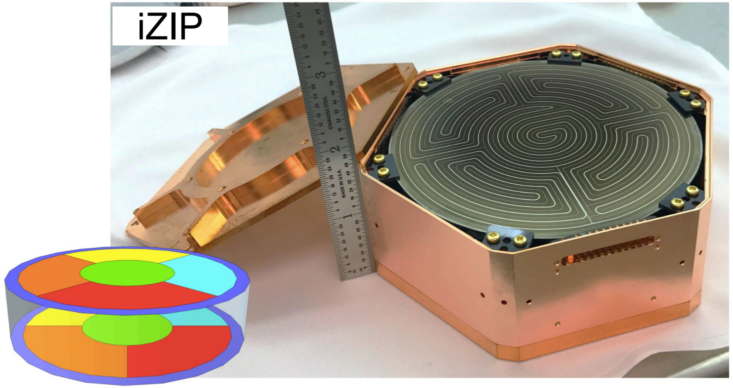


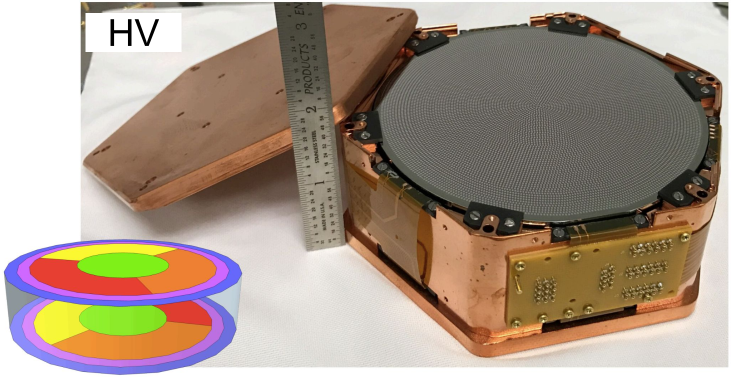
Sensors measure E_t



SuperCDMS Detectors: Posing for the Cameras

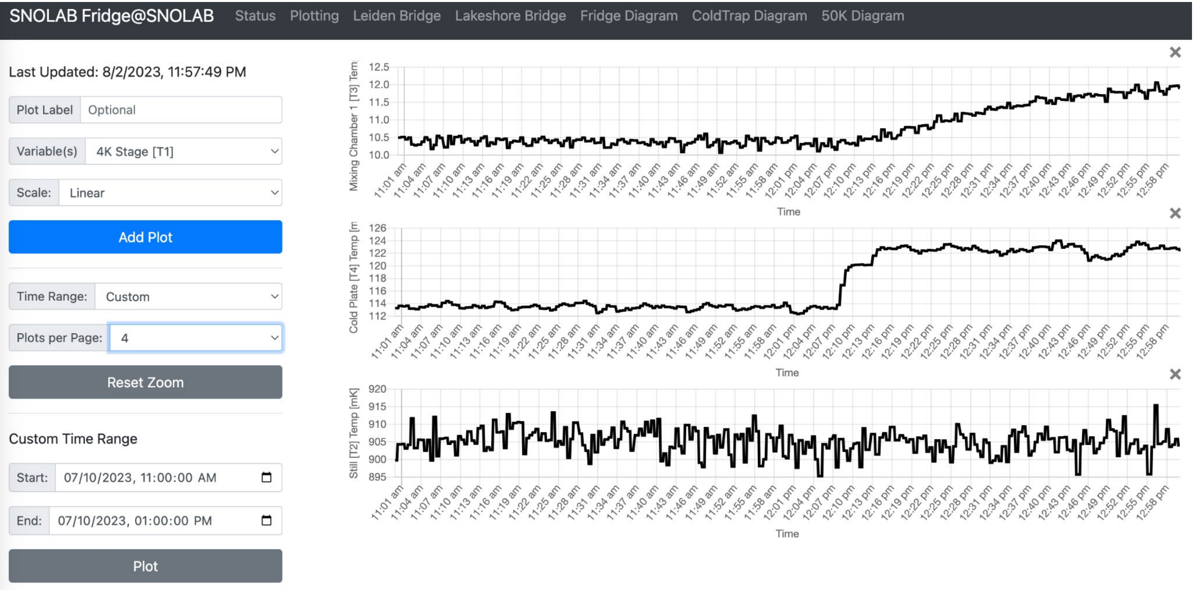
- Detectors made of high-purity Ge and Si Crystals
  - Si (0.6 kg each) provides sensitivity to lower dark matter masses
  - Ge (1.4 kg each) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
  - Athermal phonon measurement with TESs
  - Ionization measurement (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





Construction Status -- Dilution refrigerator

- Delivered underground at the end of 2022
- Got 10 mK first run before Planned Maintenance Period (PMP)
- Further integration and tuning ongoing



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Plot Label: Optional

Variable(s): 4K Stage [T1]

Scale: Linear

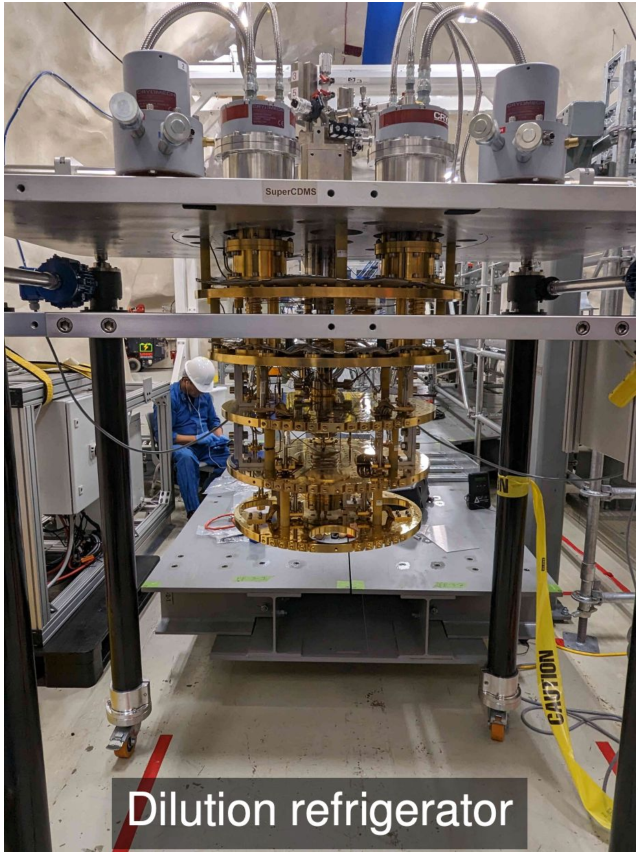
Time Range: Custom

Plots per Page: 4

Custom Time Range

Start: 07/10/2023, 11:00:00 AM

End: 07/10/2023, 01:00:00 PM

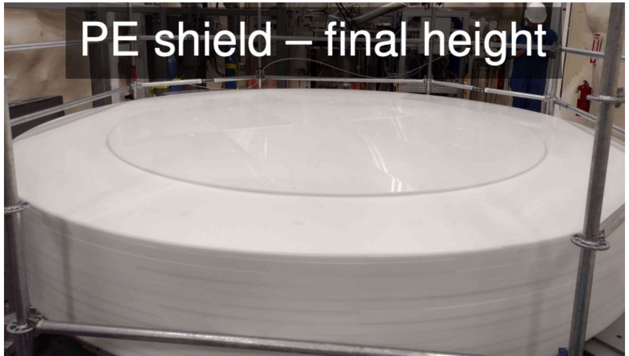


Dilution refrigerator

Construction Status -- Shield base

- Shield base assembling finished
- Ready for the cryostat

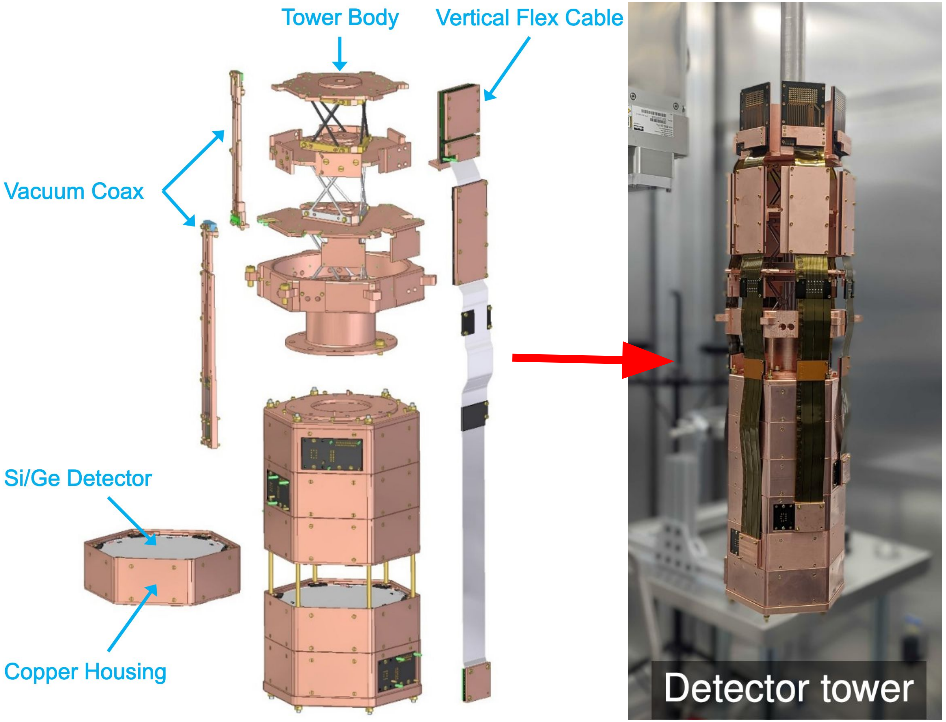
Al + Pb shield – first layers



PE shield – final height

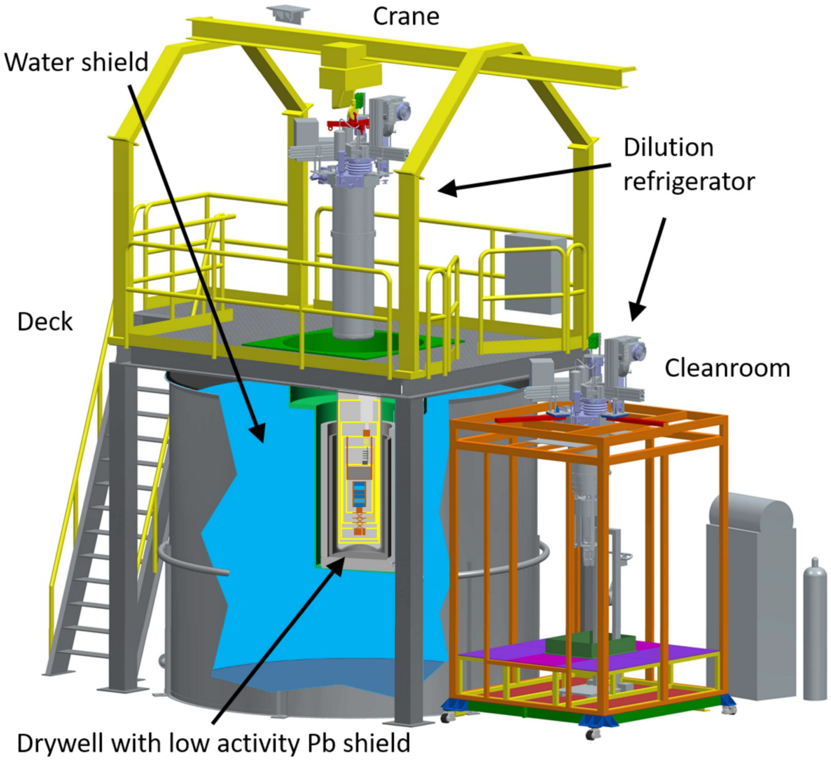
Construction Status -- Detectors and towers

- Detectors and electronics assembled into towers
  - Tested at SLAC
- First two towers arrived at SNOLAB underground
  - Cosmogenic exposure well under control
  - Huge thanks to SNOLAB operation team!
- Two more towers arriving later this year
- Towers going into CUTE for testing when PMP ends

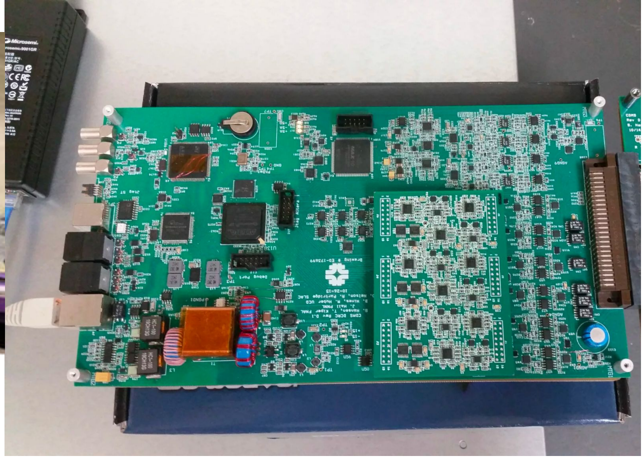


Cryogenic Underground TEst facility (CUTE)

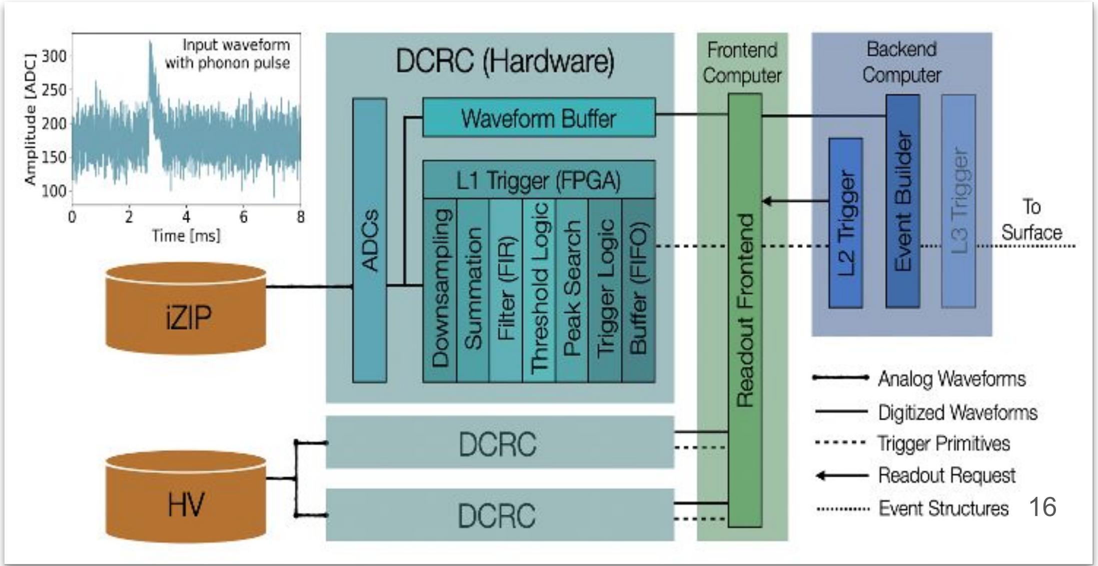
- Friendly neighbour
- Taking on critical mission of detector testing
  - Exercise and debug detectors before SuperCDMS cryostat is in place
- Same environment, same electronics → similar challenges expected
- First tower goes in later this year
- Opportunities for science results before the main experiment turns on



Data Acquisition System

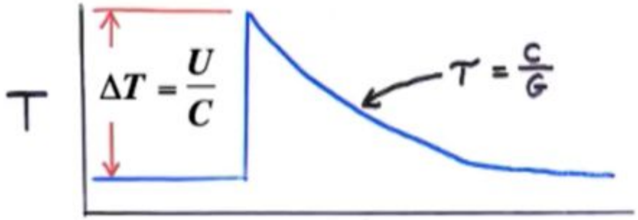


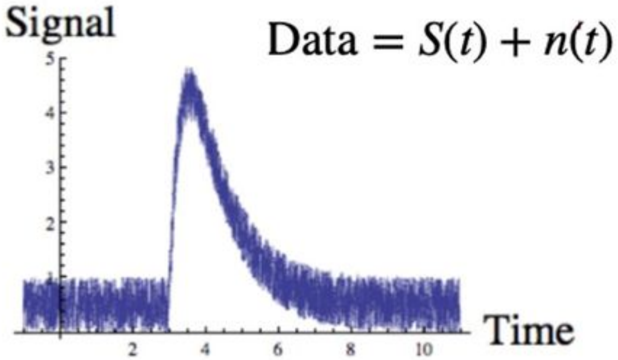
- Integrated warm electronics and data acquisition
  - Detector Control and Readout Card (DCRC)
- Ethernet-based readout, with MIDAS software
- FPGA-based L1 trigger
- Hybrid data
  - Pre-pulse and post-pulse regions are downsampled
- DAQ deployed in 2021
- Being thoroughly tested at various test facilities

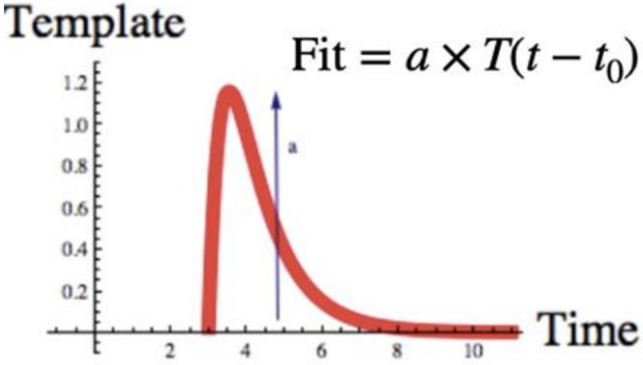


Advanced Event Reconstruction

- Pulse height proportional to energy detected
- Using optimal filter to reconstruct pulse height
  - Frequency domain χ^2 fit to reduce noise
- Detector has 12 phonon channels, and some of the noise are shared/correlated
  - Fit all 12 channels simultaneously
- Pulse shape varies based on the position of energy deposition
  - Multiple templates to accommodate shape variation
- The **NxM optimal filter**
  - Fit N channels with M templates
- Aim to achieve first 3D position reconstruction in cryogenic detectors!

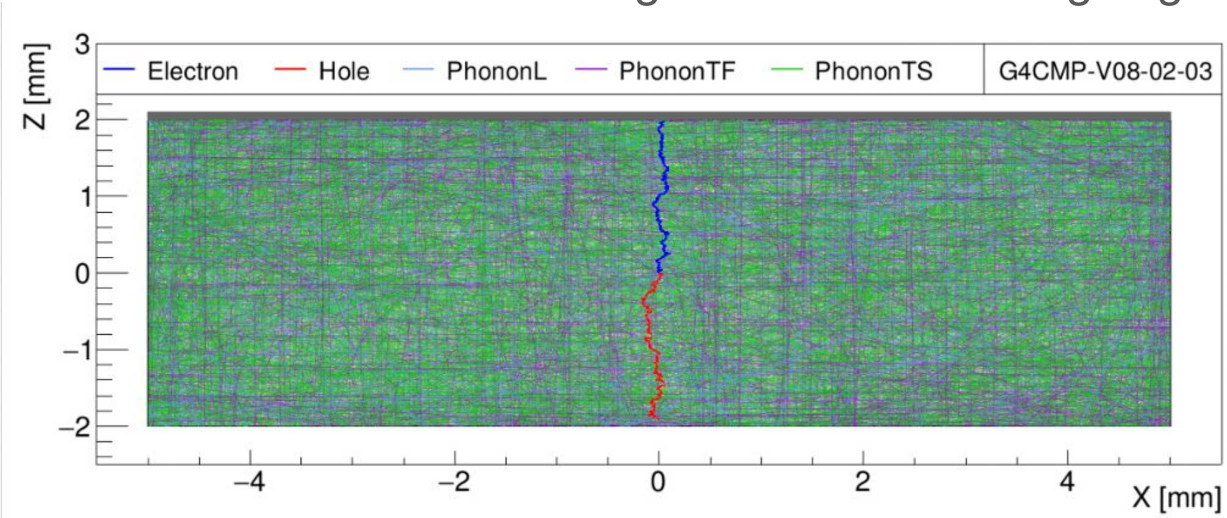


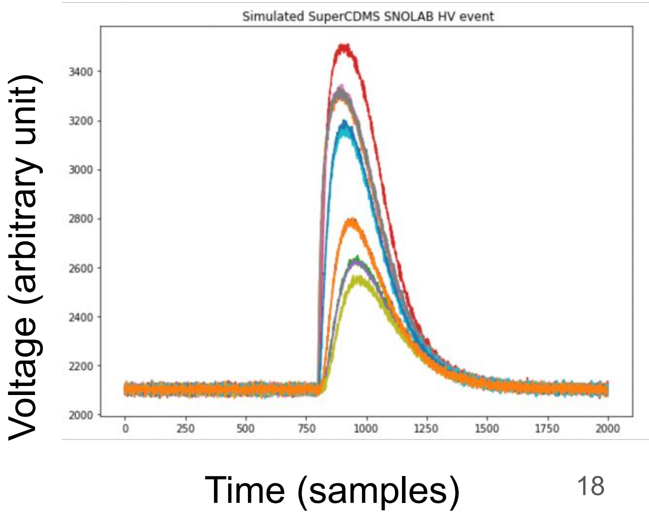




Analysis Preparation Status: Simulation

- 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

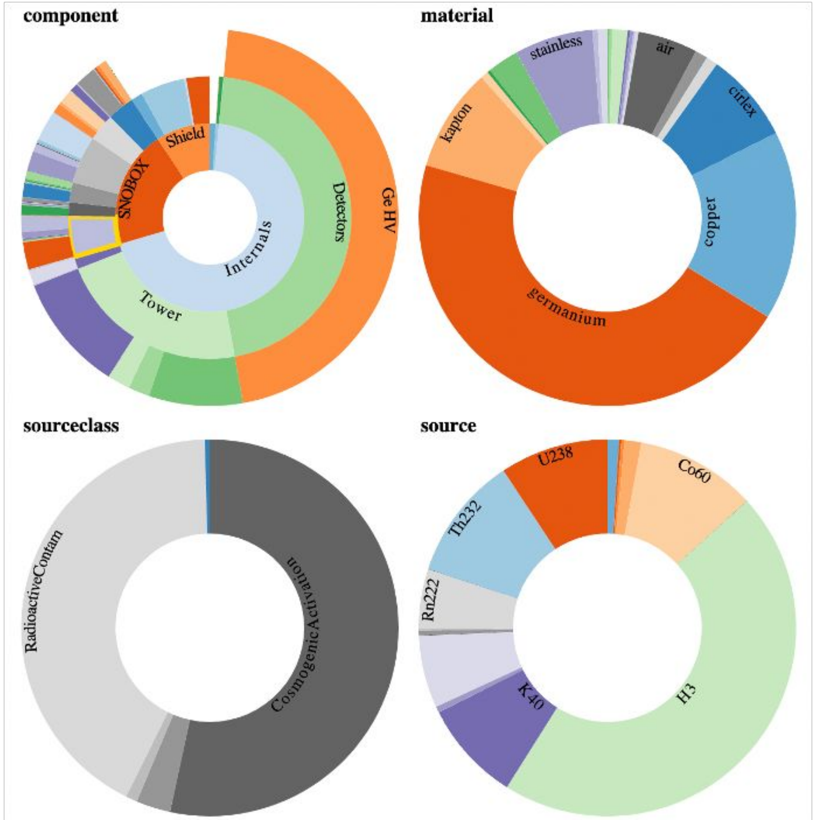




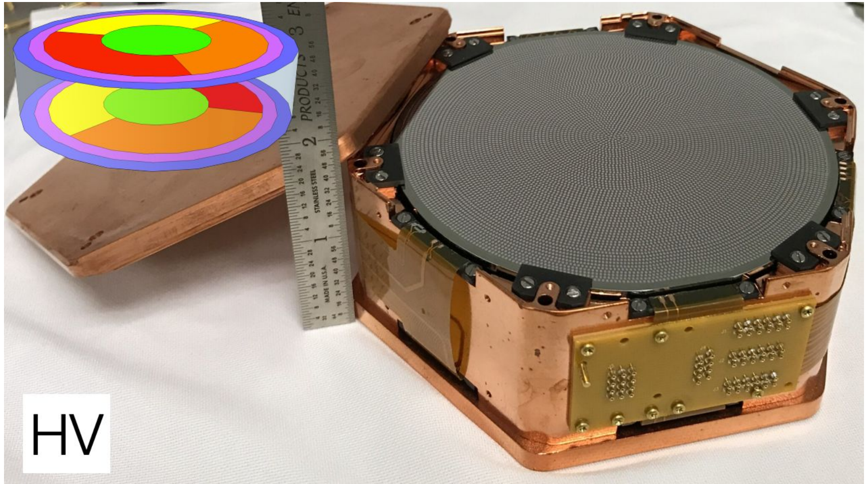
https://github.com/bloer/bgexplorer-demo

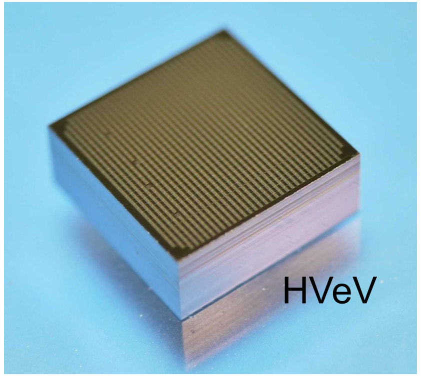
Analysis Preparation Status: background

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



Exploring the sensor limit:
HV → HVeV Detectors

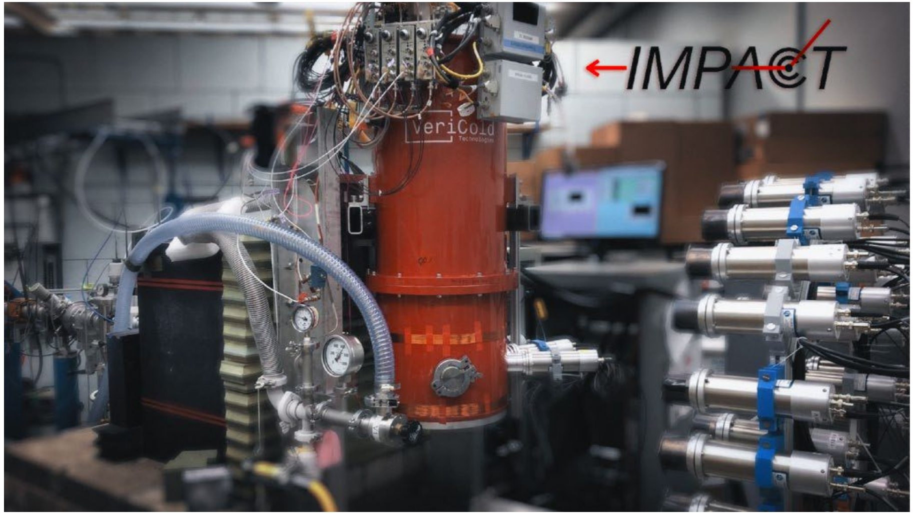




HVeV: Prototype HV detector

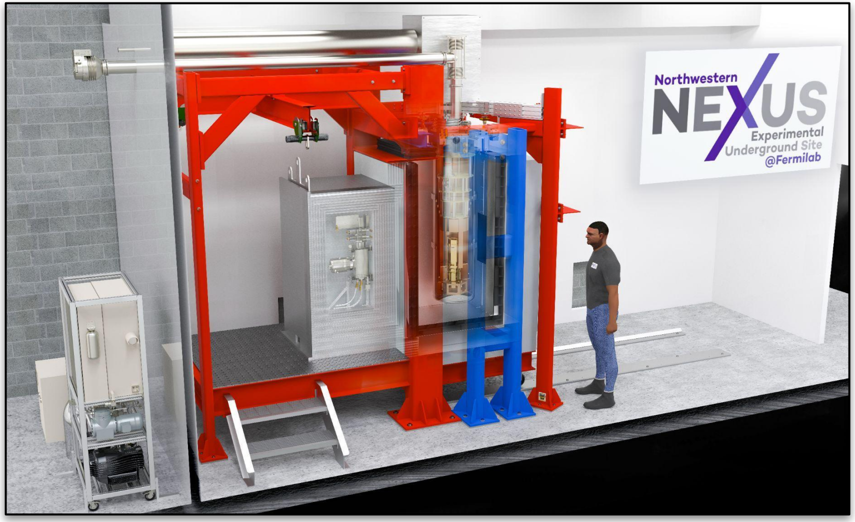
- Gram scale
- eV level resolution

Two more facilities for HVeV R&D and operations

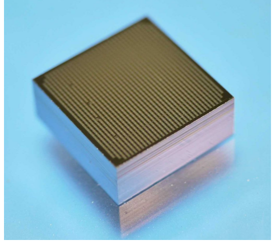


Mobile refrigerator, can be deployed in calibration facilities

Currently residing at U of Toronto!



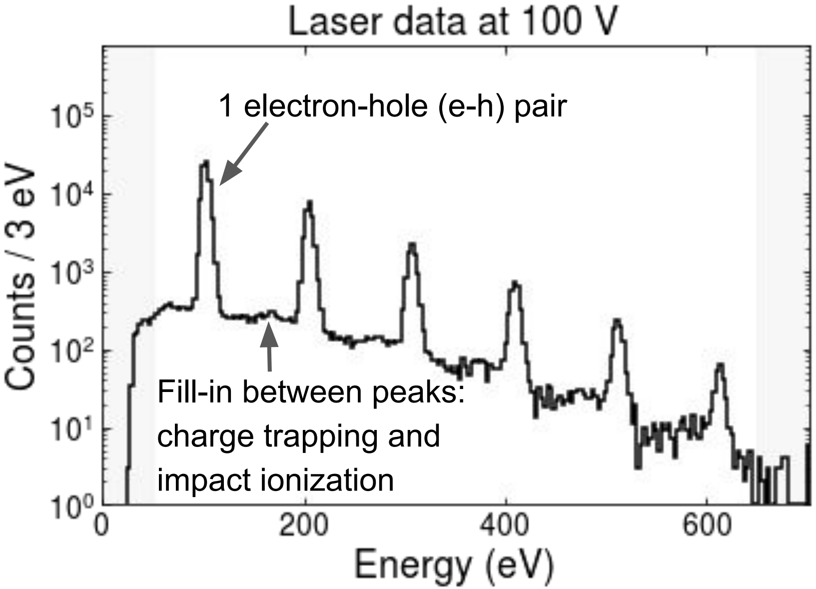
Cleanroom located ~100 m underground at Fermilab



Single electron-hole pair sensitivity

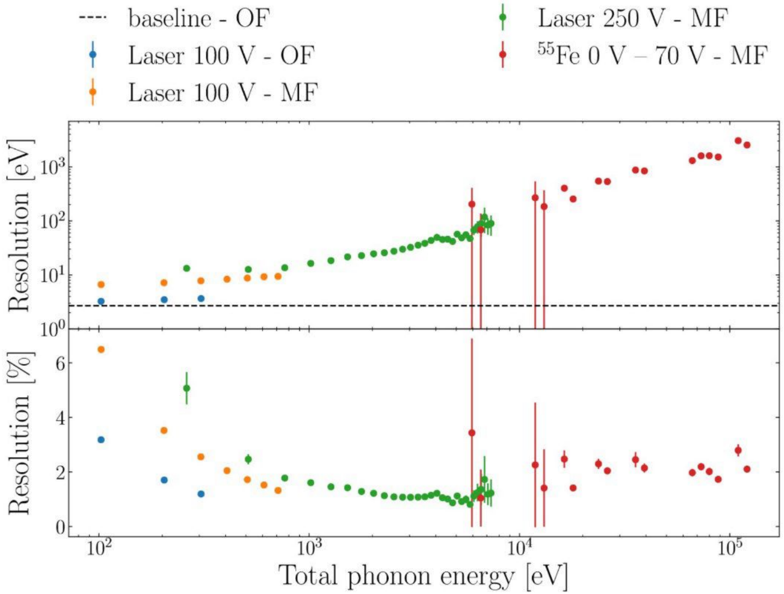
- “Version 2” of HVeV detectors
- ~3 eV resolution

- Calibrated to hundreds of keV
- Energy resolution < 5% over the full range



1 electron-hole (e-h) pair

Fill-in between peaks: charge trapping and impact ionization

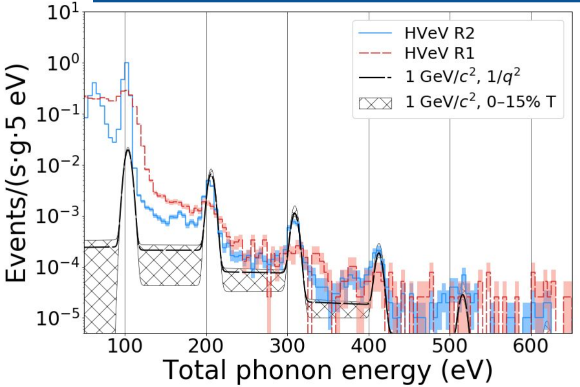


D. W. Amaral *et al.*, Phys. Rev. D 102, 091101(R), 2020
F. Ponce, et al., Phys. Rev. D 101, 031101(R), 2020
R. Ren et al., Phys. Rev. D 104, 032010, 2021

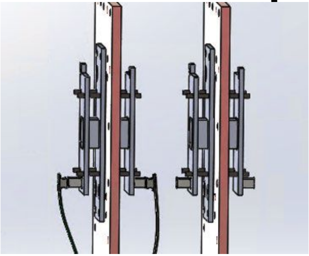
Iterations of HVeV dark matter experiments

- Burst events detection and study
- Hypothesis: originated by SiO_2 in the detector holder (PCB)

HVeV Run 2

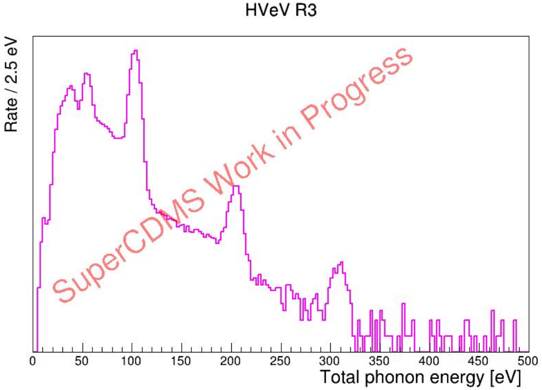


D. W. Amaral *et al.* Phys. Rev. D **102**, 091101(R)

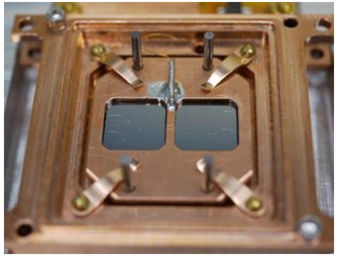


- Coincidence measurement
- Confirmed external origin of this background and its reduction with coincidence detections

HVeV Run 3

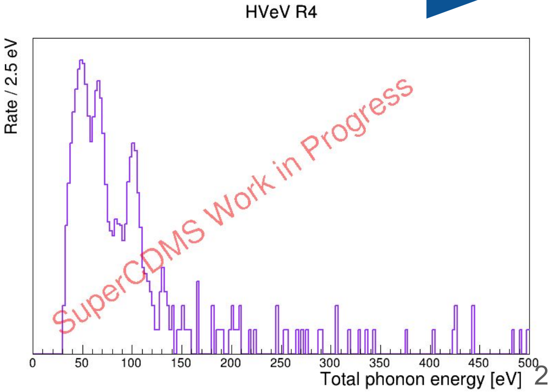


SuperCDMS Work in Progress



- Removed PCB from detector holder
- Elimination of quantized background above 1eh peak

HVeV Run 4



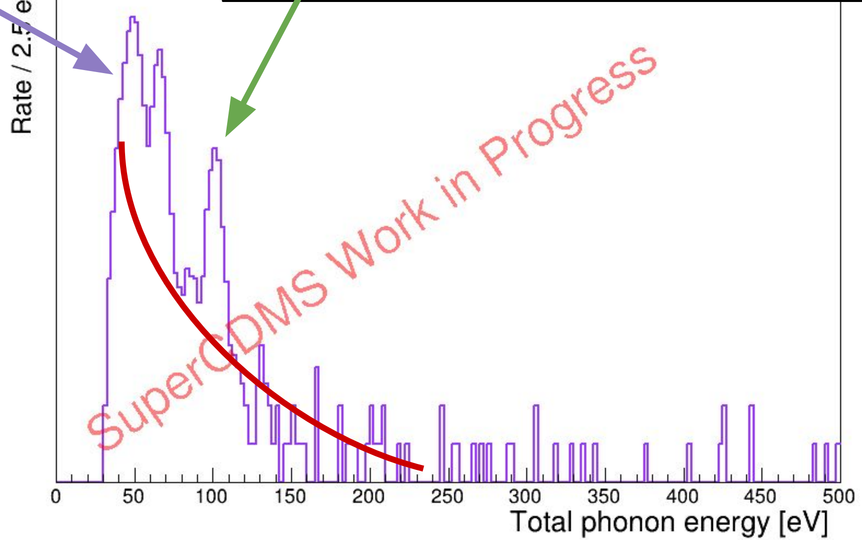
SuperCDMS Work in Progress

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

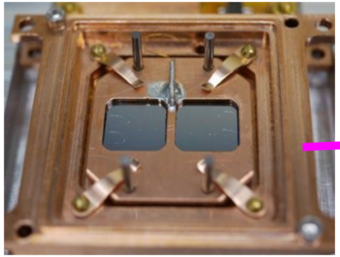
- Low energy excess
- Evidence hints different ionization from ER and NR
    - ○ “Heat only”
- Unpacking ER/NR/Heat Only components by operating with different NTL gains

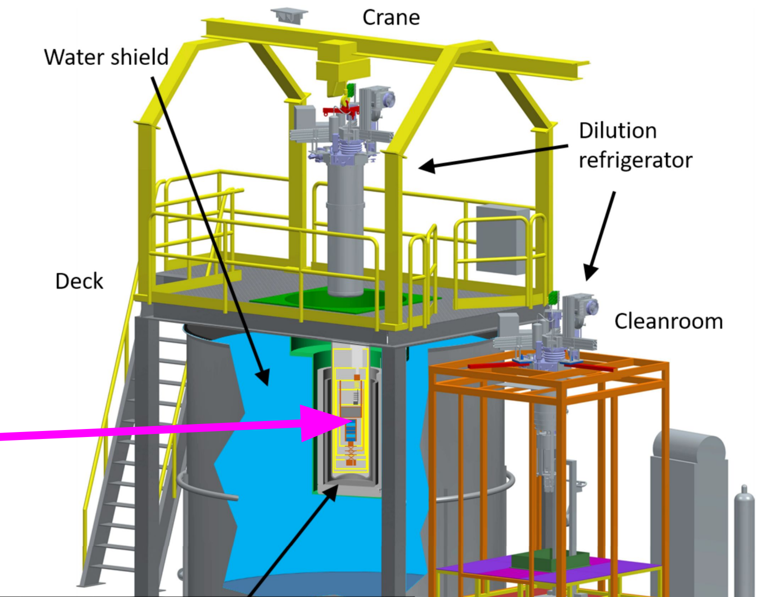


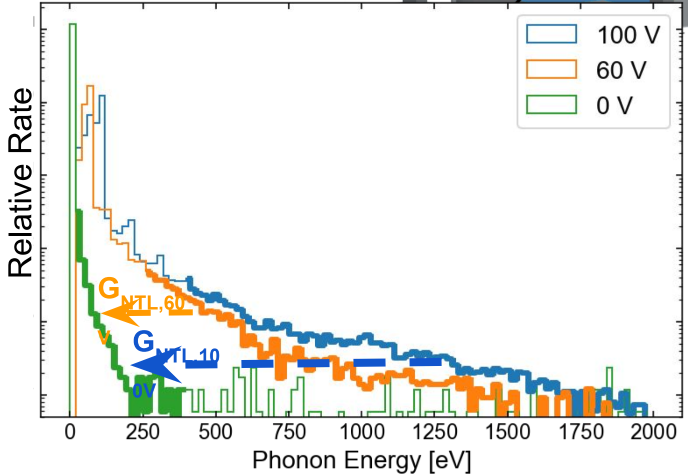
HVeV going deep underground

- Planning next HVeV run at CUTE@SNOLAB
- Established low background environment
  - < 10 DRU achieved
- Will operate at various NTL gains
  - Model ER/NR/Heat Only components

$$\underset{\substack{\uparrow\\ \text{total phonon}\\ \text{energy}}}{E_t} = \underset{\substack{\uparrow\\ \text{primary recoil}\\ \text{energy}}}{E_r} + \underset{\substack{\nwarrow\\ \text{Luke phonon}\\ \text{energy}}}{N_{eh}eV_b}$$

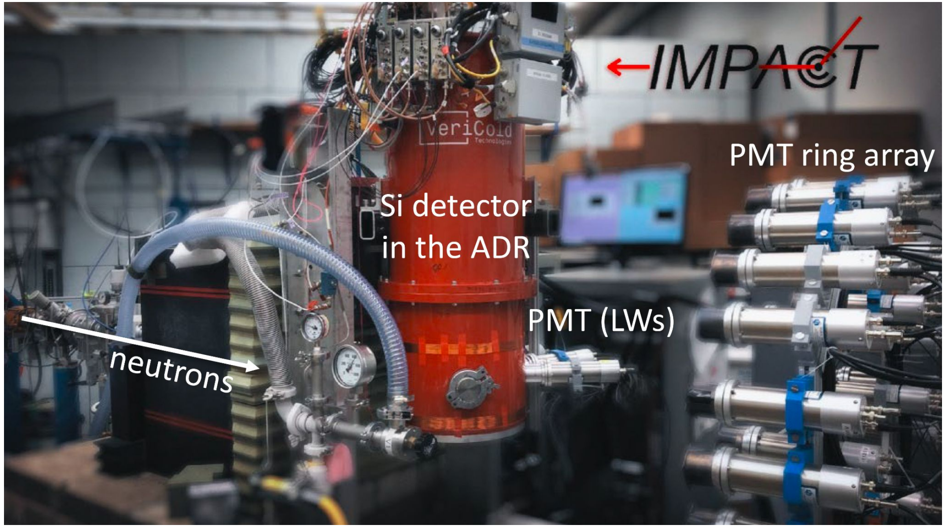






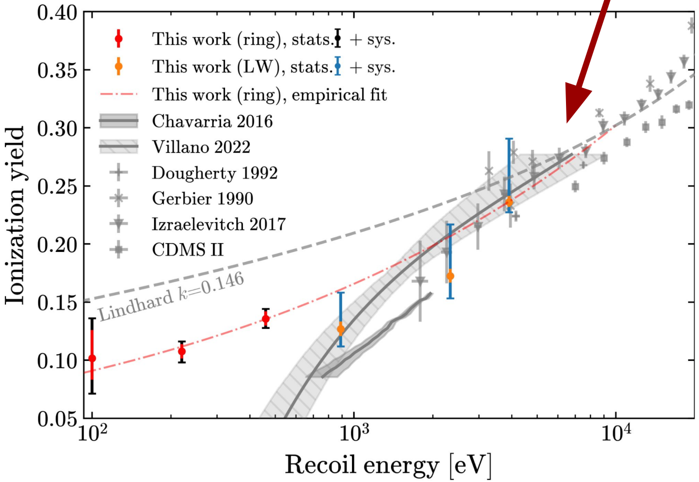
Phys. Rev. D 105, 112006 (2022)

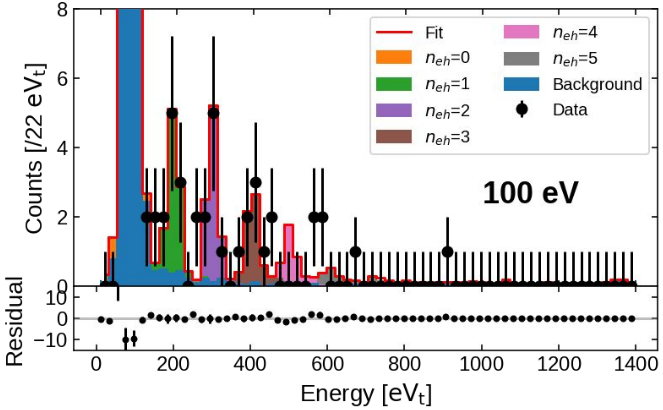
Understanding the detector: Nuclear recoil calibration



- Silicon yield (Y) measured down to 100 eV
- Germanium measurement in preparation
- Also exploring even lower energy scale
    - Exploring Lower energy neutrons with ^{51}V target

$$\begin{aligned} E_{total} &= E_{recoil} + n_{eh} eV_b \\ &= E_{recoil}(1 + eV_b/\epsilon_{eff} \cdot Y) \end{aligned}$$





M.F. Albakry et. al, arXiv: 2303.02196

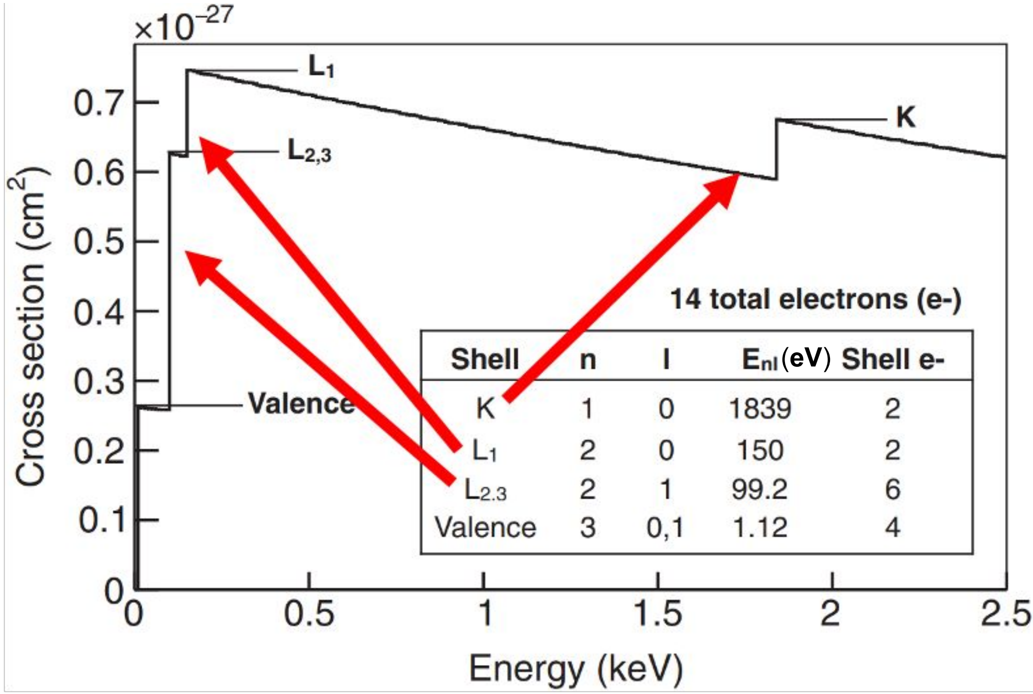
Understanding the detector:
Low energy calibration

- New detectors heavily optimized for low energy performances
  - Saturates at high energy
- Low energy calibration poses renewed challenges
- Exploring Compton steps as calibration features in HVeV
- To be applied to Si HV, which has most low-mass WIMP sensitivity

Energy	Low (few eV)	Intermediate (100 eV - few keV)		High (> 100 keV)	
Method	Optical photons	Compton steps	Activation lines	Compton Edges	Photoabsorption peaks
Ge iZIP & HV	❌	❌	✅	✅	✅
Si iZIP & HV	❌	❓	❌	✅	✅
Si HVeV	✅	❓	❌	✅	✅

Silicon Compton Steps

- Using Compton steps:
- Irradiate with O(100) keV gamma rays.
    - Scattering with atomic electrons.
- Scattering probability proportional to number of electrons that can be excited
    - Binding energies creates step-like structures
- Can be used for calibration down to 100 eV



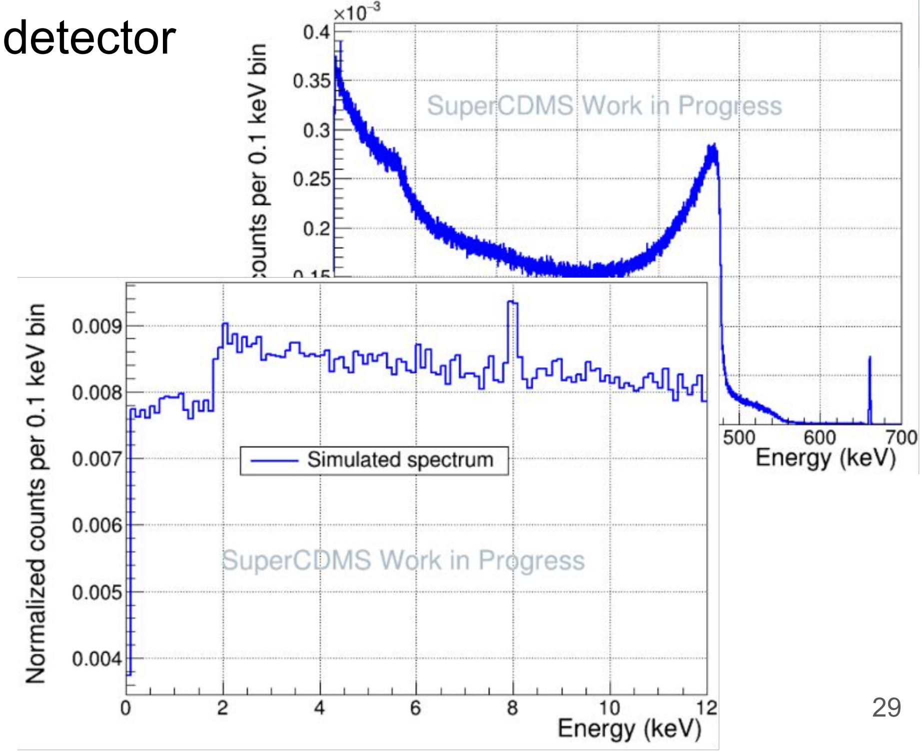
14 total electrons (e-)

Shell	n	l	E_{nl} (eV)	Shell e-
K	1	0	1839	2
L_1	2	0	150	2
$L_{2.3}$	2	1	99.2	6
Valence	3	0,1	1.12	4

Similar structure confirmed by CCD data from DAMIC-M (PhysRevD 106, 092001, 2022)

Silicon Compton Steps
Ongoing efforts

- Cs-137 calibration data with Si HVeV detector at NEXUS
- Expected features:
    - 662 keV Cs gamma line
    - 447 keV Compton edge
    - 8.04 keV Copper x-ray
        - Detector housing!
    - Si 1.84 keV Compton step
    - Si 99/150 eV Compton steps
- Cross-calibration with optical photon calibration at high voltage
    - Single e-h peaks visible up to a few keV
- Results expected this year!



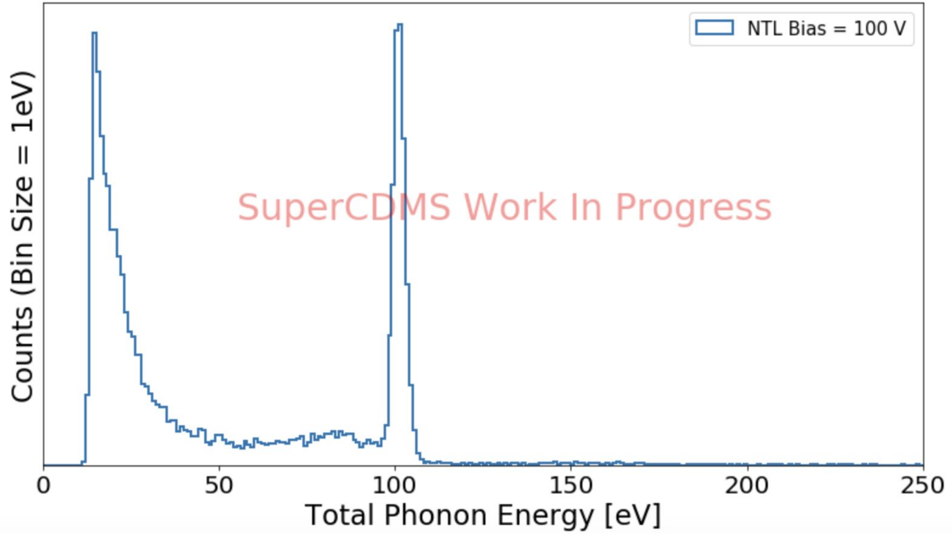
Latest Detector Performance

BEST IN CLASS

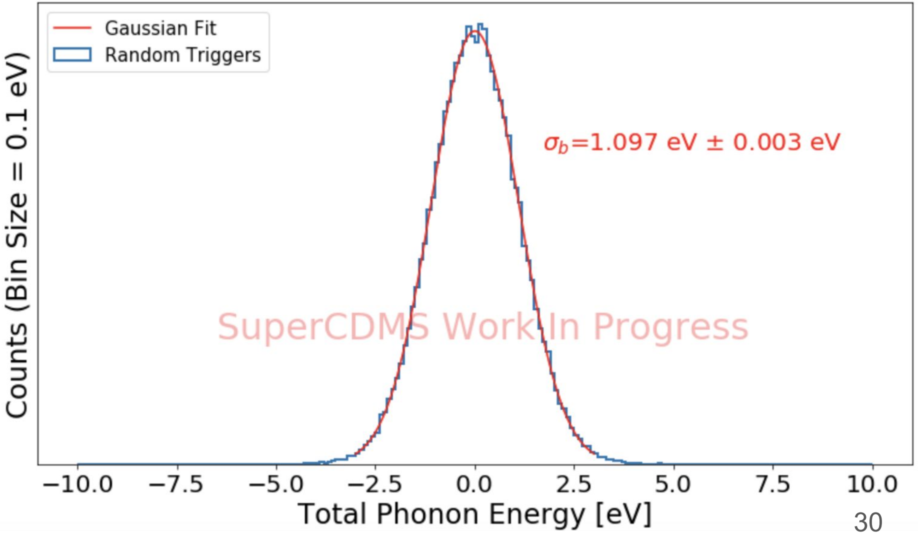
- “Version 3” of HVeV detectors
- Lower transition temperature
  - ○ Operated at NEXUS

- Achieve σ_b = 1.097 eV ± 0.003 eV
- **Below Silicon bandgap!**
- Also with SiO_2 blocking layer
  - ○ **Study of leakage ongoing**

Detector Spectrum

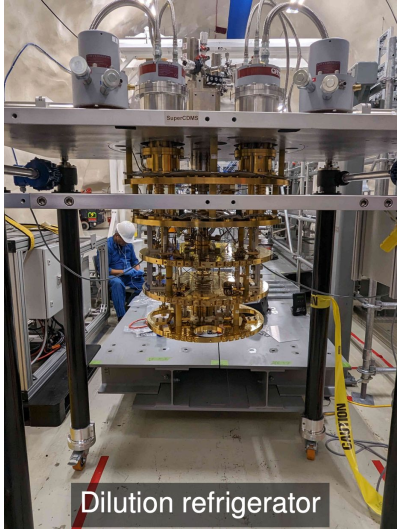


Energy of Random Triggers

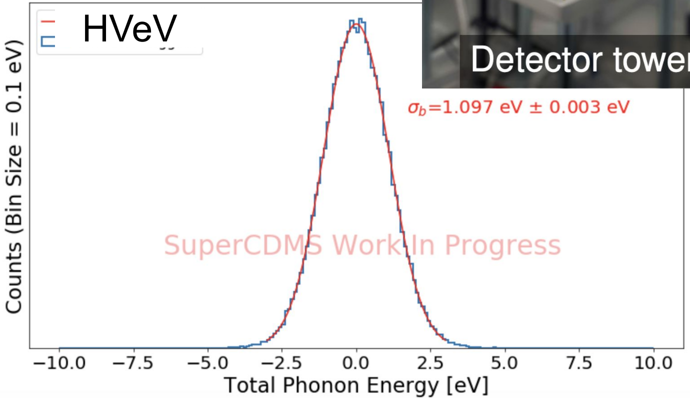


Conclusions

- 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
- HVeV detectors can achieve 1 eV phonon resolution and 0.01 charge resolution
- Low energy calibration poses renewed challenge
- More science results anticipated
- **Stay tuned!**

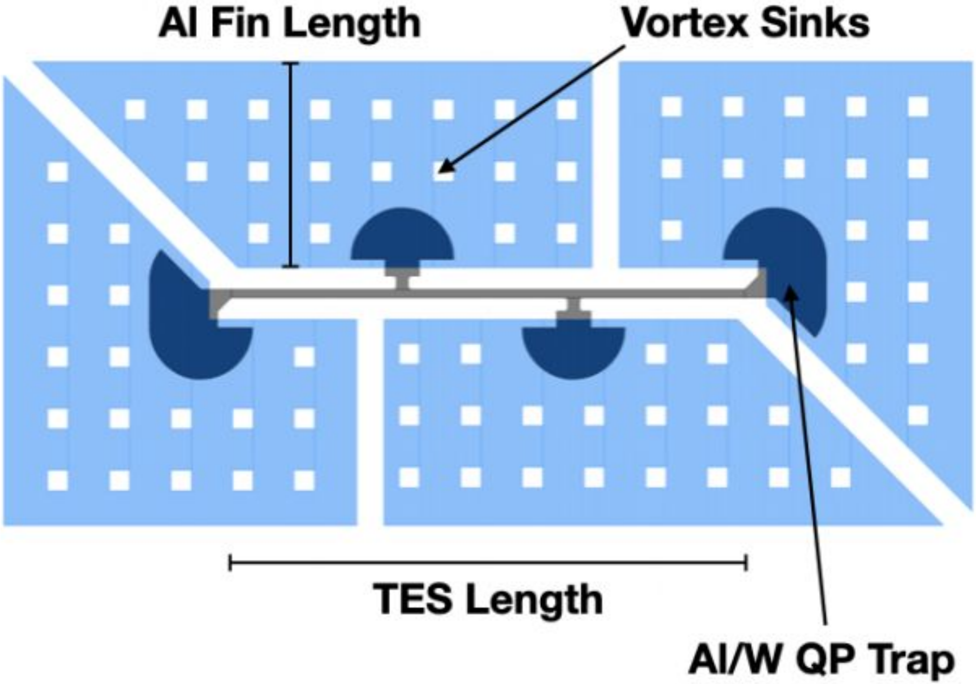

Dilution refrigerator

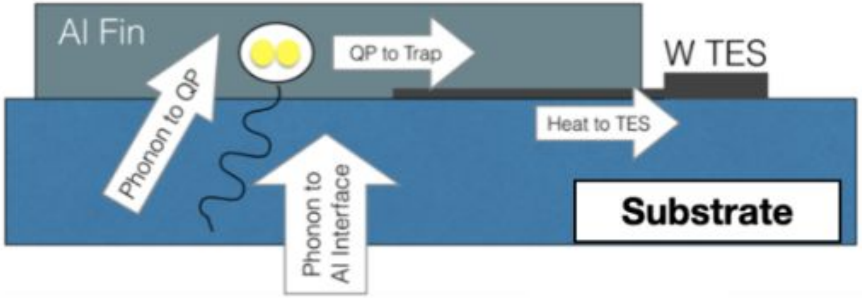

Detector tower



Bonus Slides

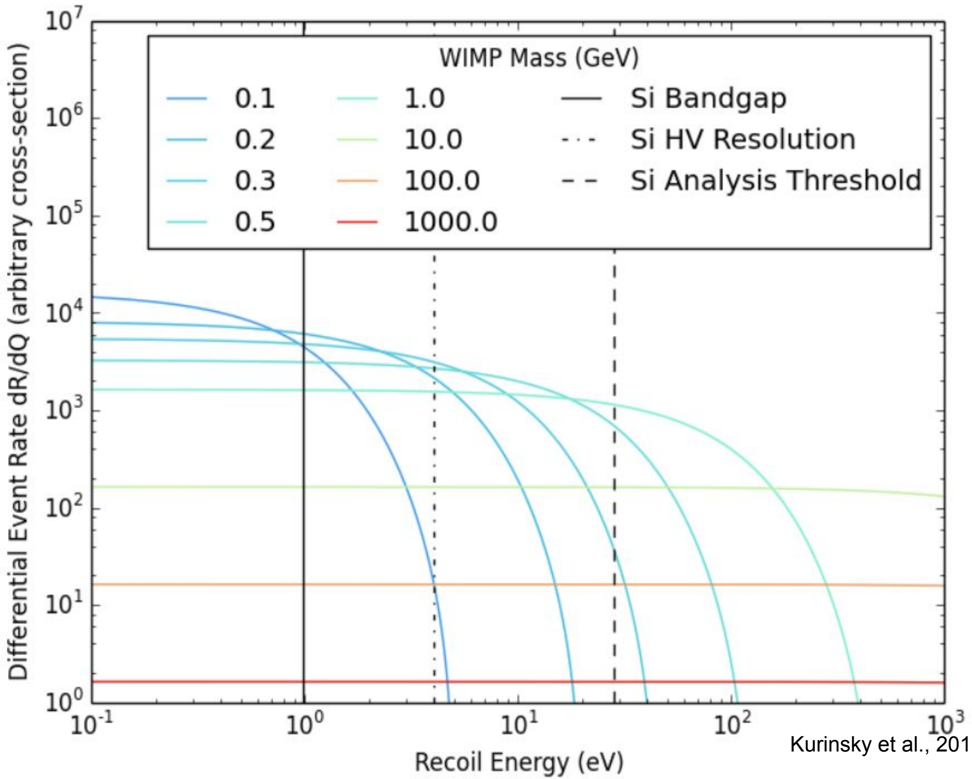
QET Design and Transport





Detecting Low Mass DM

- Low mass WIMP models predicts low recoil energies
- Direct detection experiments often **limited by energy resolution and threshold**
- Electron recoil models also require ideally single charge sensitivity



Kurinsky et al., 2016