Searching for sub-GeV Dark Matter with SuperCDMS

Ziqing Hong, University of Toronto

On behalf of the SuperCDMS Collaboration

GUINEAPIG 2023

SUPER CDMS
Cryogenic Dark Matter Search

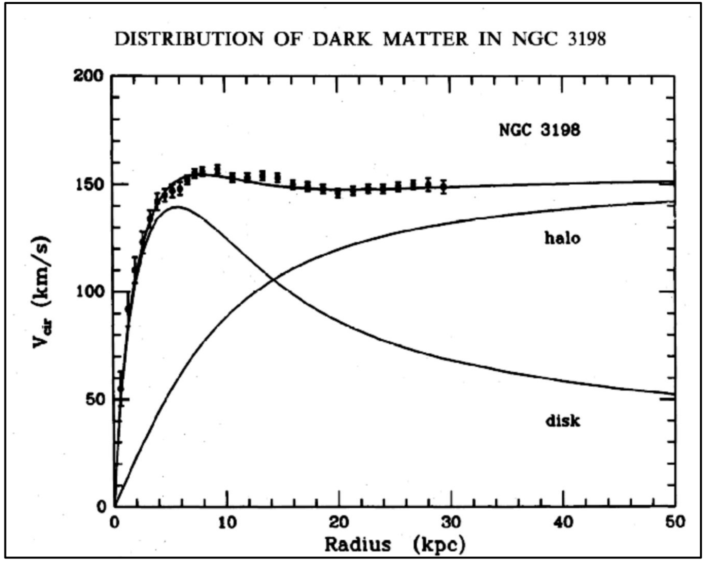
@SuperCDMS

The Evidence for Dark Matter

Gravitational Lensing

smithsonianmag.com

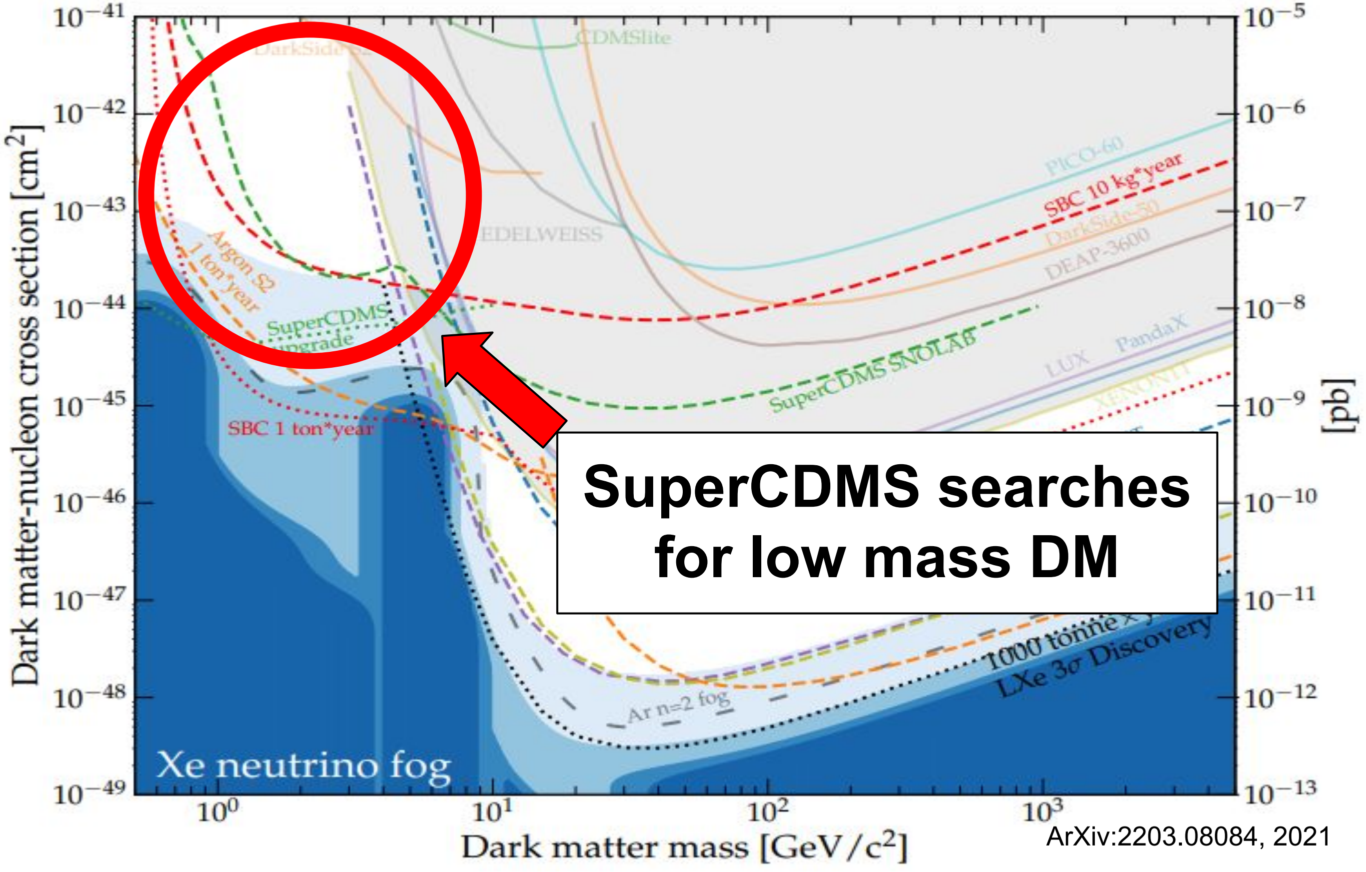
Galactic Rotation Curves



physicsanduniverse.com

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

Dark Matter Searches



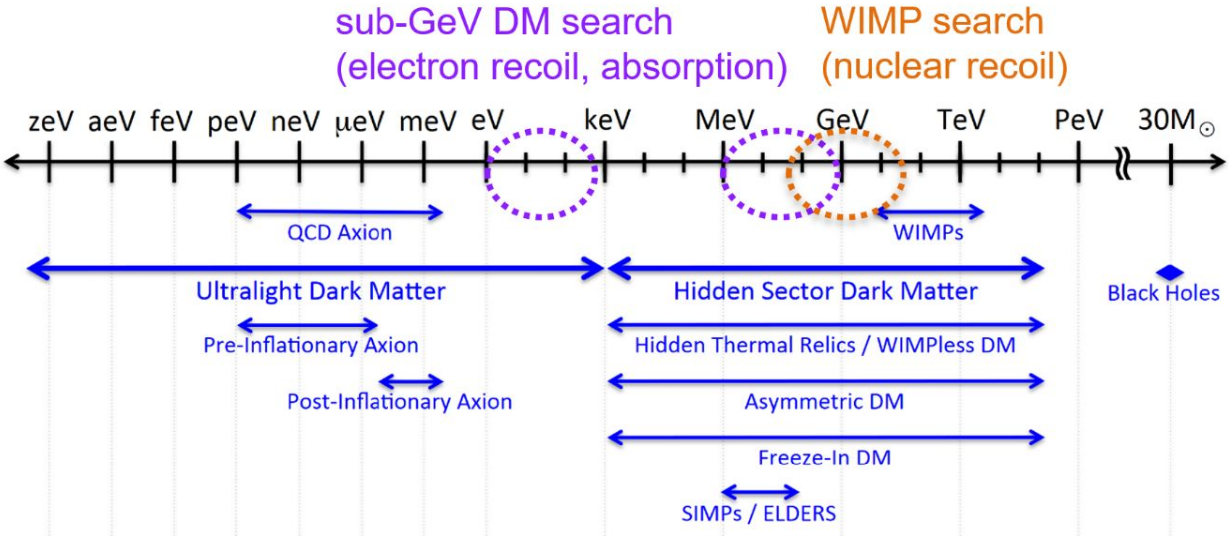
SuperCDMS searches for low mass DM

ArXiv:2203.08084, 2021

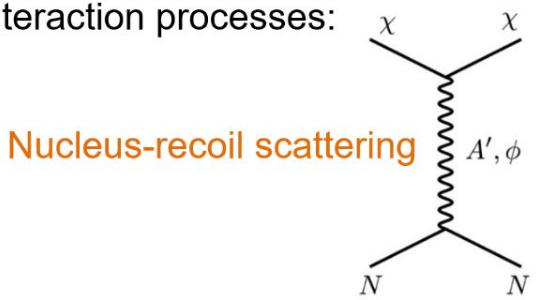
Dark Matter Candidates

Looking for a wide range of DM candidates

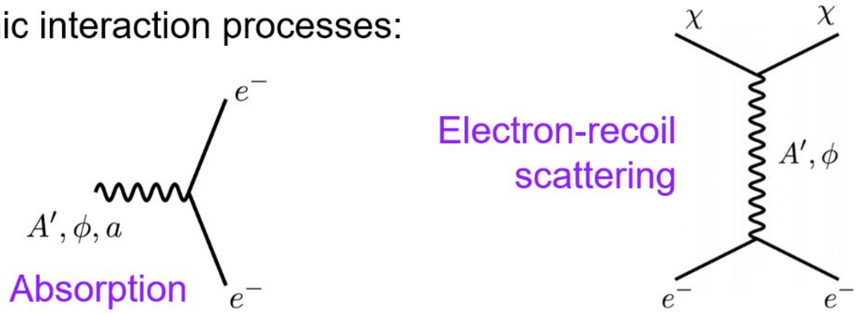
- Dark matter masses from ~5 GeV down to eV



Nuclear interaction processes:



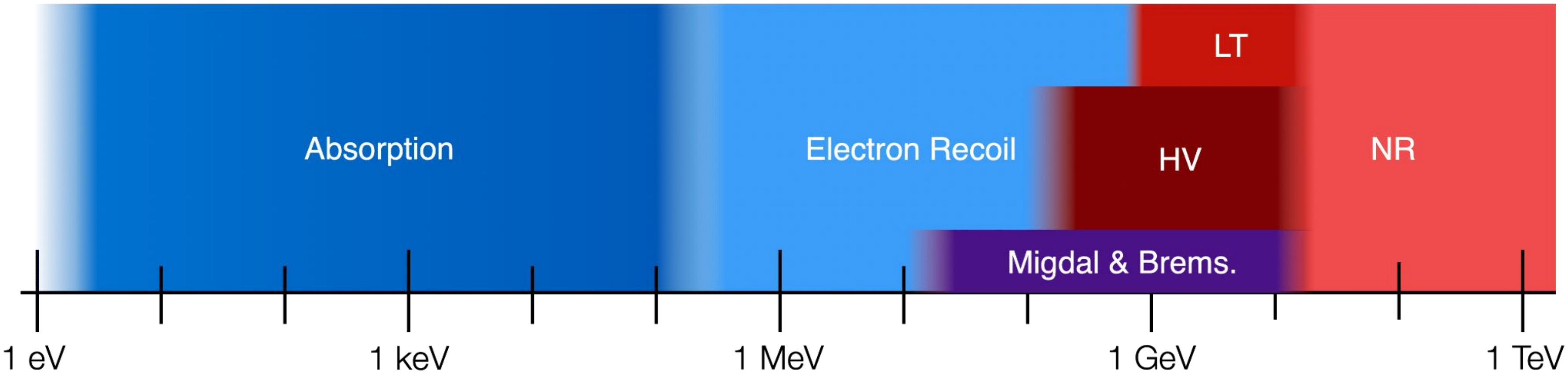
Electronic interaction processes:



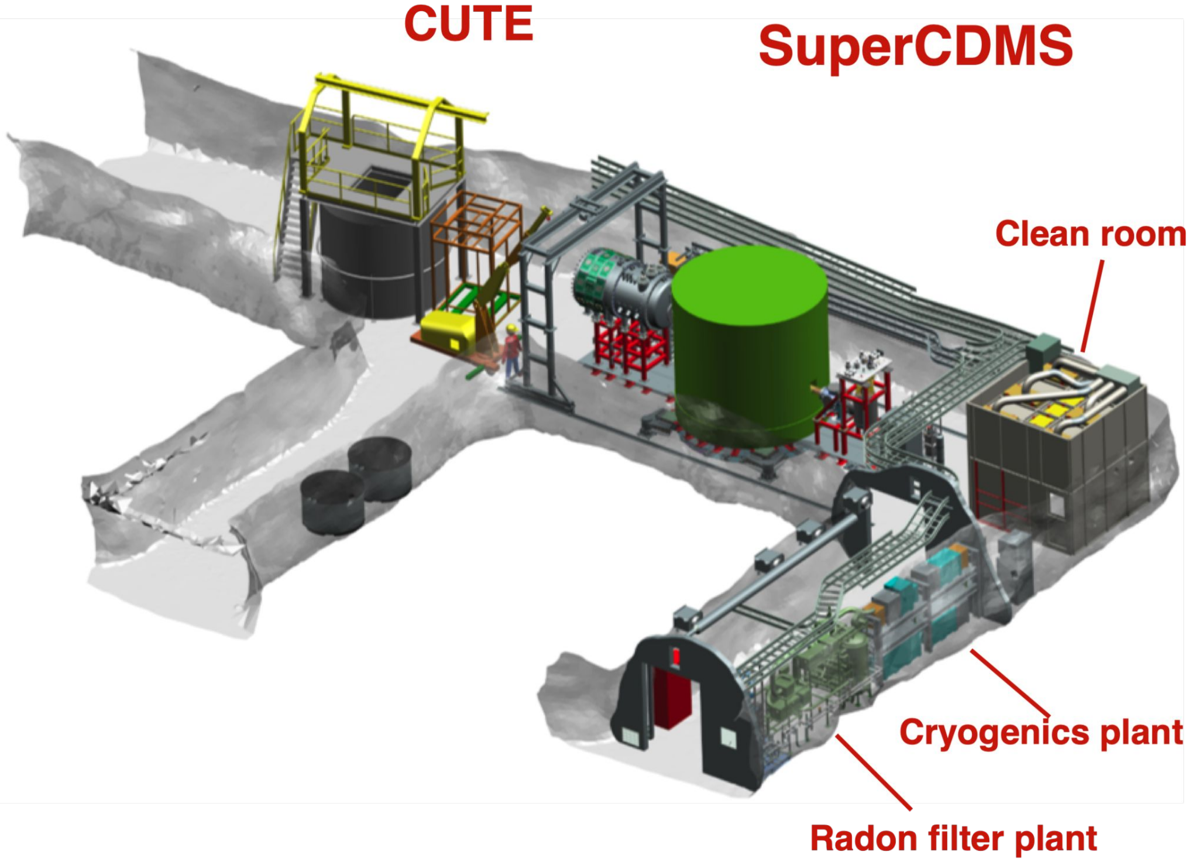
US Cosmic vision ArXiv:1707.04591

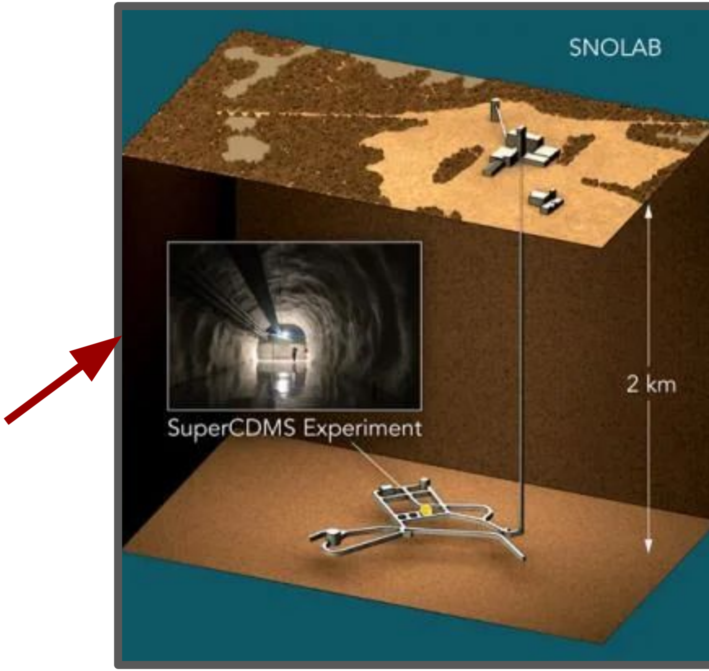
SuperCDMS Detectors & Dark Matter Mass Scales

- 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")

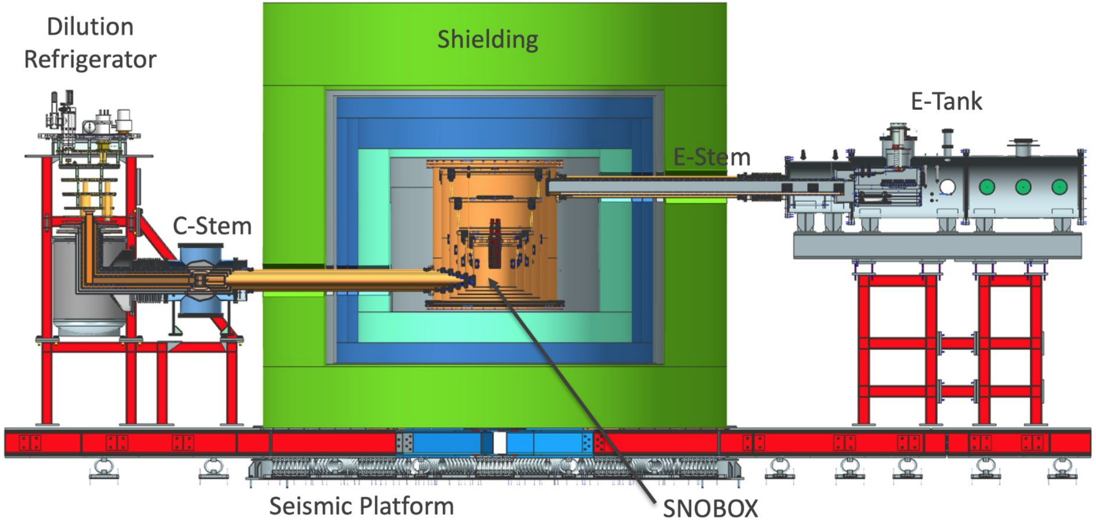


SuperCDMS @ SNOLAB





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

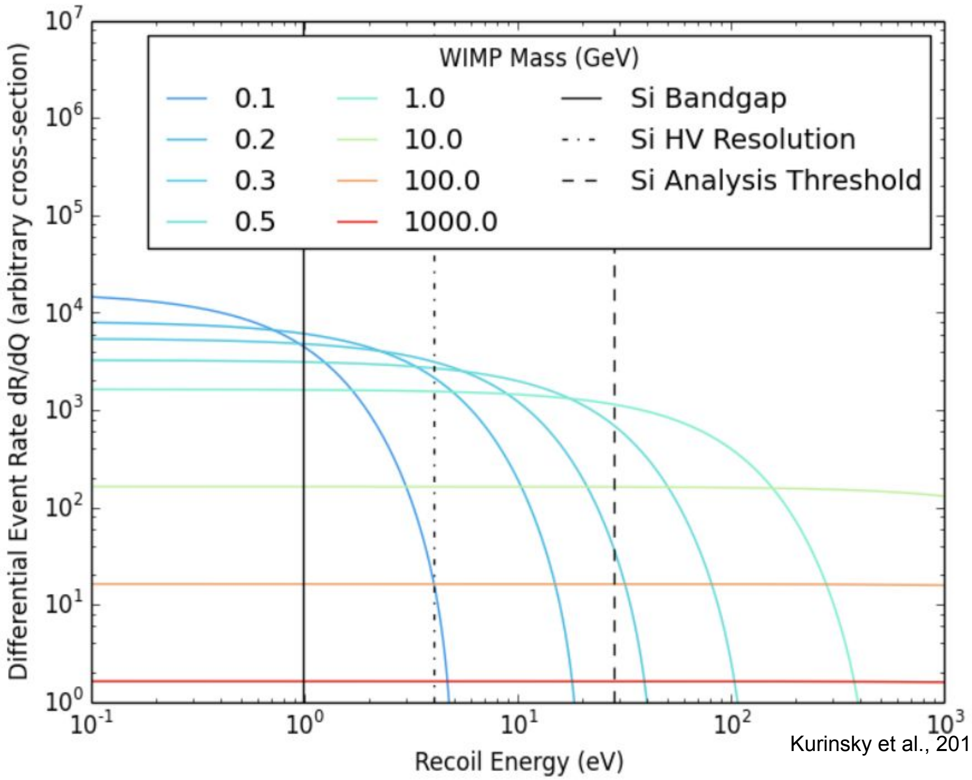
Vibration isolation:
- Seismic: spring loaded platform
- Cryo coolers: soft couplings
  - Braids, bellows
- Copper cans: hanging on Kevlar ropes

Detecting Low Mass DM

- Low mass WIMP models predicts low recoil energies

- Direct detection experiments often **limited by energy resolution and threshold**

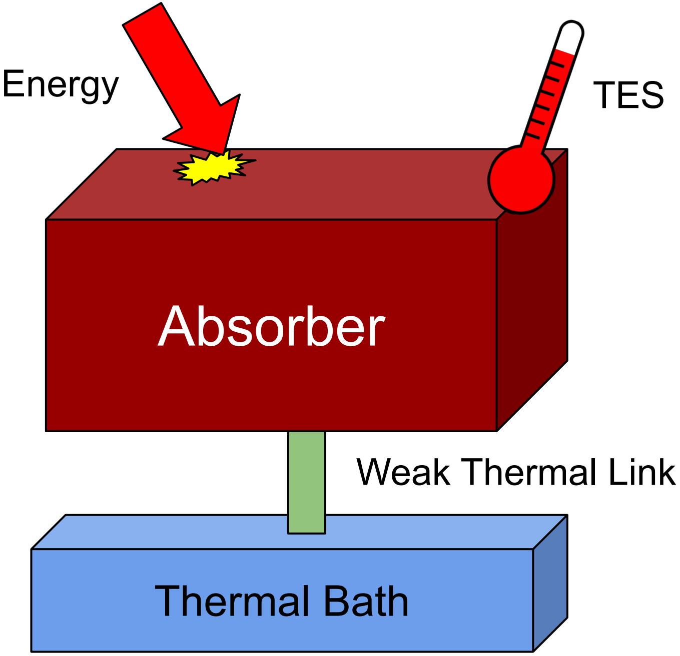
- Electron recoil models also require ideally single charge sensitivity



Kurinsky et al., 2016

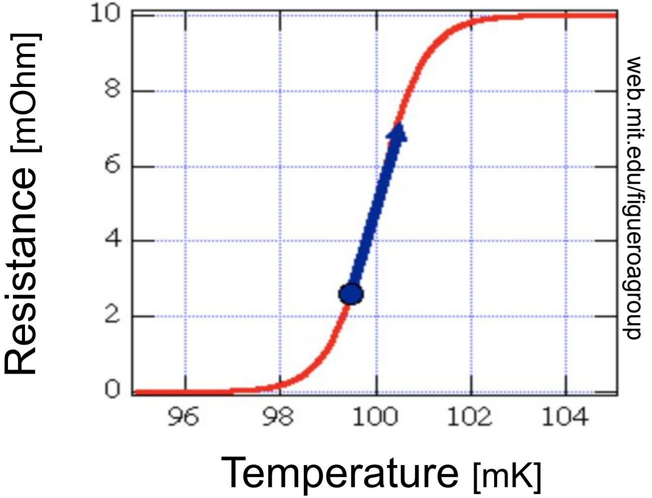
Detector Schematic

Cryogenic Calorimeter

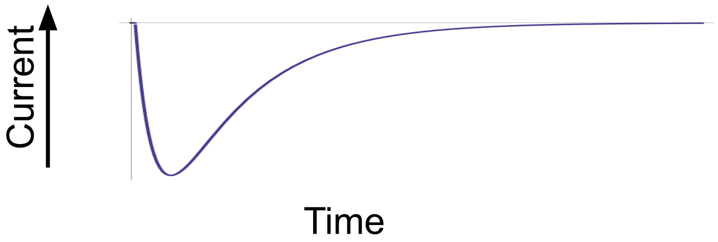


Cryogenically cooled in dilution fridge

Transition-Edge Sensor (TES)



Response of TES



SuperCDMS Detector Technology

Discriminating ~~iZIP~~ Detector:

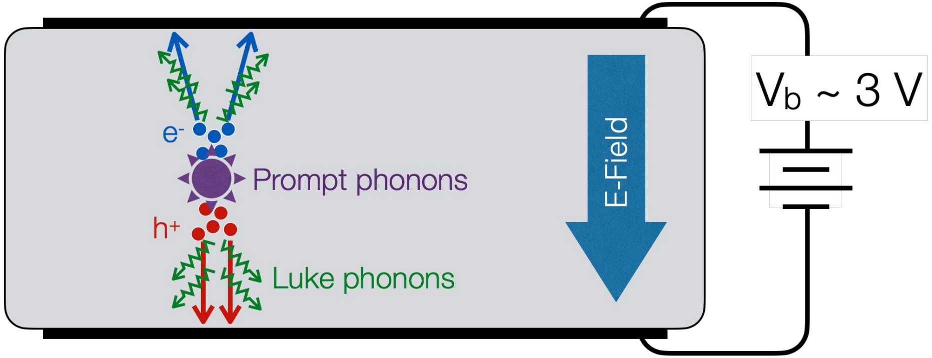
- Prompt phonon and ionization signals allow for discrimination between nuclear and electron recoil events

Low Threshold ~~HV~~ detector:

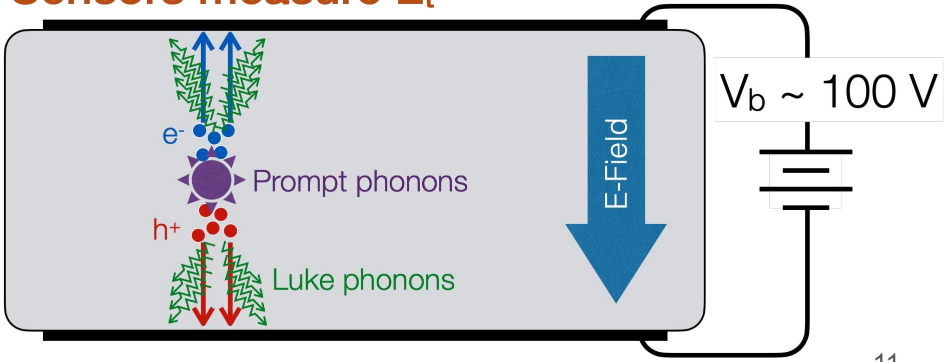
- Drifting electrons/holes across a potential (V_b) generates a large number of phonons (Luke phonons).
  - Enables very low thresholds!
  - Trade-off: No event-by-event NR/ER discrimination

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

Sensors measure E_t, and n_{eh}

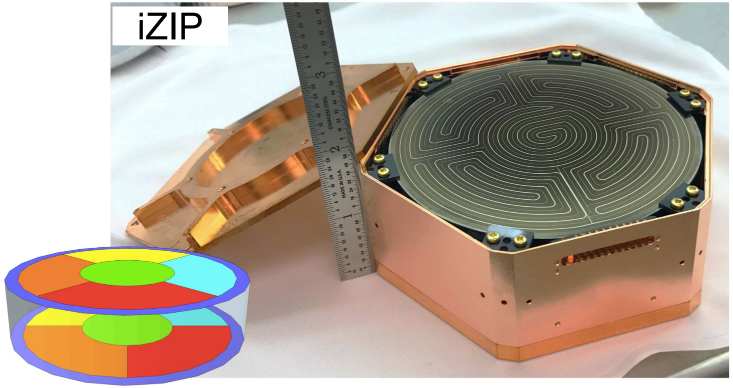


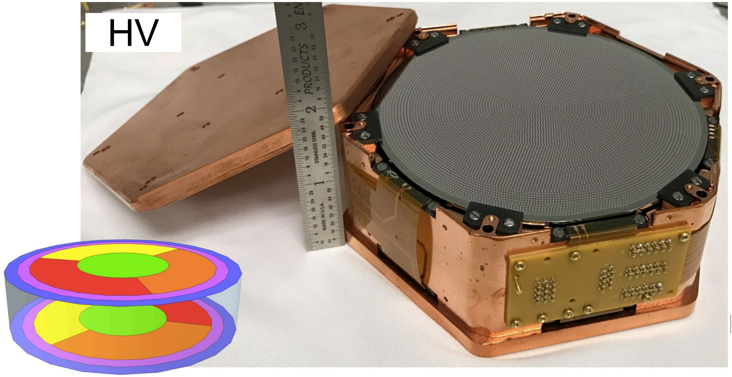
Sensors measure E_t



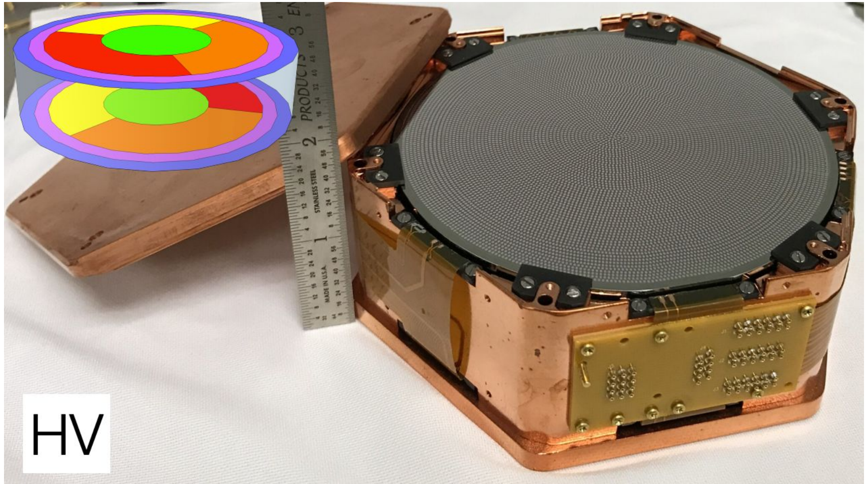
SuperCDMS Detectors: Posing for the Cameras

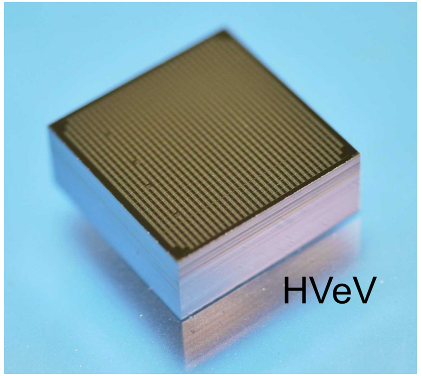
- Detectors made of high-purity Ge and Si Crystals
    - Si (0.6 kg each) provides sensitivity to lower dark matter masses
    - Ge (1.4 kg each) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
    - Athermal phonon measurement with TESs
    - Ionization measurement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





HV → HVeV Detectors



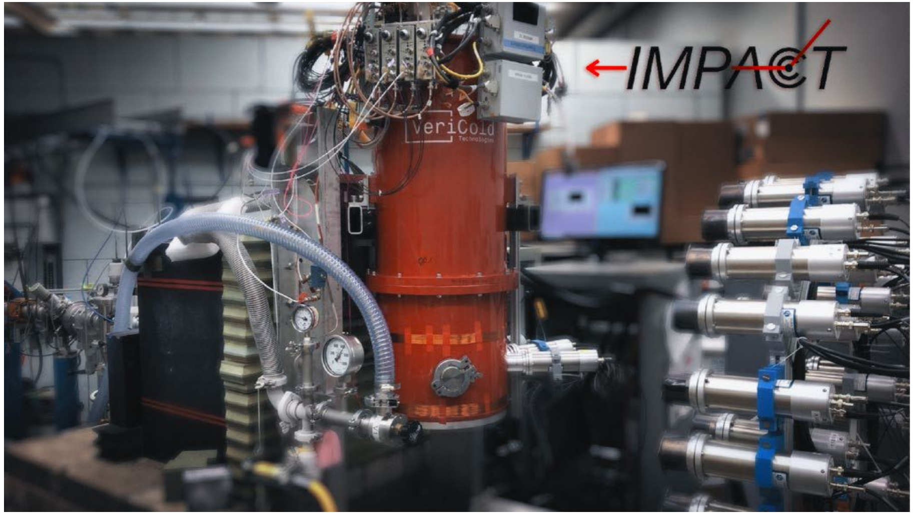


HVeV: Prototype HV detector

- Gram scale
- eV level resolution

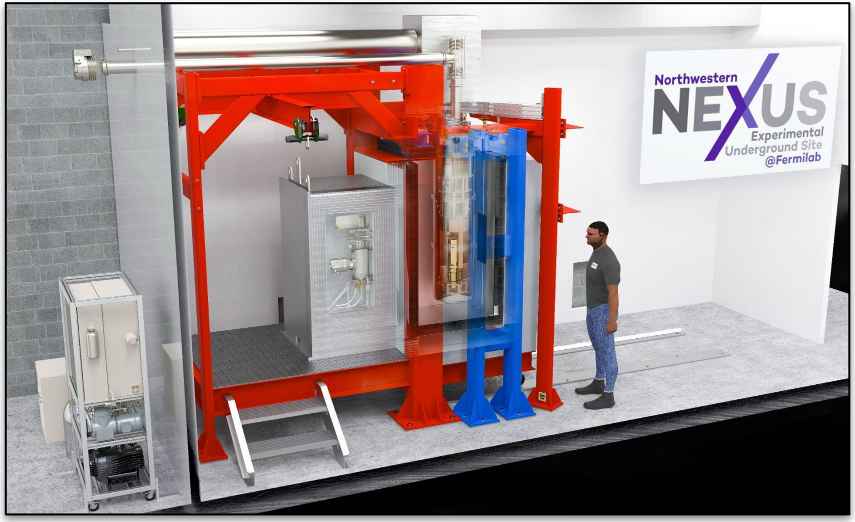
Keep exploring the sensor limit!

Two more facilities for HVeV R&D and operations



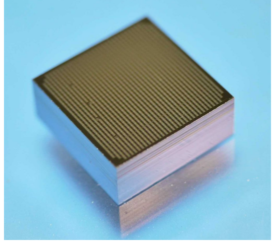
Mobile refrigerator, can be deployed in calibration facilities

Currently residing at U of Toronto!



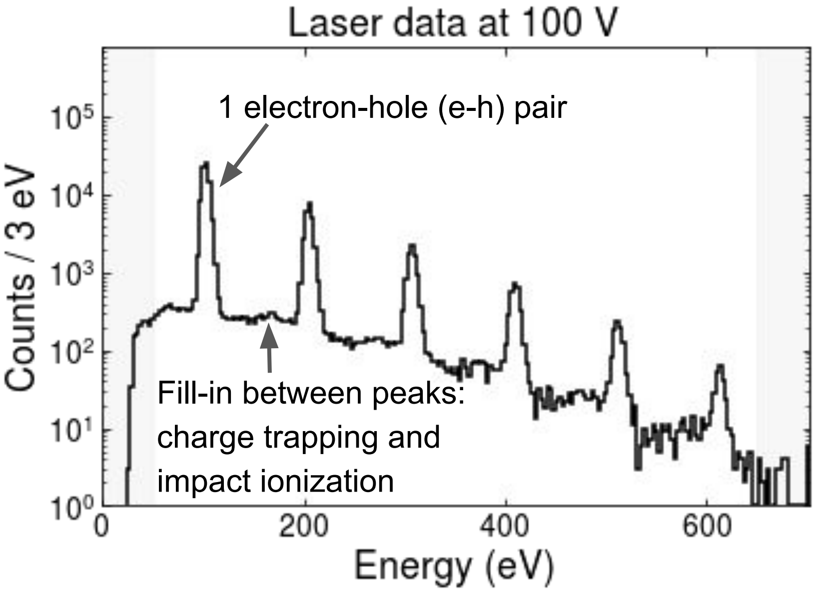
Cleanroom located ~100 m underground at Fermilab

Single electron-hole pair sensitivity



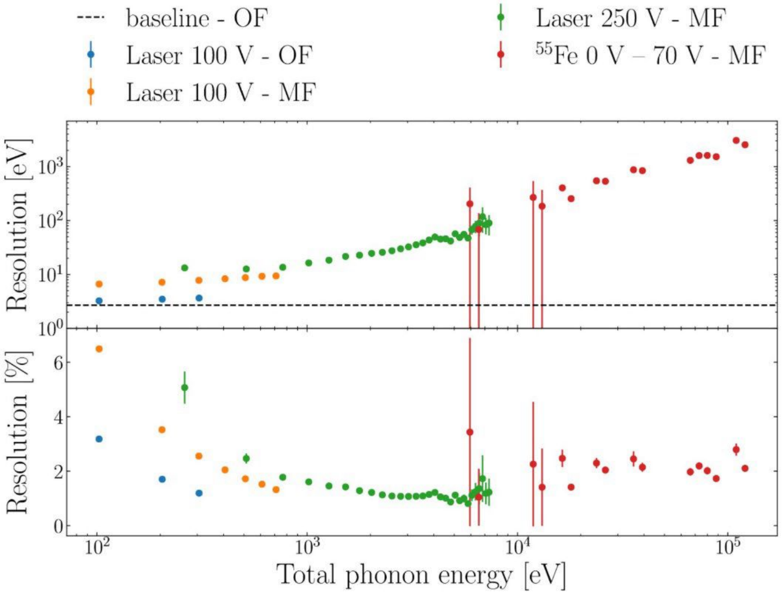
- “Version 2” of HVeV detectors
- ~3 eV resolution

- 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

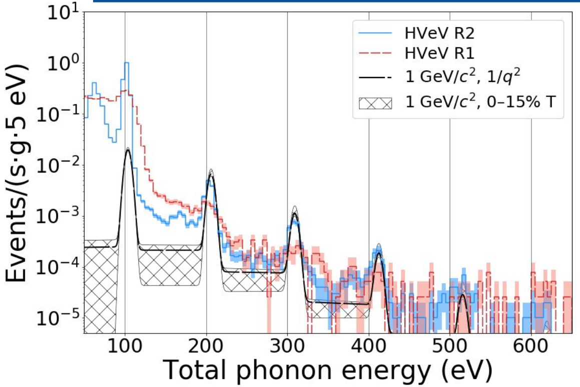


D. W. Amaral *et al.*, Phys. Rev. D 102, 091101(R), 2020
F. Ponce, et al., Phys. Rev. D 101, 031101(R), 2020
R. Ren et al., Phys. Rev. D 104, 032010, 2021

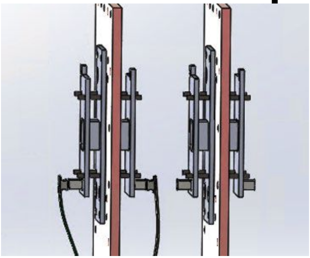
Iterations of HVeV dark matter experiments

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

HVeV Run 2

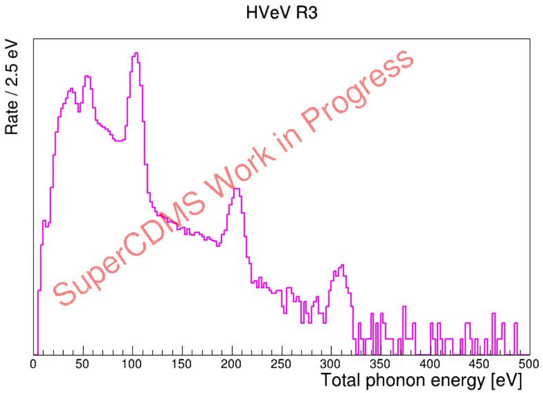


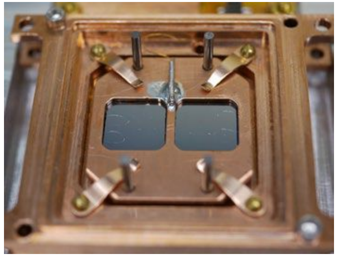
D. W. Amaral *et al.* Phys. Rev. D **102**, 091101(R)



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

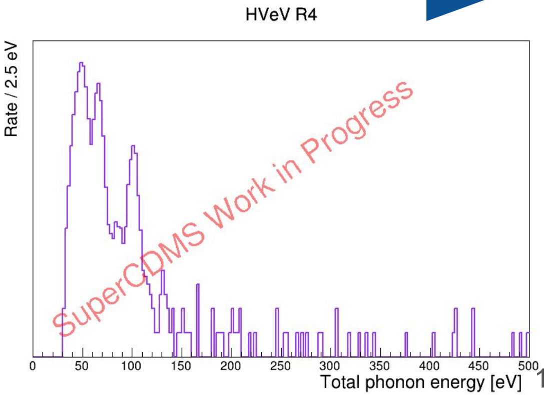
HVeV Run 3





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

HVeV Run 4

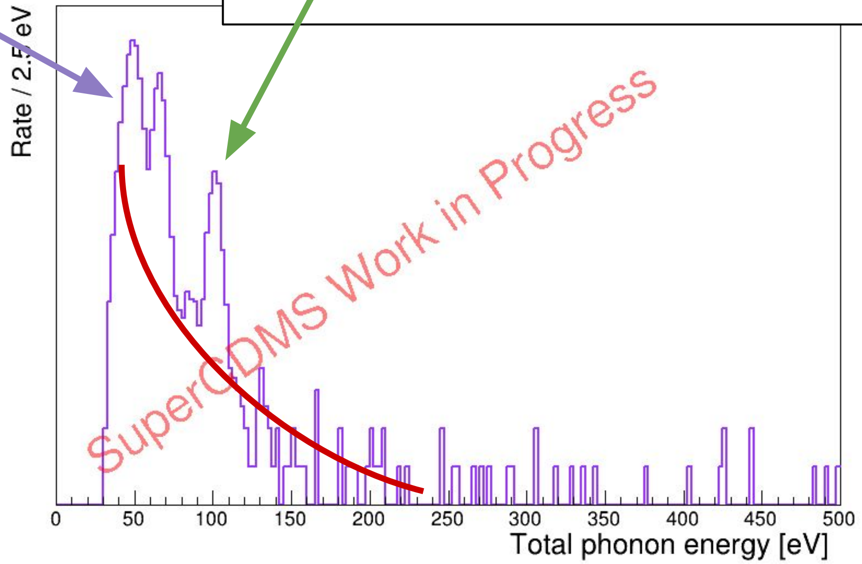


Low mass dark matter search background challenges

- 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

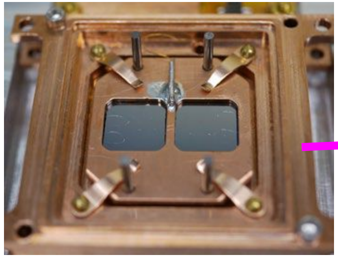
- Low energy excess
- Evidence hints different ionization from ER and NR
    - “Heat only”
- Unpacking ER/NR/Heat Only components by operating with different NTL gains

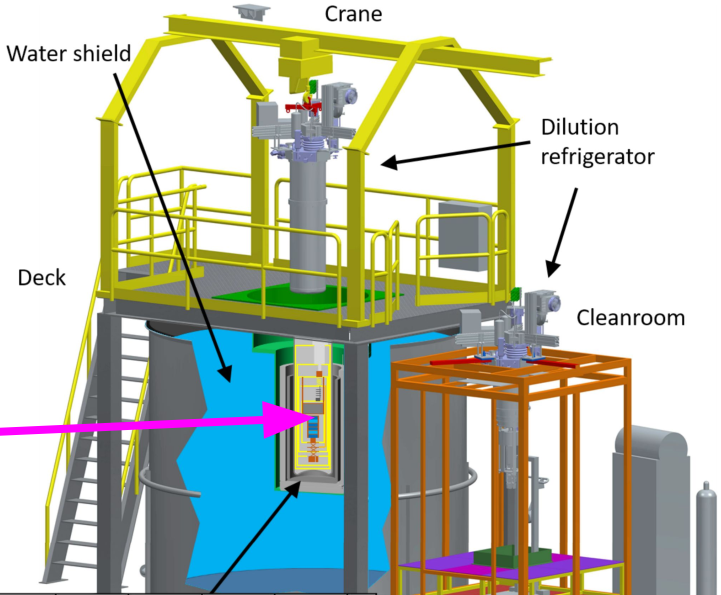


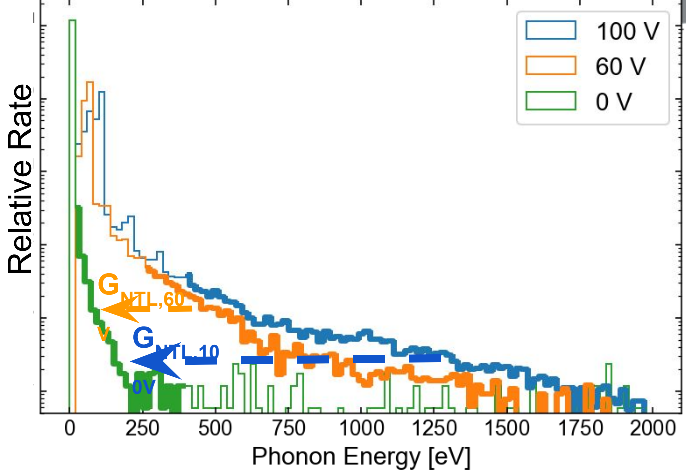
HVeV going deep underground

- 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

$$\underbrace{E_t}_{\text{total phonon energy}} = \underbrace{E_r}_{\text{primary recoil energy}} + \underbrace{N_{eh}eV_b}_{\text{Luke phonon energy}}$$

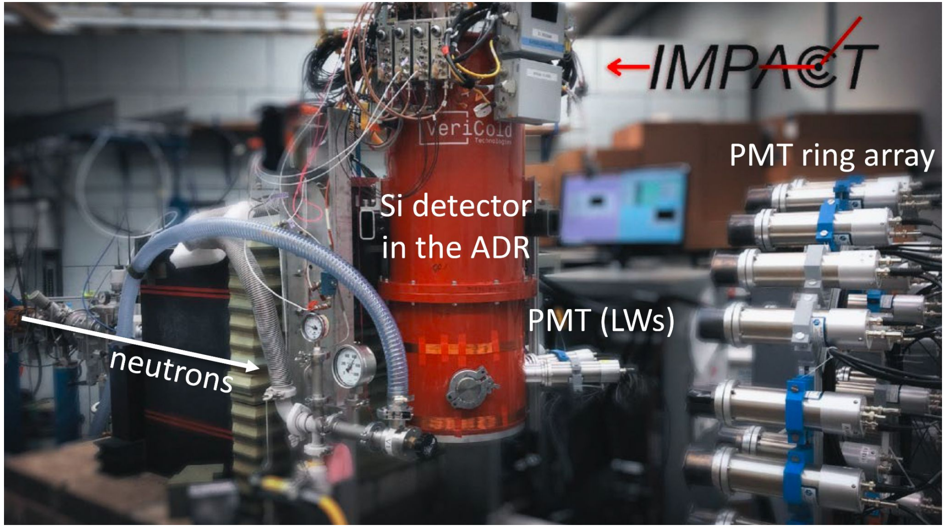






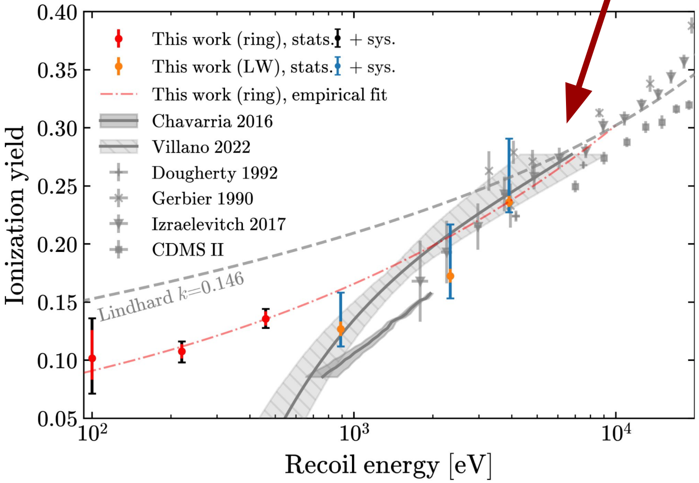
Phys. Rev. D 105, 112006 (2022)

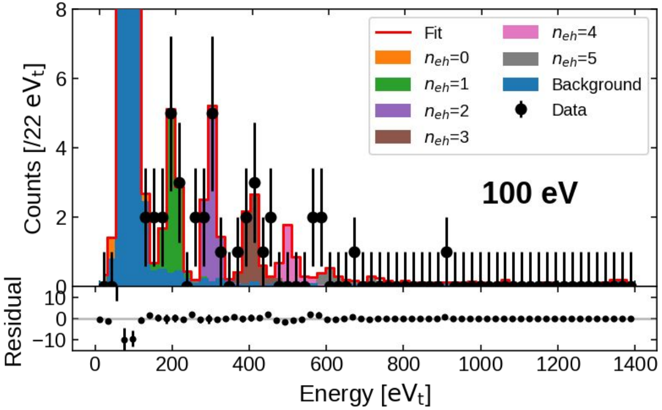
Understanding the detector: Nuclear recoil calibration



- 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

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





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

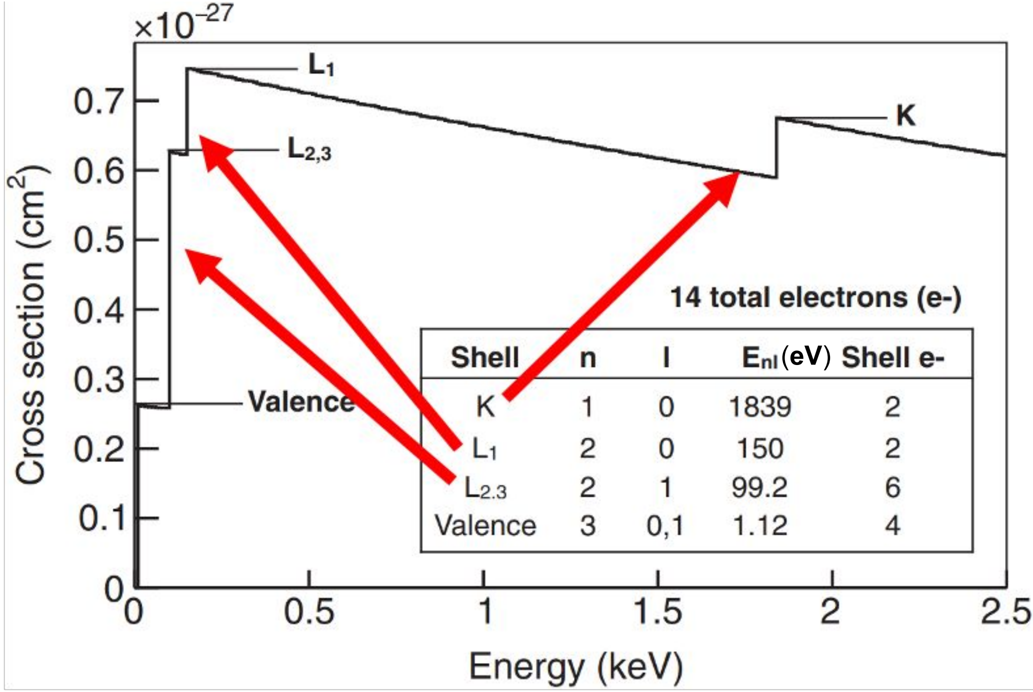
Understanding the detector:
Low energy calibration

- 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

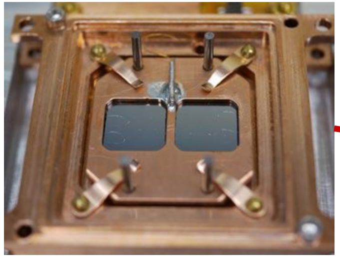


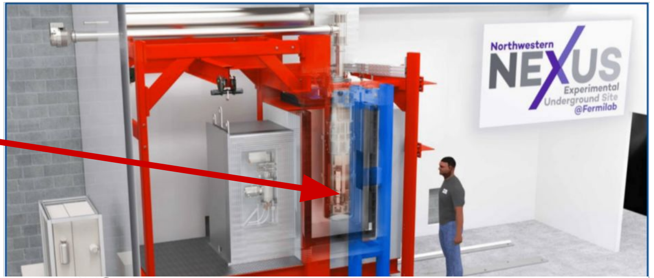
14 total electrons (e-)

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

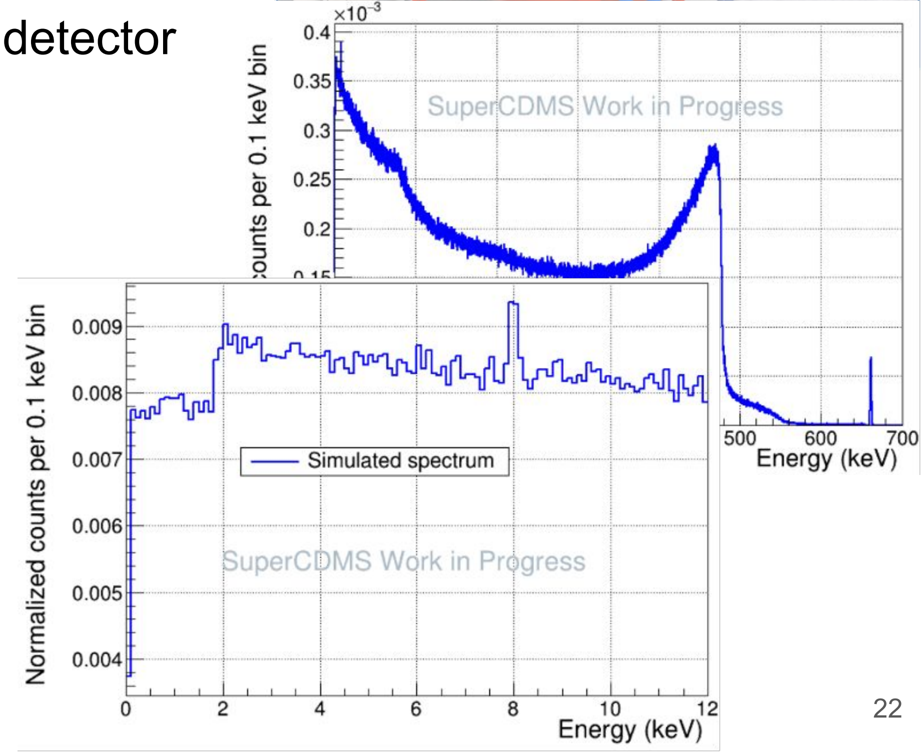
Similar structure confirmed by CCD data from DAMIC-M (PhysRevD 106, 092001, 2022)

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!



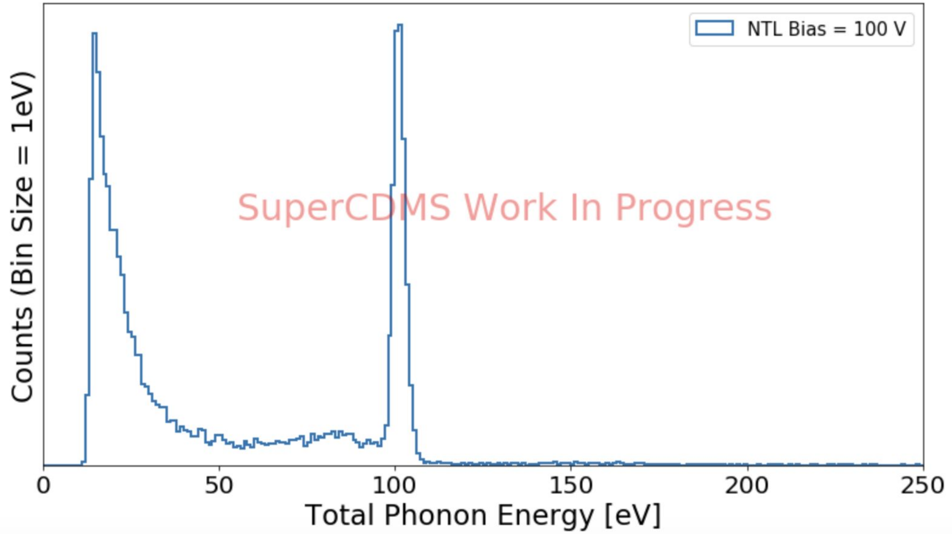
Latest Detector Performance

BEST IN CLASS

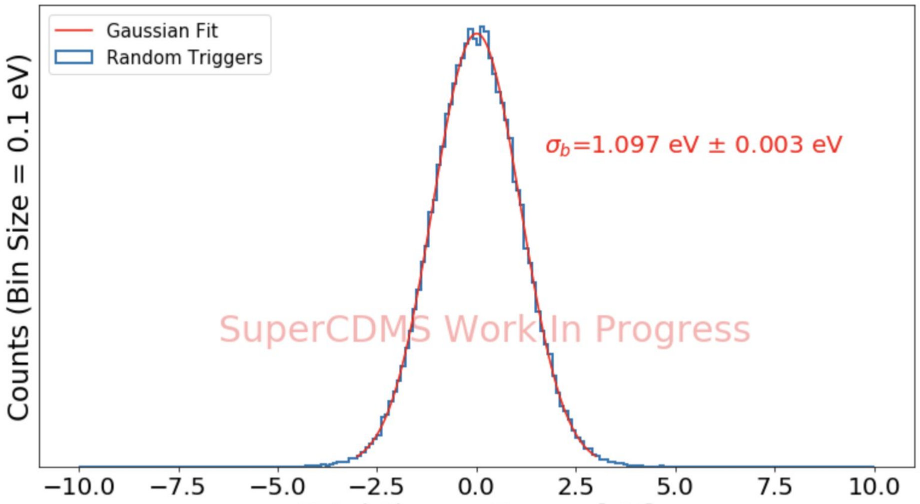
- “Version 3” of HVeV detectors
- Lower transition temperature
  - Operated at NEXUS

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

Detector Spectrum

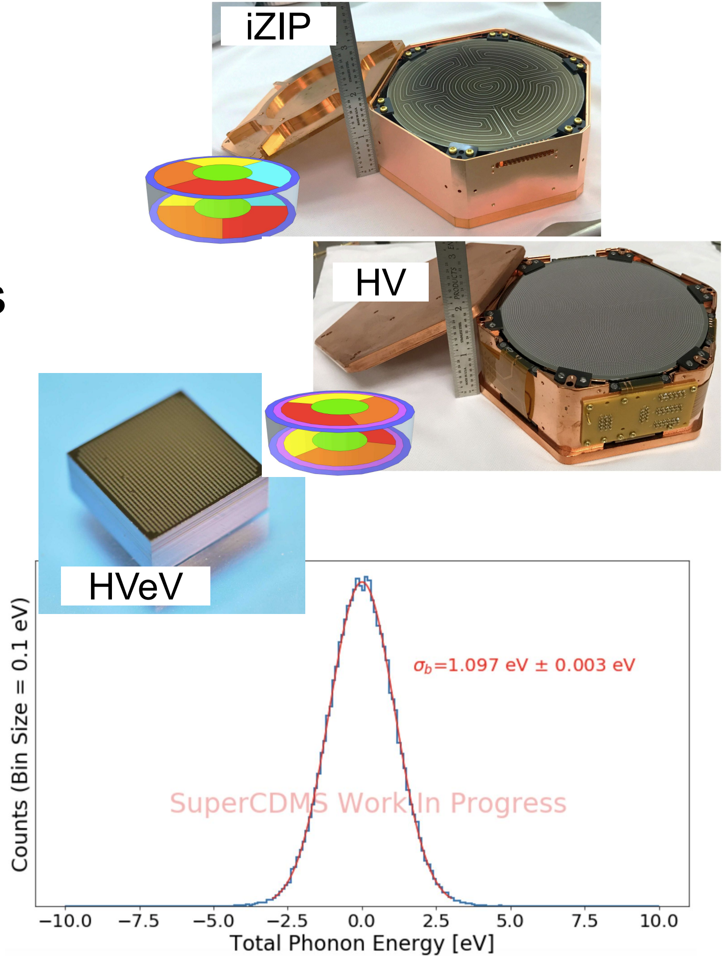


Energy of Random Triggers



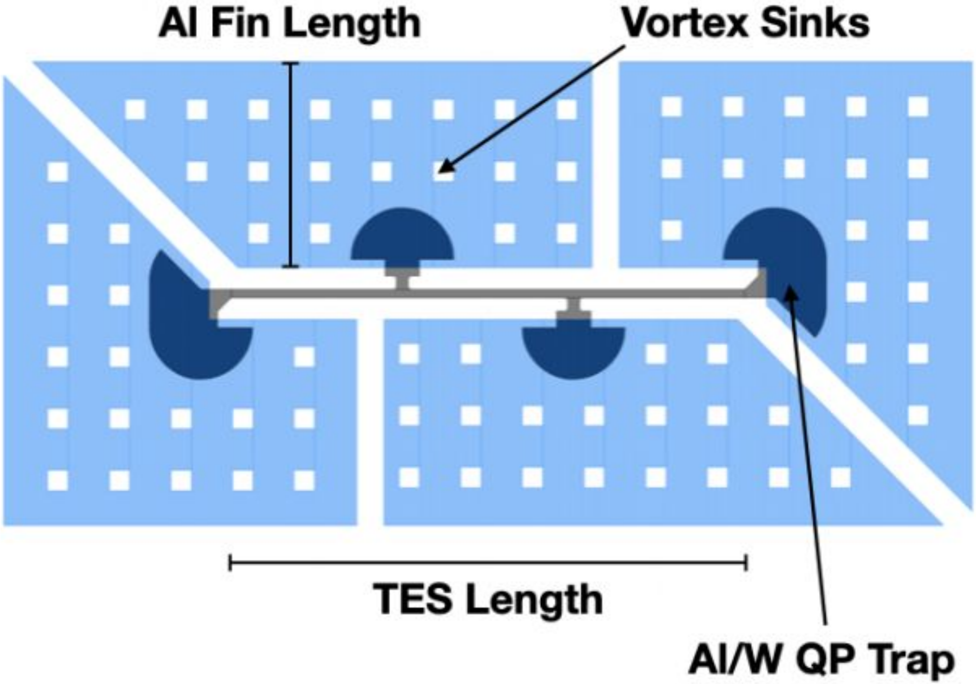
Conclusions

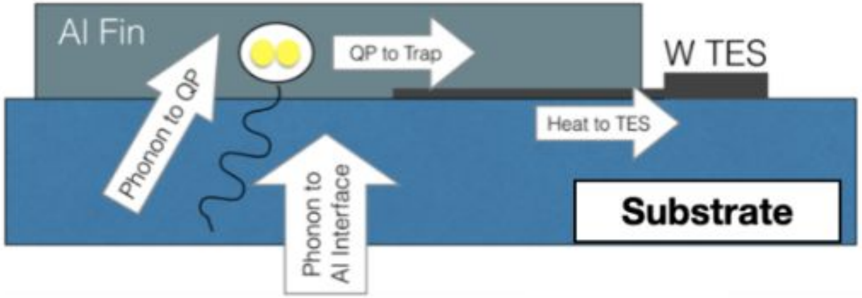
- SuperCDMS is well suited for sub-GeV DM searches
- Low threshold enables low mass NR searches
  - iZIP provides background rejection
  - HV pushes down threshold further
- ER and absorption channels benefit from single charge performances
  - HVeV detectors can achieve 1 eV phonon resolution and 0.01 charge resolution
- Low energy calibration poses renewed challenge
- More science results anticipated
- **Stay tuned!**



Bonus Slides

QET Design and Transport





Low threshold detectors also needed in CEvNS studies

- Coherent Elastic neutrino-Nucleus Scattering (CEvNS) cross section as a function of recoil energy for typical neutrino energies at
  - Spallation Neutron Source (30 MeV)
  - a reactor (3 MeV)
  - with an electron capture source (1 MeV).
- Low threshold detectors are also critical for neutrino experiments