SuperCDMS & CUTE

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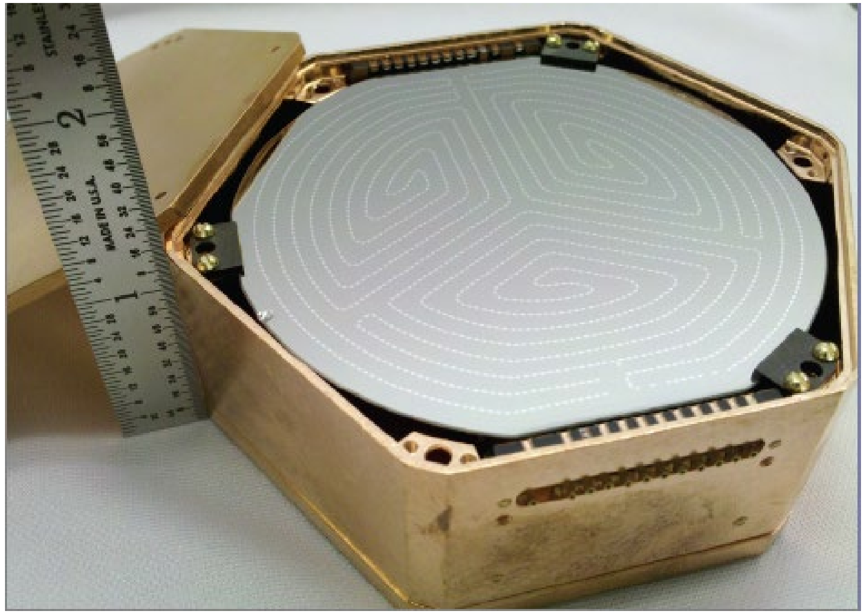
IPP AGM

June 23, 2023

SuperCDMS technology



Cryogenic semiconducting crystals (25kg Ge and 3.6kg Si in total), with phonon and ionization sensors

Heat capacity ∝ T^3:
T ~ 10’s of mK makes crystal heating, phonon signal easy to see

Dark matter interactions create phonon excitations (vibrations) as well as electron/hole pairs in proportion to energy and to yield factor *Y*:

$$N_{e/h} = \frac{Y E_r}{\epsilon}$$

$$\begin{aligned} E_{phonon} &= E_r + N_{e/h} V_{bias} e \\ &= E_r \left(1 + Y \frac{V_{bias} e}{\epsilon}\right) \end{aligned}$$

SuperCDMS SNOLAB science reach

- Aims to be the world's most sensitive experiment between 0.5-5 GeV/c^2.
- Both germanium and silicon detectors (two nuclear targets), in two different configurations: 12 HV detectors (lower mass reach) and 12 iZIPs (better background rejection)
- Also sensitive to low energy electron recoils: dark photons, axion-like particles, low mass DM.

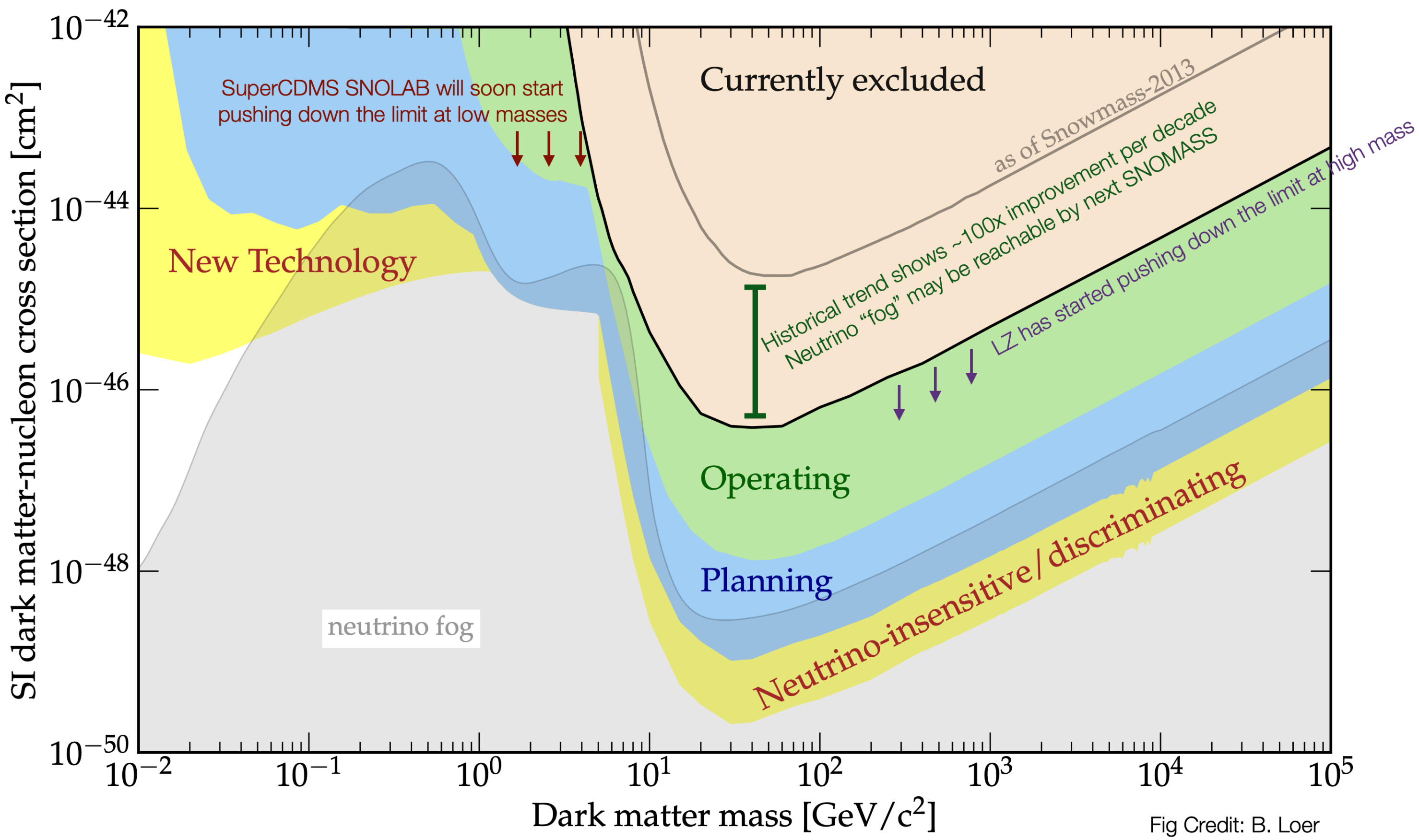
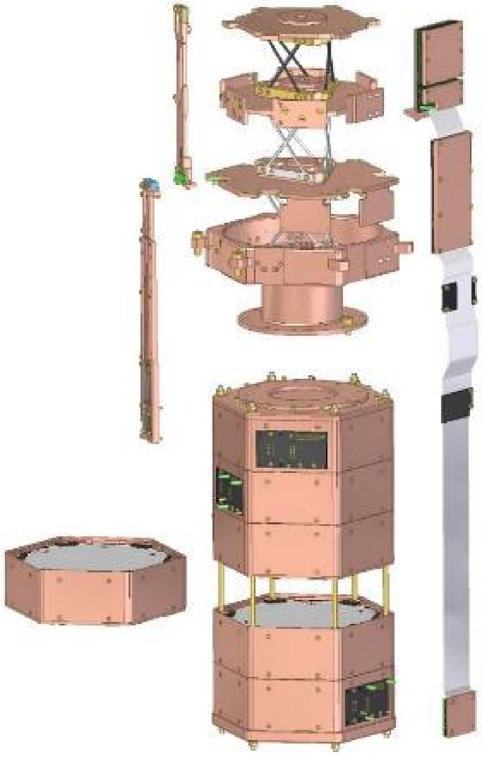
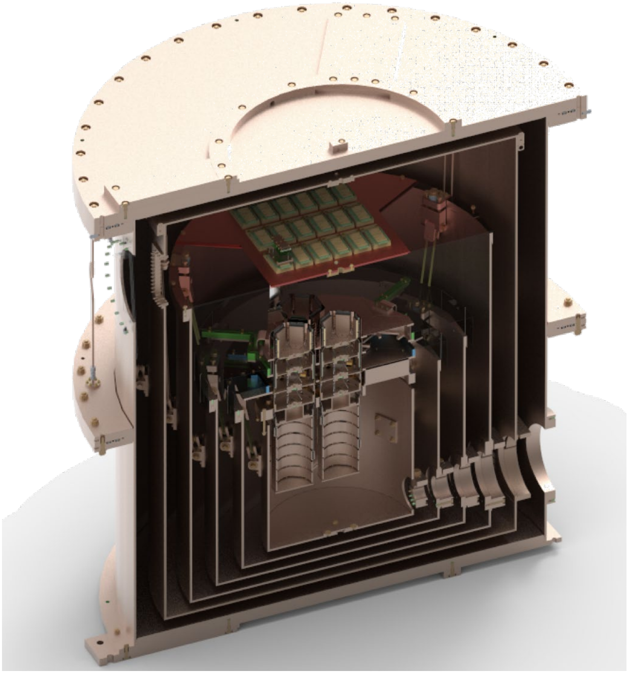
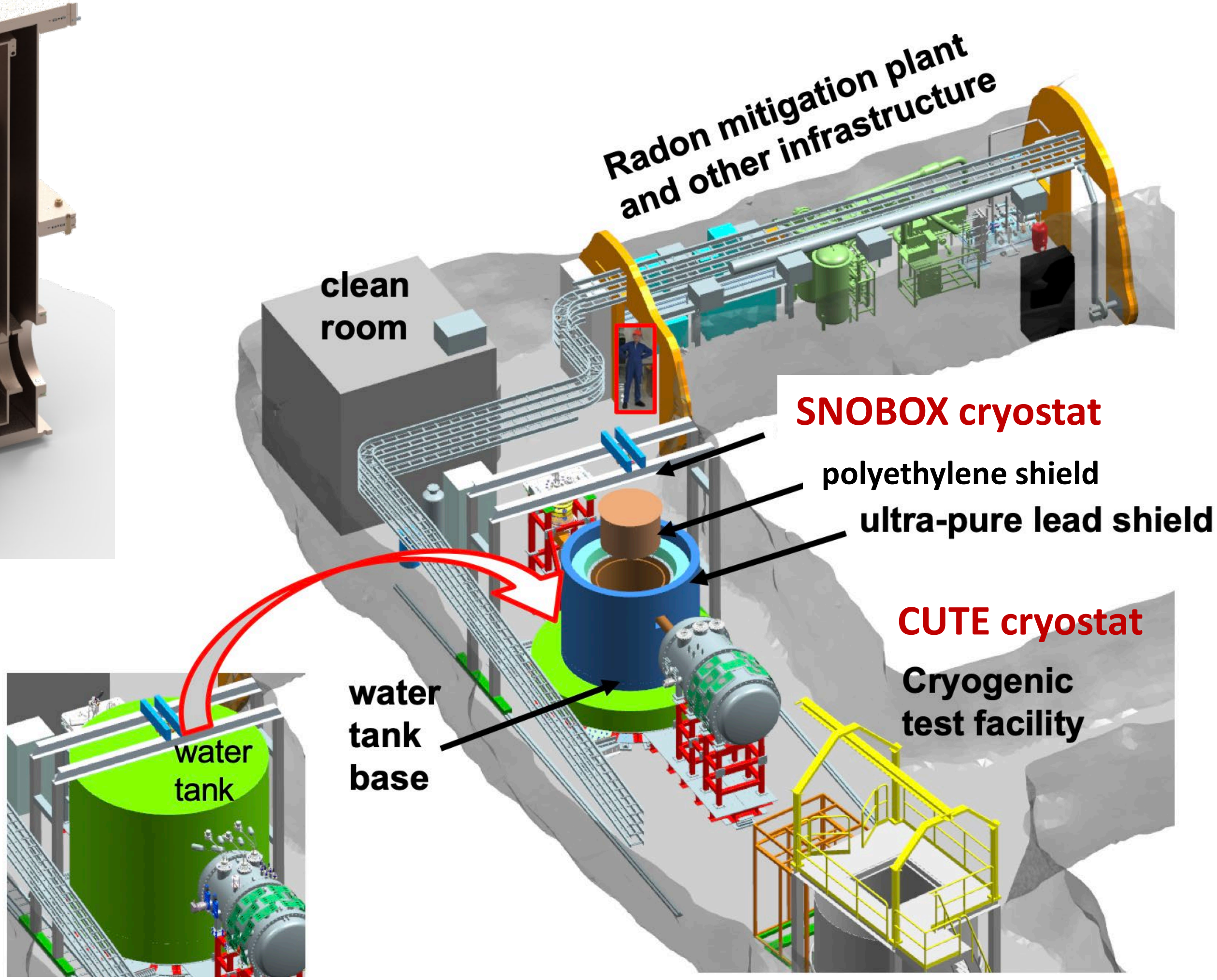


Fig Credit: B. Loer

The SuperCDMS SNOLAB Experiment







Radon mitigation plant and other infrastructure

clean room

SNOBOX cryostat

polyethylene shield

ultra-pure lead shield

CUTE cryostat

Cryogenic test facility

water tank base

water tank

First 4-Tower Payload: Strategy to meet Science Goals
Complementary Targets and Multiple Functionality

	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no ^{32}Si bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
iZIP	Nuclear Recoil Discrimination Understand Ge Backgrounds Sensitive to ^{8}B ν-scatter	Nuclear Recoil Discrimination Understand Si Backgrounds Sensitive to ^{8}B ν-scatter

“Pre-production” towers

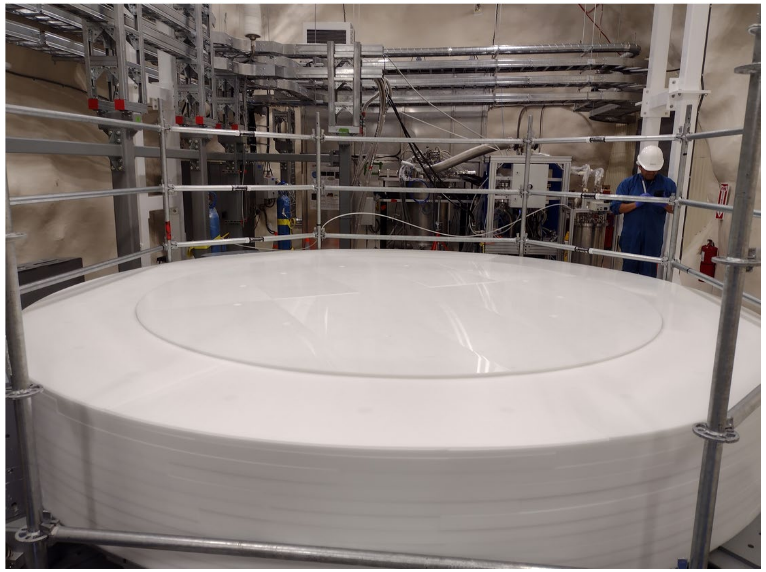
“Production” towers

Delivered to SNOLAB May 2023

Production towers have less cosmogenic exposure

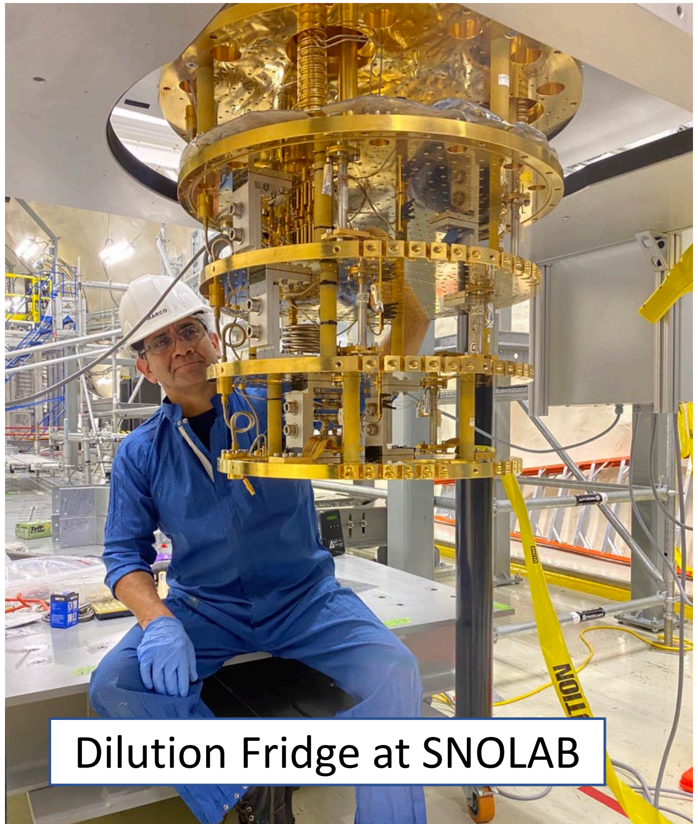
Installation Progress

Assembled tower at SLAC



Shield base assembly

Upper and Lower OVC chambers



Dilution Fridge at SNOLAB

E-tank in Lab G at FNAL

Routinely 10-14 people underground working on installation and commissioning

First detector tower shipment to SNOLAB
(cosmogenic activation clock ticking)

Arrival:
May 12,
noon EDT

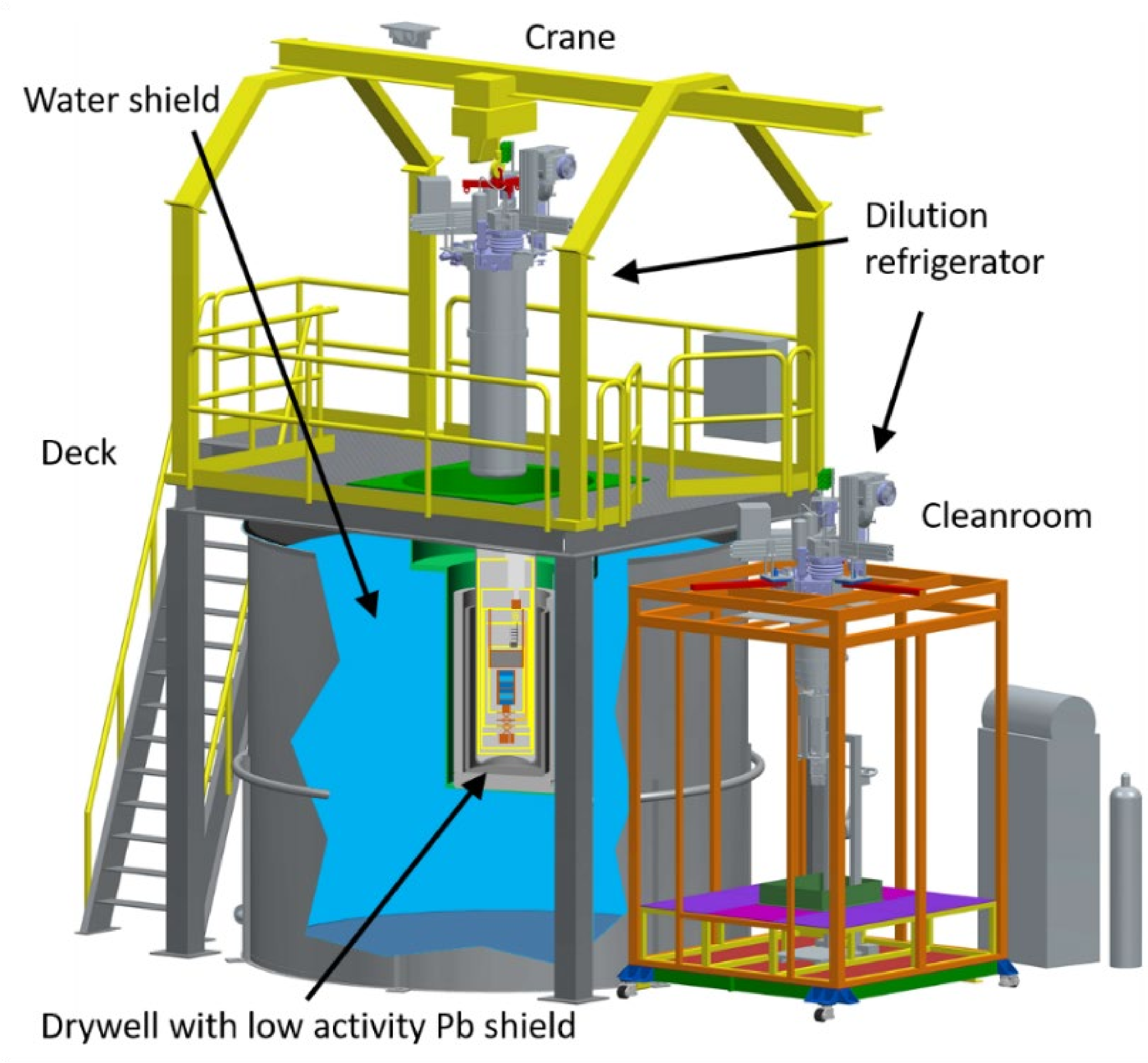
Departure:
May 9,
noon PDT

Southern route: avoid high elevations

First two towers underground in low radon cleanroom at SNOLAB

CUTE

- Underground test facility at SNOLAB, capable of operating one SuperCDMS tower or individual detectors
- Operational since 2019
- Platform for doing detector R&D in low background environment, and early science from SuperCDMS while project installation completes
- Once SuperCDMS starts, will be available for testing other cryogenic devices, including quantum computing, new detector designs, etc.



8 PIs, >6 FTE

+ 9 postdocs (will ramp down to 5 as MI ends)

+ 14 grad students

Miriam Diamond
PI
U. Toronto

Jeter Hall
Staff Scientist
SNOLAB

Ziqing Hong
PI
U. Toronto

Andy Kubik
Staff Scientist
SNOLAB

Scott Oser
PI
U. British Columbia

Wolfgang Rau
PI
TRIUMF

Alan Robinson
PI
U. Montréal

Pekka Sinervo
PI
U. Toronto


Miriam Diamond
PI
U. Toronto


Jeter Hall
Staff Scientist
SNOLAB


Ziqing Hong
PI
U. Toronto


Andy Kubik
Staff Scientist
SNOLAB

Plus one bonus "collaborator on leave":


Jodi Cooley
SNOLAB Director


Scott Oser
PI
U. British Columbia


Wolfgang Rau
PI
TRIUMF


Alan Robinson
PI
U. Montréal

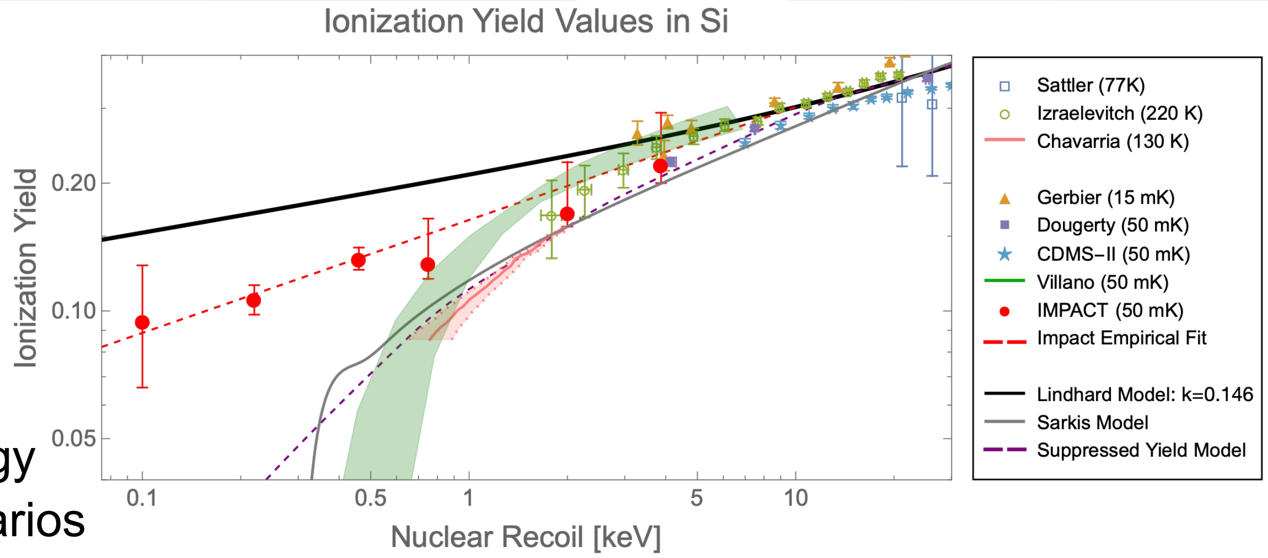

Pekka Sinervo
PI
U. Toronto

Major Canadian responsibilities

- CUTE
- DAQ
- SuperCDMS installation
- Leading role in on-site operations
- Simulation
- Data Processing
- Tier 2 Analysis System
- Calibration/backgrounds
- Ionization yield measurements w/ IMPACT, NEXUS test facilities

Significant RAP allocation from DRAC

Papers in the last year



Ionization yield at low energies

- **Si HVeV** with neutron beam: [arXiv:2303.02196]
- **Ge CDMSlite** with photo-neutron source: [arXiv:2202.07043]

Snowmass White paper

- Scientific reach of SuperCDMS based technology spanning eV – GeV mass range for upgrades scenarios given 3 incremental background detector improvements [arXiv:2203.08463]

R&D & DM Searches

- Investigating the sources of low-energy events in a SuperCDMS-HVeV detector [arXiv:2204.08038]

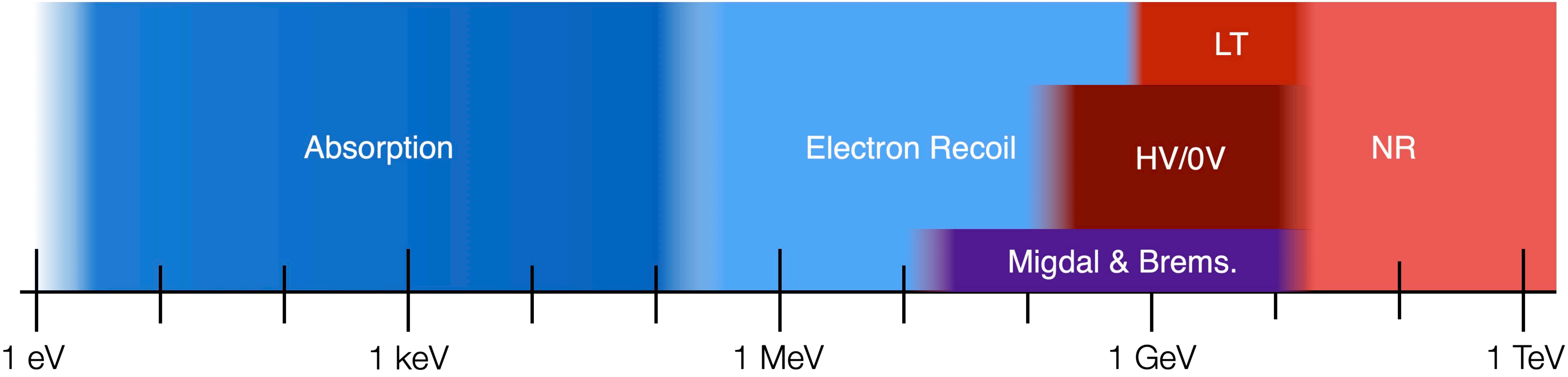
Instrumentation

- The Level-1 trigger for the SuperCDMS experiment at SNOLAB [arXiv:2204.013002]

SuperCDMS Detectors & Dark Matter Mass Scales

Dark Matter Mass Ranges

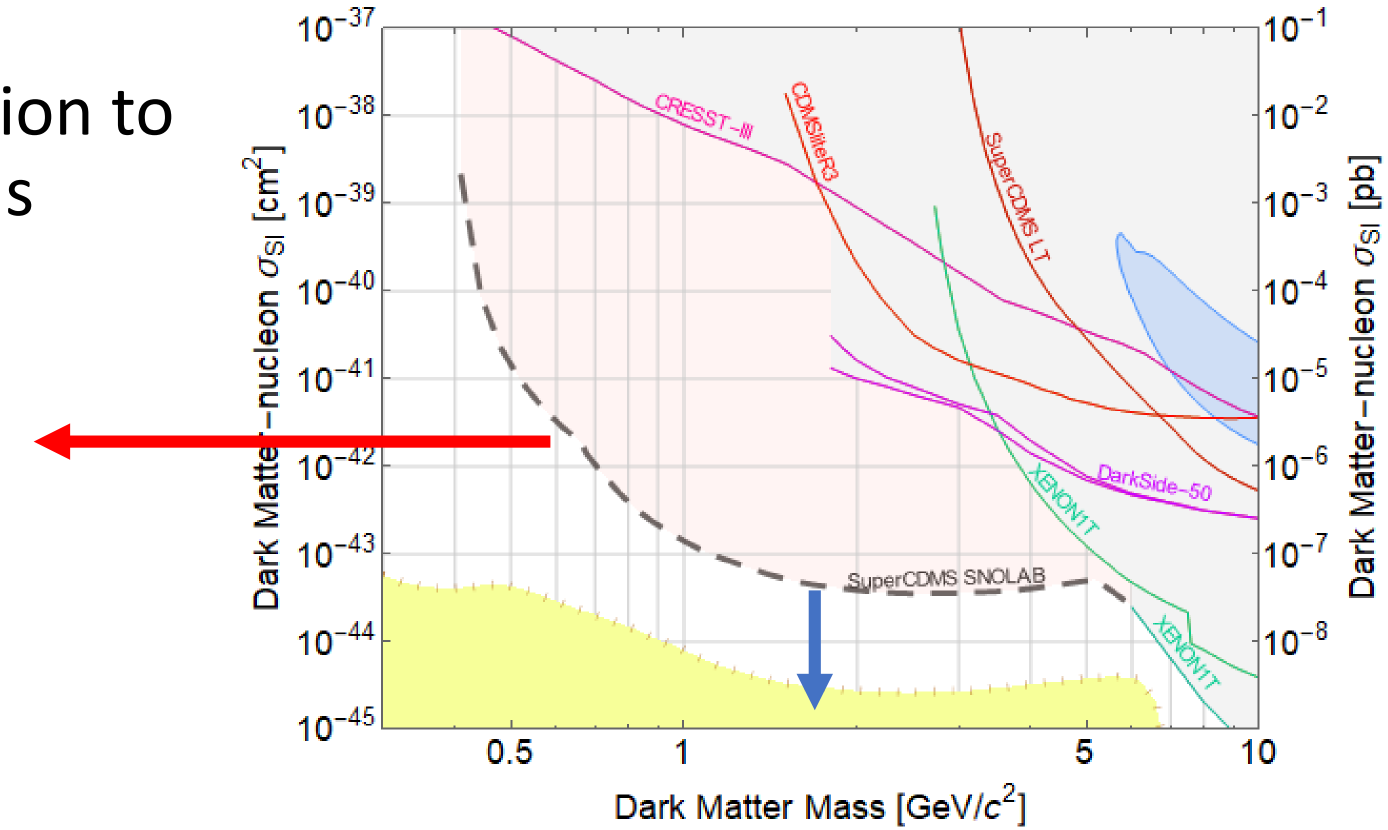
High Mass Nuclear Recoil:	Full discrimination,	≳ 5 GeV
Low Threshold NR:	Limited discrimination,	≳ 1 GeV
HV & 0V Operation:	No discrimination,	~0.3 – 10 GeV
Migdal & Brems. Search:	no discrimination,	~0.01 – 10 GeV
Electron recoil:	HV, no discrimination,	~0.5 MeV – 10 GeV
Absorption (Dark Photons, ALPs):	HV, no discrimination,	~1 eV – 500 keV (“peak search”)



Upgrade options

- Significant effort by collaboration to understand best upgrade paths

Improve phonon energy resolution to potentially reach <0.1 GeV. For example, 1 cm^3 Si detectors could reach $\sigma = \sim 10^{-42}\ \text{cm}^2$ in this region



See Sunil Golwala’s presentation at the SNOLAB Future Projects Workshop 2021 and our SNOWMASS white paper: arXiv:2203.08463

Ge iZIP detectors with improved nuclear recoil discrimination could reach the “neutrino fog”

Conclusions

- 2023-2028 science:
  - Now – late 2024: detector installation and commissioning
  - 2025 – 2028: science running, data analysis
    Best nuclear recoils limits in mass range from ~0.5-5 GeV/c^2
  - Limits on very low energy electron recoils: very light dark matter, dark photons, axion-like particles, etc.
  - R&D to understand backgrounds, improve resolution, push down in energy
- Future depends on what is seen in various experiments
  - Any signal from SuperCDMS or other experiments? This is critical issue for deciding on the next step!
  - Collaboration is exploring parallel upgrade paths that lead either to lower mass reach, or better sensitivity in the 1-10 GeV/c^2 region. All require significant R&D still, but no show-stoppers seen so far.

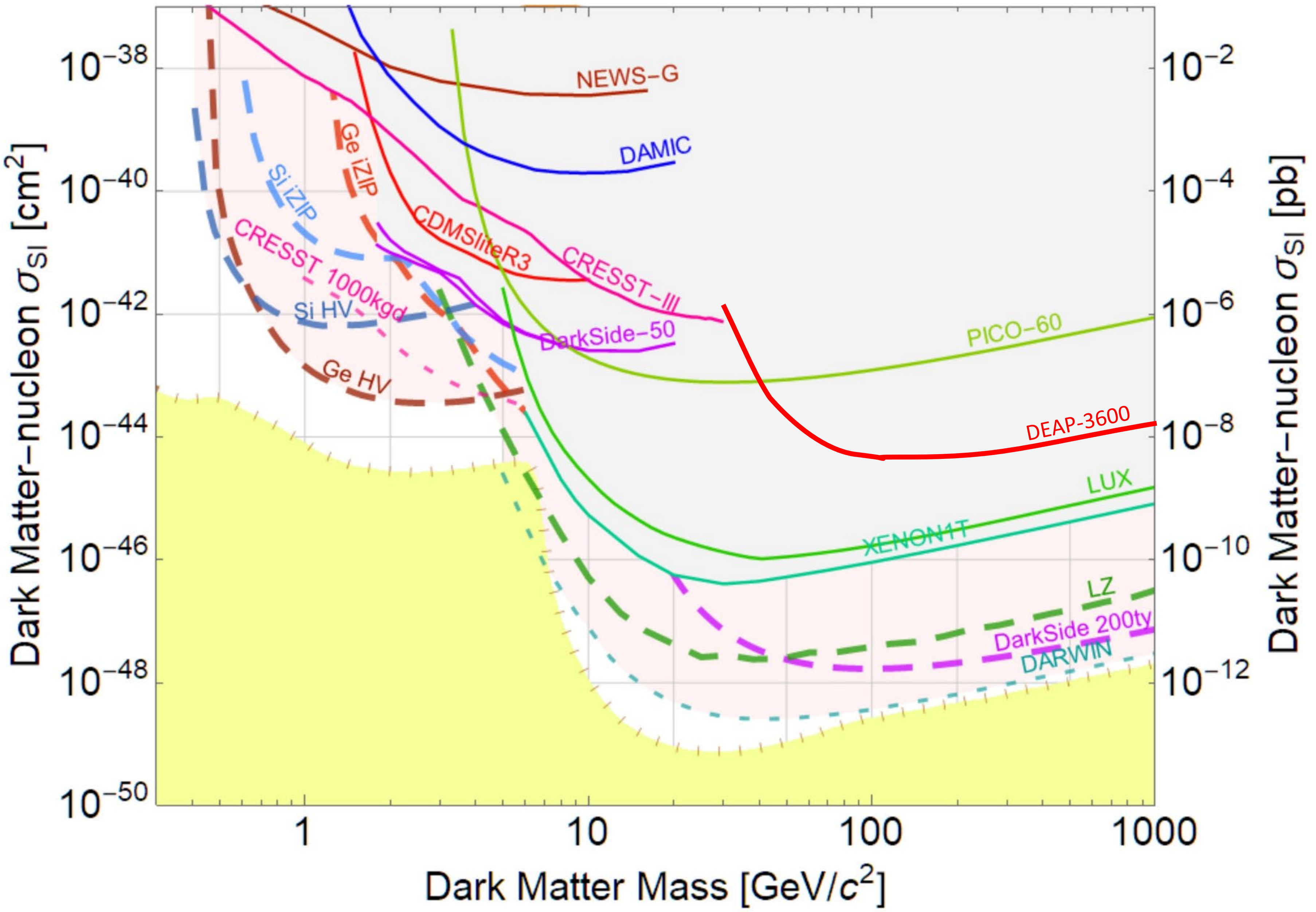
Backups

Equity and Diversity initiatives

- Instituted SuperCDMS code of conduct
- Ombudsperson program
- Annual anonymous surveys within collaboration about climate, EDI
- New since proposal submission: “SuperCDMS network for women/non-binary or GNC collaborators”. Co-led by Canadian student
- Strong track record: over half of our current postdocs and about half of our graduate students are from traditionally underrepresented groups

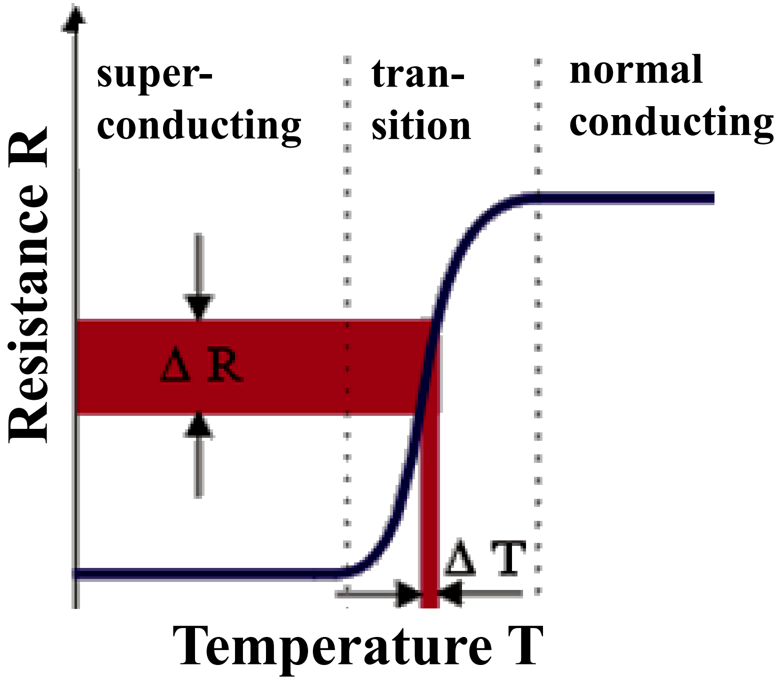
Above solid lines: currently excluded

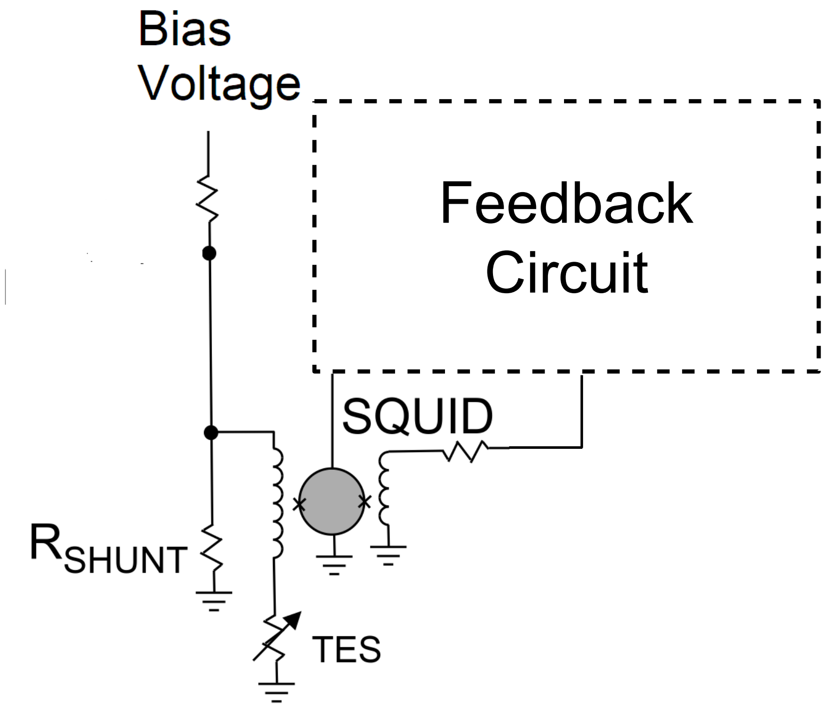
Dashed lines: projected sensitivities of selected next-generation experiments



Phonon sensors

Thin Al fins on the crystal surface absorb phonon energy and carry it to a thin tungsten film that is operated in transition between its normal and superconducting state: a **Transition Edge Sensor (TES)**



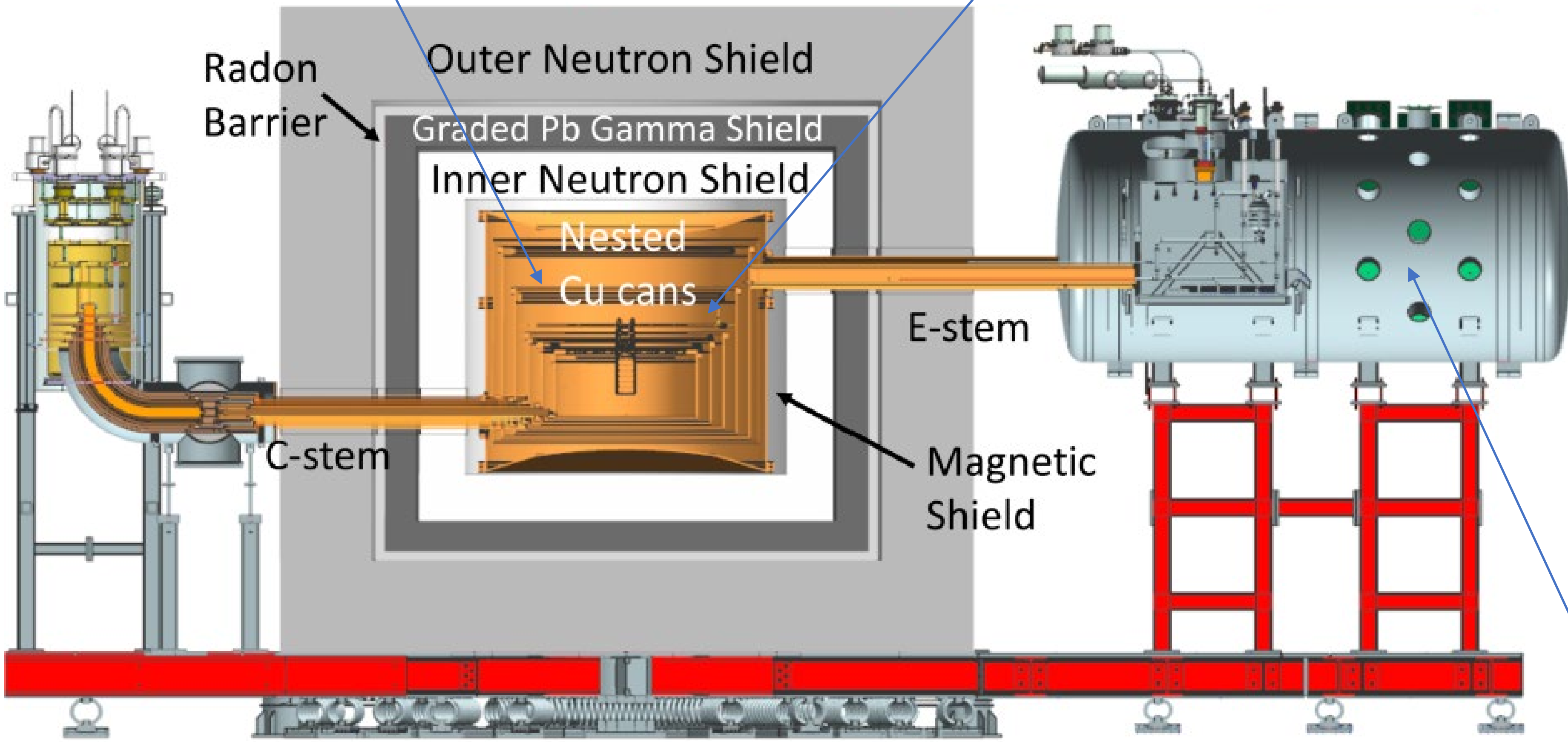


Changing TES resistance varies magnetic flux through SQUID. Feedback circuit adjusts current through a second inductor to compensate, and we measure that current.

SuperCDMS at SNOLAB (2023-)

Cryostat:
- Room for 7 towers
- 15mK base temperature

Detector payload:
- 2 HV towers
  (11.2kg Ge, 2.4 kg Si)
- 2 iZIP towers
  (14.0kg Ge, 1.2kg Si)

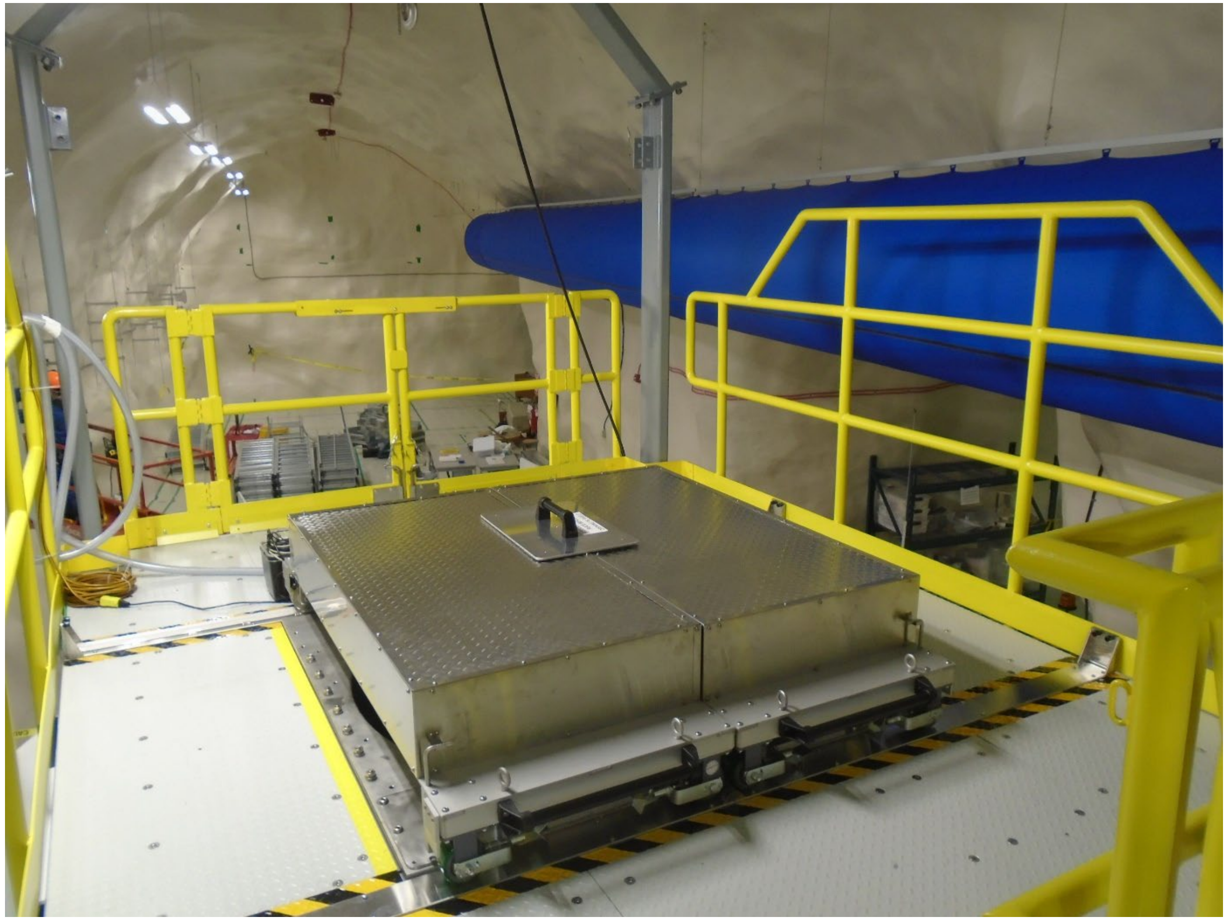


2km underground in SNOLAB
- Improved radiopurity, cleanliness, and shielding

Low noise electronics with deadtime-free trigger and new DAQ

CUTE Installation Photos

CUTE Installation Photos



CUTE Installation Photos

Science Drivers

Backgrounds:

- In energy range of interest, most important background is cosmogenic ^{3}H. Must limit unshielded exposure on surface. Careful assay and selection of materials essential

Resolution:

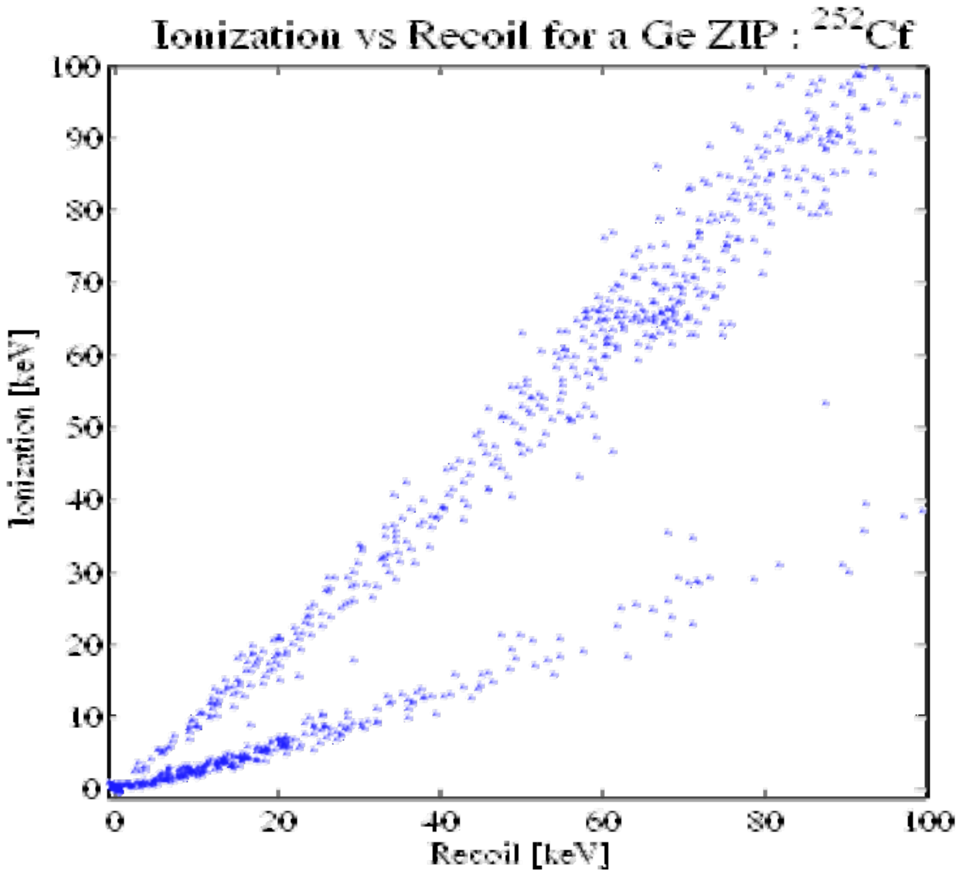
- Determines how low in energy threshold (mass) we can go
- Lower base temperature helps!
- Guard against microphonics, RF noise

Response to small energy deposits

- Optimal filter running in firmware to achieve lowest possible trigger thresholds
- Low energy calibrations to understand detector response to small energy deposits

IZIP Detectors

"Interleaved Z-Sensitive
Ionization & Phonon Detectors"



Yield for nuclear recoils is lower than for electron recoils.

Ratio of ionization to recoil energy distinguishes nuclear recoils from most backgrounds, which produce electron recoils.

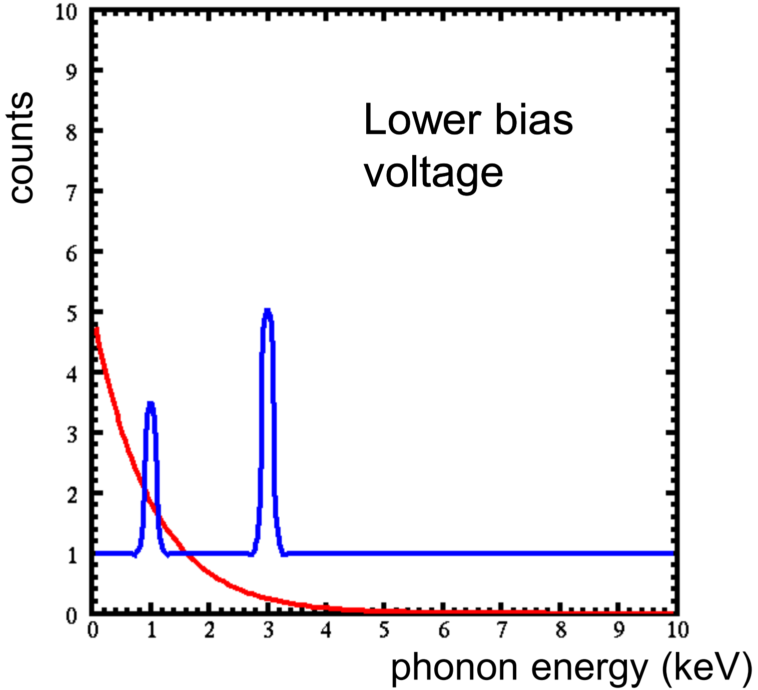
This background rejection works best at higher energies where the signal-to-noise is highest.

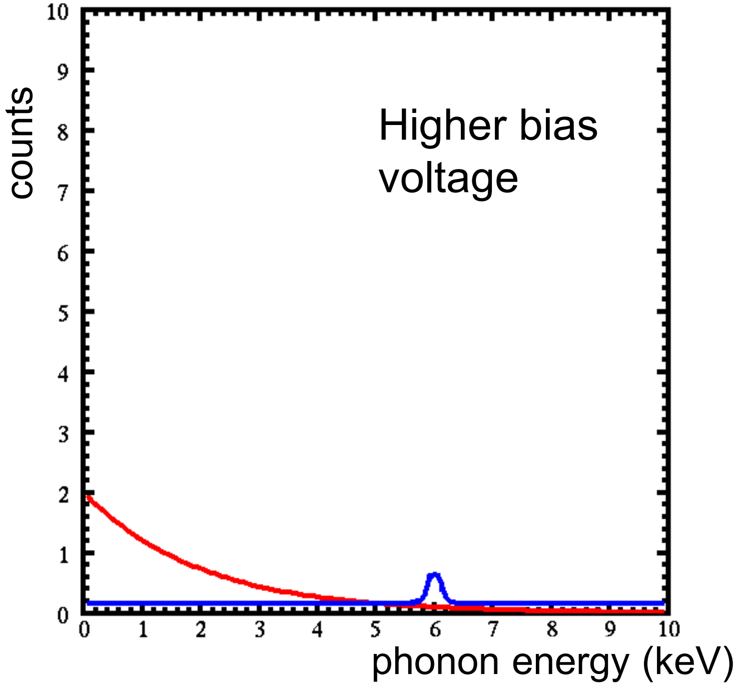
HV detectors

$$E_{phonon} = E_r\left(1 + Y\frac{V_{bias}e}{\epsilon}\right)$$

Neganov-Luke amplification: increasing V_{bias} from 4V to ~80V lowers energy threshold, giving sensitivity to much lighter WIMPs

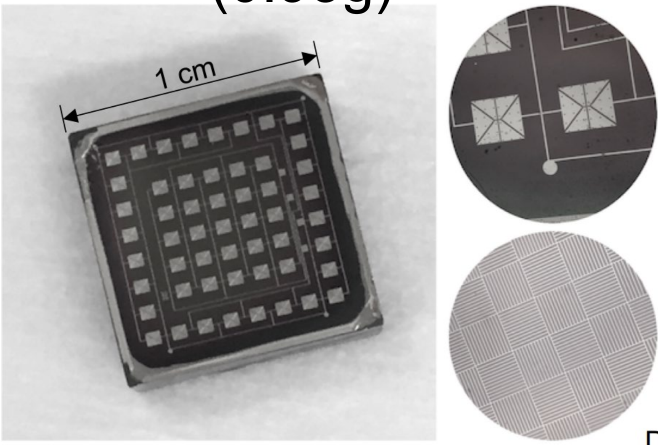
The price: lose electron/nuclear recoil discrimination. But higher Y for electron recoils pushes them out in energy relative to nuclear recoils, diluting background at low energies.

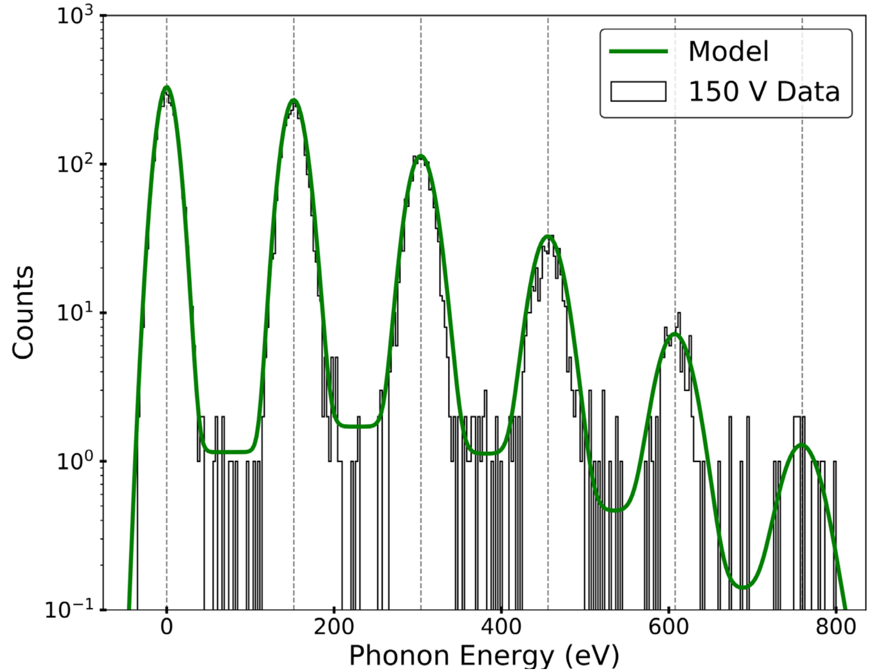




Phonon detectors sensitive to single electron/hole excitations

Si prototype detector
(0.93g)





Clearly count single excitations in phonon signal through Neganov-Luke gain!

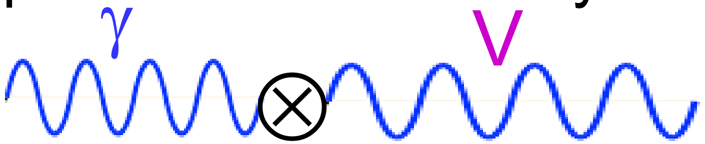
Electron recoils will dominantly occur only in peaks, while nuclear recoils, with much higher ratio of direct phonon to ionization yield, will fill in the valleys

$$E_{phonon} = E_r\left(1 + Y\frac{V_{bias}e}{\epsilon}\right)$$

Dark photons

Suppose a hidden sector contains particles with a U(1) gauge symmetry. The resulting "dark photon" will have the same quantum numbers as a photon. If the gauge symmetry is broken it may be massive.

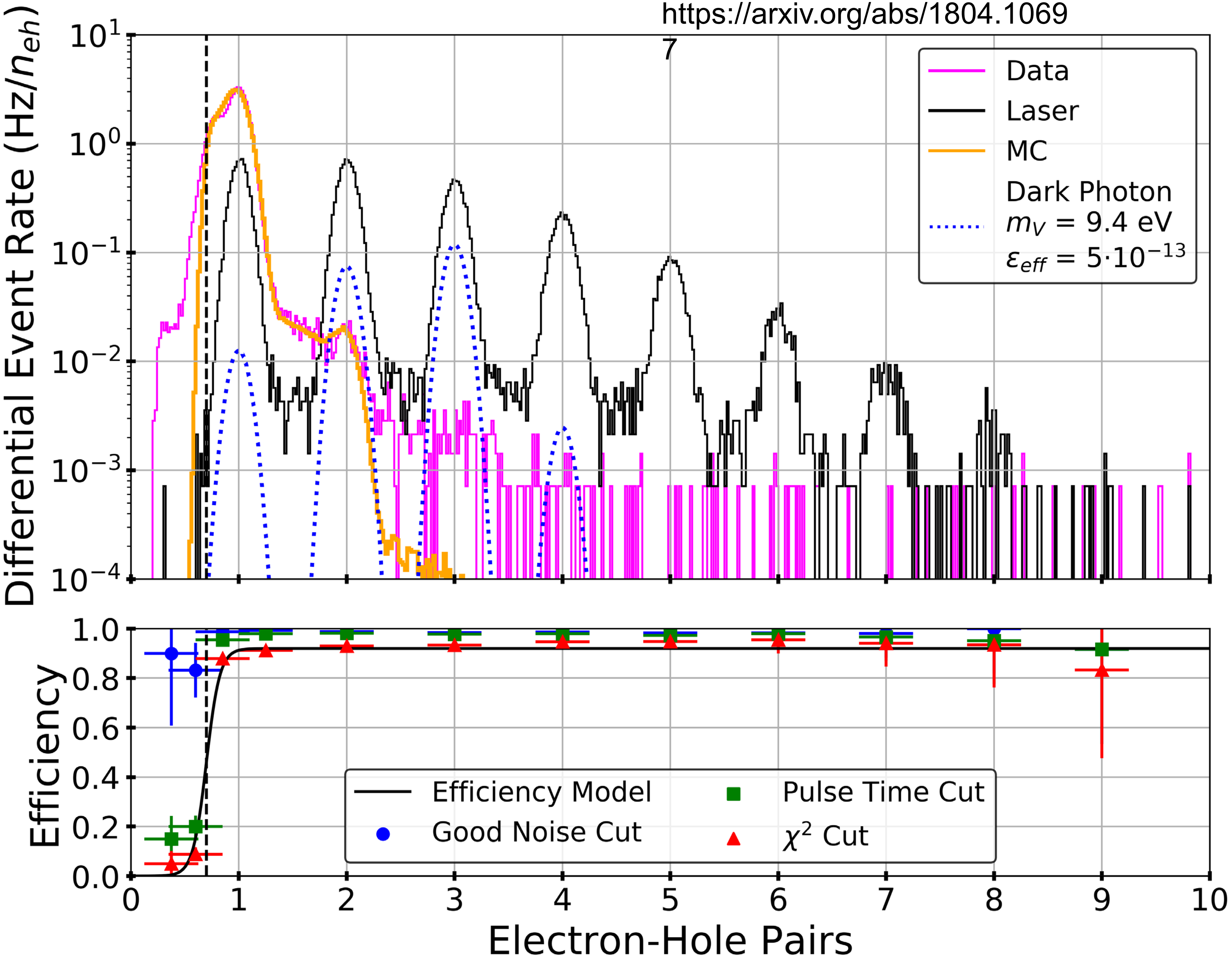
This massive dark photon can kinetically mix with the SM photon:



A dark photon interacting in our detectors can produce a "dark photoelectric" absorption, resulting in the production of one or more electron/hole pairs. The absorbed energy is the dark photon mass.

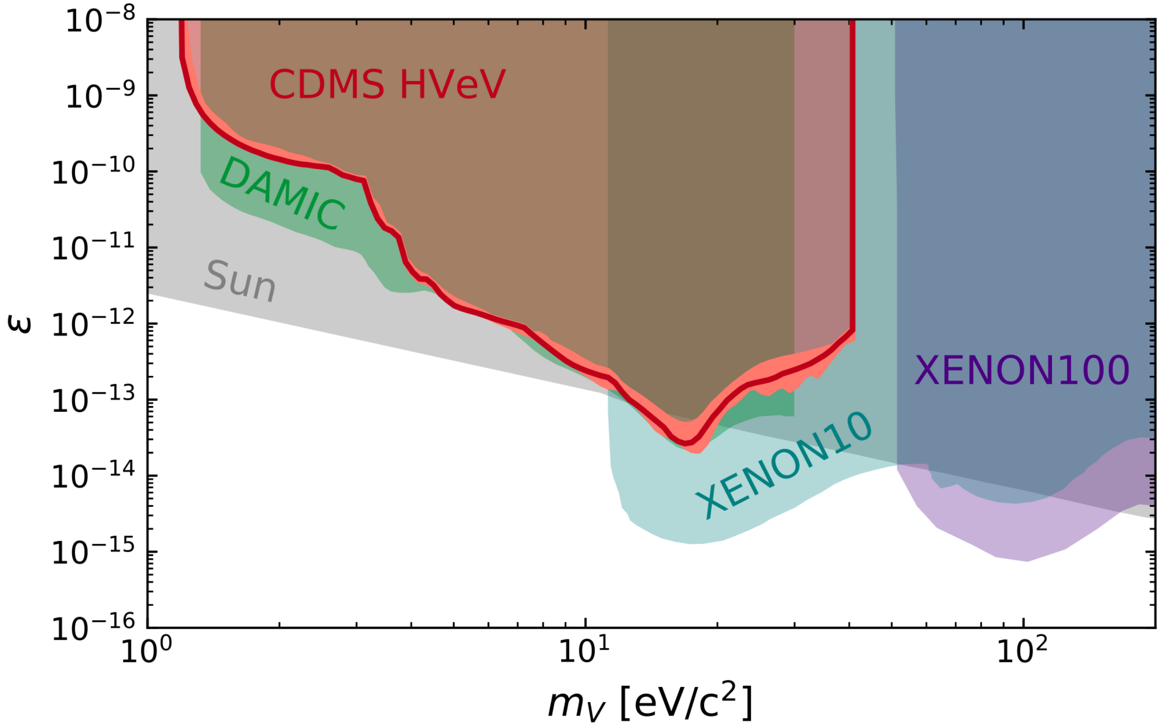
Search is sensitive down to masses given by the Si bandgap (few eV/c^2)!

https://arxiv.org/abs/1804.1069
7



Dark photon limits

$$R = V_{Det}\frac{\rho_{DM}}{m_V}\varepsilon^2_{eff}(m_V,\sigma)\sigma_1(m_V)$$



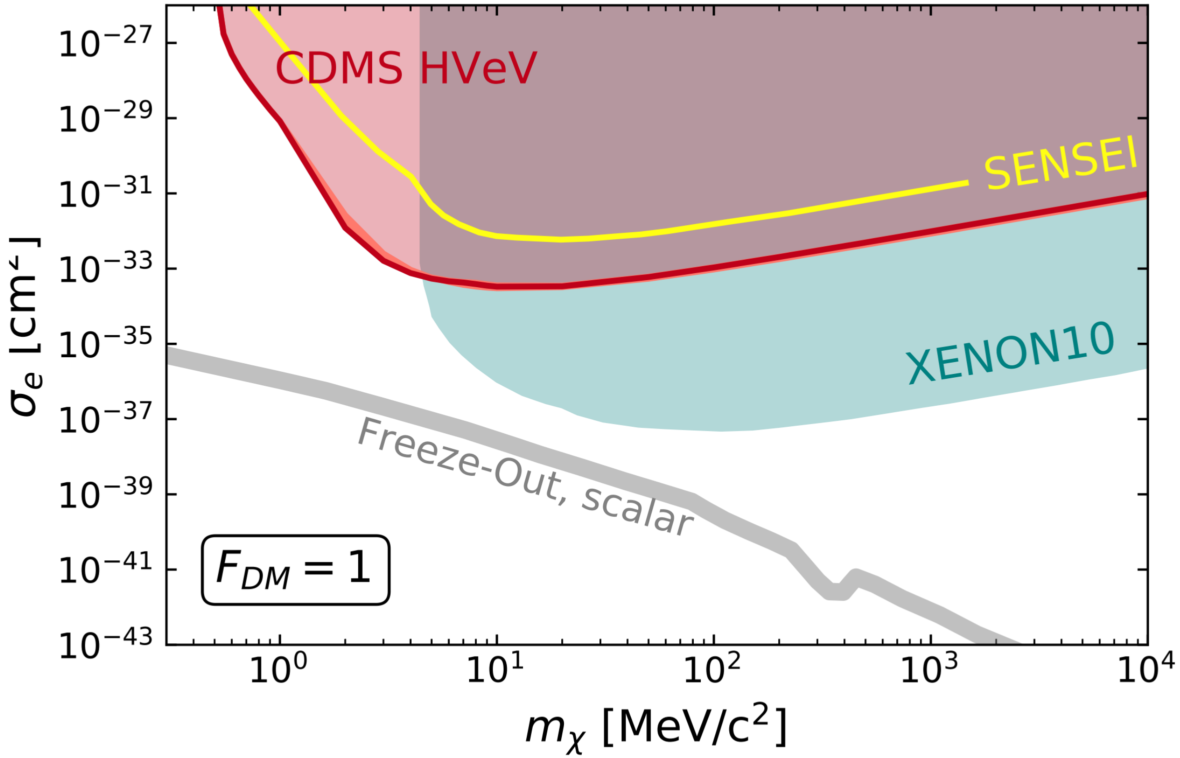
Competitive limits from just 0.49 g▪days of exposure from a test device

Mass sensitivity down to just above 1 eV!

https://arxiv.org/abs/1804.10697

Electron recoil DM

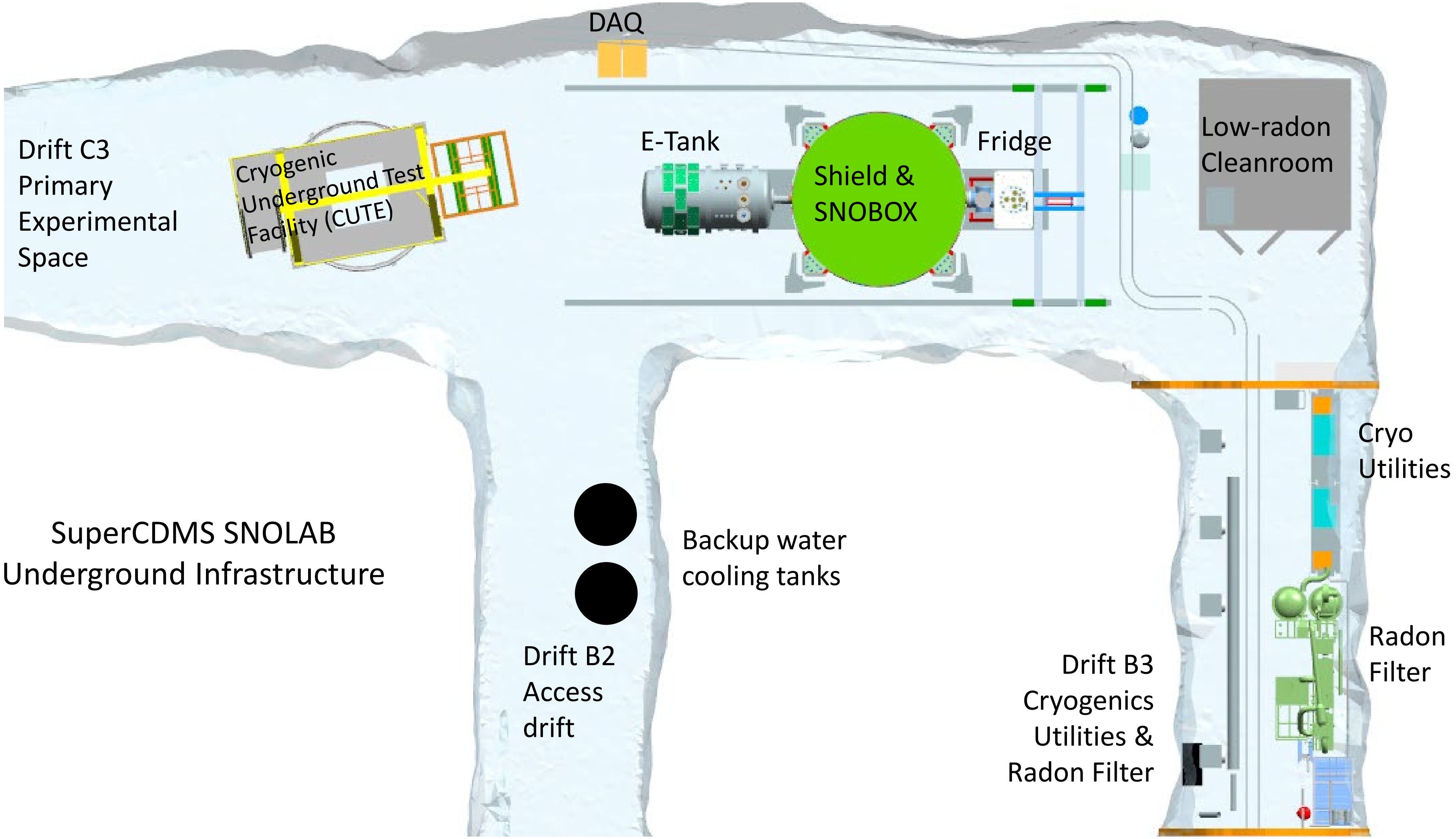
$$\frac{dR}{d(\ln(E_R))} = V_{Det}\frac{\rho_{DM}}{m_\chi}\frac{\rho_{Si}}{2m_{Si}}\bar{\sigma}_e\alpha\frac{m_e^2}{\mu_\chi^2}I_{Crystal}$$



Inelastic electron recoils can excite electrons across Si bandgap, giving us world's best limits on DM interactions with electrons at masses around 1 MeV/c^2 ... from a tiny test device!

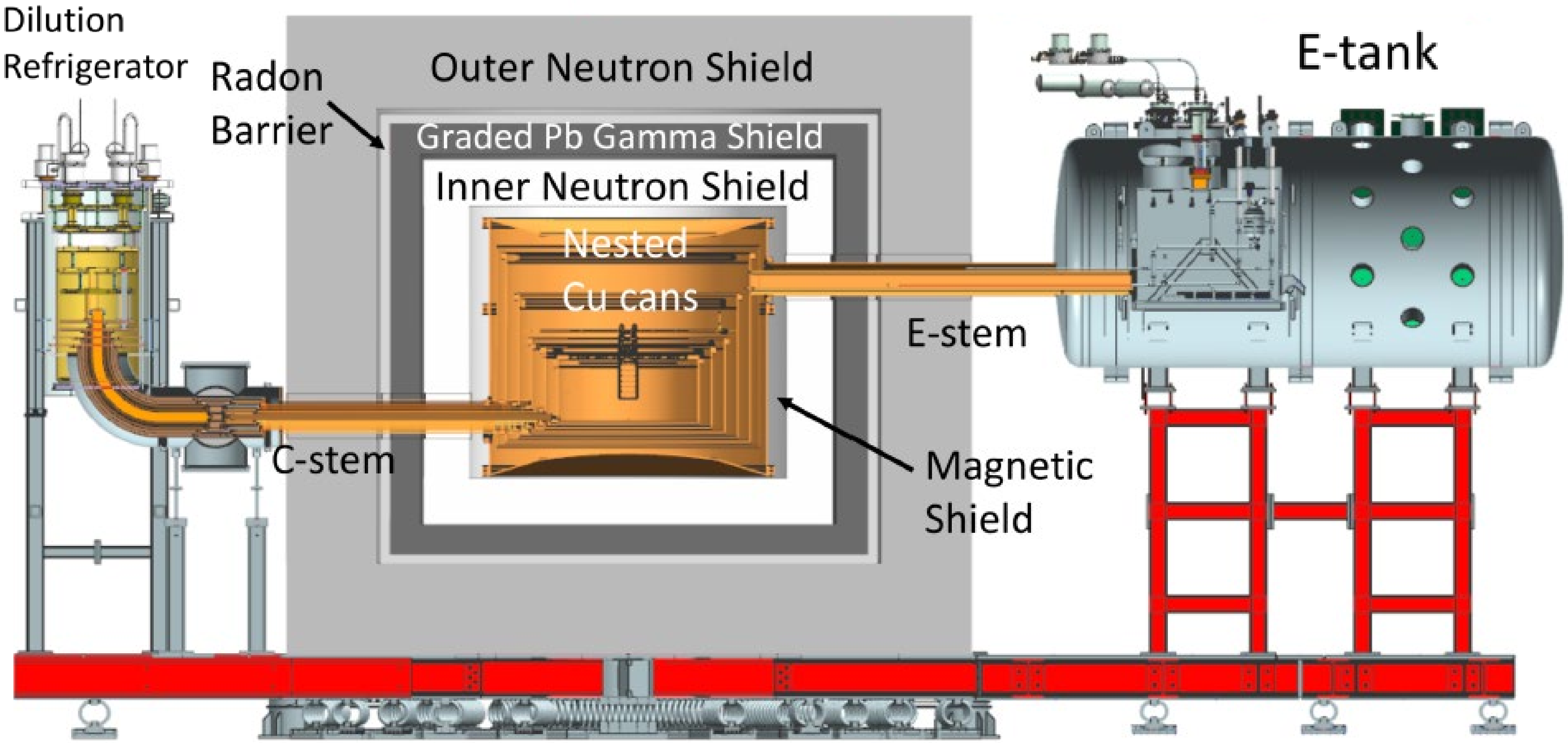
https://arxiv.org/abs/1804.10697

The Facility: SNOLAB Ladder Lab @ 6800 ft level and the SuperCDMS SNOLAB Experiment Layout

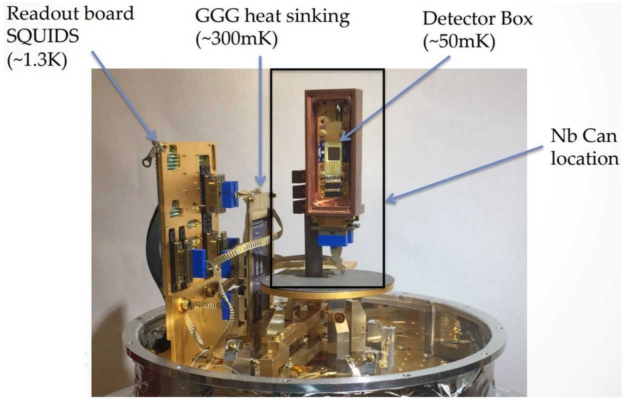


SuperCDMS SNOLAB
Underground Infrastructure

The Facility: Shielding, Fridge, and Electronics

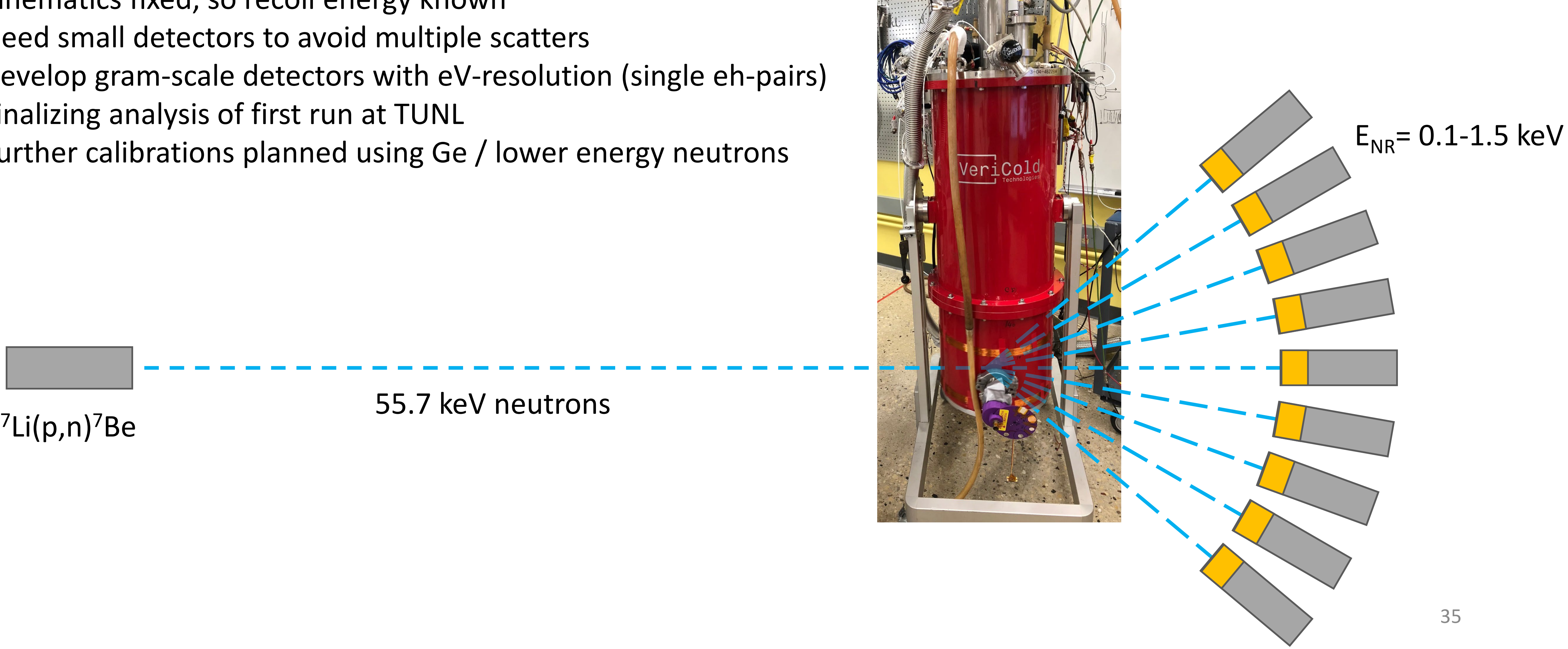


Nuclear Recoil Calibration at Low Energy

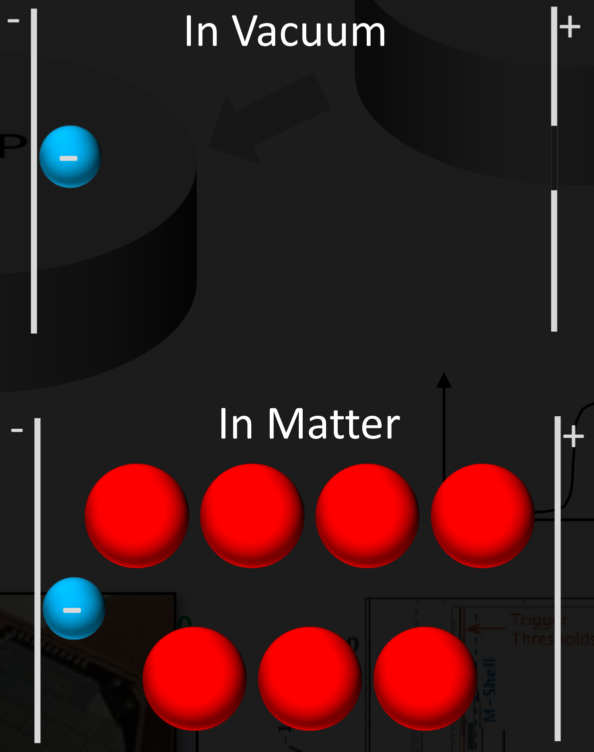


Energy scale calibration with radioactive sources → electron recoils
But need nuclear recoil energy scale, in particular: ionization efficiency

- Use pulsed low-energy neutron beam
- Measure recoils response together with scattered neutrons
- Kinematics fixed, so recoil energy known
- Need small detectors to avoid multiple scatters
- Develop gram-scale detectors with eV-resolution (single eh-pairs)
- Finalizing analysis of first run at TUNL
- Further calibrations planned using Ge / lower energy neutrons



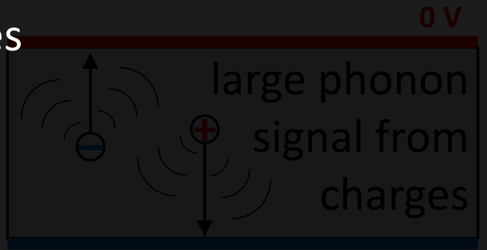
Neganov-Luke Effect



Electron gains kinetic energy
(E = q · V → 1 *e*V for 1 V potential)

Deposited energy in crystal lattice:
Neganov-Luke phonons

∝ V, # charges



- Luke phonons mix charge and phonon signal → reduced discrimination
- Apply high voltage → large final phonon signal, measures charge!!
- ER much more amplified than NR
  → gain in threshold; dilute background from ER

The SuperCDMS Collaboration

>130 scientists at 28 institutions & 6 Countries, including 3 US national labs and 2 Canadian labs

- California Inst. of Tech.
- C2N[*]
- FNAL
- KIT
- NISER
- NIST[*]
- Northeastern
- Northwestern
- PNNL
- Queen's University
- Santa Clara University
- SLAC
- South Dakota SM&T
- SMU
- SNOLAB
- Stanford University
- Texas A&M University
- TRIUMF
- U. A Madrid
- UC Berkeley
- U. Colorado Denver
- U. Florida
- U. Montréal
- U. British Columbia
- U. Minnesota
- U. South Dakota
- U. Toronto
- Zayed U

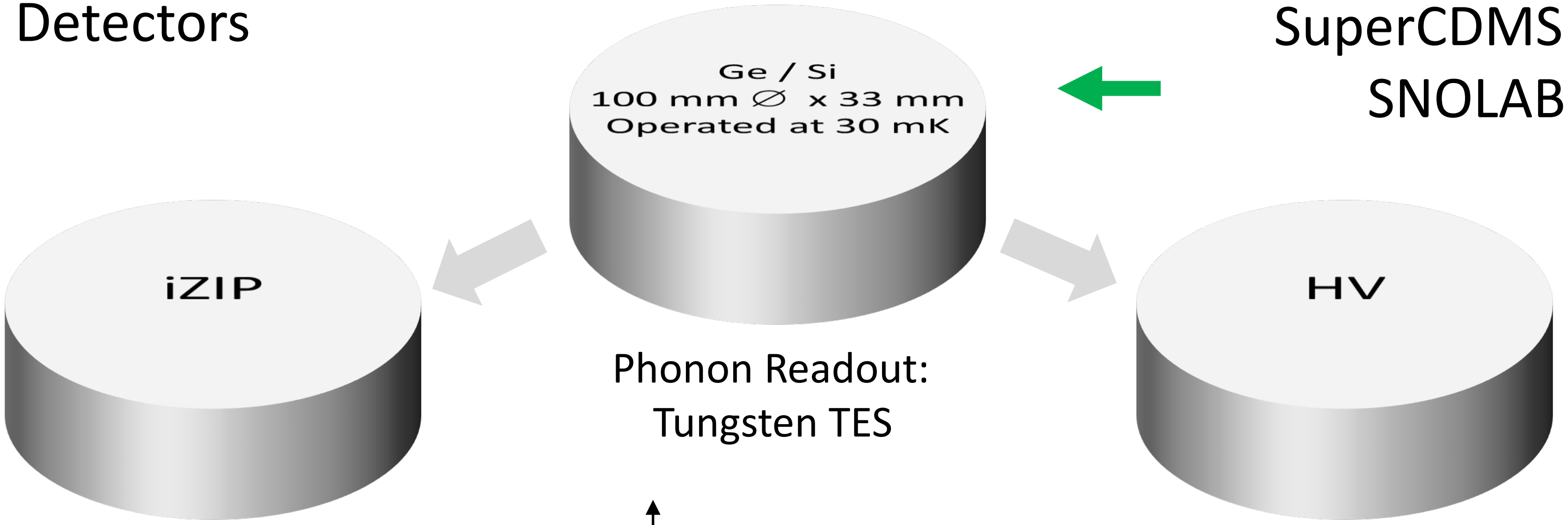
[*] Associate members

@SuperCDMS

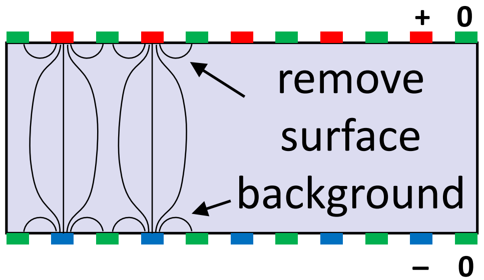
supercdms.slac.stanford.edu

Detectors

SuperCDMS
SNOLAB



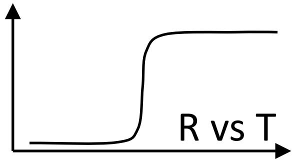
Add: charge readout (few V)
Background discrimination
Threshold < 1 keV

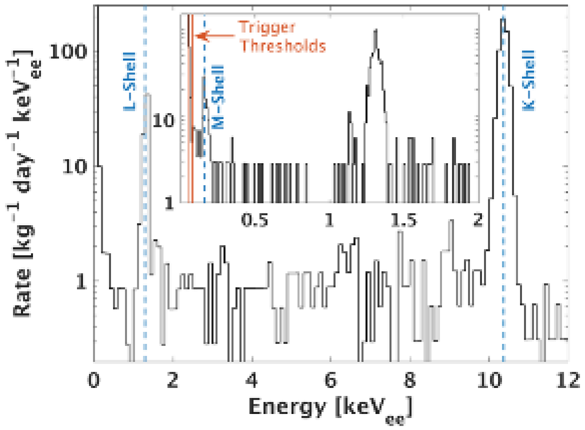


remove surface background

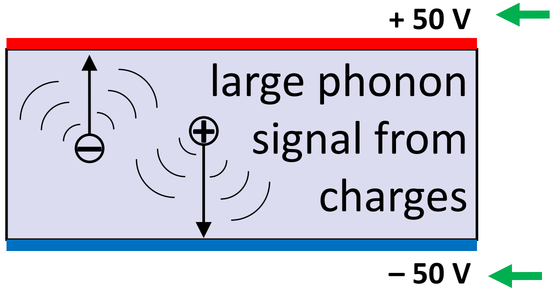
< 1 background event for
whole exposure

Phonon Readout:
Tungsten TES





Add: high voltage (~100 V)
Phonons from drifting charges
Threshold < 0.1 keV (phonon)



large phonon signal from charges

effective threshold: few
(or one) electron-hole pairs