University of South Dakota

The SuperCDMS Experiment Overview

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on behalf of SuperCDMS collaboration

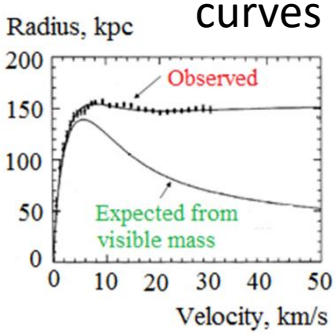
May, 2022

Outlook

- Dark matter
- SuperCDMS experiment
  - SuperCDMS in SNOLAB
  - Concept
  - Shielding
  - Detectors
  - Electronics and trigger
- Projected sensitivity
- Conclusions

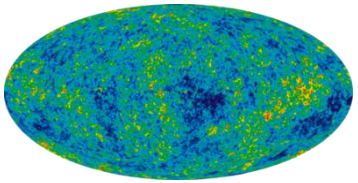
Composition of matter in the universe

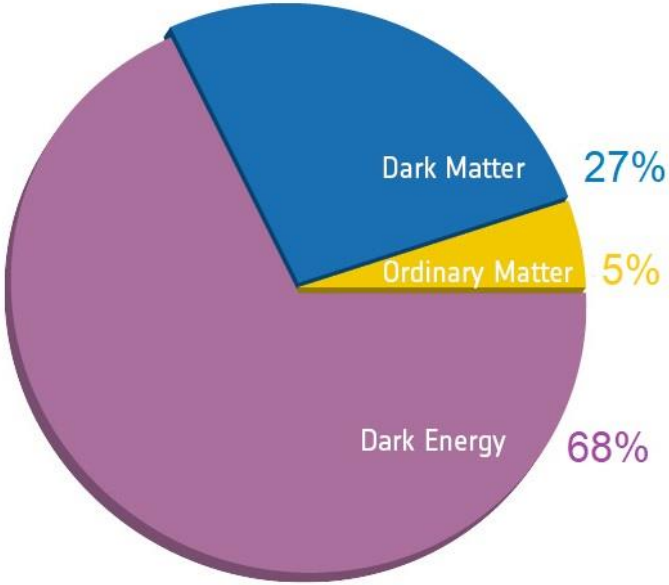
Galaxy rotation curves



Gravitational lensing

Anisotropy of CMB



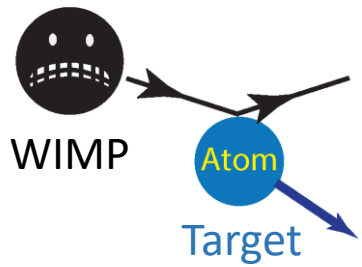


- From cosmological observations physicists believe that the universe comprises: 27% dark matter, only 5% atoms and 68% dark energy
- Around 95% of universe is not baryonic
- Dark matter has not been directly observed. The existence and properties of dark matter are inferred from its various gravitational effects such as:
  - motions of visible matter
  - gravitational lensing
  - cosmic microwave background

Image credit: ESA/Planck, planck.cf.ac.uk/results/

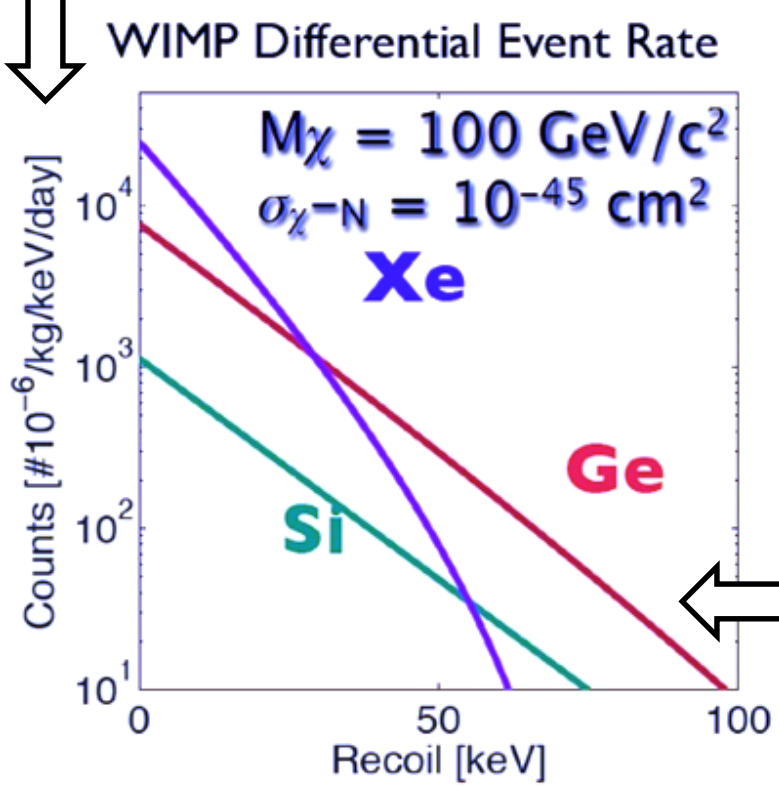
Weakly Interacting Massive Particles (WIMPs)

- May only interact through gravitational and weak forces
- Extremely difficult to detect
- WIMPs rarely induce nuclear recoils



Causes target nuclei recoil

Number of times a dark matter particle transfers a given amount of energy to a nucleus



- Galactically bound, v of order $10^{-3}c$
- Predicted by theory, but no confirmed experimental detection

increase ↑ Mass of the detector / Time of measurement ⇨ increase ↑ Probability of detection

Easier to detect but the event rate is lower

Super Cryogenic Dark Matter Search experiment

PAST — CDMS experiment evolution — PRESENT

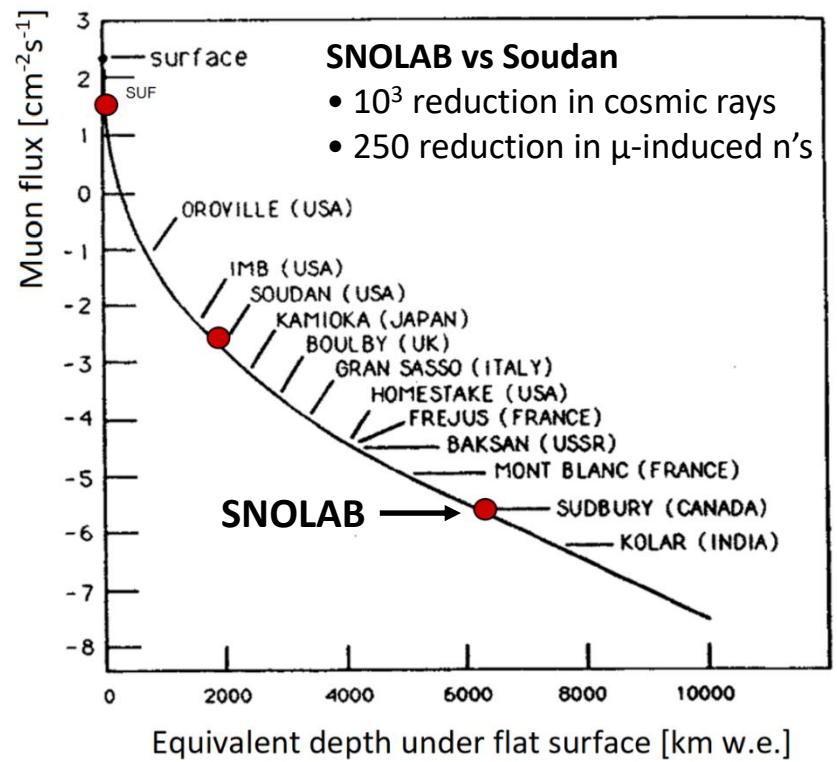
- **CDMS I**
at the Stanford Underground Facility:
first experiment to probe for supersymmetric WIMPs

- **CDMS II**
at the Soudan Underground Laboratory:
world leading limits on WIMPs for nearly a decade

- **SuperCDMS Soudan**:
New detector technologies (iZIP and CDMSlite) target low-mass dark matter

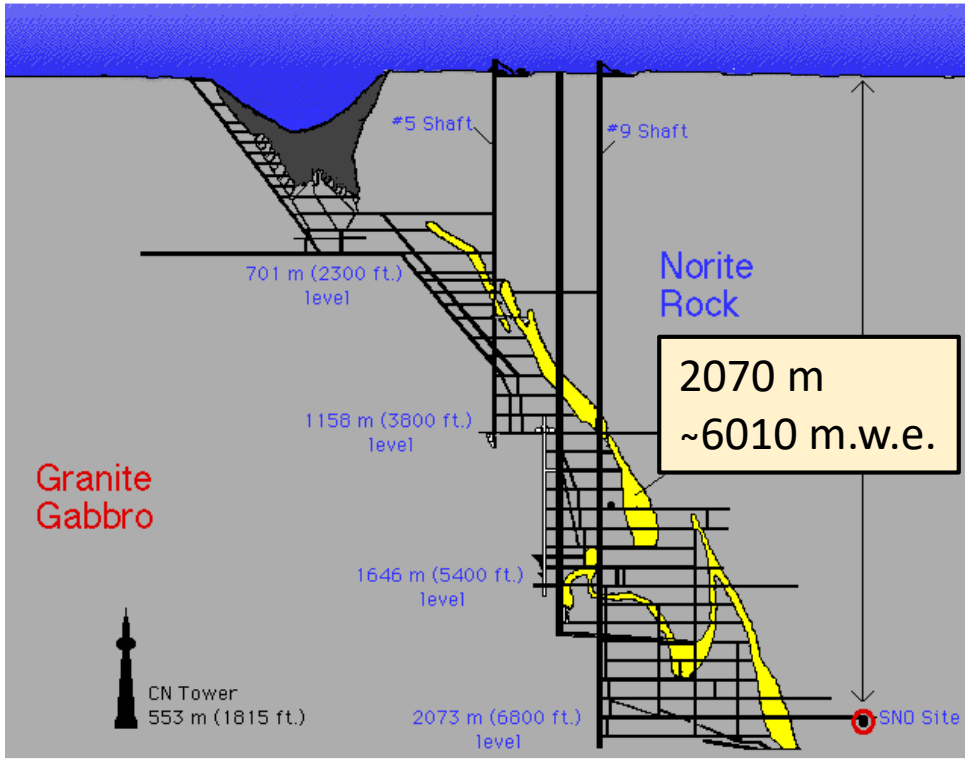
- **SuperCDMS SNOLAB**
continue the legacy, explore new parameter space and new interactions

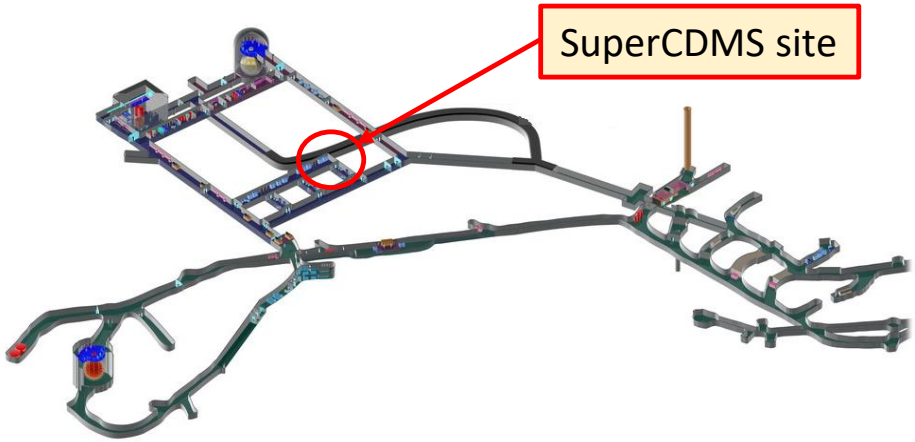
CDMS looks for scattering interactions of **low-mass** (< 10 GeV/c^2) dark matter particles with standard model particles



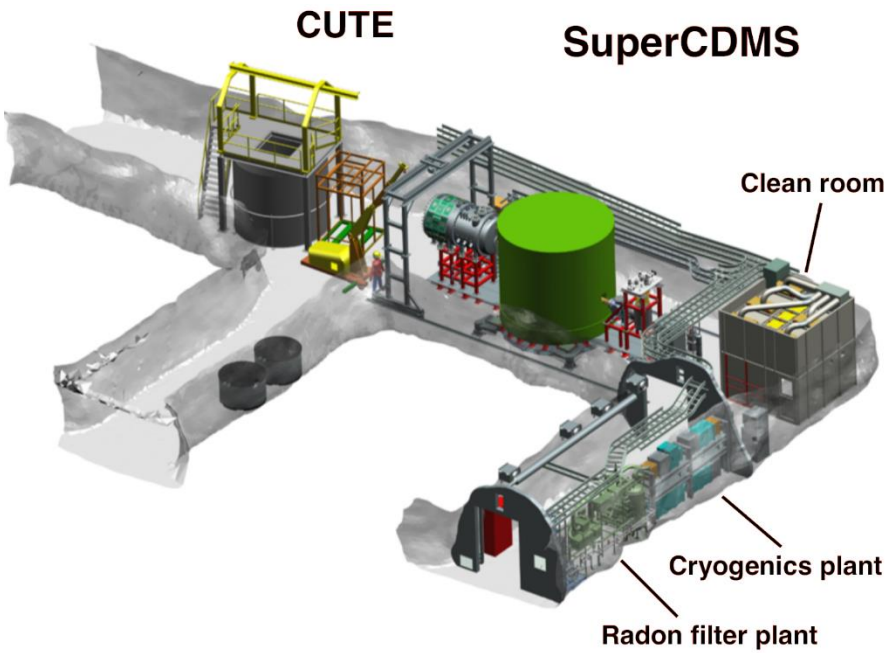
Super Cryogenic Dark Matter Search in SNOLAB

SNOLAB





SuperCDMS Utilities and Experiment



Ambient SNOLAB background:
0.27 muons $m^{-2}d^{-1}$
~4000 fast neutrons $m^{-2}d^{-1}$
4145±50 thermal neutrons $m^{-2}d^{-1}$
radon: 130 Bq/m^3

SuperCDMS experiment design

15 mK Dilution Refrigerator

Shielding

SNOBOX

E-stem

C-stem

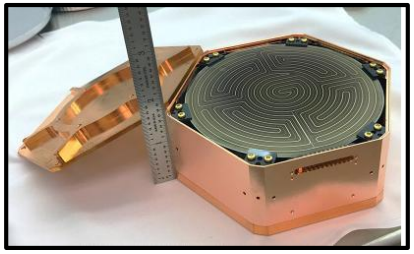
E-tank

Seismic platform

DCRC boards

Detector tower

Detector housing



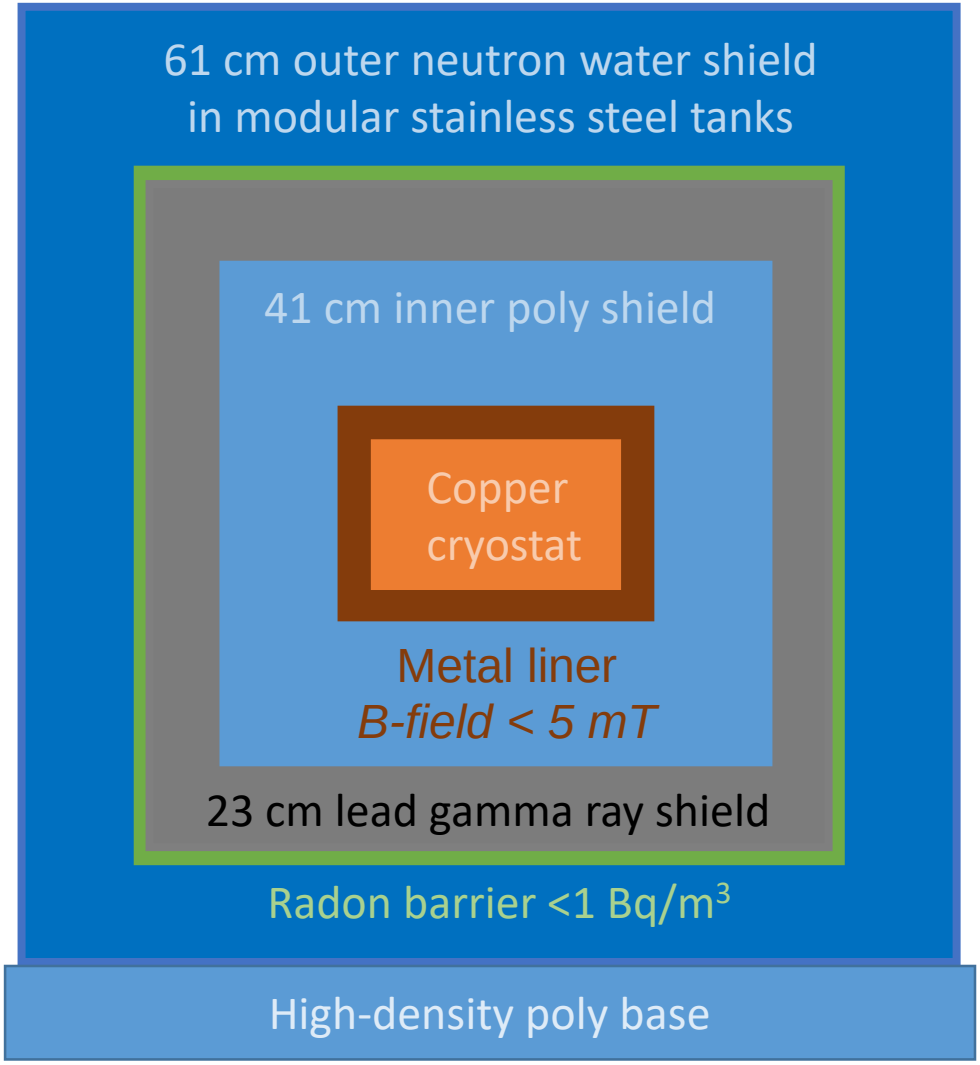
<u>C-Stem</u> (cold) is stem for heat conduction to a dilution refrigerator

<u>Shielding</u>:
- Cu cans
- Inner neutron shield
- Pb gamma shield
- Outer neutron shield

<u>E-tank</u> is the vacuum bulkhead where the detector readout boards (DCRCs) connect

<u>E-Stem</u> (electronic) carries signals out from the detectors

Low-background lead/poly shield



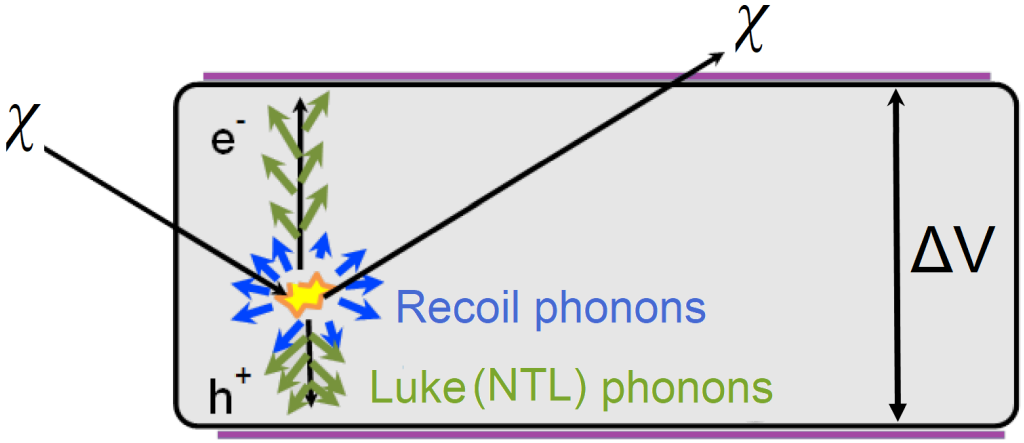
Inner 1 cm of Pb: 0.08 Bq/kg ^{210}Pb
< 0.4 mBq/kg U/Th/K

- Outer neutron shield
- Radon barrier
- Gamma ray shield
- Inner neutron shield
- Copper cans of cryostat system

Archaeological lead cast in assayed crucibles
All materials assayed by ICPMS and HPGe

Shield preassembled at the vendor's facility

SuperCDMS detectors

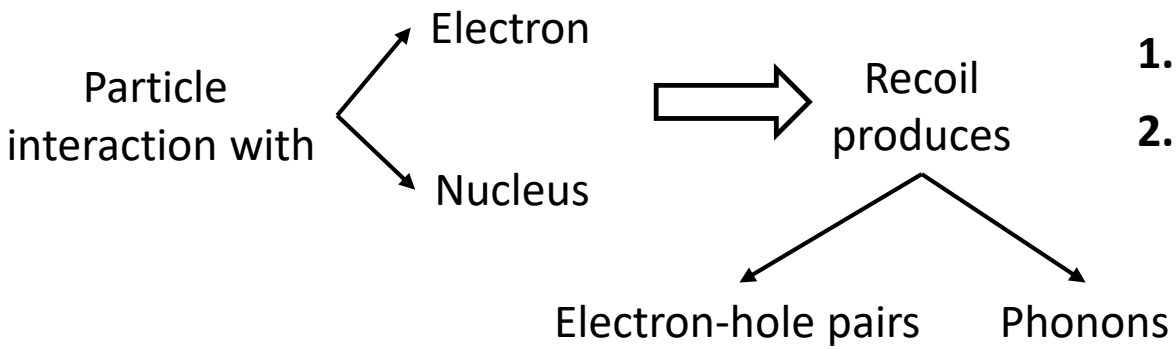


$$E_{tot} = E_r + \underbrace{e\Delta V N_{e^-/h^+}}$$

Total phonon energy — Recoil energy — Luke phonon energy

1. Low *ΔV*: Recoil phonons dominate

2. High *ΔV*: NTL phonons dominate



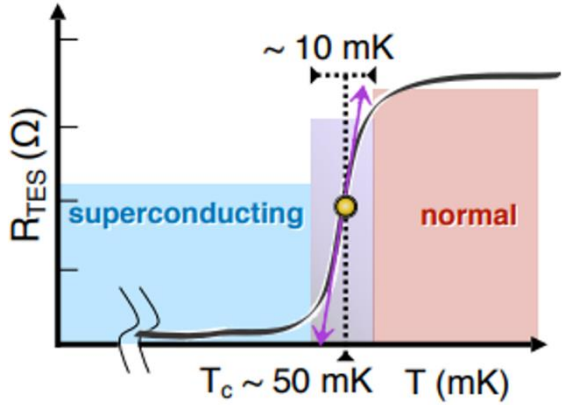
Emission of primary **Recoil** phonons:

- Majority of recoil energy not invested to electron-hole pairs production and released as phonons
- Produced electron-hole pairs relax to the bandgap releasing energy as phonons
- When the charge carriers (electron or hole) find a partner with which to recombine, they release energy as phonons

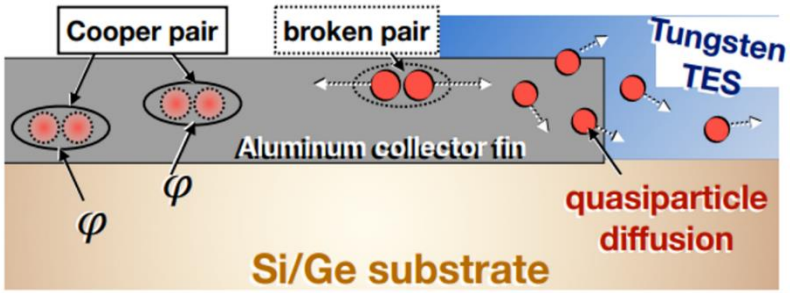
Drifting charge carriers (e^-/h^+) across a potential *ΔV* generate a large number of **Luke** phonons (NTL effect)

SuperCDMS detectors, sensors

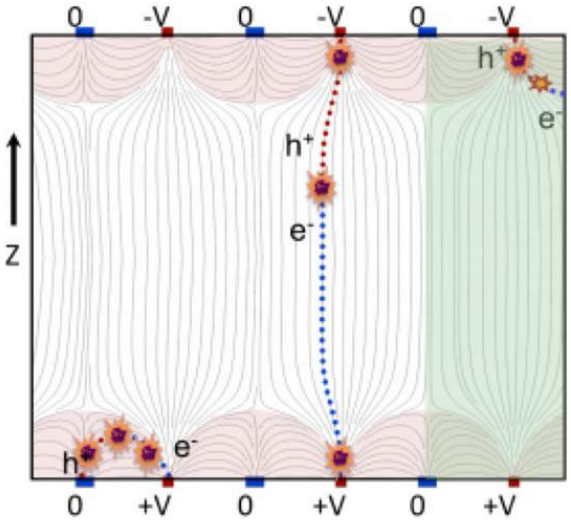
Phonons, measured via Quasi-particle trap and Electrothermal feedback Transition Edge Sensors (QETs)

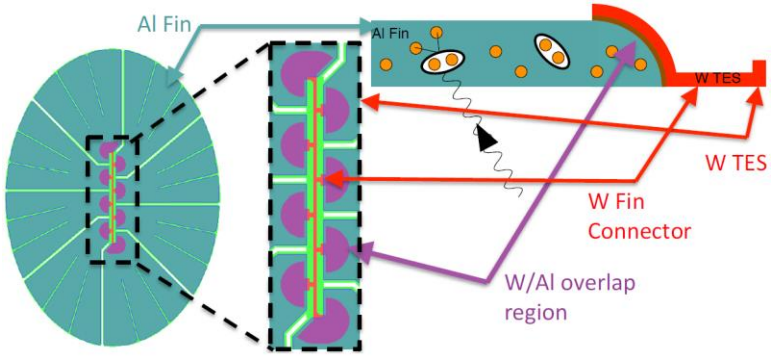


- Phonons break Cooper pairs in the aluminum fins
- Generating quasi-particles which diffuse into tungsten TES
- Temperature of a tungsten TES increases on a µsec timescale
- In the superconducting phase transition, quasi-particle diffusing from the aluminum deposit energy to the tungsten
- Then, the TES resistance sharply increases when heated



Charge, measured via interleaved electrodes

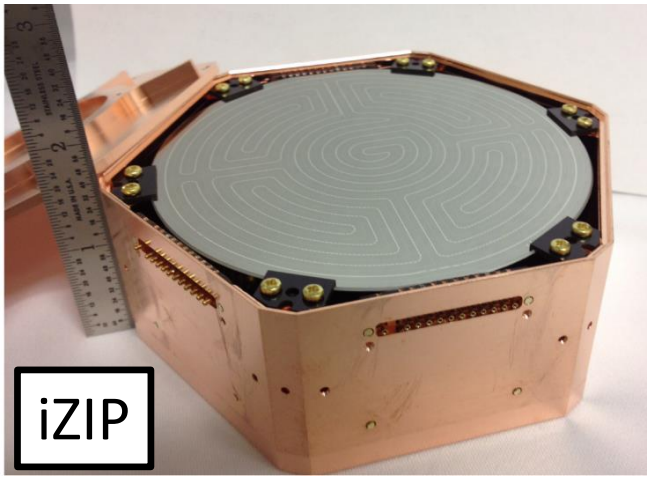




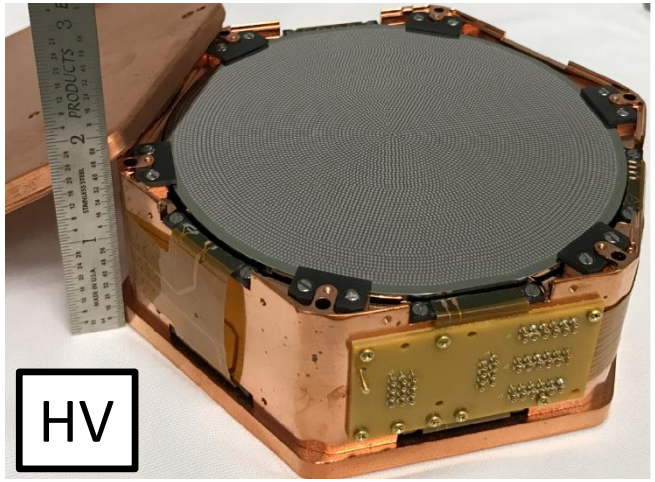
Phonon sensor design

SuperCDMS detectors

12 phonon, 4 charge channels
sensitive to ≥5GeV/c^2 DM
Ge(Si) σ_{ph}=50(25) eV σ_{ch}= 160(180) eV



12 phonon channels
sensitive to sub-GeV DM
Ge(Si) σ_{ph}=10(5) eV



Interleaved Z-sensitive Ionization and Phonon (iZIP) detector:

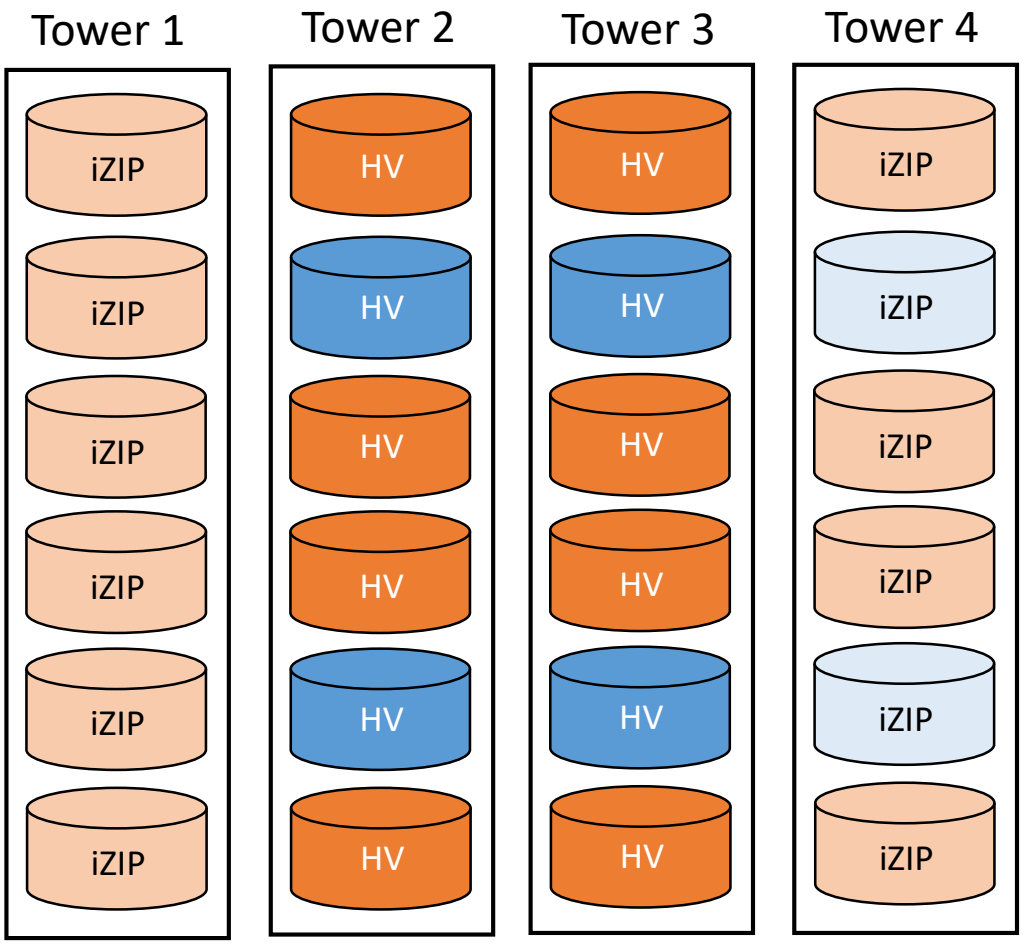
- Low bias voltage ~4 V
- Luke (NTL) phonons negligible
- Prompt phonon and ionization signals
- Allow discrimination between electron (ER) and nuclear recoil (NR) events and surface rejection
- Ge(Si) threshold$_{ph}$=350(175) eV, threshold$_{ch}$~1 keV
- **Low background**

High voltage (HV) detector:

- High bias voltage ~100 V
- NTL phonons dominate
- No ER/NR discrimination
- Ge(Si) threshold$_{ph}$=70(35) eV
- **Low threshold**

Position sensitive, Ø100 mm, h=33.3 mm
mass: Ge(Si)=1.39kg(0.61 kg)

Planned detector layout at SNOLAB



Tower

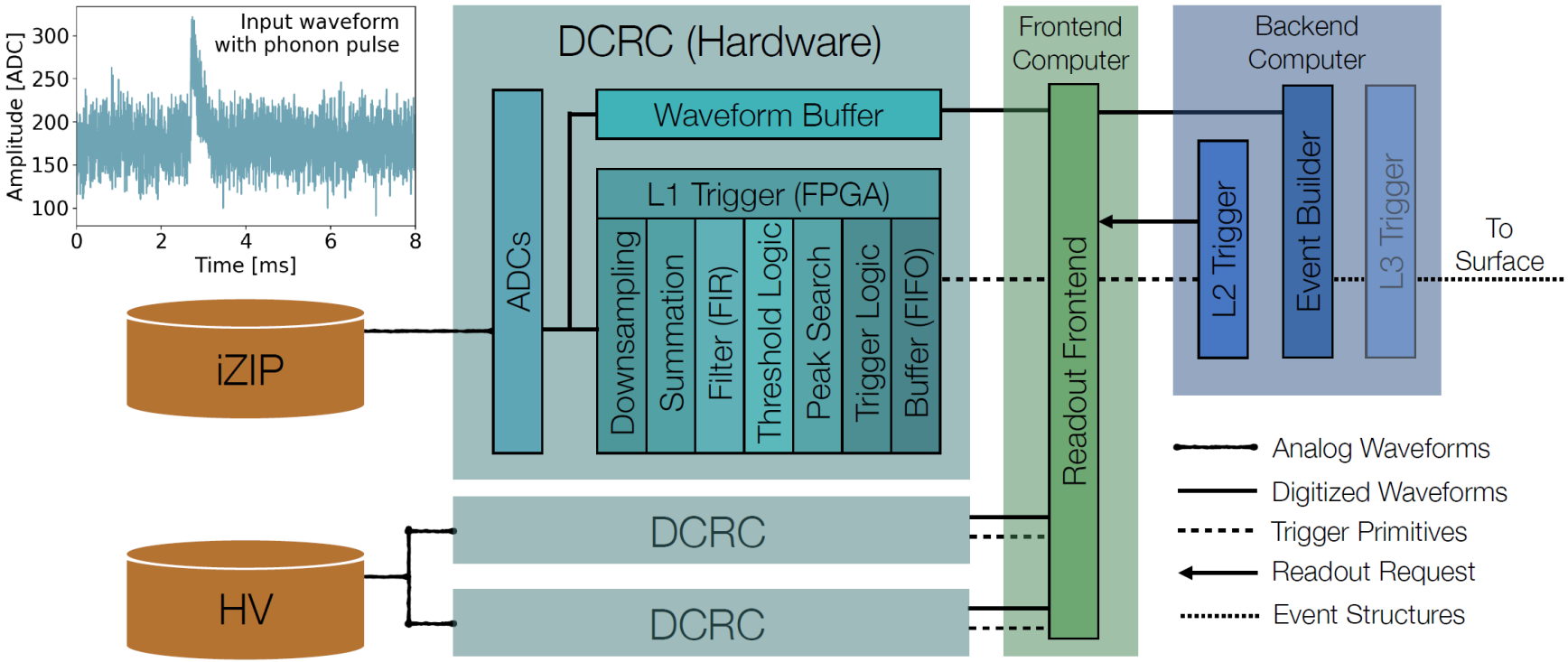
24 detectors
both Ge and Si
12 – iZIP, 12 – HV

Total mass ~30 kg

Technical goal T<30 mK

	Germanium	Silicon
HV	Low threshold for low mass DM, larger exposure, no ^{32}Si background	Lowest threshold for low mass DM, sensitive for lowest DM masses
iZIP	Nuclear recoil discrimination, understand Ge background	Nuclear recoil discrimination, understand Si background

SuperCDMS SNOLAB electronics and trigger



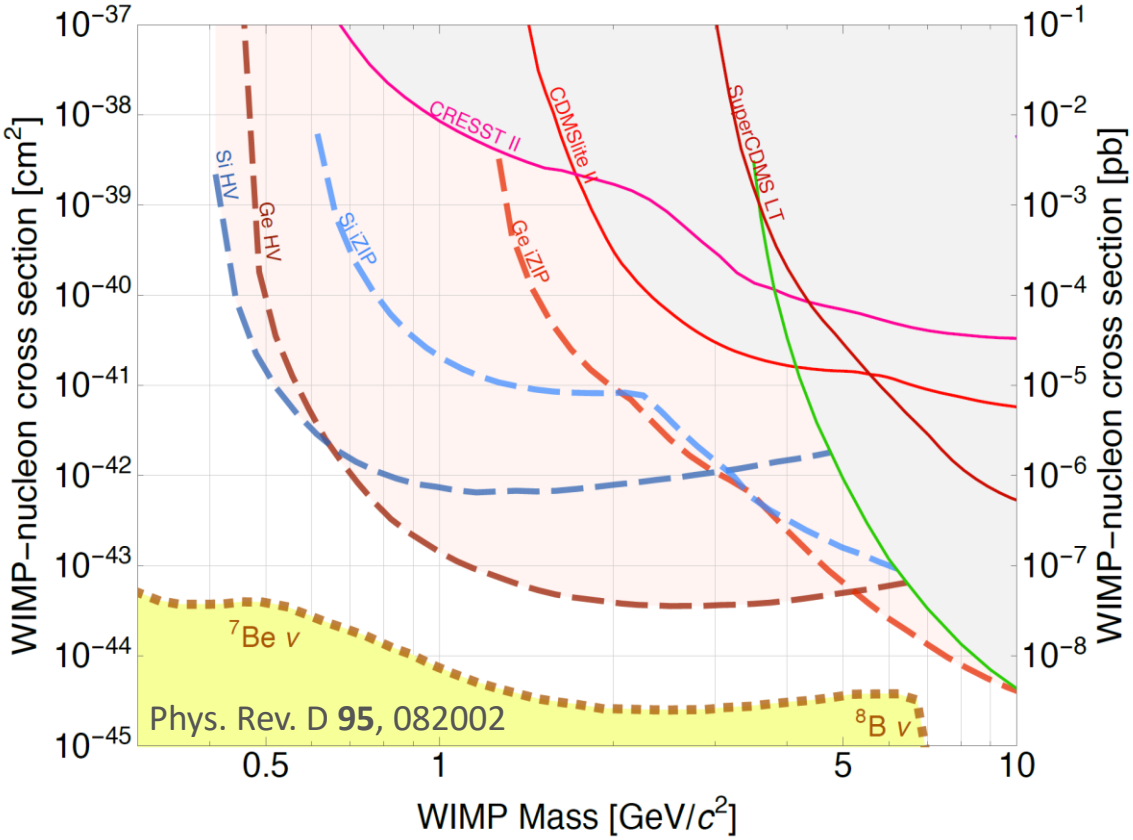
DCRC – Detector Control and Readout Card

DCRC operations: setting detector biasing and feedback parameters, performance of analog to digital conversion of detector signals, operation with LEDs for detector, neutralization and thermometers

MIDAS – Maximum Integrated Data Acquisition System

MIDAS a general purpose data acquisition system for small and medium scale experiments

SuperCDMS projected WIMP sensitivity



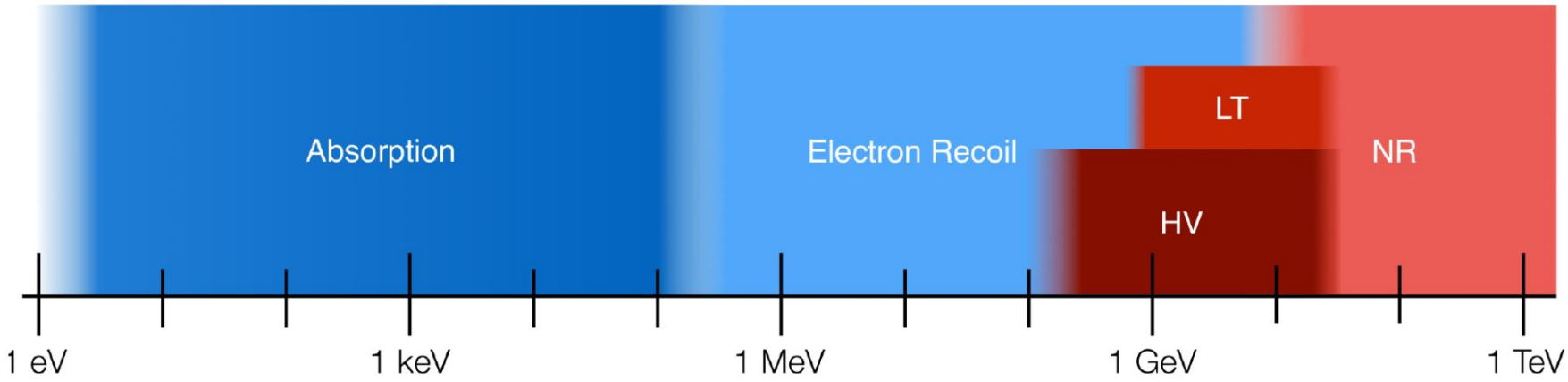
HV detectors can reach these limits with 2 years of exposure

iZIP detectors that allow ER/NR discrimination will provide information about the origin of background sources

- These sensitivity limits are determined using the optimum interval method which does not incorporate any specific knowledge of background sources
- A more sophisticated analysis that takes into account known sources of background, and uses data taken over the full 5-year timescale, would improve the sensitivity estimates

SuperCDMS: A broadband DM search

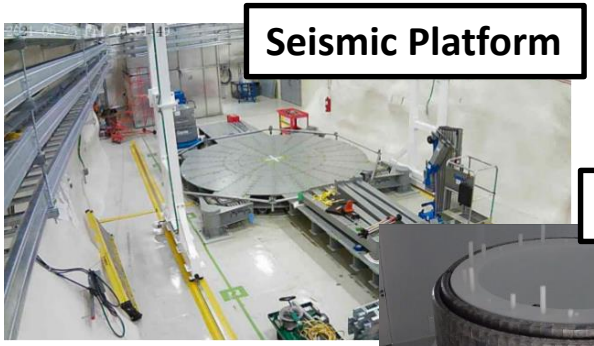
Traditional Nuclear Recoil	iZIP, Background free	>5 GeV
Low Threshold Nuclear Recoil	iZIP, limited discrimination	>1 GeV
HV mode	HV, no discrimination	0.3 - 10 GeV
Electron recoil	HV, no discrimination	0.5 MeV - 10 GeV
Absorption (Dark Photons, ALPs)	HV, no discrimination	1 eV - 500 keV

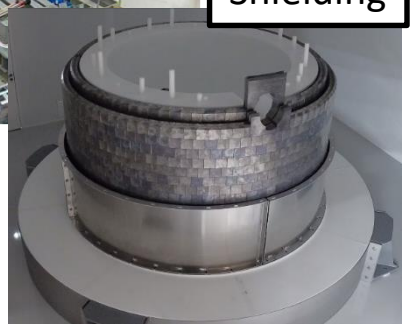


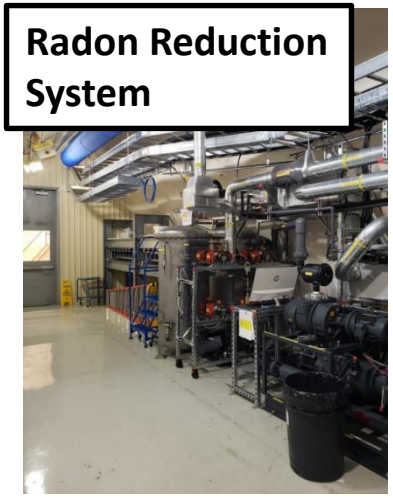
SuperCDMS installation in progress

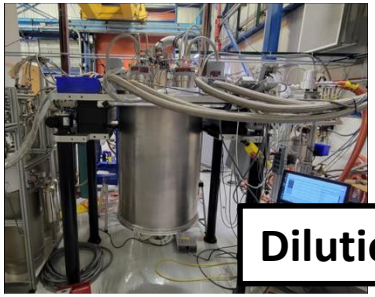
Component deliveries to SNOLAB by the construction project

Plan	Status
Seismic Platform	Installed
3T Gantry Crane	Installed
Radon Reduction System	Installed
Cleanroom	Installed
DAQ	Installed
Computing	Offsite, data transferred to SLAC and others
Calibration	Preparing to ship
Readout Electronics	Complete
Dilution Refrigerator	Received from vendor
Shielding	Received from vendor
Detector Towers	Scheduling The Work
SNOBOX	In Development









Plan is to start commissioning run in 2023!

SUPER CDMS

Cryogenic Dark Matter Search

~130 scientists at 27 institutions including 3 US national labs and 2 Canadian labs

SCDMS online Collaboration Meeting, August 2021

Conclusions

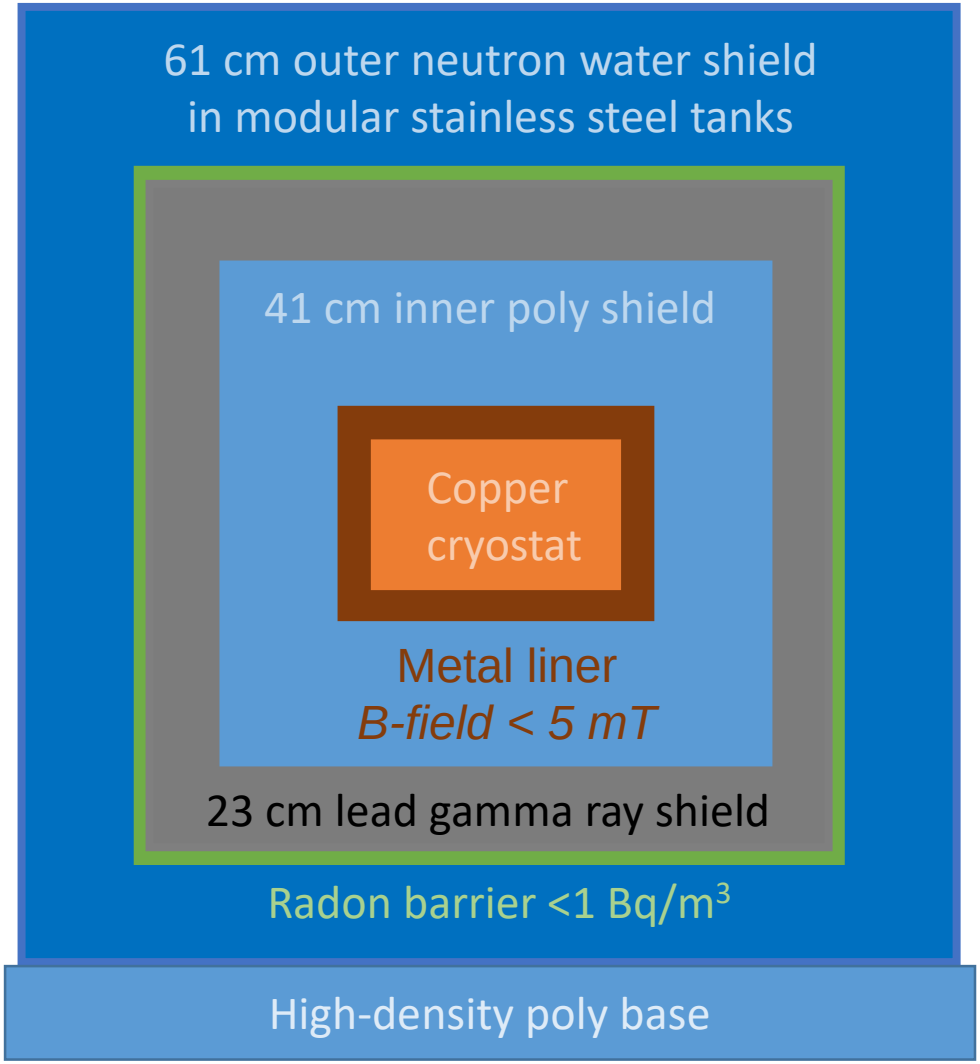
- Detector fabrication, readout electronics, cryogenic and calibration systems are complete
- Testing and characterization are happening at test facilities
- SuperCDMS SNOLAB commissioning starts in 2023
- First underground detector testing with opportunities for early science in 2024
- First science run with full detector payload early 2024. First result in early 2025
- Broadband sensitivity to new dark matter candidates

Backup

Low-background lead/poly shield

Outer neutron shield

- Reduce MeV neutrons from cavern wall by ~10^6, ~20 for μ-induced neutrons (GeV)



Gamma ray shield

- Reduces MeV gammas from cavern wall by ~10^5
- Inner layer is 1 cm ancient lead, ^{210}Pb < 1 Bq/kg
- Reduce Bremsstrahlung ^{210}Bi in shield by factor of ~20

Radon barrier

- Aluminum sheet banded around the lead shield with taped joints
- Reduce ~100 Bq/m^3 to < 0.1 Bq/m^3 (mine air)

Inner neutron shield

- Stacked 2'' thick poly sheets
- Reduces neutron rate by >10 μ-induced neutron from rock
- Neutron from lead
- Absorbs Backscatter from SNOBOX vacuum cans
- No neutron "reflection" from lead

Copper Cans of Cryostat System

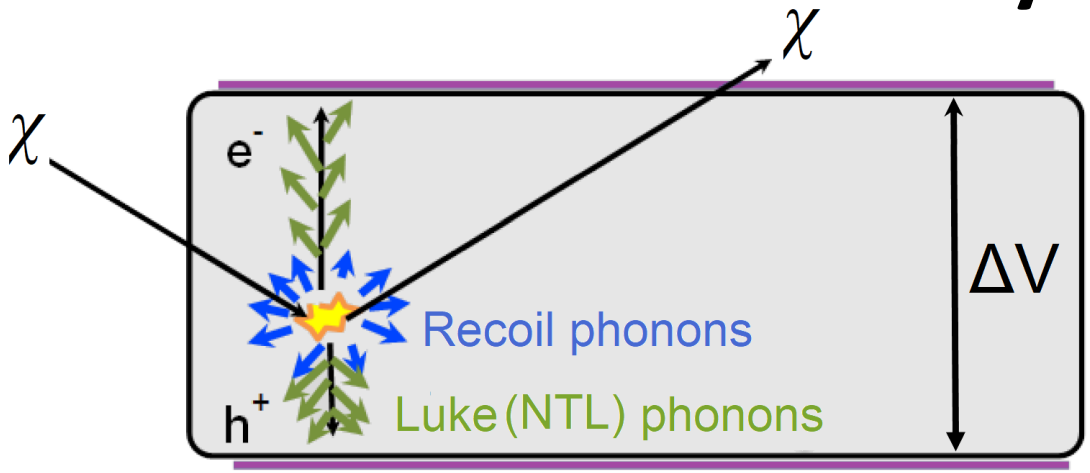
- 6.7 cm of copper in nested cans (SNOBOX)
- Copper is radiopure compared to lead
- Final gamma shield
- Reduce residual gammas by x 25
- Reduces Brem from ^{210}Bi β-decay by x 20

SNOLAB backgrounds

- Dominant background: in-crystal ^{3}H, ^{32}Si, ^{68}Ge
- Line-of-sight contamination from ^{210}Pb
- Material and cavern contamination: ^{40}K, ^{60}Co

"Singles" Background Rates (counts/kg/keV/year)	Electron Recoil				Nuclear Recoil ($\times 10^{-6}$)	
	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	0.01	0.07	–	–
Bulk Material Contamination	5.4	14.	12.	88.	440.	660.
Cavern Environment	–	–	–	–	510.	530.
Cosmogenic Neutrons					73.	77.
Total	27.	300.	22.	370.	3300.	2900.

SuperCDMS detectors are very sensitive



ΔV is bias voltage

The energy contribution from NTL phonons $E_{NTL} = e\Delta V N_{eh}$

The total energy generated by recoiling particle $E_{tot} = E_r + E_{NTL}$

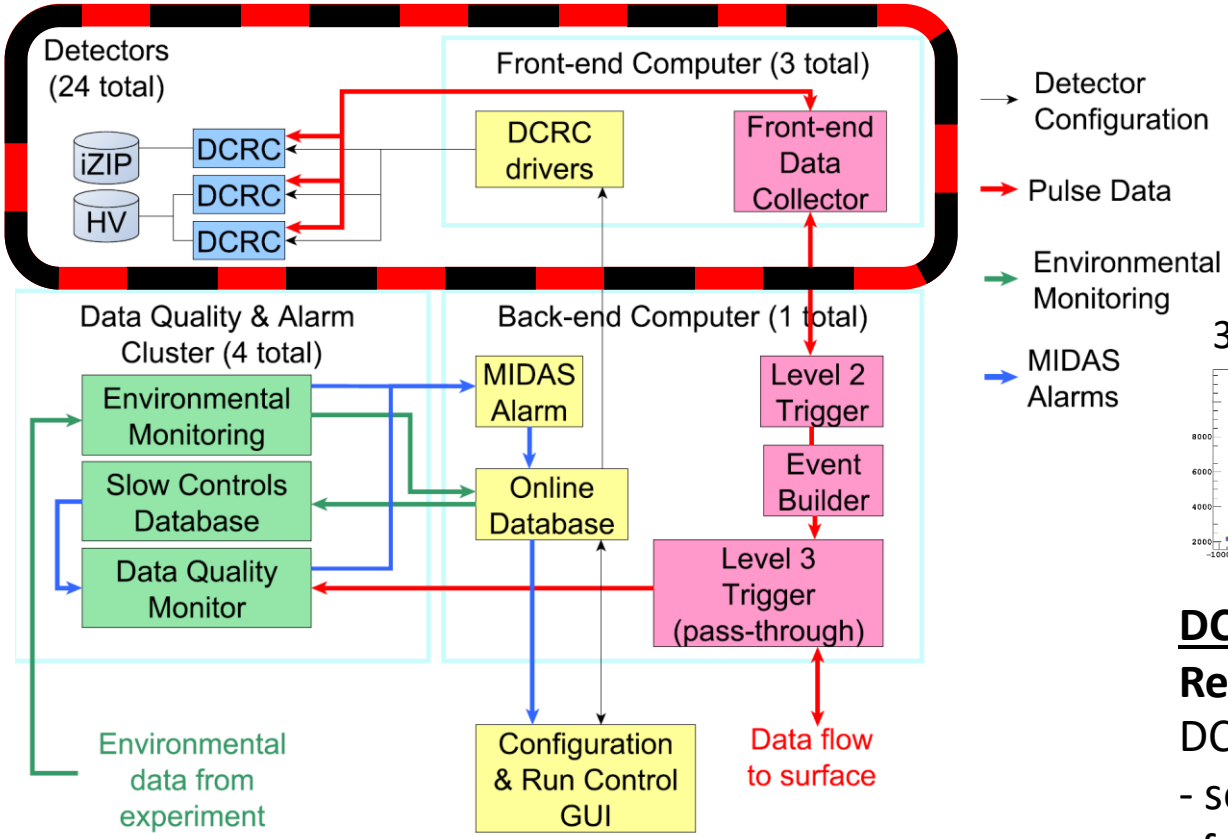
ε is the average energy required to produce 1eh pair for an electron recoil (in Ge 3eV, in Si 3.8 eV) $N_{eh} = \frac{E_r}{\varepsilon}$

$$E_{tot} = E_r + e\Delta V N_{eh} = E_r\left(1 + Y(E_r)\frac{e\Delta V}{\varepsilon}\right)$$

1. Low bias voltage: NTL phonons negligible
2. High bias voltage: NTL phonons dominant

SuperCDMS SNOLAB electronics and trigger

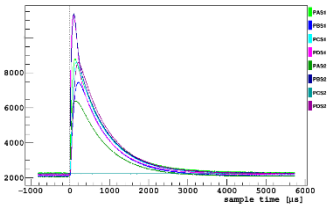
<u>MIDAS</u> Maximum Integrated Data Acquisition
flexible C++ based DAQ system



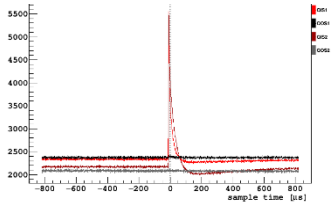
3 levels of <u>triggering</u>:
Level 1 – hardware trigger
Level 2, 3 – software triggers

Sampling frequencies:
Ionization: 2.5 MHz
Phonon: 625 kHz

3000 µs phonon



100 µs Ionization



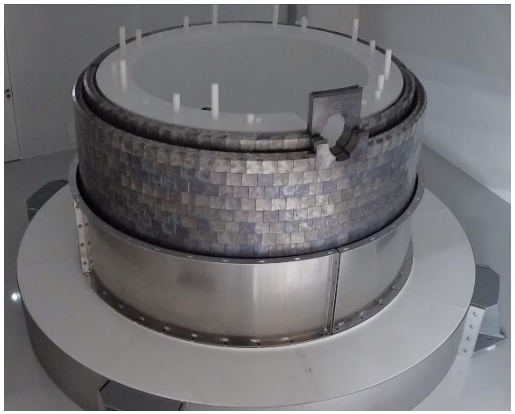
<u>DCRC</u> Detector Control and Readout Cards
DCRC operations:
- setting detector biasing and feedback parameters
- performance of analog to digital conversion of detector signals
- operation with LEDs for detector neutralization and thermometers

MIDAS organized around Online Database (ODB), Includes standard DAQ, event builder, run scheduler and "watchdog" system to detect and recover hung client processes. Supports ROOT, allows real-time analysis

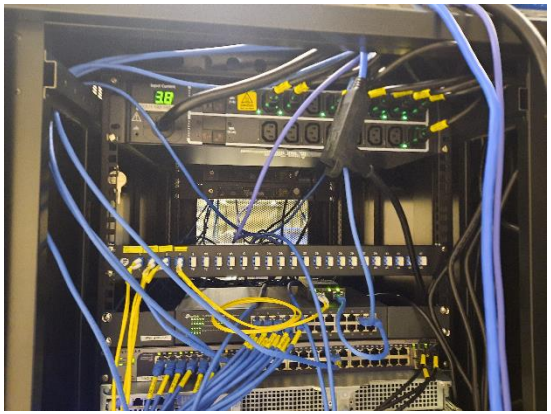
SuperCDMS installation in progress

Seismic platform

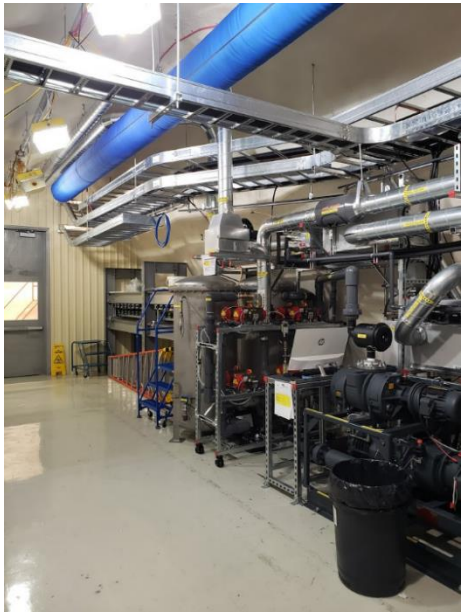
Inner lead and polyethylene shield



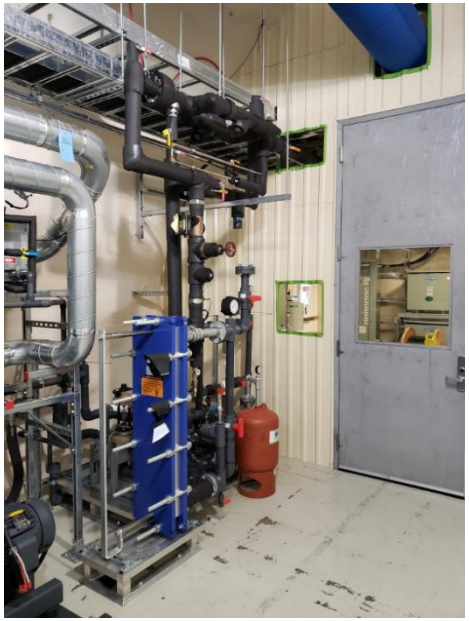
Hardware



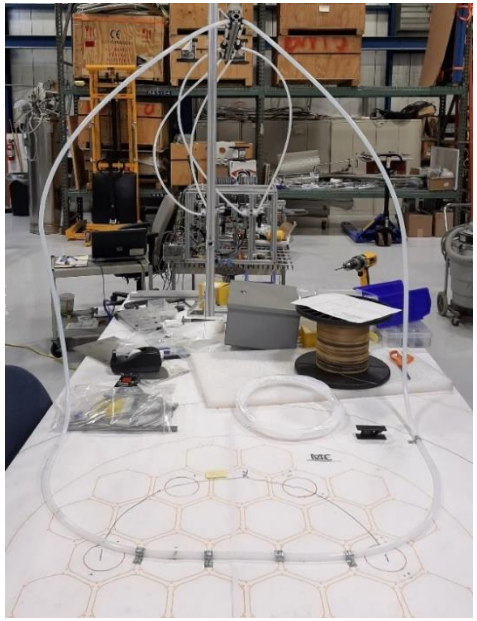
Radon filter system



Chilled waterloop



Calibration system



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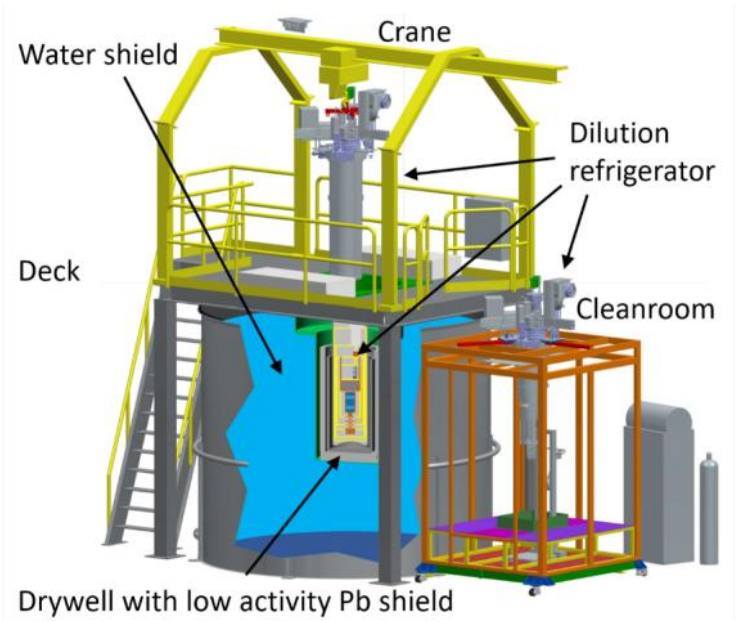
SuperCDMS test facilities

CUTE, Cryogenic **U**nderground **TE**st facility at SNOLAB



Purpose of this facility is to provide an opportunity to test detector properties that cannot be tested above ground or in an unshielded facility, due to the impact of the high background rate

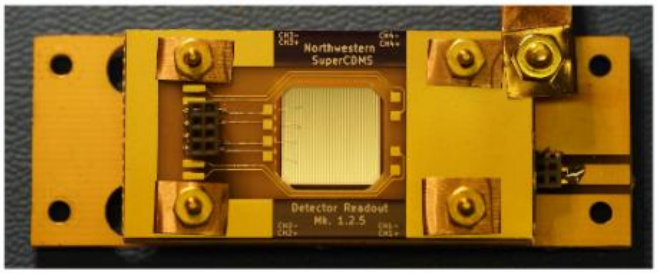
- Capacity of testing 1 SuperCDMS detector tower
- Base temperature ~12 mK (with detectors installed)
- Background *few events/(keV kg d) below few keV* ~6 events/(keV·kg·day)
- Running prototypes of HV SNOLAB detectors to study performance
- Possibility of early science result

Towers 1 and 2 arrive this June
Towers 3 and 4 arrive this September

SuperCDMS test facilities

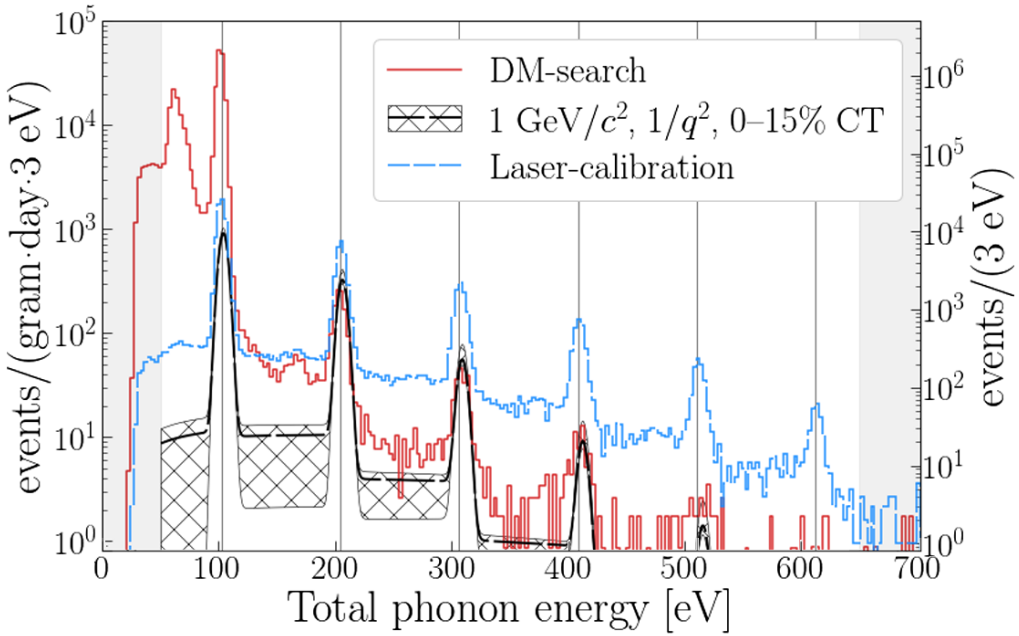
NEXUS, Northwestern **EX**perimental **U**nderground **S**ite at Fermilab

HVeV high voltage eV resolution detectors



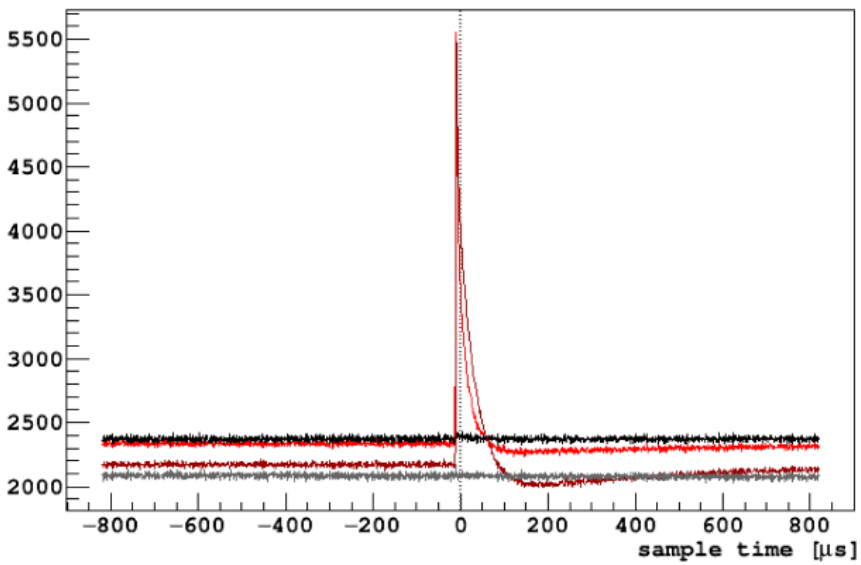
- Gram scale detectors
- Resolution: single electron-hole pair
- Ideal for studying charge transport in Si and Ge
- Sensitivity to a variety of sub-GeV DM models with gram·day exposures

D.W. Amaral et al, Phys. Rev. D 102, 091101 (2020)

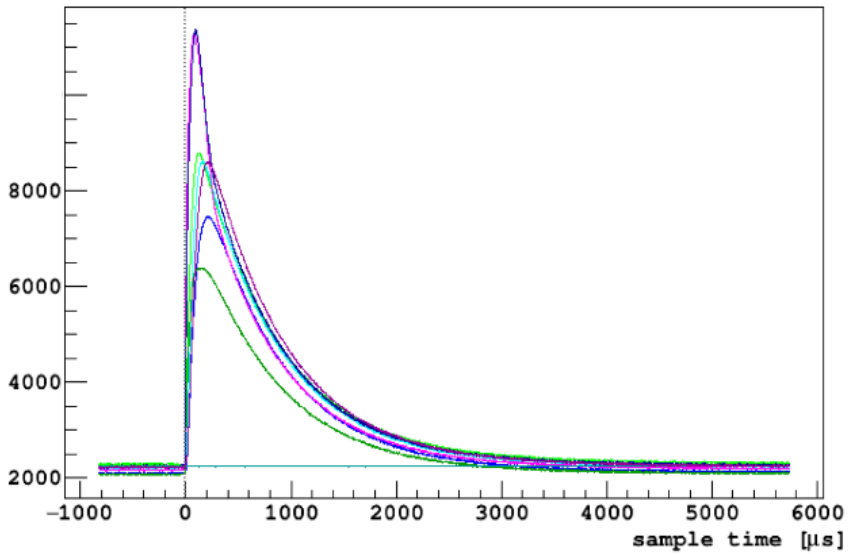


SuperCDMS, waveforms

100 µs Ionization signal



3000 µs phonon signal



Sampling frequencies:
Ionization: 2.5 MHz
Phonon: 625 kHz