SuperCMDS experiment at SNOLAB

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SuperCDMS Collaboration

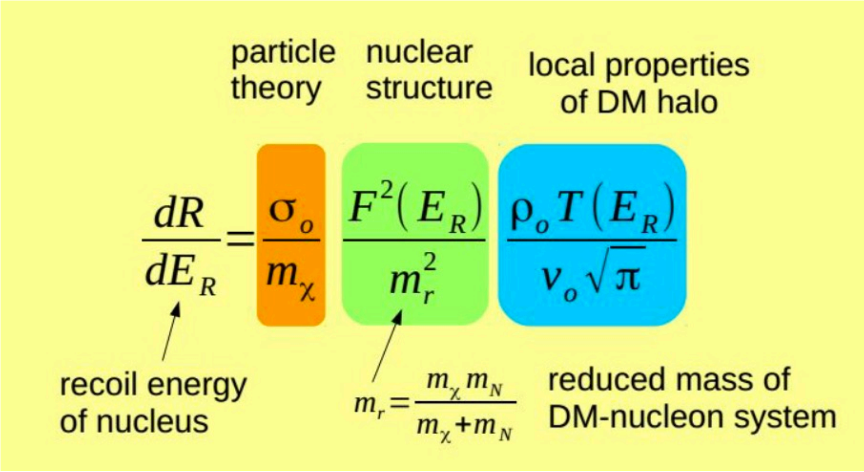
Overview

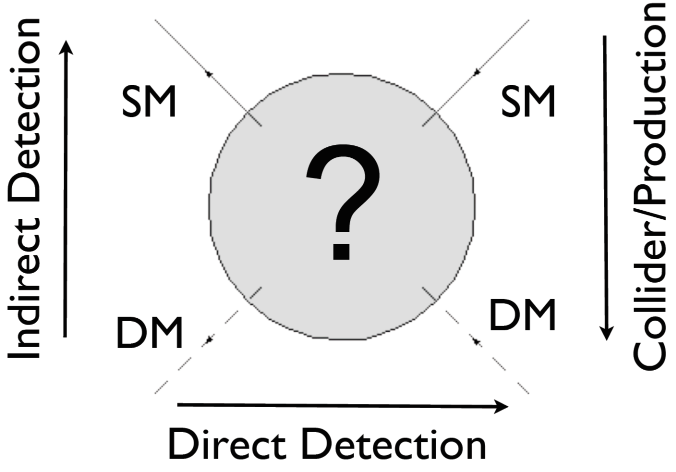
- Direct detection of dark matter
- SNOLAB facilities
- SuperCDMS detectors
- Projected sensitivity
- Searches for LIPs

Direct detection of dark matter

What we know about dark matter:

- Density ~ 0.3 GeV/cm^3
- Interaction through gravity.
- Moving ‘slowly’ (<600 km/s), non-relativistic.
  low energy transfer (~100 keV down to eV or less)





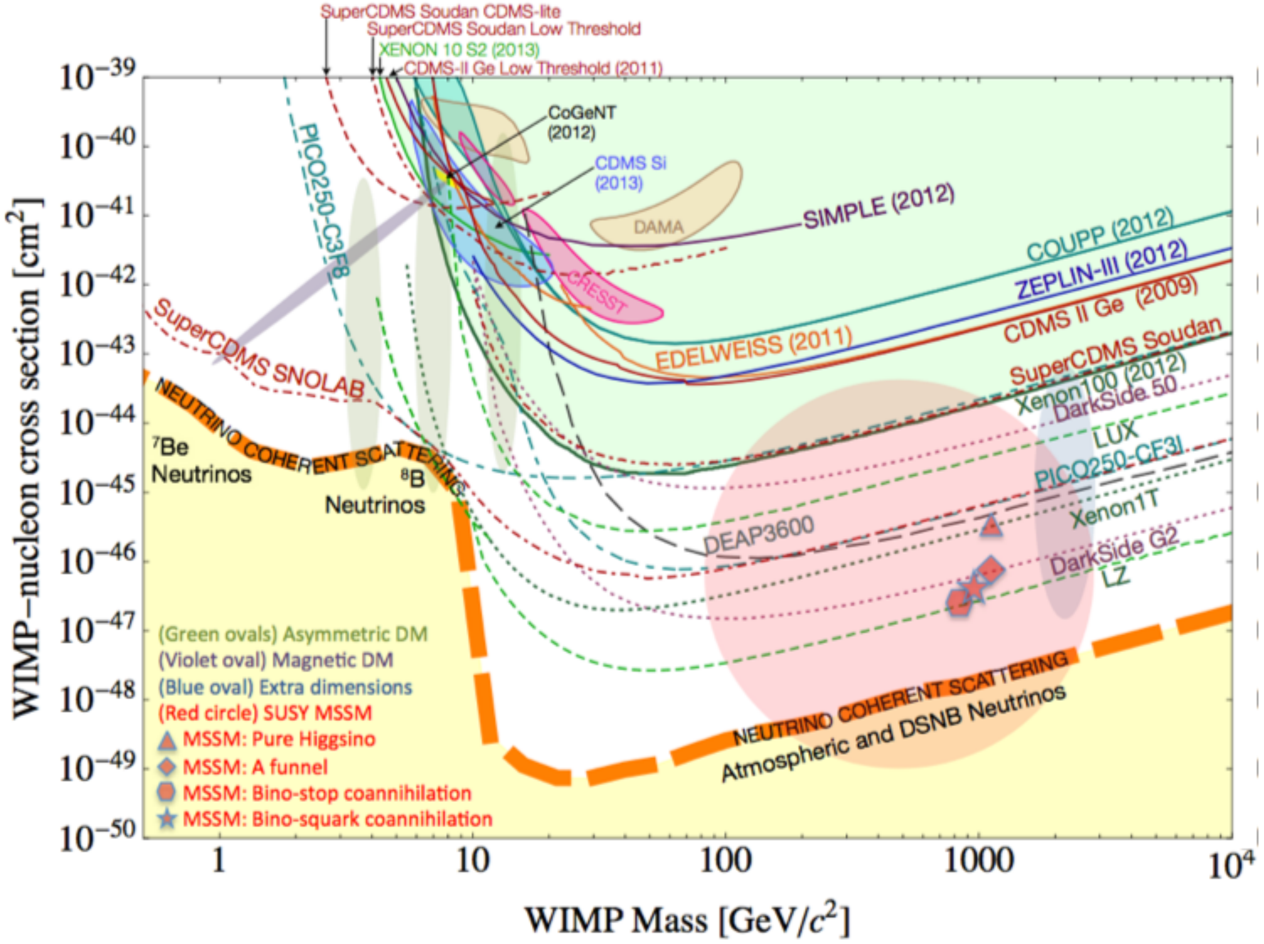
Motivation for low-mass dark matter search

Dark matter models:

- WIMPs, axions and ALPs, dark photons, sterile neutrinos…

WIMPs being the main focus of direct DM searches.

- Favored masses in the 10 GeV to 10 TeV range
- No evidence for supersymmetry shown from the LHC experiments



Searches for low-mass DM particles are important!

Goals and challenges of SuperCDMS SNOLAB

Super Cryogenic Dark Matter Search following SuperCDMS Soudan

- Improve the sensitivity for DM particles with masses $\leq$10 GeV
- Other searches for new physics: lightly ionizing paritcles (LIPs), axions, coherent neutrino scattering (CNS) of solar neutrinos

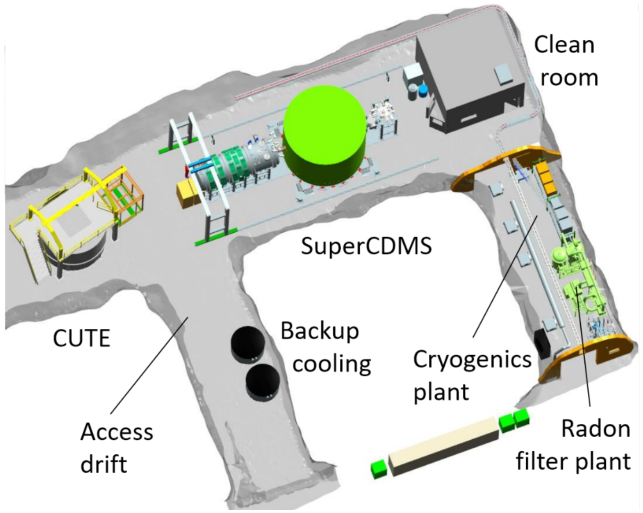
Requirements for Detectors:

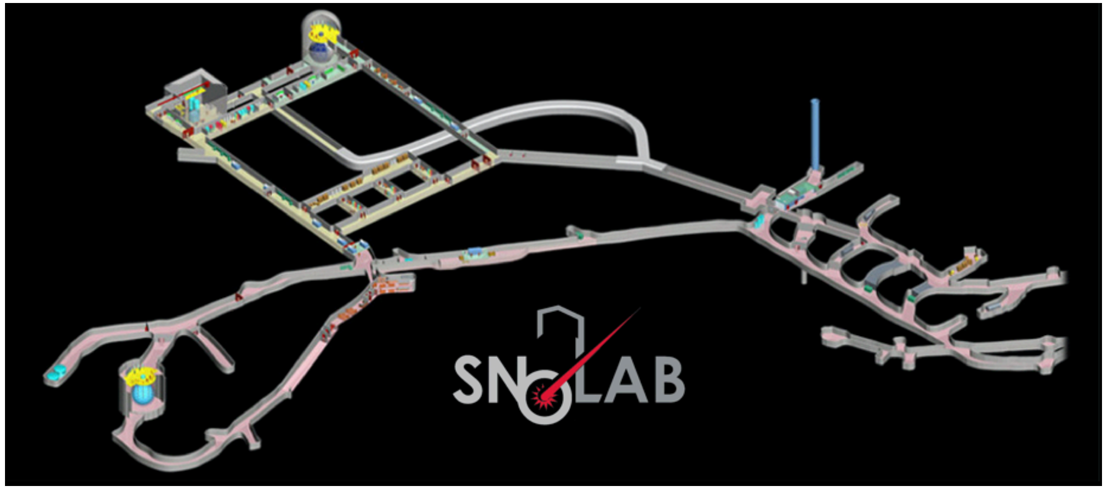
- Lower threshold in recoil energy
- Better energy resolution

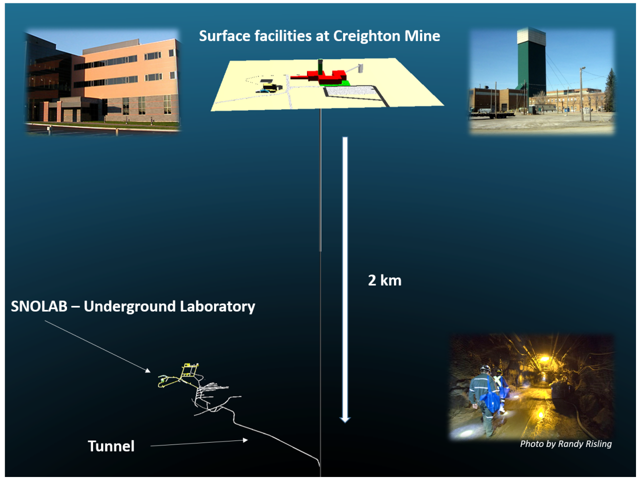
- Better shielding against backgrounds

SNOLAB (Sudbury Neutrino Observatory Laboratory)

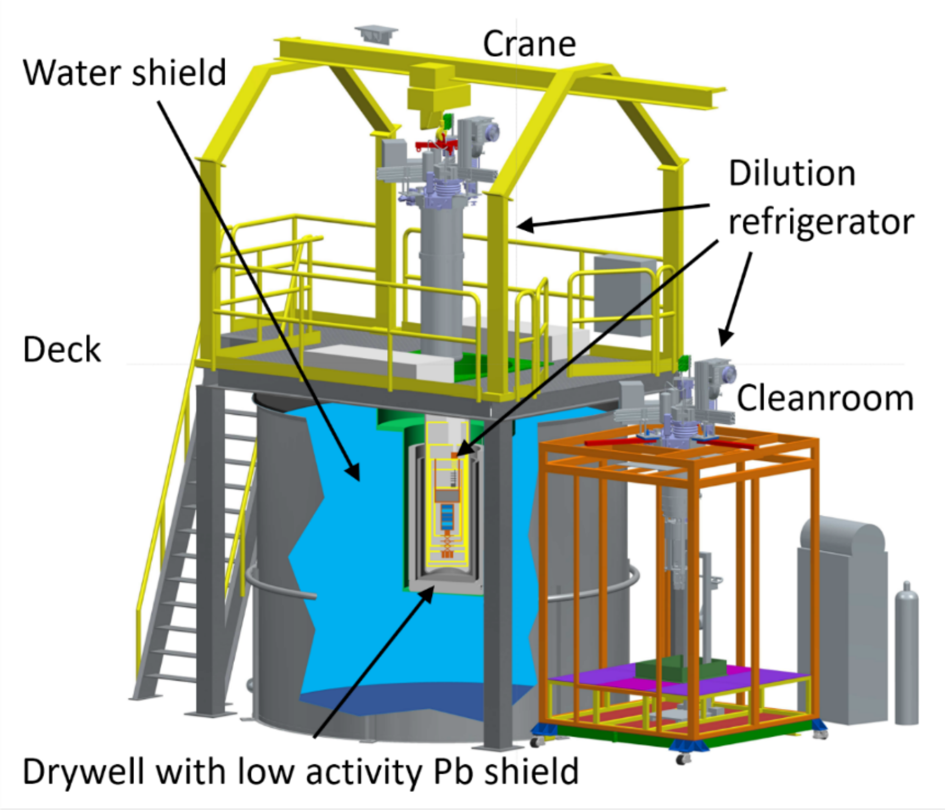
- 2 km underground (6000 m water equiv.)
- Cleanroom (class 2000 or better)
- Large lab (~5,000 m^2)
- Cosmic radiation: Muon flux from cosmic rays reduced by a factor of 10^2 compared to Soudan mine
- Surface facilities, support staff (>100)

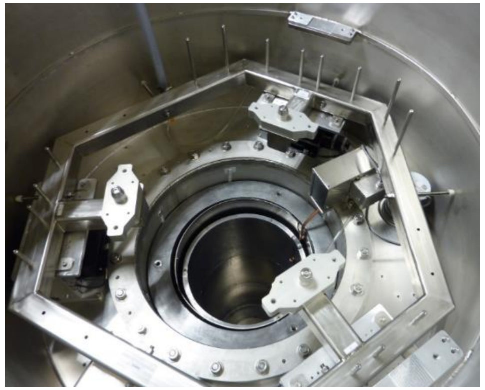


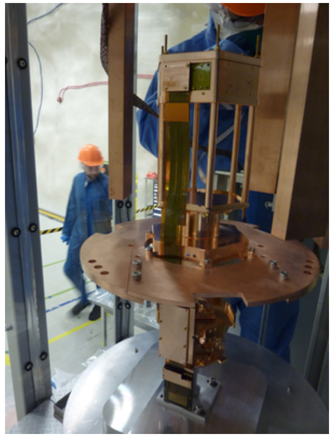


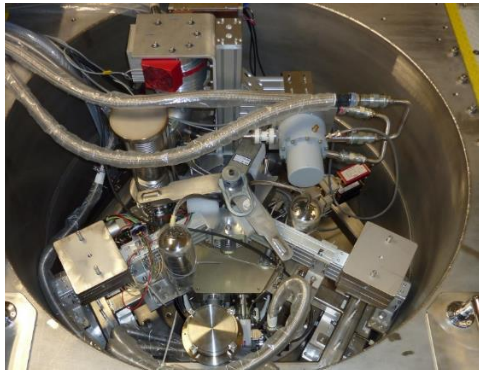


CUTE (Cryogenic Underground Tower TEst facility)









Experiment setup

Inside:

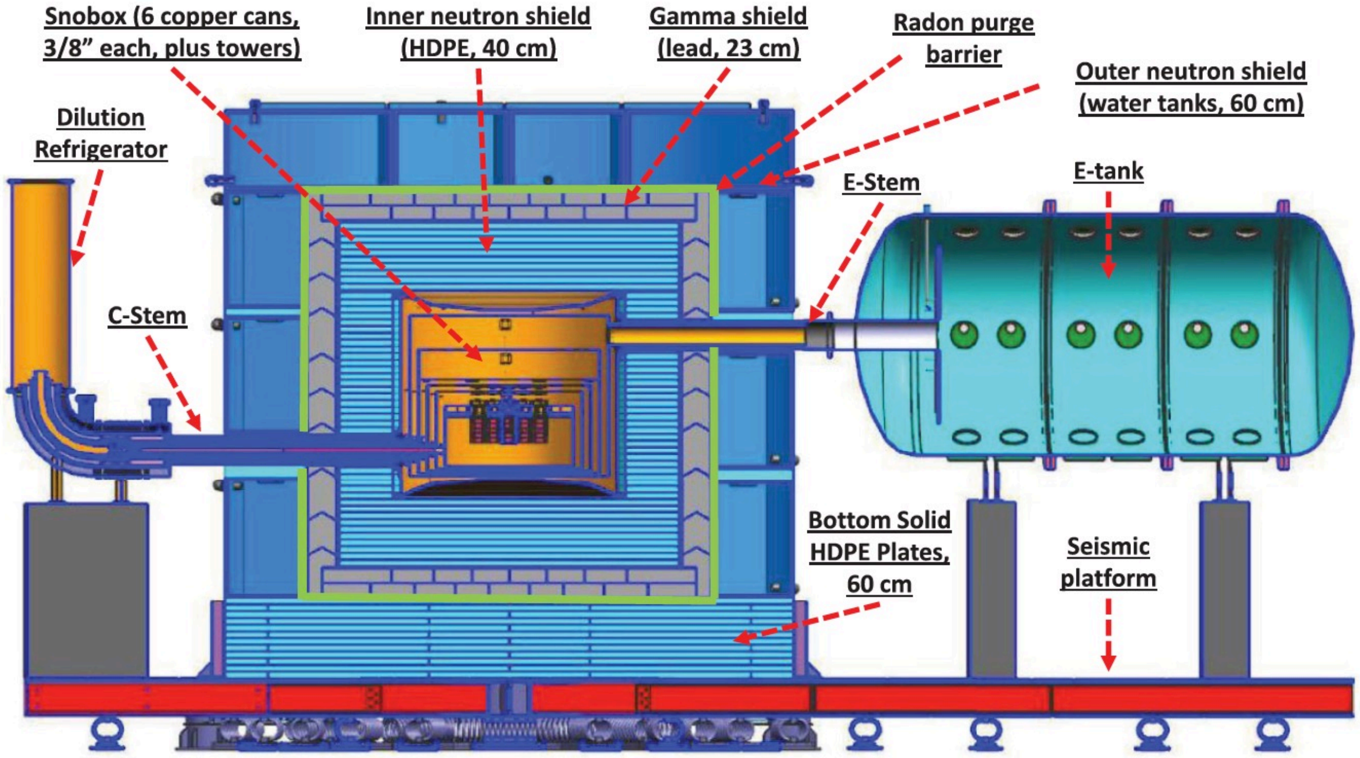
- Cryostat (SNOBOX) consisting 4 towers, 6 detectors each

Shielding:

- Water tanks
- Gamma shield (lead)
- Inner neutron shield (HDPE)

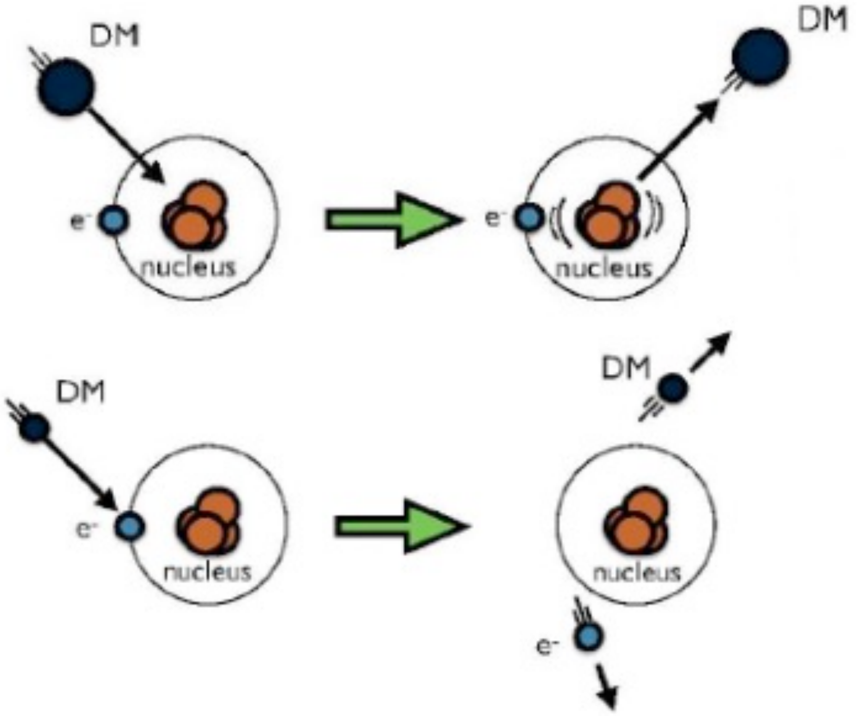
Cryogenic system and readout electronics

Seismic platform



SuperCDMS detectors

Electron recoils (ER) and nuclear recoils (NR)

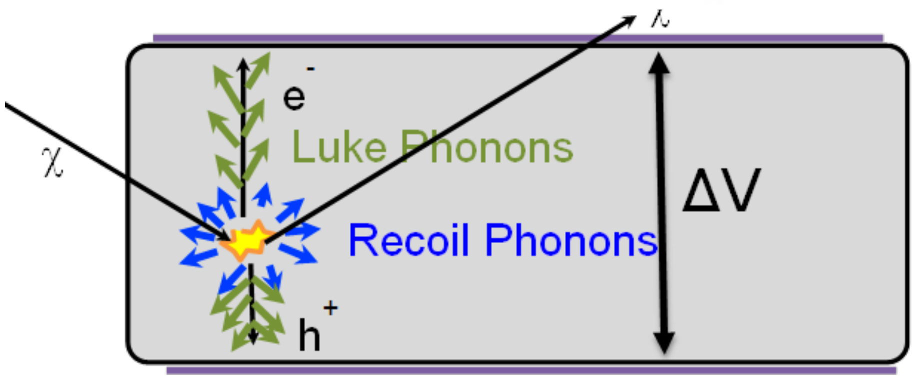


Neganov-Luke Effect

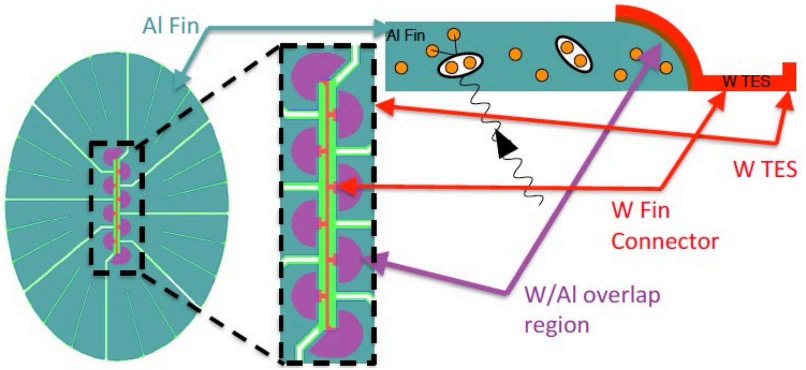
- Energy deposited in crystal lattice creates electron-hole pairs
- Drifted by the applied voltage
- Additional phonons generated

  ➡ Amplification!

$$E_{PT} = E_R + E_{\text{Luke}} = E_R + \eta \frac{yE_R}{\epsilon} e\Delta V$$



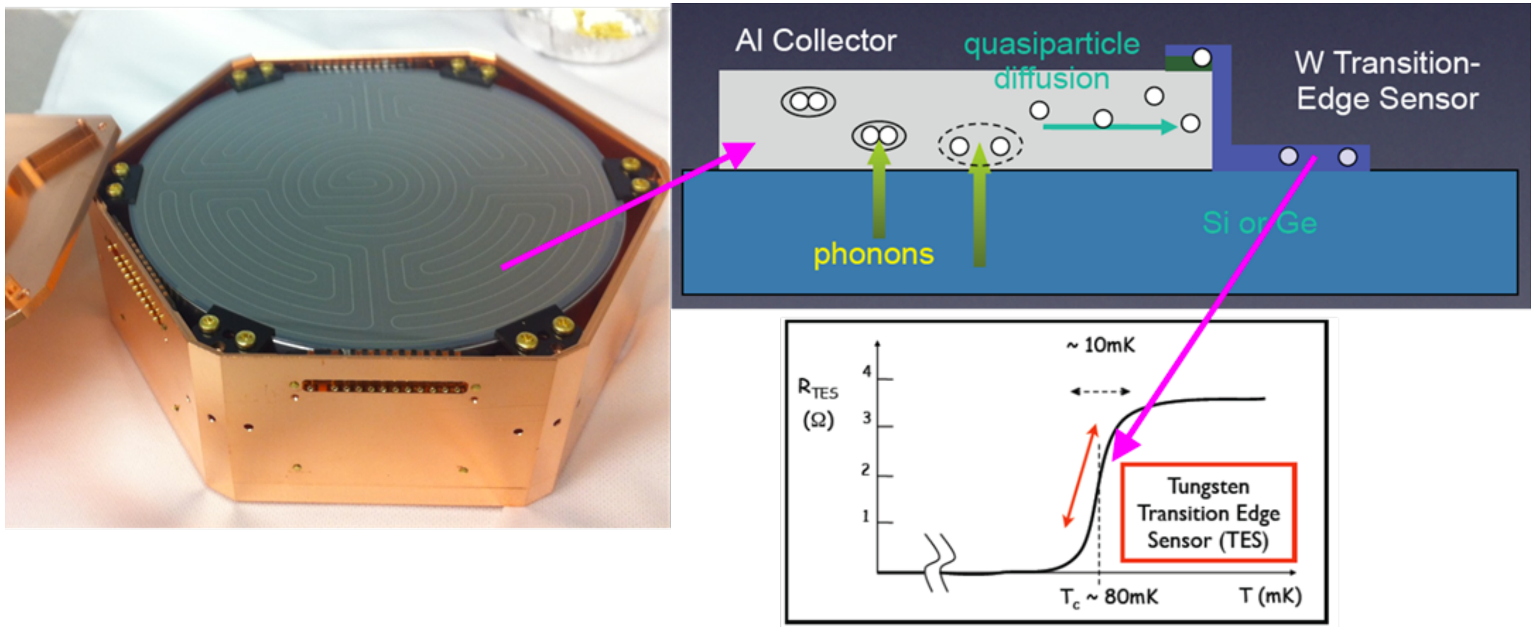
SuperCDMS detectors



How to measure the phonon energy?

➡ Tungsten Transition Edge Sensor (TES)

- Phonons absorbed by Al
- Quasiparticles generated
- Trapped into Tungsten
- Small ΔT ➡ large ΔR

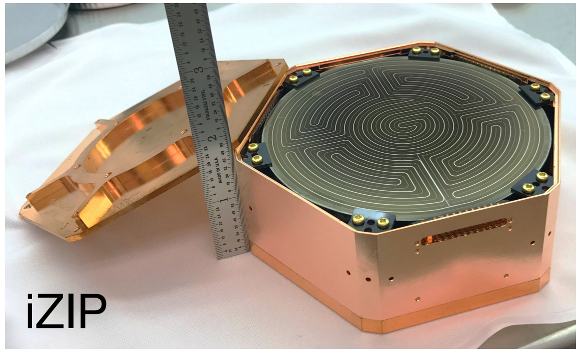


SuperCDMS detectors

Ge/Si crystals, 100 mm x 33 mm, operated at 30 mK

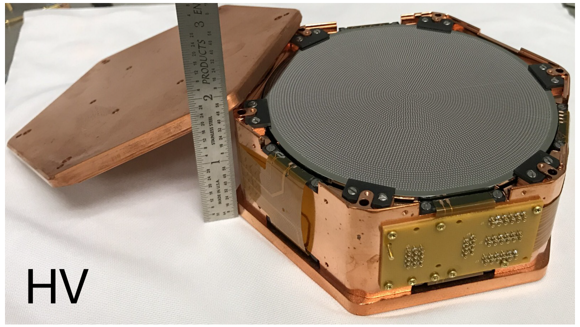
iZIP: (interleaved Z-dependent Ionization and Phonon)

- Voltage ~ 5 -10 V
- Readout charge → background discrimination
- Threshold ~ 1 keV



HV:

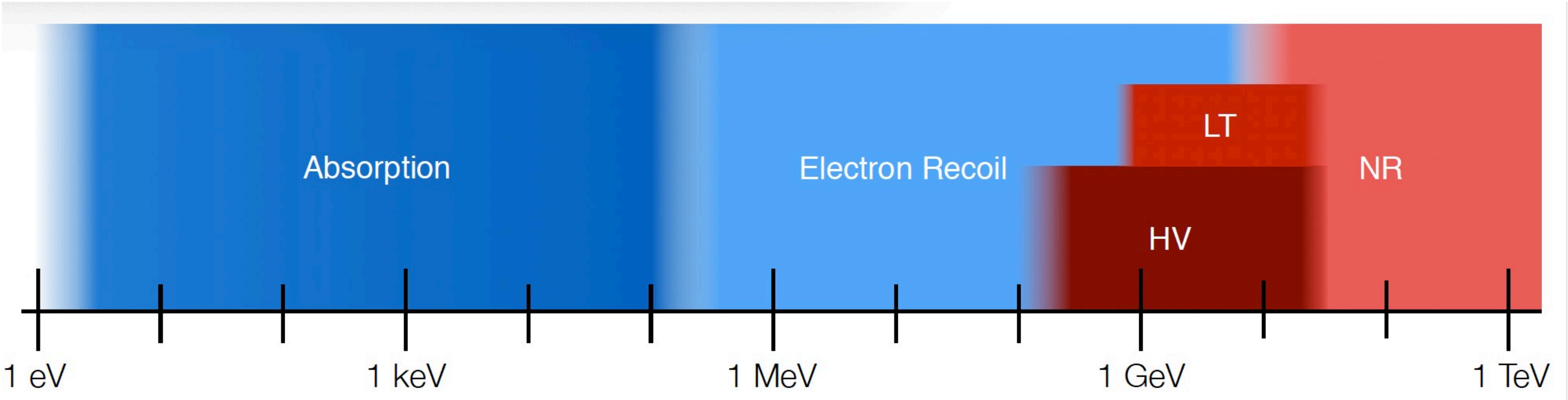
- High Voltage ~ 100 V → lots of phonons
- Enable very low threshold ~ 0.1 keV
- Tradeoff: no discrimination between recoils



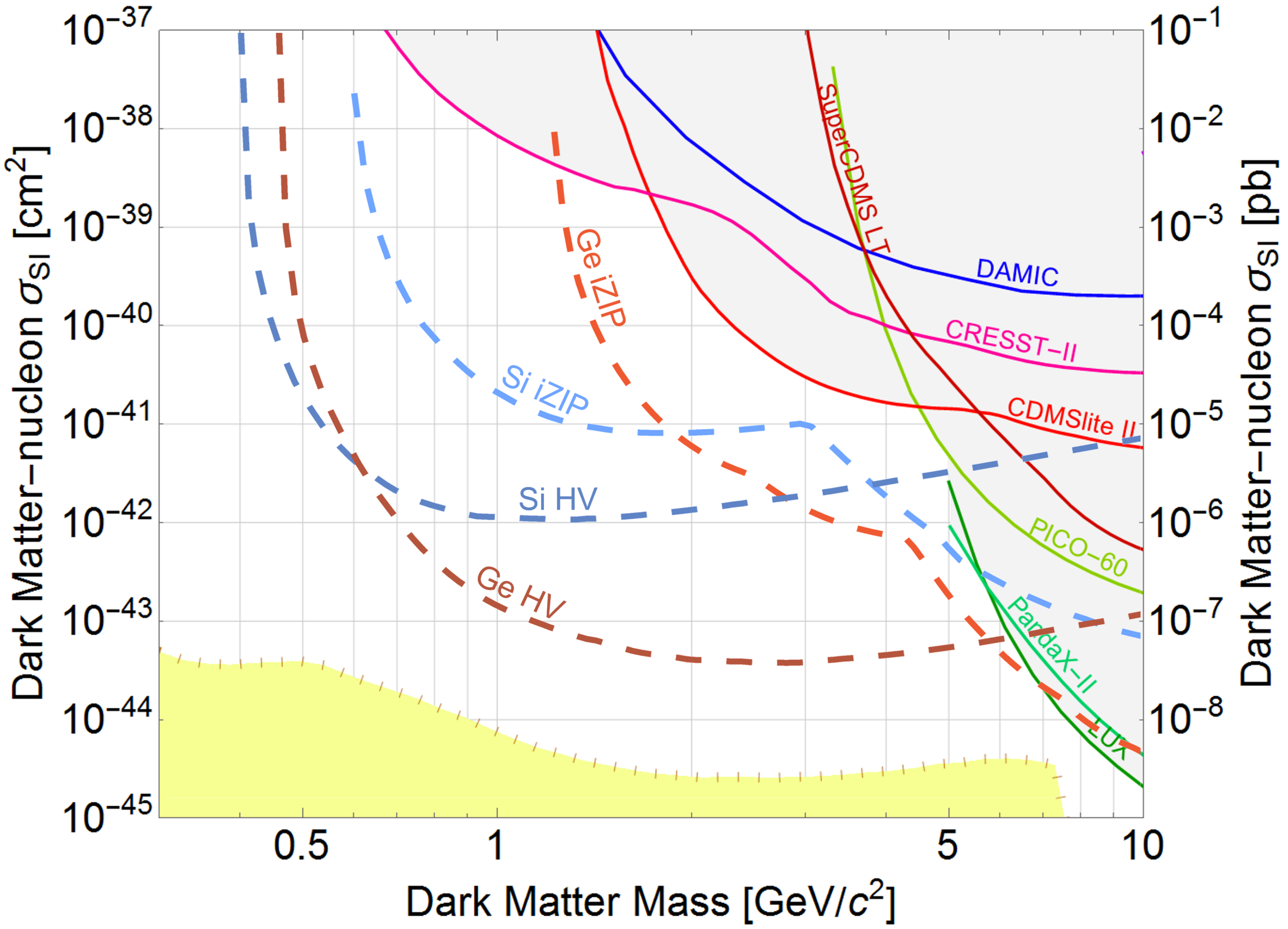
Projected Sensitivity

Dark Matter Mass Ranges

- Traditional NR: iZIP, Background free, $\gtrsim$ 5 GeV
- Low threshold NR: iZIP, limited discrimination, $\gtrsim$ 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 ("peak search")



Projected Sensitivity



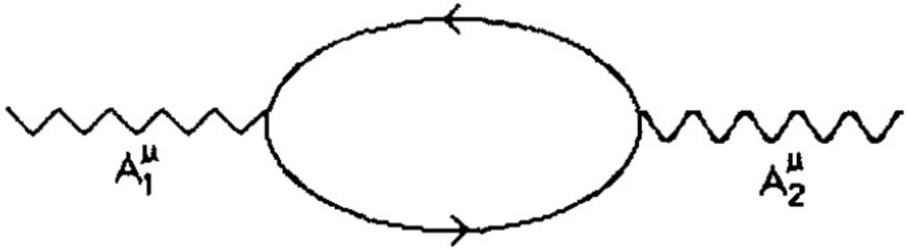
PhysRevD.95.
082002 (2017)

Lightly Ionizing Particles (LIPs)

- LIPs are free fractional charged particles (FCPs) with $q = f\ e$, whose electromagnetic interactions are suppressed as f^2
- Not included in the SM, but can be a result from some extensions to the SM, e.g. extra U(1) gauge symmetries.
  - f_{12} fermions contribute to the off-diagonal vacuum polarization
  - Intuitively, f_1 fermion will have an effective f_2 charge $\varepsilon\ e$

A dark photon with a small kinetic mixing with the SM photon can confer an effective (very small) charge to particles in a hidden sector.

$$\epsilon = \left(- \frac{e^2}{6\pi^2} \sum_i Q_i Q_i' \ln m_i \right) \frac{e'^2}{e^2} .$$



B. Holdom, Phys. Lett. B 166 (1986) 196.

Searches for LIPs

- Collider-based experiments: OPAL, ArgoNeut
- Astrophysical experiments ("direct searches"): MACRO, CDMS II, SuperCDMS Soudan
  - Having sensitivity to FCPs with masses inaccessible to collider-based experiments.
  - Being able to Probe smaller values of f than other techniques.
  - Sensitivity limited by detector size and experimental livetime.

Experiment	Time	Lowest f	Best vertical intensity limit / $cm^{-2}s^{-1}sr^{-1}$
MACRO	2006	1/6	6.1×10^{-16}
CDMS II	2015	5×10^{-3}	7×10^{-9}
Majorana	2018	10^{-3}	2×10^{-9}
SuperCDMS Soudan	2020	10^{-8}	1.36×10^{-7}

LIPs Analysis

- Components necessary for the computation of a final LIP intensity limit:
  - Analysis window over which to look for LIPs — 100eV to 2keV
  - The measured data spectrum in that window — CDMSlite Run2 Period1
  - The efficiency and exposure of all cuts over that range — modified WIMPs cut
  - A PDF of the energy deposition for each f, $\beta\gamma$ and mass — Geant4-based simulation

SNOLAB LIPs analysis

- Lower threshold, lower background, better background modeling
- Tower analysis and single detector analysis
- Smaller charge focus, Ionization being the dominant process
- Might start with HVeV data, not competitive but still first try for smaller charge

Summary

- Cosmologic observations provide evidence for the existence of DM.
- SuperCDMS SNOLAB is a next generation direct detection experiment with low-mass focus.
- Two types of cryogenic detectors, HV and iZIP
- From the projected sensitivity studies, SuperCDMS is very competitive at low mass range.
- LIPs search for smaller charge with better sensitivity can be expected from SuperCDMS SNOLAB.

Backup Slides

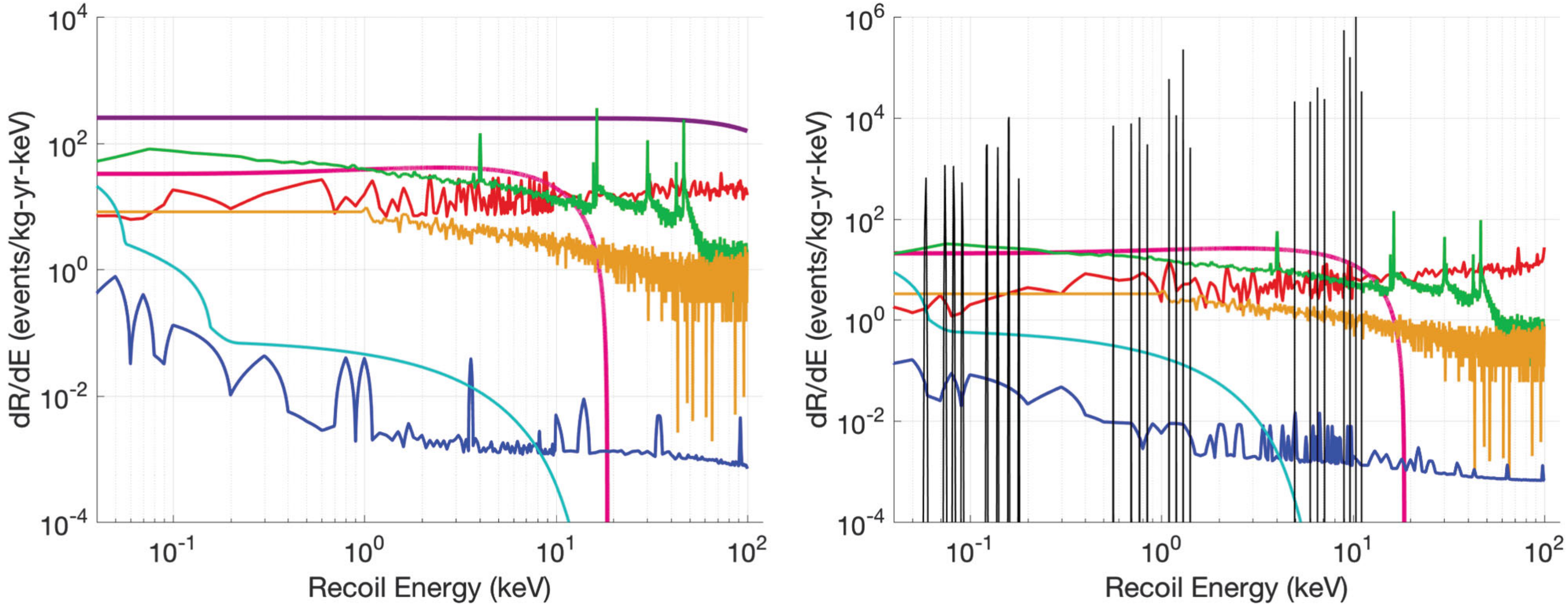
Background Sources

A. Bulk event background sources

- Detector contamination (Cosmogenically produced ^{3}H, Naturally occurring ^{32}Si, Ge activation lines)
- Material activation (the cosmogenic activation of copper)
- Material contamination (^{238}U, ^{232}Th, ^{40}K, ^{60}Co)
- Non-line-of-sight surfaces
- Cavern environment (Gamma rays, neutrons, radon)
- Coherent neutrino interactions

B. Surface event background sources

Background Sources



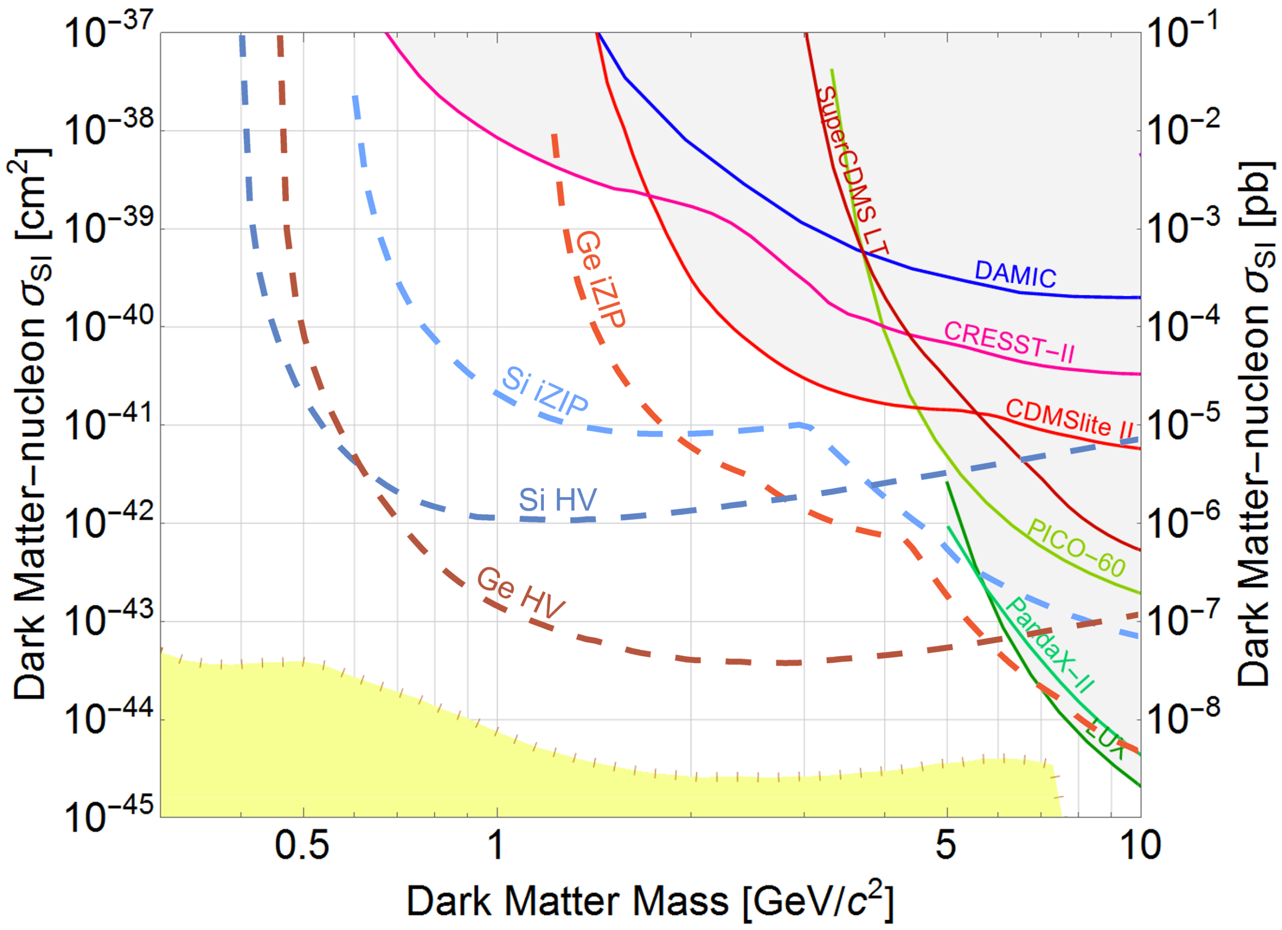
- Si (left) and Ge (right) from the Monte Carlo simulation.
- ^3H (pink), ^{32}Si (purple), gamma rays (red), surface betas (green), surface ^{206}Pb recoils (orange), neutrons (blue) and coherent elastic neutrino-nucleus scattering (cyan).

CUTE (Cryogenic Underground Tower TEst facility)

Main motivations

- Perform a functionality test for at least the first full SuperCDMS tower to arrive at SNOLAB
- Test towers from EURECA and towers that may be deployed later as part of an upgrade to ensure fully functional and efficient detectors.
- Test the influence of the general noise environment in the laboratory on the detector performance.
- Test background rejection power of detectors, especially surface event discrimination.
- If a sufficiently low background is reached, measure the cosmogenic tritium production rate in Ge and Si, using detectors that have been exposed to cosmogenic radiation for extended periods.

Projected Sensitivity



- using "goal" parameters
- spin-independent dark matter-nucleon cross section under standard halo assumptions (J. Lewin and P. Smith, Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil.)
- sensitivity limits determined using the optimum interval method (PhysRevD.66.032005)
- dark matter discovery limit (arXiv:1408.3581)

Calculation of Intensity limit

- Two LIPs flux models:
  - isotropic — negligible atmospheric shielding
  - $cos^2\theta$ distribution — shielding observed for cosmic muons

- The 90% confidence upper limit on the observed LIPs event, $N^{90}(f)$, is calculated using Optimal Interval (OI) method.

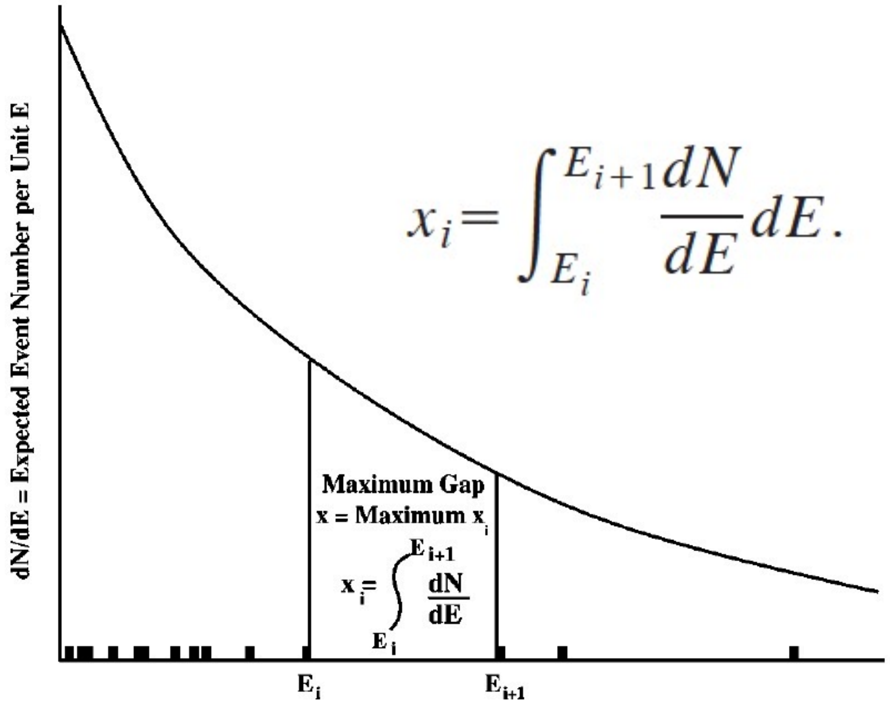
$$I_v^{90}(f) = \frac{N^{90}(f)}{\tau \times \int_{100\ \mathrm{eV}}^{2000\ \mathrm{eV}} \int \underbrace{(\epsilon(E) \times \mathrm{PDF}(f, E, \theta))}_{\text{detection efficiency}}\ \mathrm{d}E \times \underbrace{2\pi A(\theta) \sin\theta}_{\text{geometric factor}}\ \mathrm{d}\theta}$$

Optimal Interval method

- Unknown backgrounds exist
- the probability of the maximum gap size being smaller than a particular value of x

$$C_0(x,\mu)=\sum_{k=0}^{m}\frac{(kx-\mu)^k e^{-kx}}{k!}\left(1+\frac{k}{\mu-kx}\right)$$

- Increase σ until μ and the observed x are
- such that C_0 reaches 0.9



$$x_i=\int_{E_i}^{E_{i+1}}\frac{dN}{dE}dE.$$