The SuperCDMS experiment at SNOLAB

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University of British Columbia - TRIUMF

The GUINEAPIG workshop

September 8th 2022

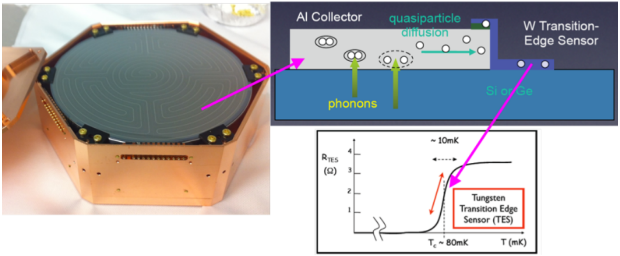
The SuperCDMS Collaboration

$\sim$ 100 scientists at 27 institutions from 6 countries

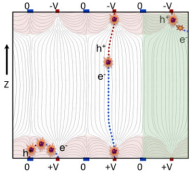
SuperCDMS detector technology

When a particle scatters in a Si/Ge crystal lattice its transferred energy is dissipated via **heat** and **ionization**. If we can measure those, we'll have a clear signature of its interaction and we can infer its properties.

- **Phonons**, measured via Quasi-particle trap assisted Electrothermal feedback Transition edge sensors (QETs)



- **Charge**, measured via interleaved electrodes



SuperCDMS detectors

Interleaved **Z**-sensitive **I**onization and **P**honon detector:

- 12 phonon, 4 charge channels
- Small bias voltage ($< 10\,\mathrm{V}$) across the detector
- Measurement of phonon and ionization signals for discrimination between nuclear and electron recoil events
- ~ 1 keV threshold with ER/NR discrimination power

HV detector:

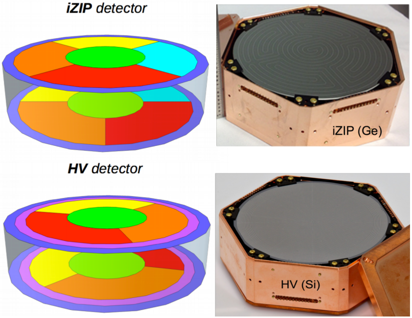
- Only 12 phonon channels
- Larger bias voltage ($\sim 100\,\mathrm{V}$) across the detector
- Dominant phonon energy contribution is from phonons created by drifting charges (Neganov-Trofimov-Luke (NTL) effect)
- Additional NTL energy boost particle interaction signal without degrading resolution
- Push threshold down to ~ 100 eV, but no event by event ER/NR discrimination

SNOLAB SuperCDMS detectors

Successful campaign in Soudan finished, now moving to SNOLAB.

Detectors improvements:

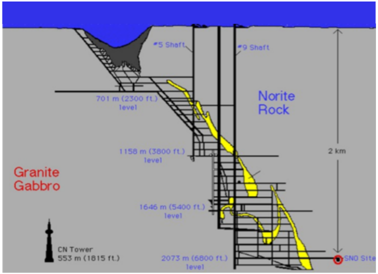
- Bigger (more fiducial volume) and higher purity (fewer radioactive impurities) crystals
  - Ge (1.4 kg crystals) larger exposure
  - Si (0.6 kg crystals) lower mass reach

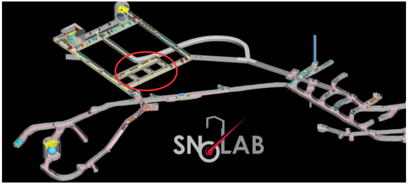


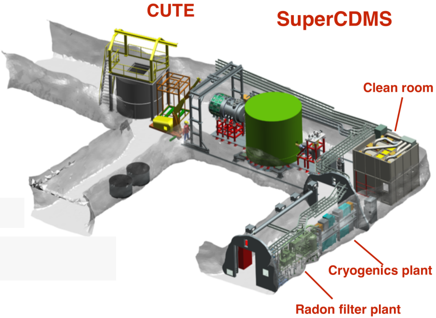
- Critical temperature T_c reduced from 90 to 40 mK, resolution scales as T_c^3
- Newly optimized QET geometry to enhance the phonon collection efficiency
- More channels for better event position reconstruction

Moving to SNOLAB

- 2 km underground (6800 m water equivalent)
- Cleanroom (class 2000 or better)
- Muon flux from cosmic rays reduced by a factor of 100 compared to the Soudan mine

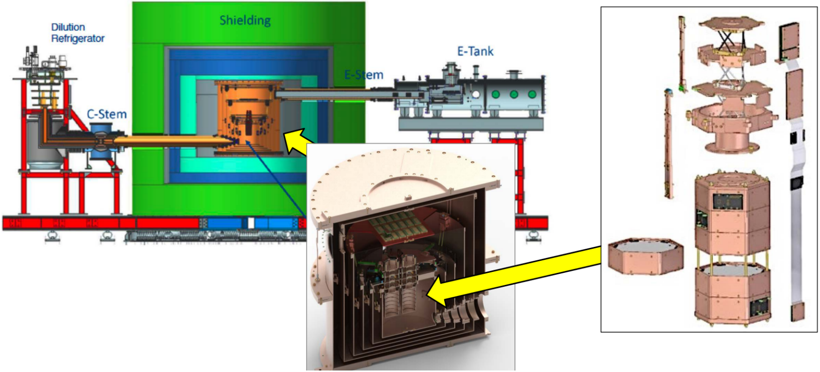






SuperCDMS SNOLAB Experiment

Initial payload: ~ 30 kg total, 4 towers with 6 detectors per tower (12 iZIP, 12 HV)



- ν-dominated nuclear recoil bkg
- $\mathcal{O}(0.1)$ cts/(keV kg d) γ bkg
- 15 mK base temperature
- Vibration isolation

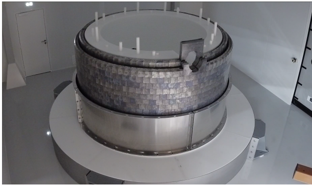
Installation is happening!

Seismic platform installed

Radon filter system

Chilled water loop

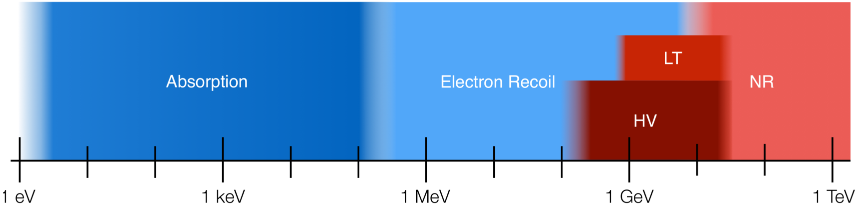
Inner lead and polyethylene shield



Plan is to start commissioning run in 2023!

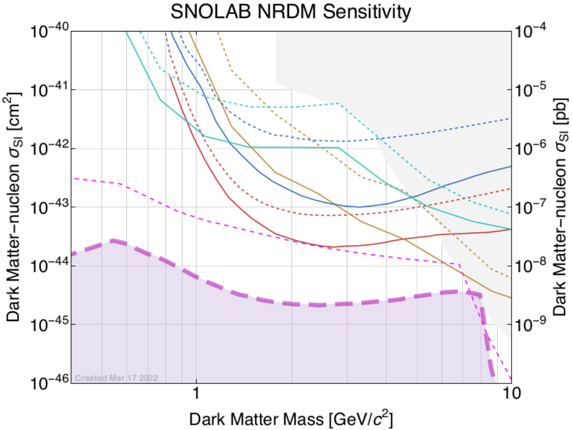
SuperCDMS sensitivity: a broadband DM search

Traditional Nuclear Recoil:	iZIP, Background free	>5 GeV
Low Threshold NR:	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 ("peak search")



SuperCDMS SNOLAB nuclear recoil projected sensitivity (arXiv:2203.08463)

Estimate based on 4-y exposure and current knowledge of bkg

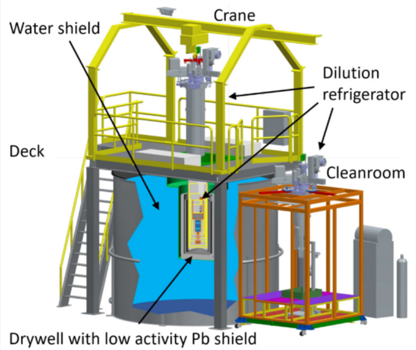


Optimum interval (dashed) and profile-likelihood ratio (solid), (red-brown) Ge HV; (blue) Si HV; (mustard) Ge iZIP; (cyan) Si iZIP, (magenta short dashed) single neutrino sensitivity

How do we get there? Testing, R&D, parallel measurements

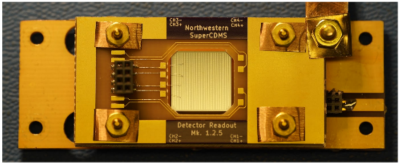
Not just installing SuperCDMS... the Cryogenic Underground TEst

- Close collaboration with SuperCDMS
- Facility background level similar to the Soudan campaign
- Running right now prototypes of HV SNOLAB detectors to study performances
- Capacity of testing 1 SuperCDMS detector tower
  - Si and Ge prototype detectors being tested now
  - Towers 1 + 2 arrive this fall
- Possibility of early science result!

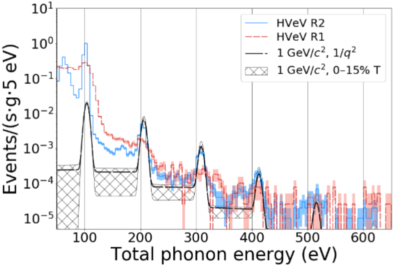


Not just installing SuperCDMS... the HVeV program

- The HVeV are small gram scale R&D detectors:
  - Single electron-hole pair resolution devices!
- Ideal for studying charge transport in Si and Ge
  - Minimize charge leakage in all SuperCDMS devices
- Sensitivity to a variety of sub-GeV DM models with gram*day exposures
- Physics runs happening now in NEXUS (FNAL) test facility

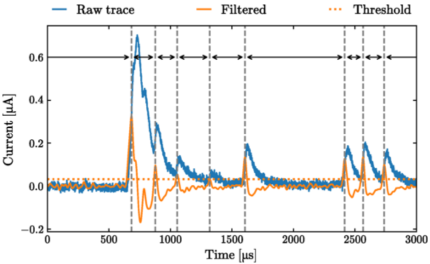


PRD 102, 091101, 2020

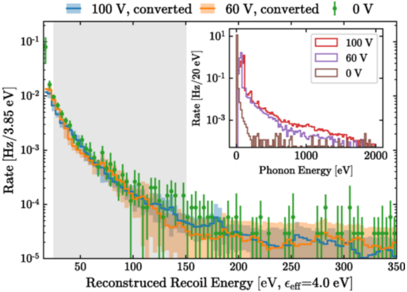


HVeV program and the low energy excess

- Utilize the extreme resolution to study the low energy excess
- New publication comparing 0V, 60V and 100V data
  PRD 105, 112006, 2022
- Many clues all pointing to the production of few eV luminence events from the PCB around the detectors



Burst events: first high energy event followed by train of single charge events



100 and 60V matches 0V energy spectrum if scaled by NTL gain assuming ϵ_{eff}=4 eV

New detector holder design with no PCB → new data show strong reduction of quantized bkg above first electron-hole peak (analysis ongoing)

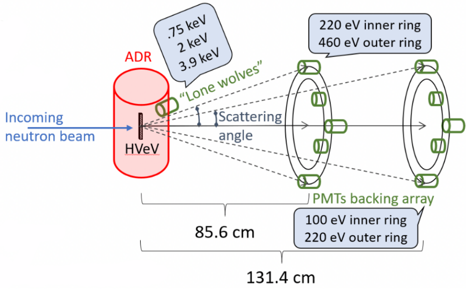
Understanding the Nuclear Recoil Scale: IMPACT

- Ionization yield $Y(E_{\text{Recoil}})$ is energy dependent and not well known at lower energies
- Necessary input for our understanding of the HV detector data

IMPACT

Ionization Measurement with Phonons at Cryogenic Temperatures

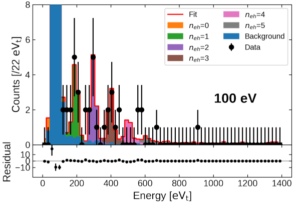
- Determination of the yield via measurement of the total phonon energy and kinematic measurement of the recoil energy via a coincident detection of the scattered neutron
- 55.7 keV neutrons beam at Triangle Universities Nuclear Laboratory
- Total phonon energy measured with Si HVeV detector at 100 V with ~ 3 eV resolution
- Set of liquid scintillator detectors coupled to 2-inch PMTs to measure scattered neutrons at various angles

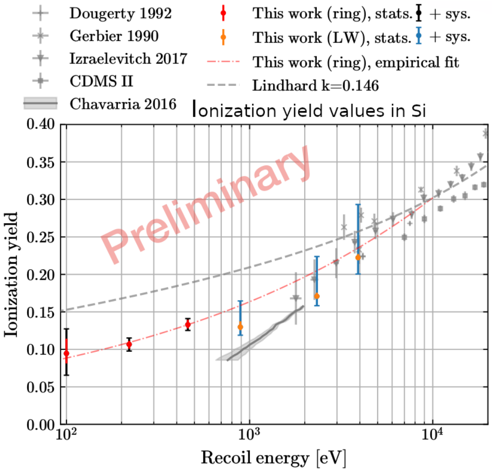


Understanding the Nuclear Recoil Scale: IMPACT

1. Measurement of total phonon energy spectrum for coincidence events
2. Simulation of recoil energy spectrum for coincidence events
3. Determine Y by fitting the simulation to the HV measurement

Example of fit, 100 eV
Single e-h sensitivity for NR!





Paper will be out soon! Working towards a Ge HVeV measurement soon.

Understanding the Nuclear Recoil Scale: photoneutron measurement at Soudan

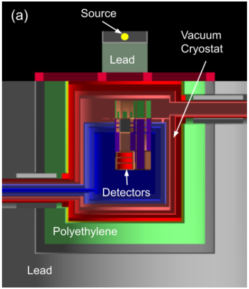
- Photoneutron sources: high rate gamma sources (^{88}Y and ^{124}Sb) on top of a ^{9}Be wafer to produce mono-energetic neutrons
- Neutrons irradiated 2 old-style Ge HV detectors, run at 70 and 25 V, at the end of Soudan campaign
- Full Geant4 simulation of neutron signal
- Electron recoil background spectrum dominated by Compton, modeled analytically and validated using source data without ^{9}Be wafer

arXiv:2202.07043

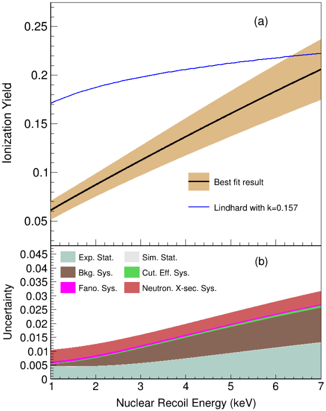
Ionization yield extract with likelihood fit to data using a linear generalization of the standard Lindhard model

$$Y_r = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

$$k(E_r) = k_{low} + \frac{k_{high} - k_{low}}{E_{high} - E_{low}}(E_r - E_{low})$$

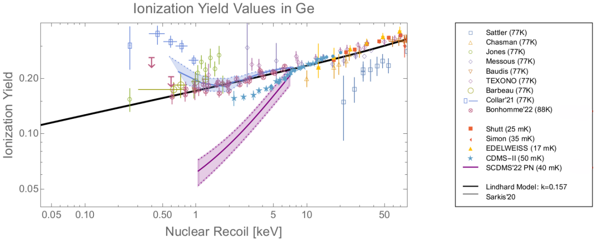


Understanding the Nuclear Recoil Scale: photoneutron measurement at Soudan



arXiv:2202.07043

Obtained yield significantly suppressed wrt Lindhard in the few keV range



Possibility of dependence on T or V bias or type of detector.

Need for theoretical input!

Looking further away.. Now is the right time to start planning for 5 years in the future

New possible directions for LDM searches at SuperCDMS - arXiv:2203.08463

Focus on detector improvements especially to improve phonon resolution, for SuperCDMS further bkg reduction is extremely expensive and time consuming:

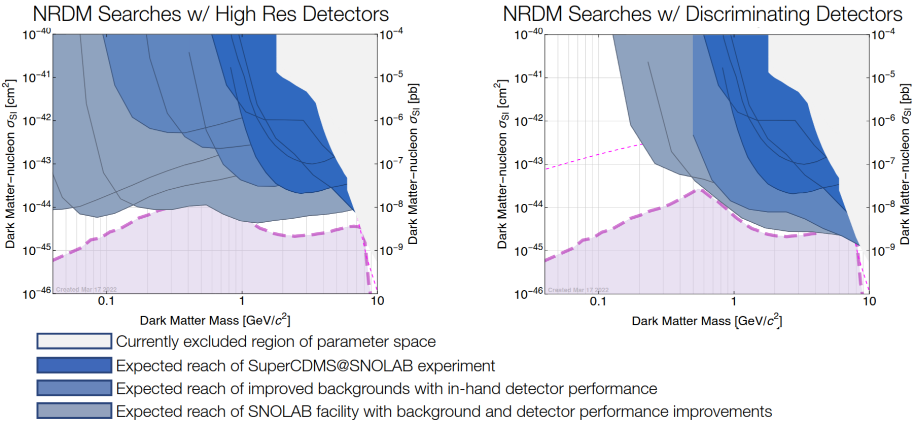
- Smaller detectors sizes (1 cm^3, 10 cm^3) with improved phonon energy resolution
- Alternative detector types
  - phonon iZIP (piZIP): iZIP electric field configuration, measures ionization yield by separating primary and NTL phonon components
  - 0V: simplified design, 1 phonon sensor, ideal for sub-GeV nucelon-coupled DM
- 3 upgrade detector performance scenarios with increasing maturity

Detector Type	Detector Size	Dimensions	mass [kg] Ge	mass [kg] Si	number of Detectors	raw exposure [kg·yr] Ge	raw exposure [kg·yr] Si
SNOLAB	HV/iZIP	⌀10 cm × 3.3 cm	1.4	0.61	12	54	23
	piZIP				6	27	12
10 cm^3	HV	$3 \times 3 \times 1.2$ cm^3	0.057	0.025	36	6.6	2.9
	iZIP				24	4.4	1.9
	piZIP				12	2.2	1.0
	0V				144	26	12
1 cm^3	0V	$1 \times 1 \times 0.4$ cm^3	0.0021	0.00093	144	1.0	0.42

Assumptions in the projections

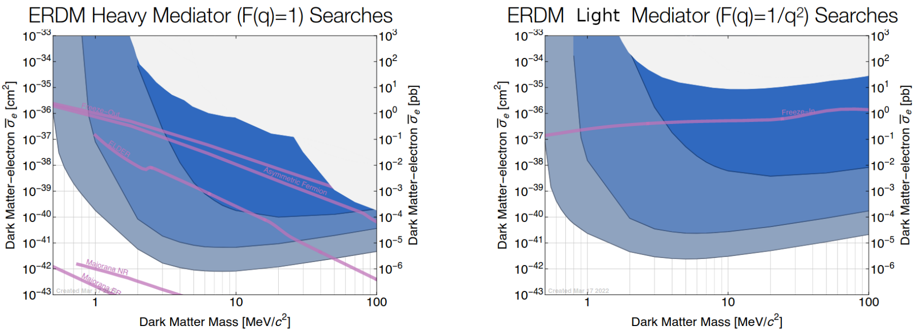
Forecasted sensitivity for NRDM

arXiv:2203.08463



Forecasted sensitivity for ER recoil LDM

arXiv:2203.08463



Currently excluded region of parameter space

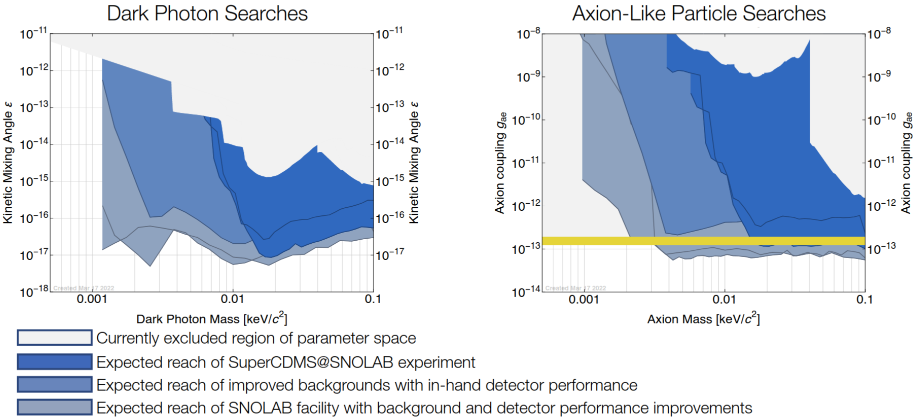
Expected reach of SuperCDMS@SNOLAB experiment

Expected reach of improved backgrounds with in-hand detector performance

Expected reach of SNOLAB facility with background and detector performance improvements

Forecasted sensitivity for ALPs and dark photons

arXiv:2203.08463

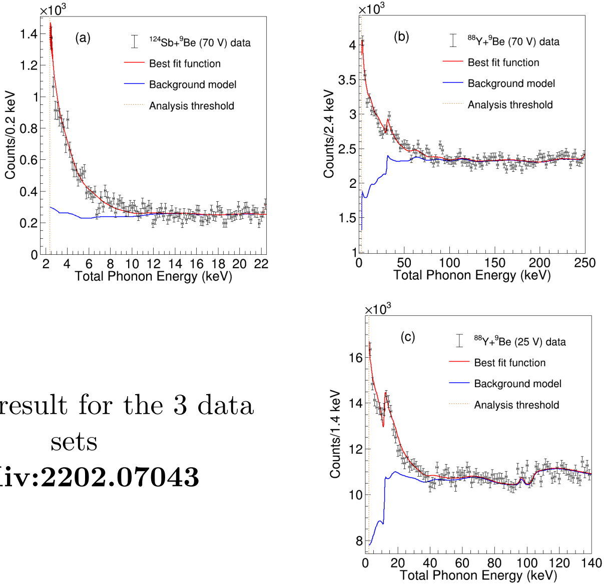


Conclusion

- Exciting time ahead!
- The SuperCDMS SNOLAB Project is on track
  - Detector fab is complete and SNOLAB infrastructure is well advanced
  - Testing and characterization is happening at test facilities
  - The parameter space that SuperCDMS will explore is world-leading and unique
- First results on the nuclear recoil scale at low energies
- Intense and fruitful R&D effort ongoing to already develop the detector technology for the future
- Multiple avenues are being explore to push the sentitivity even further!

Backup

Understanding the Nuclear Recoil Scale: photoneutron measurement at Soudan



Best fit result for the 3 data sets

arXiv:2202.07043

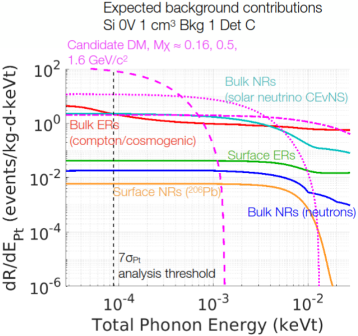
Forecasted sensitivity - asssumptions table

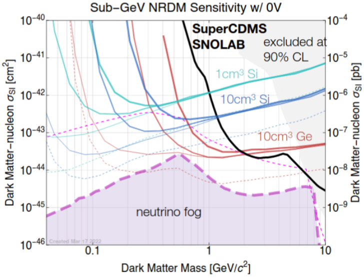
arXiv:2203.08463

Quantity	Detector Type	Detector Size	A Si	A Ge	B Si	B Ge	C Si	C Ge
phonon energy resolution [eV]	0V	1 cm^3	0.5		0.13	0.28	0.013	
		10 cm^3	2.5	4.5	0.7	1.5	0.07	0.14
	HV	10 cm^3	3.3	4.5				
		SNOLAB-sized	12.	21.	4.	6.	0.6	0.7
	iZIP	10 cm^3	2.5	4.5	0.7	1.5		
		SNOLAB-sized	12.	21.	3.4	6.		
	piZIP	10 cm^3	3.3	4.5	1.2	1.5	0.19	0.21
		SNOLAB-sized	12.	21.	4.	6.	0.6	0.7
ionization energy resolution [eV_{ee}]	iZIP	10 cm^3	50.	60.	17.	17.		
	piZIP	10 cm^3	8.	11.	3.	6.	0.5	0.5
		SNOLAB-sized	30.	53.	10.	15.	1.5	1.8
ionization leakage current [Hz/gm]	HV			1.0		0.1		0.01
impact ionization probability	HV			0.02		0.01		0.01
charge trapping probability	HV			0.01		0.01		0.001

Forecasted sensitivity for NRDM

arXiv:2203.08463





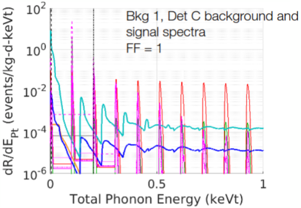
single neutrino sensitivity
Line thickness indicates upgrade scenario (**Det A**, Det B, Det C)

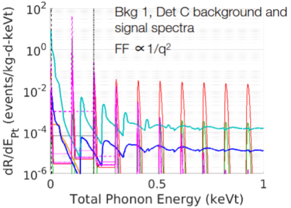
Dotted lines: Det C, 20x payload

- Bulk ERs and neutrinos dominate backgrounds
- Mass reach improves with decreasing phonon resolution
- Cross section reach improves with increasing exposure
- Det C x20 payload demonstrates these scenarios are exposure limited

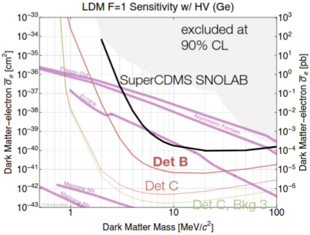
Forecasted sensitivity for ERDM

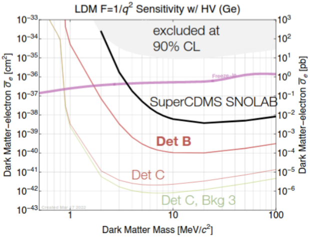
arXiv:2203.08463





$7\sigma_{Pt}$ analysis threshold
Bulk ERs (compton/cosmogenic)
Surface ERs
Surface NRs (^{206}Pb)
Bulk NRs (neutrons)
Bulk NRs (solar neutrino CEvNS)
Candidate DM, $M_\chi \approx$ 1, 3, 10, 30 MeV/c^2





SuperCDMS SNOLAB envelope
HV SNOLAB-sized Ge.
Line thickness indicates upgrade scenario (**Det B**, Det C)
Det C, Bkg 3

Science targets from 2017 Cosmic Visions Report

Not shown for plot clarity: Si SNOLAB-sized HV (very similar to Ge)

Summary table

arXiv:2203.08463

Detector		Science Goals Accessible with Detector Upgrade Scenario					
		A		B		C	
Type	Size	Si	Ge	Si	Ge	Si	Ge
0V	1 cm^3	1, 3, 4, **5**	4	1, 3, 4, **5**	3, **4**	1	
	10 cm^3	1, 4	1, 4	1, 3, 4, **5**	1, 3, 4	1, 3, 4	1, 3, **4**
HV	10 cm^3	2	2				
	SNOLAB-sized	3, 4, **5**	3, 4, **5**	2, 3, 4, **5**	2, 3, 4, **5**	3, 4, **5**	3, **4**, **5**
iZIP	10 cm^3		2		2		
	SNOLAB-sized				2		
piZIP	10 cm^3	2	2	2	2	2	2
	SNOLAB-sized	2	2	2	2	2	2

Table 4 from 2203.08463: Relevance of various detector types, sizes, and upgrade scenarios to science goals.

- Colour indicates maturity (e.g. bright green = already demonstrated)
- Numbers indicate science goals
  - 1: sub-GeV NRDM
  - 2: GeV scale NRDM
  - 3: DP DM
  - 4: ALP DM
  - 5: LDM
- iZIP and piZIP detectors only address GeV scale NRDM