Pacific Northwest NATIONAL LABORATORY

SUPER CDMS Cryogenic Dark Matter Search

The SuperCDMS dark matter experiment

1 December 2023

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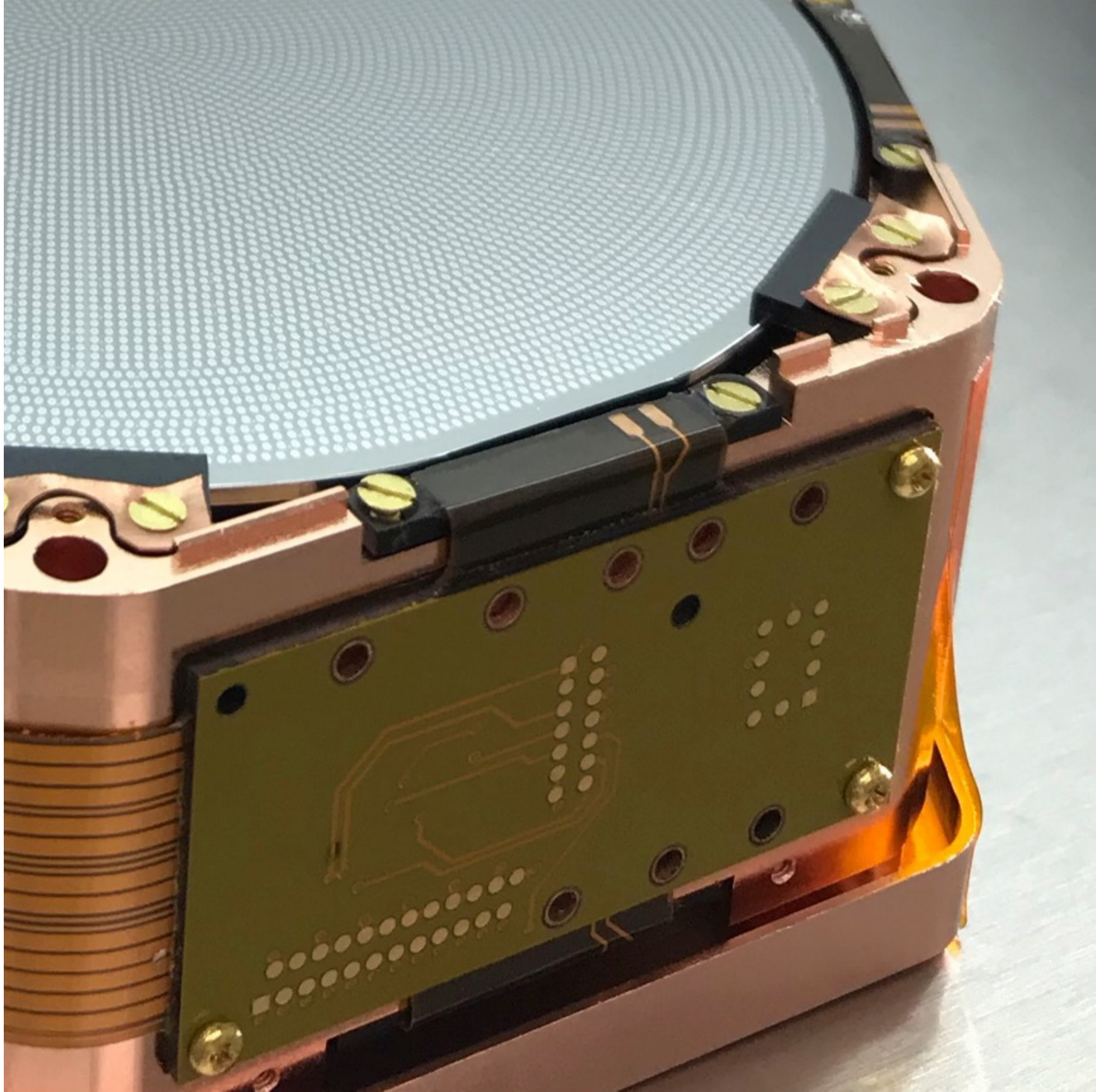
Research Scientist

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL-SA-192864

PNNL is operated by Battelle for the U.S. Department of Energy



Outline

- SuperCDMS SNOLAB
  - Design & Detectors
  - Sensitivity
- Backgrounds
  - Overview
  - Tritium from cosmic rays
  - Cu surfaces & bulk ^{210}Pb
  - Kapton & Cirlex
- R&D detectors
  - HVeV
- Status
- Summary

@SuperCDMS

supercdms.slac.stanford.edu

SuperCDMS gratefully acknowledges agency support

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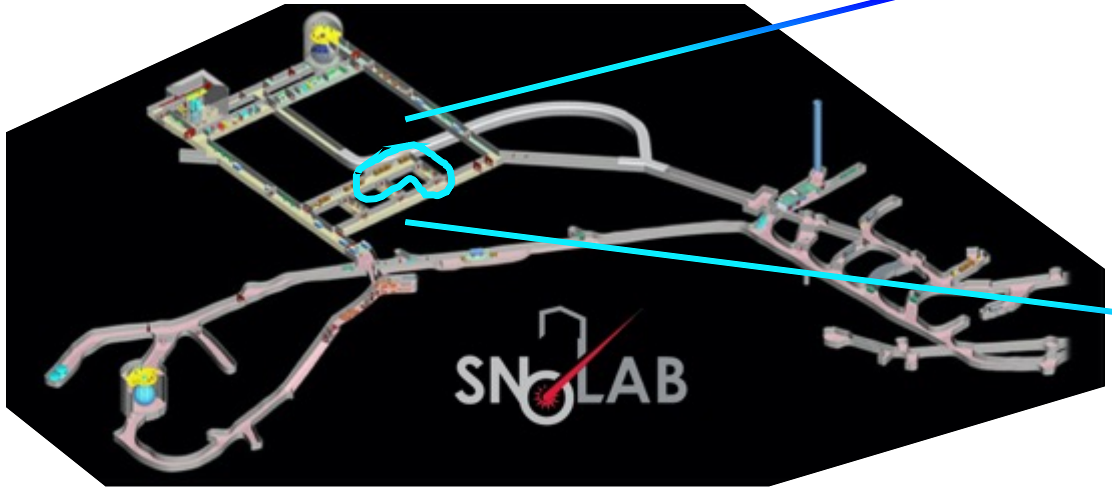
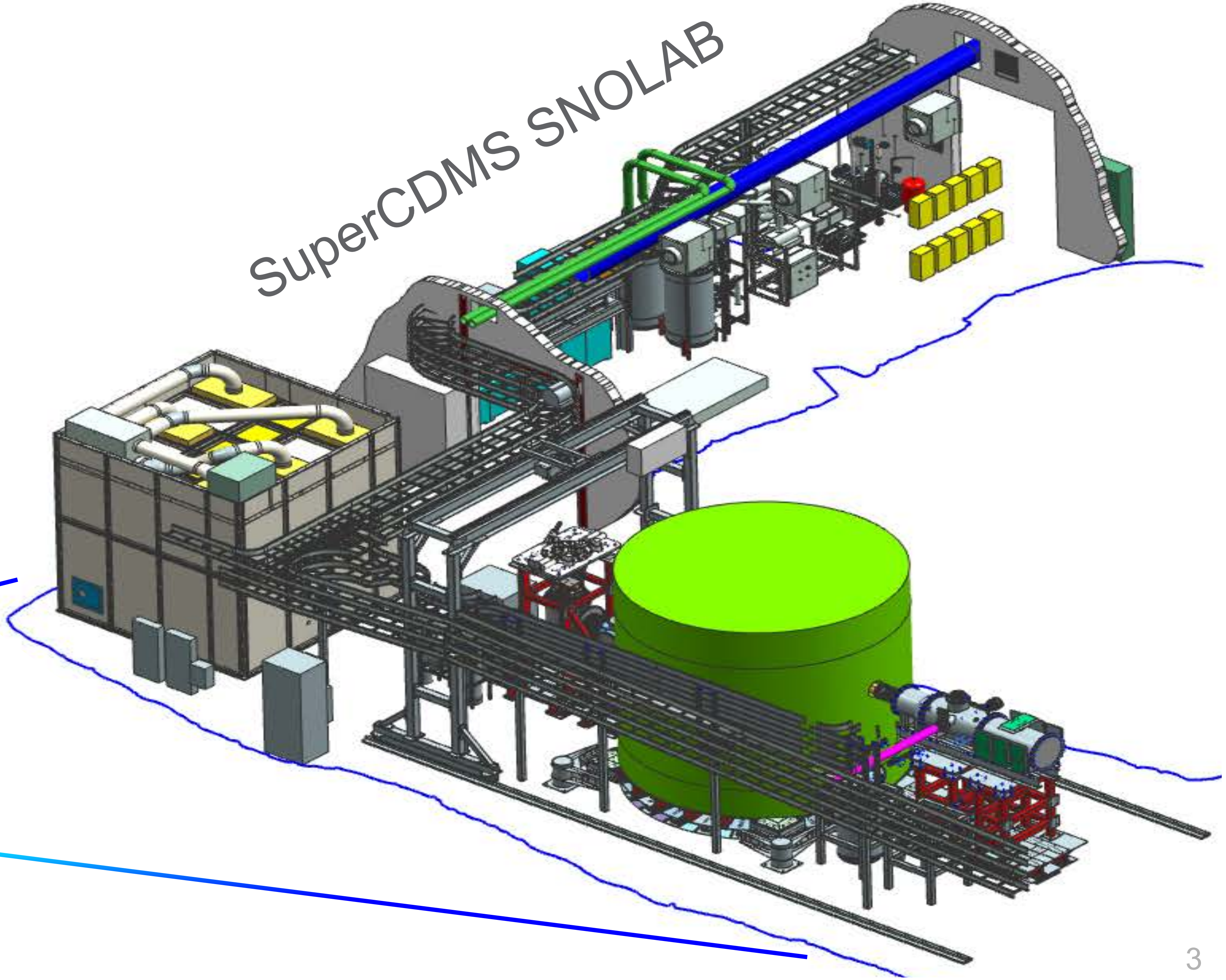
SUPER CDMS Cryogenic Dark Matter Search

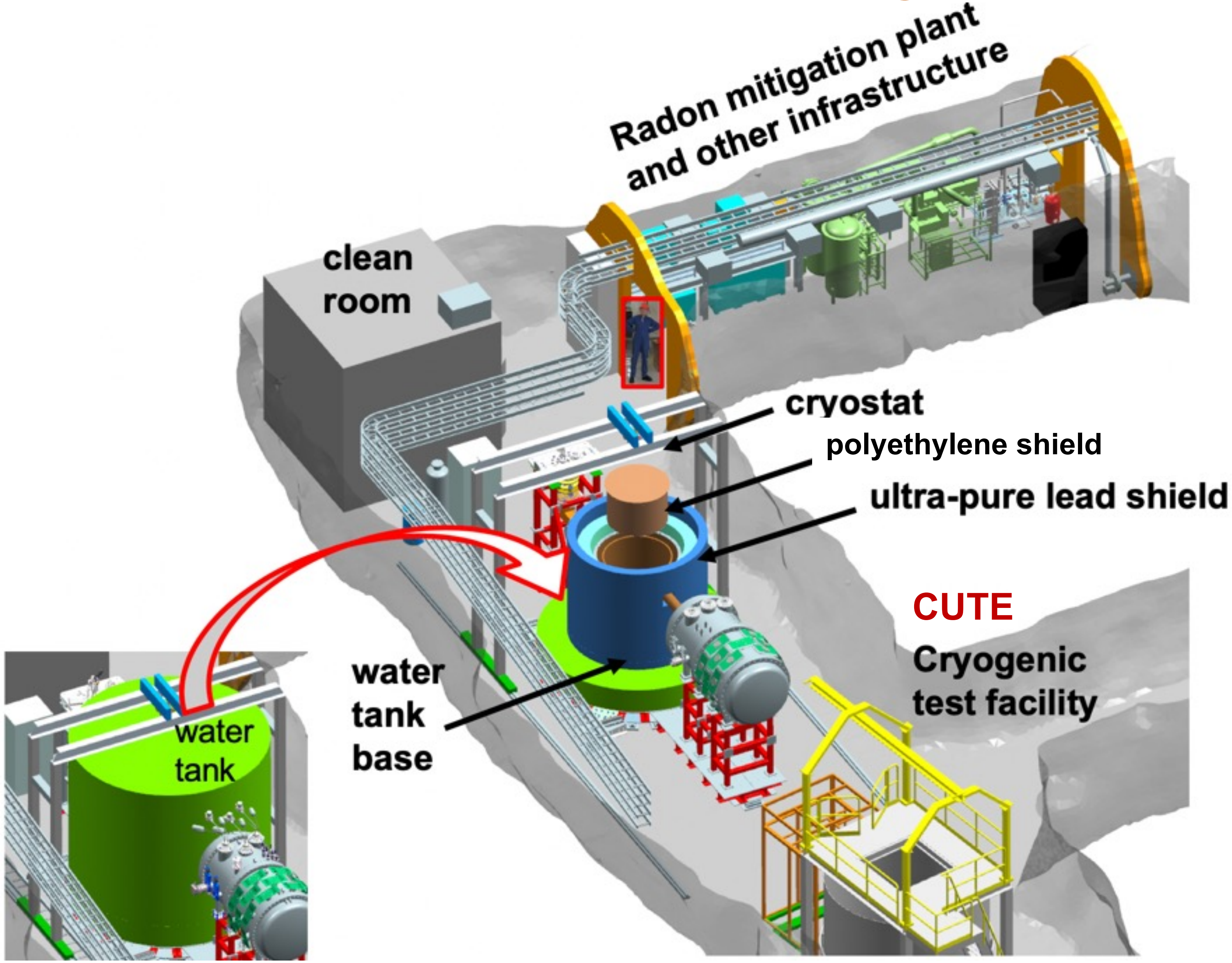
Experiment located at SNOLAB

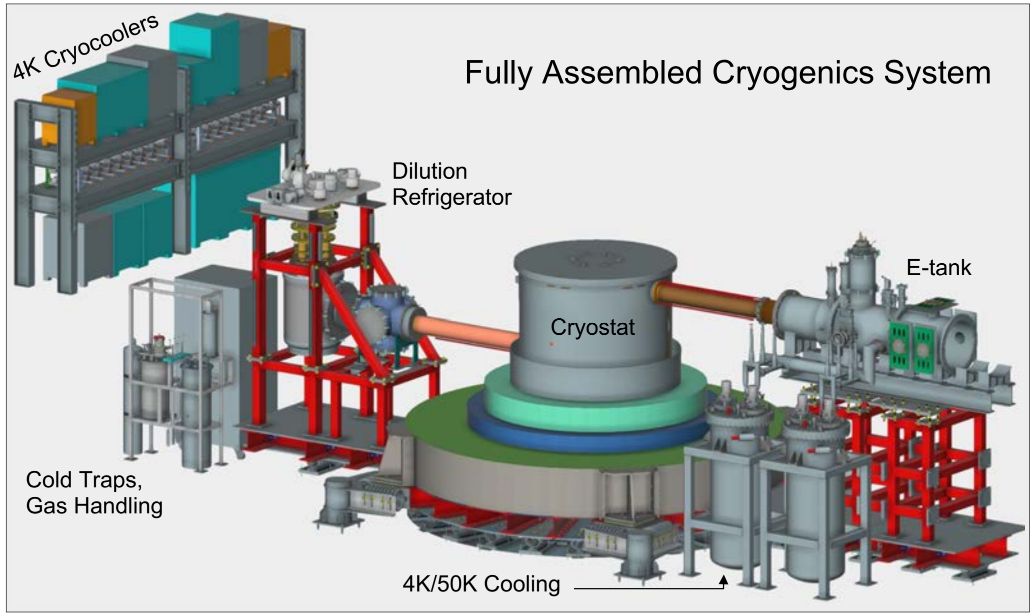
2 km underground…



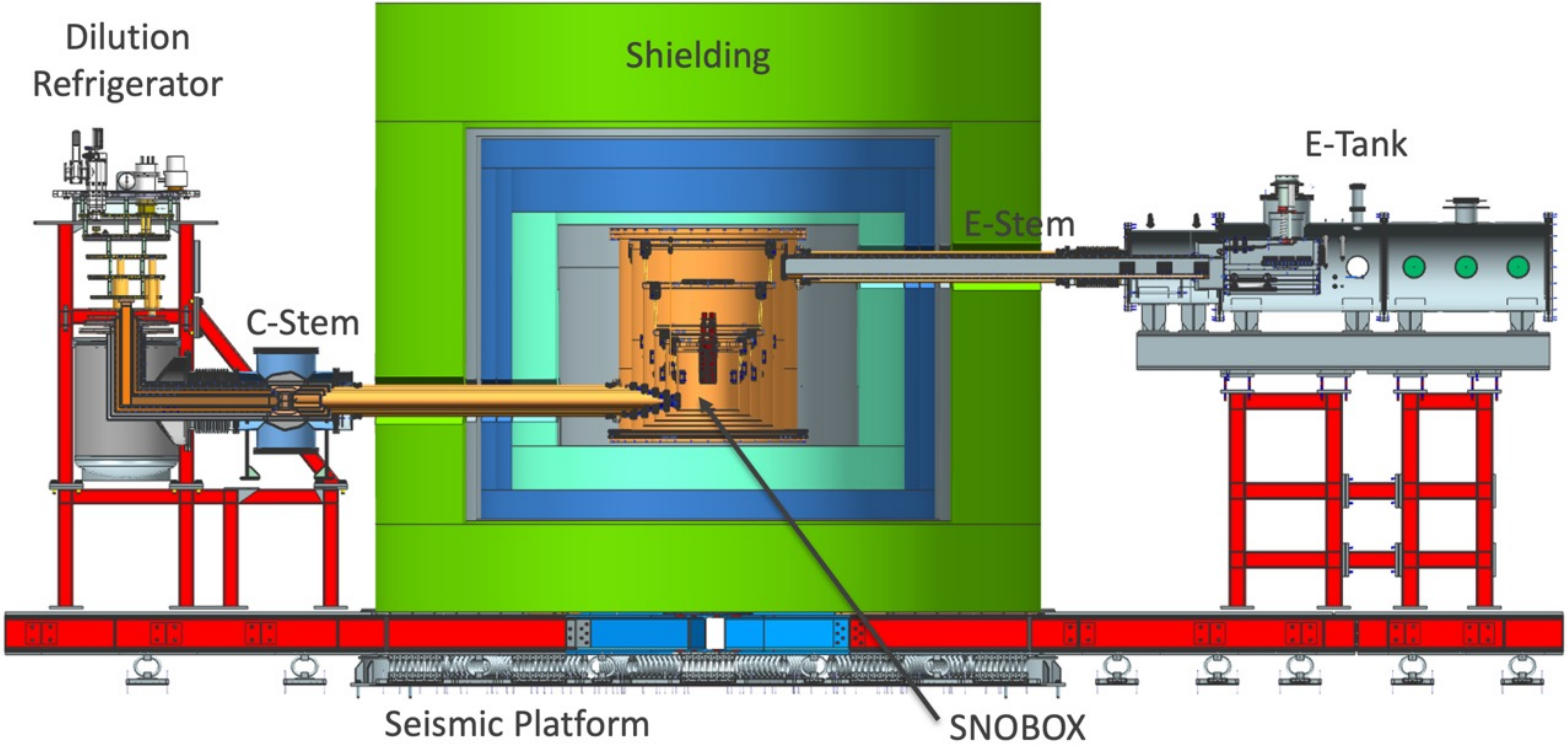


SuperCDMS facility at SNOLAB

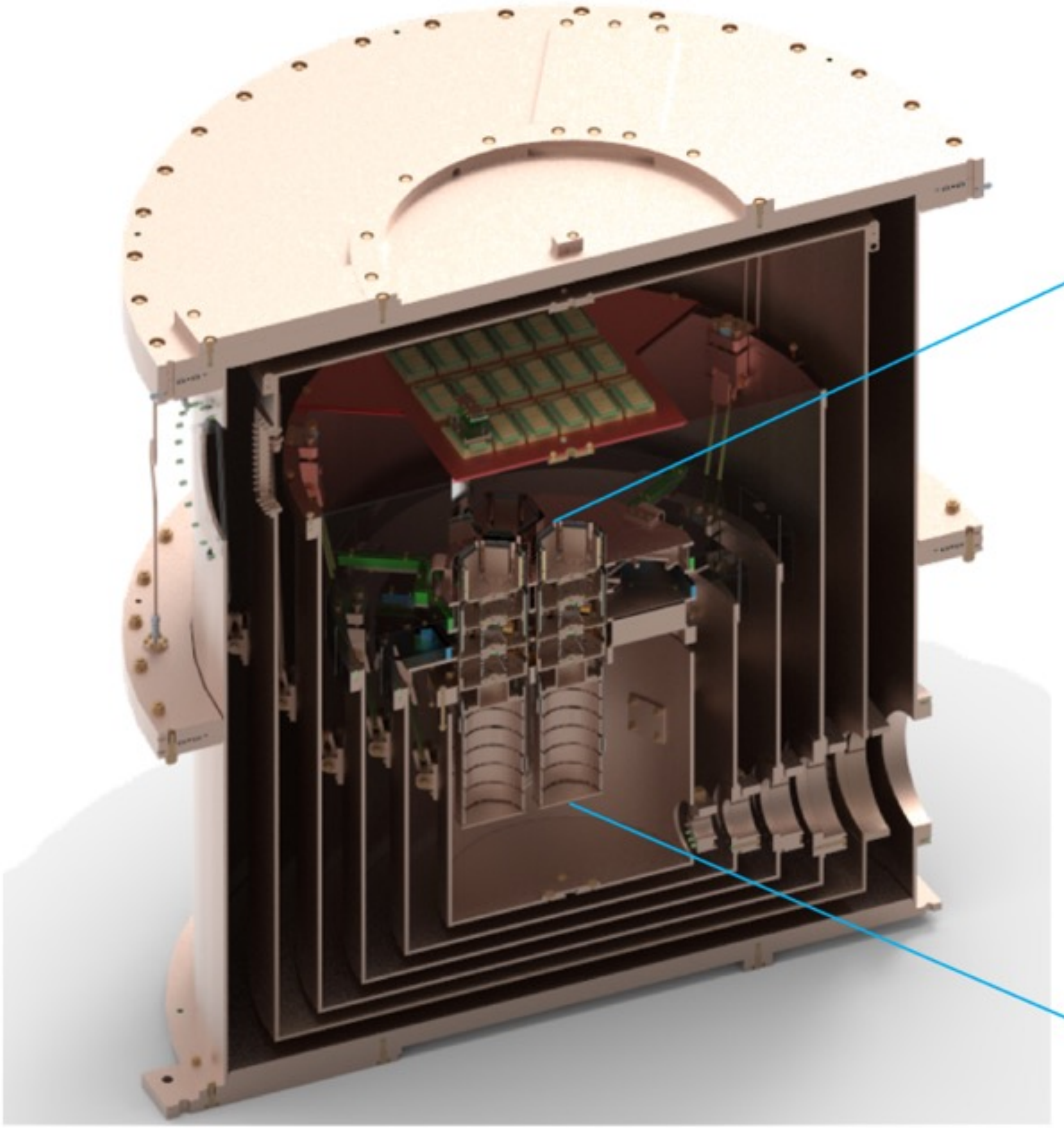


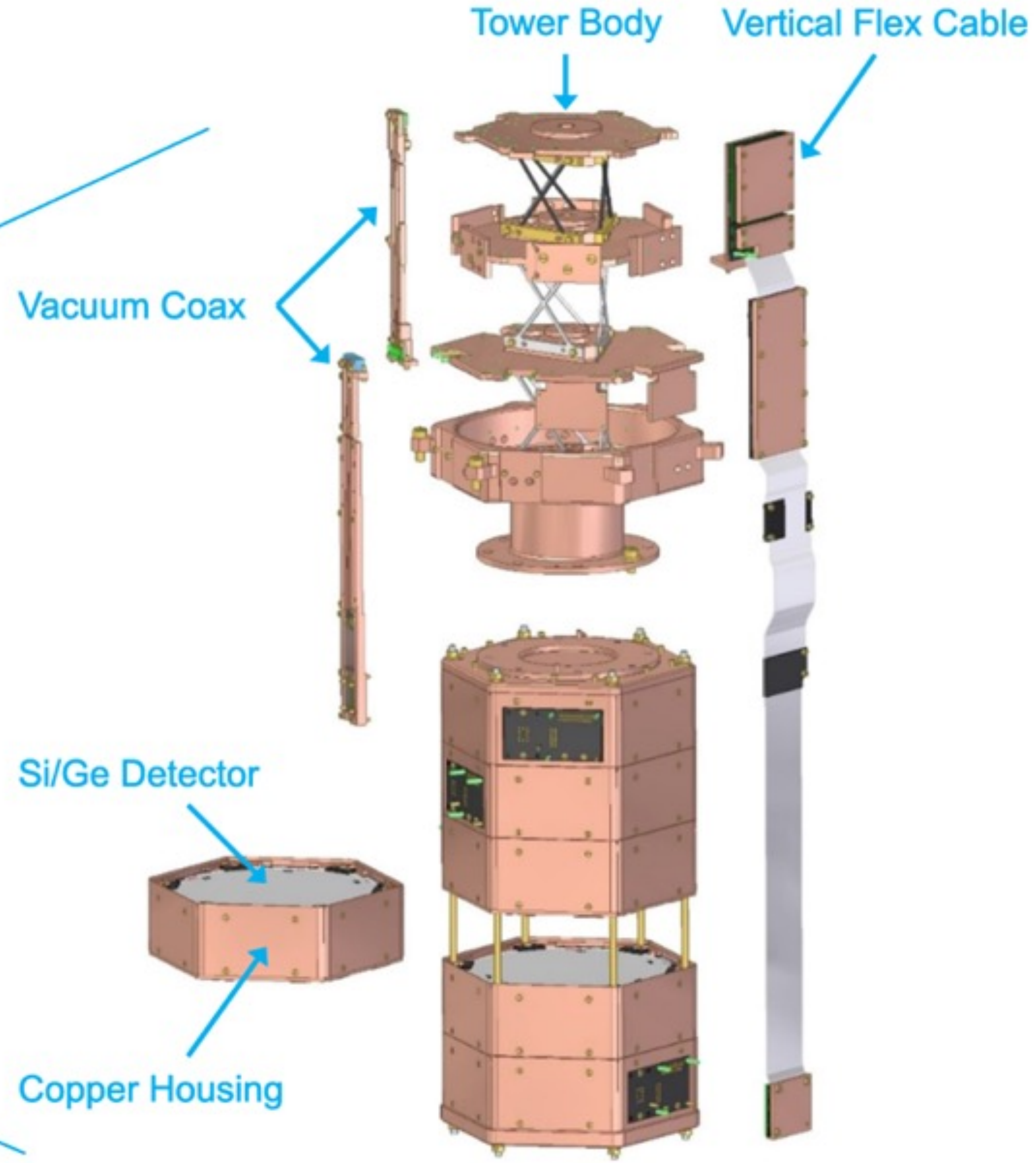


Experimental design



SNOBOX Cryostat and Detector Towers

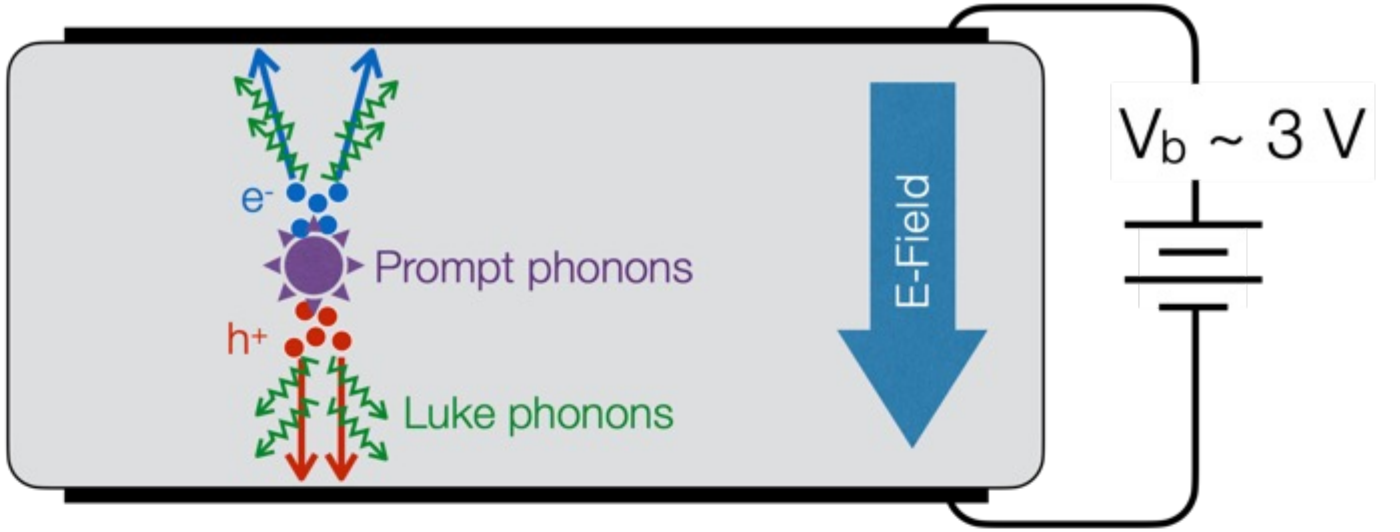




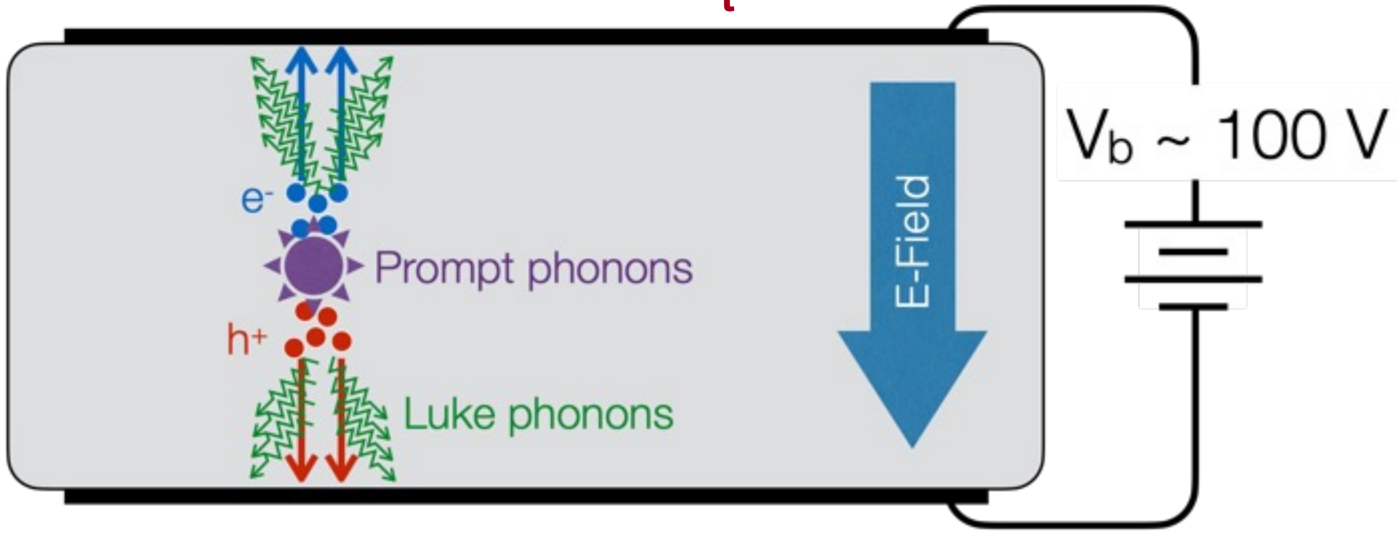
Two complementary detector readout approaches

- iZIP Detector
  - Prompt phonon & ionization signals allow discrimination between nuclear and electron recoil events
  - Event discrimination → low background
  - Trade-off:
    - ✓ Higher energy analysis threshold
- HV Detector
  - Drifting electrons and holes across a potential (V_b) generates many Luke phonons
  - Enables very low energy thresholds
  - Trade-off:
    - ✓ No event-by-event nuclear vs electron recoil discrimination

iZIP sensors measure E_t, and n_{eh}



HV sensors measure E_t



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Solid-state cryogenic detectors

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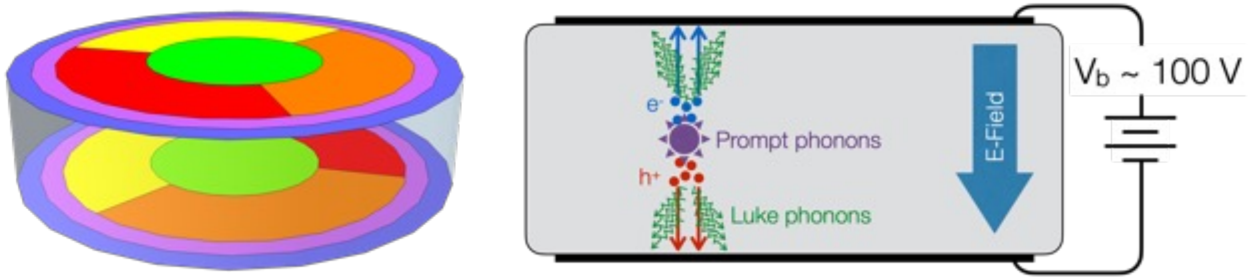
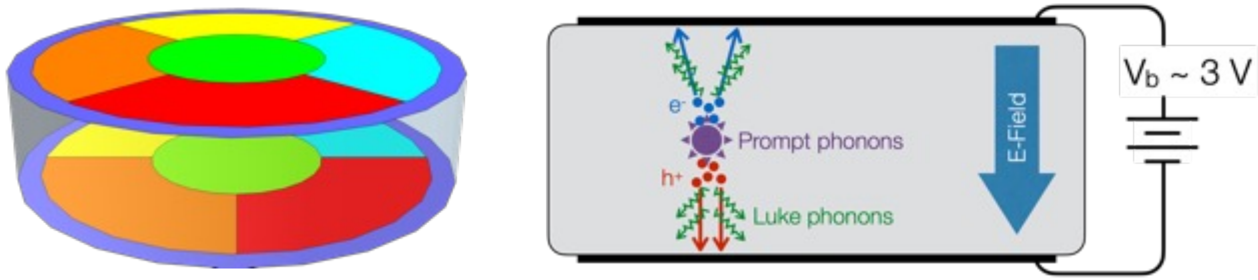
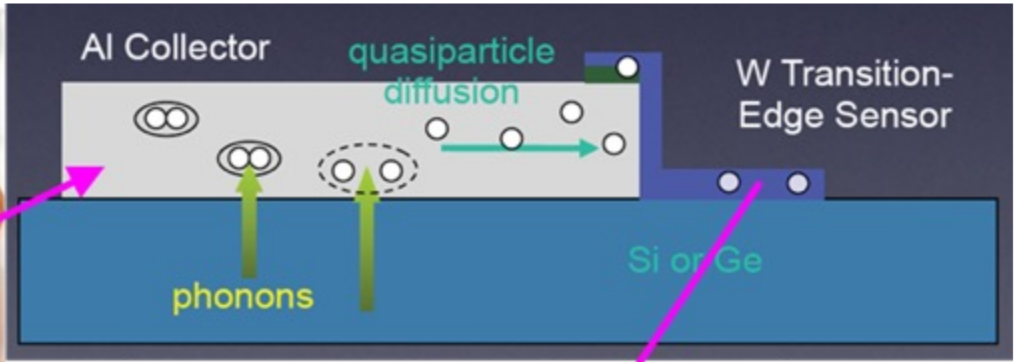
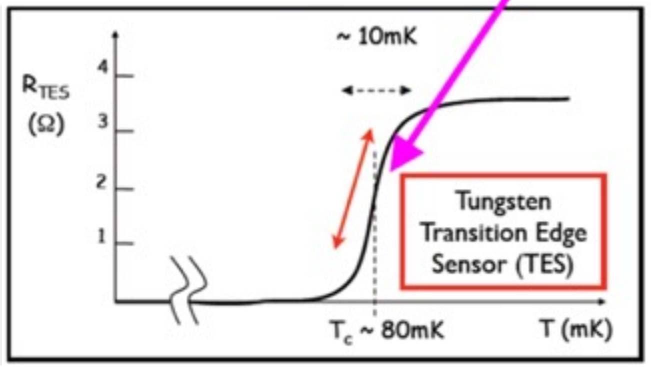
- High Voltage (HV) – Phonon-only measurement of ionization charge



- interleaved Z-dependent Ionization & Phonon (iZIP) – NR/ER discrimination





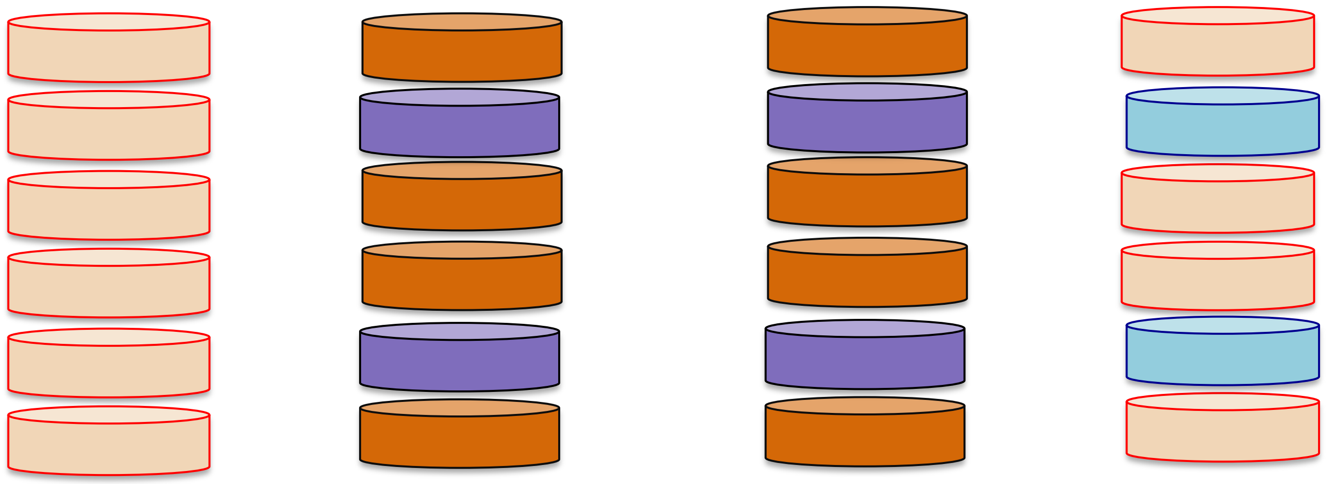


Athermal phonon sensor technology

Used on both detector designs

Complementary targets with multiple functionality

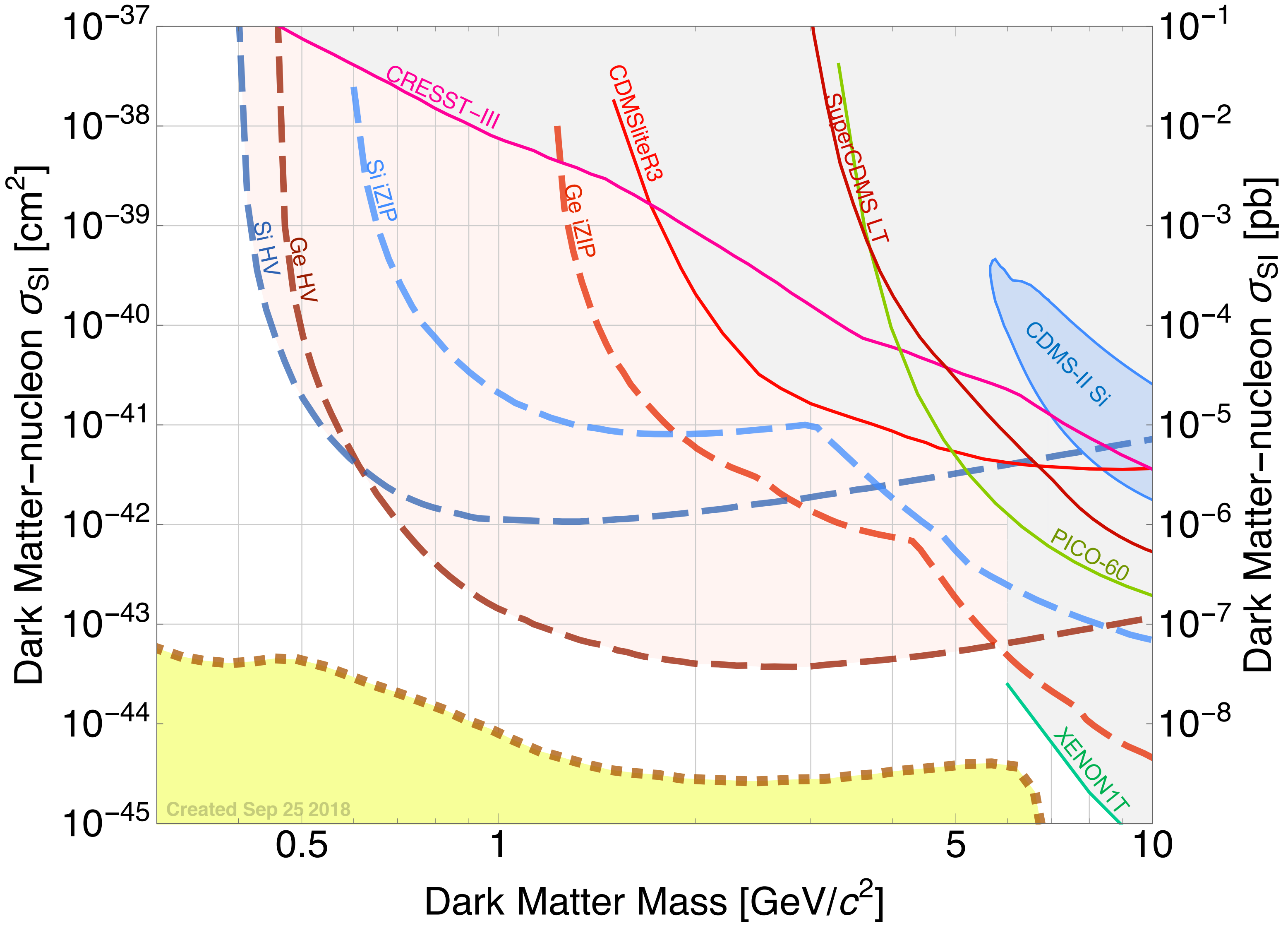
	Germanium	Silicon
HV	Lowest threshold for low mass DM *Larger exposure, no ^{32}Si background*	Lowest threshold for low mass DM *Sensitive to lowest DM masses*
iZIP	Nuclear Recoil Discrimination *Understand Ge backgrounds*	Nuclear Recoil Discrimination *Understand Si backgrounds*

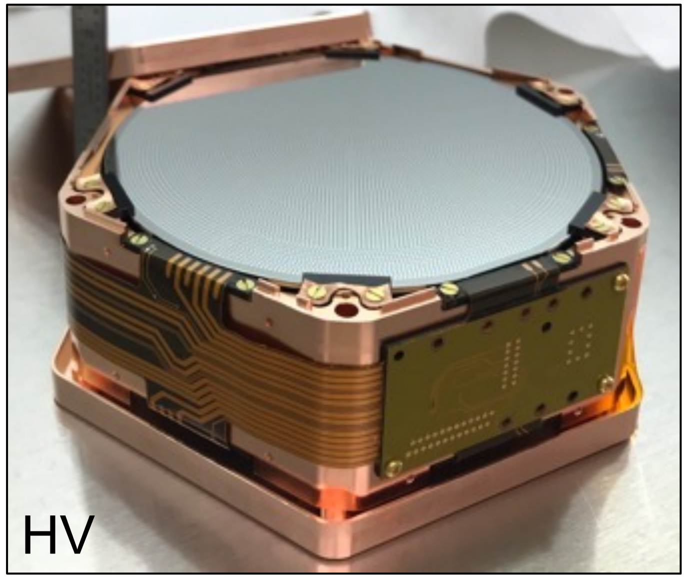


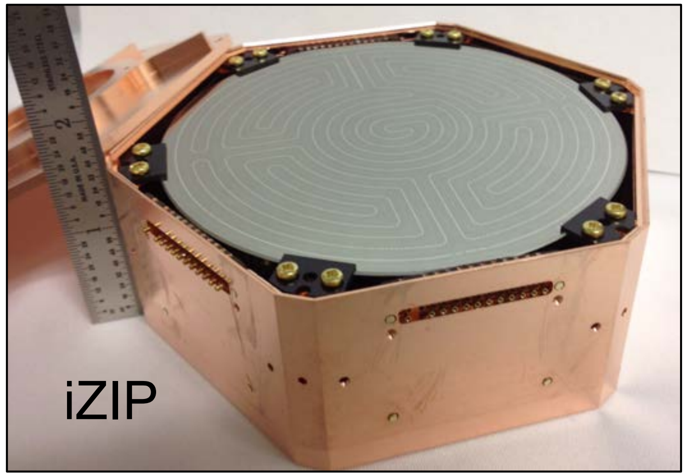
Two nuclear targets provide for different dark matter scattering interaction rates

Sensitivity reach of SuperCDMS

- Direct detection search for spin-independent dark matter interactions

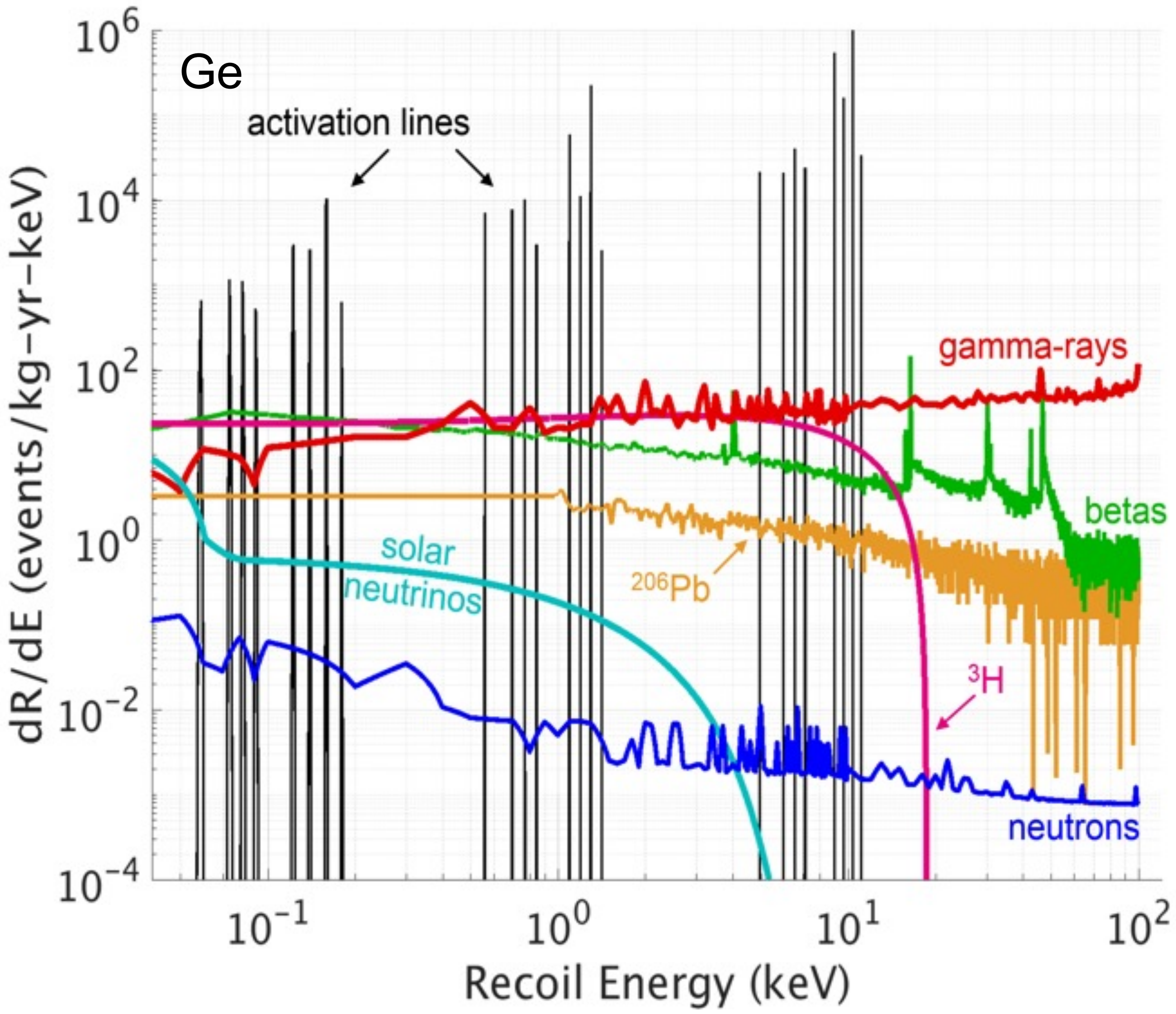


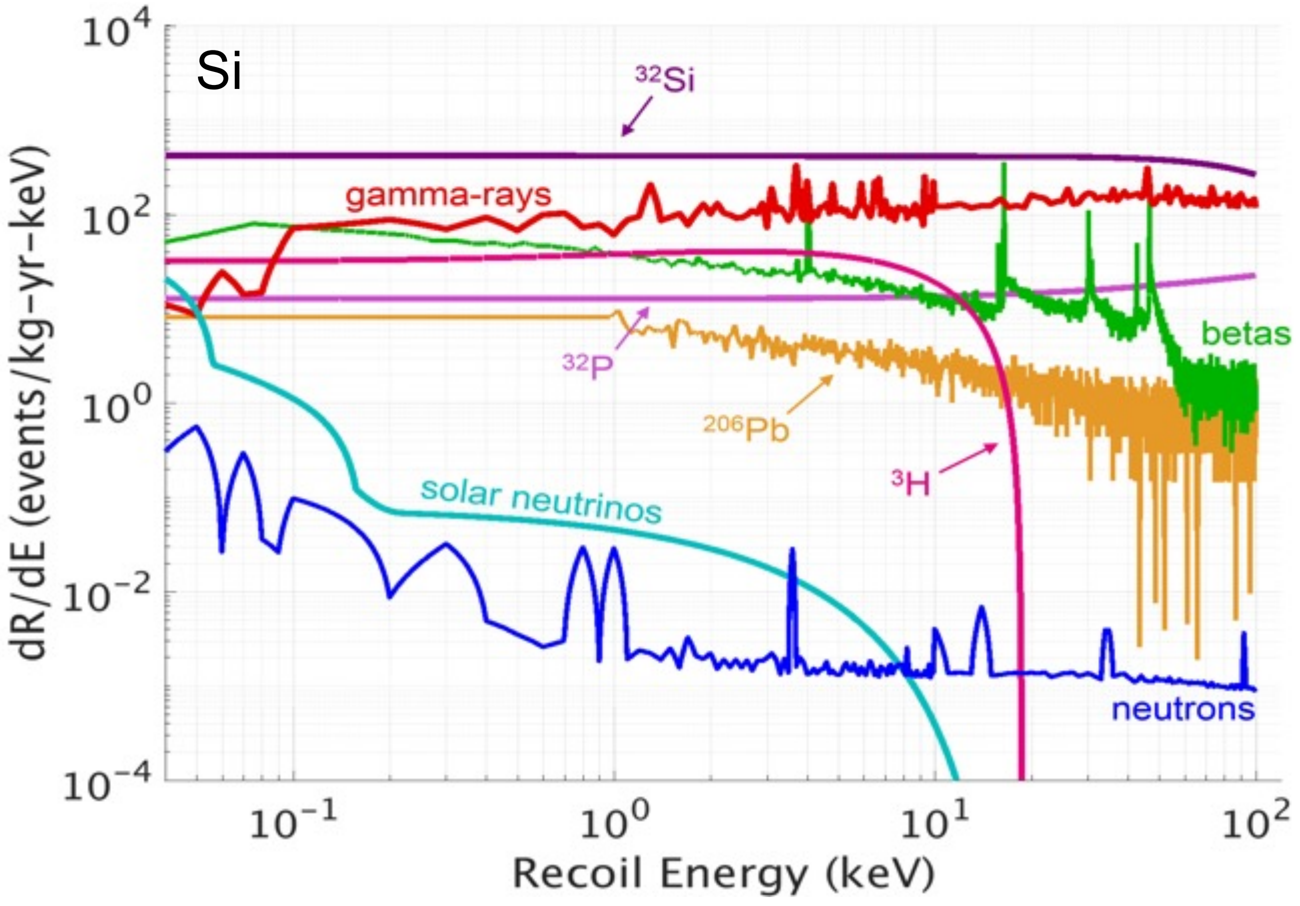




Backgrounds overview

- Tritium, ^{32}Si (in Si), activated copper, surface Rn progeny, material impurities





Spectra shown before detector resolution and application of single-scatter, fiducial volume, and nuclear recoil cuts

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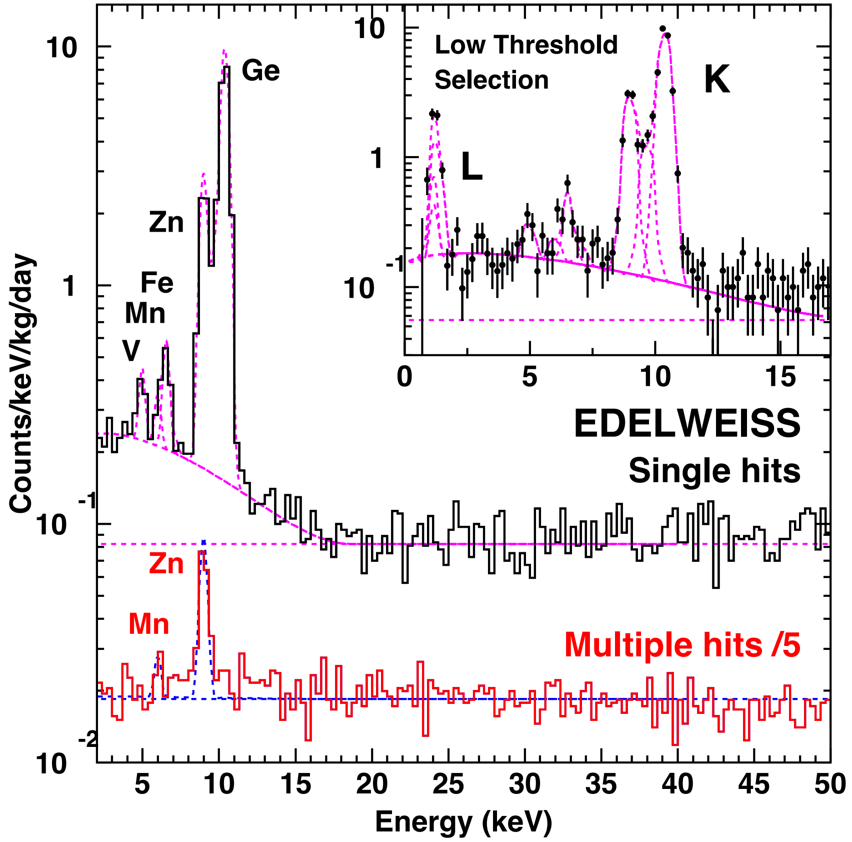
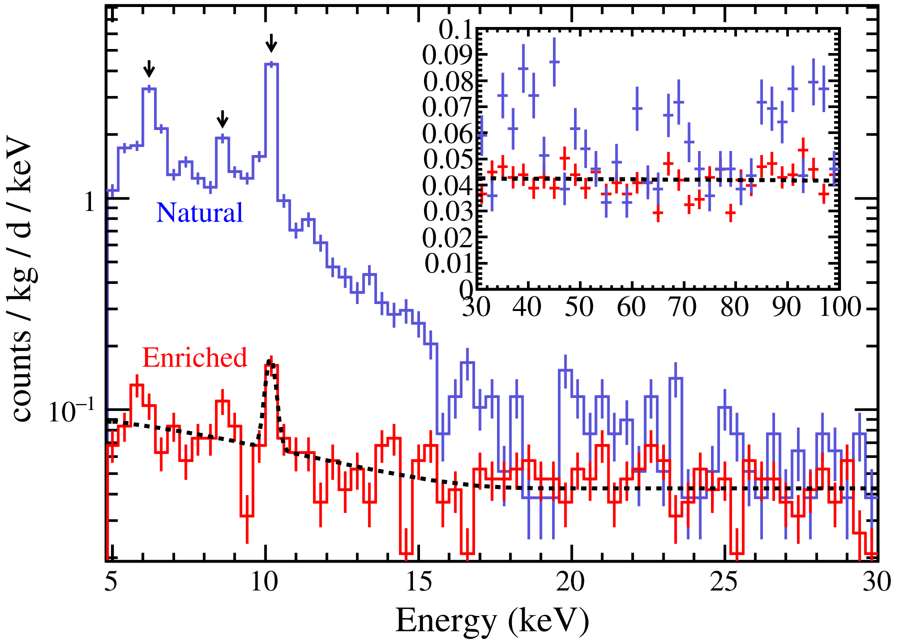
Tritium from cosmic ray spallation

SUPER CDMS
Cryogenic Dark Matter Search

- Exposure of Ge & Si crystals to secondary cosmic rays (*e.g.*, n, p, μ) causes nuclear spallation producing a variety of long-lived, unstable nuclei
  - Tritium (^{3}H) is especially problematic: $t_{½}$ = 12.3 yr, pure β-decay, E_{β}^{End} = 18.6 keV

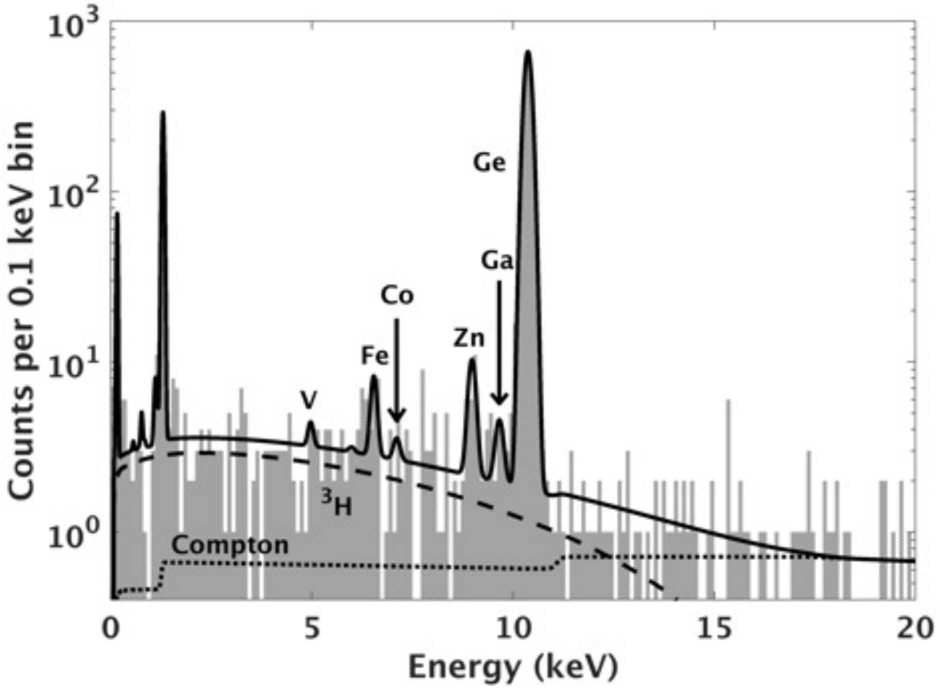


E. Armengaud *et al.*,
Astropart. Phys. 91 (2017) 51-64



MAJORANA DEMONSTRATOR

N. Abgrall *et al.*,
NIM A 877 (2018) 314-322



CDMSlite Run 2 (Soudan)

R. Agnese *et al.*,
Astropart. Phys. (2019) 1-12

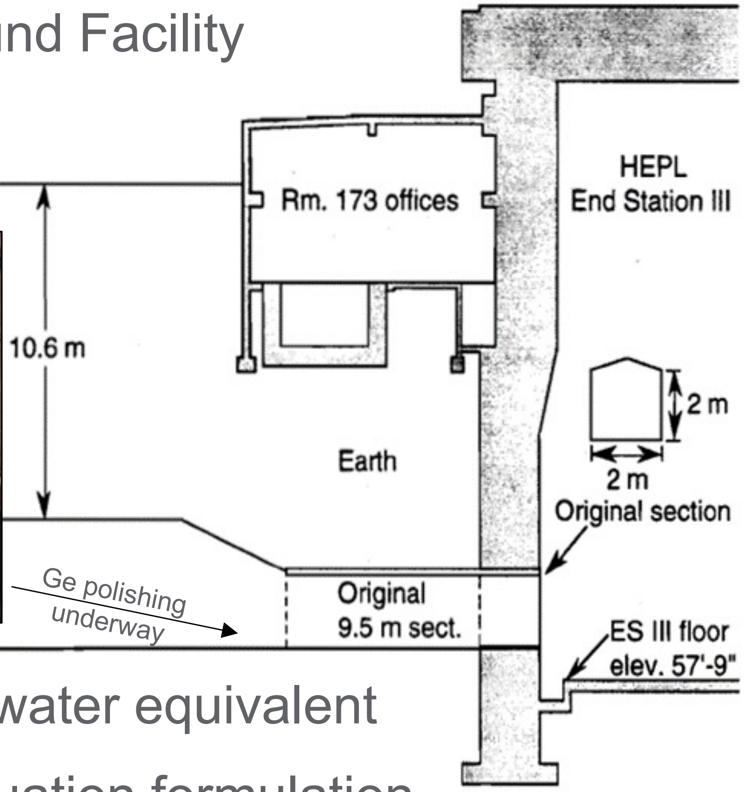
Tritium from cosmic ray spallation

- SuperCDMS SNOLAB Goal: Less than 60 days sea level equivalent exposure
  - One of four towers is composed of iZIPs with longer surface exposure
  - Crystals had <8 days seal level equivalent after shipment from Europe to SLAC

Thank you
MAJORANA & GERDA!

Shielded shipping container critical to meet exposure goal

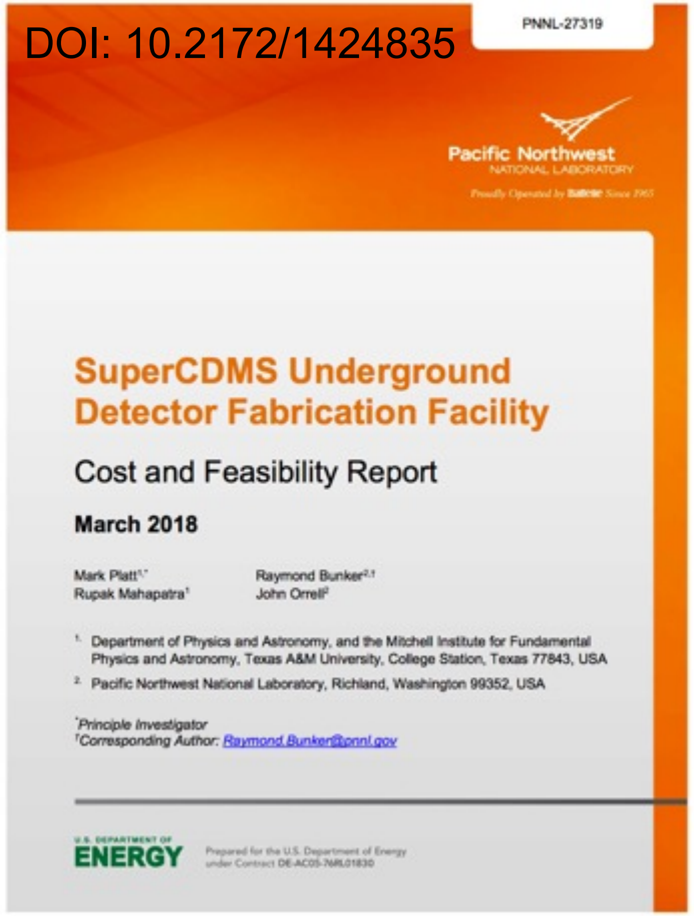
Underground storage & polishing at Stanford Underground Facility



Depth 25±2 meter water equivalent

Evaluated via attenuation formulation employed by muon-tomographers

Barbouti & Rastin
J. Phys. G 9 (1983)1577


DOI: 10.2172/1424835

PNNL-27319

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SuperCDMS Underground Detector Fabrication Facility

Cost and Feasibility Report

March 2018

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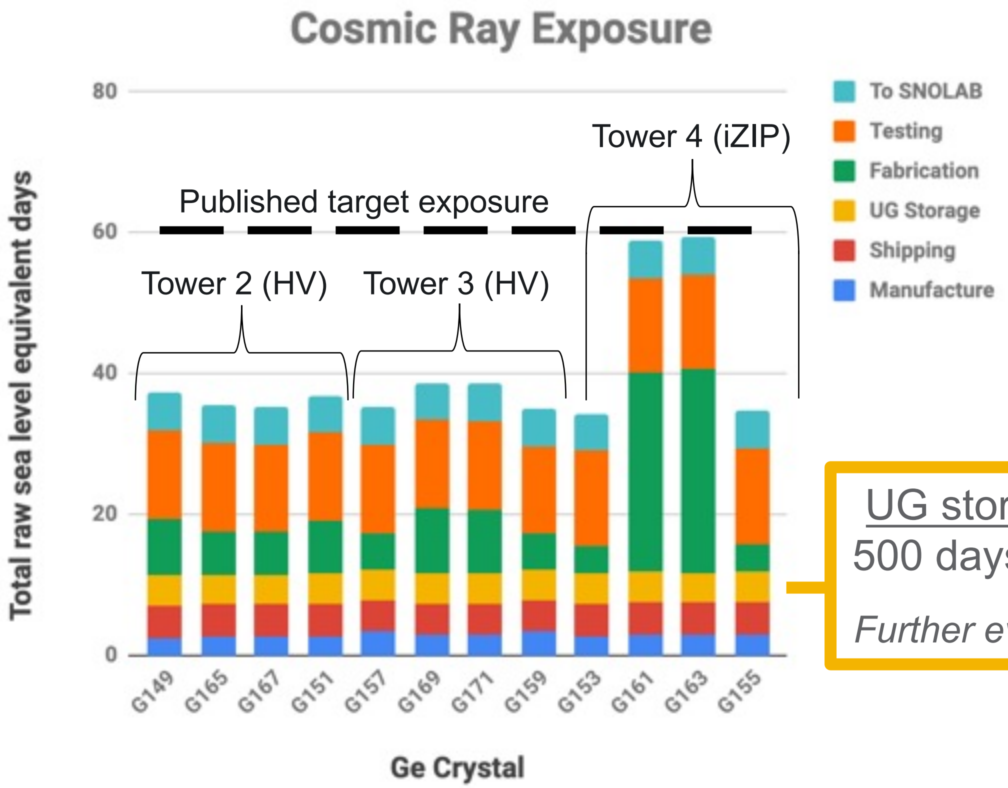
U.S. DEPARTMENT OF ENERGY

Available on www.OSTI.gov

Detector exposure status

- All SuperCDMS detector are underground at SNOLAB
  - Shipment #1: Towers 3 & 4 → 9-12 May 2023 (route shown below)
  - Shipment #2: Towers 1 & 2 → 13-16 November 2023

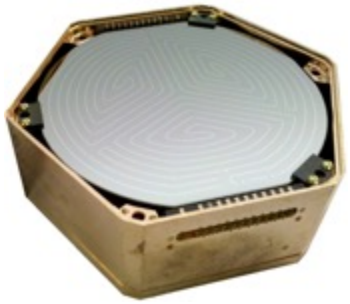


UG storage assumption
500 days UG = 1 day AG
Further evaluation underway

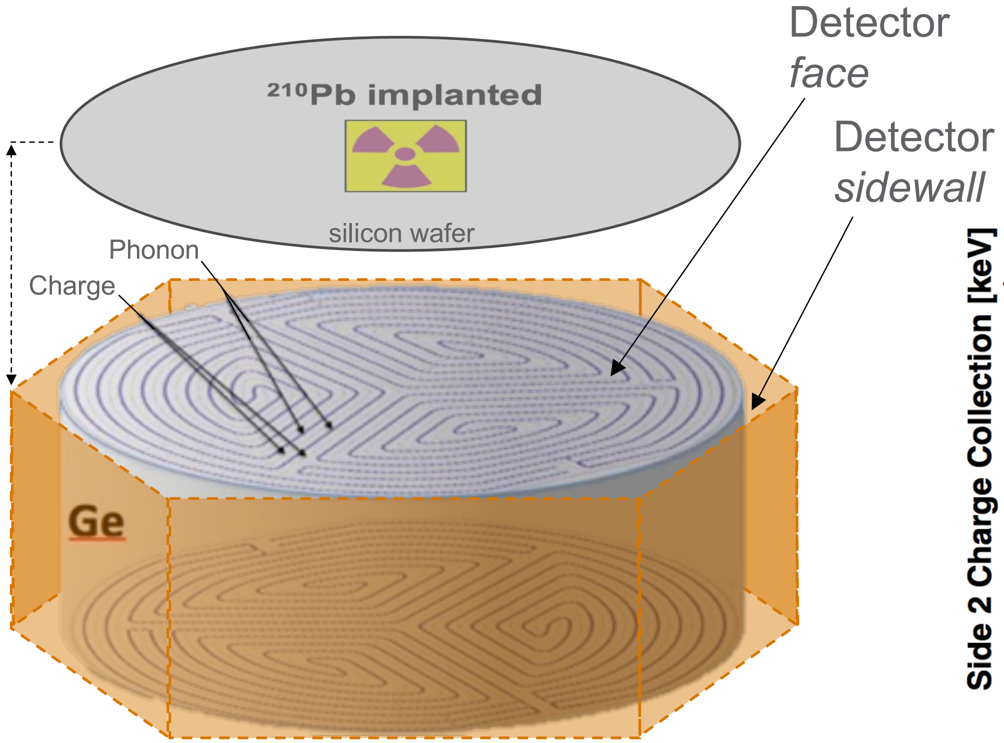
Tower 1 (iZIP) made from previously available crystals (long exposure time)

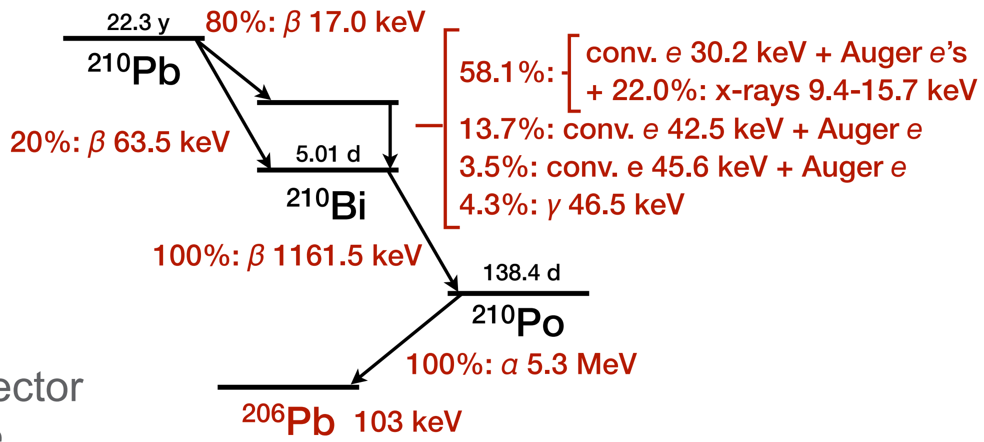
Surface backgrounds (Rn progeny)

- Radon progeny (long-lived ^{210}Pb) are potential surface background sources



Soudan iZIP



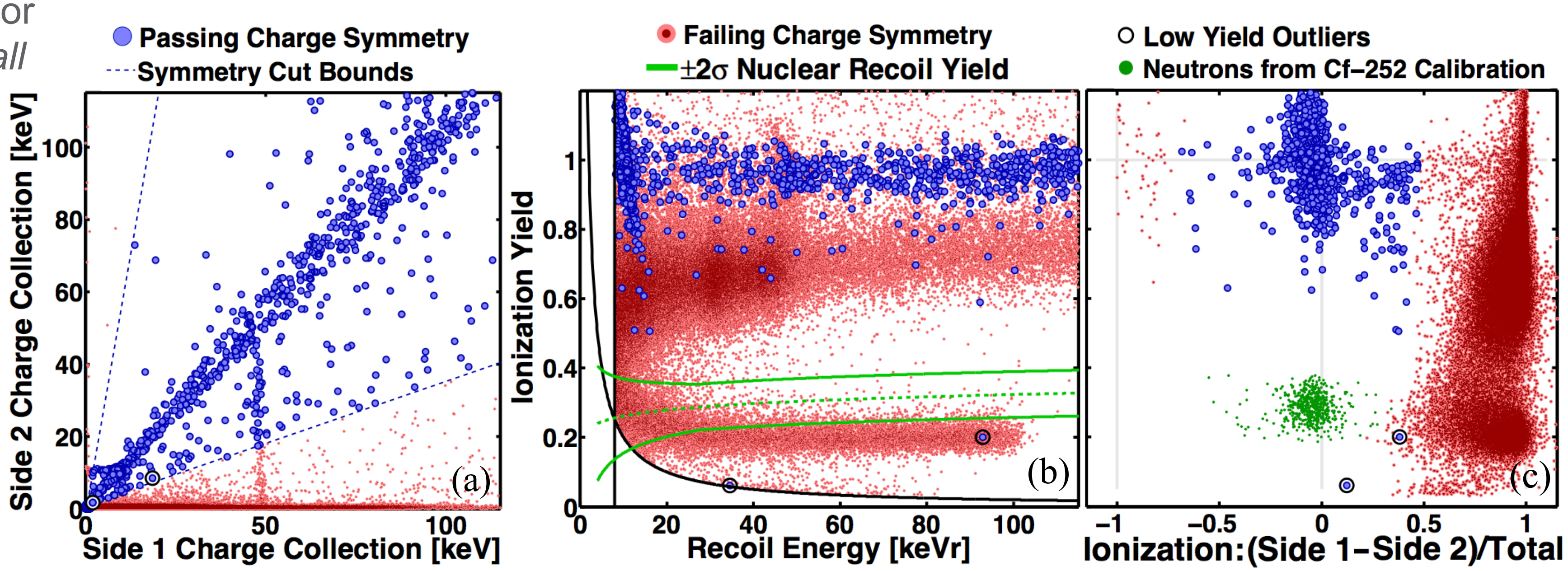


Demonstration of surface electron rejection with interleaved germanium detectors for dark matter searches

R. Agnese *et al.*,
Appl. Phys. Lett. 103 (2013) 164105

Caveats

Performed with iZIP, not HV detector
Surface source only irradiated detector *face*



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Cu surface background at detector sidewall

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- SuperCDMS progressing from Soudan

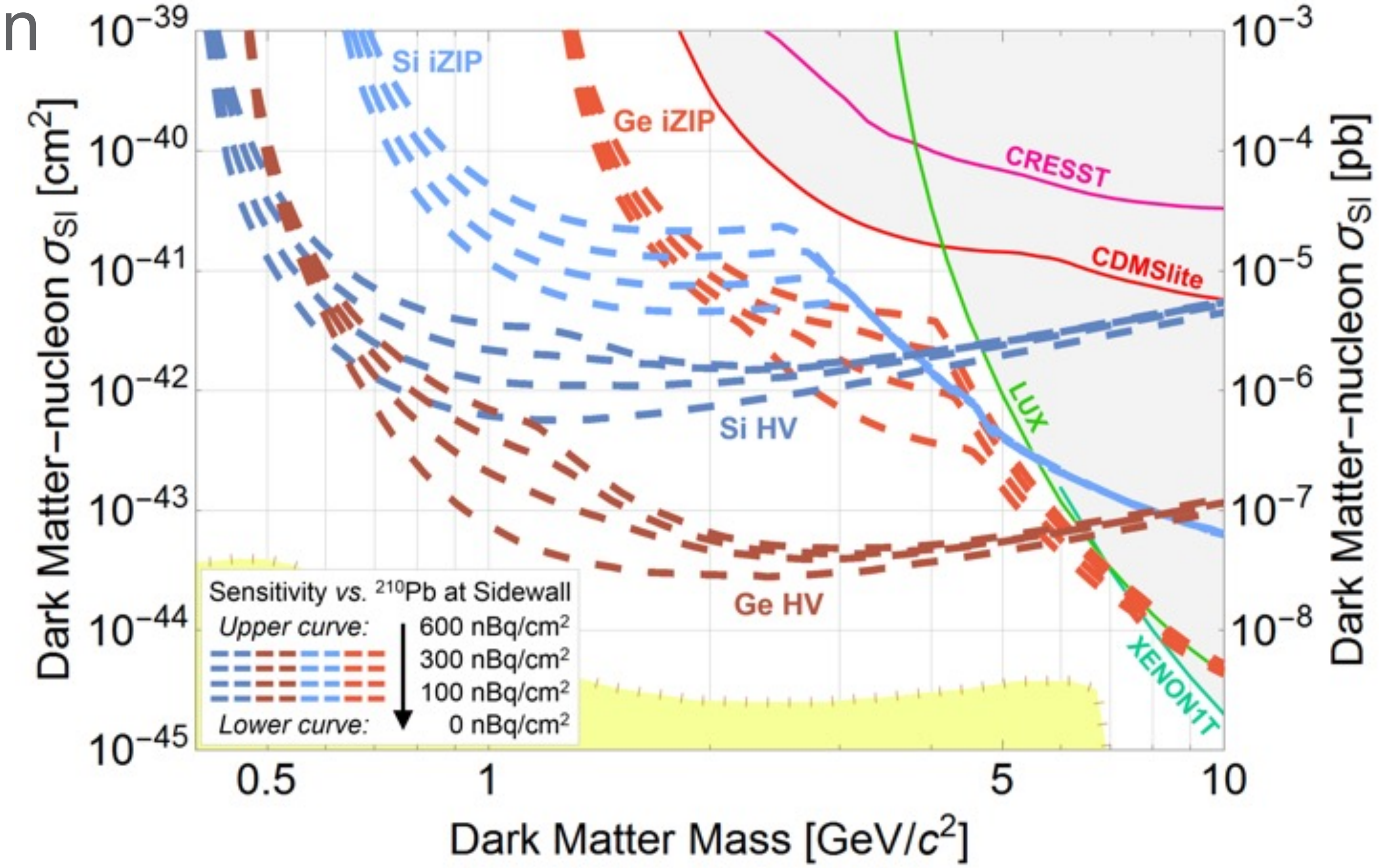
<u>At Soudan:</u> (based on T2Z1)

- Bottom face: 20 nBq/cm^2
- Sidewall total: 1000 nBq/cm^2

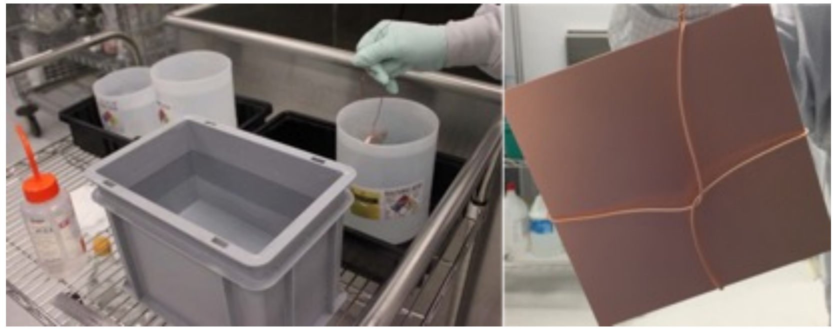
<u>SNOLAB Goals:</u>

- Detector faces: 25 nBq/cm^2
- Sidewalls: 50 nBq/cm^2

Sensitivity study vs. sidewall activity



- Summary concern → Cu cleanliness
  - Using acidified-peroxide etching followed by citric acid passivation



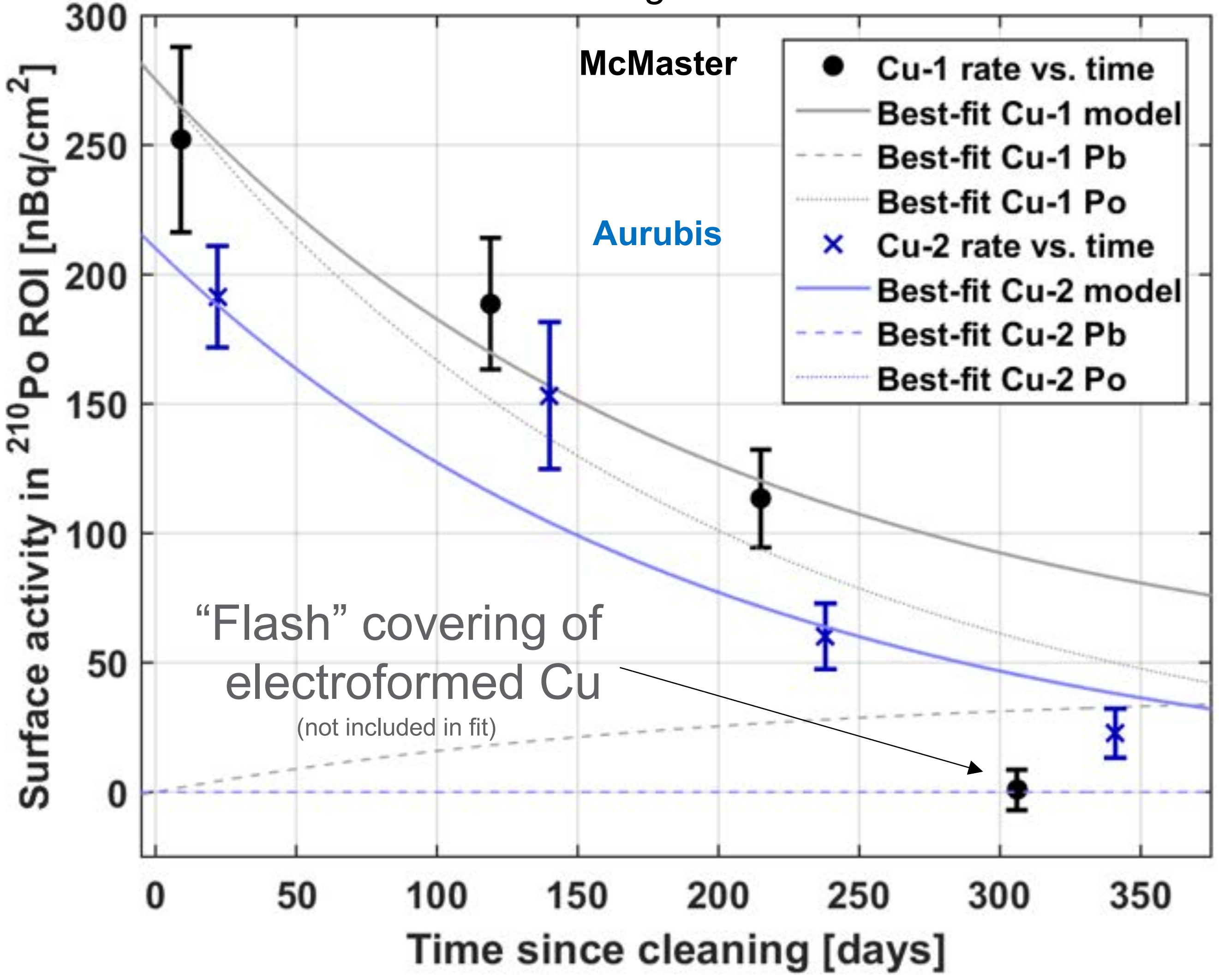
  - Tested on McMaster and Aurubis copper

Cleanliness tested with XIA Ultra-Lo1800 alpha counter by measuring polonium (^{210}Po), not lead (^{210}Pb) !!!

Cu surface background evaluation

- One year's worth of XIA Ultra-Lo1800 measurements on cleaned Cu surfaces
  - Shows unsupported ^{210}Po on Cu surface
  - Electroformed Cu doesn't show effect
  - Suggests ^{210}Pb in bulk of Cu

XIA Ultra-Lo1800 background subtracted rates



- XMASS measured ^{210}Po in bulk Cu
  - Inferring 17-40 mBq of ^{210}Pb per kg Cu
  - K. Abe *et al*., NIM A 884 (2018) 157-161

- In summary:
  - Cu surfaces are clean for SuperCDMS
  - Bulk ^{210}Pb in Cu is out of ^{238}U equilibrium
  - R. Bunker *et al*., NIM A 967 (202) 163870

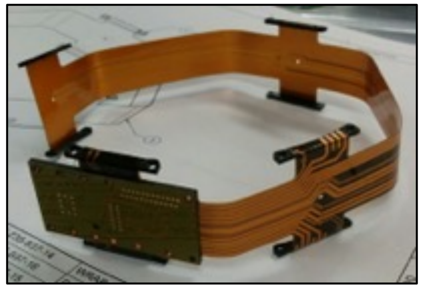
Kapton & Cirlex trace radio-impurities

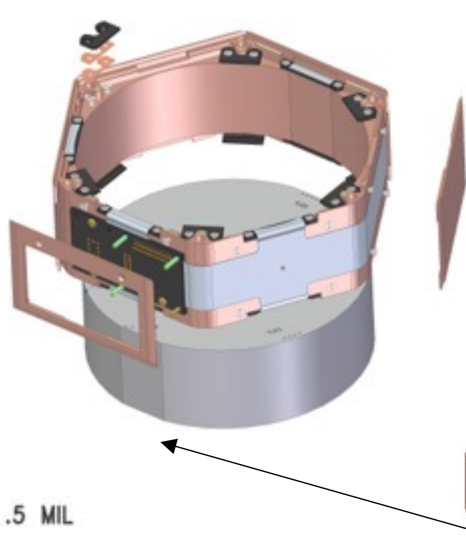
- SuperCDMS uses Kapton & Cirlex in electrical readout from detector towers
  - Anticipated 17% of Ge HV background of SuperCDMS SNOLAB experiment
  - Of this 17%… 81% is from equally Th and ^{40}K
- Kapton:
  - DuPont polyimide film

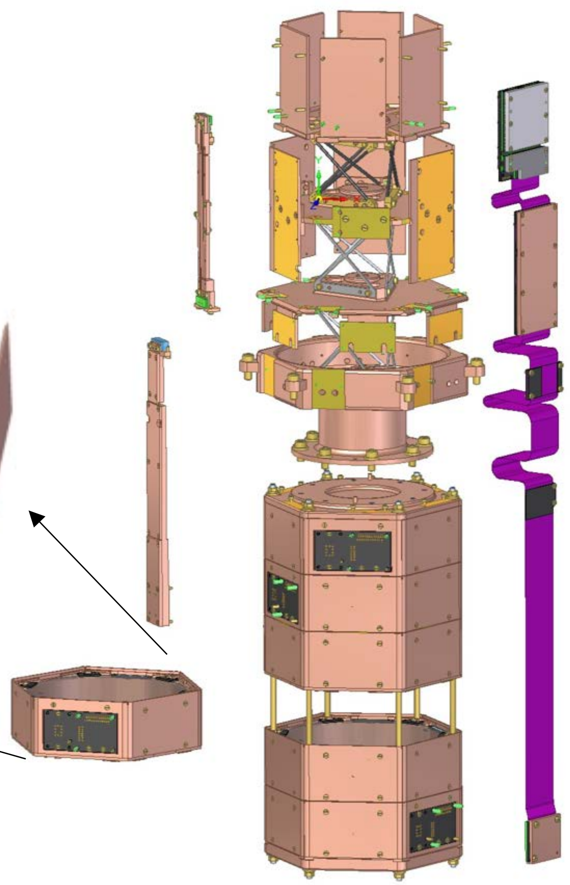
- Cirlex
  - Fralock product
  - Adhesively layered Kapton

Acceptable, but a target for materials R&D
See next slide!

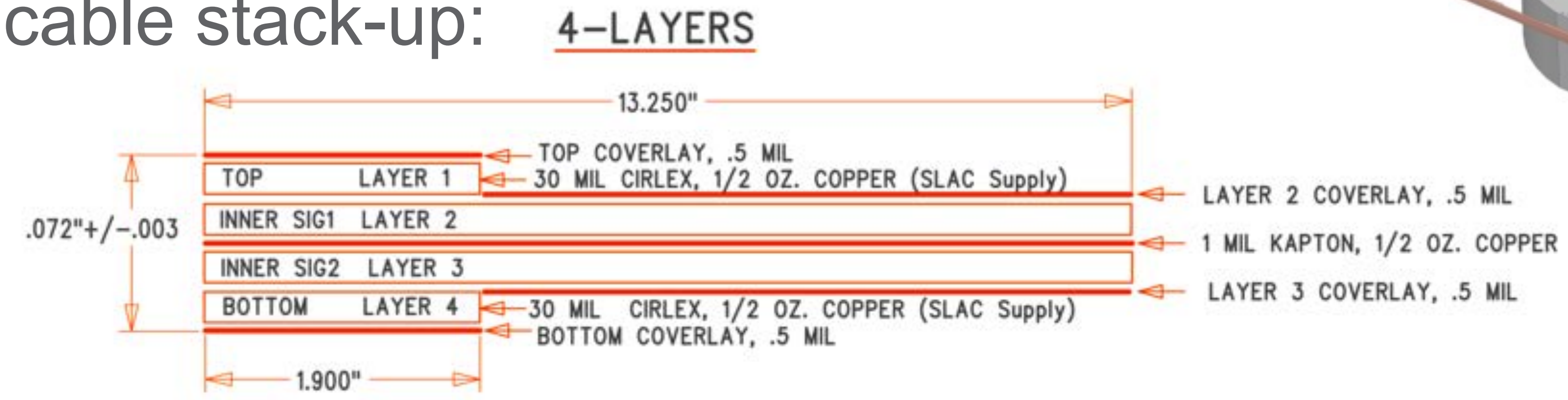
Detector Tower







- SuperCDMS flex cable stack-up:



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PNNL efforts on clean Kapton

Sponsors

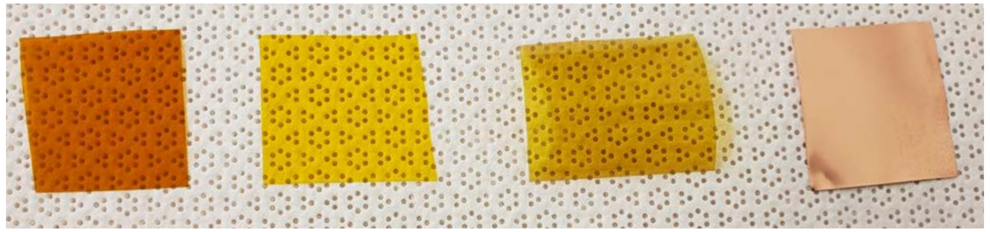
SBIR·STTR America's Seed Fund

Partners

DUPONT

Q-FLEX INC.

- Ultra-low radioactivity Kapton and copper-Kapton laminates
  - IJ Arnquist *et al.*, **Nucl. Instrum. Meth. in Phys. Res. Sec. A** 959 (2020) 163573



Kapton	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
Commercial HN	1080 +/- 40	250 +/- 8	44 +/- 18
Radiopure R&D	12.3 +/- 1.9	19 +/- 2	34 +/- 14

Kapton-Cu Laminates	^{238}U [pg/g]	^{232}Th [pg/g]	^{nat}K [ng/g]
Commercial	158 +/- 6	24.1 +/- 0.9	< 210
Radiopure	9 +/- 4	20 +/- 14	160 +/- 80

- Ultra-low radioactivity flexible printed cables
  - IJ Arnquist *et al.*, **EPJ Techniques and Instrumentation** 10 (2023) 17

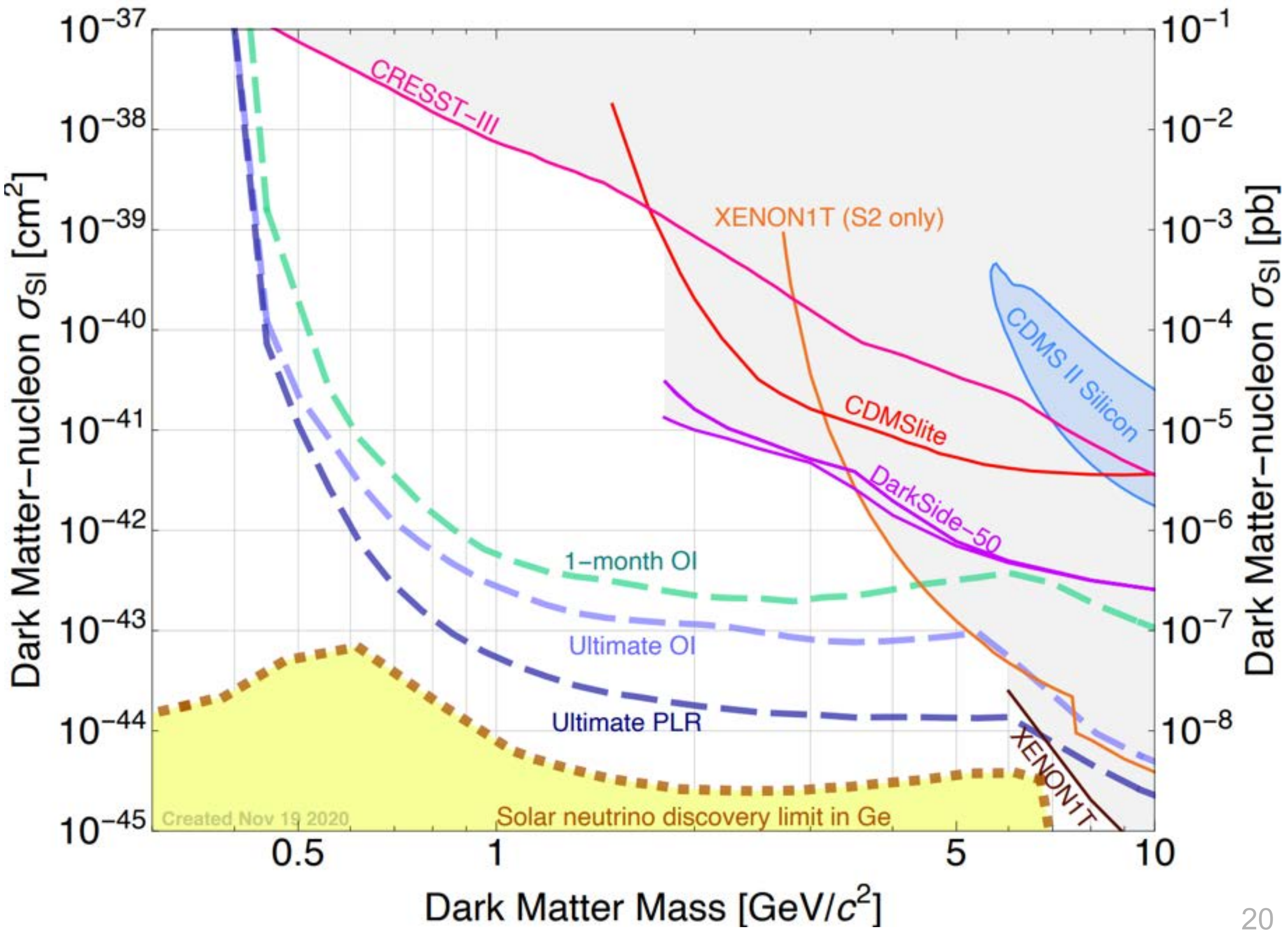
Blue: Standard Step
Orange Outline: Modified Step
Orange: New Step
Green: Step done at PNNL

Cables	^{238}U [ppt]	^{232}Th [ppt]	^{nat}K [ppb]
Commercial	2670 +/- 30	260 +/- 10	170 +/- 50
Clean	31 +/- 2	13 +/- 3	550 +/- 20

SuperCDMS HV sensitivity in stages of study

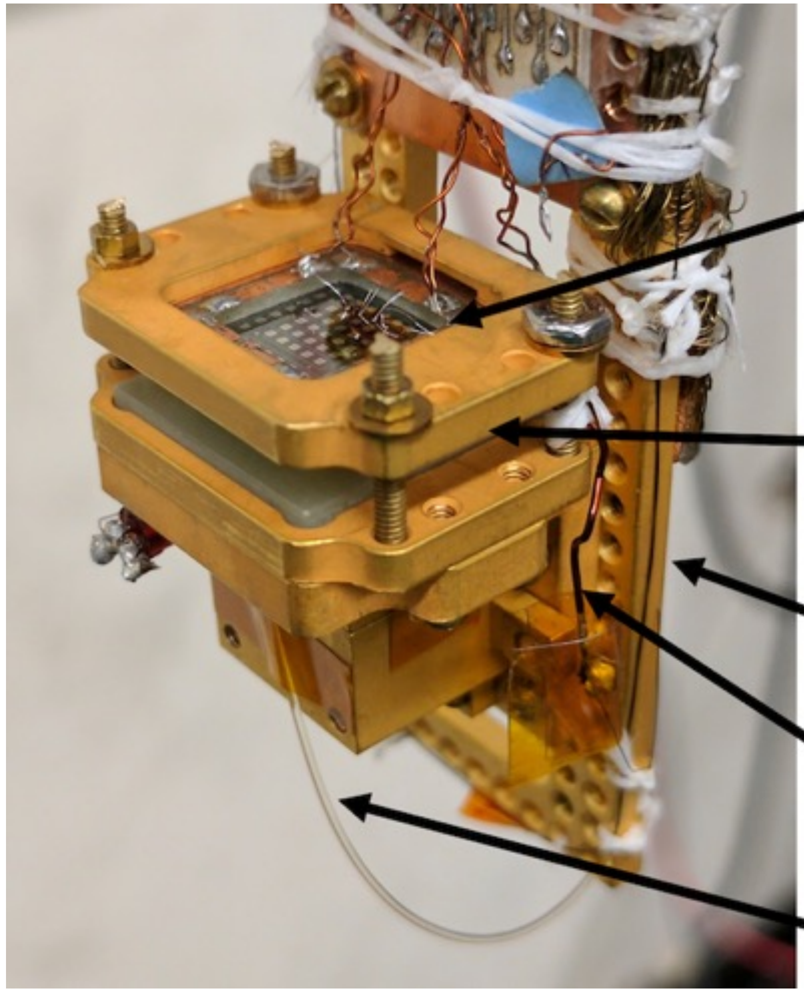
Projected Limits

- OI – Optimal Interval
  - No background assumption
- PLR – Profile Likelihood Ratio
  - Employs background model



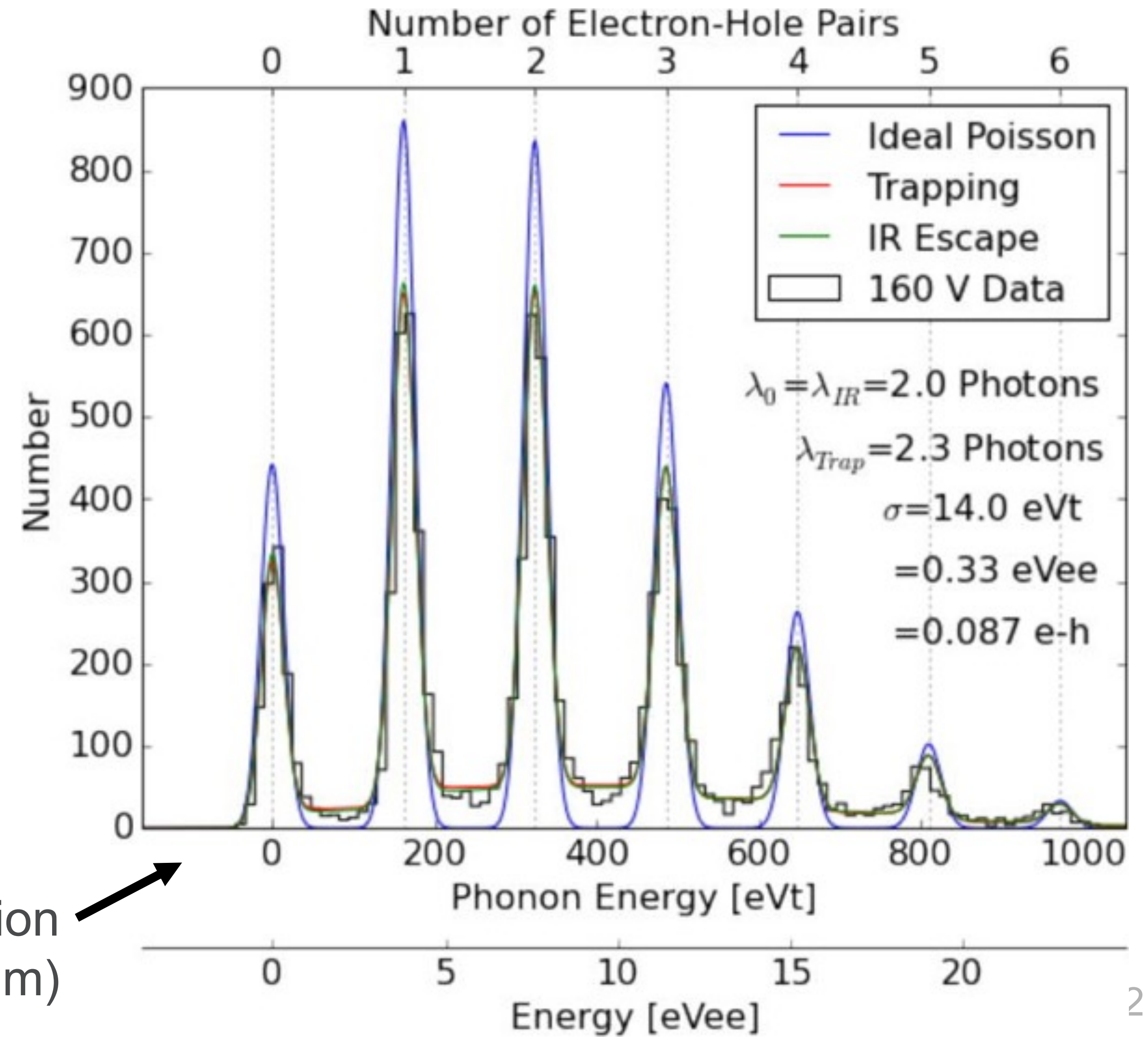
R&D HVeV detectors

- Developments using the athermal phonon sensor technology
  - R.K. Romani *et al.*, Appl. Phys. Lett. 112 (2018) 043501



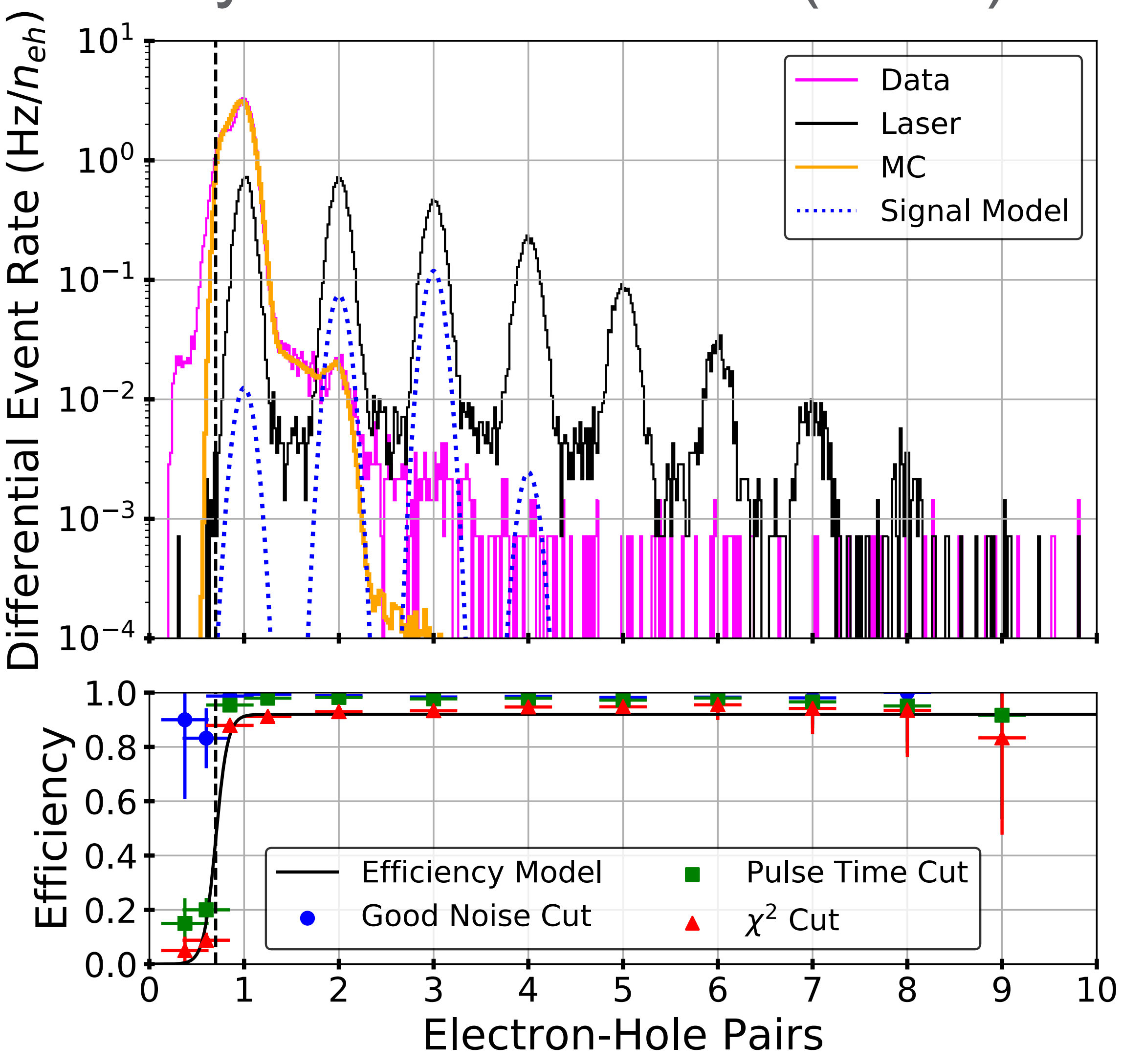
1 cm² by 4 mm thick silicon crystal (0.93 g)

… Illumination (650 nm)

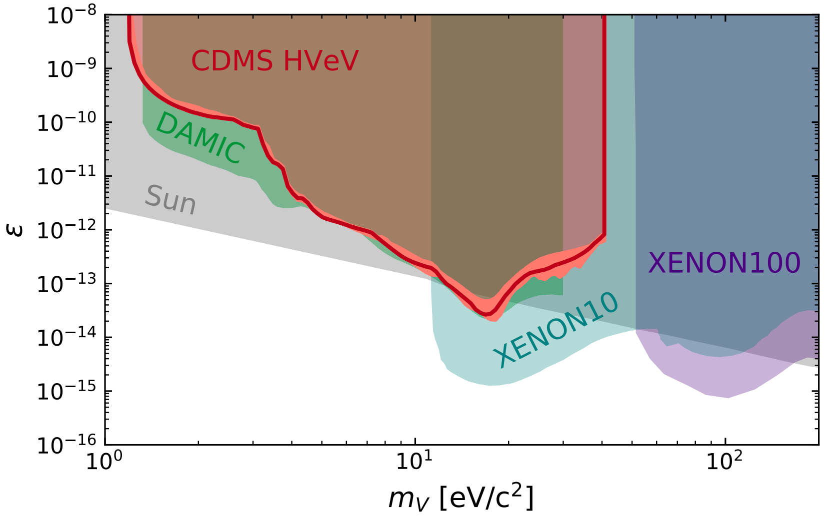


R&D HVeV detectors

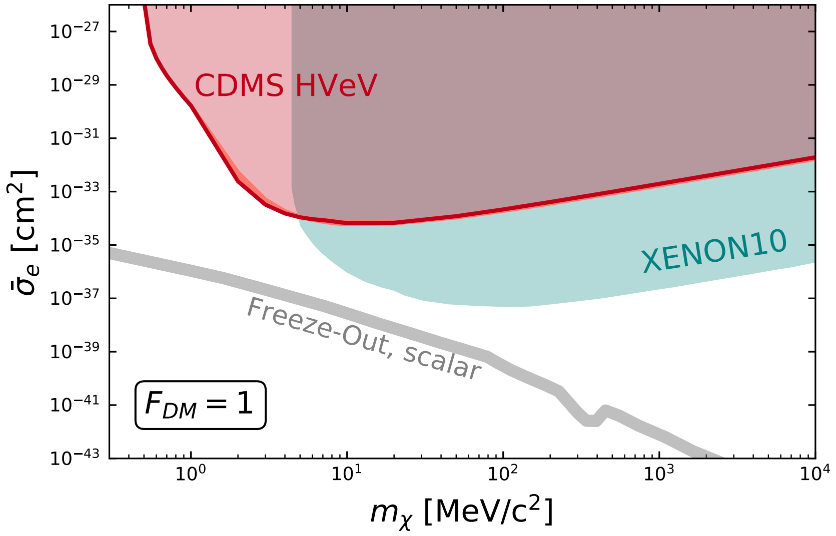
- R. Agnese *et al.*, Phys. Rev. Lett. 121 (2018) 051301



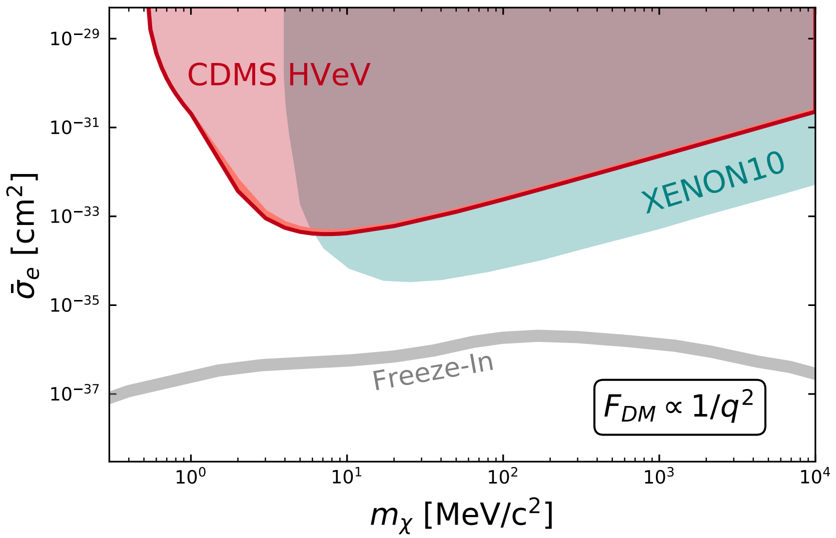
dark photon kinetic mixing



heavy dark photon



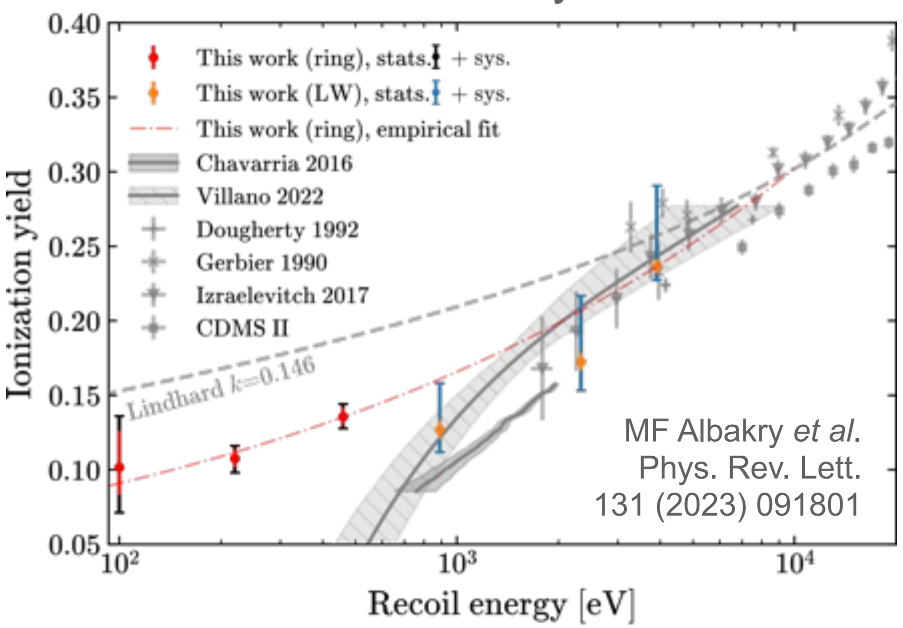
ultra-light dark photon



Optimum interval 90% C.L. limits
No background subtraction

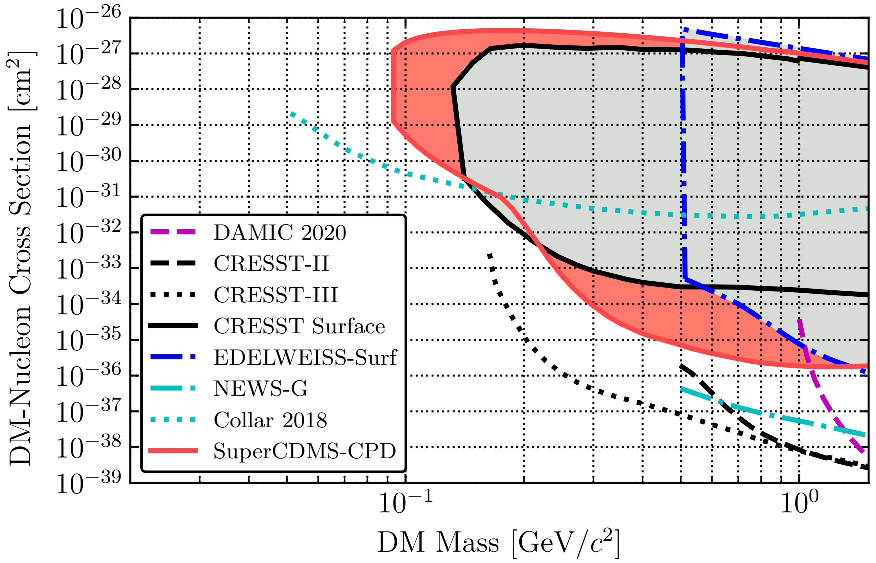
Recent HVeV results & Cryogenic PhotoDetector (CPD)

Nuclear-recoil ionization yield in silicon HVeV

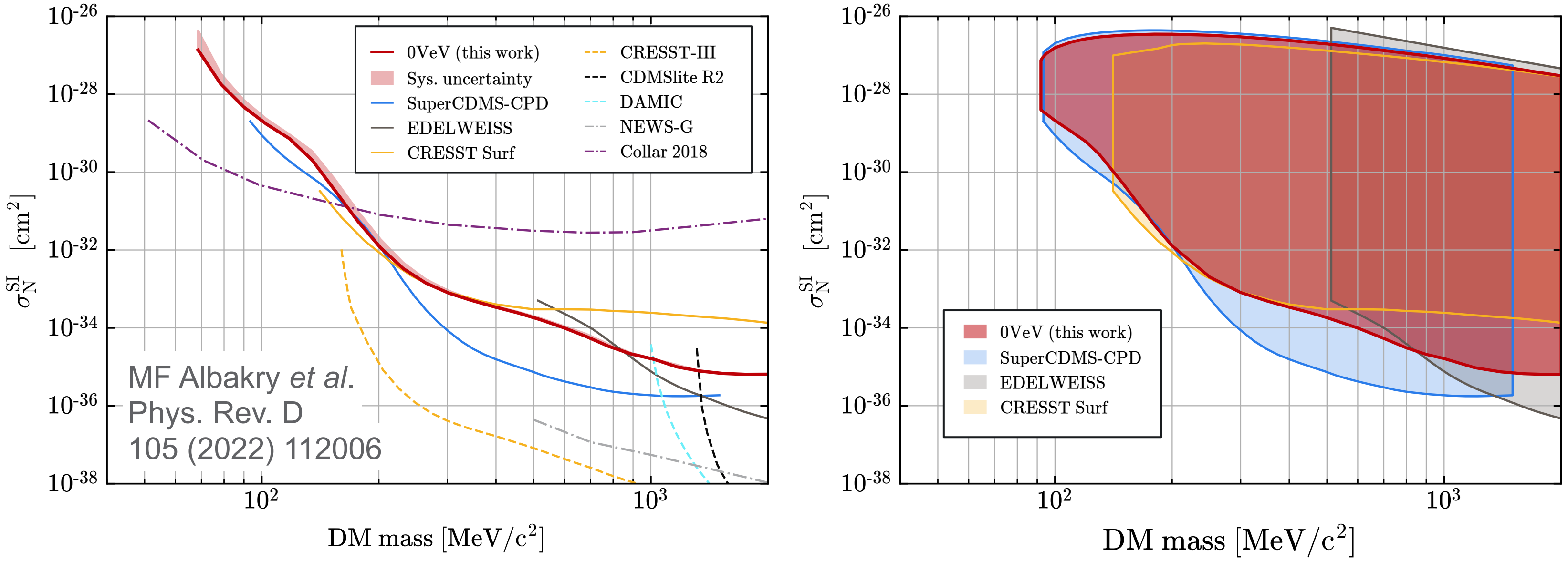


Cryogenic PhotoDetector (CPD)

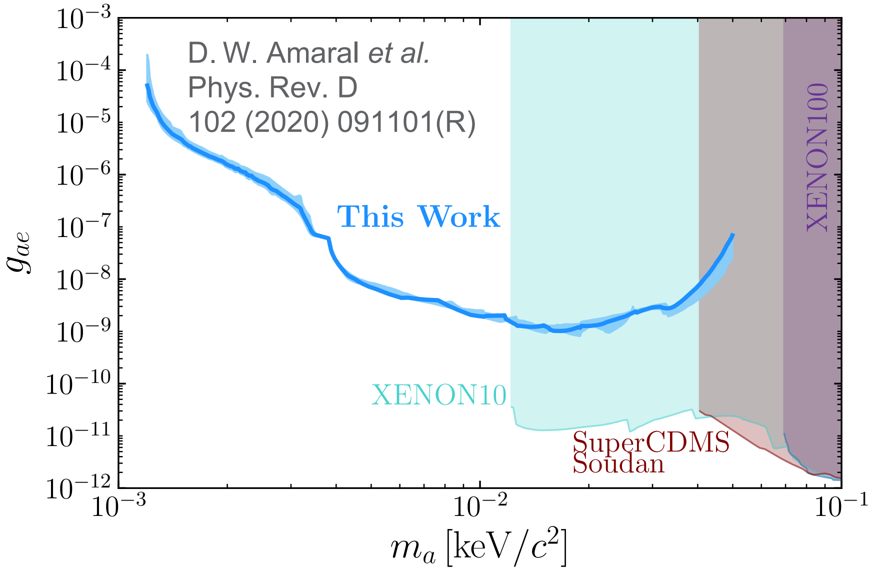
I Alkhatib *et al.*, Phys. Rev. Lett., 127 (2021) 061801



Limits from HVeV detector operated at 0 V bias



Axion-like particle limits from silicon HVeV

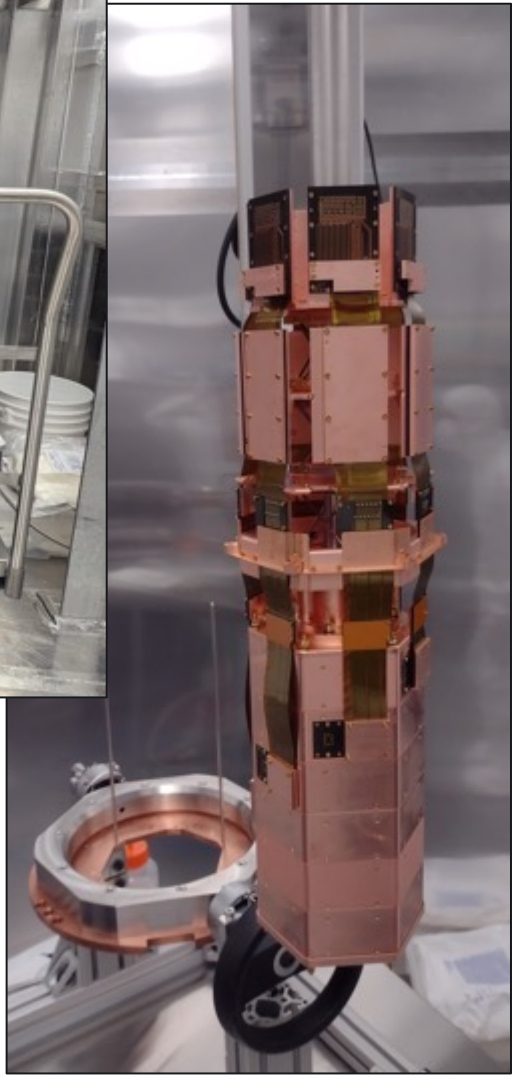


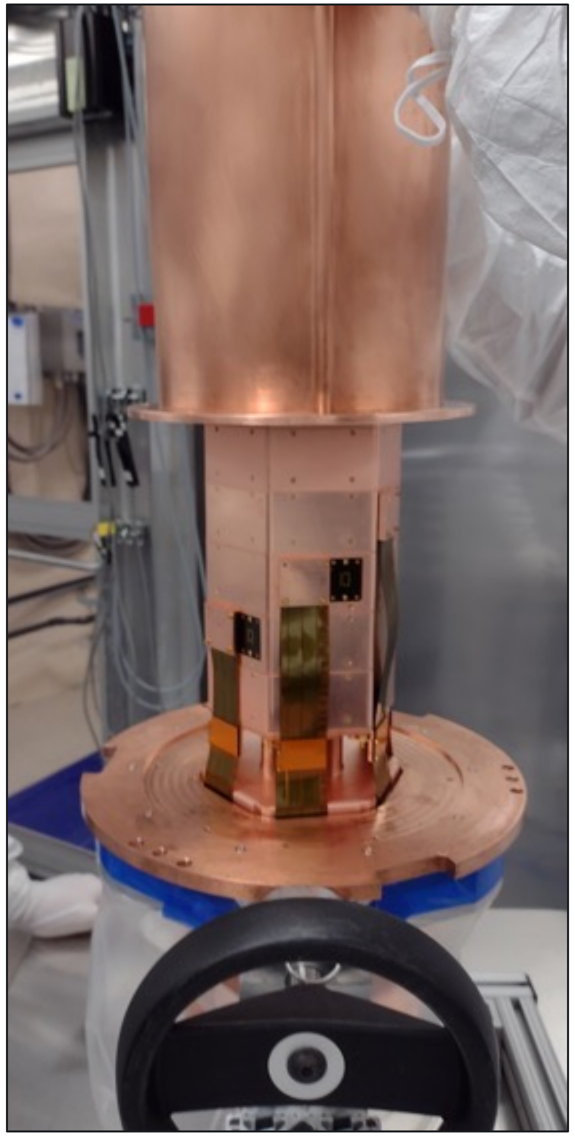
Detectors underground, CUTE testing getting underway

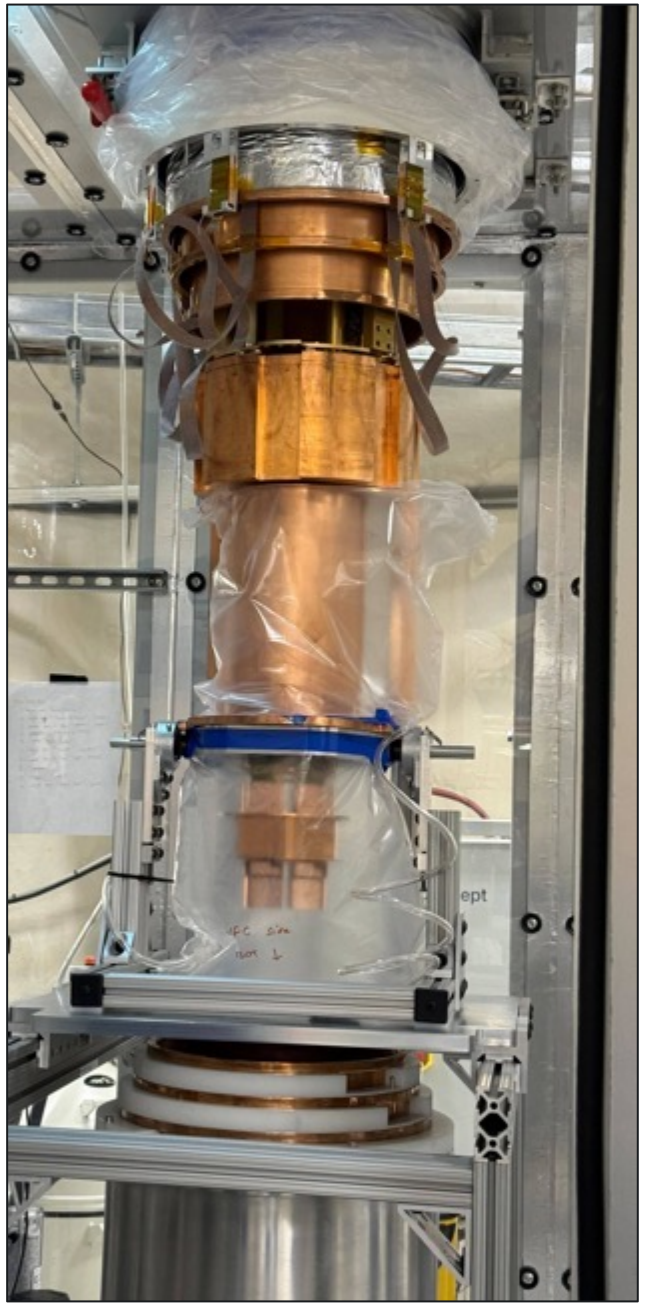
- All SuperCDMS detector are underground at SNOLAB

Towers in storage

HV Tower





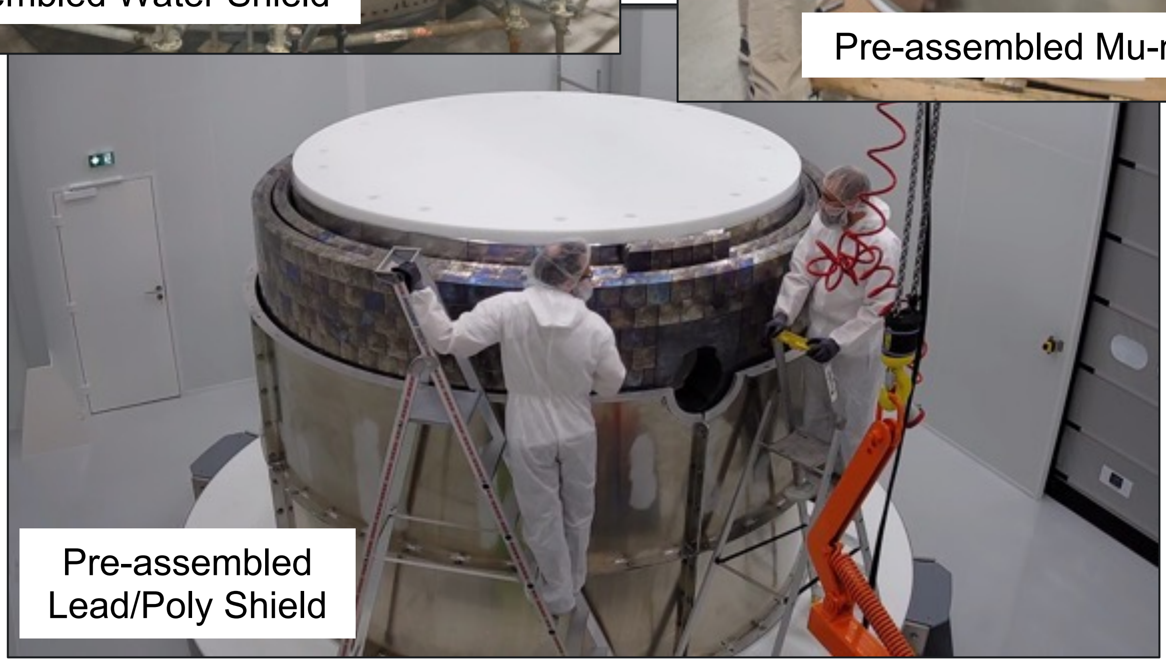


In CUTE

Shield components coming together


Pre-assembled Water Shield


Pre-assembled Mu-metal Shield


Pre-assembled Lead/Poly Shield

Above ground pre-assemblies

Underground progress

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Summary

SUPER CDMS Cryogenic Dark Matter Search

- SuperCDMS searching for direct detection of low mass dark matter
  - Projected reach $\sigma \sim 10^{-43}$ cm^2 at 1 GeV/c^2 dark matter mass
  - All detector towers underground at SNOLAB
  - Main shield construction underway and detector operation in CUTE is active
- Anticipated backgrounds: Tritium, ^{32}Si, Rn progeny, material impurities
  - Developments during construction show paths to further reduction in the future
  - Highlighted background sources are of relevance to neutrinoless double beta decay
- Future detectors expected to probe yet lower mass dark matter candidates
  - Anticipate further R&D detector development in parallel with SuperCDMS construction
  - Developments will likely also improve sensitivity to 1-5 GeV/c^2 dark matter candidates

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SUPER CDMS Cryogenic Dark Matter Search

Thank you