DM Direct Detection with SuperCDMS

SUPER CDMS
Cryogenic Dark Matter Search

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2024 CAP Congress

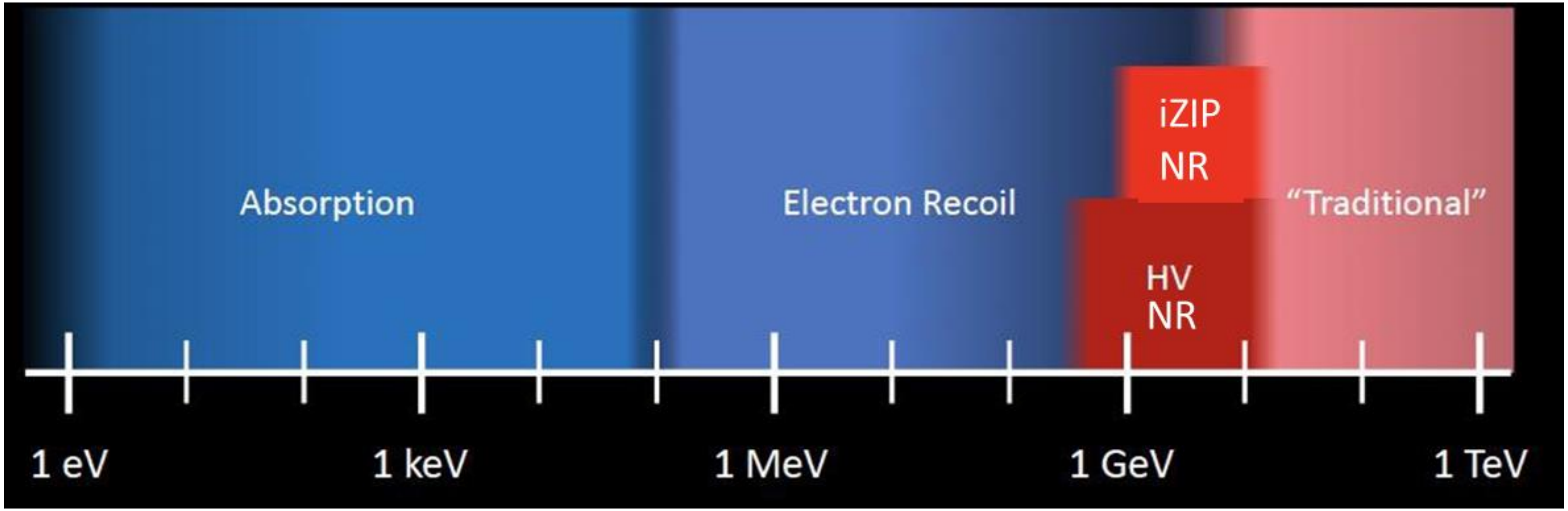
Dark Matter & Neutrinos (PPD) Symposium

May 29, London ON

https://indico.cern.ch/event/1316311/contributions/5880039/

SuperCDMS@SNOLAB at a Glance

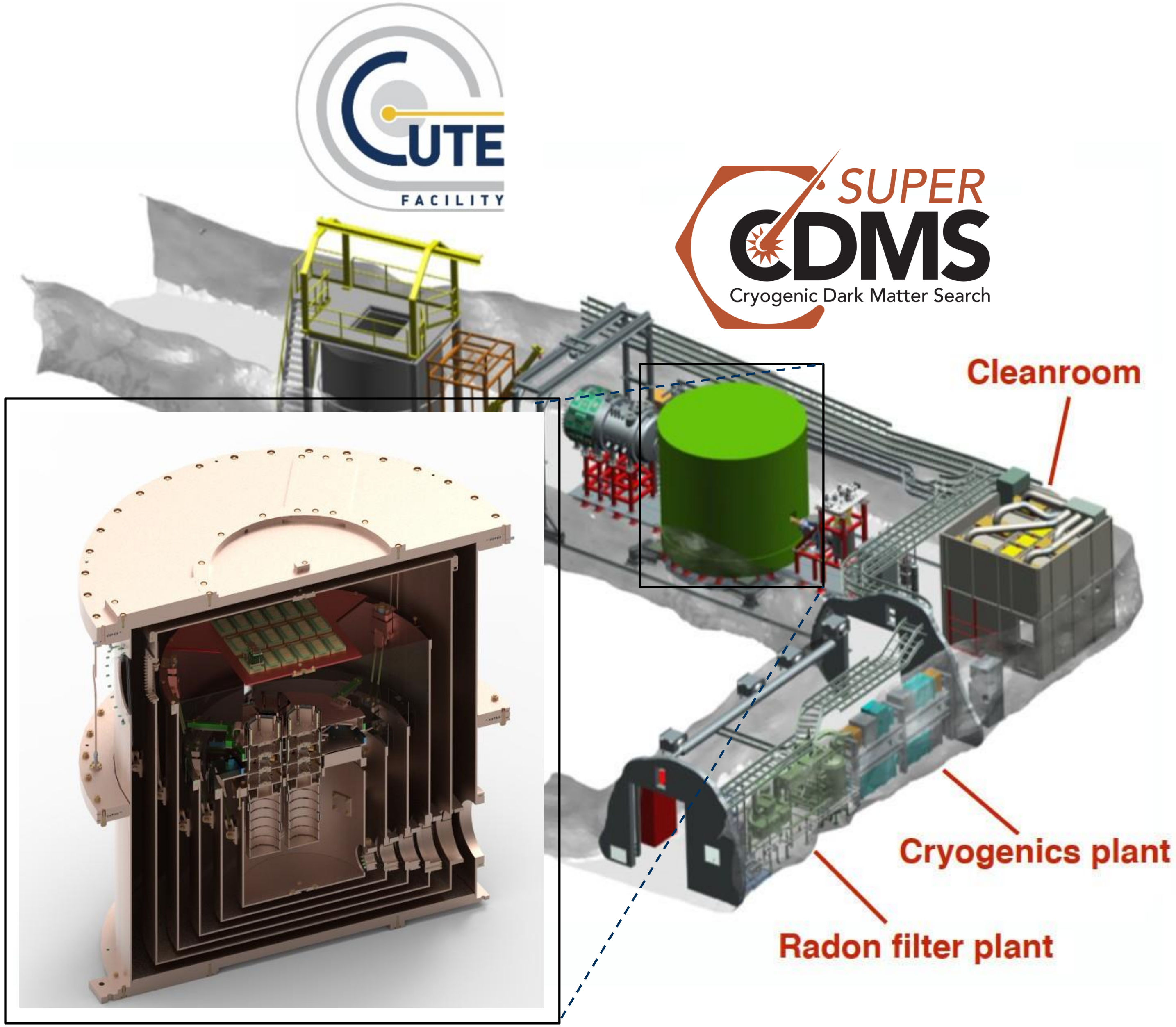
- **Primary science goal: world-leading sensitivity to low-mass WIMPs**
- **Secondary science goals: electron recoil & dark absorption searches for dark photons, axions, lightly-ionizing particles, etc.**
- **Cryogenic semiconductor crystals with quantum sensors**
- **Two detection schemes:**
  - **Ionization + phonon ('iZIP' detectors) for nuclear vs electron recoil discrimination**
  - **(Amplified) phonon only ('HV' detectors) for low thresholds**



SuperCDMS@SNOLAB at a Glance

- Class-2000 cleanroom lab, 2 km rock overburden
- Dilution refrigerator with closed-loop cryogenics system
- Initial payload: 24 semiconductor crystal detectors
  - 'iZIP' towers: 10 Ge + 2 Si crystals
  - 'HV' towers: 8 Ge + 4 Si crystals
- Collaboration with CUTE (Cryogenic Underground TEst) facility for tower testing

SuperCDMS infrastructure currently under construction!



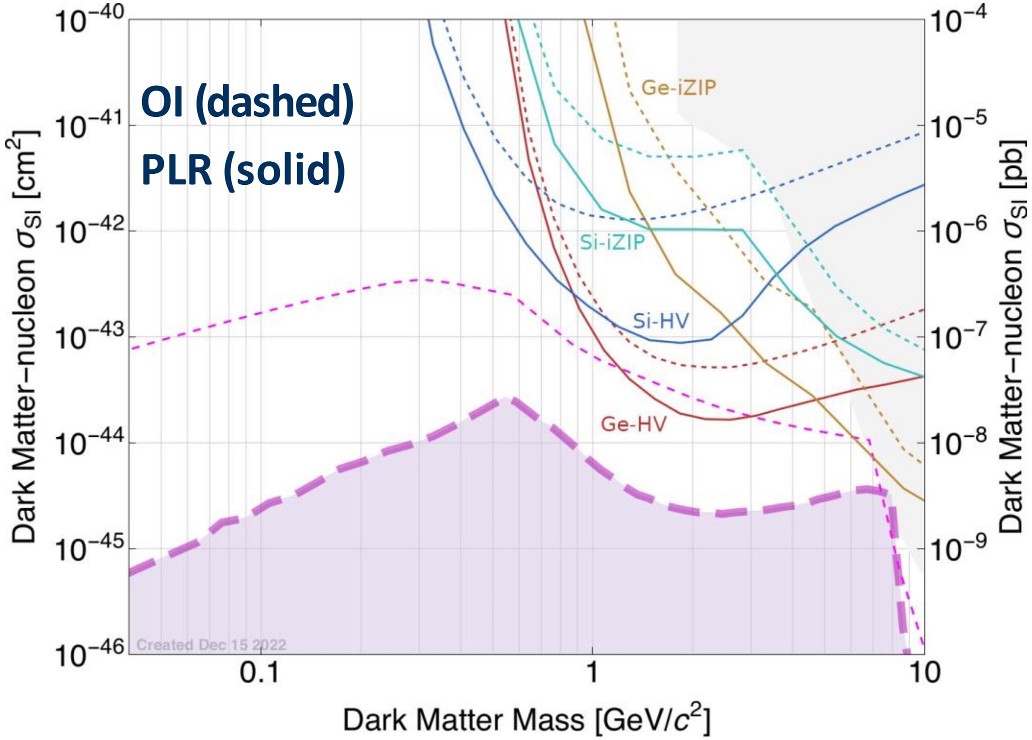
Slide credit: Stefan Zatschler

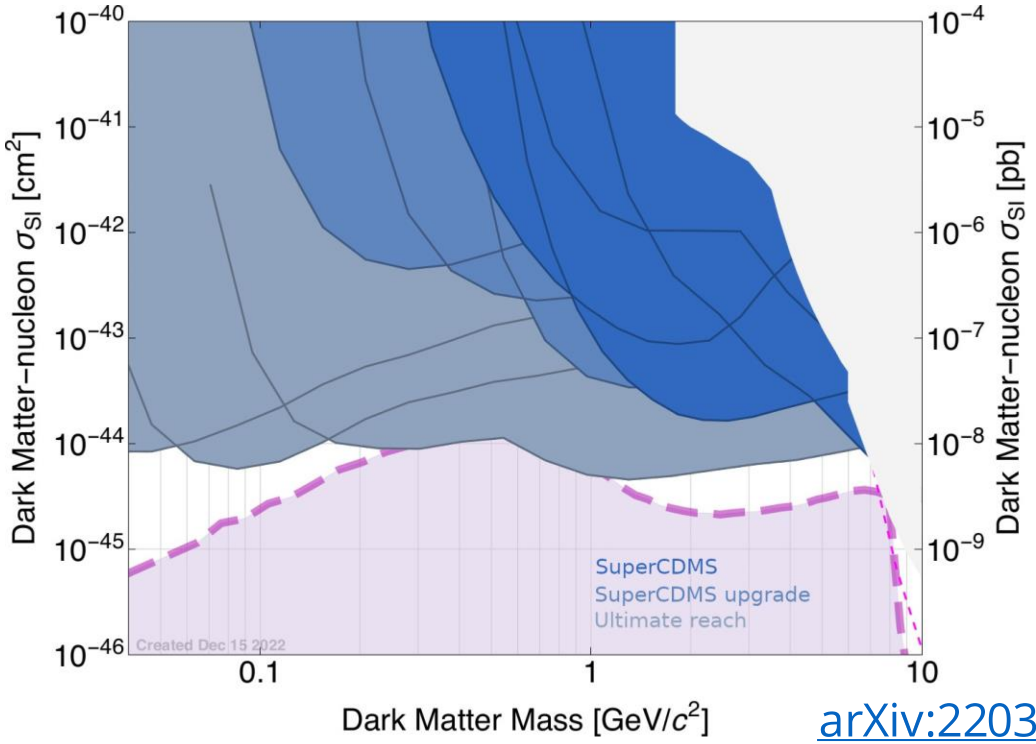
Topics

- **Science reach**
- **Detector principles**
- **Highlights of "HVeV" prototype program**
  - **Nuclear recoil ionization yield measurements**
  - **Electron recoil DM & dark absorption limits**
- **Detector response modelling**
- **Backgrounds**
- **SuperCDMS@SNOLAB installation status**
  - **Detector testing in CUTE facility: see Yan Liu's talk** https://indico.cern.ch/event/1316311/contributions/5861281

SuperCDMS Science Reach

NRDM SuperCDMS SNOLAB



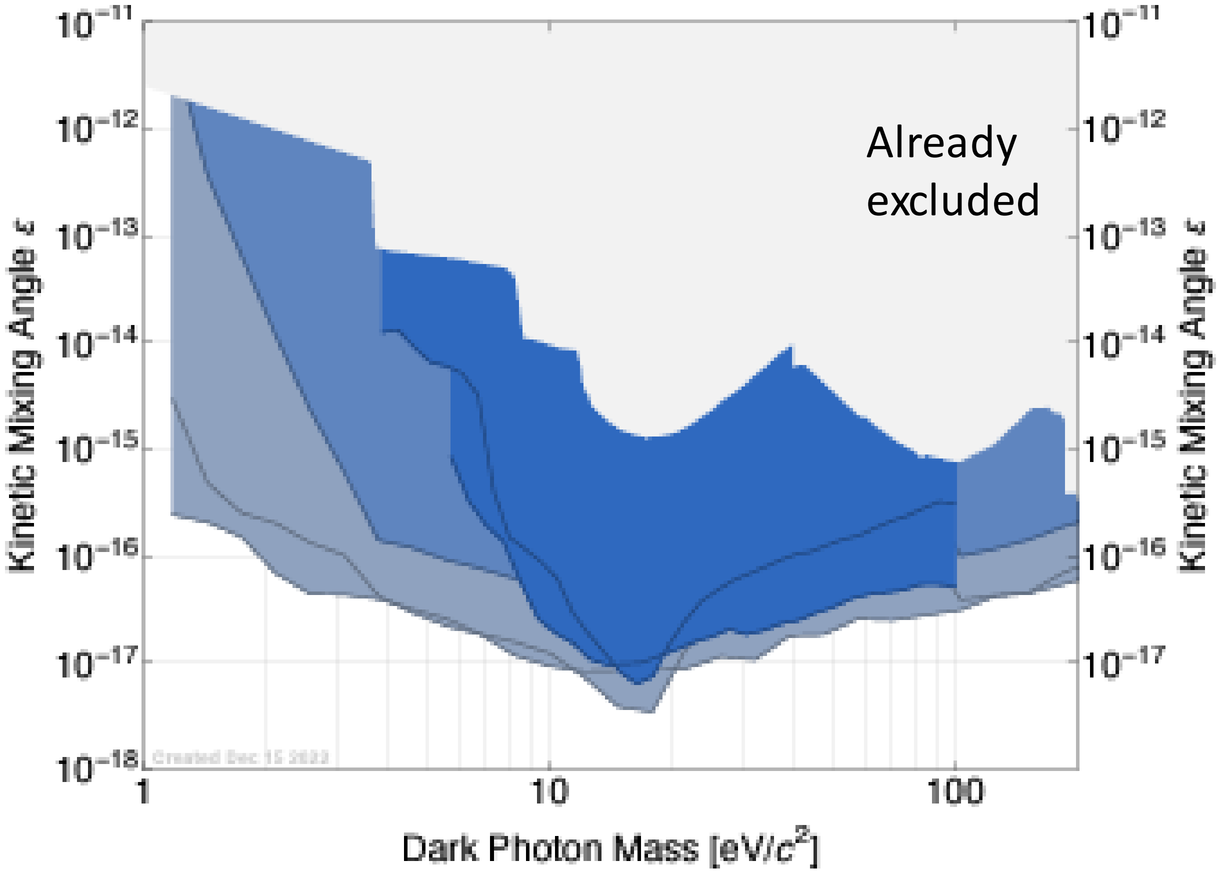


arXiv:2203.08463

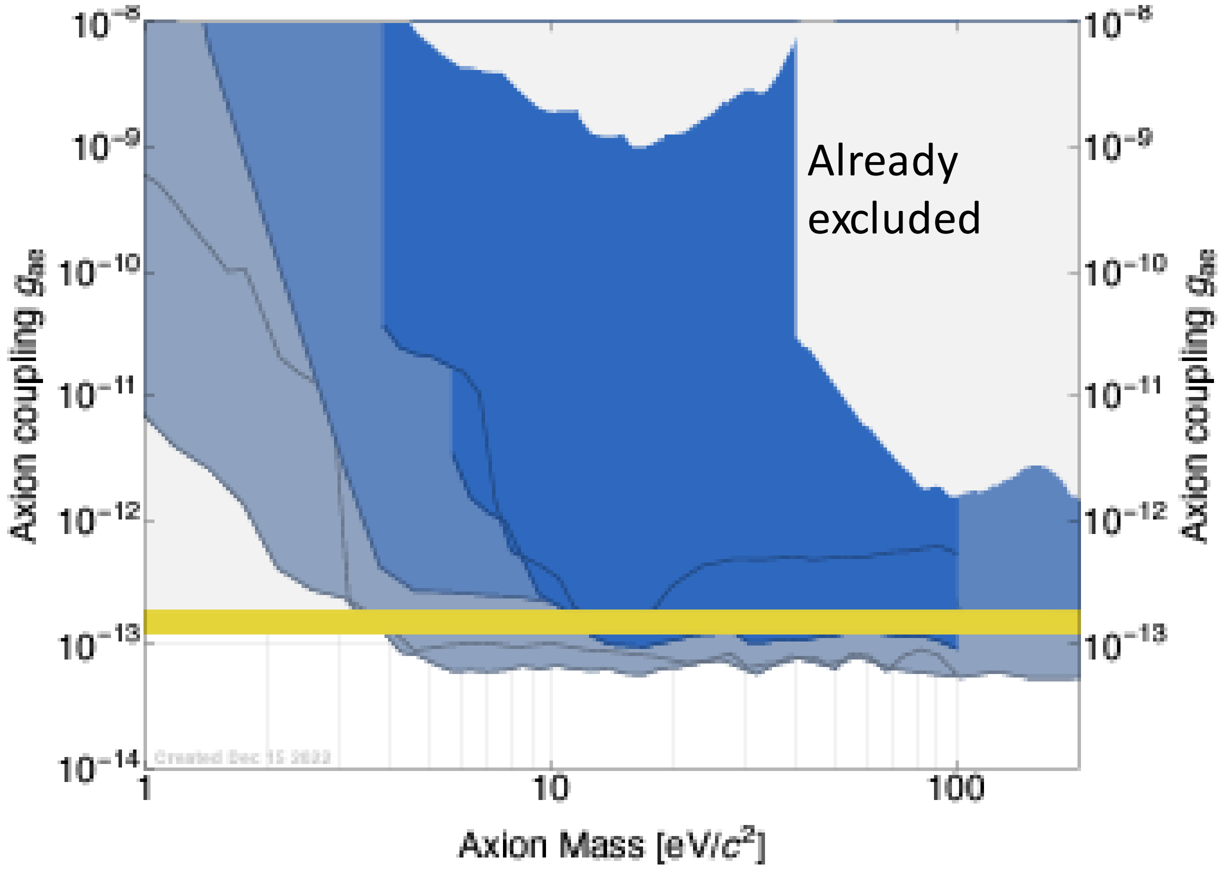
- **Understanding detector response down to the semiconductor bandgap energy crucial for maximizing sensitivity to sub-GeV DM masses**
- **Recent SNOWMASS projections, for different statistical methods and DM models**
  - ▶ **Optimum Interval (OI): signal-only assumption**
  - ▶ **Profile-likelihood ratio (PLR): signal + <u>background</u>**

SuperCDMS Science Reach

Dark Photon



Axion-Like Particle DM



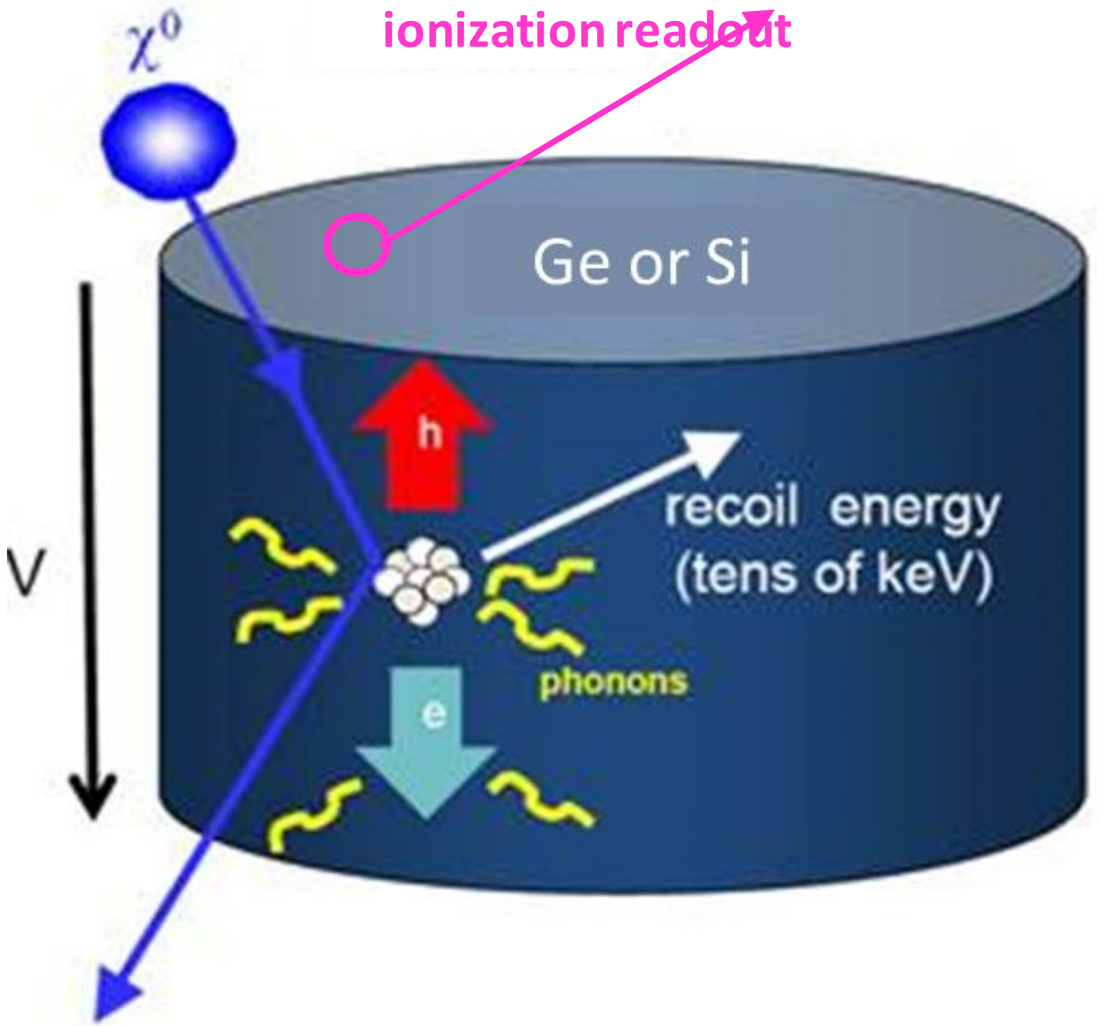
arXiv:2203.08463

SuperCDMS Detector Principles

- **Cryogenic calorimeters at ~ 10 – 15 mK**
- **Energy deposit creates e−/h+ pairs and prompt phonons in crystal**
- **Charges drift in external electric field**
- **Drifting charges emit Luke phonons: signal amplification**

Driving questions:

- **Condensed matter physics (phonons, charge transport, etc) in detectors**
- **Detector response modeling**
- **Nuclear ionization yield**
- **Dominating backgrounds**
- **Low-energy calibration**



SuperCDMS Detector Principles

HV detectors – low threshold

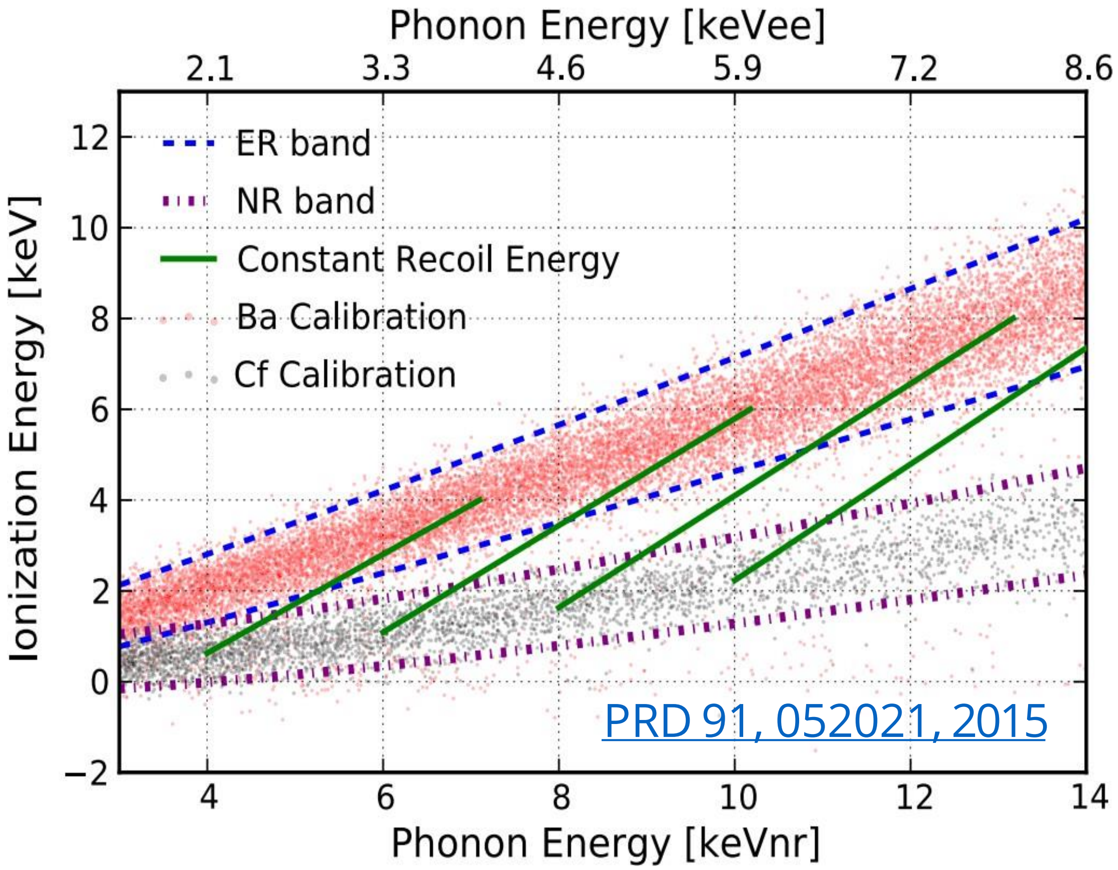
- High resolution total phonon measurement
- No yield discrimination, limited fiducialization
- Typical thresholds below 0.1 keV (4 eV_{ee}) !

HVeV detectors – low threshold gram-scale prototypes

- Single electron-hole pair sensitivity
- Runs at test facilities provide insight into backgrounds and calibrations for HV
- Already set some world-leading low-mass DM constraints

iZIP detectors – low background

- High resolution phonon and charge readout
- Discrimination of surface and ER back-grounds from NR signal region



PRD 91, 052021, 2015

Slide credit: Stefan Zatschler

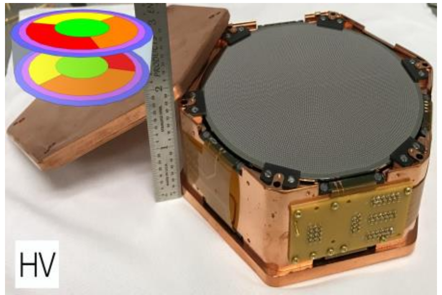
SuperCDMS detector principles

HV detector → low threshold

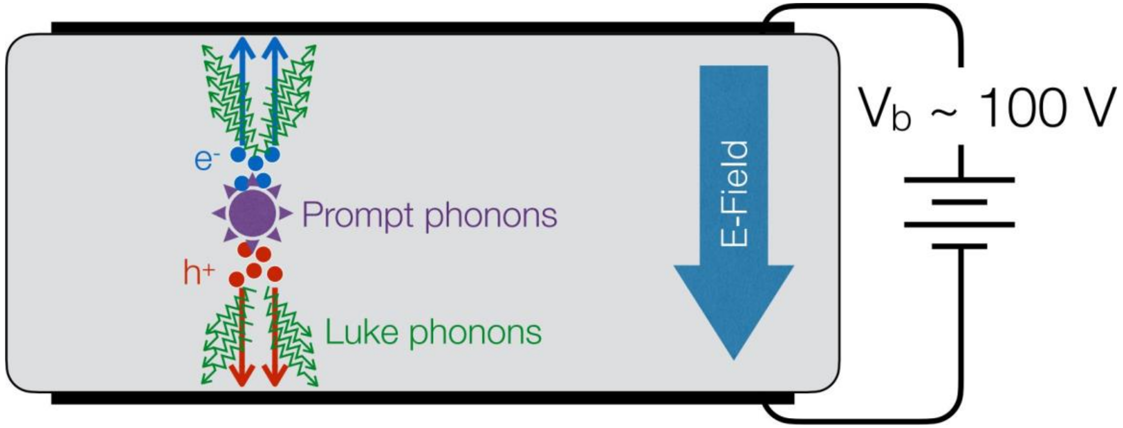
- Drifting charge carriers (e^-/h^+) across a potential (V_b) generates a large number of Luke phonons (NTL effect)

$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$

total phonon energy — primary recoil energy — Luke phonon energy

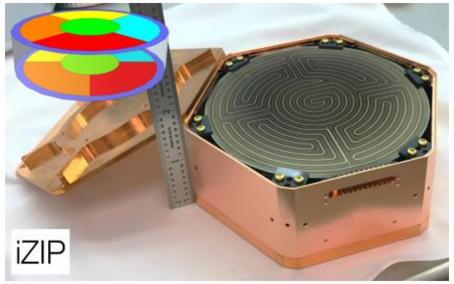


Sensors measure E_t



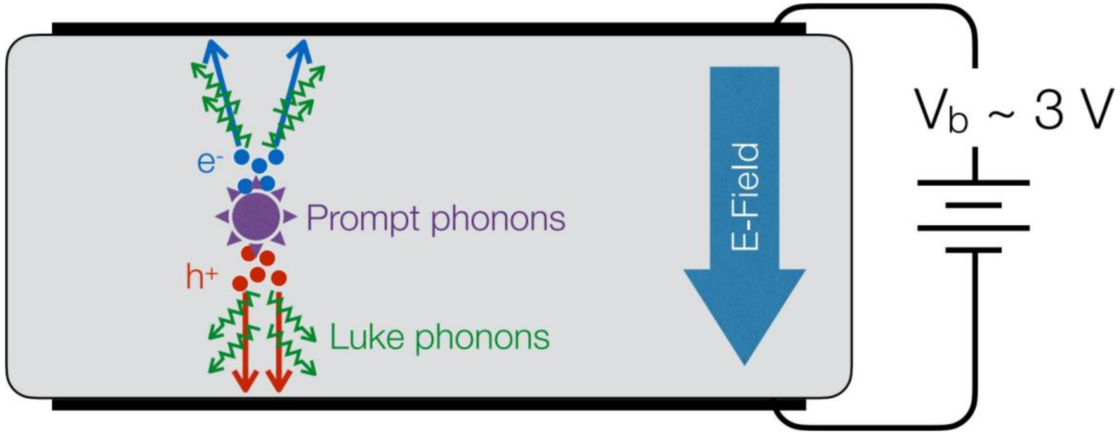
iZIP detector → low background

- **I**nterleaved **Z**-sensitive **I**onization and **P**honon detector



PRD 95, 082002, 2017

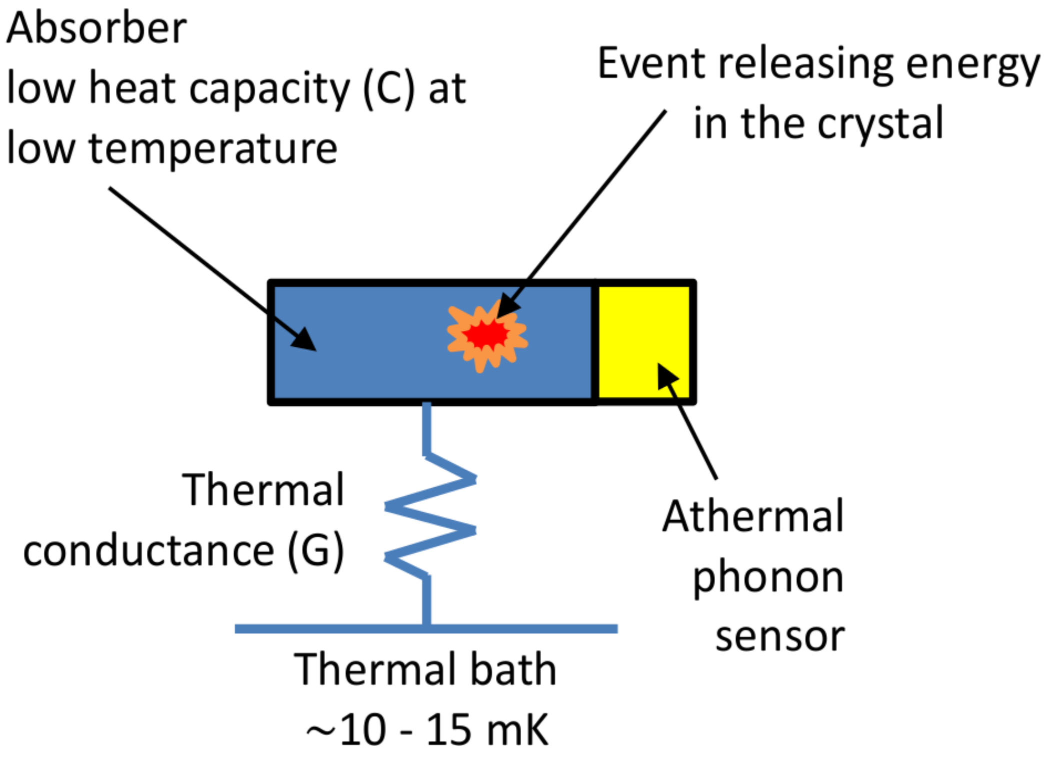
Sensors measure E_t and N_{eh}

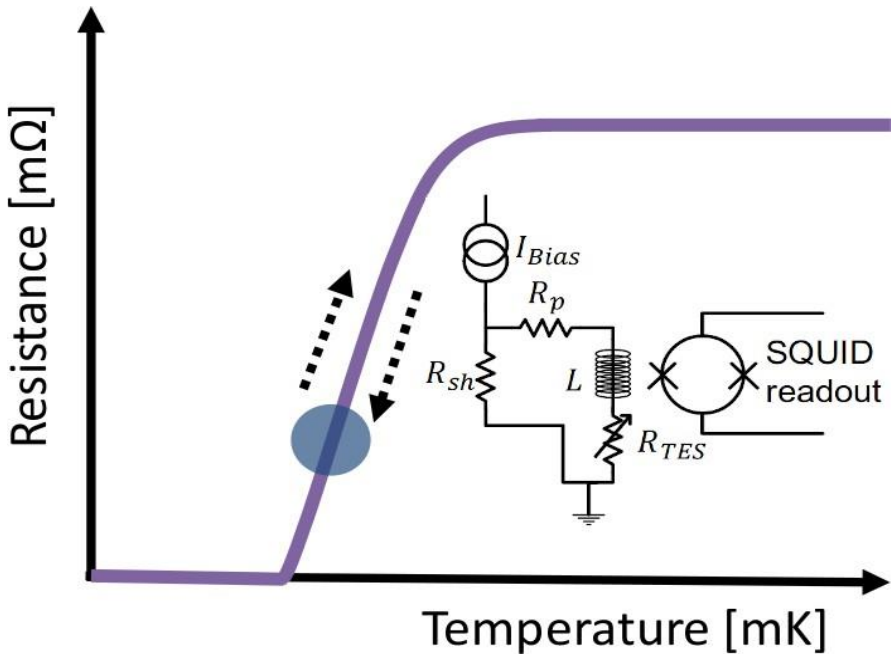


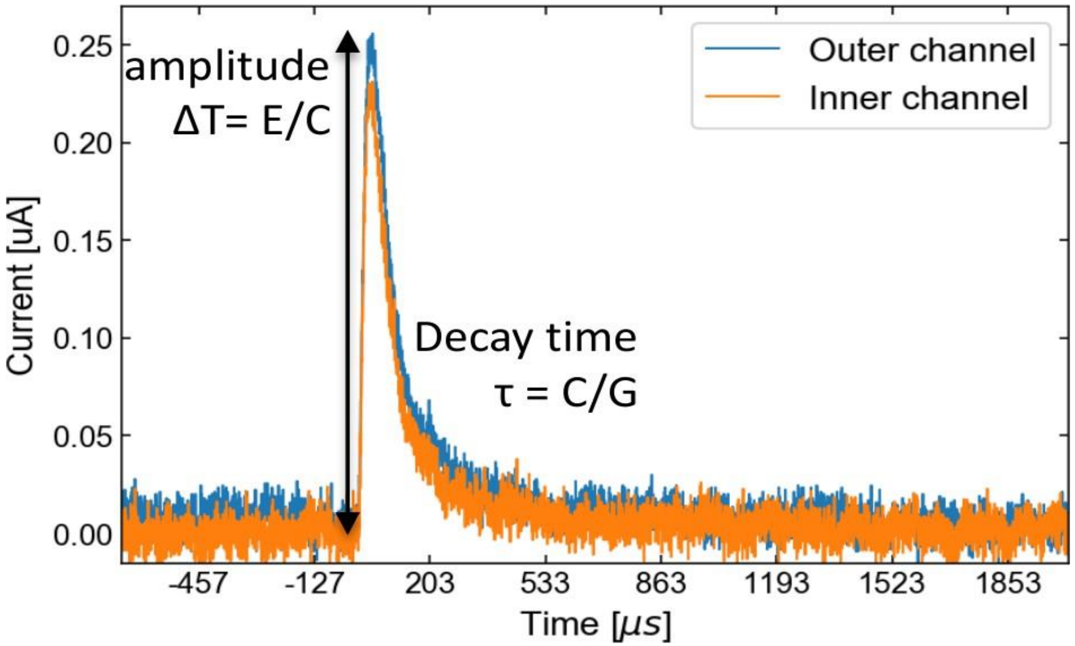
Slide credit: Stefan Zatschler

SuperCDMS detector principles

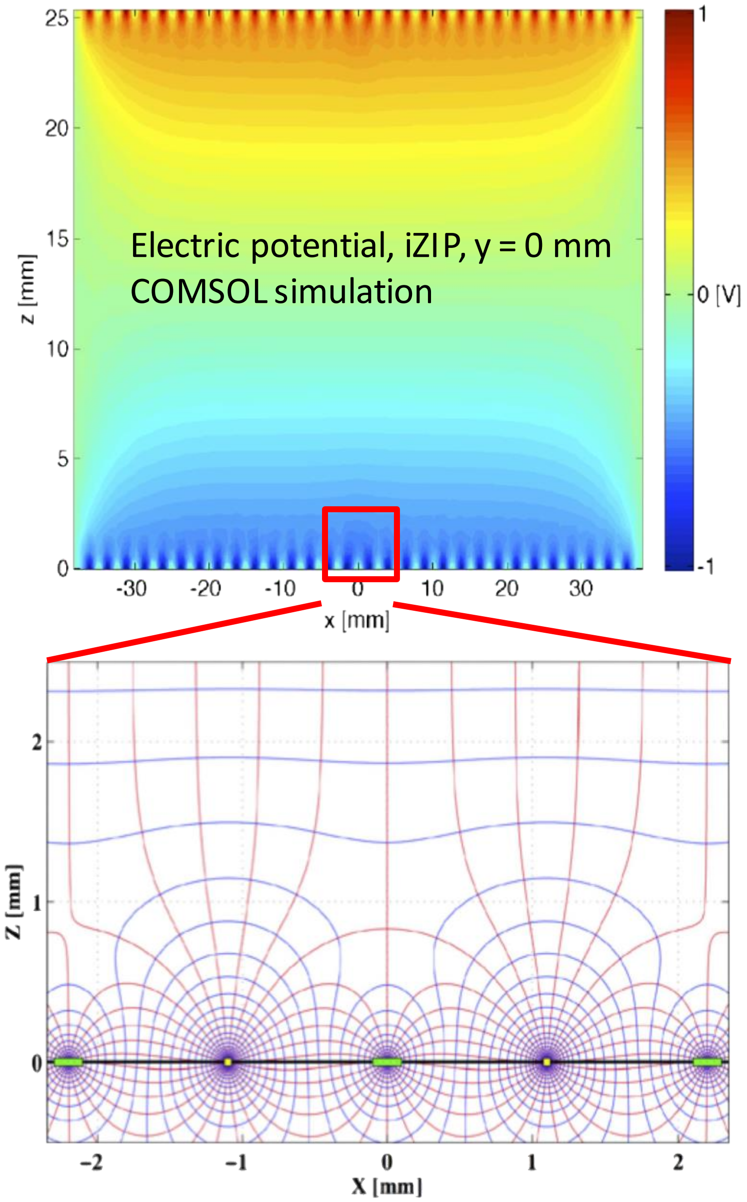
- **Athermal phonon collection with QETs (Quasiparticle trap-assisted Electrothermal feedback TESs)**
- **Pulse reconstruction**
- **Measure of energy deposit**







iZIPs



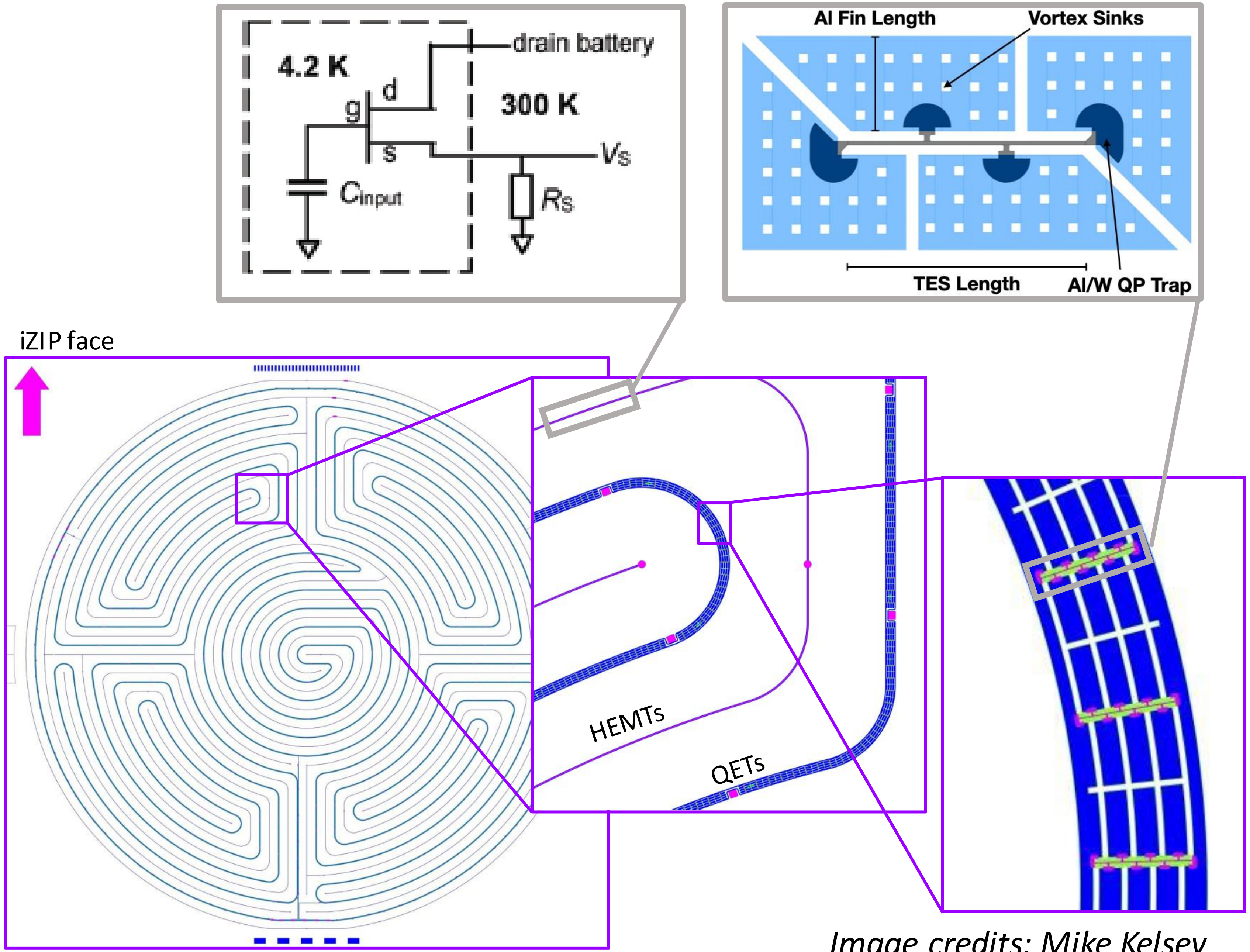
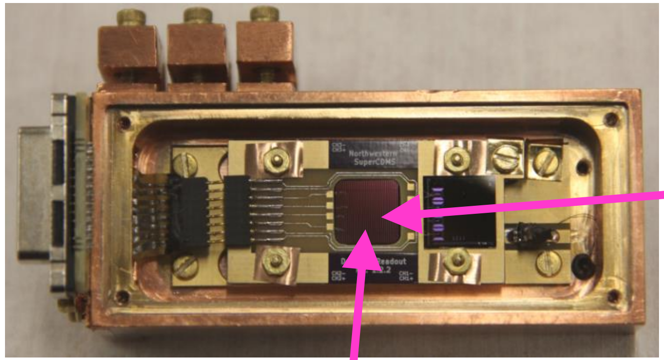
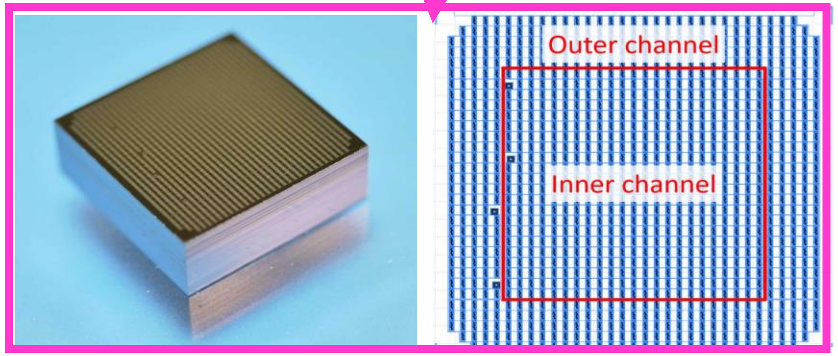
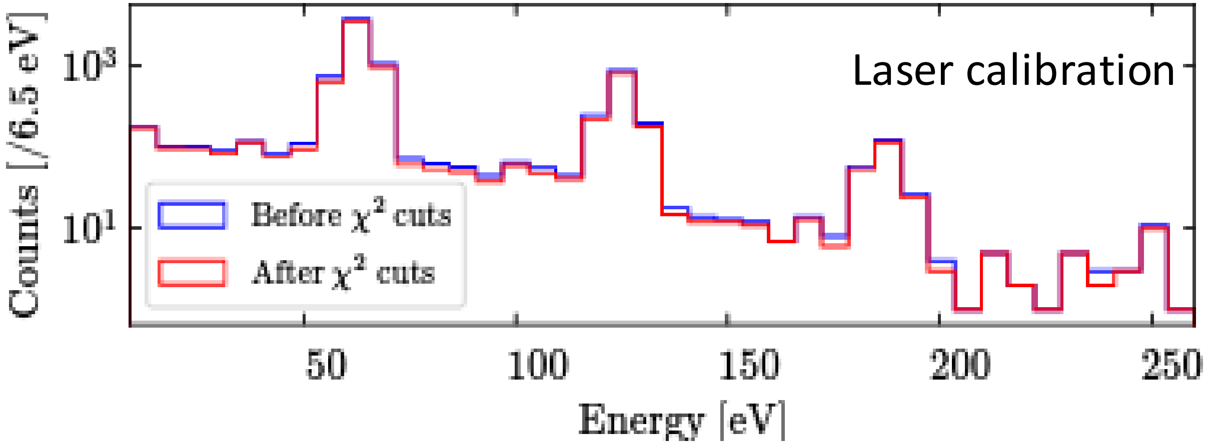


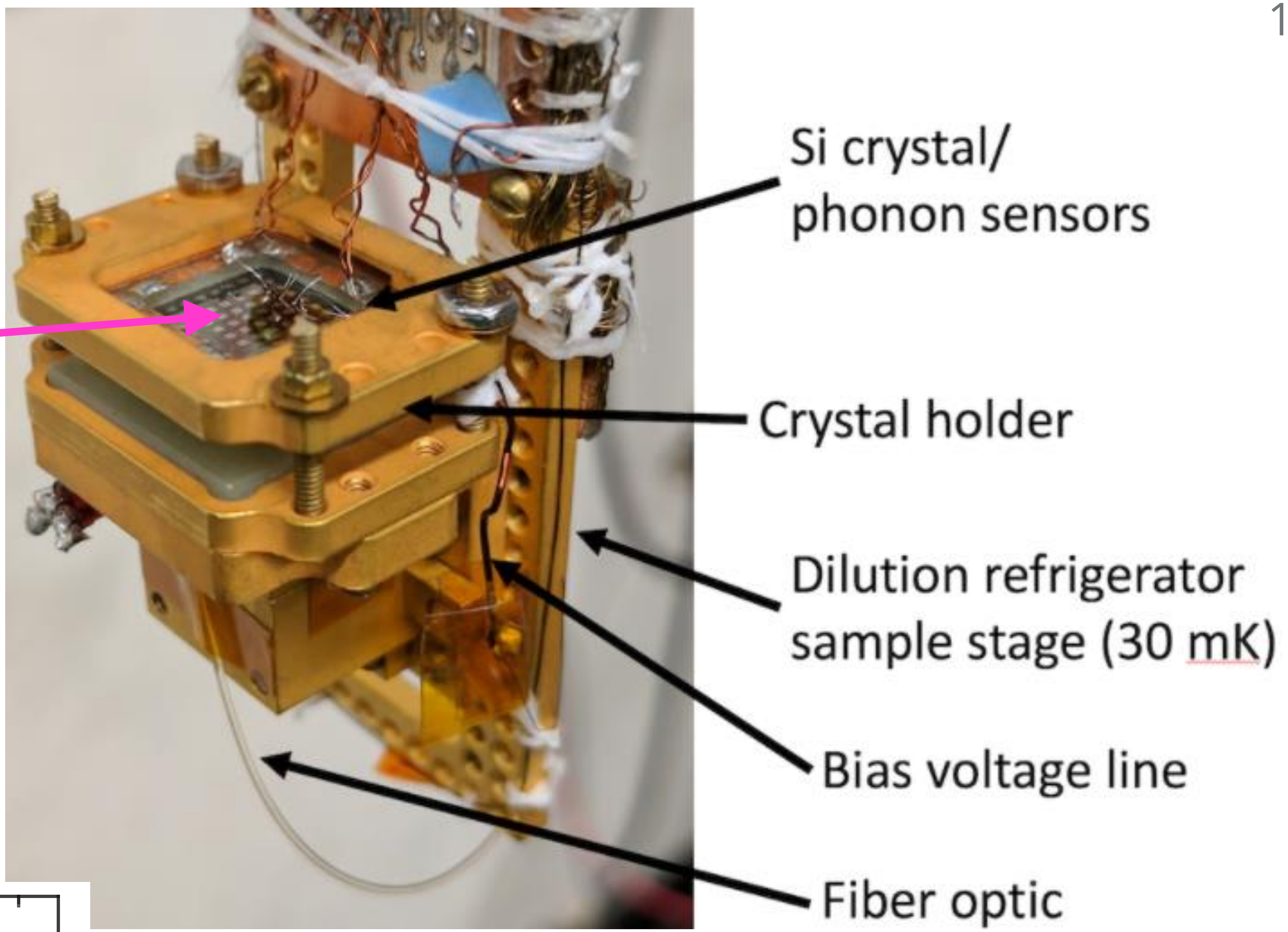
Image credits: Mike Kelsey

HVeVs







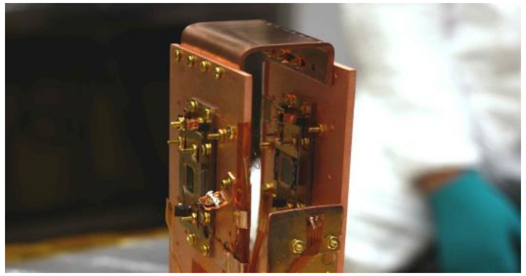


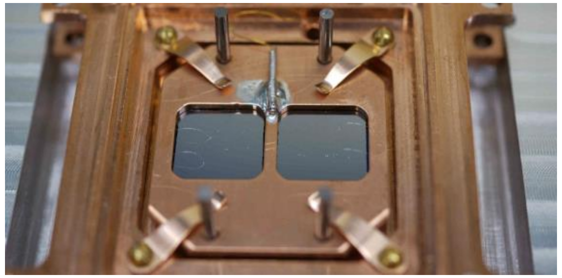
Few eV phonon resolution, can see single e-h pairs!

D. W. Amaral *et al.*, Phys. Rev. D 102, 091101(R), 2020
F. Ponce, et al., Phys. Rev. D 101, 031101(R), 2020
R. Ren et al., Phys. Rev. D 104, 032010, 2021

Highlights of HVeV Detector Program

PRD 102, 091101(R), 2020

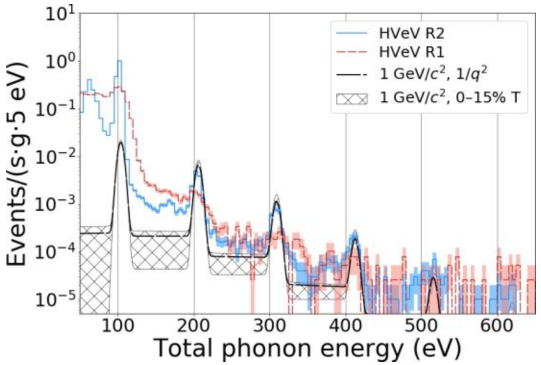




Stay tuned!

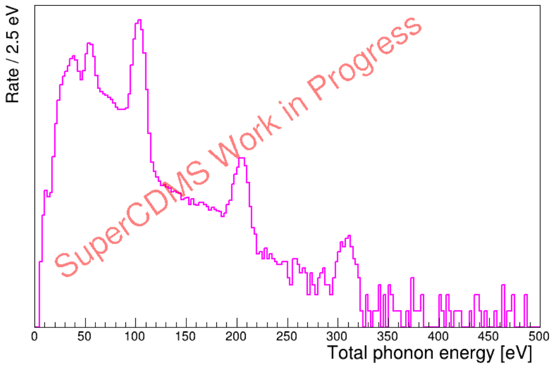
HVeV Run 2

- **Detection and study of 1 e^-/h^+ "burst events"**
- **Hypothesized source: PCB holder**



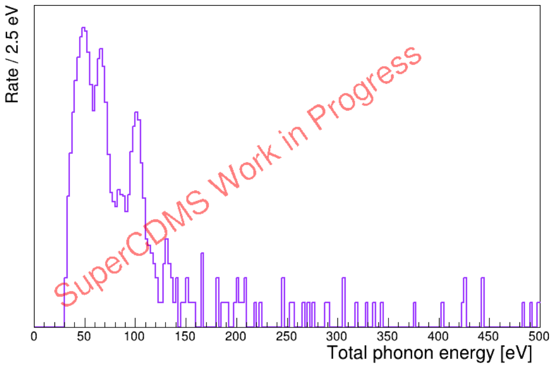
HVeV Run 3

- **Coincidence measurement**
- **Confirmed external origin of burst events**



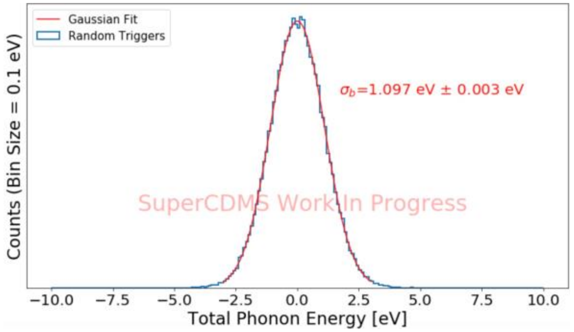
HVeV Run 4

- **Coincidence measurement, with no PCB**
- **Elimination of multi e^-/h^+ peaks**



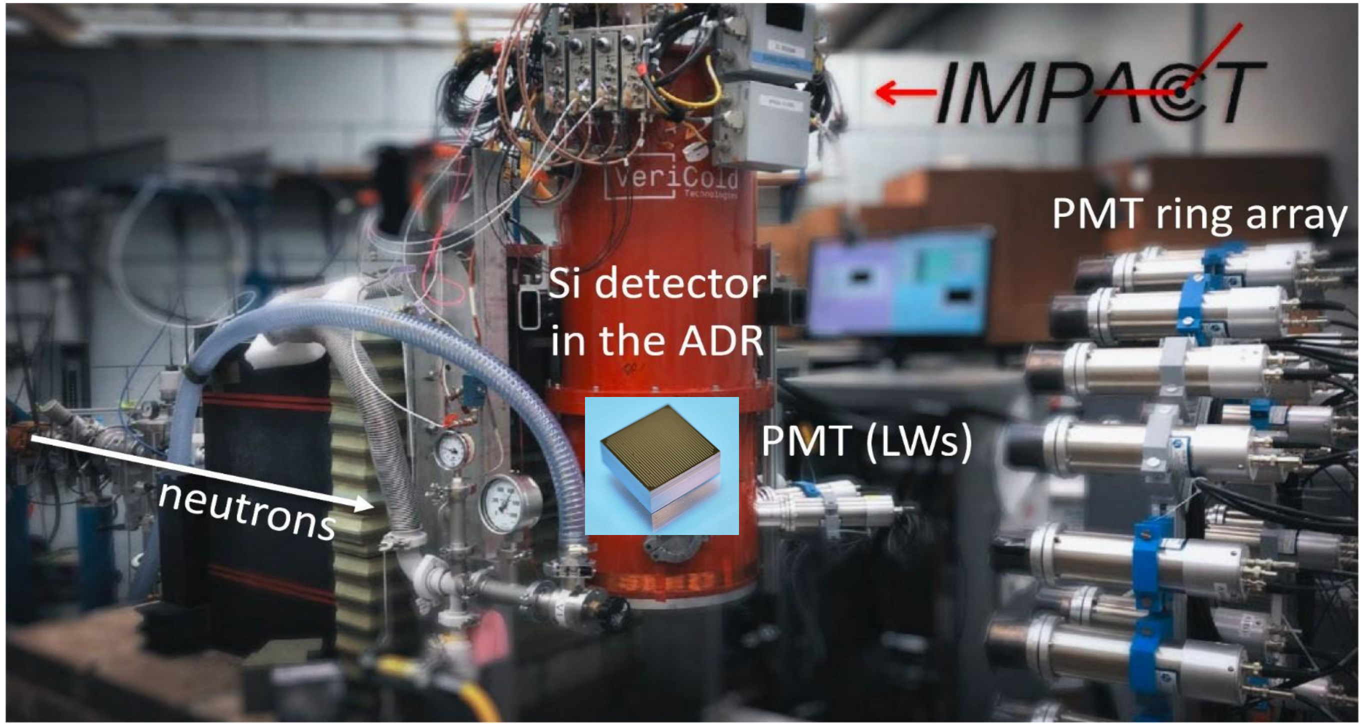
Latest performance

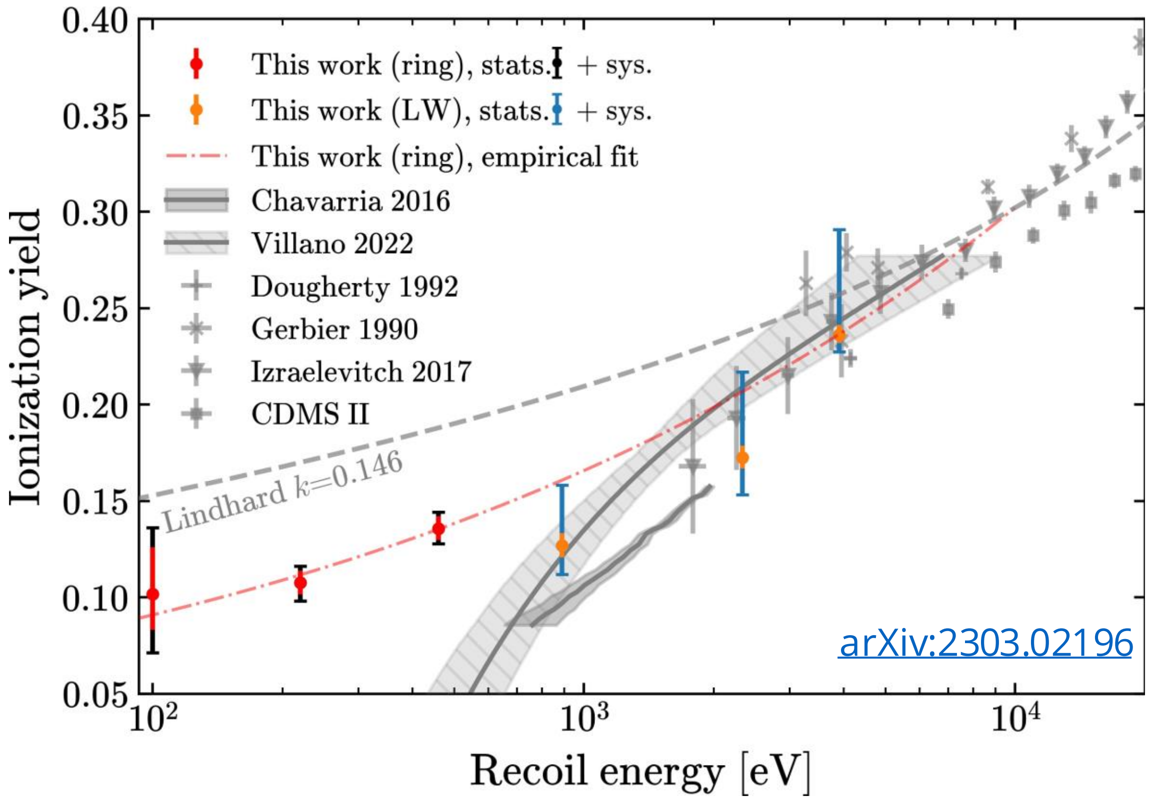
- **V3 of HVeV**
- **Greatly improved baseline resolution (σ_b = 1.097 ± 0.003 eV)**



Slide credit: Stefan Zatschler

HVeVs for Measuring Nuclear Recoil Ionization Yield





arXiv:2303.02196

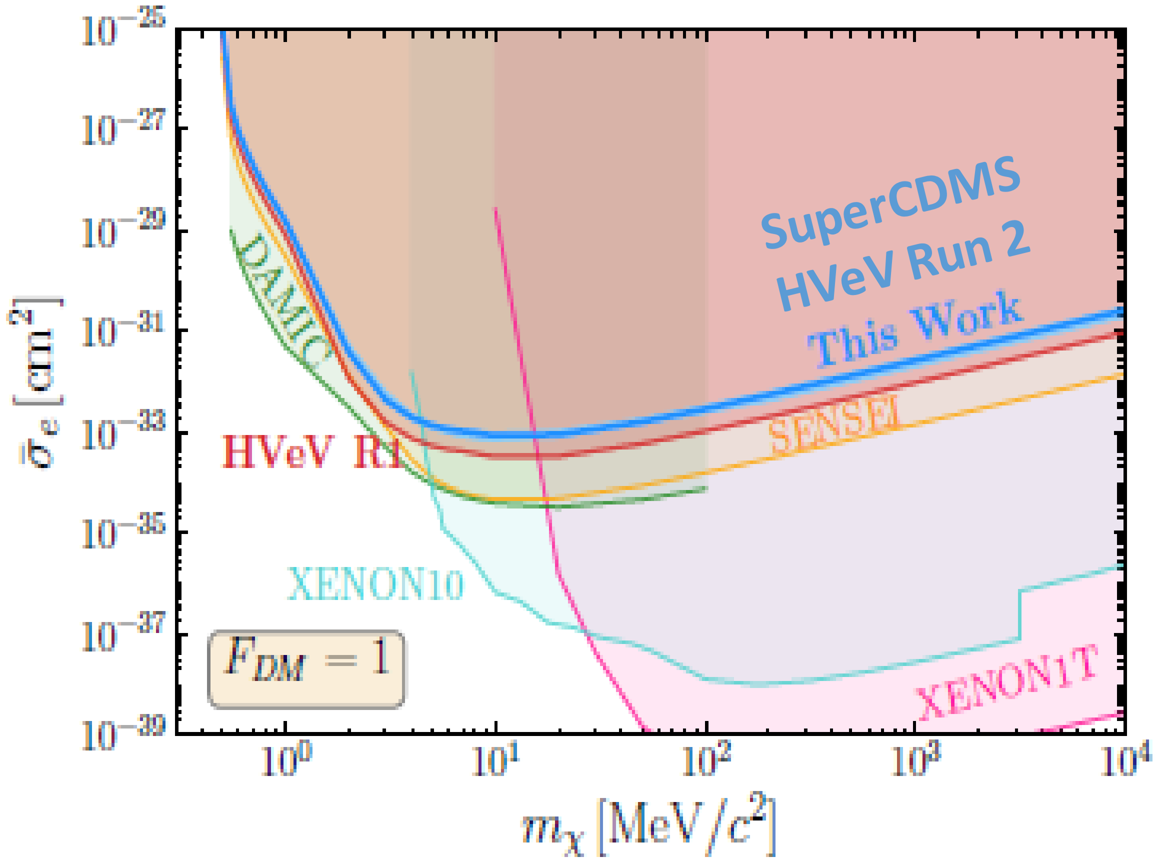
- Ionization yield (*Y*) measurement down to 100 eV with Si HVeV in a neutron beam
  - ▶ Significant deviations from “Lindhard model”
  - ▶ No indication for ionization threshold in Si
- Ge yield measurement in preparation

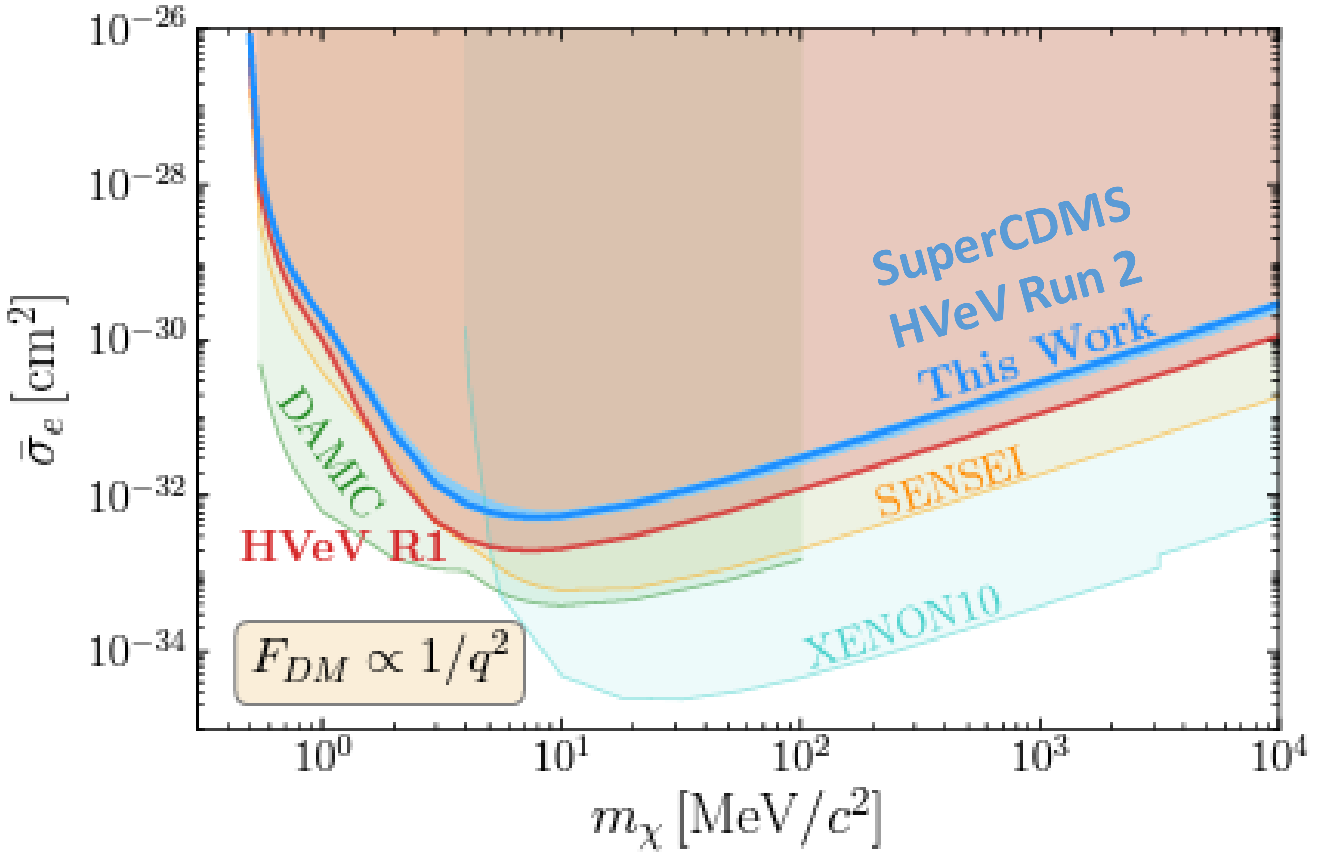
Total phonon energy and yield

$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$
$$= E_r \cdot (1 + e \cdot V_b / \varepsilon_{pair} \cdot Y(E_r))$$

Slide credit: Stefan Zatschler

HVeV Electron Recoil DM Limits

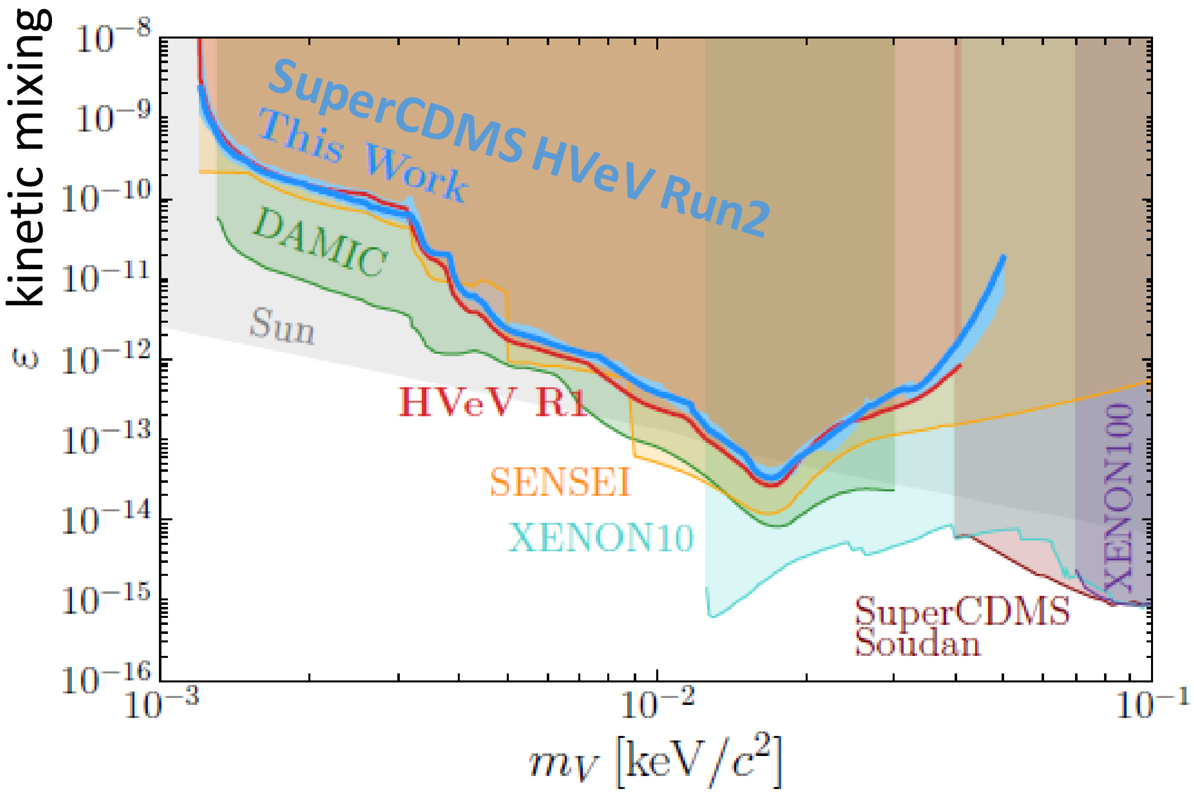




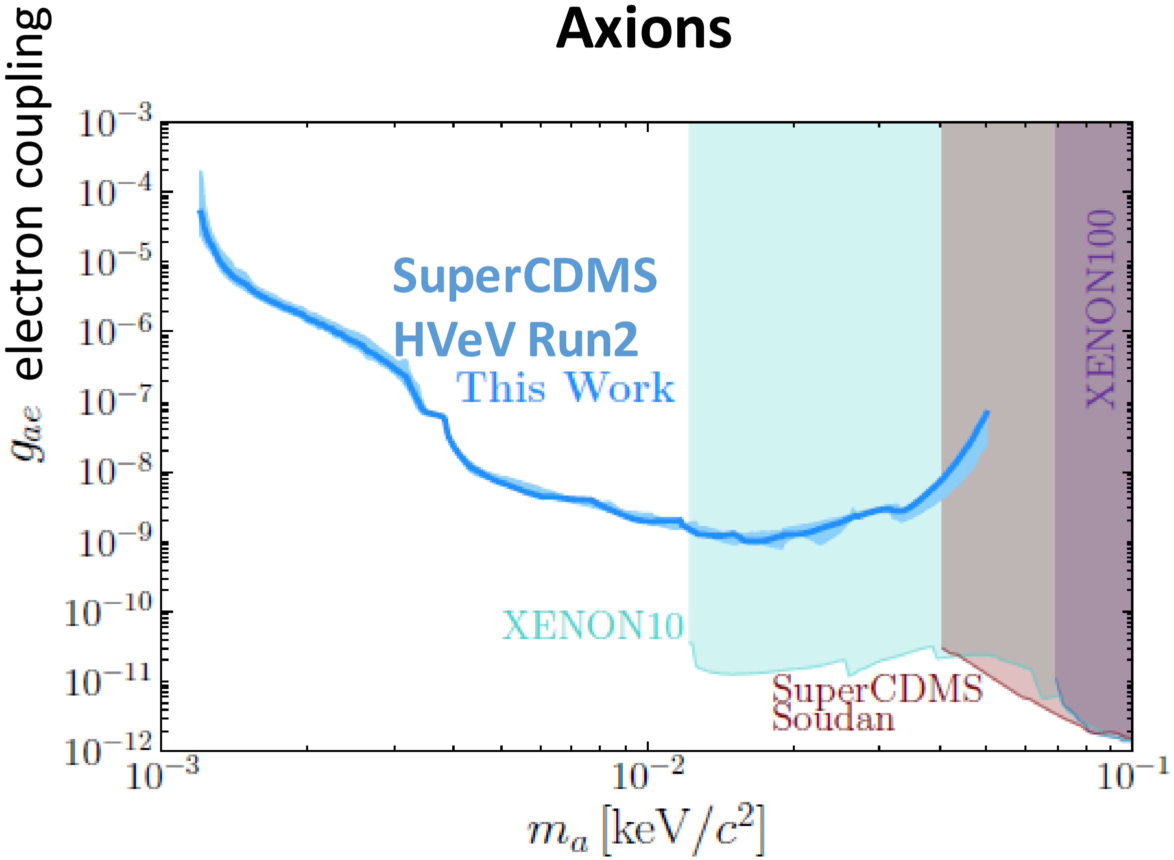
PRD 102, 091101(R), 2020

HVeV Dark Photon & Axion Limits

Dark Photons

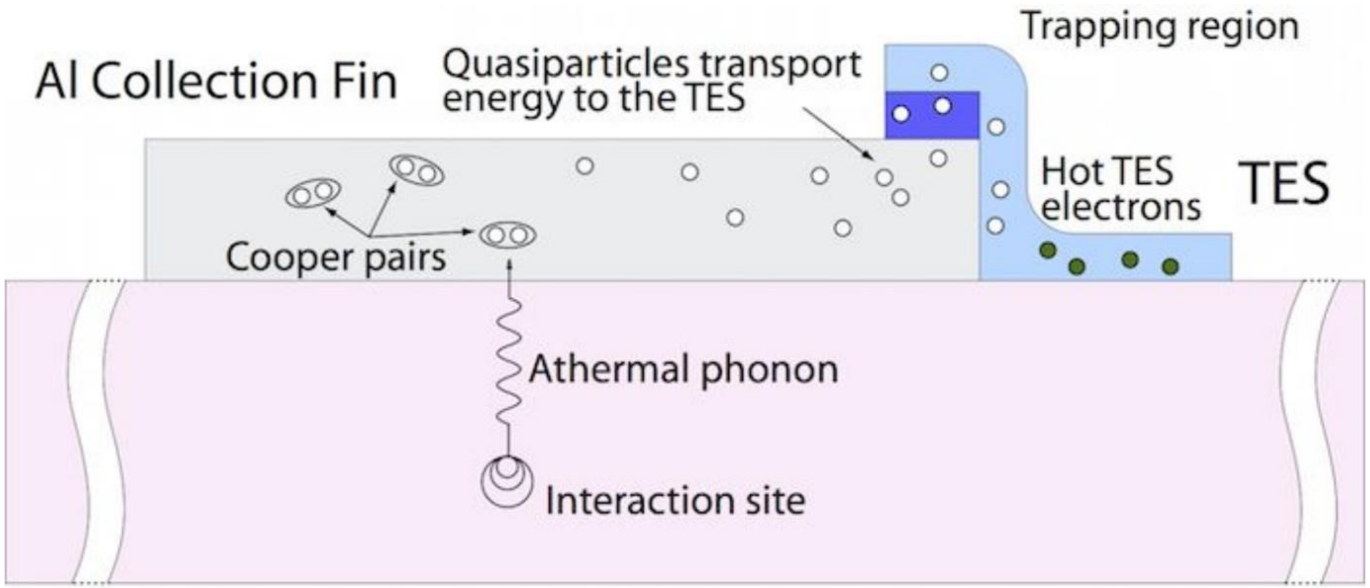


Axions

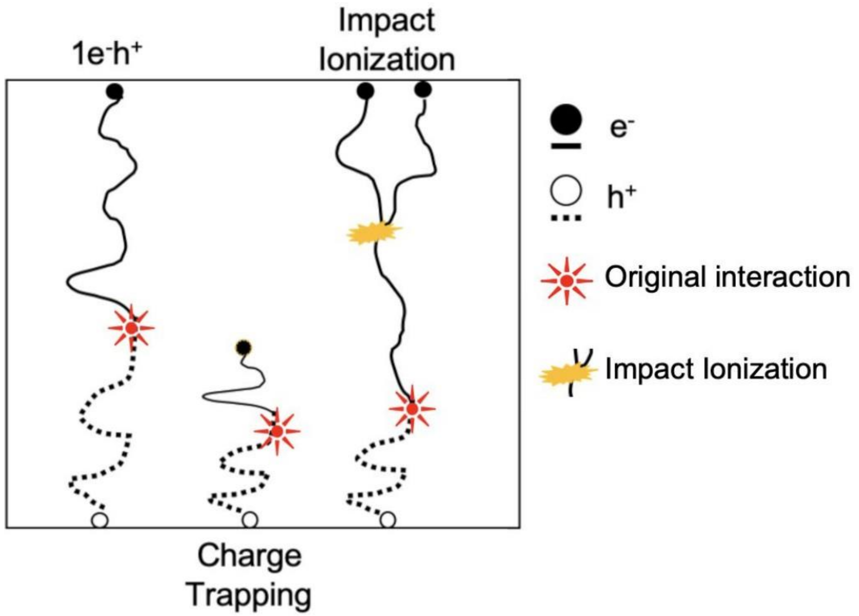


PRD 102, 091101(R), 2020

Detector Response Modeling



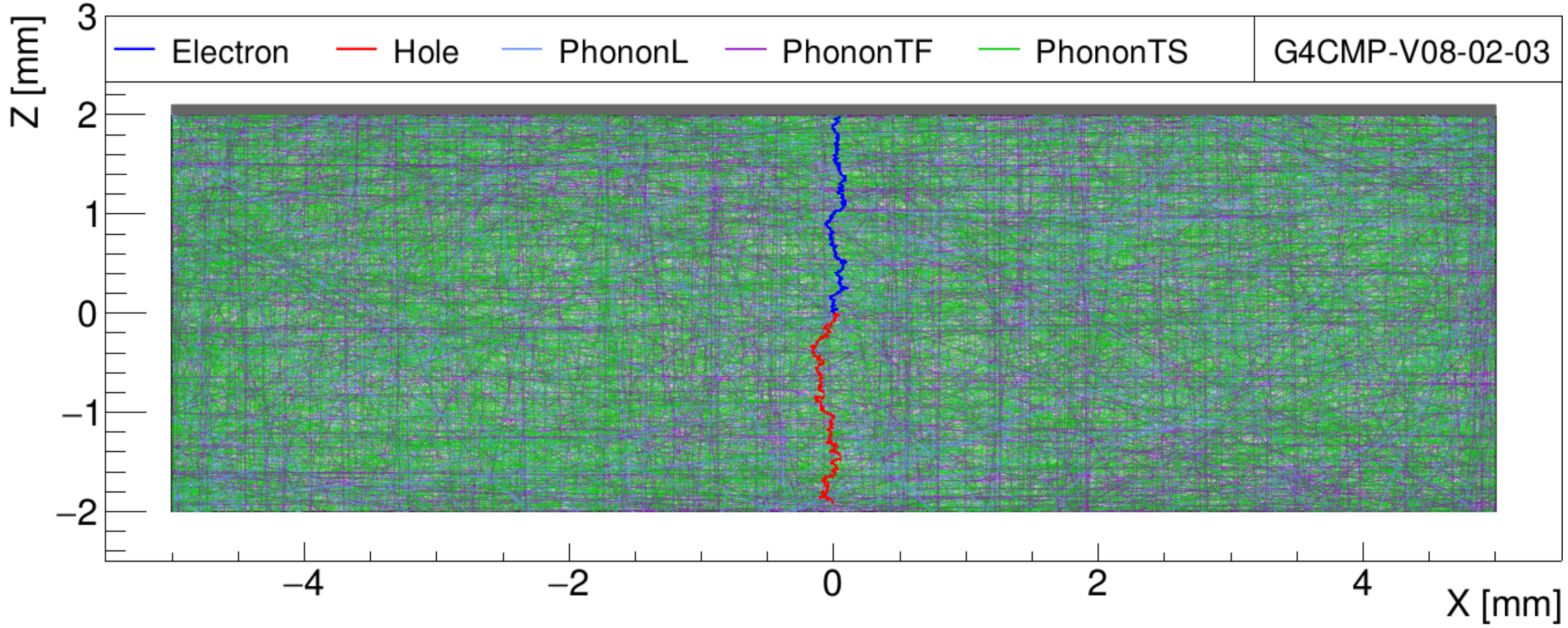
https://figueroa.physics.northwestern.edu

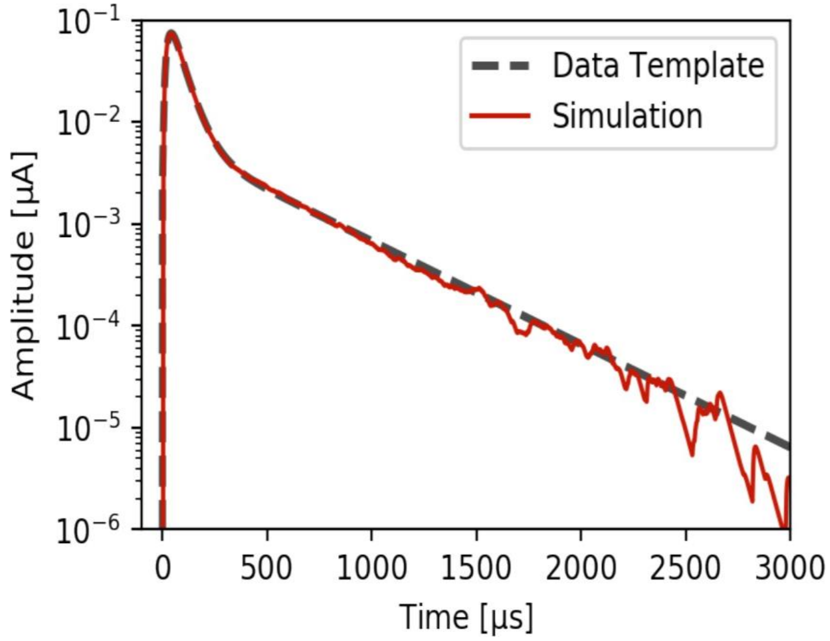


- **Sophisticated GEANT4-based framework, "G4DMC", models crystal and sensor response with help of G4CMP (GEANT4 Condensed Matter Physics) package**
  - **Crystal dynamics: lattice definition, charge transport, phonon scattering, etc.**
  - **Impurity effects: Charge Trapping, Impact Ionization**
  - **TES configuration: physical layout, circuitry, electro-thermodynamics**

Slide credit: Stefan Zatschler

Detector Response Modeling





NIM A 1055, 168473, 2023 (code: github.com/kelseymh/G4CMP)

PRD 104, 032010 (2021)

Example: simulation of single e^-/h^+ pair in Si HVeV ($10\times10\times4$ mm^3)

Goal: Same reconstruction path for real and simulated raw data!

▶ Would be suitable for testing advanced reconstruction algorithms, Machine Learning techniques, etc.

Slide credit: Stefan Zatschler

Backgrounds

Bury our detectors in dark secret (shielded) underground (clean-room) lairs

… Why?...

Backgrounds, backgrounds, backgrounds!

Cosmogenic

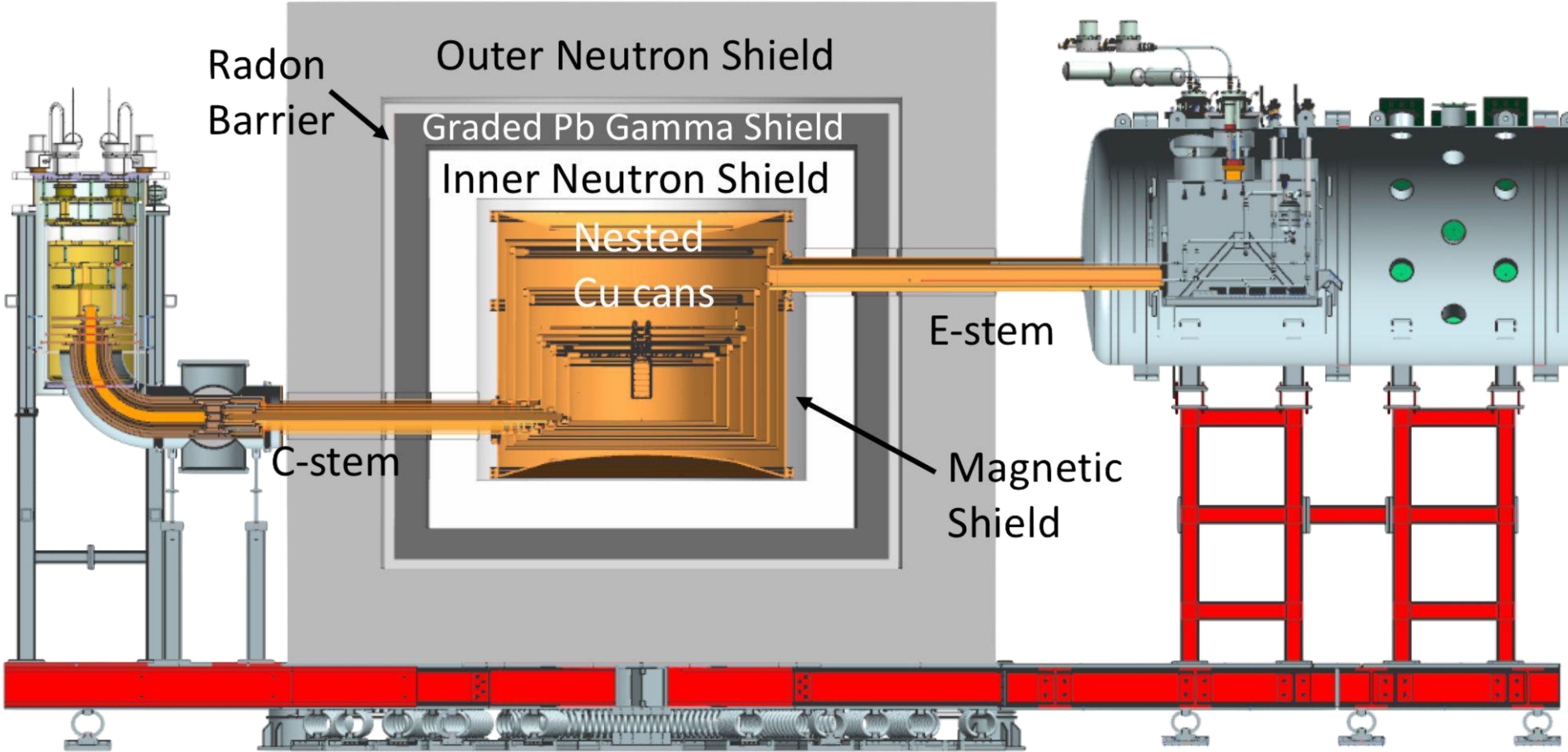
- **Cosmic ray muons**
- **Spallation neutrons**
- **Activated materials**

Environmental

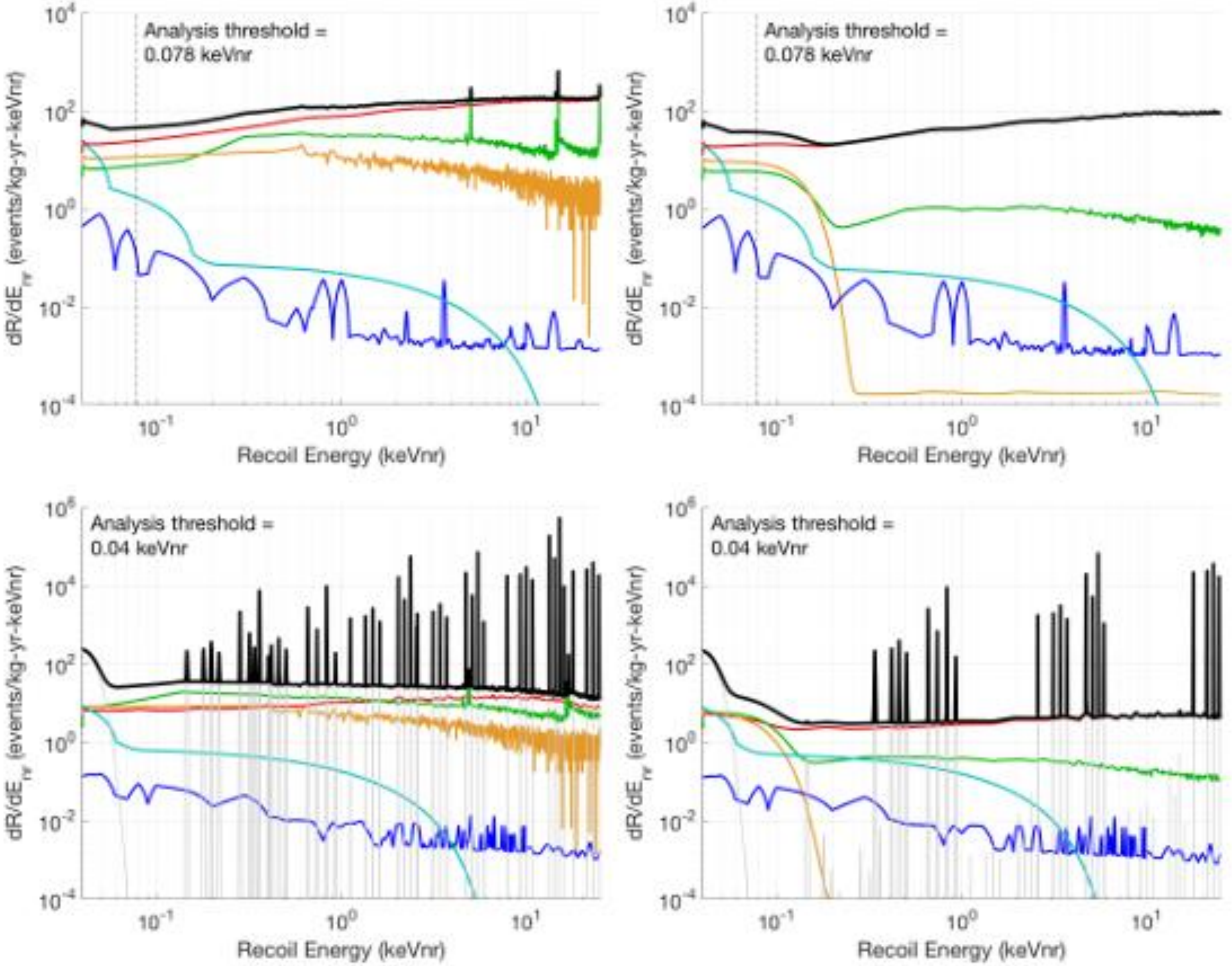
- **Airborne radon & daughters**
- **Radio-impurities in materials**

Backgrounds

Multiple shielding layers to reduce backgrounds



Backgrounds



SuperCDMS@SNOLAB HVs background spectra projections, before (left) and after (right) analysis cuts, in Si (top) and Ge (bottom)

Black: total bg

Red: ERs from Compton γ's, H, Si

Grey: Ge activation lines, convolved with 10 eV r.m.s. resolution

Green: surface β's

Orange: surface Pb recoils

Blue: neutrons

Cyan: CEvNS

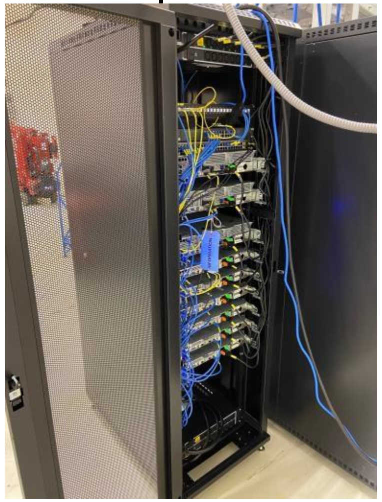
arXiv:2203.08463

SuperCDMS@SNOLAB Installation Status

✓ Fridge Commissioning 2023

✓ Detector tower testing @CUTE 2023-2024

……… .



✓ DAQ installation 2021

✓ Shield base installation 2023

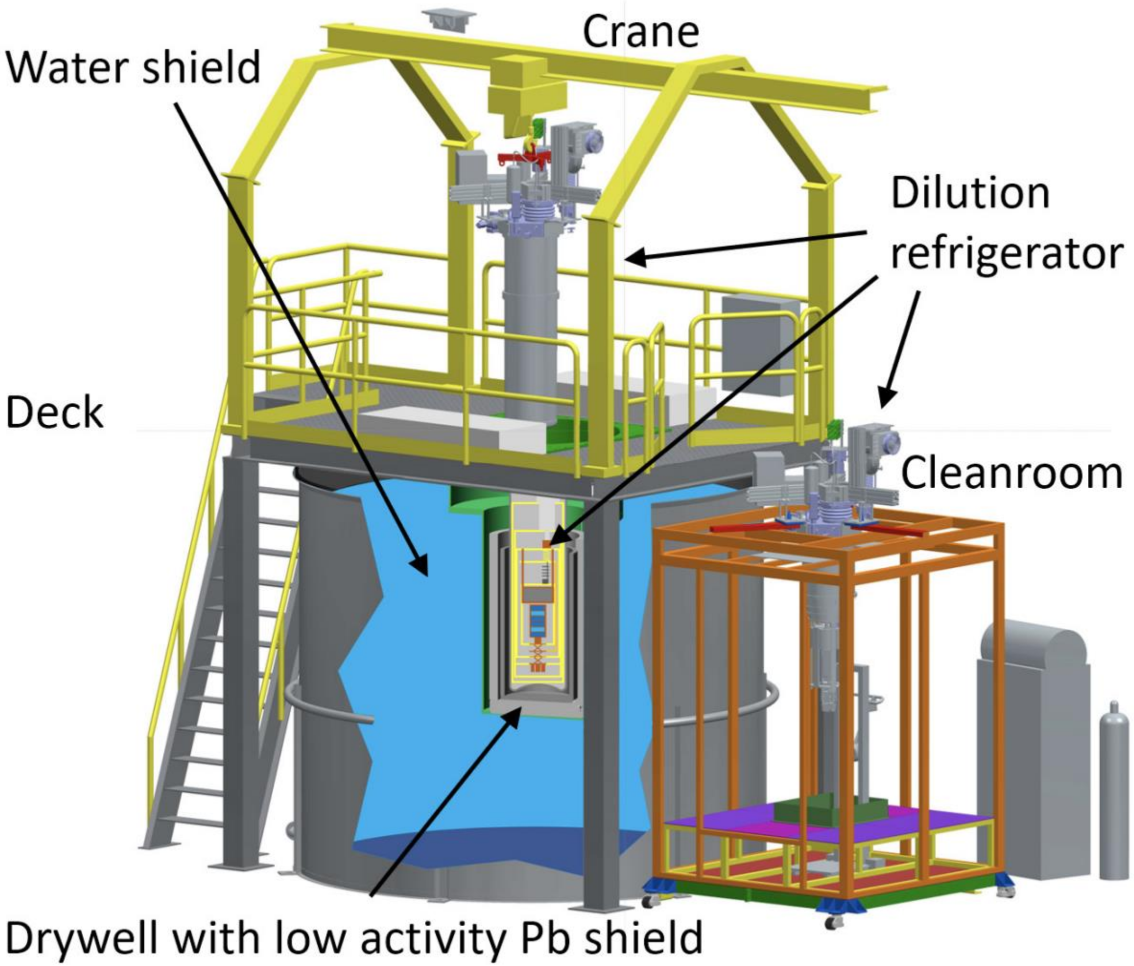
SNOBOX & eTank testing in progress

Slide credit: Aditi Pradeep

Cryogenic Underground Test (CUTE) Facility

- **Operates down to T = 12 mK**
- **Low radioactive backgrounds**
- **Low EM interference**
- **Minimal mechanical vibrations thanks to cryostat suspension system**
- **Calibration sources (γ, neutron)**
- **Class 300, low Rn (< 15 mBq/m^3) cleanroom for payload changes**

(Quark & Qubit the CUTE Guinea Piggies)

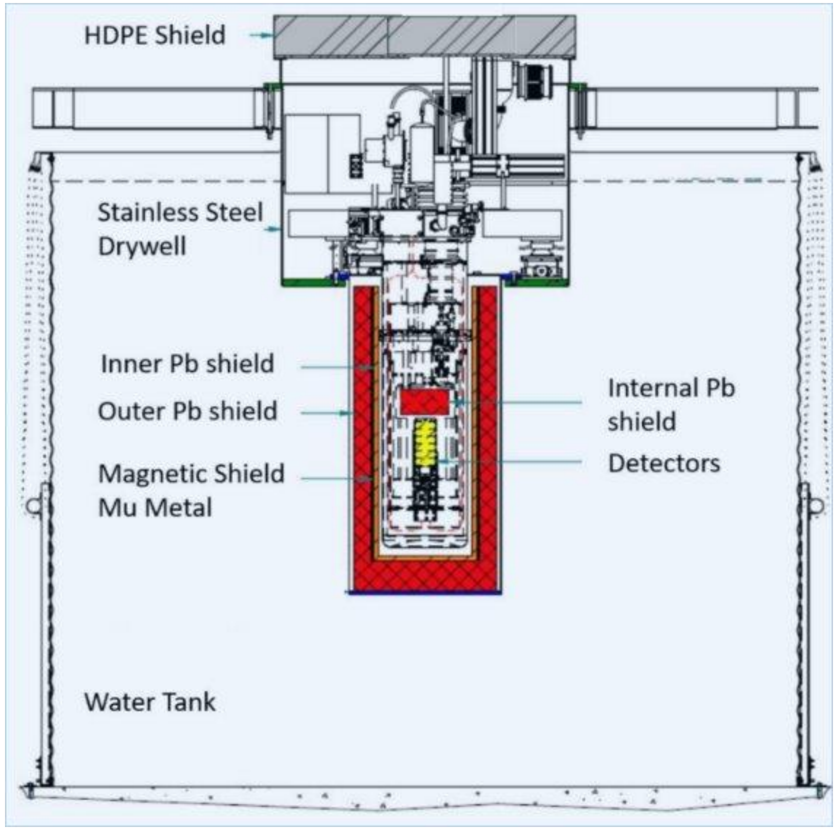


See Matthew Stukel's talk

https://indico.cern.ch/event/1316311/contributions/5868952

Tower Testing at CUTE

- **1 HV tower payload: 4 Ge, 2 Si detectors**
- **5-month international effort**
- **First tests in very low-bg environment**



Analyses underway:

- ✓ **Detector calibration**
- ✓ **Noise modelling**
- ✓ **Background rates**
- ✓ **Phonon signal amplification with NTL effect**
- ✓ **Sensitivity estimation**
- ✓ **Potential DM search**

See Yan Liu's talk

https://indico.cern.ch/event/1316311/contributions/5861281

Slide credit: Aditi Pradeep

Summary

- **SuperCDMS SNOLAB is a world-leading DM direct detection experiment currently under construction**
- **Targeting sub-GeV DM masses**
- **Rapidly ramping up to commissioning phase**
- **Detector tower testing recently completed at CUTE facility, several analyses in-progress to better understand our detectors**
- **Expecting early science results by next year!**

SUPER CDMS
Cryogenic Dark Matter Search

@SuperCDMS

https://www.snolab.ca/experiment/supercdms/