DM Direct Detection with SuperCDMS

SUPER CDMS
Cryogenic Dark Matter Search

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McDonald Institute National Meeting

Aug 9 2024, Kingston ON

https://indico.cern.ch/event/1412503/contributions/6064462/

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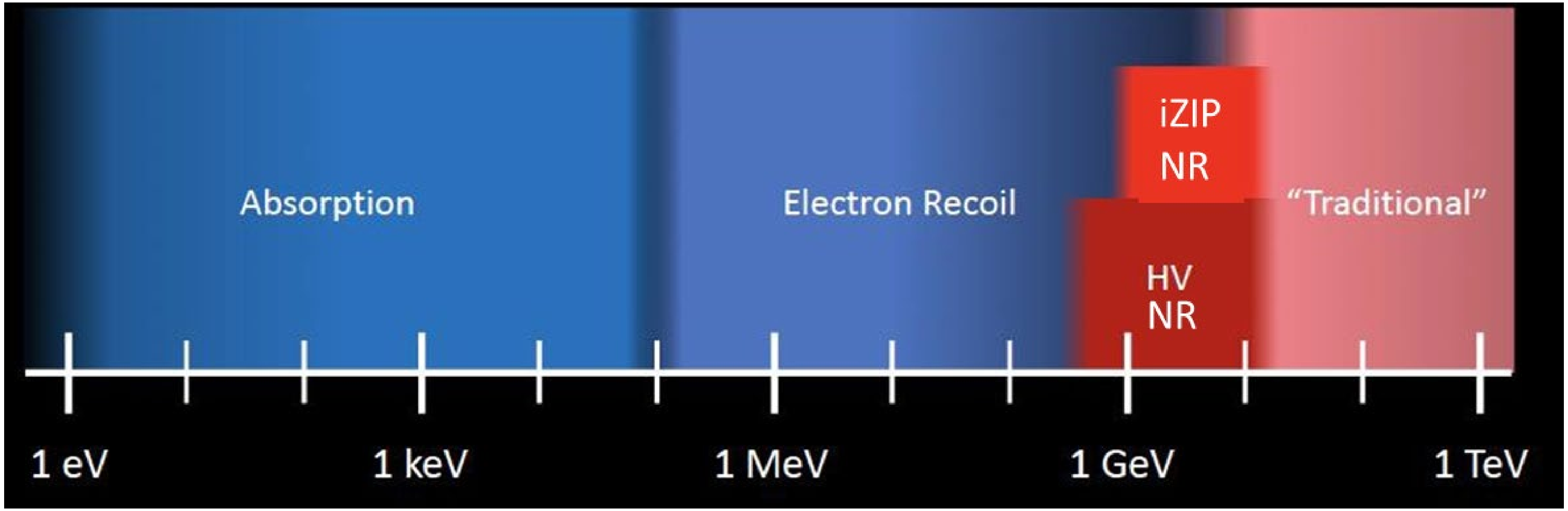
SuperCDMS@SNOLAB at a Glance

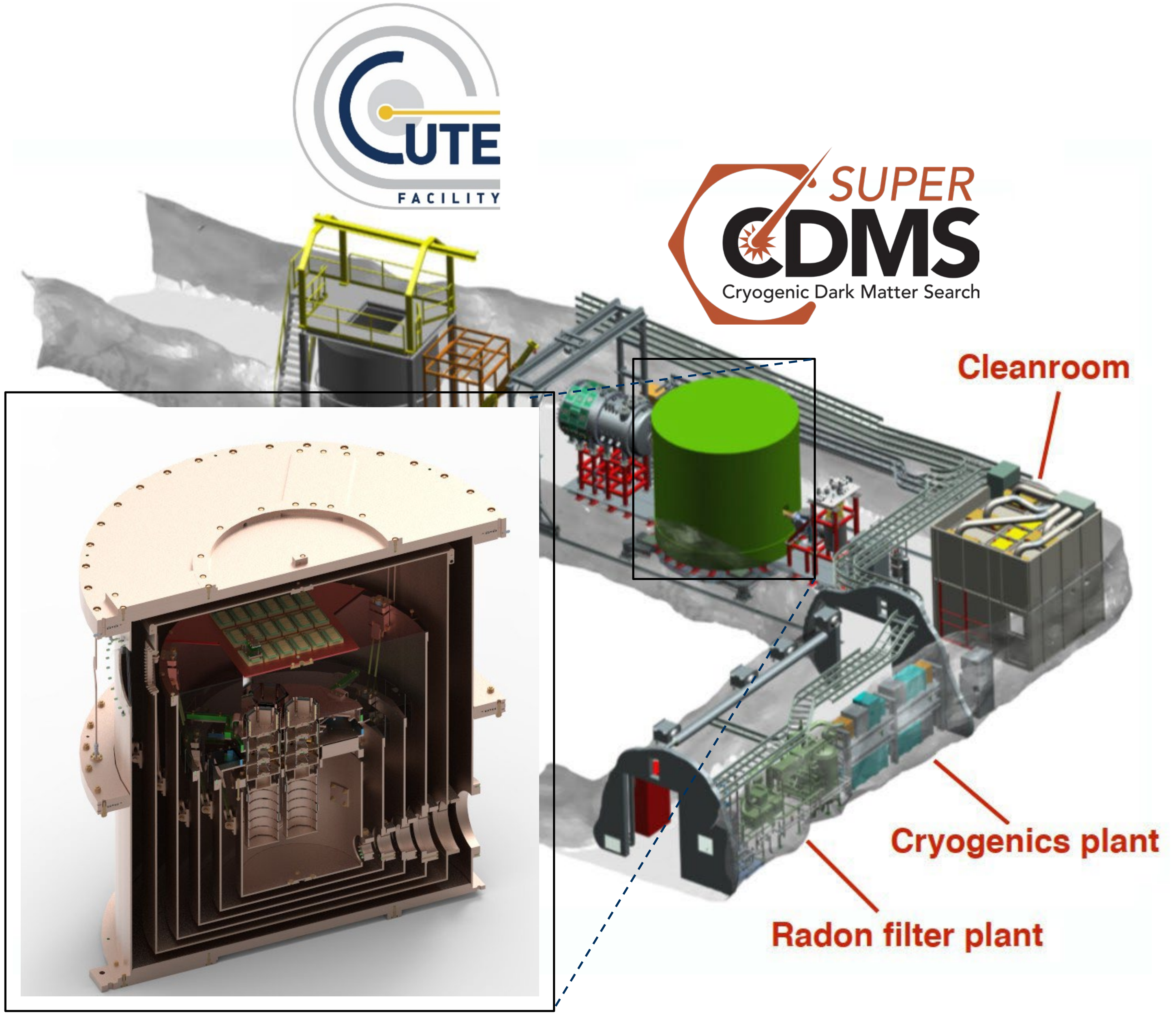
- **Primary science goal: world-leading sensitivity to low-mass WIMPs**
- **Secondary science goals: electron recoil & dark absorption searches for dark photons, axions, lightly-ionizing particles, etc.**
- **Cryogenic semiconductor crystals with quantum sensors**
- **Two detection schemes:**
  - **Ionization + 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!



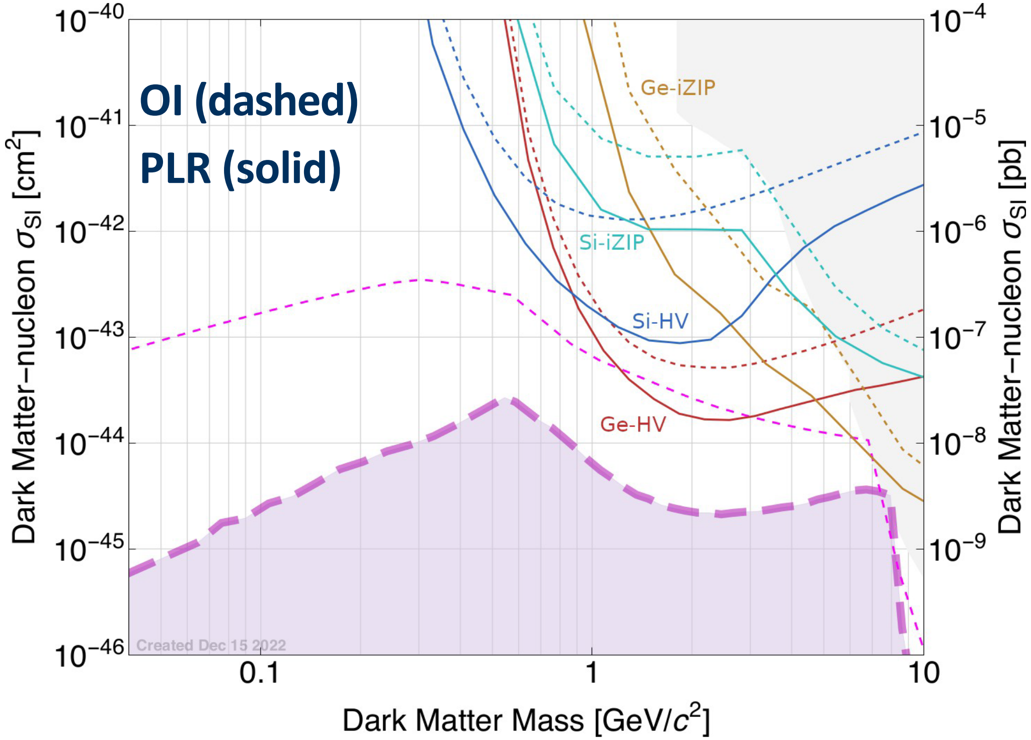
Slide credit: Stefan Zatschler

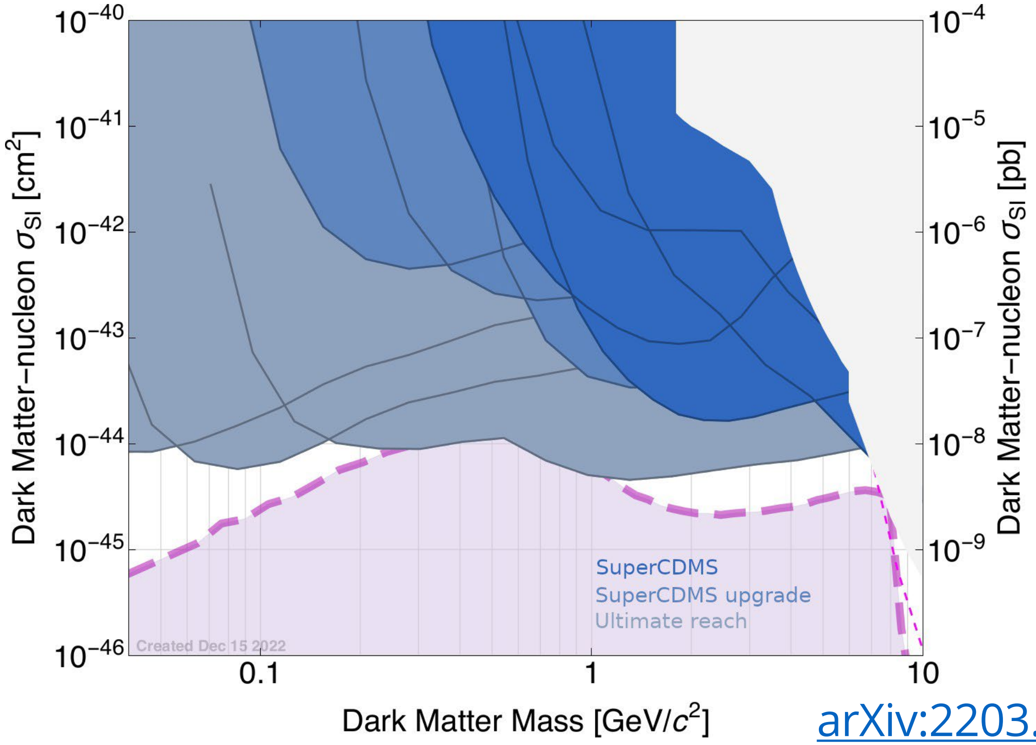
Topics

- **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**

SuperCDMS Science Reach

NRDM SuperCDMS SNOLAB



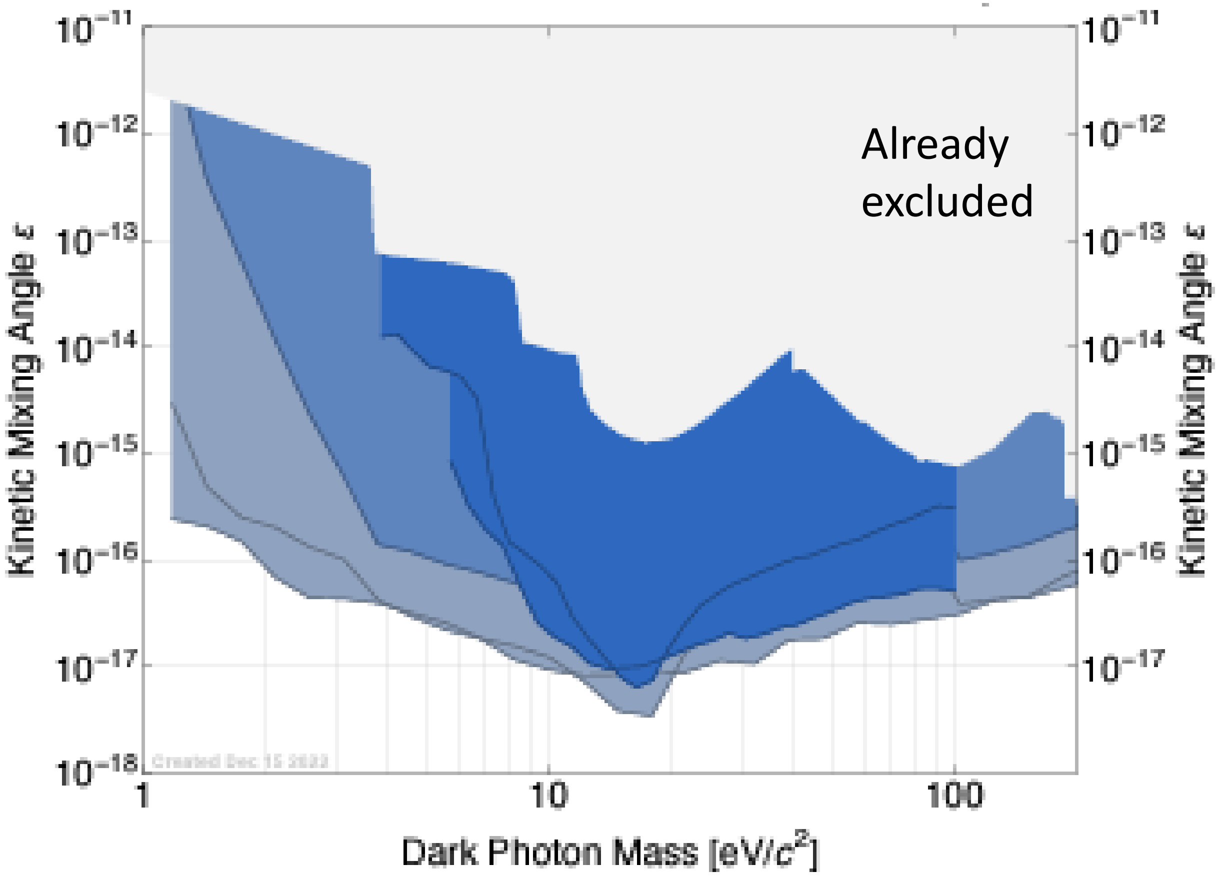


arXiv:2203.08463

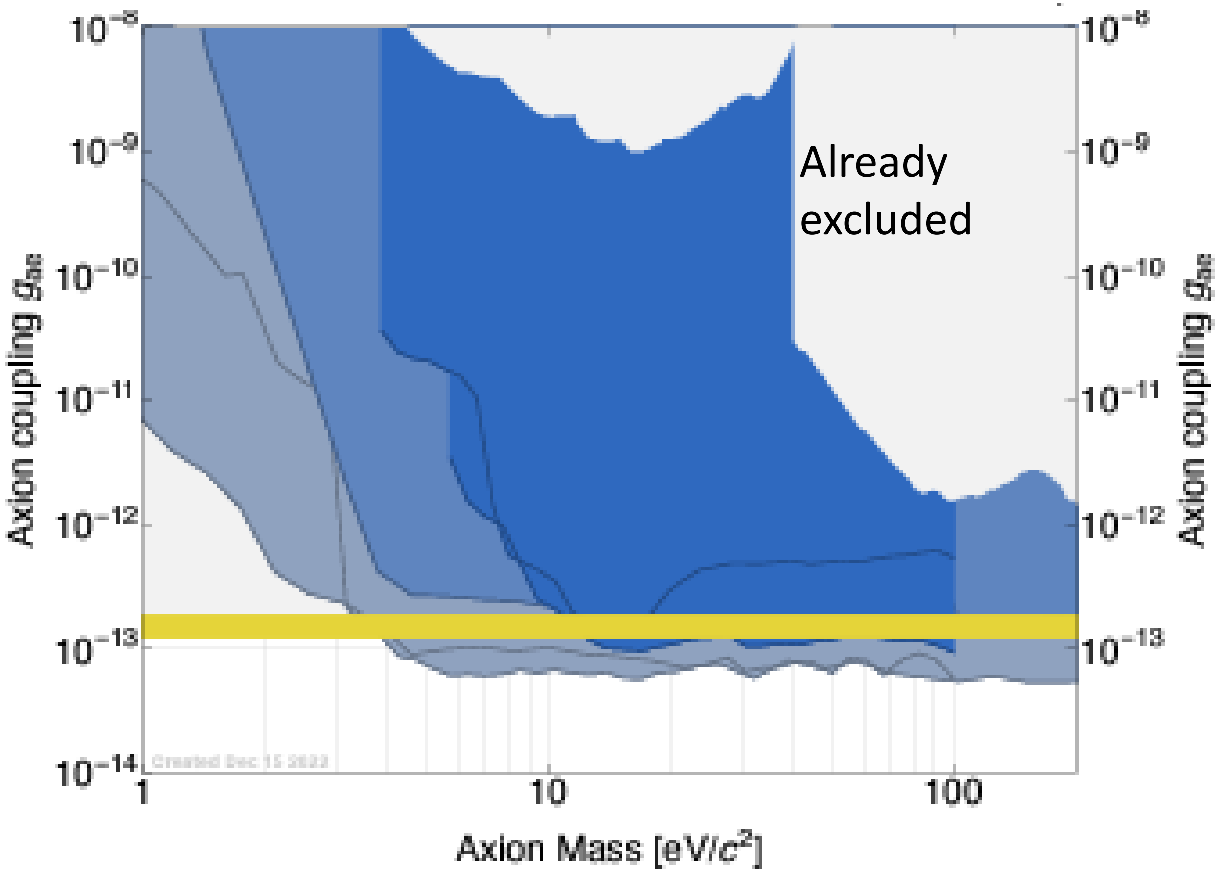
- **Understanding detector response down to the semiconductor bandgap energy crucial for maximizing sensitivity to sub-GeV DM masses**
- **Recent SNOWMASS projections, for different statistical methods and DM models**
  - ▶ **Optimum Interval (OI): signal-only assumption**
  - ▶ **Profile-likelihood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

SuperCDMS Science Reach

Dark Photon



Axion-Like Particle DM



arXiv:2203.08463

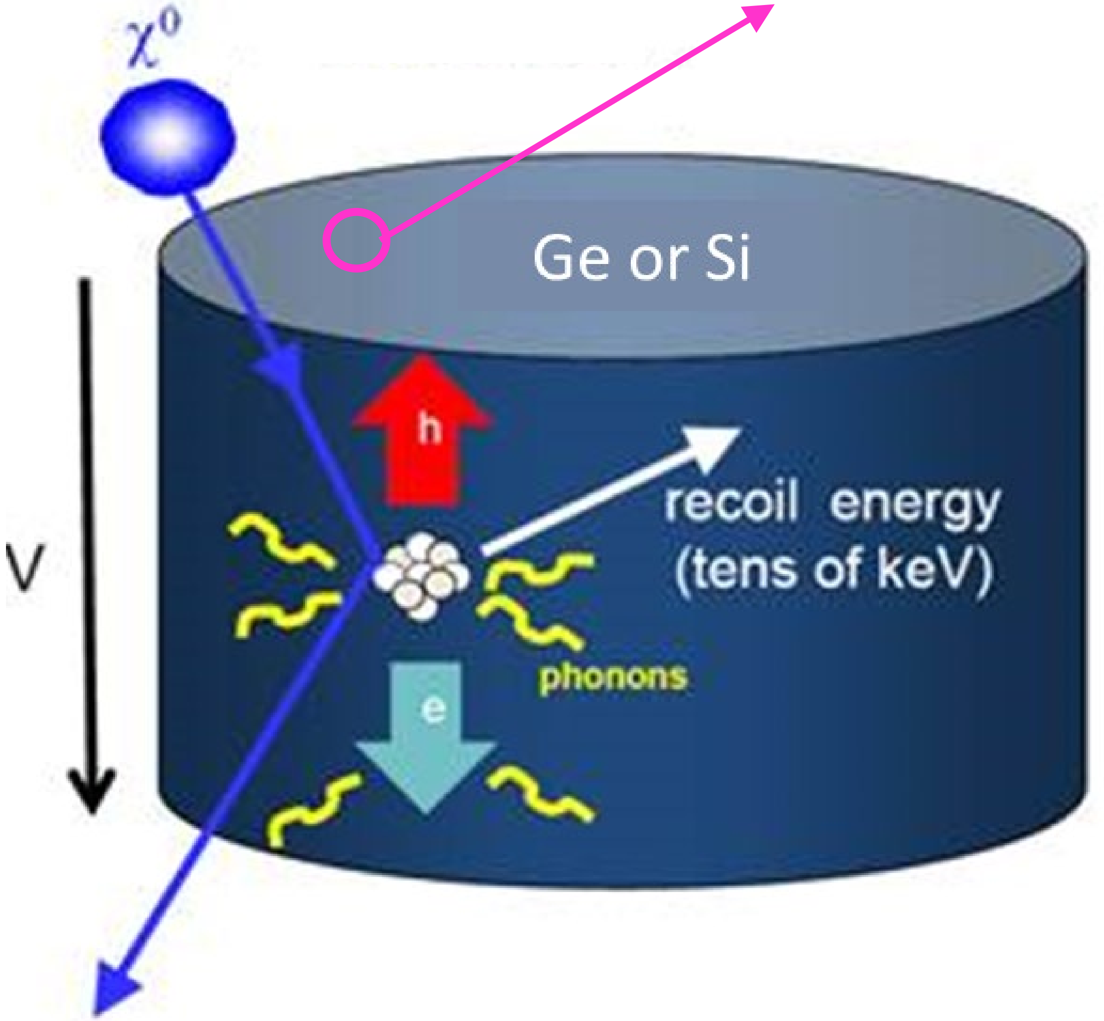
SuperCDMS Detector Principles

- **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**

<u>Driving questions:</u>

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

Transition Edge Sensor (TES) phonon readout
High Electron Mobility Transistor (HEMT) ionization readout



SuperCDMS Detector Principles

HV detectors – low threshold

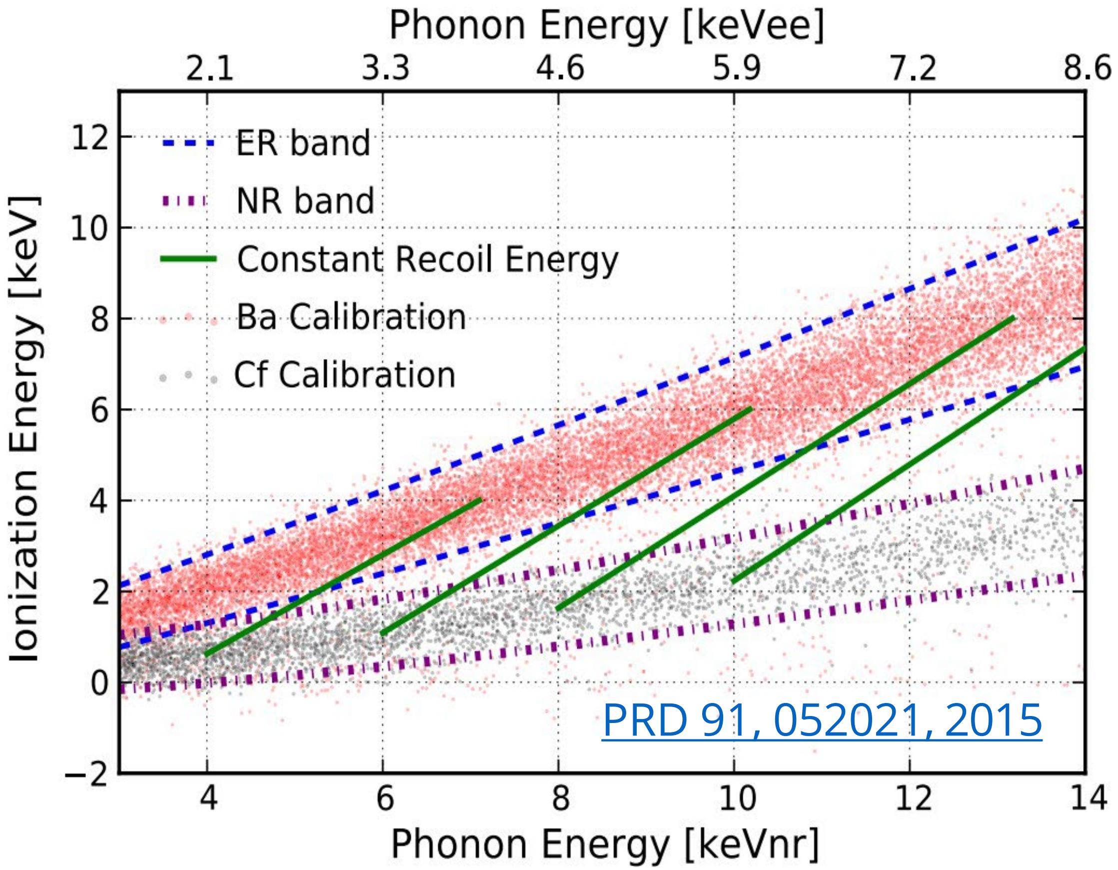
- High resolution total phonon measurement
- No yield discrimination, limited fiducialization
- Typical thresholds below 0.1 keV (4 eV_{ee}) !

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

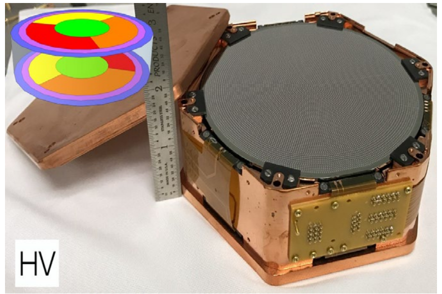
SuperCDMS detector principles

HV detector → low threshold

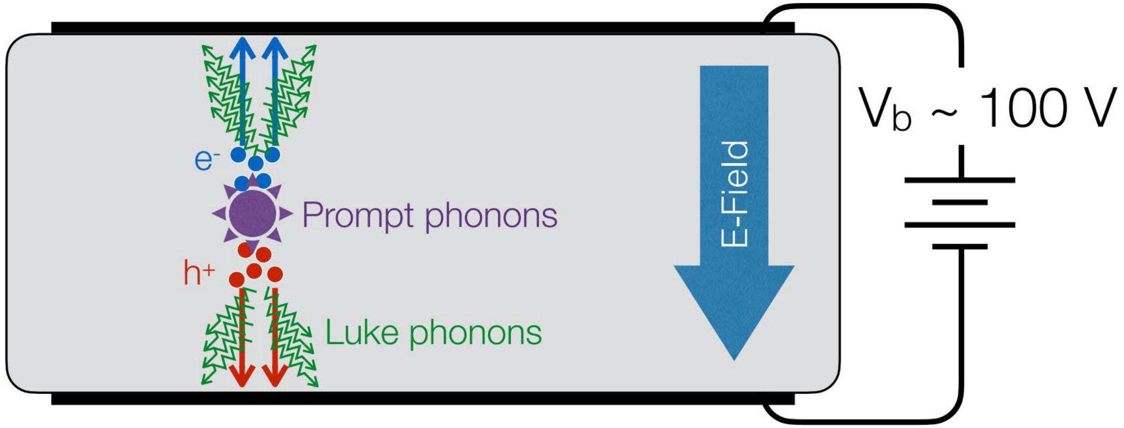
- Drifting charge carriers (e^{-}/h^{+}) across a potential (V_b) generates a large number of Luke phonons (NTL effect)

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

total phonon energy — primary recoil energy — Luke phonon energy

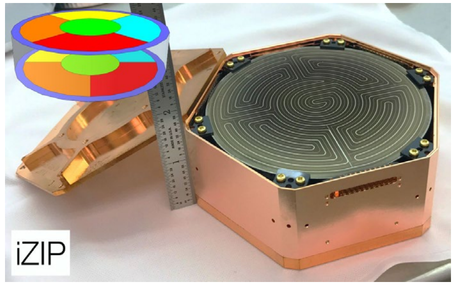


Sensors measure E_t



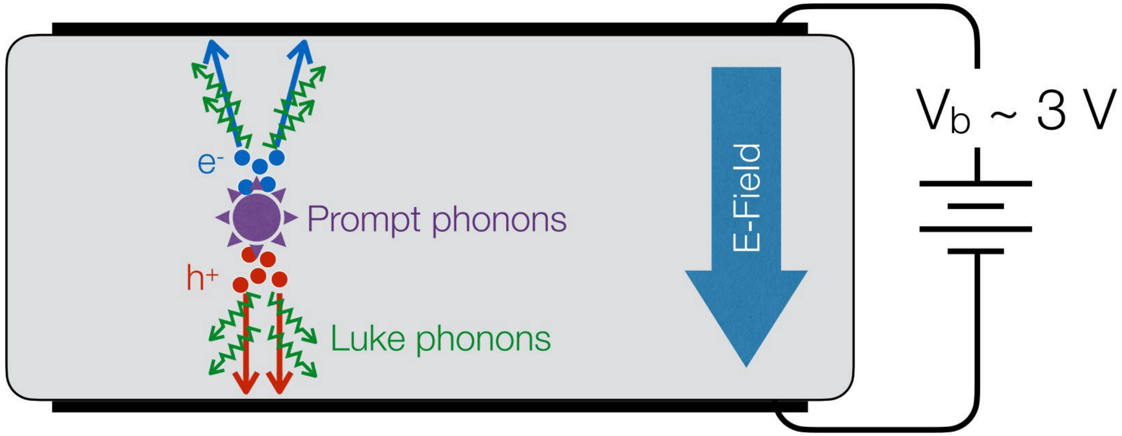
iZIP detector → low background

- Interleaved Z-sensitive Ionization and Phonon detector



PRD 95, 082002, 2017

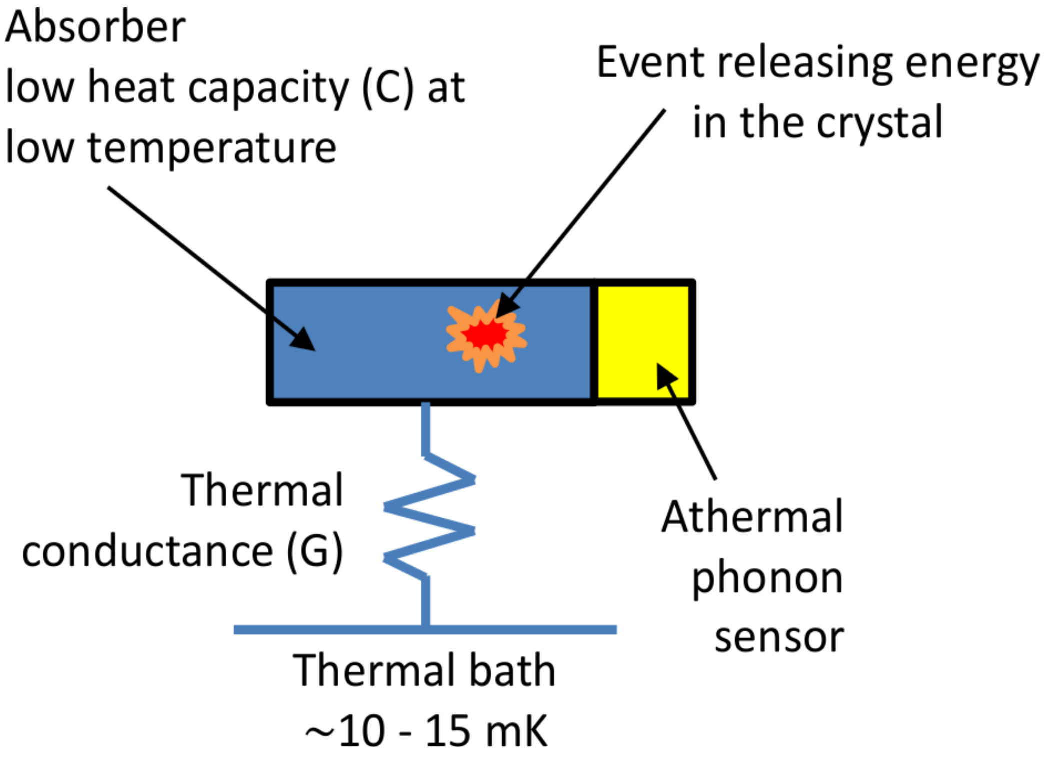
Sensors measure E_t and N_{eh}

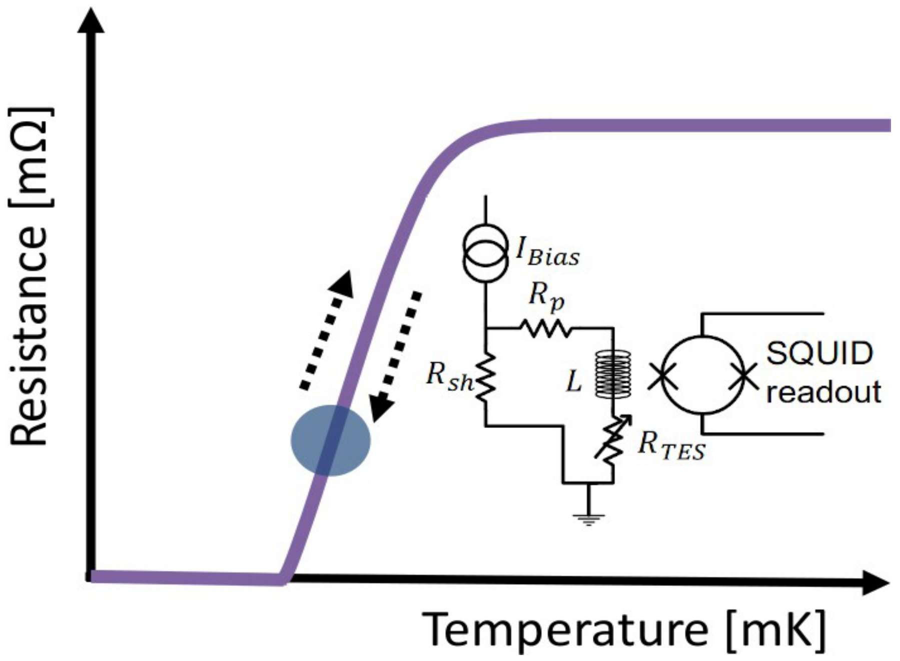


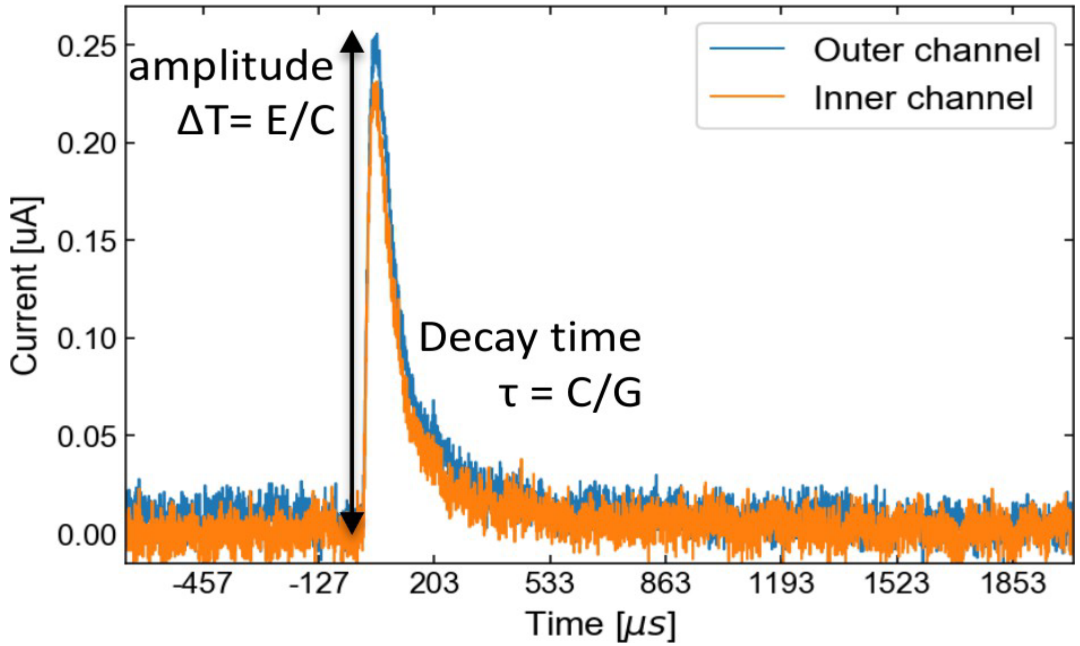
Slide credit: Stefan Zatschler

SuperCDMS detector principles

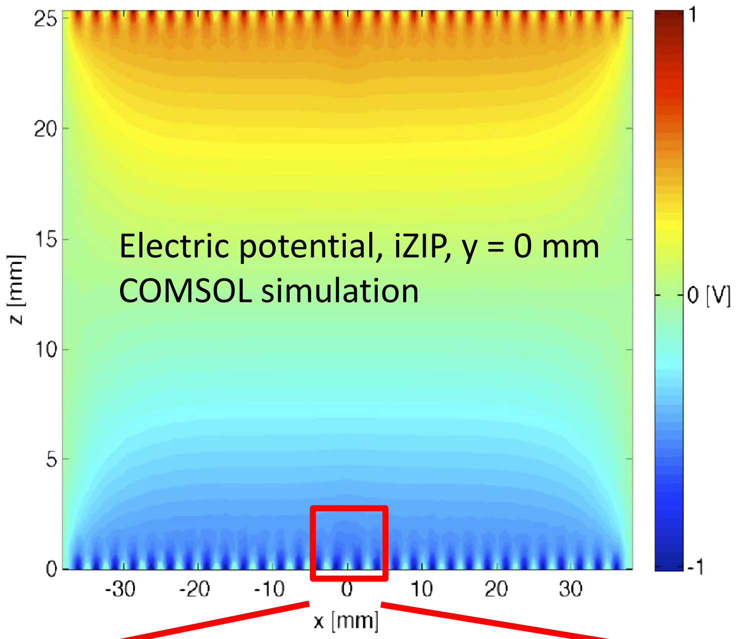
- **Athermal phonon collection with QETs (Quasiparticle trap-assisted Electrothermal feedback TESs)**
- **Pulse reconstruction**
- **Measure of energy deposit**

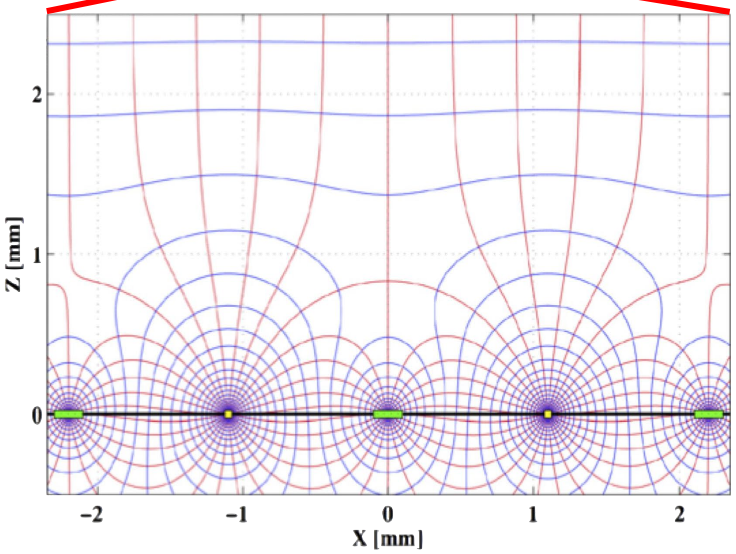






iZIPs





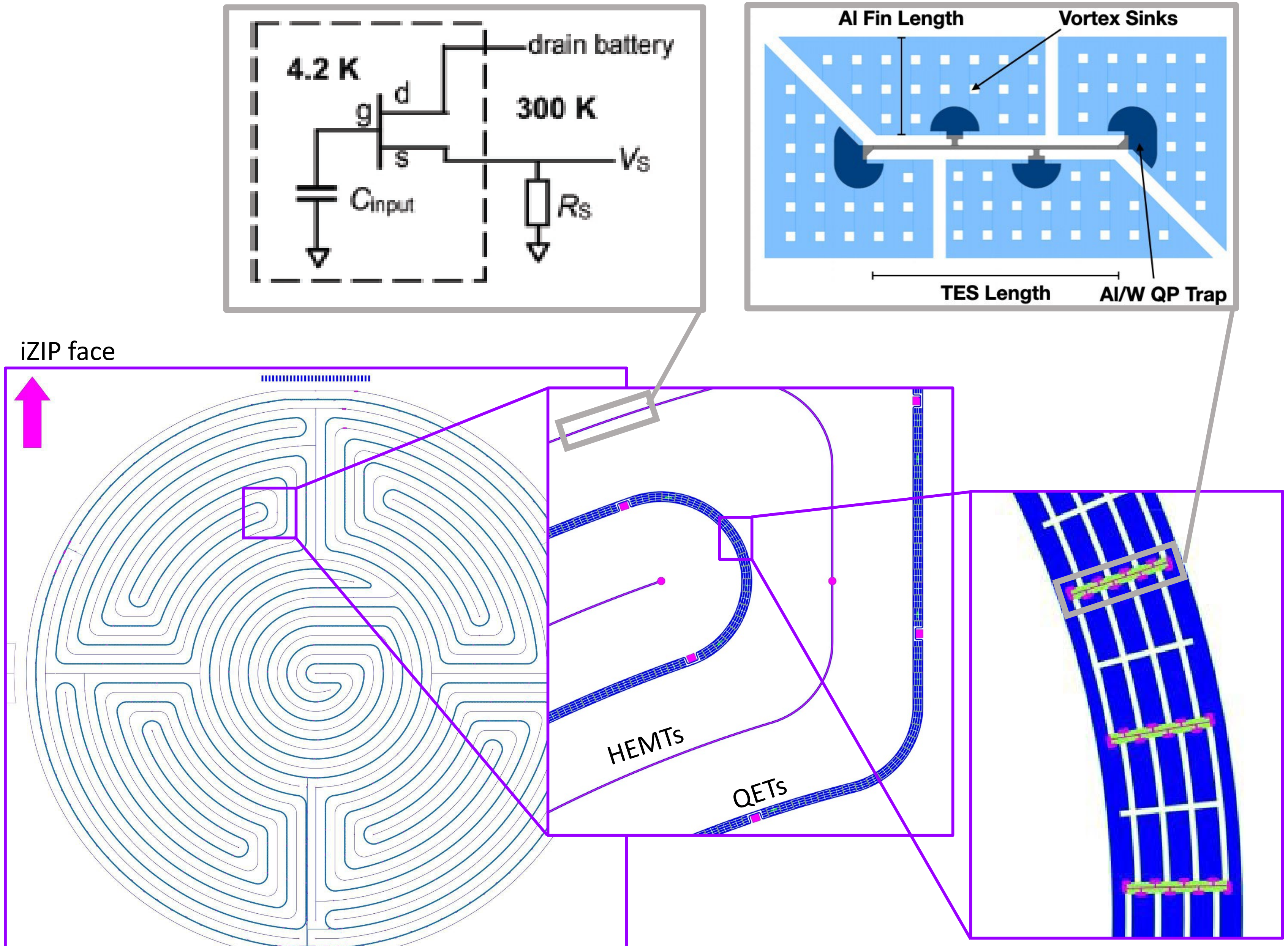
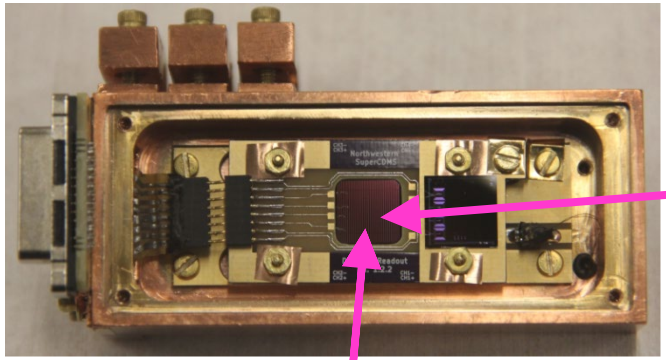
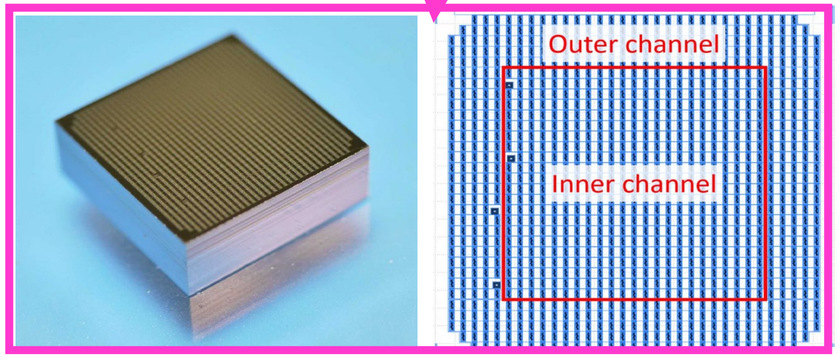
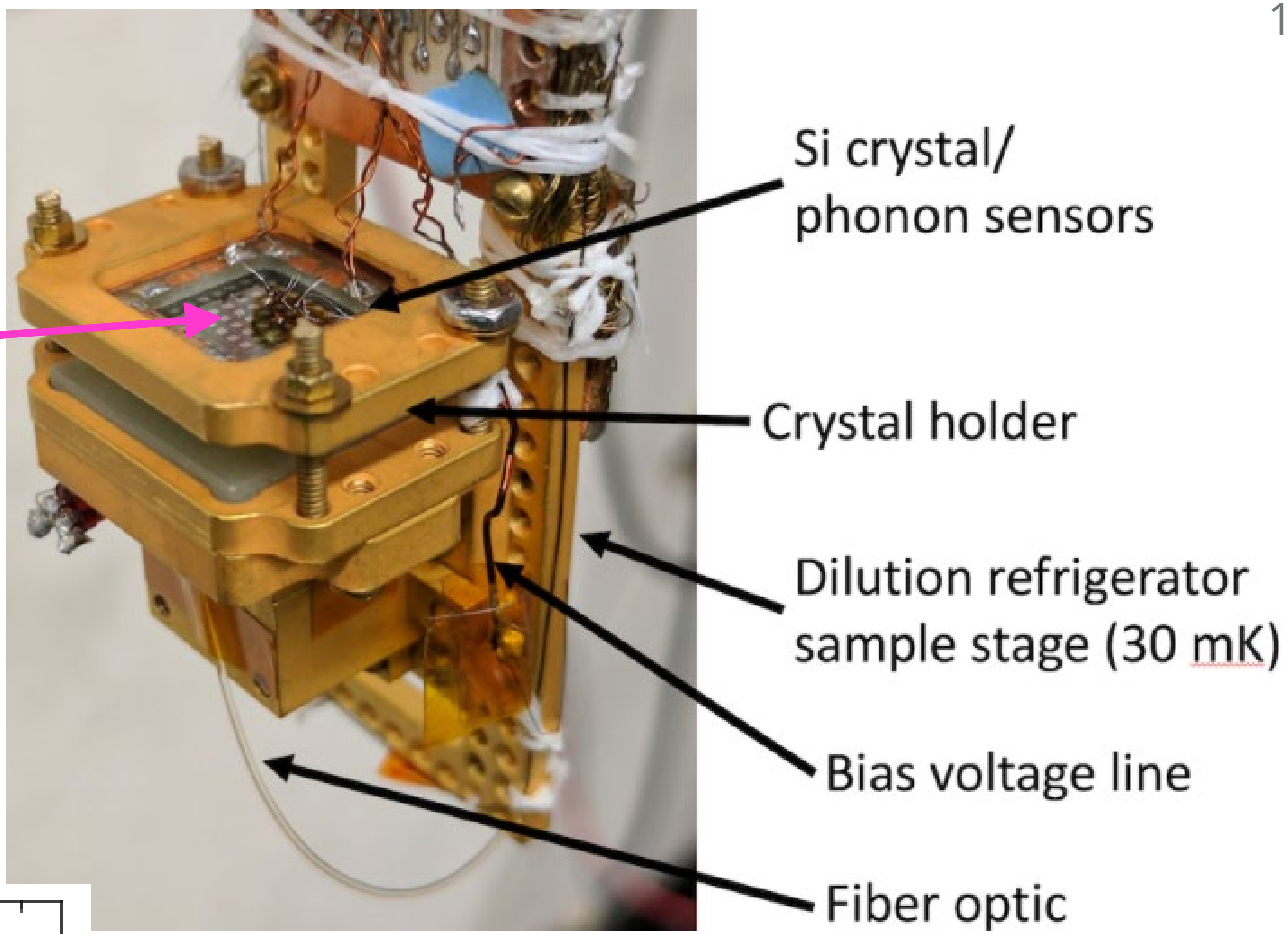


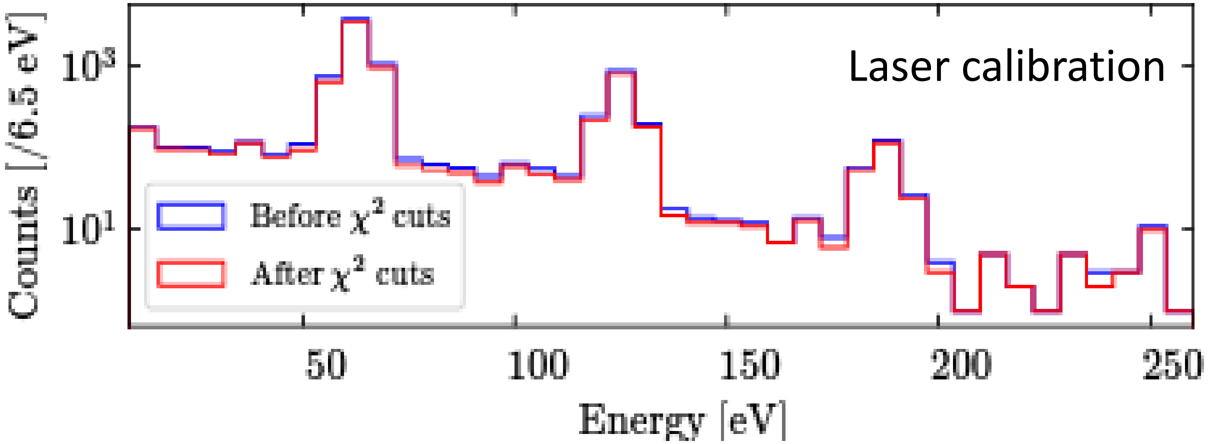
Image credits: Mike Kelsey

HVeVs







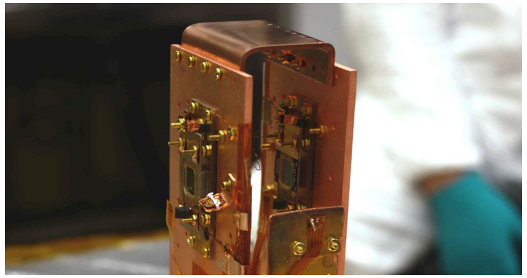


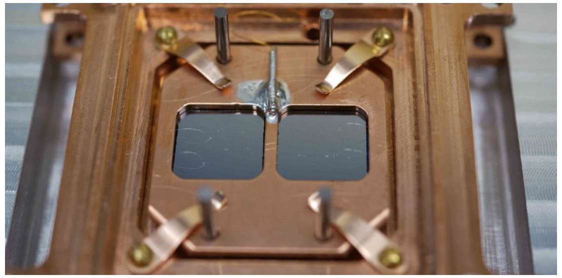
Few eV phonon resolution, can see single e-h pairs!

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]

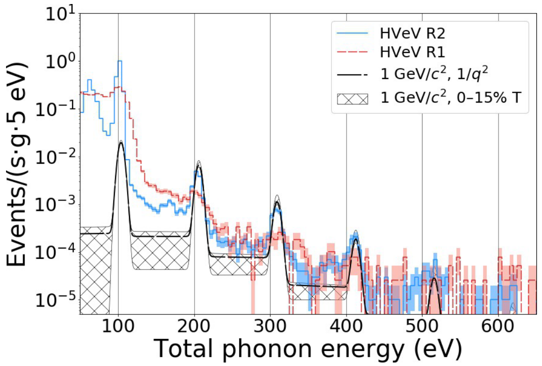




Stay tuned!

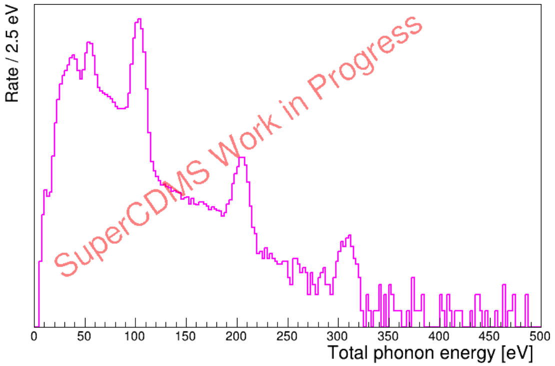
HVeV Run 2

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



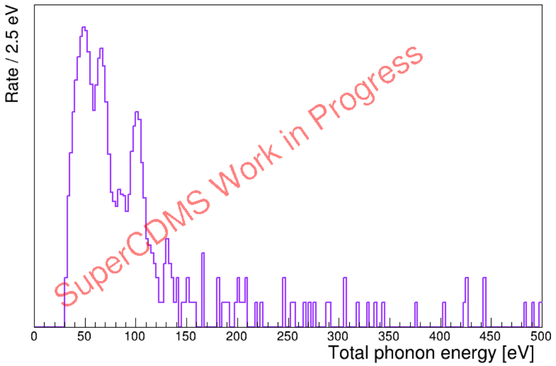
HVeV Run 3

- Coincidence measurement
- Confirmed external origin of burst events



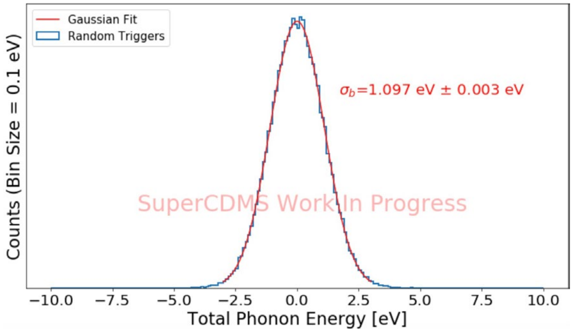
HVeV Run 4

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



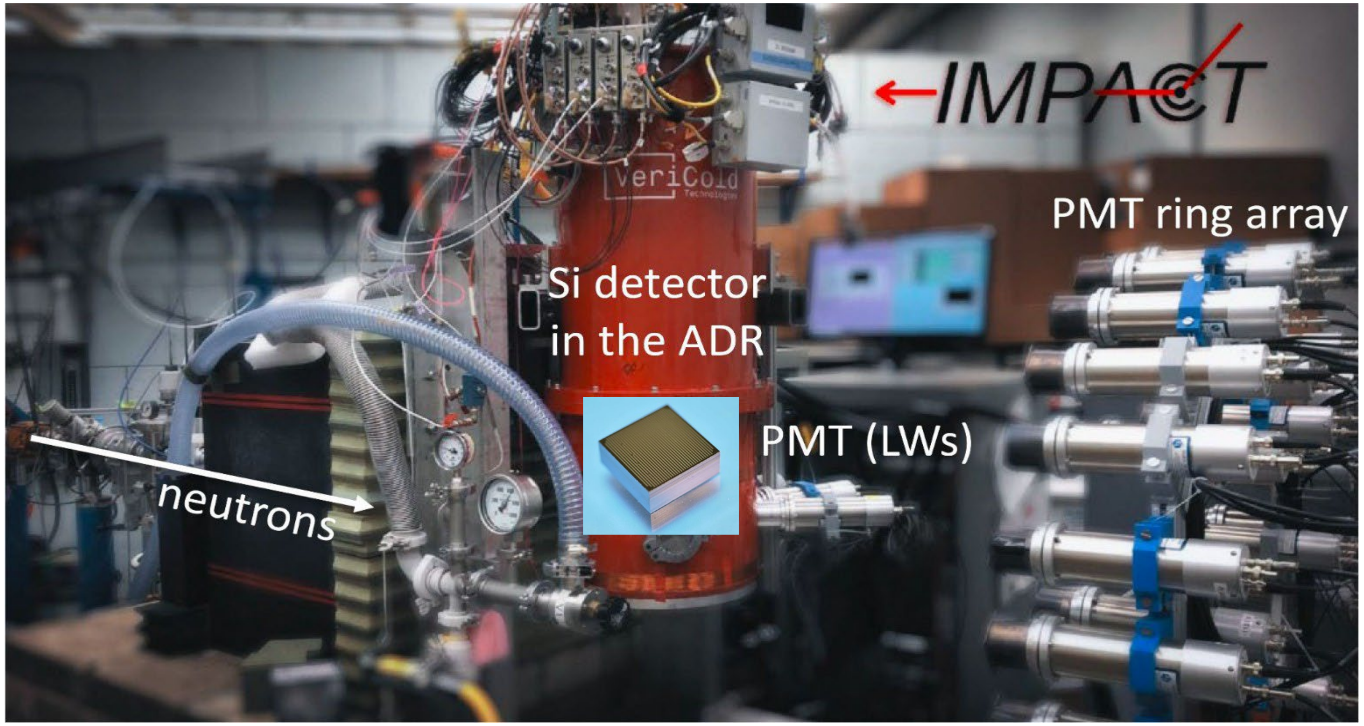
Latest performance

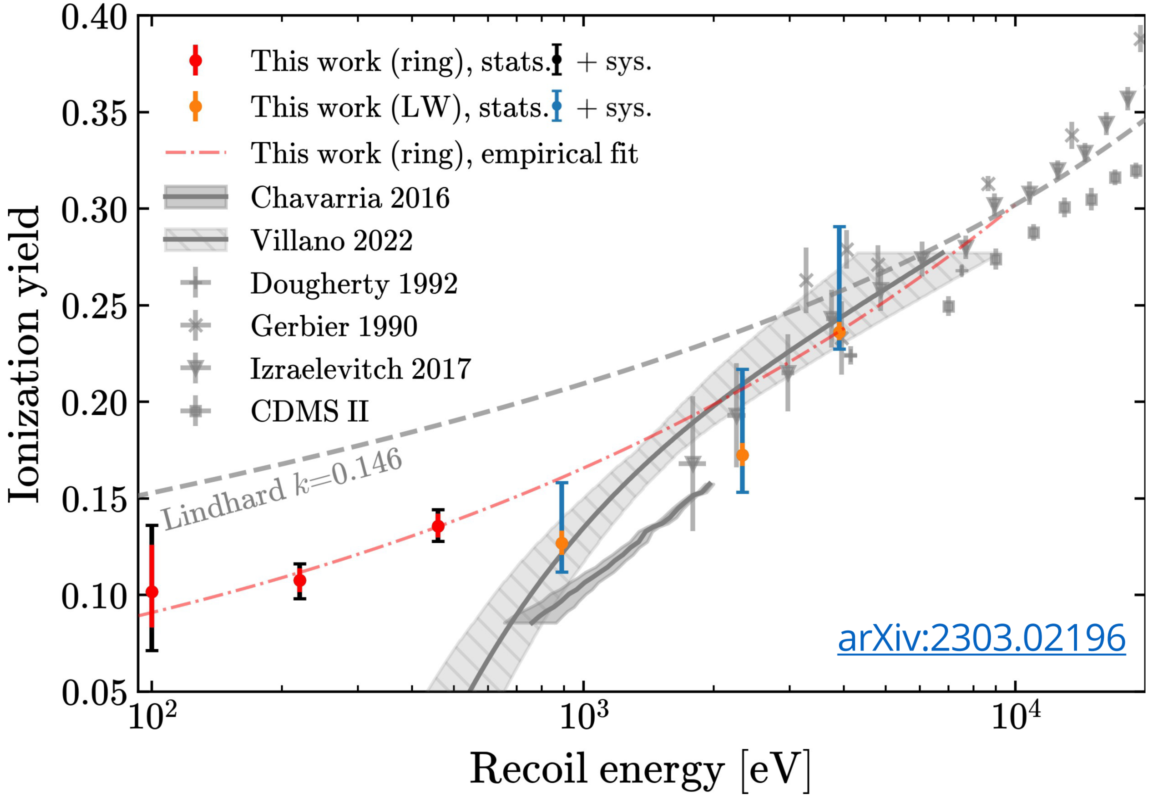
- V3 of HVeV
- Greatly improved baseline resolution (σ_b = 1.097 ± 0.003 eV)



Slide credit: Stefan Zatschler

HVeVs for Measuring Nuclear Recoil Ionization Yield





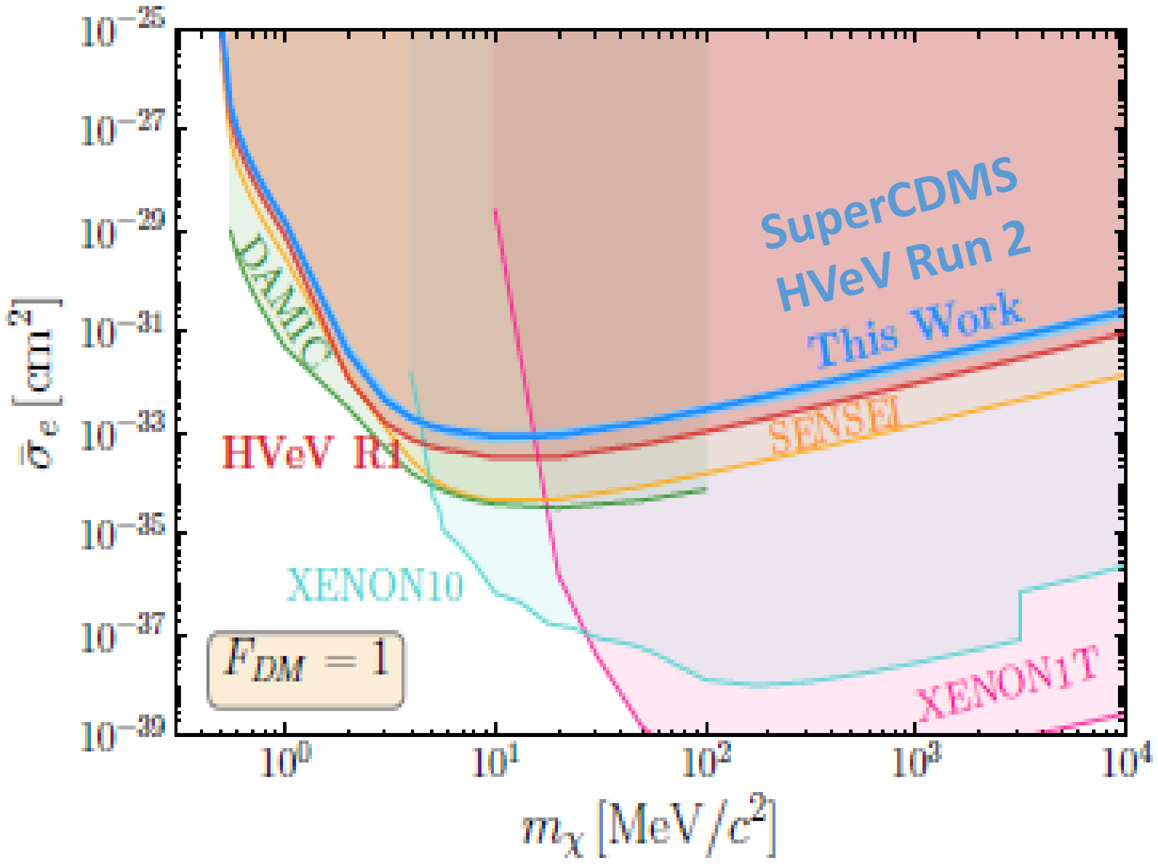
- Ionization yield (Y) measurement down to 100 eV with Si HVeV in a neutron beam
  - ▸ Significant deviations from "Lindhard model"
  - ▸ No indication for ionization threshold in Si
- Ge yield measurement in preparation

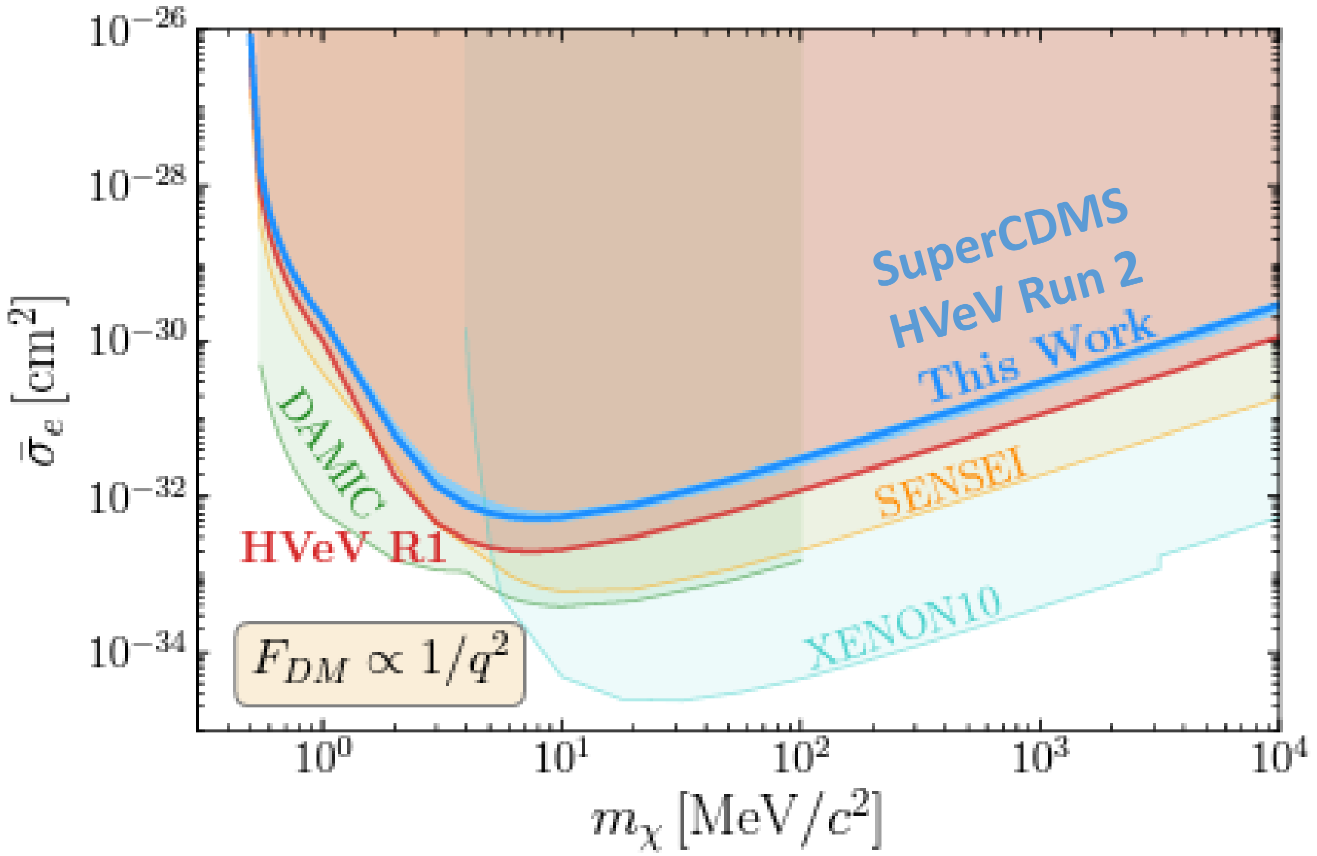
Total phonon energy and yield

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

Slide credit: Stefan Zatschler

HVeV Electron Recoil DM Limits

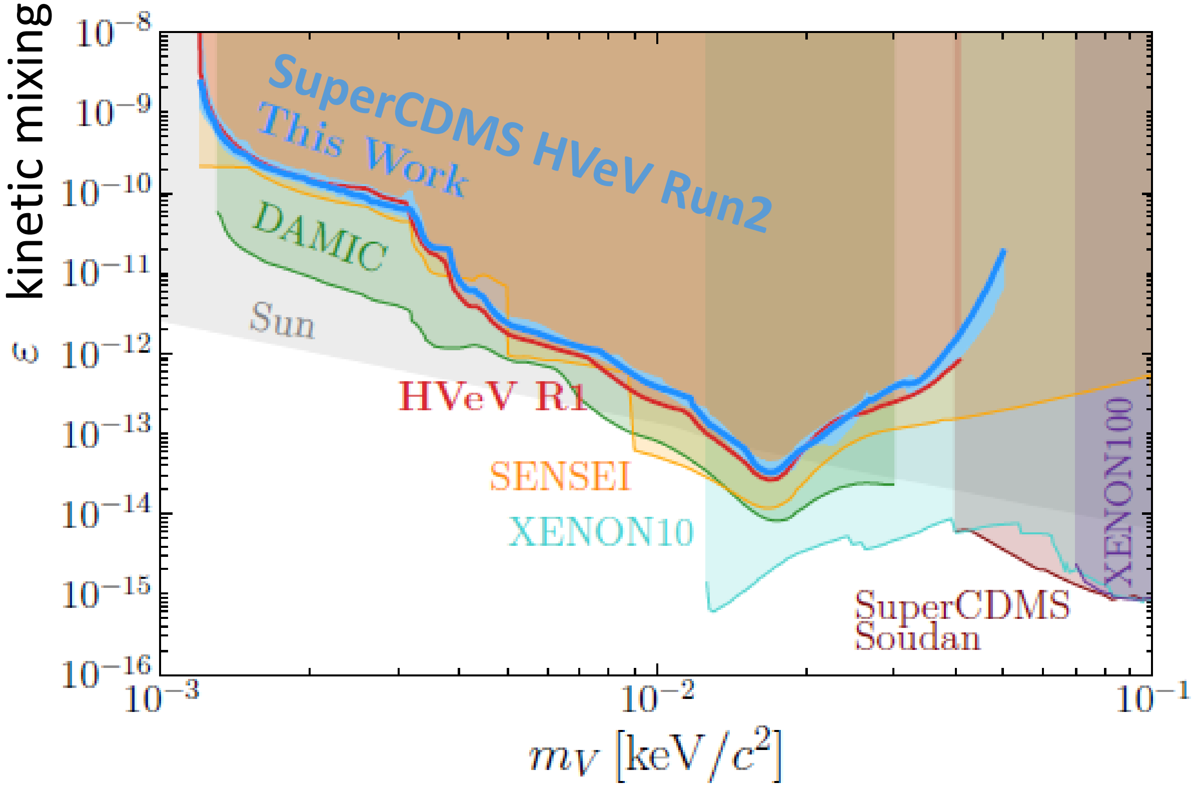




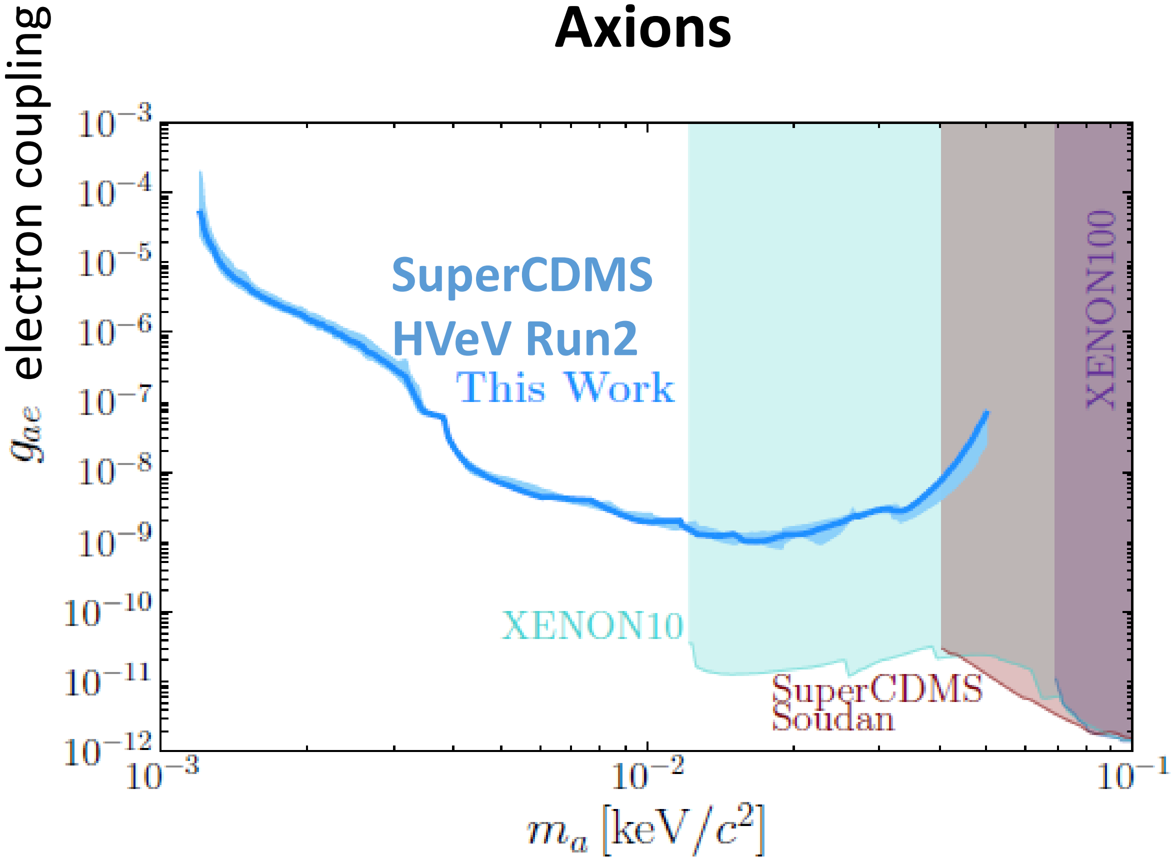
PRD 102, 091101(R), 2020

HVeV Dark Photon & Axion Limits

Dark Photons

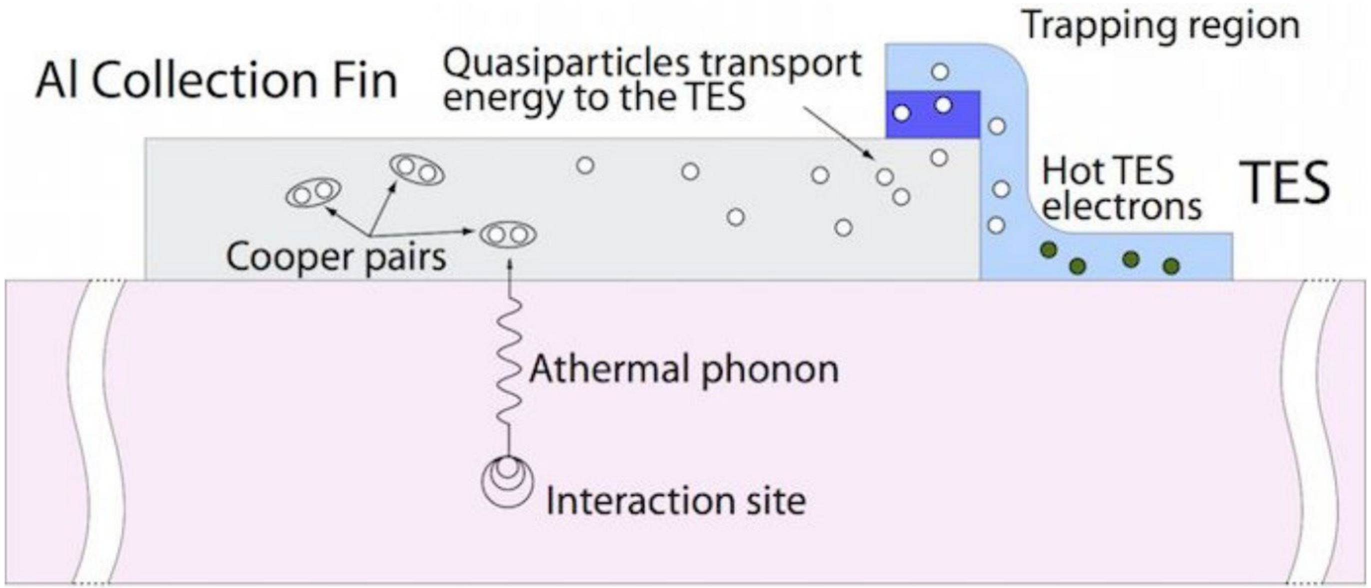


Axions

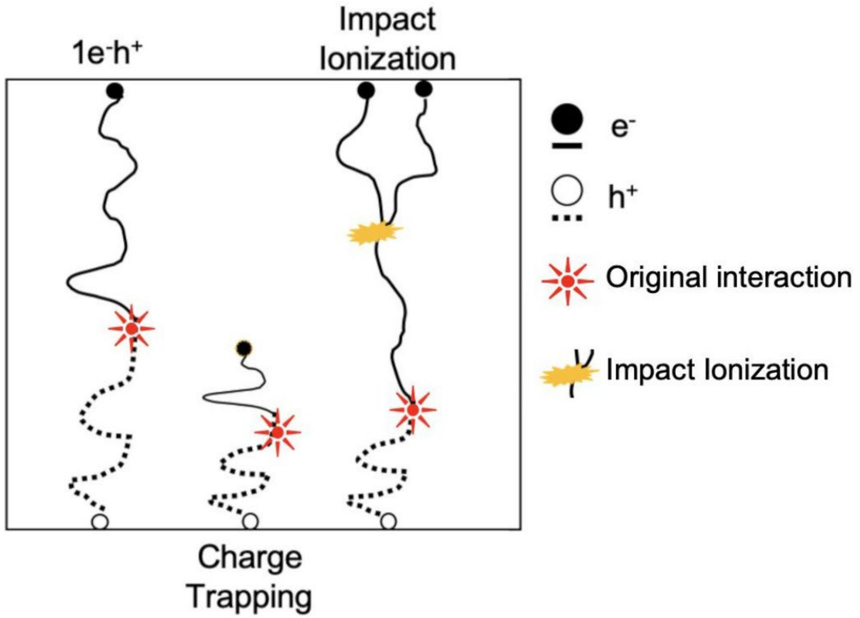


PRD 102, 091101(R), 2020

Detector Response Modeling



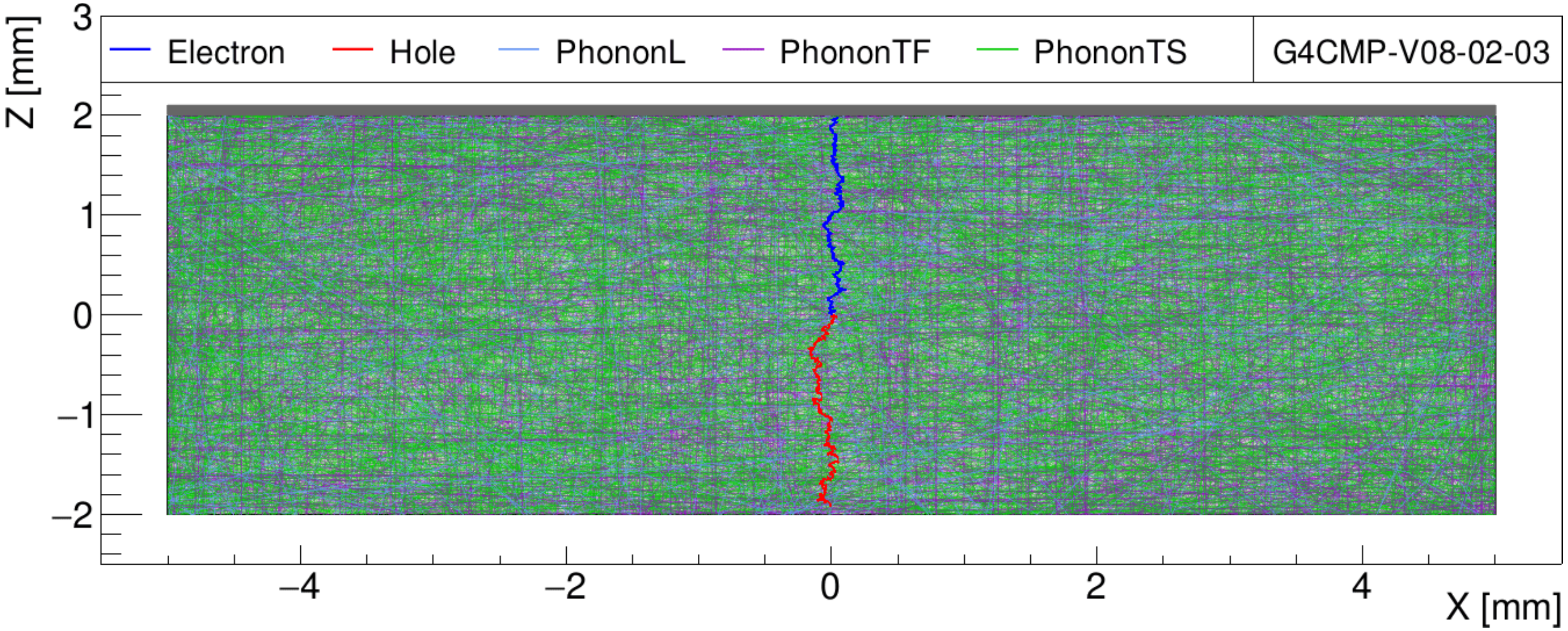
https://figueroa.physics.northwestern.edu

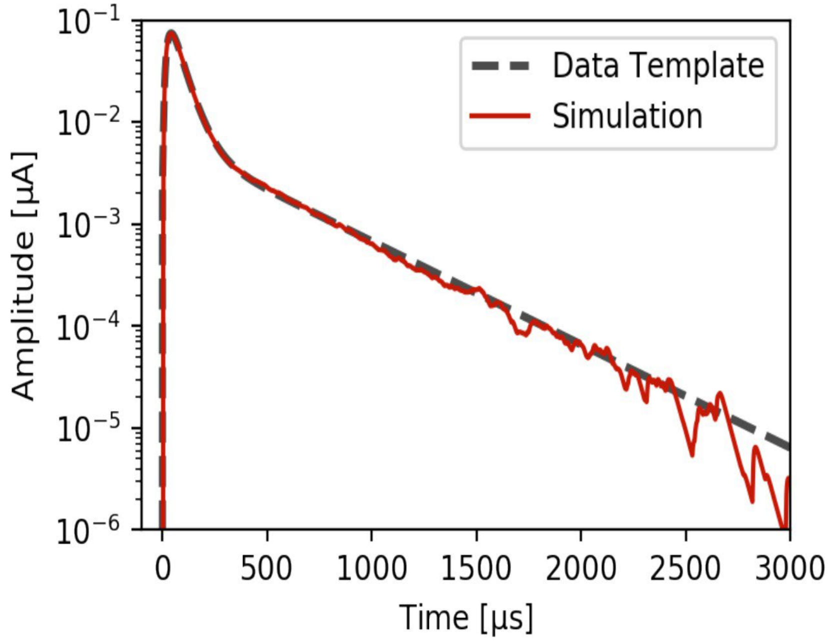


- **Sophisticated GEANT4-based framework, "G4DMC", models crystal and sensor response with help of G4CMP (GEANT4 Condensed Matter Physics) package**
  - **Crystal dynamics: lattice definition, charge transport, phonon scattering, etc.**
  - **Impurity effects: Charge Trapping, Impact Ionization**
  - **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 (10×10×4 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

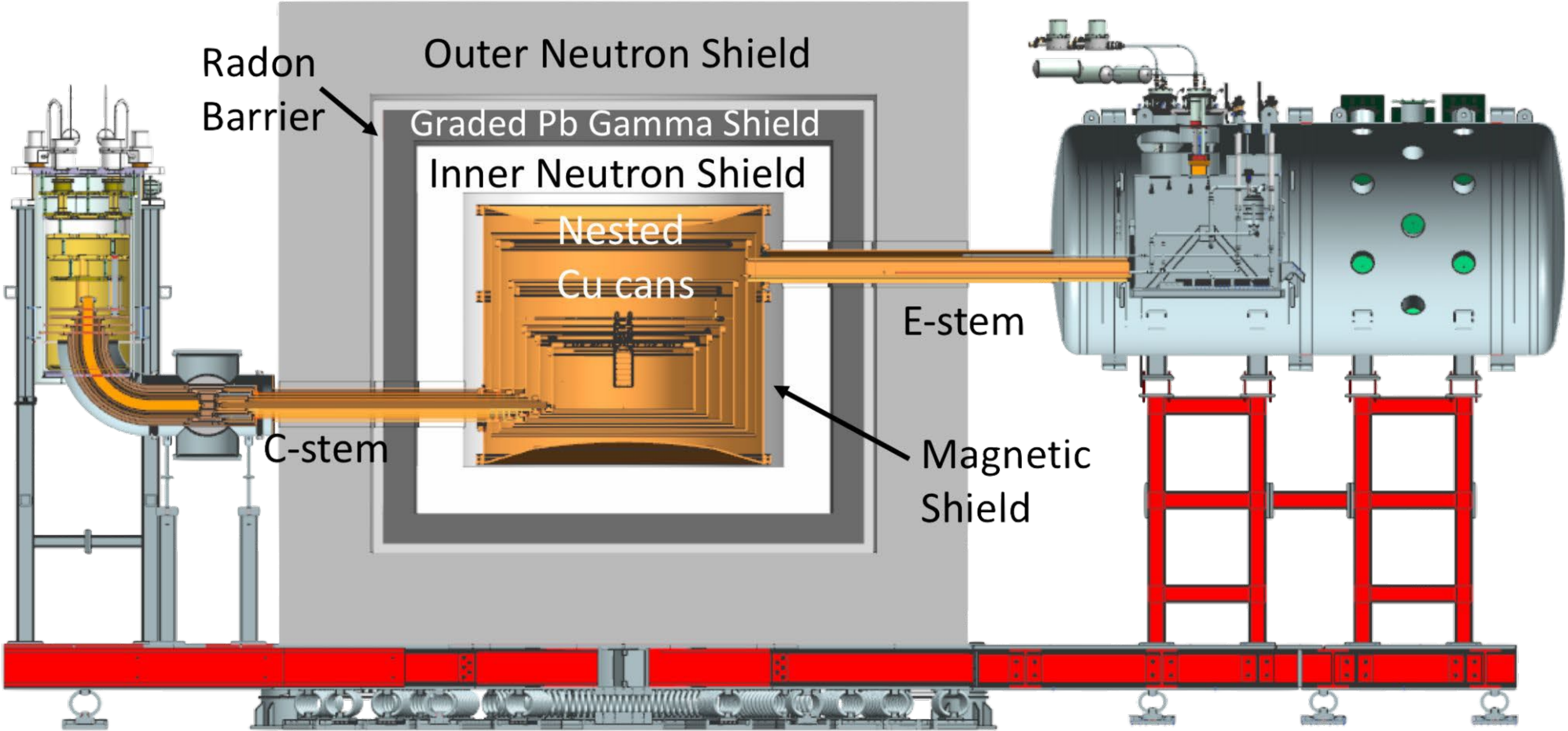
Backgrounds

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

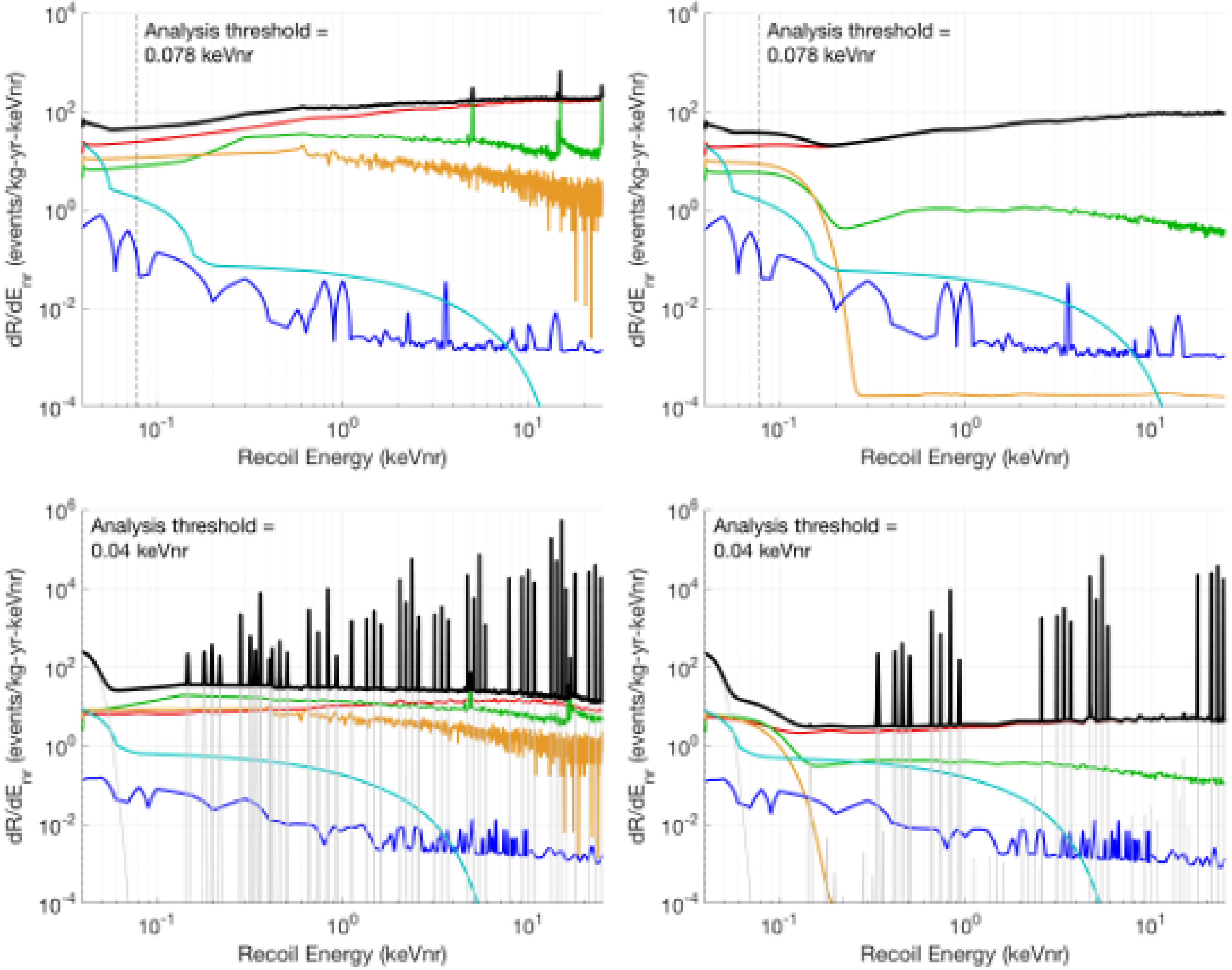
… Why?…

Backgrounds

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

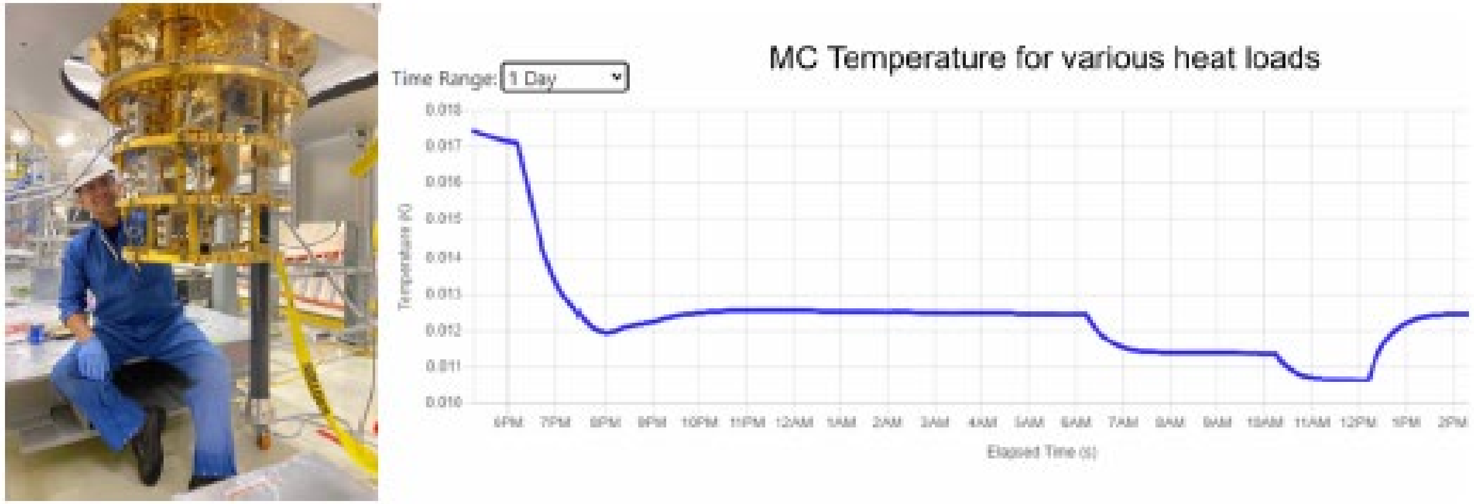
arXiv:2203.08463

SuperCDMS@SNOLAB Installation Progress in Past Year

Slide credit: Yan Liu

All 4 towers delievered underground at SNOLAB

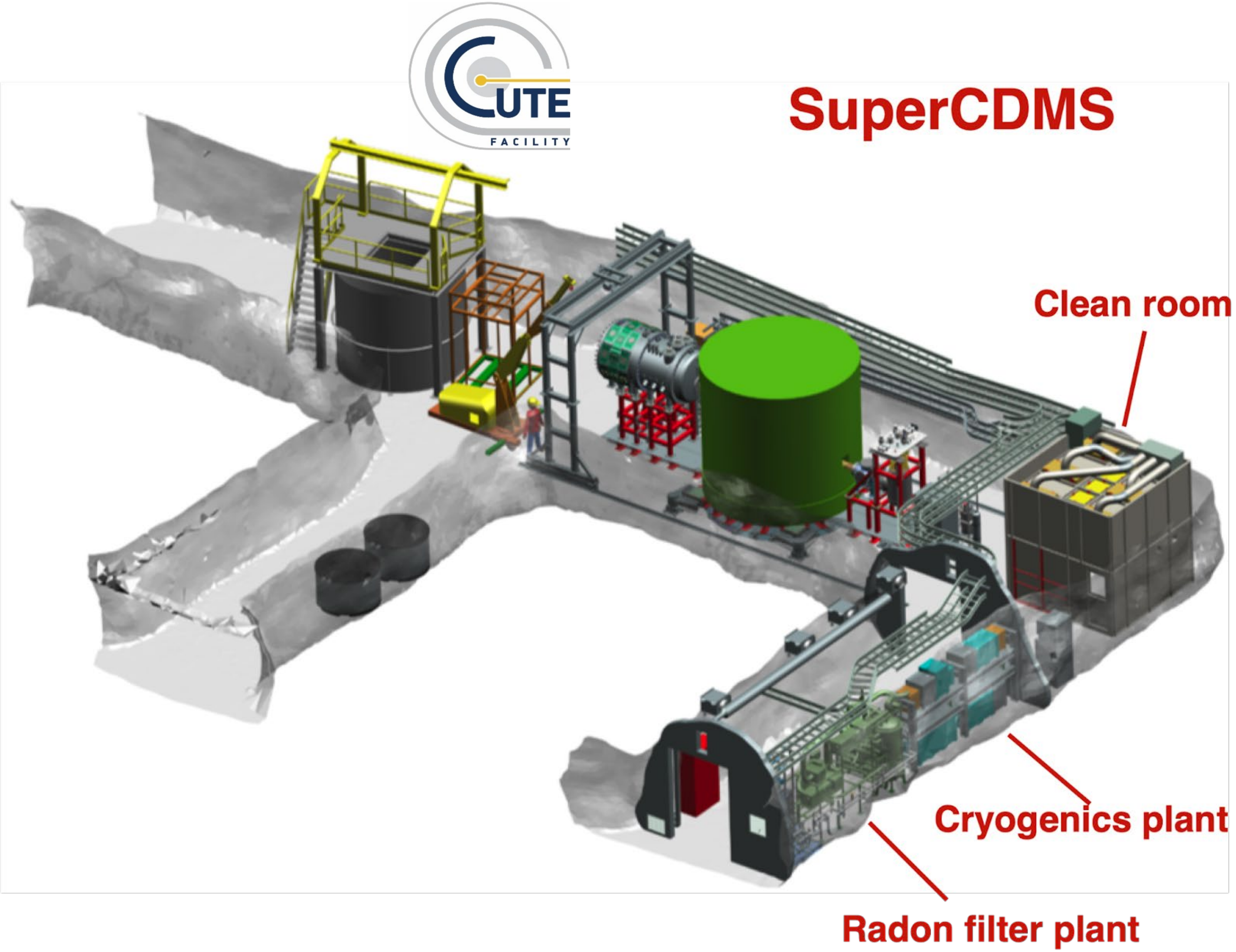
Cryostat pre-assembly accomplished at SLAC



Standalone test of the dilution fridge demonstrated base temperature

Shield base installation completed

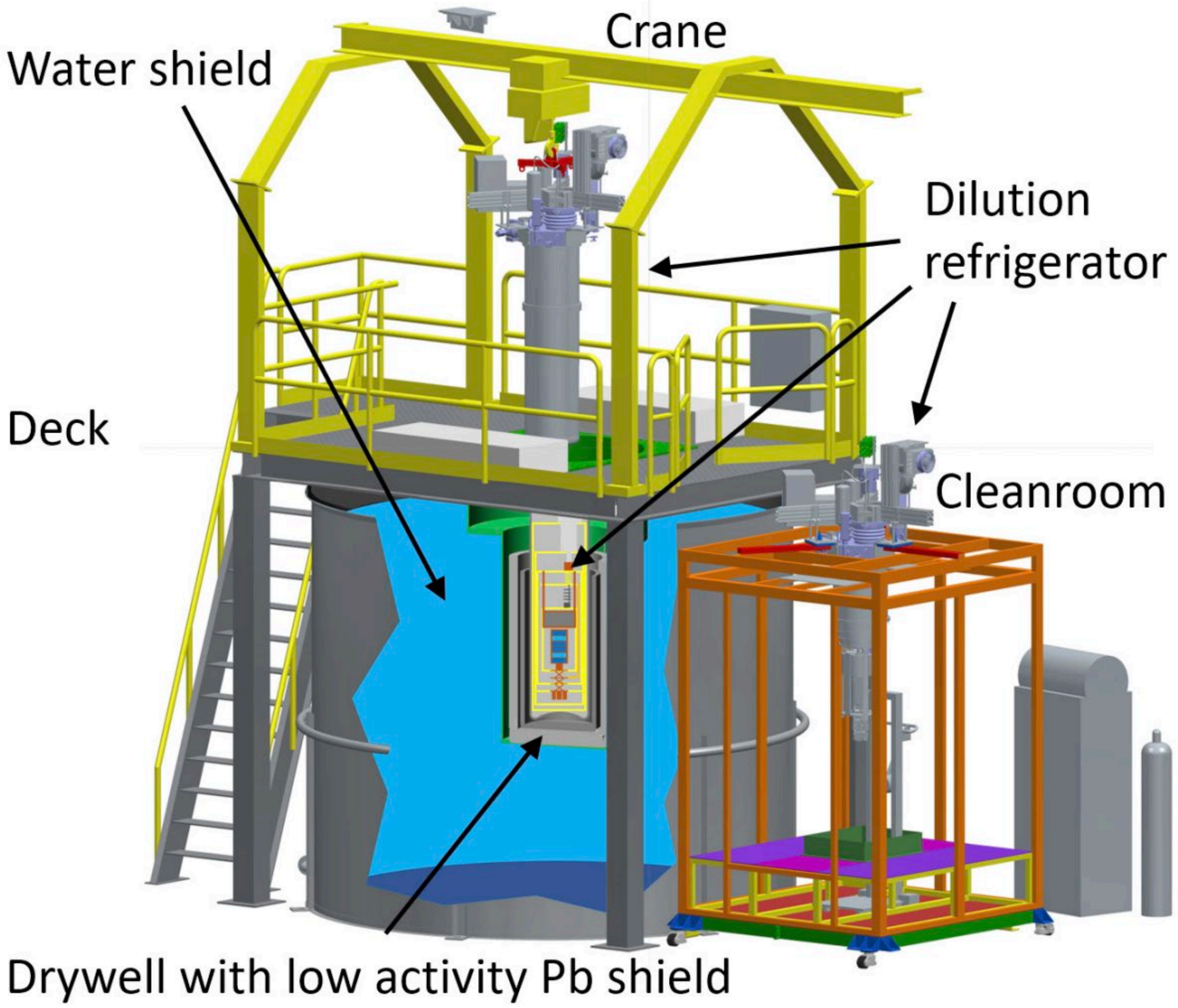
Cryogenic Underground Test (CUTE) Facility



(Quark & Qubit
the CUTE
HQPiggies)

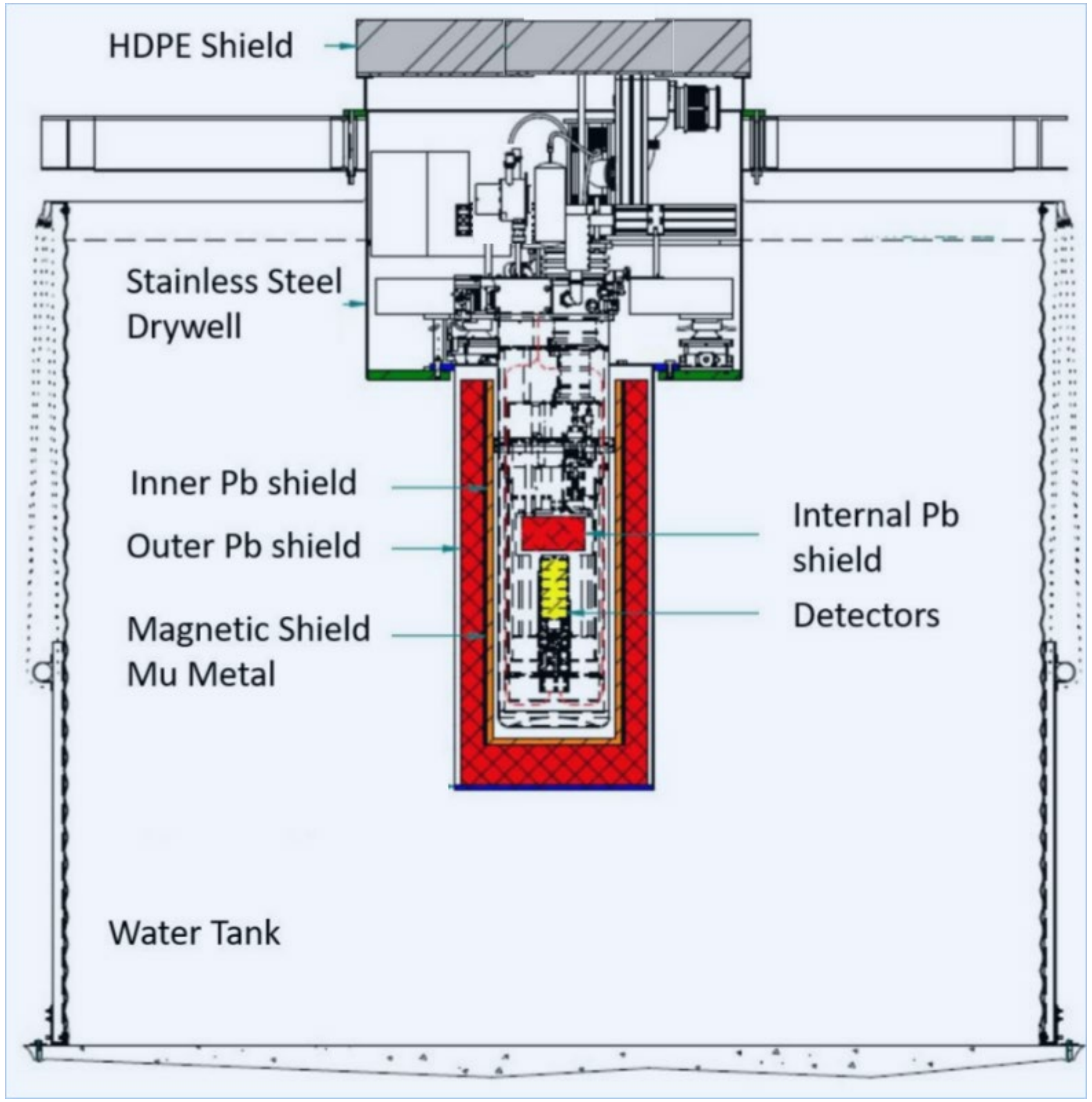
Cryogenic Underground Test (CUTE) Facility

- **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**

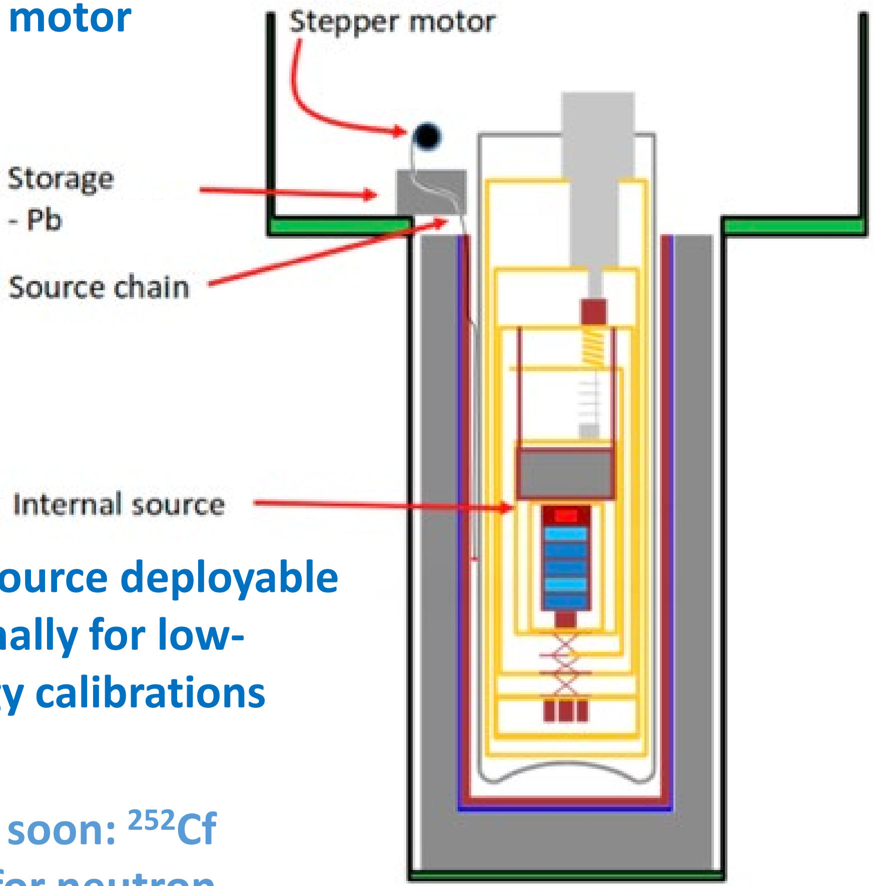


Slide credit: Andrew Kubik

Cryogenic Underground Test (CUTE) Facility



^{133}Ba γ source deployable inside shielding, using stepper motor



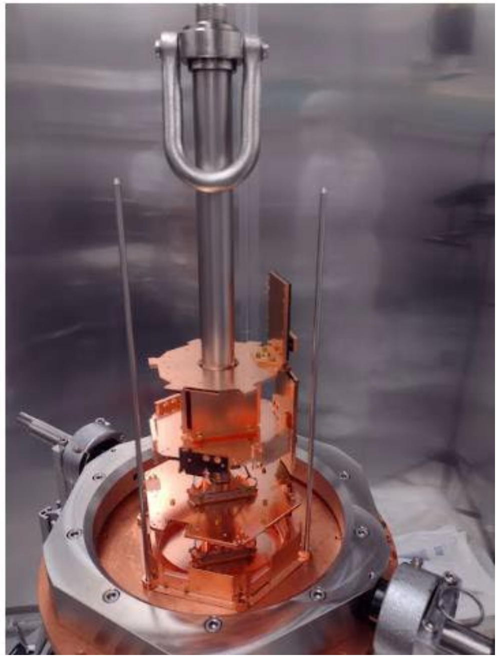
^{55}Fe source deployable internally for low-energy calibrations

Coming soon: ^{252}Cf source for neutron calibrations

Slide credit: Andrew Kubik

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

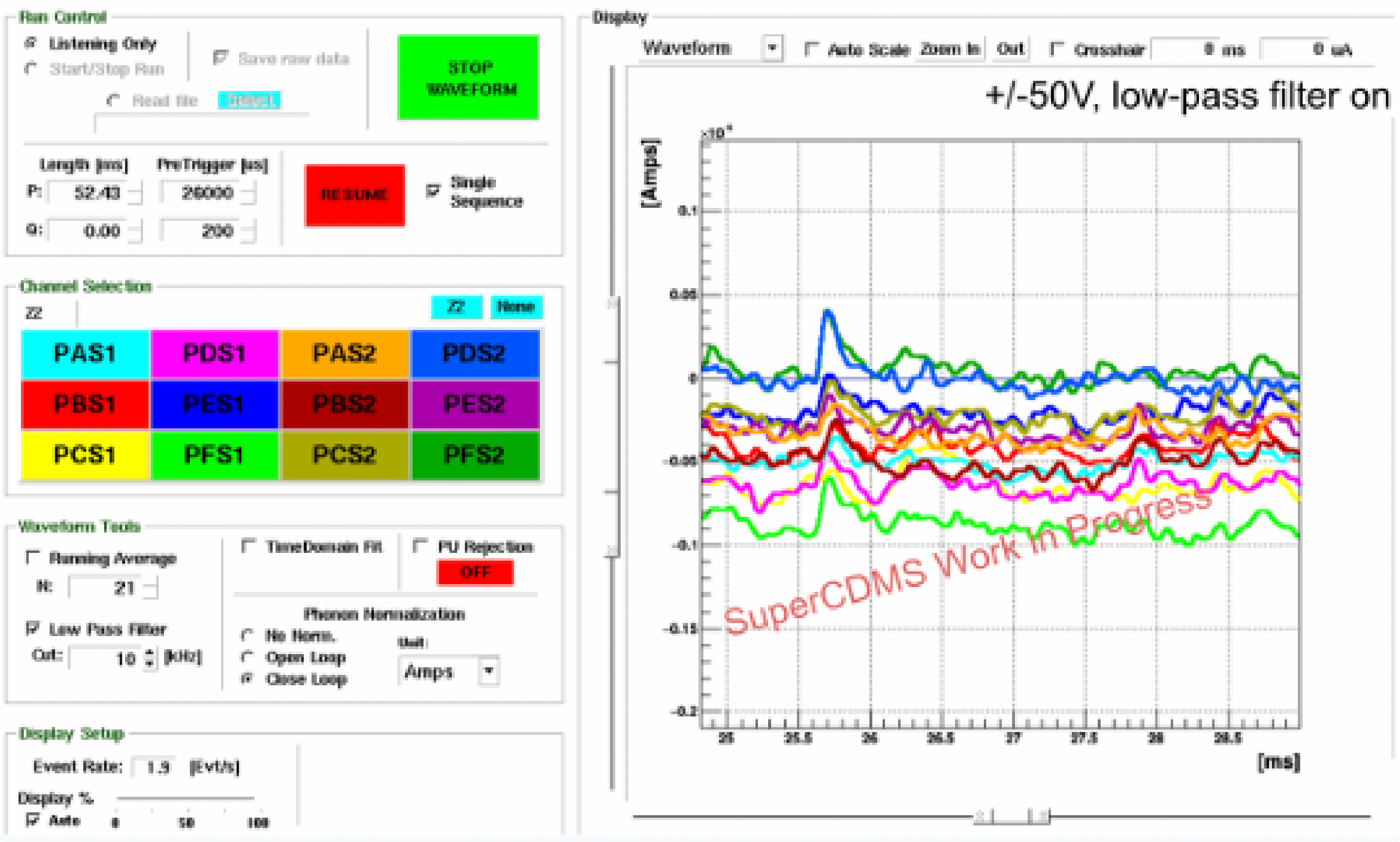
✓ Sensitivity estimation

✓ Potential DM search

Slide credit: Aditi Pradeep

Tower Testing at CUTE

- 151 days covering 4 thermal cycles
- Total data volume: 400 detector days
- ~2 month of calibration data
- ~2 weeks of low background data



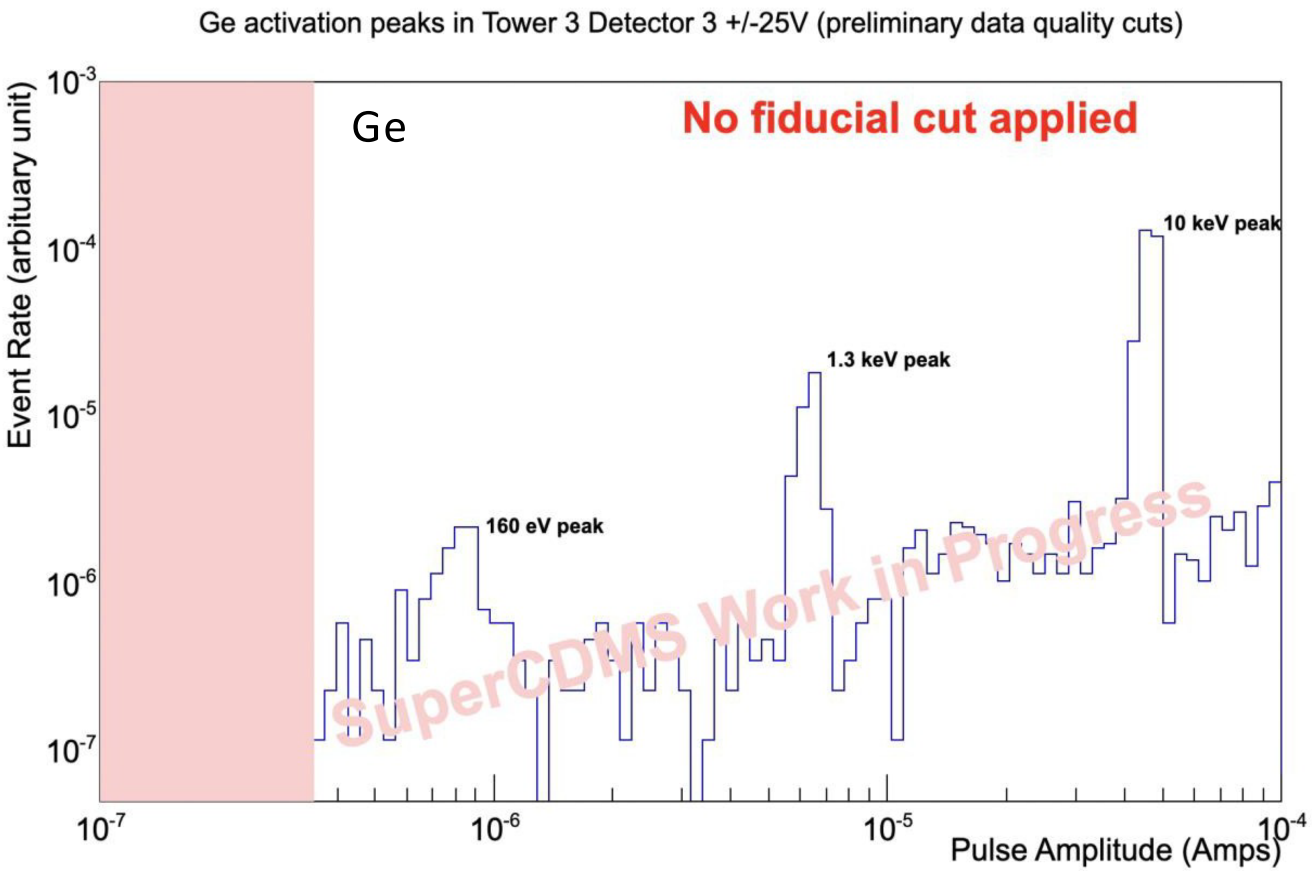
Example pulses from a Silicon detector operated at 100V

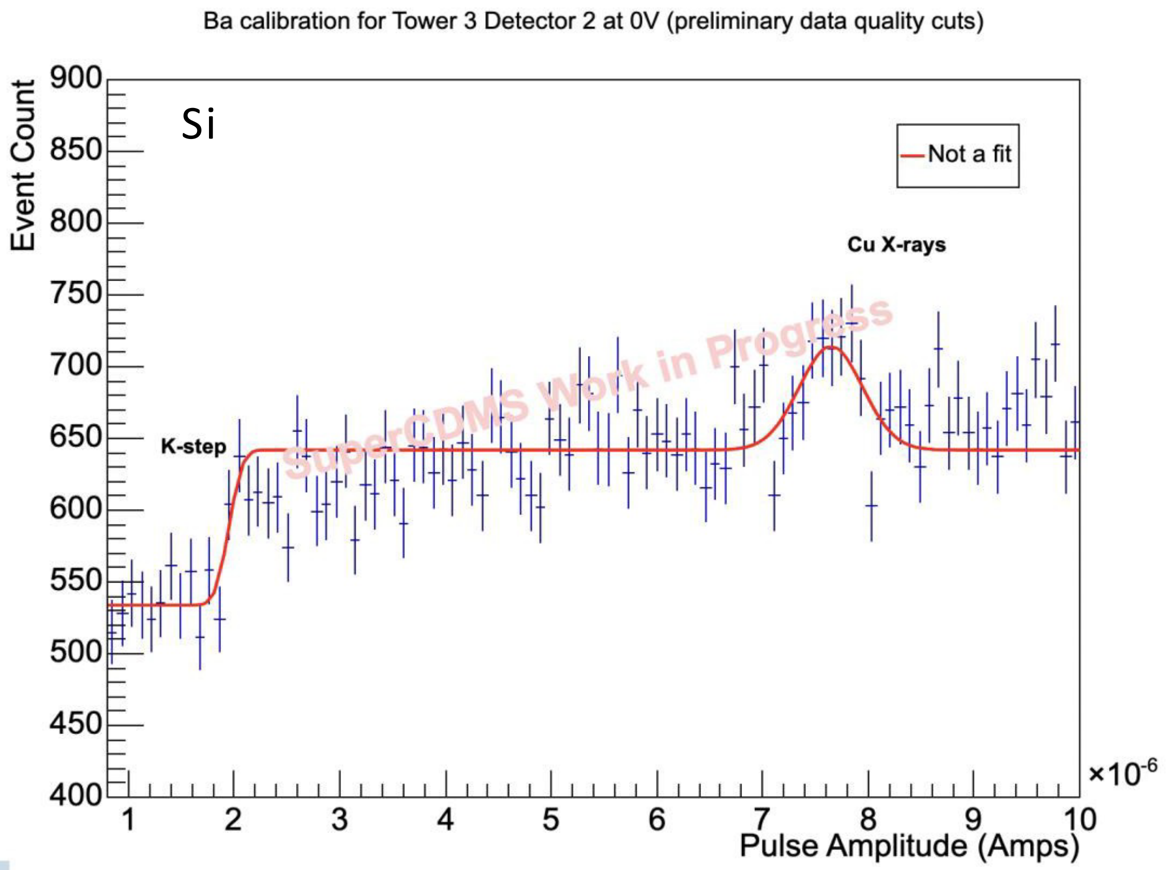
Slide credit: Yan Liu

Tower Testing at CUTE

Slide credit: Aditi Pradeep

✓ **Demonstrated calibration capability for Ge and Si detectors**





Ge detector calibration dataset: ~90 hours
Irradiating Ge with *n* produces ^{71}Ge (τ=11.4 days)
Lines from ^{71}Ge e^- capture: 10 keV, 1.3 keV, 160 eV

Ba source data, Si detector at 0V: ~90 hours
Characteristic steps, due to binding energy of shell electrons, can be used for calibration!

Summary

- **SuperCDMS SNOLAB is a world-leading DM direct detection experiment currently under construction, targeting sub-GeV DM**
- **Rapidly ramping up to commissioning phase**
- **Recent HV tower testing at CUTE marked the first operation of these detectors in underground low-background environment**
- **Several analyses of tower testing data in-progress to better understand the detectors**
- **Expecting early science results by next year!**

SUPER CDMS
Cryogenic Dark Matter Search

@SuperCDMS

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