Putting SuperCDMS in a super position to find DM

SUPER CDMS
Cryogenic Dark Matter Search

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- Introduction to SuperCDMS
- Background modeling
- Detector simulations
- Cryogenic Underground Test facility

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SUPER CDMS
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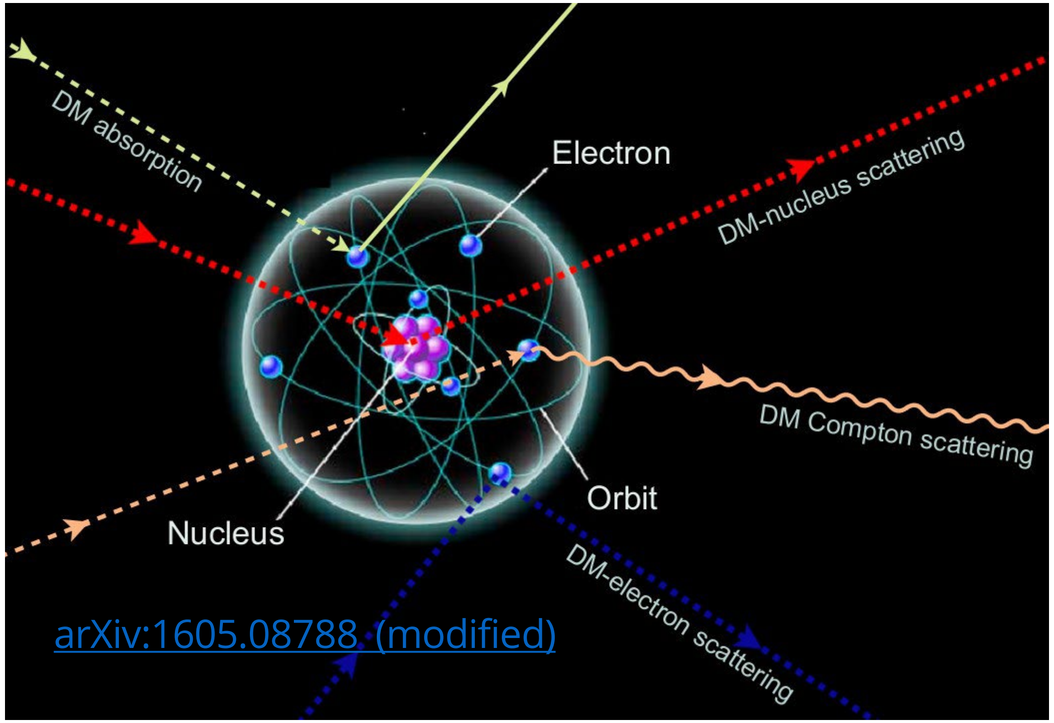
SuperCDMS (Cryogenic Dark Matter Search)

- Science reach
- Detector principles
- “HVeV” detector R&D
- Recent low-mass DM limits

Dark Matter (DM) direct detection

Principal idea: DM is made of **particles** which **interact** with atoms in different ways.

- Any observable interaction counts!
  - NR = nuclear recoil
  - ER = electronic recoil
  - “dark absorption”



arXiv:1605.08788 (modified)

Estimate of DM flux on Earth

→ 110 000 DM particles per cm^2 per s
  - DM Density: 0.3 GeV/cm^3
  - DM Mass: 60 GeV
  - Relative velocity: 220 km/s

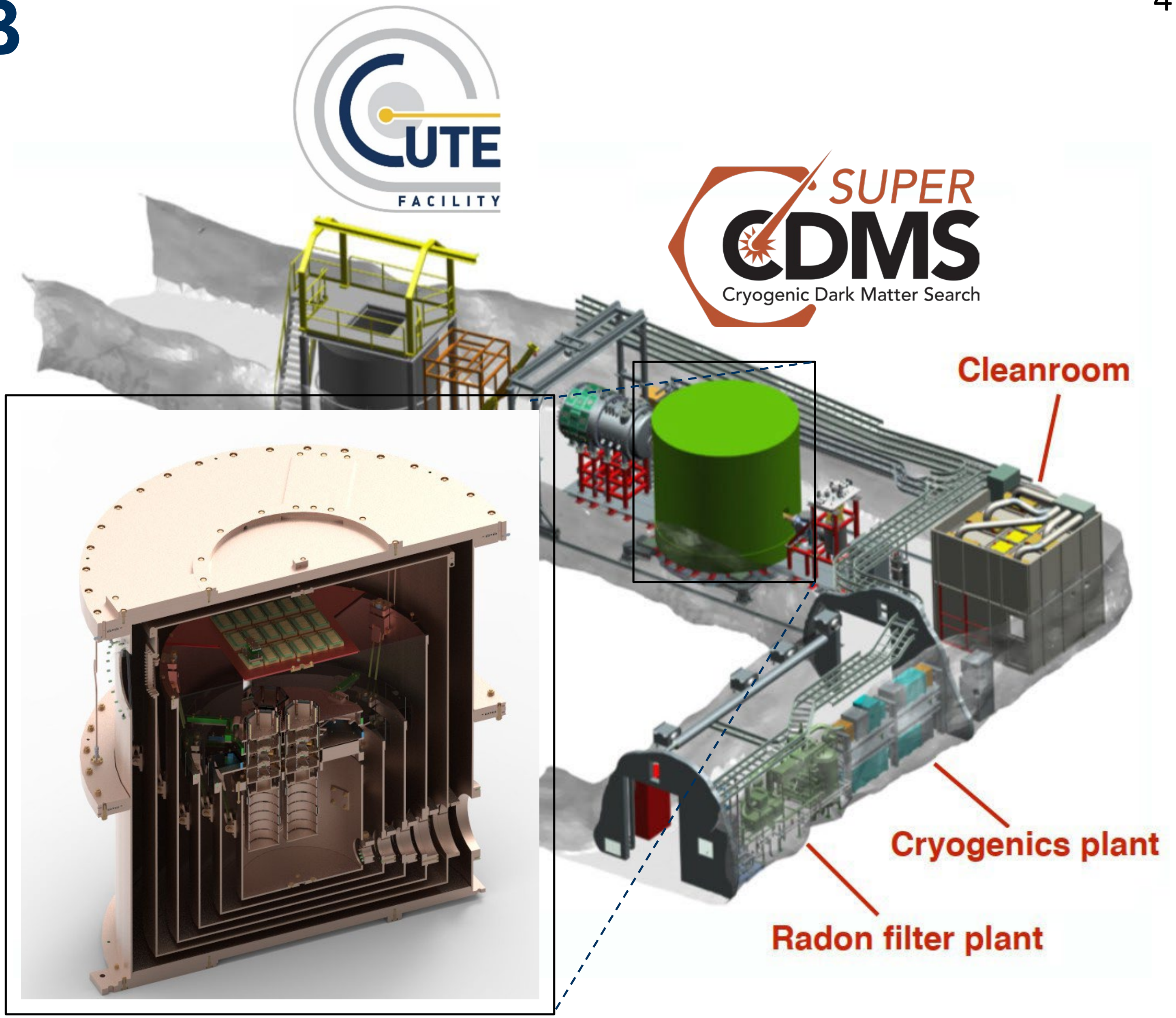
ESO, L. Calçada

Slide credit: Stefan Zatschler

SuperCDMS at SNOLAB

- Class 2000 cleanroom lab with 2 km of rock overburden
- **Dilution refrigerator** with a closed-loop cryogenics system
- **Initial payload:** 24 detectors
  - iZIP towers: 10 Ge + 2 Si crystals
  - HV towers: 8 Ge + 4 Si crystals
- Collaboration with **CUTE**
  - Cryogenic Underground TEst facility
  - Tower testing now underway

SuperCDMS infrastructure is under construction!



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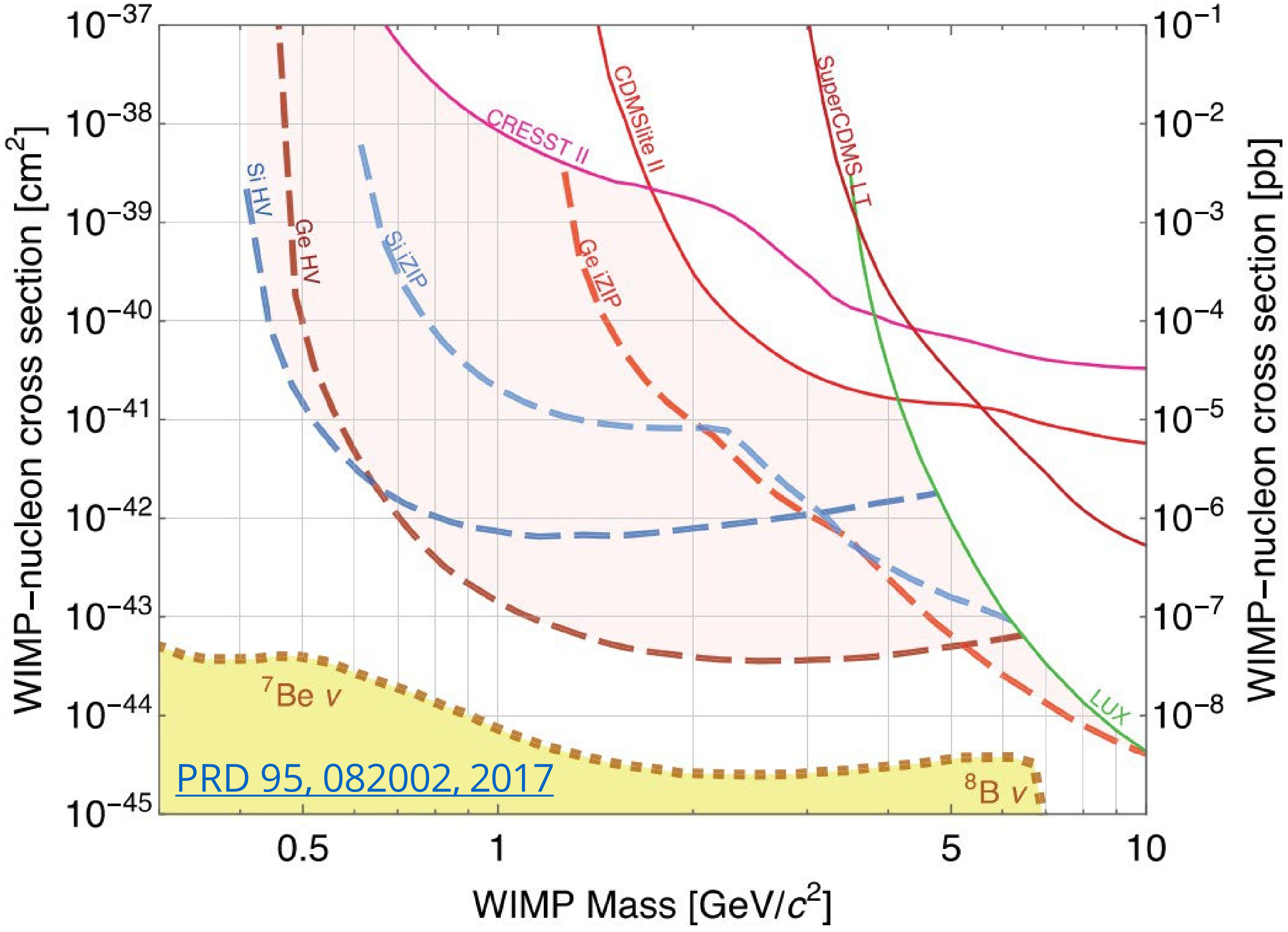
SuperCDMS science reach



PRD 95, 082002, 2017

- Aiming for **world-leading sensitivity** to low-mass WIMPs
- **Unique approach** with complementary detector designs
  - **Ge/Si iZIP & HV detectors**
  - **iZIP:** NR/ER discrimination → background studies
  - **HV:** low-threshold → low-mass sensitivity

Challenges

- Understanding detector response down to semiconductor bandgap
  - Dominating backgrounds
  - Low-energy calibration
  - Detector response modeling

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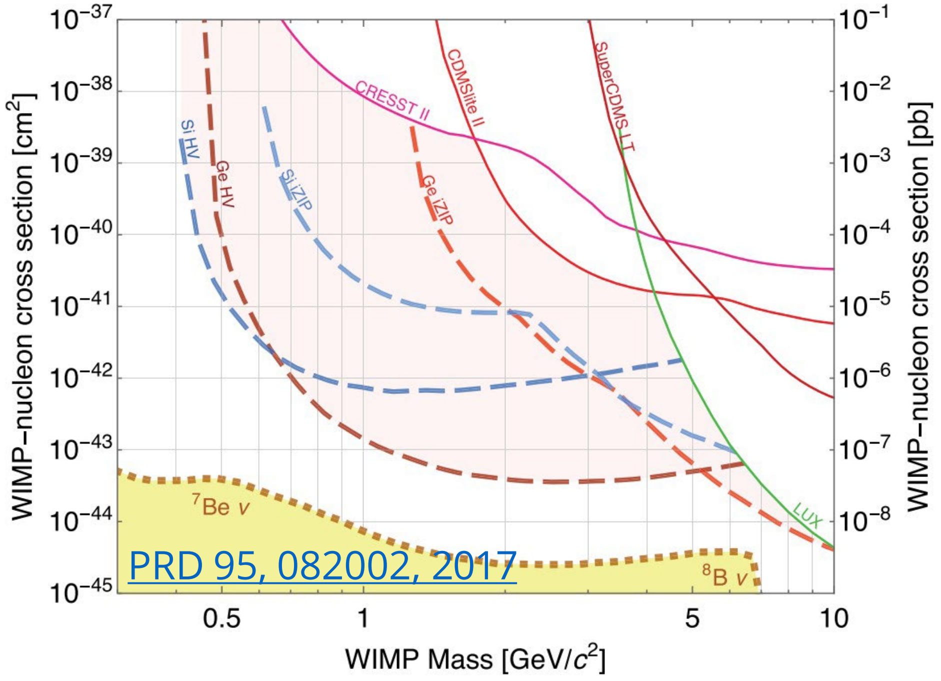
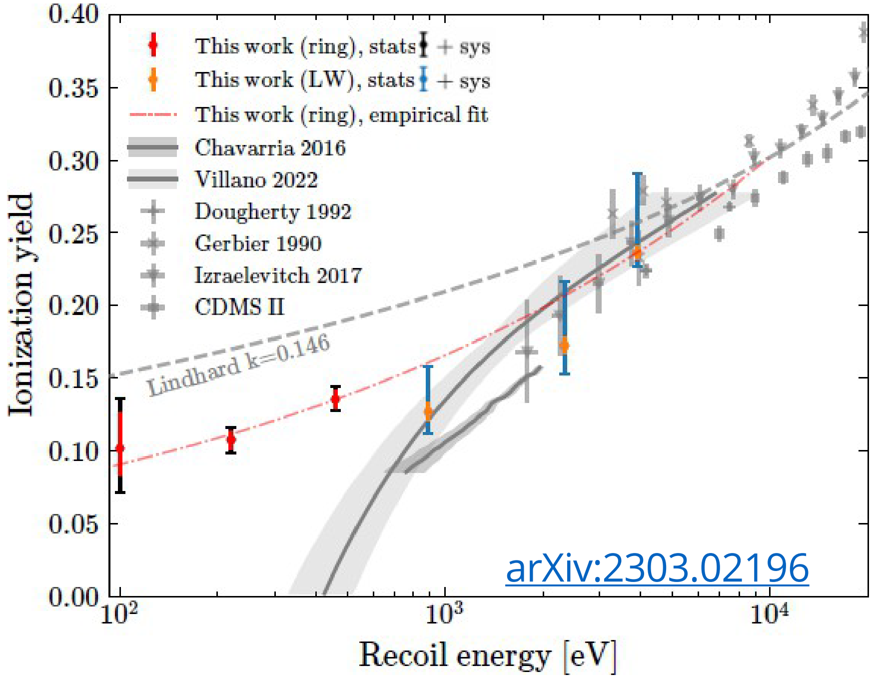
SuperCDMS science reach

Understanding the detector response down to the semiconductor bandgap energy is crucial to extend sensitivity (*left*) towards lower DM masses and cross-sections!





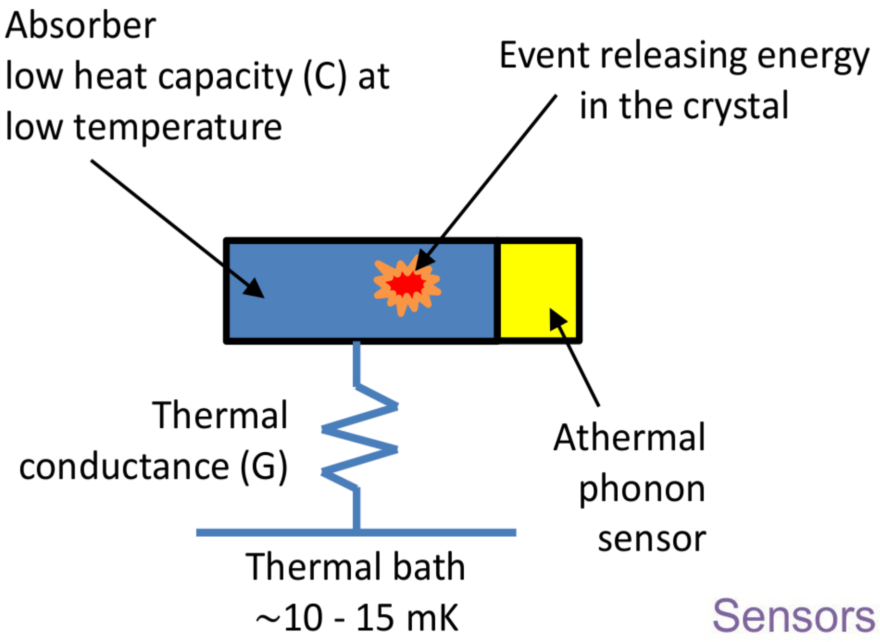
Driving questions:

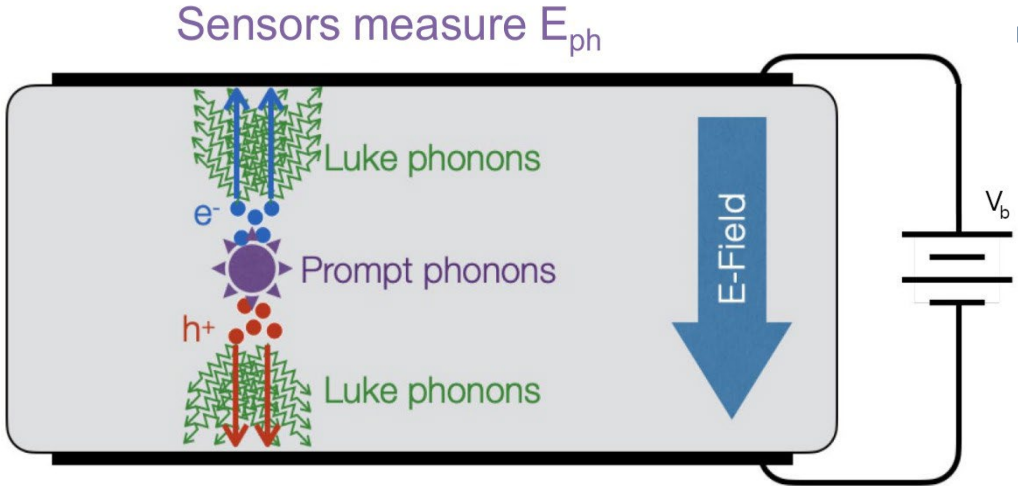
- Detector physics (phonon, charges, etc.) independently of the DM model (WIMPs, ERDM)
- Discrepancy of nuclear yield models and recent measurement campaigns (*right*)

Slide credit: Stefan Zatschler

SuperCDMS detector principles

- Cryogenic calorimeters at temperatures ~ 10 – 15 mK
- Athermal phonon sensors – Transition Edge Sensors (TES)



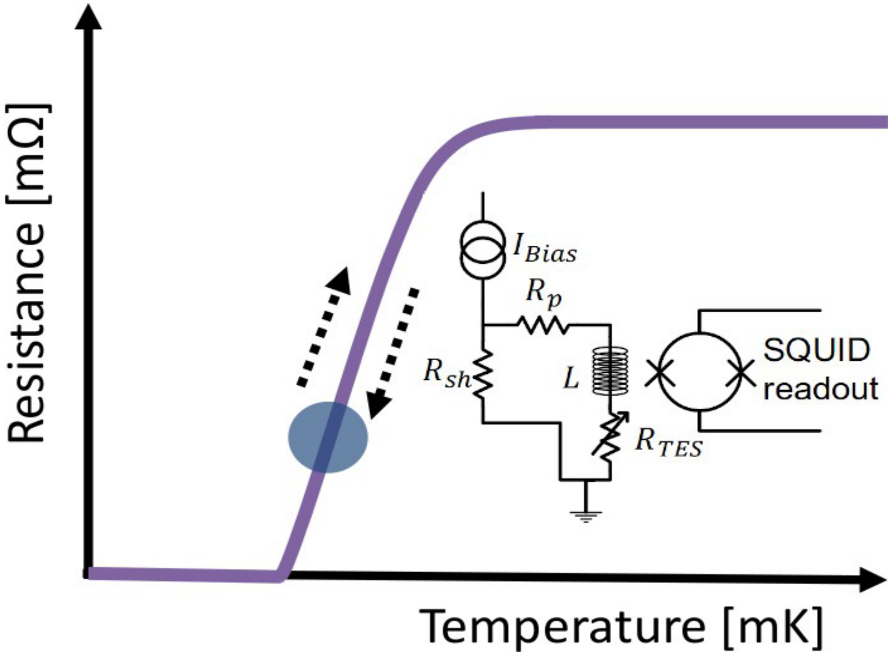


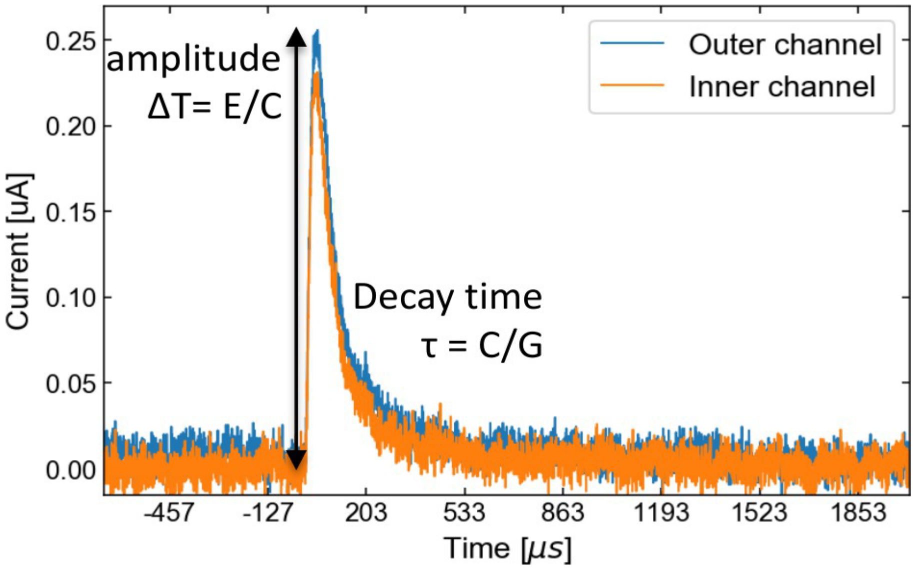
Signal formation

- Energy deposit creates e^{-}/h^{+} pairs and prompt phonons in crystal
- Charges drift in external electric field
- Drifting charges emit Luke phonons
  - Signal amplification
  - Sensitivity to single e^{-}/h^{+} pairs
- Phonon collection with TES
  - Pulse reconstruction
  - Measure of energy deposit

Slide credit: Stefan Zatschler

SuperCDMS detector principles





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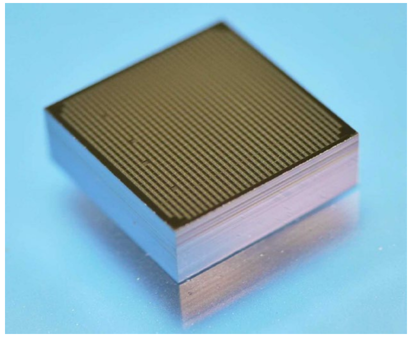
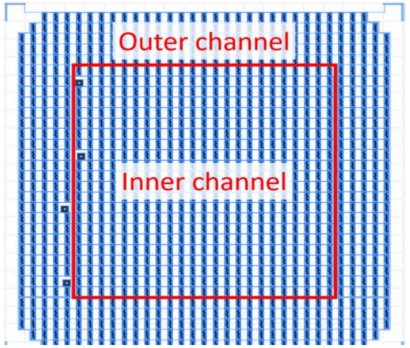




Slide credit: Stefan Zatschler

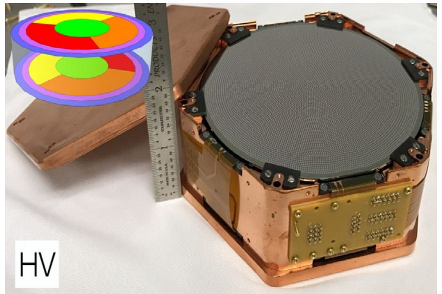
SuperCDMS detector principles

HV detector → low threshold

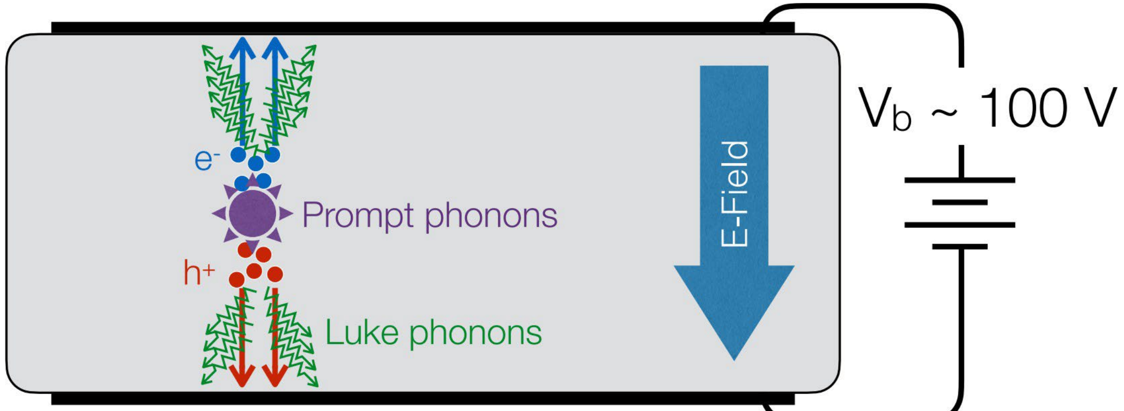
- Drifting charge carriers (e^-/h^+) across a potential (V_b) generates a large number of Luke phonons (NTL effect)
- Trade-off: no NR/ER discrimination

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

total phonon energy — primary recoil energy — Luke phonon energy

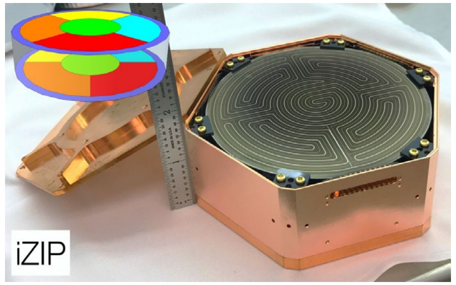


Sensors measure E_t



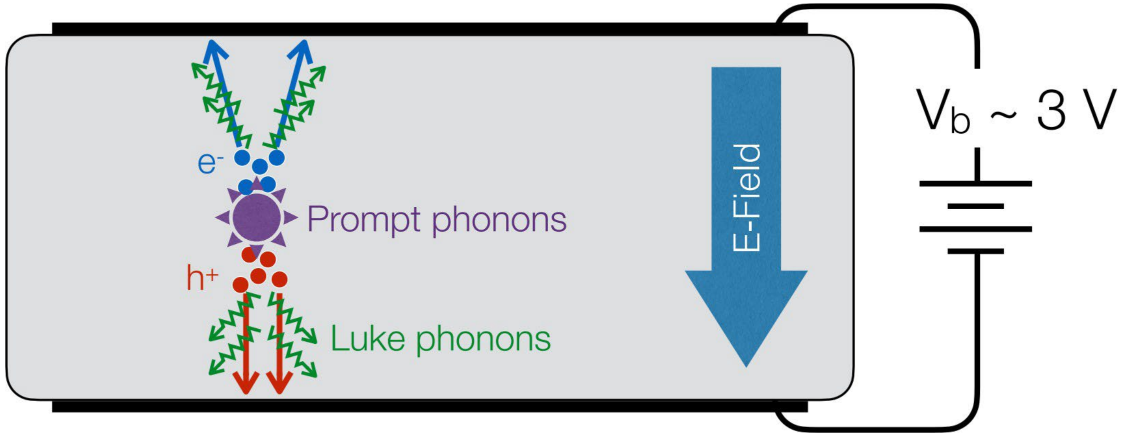
iZIP detector → low background

- Interleaved Z-sensitive Ionization and Phonon detector
- Prompt phonon and ionization signals allow for NR/ER event discrimination



PRD 95, 082002, 2017

Sensors measure E_t and N_{eh}



Slide credit: Stefan Zatschler

Low-threshold vs. low-background modes

HV detectors – low threshold

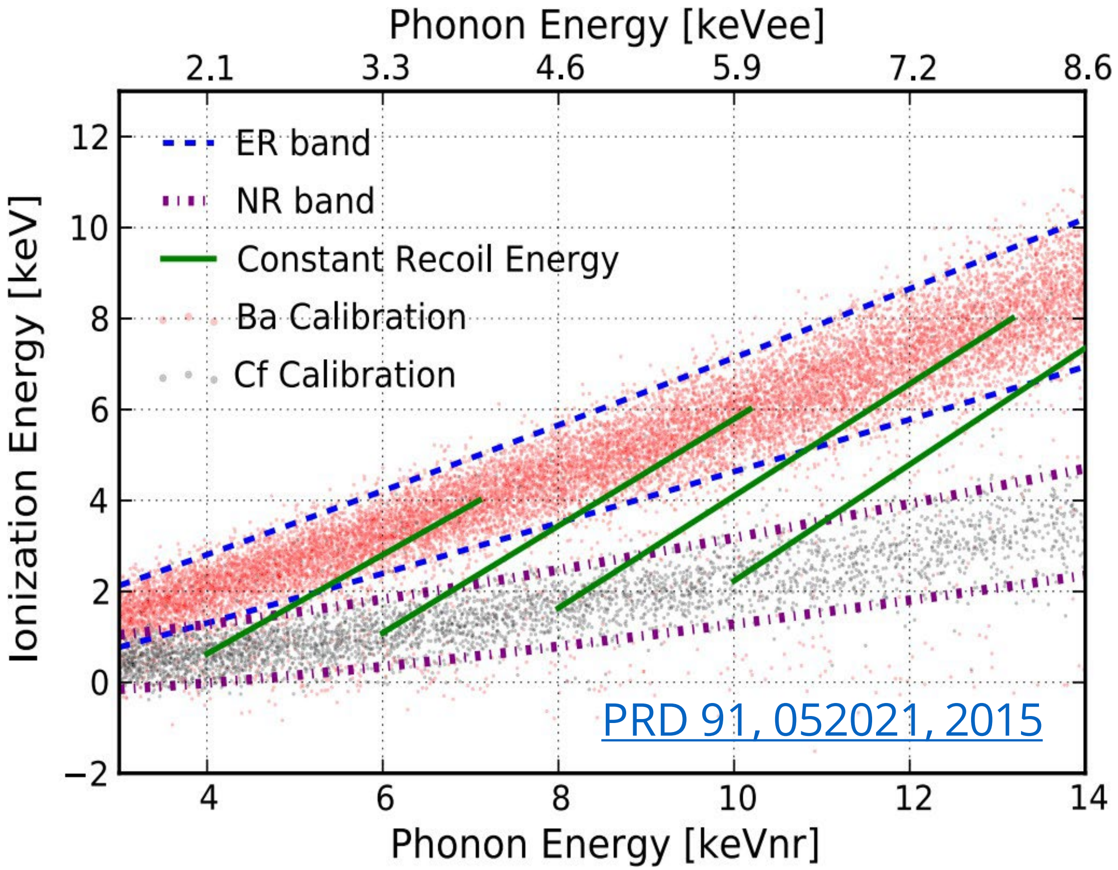
- High resolution total phonon measurement
- No yield or surface discrimination
- Typical thresholds below 0.1 keV (4 eV_{ee}) !

iZIP detectors – low background

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

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



PRD 91, 052021, 2015

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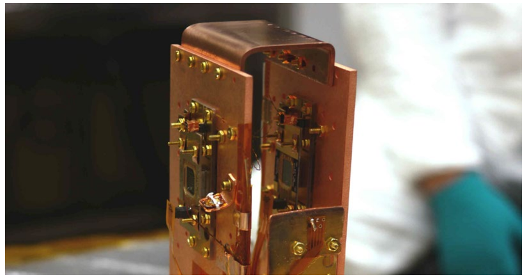
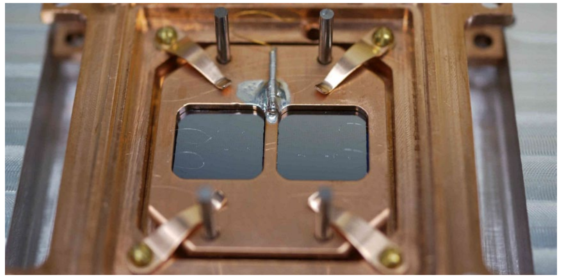
Highlights of "HVeV" detector R&D program

[PRD 102, 091101(R), 2020]

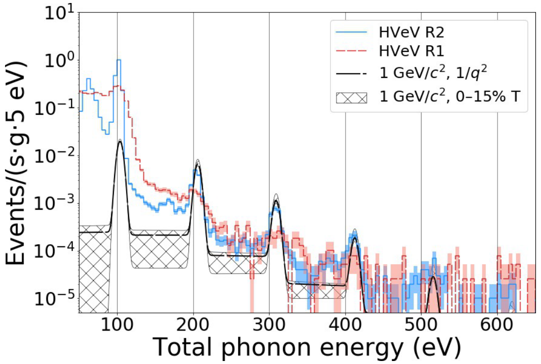




Stay tuned!

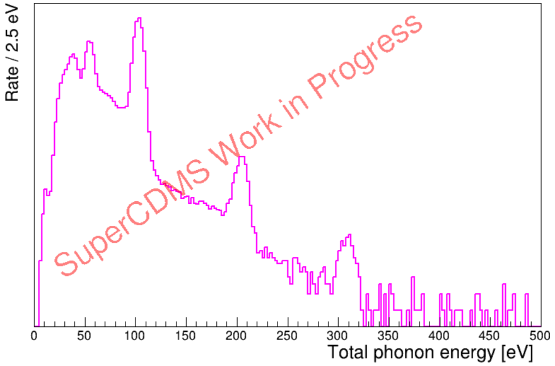
HVeV Run 2

- Detection and study of 1 e^-/h^+ burst events
- Hypothesis: originate in PCB holder



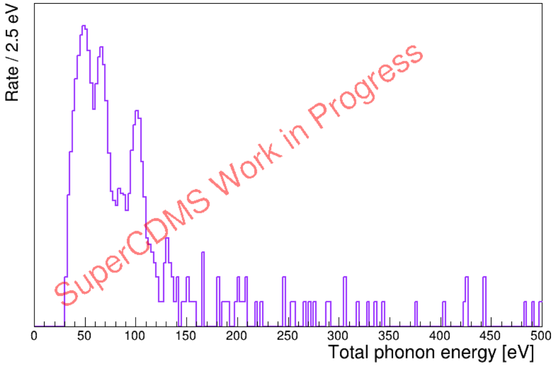
HVeV Run 3

- Coincidence measurement with HVeVs
- Confirmed external origin of burst events



HVeV Run 4

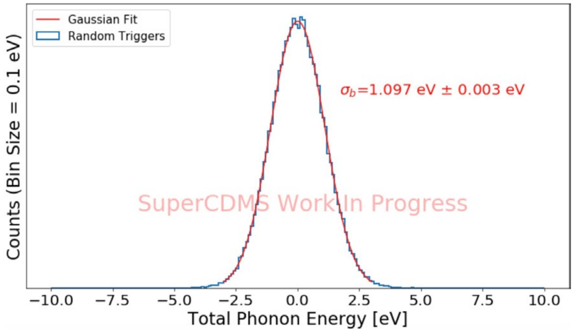
- Replaced PCB + coincidence measurement
- Elimination of higher-order e^-/h^+ peaks



Latest performance

- V3 of HVeV detectors
- Achieved lowest baseline resolution in class!

$\rightarrow \sigma_b = 1.097 \pm 0.003$ eV



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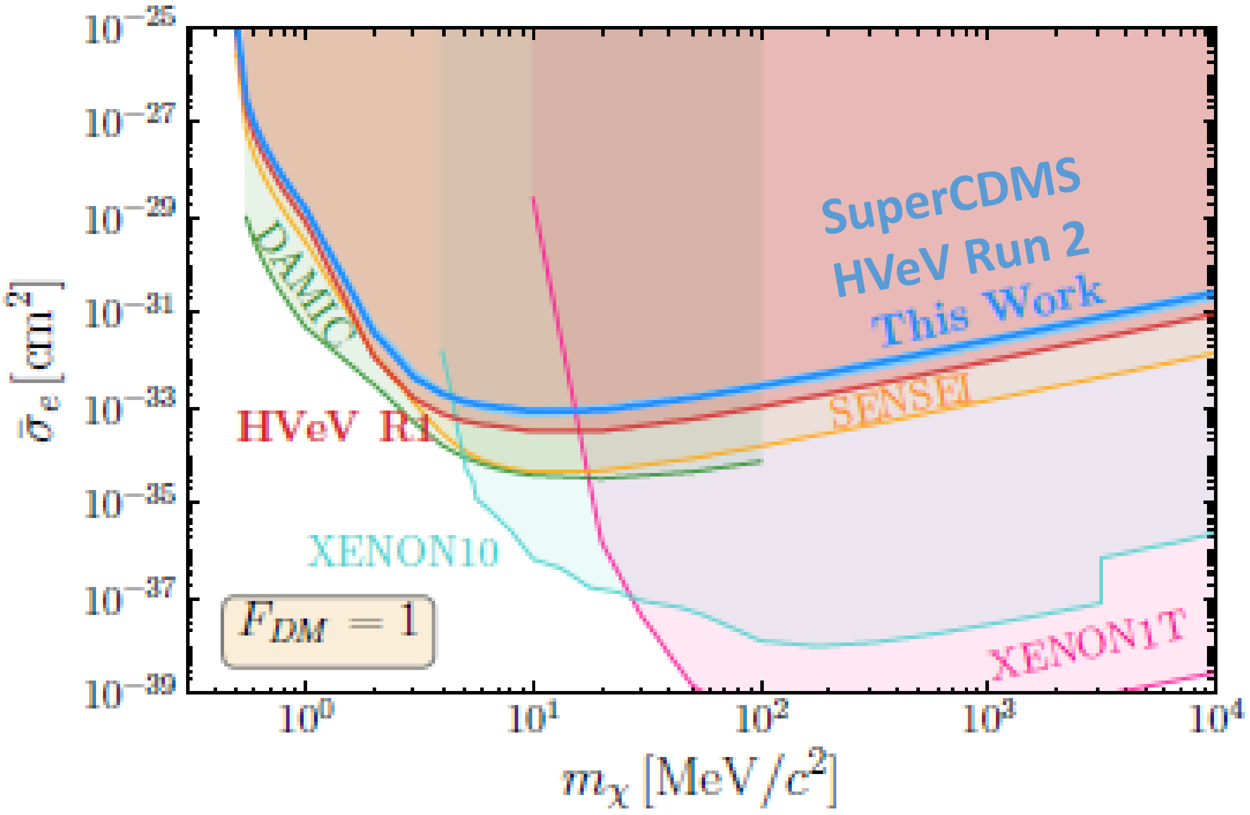
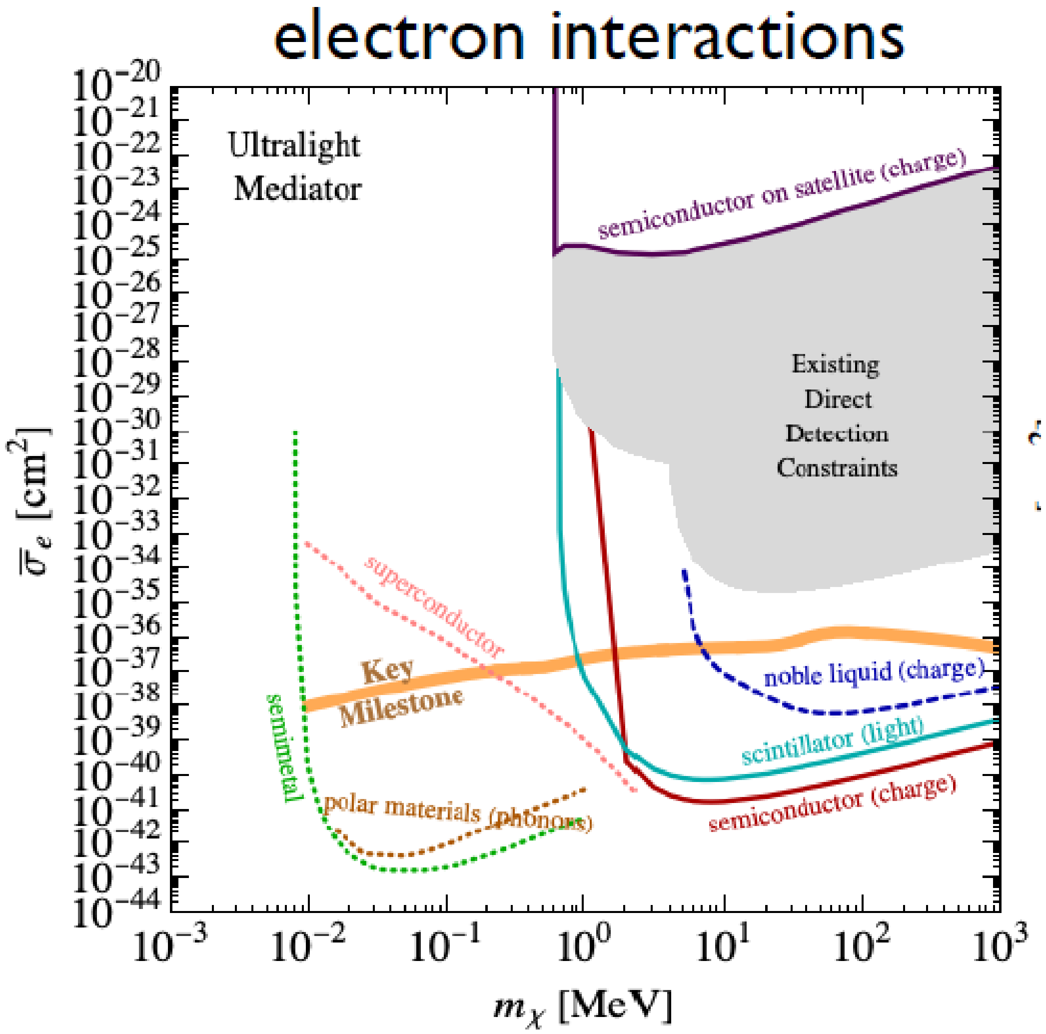
Recent electron recoil limits

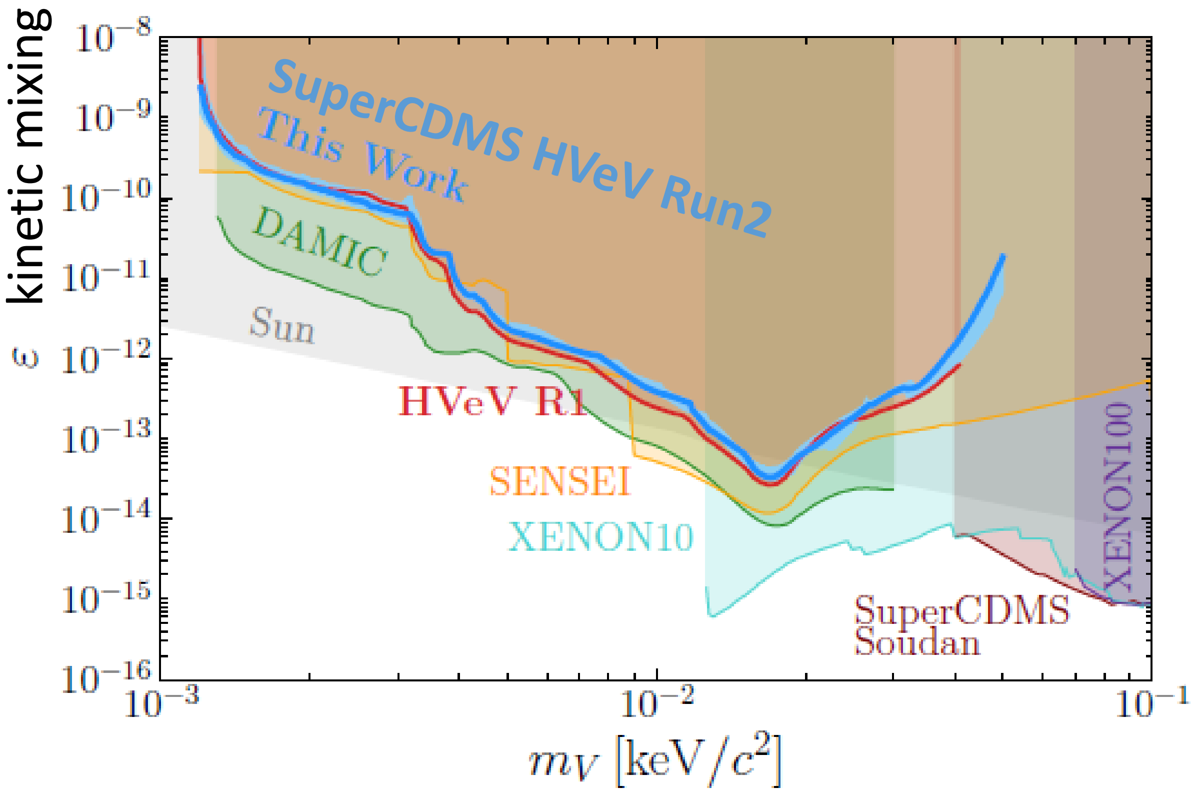


https://arxiv.org/abs/2005.14067

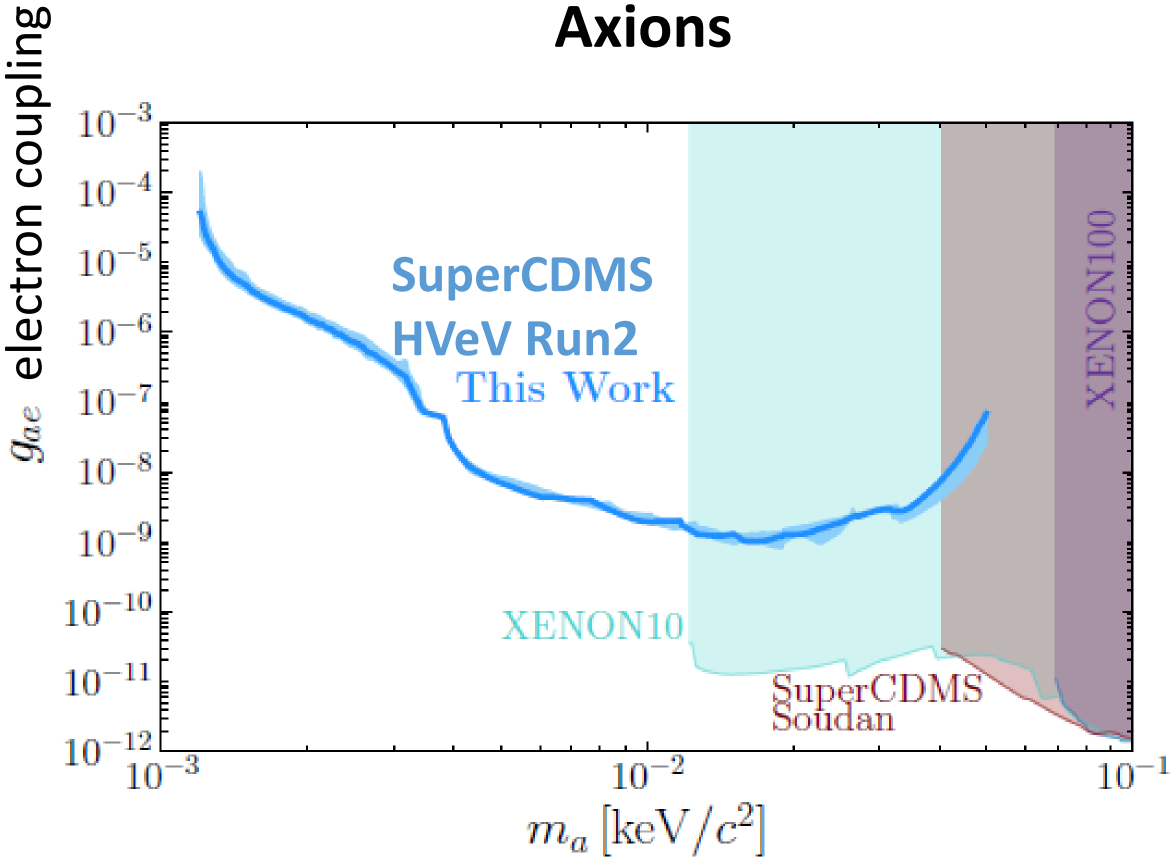


Recent dark photon & axion limits

Dark Photons



Axions



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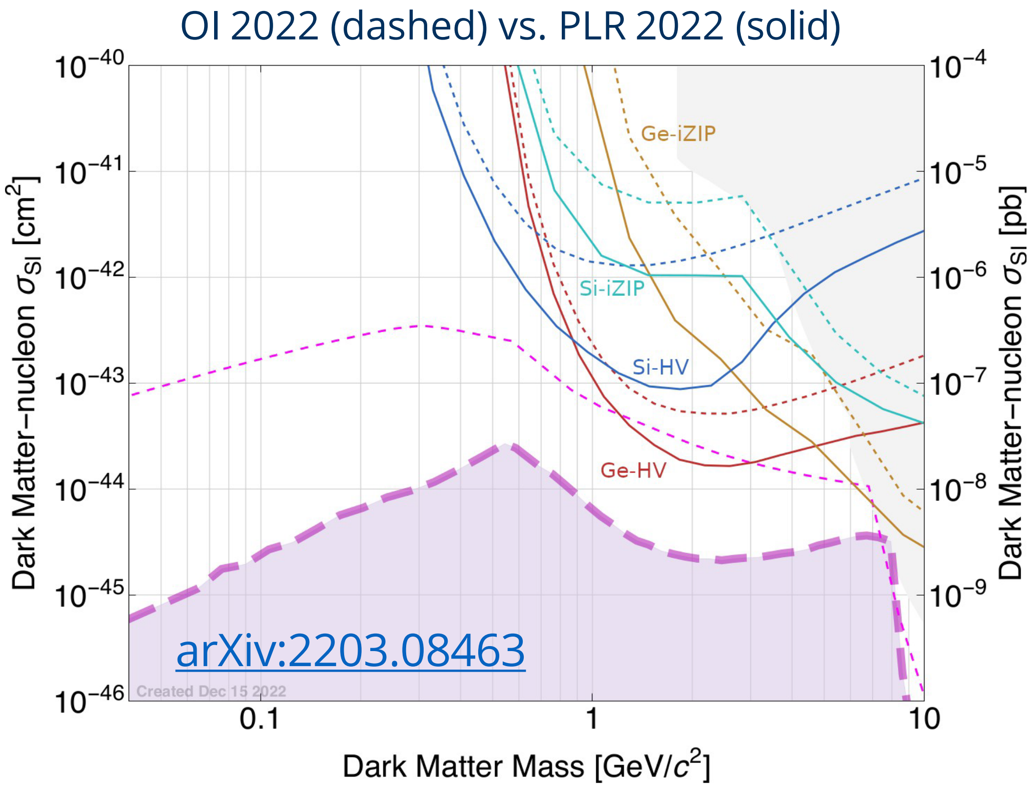
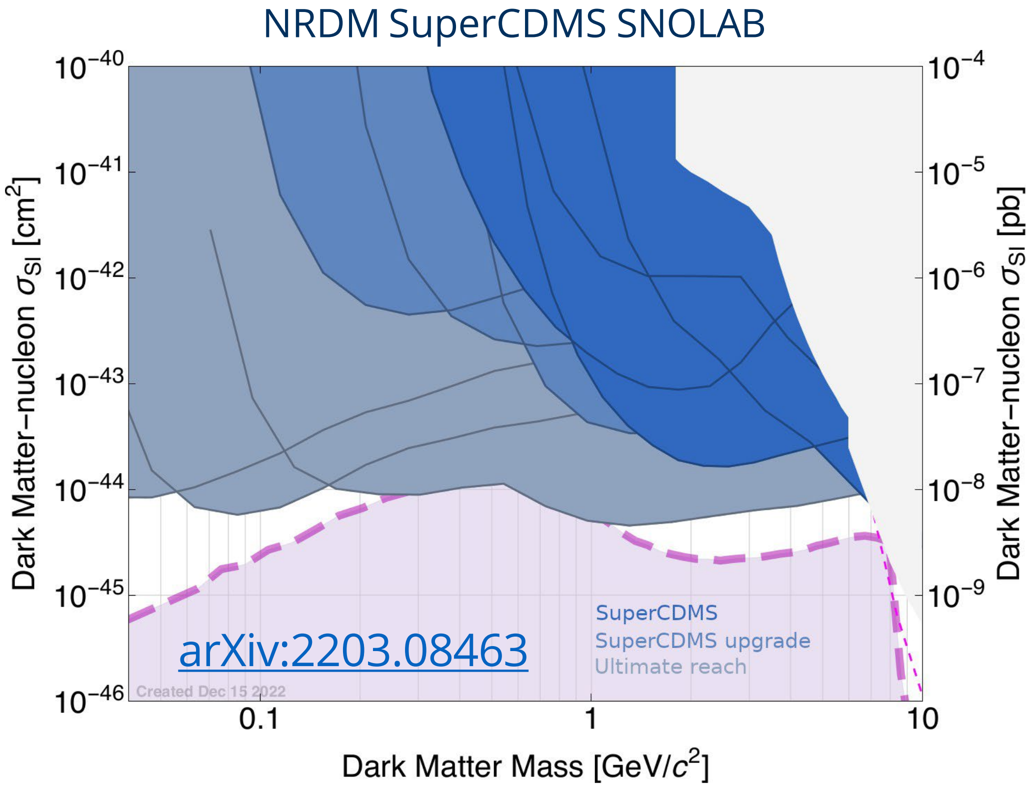
SNOWMASS sensitivity forecasts





- Recent exercise for SNOWMASS: refine the sensitivity projections, for different statistical methods and DM models
  - Optimum Interval (OI): signal-only assumption
  - Profile-likelihood ratio (PLR): signal + background
- Facilitates detailed study of upgrade scenarios for SuperCDMS SNOLAB facility

Slide credit: Stefan Zatschler

SUPER CDMS
Cryogenic Dark Matter Search

Backgrounds

- Sources
- Keeping track
- Assays
- Simulation campaigns

Underground dark secret lairs

Hide the detectors in shielding and bury them in an underground clean-room.

Why?

Backgrounds, backgrounds, backgrounds!

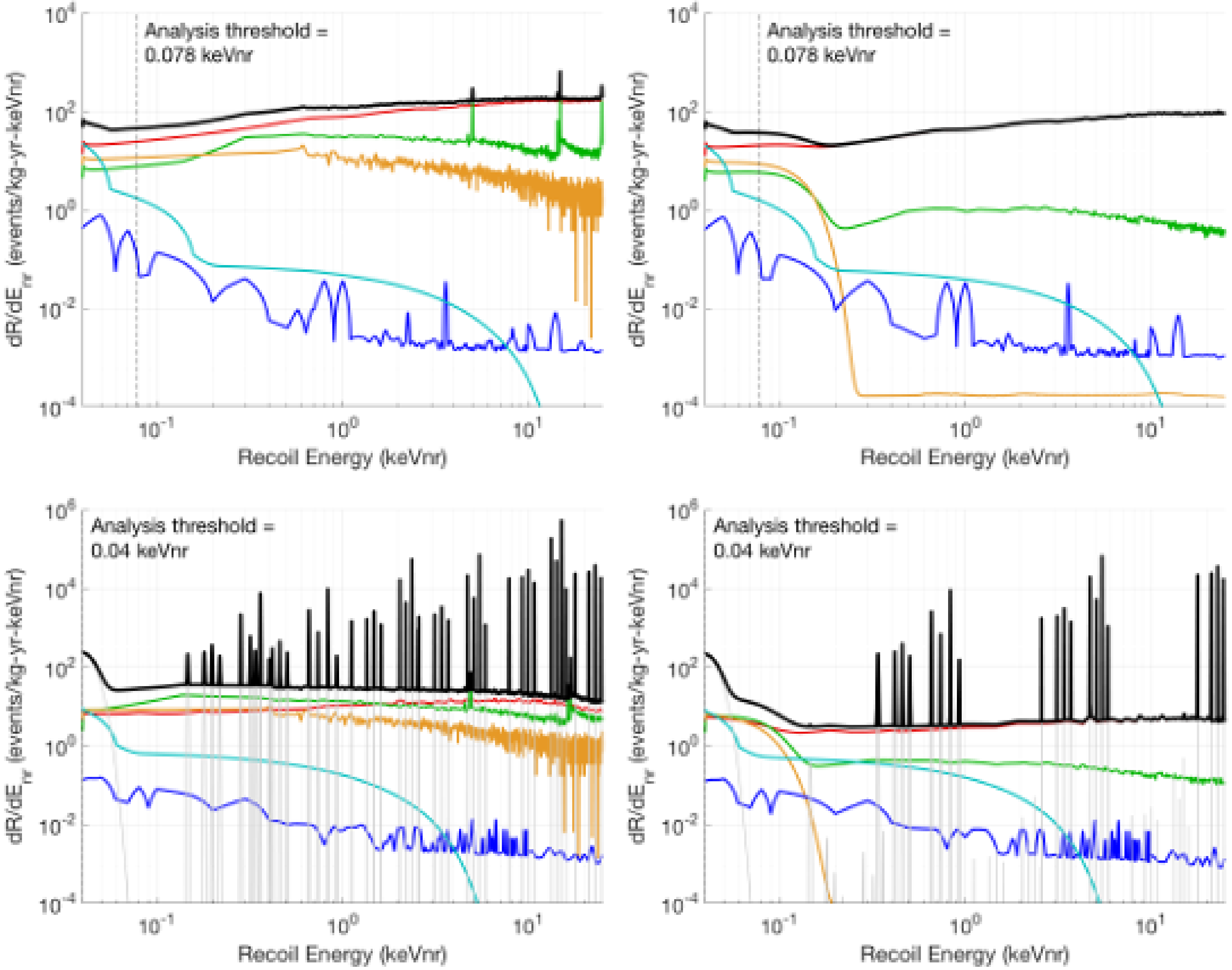
Cosmogenic

- Cosmic ray muons
- Spallation neutrons
- Activated materials

Environmental

- Airborne radon & daughters
- Radio-impurities in materials

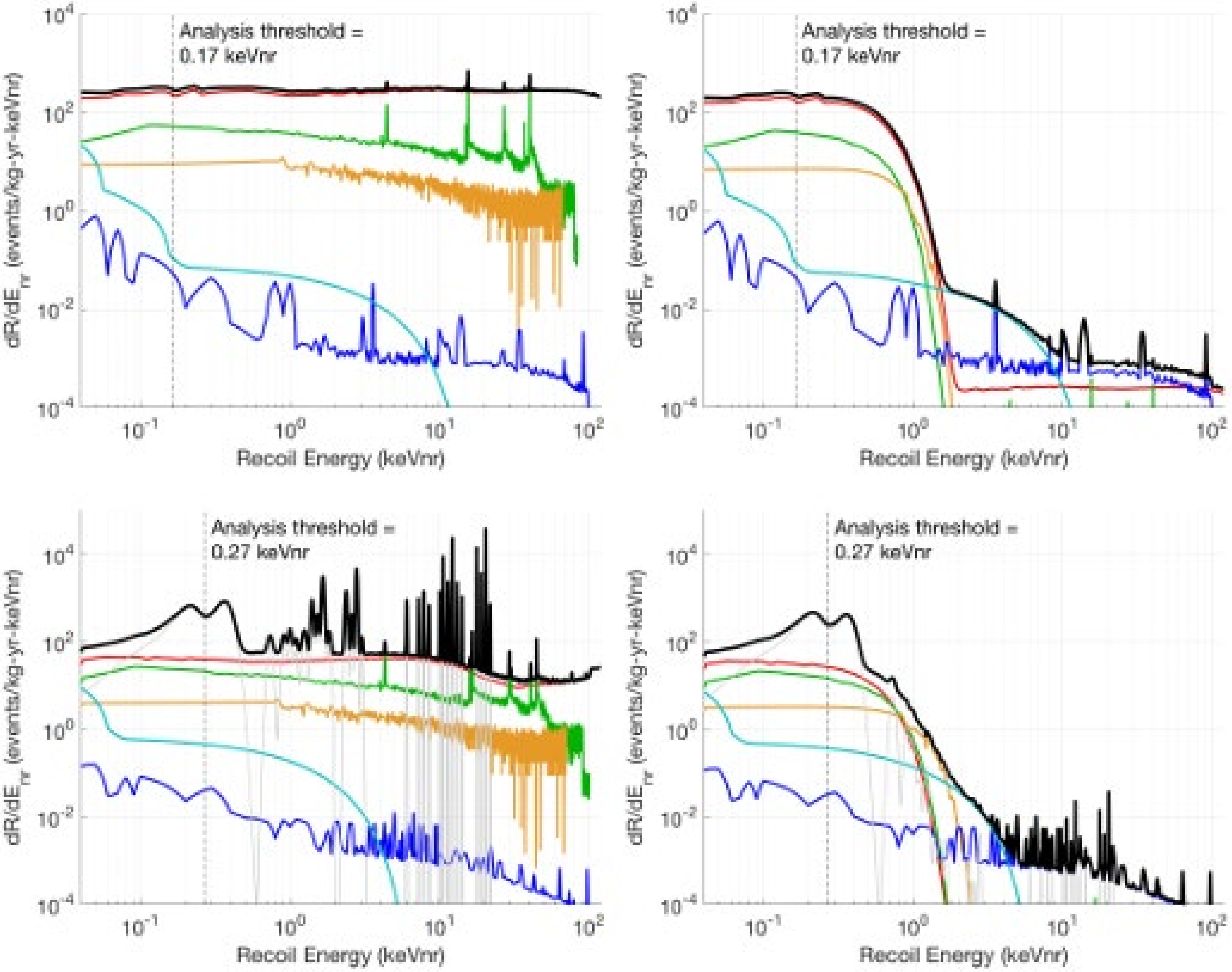
Background projections



Background spectra, before (left) and after (right) analysis cuts in Si (top) and Ge (bottom) HV detectors, as a function of nuclear recoil energy (keVnr)

Thick black: total background
Red: electron recoils from Compton gamma-rays, H, Si
Grey: Ge activation lines, convolved with 10 eV r.m.s. resolution (for an actual detector, expect more smeared-out reconstruction in pre-cut spectrum)
Green: surface betas
Orange: surface Pb recoils
Blue: neutrons
Cyan: CEvNS

Background projections



Background spectra, before (left) and after (right) analysis cuts in Si (top) and Ge (bottom) iZIP detectors, as a function of nuclear recoil energy (keVnr)

Thick black: total background
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Green: surface betas
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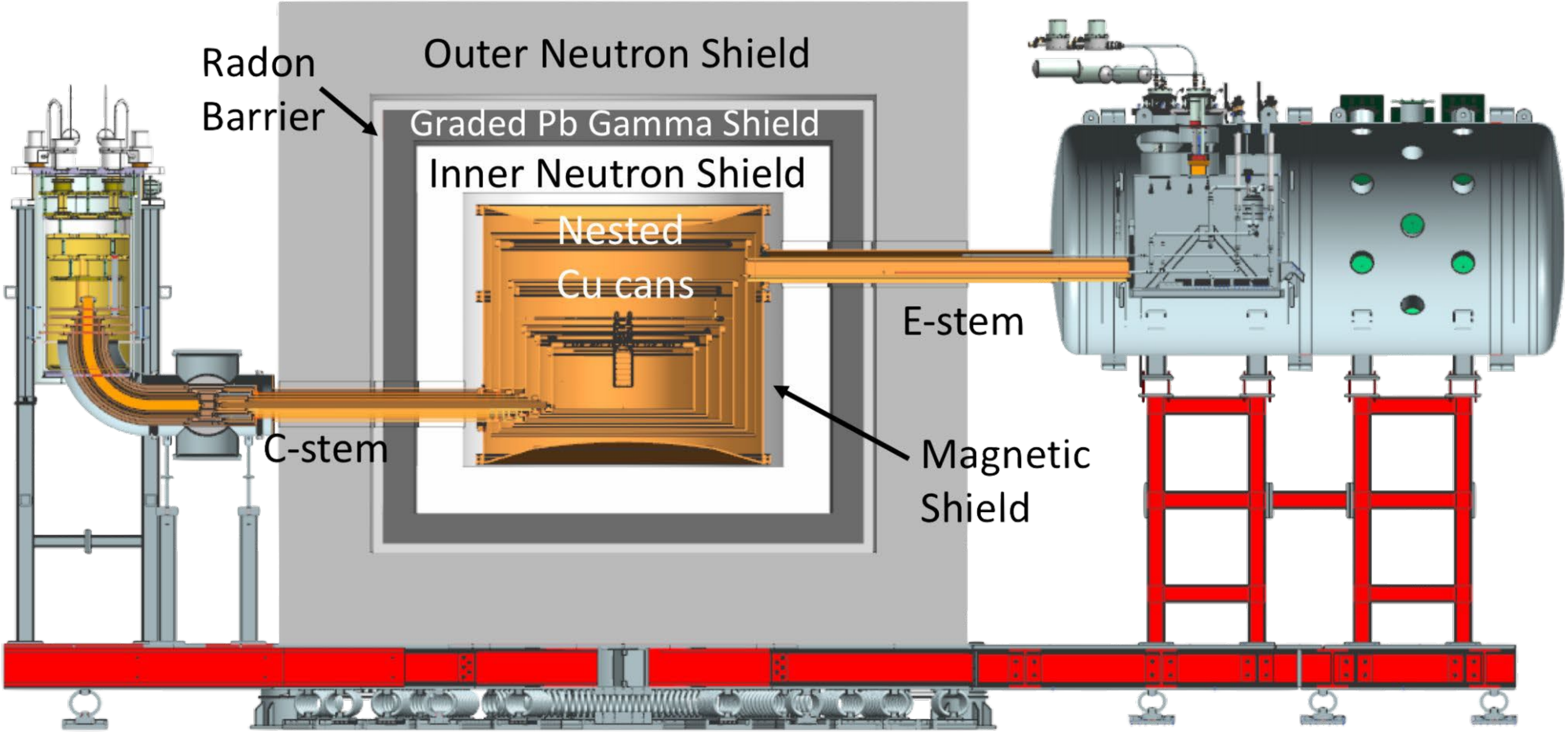
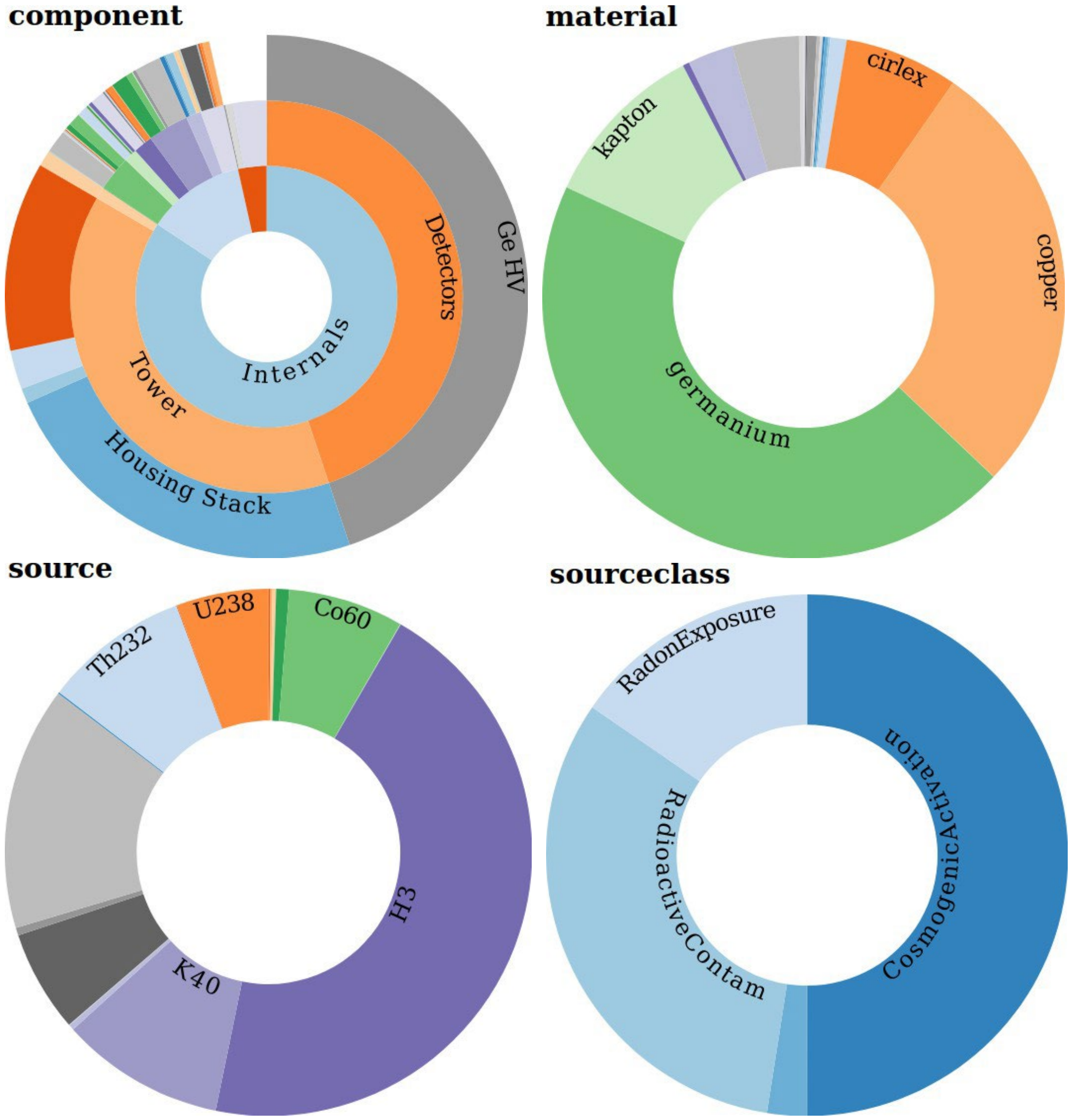
Blue: neutrons
Cyan: CEvNS

Shielding to help reduce backgrounds



Keeping track of background contributions



BackGround EXplorer

https://github.com/bloer/bgexplorer

- BGexplorer provides a background estimate based on material assay results.
- Visualizes the BG contribution in pie charts, spectra and tables.
- Enables easy identification of dominating BGs.

Slide credit: Birgit Zatschler

Background assay types

Radioactive Contamination

- Long-lived radioactive isotopes are contained in traces in all materials.
- Screen each component/material to get the specific activity of the contained radioactive isotopes.

Radon exposure

- Air above surface and underground contains traces of ^{222}Rn, whose decays can implant ^{210}Pb into the surface of exposed materials.
- Need to know the radon level and exposure time to mine air to estimate the decay rate.

Cosmogenic Activation

- Neutrons originating from cosmic showers can activate materials residing on Earth's surface.
- Monitor component's time on Earth's surface and cooldown time until the experiment starts.

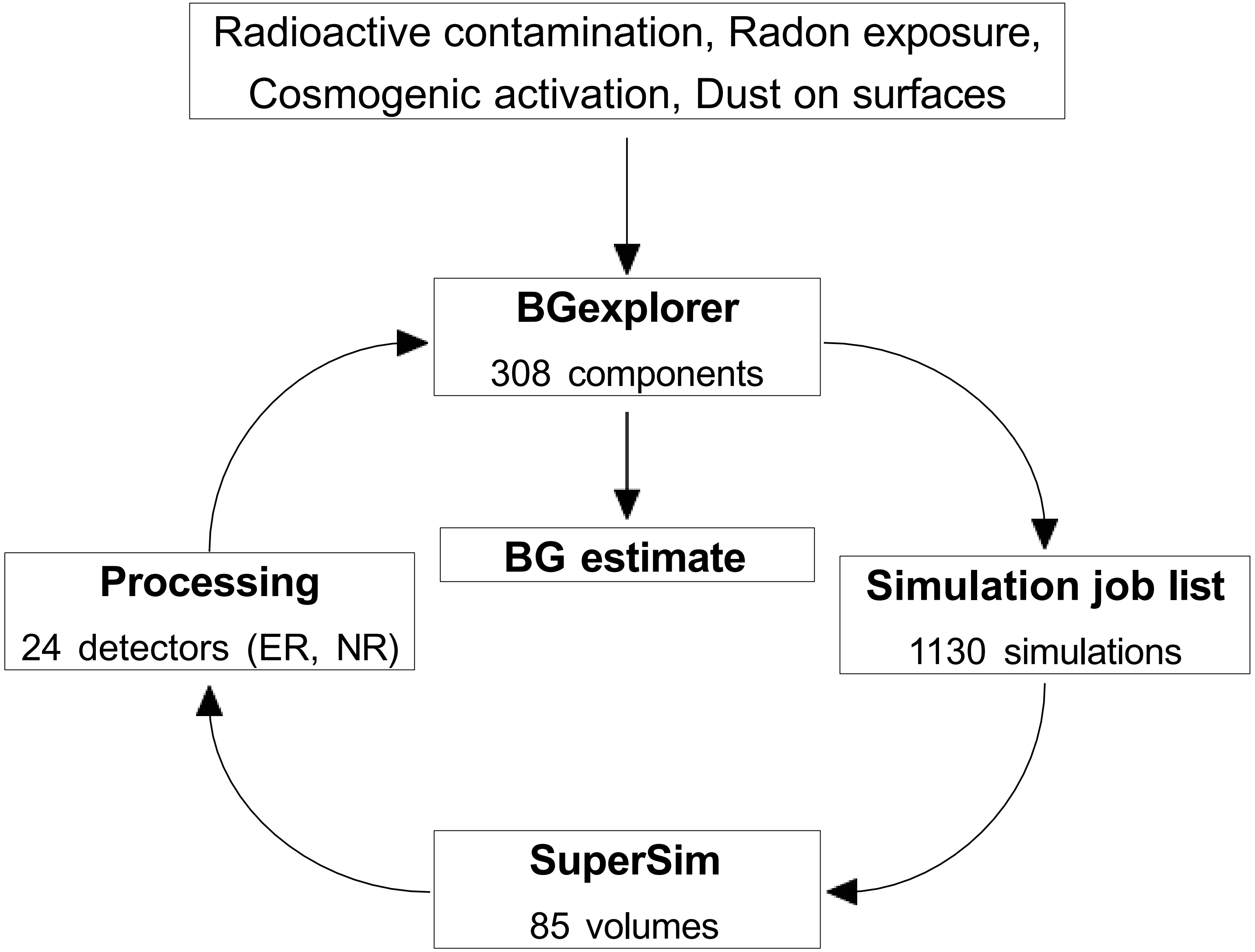
Dust on surfaces

- Dust can accumulate on surfaces and can contain radioactive contaminants.
- Need to know the type and concentration of radioactive contaminants, accumulation rate and mass of the dust.

Slide credit: Birgit Zatschler

Background simulation campaign

- Screen each component to get assays of contained radioactive isotopes.
- Monitor component's time on Earth's surface, exposure time to mine air, time in clean room accumulating dust.
- BGexplorer calculates the emission rate for each component and isotope.
- SuperCDMS' GEANT4 application SuperSim propagates emitted particles through setup and records detector hits.
- BGexplorer calculates component's BG contribution from processed spectra.



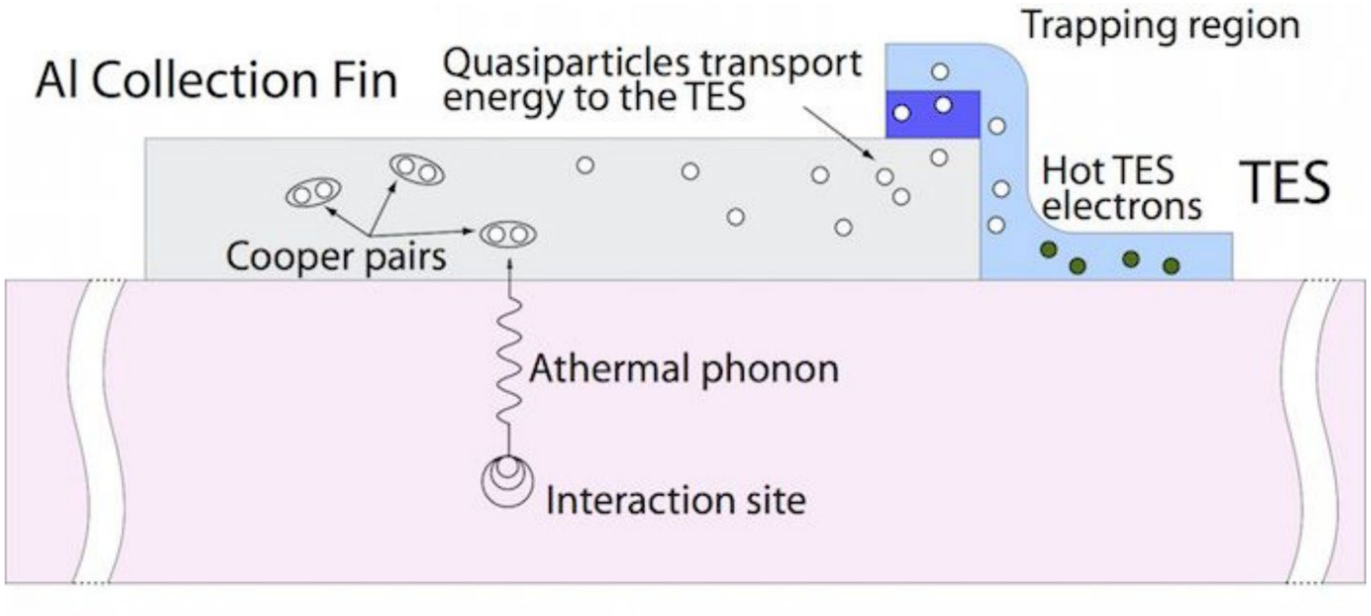
Slide credit: Birgit Zatschler

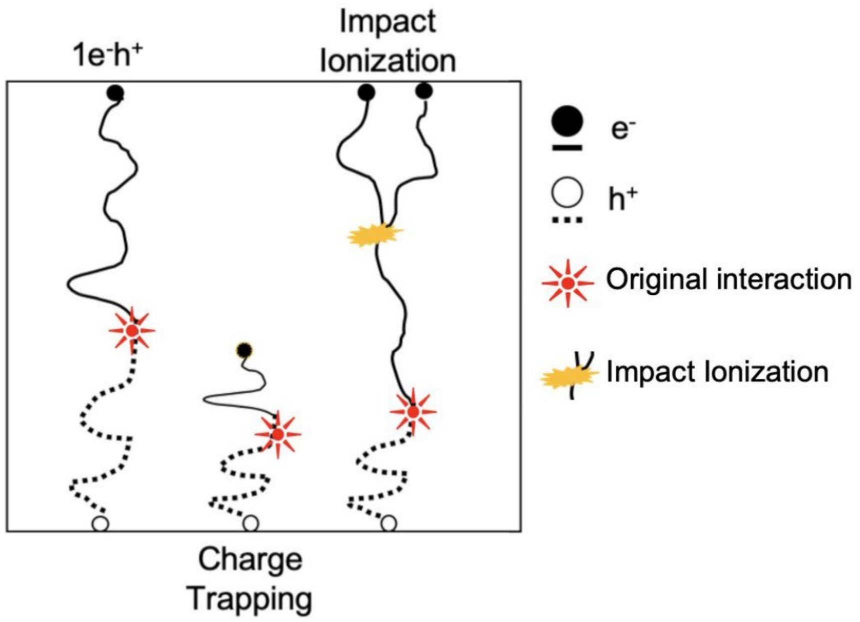
SUPER CDMS
Cryogenic Dark Matter Search

Detector Simulations

- G4CMP : Condensed Matter Physics for Geant4
    - Lattice structure
    - Charge transport
    - Phonon transport
- SuperCDMS phonon and charge simulations
- Electric field modeling

Detector response modeling: it's complicated





https://figueroa.physics.northwestern.edu

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

Slide credit: Stefan Zatschler

GEANT4 and "Detector Backgrounds"

- What GEANT4 does: Particle transport through materials, interactions of particles with atoms ("EM processes") or nuclei ("hadronic processes")
  - Processes implemented for energies ~100 eV to ~10 TeV
  - Particles tracked until all energy lost (e.g. through dE/dx), or decay
  - Transport assumes simple relativistic kinematics
- Electromagnetic fields handled by user-written functions defining field shape, extent
- Many natural sources of radiation are "backgrounds" to signals of interest; artification sources can be used for detector calibration
- SuperSim defines the full apparatus geometry in GEANT4, and generates events with sources incident on apparatus and detector crystals
- Interactions lead to energy deposited (**hits**) at locations in crystals; EM interactions transfer energy to atomic electrons (ionization, dE/dx)

Slide credit: Michael Kelsey

Example: Neutron interactions in crystal

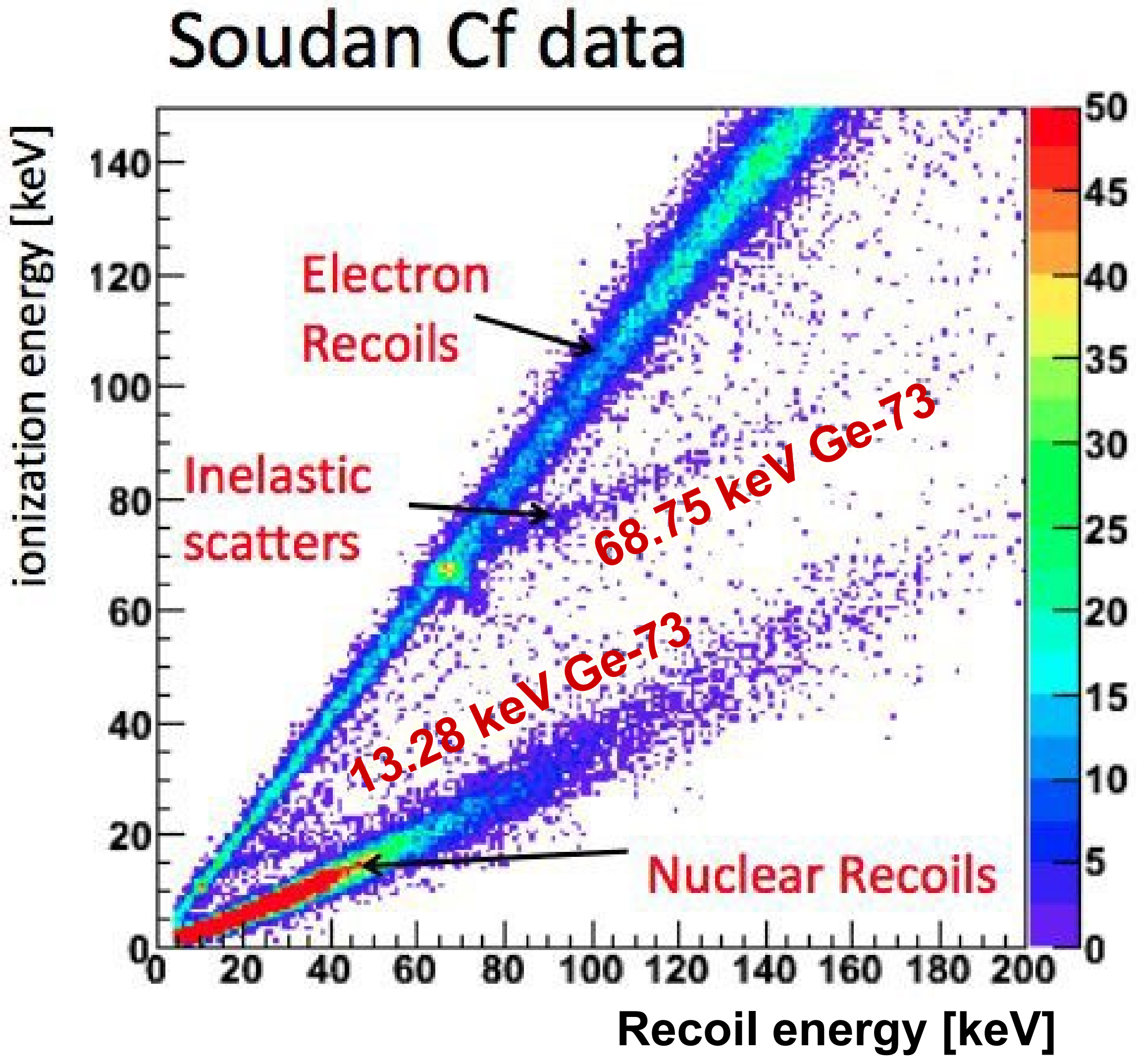
Neutron interactions are complex

- Simple elastic scatter, nuclear recoil
- Inelastic collision, excited nuclear state
- Neutron captures, induced radioactivity
- Multiple (~2.2) interactions per crystal

dE/dx vs. total energy has structure

- **Electron recoils** are pure dE/dx
- **Nuclear recoils** are NIEL deposits
- Bands due to excitation gammas

Simulation reproduces Soudan calibration data taken with Cf source (previous generation of SuperCDMS)



Slide credit: Michael Kelsey

G4CMP : Condensed Matter Physics for Geant4

Transport of **eV-scale** (conduction band) **electrons** and **holes** in crystals

- Anisotropic transport of electrons
- Scattering, phonon emission (NTL), trapping

Transport of **meV-scale** (acoustic) **phonons** in deeply cryogenic crystals

- Mode-specific relationship between wavevector and group velocity
- Impurity scattering (mode mixing), anharmonic decays

Production of electron/hole pairs and phonons from energy deposits

Utility classes to support detector response

- Finite-element mesh electric fields (2D and 3D)
- Phonon absorption, detection in superconducting films

Slide credit: Michael Kelsey

Solid-state physics in G4CMP: lattice structure configuration data

- Lattice structure (e.g. diamond cubic for Si and Ge), spacing, stiffness tensor
- Phonon scattering parameters, density of states for acoustic modes, sound speeds (longitudinal and transverse)
- Electronic band structure (bandgap, pair energy, effective masses) Electron primary valley directions and mass tensor components
- Fano factor, fitted parameters for empirical scattering rate functions

Slide credit: Michael Kelsey

Solid-state physics in G4CMP: charge transport, scattering and valleys

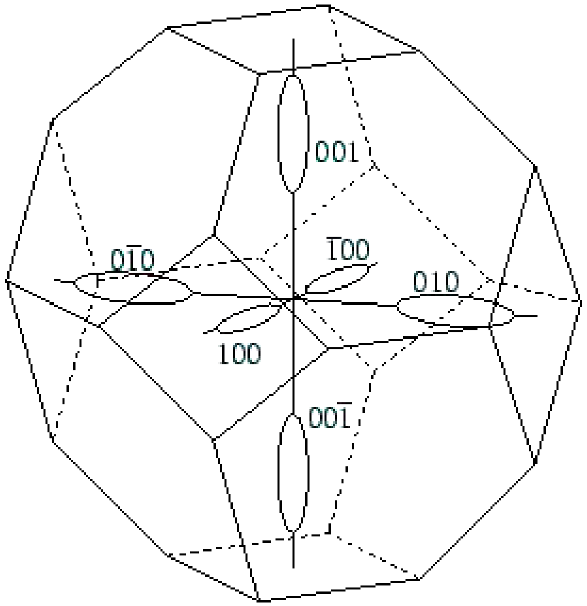
Incident particles promote electrons to conduction band, also creates holes (positive charge carriers)

Lowest energy bands have particular orientations (**valleys**)

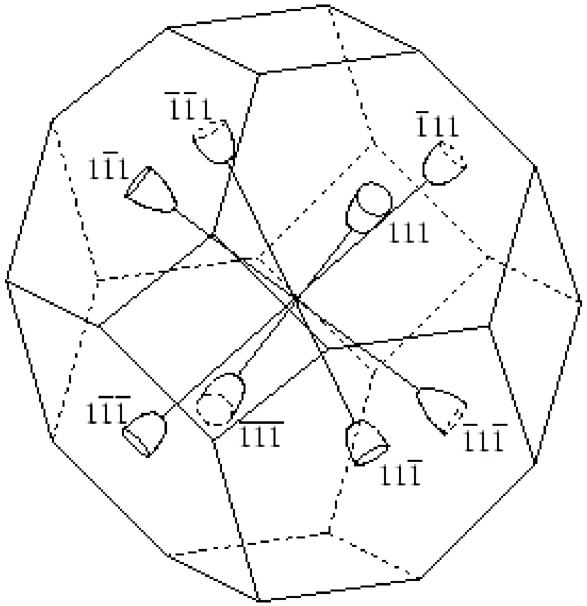
Electrons travel along valleys, with scattering between them

Charges accelerated in electric field radiate phonons

Charges interact with impurities, recombine with partner types



Silicon



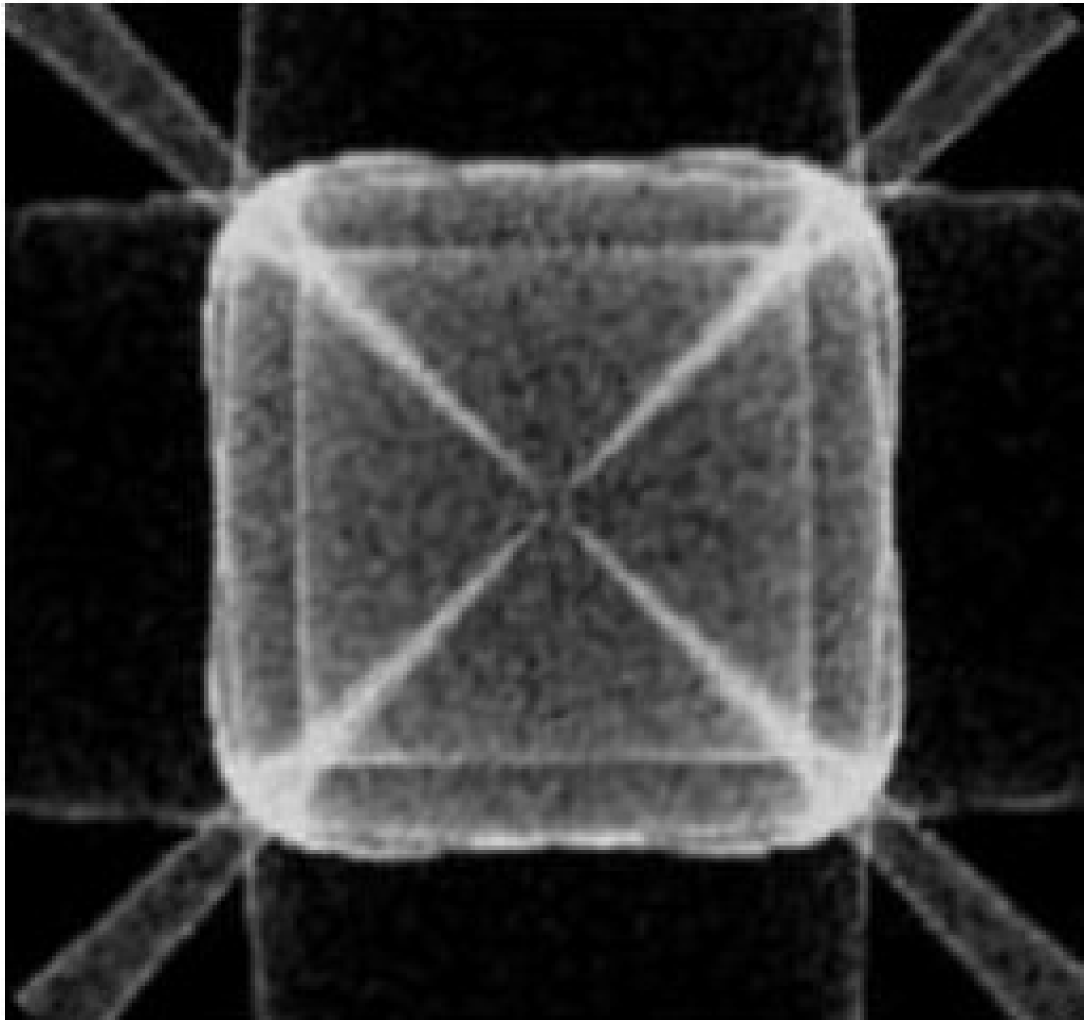
Germanium

Slide credit: Michael Kelsey

Solid-state physics in G4CMP: phonon transport, scattering, equipartition

- Quantized lattice oscillations: longitudinal (compression waves), transverse (shear waves)
- Lower energy (“acoustic”) and higher energy (“optical”) states
- Dispersion relations, $\vec{v}_g = f(\vec{k})$, for each mode

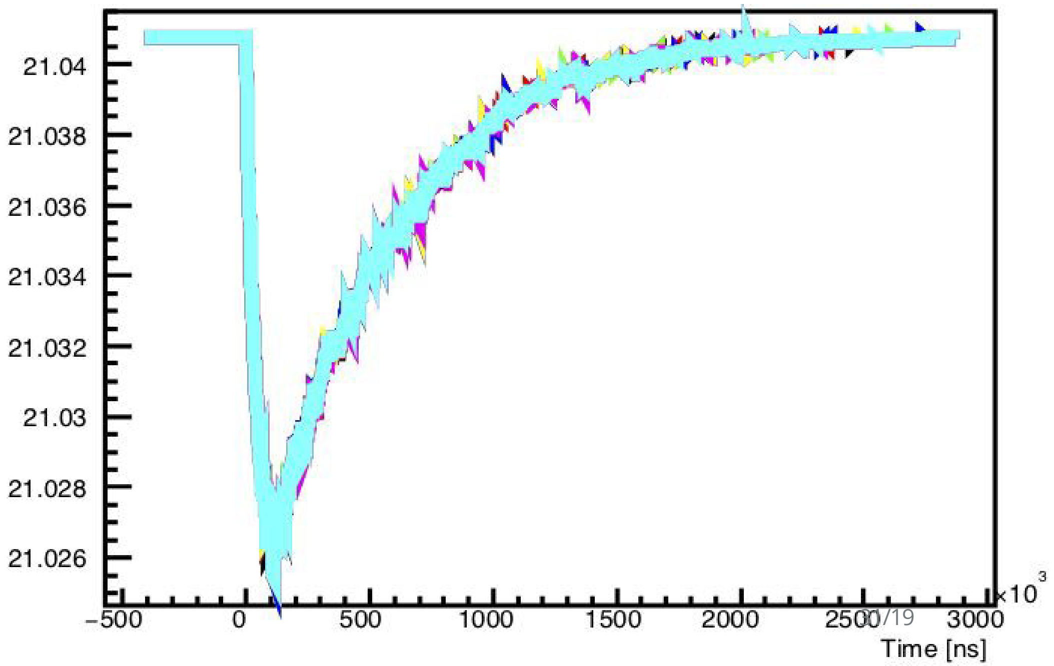
- Higher energy (tens of meV) phonons scatter off of impurities / defects
  - Scatter and transform from one mode to another, rate ~ E^4
  - Some split into two lower energy phonons, rate ~ E^5
- Low energy phonons rarely scatter



Slide credit: Michael Kelsey

Phonon signal simulation

- SuperSim implements phonon collection outside G4CMP
- Geometry model includes QET pads on detector surface Phonon incident on QET pad triggers thin-film simulation
  - Phonon is killed by absorption
  - Energy reported back from G4CMPKaplanQP as “absorbed” recorded as energy deposit (or “hit”) from incident phonon
  - List of “re-emitted” or “reflected” energies become new secondary phonons
- Prompt and NTL phonons arrive quickly, max when charges stop
- Downconversion, QET re-emission after prompt arrivals
  - Long tail of low energy phonons
  - Several milliseconds to collect
- Integral measures total energy deposit
- Peak can be used as proxy as well



Slide credit: Michael Kelsey

Charge signal simulation

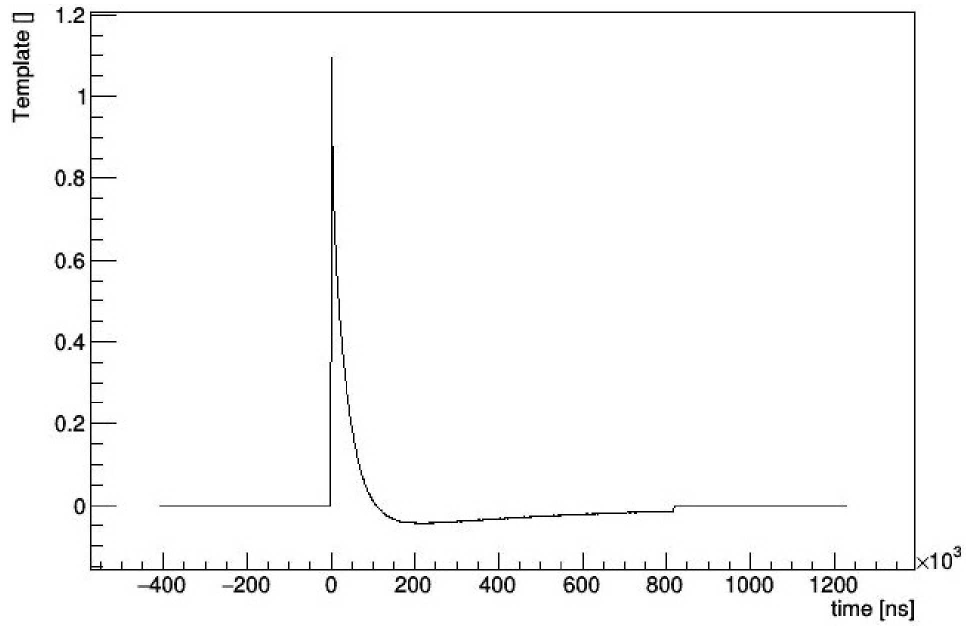
SuperSim also implements charge collection outside of G4CMP

Shockley-Ramo theorem: induced current $i = q\,\hat{\mathbf{E}} \cdot \mathbf{v}_q$, $q = \pm 1$

- Special field $\hat{\mathbf{E}}$: signal electrode 1V, others 0V
- Charges travel much faster than DAQ readout (20-30 km/s, about 1 μs across detector)
- Path integral, $Q_{\text{ramo}} = q \cdot V_{\text{ramo}}$
- Sum over all charges, for all electrodes

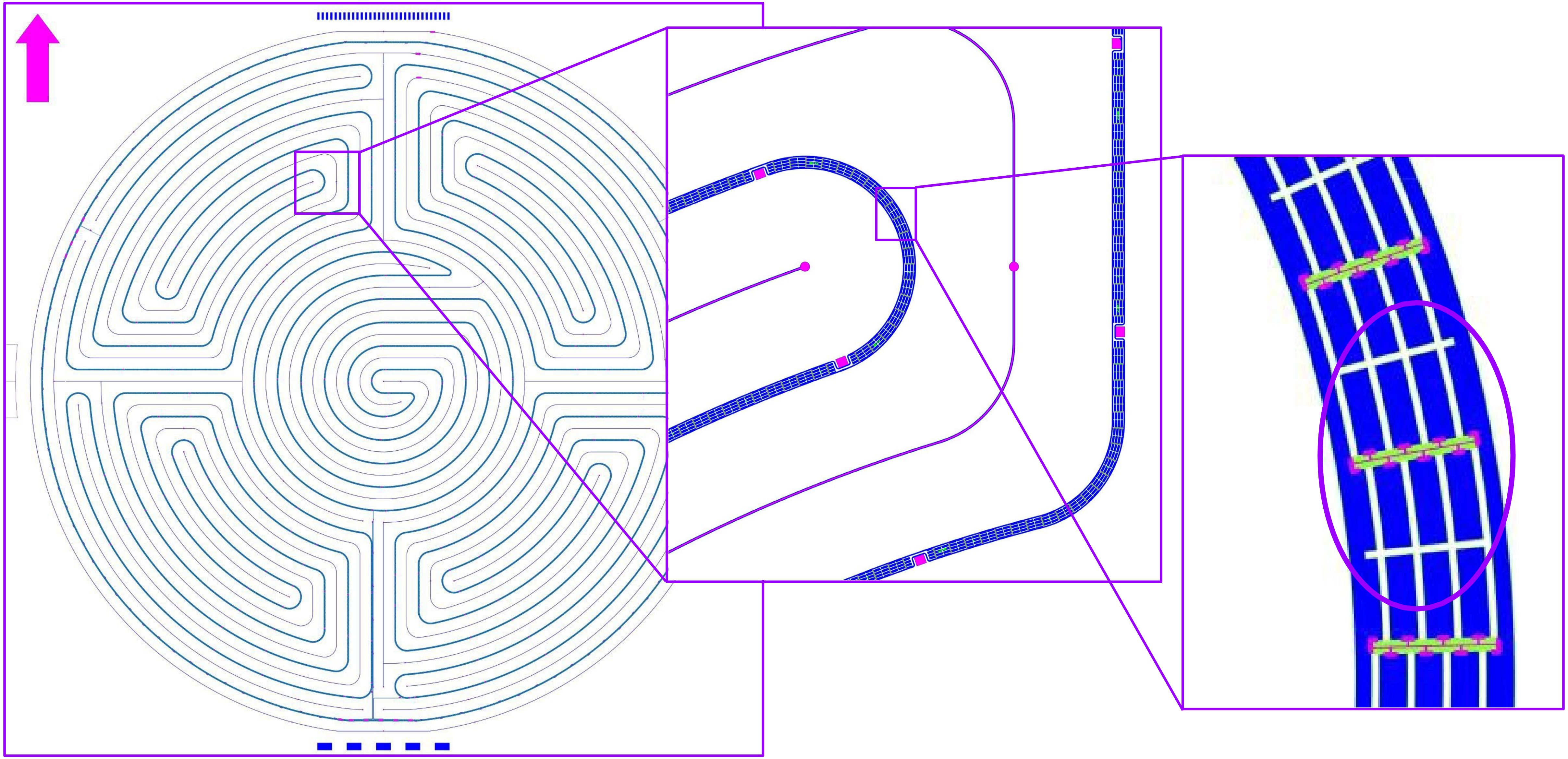
Model circuit elements, capacitance matrix

Signal amplitude proportional to total charge, tail due to electronic response (RC circuit)



Slide credit: Michael Kelsey

Detector sensor layout: it’s complicated



SNOLAB iZIP7 with QETs

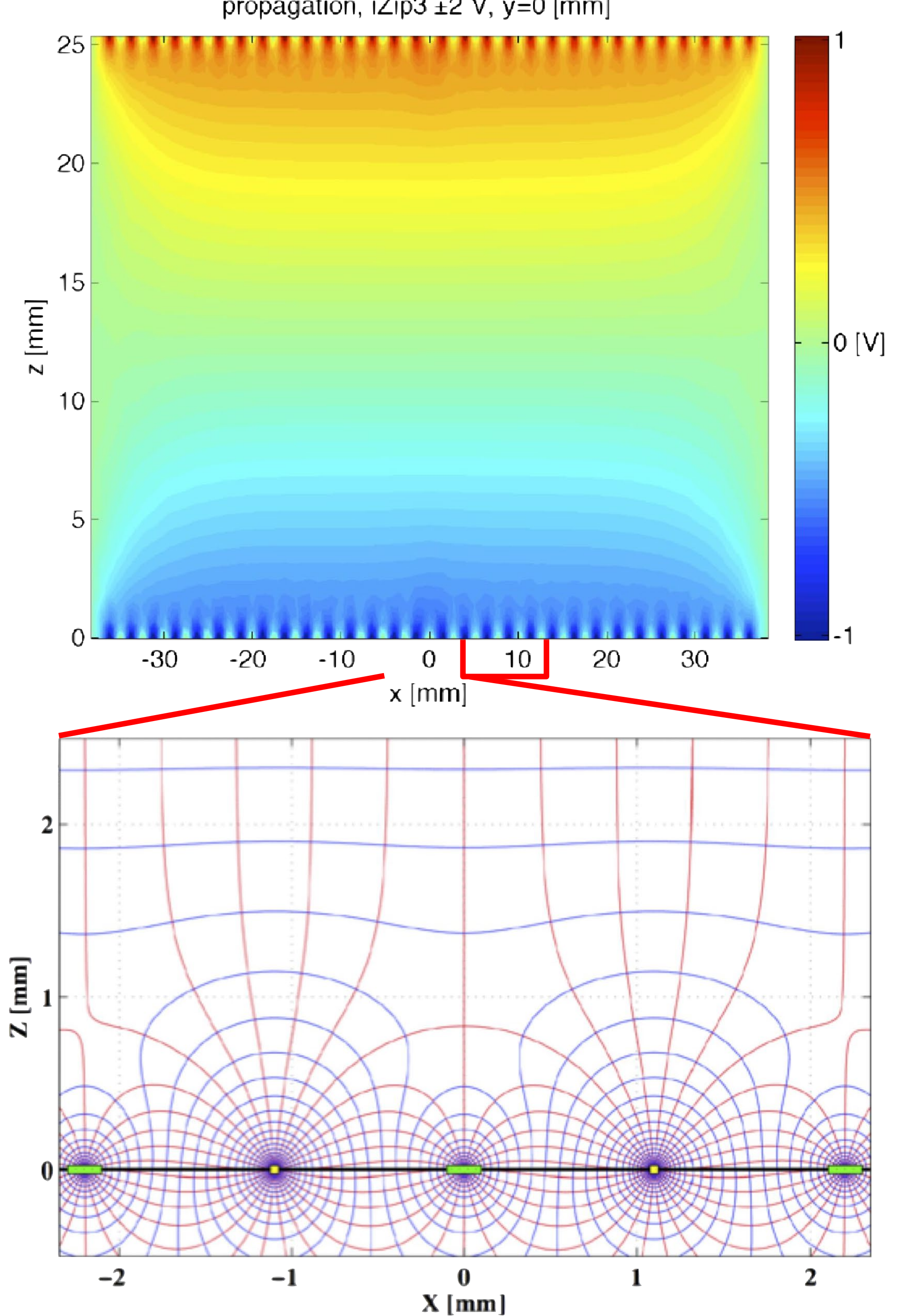
Slide credit: Michael Kelsey

Finite Element modeling of electric fields

Large detectors can have complex shapes and electrode layout

COMSOL, FEniCS, other physics modeling packages can generate a tetrahedral mesh of voltage at coordinates

G4CMP processes table of mesh points and tetrahedral, and handles mesh in detector-local coordinates



Slide credit: Michael Kelsey

G4CMP Software Package

Open-source: code available from https://github.com/kelseymh/G4CMP.git

- README file describes how to build, configuration parameters
- Example standalone applications in distribution (very limited)
- Descriptive paper: arXiv:1403.4984
- “Physics list" for G4CMP-only simulations, “Physics builder" for integration with Geant4 simulations
- Usage by non-SuperCDMS groups includes:
  - LiteBIRD : CMB experiment, superconducting polarimeters
  - Spatial Imaging of Charge Transport in Silicon (C.Stanford *et al.*)
  - Athermal Phonons in KID Sensors (M.Martinez *et al.*)
  - Superconducting Qubits (Several groups at FNAL, PNNL, others)

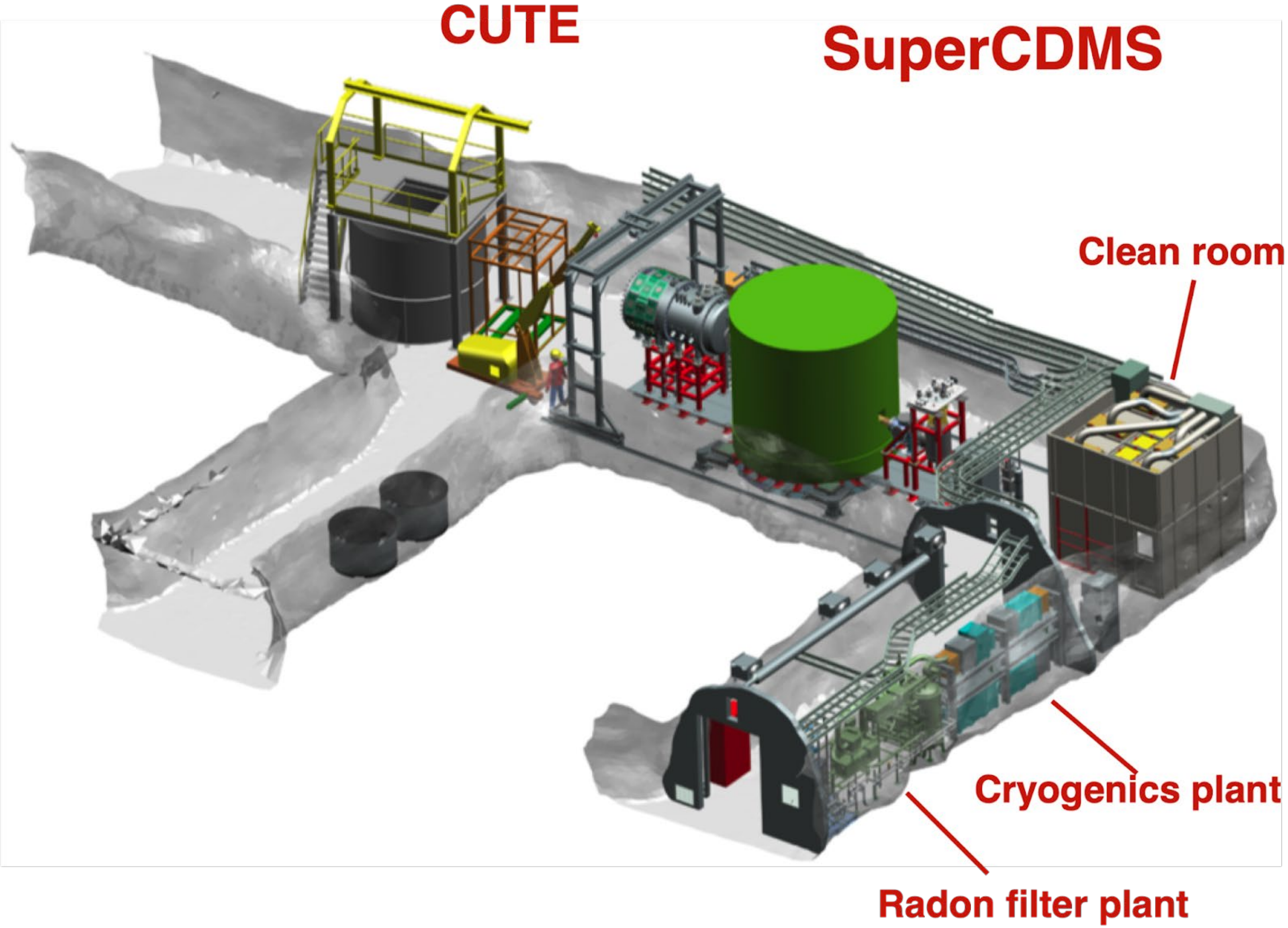
Slide credit: Michael Kelsey

Cryogenic Underground TEst facility

- Facility capabilities: dilution fridge, background reduction features, operations
- Backgrounds: budgets and predictions
- Plans: near and long term

(Quark and Qubit the Guinea Piggies are CUTE, too.)

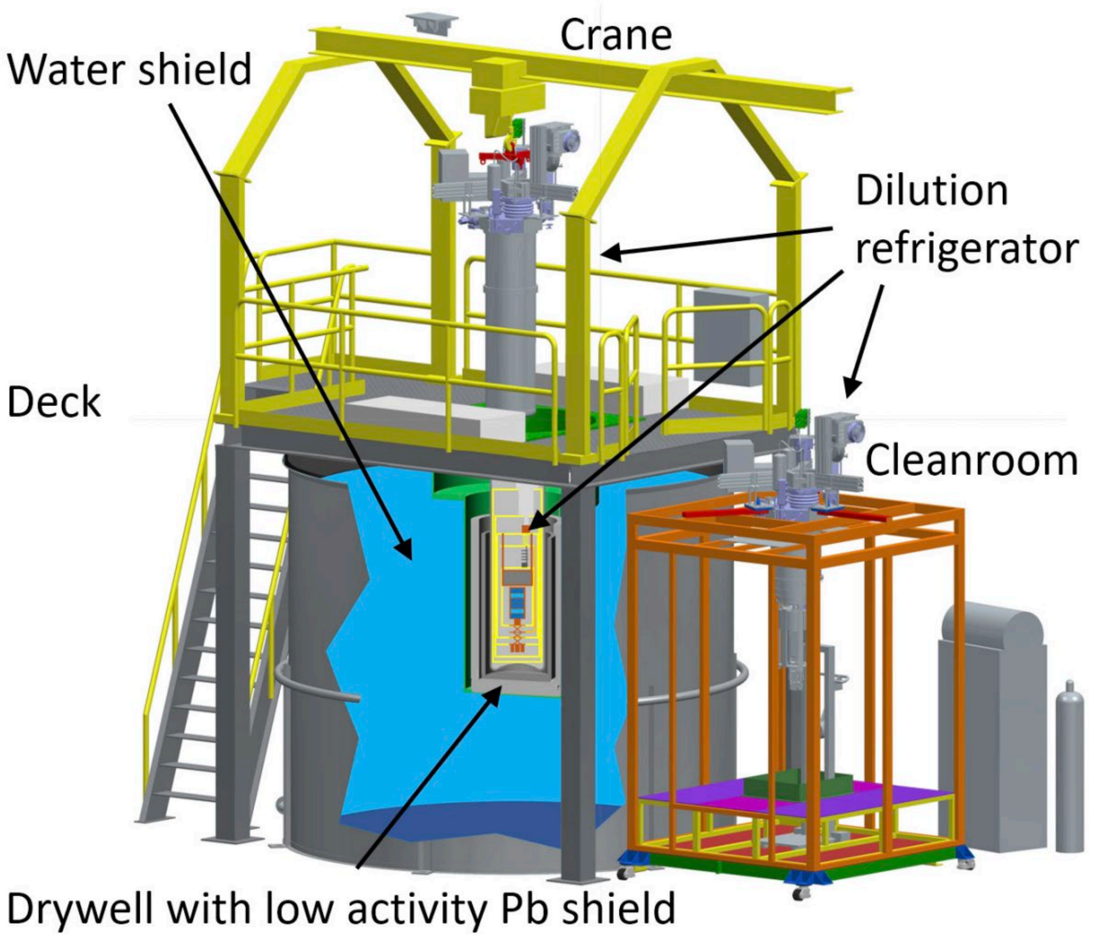
Cryogenic Underground TEst facility



TEst Facility Overview

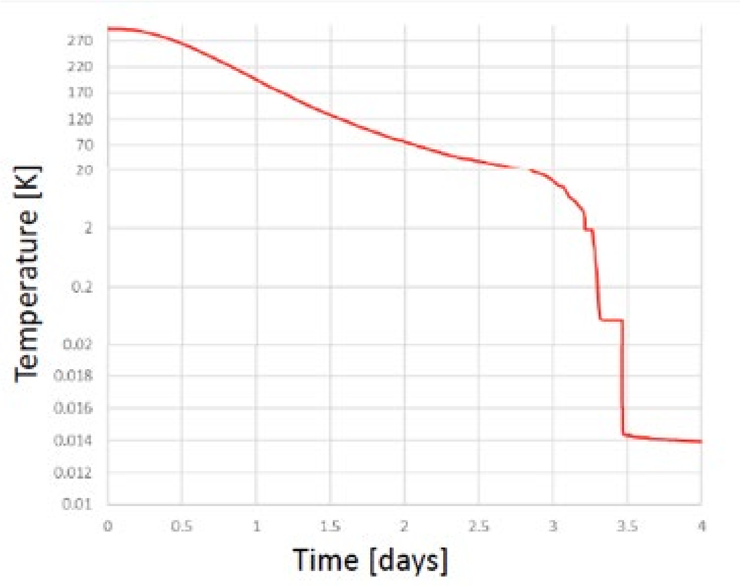
What the CUTE Facility can offer:

- Operational temperature as low as 12 mK
- Low overall radioactive background
- Minimal mechanical vibrations thanks to cryostat suspension system
- Low level of electromagnetic interference
- Availability of calibration sources (gamma, neutron)
- Low-radon, class 300 cleanroom to change payload
    - Typical Rn level < 15 mBq/m^3



Slide credit: Andrew Kubik

Cryogenics



Dilution Fridge:

- Base temperature ~ 12 mK with payload
- Cooldown time ~ 3 ½ days, largely driven by ~100 kg internal Pb shielding
- Fridge can run unattended for extended periods, critical in the underground environment
  - New Liquid Nitrogen refill system allows for continuous running for ~ 2 months

Slide credit: Andrew Kubik

Clean Room

We keep it clean:

- All payload and fridge work done in our class 300 clean room (clean room inception!)
- Low radon air supplied from surface and passed through HEPA filters
- Typical radon levels < 15 Bq/m^3, but more often ~ 5 Bq/m^3 (depends on weather at surface)

Upgrade to SCDMS RRS:

- SuperCDMS Radon Reduction System recently fully commissioned and brought online
- Can supply low radon air to CUTE
    - Design allows for simultaneous operation
- < 0.02 Bq/m^3 achieved

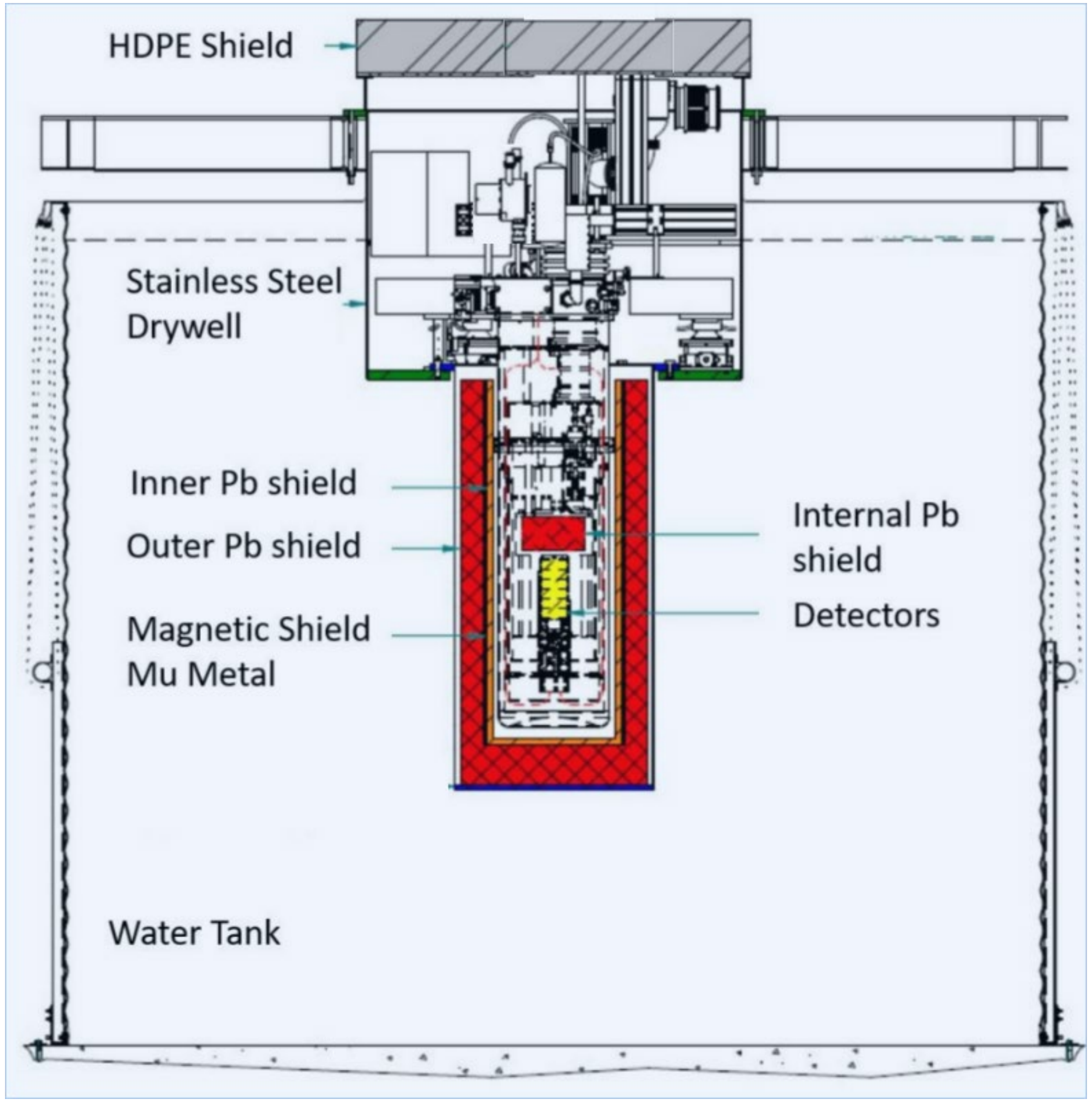
S. Jess & J. Gauthier

Slide credit: Andrew Kubik

Shielding

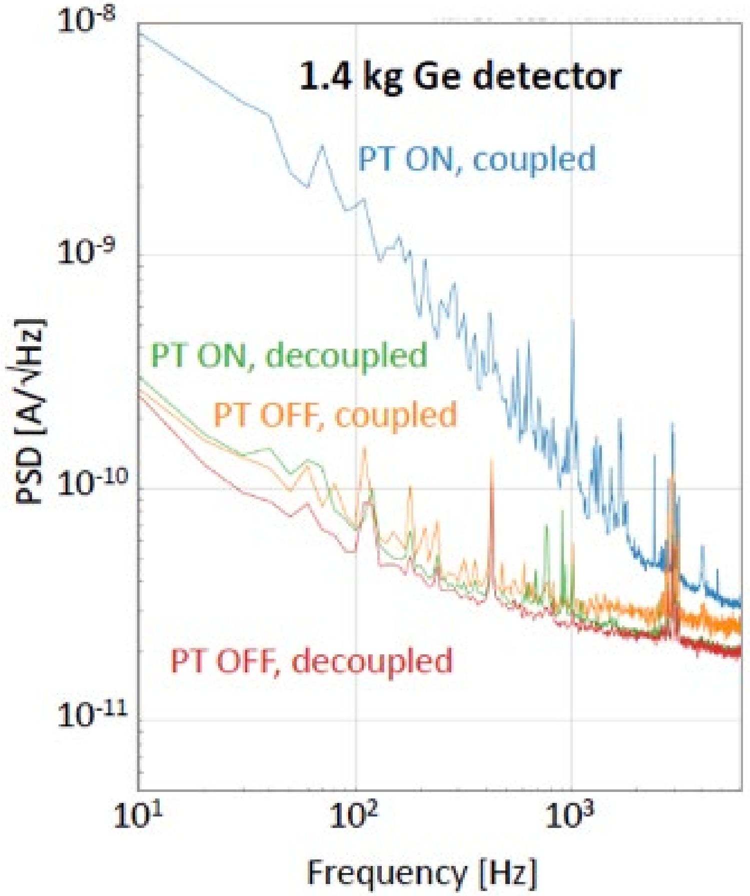
Shielding:

- ~ 10 cm low activity Lead in drywell
- Mu-metal reduces external B-field by ~x50
- ~1.5 meter of water and 20 cm Polyethylene lid
- 15 cm Lead “plug” inside of cryostat
- Active low radon air purge in drywell



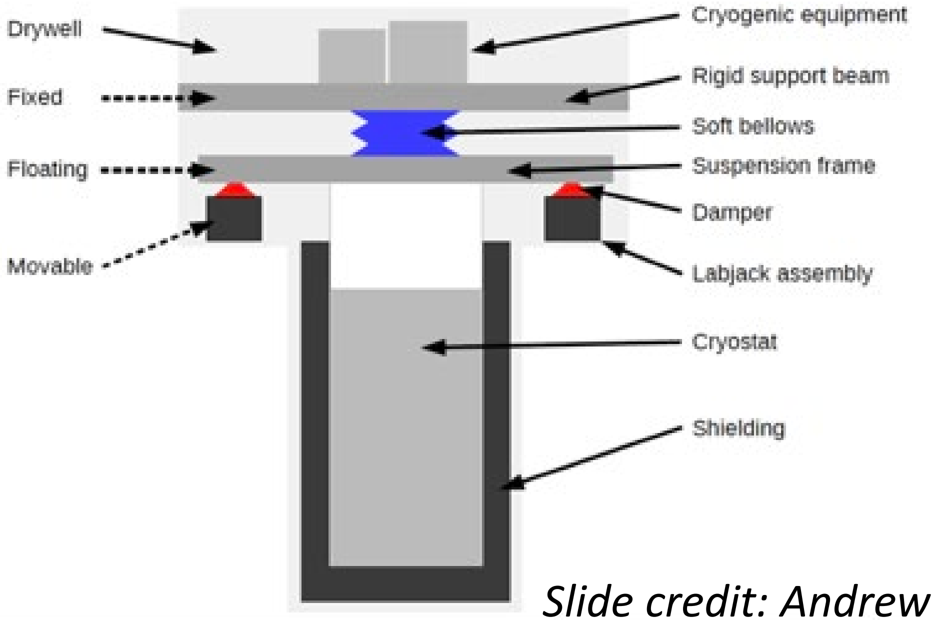
Slide credit: Andrew Kubik

Vibrational Isolation



<u>Vibrations:</u>

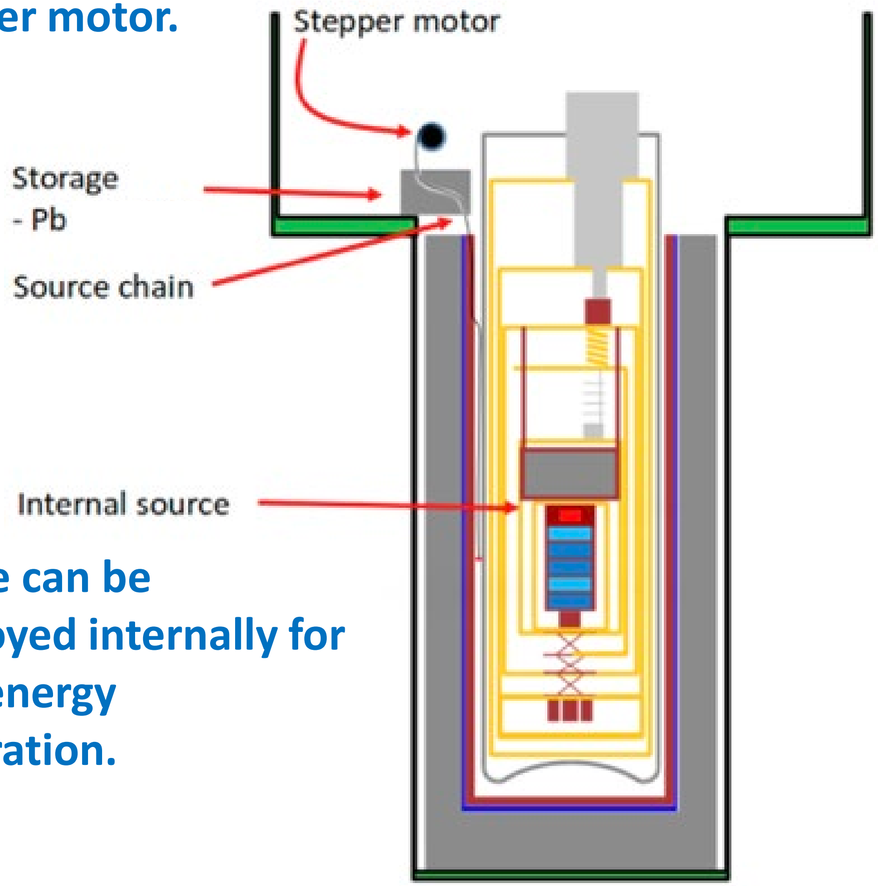
- Suspension system decouples cryostat from pulse tube and environmental vibrations coupling in through the deck.
- We can quantify the impact of vibrations with our detectors!
- Only marginal differences are seen in noise with suspension system active when we turn on and off the pulse tube cooler (one of our biggest sources of vibration)



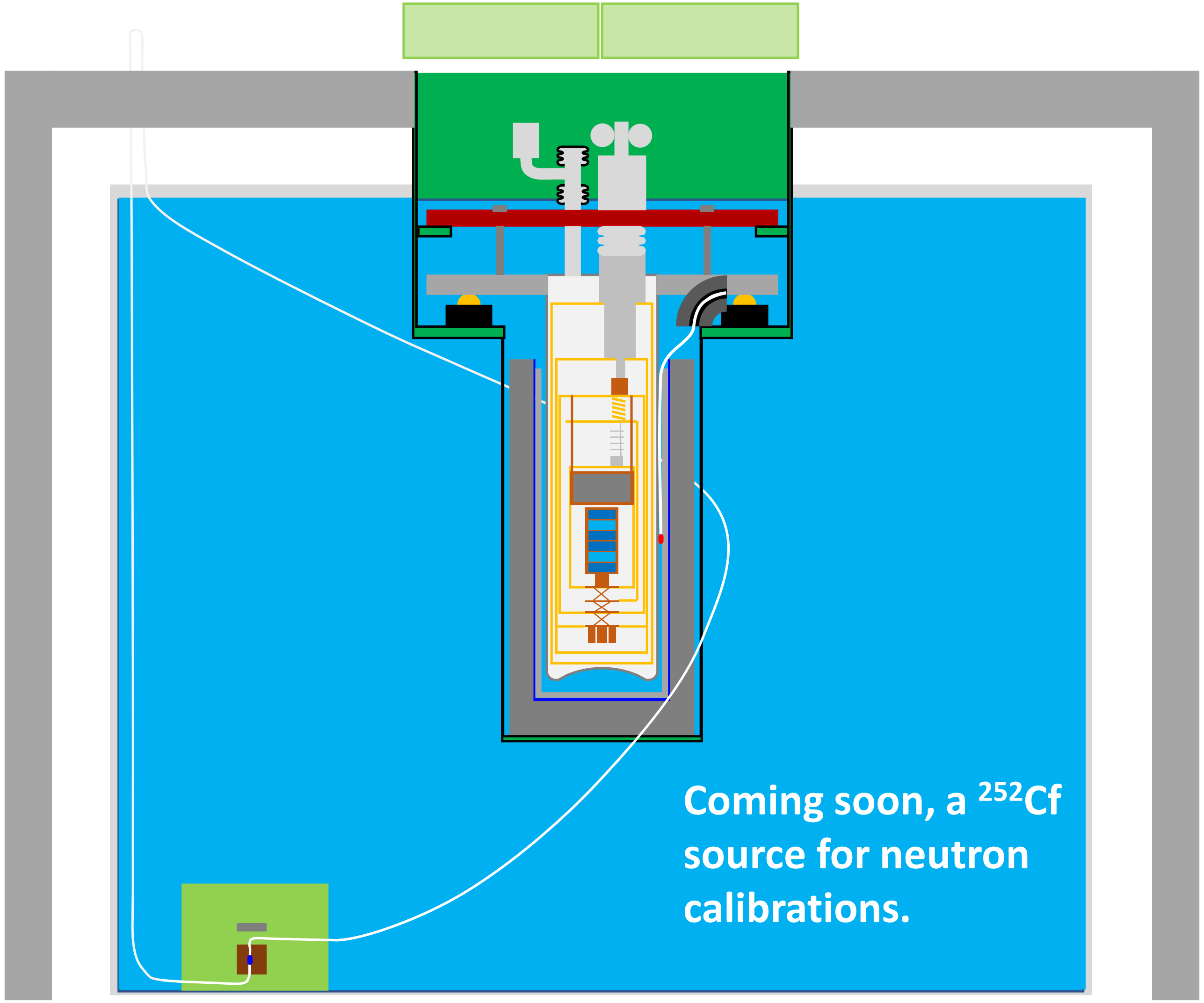
Slide credit: Andrew Kubik

Calibration

A ^{133}Ba gamma source can be deployed into the shielding with a stepper motor.



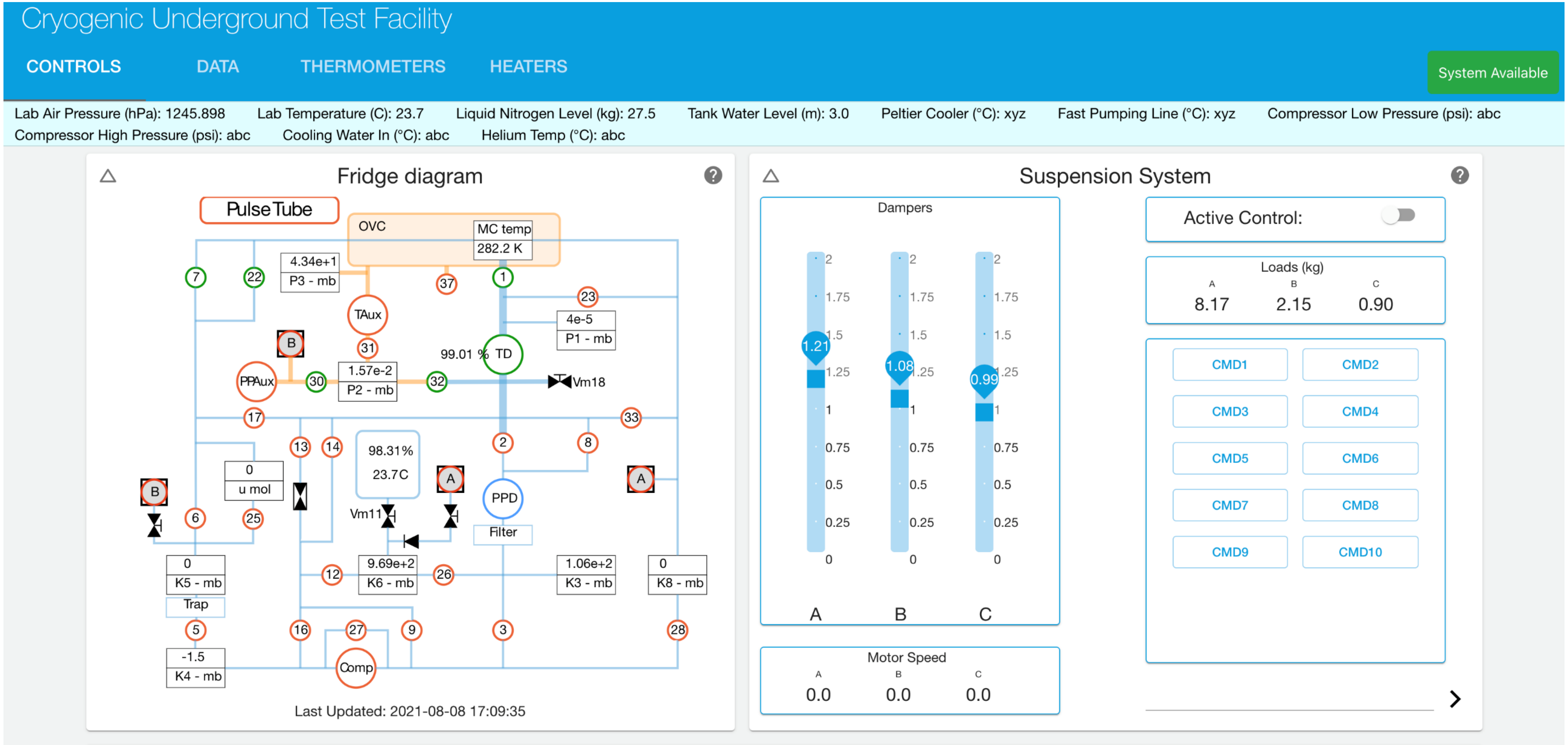
A ^{55}Fe can be deployed internally for low-energy calibration.



Coming soon, a ^{252}Cf source for neutron calibrations.

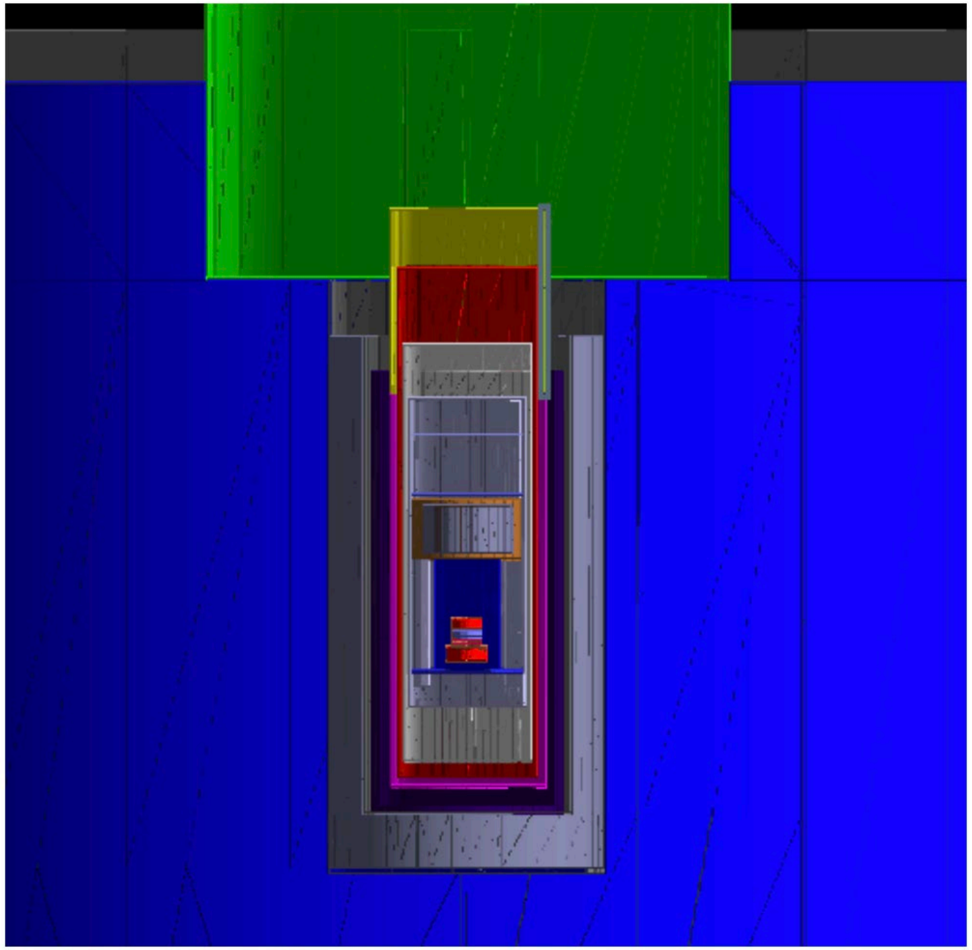
Slide credit: Andrew Kubik

Remote Operations



Slide credit: Andrew Kubik

Backgrounds

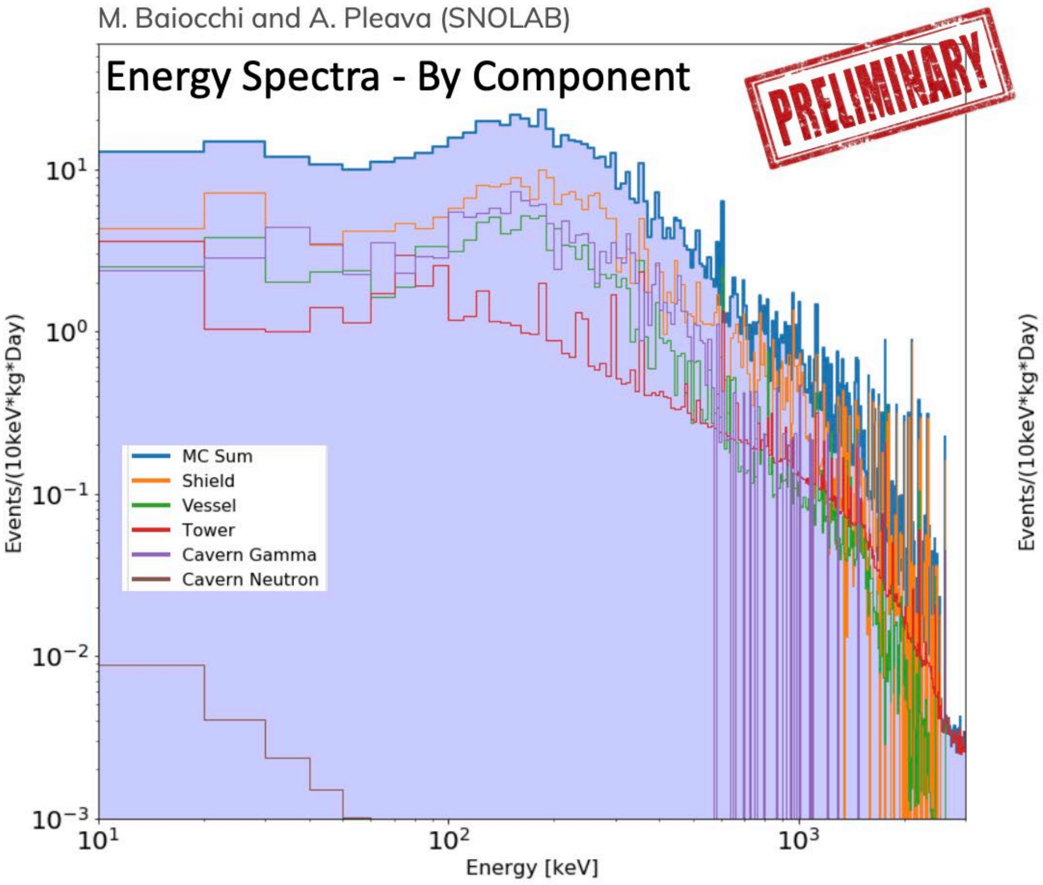

Geant4 visualization of the CUTE geometry

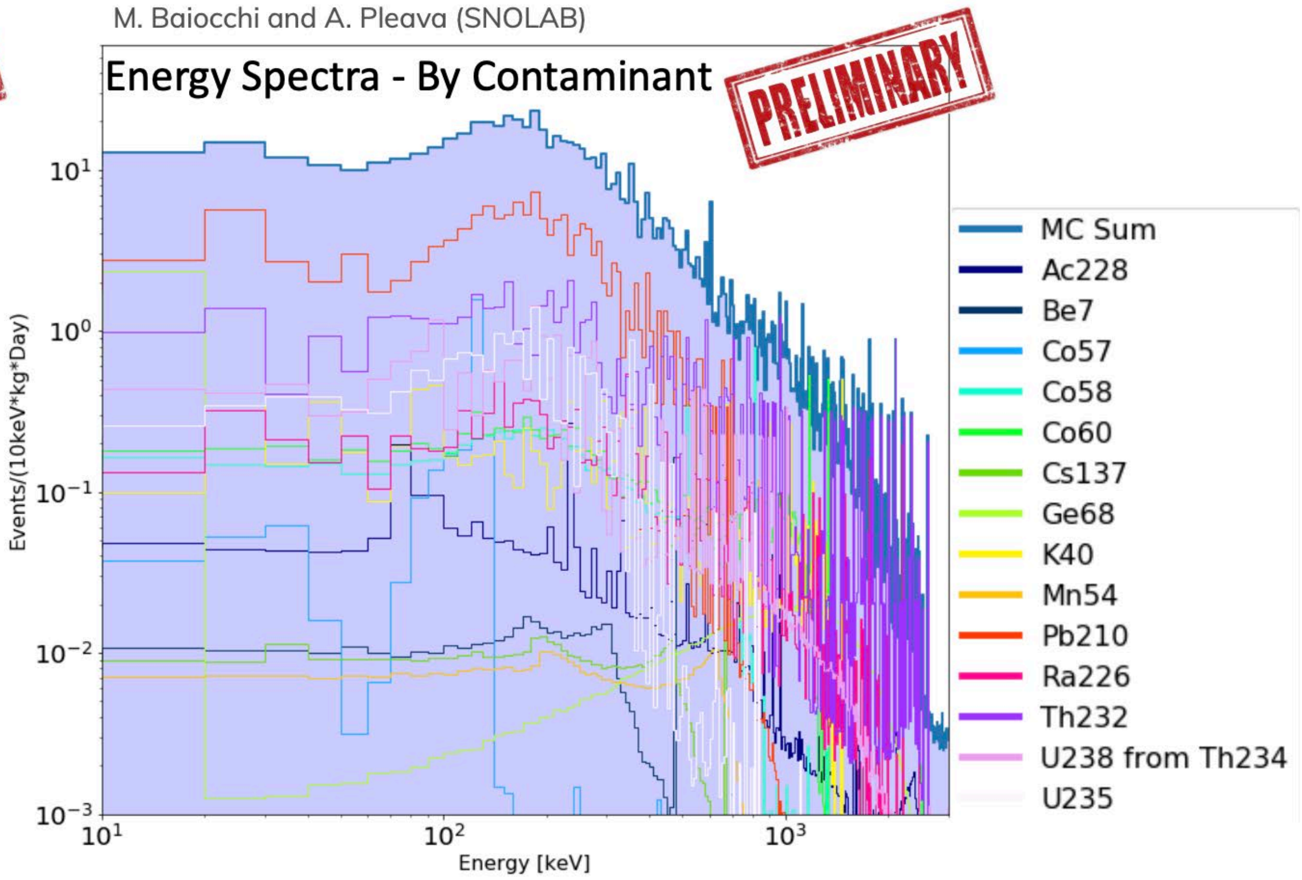
Backgrounds:

- Shielding and clean underground environment lead to low backgrounds
- All materials screened for activity using HPGe background counting facility at SNOLAB
- Create a full bill of materials in the facility
- Along with a detailed GEANT4 simulation, propagate background for each contaminate to <insert your favourite detector>
- Use Background Explorer tool to normalized contribution and generate expected event rate

Slide credit: Silvia Scorza

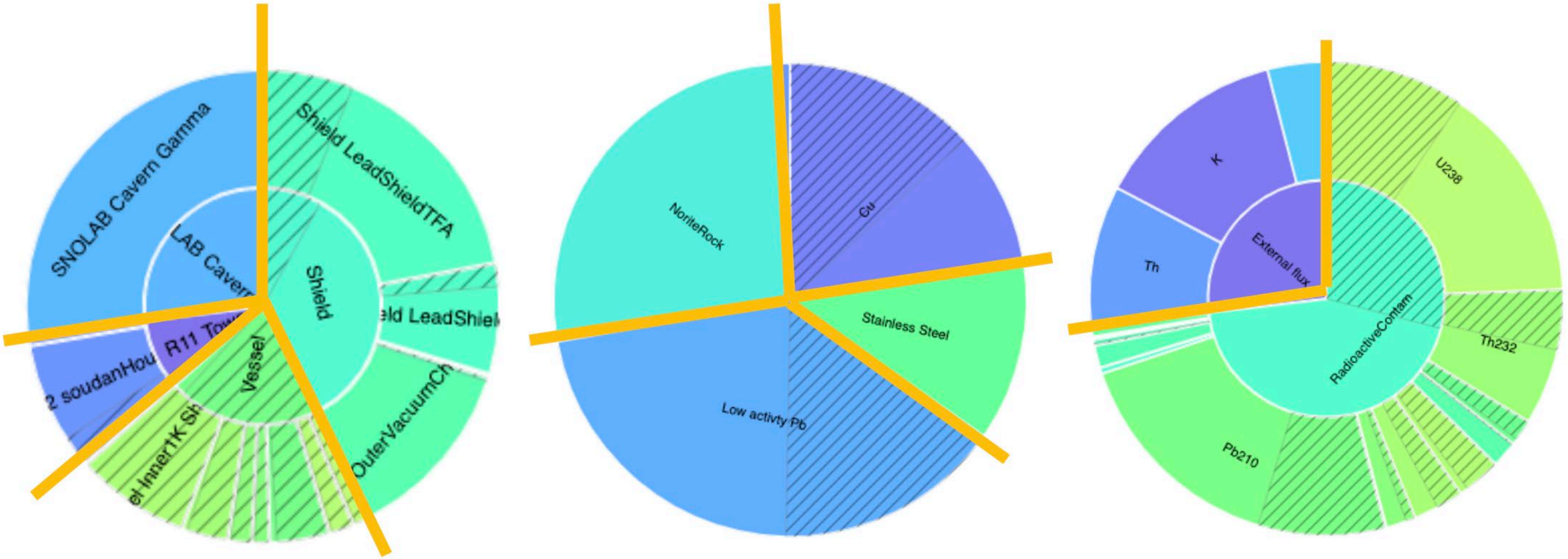
Background Budget





Slide credit: Silvia Scorza

Background Budget



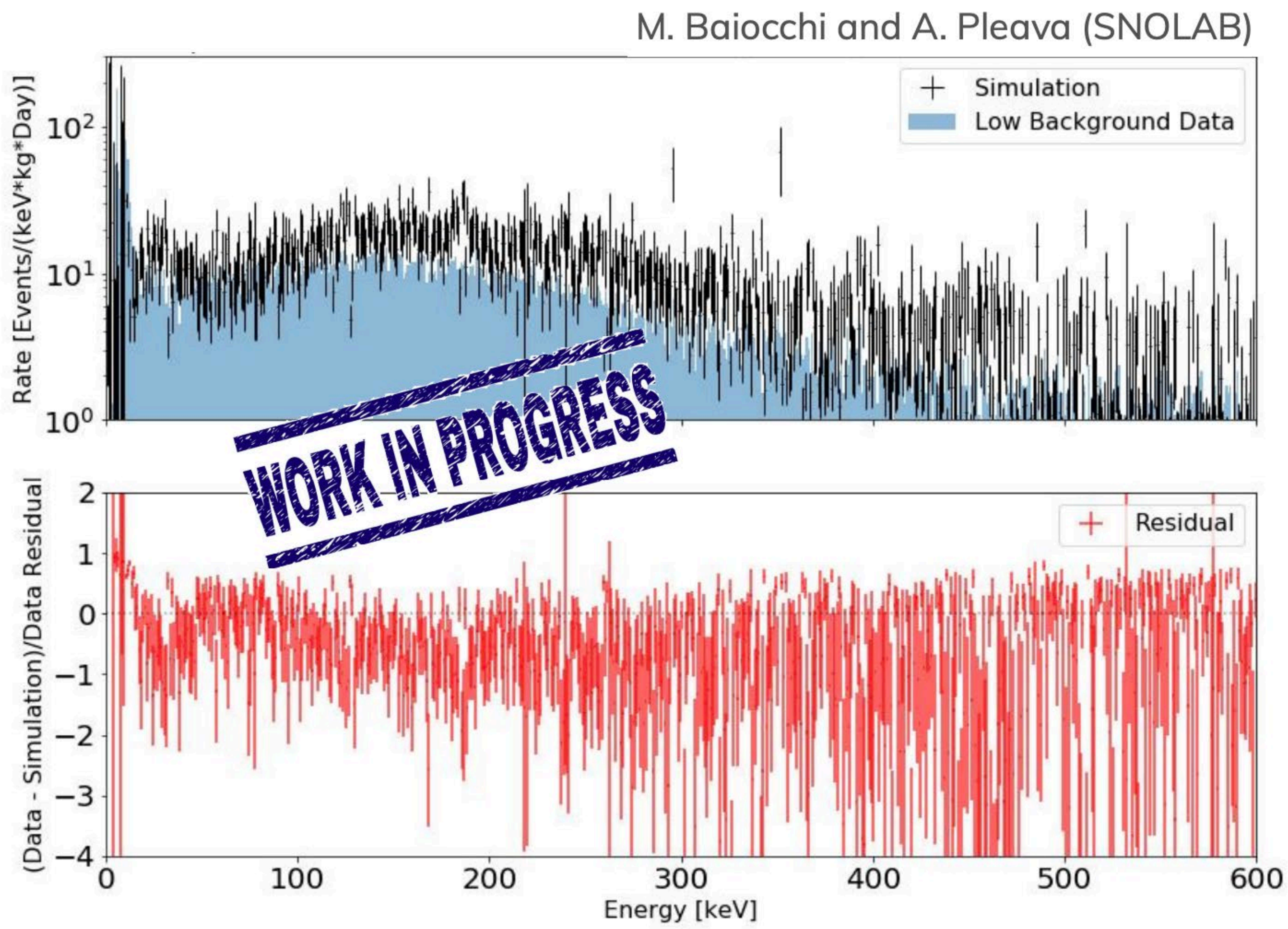
Component

Material

Contaminant

Slide credit: Silvia Scorza

Validating Background Predictions



Backgrounds:

- Simulation validated with real data
- 600 g Ge detector
- Agreement is pretty good
- Suspect that remaining discrepancy may be from low counting statistics in HPGe screening
- Total rate (including the detector itself)
  - 6.2 +/- 0.7 evts/kg/keV/day [1-1000 keV]
- Rate from facility only
  - 5.6 +/- 0.6 evts/kg/keV/day [1-1000 keV]

Slide credit: Silvia Scorza

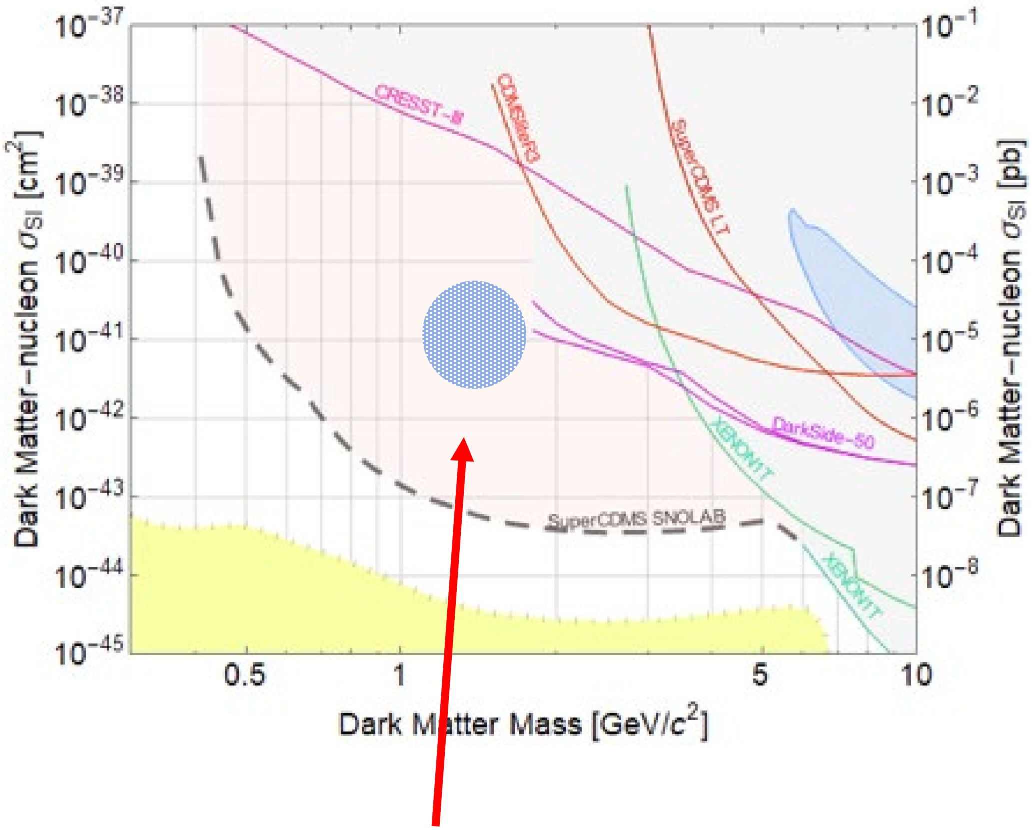
Near Term Plans

<u>SuperCDMS Detector Testing:</u>

- Single SuperCDMS Ge HV (1.4 kg)
- Single SuperCDMS Si HV (~600g)
- First full "tower" of 4 Ge and 2 Si HV detectors (happening now), focusing on:
  - Facility performance
  - Calibration
  - Noise hunting
  - Preparing for full SuperCDMS SNOLAB data

<u>DM Searches with SuperCDMS detectors:</u>

- Use detector payload or test devices and do some searching!
- Science with full SuperCDMS tower before SuperCDMS starts up



Potential CUTE Reach with SCDMS HV

Slide credit: Andrew Kubik

Long Term Plans

SNOLAB User Facility:

- **CUTE is a SNOLAB user facility!**
- SNOLAB-maintained and continuously improved
  - Collect proposals
  - Expert committee will make recommendations, CUTE management will negotiate details
  - Work with users to implement their experiment

Future Uses

- **Detector testing**
  - Future DM detectors (total mass of ~ 20 kg are possible)
  - Rare event searches (e.g. ^{50}V rare nuclear decay search)
  - HVeV devices
  - Single photon IR sensors ("Nanowire)
  - Testing effect of backgrounds on superconducting qubits
  - <insert your idea here>

Interested?

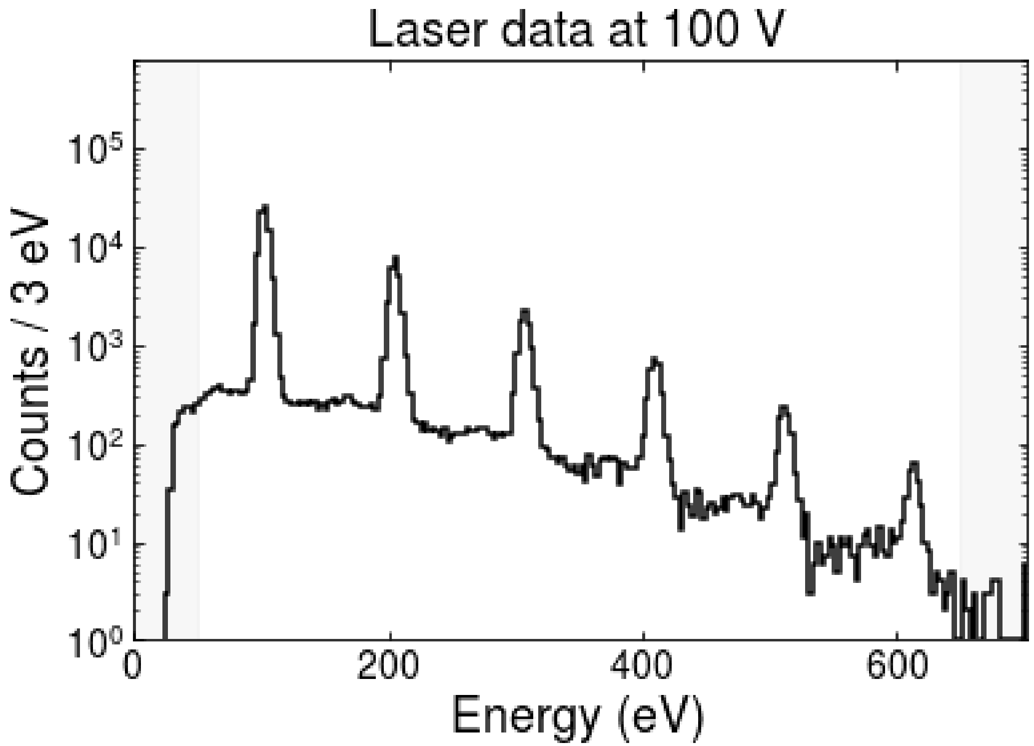
Have a project that would benefit from running at CUTE?

Please let the CUTE team know!

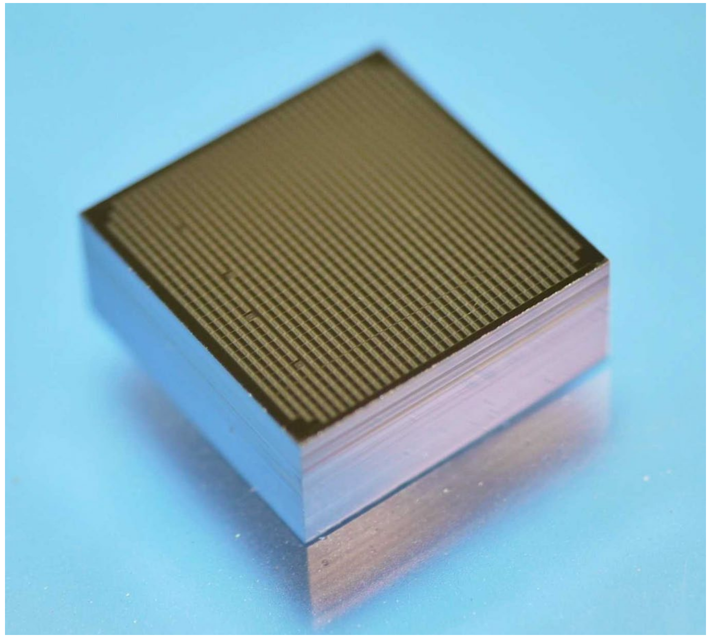
Slide credit: Andrew Kubik

CUTE Plan Example: HVeV Operations

- **HVeV Detectors Underground**
  - **Proposal for 5 detectors**
  - **Plan for readout and installation underway**



1 electron-hole (e-h) pair
Fill-in between peaks: charge trapping and impact ionization



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

Slide credit: Andrew Kubik

The CUTE Team

PI	until 2020: G. Gerbier (W. Rau: Co-PI)
	since 2020: W. Rau
Project Manager	until 2017: Ph. Camus
	2018-2020: S. Nagorny
Operations Manager	until 2022: S. Scorza, A. Kubik interim
SNOLAB team	A. Kubik, J. Hall, S. Scorza (until 2022) (Research Scientists)
	J. Gauthier (until 2022) (Operations Engineer)
	R. Schleehahn (Operations Engineer)
	J.M. Olivares (Technical support)
	M. Baiocchi, A. Pleava, S. Jess, Y. Esenullah (students)
	Support from SNOLAB technical team
On-site work	J. Corbett, M. Ghaith, S. Nagorny (until 2020)
Off-site	R. Germond (slow control)
	Z. Hong (facility upgrades)
	T. Aramaki (payload)
	B. Serfass, E. Fascione, E. Michielin,
	R. Underwood, Y. Liu et al (DAQ)
	A. Mayer, S. Pandey, T. Reynolds, A. Reyes, V. Iyer, A. Pradeep, M. Al-Bakry,
	R. Bhattacharyya, S. Dharani
	P. Pakarha (2018/19, calibration)
	K. Dering, S. Crawford (design engineering, until 2019/20)

Slide credit: Andrew Kubik