# SuperCDMS Simulation Framework

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Vienna Workshop on Simulations
25-27 April 2024

# Overview

SuperCDMS is a dark matter search using cryogenic semiconductor crystals, being assembled at SNOLAB in a mine in Ontario. The experiment is expected to finish construction in late 2024, and begin science running in 2025.

If dark matter exists, its interactions will be extremely rare (maybe a few per year of data), and every source of background radiation will be significant.

Understanding those sources, and quantifying both their overall rate and what their signals look like in our detectors, is critical to achieving the necessary sensitivity to dark matter.

# Overview

We have an extensive simulation framework in SuperCDMS, based on Geant4, to understand the detector response to background radiation and dark matter signals, and to evaluate our sensitivity to dark matter.

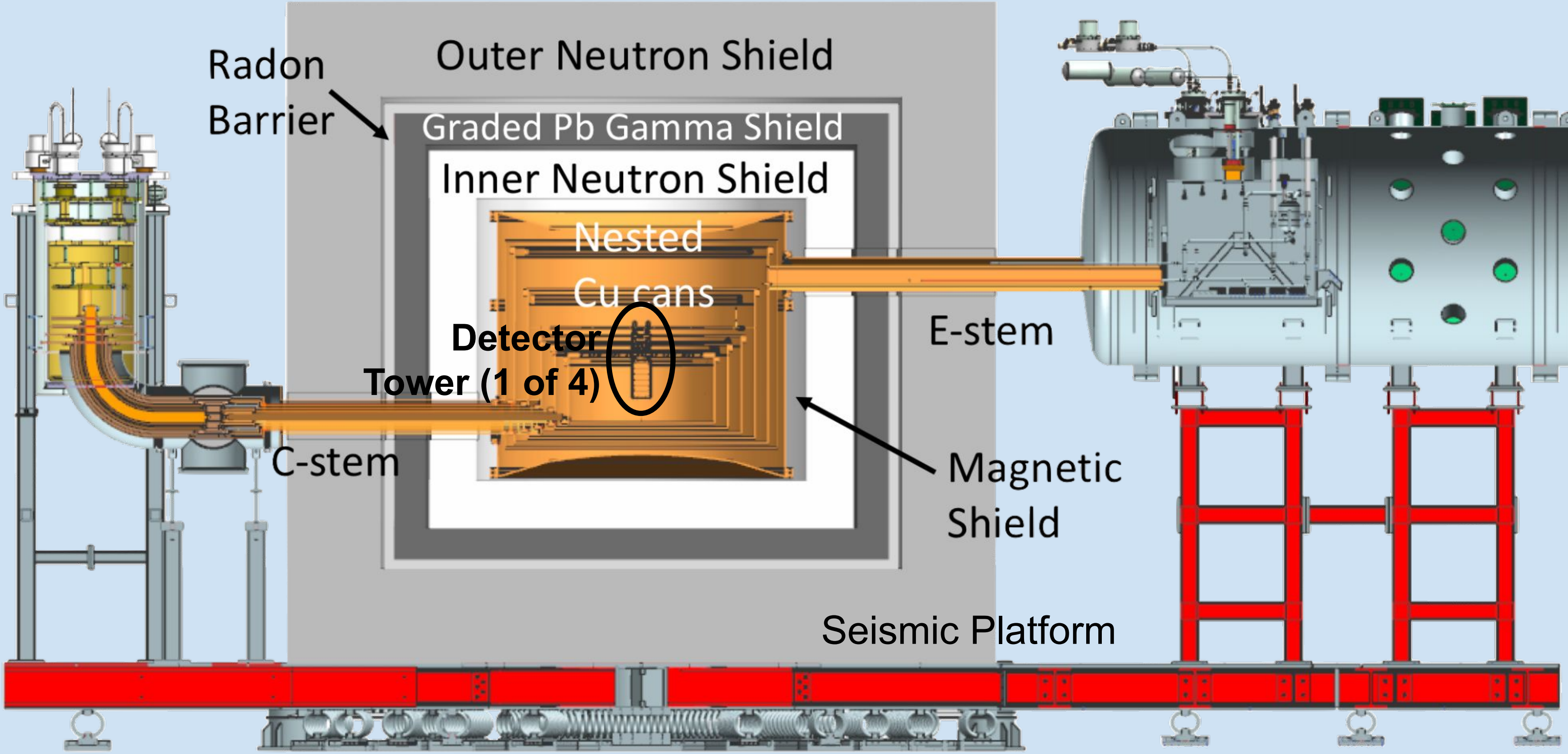
We have tried to make the framework comprehensive and configurable, with the following features:

- Full geometry of apparatus and cavern, as well as test facilities
- Wide variety of sources for external and internal backgrounds
- Detailed simulation of detector and sensor response
- Conversion of simulation to raw data format, event reconstruction

# Outline

- SuperCDMS Experiment
- Configuring Simulations at Runtime
- Sources for Backgrounds and Signal
- Detector Response Modeling
- Parameterized Response Model
- Data Acquisition/Readout Emulation
- Comparisons With Data
- Summary and Outlook

# SuperCDMS Experiment



# Detector Towers

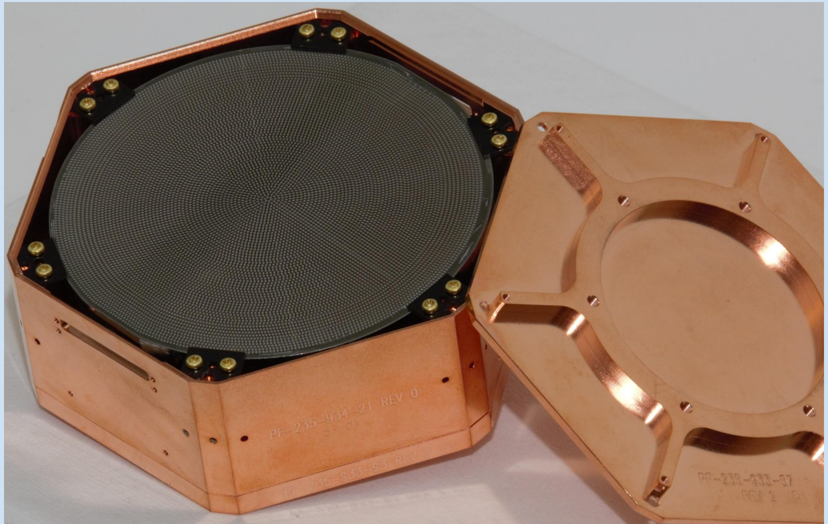
50 mK base temperature, 6-stage fridge

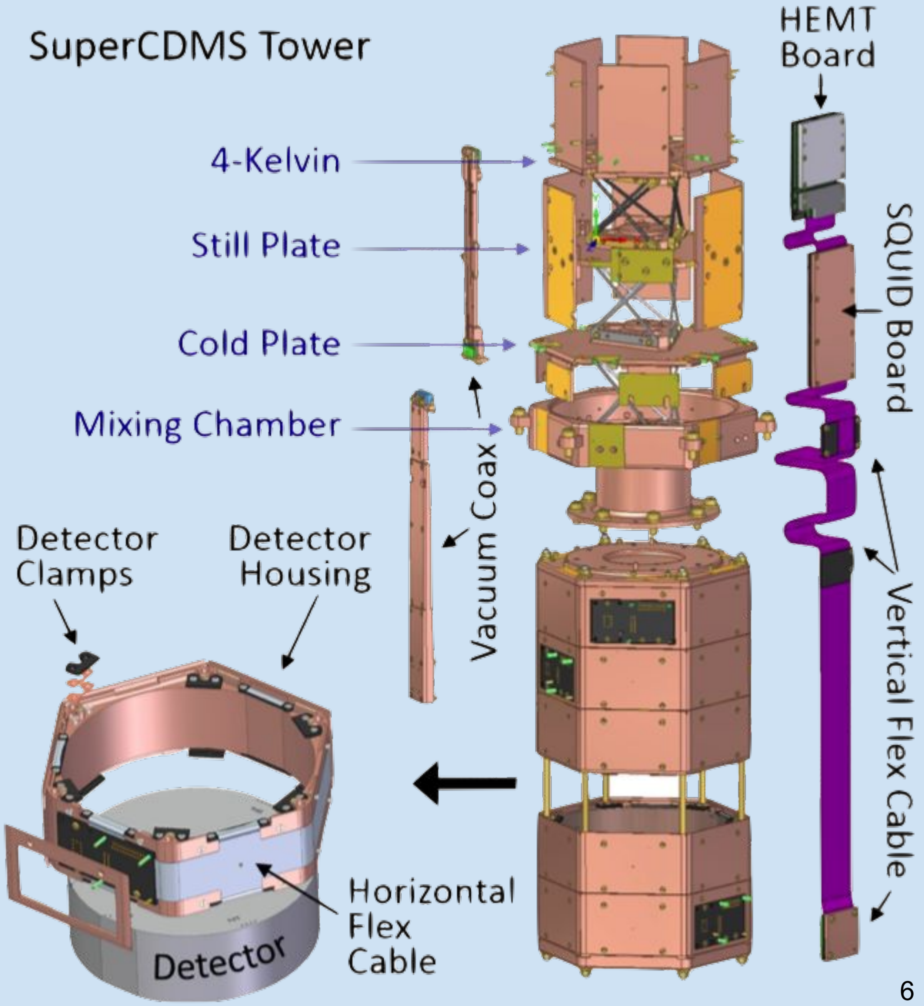
4 towers, 6 detectors each

Germanium, silicon detectors 100×33 mm

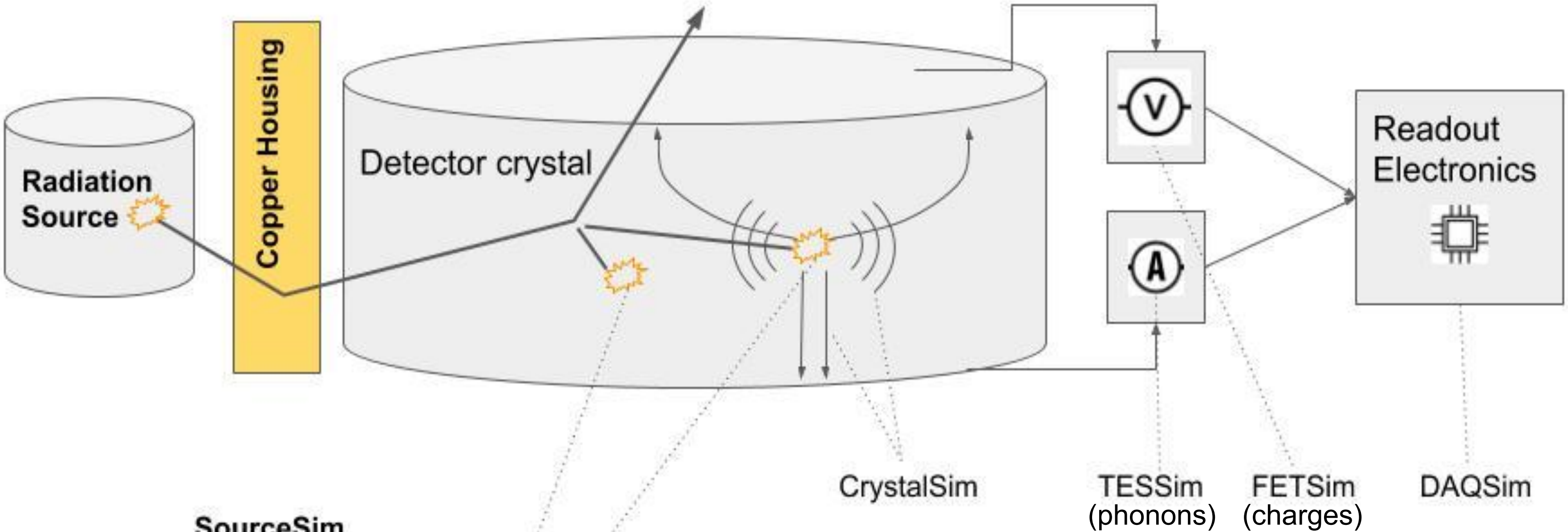
High (100V) and low (4V) voltage

Charge and phonon sensors





# SuperCDMS Geant4 Simulation Framework




**SourceSim**

Simulation of particles that travel through things and eventually hit the detector or decay directly in the detector

*Output:* Recoil particle, energy and position in the detector

**DetectorSim**

Simulation of Crystal response to phonons and electron holes, the TES and FET as well as the DAQ

*Output:* Raw Data format

# Geometry Configuration

Main experimental apparatus

- SuperCDMS SNOLAB and CUTE
- SCDMS Soudan
- Several test facilities
- Shielding configurations for each facility

Experimental halls (caverns)

- SNOLAB
- Soudan Mine
- NuMI Tunnel at Fermilab
- SLAC Cleanroom and BluFors

Individual detectors with or without housings, cabling

Detector response configurations

- Detector voltages and electric field model
- Crystal lattice orientation

# Signal and Background Sources

Sources can be assigned to any G4 volume, volume surfaces, or shape surfaces placed within geometry

- Gamma lines from 14 common contaminants
- Continuous n, γ spectra for various U-Th style contaminants
- Neutron spectra taken from assays of materials, components
- Cavern wall backgrounds generated from cosmic rays
- Calibration sources including source capsules and emplacement
- Search signals: WIMP-nucleus interactions, Fractionally-charged particles
- Direct energy deposits for validating detector response

# Example: Neutron Interactions in Crystal

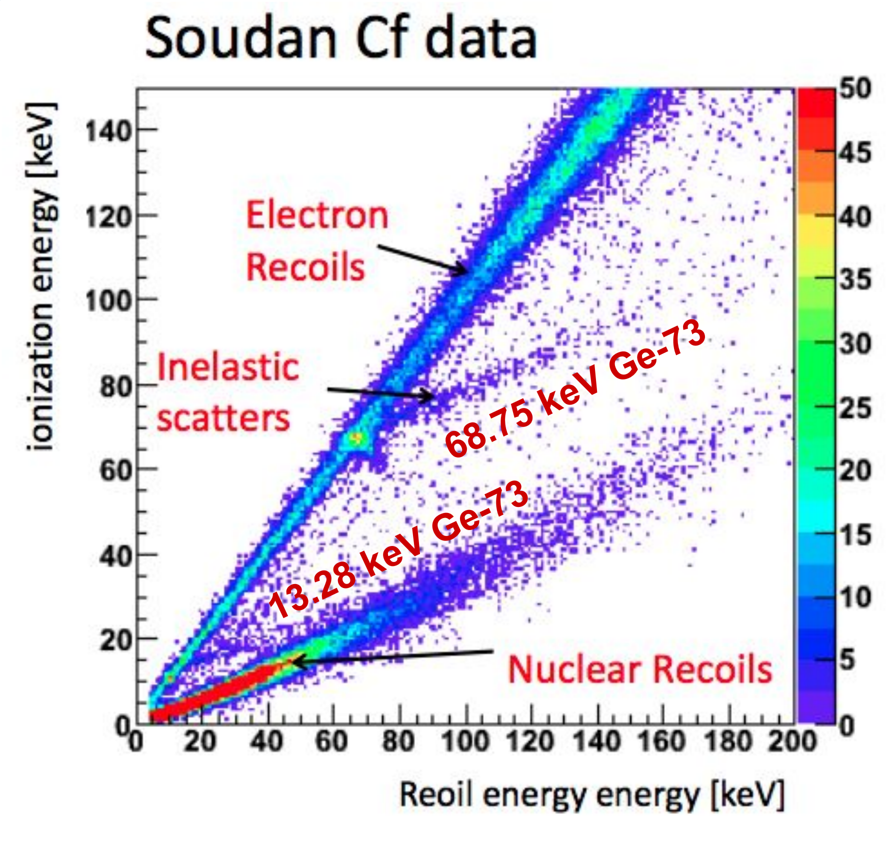
Neutron interactions are complex

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

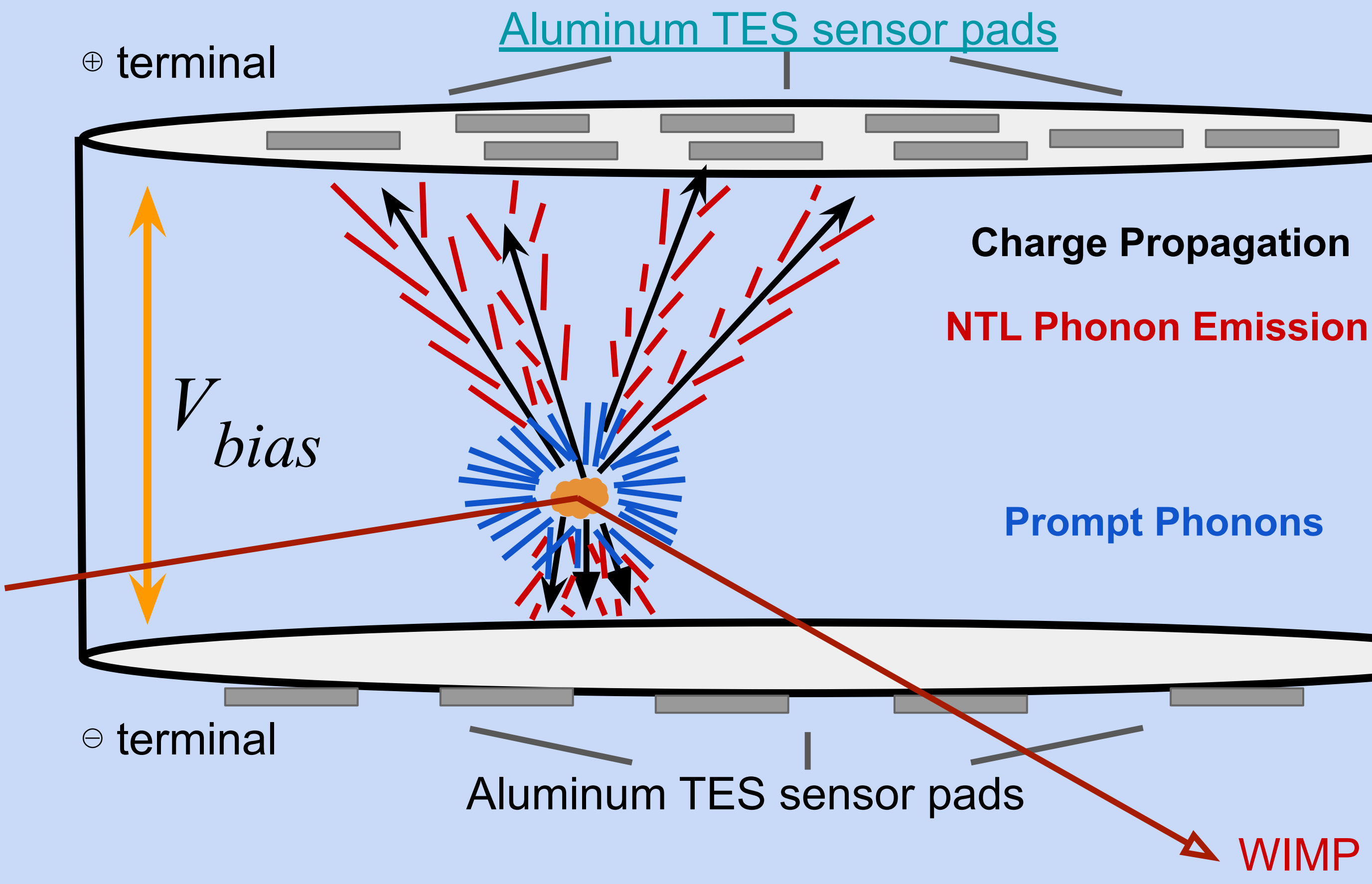
dE/dx vs. total energy has structure

- **Electron recoils** are pure dE/dx
- **Nuclear recoils** are NIEL deposits
- Bands due to nuclear excitations

Simulation reproduces Soudan data



# Detector Response



# Charge FET/HEMT Signals

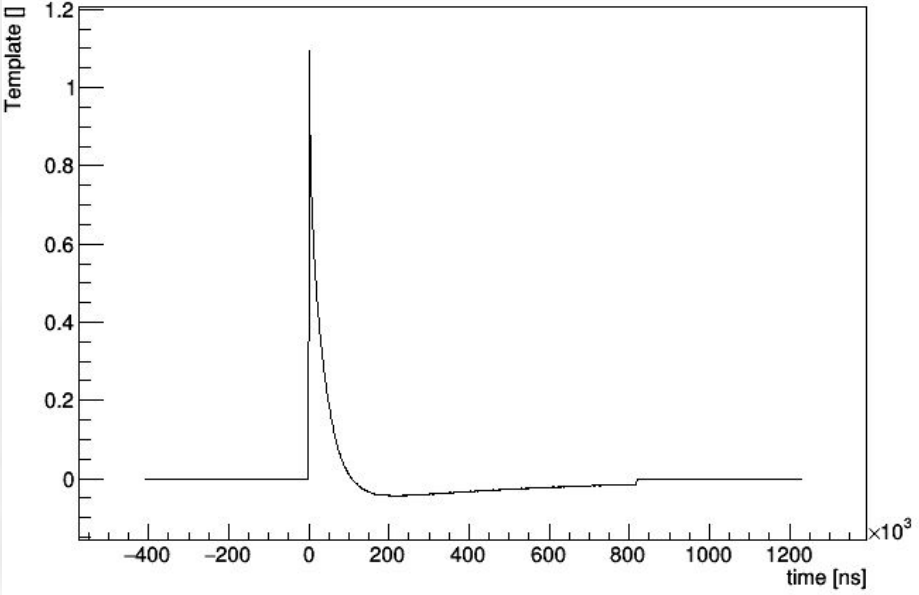
Particles incident on detector create electrons (-ve) and holes (+ve)

Voltage bias carries charges to electrodes on opposite sides

Spike proportional to total charge

Undershoot and tail due to readout circuit (RC components)

Crosstalk (+ or −) due to capacitance between channels



# Phonon QET Signals

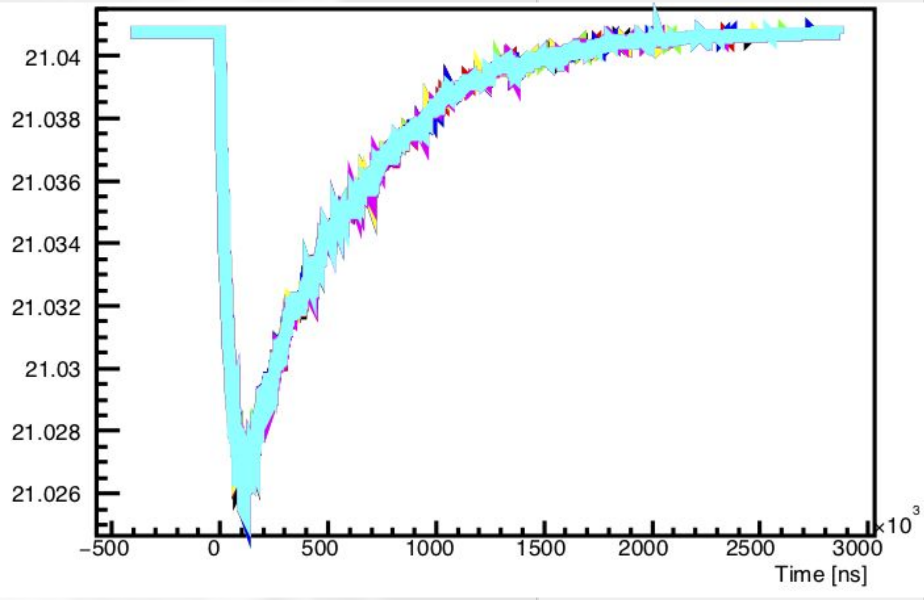
Charges gain energy in voltage, radiate phonons as they move

Phonons near surfaces arrive first, maximum after charges arrive

Long tail of late phonons “bouncing around” in detector

Integral measures total phonon energy

*Superconductor has less current when warm (after energy absorbed)*

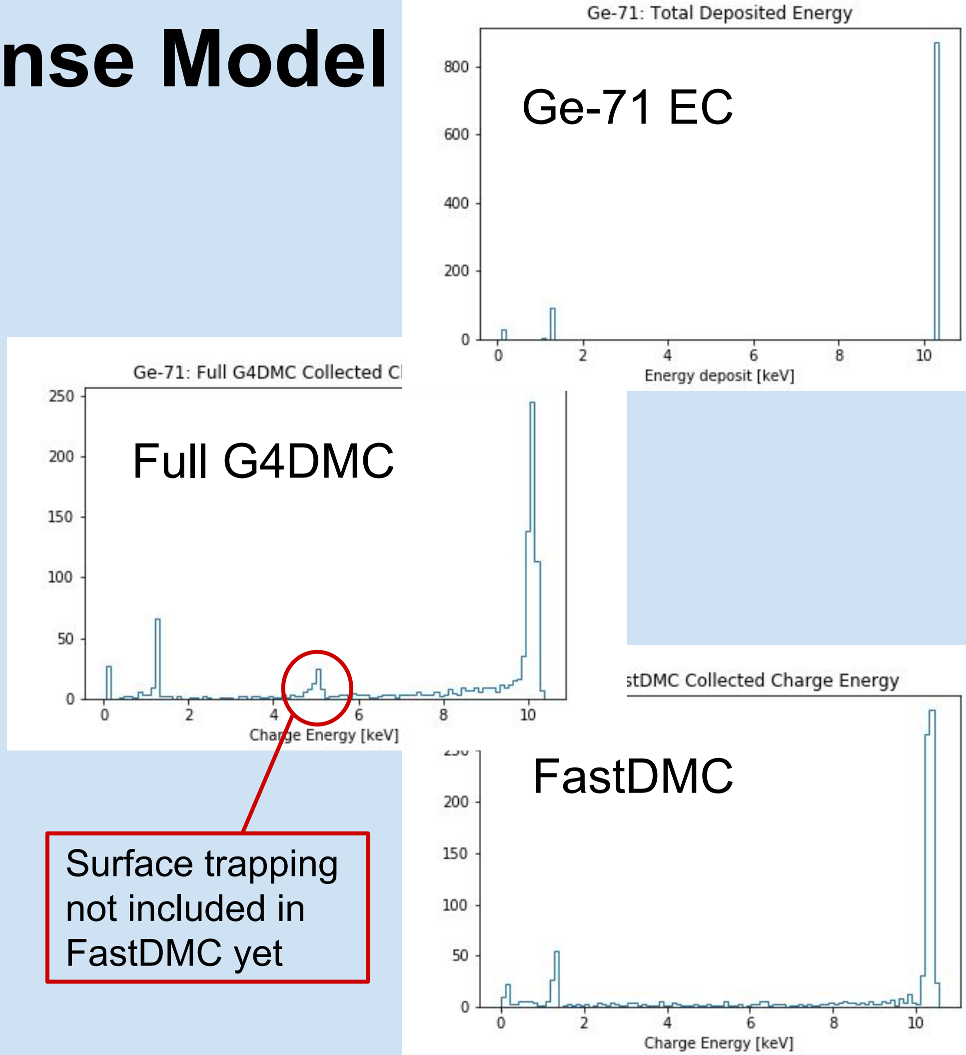


# Parameterized Response Model

Detector response simulation is extremely slow, tens of CPU minutes per event.

Parameterized model is much faster

- Functions fitted to full sim output
- Map energy deposits directly to phonon energy and charge collection by detector channels
- Generate readout traces by scaling preset shapes to energy

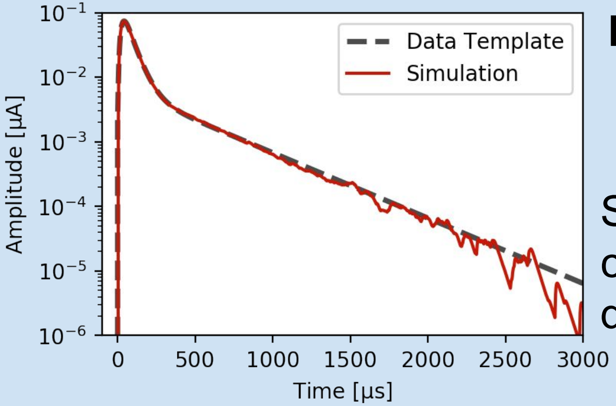


# Readout Emulation

Detector response output is "ideal" pulses, without noise and with physical-unit floating point values for each time bin

With noise spectra (PSDs or ASDs) for each detector, we generate "random traces" to add onto ideal pulses

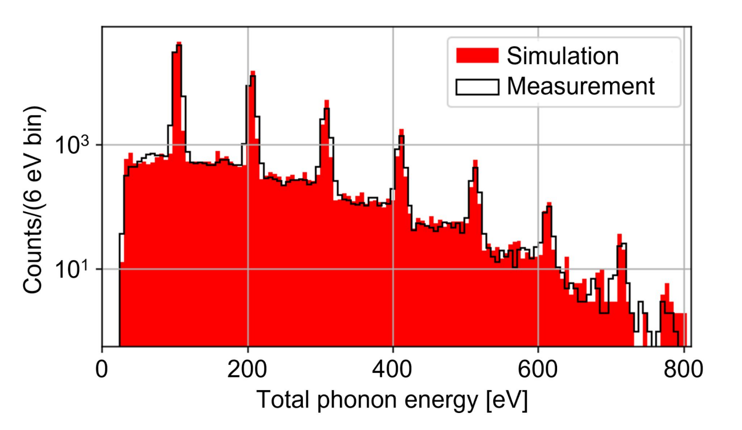
Data is written out in same format and structure as real data from experiment, including additional "random traces" representing random-trigger events



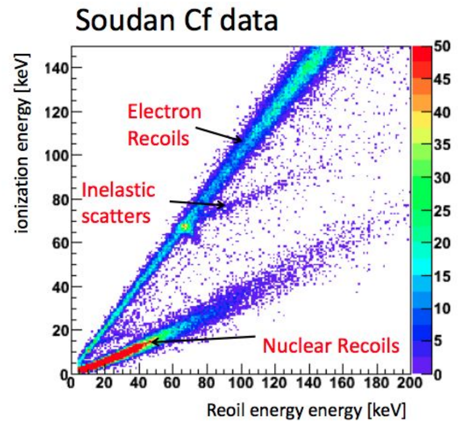

**HVeV R&D chip, 100V bias**
1.95 eV laser photons

Simulated phonon readout compared with averaged data traces

Energy spectrum showing individual e/h pairs, with charge trapping in between

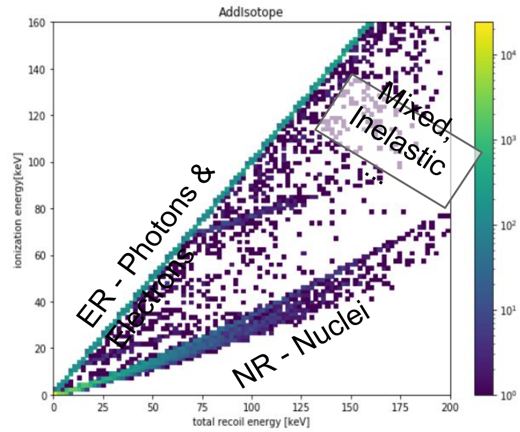



# Comparison With Data




**Cf-252 Source, SCDMS Soudan**
Inserted along cryogenic pipe

⟸ Reconstructed events compared with simulation ⟹ recoil energy vs. ionization



# Summary and Conclusions

SuperCDMS has developed a comprehensive simulation framework to model past experiments, the experiment under construction, test facilities and R&D devices

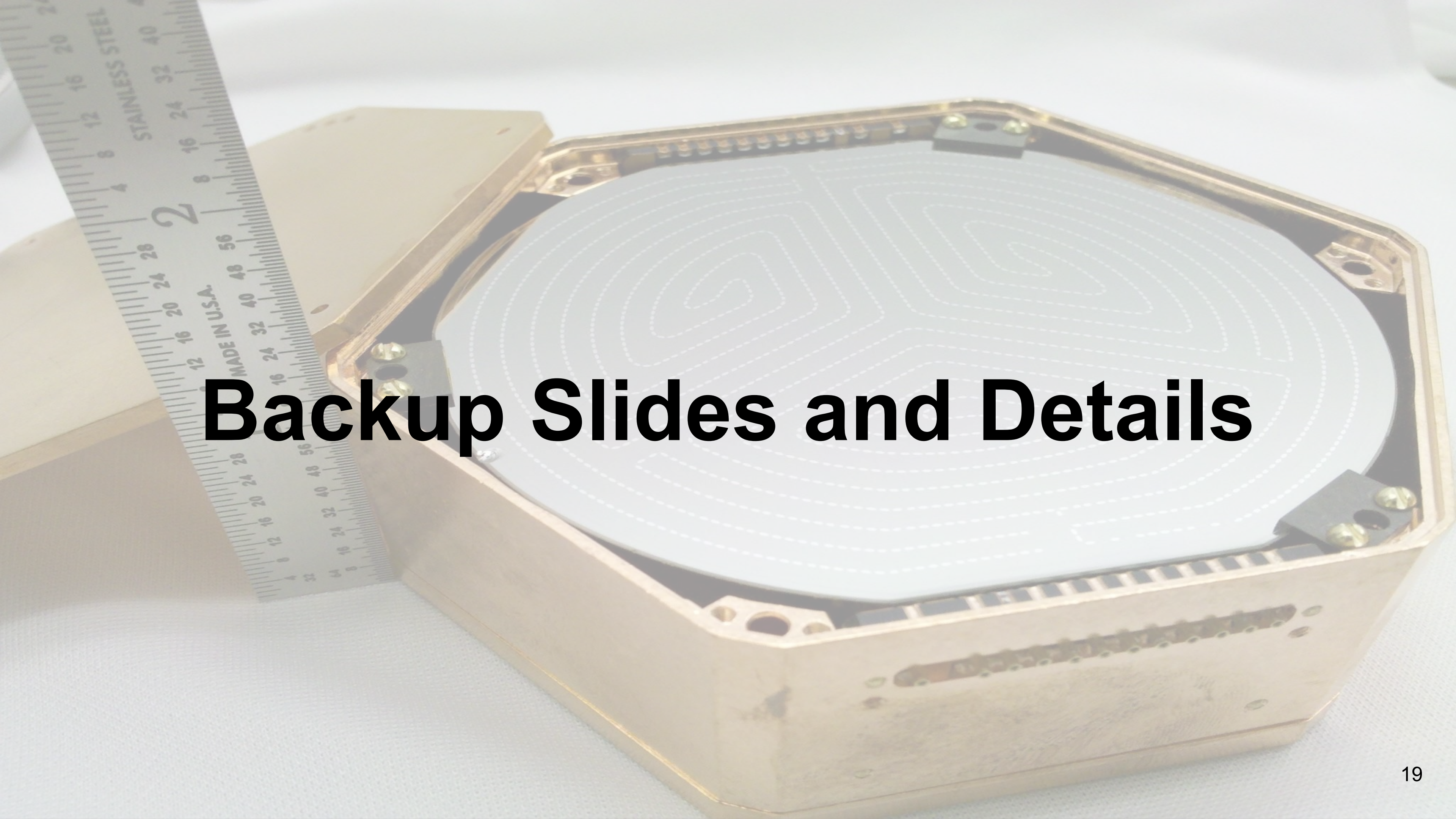
The complete data chain, from Geant4-generated events through detector readout signals in raw data format, and reconstruction of physics quantities, is simulated and available for analysis

Tens of billions of environmental background events have been generated, along with millions of full detector response events

Fidelity of simulation to real detectors is excellent

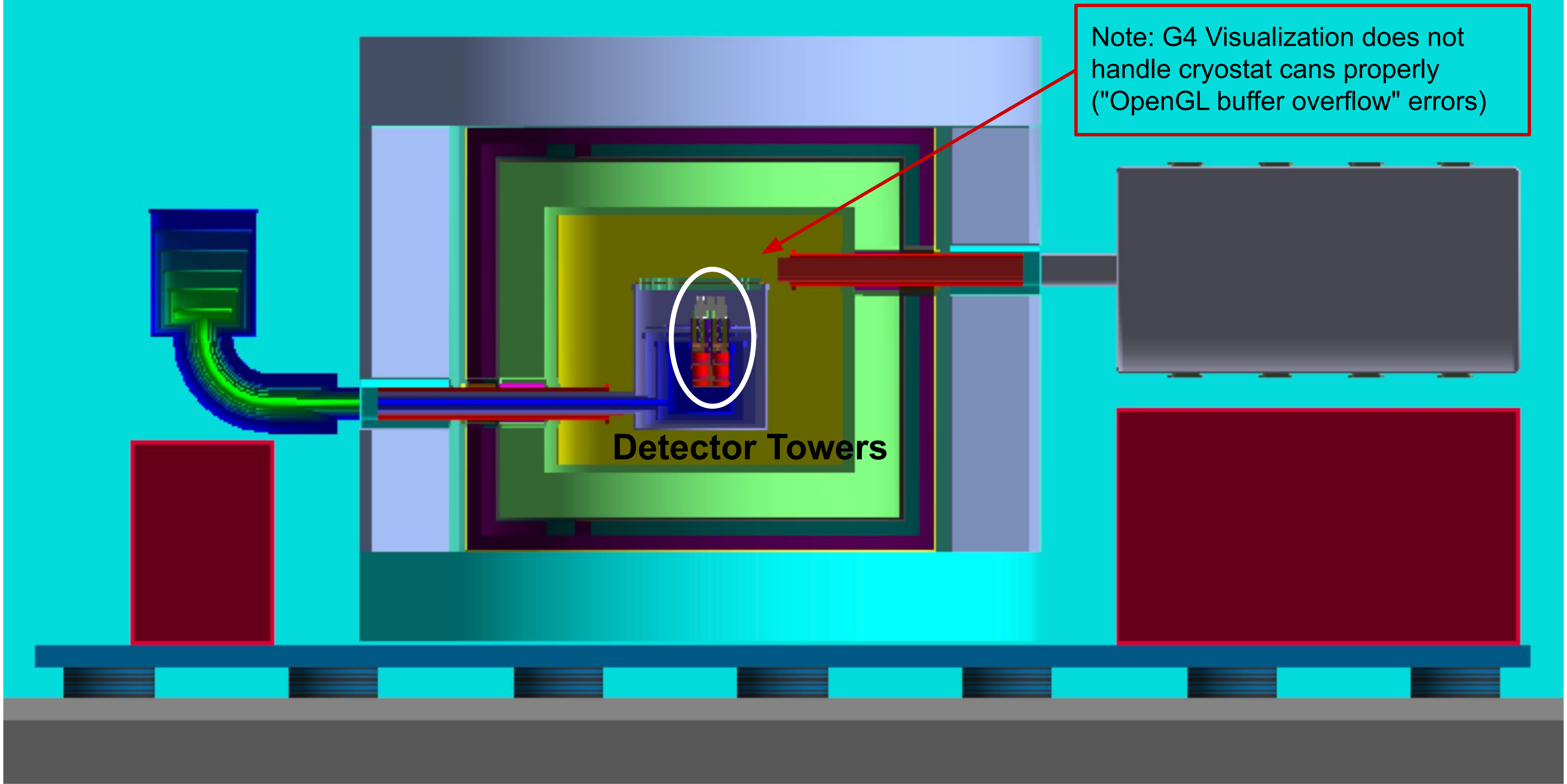

@SuperCDMS

supercdms.slac.stanford.edu




# Backup Slides and Details

# SuperCDMS Geometry in Simulation



# SuperCDMS Detectors

High purity single crystals, 100×33 mm thick, 0.6 (Si), 1.5 (Ge) kg

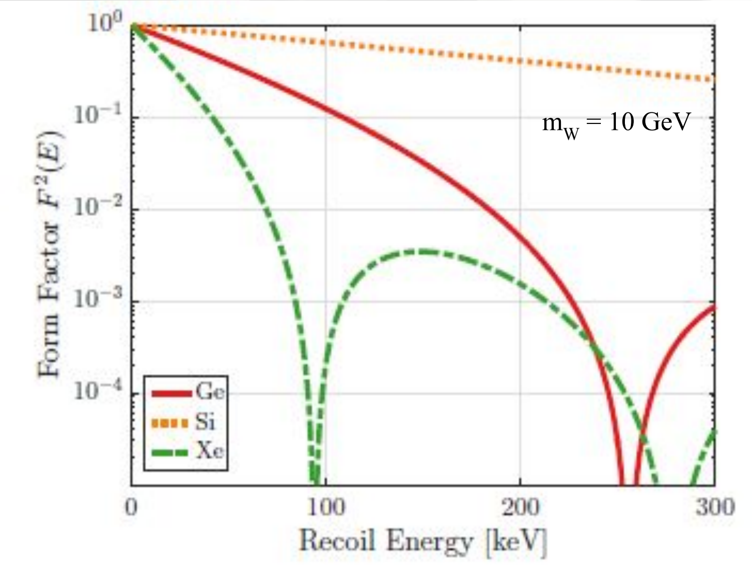
Precise crystal orientation, machined and polished dimensions

Some germanium, some silicon

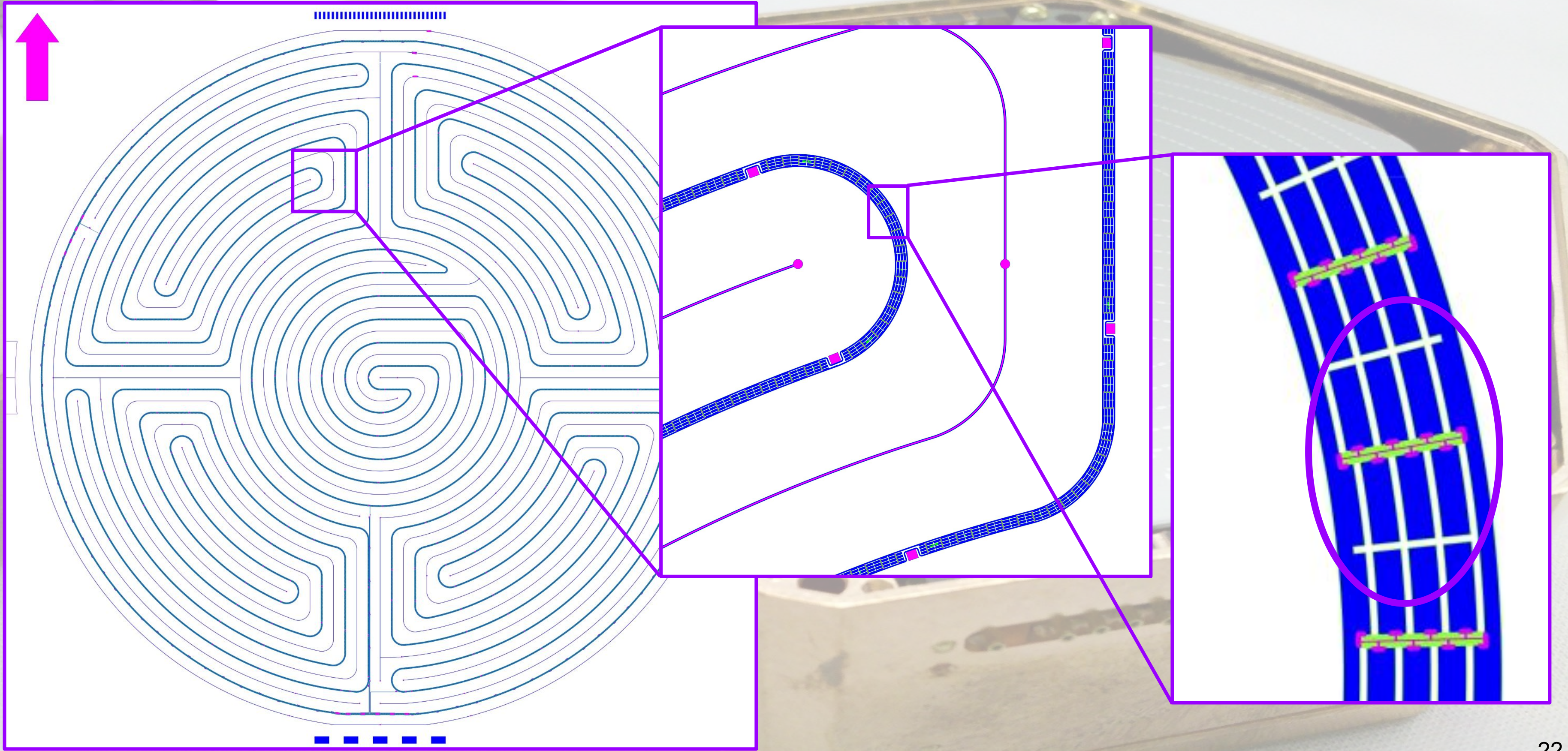
- Different atomic masses will produce different recoil signals
- Protons vs. neutrons, nuclear spin, may be sensitive to specific theoretical interactions

Cooled to 50 millikelvins

- Suppresses thermal noise
- Sensors and readout superconducting



# Detector Sensor Layout



SNOLAB iZIP7 with QETs

# SuperSim Example Configuration

```
/CDMS/Physics/DMC
/CDMS/Physics/ApplyProductionCuts true
/CDMS/Physics/ElectronCut 1 mm
/CDMS/Physics/PositronCut 1 mm
/CDMS/Physics/GammaCut 1 mm
/CDMS/Physics/HadronCut 1e-9 mm
/process/em/deexcitationIgnoreCut false

/g4cmp/samplingEnergy 200 eV
/g4cmp/maxLukePhonons 300000

/CDMS/Lab SNOLAB
/CDMS/Detector SNOLAB
/CDMS/UseShield
/CDMS/AlignToCavern
```

Physics

DMC

Geometry

```
/CDMS/Source calib
/CDMS/CalibSource/AddSpectrum Cf252N
/CDMS/CalibSource/Pipe cryo

/CDMS/updateGeom
/CDMS/TESSim/Enable
/CDMS/FETSim/Enable

/CDMS/writeFilePrefix VIEWS-demo
/CDMS/writeTrees true

/run/numberOfThreads 20
/run/autoSeed true
/run/printProgress 100
/run/beamOn 100000
```

Source

Readout

Output

# QET: SuperCDMS's "Enhanced" TES

***Q**uasiparticle trap assisted **E**lectrothermal feedback*
***T**ransition edge sensor*

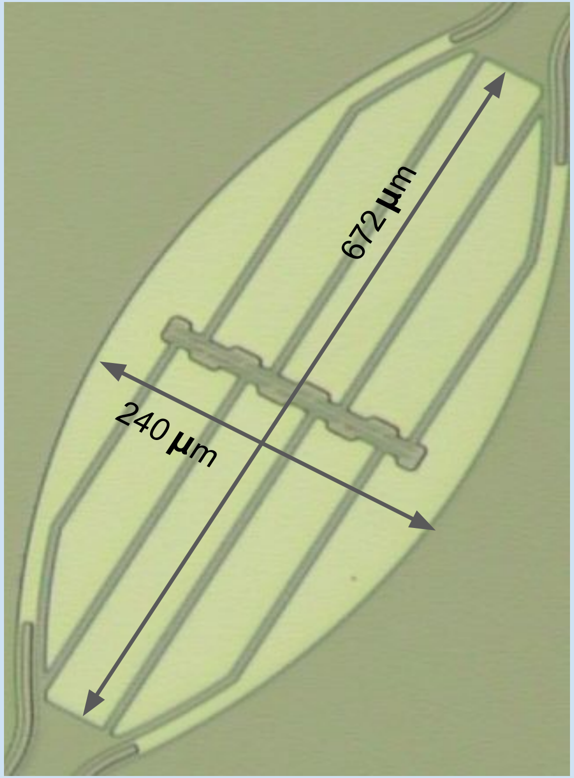
Absorbs phonons, produces change in current

Thin tungsten TES connected to readout lines

- On edge of superconducting transition
- Small δT ⇒ large δR ⇒ measurable δI

Attached to superconducting aluminum fins

- Phonons incident on Al break Cooper pairs
- Recombination re-emits phonons within Al
- Energy transfers into TES, raises temperature



# Phonon Readout Model

Phonon energy deposit collected in time bins, matching readout

Coupled differential equations model electrothermal response of TESes, bias current, inductive (SQUID) coupling, etc.

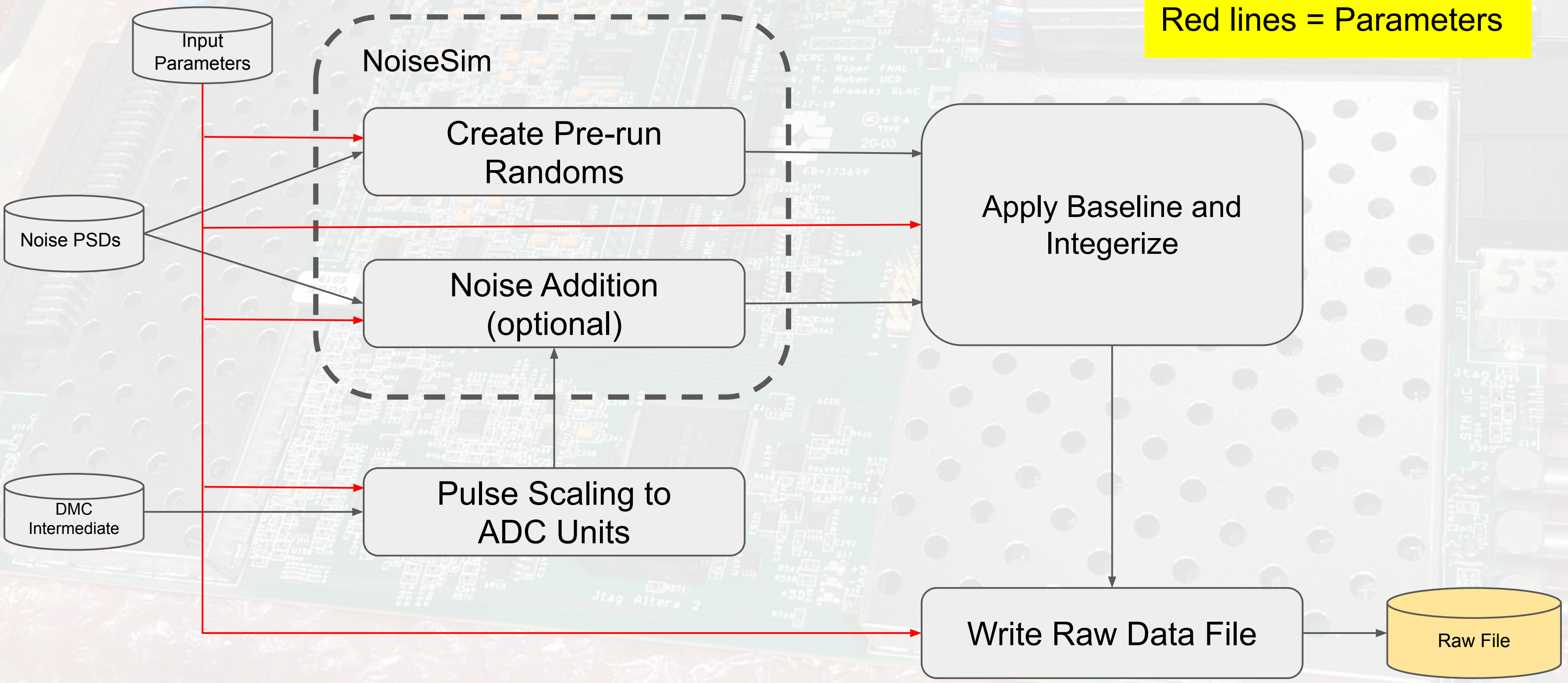
Use CVODE (from LLNL) to solve for current output in each time bin

Configuration files specify detector components, characteristics

- Heat flow, resistances inductance, TESes per channel, etc.

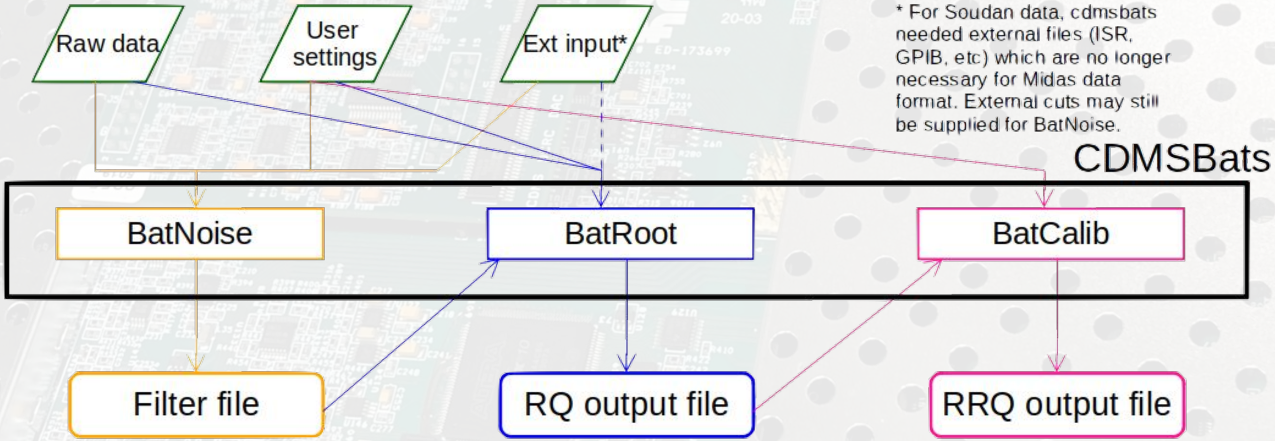
# Readout Emulation

Black lines = Data
Red lines = Parameters



# Event Reconstruction

Same reconstruction software is used to process real experiments' data and simulation output




Directly comparable results: simulation can be optimized to match observed performance of real detectors