Stefan Zatschler on behalf of SuperCDMS

University of Toronto

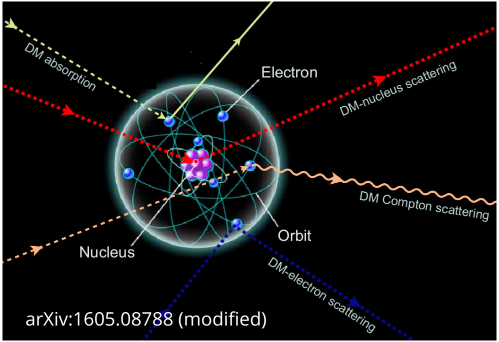
Modeling cryogenic Dark Matter detectors for SuperCDMS

CAP Congress 2023 // Fredericton, June 22nd 2023

Dark Matter direct detection

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

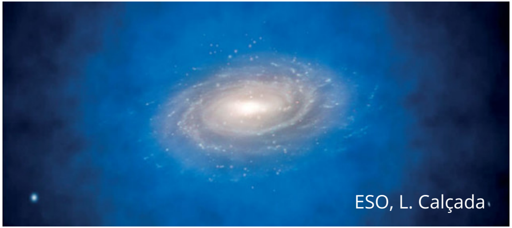
- **Any observable interaction counts!**
  - NR = nuclear recoil
  - ER = electronic recoil

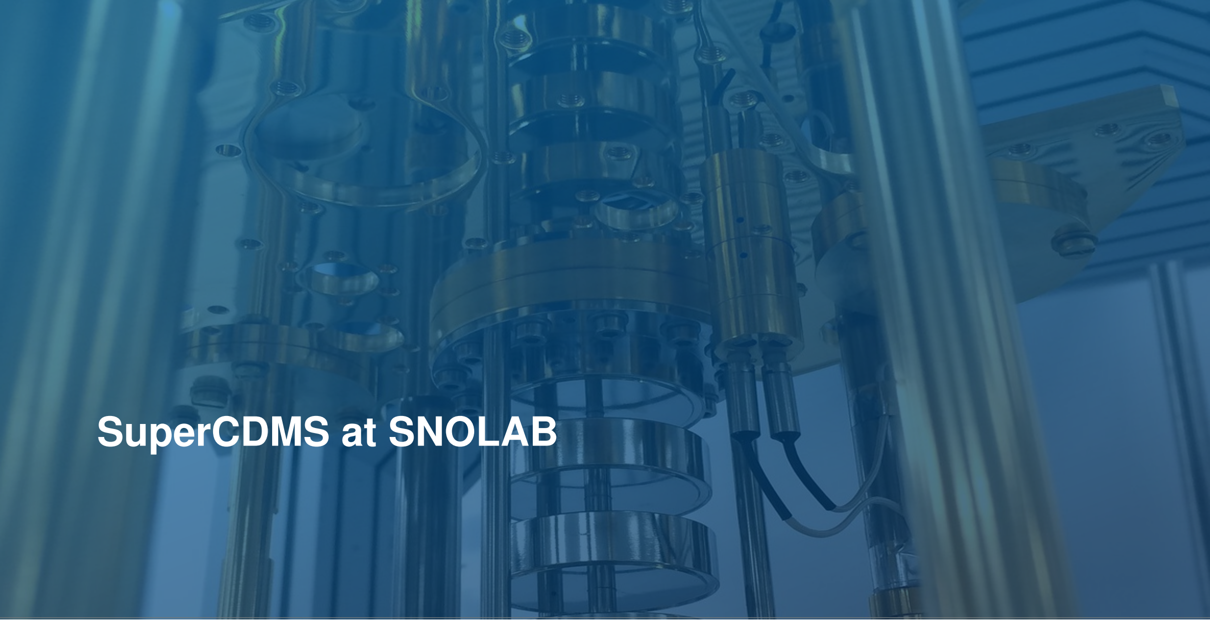


arXiv:1605.08788 (modified)

Estimate of DM flux on Earth

→ **110 000 DM particles per cm² per s**
- DM Density: 0.3 GeV/cm³
- DM Mass: 60 GeV
- Relative velocity: 220 km/s


ESO, L. Calçada

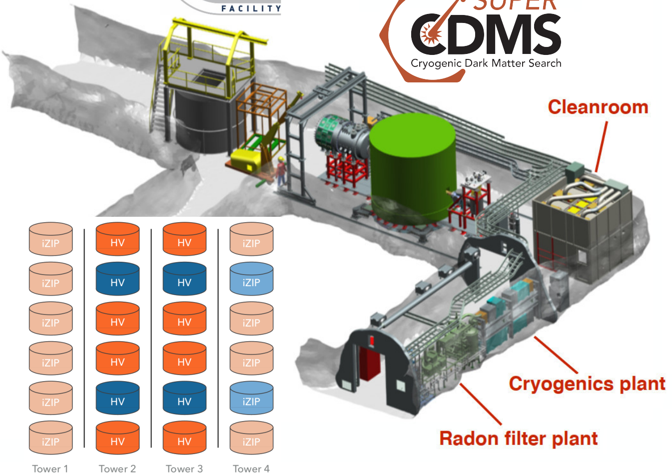


SuperCDMS at SNOLAB

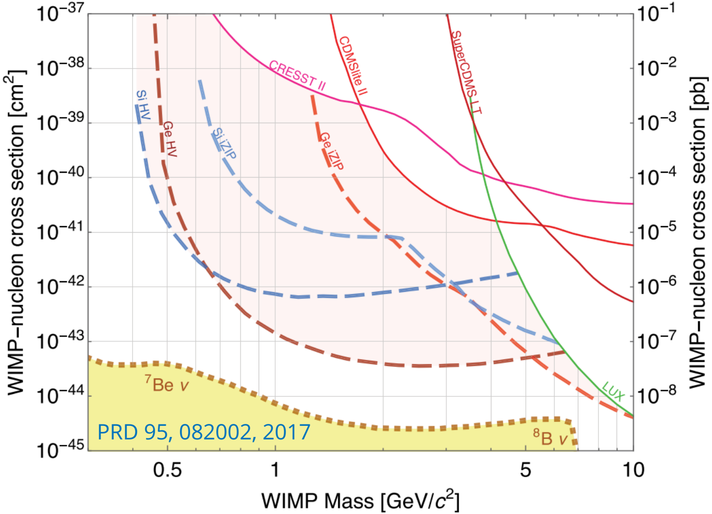
SuperCDMS at SNOLAB

- **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
  - Complementary science reach
- Collaboration with **CUTE**
  - **C**ryogenic **U**nderground **TE**st facility

SuperCDMS infrastructure being installed right now!



SuperCDMS science reach



- Aiming for **world-leading sensitivity** to low-mass WIMPs
- Complementary target materials and detector technologies
  - **iZIP:** NR/ER discrimination → background studies
  - **HV:** low-threshold → low-mass sensitivity

Challenges

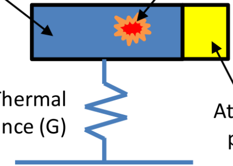
- Understanding detector response down to semiconductor bandgap
  - Crystal physics
  - Sensor response

SuperCDMS detector technology

How to measure Dark Matter interactions?

Setting: Low-energy deposit of DM particle recoiling on detector lattice

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



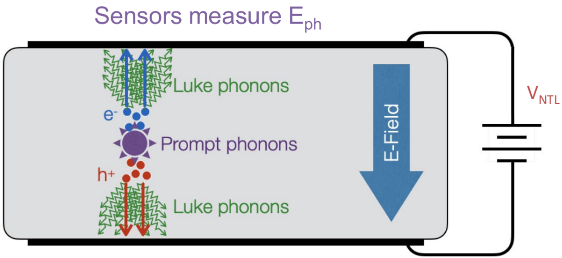
Signal formation

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

How to measure Dark Matter interactions?

Setting: Low-energy deposit of DM particle recoiling on detector lattice

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



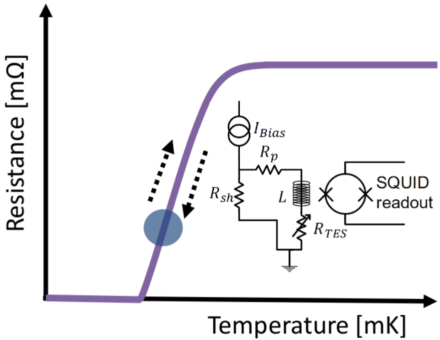
Signal formation

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

How to measure Dark Matter interactions?

Setting: Low-energy deposit of DM particle recoiling on detector lattice

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



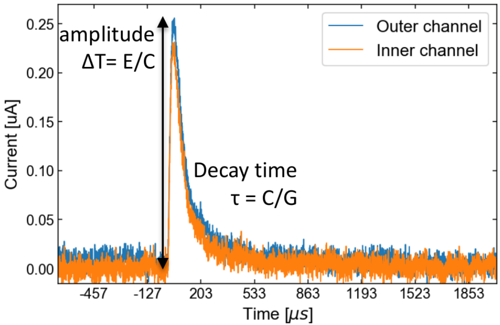
Signal formation

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

How to measure Dark Matter interactions?

Setting: Low-energy deposit of DM particle recoiling on detector lattice

- Cryogenic calorimeters at temperatures $\sim$ 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 NTL phonons
  - Signal amplification
  - Sensitivity to single e^-/h^+ pairs
- Phonon collection with TES
  - Pulse reconstruction
  - Measure of energy deposit

SuperCDMS detectors

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

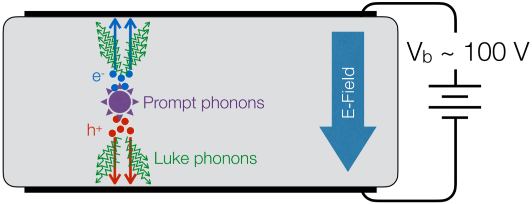
$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$

E_t: total phonon energy; E_r: primary recoil energy; $N_{eh} \cdot e \cdot V_b$: Luke phonon energy

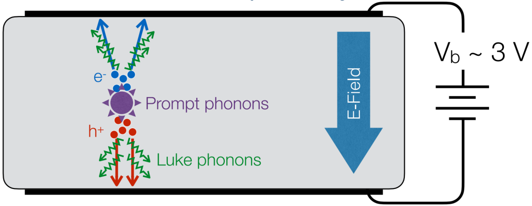
iZIP detector → low background

- **I**nterleaved **Z**-sensitive **I**onization and **P**honon detector
- Prompt phonon and ionization signals allow for NR/ER event discrimination

Sensors measure E_t



Sensors measure E_t and N_{eh}



SuperCDMS detectors

HV detector → low threshold

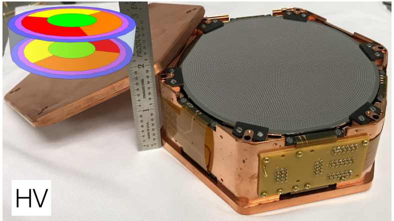
- Drifting charge carriers (e^-/h^+) across a potential (V_b) generates a large number of Luke phonons (NTL effect)
- Trade-off: no NR/ER discrimination

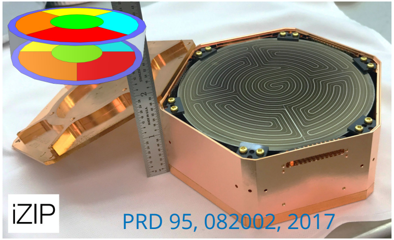
$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$

E_t: total phonon energy; E_r: primary recoil energy; $(N_{eh} \cdot e \cdot V_b)$: Luke phonon energy

iZIP detector → low background

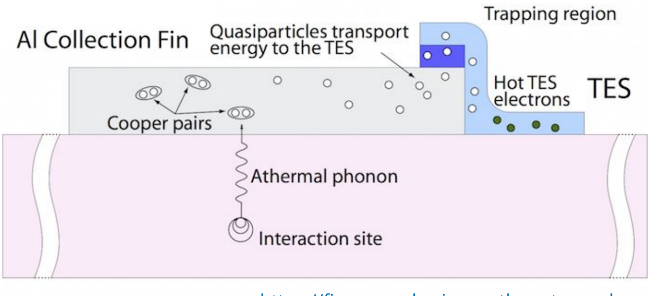
- **I**nterleaved **Z**-sensitive **I**onization and **P**honon detector
- Prompt phonon and ionization signals allow for NR/ER event discrimination



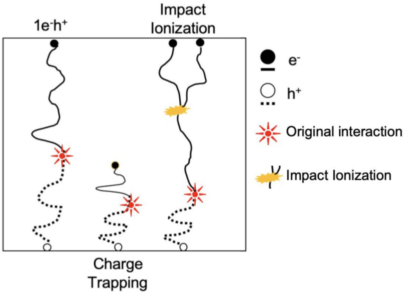


SuperCDMS phonon sensor – QET

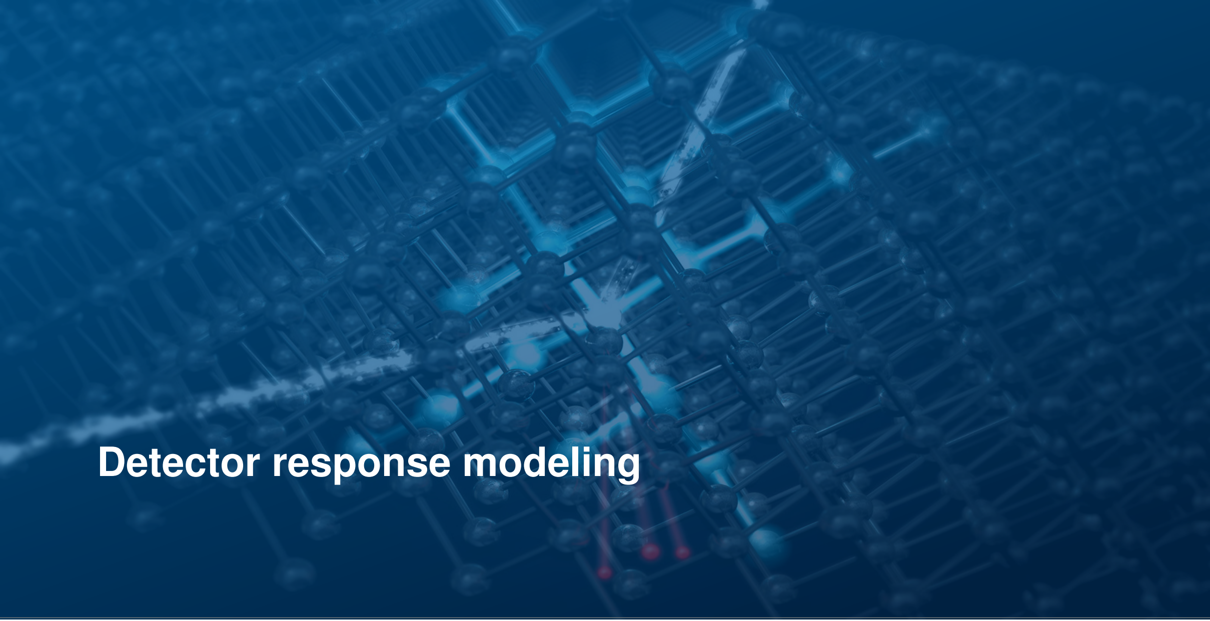
QET – **Q**uasiparticle trap assisted **E**lectrothermal feedback **T**ransition edge sensor



https://figueroa.physics.northwestern.edu

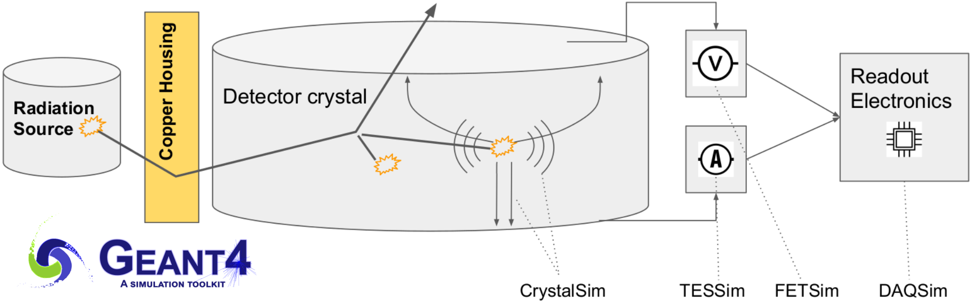


- **Sophisticated GEANT4-based framework** to model crystal and sensor response
  - **Crystal dynamics:** lattice definition, charge and phonon scattering, etc.
  - **Impurity effects:** Charge Trapping, Impact Ionization
  - **TES configuration:** physical layout, circuitry and electro-thermodynamics



Detector response modeling

Detector response modeling with G4DMC



- Particle tracking with GEANT4 application (*SourceSim*)
  - Modeling of condensed matter physics with **G4CMP** (available on GitHub)
- Detector response = *SourceSim* + *CrystalSim* + *TESSim/FETSim* + *DAQSim*
- **Goal:** Same reconstruction path for real and simulated data!

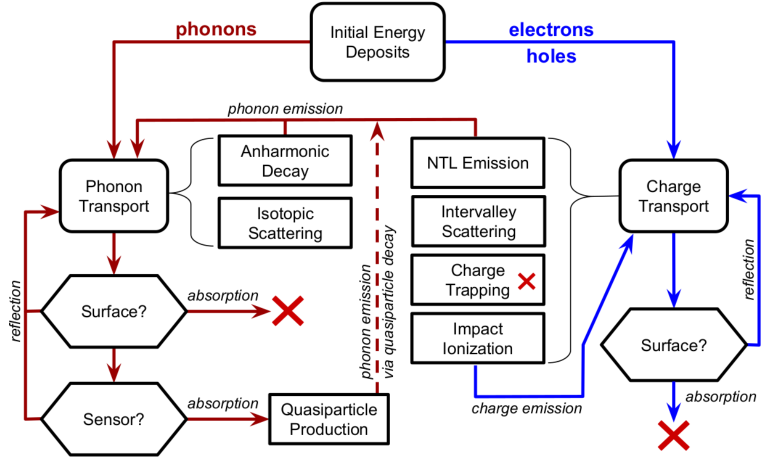
G4CMP: Physics processes

G4CMP – **C**ondensed **M**atter **P**hysics library for GEANT4

1) **Production of e^-/h^+ pairs and phonons from $\mathcal{O}$(keV) GEANT4 energy deposits**
2) **Transport** of **eV-scale** (conduction band) **electrons and holes** in crystals
   - Anisotropic transport of electrons
   - Scattering, phonon emission (NTL), charge trapping, impact ionization
3) **Transport** of **meV-scale** (acoustic) **phonons** in deeply cryogenic crystals
   - Mode-specific relationship between wave vector and group velocity
   - Impurity scattering (mode mixing), anharmonic decays
4) **Sensor modeling** (SuperCDMS example: QET)
   - User application implements phonon collection
   - Phonons incident on QET trigger thin-film simulation (*G4CMPKaplanQP*)

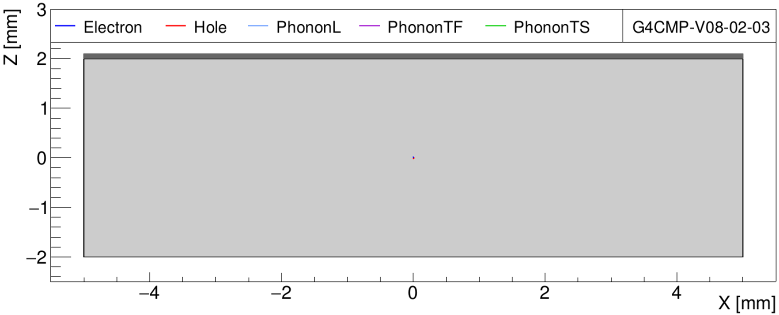
More details: arXiv:2302.05998 (accepted by NIM A)
Source code: https://github.com/kelseymh/G4CMP

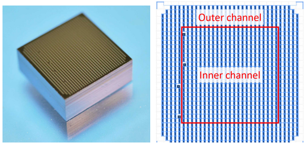
G4CMP: Event processing flow



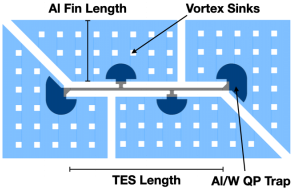
arXiv:2302.05998

SuperCDMS Si-HVeV prototype modeling



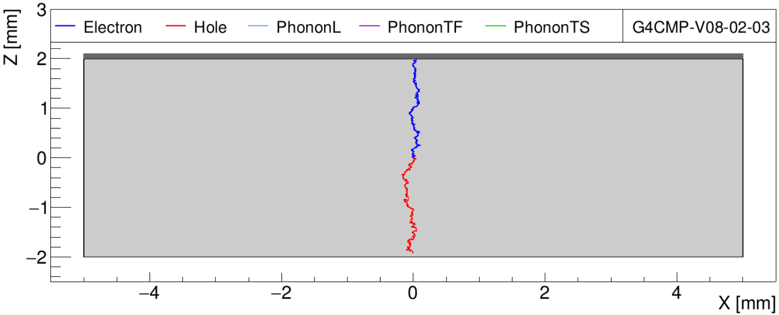


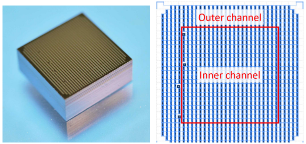
PRD 104, 032010 (2021)



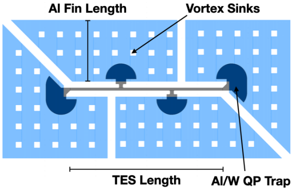
- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About ∼5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About ∼50k phonon tracks with $\mathcal{O}(100) - \mathcal{O}(1000)$ steps each (mainly surface reflections)

SuperCDMS Si-HVeV prototype modeling



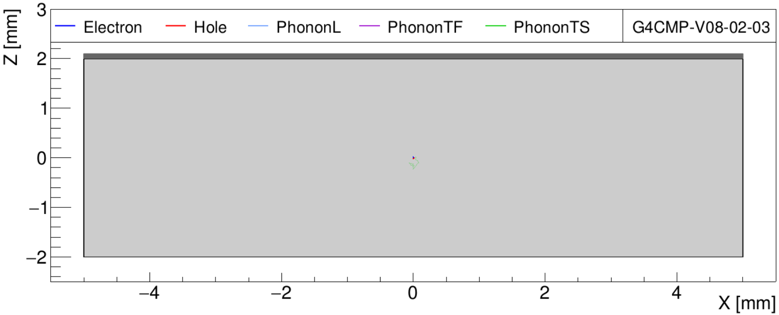


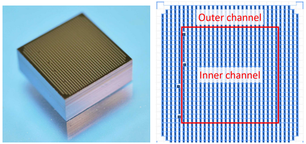
PRD 104, 032010 (2021)



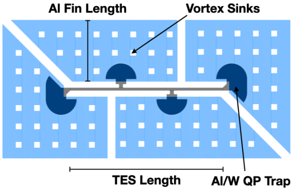
- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About ~5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About ~50k phonon tracks with $\mathcal{O}(100) - \mathcal{O}(1000)$ steps each (mainly surface reflections)

SuperCDMS Si-HVeV prototype modeling



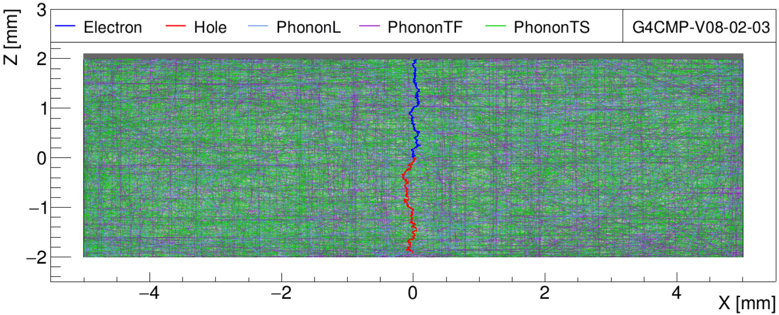


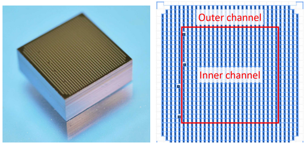
PRD 104, 032010 (2021)



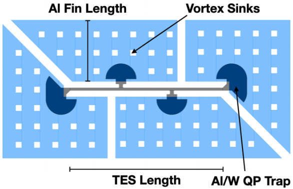
- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About $\sim$5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About $\sim$50k phonon tracks with $\mathcal{O}(100) - \mathcal{O}(1000)$ steps each (mainly surface reflections)

SuperCDMS Si-HVeV prototype modeling



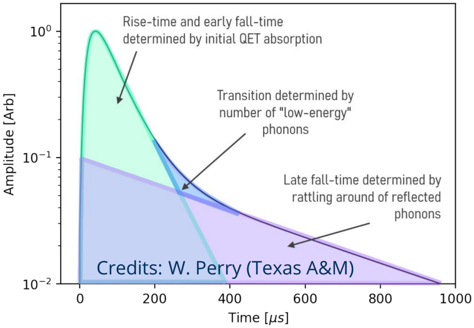


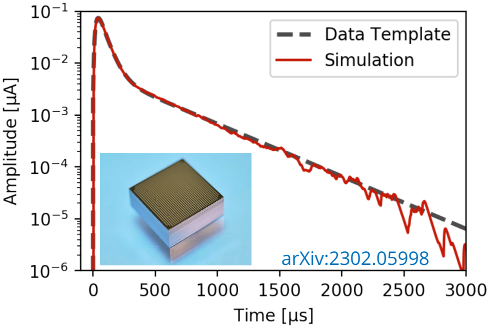
PRD 104, 032010 (2021)



- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About $\sim$5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About $\sim$50k phonon tracks with $\mathcal{O}(100) - \mathcal{O}(1000)$ steps each (mainly surface reflections)

G4DMC parameter tuning for Si-HVeV

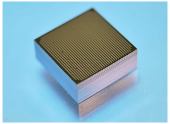


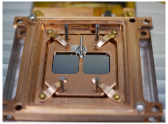


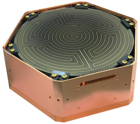
- **Goal:** Match experimental phonon pulse template with G4DMC simulation
- Multi-dimensional parameter tuning of *CrystalSim* + *TESSim*
  - TES characteristics (T_C, T_W, circuitry), impurity densities, etc.
- Ongoing data-taking runs at test facilities (CUTE, NEXUS)
  - SuperCDMS detector tower testing at CUTE is just around the corner!

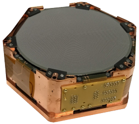
Summary

- **Detector response modeling** is crucial for understanding SuperCDMS' sensitivity
  - Sophisticated Detector Monte-Carlo framework based on GEANT4 and G4CMP
  - Successful DMC parameter tuning using prototype Si-HVeV detector data
  - G4CMP technical paper: arXiv:2302.05998 (accepted by NIM A)
- **Outlook**
  - Analysis of latest Si-HVeV data taken at test facilities is ongoing
  - Moving to more complex SuperCDMS SNOLAB detectors (iZIP, HV)









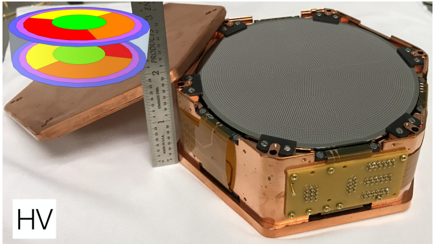
SuperCDMS Collaboration Meeting @ UofT

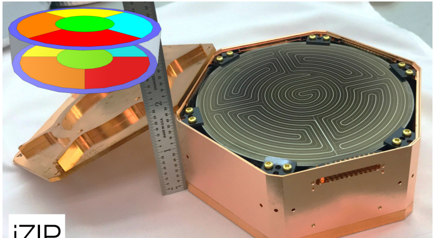
@SuperCDMS   supercdms.slac.stanford.edu

Appendix

SuperCDMS detectors: Ge/Si HV & iZIP

- **Made of high-purity Ge and Si crystals**
  - **Si detectors** (0.6 kg each) provide sensitivity to **lower DM masses**
  - **Ge detectors** (1.4 kg each) provide sensitivity to **lower DM cross-sections**
- **Low operation temperature: ∼ 15 mK**
  - Phonon measurement with TESs (HV, iZIP)
  - Ionization measurement with HEMTs (iZIP)
- **Two-sided readout** with multiple channels to identify **event position**

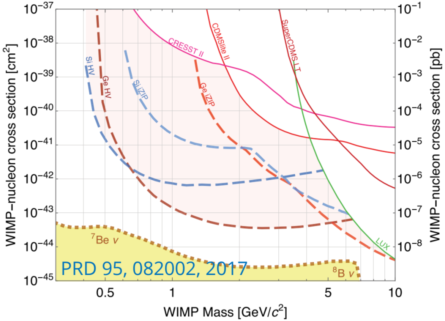


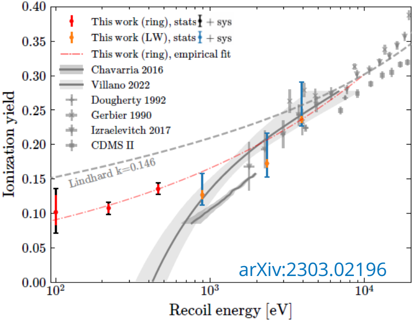


PRD 95, 082002, 2017

Science reach of SuperCDMS – Challenges

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





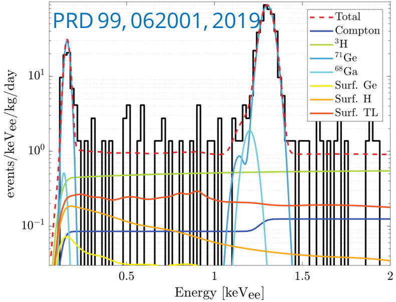
Driving questions:

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

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 backgrounds from NR signal region