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Status and prospects of the SuperCDMS Dark Matter experiment

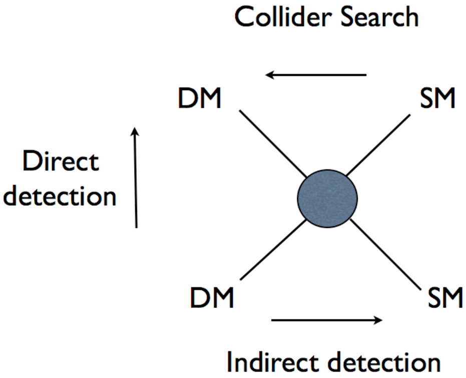
GUINEAPIG 2024 // Toronto, August 20th 2024

Outline

- Direct detection in a nutshell
- SuperCDMS at SNOLAB
- Detector technology
- Science strategy
- Summary & Takeaways

Direct detection in a nutshell

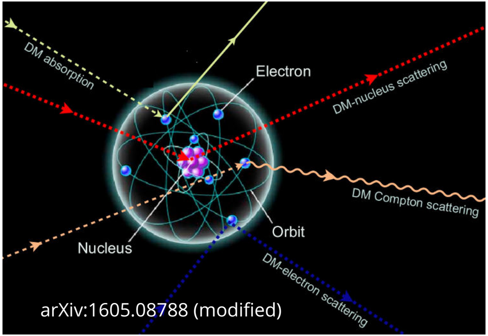
How to search for Dark Matter?



Three common ways to look for DM:

- **Collider search**
  - DM production in SM interactions
  - Signal: "missing" momentum (p_T, E_T)
- **Indirect detection**
  - DM annihilation into SM particles
  - Signal: Excess in cosmic rays (e^+, p, γ-rays)
- **Direct detection**
  - DM scattering off of target (atoms)
  - Signal: nuclear / electronic recoil (NR / ER)
  - Challenge: $\mathcal{O}$(eV–keV) of recoil energy
  - Any observable interaction counts!

How to search for Dark Matter?



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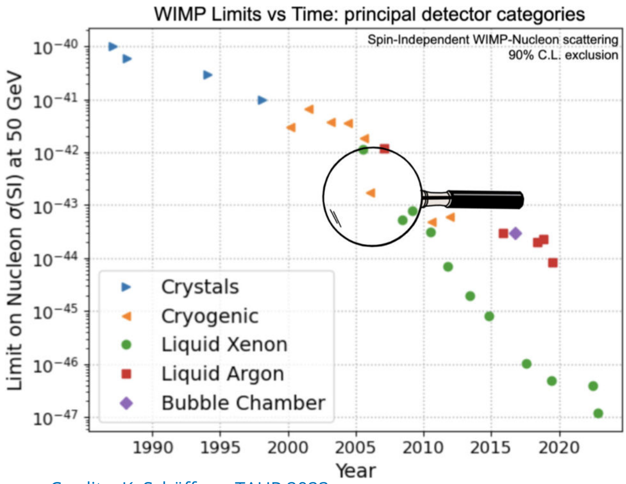
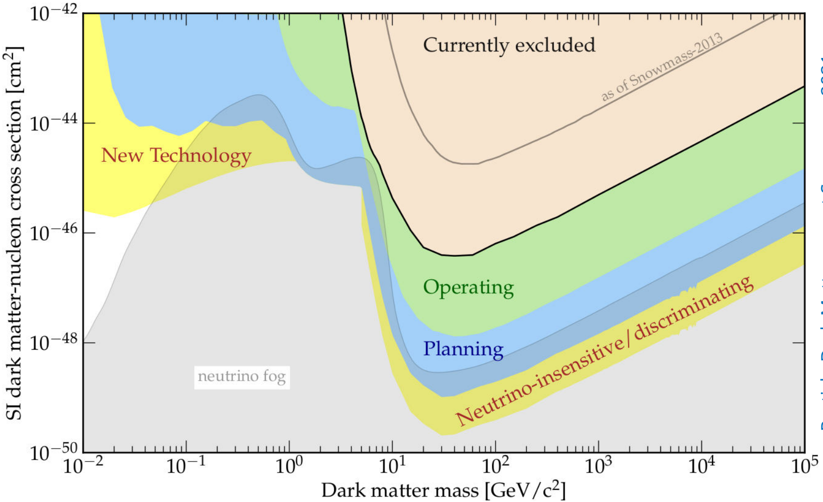
A brief flash of history



Credits: K. Schäffner, TAUP 2023

- **Crystal and cryogenic detectors** started the "WIMP hunt" more than 30 years ago
  - NaI: DAMA (DM modulation claim)
  - Ge/Si: CDMS-II, SuperCDMS
  - Ge: Edelweiss, CDMS, CDMSlite
- **Breakthrough:** particle discrimination in cryogenic detectors
  - Combine detection channels (e.g. charge + heat, light + heat)
  - Powerful background suppression
- **Up-scaling of target mass**
  - Xe: XENON-1T, LZ
  - Ar: DarkSide, DEAP

The "Big Picture"

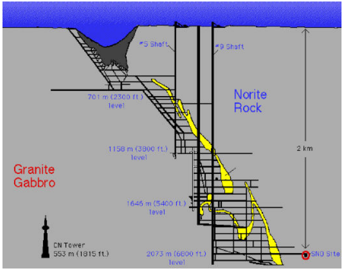


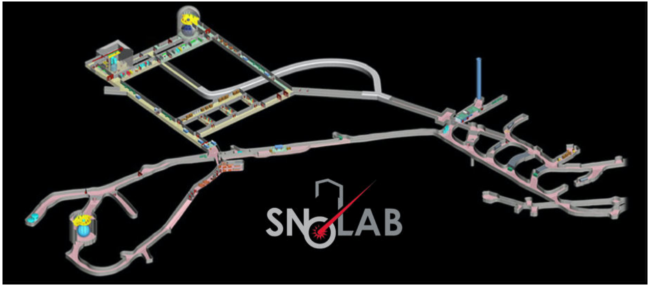
Particle Dark Matter report Snowmass 2021

SuperCDMS at SNOLAB

SNOLAB infrastructure

- Rock overburden of 2 km (6000 m.w.e.)
  - Cosmic muon flux reduced by 50 million
- Large lab space ($\sim$ 5000 m^2)
  - Cleanroom (class 2000 or better)
  - Surface facilities with support staff (>100)

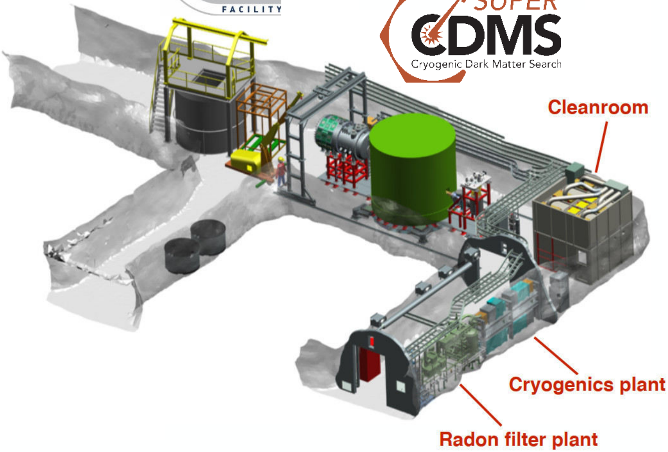




SuperCDMS at SNOLAB

- **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!
- Close collaboration with **CUTE**
  - **C**ryogenic **U**nderground **TE**st facility (open to proposals!)
- **Concluded HV tower testing**
  - See Yan Liu's talk from today

SuperCDMS infrastructure is under construction!



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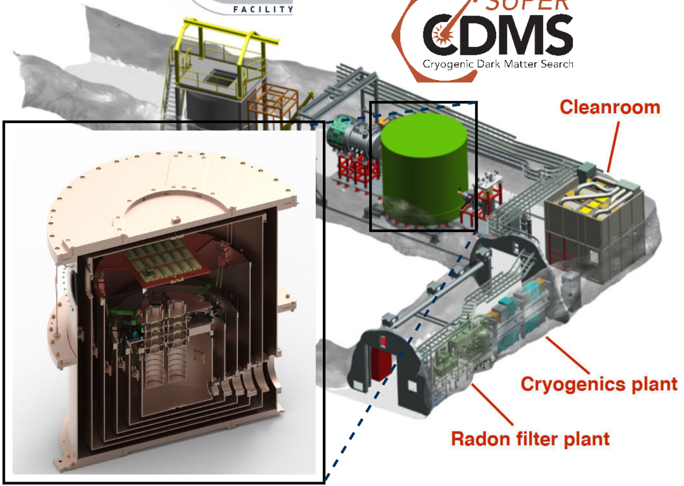

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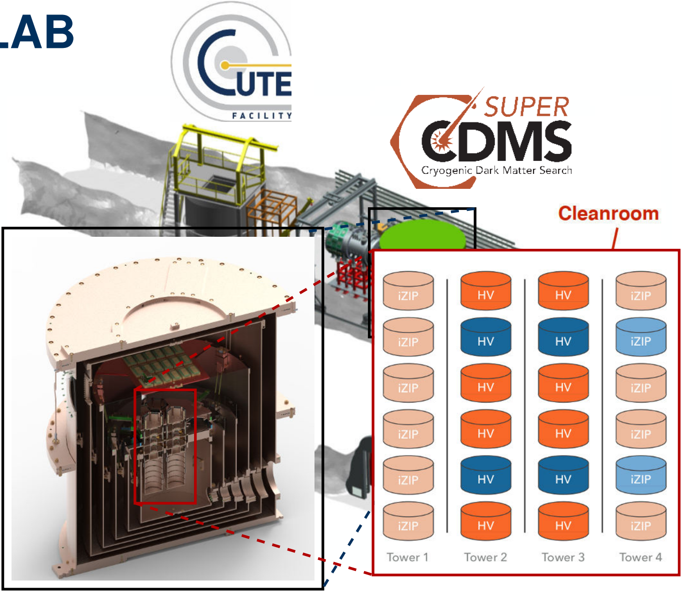
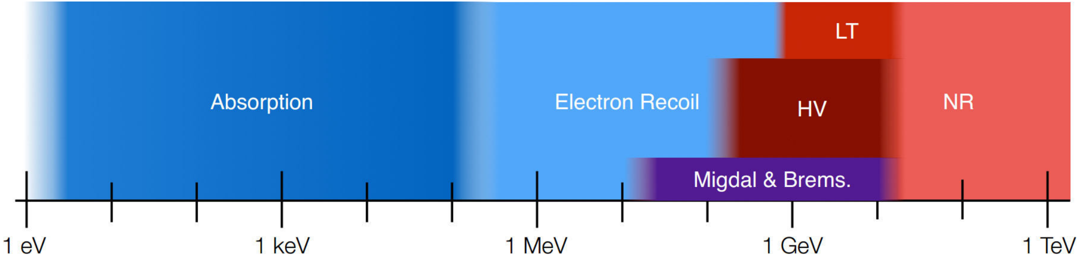


SuperCDMS: A broadband DM search

Absorption (Dark Photon, ALP):	$\sim$ 1 eV – 0.5 MeV	peak search (HV)
Electron Recoil (ER):	$\sim$ 0.5 MeV – 10 GeV	no NR/ER discrim. (HV)
Migdal & Bremsstrahlung:	$\sim$ 0.01 – 10 GeV	no NR/ER discrim. (HV + iZIP)
HV Detector (LT, NR):	$\sim$ 0.3 – 10 GeV	no NR/ER discrim. (HV)
Low Threshold (LT) NR:	$\gtrsim$ 1 GeV	limited NR/ER discrim. (iZIP)
Traditional Nuclear Recoil (NR):	$\gtrsim$ 5 GeV	full NR/ER discrim. (iZIP)



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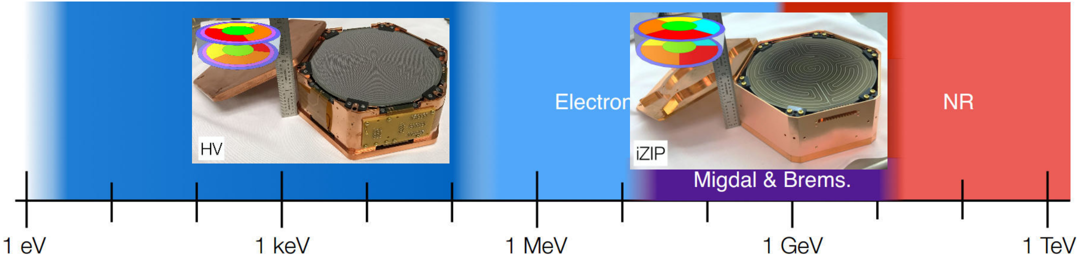
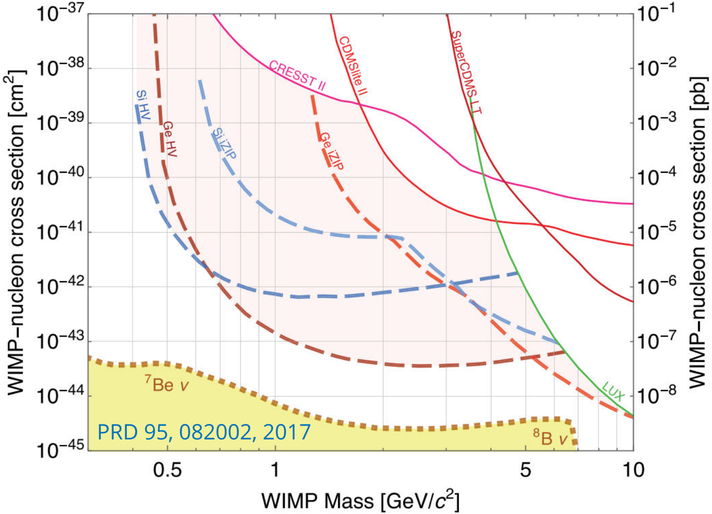


SuperCDMS science reach



- Aiming for **world-leading sensitivity** to sub-GeV DM
- **Unique approach** with complementary detector designs
  - **Ge/Si iZIP & HV detectors**
  - **iZIP:** NR/ER discrimination $\rightarrow$ background studies
  - **HV:** low-threshold $\rightarrow$ low-mass sensitivity

Challenges

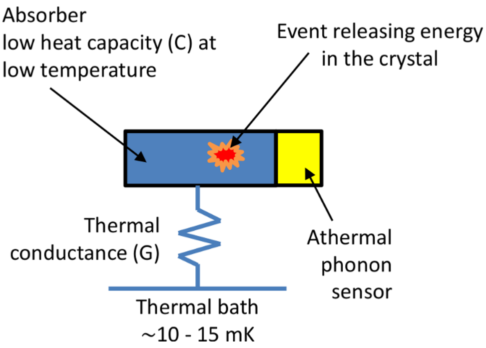
- Understanding detector response down to semiconductor bandgap
  - Dominating backgrounds
  - Low-energy calibration
  - Detector response modeling

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 Luke phonons
  - Signal amplification
  - Sensitivity to single e^-/h^+ pairs
- Phonon collection with TES
  - Pulse reconstruction
  - Measure of energy deposit

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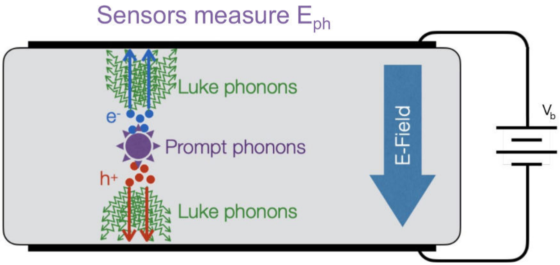

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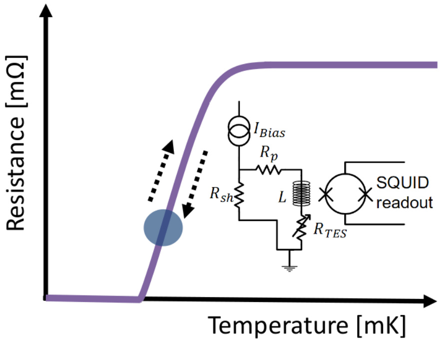

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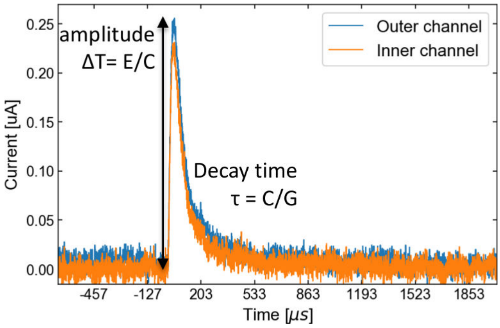

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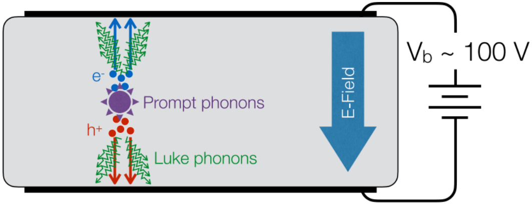
SuperCDMS detectors

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

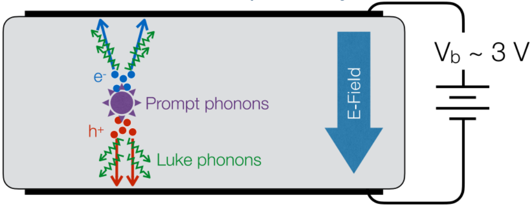
$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$

total phonon energy — primary recoil energy — 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



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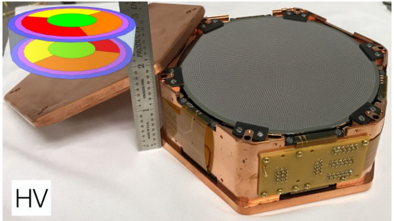
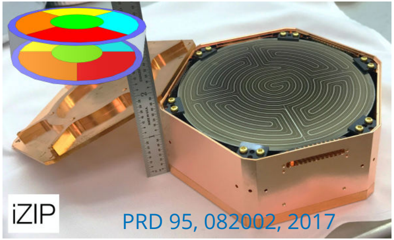




PRD 95, 082002, 2017

Science strategy

Science strategy

SuperCDMS main experiment

- **Installation activities at SNOLAB**
  - Concludes 10 years of engineering work!
- **Background projection and modeling**
  - Material assaying and Rn monitoring
  - Simulate contaminants, cosmogenics, etc.
- **Signal modeling** (NRDM, ERDM, LIPs, ...)
- Data handling and data provenance
- **HV tower testing at CUTE**
  - See Yan Liu's talk from this morning
  - Performance, calibration, experience, ...

SuperCDMS is finally getting ready for commissioning and data-taking!

Detector R&D

- Focus on HVeV detectors with athermal phonon readout (see highlights slide)
  - HVeV = high-voltage with eV-scale resolution

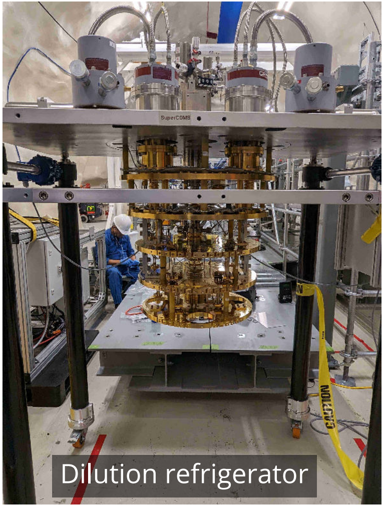
Ancillary measurements

- Ionization yield measurement in Si and Ge
  - IMPACT: PRL 131, 091801, 2023
  - Photo-neutron: PRD 105, 122002, 2022

Detector response modeling

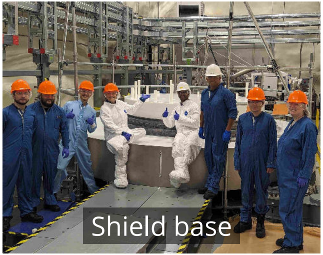
- Analytic modeling (e.g. impurity effects)
- Charge/phonon simulations (G4CMP)

SuperCDMS construction at SNOLAB



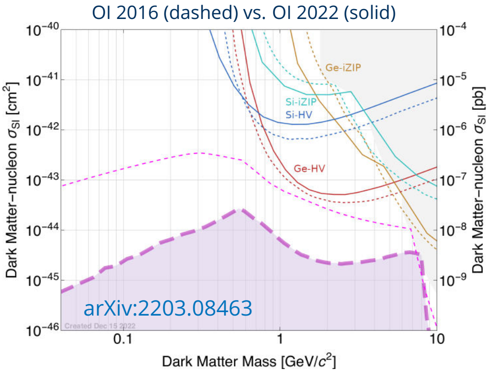
Dilution refrigerator

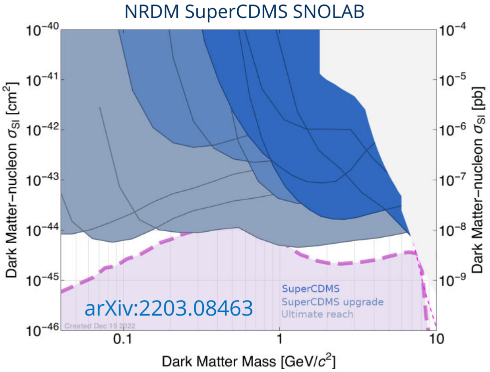
Detector tower



Shield base

SNOWMASS sensitivity updates





- Sensitivity projections for different statistical methods and DM models (here: NRDM only)
  - Optimum Interval (OI): no assumption about background (no potential for discovery)
  - Profile-likelihood ratio (PLR): signal + background assumptions (discovery potential)
- Detailed study of upgrade scenarios for SuperCDMS SNOLAB facility

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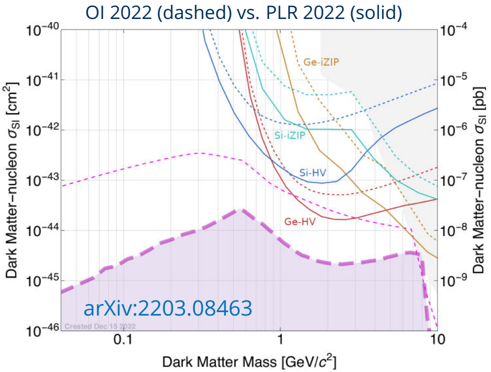

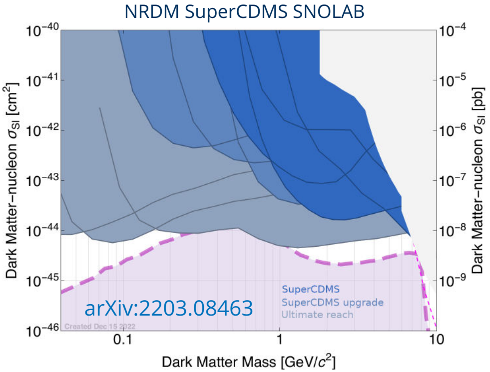

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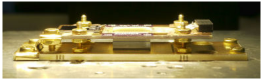
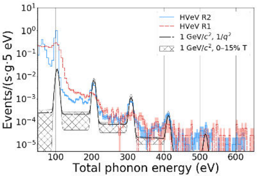
Highlights of HVeV R&D detector program

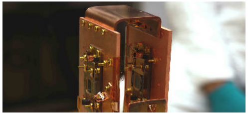


PRD 102, 091101(R), 2020

HVeV Run 2

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

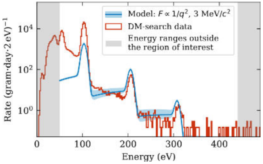


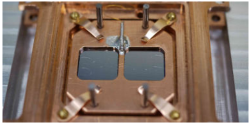


arXiv:2407.08085

HVeV Run 3

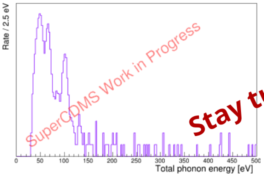
- Multi-detector run at NEXUS (300 m.w.e.)
- Confirmed external origin of burst events

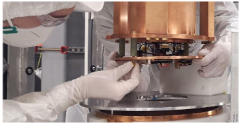




HVeV Run 4

- Same facility but PCB-free mounting
- Elimination of higher-order e^-/h^+ peaks

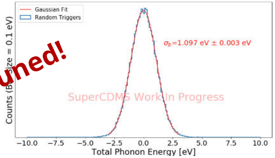




HVeV @ CUTE

- Run 4 + V3 HVeV design (SiO_2 insulation)
- World class resolution

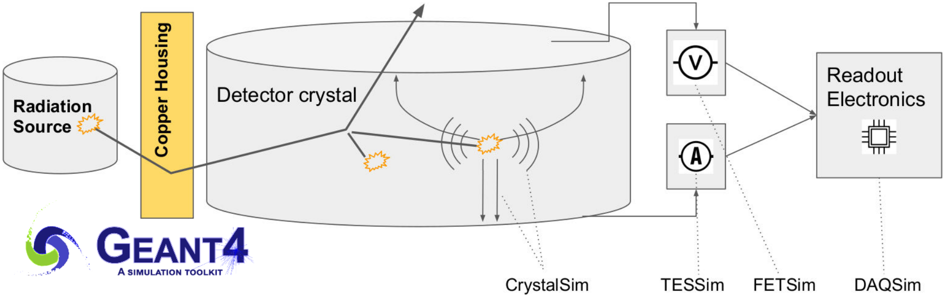
$\rightarrow$ $\sigma_b = 1.097 \pm 0.003$ eV



Detector response modeling

SuperCDMS phonon sensor – QET

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



- **Sophisticated GEANT4-based framework** to model crystal and sensor response
  - **Crystal dynamics:** lattice definition, charge and phonon scattering, etc.
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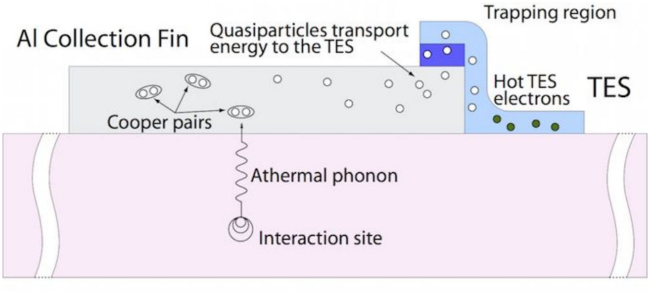
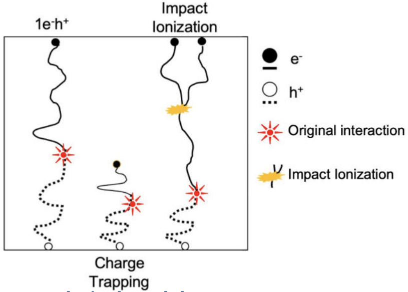


https://figueroa.physics.northwestern.edu



Analytical model: PRD 109, 112018 (2024)

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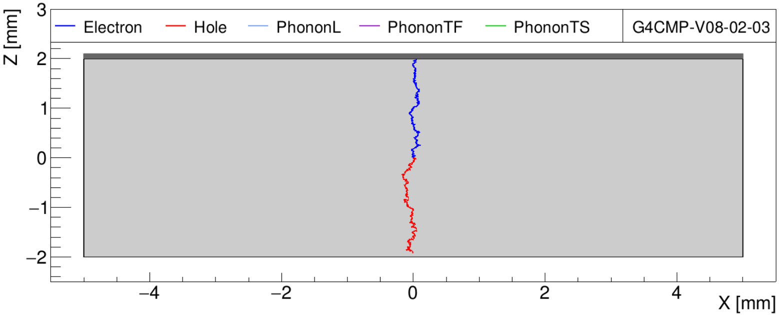
G4CMP – "in-house" physics library

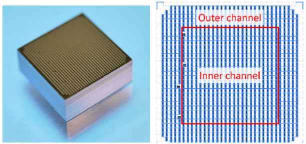
G4CMP – **C**ondensed **M**atter **P**hysics library for GEANT4

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*)

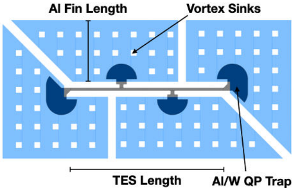
More details: NIM A 1055, 168473, 2023 (arXiv:2302.05998)
Source code: https://github.com/kelseymh/G4CMP

SuperCDMS Si-HVeV prototype modeling



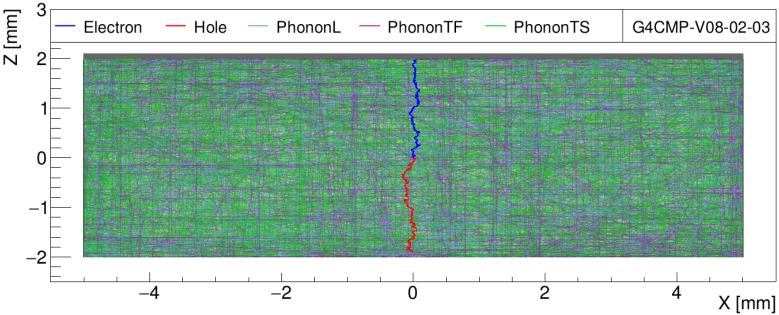


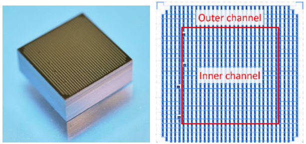
PRD 104, 032010 (2021)



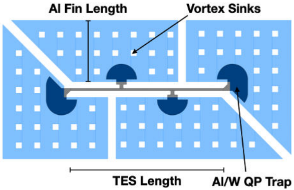
- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About ∼5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About ∼50k phonon tracks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

SuperCDMS Si-HVeV prototype modeling





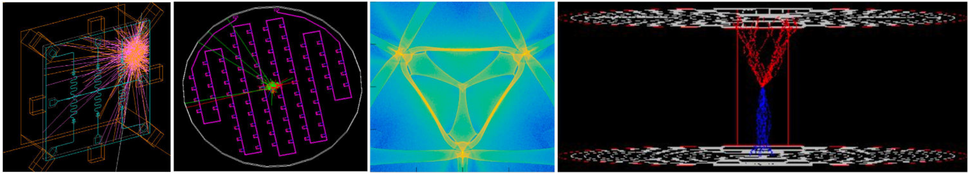
PRD 104, 032010 (2021)



- **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)

Advertisement: G4CMP community activities

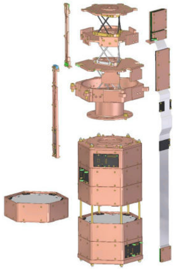
- **Joint effort between CDMS developers and QIS community**
  - Coordinated by M. Kelsey (Texas A&M), N. Kurinsky (SLAC), R. Linehan (FNAL)
  - Initiated by VIEWS 2024 and RISQ 2024 workshops
- **Confluence web space:** G4CMP: GEANT for Condensed Matter Physics
  - Onboarding material, mailing list, meeting notes, workshops, etc.
- **Regular community meetings**
  - Monthly high-level discussion and planning
  - Bi-weekly technical developer meetings

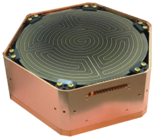


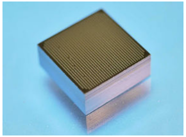
Summary

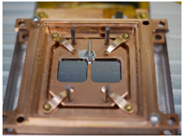
Summary & Takeaways

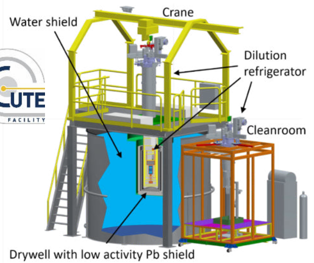
- **SuperCDMS is well-suited for sub-GeV DM searches**
  - Complementary detector technology (iZIP, HV)
  - Infrastructure at SNOLAB under construction
- **Completed full-scale HV tower testing at CUTE**
  - Detector performance, reconstruction, simulation validation
- **Very successful HVeV R&D detector program**
  - Expect results from HVeV Science Run 4 soon!
  - Moving to SNOLAB – HVeV @ CUTE happens right now!











Appendix

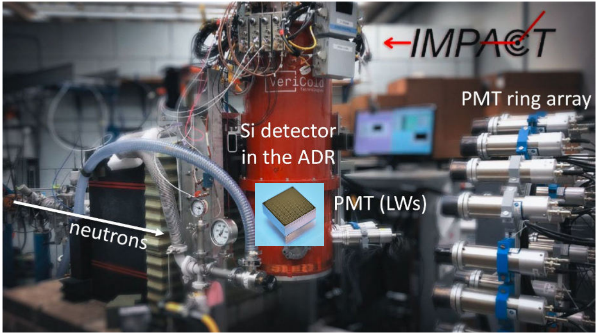
SuperCDMS Collaboration

@SuperCDMS supercdms.slac.stanford.edu

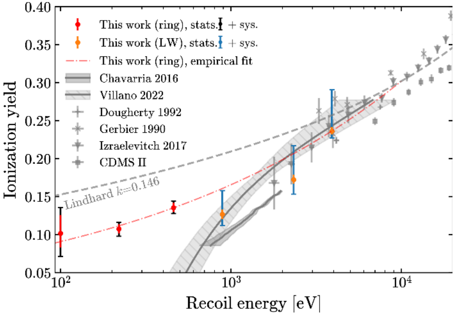
Recent publications

- **Improved modeling of detector response effects in phonon-based crystal detectors used for dark matter searches**
  - Published in Phys. Rev. D 109, 112018 (2024)
- **Light Dark Matter Constraints from SuperCDMS HVeV Detectors Operated Underground with an Anticoincidence Event Selection**
  - HVeV Run 3, under review by PRD, pre-print arXiv:2407.08085
- **First measurement of the nuclear-recoil ionization yield in silicon at 100 eV**
  - Published in PRL 131, 091801, 2023
- **G4CMP: Condensed Matter Physics Simulation Using the Geant4 Toolkit**
  - Published in NIM A 1055, 168473, 2023
- **A search for Low-mass DM via Bremsstrahlung and the Migdal Effect in SuperCDMS**
  - Published in PRD 107, 112013, 2023
- **Investigating the sources of low-energy events in a SuperCDMS-HVeV detector**
  - Published in PRD 105, 112006, 2022
- **Snowmass contribution: Low-Mass DM Searches with SuperCDMS SNOLAB**
  - Available as pre-print arXiv:2203.08463

Nuclear recoil ionization yield measurement



PRL 131, 091801, 2023



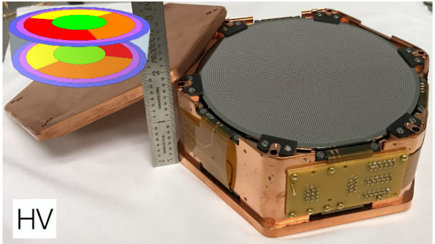
- Ionization yield (Y) measurement down to 100 eV with Si-HVeV prototype detector in a neutron beam
  - HVeV = HV prototype detector with eV-scale resolution
  - No indication for ionization threshold in Si!
- Ge yield measurement in preparation

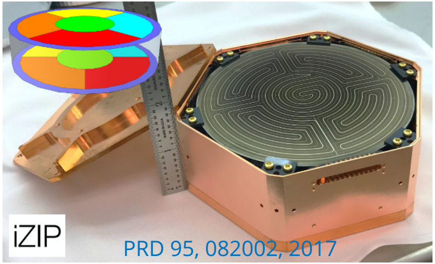
Total phonon energy and yield

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

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: $\sim$ 15 mK**
  - Phonon measurement with TESs (HV, iZIP)
  - Ionization measurement with HEMTs (iZIP)
- **Two-sided readout** with multiple channels to identify **event position**

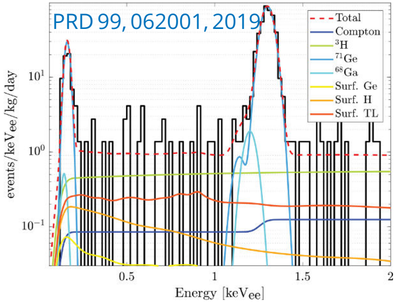




Low-threshold vs. low-background modes

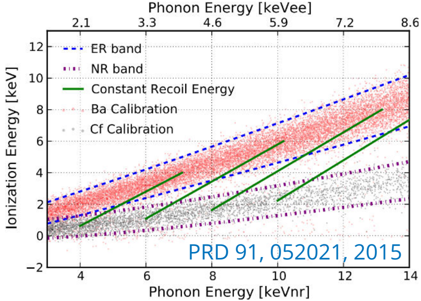
HV detectors – low threshold

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

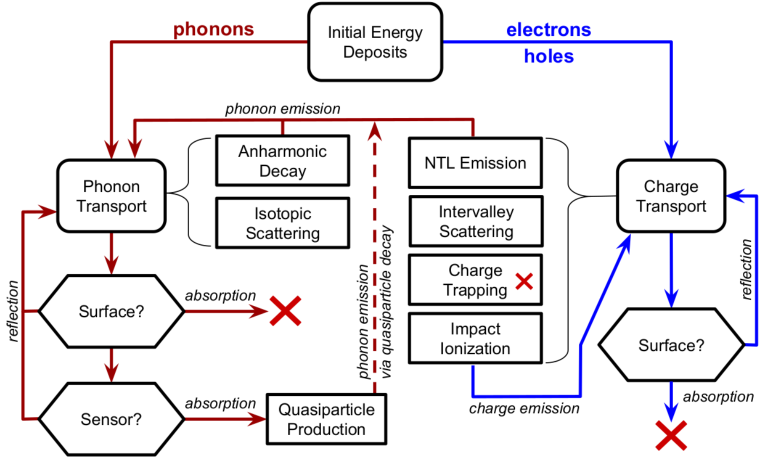


iZIP detectors – low background

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

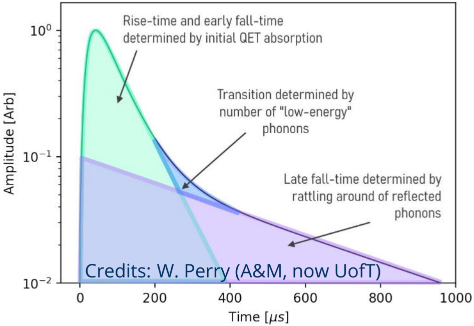


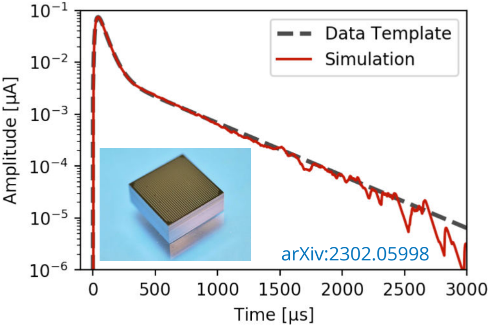
G4CMP – Event processing flow



arXiv:2302.05998

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.
- Data input from data-taking runs at test facilities (CUTE, NEXUS)