

CALIBRATION STRATEGY FOR SUPERCDCMS HIGH-VOLTAGE DETECTORS
OPERATIONS

By

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To Mom

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I cannot fathom starting an acknowledgement without thanking my family. You have fought through countless difficulties, and I do mean countless. That ended up shaping my resilience, self-reliance, and maturity. All of that while also keeping the fire of my curiosity raging. Not sure if this was by design or by accident, but I really appreciated it nonetheless. My mom and dad, especially, deserve more than I can put down in writing. Through all life's chaos and from tolerating my endless "why" questions as a kid to supporting me through graduate school, you've been a bedrock I built all my achievements on.

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LIST OF ABBREVIATIONS

ADR	Adiabatic Demagnetization Refrigerator
BORR	Begin-Of-Run Random
CMB	Cosmic Microwave Background
CUTE	the Cryogenic Underground TESting facility at SNOLAB
DAQ	Data Acquisition
DCRC	Detector Control and Readout Cards
DM	Dark Matter
ETF	Electrothermal Feedback
FIR	Finite Impulse Response
G4DMC	Geant4 Detector Monte Carlo
HV	High Voltage
HVeV	High-Voltage electron Volt scale
IICT	Impact Ionization and Charge Trapping
IMPACT	Ionization Measurement with Phonons At Cryogenic Temperatures experiment
IRR	In-Run Random
LF	Low Frequency
LDM	Light Dark Matter
LW	Lone Wolf
MCMC	Markov Chain Monte Carlo
MF	Matched integral Filter
NTL	Neganov-Trofimov-Luke effect

OF	Optimal Filter
PBHs	Primordial black holes
PMT	Photo Multiplier Tube
PSD	Power Spectral Distribution
QET	Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge sensor
RQ	Reduced Quantity
SM	Standard Model
SQUID	Superconducting QUantum Interference Device
SuperCDMS	Super Cryogenic Dark Matter Search
TES	Transition Edge Sensor
TOF	Time-Of-Flight
TUNL	the Triangle Universities Nuclear Laboratory
WIMP	Weakly Interacting Massive Particle

Abstract of Dissertation Presented to the Graduate School
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The Super Cryogenic Dark Matter Search (SuperCDMS) experiment at SNOLAB is designed to probe dark matter candidates in the 1–10 GeV/c² mass range. Located 2 km underground in Canada’s SNOLAB laboratory, the experiment will deploy 24 silicon and germanium detectors arranged in four towers. The detector payload combines high-voltage (HV) phonon detectors, excellent low-energy sensitivity, with iZIP phonon–ionization detectors that enable background rejection. This thesis presents two projects that contribute to the preparation for the first science run.

The first project centers on a detector tower testing campaign, where a tower of six HV detectors was deployed and tested at the Cryogenic Underground TEST facility (CUTE). This effort included detector characterization, development of calibration strategies, and demonstration of sustained in-situ operation. I contributed to both operations and data analysis, with a focus on establishing calibration procedures that spanned from low-energy, low-background setups to high-energy calibrations in both high and no voltage bias conditions.

The second project involves ionization yield measurements performed at the Ionization Measurement with Phonons At Cryogenic Temperatures (IMPACT) experiment. In this study, the ionization yield in silicon was measured down to 100 eV for the first time. My work concentrated on the second phase of the analysis, which aimed to identify single electron–hole pair events.

While noise levels prevented observing such events, the analysis confirmed that electron–hole pair production exhibits no threshold even at these low energies.

Together, these projects deliver critical calibration tools, analysis pipelines, and performance benchmarks that will support the commissioning of SuperCDMS SNOLAB, now underway.

CHAPTER 1 DARK MATTER INTRODUCTION AND MOTIVATION

Since the 1930s, accumulating empirical evidence has implied that visible matter is not the only kind of matter in our universe [1]. However, the evidence was not widely recognized, as most opted to question some of the assumptions used in the analysis of such measurements. Zwicky's work on the mass of clusters is an example of this. Nonetheless, the field gained momentum in the 1970s when several new observations of the velocity curves of a multitude of spiral galaxies indicated that there must be more mass than initially thought. In fact, it did not take much for the community to realize that our universe is mainly dominated by a dark class of matter. This chapter will enumerate some evidence of existence, inferred properties, and a few of the proposed particle candidates.

1.1 Dark Matter Motivation

1.1.1 Rotation Curves of Galaxies

The rotation velocity for the accretion disk of a galaxy is one of the first pieces of evidence for dark matter. Spiral galaxies typically consist of a central bulge and an accretion disk. We can approximate the mass distribution to be uniform $M(R) = 4\pi R^2 \sigma$ where σ is the density of the planar mass. However, a simplification can be imposed when dealing with spiral galaxies, which is to consider that most of the mass is concentrated in the center of the galaxy, resulting in a simple average potential at an arbitrary point R in Equation 1-1. Applying the viral theorem yields the velocity as a function of distance from the center of the galaxy, as indicated in 1-2

$$\langle V \rangle = -\frac{GM_{tot}}{R} \quad (1-1)$$

$$v = \sqrt{\frac{GM_{tot}}{R}} \quad (1-2)$$

A similar treatment can be performed without the mentioned simplification, resulting in a similar velocity profile shown in 1-3 where α is a constant determined by the geometry of the mass distribution ($\alpha \leq 1$ for uniform symmetric distributions) .

$$v = \sqrt{\alpha \frac{GM_{tot}}{R}} \quad (1-3)$$

Measurements performed by Fritz Zwicky in 1933 showed a disparity between expectation and observation. These measurements remained a point of contention until the 1970s, when multiple studies published significant deviations from theoretical expectations, as seen in Figure 1-1. The measurements imply the existence of non-luminous matter mostly with a halo structure around these types of galaxies. Additionally, this type of matter is concluded to be electrically neutral, considering the lack of its interaction with light.

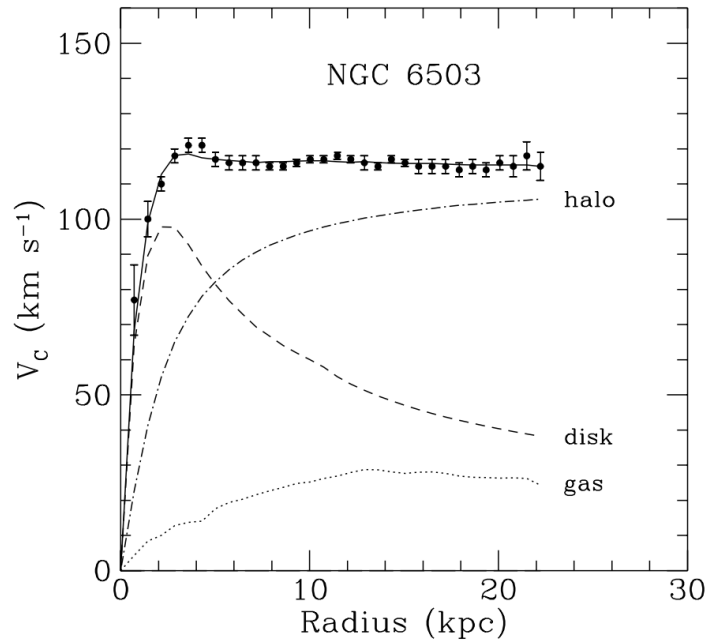


Figure 1-1. Measurement and the best-fit result for an observation captured by [2]. The fit was created by mixing three mass distributions as indicated in the plot.

1.1.2 Gravitational Lensing

Gravitational lensing is the bending of light's trajectory due to a massive object bending the space-time around it. This phenomenon was first described by Albert Einstein in his theory of general relativity. The theory predicts that for a spherically symmetric mass distribution, there should be a deflection angle of magnitude $\frac{2R_s}{r}$ where R_s is the Schwarzschild radius. Although this assumption is not very realistic, it can, to a first order, demonstrate the effect. Matching the deflection angle and the observation angle θ_{obs} leads to the possibility of determining the mass of the "lens" as seen in equation 1-4 where d is the distance to the lens and G is the gravitational constant.

$$M = \frac{c^2 d \tan(\theta_{obs})(\pi - 2\theta_{obs})}{4G} \quad (1-4)$$

For more realistic mass distributions, gravitational lensing is used to map the gravitational potential, which can be used to infer the mass distribution [3]. Several measurements, built on this principle, showed that the lensing effects has been amplified in specific regions that do not match the observed luminous matter. A famous example of this discrepancy is the lensing of the bullet cluster merger [4]. Combining the measurements of the Magellan optical telescope and the Chandra X-ray telescope enables tracing the mass distribution contours. The gravitational lens map not only indicated that most of the mass is non-ordinary matter but also that it can only interact weakly with itself, as most of it emerged from the collision almost unaffected as shown in 1-2.

1.1.3 Cosmic Microwave Background

Another strong piece of evidence backing the existence of dark matter (DM) is the cosmic microwave background (CMB). CMB measurements have been a powerful tool in testing cosmological models as they impose strong constraints on the densities of different components of the universe. Most successful and widely adopted cosmological model explain the anisotropies in

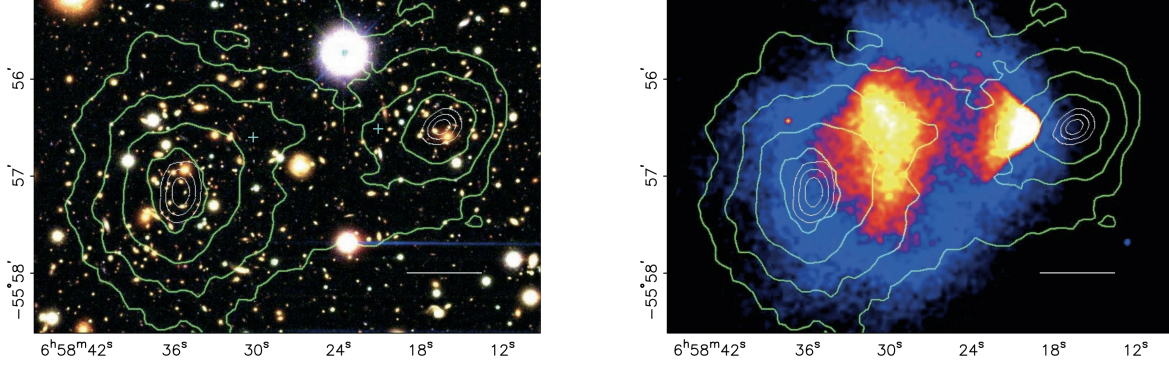


Figure 1-2. (Left) Color image from the Magellan images of the merging cluster. (Right) Chandra image of the cluster. Shown in green contours in both panels are the weak-lensing reconstructions. Figure is copied from [4].

the CMB with the existence of a dark energy component (driving the expansion of the universe) and a dark matter component (damping the expansion along with baryonic matter).

The Planck collaboration measurement of the anisotropies in CMB (shown in fig 1-3) and subsequent fitting revealed the necessity of the DM component. The fit was obtained by fitting for 7 parameters that include the energy densities of different components. The fit gives a matter density of $\Omega_M = 0.313 \pm 0.013$ and a relative baryon density to dark matter density of:

$$\frac{\Omega_c}{\Omega_b} \approx 5.4 \quad (1-5)$$

showing a great consensus with different independent estimates for DM.

1.1.4 Large-structure Formation

Since the first attempts at mapping the universe in the 1980s, a web-like structure has appeared on large scales (10 - 200 Mpc)[6]. The discovery of filaments and galaxy clusters created a new fundamental puzzle, as the expectation was a uniformly distributed baryonic matter across space. The puzzle became more severe when earlier explanations used only baryonic and radiation components, and the distribution of densities imprinted in the CMB to model the evolution of large-scale structure. The models did not reproduce the observed structure.

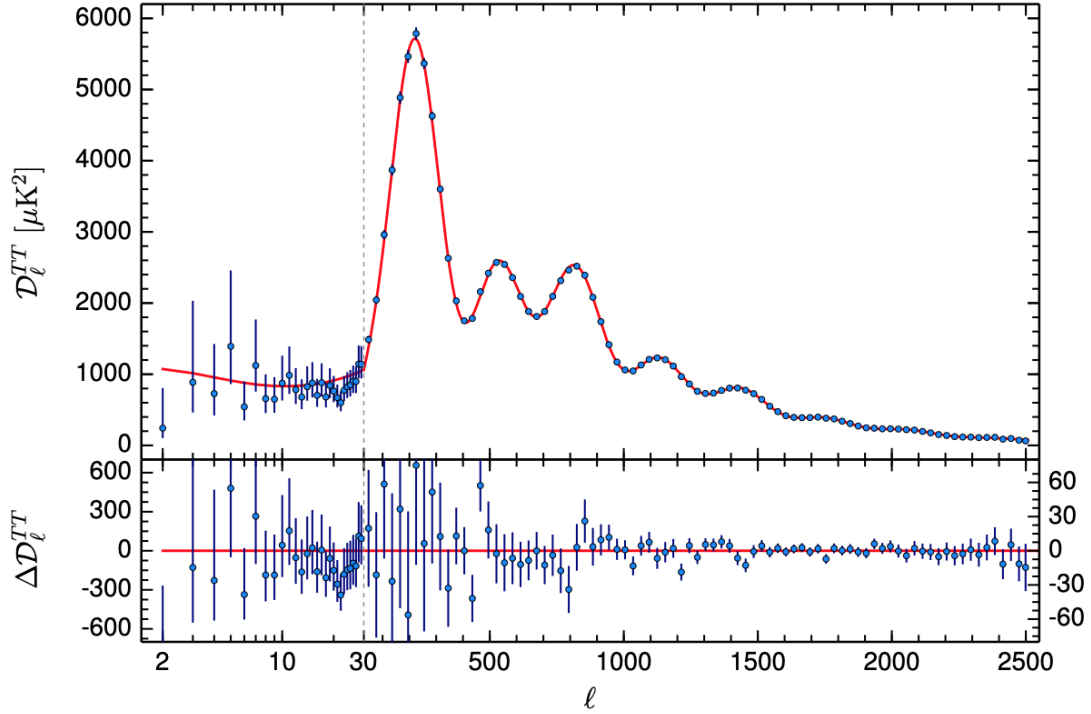


Figure 1-3. CMB power spectrum measurement and fit as published by the Planck collaboration [5]

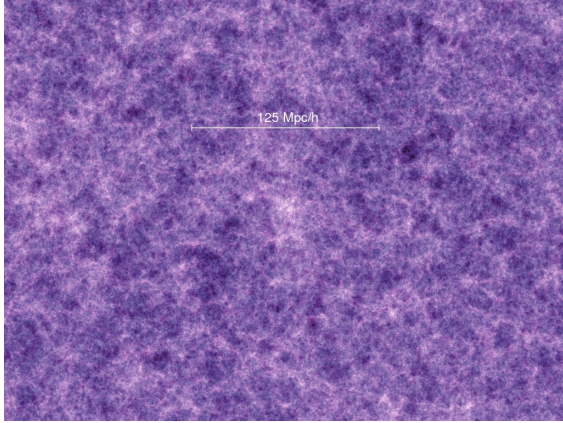
The issue stemmed from the strong coupling between baryons and radiation before recombination, limiting structure formation through gravitational instability [7]. A collisionless and electromagnetically decoupled DM would allow clustering earlier, as soon as the universe is dominated by matter. Numerical simulations showed that DM would form the nodes and skeleton for clusters and filaments where baryons end up 1-4. The abundance needed to form a similar structure to astrophysical observations is consistent with the abundance predicted from Λ CDM [8, 9].

1.2 Dark Matter Properties

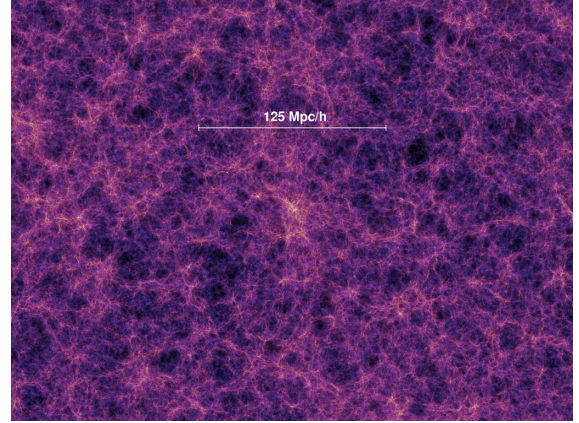
1.2.1 General Properties

As the CMB observations indicate that DM is non-baryonic. The motivations looking beyond the SM for DM candidates. Additionally, other motivations impose a few general properties constraining building beyond-SM theories. The properties include:

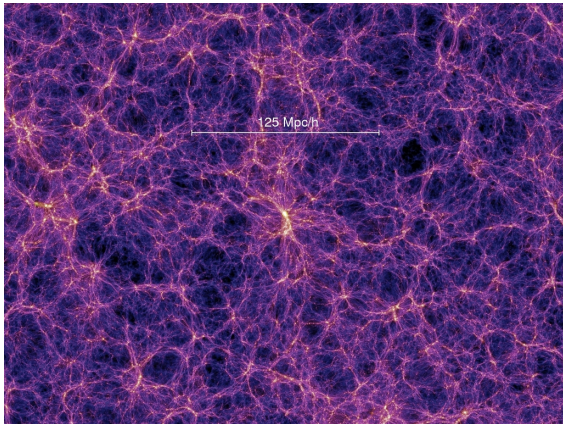
- **Massive:** DM candidates should have mass since the only observed coupling is through gravity.



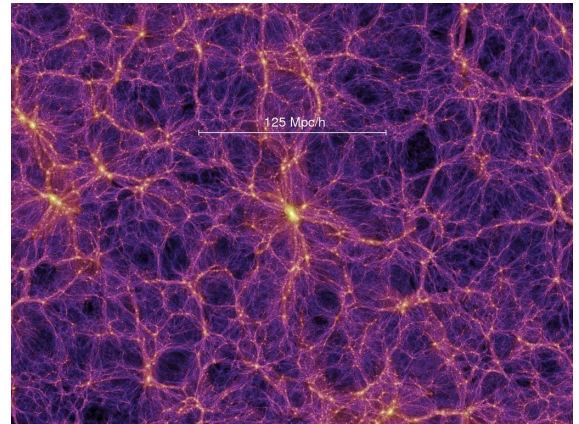
(a) $z = 18.3$



(b) $z = 5.7$



(c) $z = 1.4$



(d) $z = 0$

Figure 1-4. Slices of simulated large structure formations at different red shifts [8].

- **Neutral (or millicharged):** DM are, as the name implies, "Dark". Meaning, DM does not interact through EM or QCD interactions, so they cannot have any considerable charge.
- **Non-relativistic:** Galactic formation implies that DM must be "cold" or non-relativistic. This is necessary for large-scale structure formation [10].
- **Weakly-Interacting:** DM has to be very long-lived or stable to exist with the current observed abundance, given it was produced in the early universe.
- **Maintains SM successes:** DM has not been observed to cause violations of conservation laws of energy, momentum, angular momentum, and charges.

1.2.2 Local Properties

1.2.2.1 Local Mass Density

Some of the motivations for proposing DM can be used to estimate the local density. This estimation is important for direct detection experiments as the signal rate depends on the density, as it will be discussed later. The most widely used method is simulating galactic kinematics based on observed trajectories of stars in galaxies.

Most models typically follow the widely accepted Standard Halo Model (SHM), which describes the dark matter distribution in galactic halos as an isotropic, isothermal sphere. Combined with the fact that gravitational potential can be described by a Poisson's equation (Equation 1-6), one can yield a system of Jean-Poisson equations that can be compared to observed distributions. References [11, 12, 13] detail distribution-dependence on the nature of the calculations and modeled components.

$$4\pi G\rho = \nabla^2\Phi \quad (1-6)$$

where G is the gravitational constant, ρ is the total mass density and Φ is the gravitation potential.

Measurements for the Milky Way over the last decade have converged to a local mass density of $\rho_\chi \sim 0.3 \text{ GeV}/c^2$ [1, 14]. Though it's worth mentioning that this measurement is heavily reliant on the assumed SHM. Any refinement can lead to a different conclusion. For instance, [15] argues that adding more complex kinematics for DM will result in a local mass density of $\rho_\chi \sim 0.5 \text{ GeV}/c^2$.

Overall, different models vary the local mass density within the range of $\pm 0.2 \text{ GeV}/c^2$ [16]. This seemingly large variance, however, does not resemble such a big concern for DM direct detection experiments as the signal rate is linearly dependent on the local DM mass density.

1.2.2.2 Velocity Distribution

The final component is the velocity distribution of dark matter in the galactic halo, $f(v)$. Assuming SHM leads to a Maxwell-Boltzmann velocity distribution in the galactic frame, truncated at the galaxy's escape velocity v_{esc} :

$$f(v) = \frac{1}{N} \begin{cases} e^{-v^2/v_0^2}, & v < v_{esc} \\ 0, & v > v_{esc} \end{cases} \quad (1-7)$$

where v_0 is the circular speed of the Sun about the center of the Milky Way (approximately 220 km/s), and N is a normalization constant ensuring that the integral over velocity space equals unity. The escape velocity is typically taken to be 600 km/s.

This velocity distribution is formulated in the galactic frame and must be transformed to the detector (Earth/Lab) frame:

$$f_L(\vec{v}, \vec{v}_e) = f(\vec{v} + \vec{v}_e) \quad (1-8)$$

where $\vec{v}_e$ is the Earth's velocity relative to the galactic center. The Earth's velocity comprises several components: the circular speed of the Sun about the galactic center, the Sun's peculiar velocity, and the Earth's orbital velocity about the Sun. This last component changes over the course of a year, leading to a non-trivial annual modulation in the expected WIMP rate-dependent signals; a signature that motivates dedicated searches for time. For long-running experiments, the time-averaged value of Earth's orbital speed is used, and the time dependence is neglected.

The velocity integral can be formally defined as:

$$g(E_R) = \int_{v_{min}}^{v_{esc}} \frac{f(\vec{v} + \vec{v}_e)}{v} d^3v \quad (1-9)$$

In this formulation, we see that we can detect a modulation signal arising from the Earth's orbital motion. This is the assumption made by the much-contested DAMA/LIBRA results [17]. This assumption, however, is not necessarily true as recent measurements using Gaia satellite shed some doubts on the Maxwellian nature of the velocity distribution. [18] (and references therein) analysis argues the existence of dark shard streams which are not attributed in the traditional SHM. These streams, when boosted to the lab frame, introduce features that cause deviations from the Gaussian shape assumed earlier (see Figure 1-5).

These irregularities in the shape of the velocity distribution open the door to reinterpret the results of DAMA/LIBRA and all modulation DM search experiments. Additionally, the feature at the tail of the distribution will introduce an enhancement in the detection signal for lighter DM candidates like ALPs and Axions. For heavier candidates, however, the nuclear recoil search will not experience significant deviations from the typical distribution of SHM. Figure 1-6 summarizes the effects of the proposed non-Maxwellian velocity distribution.

1.3 Candidates

The aforementioned DM properties are very loose, and depending on the production mechanisms, one can devise several theoretical candidates modeling DM. The current status of the field consists of several candidates spanning a mass range of more than 50 orders of magnitude. Some of the theories were initially proposed to solve other issues in other fields, like the Weakly Interacting Massive Particles (WIMPs) and Axions.

1.3.1 Thermal DM

The thermal DM hypothesis can reproduce the measured dark matter abundance from a minimal set of assumptions, making it also more appealing. In the remainder of this section, I will discuss the 2 production mechanisms of DM as discussed in [20] and [21].

The contents of the early universe can be analyzed in terms of the equilibrium densities. If particles undergo rapid interactions, they can be described by a common temperature T . When rapid reactions can change the number of particles, the number density will approach a

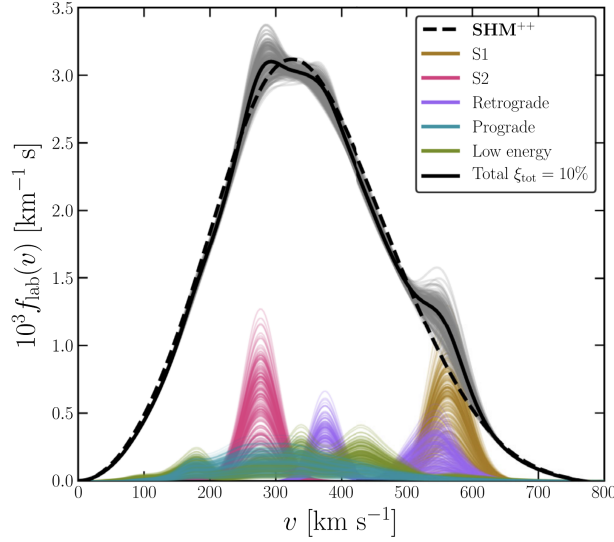


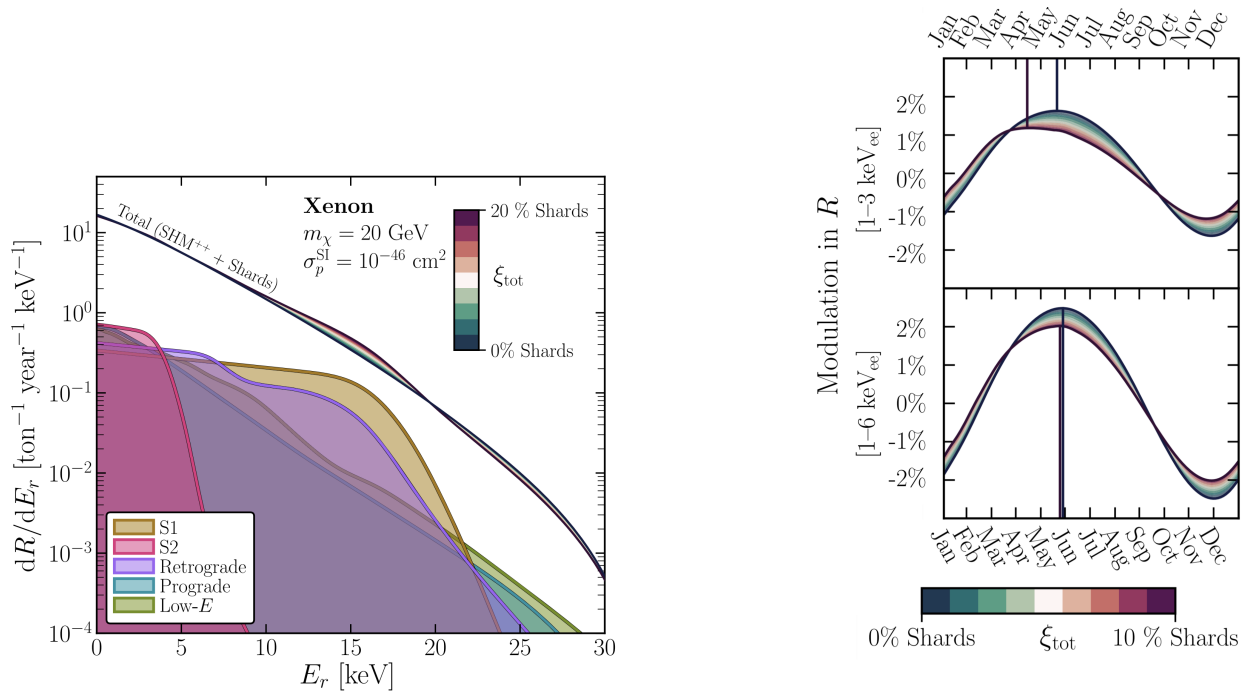
Figure 1-5. Speed distribution in lab frame as modeled in [18]. The black solid line shows the distribution accounting for substructure components assuming ζ_{tot} of 10% (the percentage of DM in the dark shards).

Maxwell-Boltzmann distribution. This equilibrium distribution exhibits dramatically different behavior depending on how the temperature compares with the particle mass.

This can be seen clearly through the evolution on the number density (n) through a Boltzmann equation that accounts for the expansion of the universe (through the Hubble parameter H) and the annihilation process.

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle[n^2 - n_{eq}^2] - \Gamma[n - n_{eq}] \quad (1-10)$$

Equation 1-10 contains three physically distinct terms. The term $3Hn$ represents "Hubble friction," accounting for the dilution of particle density due to the expansion of the universe. The right-hand side represents collision terms: annihilation (proportional to n^2), production (proportional to n_{eq}^2), and the decay term (proportional to n). The Hubble parameter itself scales as $H \sim g_* T^2 / M_{Pl}$, where g_* counts the effective number of relativistic degrees of freedom and M_{Pl} is the Planck mass.



(a) Effect on nuclear recoil rates.

(b) Effect on modulation rates.

Figure 1-6. A summarized effect of the dark shard streams on DM direct detection experiments. (Left) The time-averaged nuclear recoil rate for as a function of energy for a 20 GeV WIMP-like particle scattering through a spin-independent interaction with xenon. (Right) The modulation of the integrated event rate in two ionization energy bins of 1–3 and 1–6 keV (top and bottom panels in each column, respectively). Both figures are adapted from [18].

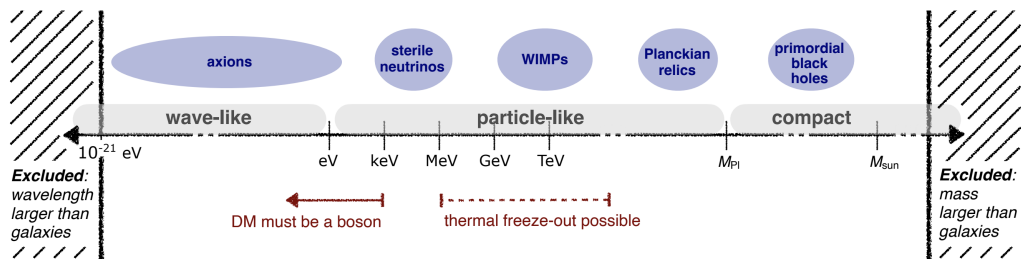


Figure 1-7. Candidates summary of particle DM. Figure is adapted from [19].

When Γ or $(n_{eq}\langle\sigma v\rangle)$ is large compared to H , the number density n is driven toward its equilibrium value (ie; the interactions are strong enough to maintain thermal equilibrium). This is called for freeze-out mechanism. Conversely, when H is large, the interactions are insufficient to maintain equilibrium: n becomes frozen and simply scales with the expansion of the universe (ie; freeze-in). For DM, most hypotheses (but not necessarily all) assume a Z_2 symmetry, killing the decay term, which simplifies modeling production further.

The **freeze-out** mechanism for DM begins with DM in chemical equilibrium with the SM plasma at early times, with equilibrium maintained by scattering processes where pairs of DM annihilate into Standard Model particles ($\chi + \chi \rightarrow \text{SM} + \text{SM}$) and the reverse. However, the expansion of the universe eventually results in a departure from equilibrium. Because the density n_{eq} falls exponentially for temperatures below the mass, all interactions involving massive particles are likely to fall out of equilibrium at sufficiently late times. The DM particles become sufficiently diluted that they can no longer find each other to annihilate, and they cease tracking the Boltzmann distribution (See Figure 1-8).

This can also be interpreted the other way around. Once A frozen-out DM's mass and cross section for annihilation into SM particles are specified, the relic density can be predicted. The remarkable feature is that one simple, reasonable assumption (that dark matter is in equilibrium with the SM at early times) is sufficient to predict the dark matter density today in terms of the particle physics properties of DM.

Freeze-in operates under opposite assumptions: it assumes a negligible initial number density and requires small couplings such that the particle never reaches its equilibrium number density. If the couplings governing freeze-in are sufficiently small, the resulting particle's lifetime could be large enough for it to constitute dark matter, even if it is not strictly stable. This differs fundamentally from freeze-out, where the relevant interactions must be strong enough to maintain equilibrium at early times.

Different interaction types lead to different systematics and consequently different phase diagrams for DM production. For example, [20] discusses 2 different scenarios, one with a quartic

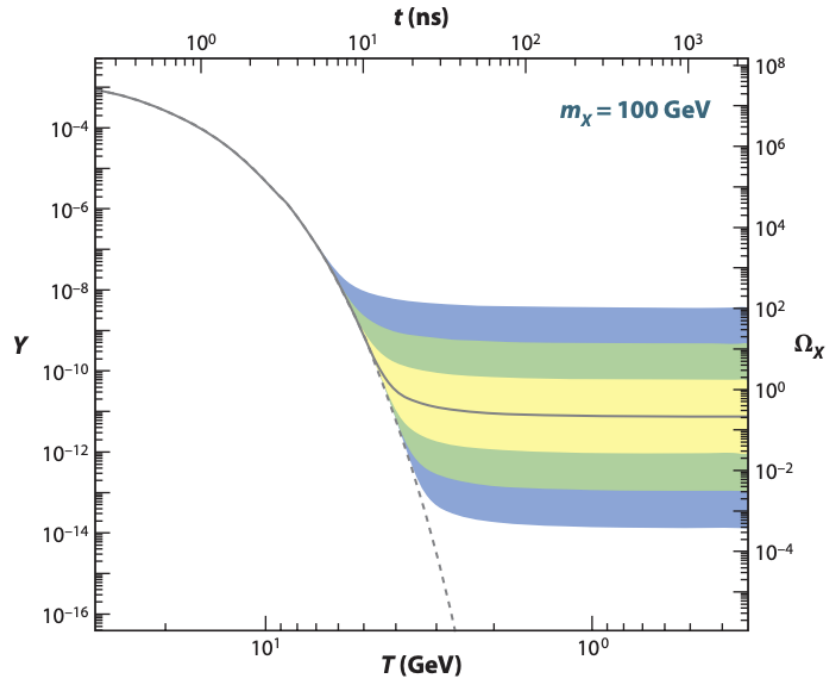


Figure 1-8. The comoving number density Y (left) and resulting thermal relic density (right) of a 100-GeV DM particle as a function of temperature T . The solid gray contour is for an annihilation cross section that yields the correct relic density, and the shaded regions are for cross sections that differ by order to three orders of magnitude above and below the correct relic value. The dashed gray contour is the number density the thermal equilibrium case. Figure is adapted from [21].

interaction of the form $(\chi^2 \cdot SM \cdot SM)$ allowing for a χ that is exactly stable and interacts with pairs of SM particles in the thermal bath. Alternatively, a Yukawa interaction of the form $(\chi \cdot \psi_1 \cdot \psi_2)$, where χ is the DM, ψ_1 is a heavier dark sector particle, and ψ_2 is a SM fermion, produces a rich parameter space with regions corresponding to non-relativistic or relativistic freeze-out, freeze-in parameter space for χ .

Since the mass range varies from few eVs to several TeVs, it warrants a different detection mechanism, either through nuclear or electron recoil. Figure 1-9 summarizes the thermal DM candidates and possible detection interactions. In the remainder of this subsection, I will talk about a few candidates that are related to the detectors I worked on as part of my thesis.

1.3.1.1 WIMPs

The Weakly Interacting Massive Particles (WIMPs) theories represent some of the most studied candidates. WIMPs are loosely defined as DM candidates that are stable, interacting with SM through gravity and one other force that is at least as weak as the weak nuclear force. WIMPs are produced in thermal equilibrium in the early universe. The WIMP hypothesis falls into the freeze-out production mechanism. To correctly reproduce the observed abundance of DM, the mass range for such candidates has to be within the GeV to few TeV mass range.

WIMPs arise naturally in popular SM extensions like supersymmetry and sterile neutrino theories, which also address other open questions in particle physics. The "WIMP miracle"—that weak-scale particles naturally produce the correct dark matter abundance—combined with multiple SM extensions predicting candidates at precisely this mass range, makes WIMPs compelling dark matter candidates and strongly motivates experimental searches.

However, it is important to note that the cosmological history of the universe at temperatures above approximately 1 MeV (before Big Bang Nucleosynthesis) represents an extrapolation based on the Standard Model plus additional ingredients such as dark matter. Features such as inflation, the existence of dark matter itself, and the baryon asymmetry all indicate that our understanding of earlier epochs remains incomplete. This uncertainty means that while the freeze-out calculation provides strong motivation for the WIMP hypothesis, alternative

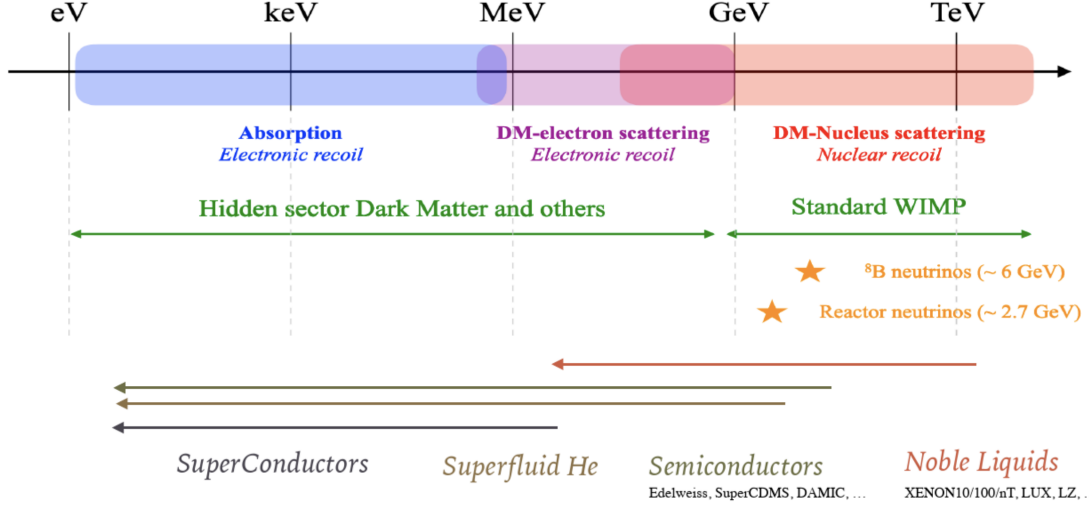


Figure 1-9. DM candidates and a summary of detection mechanisms for thermal DM. Figure is adapted from [22].

production mechanisms and modifications to the standard cosmological picture cannot be ruled out without direct experimental evidence.

Expected Signal Model

Since WIMPs are non-relativistic and massive, the expected interaction with a SM target can be modeled as two-body elastic scatter of a WIMP off a target nucleus. The recoil energy (E_R) carried by the nucleus after such an interaction can be calculated using simple kinematics:

$$E_R = \frac{\mu_A^2 v^2}{m_A} (1 - \cos \theta) \quad (1-11)$$

where m_A is the mass of the target nucleus, $\mu_A = m_\chi \cdot m_A / (m_\chi + m_A)$ is the reduced mass of the WIMP-target nucleus, v is the velocity of the incoming WIMP, and θ is the angle between the final trajectories of the two particles. To estimate the average expected event rate (R) in a detector, we begin with a general expression:

$$R = N_T \cdot n_\chi \langle v \rangle \cdot \sigma \quad (1-12)$$

where N_T is the number of target, and σ is the total WIMP-nucleus scattering cross section.

Additionally, we can account for the dependence of the cross section on the recoil energy and velocity distribution. Expressing the rate per unit detector mass rather than for a specific number of target nuclei provides a more general description. The differential rate per unit recoil energy per unit detector mass can be written as:

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R} dv \quad (1-13)$$

The $f(v)$ is the normalized distribution of WIMP speeds within the galactic halo.

Additional parameterizations were implemented to help generalize the rate equation, like the local DM number density n_χ expressed as ρ_χ/m_χ . The lower limit of integration, v_{min} , represents the minimum velocity required to produce a recoil with energy E_R derived from equation 1-11 as

$$v_{min} = \sqrt{\frac{E_R m_A}{2\mu_A^2}}.$$

The cross-section term can also be described in terms of zero-momentum transfer cross-section (σ_0), and a form factor function $F^2(E_R)$ (as in Equation 1-14). This encodes suppression terms arising from the nuclear structure of the target nuclei.

$$\frac{d\sigma}{dE_R} = \frac{m_A \sigma_0}{2\mu_A^2 v^2} F^2(E_R) \quad (1-14)$$

To calculate the cross-section's dependence on energy, one has to consider the full effective Lagrangian of the entire interaction. Most frameworks assume canonically that WIMPs are spin- $\frac{1}{2}$ Majorana particles (see [23, 24, 25]). In the low momentum transfer regime relevant to direct detection, the Lagrangian is simplified to split into a spin-spin interaction (spin-dependent) and a scalar interaction (spin-independent).

$$\sigma_0 = \sigma_0^{SI} + \sigma_0^{SD} \quad (1-15)$$

$$\sigma_0^{SI} = \frac{4\mu_A^2}{\pi} (Zf_p + (A - Z)f_n)^2 \simeq \frac{4\mu_A^2}{\pi} A^2 f^2 \quad (1-16)$$

where Z is the number of protons in the target nucleus, $(A - Z)$ is the number of neutrons, and f_n and f_p are the WIMP couplings to neutrons and protons, respectively, and they are typically assumed to be equal.

$$\sigma_0^{SD} = \frac{32G_F^2\mu_A^2}{\pi} \frac{J+1}{J} (a_p\langle S_p\rangle a_n\langle S_n\rangle)^2 \quad (1-17)$$

where G_F is Fermi's constant, J is the total nuclear spin, S_p , S_n are the proton and neutron spins, and a_p , a_n are the couplings to protons and neutrons.

After factorizing the constants to simplify the expression and scaling the rate by the total target mass for the measured rate to:

$$\frac{dR_{Target}}{dE_R} = \frac{M\sigma_0\rho_\chi}{2\mu_A^2 m_\chi} F^2(E_R) \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv \quad (1-18)$$

It is worth mentioning that the form factor also depends on whether the interaction is spin-dependent or not. References [25] and [26] discuss in detail how the form factor can be calculated for the different cases.

The primary unknowns—the WIMP mass (m_χ) and the WIMP-nucleon cross section (σ_N^{SI})—are the main targets of direct detection experiments. By measuring the energy spectrum and rate of nuclear recoils, experiments aim to constrain or determine these fundamental parameters, ultimately testing whether the WIMP hypothesis correctly describes dark matter.

1.3.1.2 LDM

The lack of discoveries for WIMPs motivated the need to look for DM elsewhere. One direction is Light Dark Matter (LDM) (also referred to as Dark Sector candidates) with candidates within the mass range of keV/c^2 to a few GeV/c^2 . The production mechanisms for such candidates are either through Freeze-in or through secluded freeze-out [27]. Detection of these

candidates is, however, difficult through the typical nuclear recoil signal described in the previous subsection. This is due to the maximum energy transfer possible (described by Equation ??) is on the limit of detector resolution thresholds of around 100 eV of deposited energy.

$$\Delta E_{max} = \frac{2\mu^2 v_\chi^2}{m_T} \quad (1-19)$$

The workaround is to consider inelastic scattering off electrons rather than elastic nuclear recoil considered earlier. It can be shown [28] that the maximum energy transfer scale is much larger and detectable by many existing experiments. Additionally, experiments can track models describing the absorption of DM rather than scattering. In the remainder of the section, I will describe some of the models explored by semiconductor experiments like SuperCDMS and DAMIC.

$$\Delta E_{max} \leq \frac{1}{2} \mu v_\chi^2 \quad (1-20)$$

DM-electron scattering can be modeled in the same fashion as the nuclear recoil candidates, with the caveat of introducing a mediator A' . The interaction rate can be as shown below [28]:

$$\frac{dR_{crystal}}{d \ln E_R} = \frac{M \rho_\chi}{m_\chi \mu_A^2} \cdot \bar{\sigma}_e \alpha m_e^2 \int d \ln q \left(\frac{E_e}{q} \right) \eta(v_{min}(q, E_e)) \cdot F_{DM}(q)^2 |f_{crystal}(q, E_e)|^2 \quad (1-21)$$

where q is the transferred momentum, α is the fine structure constant, m_e is the mass of the electron, and η is the integral over the velocity distribution. Here, the form factor is for the DM

and electron system can depend on the relative mass between the mediator and electrons:

$$F_D M \simeq \begin{cases} \alpha^2 m_e^2 / q^2, & m_{A'} \ll \alpha m_e \\ 1, & m_{A'} \gg \alpha m_e \end{cases} \quad (1-22)$$

Appendix A in [28] details the derivation for the rate accounting for crystal excitation, along with the formulation for crystal form factor $f_{crystal}(q, E_e)$ used to account for the band structure.

Absorption models also gained momentum in the past decade as a possible DM detection signal. The concept is similar to the photoelectric effect, where a Dark Sector particle is absorbed, causing an ionization signal. SuperCDMS detectors are sensitive, with varying degrees, to these candidates depending on the detector deployed.

The first candidate to consider is Dark Photons (DPs). DPs are hypothetical massive vector bosons that kinetically mixes with a SM dark hypercharge. If the mixing parameter of these candidates and SM is sufficiently low and mass of the DP is smaller than 1/2 the mass of the electron, the decay lifetime is larger than the age of the universe (see [29] and references therein).

The interaction rate can be shown as:

$$R = \frac{\rho_\chi}{\rho_T m_{A'}} \varepsilon_{eff}^2 \Re \Pi(m_{A'}) \quad (1-23)$$

where ρ_T is the density of the target, $m_{A'}$ is the mass of the DP, $\Pi(m_{A'})$ is the complex conductivity of the target, and ε_{eff} is the effective mixing parameter after accounting for target material modulation. Reference [30] has estimated the effective mixing parameter as:

$$\varepsilon_{eff}^2 = \frac{\varepsilon^2 m_{A'}^4}{[m_{A'}^2 - \Re \Pi(m_{A'})]^2 + [\Im \Pi(m_{A'})]^2} \quad (1-24)$$

The second absorption DM candidate is the Axion-Like Particles (ALPs), though they are not necessarily produced thermally as discussed earlier [31]. They follow the same rationale as DPs, where they get absorbed by ionizing an electron in what is described as the axioelectric

effect [32]. ALPs coupling to SM is model-dependent. For recoil DM detection, ALPs abundance is assumed to be solely by a candidate (a) of mass m_a with interaction of [29]:

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - 1/2m_a^2 a^2 + ig_{aee} a \bar{e} \gamma^5 e \quad (1-25)$$

with a rate of:

$$R = \rho_\chi \sigma_{pe}(m_\chi) \cdot \frac{3g_{aee}^2 m_\chi}{16\pi\alpha m_e^2} \quad (1-26)$$

where g_{aee} is the interaction coupling, σ_{pe} is the photoelectric cross-section of the target.

1.3.2 Beyond Thermal DM

As mentioned earlier, the range of DM candidates spans more than 50 orders of magnitude of mass. In this subsection, I will briefly mention some of the candidates despite the rest of the thesis does not address them. They are mentioned in an attempt of completeness, though the reader might find a more comprehensive review in [33].

Primordial black holes (PBHs) are black holes formed from overdensities in the early Universe. The interest in this possibility surged following the discovery of gravitational waves from mergers of tens of solar mass black hole binaries by LIGO-Virgo. Unlike WIMPs, PBH can emit gravitational waves that interact with regular matter, and their existence in the early universe could explain some observed gravitational lensing effects that could not arise from ordinary matter. PBHs can produce dark matter non-thermally through their evaporation, with early matter domination leading to black hole formation that subsequently evaporates before big bang nucleosynthesis, potentially producing dark matter in the $100 \text{ GeV}/c^2 - 10 \text{ TeV}/c^2$ mass range [34, 35].

Sterile neutrinos were proposed in 1993 as an additional neutrino species without the electroweak interactions of SM neutrinos, which could be produced in the early Universe through oscillations of SM neutrinos. One production mechanism involves sterile neutrinos in the $100 \text{ eV}/c^2$ to $10 \text{ keV}/c^2$ mass range produced via lepton number-driven resonant MSW

(Mikheyev-Smirnov-Wolfenstein) conversion of active neutrinos, resulting in a non-thermal energy spectrum that allows these particles to revert to non-relativistic kinematics at an early epoch [36]. Sterile neutrinos with masses of a few keV/c^2 are common warm dark matter candidates, as they freeze out before reaching thermal equilibrium and their properties are consistent with astrophysical bounds from structure formation.

Bosonic DM candidates can be very light with an upper bound of $60 \text{ keV}/c^2$ with an unrestricted lower bound. They are long-lived, making them good candidates for DM. QCD Axions stand out the most in this class since they also could solve the strong CP problem, if their mass lies within the range of $10^{-3} - 10^{-6} \text{ eV}/c^2$ by the Peccei-Quinn solution [37]. Recent experimental constraints from the Axion Dark Matter eXperiment (ADMX) using an ultralow noise Josephson parametric amplifier cavities have excluded axions with masses between 2.64 to $5.4 \mu\text{eV}/c^2$ at 90% confidence level, assuming a SHM [38]. This experiment aims to extend the range by deploying multiple cavities in hopes of widening the mass range.



Figure 1-10. Summary of possible DM candidates. The visualization is adapted from [33]. This visualization is inclusive or exclusive of all remaining DM candidates; rather, it lists some of the ones with active contributions in the community.

CHAPTER 2

DARK MATTER DIRECT DETECTION

In this chapter, I will discuss the main concepts for direct detection of thermal D,M including basic target choices, excitation signals, and the working principle of several existing experiments. The will then end with detector physics for the SuperCDMS experiment.

2.1 Target Material Selection

The choice of target material in direct detection experiments is constrained by the kinematics of elastic DM-target scattering. For simplicity, I will focus on DM-nucleus scattering. When calculating the integral expected rate from equation 1-18 given the maximum recoil energy discussed in equation 1-19, we can see that heavier targets are always better. We, however, have neglected a key factor, which is the experimental energy threshold.

Realistically, the lower bound for the integral rate is not set to zero, since each experiment has to set its own threshold. Below this threshold, the confidence in either event reconstruction or discrimination from backgrounds cannot be guaranteed. Typically, larger target experiments (like noble gases) have a higher energy threshold. Also, as discussed earlier, lighter targets maximize the energy transfer for the light candidate case. Additionally, for a larger target, the form factor is severely diminished, resulting in a smaller rate. This presents a trade-off between exposure and sensitivity.

For light WIMP masses in the sub-GeV to few-GeV range, experiments favor lighter target nuclei such as silicon and germanium. Silicon, with atomic mass $A = 28$, is employed by the SuperCDMS and DAMIC collaborations and provides optimal sensitivity for WIMPs in the mass range $m_\chi \sim 1\text{--}10 \text{ GeV}/c^2$. Lighter targets enable detectors to achieve lower energy thresholds, with SuperCDMS demonstrating thresholds as low as $\sim 30 \text{ eV}$ nuclear recoil energy in silicon for large-scale detectors [39].

Germanium, with atomic mass $A = 73$, represents an intermediate target material utilized by SuperCDMS, CDEX, and EDELWEISS experiments [19, 22]. Germanium provides sensitivity to WIMPs in the mass range $m_\chi \sim 5\text{--}100 \text{ GeV}/c^2$, offering a compromise between the advantages of

light and heavy targets. A key advantage of this substrate is its mature technology of crystal growth. This has enabled the production of ultra-pure crystals with minimal contamination.

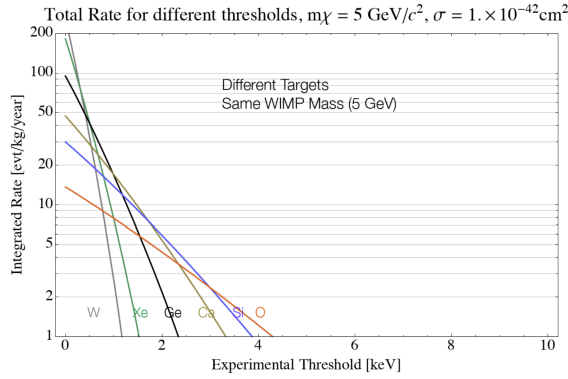
For high-mass WIMPs above $m_\chi \sim 10 \text{ GeV}/c^2$, the field is dominated by liquid noble gases. Xenon, with atomic mass $A = 131$, can be used to construct multi-tonne liquid detectors maximizing target exposures. Xenon is employed by the LZ, XENONnT, and PandaX-4T collaborations. Liquid argon represents another noble liquid approach, with the DarkSide-20k experiment exploiting argon depleted in the cosmogenic ^{39}Ar isotope. Argon, with atomic mass $A = 40$, targets WIMPs in the mass range $m_\chi \sim 10\text{--}1000 \text{ GeV}/c^2$. The scintillation pulse shape in liquid argon differs between nuclear and electron recoils due to different populations of singlet and triplet excited states, enabling pulse-shape discrimination as an additional background rejection tool [22, 40].

Several experiments employ sodium iodide crystals, particularly to test the annual modulation signal reported by the DAMA/LIBRA collaboration. The ANAIS and COSINE experiments use NaI scintillating crystals with the same target material as DAMA to perform an independent test of the modulation signature [17].

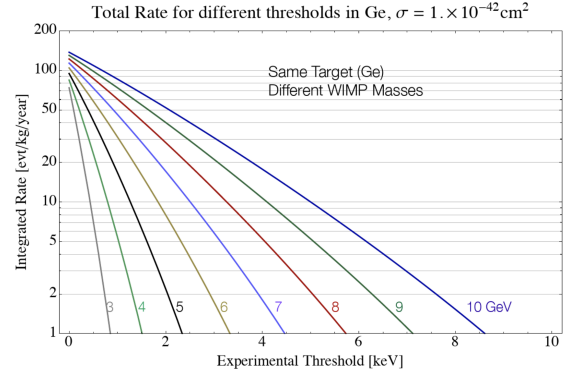
This physics and the large possible mass range motivate a complementary approach. Heavy targets for high-mass DM searches, while light targets for lighter candidates. The multi-target strategy employed by the dark matter community ensures comprehensive coverage of theoretically motivated parameter space across four orders of magnitude in DM mass.

2.2 Excitation Channels

The deposited energy is partitioned among multiple excitation channels depending on the target properties. DM-nucleus interactions produce three primary signals: ionization, scintillation, and heat (lattice vibrations). Each channel carries distinct information about the interaction, and combining them enables background rejection. Figure 2-2 summarizes direct detection experiments with their underlying signals.



(a) Different target.



(b) Different masses.

Figure 2-1. Variation of event rates with energy threshold for (Left) different targets with fixed masses and (right) different low WIMP masses with Ge target. The experimental thresholds on the x-axis are just absolute values and are not related to the possible experimental setup. We notice that for Xe to be more competitive for such a low mass candidate, the threshold has to be below 1 keV. Figures are courtesy of Enectali Figueroa-Feliciano.

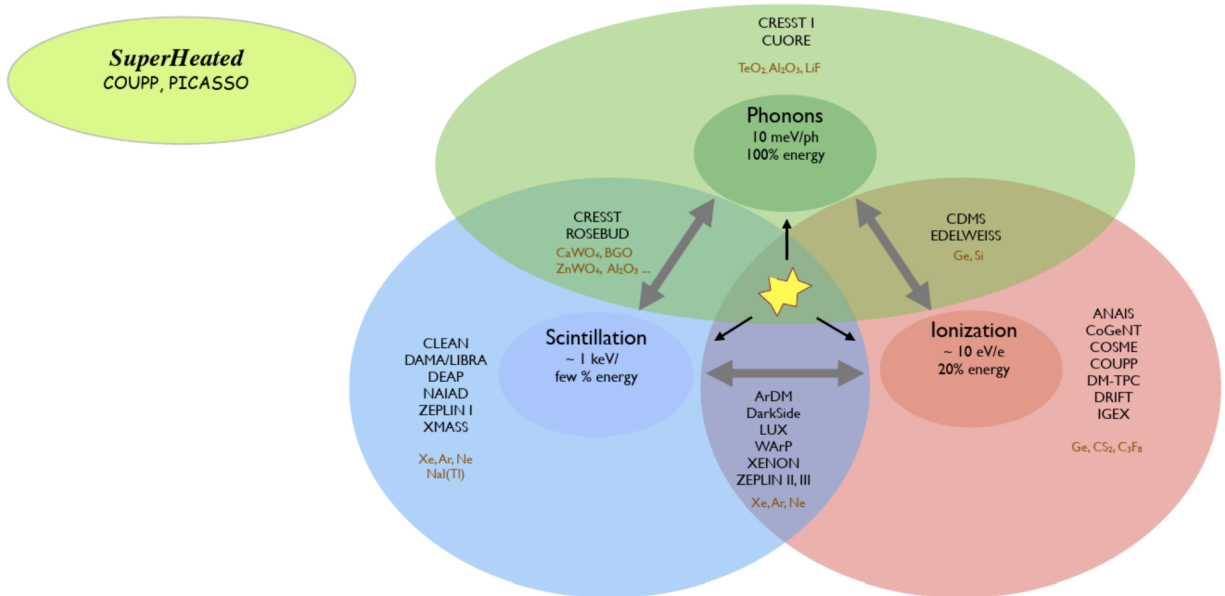


Figure 2-2. Summary of excitation channels possible for DM-nucleus and DM-electron recoils. Figure is adapted from [22].

2.2.1 Scintillation Signal

In noble liquid detectors such as liquid xenon and liquid argon, particle interactions produce prompt scintillation light through the formation and decay of excimer states. When energy is deposited in the liquid, atoms are excited or ionized. Excited atoms and electron-ion pairs can combine to form temporary diatomic molecules (excimers) in either singlet or triplet configurations. These excimers decay, emitting photons.

The number of scintillation photons produced is given by

$$N_\gamma = \frac{E_R}{W_{ph}} \cdot (S_{ee}/S_{nr}), \quad (2-1)$$

where W_{ph} is the mean energy per scintillation photon and S_{ee}/S_{nr} represents the relative scintillation efficiency for electron recoils versus nuclear recoils.

The measurement of scintillation light is done by arrays of photomultiplier tubes (PMTs) or silicon photomultipliers (SiPMs) that surround the detector in a time projection chamber (TPC). The decay time of the scintillation pulse contains information about the type of interaction. In liquid argon, this difference is particularly pronounced, with singlet states decaying with ~ 6 ns time constants and triplet states decaying with ~ 1.6 μ s time constants. Nuclear recoils produce a higher fraction of triplet states compared to electron recoils, resulting in scintillation pulses with longer tails. This pulse shape variation provides a strong tool for background discrimination [40].

In liquid xenon detectors operated in dual-phase mode, ionization electrons that escape recombination are accelerated upward through the liquid into a thin gas layer above the liquid surface, causing them to produce secondary scintillation light. The secondary pulse (S2) is detected by the same PMT arrays and is proportional to the ionization charge, while the primary scintillation signal (S1) is proportional to the total energy. The ratio between the pulses can discriminate between nuclear recoils and electron recoils [41].

2.2.2 Ionization

When a particle deposits energy E_R in a semiconductor crystal, a fraction of this energy is converted into electron-hole pairs through impact ionization. The energy partitioned into ionization is described by the ionization yield $y(E_R)$:

$$E_{\text{ion}} = E_R \cdot y(E_R) \quad (2-2)$$

The ionization yield depends on the type of recoiling particle, with electron recoils exhibiting $y_{\text{ER}} \approx 1$ (nearly all energy goes into ionization) while nuclear recoils have $y_{\text{NR}} < 1$. This difference in ionization efficiency forms the basis for discriminating nuclear recoils from DM signals from electron recoil backgrounds.

The number of electron-hole pairs created by the ionization energy is determined by the average energy required to produce one electron-hole pair ϵ :

$$N_{e/h} = \frac{E_{\text{ion}}}{\epsilon}. \quad (2-3)$$

At the cryogenic operating temperatures of SuperCDMS detectors (~ 15 mK), the mean ionization energy is $\epsilon_{\text{Si}} = 3.8$ eV for Si and $\epsilon_{\text{Ge}} = 3.0$ eV for Ge. These values are slightly higher than room-temperature values. This is due to thermal contraction during cool-down that shifts the band gap.

The measurement of the ionization signal proceeds by applying a bias voltage across the crystal. The electric field drifts the electron-hole pairs to the collection electrodes on the surface of the detector. The collected charges induce a spike current in the readout electrodes to produce a voltage pulse proportional to the total collected charge.

2.2.3 Heat Signal

Superheating technology is usually deployed in bubble chambers. Typically, targets are kept at very high pressures and temperatures. When DM particle scatters off the substrate, the substrate boils, resulting in small bubbles. The chambers are constantly imaged. The images are

then analyzed for energy reconstruction. PICO collaboration has demonstrated that this technology can present a competitive limit on WIMPs [22, 1, 19].

Phonons detection is another crucial signal used for DM, especially in cryogenic detectors like SuperCDMS experiments. At the millikelvin, thermal phonon populations are negligible, and the phonon system can act as a sensitive bolometer that measures the total energy deposited by particle interactions. The phonon signal consists of three distinct components: primary phonons, recombination phonons, and Luke phonons.

2.2.3.1 Primary Phonons

The fraction of deposited energy not converted into ionization is immediately released as high-frequency phonons. These primary phonons carry energy:

$$E_{\text{primary}} = E_R \cdot [1 - y(E_R)], \quad (2-4)$$

For nuclear recoils with an ionization yield of $y \sim 0.3$, approximately 70% of the recoil energy is converted into primary phonons. For electron recoils with $y \approx 1$, nearly all energy initially goes into ionization.

The primary phonons generated by particle interactions are athermal, with frequencies typically in the terahertz. These phonons propagate through the crystal at a fraction of the speed of sound, which is approximately $v_s \sim 5$ km/s in Si. As phonons propagate through the crystal, they undergo multiple reflections at the surfaces, ions, and impurities. Through these quasi-elastic reflections, phonons gradually down-convert in frequency, populating lower-energy states at a rate proportional to f^5 [42]. Eventually, phonons reach the detector surfaces where they are absorbed, which converts the phonon energy into measurable electrical signals.

2.2.3.2 Recombination Phonons

The electron-hole pairs created by ionization carry energy E_{ion} that is temporarily stored in the electronic system. In the absence of an applied voltage or after charge collection in biased detectors, these charge carriers eventually recombine. When an electron and a hole recombine,

they release their remaining kinetic energy along with the band gap energy. The total energy is emitted as phonons:

$$E_{\text{recomb}} = E_{\text{ion}} = E_R \cdot y(E_R). \quad (2-5)$$

Similar to the primary phonons, the recombination phonons do not travel ballistically. There is also a delay between the emission of these phonons, which depends on the recombination site. That is why these phonons contribute to the extended tail in the pulse shape. This effect, however, is highly pronounced since the range of delay is of the order of $O(\mu s)$.

The total energy measured by the phonon system is the sum of primary and recombination components if there is no voltage bias applied:

$$E_{\text{phonon}}^{0V} = E_{\text{primary}} + E_{\text{recomb}} = E_R[1 - y(E_R)] + E_R y(E_R) = E_R. \quad (2-6)$$

This energy conservation ensures the phonon measurement provides a calorimetric determination of the recoil energy, independent of the partition between ionization and phonon energy.

2.2.3.3 Luke Phonons and the Neganov-Trofimov-Luke Amplification

In high-voltage detectors, an electric field is applied across the substrate to drift charge carriers toward collection electrodes or the surface. As electrons and holes drift through the crystal, they gain kinetic energy from the applied field. This kinetic energy is continuously dissipated into the lattice through phonon emission. Each charge carrier, as it drifts through the potential difference, converts its gained potential energy into phonons. This process, known as the Neganov-Trofimov-Luke (NTL) effect [43], generates Luke phonons with total energy

$$E_{\text{Luke}} = N_{e/h} \cdot eV = \frac{E_{\text{ion}}}{\epsilon} \cdot eV \quad (2-7)$$

where e is the elementary charge, V is the applied voltage, and ϵ is the mean ionization energy. The Luke phonon energy is proportional to both the ionization signal and the applied voltage.

The NTL mechanism provides significant amplification of the ionization signal. For typical high-voltage Ge detectors operated at $V \sim 100$ V with $\epsilon \sim 3$ eV, the amplification factor is ~ 30 . This amplification is the key to achieving ultra-low energy thresholds in SuperCDMS HV detectors.

The total phonon energy measured in a high-voltage detector includes all three components:

$$E_{\text{phonon}}^{\text{HV}} = E_{\text{primary}} + E_{\text{recomb}} + E_{\text{Luke}} = E_R[1 - y(E_R)] + E_R y(E_R) + \frac{E_R y(E_R)}{\epsilon} \cdot eV \quad (2-8)$$

This simplifies to

$$E_{\text{phonon}}^{\text{HV}} = E_R \left[1 + y(E_R) \cdot \frac{eV}{\epsilon} \right] \quad (2-9)$$

For a nuclear recoil with $E_R = 10$ eV and $y \sim 0.3$, the total phonon signal is approximately 110 eV, well above typical phonon baseline noise levels of ~ 70 eV. This amplification enables the detection of recoil energies that would be completely buried in noise in a zero-bias detector.

It is important to note that full NTL amplification occurs only during the charge drift across the entire lattice. Near detector surfaces or edges where electric field non-uniformities exist, incomplete charge collection leads to reduced Luke phonon signals. Similarly, if charge carriers become trapped at crystal defects or impurities, the full Luke phonon energy is not achieved.

2.2.4 Ionization Yield

We have used the ionization yield in the last section without formally modeling it. As defined in equation 2-2, it is the ratio of ionization energy to total recoil energy. Until a decade ago, the Lindhard model was the most widely accepted. The model focuses on the partition of energy between electronic and nuclear stopping.

The model assumes electrons' share of initial energy deposition is negligible, and most of the energy goes to the nucleus. The model treats the slowing-down process of the nucleus as a cascade of successive collisions, where the recoiling ion loses energy through two competing mechanisms: inelastic collisions with electrons producing ionization (coined as electronic

stopping) and elastic collisions with other ions (referred to as nuclear stopping). The rates of these mechanisms are computed given that the electrons produce minimal electronic recoil, and the binding energy is much smaller than the deposited energy and can be neglected [44, 45].

The Lindhard model can be formulated as

$$y(E_R) = \frac{k g(\varepsilon)}{1 + k g(\varepsilon)}, \quad (2-10)$$

where the material-dependent parameter is $k = 0.133Z^{2/3}A^{-1/2}$, and the energy-dependent function is $g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon$. The dimensionless energy variable is defined as $\varepsilon = 11.5E_RZ^{-7/3}$, where E_R is expressed in keV and Z is the atomic number. At low recoil energies ($E_R < 1$ keV), the Lindhard yield varies approximately as $y \propto E_R^{0.15}$, decreasing slowly as energy decreases.

Experimental measurements of ionization yield in silicon and germanium at low energies show deviations from the Lindhard prediction, with measured yields typically 10–30% lower than predicted [46, 47, 48]. In the latter part of this thesis, I will discuss a measurement of the yield down to 100 eV of recoil energy, reaffirming deviations

CHAPTER 3 SUPERCDMS DETECTOR DESIGN AND CONCEPT

The SuperCDMS experiment employs silicon and germanium targets operated at millikelvin temperatures, covered with superconducting transition-edge sensors (TES) for phonon detection. Three distinct detector designs have been developed to optimize sensitivity across different WIMP mass ranges: iZIP (interleaved Z-sensitive Ionization and Phonon) detectors provide excellent background rejection for WIMP masses, HV (High Voltage) detectors extend sensitivity down with improved thresholds through maximum Luke phonon amplification, and HVeV (High Voltage eV-resolution) prototype detectors achieve world-leading sensitivity to sub-GeV WIMPs.

3.1 SuperCDMS Detector Technologies

3.1.1 Transition-Edge Sensors

All SuperCDMS phonon measurements rely on transition-edge sensors (TES), a thin film of tungsten biased at near superconductivity. The idea exploits the steep resistance-temperature relationship in the superconducting-to-normal transition region. A single tungsten TES film has dimensions typically $20\ \mu\text{m} \times 2.5\ \mu\text{m} \times 40\ \text{nm}$ patterned on the detector surface. The critical temperature of the tungsten film is tuned to approximately $T_c \sim 45\ \text{mK}$, which is above the crystal temperature of $\sim 15\ \text{mK}$ [39].

Along the TES, SuperCDMS implements a thin superconducting Al film between the crystal and the TES, creating a Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge sensors (QETs) device. When the athermal phonons propagate to the Al film, they break Cooper pairs, which get collected by the TES, improving energy collection (see Figure 3-1) [49, 50, 51, 52].

The TESs are operated in the transition region since this region of the transition curve is relatively linear in the small signal approximation, which simplifies event energy reconstruction. The TES resistance varies steeply with temperature as parametrized with $\alpha \equiv \partial \ln R / \partial \ln T$ [53]. This high sensitivity enables the detection of small energy depositions.

When a phonon deposits energy in the QET, the temperature rises and the resistance increases. The increased resistance reduces the current (at fixed voltage bias), and this current

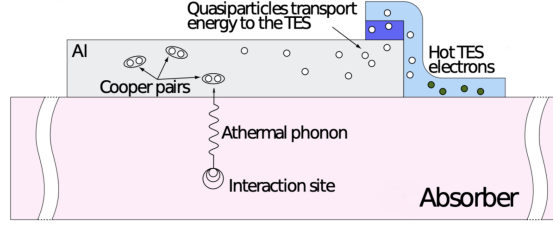


Figure 3-1. A general schematic of detector physics with the top plot showing propagation of phonons to the TESs.

decrease is measured by the SQUID as a voltage pulse. The magnitude of the current change is proportional to the phonon energy absorbed.

The fixed voltage bias configuration creates an electrothermal feedback (ETF), stabilizing the sensor. When the TES temperature increases due to either phonon absorption or a thermal fluctuation, the resistance increases, causing the Joule power $P = V^2/R$ to decrease. This reduced heating, creating negative feedback.

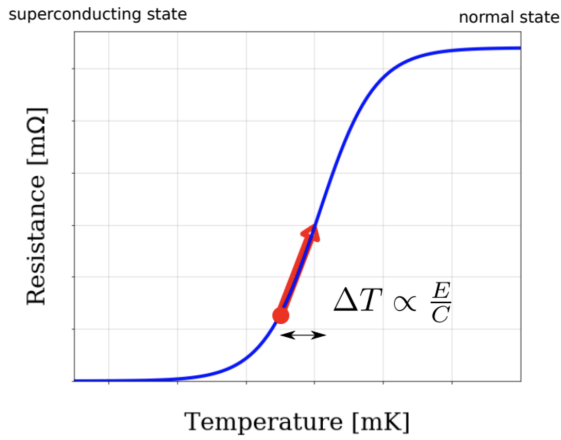
The energy resolution of a TES is limited by thermal fluctuation noise arising from the exchange of phonons between the sensor and the heat bath. The thermal fluctuation noise power is given by

$$N_{\text{TFN}}^2 = 4k_B T^2 G \quad (3-1)$$

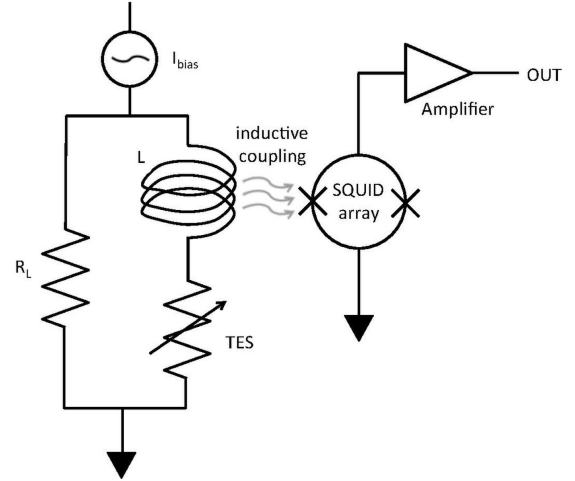
where k_B is Boltzmann's constant, T is the operating temperature, and G is the thermal conductance between the sensor and the heat sink. Integrating this noise power over the effective measured signal gives the energy resolution:

$$\sigma_E^2 = c k_B \frac{V T^2}{\epsilon^2} \quad (3-2)$$

where ϵ is the energy transfer efficiency, c is the specific heat, and V is the volume of the TESs. This relation highlights the tradeoff needed when designing a detector; the bigger the volume of the TES, the lower the operation temperature has to be. More details can be found in Appendix E in [50]. For SuperCDMS, detectors target a baseline energy resolution of



(a) TES transition curve.



(b) TES signal readout.

Figure 3-2. Demonstration of (left) TES transition curve and (right) readout.

approximately $\sigma_E \sim 50$ eV and ~ 30 eV for germanium and silicon detectors, respectively [39].

Additional noise sources include Johnson noise from the resistance of the TES and readout electronics, amplifier noise from the SQUID, and electrical interference from the experimental environment.

An interesting feature of the TES design is the pulse shape is independent of the energy deposited in the small pulse approximation. This is because the rise time is dominated by the LR circuit time constant, while the fall time relies on the thermal conductance and heat capacity ($\tau_{fall} \propto \frac{C}{G_{eff}}$). This enables a simple, rigorous event energy reconstruction. I refer the reader to [53], [50] and [54] for more detailed analysis of pulse shapes.

3.1.2 iZIP Detectors

The interleaved Z-sensitive Ionization and Phonon (iZIP) detector combines ionization charge along with phonon collection. This enables powerful discrimination between nuclear recoil signals and electron recoil backgrounds. Each iZIP detector consists of a crystal with a diameter of 100 mm and a thickness of 33.3 mm, resulting in masses of approximately 1.4 kg for germanium and 0.6 kg for silicon.

Both the top and bottom surfaces of the crystal are covered with phonon sensors and charge electrodes arranged in an interleaved pattern. The phonon side of each face contains six TES

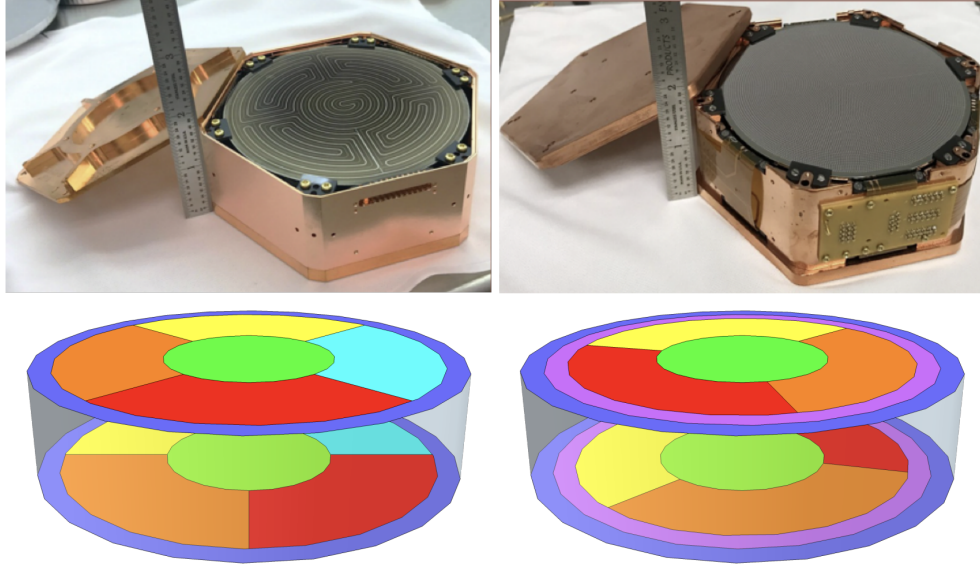


Figure 3-3. (Left) iZIP. (Right) HV. (Top) detectors in their housings. (Bottom) Channel layout. Each channel contains hundreds of lithographically defined QETs. The wedge channels on the bottom surface are rotated by 45deg with respect to those on the top for iZIP detectors and 60deg for HV detectors.

sensor channels that could provide position-sensitive phonon detection. Each channel consists of approximately 1000 individual TES elements connected in parallel. The charge electrodes are split into inner and outer electrodes that resemble a series of concentric rings. This electrode geometry is replicated on both detector faces but in reverse polarity.

The surface event rejection is enabled by the asymmetric charge collection that occurs for near-surface interactions. When a particle interacts within a few micrometers of one detector surface, the ionization charge is created very close to the electrodes on that face. As a result, charge collection on the interaction face near the interaction site is dominant. For bulk interactions, charges on both faces drift across the entire crystal, resulting in symmetric collection on top and bottom faces.

3.1.3 HV Detectors

The High Voltage(HV) detector design is an evolution of the iZIP concept to maximize sensitivity to low mass WIMPs by incorporating voltage amplification. HV detectors use the same

crystal dimensions as iZIP (100 mm diameter, 33.3 mm thickness) and expand the phonon channel segmentation to 12 channels (6 per face).

A voltage difference of 50–100 V is applied between the two faces, creating a uniform electric field of approximately 15–30 V/cm throughout the crystal volume. This aims to maximize NTL amplification while avoiding dielectric breakdown.

In HV detectors, NTL amplification is a factor ~ 30 larger than the direct phonon signal. Since the phonon collection has excellent baseline resolution, the threshold is significantly improved over iZIP. For instance, nuclear recoil events with energies as low as 100 eV produce phonon signals of approximately 500 eV, well above the baseline noise. The lower threshold extends WIMP sensitivity to masses approaching $1 \text{ GeV}/c^2$.

The HV design’s excellent sensitivity comes with a compromise. The high voltage creates the possibility of incomplete charge collection, particularly near detector sidewalls where field non-uniformities occur. Events with incomplete charge collection have reduced Luke phonon signals, which can lead to systematic uncertainties in energy reconstruction. Additionally, the strong electric field can cause charge trapping at crystal defects, preventing some carriers from contributing to the Luke phonon signal. Figure 3-4 demonstrates some of the possible scenarios for charge propagation. The twelve-channel phonon readout aims to preserve position information. This could enable fiducialization, rejecting events with less-than-ideal amplification.

3.1.4 HVeV Detectors

The High Voltage eV-resolution (HVeV) prototype detector design represents a possible optimization for maximum sensitivity to low-mass WIMPs. The crystal geometry of HVeV detectors differs significantly from iZIP and HV. It uses thin crystals with a size of only $10 \times 10 \times 4 \text{ mm}^3$ [55]. The reduced thickness decreases the charge drift distance, ensuring more complete charge collection at high applied voltages.

The phonon readout of HVeV detectors is also simplified compared to iZIP and HV. Two TES channels cover only one surface of the detector. Like HV detectors, HV detectors employ NTL amplification with an applied voltage is typically 100–150 V [55, 56].

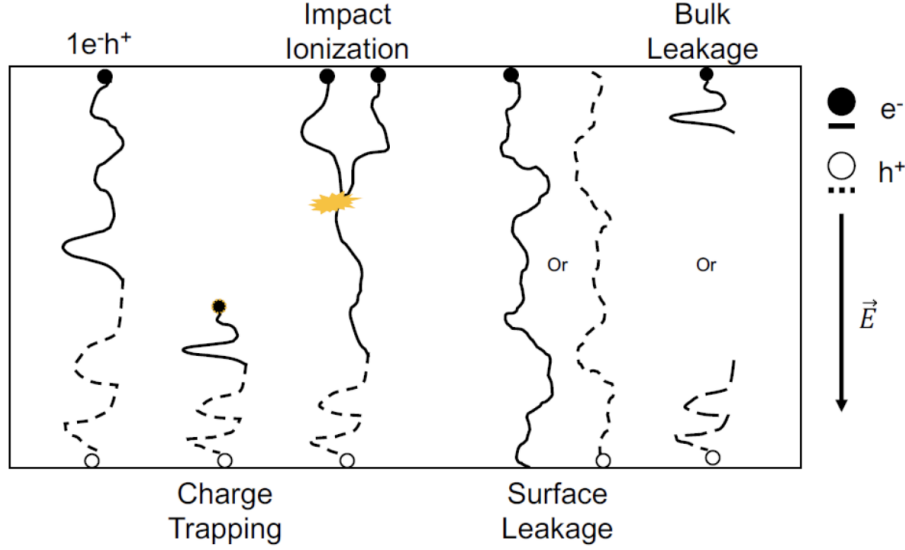


Figure 3-4. Possible scenario of what charges can experience in the crystal. The nominal behavior is shown at the left-most graph, while charge trapping (CT), impact ionization (II), and leakage are demonstrated.

The reduced overall TES volume improves the baseline resolution, significantly improving the analysis threshold. Recent HVeV science runs have shown an impressive resolution of $\sim O(1)$ eV [57]. This provides a competitive edge in the search for ERDM candidates. Deployment of several HVeV detectors is hypothesized to improve the sensitivity also for low-mass nuclear recoil candidates significantly [39].

3.2 Signal Processing: Optimal Filtering

Since the pulse shape does not change within the amplitude range of interest ignoring position dependence, SuperCDMS employs optimal filtering techniques based on matched filter theory. The optimal filter is designed to maximize the signal-to-noise ratio by weighting frequency components according to their signal content and noise power. Two variants are employed: single-channel (1×1) optimal filtering for independent channel analysis, and multi-channel-multi-template ($N \times M$) optimal filtering that exploits noise correlations between channels and possible pulse shape variation to improve performance.

3.2.1 Single-Channel Optimal Filter

Consider a measured time-series $d(t)$ that contains a signal pulse $s(t)$ with unknown amplitude A plus additive noise $n(t)$:

$$d(t) = A \cdot s(t) + n(t) \quad (3-3)$$

The signal pulse has a known shape (the template) but unknown amplitude, which is proportional to the deposited energy. The noise is assumed to be stationary and Gaussian with known power spectral density $J(f)$. The goal is to estimate the amplitude A from the measured data $d(t)$ in a way that minimizes a frequency-domain χ^2 described by equation 3-5.

The optimal filter is typically most expressed in the frequency domain. Taking Fourier transforms of the data, signal, and noise gives

$$\tilde{d}(f) = A \cdot \tilde{s}(f) + \tilde{n}(f), \quad (3-4)$$

$$\chi^2 = \int_{-\infty}^{\infty} \frac{|\tilde{d}(f) - A\tilde{s}(f)|^2}{J(f)} df \quad (3-5)$$

where tildes denote Fourier transforms. Minimizing χ^2 yields an amplitude:

$$\hat{A} = \frac{\int \tilde{s}^*(f) \tilde{d}(f) / J(f) df}{\int |\tilde{s}(f)|^2 / J(f) df} \quad (3-6)$$

implying the filter can be expressed as $\tilde{\phi}(f)$:

$$\tilde{\phi}(f) = \frac{\tilde{s}^*(f)}{J(f)} \quad (3-7)$$

The variance of this estimator is

$$\sigma_A^2 = \left[\frac{1}{2} \frac{\partial^2 \chi^2}{\partial A^2} \right]^{-1} = \int_{-\infty}^{\infty} |\tilde{\phi}(f)|^2 J(f) df \quad (3-8)$$

which achieves the minimum possible variance given a Gaussian noise with the signal-to-noise ratio of:

$$\text{SNR}^2 = \int \frac{|\tilde{s}(f)|^2}{J(f)} df \quad (3-9)$$

This filter, in an intuitive form, weights each frequency component of the signal template by the inverse of the noise power at that frequency. Frequencies with large signal content and low noise receive high weight, while frequencies with small signal or large noise are suppressed.

So far, we assumed we have the pulse and template aligned. This is not the case in general. The time shift propagates as a phase in the frequency domain. The calculation tracks the same steps with minimal computational complexity, with an amplitude of:

$$\hat{A} = \frac{\int e^{i\omega t_0} \tilde{s}^*(f) \tilde{d}(f) / J(f) df}{\int |\tilde{s}(f)|^2 / J(f) df} \quad (3-10)$$

where t_0 is the time delay. In practice, the implementation of optimal filtering proceeds as follows:

- a pulse template is generated by averaging many high-signal-to-noise calibration pulses. The pulses are aligned in time by identifying a fiducial point, such as the peak or a threshold crossing. The average is normalized to unit amplitude. The template is Fourier transformed to obtain $\tilde{s}(f)$.
- The noise power spectral density is estimated by computing the Fourier transform of many baseline (no-pulse) traces, squaring the magnitude, and averaging. This gives the estimate $\hat{J}(f) = \langle |\tilde{n}(f)|^2 \rangle$.
- For each event, the raw data trace is Fourier transformed and the optimal filter is applied in the frequency domain by computing the numerator and denominator integrals. In discrete implementation with sampling frequency f_s and N samples, the integrals become sums over the discrete Fourier transform bins.

A few assumptions were introduced implicitly along the way. The first is that the pulse template captures the pulse shape variation fully. This is difficult, especially for large detectors, because positional dependence may introduce pulse shape variation that is not TES-related. The second assumption is noise power spectrum measurement is Gaussian and captures the true noise characteristics of the detector and readout electronics. Realistically, cross-talk noise is sometimes significant and correlated across different channels. This is why NxM OF was introduced.

3.2.2 NxM Optimal Filtering

Since different channels are not independent; they share common noise sources, have cross-talk, and are subject to position-dependent pulse shape variations, a 1x1 OF becomes non-optimal leading to biased amplitude estimates and degraded energy resolution. The historical solution was to fit the summed pulse from all channels washing out position information. This, nevertheless, fails to account for correlated noise. Multi-channel multi-template (NxM) optimal filtering exploits the correlations between channels and accommodates pulse shape variations.

Consider a detector with N channels, each corresponding to the same physical event. The data prediction for channel c in the time domain with M templates is

$$\hat{d}_c(t) = \sum_{i=1}^M a_{ci} T_{ci}(t_c) \quad (3-11)$$

where T_{ci} is the i -th template for channel c , a_{ci} is its amplitude, and t_c is the time delay for that channel. All templates from the same channel share a common time delay t_c to avoid degeneracies with amplitude parameters that would result in unstable fits with multiple local minima.

The time delays themselves carry position information. For large detectors, the time required for phonons to propagate from the interaction site to different sensors vary considerably. For a SuperCDMS SNOLAB HV detector (100 mm diameter, 33.33 mm thick) with phonon velocities of approximately 5 km/s, the time delay difference between channels can reach 25 μ s, corresponding to roughly 16 time bins at the 625 kHz sampling rate. This time delay variation is one of the most sensitive probes of event position.

The Fourier transform of a time-shifted template $T(t - t_c)$ is $\tilde{T}(f)e^{-2\pi i f t_c}$, which rotates the complex Fourier coefficients by angle $\phi = 2\pi f t_c$. To handle this while maintaining a real covariance formalism, we construct a data vector $\tilde{\mathbf{d}}_f$ of length $2N$ containing alternating real and imaginary components from all channels:

$$\tilde{\mathbf{d}}_f = \begin{pmatrix} \text{Re}(\tilde{d}_1) \\ \text{Im}(\tilde{d}_1) \\ \text{Re}(\tilde{d}_2) \\ \text{Im}(\tilde{d}_2) \\ \vdots \\ \text{Re}(\tilde{d}_n) \\ \text{Im}(\tilde{d}_n) \end{pmatrix} \quad (3-12)$$

The time shift is then implemented as a phase rotation through a block-diagonal rotation matrix $\mathbf{R}(\vec{t})$ of size $2N \times 2N$:

$$\mathbf{R}(\vec{t}) = \begin{pmatrix} \cos \phi_1 & \sin \phi_1 & & & \mathbf{0} \\ -\sin \phi_1 & \cos \phi_1 & & & \\ & & \ddots & & \\ & & & \cos \phi_n & \sin \phi_n \\ \mathbf{0} & & & -\sin \phi_n & \cos \phi_n \end{pmatrix} \quad (3-13)$$

where $\phi_c = 2\pi f t_c$. Each 2×2 block rotates the real and imaginary components of channel c by the appropriate phase.

The template matrix $\tilde{\mathbf{T}}_f$ has size $2N \times (N \times M)$ and contains the real and imaginary parts of all Fourier-transformed templates arranged in a block-diagonal structure. The model prediction is then

$$\hat{\mathbf{d}}_f = \mathbf{R}(\vec{t}) \cdot \tilde{\mathbf{T}}_f \cdot \vec{a} \equiv \mathbf{A}_f \cdot \vec{a} \quad (3-14)$$

where $\mathbf{A}_f = \mathbf{R}(\vec{t}) \cdot \tilde{\mathbf{T}}_f$ is a $2N \times (N \times M)$ matrix that projects the fit parameters onto the predicted data.

The noise is characterized by a $2n \times 2n$ real, symmetric covariance matrix $\mathbf{V}_f$ at each frequency. This matrix encodes both auto-correlations within each channel and cross-correlations between channels:

$$\mathbf{V}_f = \begin{pmatrix} J_{11}^{\text{RR}} & J_{11}^{\text{RI}} & J_{12}^{\text{RR}} & J_{12}^{\text{RI}} & \cdots \\ J_{11}^{\text{IR}} & J_{11}^{\text{II}} & J_{12}^{\text{IR}} & J_{12}^{\text{II}} & \cdots \\ J_{21}^{\text{RR}} & J_{21}^{\text{RI}} & J_{22}^{\text{RR}} & J_{22}^{\text{RI}} & \cdots \\ J_{21}^{\text{IR}} & J_{21}^{\text{RI}} & J_{22}^{\text{IR}} & J_{22}^{\text{II}} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}_f, \quad (3-15)$$

where J_{ij}^{RR} represents the covariance between the real parts of channels i and j , J_{ij}^{RI} represents the covariance between the real part of channel i and the imaginary part of channel j , and so forth.

Critically, the real covariance formulation preserves correlations between the real component of one channel and the imaginary component of another which are correlations that reflect time delay differences between channels and would be missed or miscounted by a simple complex covariance matrix formulation.

Treating the real and imaginary parts of the data residual as independent measurements, the χ^2 at a single frequency is

$$\chi_f^2 = (\tilde{\mathbf{d}}_f - \mathbf{A}_f \cdot \vec{a})^T \mathbf{V}_f^{-1} (\tilde{\mathbf{d}}_f - \mathbf{A}_f \cdot \vec{a}). \quad (3-16)$$

For stationary noise, the power spectral density does not change with time, and a key consequence is that noise is uncorrelated between different frequencies. This allows the covariance matrix between different frequencies to be zero, and the total χ^2 can be written as a sum over frequencies:

$$\chi^2(\vec{t}, \vec{a}) = \sum_f (\tilde{\mathbf{d}}_f - \mathbf{A}_f \cdot \vec{a})^T \mathbf{V}_f^{-1} (\tilde{\mathbf{d}}_f - \mathbf{A}_f \cdot \vec{a}) \quad (3-17)$$

The χ^2 depends non-linearly on the time delays but linearly on the amplitude parameters $\vec{a}$. A complete solution would require searching over all possible combinations of channel time delays—for a 12-channel detector with a ± 5 bin search window, this would require evaluating χ^2 approximately $12^{10} \approx 10^{11}$ times, which is computationally prohibitive. The standard approach is to use time delay estimates from single-channel optimal filter fits as fixed inputs to the NxM filter, reducing the problem to amplitude estimation only. There is a systematic uncertainty associated with this approximation, but it enables practical implementation.

With fixed time delays, minimizing χ^2 with respect to $\vec{a}$ yields an analytical solution. Taking the derivative and setting it to zero gives the optimal amplitude estimator:

$$\vec{a} = \left(\sum_f \mathbf{A}_f^T \mathbf{V}_f^{-1} \mathbf{A}_f \right)^{-1} \sum_f \mathbf{A}_f^T \mathbf{V}_f^{-1} \tilde{\mathbf{d}}_f \quad (3-18)$$

Since for uncorrelated white noise with equal noise power in each channel, the single-channel filter achieves a $\sqrt{N}$ improvement in amplitude resolution simply by combining information from N channels. When channels have correlated noise or cross-talk, as is typical in SuperCDMS detectors, the multi-channel filter performs even better by subtracting the correlated components. These better amplitude reconstruction and time-delay resolution enable fiducialization, allowing rejection of events near detector edges where charge collection or phonon collection may be degraded.

3.3 SuperCDMS SNOLAB: Configuration and Projected Sensitivity

The SuperCDMS SNOLAB experiment represents the next-generation deployment of SuperCDMS technology, designed to achieve world-leading sensitivity to low-mass WIMPs. The experiment is being installed in SNOLAB, a facility located 2 km beneath the surface in Sudbury, Ontario, Canada, which provides exceptional shielding from cosmic ray backgrounds.

3.3.1 Facility and Underground Location

SNOLAB occupies former mining caverns in the operational Creighton Mine of Vale Inco, at a depth of 2070 m below the surface. The overburden, taking into account the average density

of the rock, provides shielding equivalent to approximately 6000 meters water equivalent (m.w.e.). Figure 3-5 shows that the extreme depth reduces the cosmic ray muon flux by approximately seven orders of magnitude relative to the surface muon flux. The residual muons that reach the experimental halls at this depth are primarily high-energy muons from the tail of the cosmic ray spectrum, with typical energies exceeding 300 GeV.

The reduction in muon flux directly diminishes the radiogenic neutron background, one of the most challenging backgrounds for direct detection experiments. Muons traversing detector materials or surrounding rock can produce neutrons through spallation, photonuclear reactions, and muon capture. These neutrons can scatter elastically from detector nuclei, producing nuclear recoils that mimic WIMP signals. Combined with passive shielding, SuperCDMS SNOLAB expects fewer than one neutron-induced nuclear recoil per year in the signal region [58].

The SNOLAB facility also maintains strict contamination protocols, including underground cleanrooms, radon filtration systems, and materials screening programs, ensuring that detector components achieve the required radiopurity.

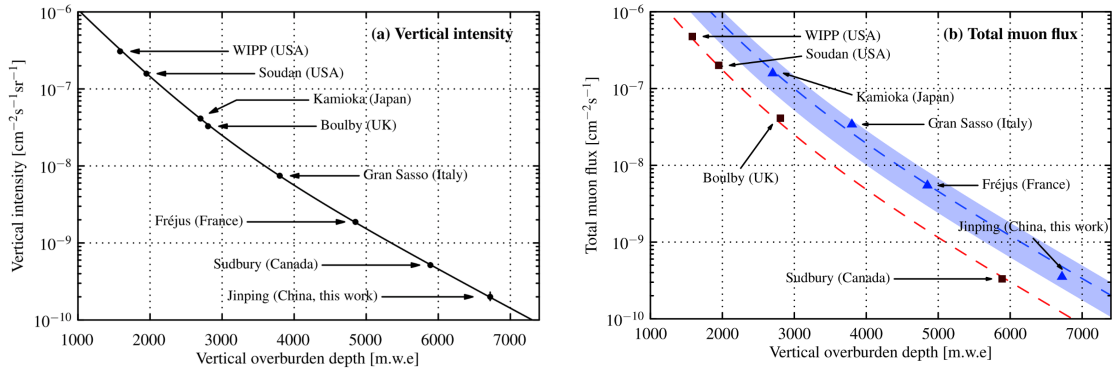


Figure 3-5. The vertical intensity (a) and total muon flux (b) at different underground laboratory sites. The red dashed line in (b) is the empirical formula for the down mine shaft case. The blue dashed line and shade in (b) are the fitting result and uncertainty. Figure is adapted from [58].

3.3.2 Detector Configuration and Target Masses

The SuperCDMS SNOLAB detector array comprises 4 detector towers with 2 distinct detector types. The total configuration will include 12 iZIP detectors and 12 HV detectors, distributed between silicon and germanium targets as shown in Figure 3-6.

The iZIP detector array forms the foundation for background studies. This array consists of 10 germanium iZIP detectors providing an exposure of 56 kg·year. Additionally, 2 silicon iZIP detectors contribute 4.8 kg·year of exposure.

The HV detector array extends sensitivity to lower WIMP masses in the range 1–10 GeV/ c^2 by employing NTL amplification to reduce thresholds. This array includes 8 germanium HV detectors (44 kg·year total) and 4 silicon HV detectors (9.6 kg·year total), operating at voltages of 100 V [49].

3.3.3 Cryogenic System and Shielding

The SuperCDMS SNOLAB installation is designed to operate under ultra-low background conditions. Hence, the shielding is multilayered, consisting of an outer water tank, active radon purge systems, ultrapure lead, and polyethylene layers. The entire apparatus is mounted on a seismic isolation platform to mitigate vibrational noise as demonstrated by Figure 3-7.

All SuperCDMS detectors operate at base temperatures around 15 mK, maintained by a custom-designed dilution refrigerator system. The innermost region, the SNOBOX, consists of nested copper cans housing the four detector towers. A detailed discussion of the experimental setup can be found in [39].

3.3.4 Expected Background Sources

The backgrounds are broadly categorized into radiogenic backgrounds arising from radioactive contamination, neutron backgrounds from both environmental and cosmogenic sources, and electromagnetic backgrounds from electrons and photons. The anticipated backgrounds fall into two categories. Bulk events occurring throughout the detector volume and surface events localized near detector faces.

Bulk backgrounds include detector contamination from cosmogenic tritium (^3H , 18.6 keV endpoint) produced by cosmic-ray exposure before deployment. In Si detectors, the naturally-occurring ^{32}Si also considerable (80^{+110}_{-65} decays/kg/day). Germanium detectors face additional cosmogenic activation producing electron-capture isotopes including ^{68}Ge , ^{65}Zn , and ^{73}As . External sources include radioactive contamination in construction materials (particularly

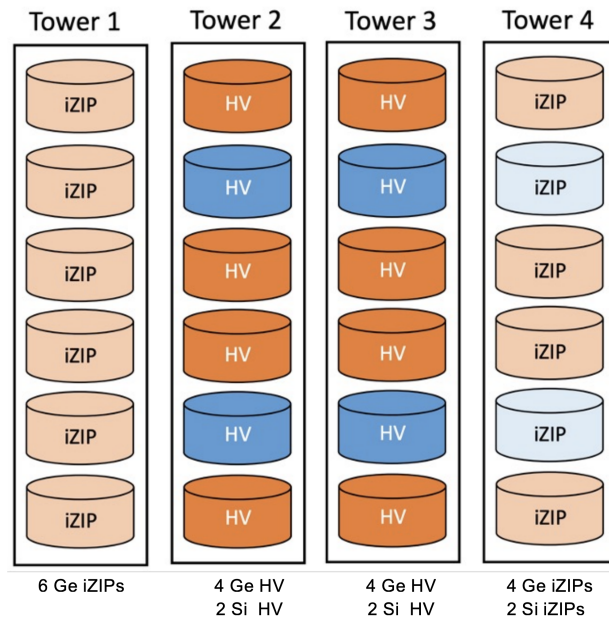


Figure 3-6. SuperCDMS SNOLAB detector Configuration. The detector tower arrangement with the type of target substrate indicated.

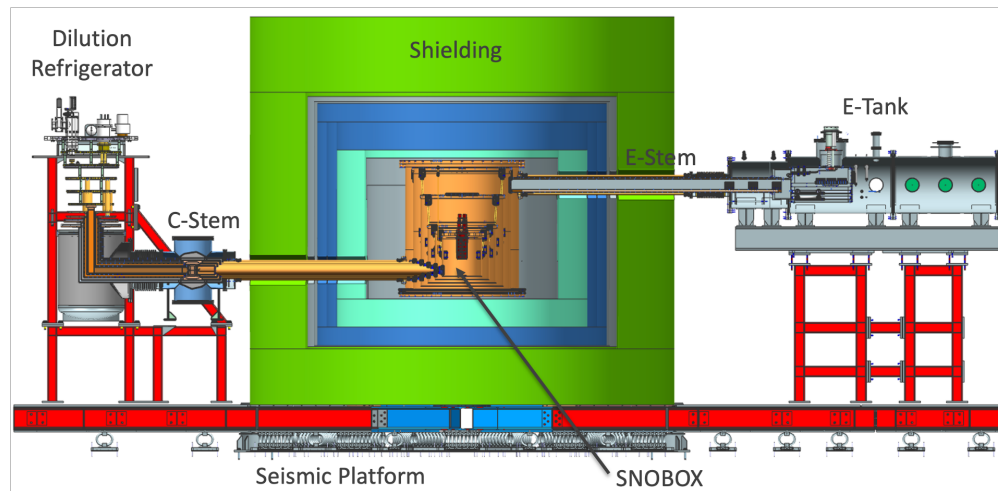


Figure 3-7. Overview of the SuperCDMS SNOLAB experiment setup. The assembly rests on top of a seismic platform to provide isolation from major seismic events. The outer water tanks provide protection from cavern neutrons. A gamma shield protects from external gamma-rays, and the inner polyethylene layers serve to absorb radiogenic neutrons emitted from the cryostat and gamma shield. Figure is adapted from [39]

copper components), environmental radioactivity from cavern walls and air (^{238}U , ^{232}Th , ^{40}K), and muon-induced neutrons in the overburden. At the lowest energies, coherent elastic neutrino-nucleus scattering from solar neutrinos represents a fundamental background floor for future low-mass searches, though they are not necessarily within the targeted sensitivity for the foreseeable runs.

Surface backgrounds arise primarily from ^{210}Pb contamination deposited during detector fabrication and handling when radon daughters plate out on exposed surfaces. The ^{210}Pb decay chain produces multiple signatures: ^{210}Pb itself yields low-energy betas and X-rays (63 keV endpoint), ^{210}Bi produces harder betas (1.16 MeV endpoint), and critically, ^{210}Po alpha decay creates ^{206}Pb nuclear recoils with 103 keV energy that can mimic WIMP signals if directed into the detector. Additional surface contamination from ^{14}C and ^{39}Ar (from fabrication processes and citric acid passivation) contributes electron recoil backgrounds.

To deal with these backgrounds, iZIP detectors can discriminate surface backgrounds, while radial fiducialization rejects sidewall events. Adjacent detector vetoes can also be implemented to further suppress backgrounds from alpha-recoil coincidences and multi-site depositions. Reference [39] and references therein go into a detailed discussion of the expected backgrounds and their effect on sensitivity.

3.3.5 Projected Sensitivity

The sensitivity curves are calculated using the optimum interval method [59, 60], which determines a 90% confidence level exclusion cross section without background subtraction. Background events are drawn randomly from post-cut background spectra, and the expected dark matter spectrum is compared to determine the median exclusion limit across many pseudo-experiments.

Analysis thresholds are set by the larger of two criteria: 7 times the phonon sensor resolution ($7\sigma_{\text{Ph}}$) or the NTL phonon energy from a single electron-hole pair. This yields nuclear recoil thresholds of 40 eV for Ge HV, 78 eV for Si HV, 272 eV for Ge iZIP, and 166 eV for Si iZIP

detectors. The analysis energy range extends from these thresholds up to 25 keV for HV detectors and 120 keV for iZIP detectors [49].

In the projection shown here, it was assumed a signal acceptance efficiency is approximately 85% for HV detectors and 75% for iZIP detectors after fiducialization. For iZIP detectors, the combination of fiducial-volume and yield cuts removes enough surface and electron recoil backgrounds that coherent elastic neutrino-nucleus scattering (CE ν NS) dominates at some energies around the 5 – 10 GeV/ c^2 mass range [49, 39].

The experiment targets initial sensitivity to nuclear recoil cross sections of $\sim 1 \times 10^{-43}$ cm² for 1 GeV/ c^2 dark matter mass. Ge HV detectors achieve best sensitivity around 1 GeV/ c^2 , while Si HV detectors extend sensitivity to sub-GeV masses.

The projected sensitivities represent over a few orders of magnitude improvement on current experimental limits for 1 GeV/ c^2 nucleon coupled DM and for DP candidates. Figure 3-8 summarizes the projected world-leading sensitivity for different candidates. The Sensitivity for ALPs, however, is not as significant, as projections do not improve on the limits set by astrophysical observation (see Figure 3-9).

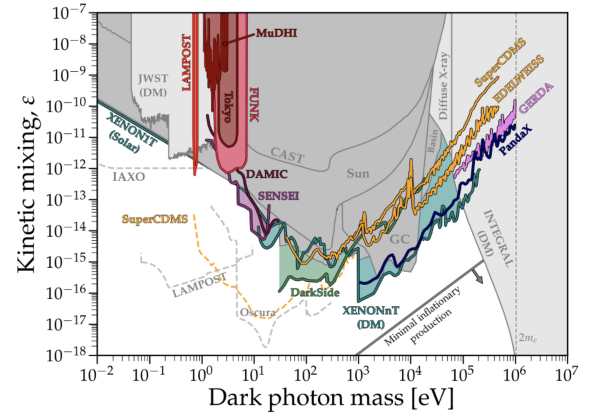
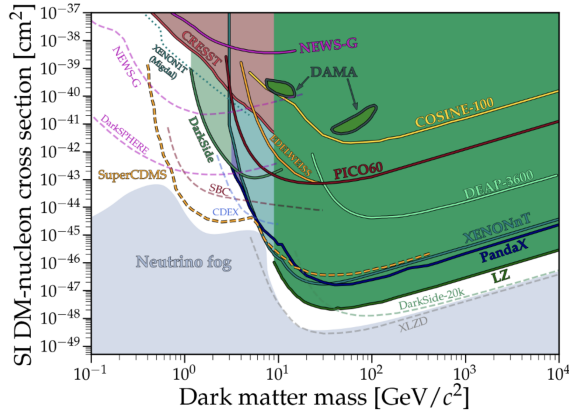


Figure 3-8. Projected sensitivity for DM search for spin-independent nucleon-coupled DM candidates (left) and DP candidates (right). Solid lines present current limits while dashed lines indicate projected sensitivity. The plot is generated using Ciaran O’Hare’s library found in [61]. The plot was generated from published limits before April 2025.

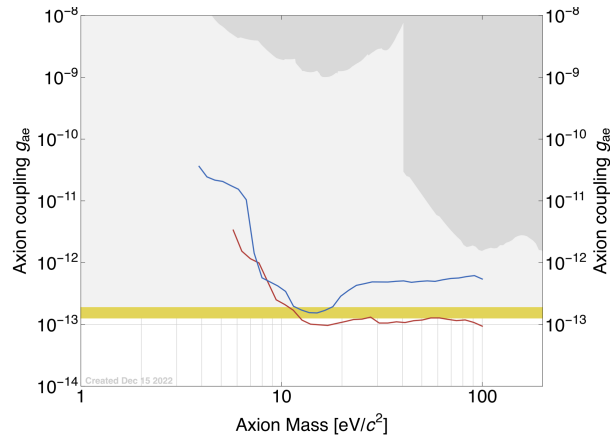


Figure 3-9. Median expected sensitivity for HV detectors (Si: blue; Ge: red) for ALPs. Light shaded regions show all existing limits up to 2022, while the dark shaded regions highlight current exclusion limits from searches for ALP absorption in terrestrial targets. The yellow band indicates the ALP stellar cooling hint.

CHAPTER 4

DETECTOR CALIBRATION AND CUTE TOWER TESTING

In preparation for the SuperCDMS SNOLAB science run, one of two HV detector towers was tested at the Cryogenic Underground TEsting facility (CUTE) at SNOLAB. The main goals were characterizing the HV detectors, assessing their performance, and calibrating them. In this chapter, I showcase the results of the effort, with emphasis on the Ge detectors, as the Si detectors are still work in progress.

The campaign spanned the period between October 2023 to March 2024, and was split into 4 fridge runs. The first two runs focused on building the basics of the operability of the detectors, readout system, and DAQ in a setup similar to SuperCDMS. The last two targeted calibration at both 0V and HV configuration, neutralization, noise studies, and HV response studies.

The tested detector tower consisted of 6 individual HV detectors. Four detectors were Ge detectors, while only 2 were Si. The detectors are named depending on the plane of installation, with Z1 being closer to the tower structure. Figure 4-1 shows the detector configuration. One of the Ge detectors (Z4) had issues in multiple channels regarding SQUID performance and the readout cables, leading to halting the detector operation entirely.

4.1 Ge Detectors

4.1.1 Calibration Theory

For Ge detectors, the primary calibration strategy involved using internal activation triggered by MeV neutrons emitted from a ^{252}Cf source. The neutrons are captured by ^{70}Ge producing ^{71}Ge . The resultant decays with a life-time of 11.4 days to ^{71}Ga through electron capture, emitting X-rays and Augere electrons. The emission corresponds to distinct peaks in the energy spectrum corresponding to energies 10.37, 1.3, and 0.16 keV with probabilities of 87.6, 10.5, and 1.78 % (referred to as K-, L-, and M-shell, respectively)[62, 63].

At higher energies, a 37-kBq ^{133}Ba source is deployed to irradiate the detectors with gammas produced by the ^{133}Ba decay via electron capture. The resultant energy lines are 276.4, 302.9, 356.0, and 383.9 keV [64, 65].

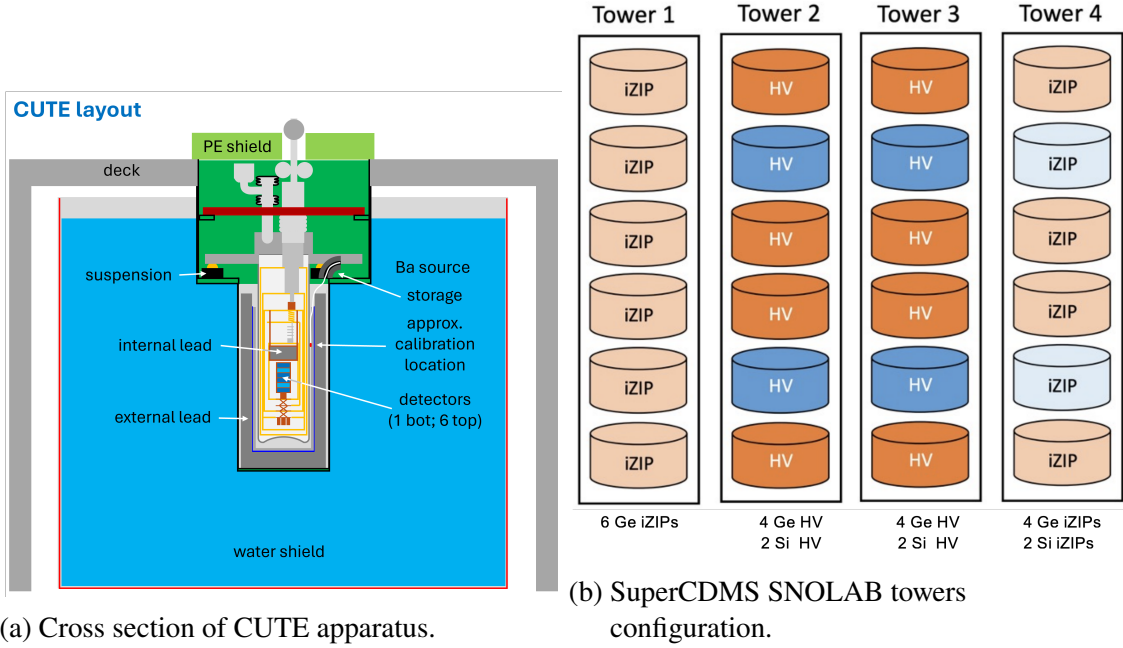


Figure 4-1. A schematic of the CUTE experiment setup and SuperCDMS tower configuration.

4.1.2 Data Acquisition & Event Reconstruction

4.1.2.1 Data Acquisition

A multi-stage trigger system originally designed for SuperCDMS SNOLAB was implemented to enable data acquisition of a small fraction of the continuous waveform for analysis. The reduction is needed to accommodate the maximum data rate limits of the detector control and readout cards (DCRCs).

The first level (L1) processes six channels on one side of a detector. A finite impulse response (FIR) filter is used to highlight certain features in the data by convolving a signal with the FIR coefficients. The coefficients are calculated from the noise PSD of real data and a template signal to represent an optimal filter. The template signal is the averaged pulse shape from random series. Since no quality cuts are applied to the sample generating this average, the trigger threshold is set well below the noise amplitudes to avoid cases where the templates do not match the actual pulse shape, making the triggering efficiency for events within the studied amplitudes virtually 100%. A more detailed discussion of the L1 trigger can be found in [66].

Level 2 (L2) trigger is mainly responsible for defining the type of trigger and the coincidence between the sides of a detector, along with other detectors. This is done based on a user-set configuration file. For example, a trigger on one side that is within 1.5 ms of a trigger on the other side is combined into a single trigger ID. A detector trigger with 2.0 ms from another detector's trigger is assigned as a coincident event. The trigger types are split into in-run-random triggers (IRR) at a rate of 0.5 Hz, begin-of-run-random triggers (BORR) at a rate of 2 Hz, and physics triggers. BORR triggers are used to calculate the noise PSD of the series, and IRR triggers are used to monitor noise changes. The physics triggers are above-threshold events used for science analysis.

4.1.2.2 Event Reconstruction

Triggered events are recorded as 52-ms-long traces with a sampling frequency of 625 kHz. An OF is implemented to retrieve pulses' amplitudes, which are later calibrated to the energy scale, as we will discuss in a different section. The noise PSD of each series is extracted as the discrete Fourier transform of BORR events for each data series. The OF, as discussed in section 3.2.1, also requires a template capturing the general pulse shape.

To generate the template, a preliminary prompt processing was needed to extract reduced quantities (RQs). These RQs are then used for event selection for template generation. Typically, the event selection targets events with above-noise low amplitude events as shown in Figure 4-2. The selected pulses are aligned either using a percentage of the maximum after a low-pass filter is applied or using the delay parameter. The aligned pulses are averaged and normalized to a maximum of 1, and the baseline is subtracted. A four-exponential functional form - described by equation 4-1 - is implemented to fit the averaged signals. The fits are performed to all channels individually in addition to the sum of all channels (PT) and the sum of each side (PS1 & PS2); ie, a total of 15 channels for each detector.

$$f(x) = A_1 e^{\frac{-(x-pt)}{sr * t_2}} + A_2 e^{\frac{-(x-pt)}{sr * t_3}} + A_3 e^{\frac{-(x-pt)}{sr * t_4}} - (A_1 + A_2 + A_3) e^{\frac{-(x-pt)}{sr * t_1}} \quad (4-1)$$

where:

A_i = the amplitude of the i th falling exponential

t_1 = the rise time

t_{i+1} = the fall time constant of the i th decaying exponential

sr = the sampling rate

pt = the trigger time sample

x = the array of time samples

Because the templates generation algorithm is sensitive to the preliminary processing RQs (specifically, delay parameters) or relative channel calibration (described in a later section), this algorithm is iterated until the template shape does not change. The template generation process is performed on low-background, high-energy, and HV scan data sets at their different voltage configurations.

Additionally, to decouple the reconstruction of events from position dependence, it was settled that the sum of individual channel amplitudes is used (designated as PSum) instead of the OF fitting the summed signals. The latter fit (designated as PTOFamps) was used in evaluating the cuts. Finally, an implementation of a version of the $N \times M$ OF was used for the first time in a new analysis. This allows for the simultaneous fitting of N channels using a superposition of M different templates to account for pulse shape variations. In doing so, the $N \times M$ OF algorithm also accounts for correlated noise. For this analysis, we only take advantage of the $N \times M$ reconstruction by implementing a 12×1 OF to reduce computational cost. We, also, fix the start time for each channel to the value derived by the standard OF algorithm rather than allowing each channel individually to shift in time.

4.1.2.3 Relative Channel Calibration

In an ideal situation, the energy collected across the different channels should be equal on average, given equal illumination of the detector when the Ge substrate is activated. This is not the case as the ^{252}Cf illuminates the detector from one side. This is, however, not the largest contributor to variation in collected energy. The TES characteristics of different channels and

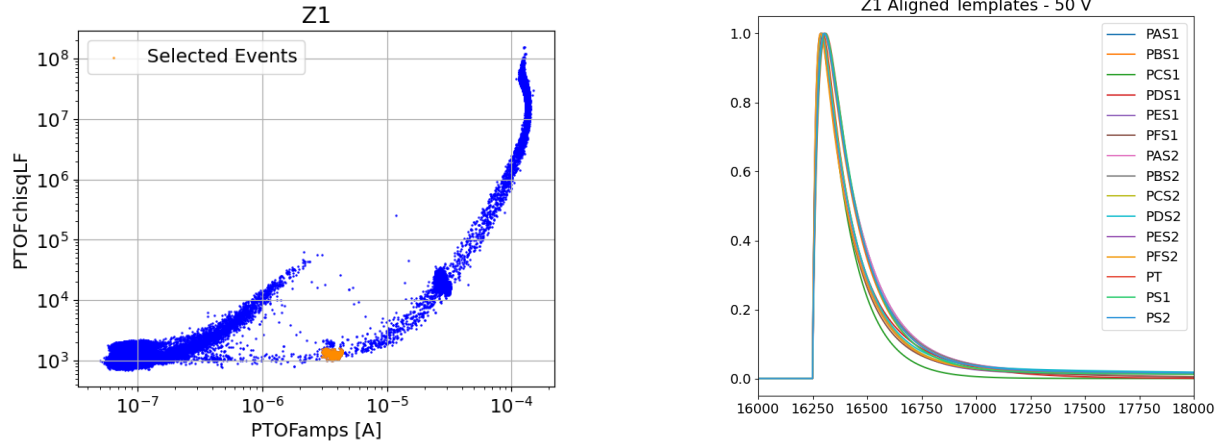


Figure 4-2. (Left) An example of event selection for events taken by detector Z1 at 50V. PTOFamps represents the OF amplitude of the sum of all channels on both sides. PTOFchisq represents the frequency domain OF χ^2 described in section 3.2.1. (Right) An example of aligned fits used as templates for Z1 low background data taken at 50V.

their different parasitic powers lead to a significant position dependence in reconstruction. This is corrected for by assigning weights to different channels, which I will refer to as relative calibration factors.

A simulation based on a superCDMS-specific simulation engine called Geant4 Detector Monte Carlo (G4DMC). The engine is an adaptation of the Geant4 Condensed Matter Physics package [67, 68], simulating relevant physics processes in the semiconductor target. Specifically, the simulation focuses on charge creation and phonon propagation in the semiconductor with a voltage bias applied. The simulation also registers where the phonons and charges hit the top and the bottom surfaces. This opens the road to using the simulation to find the ratios of the energy collected by each channel in an ideal situation and then comparing with real data.

For 0V data, one thousand 10 keV energy depositions spread across the bulk of the detector were simulated, and a thousand 1 keV were simulated at 50 V. The energy depositions are specified as single-hit electron-recoil events simulating the deposition in the detectors. Looking at the geometry of the HV detectors shown in Figure 4-3, we can expect the wedge channels' spectra to be equal on average. A parameterization was used to project the spectra into 2D as indicated by

the equations 4-2 and 4-3. The expected shape of a well-balanced energy distribution should be an equilateral triangle, and the weights can be adjusted to satisfy that and match the simulation. As for the central and the ring channels, no obvious geometric shape can be used, highlighting the need for the simulations. The same 2D projection was implemented to align the main features in both the simulation and real data. Figure 4-4 shows examples of the projection after applying relative calibration for Z1. The K-shell peak at 0V and the L-shell peak at HV were used for this study.

$$x = \frac{w_1 A_1 \cos(0^\circ) + w_2 A_2 \cos(120^\circ) + w_3 A_3 \cos(240^\circ)}{w_1 A_1 + w_2 A_2 + w_3 A_3} \quad (4-2)$$

$$y = \frac{w_1 A_1 \sin(0^\circ) + w_2 A_2 \sin(120^\circ) + w_3 A_3 \sin(240^\circ)}{w_1 A_1 + w_2 A_2 + w_3 A_3} \quad (4-3)$$

where:

A_i = the amplitude of one of the channels

w_i = the assigned relative calibration

It's worth noting that some of the channels in the simulation, the ring channels, showed significantly larger amplitudes than those taken by real data. This could be due to ill-tuned TES parameters in the simulation. This, however, does not affect the outcomes of this study, as we are only concerned with aligning the features in the data on average, not the actual amplitudes.

4.1.3 Data Quality Cuts

A total of 14 data quality cuts were implemented to remove events that were taken during a period of instability or unstudied features in the data. Some of the cuts are basic cuts specifying the detector under analysis (cTrigDetNum), whether the event is meant for physics study or noise studies (cTrigType), discarding ill-recorded events (cGoodFit), and removing events recorded when the LEDs were flashing or baking the detectors (cLED).

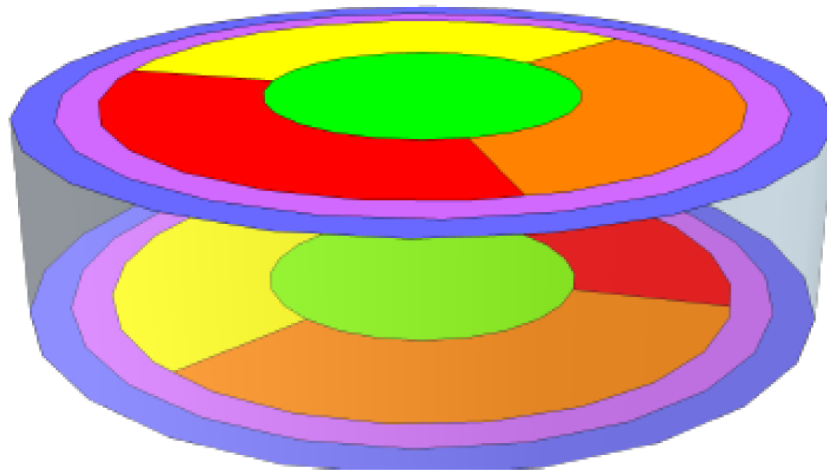


Figure 4-3. Layout of the HV detectors deployed at CUTE and SNOLAB. Each side has 6 channels, as noted by the colors (1 central (F), 3 wedges (named E, D, C), and 2 ring channels (named A, B). All channels have the same effective coverage.

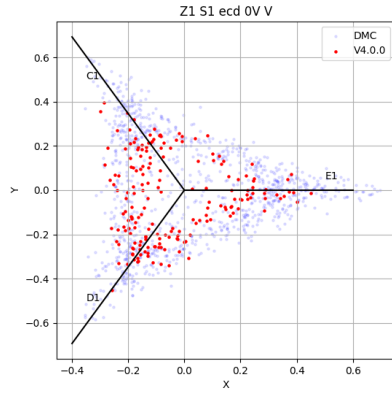
4.1.3.1 cDuplicate

During the main calibration run, it was noticed that a considerable but not significant number of events across a large period of time included duplicate pairs of events. The pairs shared the same raw pulses and different RQs values; however, they were tagged with different event numbers, trigger IDs, and trigger amplitudes. Additionally, there was a category of events where pairs of events had an identical set of RQs across all except for the detector they triggered on. Usually, one of them triggered on one of the 6 detectors and the other on a virtual detector that is used for trigger testing.

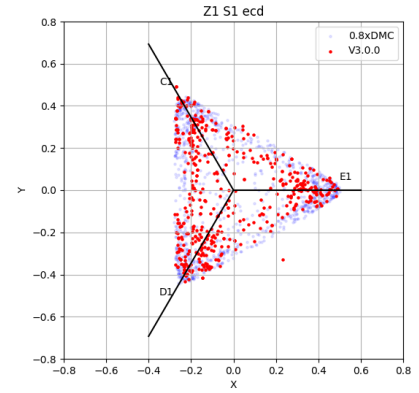
After investigation, it was found that one of these pairs usually triggers on one side of the detectors near the end of an L1 trigger polling cycle, resulting in duplication with different readout times despite having the same trigger times. A crude cut was used to compare all events within a given dataset, eliminating events with identical RQs. The cut overall removes around $\sim 0.5\%$ of events.

4.1.3.2 cPileUp

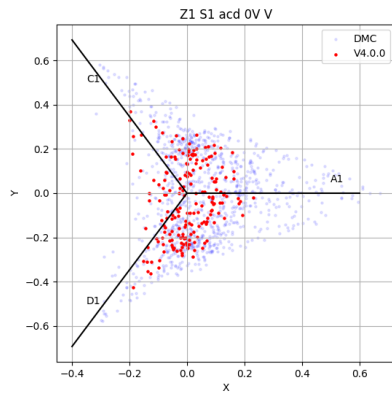
For high-energy calibration data, the ^{133}Ba source caused a high event rate in all detectors, resulting in a high rate of pile-up. Pile-up occurs if a single triggered 52-ms trace contains



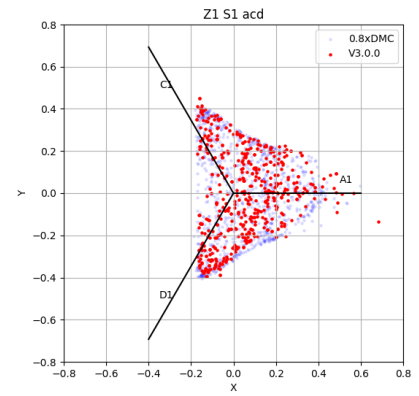
(a) ECD at 0V



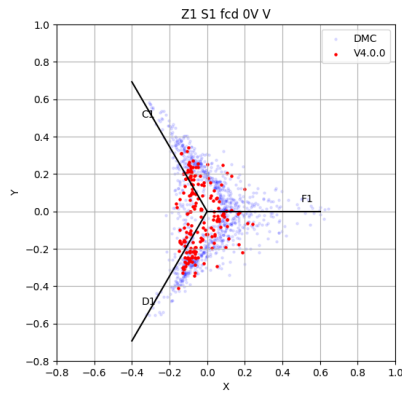
(b) ECD at 50V



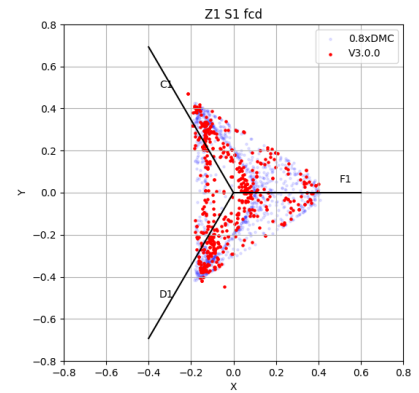
(c) ACD at 0V



(d) ACD at 50V



(e) FCD at 0V



(f) FCD at 50V

Figure 4-4. Examples of feature alignment in real data compared to G4DMC simulations. The examples shown are only for low background data taken by detector Z1 and Side 1 (S1). The x and y values are derived from the triangular projection defined in equations 4-2 and 4-2. The names of the channels are defined in figure 4-3.

multiple signals. A peak counting algorithm was implemented from the ROOT package to count the number of peaks after Markov sampling and Gaussian deconvolution. The algorithms look for peaks above the pre-trigger baseline noise by 7 sigma and separated by more than 10 time samples (16 μ s). After implementation, it was noticed that some noisy channels had a very high rate of false positives, motivating the application of an upper threshold on the average number of peaks of all channels.

Additionally, there few cases where a very high energy deposition forces the QETs deep into saturation, where the signal response becomes flat, degrading the peak counting efficiency. This affects the pre-trigger baseline calculation, leading to a few false negatives. To reject these events, a lower threshold was set at high amplitudes to reject events with an average number of peaks less than 1. Figure 4-5 shows an example of the cut applied, and one of the high-energy events.

4.1.3.3 cEventTime

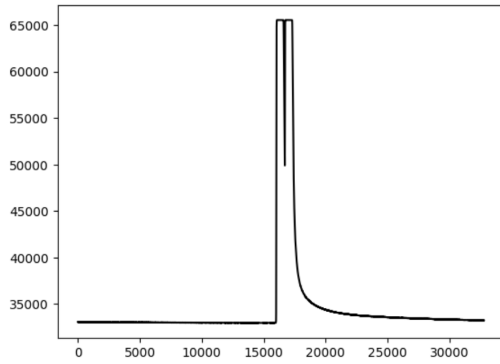
During the run, pulses from specific time periods showed elevated low-frequency χ^2 . This observation was initially observed when studying the M-shell of high-voltage low-background calibration data. During these periods, pulses showed what looks like telegraphic noise. It was decided to remove all data sets with an elevated low-frequency χ^2 for the noise peak. Figure 4-6 highlights the affected series removed.

4.1.3.4 cBaseline

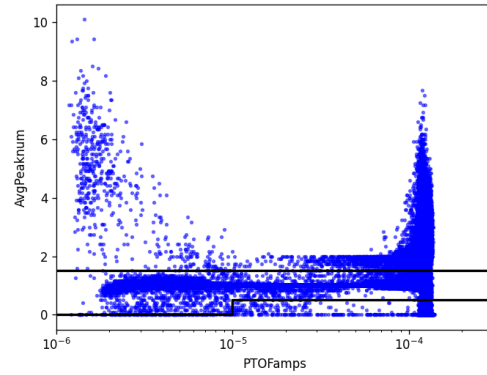
The preceding two cuts were not enough to remove pulses with elevated noise. A threshold was set on each channel's pre- and post-trigger baseline standard deviation depending on the channel and voltage configuration. A summary of the applied cuts is shown in Table 4-1.

Table 4-1. Summary of baseline cut applied where std refers to the standard deviation and the suffix refers to the pre- o post signal.

Data	Cut applied
Low-backgorund 0V	stdpre < 6e-8
Low-backgorund 0V	stdpre < 6e-8 + stdpost < 6e-8
High-energy 0V	stdpre < 1e-7
High-energy 50V	stdpre < 6e-8 + stdpost < 6e-8
Voltage scan 0V	stdpre < 6e-8 + stdpost < 6e-8



(a) Pulse with a single detected peak



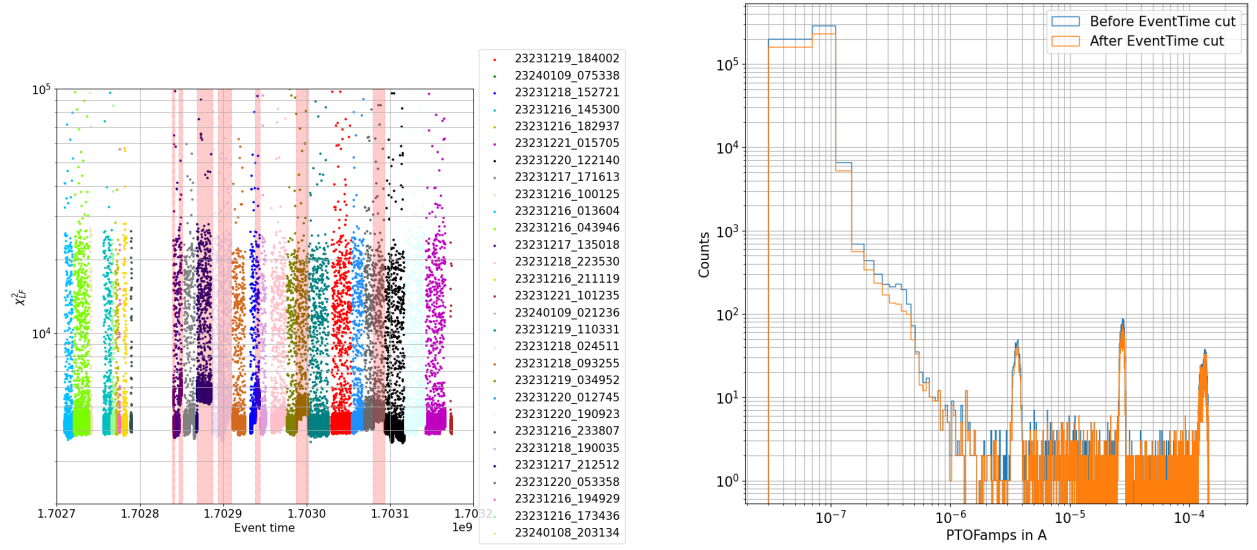
(b) Cut threshold example

Figure 4-5. (Left) An example of a pulse where the algorithm counted a single signal, although visually there are 2 and separated by more than 10 time bins. The x-axis is the time samples and the y-axis is the amplitude in ADC count units. (Right) An example of the applied cut on Z1 for high-energy high-voltage data is shown as the solid black lines. The x-axis represents the amplitude of the summed trace, while the y-axis represents the average peak number calculated.

4.1.3.5 cDelaytime Window

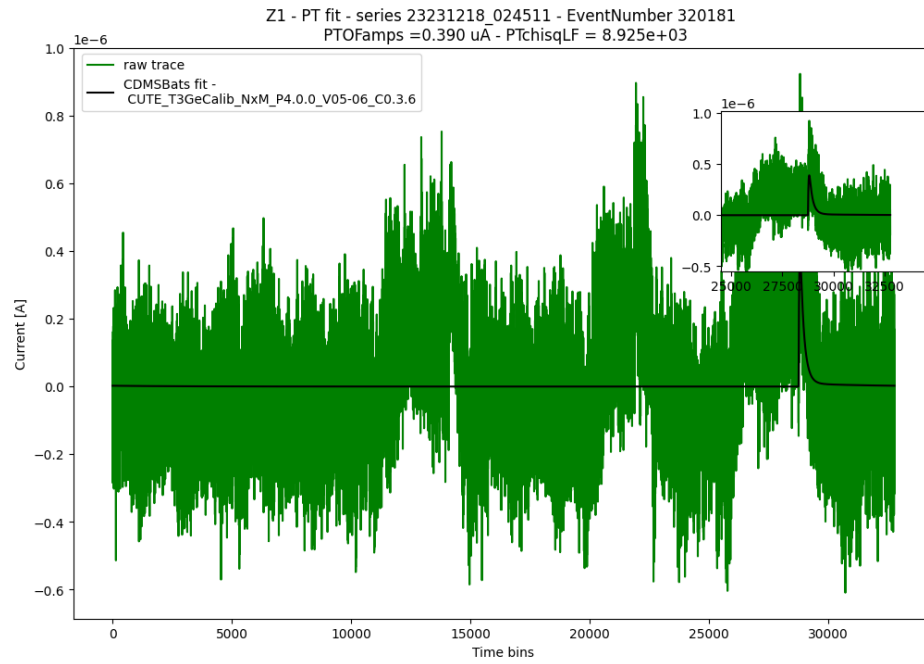
In an optimal trigger configuration, the L2 trigger should realign pulses such that the trigger point is set to the middle of the trace (26 ms time bin). However, it was noticed that a non-negligible number of events were misaligned. This was either due to a misconfiguration of the trigger itself, an artifact of the OF trigger on large-amplitude pulses, or odd pulses with a long noisy falling edge. All these factors introduced a shift of a few milliseconds in the pulses in some or all the channels.

To remove these pulses, an OF delay cut was introduced. During development, a couple of thresholds were tested, where one was a tight cut allowing events within ~ 0.5 ms from the center point of the trace, and the other allowed a variation within 8 ms. Figure 4-7 shows the introduced cuts and the effects on pulse reconstruction quality. Further investigation into some low-amplitude events with a high shift showed pulses with unstable features (see figure 4-7). The safest option is to apply a strict cut for low-amplitude events ($\text{PTOFamps} < 20\mu\text{A}$), and the looser cut for pulses with higher amplitudes.



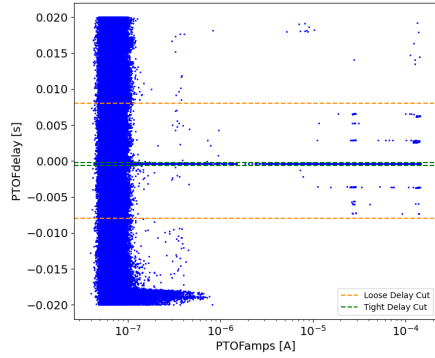
(a) χ^2_{LF} as a function of series number.

(b) Spectrum before and after the cut is applied.

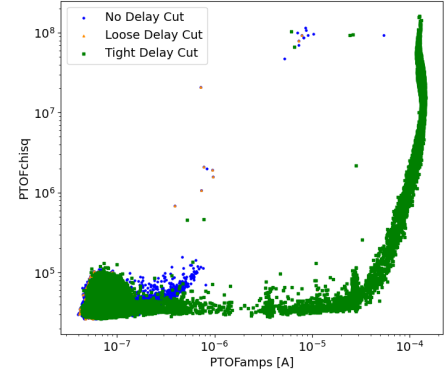


(c) Example of pulse with elevated noise rejected by the cut.

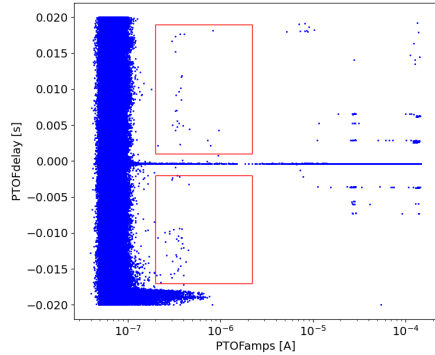
Figure 4-6. (Left) Example of rejected region in gray for HV low-background data of Z1. (Right) Amplitude spectrum before and after applying the cut for the combined series shown on the left.



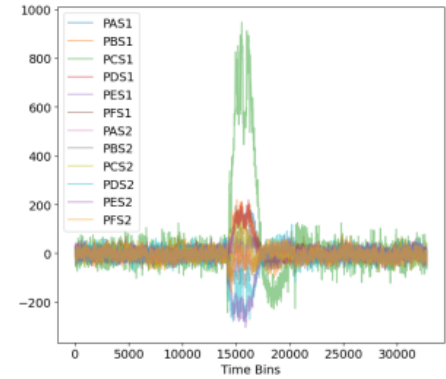
(a) Delay parameter joint distribution with pulse amplitude. The dashed lines note the cut definitions.



(b) χ^2 joint distribution with pulse amplitude. The figure highlights the effect of cuts on pulse quality.



(c) Delay parameter joint distribution with pulse amplitude. Selection of events with significant delay shift.



(d) Example of trace with low amplitude with a high shift. Some of those signals show telegraphic noise.

Figure 4-7. Examples of delay parameter definition for low-background HV calibration data for detector Z1.

4.1.3.6 cChisq & cPmin

After applying all these cuts, most, if not all, bad events were removed from the low-background data. On the other hand, the high-rate high-energy calibration series still showed a worsening reconstruction (high χ^2_{LF}) with amplitude. Additional χ^2_{LF} cut was introduced to remove these misconstructions. Most of the rejected events were signals with a decaying baseline, implying the events followed a high-energy event that heated the crystal up. A linear interpolation between hand-chosen points was used to set up a threshold on allowed χ^2_{LF} values as a function of amplitude. This was implemented on high-rate high-energy data as explained in Figure 4-8. For consistency's sake, the same cut was implemented on the low-background data.

Additionally, some of the detector Z3 pulses exhibited an odd behavior around the M-shell peak when operated at HV configuration. These pulses are very close to the noise threshold, and different cuts do not perform as well at that amplitude range. A simple flat cut on the minimum of each channel's trace was applied across the various data types.

4.1.3.7 cRadial

In SuperCDMS detectors, the electric fields should be uniform across the detector; however, the fields near the side walls are not uniform. This non-uniformity could lead either the holes or the electrons to end up on the walls and not traverse the whole crystal. This lessens the

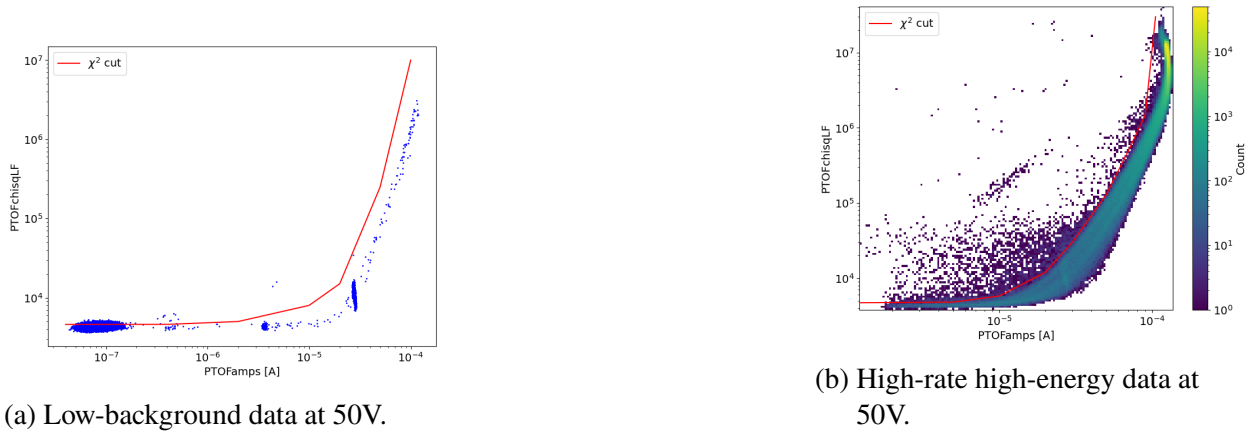


Figure 4-8. Examples of χ^2_{LF} cut definition for HV calibration data for detector Z1.

amplification effect of NTL and degrades resolution. That is why it is crucial to develop a radial fiducial volume cut.

Initial attempts considered the time delay difference between different channels. This, unfortunately, did not perform well in terms of resolution improvement because this method is sensitive to the discretizations of recording the data. In addition, this method relies heavily on the goodness of the fit of the OF filter, which is not guaranteed at higher amplitudes when the saturation takes effect.

Eventually, a threshold is put on the difference between the inner-most and outer-most channels' amplitude on both sides relative to the total trace amplitude as shown in equation 4-4. The threshold is set by iterative fitting to the calibration peaks of the low-energy low-background calibration shell peaks until the best response is achieved. It is worth mentioning that, for detector Z3, one of the outer ring channels was not operated, so the cut was modified to only include the channels from the fully operational side with half the threshold. Events rejected by this cut represent the bulk of the above noise threshold rejected events with $\sim 85\%$.

$$R = \frac{w_{\text{PFS1}}A_{\text{PFS1}} + w_{\text{PFS2}}A_{\text{PFS2}} - w_{\text{PAS1}}A_{\text{PAS1}} - w_{\text{PAS2}}A_{\text{PAS2}}}{A_{\text{PT}}} \quad (4-4)$$

where:

A_i = the amplitude of one of the channels

w_i = the assigned relative calibration

4.1.4 Calibration

4.1.4.1 Low Energy Calibration

After implementing all standard and data quality selection criteria—including low-radius event selection for data acquired under finite detector bias conditions. The spectral peaks originating from ^{71}Ge decay were identified for a long running low background data taken at 0V and 50V.

Peak position determination employed a two-stage fitting approach. Initially, each peak in the binned histogram underwent Gaussian fitting using least-squares fit. This preliminary fit informed the event selection, which retained events within the three-sigma region of each identified peak. Subsequently, the selected events underwent a second Gaussian fit using unbinned negative log-likelihood optimization. The final calibration and resolution assessment relied on results from this second fitting stage.

Under zero bias conditions, both K-shell and L-shell peaks were successfully identified in detectors Z1 and Z3, with peak positions exhibiting consistency with linear calibration. For detector Z6, only the K-shell peak could be reliably identified, precluding linearity assessment.

At 50 V bias, the energy scale demonstrated slight non-linearity (10% deviation at the K-shell peak). This behavior stems from saturation effects, consequently causing energy underestimation when employing energy-independent template fitting. While simple pulse integration maintains linearity across much higher energy ranges (as will be discussed in the high energy calibration section), it yields inferior resolution compared to the OF method.

To achieve linear energy scaling while preserving OF resolution advantages, we applied a logarithmic correction function described by equation 4-5. The inverse transformation generates a corrected energy scale based on OF measurements, yielding peak positions consistent with linear calibration.

$$A_{OF} = a \log(b \cdot A_{INT} + 1) \quad (4-5)$$

where:

A_{OF} = the amplitude of the OF estimator

A_{INT} = the amplitude of the integral estimator

a, b = fitting parameters

Figure 4-9 presents uncalibrated OF spectra for detector Z1 under both 0 V and 50 V bias as an example for the calibration process. Table 4-2 provides the calibration constants and fitting

parameters necessary for converting measured OF amplitudes to recoil energies after applying the linearization for 50V.

4.1.4.2 Resolution

Baseline Resolution

The baseline resolution analysis examined three energy estimators through their respective distributions. Analysis focused exclusively on beginning-of-run random events, where only phonon pulse amplitudes were considered under the assumption of simultaneous occurrence with the trigger (no-delay).

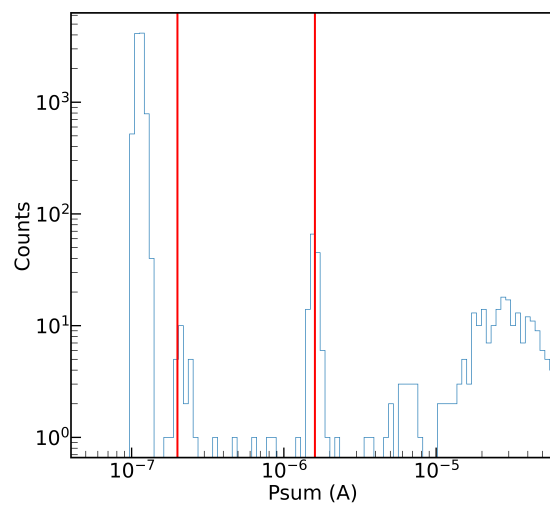
Each distribution underwent binned Gaussian least-squares fitting. The resulting fitted mean and standard deviation values were converted to eV units using calibration factors derived from linear fits of the activation peaks. The Gaussian fit standard deviation represents the detector's baseline resolution. These converted values were subsequently plotted (Figure 4-10) to demonstrate baseline resolution dependence on energy estimator selection.

The analysis encompassed two operational scenarios: single detector and multi-detector configurations. Single detector operation involved activating one detector while deactivating all other DCRCs during data acquisition, whereas multi-detector operation maintained simultaneous operation of multiple detectors.

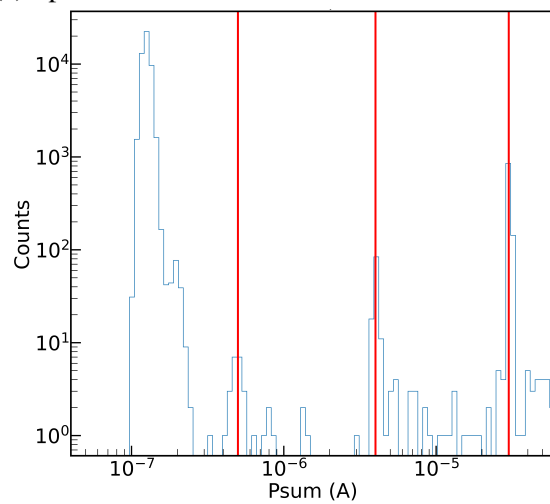
Multi-detector operation consistently degraded resolution due to increased electronic noise pickup from readout systems and elevated parasitic power. This behavior was confirmed for detectors Z1 and Z3, where single detector data yielded superior resolution compared to

Table 4-2. Calibration factors for the OF-based energy scale at 0 V (C_0), and linearization constants a and b (see Equation 4-5) and calibration factor for the linearized OF-based energy scale at 50 V (C_{50}). Note that the inverse of Equation 4-5 converts the OF scale into integral units, explaining the different magnitude of C_{50} when compared to C_0 .

Det	0 V	50 V		
	C_0 [keV/ μ A]	a [mA]	b [1/ μ A]	C_{50} [keV/mA]
Z1	6.55 $\pm$ 0.03	0.188 $\pm$ 0.020	19.8 $\pm$ 2.3	20.9 $\pm$ 0.1
Z3	3.66 $\pm$ 0.01	0.223 $\pm$ 0.024	19.2 $\pm$ 2.4	13.9 $\pm$ 0.2
Z6	7.47 $\pm$ 0.01	—	—	—



(a) Spectrum at 0V.



(b) Spectrum at 50V.

Figure 4-9. Detector Z1 amplitude spectra with all cuts applied. The red vertical lines are approximate locations of the activation peaks.

multi-detector configurations. However, detector Z6 exhibited anomalous behavior, showing apparent resolution improvement during multi-detector operation.

Detailed channel-by-channel analysis revealed that Z6's improved overall resolution resulted from significant degradation in three individual channels, while remaining channels maintained stable or improved performance. This suggests that detector isolation positively impacts Z6 as well, but environmental factors affecting the three compromised channels dominated the aggregate measurement due to their magnitude.

Table 4-3 summarizes the baseline resolution results for both single detector and multi-detector operational series, providing quantitative comparison of the performance differences observed across all detector configurations.

Resolution Model

The detector resolution model employed in this analysis models three components that account for the dominant sources of energy resolution degradation as described by Equation 4-6. The radical term ($A \cdot E_R$) captures the statistical uncertainty in electron-hole pair production during energy deposition. While this process fundamentally follows Poisson statistics, the spread is reduced by the Fano factor. The coefficient A relates to an effective Fano factor ($A = F_{eff} \cdot \epsilon$), where additional effects beyond the intrinsic Fano limit may contribute, resulting in $F_{eff} \geq F_{Fano}$. While the linear term ($(B \cdot E_r)^2$) is primarily driven by spatial variations in TES response, electric field non-uniformities, and other detector response variations across the crystal volume.

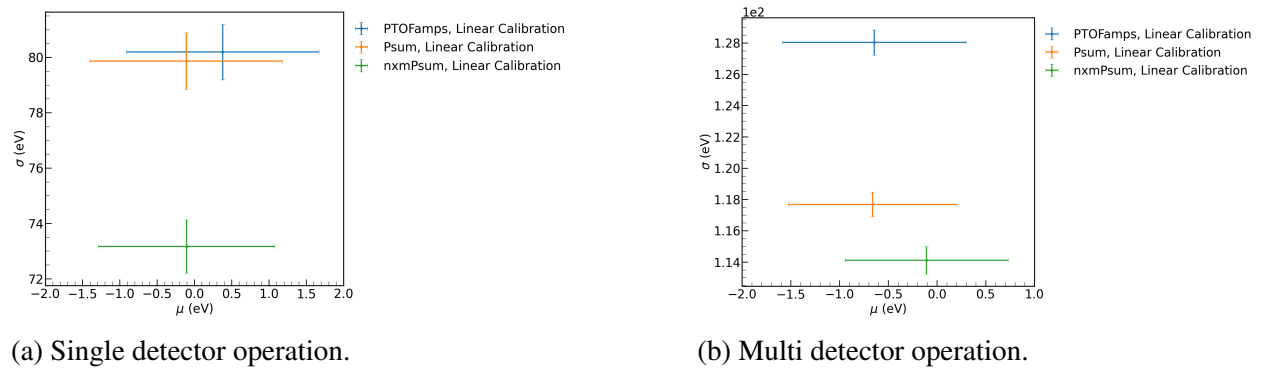


Figure 4-10. Detector Z3 baseline resolution at 0 V comparison between detector operation conditions and estimator used.

Table 4-3. Single-detector operation baseline resolution for each detector. In all cases, the NxM OF leads to a resolution that is a few percent worse than when using the 1x1 OF, indicating that correlated noise is not well accounted for in the current implementation.

Baseline res.	Z1	Z3	Z6
1x1 OF [eV]	89.2 ± 0.7	80.2 ± 1.0	212 ± 1.0
NxM OF [eV]	102.7 ± 0.7	85.6 ± 1.3	363 ± 3

$$\sigma_t(E_r) = \sqrt{\sigma_{bl}^2 + A \cdot E_r + (B \cdot E_r)^2} \quad (4-6)$$

where:

E_r = The recoil energy

σ_t = The total resolution

σ_{bl} = The baseline resolution

A and B = Fit parameters

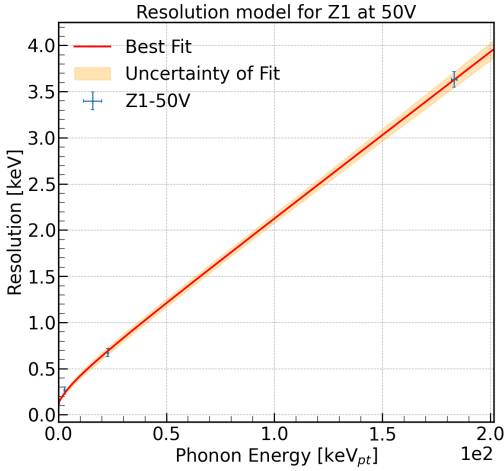
The model was fitted to experimental data using least-squares optimization for the 50 V bias conditions in detectors Z1 and Z3, utilizing the PTOFamps energy estimator after applying linearization and calibration. Detector Z6 provided insufficient data points (only baseline and K-shell resolution) for reliable three-parameter fitting. Results are reported in Figure 4-11.

The extrapolated effective Fano factors ($0.28^{+0.06}$ and $0.47^{+0.1}$ for Z1 and Z3 respectively) are significantly larger than the theoretical literature value of 0.13 [69], but consistent with previous CDMSlite measurements (0.21-0.29 for Runs 2 and 3 [70, 71]).

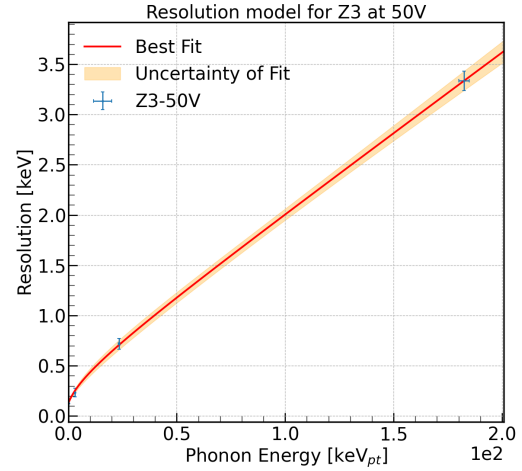
4.1.4.3 High Energy Calibration

Understanding their high-energy response provides valuable insights into the radioactive background environment, ultimately improving dark matter sensitivity constraints. While standard OF becomes unreliable due to saturation effects, simple trace integration (referred to PTIntAll)maintains energy sensitivity across much higher energy ranges with degraded resolution.

The 37-kBq ^{133}B gamma source was positioned behind internal lead shielding due to the source's excessive activity for direct exposure. This configuration resulted in highly



(a) Detector Z1.



(b) Detector Z3.

Figure 4-11. Resolution model for 50 V Z1 and Z3 using the baseline resolution, M-, L- and K-shell activation peaks.

inhomogeneous illumination, with Ba-induced events concentrated near detector edges. Detector Z1 provided optimal geometry for both 0 V and 50 V bias measurements, while detector 6 remained almost completely blocked.

Initial analysis using data preliminary processing with uniform relative calibration factors revealed the distinct source spectral features using the integral energy estimator. However, transitioning to optimized processing where relative calibration factors were derived from unsaturated events, significantly deteriorated high-energy resolution. Rather than re-optimizing calibration factors for saturated events, we defined a new parameter (PTIntSumAll) representing the unweighted sum of individual channel integrals, successfully recovering the spectral features.

The 0 V spectrum exhibited four expected peaks, though analysis focused on the three highest-energy features due to limited statistics for the 276 keV line. Calibration utilized the prominent 356 keV gamma peak as reference for linear calibration, with subsequent peak fitting revealing excellent agreement between observed and expected energies: 383.9 keV (expected) versus 382.3 ± 1.7 keV (measured), and 302.9 keV (expected) versus 302.1 ± 1.1 keV (measured). Systematic uncertainties from non-flat backgrounds were assessed through combined fitting with

reverse sigmoid background models, confirming potential systematic shifts below the percent level.

At 50 V bias, detector response exhibited clear non-linearity. The expanded energy range revealed both high-energy peaks and low-energy activation lines, providing seven calibration points total. The L-shell peak required selection using OF peak-selection followed by integral fitting due to its proximity to noise peaks of the integral estimators.

A second-degree polynomial calibration function ($y = ax^2 + bx$) was fitted using weighted least-squares methodology accounting for uncertainties in both energy and measured position coordinates. Systematic uncertainties were conservatively estimated through alternative fitting approaches using single-sided Crystal Ball functions with reverse sigmoid backgrounds, yielding systematic shifts generally below 1% except for the poorly constrained 276 keV peak (up to 2% deviation).

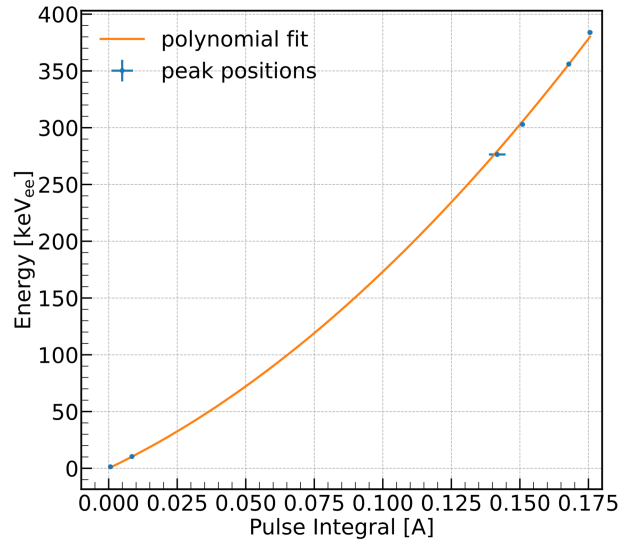
The resulting calibrated spectra (Figure 4-12) demonstrate the possibility of high-energy measurements with HV detectors, providing a capability for background characterization studies while maintaining the primary low-energy optimization.

4.1.5 HV Study

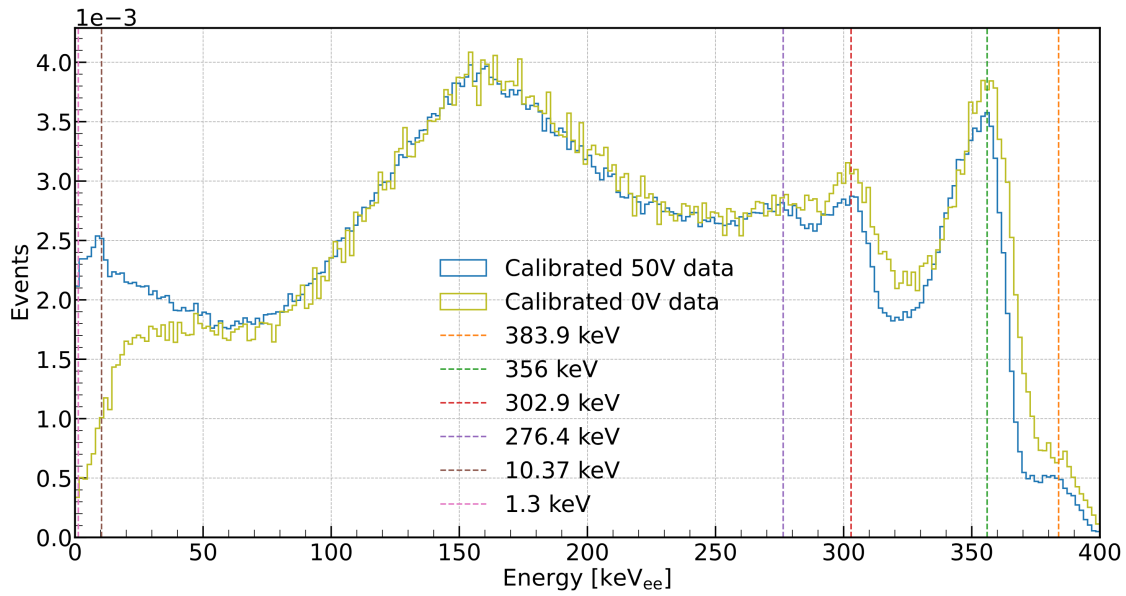
4.1.5.1 NTL Amplification

Previous observations in Si HVeV detectors revealed NTL amplification factors exceeding theoretical predictions [56], prompting systematic investigation of similar effects in germanium large scale detectors. Coincidentally, the study provides an excellent opportunity to understand detector breakdown under voltage like what has been observed in CDMSlite where different detectors exhibited breakdown at voltages of 30 V and higher [72, 71, 73].

A comprehensive voltage scan was conducted across all three germanium detectors (Z1, Z3, Z6) with bias voltages ranging from 0 V to 90 V. The activation peaks served as calibration references, with peak positions determined through both binned least-squares followed by an unbinned Poisson negative log-likelihood fitting for events within 3-sigma.



(a) HV quadratic calibration fit.



(b) Calibrated high energy spectra at 0 V and 50 V.

Figure 4-12. Calibration summary at high-energy range for Z1. Calibrated 0 V and 50 V energy spectra, with lines showing the expected peak positions. The difference between the two spectra at low energy is believed to be dominated by the trigger conditions as during the 0 V data set, the DAQ did not record coincident events.

Linear response was maintained up to approximately 40 V for K-shell peaks using the OF estimators, beyond which saturation effects caused deviations from linearity. The integral estimator extended this linear range to ~ 60 V for detectors Z1 and Z6, while Z3 experienced earlier degradation due to pulse clipping effects. In contrast, L-shell peaks demonstrated linear response across the entire voltage range for all detectors, though limited statistics reduced their calibration utility.

Cross-validation through zero-intercept linear fitting of unsaturated HV peak amplitudes yielded high reduced correlation coefficients ($R^2 \geq 0.99$). This implies strong linearity up to 120 keV_t within the unsaturated regime (See Figure 4-13).

While Figure 4-13 suggest linearity all across the entire voltage range, it can be shown that there are small but significant deviations. To study this, the 0V peak position was used to create expected positions for the rest of the K-shell positions and the L-shell position at 0V (assuming linearity at 0V) using the PSum estimator. For the integral estimator, the K-shell position at 0V was used to create the expected positions similarly. The ratio between the measured position and expected position is then plotted as a function of the applied bias voltage, as seen in Figure 4-14.

Two clear observations are that a) the K-shell ratio drop as function of voltage much earlier than thought, and b) while some individual L-shell HV measurements are compatible with the 0-V K-shell data point, most of them are not, and if we look at the mean of the L-shell data points or the L- and K-shell data points (all at HV between 5 and 90-V), it is clear that they are not compatible with the 0-V data by a large margin.

The first of the two observations may possibly be related to saturation; the second one is very similar to the overamplification observations made in [56], where the NTL amplification was also observed to be larger than expected. When quantifying the overamplification, it is revealed overamplification factors of approximately 12-15% across all detectors. Table 4-4 summarize the factors.

This is the first time this effect has been demonstrated in Ge detectors; it is also the first time that it could be shown that there is no significant voltage dependence over a wide range of voltage

Table 4-4. Over-amplification observed in the three detectors, determined by the L-shell peak position. The error on mean is the quadrature sum of uncertainty of weighted mean and stranded deviation of central values.

Detector	1	3	6	Mean
Over-ampl. (%)	14.9 $\pm$ 2.1	11.4 $\pm$ 2.0	14.7 $\pm$ 2.8	13.4 $\pm$ 2.1

biases. This could be an indication that it is related to differences between bulk and surface charge-carrier recombination, though further studies are required to draw firm conclusions.

4.1.5.2 Baseline Resolution Variation with Voltage

Here's the combined and paraphrased version:

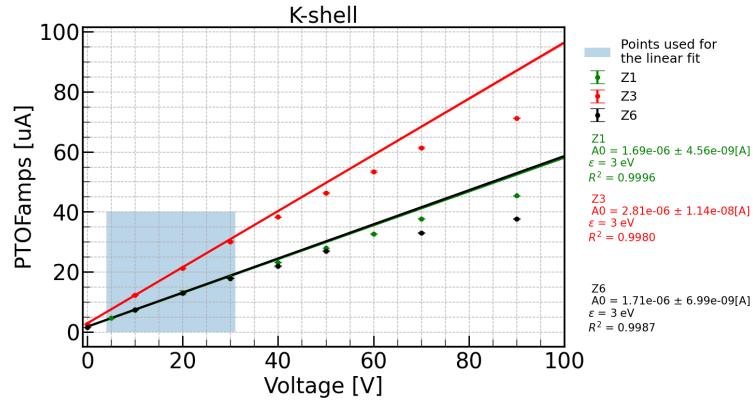
The baseline resolution performance under varying bias voltage conditions was also investigated across the three germanium detectors Z1, Z3, and Z6. The high voltage operation can introduce multiple noise sources that could compromise detector sensitivity. This analysis employed same approach as the baseline resolution estimation of the low background data sets.

Baseline resolution was extracted from the standrad deviation of a Gaussian fitting of event distributions within mean $\pm 2\sigma$ ranges to avoid fit bias. Both 1×1 and $N \times M$ OF configurations were studied, with the latter consistently providing better resolution performance, implying the presence of correlated noise components.

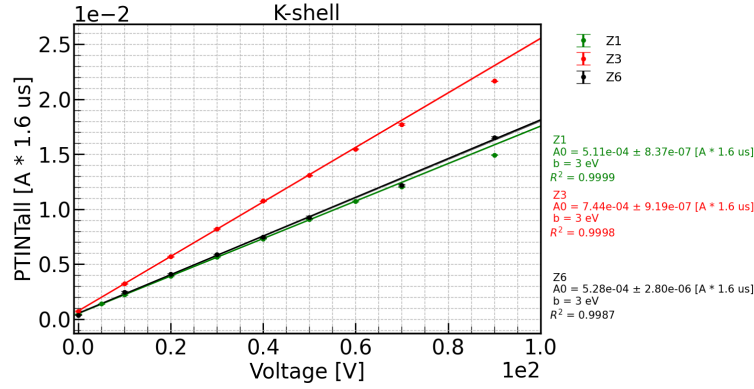
The dominant observation across all detectors was systematic baseline resolution degradation with increasing bias voltage. However, counterintuitively, resolution improved between 0 V and 10 V before following a degradation pattern at higher voltages (See Figure 4-15a). The cause of the improvement is different for the various detectors. For Z6, this could be due to overamplification of sub-threshold IR events out of the noise range.

Detectors Z1 and Z3 demonstrated modest, gradual resolution deterioration with voltage, consistent with expected electronic noise scaling. However, detector Z6 exhibited dramatically enhanced voltage sensitivity, showing significant baseline resolution degradation substantially exceeding the other detectors.

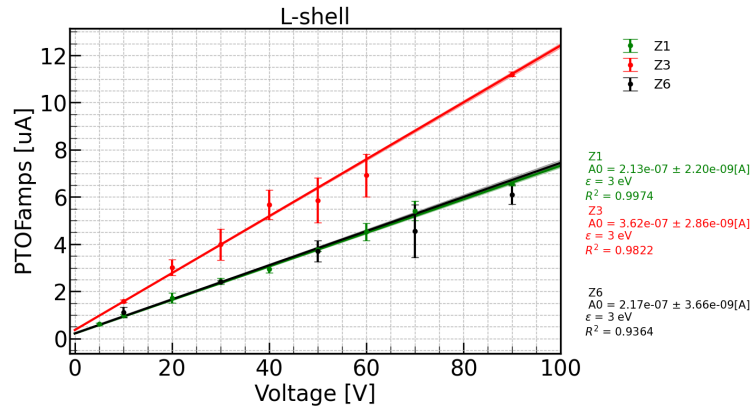
Individual channel analysis revealed substantial magnitude differences in baseline resolution between channels within single detectors (Shown in 4-15b), accompanied by large fluctuations



(a) K-shell Peak position using OF estimator.



(b) K-shell Peak position using integral estimator.



(c) L-shell Peak position using OF estimator.

Figure 4-13. A summary of the peak position as a function of voltage for the germanium detectors for the PTOFamps estimator. The linear fits the unsaturated HV peaks to extrapolate the peak position at 0 V ($A0$), where ϵ is fixed to 3 eV. The shaded region around each line represents the 1-sigma uncertainty.

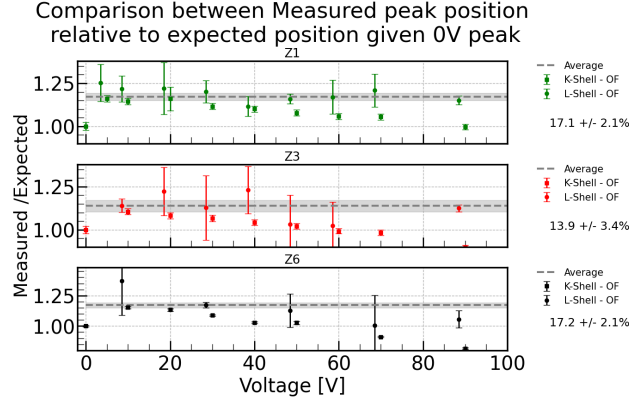


Figure 4-14. Summary of the ratios for OF estimators. The percentages are the average of the overamplification.

within individual channels. These variations suggest variable noise pickup by the DCRCs as the primary mechanism, indicating that electronic system optimization could yield some performance improvements.

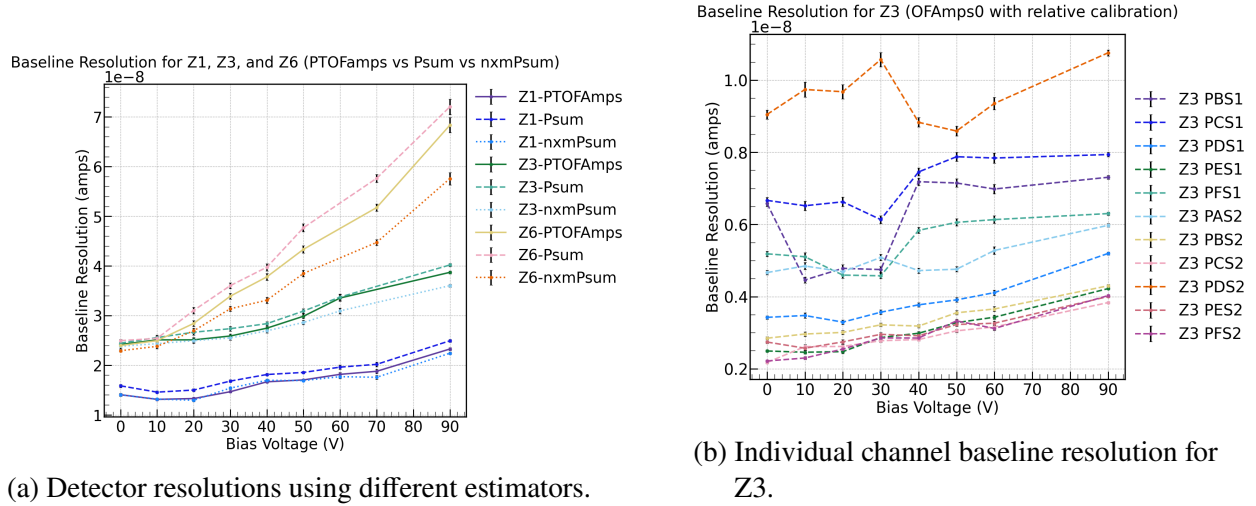
4.2 Silicon Detectors

4.2.1 Low-Energy Calibration Challenges

The calibration of Si detectors is a significantly greater challenges compared to Ge detectors, particularly in the low-energy regime below 10 keV where sensitivity to low-mass dark matter candidates is maximal. Unlike Ge, which benefits from internal activation via neutron capture producing ^{71}Ge discussed earlier, Si lacks analogous low-energy activation peaks [74].

Silicon's stable isotopes lack comparable neutron capture possibilities that produce radioactive daughters with convenient half-lives and appropriate low-energy decay signatures. While $^{28}\text{Si}(n, \gamma)^{29}\text{Si}$ does occur, the product nucleus is stable.

Previous SuperCDMS Si HVeV detector calibrations utilized optical photons from LEDs to produce monoenergetic electron-hole pairs under high-voltage bias conditions [56, 51, 55]. In this approach, photons of a known energy (typically in the 1.5-3 eV range) create single electron-hole pairs in the silicon crystal. Charges while drifting, can induce additional ionization across the crystal. This produces a spectrum of discrete peaks separated by $(E_{\text{photon}} + eV)$, enabling precise calibration (see Figure 4-16).



(a) Detector resolutions using different estimators.

(b) Individual channel baseline resolution for Z3.

Figure 4-15. Uncalibrated baseline resolution comparison between different detectors and different estimators, in addition to the baseline resolution of individual channels. Note that detectors 1 and 3 were operated simultaneously while detector 6 was operated separately.

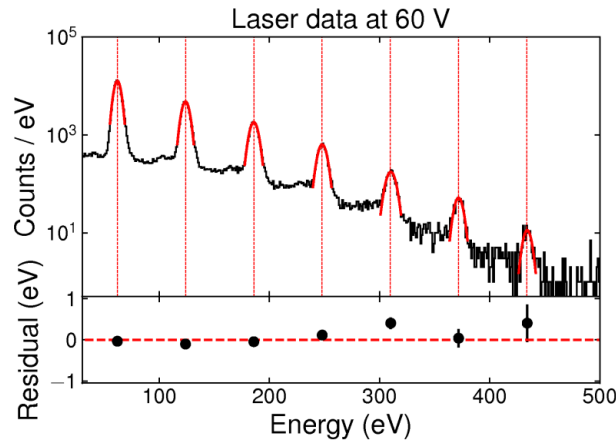


Figure 4-16. combined spectra of laser data (black histogram) at 60 V and the calibration of HVeV R1 data [55]. The red curves represent Gaussian fits to each individual peaks. Bottom panel displays the residuals between the laser peak position after the calibration and the expected value.

However, LED-based calibration suffer several limitations for large-scale detectors. LED photons deposit their energy at the detector surface within the absorption depth, creating interactions that will not be full amplified by the NTL effect. In HVeV detectors, this is resolved by applying a high voltage (more than ~ 60 V [56, 51]) so some of the surface charges cross the thin crystal. In large scale detectors, at such high voltages, crystal breakdowns are frequent limiting the prospects of this method increasingly with volume.

The SuperCDMS CDMSlite runs demonstrated these scaling limitations. Different CDMSlite Ge detectors (dimensions 7.6 cm diameter $\times$ 2.5 cm thick) experienced breakdown at voltages ranging from 30 V to 75 V depending on the individual detector's characteristics [73, 75, 71]. These breakdown events appeared as sudden increases in leakage current or noise bursts. The variability in breakdown voltage between seemingly identical detectors highlights that breakdowns are sensitive to crystal defects, surface preparation quality, and electrodes-substrate interface conditions. All are difficult to control perfectly in large-scale detector production.

4.2.2 Compton Step Calibration Strategy

To address these calibration challenges, we implemented a Compton scattering step features approach, following the methodology recently demonstrated by the SuperCDMS collaboration for HVeV detectors operated at NEXUS [74]. This technique exploits fundamental atomic physics that manifests in the differential cross section for photon-electron Compton scattering.

The Compton scattering process happens when an incident photon transferring momentum to an atomic electron, with the photon scattering at angle θ and the electron recoiling. Conservation of energy and momentum yields the standard Compton equation:

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)} \quad (4-7)$$

where E_γ and E'_γ are the incident and scattered photon energies, and $m_e c^2 = 511$ keV is the electron rest mass. The energy transferred to the recoiling electron is $E_{recoil} = E_\gamma - E'_\gamma$.

However, this classical treatment implicitly assumes free electrons. For bound atomic electrons, the scattering process must overcome the electron’s binding energy E_b before scattering can occur. When the energy transferred to the electron becomes less than the binding energy of the electron’s atomic shell, they, in that shell, can no longer participate in the scattering process [74, 76]. This absence of available scatterings produces a discontinuous decrease in the differential cross section at energy transfers corresponding to each shell’s binding energy, manifesting experimentally as step-like features in the deposited energy spectrum.

For silicon, these Compton steps occur at energies corresponding to the electron shell binding energies: approximately 1.839 keV for the K-shell, 149 eV for the L₁-shell, and 99 eV for the degenerate L₂/L₃-shells [77, 78]. These energies span the critical range for SuperCDMS SNOLAB dark matter searches targeting WIMP masses in the 0.3-10 GeV/c² range [49]. The step heights scale with the number of electrons in each shell and the photon energy, with the K-shell step typically producing the most prominent feature due to its relatively high binding energy.

The SuperCDMS HVeV Compton step calibration built upon this foundation while addressing the unique challenges of cryogenic operation at sub-eV energy thresholds. The work successfully identified K-shell steps and resolved L-shell steps near 100-150 eV [74]. Additionally, the study revealed that detector response at 0 V bias differs by approximately 30% from high-voltage operation for equivalent phonon energy depositions; a feature similar to the one observed in [56] and the Ge overamplification observation presented earlier.

4.2.3 Implementation at CUTE

During the CUTE campaign, Tower 3 silicon detectors were irradiated with a ¹³³Ba gamma source emitting primary lines at 276.4, 302.9, 356.0, and 383.9 keV [64, 65].

The resultant Compton scattering spectrum exhibits several calibration features exploitable for energy calibration. First, the K-shell Compton step at ~1.84 keV provides a robust calibration point observable at both 0 V and high-voltage configurations. Second, hints of L-shell steps appear in high-voltage data, though the L-shell steps’ proximity to noise thresholds makes their use more challenging. Third, the gamma rays induce fluorescence in the copper detector housing

line at ~ 8.05 keV [79]), creating well-defined calibration peaks that supplement the Compton step calibrations at higher energies. Figure 4-17 demonstrates the K-shell step structure and copper fluorescence peak observed for Tower 3 Detector 2 under zero-bias operation.

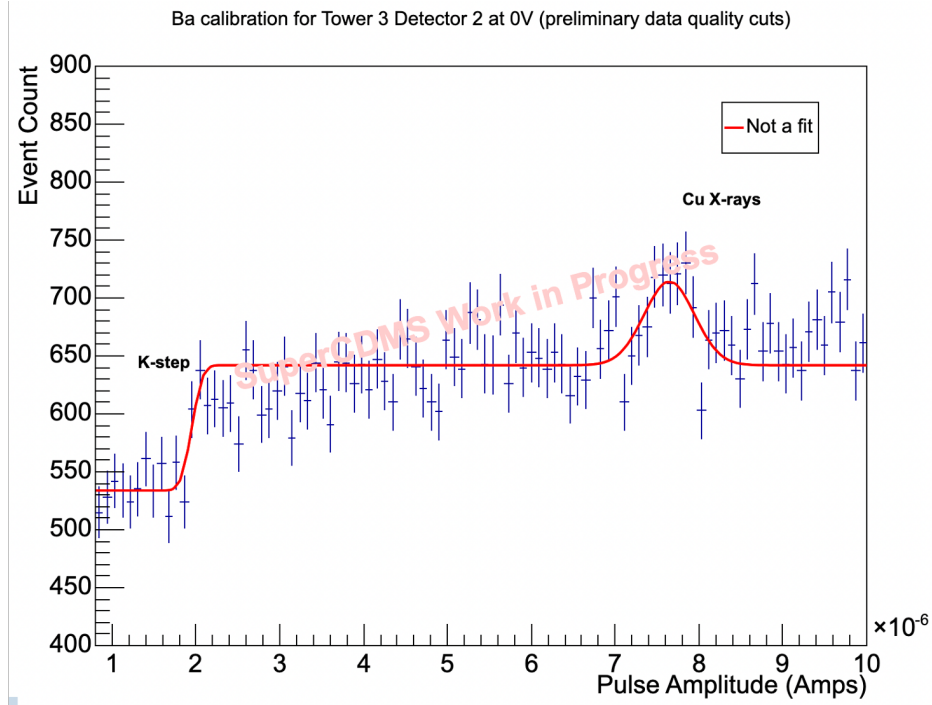


Figure 4-17. Uncalibrated amplitude spectrum for Tower 3 Detector 2 at 0 V bias during ^{133}Ba gamma irradiation. The K-shell Compton step ($E \sim 1.8$ keV) and copper fluorescence X-rays ($E \sim 8$ keV) are visible. The solid line serves to guide the eye rather than represent a fitted model. The error bars are indicators of the statistical uncertainty in each bin

Though the analysis is not complete at the time of writing this thesis, the successful identification of K-shell Compton steps and copper X-ray in Tower 3 silicon detector data at both 0 V and 50 V bias conditions validates this calibration approach for large-scale SuperCDMS SNOLAB silicon detectors. The preliminary indications of L-shell step features in high-voltage data suggest that sub-keV calibration is possible with reduced noise and improved statistics. Together, these features span the critical 0.1-10 keV energy range where silicon detector sensitivity to low-mass dark matter candidates is optimized.

4.3 Outlook

These calibration studies integrate with the broader SuperCDMS SNOLAB detector commissioning program, which aims to comprehensively characterize all deployed detectors prior to science data collection. The calibration methodologies validated at CUTE will directly transfer to SNOLAB operations, where maintaining accurate energy scales throughout multi-year data collection campaigns requires reliable calibration techniques. The Si Compton step and Ge activation peaks approaches provide the strategies necessary to maintain the systematic uncertainties below the statistical sensitivity of SuperCDMS SNOLAB's projected dark matter search.

CHAPTER 5

IONIZATION YIELD MEASUREMENT IN SILICON AT THE IMPACT EXPERIMENT

5.1 Motivation

Since the search for dark matter particles has driven the development of increasingly sensitive detector technologies, current-generation experiments like SuperCDMS target nuclear recoil detections with energies as low as a few hundred eV. This ever-increasing sensitivity has revealed a gap in our understanding of the semiconductor crystals' response to such low-energy nuclear recoils.

One of these responses is the ionization yield (Y), which defines the ionization response to an energy deposition, either for nuclear or electronic recoil. For decades, the Lindhard model [44] provided an adequate description of ionization yield in silicon for nuclear recoils above 4 keV [80, 81]. However, recent measurements have revealed significant deviations from this model at lower energies, with some experiments suggesting the possibility of an ionization threshold that could fundamentally limit detector sensitivity [82, 83].

These deviations create uncertainty in the calibration of dark matter detectors operating in the sub-keV regime. Different experiments have reported conflicting results, with some measurements suggesting a quick falloff of ionization yield at low energies while others indicate more gradual changes. The disagreement between measurements highlights the critical need for independent, high-precision measurements of ionization yield in the 100 eV to 1 keV range, which is the energy region most relevant for next-generation dark matter searches. Figure 5-1 shows some of the recent contradicting measurements along with Lindhard.

The Ionization Measurement with Phonons At Cryogenic Temperatures (IMPACT) experiment was launched to address this gap. IMPACT aims to provide a solid measurement of ionization yield in silicon down to 100 eV, lower than any previous measurement.

5.2 Experimental Concept and Setup

5.2.1 Overview

The IMPACT experiment was conducted at the Triangle Universities Nuclear Laboratory (TUNL) using the FN Tandem Van de Graaff Generator facility. The experimental approach relies

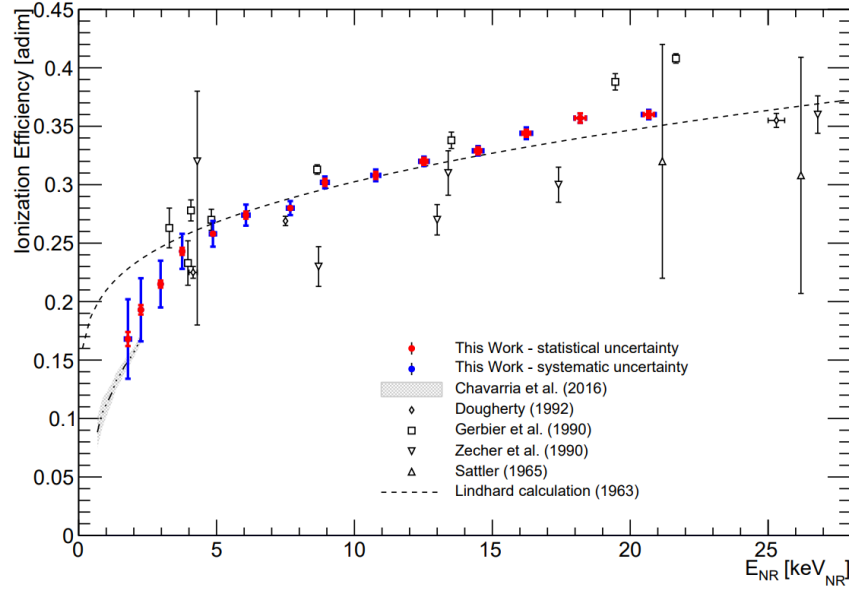


Figure 5-1. Different measurements of the yield as cited in [82] and references therein. This work indicates the publication of F. Izraelevitch et al. in 2017.

on measuring nuclear recoils of known energy through neutron elastic scattering, combined with precise phonon energy measurements using a cryogenic HVeV detector.

The fundamental principle exploits the NTL response of the phonon energy (E_{phonon}) to the recoil energy (E_{recoil}), given the applied voltage bias (V) in a semiconductor detector:

$$Y = \left(\frac{\epsilon}{eV} \right) \times \left(\frac{E_{phonon}}{E_{recoil}} - 1 \right) \quad (5-1)$$

where ϵ is the average energy to create an electron-hole (eh) pair (3.8 eV in silicon), and e is the elementary charge.

5.2.2 Neutron Beam Generation

A pulsed proton beam with 2.5 MHz rate was directed onto a 100 nm monolayer LiF target, inducing the nuclear reaction ${}^7\text{Li}(p, n){}^7\text{Be}$ to produce monoenergetic neutrons with approximately ~ 56 keV energy [84]. The beam current was monitored continuously throughout data acquisition to ensure stable neutron production rates.

A series of collimators shaped the neutron beam and directed it toward the detector cryostat. The beam intensity was optimized to provide sufficient statistics while maintaining low enough rates to avoid detector saturation and preserve energy resolution.

5.2.3 Phonon Energy Detection

The phonon energy was measured by the gram-scale HVeV silicon detector suspended within an adiabatic demagnetization refrigerator (ADR) and maintained at a stable operating temperature of 52 mK. This detector's baseline energy resolution was measured of approximately 4.5 eV in a previous DM search at 0 V bias.

Two voltage configurations were employed: a 100V bias optimized for measuring recoils in the 100-460 eV range, and a 180V bias designed to probe the lowest accessible energies to see if a single electron-hole pair event can be detected.

5.2.4 Neutron Detection

Two distinct arrays of liquid scintillators and photomultiplier tubes (referred to collectively as PMTs) in a ring configuration provided neutron detection capability at different scattering angles. The "lone wolves" (LW) detectors were positioned at fixed angles near the ADR to measure recoils in the 750-4000 eV range (ordered from highest energy to lowest), covering energies previously explored by other experiments for validation purposes.

The "ring detectors" comprised the core measurement system, positioned at two different distances from the target to sample three distinct recoil energies in the unexplored 100-400 eV range. This configuration enabled simultaneous measurement across multiple energy points, improving statistical precision.

A beam pickup monitor upstream of the LiF target provided a timing reference for time-of-flight calculations. Coincidence windows of 400 ns were established to correlate neutron detection events with phonon signals in the silicon detector. A schematic of the experiment is shown in Figure [5-2](#).

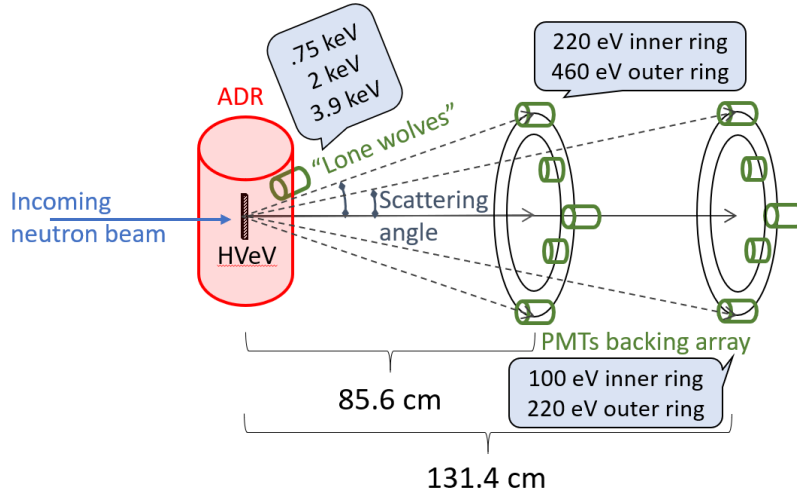


Figure 5-2. A schematic of the IMPACT experiment setup displays the PMTs configuration relative to the ADR and the HVeV detector.

5.3 Analysis

5.3.1 Data Acquisition and Processing

My primary responsibility as principal analyzer for the 180V run involved developing and implementing the complete analysis pipeline for extracting ionization yield measurements. The 180V configuration represented the most challenging aspect of the experiment, attempting to verify measurements of the ionization yield and detect single eh events. The 100V measurement aimed to precisely nail down the yield at unprecedentedly low energies down to 100 eV.

The detector operated in continuous data acquisition mode at 1.5 MS/s sampling frequency. An offline trigger with 50 eV threshold was applied to identify energy depositions while avoiding near-threshold artifacts that could bias low-energy measurements [52]. This conservative threshold was crucial for the 180V analysis, where the signal energies approached the detector's noise resolution.

Daily laser calibration data were acquired to track and correct gain variations induced by ADR thermal cycles. The target was to develop calibration procedures that achieved a 5% uncertainty requirement across the full dynamic range from 100 eV to 109 keV.

This was achieved by employing the following strategies:

- Low power laser at 100 V: this data set was taken every day, serving the purpose of cross-calibrating the detector for day-to-day variation. Covering the energy range of ~ 0 -600 eV.
- Low power laser at operation voltage at 0.5 Hz: this data was taken during the last week of operation, to study detector behavior variation throughout a day. Covering the energy range of ~ 0 -600 eV.
- High power laser at 250 V: this data set was taken on two days only, serving the purpose of calibration up to 7.5 keV with 30 eh pairs @ 250 V. Covering the energy range of 250 eV-7 keV.
- ^{55}Fe at voltages up to 70 V: this data set was taken once, serves the purpose of calibration from 6 keV to 120 keV, with k-alpha at 5.9 keV and k-beta at 6.5 keV. Covering the energy range of 6 keV- 120 keV.
- ^{57}Co at 0V: this data set was taken once, serves the purpose of calibration at high energy, with no NTL gain. Covering the energy range of ~ 100 keV.

The wide range of energies explored necessitated exploring different energy estimators other than the typical OF used in CUTE. A hybrid matched (MF) integral estimator where the pulse was integrated up to the 90% point from the maximum, while the rest was integrated from the template after matching the tails of the pulses and template (See Figure 5-3). Additional baseline corrections were imposed to correct for thermal drift throughout operations.

5.3.2 Coincidence Analysis and Event Selection

The analysis pipeline begins with offline correlation of phonon signals with PMT neutron detection events. For each PMT trigger, time-of-flight (TOF) calculations determine the neutron arrival time at the silicon detector. Events falling within the 400 ns coincidence window are selected for further analysis. The threshold was defined by a Geant4 simulation. Similarly, the time difference between a phonon trigger and a PMT trigger was recorded (dt). Its distribution was used to apply a coincidence cut and determine the background spectra. Figure 5-4 shows the distributions and implemented cuts.

Shifting baseline and degraded event reconstruction necessitated the development of robust data quality cuts, especially considering the HVeV detector saturates around 10 keV of phonon energy. One cut is the deviation of the pre-trigger baseline of each pulse relative to the mean

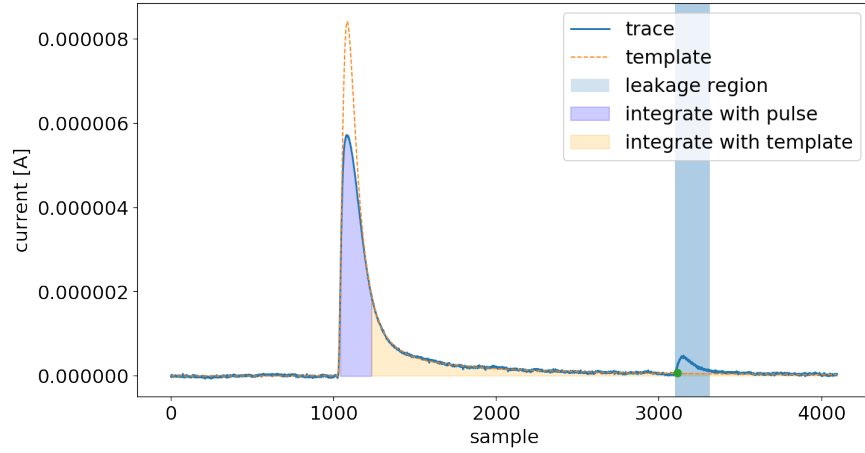
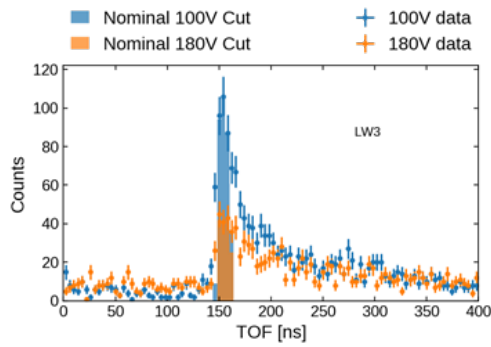
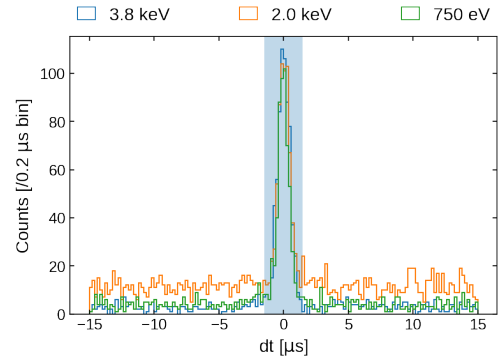


Figure 5-3. Demonstration of the energy estimator MF using an event. The purple region of the trace is above the threshold, and the contribution to MF from this region is the integral of the trace. The yellow region of the trace is below the threshold, where the contribution is calculated from the integral of the fitted template. MF equals is to the summation of the purple region and the yellow region. The grey region represents leakage or pileups and is rejected.



(a) TOF distribution for LW3 for both the 180V and 100V data.



(b) dt distribution for all LWs only considering the 180V data sets.

Figure 5-4. Demonstration of the TOF and dt distributions. The TOF cuts applied did not change between the 2 runs, similar to dt.

baseline. The distributions show that the 180V data show a much higher baseline shift. This is attributed to the fact that the detector was not optimized to handle such high voltage, causing a lot of leakage events (Figure 5-5).

Additional cuts were applied to remove bad reconstruction, highly saturated pulses, and periods of unstable PMT operation. After all the cuts were applied, around $\sim 0.5\%$ of the 100V data, and $\sim 0.2\%$ of the 180V data passed all cuts.

Background discrimination proved particularly challenging for the lowest energy measurements. The background model aimed to incorporate ambient neutron backgrounds, detector noise, and potential electronic pickup. The background rates were measured during anti-coincidence periods and subtracted statistically from the coincidence spectra. Figure 5-6 shows the selection criteria for background events and the spectra for the 100V data.

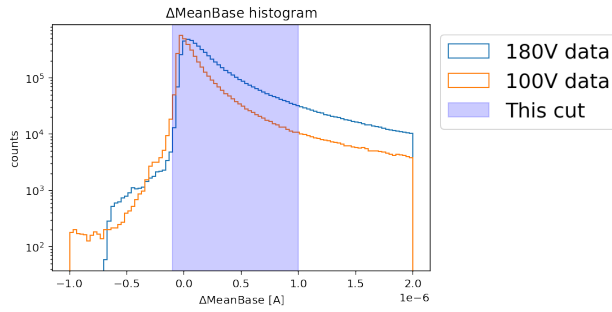
Looking at the final spectra 5-7, one can see how the 180V spectra is significantly reduced complicating the ionization yield estimations. This is due to reduced run time and higher leakage.

5.3.3 Monte Carlo Simulation and Systematic Studies

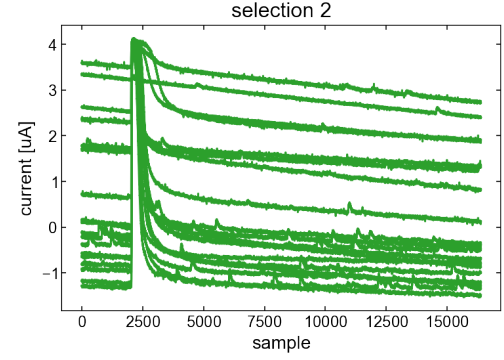
A GEANT4-based Monte Carlo simulation to model the detector response and extract ionization yields from the measured phonon energy spectra was developed. The simulation incorporates the neutron beam energy distribution, elastic scattering spectra and detector geometry.

The yield extraction relies on forward-folding the simulation through the detector response and comparing it to measured energy spectra. For each trial yield value, the simulation predicts the expected phonon energy distribution, which is then convolved with detector resolution, charge trapping effects (12.7% probability), and impact ionization (0.6% probability) measured previously with the same detector used [55].

The analysis also involved modeling the Fano factor (F), which characterizes the variance in ionization production beyond Poisson statistics. For nuclear recoils at these low energies, the Fano factor is not fully constrained, so flexible models were used to account different cases like using



(a) Mean baseline deviation distributions.



(b) Example of rejected pulse by the cut.

Figure 5-5. Demonstration of events with very high baseline shift are due to unstable operation, pileups, and leakage current. The example pulse shown is from the 180V data set.

Poisson ($F = 1$), binomial ($F < 1$), and negative binomial ($F > 1$) distributions as appropriate for different energy regimes.

5.3.4 MCMC Fitting Methodology

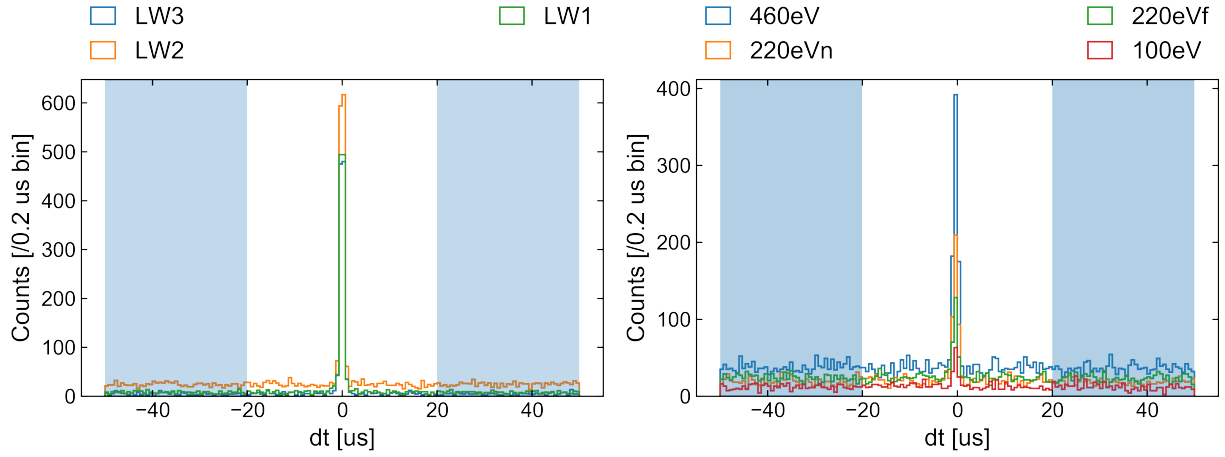
I employed a Markov Chain Monte Carlo (MCMC) approach using the Metropolis-Hastings algorithm to extract yield values and their uncertainties. The MCMC sampler explores the parameter space defined by ionization yield, Fano factor, and normalization for each energy point, utilizing a binned log-likelihood comparison between data and simulation.

The fitting procedure simultaneously determines yields at measured recoil energies for ring and LWs separately, incorporating correlations between energy points through shared systematic parameters of each group of spectra. The resulting posterior samples provide full uncertainty information including correlations between fitted parameters. Figure 5-8 shows the work flow of the MCMC calculations.

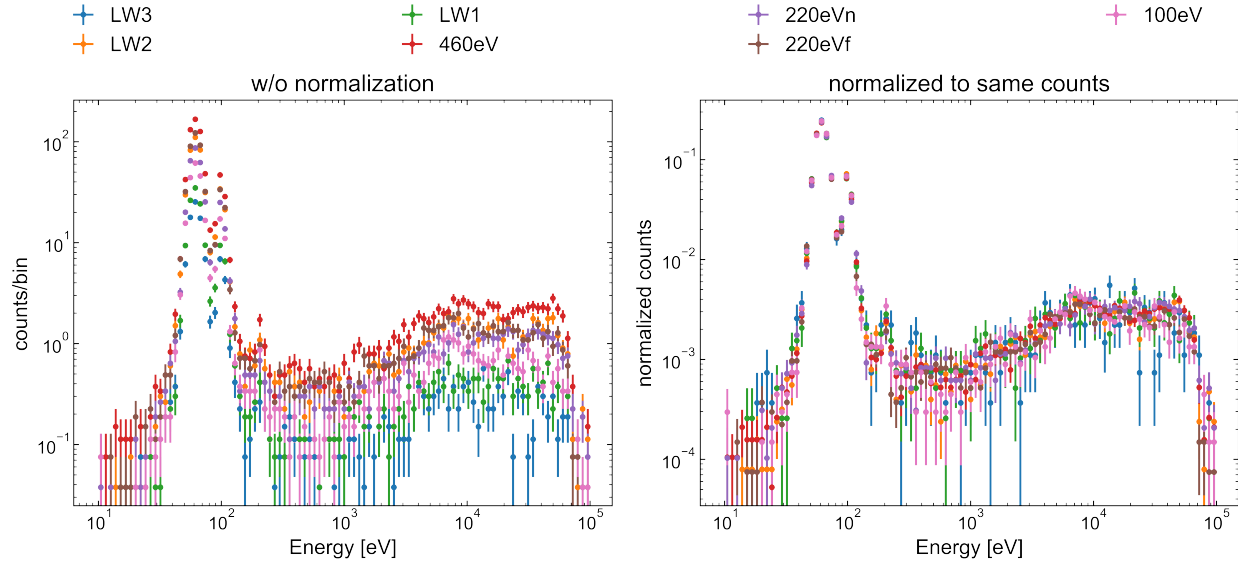
5.3.5 Systematic Uncertainty Assessment

The dominant systematic sources were identified as:

- **Detector Calibration:** Energy scale uncertainties propagate directly to yield measurements through the relationship between phonon and recoil energies. Also, the energy calibration is very sensitive to the HVeV detector position in the ADR which hold an uncertainty that can change the calibration by 20% for LWs with a negligible effect on ring energies. Finally, we account for the uncertainty in energy reconstruction also in this category.

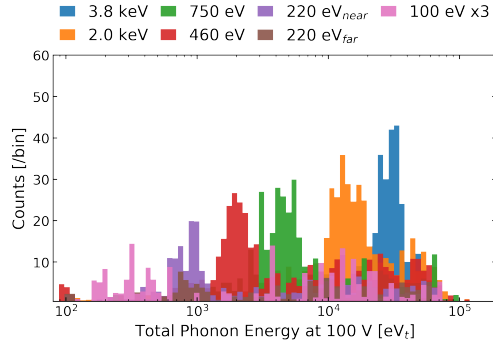


(a) Background event selection.

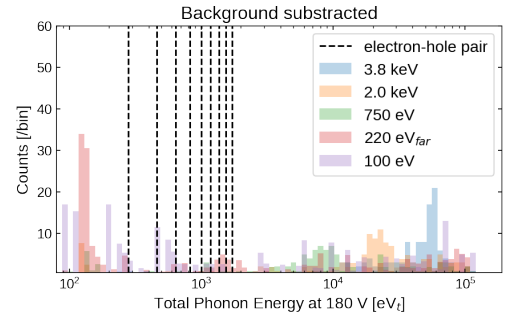


(b) Background spectra.

Figure 5-6. dt distribution and the dt cut from $-50 \mu s$ to $-20 \mu s$ and from $20 \mu s$ to $50 \mu s$ to estimate the background after applying all the cuts. The right panel of the background spectra is normalized to the same total counts, showing that the spectral shapes are compatible.



(a) 100V data spectra.



(b) 180V data spectra.

Figure 5-7. Combined spectra of all energies for both the 100V and 180V runs. Spectra corresponding to 100 eV recoil energy were multiplied by factors for visibility. The vertical dashed lines correspond to the multiple of eh energies.

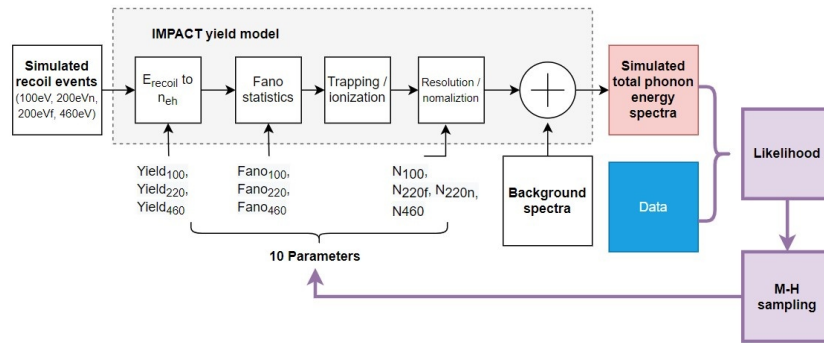


Figure 5-8. A flow chart illustrating the fitting algorithm for the ring recoil energies. The same approach was used with the LWs

- **Beam Energy:** Neutron energy uncertainties affect the calculated recoil energies through elastic scattering kinematics. The source produce a 3 keV spread in neutron energies. We produced simulations for expected deposited energies with high and low bounds of the spread and fed it to the MCMC.
- **Charge Trapping and Impact Ionization:** The measured values of charge trapping (12.7%) and impact ionization (0.6%) carry uncertainties that affect the detector response model [55]. I propagated these uncertainties through the full simulation chain.
- **Fano Factor Modeling:** The unknown Fano factor for nuclear recoils introduces model-dependent uncertainties. Different functional forms and parameter ranges were implemented to assess the sensitivity of yield measurements to Fano factor assumptions.
- **Time-of-Flight Systematics:** Since the TOF cut is set according to the simulation, with nominal boundaries defined to be at the locations where the time of flight peak is 0.3 times its maximum (peak) value. To test other cut boundaries, I use a narrower cut (set at 0.2*maximum) and a wider cut (0.5*maximum). The three TOF intervals roughly correspond to neutron energy spread of ± 1 keV, ± 2 keV and ± 3 keV, which are reasonable choices based on the estimated standard deviation of neutron energy of 3 keV.

100 PEs were generated for each variation in the sources of the uncertainties. The median values for each recorded parameter were recorded and their averages were taken to be the nominal values with uncertainties equating their standard deviation. The systematic uncertainty of a single source of uncertainty was taken as one-sided if the two variations were on opposite sides of the nominal value, and two-sided if they were on the same side with the larger deviation as the uncertainty. Figure 5-9 summarizes the uncertainties.

5.3.6 Yield Parameterization

The final step of my analysis involved parameterizing the measured yields as a function of recoil energy. An empirical power-law function was used to model the ionization yield as shown in equation 5-2:

$$Y(E_r) = Y_{10keV} \times (E_r/10000)^B \quad (5-2)$$

where $Y_{10keV} = 0.302$ is fixed to match the Lindhard model prediction at 10 keV, and B is the fitted power-law index.

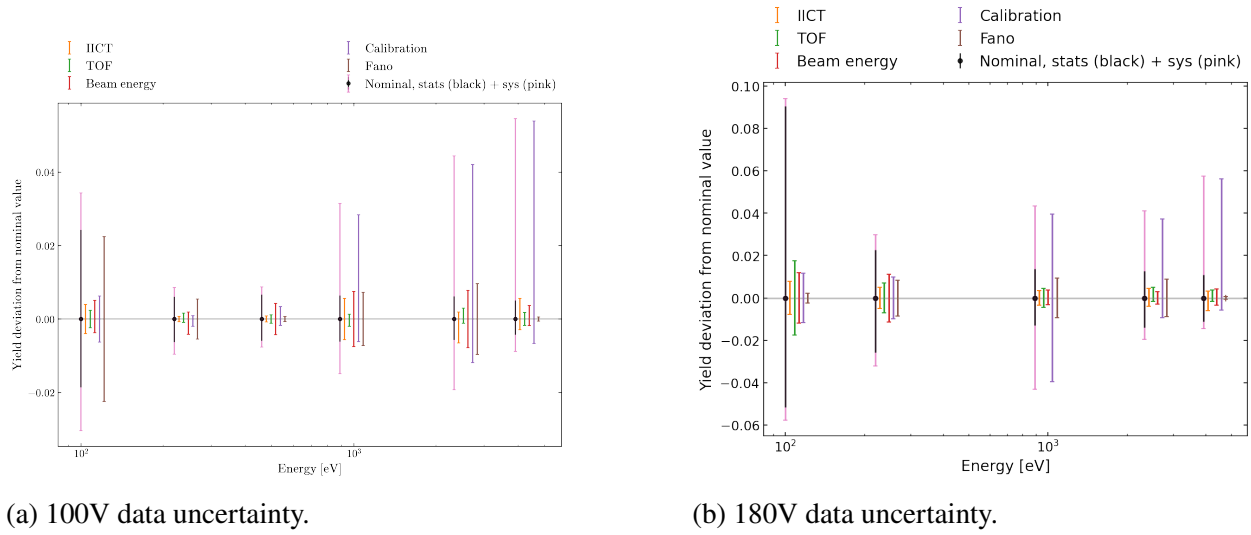


Figure 5-9. Summary between the systematic and statistical uncertainties for both data sets. The statistical uncertainty dominates the 180V data sets resulting in a low confidence values. The calibration uncertainty dominates the LWs systematics which is expected given their proximity to the detector.

The power-law fit was performed using least-squares minimization incorporating the full covariance matrix from statistical and systematic uncertainties.

5.4 Results

5.4.1 Ionization Yield Measurements

Both runs have been analyzed and fitted separately. Both have successfully measured ionization yield in silicon across an unprecedented energy range, down from 100 eV to approximately 4 keV. These measurements represent the lowest-energy direct measurements of nuclear recoil ionization yield in any semiconductor material [52].

The measured yields of the higher energy depositions are consistent with the measurements in the literature [82, 85, 46, 83]. This, however, cannot be said about the ring energies (100 - 400 eV), where the measurements do not find any evidence to ionization production threshold down to 100 eV unlike findings of [85, 46]. This tension, however, can be attributed to the different experiment setup (using neutron capture rather than scattering) and different fitted models. Across the entire energy range, the yield was found to be smaller than what the Lindhard model predicted.

The absence of an ionization threshold down to 100 eV contradicts suggestions from some theoretical models and experiments that predicted rapid falloff of ionization efficiency at low energies [45]. Instead, the smooth power-law behavior observed suggests that silicon detectors maintain substantial sensitivity to nuclear recoils well below previously explored energy ranges.

The power-law fit was performed separately for both runs. The fit to the 100V dataset yields $B = 0.261^{+0.017}_{-0.011}$, while $B = 0.216^{+0.169}_{-0.282}$ for the 180V data set. The results are within 1σ from each other with 180V having a very wide spread due to the discussed issues above. The results of the 100V analysis was published in [52].

5.4.2 Implications for Dark Matter Detection

These results have significant implications for current and future dark matter detection experiments using silicon targets. The measured yield values enable improved detector calibration and background modeling for experiments like SuperCDMS SNOLAB, which will search for dark matter with recoil energies in the range studied by IMPACT.

The absence of an ionization threshold down to 100 eV is particularly encouraging for low-mass dark matter searches, as it indicates that detector sensitivity does not suffer a reduction. However, the deviations from Lindhard predictions must be accurately accounted for in detector response modeling and analysis procedures.

5.4.3 Future Prospects

The IMPACT technique has demonstrated the capability to measure nuclear recoil ionization yield with precision sufficient to guide detector optimization. Future iterations of the experiment could extend measurements to even lower energies, explore temperature dependence, or investigate other semiconductor materials such as germanium.

The analysis framework developed for the TUNL runs provide a foundation for these future measurements planned by the SuperCDMS collaboration. As, it intends to implement similar experimental concept to measure ionization yield for germanium in its testing facility in Fermi laboratory. The experiment at the Northwestern EXperimental Underground Site at Fermilab

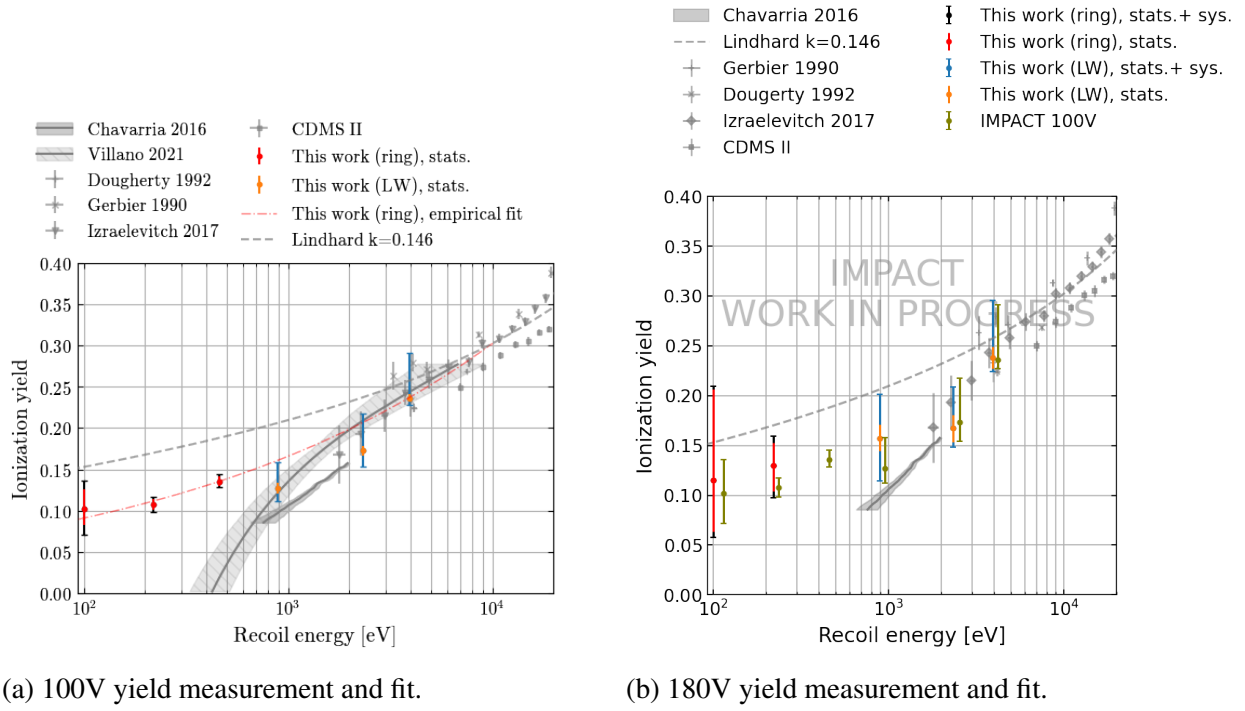


Figure 5-10. Yield results for the 100V and 180V runs with their respective power-law fits. Measurements of [85] were removed from the 180V results for visibility.

(NEXUS) is designed to utilize upgraded shielding, improved PMT sensitivity and more consistent calibration sources to improve the measurements.

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BIOGRAPHICAL SKETCH

Moaaz Elwan's doctoral research focuses on dark matter direct detection with the Super Cryogenic Dark Matter Search (SuperCDMS) collaboration, specifically targeting nucleon-coupled dark matter candidates and electron recoil candidates. His academic journey began at the University of Science and Technology - Zewail City, Giza, Egypt, where he earned a B.S. in Physics of Earth and Universe in 2020, graduating with summa cum laude and a cGPA of 3.75/4.00. Throughout his undergraduate studies, he was consistently recognized on the Provost's Honor Roll. Moaaz then pursued a non-thesis master's degree from the University of Florida as part of his pursuit of a doctoral degree, which he completed in 2022.

As a Graduate Assistant at the University of Florida from 2021 to 2026, Moaaz has gained valuable experience in both research and teaching, leading laboratory and discussion sections for different introductory physics courses. Within the SuperCDMS collaboration, he has taken on responsibilities, including serving as the SuperCDMS Council Secretary and as a committee member on the Graduate Student and Postdoctoral Fellows board, where he represents his peers within the collaboration's administrative structure. His direct research contributions to the collaboration include participation in a world-leading measurement with the IMPACT experiment and CUTE tower testing, paving the way for the SuperCDMS SNOLAB experiment. Moaaz's dissertation aims to provide a framework for analyzing data from dark matter experiments, and he intends to continue his contributions to the field of particle astrophysics in his future research. He received his Ph.D. from the University of Florida in 2026.

A comprehensive list of publications can be found through the ORCID profile of [0009-0002-0034-0147](https://orcid.org/0009-0002-0034-0147)