

SIMULATING THE DETECTOR RESPONSE AND PRODUCING LONG-TERM  
SENSITIVITY PROJECTIONS FOR THE SUPERCDMS EXPERIMENT

By

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To my mother

## ACKNOWLEDGEMENTS

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Abstract of Dissertation Presented to the Graduate School  
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While the concept of dark matter is well established and the evidence for it is compelling, detection of it continues to elude scientists. The SuperCDMS series of experiments has used semiconductor detectors that can measure ionization and phonon energy in an attempt to detect dark matter. The next iteration of the experiment, SuperCDMS SNOLAB, is set to begin taking data later this year. In parallel with SuperCDMS SNOLAB's development, the IMPACT calibration experiment was run to measure the ionization yield of silicon at sub-keV recoil energies. The SuperCDMS collaboration employs a set of software packages to simulate detector events end-to-end from initial interaction to readout signal. This dissertation covers a series of simulations run using these software packages to better understand the parameters of the sensors used to measure phonon energy during IMPACT and the low-energy tails present in energy histograms of IMPACT data, along with a set of improvements made to the code that handles phonon tracking. The collaboration also employs a set of software packages to generate sensitivity projections for both SuperCDMS SNOLAB and future detector proposals. This dissertation also covers a series of simulations run using these software packages to determine the viability of a variety of motivated detector proposals, along with a set of improvements made to the underlying code, including the addition of two new detector types and a change to the backgrounds calculation that dramatically sped up the code.

## CHAPTER 1 DARK MATTER BACKGROUND

### 1.1 Motivation and Evidence

There are many pieces of evidence that point to the existence of a significant population of non-luminous matter, referred to as dark matter, distributed throughout the universe. Here, the most influential, as well as arguably the two most significant pieces of evidence, will be considered.

#### 1.1.1 Galactic Rotation Curves

The first significant evidence for dark matter came from studies of the rotation curves of spiral galaxies. Such a curve corresponds to the orbital velocity of a galaxy as a function of distance from its center. The dependence of such curves comes from Newton's law of universal gravitation, which says that an object a distance  $r$  away from the center of another object of mass function  $M(r)$  such that  $M$  is the mass contained within  $r$  will orbit with velocity:

$$v(r) = \sqrt{\frac{GM(r)}{r}}. \quad (1-1)$$

Thus, the rotation curve of a galaxy is entirely determined by its mass distribution. The original model of the mass distribution of spiral galaxies consisted of a uniform sphere at the center (i.e.  $M \propto r^3$ ) and a massless region surrounding it. Such a mass distribution would imply that the galactic rotation curve would increase linearly from the center until the massless region was reached, after which it would decrease by  $v \propto r^{-1/2}$ .

However, it has been observed that, while the model of the galactic center is correct, instead of the rotation curve starting to decrease afterwards, it actually flattens out. This is illustrated in Fig. 1-1, which shows many such observed curves [1]. This would imply that there is an additional halo of mass with  $M \propto r$  surrounding the central mass. The fact that such halos are seemingly invisible entails that its constituent matter must not emit photons or interact through the electromagnetic force in general. This type of matter is what is referred to as dark matter.

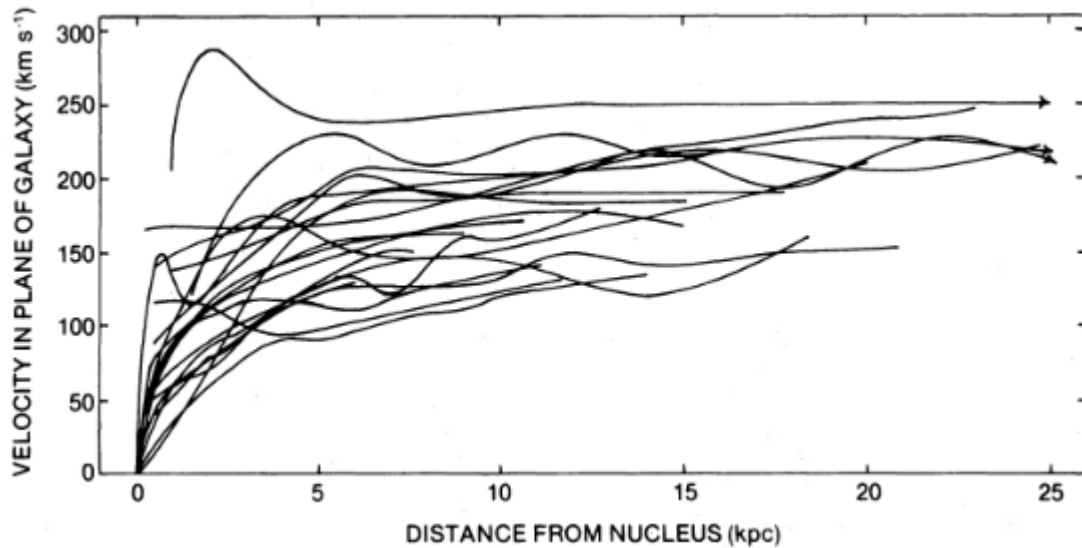


Figure 1-1. The rotation curves for a set of spiral galaxies.

### 1.1.2 Gravitational Lensing

One consequence of general relativity is that light bends around massive objects to a degree that increases with the object's mass. This is referred to as gravitational lensing. Such behavior is a potential indicator of dark matter as, if light is observed to bend around an object more significantly than its observed mass would suggest, there must be some additional unseen mass to account for the discrepancy.

Observations of what is referred to as the Bullet Cluster, but what is actually two colliding clusters, provide an example of such a scenario. It is important to note that the collision is at a point where the clusters are now moving away from one another. A map of the x-ray emission, which only occurs when ordinary matter interacts electromagnetically, shows that the centers of such mass are fairly close, whereas a map of the gravitational lensing, which is determined by the entire mass of the clusters, shows that the centers of total mass are quite far apart. The remaining mass must then be non-luminous dark matter. The maps are shown side by side in Fig. 1-2, with the gravitational lensing one on the left and the x-ray emission one on the right [2].

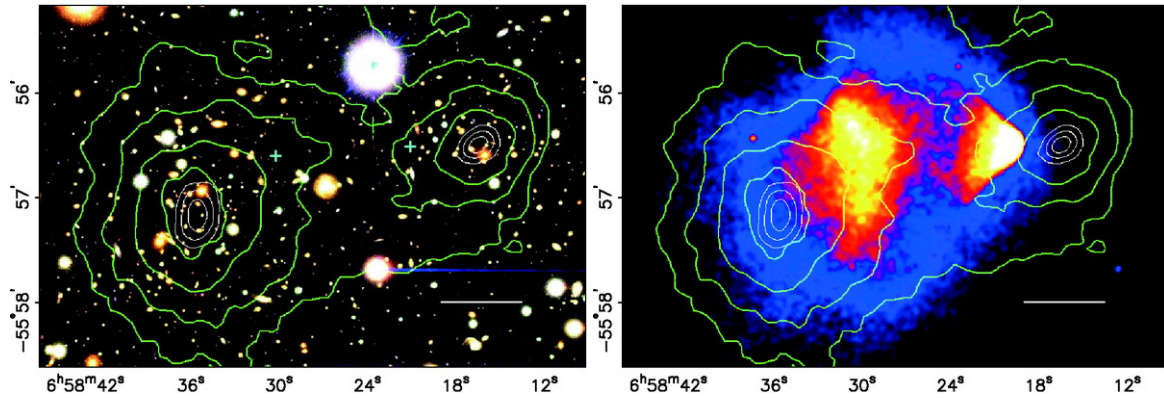


Figure 1-2. Images of the Bullet Cluster as a map of gravitational lensing (X-ray emission) on the left (right).

### 1.1.3 Cosmic Microwave Background

The most compelling evidence for dark matter comes from the cosmic microwave background. Right after the Big Bang, the universe was extremely hot. After a microsecond, quarks and gluons were able to coalesce and form hadrons which, along with electrons, interacted frequently with photons, preventing light from travelling far. After 3 minutes, hadrons were able to coalesce and form nuclei. After about 379,000 years, the universe had cooled to the point that electrons and nuclei could coalesce and form atoms, which, being electrically neutral, interact with photons much less often, allowing light to essentially travel freely. These released photons then became a background, referred to as the cosmic microwave background (CMB), that permeates the universe to this day.

The CMB is nearly isotropic due to cosmic inflation having smoothed both matter and space out beforehand. However, slight anisotropies are present due to quantum fluctuations in the field that caused inflation. Since the photons all come from the same point in time, the map of anisotropies is on the surface of a sphere. This map can be turned into an angular power spectrum where it is expressed as a sum of spherical harmonics. This spectrum is shown in Fig. 1-3 [3].

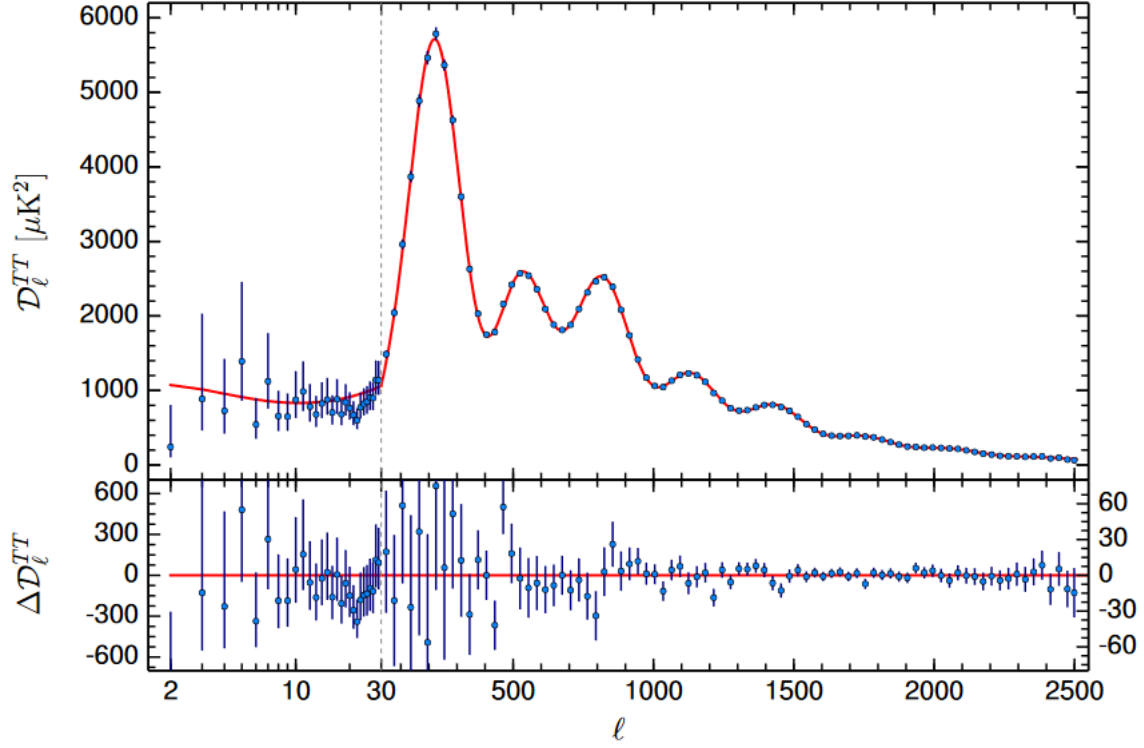


Figure 1-3. The angular power spectrum of anisotropies in the cosmic microwave background.

The position of the first peak is determined by the spatial curvature of the universe. The height of the successive even and odd peaks is determined by the abundance of ordinary and dark matter respectively [4]. The separation is due to the fact that, while both types of matter are subject to gravitational forces that tend to create denser regions, only ordinary matter is also subject to radiation pressure that tends to push those overdense regions apart. These competing effects on ordinary matter produce density oscillations analogous to sound waves. The even-numbered modes of these density waves correspond to underdense regions consisting of ordinary matter, while the odd-numbered modes correspond to overdense regions consisting of dark matter. The fact that the odd peaks are so pronounced is clear evidence for dark matter.

Beyond that, the relation between the height of the odd (mainly the third) and even (mainly the second) also gives a numerical value for the abundance of dark matter in relation to that for ordinary matter. Of the matter in the universe, around 84% is dark matter while only 16% is ordinary matter.

## 1.2 Characteristics and Models

### 1.2.1 Properties

Obviously, dark matter must be electrically neutral. However, it must also be non-baryonic, as the ordinary matter that impacts the even peaks of the angular power spectrum of the cosmic microwave background includes even electrically neutral baryons.

Beyond its composition, dark matter must be non-relativistic because, otherwise, it would not have been able to coalesce into the structures seen in galaxies. It must also be long-lived, as it has been present with significant abundance since the early universe. Finally, it must be weakly self-interacting, as populations of dark matter pass through one another much more quickly than many populations of ordinary matter do, as seen in the Bullet Cluster observations for instance.

### 1.2.2 Freeze-out vs Freeze-in of Relic Abundance

The abundance of dark matter was not constant over the entire course of the early universe. One model for the abundance is the freeze-out model, which assumes that the initial density of dark matter was very large and in equilibrium with the thermal bath, being produced and annihilated at equal rates. Then, once the temperature decreased below the dark matter particle mass, the production process became kinematically forbidden, leaving only the annihilation process and causing the dark matter density to decrease. Finally, once the universe expanded to the point where the annihilation process became spatially impossible, the dark matter density flattened back out.

Another model is the freeze-in model, which assumes that the initial density of dark matter was very small and coupled to the thermal bath in such a way that there was only a production process, causing the dark matter density to increase. Then, like with the freeze-out model, the production process became forbidden after the temperature fell too low and the dark matter density flattened out.

The two models are contrasted graphically in Fig. 1-4, with the solid and dashed lines corresponding to freeze-out and freeze-in models of different coupling strengths respectively [5].

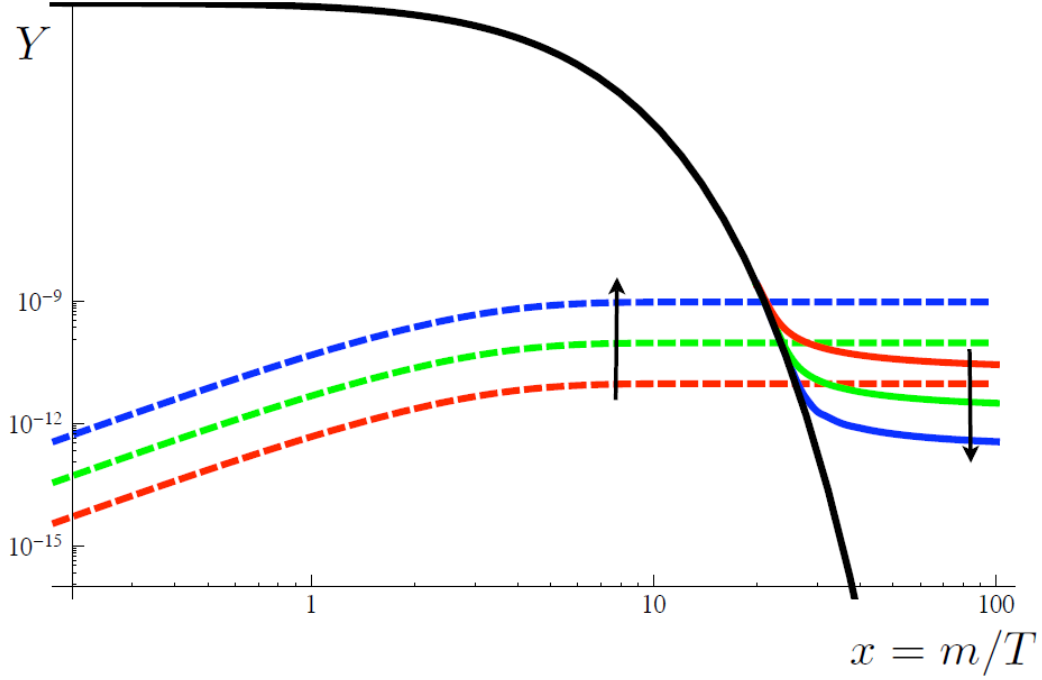


Figure 1-4. The relic abundance of dark matter as a function of time in the freeze-out (in solid) and freeze-in (in dashed) models.

### 1.2.3 Galactic Halos

If the mass function of the dark matter halo is supposed to increase linearly, it should be the case that  $\rho(r) \propto r^{-2}$ . With this in mind, the simplest analytic model is given by taking a pseudo-isothermal halo:

$$\rho(r) = \frac{\rho_0}{1 + \left(\frac{r}{r_c}\right)^2}, \quad (1-2)$$

where  $\rho_0$  is the density at the center and  $r_c$  is the radius of the core [6]. However, images of galaxies clearly show that taking the region beyond the galactic center to be massless is a rough approximation. For instance, the outer arms of spiral galaxies, the defining characteristic of such galaxies, provide small but noticeable contributions to the overall mass function. To maintain consistency with observations, this would require that the dark matter density function fall off faster. A numerical model that indirectly takes this into account is the Navarro-Frenk-White (NFW) profile:

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s} \left(1 + \frac{r}{R_s}\right)^2} \quad (1-3)$$

where  $R_s$  is a tunable parameter to fit particular galactic halos [6]. However, this model is only a rough approximation as well [7]. For one thing, it is likely that the dark matter halos are flatter, or that halos are more dense around the galactic plane, than the above models indicate. For another, it is likely that there is some amount of substructure in dark matter halos, while the above models clearly suggest smoothly distributed halos.

## 1.3 Candidates

### 1.3.1 Weakly Interacting Massive Particles

As the Standard Model leaves several problems unexplained, many theories have been proposed as either alterations to or extensions of the model. One such class of extensions is supersymmetry, the central premise of which is that every Standard Model fermion (boson) has a bosonic (fermionic) counterpart referred to as a superpartner. Both the neutralino (a mixture of the superpartners of the Z boson, photon, and Higgs boson) and the sneutrino (the superpartner of the neutrino) are dark matter candidates, as they are both clearly electrically neutral and non-baryonic [8, 9]. They both have masses on the order of 10 GeV at the minimum, so they are also non-relativistic. Even though they both are rather massive, they are actually quite light for superpartners, with one even being the lightest such particle (depending on the particular model), it cannot decay into other supersymmetric particles. If R-parity is imposed, which forbids decay into Standard Model particles. This implies that the lighter particle is also stable.

A related concept is the weakly interacting massive particle (WIMP). These are particles that only interact on the scale of the weak nuclear force at the most. The lightest supersymmetric particle is an example of a WIMP, but WIMPs can also refer to non-supersymmetric particles. This additional descriptor is important because its characteristic allows the particle to satisfy the final dark matter property. One particular theoretical advantage of WIMPs is that the relic abundance of such particles in the 1 – 1000 GeV mass range with a velocity-averaged cross section on the order of the weak scale is similar to the observed relic abundance of dark matter today [10].

WIMPs have been one of the leading candidates for dark matter for decades. In particular,

WIMPs of mass on the order of 10 GeV or larger and cross section on the order of the weak scale have been favored. However, between various detection experiments failing to pick up signals of such WIMPs and particle colliders failing to pick up signals of supersymmetry in general, recent attention has turned to lower mass WIMPs, as well as other candidates altogether.

### 1.3.2 Dark Sector Dark Matter

Dark sector models posit that there is a hidden sector beyond the Standard Model that interacts with the Standard Model through a new force mediated by a new boson, which is most commonly taken to be a vector boson [11]. This boson, referred to as the dark photon  $A'$ , has a mass  $m_{A'}$  and undergoes kinetic mixing with the Standard Model photon that is parameterized by the kinetic mixing angle  $\epsilon$ . The fermionic dark matter component of the dark sector,  $\chi$ , has a mass  $m_\chi$ .

There are three models for the relic abundance of dark sector dark matter over time [12]. The first, which could happen if  $m_\chi > m_{A'}$ , is that  $\chi$  underwent freeze-out to  $A'$  through secluded annihilation (i.e.  $\chi\chi \rightarrow A'A'$ , followed by decay to standard model particles). In this case,  $\chi$  is a complex scalar. The second, which could happen if  $m_\chi < m_{A'}$ , still involves  $\chi$  undergoing a freeze-out process, but to Standard Model particles through direct annihilation. In this case,  $\chi$  is a Dirac fermion. And the third is that  $\chi$  underwent freeze-in through the annihilation of Standard Model particles, which could only occur if  $\epsilon$  is very small.

Given its nonzero mass, there are also dark sector models that take the dark photon itself to be dark matter. Going forward, dark photon dark matter (DPDM) will refer to these models, while light dark matter (LDM) will refer to the previous models.

### 1.3.3 Axion-Like Particles

The axion is a consequence of a proposed solution to the strong CP problem. This is that, even though it is possible for CP-symmetry to be violated in strong force interactions, no such violation has ever been observed. The theory of such interactions, quantum chromodynamics, has a Lagrangian that is typically written with any CP-symmetry violation contained in a single term characterized by an angle  $\theta$  [13]. At the naturally expected scale of  $\theta$  of order 1, the neutron

should have a noticeable electric dipole moment. However, no experiment has ever detected even a nonzero neutron electric dipole moment.

One solution to this is to introduce a new global symmetry, referred to as the Peccei-Quinn symmetry, that is spontaneously broken at the energy scale  $f_a$ , which produces the axion as a pseudo-Goldstone boson [14]. This explicitly sets  $\theta$  to 0, removing any potential for CP-symmetry violation.

The axion's mass is directly proportional to  $f_a$ . Relaxing this relationship defines a class of particles referred to as axion-like particles (ALPs). Unlike the axion, these particles cannot solve the strong CP problem, but they can behave as dark matter in a similar way [12]. Going forward, only ALPs will be considered here.

## CHAPTER 2 SUPERCDMS EXPERIMENT

### 2.1 General Experimental Concept

The Super Cryogenic Dark Matter Search (SuperCDMS) experiment uses semiconductor-based detectors that are operated underground at cryogenic temperatures and are equipped to measure ionization and phonon energy. Semiconductors are useful for dark matter detection because of their low band gap (on the order of an eV), allowing even quite low energy recoils to produce an ionization signal. Their use underground reduces backgrounds, particularly those caused by cosmic rays. Their operation at cryogenic temperatures is twofold, it reduces thermal noise that would otherwise obscure the phonon signal, and it allows for the use of transition-edge sensors (TESs), which exploit the fact that materials are highly sensitive to energy inputs while in their superconducting transition state. The collection of both ionization and phonon energy further improves background rejection by allowing for the discrimination of a type of recoil associated with background.

The first iteration of the experiment, CDMS I, was conducted in the Stanford Underground Facility and collected data from 1998 to 2002. The next iteration, CDMS II, was conducted in the Soudan Underground Laboratory (SUL) and collected data from 2006 to 2008. After that was SuperCDMS Soudan, which was also conducted in SUL and collected data from 2011 to 2015. The upcoming iteration, SuperCDMS SNOLAB, will be conducted in an expansion of the Sudbury Neutrino Observatory (SNO) referred to now as SNOLAB and will collect data from 2023 to 2027.

### 2.2 Detector Specifics

#### 2.2.1 iZIP Detectors

The standard detector SuperCDMS has used to detect dark matter is the interdigitated, z-sensitive, ionization and phonon (iZIP) detector. They are composed of cylindrical crystals of either silicon or germanium 100 mm in diameter and 33.3 mm thick. This gives them a mass of 0.61 (1.39) kg for Si (Ge). There are six phonon sensors on each face, with a central circular one, four wedge-shaped ones arranged in a ring that surround the central one, and one ring-shaped one

on the edge, as well as two charge sensors interleaved with the phonon sensors such that one shares the area of the first five while the other shares the area of the outer ring. This sensor arrangement is illustrated in Fig. 2-1.

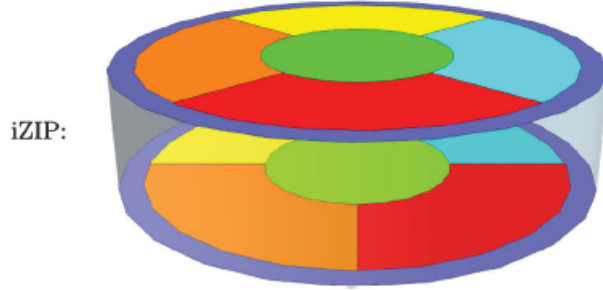


Figure 2-1. The phonon channel layout of an iZIP detector.

Voltage biases of  $\pm 4$  ( $\pm 3$ ) V are applied to the charge sensors on the top and bottom of Si (Ge) detectors so that there's a weak electric field perpendicular to the faces throughout the detector, whereas the phonon sensors are grounded so that there are stronger electric fields along the faces. The bulk field allows charges created by events in the detector to accelerate towards the charge sensors, while the surface fields allow for the rejection of events near the faces. The map of the full electric field near a surface is shown in Fig. 2-2.

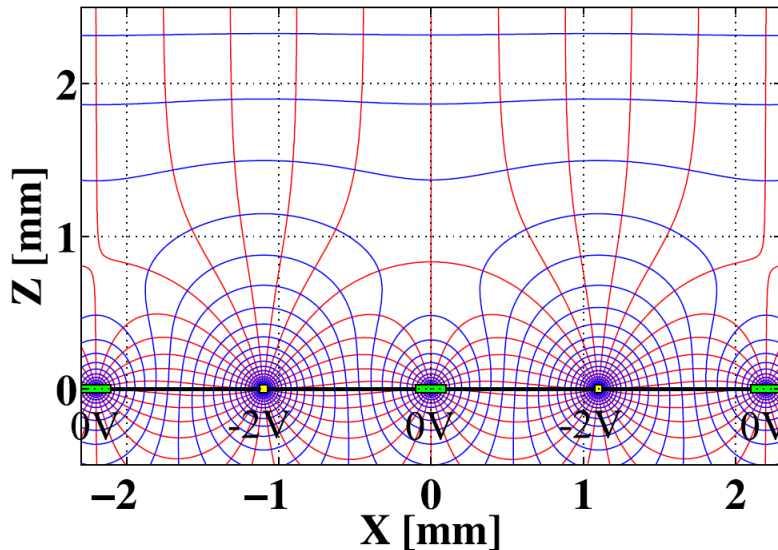


Figure 2-2. The electric field near the surface of an iZIP detector.

A special property of iZIPs is their ability to discriminate between nuclear recoils, which

are associated with WIMP interactions and electron recoils, which are associated with background events. This is due to the fact that electron recoils create many more charge pairs than nuclear recoils of the same energy, meaning that the ratio of collected charge energy to collected phonon energy is much greater for electron recoils.

In addition to the electric field at the surfaces, the combination of the inner and outer charge sensors allows for a broad rejection of surface events, which is necessary because such events exhibit reduced charge collection. For events near the sidewall, this is due to there being a greater proportion of imperfections in the crystal there that are potential wells that can trap charges, while, for events near the faces, this is due to the potential for charges to diffuse into a sensor on that face without being accelerated across the detector. Sidewall events can be identified as those where the majority of the charge collections occurs in the outer sensor, while face events can be identified as those with asymmetrical charge collection between the two faces, with the electric fields around the sensors ensuring that every such event results in such a signal and can hence be rejected.

iZIP detectors are only sensitive to WIMPs of mass above 5 GeV. This is due to the low voltages applied across iZIPs. This cannot be altered as operation at higher voltages would leave the phonon sensors unable to be grounded, which would remove the ability to reject face events. As the WIMP parameter space actively being explored is shifted to lower masses, the development of a second type of detector that could be operated at high voltages became necessary.

### **2.2.2 HV Detectors**

This newer detector is the high voltage (HV) detector. They are composed of crystals of the same material, dimensions and mass as those for iZIP detectors. They also have a similar distribution of phonon sensors, just with three wedge-shaped ones around the central one instead of four and two concentric ring-shaped ones on the edge instead of one. This sensor arrangement is illustrated in Fig. 2-3. The main differences are that HV detectors are operated at a voltage bias of 100 V and they have no charge sensors, as they are not necessary at such large voltages. This is

due to the fact that, at high voltages, the phonon signal becomes dominated by those generated by the accelerating charges. Since the number of such phonons is proportional to the number of charges, this means that the two corresponding signals are essentially degenerate.

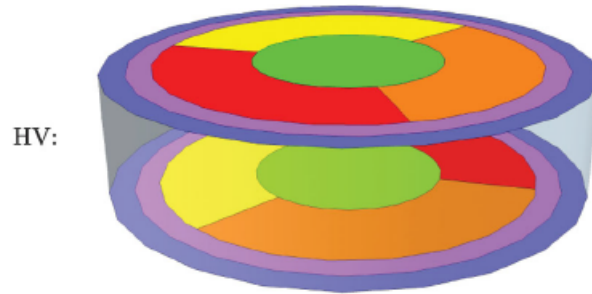


Figure 2-3. The phonon channel layout of an HV detector.

Without charge sensors, there is only the electric field perpendicular to the faces present. The multiple outer phonon sensors allow for the improved rejection of sidewall events, but, while the ability to reject face events, along with that to differentiate between nuclear recoils and electron recoils, is about the same, with no charge sensors, the use of statistical discrimination is required for that to be the case. HV detectors are sensitive to WIMPs of mass well below 5 GeV, and hence are well suited for detecting such particles in the current region of interest.

## 2.3 SuperCDMS SNOLAB

### 2.3.1 SNOLAB-Generation Developments

Many improvements have been made from SuperCDMS Soudan to SuperCDMS SNOLAB. First, SNOLAB is located 2,070 m below ground, while SUL is only located 714 m below ground, which will reduce background levels. Second, SuperCDMS SNOLAB will use 18 Ge crystals, each of mass 1.39 kg, and 6 Si crystals, each of mass 0.61 kg, while SuperCDMS Soudan only used 15 Ge crystals each of mass 0.6 kg, which will affect the sensitivity in two ways. One, the exposure, the product of the total crystal mass and data taking time, will increase by a factor of three. And two, while Ge crystals are more likely to cause a WIMP recoil compared to Si ones due to the fact that Ge nuclei are larger, Si crystals are more likely to cause WIMPs below a certain mass to produce a detectable recoil due to the fact that Si nuclei are lighter, so the

usage of Si detectors will push the sensitivity down to lower WIMP masses. Note that CDMS II used both Ge and Si detectors as well. Third, SuperCDMS SNOLAB will use detectors with six phonon channels, while the detectors used with SuperCDMS Soudan only had four channels, which will reduce positional uncertainties in event reconstruction. Finally, SuperCDMS SNOLAB will be the first iteration to utilize HV detectors, which will push the sensitivity down to much lower WIMP masses.

When combined, these updates will produce a significant improvement in the experiment's sensitivity. This can be seen in Fig. 2-4, which shows a collection of sensitivity curves for various experiments, with solid lines representing ongoing or completed searches and the dashed lines representing upcoming searches:

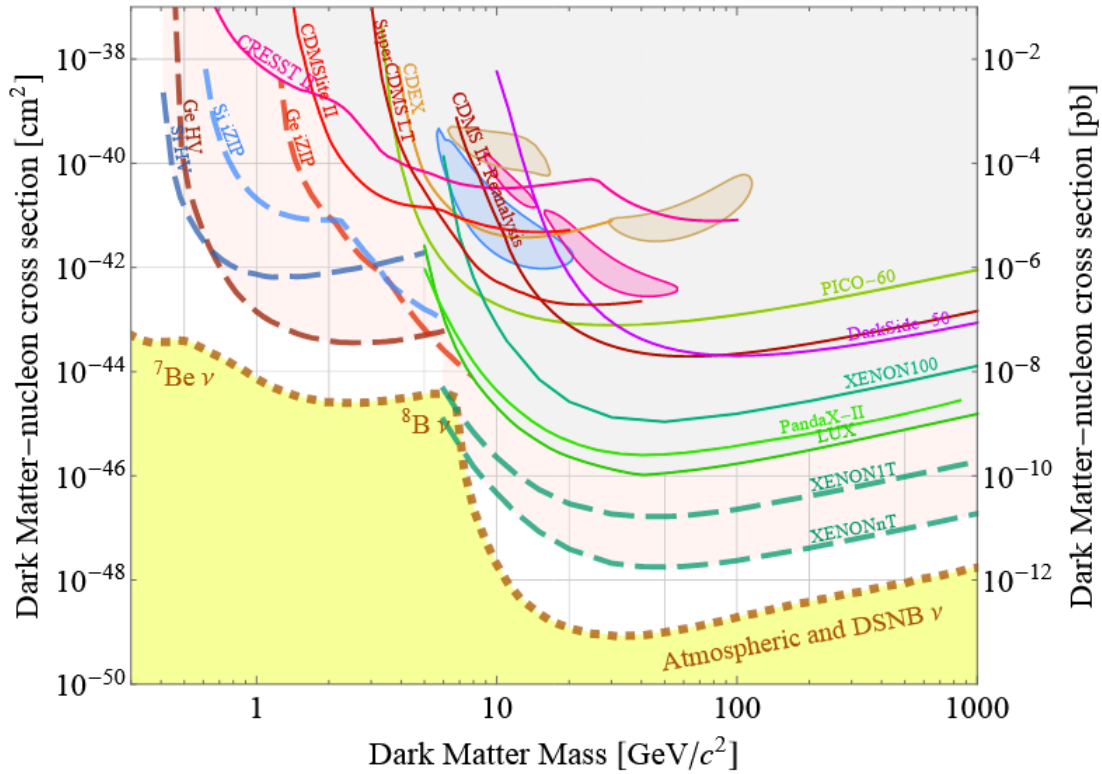


Figure 2-4. The sensitivity limits of various dark matter detection experiments, including SuperCDMS.

### 2.3.2 SNOLAB-Iteration Design

As previously described, SuperCDMS SNOLAB will use 18 Ge and 6 Si detectors. 10 of the Ge and 2 of the Si ones will be iZIPs, while the remaining 8 Ge and 4 Si ones will be HVs.

They will be arranged in four towers of six detectors each. They will then be placed in the center of six concentric cylindrical copper cans that are each mapped onto a thermal stage of a dilution refrigerator, with the innermost can being the coldest. A dilution refrigerator works by cooling  $^3\text{He}$  to 77K with liquid nitrogen, then to 4K with liquid  $^4\text{He}$ , then to 1K with vacuum-pumped  $^4\text{He}$ , then to  $\sim 600\text{mK}$  with a still. At that final temperature, there's a phase separation in  $^3\text{He}$ - $^4\text{He}$  mixtures between a concentrated phase ( $\sim 100\%$   $^3\text{He}$ ) and a dilute phase (6.6%  $^3\text{He}$ ). The process of moving  $^3\text{He}$  through the boundary of such a mixture absorbs heat. This allows the incoming  $^3\text{He}$  to cool to as low as 2mK. The still works by taking the outgoing  $^3\text{He}$  and using it to cool further incoming  $^3\text{He}$ . The outgoing  $^3\text{He}$  ends up in pumps, which prepare it to reenter the fridge, creating a cycle. This system is referred to as the SNOBOX.

The SNOBOX will be surrounded by five shielding layers. The innermost is a mu-metal layer, which will attenuate the Earth's magnetic field. After that is a 40-cm-thick polyethylene layer, which will absorb neutrons produced by natural radioactive decays in the fridge materials. After that is a 23-cm-thick layer of very old lead (meaning that the lead has low radioactivity levels which would otherwise present its own background), which will mitigate photons from various sources. After that is a thin aluminum layer, which will block radon present in the surrounding air from diffusing into the interior and emitting photons there as it decays. Finally, there is a layer of polyethylene and water tanks, which will block external neutrons produced by radioactive decays in the rock of the cavern environment. This system will be placed on a seismic platform to attenuate vibrations caused by seismic events.

There will be two openings from the outside to the SNOBOX, one for a cryogenics stem (C-stem) that connects the copper cans to the refrigerator, and one for an electronics stem (E-stem) that connects the detector channels to external readout systems present in what is referred to as an electronics tank (E-tank).

A schematic of this design is shown in Fig. 2-5:

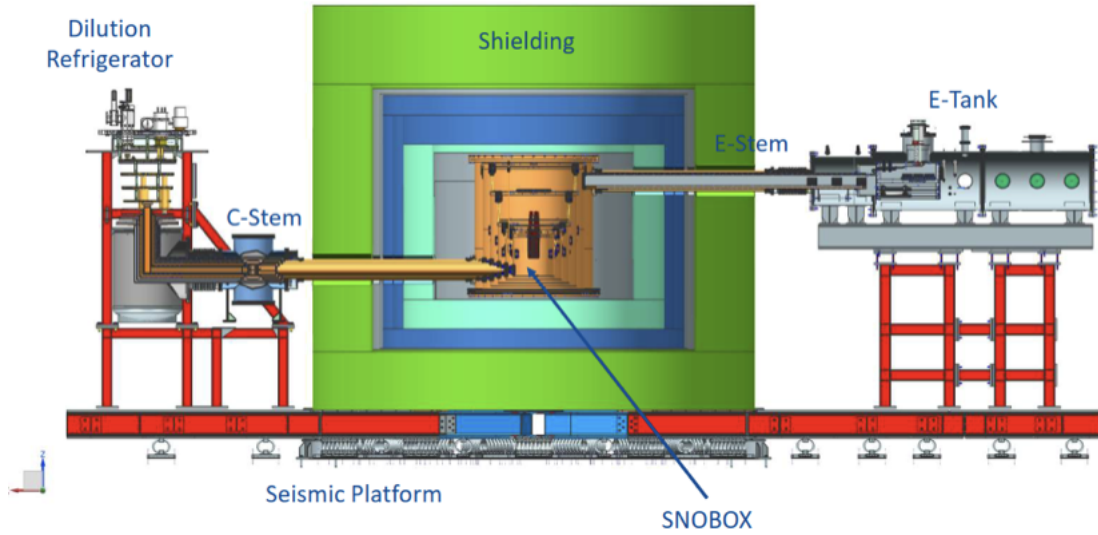


Figure 2-5. A schematic of the SuperCDMS SNOLAB experiment.

## 2.4 IMPACT

A calibration study within SuperCDMS is the Ionization Measurement with Phonons at Cryogenic Temperatures (IMPACT) experiment. While the number of charge pairs created by an electron recoil is directly proportional to the recoil energy, the relation for nuclear recoils is more complex. A measure of this is the ionization yield  $Y$ , which is the fraction of recoil energy that goes into charge pair production. For electron recoils,  $Y = 1$ , while, for nuclear recoils,  $Y < 1$  and increases with recoil energy. The standard model for the nuclear recoil yield comes from Lindhard theory. Measurements have indicated that it is a good fit at higher recoil energies, but they have also shown that, below a certain point, the Lindhard model begins increasingly overestimating the yield. For silicon, this point is around 4 keV, and experiments have gone down to 700 eV. This can be shown in Fig 2-6, with the dashed line corresponding to the Lindhard model and the points corresponding to data from various experiments [15]. IMPACT seeks to collect more data between 700 eV and 4 keV, and, more importantly, to probe down to 100 eV.

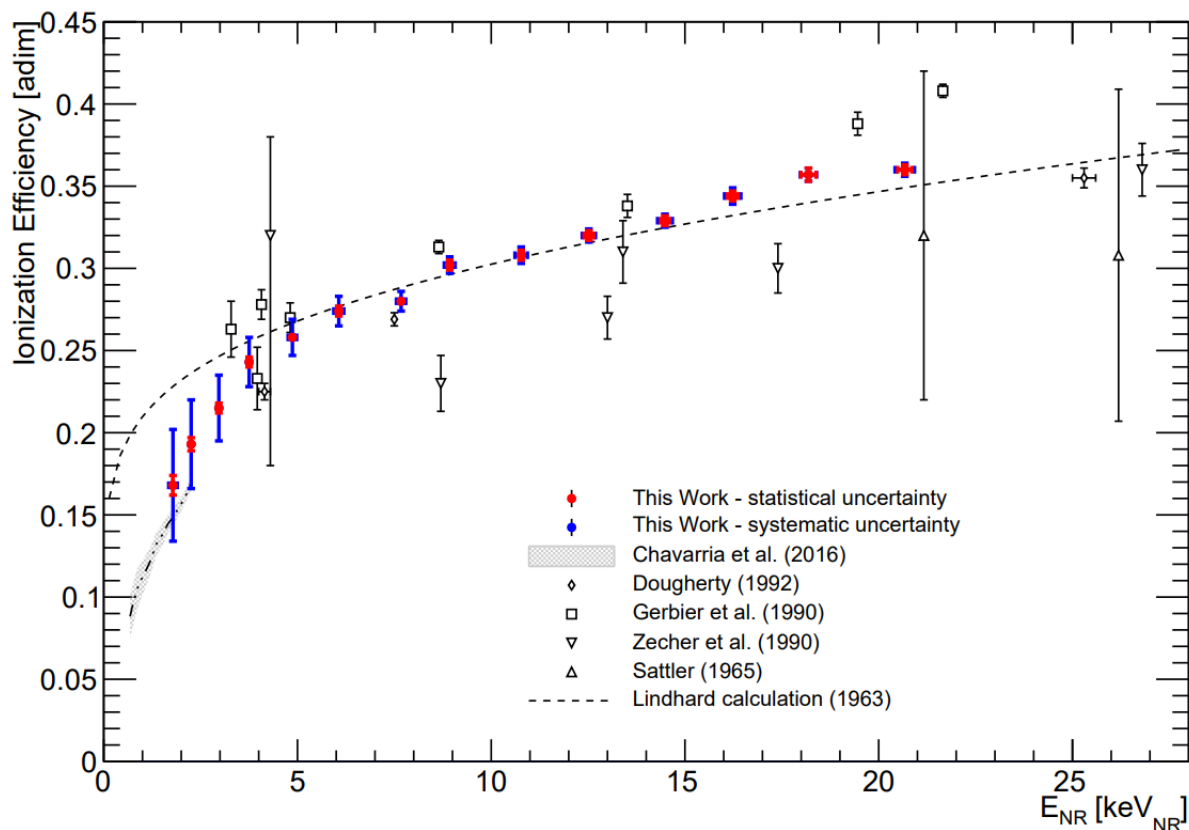


Figure 2-6. The ionization yield for silicon given by the Lindhard model (various observations) as the dashed line (points).

Multiple runs have been proposed, with at least one using a silicon detector and at least one more using a germanium one. A first run with a silicon detector was completed over the first three weeks of July 2019 at Triangle Universities Nuclear Laboratory (TUNL) at Duke University. Located at TUNL is a Tandem Van de Graaff generator with a maximum terminal voltage of 10 MV that can, among other things, produce a beam of protons.

For the IMPACT measurement, the Van de Graaff generator was operated at 0.94 MV, which gave the protons in the beam an energy of 1.889 MeV. The beam had a pulse rate of 2.5 MHz. First, the beam passed through a beam pickup monitor that, along with the photomultiplier tubes (PMTs) at the very end of the setup, provided time-of-flight measurements on a nanosecond scale.

The beam then entered a collimator and hit a LiF target housed inside. When a proton hits a  ${}^7\text{Li}$  atom, it gets absorbed by the atom, causing it to beta decay into a  ${}^7\text{Be}$  atom with the emission

of a neutron [16], meaning that it turns a proton beam into a neutron one. A neutron beam is necessary as protons would be electrically repelled by nuclei before being able to recoil off them. The neutrons had an energy of 55.7 keV, which corresponds to a resonance of silicon nuclei to interactions with neutrons. The collimator was composed of polyethylene and served to block neutrons that were not emitted along the beam line.

The beam then entered an adiabatic demagnetization refrigerator (ADR) and hit a high voltage electron volt (HVeV) detector housed inside. An ADR works by thermally connecting a paramagnetic material to the object that needs to be cooled. First, a strong magnetic field is applied to the material, which aligns the moments of the magnetic regions. Then, the field strength is lowered, which lowers the entropy of the material in that state, tending it to absorb heat from the object to unalign the magnetic moments.

HVeV detectors are similar to HV detectors, except they are square in shape, are much smaller, having a side length of 10 cm and a thickness of 4 cm, giving them a mass of 0.93 g, and only have two phonon sensors, a central solid square one referred to as the inner channel and a hollow square one that surrounds the central one referred to as the outer channel. The HVeV detector was also operated at a set of voltage biases, specifically at 0, 20, 100, and 180 V during various times in the experiment. The much smaller size gives HVeV detectors a better energy resolution, down to 3 eV. The ADR was operated at 52 mK due to the TESs having a superconducting transition temperature of 65 mK.

The neutrons that scattered could enter one of 29 PMTs, three arranged in a flat arc attached to the ADR, referred to as lone wolves, and 26 arranged in two concentric rings, with eight in the inner ring and 18 in the outer one all attached to an aluminum frame behind the ADR, referred to as the backing array. The PMTs were coupled to liquid scintillator cells, which had lead shields in front to block background photons. The lone wolf PMTs were placed to identify neutrons that had deposited recoil energies of 0.75, 2, and 3.9 keV, while the backing array PMTs identified neutrons that had recoil energies of 100, 220, and 460 eV. The backing array PMTs being associated with three different recoil energies was made possible by moving the backing array

once during the experiment such that the inner ring PMTs in the closer position measured the same recoil energy as the outer ring PMTs in the farther position.

A schematic of this design is shown in Fig. 2-7:

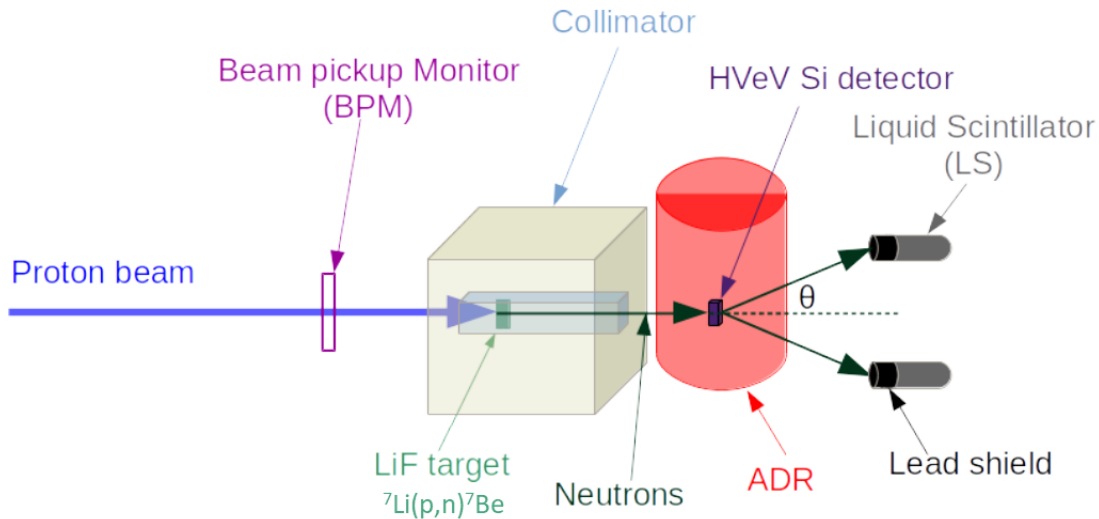


Figure 2-7. A schematic of the IMPACT experiment.

There was an energy calibration procedure that made use of three signals. For low energies, a laser that emits photons of energy 1.95 eV was used. Laser data was taken with the detector biased to 100 V and 250 V. For high energies, an  ${}^{55}\text{Fe}$  source and a  ${}^{57}\text{Co}$  source were used. Both isotopes decay via electron capture, with photons emitted during  ${}^{55}\text{Fe}$  decays having energies of 5.89 keV, 5.90 keV, and 6.49 keV and those emitted during  ${}^{57}\text{Co}$  decays having an energy of 122 keV.  ${}^{55}\text{Fe}$  data was taken with the detector biased to a range of biases from 0 V to 70 V, while  ${}^{57}\text{Co}$  data was taken at 0 V. The reason for having two high energy signals is that the corresponding crystal response to both types of events is dominated by two distinct populations of phonons.

## CHAPTER 3 DARK MATTER DETECTION WITH SUPERCDMS DETECTORS

### 3.1 Dark Matter Interaction Theory

#### 3.1.1 WIMP Interactions

The rate of dark matter interactions  $R$  in a target crystal is the product of the dark matter flux in the vicinity, which itself is the product of the dark matter number density  $n_\chi$  and speed  $v$ , and the effective area of the target, which itself is the product of the number of atoms (and hence number of nuclei) the target crystal is composed of  $N_T$  and the interaction cross section  $\sigma$ . In other words:

$$R = n_\chi v N_T \sigma. \quad (3-1)$$

Noting that  $n_\chi$  is the dark matter density  $\rho_\chi$  divided by the mass of a dark matter particle  $m_\chi$  and  $N_T$  is the total mass of the target  $M_T$  divided by the mass of an individual target nucleus  $m_N$ , taking the derivative of both sides with respect to the recoil energy  $E_R$ , and accounting for the fact that  $v$  does not have a precise value, but instead has a distribution with probability  $f(v)$ , the above equation can be rewritten:

$$\frac{dR}{dE_R} = \frac{\rho_\chi M_T}{m_\chi m_N} \frac{d\sigma}{dE_R} \int_{v_{\min}}^{v_{\max}} v f(\mathbf{v}) d^3v, \quad (3-2)$$

where  $v_{\min}$  and  $v_{\max}$  represent the limits of possible dark matter velocities. This is the principal formula for calculating dark matter detection rates. The formula can be rewritten to calculate the total number of dark matter interactions  $N$  as, simply:

$$N = \frac{1}{M_T} \int_{E_{\min}}^{E_{\max}} \frac{dR}{dE_R} \varepsilon(E_R) dE_R, \quad (3-3)$$

where  $E_{\min}$  and  $E_{\max}$  represent the limits of detectable energies and  $\varepsilon(E_R)$  is the exposure, which, ideally, is just the product of the target mass and total detection time. However, in real detectors, the exposure is further multiplied by a factor less than one that accounts for the various energy-dependent data cuts imposed during analysis.

The dark matter velocity probability distribution  $f(\mathbf{v})$  is commonly assumed to be

Maxwell-Boltzmann-like:

$$f(\mathbf{v}) = e^{-(\mathbf{v}+\mathbf{v}_E)^2/v_0^2}, \quad (3-4)$$

where  $\mathbf{v}_E$  is the velocity of the Earth relative to the dark matter halo and  $v_0$  is the galactic rotation velocity [17]. The missing  $v^2$  factor is accounted for in the spherical Jacobian  $d^3v$  in the equation for the differential interaction rate.  $\mathbf{v}_E$  has three terms, one due to the galaxy's rotation  $v_0 \approx 230$  km/s, another due to the Sun's mean motion relative to nearby stars  $v_s \approx 17$  km/s, and a final one due to the Earth's orbit relative to the Sun  $v_{E,\text{sun}} \approx 30$  km/s. The latter is periodic in direction and, due to the non-zero eccentricity of the Earth's orbit, in magnitude as well. This effect is referred to as annual modulation. Combined, this gives an approximate numerical formula:

$$|\mathbf{v}_E(t)| = 244 + 15 \sin(2\pi t) \text{ km/s}, \quad (3-5)$$

where  $t$  is the time in years starting from March 2nd [17].

The recoil energy  $E_R$  can be found by noting that an interaction just corresponds to a dark matter particle elastically colliding with a target crystal nucleus. Considering the collision from the center-of-mass frame where the two momentum vectors have equal magnitude and opposite direction, the momentum transfer to the nucleus  $q$  is:

$$q^2 = 2p^2(1 - \cos \theta), \quad (3-6)$$

where  $p$  is the momentum of the dark matter particle and  $\theta$  is the angle at which the nucleus is scattered. To express the recoil energy  $E_R$  in terms of the velocity of the particle in the lab frame, the mass used must be the reduced mass  $\mu_{\chi N}$ . This gives that  $E_R$  is:

$$E_R = \frac{\mu_{\chi N}^2 v^2}{m_N} (1 - \cos \theta). \quad (3-7)$$

The minimum speed  $v_{\min}$  a dark matter particle can have to cause a nucleus to recoil with particular energy  $E_R$  corresponds to the case where  $m_\chi = m_T$  and  $\theta = 180^\circ$ . The above equation

then gives:

$$v_{\min} = \sqrt{\frac{2E_R}{m_\chi}}. \quad (3-8)$$

The maximum speed  $v_{\max}$  a dark matter particle can have is the galactic escape velocity, since, above that, the particle would no longer be constrained to the particular dark matter halo. This  $v_{\text{esc}} \approx 600$  km/s.

The differential cross section  $d\sigma/dE_R$  is the product of two factors, the standard point-like cross section  $\sigma_0$ , and a nuclear form factor  $F(q)$ . The form factor accounts for the fact that taking the particles in an interaction to be point-like is just an approximation, giving a measure of the target particle's true size. The full expression for  $d\sigma/dE_R$  is:

$$\frac{d\sigma}{dE_R} = \frac{\sigma_0}{E_R^{\max}} F^2(q), \quad (3-9)$$

where  $E_R^{\max}$  is the maximum recoil energy that can be imparted by a particular dark matter particle [18]. Following a similar process to that used to solve for  $v_{\min}$  gives the following formula for it:

$$E_R^{\max} = \frac{2\mu_{\chi N}^2 v^2}{m_N}. \quad (3-10)$$

There are many models of the nuclear form factor, but the standard analytic one used for dark matter interactions is the Helm parameterization, which is based on the assumption that the volume covered by the target nucleus is the same as that of its charge distribution. In that case:

$$F(qR) = \frac{3j_1(qR)}{qR} e^{-(qs)^2/2}, \quad (3-11)$$

where  $q$  is the momentum transfer,  $R$  is the effective nuclear radius,  $s$  is the nuclear skin depth, and  $j_1$  is a spherical Bessel function [17]. There are two expressions for the point-like cross section depending on whether the interaction is spin-independent or not. In the spin-independent case:

$$\sigma_0^{(\text{SI})} = \frac{4\mu_{\chi N}^2}{\pi} (Zf_p + (A-Z)f_n)^2, \quad (3-12)$$

where  $Z$  and  $A$  are the atomic number and atomic mass of the nucleus respectively, and  $f_p$  and  $f_n$

are the WIMP couplings to the proton and neutron respectively [10]. Since there are many models of the WIMP, there are just as many expressions for the nucleon couplings. However, in most cases,  $f_p \sim f_n$ , meaning that  $\sigma_0^{(\text{SI})} \propto A^2$ . This confirms that crystals of heavier elements are more likely to cause a WIMP interaction. In the spin-dependent case:

$$\sigma_0^{(\text{SD})} = \frac{32G_F^2\mu_{\chi N}^2}{\pi} \frac{J+1}{J} (a_p \langle S_p \rangle + a_n \langle S_n \rangle), \quad (3-13)$$

where  $G_F$  is the Fermi constant,  $J$  is the total angular momentum of the nucleus,  $a_p$  and  $a_n$  are the now spin-dependent WIMP couplings to the proton and neutron respectively, and  $\langle S_p \rangle$  and  $\langle S_n \rangle$  are the expectation values of the spins of the proton and neutron respectively [10].

There are some other factors that need to be considered to account for the fact that no detector is ideal. For one thing, real detectors have an imperfect resolution, meaning that recoils of the same true energy have a spread in observed energy. This distribution is commonly assumed to be Gaussian-like:

$$\frac{dR}{dE_R} = \frac{1}{\sqrt{2\pi}} \int \frac{1}{\Delta E} \frac{dR}{dE'_R} e^{-(E_R - E'_R)^2 / 2\Delta E^2} dE'_R, \quad (3-14)$$

where  $\Delta E$  is a measure of the energy resolution and  $E'_R$  is the true recoil energy [17]. Real detectors also have an energy threshold to account for intrinsic rates and coincidence counting becoming issues at low energies. This value corresponds to  $E_{\min}$ .

### 3.1.2 Electron Recoil Dark Matter Interactions

The differential rate for dark sector dark matter scatters is similar to that for WIMP interactions. In particular:

$$\frac{dR}{d \ln E_R} = \frac{\rho_\chi M_T m_e^2}{m_\chi m_{\text{cell}} \mu_{\chi e}^2} \sigma \alpha \int_{v_{\min}}^{v_{\max}} F_{DM}^2(q) f_{\text{crystal}}^2(q, E_R) \frac{E_R}{q} v f(\mathbf{v}) d^3 v d \ln q, \quad (3-15)$$

where  $m_{\text{cell}}$  is the mass of the crystal unit cell,  $m_e$  is the mass of the electron,  $\mu_{\chi e}$  is the electron recoil reduced mass,  $\alpha$  is the fine-structure constant,  $F_{DM}$  is the dark matter form factor, and  $f_{\text{crystal}}$  is the crystal form factor, with the latter being analogous to the nuclear form factor relevant for WIMP interactions [19].

The crystal form factor can be found by summing the wavefunctions of each electron

energy level in the periodic lattice. In particular, if  $i$  and  $i'$  are the discrete band indices for filled and unfilled bands respectively,  $\mathbf{k}$  is the continuous wavevector in the first Brillouin Zone (BZ),  $\{i, \mathbf{k}\}$  and  $\{i', \mathbf{k}'\}$  represent valence and conduction levels, and  $\mathbf{G}$  is the reciprocal lattice vector:

$$|f_{\text{crystal}}(q, E_R)|^2 = \frac{2\pi^2(\alpha m_e^2 V_{\text{cell}})^{-1}}{E_R} \sum_{i,i'} \int_{\text{BZ}} \frac{V_{\text{cell}} d^3 k}{(2\pi)^3} \frac{V_{\text{cell}} d^3 k'}{(2\pi)^3} \times \\ E_R \delta(E_R - E_{i'\mathbf{k}} + E_{i\mathbf{k}}) \sum_{\mathbf{G}'} q \delta(q - |\mathbf{k}' - \mathbf{k} + \mathbf{G}'|) |f_{[i\mathbf{k}, i'\mathbf{k}', \mathbf{G}]}|^2, \quad (3-16)$$

where  $V_{\text{cell}}$  is the volume of the crystal unit cell [19]. Note that this expression is not an approximation like that taken for WIMP interactions is.

The dark matter form factor is:

$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2}. \quad (3-17)$$

In particular, if  $m_{A'} \gg \alpha m_e$ , which is around equivalent to saying  $m_{A'} > 2m_\chi$ ,  $F_{DM}(q)$  can be taken to be 1. This corresponds to the freeze-out scenarios. On the other hand, if  $m_{A'} \ll \alpha m_e$ ,  $F_{DM}(q)$  can be taken to be  $(\alpha m_e/q)^2$ , or just proportional to  $1/q^2$  [19]. This corresponds to the freeze-in scenario.

The scattering cross section is given by:

$$\sigma_e = \frac{\mu_{\chi e}^2 |\mathcal{M}_{\text{free}}(\alpha m_e)|^2}{16\pi m_\chi^2 m_e^2}, \quad (3-18)$$

where  $\mathcal{M}_{\text{free}}$  is the scattering matrix element [19].

Now, dark sector dark matter can also exchange a dark photon that gets absorbed by the electron in a process analogous to the photoelectric effect. The corresponding absorption cross section is given by:

$$\sigma_{A'} = \frac{\varepsilon^2}{v_{A'}} \sigma_{\text{PE}}, \quad (3-19)$$

where  $v_{A'}$  is the velocity of the dark photon and  $\sigma_{\text{PE}}$  is the cross section for the photoelectric effect [20].

ALP dark matter also interacts with a similar absorption process. The ALP cross section is

given by:

$$\sigma_{\text{ALP}} = \frac{3g_{ae}^2 E_a^2}{16\pi\alpha v_a m_e^2} \left(1 - \frac{1}{3}v_a^{2/3}\right) \sigma_{\text{PE}}, \quad (3-20)$$

where  $g_{ae} = 2m_e/f_a$  is the ALP-electron coupling and  $E_a$  and  $v_a$  are the energy and velocity of the axion respectively [20].

### 3.1.3 Background Interactions

The backgrounds external to the detector can be sorted into six categories by the type and location of the corresponding interaction. There are bulk electron and nuclear recoils, surface bulk and nuclear recoils, neutrino recoils, and cosmogenic activation lines. Each of these categories will be elaborated on in turn.

There are three primary sources of bulk electron recoil backgrounds. One is tritium ( $^3\text{H}$ ), which is created when detector crystals are above ground and thus exposed to cosmic rays [21]. When such a high-energy particle collides with a crystal nucleus, it causes the nucleus to spallate, one of the products of which is tritium. Tritium undergoes beta decay and has a half-life of 12.3 years. The electrons produced with beta decays have a continuous recoil energy spectrum which, for tritium, has an endpoint energy at 18.6 keV [22].

Another source is  $^{32}\text{Si}$ , which is also a cosmic ray spallation product, but with a more involved contamination process. When cosmic rays collide with argon atoms in the atmosphere, one of the products is  $^{32}\text{Si}$  atoms. The  $^{32}\text{Si}$  atoms can then fall to the ground when there is precipitation, where it can contaminate existing silicon deposits that are sourced for detector crystals [23].  $^{32}\text{Si}$  undergoes beta decay and has a half-life of 153 years, with measurements showing that it decays in silicon crystals at a rate of  $80_{-65}^{+110}$  decays/kg/day [24]. The resulting  $^{32}\text{P}$  also undergoes beta decay and has a half-life of 14.3 days.

A final source is  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , and  $^{60}\text{Co}$ , which are all naturally present in most materials. This includes many of those used in the experimental design, as well as the rock that surrounds the cavern the experiment is present in.  $^{238}\text{U}$  and  $^{232}\text{Th}$  both have long decay chains, the relevant steps of which are gamma decays caused by nuclei not being in their ground state after certain alpha or beta decay steps,  $^{40}\text{K}$  can decay in one of three ways, one of which is a

one-step electron capture process that results in a photon, and  $^{60}\text{Co}$  has a one-step beta decay that ends up producing two photons. These photons can Compton scatter with a very broad range of recoil energies.

There are two primary sources of bulk nuclear recoil backgrounds. One is the same  $^{238}\text{U}$  and  $^{232}\text{Th}$  contamination in the cavern rock. This time, the relevant steps of the decay chains are the alpha decays, the resulting alpha particles of which produce neutrons through the  $(\alpha, n)$  reaction. The  $^{238}\text{U}$  present in every material can also produce neutrons when it undergoes nuclear fission.

The other source is cosmic ray muons interacting with the cavern rock. At the highest energies, around 500 GeV, these muons can penetrate around 15,000 meter water equivalent [25], which is equivalent to around 5,000 meters of rock of the kind present around SNOLAB, far below the depth of the cavern. These muons cause nuclei to spallate and produce neutrons which, if done near the cavern, can reach the experimental setup.

There are two primary sources of surface backgrounds. One is  $^{222}\text{Rn}$  present in the air during detector fabrication, testing, and installation.  $^{222}\text{Rn}$  has a long decay chain, and, when it decays near the detector, its daughters can plate out onto the surface of either the detector or its housing. The nuclei in the decay chain down to  $^{210}\text{Pb}$  do not contribute to the background due to each of them having fairly short half-lives. However,  $^{210}\text{Pb}$  is both long-lived and can become implanted into surfaces. The remainder of the decay chain is shown in Fig. 3-1 [26]. The electrons produced when  $^{210}\text{Pb}$  beta decays have an endpoint energy at 63.5 keV. The Auger electrons and photons produced when  $^{210}\text{Bi}$  loses energy add a set of spectral lines. The electrons produced when  $^{210}\text{Bi}$  then beta decays have an endpoint energy at 1.16 MeV. Finally, the  $^{206}\text{Pb}$  produced when  $^{210}\text{Po}$  alpha decays can cause one of two types of recoils. If the original  $^{210}\text{Pb}$  atom was implanted in the detector, a spectral line at 103 keV results, while, if the atom was implanted in a nearby surface, a continuous spectrum with an endpoint energy of 103 keV results. This last spectrum is the principal source of surface nuclear recoil backgrounds.

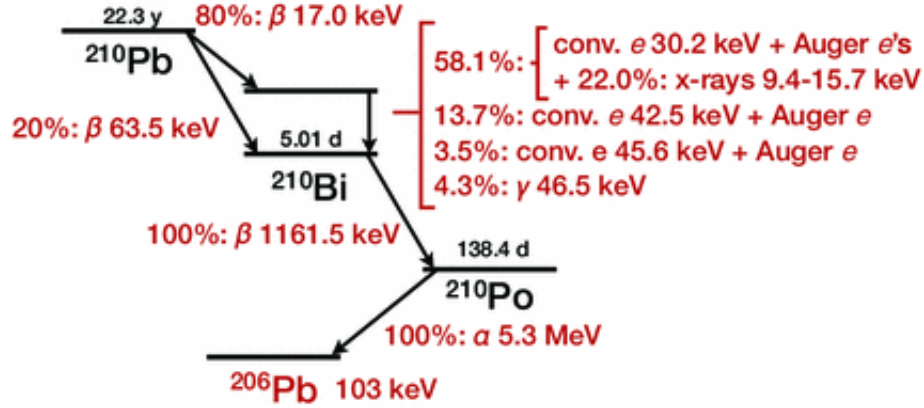


Figure 3-1. The decay chain of  $^{210}\text{Pb}$ .

The other source is  $^{14}\text{C}$  and  $^{39}\text{Ar}$ , which are introduced in the detector fabrication process.  $^{14}\text{C}$  comes from the citric acid used to passivate nearby copper surfaces after etching. The electrons produced when it beta decays have an endpoint energy at 163 keV.  $^{39}\text{Ar}$  comes from the argon used to deposit thin films onto the surfaces of sensors. The electrons produced when it beta decays have an endpoint energy at 565 keV. These two spectra, together with the non- $^{206}\text{Pb}$  associated spectra represent the surface electron recoil background.

The primary source of neutrino backgrounds is solar neutrinos, which are produced during most steps of the Sun's nuclear fusion process. This includes proton-proton ( $pp$ ) fusion, proton-electron-proton ( $pep$ ) fusion,  $^3\text{He}$ -proton ( $hep$ ) fusion,  $^7\text{Be}$ -electron ( $^7\text{Be}$ ) electron capture,  $^8\text{B}$  beta-plus decay, and the carbon-nitrogen-oxygen (CNO) cycle [27]. They interact through coherent elastic neutrino-nucleus scattering (CEvNS). There are also contributions from atmospheric neutrinos produced by the decay of pions produced by cosmic ray spallation into muons or directly into electrons [28], as well as from the diffuse supernovae neutrino background (DSNB), which has three contributions due to the different temperatures of certain neutrino flavors [29], but they are only significant at very high energies. The spectra of each of these components is shown in Fig. 3-2 [30].

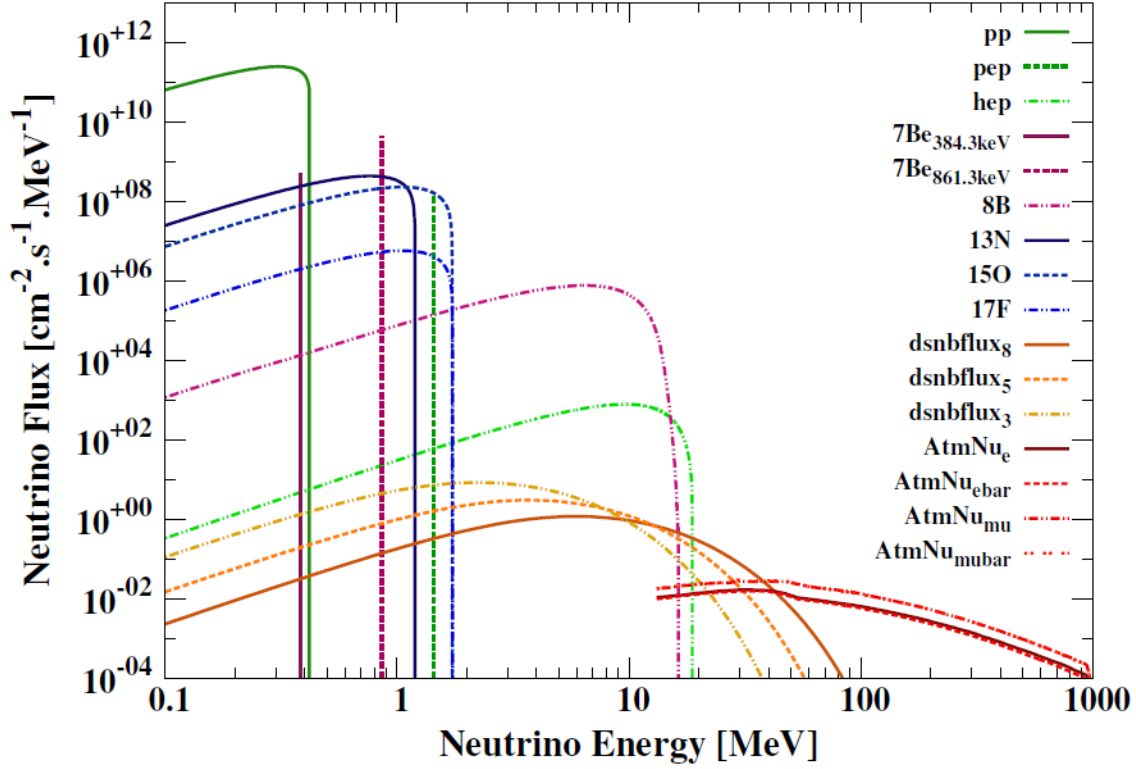


Figure 3-2. The spectra of the neutrino backgrounds, separated by individual source.

The cosmogenic activation line background is technically a bulk electron recoil background but is quite distinct from the others. It arises from radioactive isotopes produced by cosmic ray spallation in crystals that decay through electron capture rather than beta decay. One difference is that it are only relevant for germanium, which, when exposed to cosmic rays, can produce  $^{68}\text{Ge}$  (which has the radioactive daughter  $^{68}\text{Ga}$ ),  $^{65}\text{Zn}$ ,  $^{73}\text{As}$ ,  $^{57}\text{Co}$ ,  $^{55}\text{Fe}$ ,  $^{54}\text{Mn}$ , and  $^{49}\text{V}$  through electron capture from the K, L, or M shell [31]. This leads to there being a total of 24 cosmogenic lines. These isotopes are relevant because they have half-lives that range from hundreds of days to tens of years and thus decay frequently enough to produce a significant background but not so quickly that they decay away before the detector is live. This is why other isotopes are not considered, as well as why this background is not considered at all for silicon, no other possible isotope in either crystal material has a half-life within that window. Another difference is that, since they all decay via electron capture, the resulting spectrum is not continuous, but instead is a series of discrete lines, which is why the background is referred to the way that it is.

Backgrounds internal to the detector are condensed matter rather than nuclear effects, but they are important to understanding the scale of the HV detector external backgrounds. This background is referred to as charge leakage and is composed of four related processes that all stem from the presence of imperfections in the crystal lattice that act as potential wells that can trap charges. This includes charge trapping, where a charge produced due to an interaction is gets trapped in one of the potential wells, impact ionization, where a produced charge frees a trapped charge, and bulk and surface leakage, where a trapped charge is spontaneously freed in the bulk or near the surface respectively. These processes are illustrated in Fig. 3-3 [32]. They lead to discrepancies between the phonon energy associated with the number of charge pairs created due to an interaction and the phonon energy collected by the sensors, which inhibits event reconstruction, especially at low energies where only a few charge pairs are created. They have a greater effect the higher the voltage.

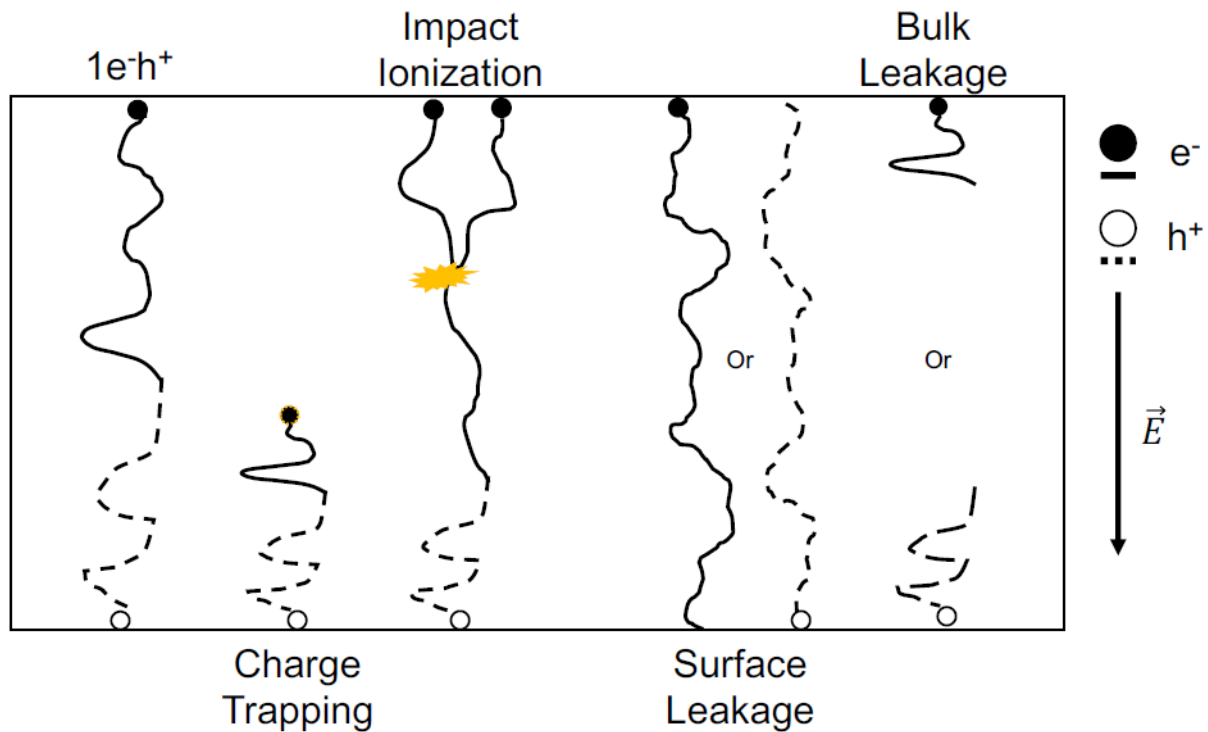


Figure 3-3. An illustration of each charge leakage process.

### 3.1.4 Dark Matter and Background Spectra

The spectra relevant for WIMPs, which can be detected by both iZIP and HV detectors, are considered first. The spectra for iZIPs is shown in Fig. 3-4, with those for a germanium crystal on the left and those for a silicon one on the right. The background spectra consist of bulk electron recoils in red, bulk nuclear recoils in blue, surface electron recoils in green, surface nuclear recoils in mustard, neutrino events in cyan, and cosmogenic lines in gray. The WIMP spectra, in pink, consist of those at the masses 1.6 GeV (dashed), 5 GeV (dotted), and 16 GeV (dash-dotted) and the cross sections given by the calculated exclusion limits at those masses. The vertical black dashed line is the analysis threshold, which is equal to seven times the phonon energy resolution for scale. This plot arrangement and legend will apply to all other such plots except where otherwise specified.

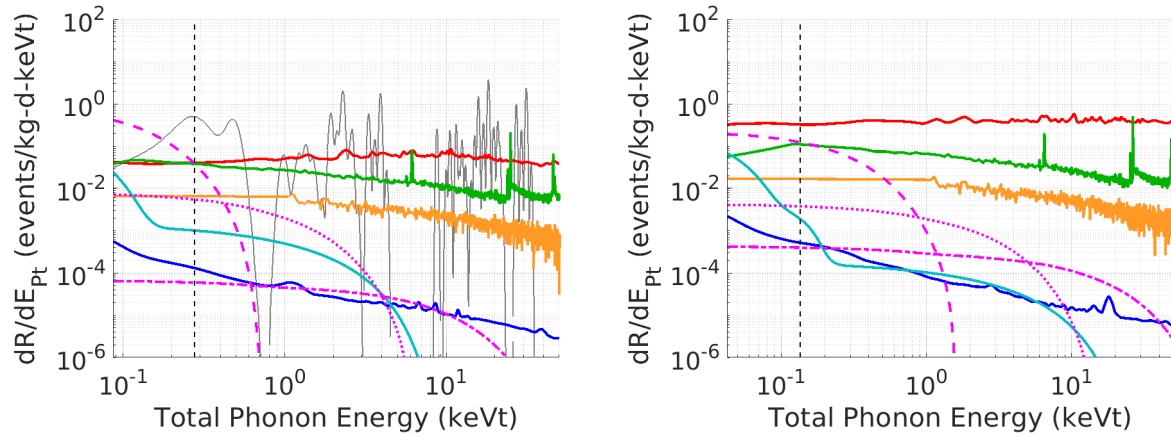


Figure 3-4. Background and WIMP spectra for an iZIP detector.

Note how, even though the true cosmogenic line spectrum is a series of lines, to account for the fact that no detector's resolution is perfect, a Gaussian smearing like that described in the previous section has been applied. This is why the detector-specific cosmogenic line spectrum is mostly continuous. Now, the smearing is applied to every background, but, because the spectra of the others are already mostly continuous, it does not have a significant effect on them. Also note how the cosmogenic line background is only present in the germanium spectra, as expected, and the bulk electron recoil spectrum for silicon is higher than that for germanium due to the

contribution of  $^{32}\text{Si}$ .

The spectra for HVs is shown in Fig. 3-5. The WIMP spectra are now at the masses 0.5 GeV (dashed), 1.6 GeV (dotted), and 5 GeV (dash-dotted). In addition, there is now a second vertical black line, this one dotted, which corresponds to the masking threshold. This is set due to the effect of charge leakage, which is significant in the first few peaks of the bulk electron recoil spectrum. In particular, the region between those peaks is not well understood, which is attributed to an incomplete understanding of charge trapping and impact ionization specifically. The masking threshold is taken to be just above the last of those peaks. This threshold actually takes the place of the previously defined analysis threshold for HV detectors, but the latter is still shown to give a sense of the resolution.

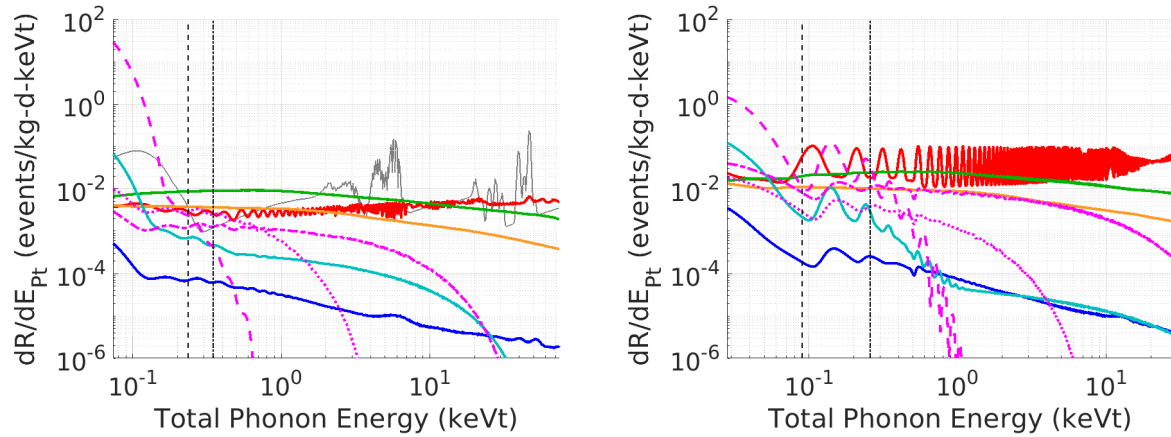


Figure 3-5. Background and WIMP spectra for an HV detector.

Note how the bulk electron recoil spectrum is a series of equally separated peaks. This is due to the fact that HV detectors have single electron-hole pair resolution and, at high voltages, the NTL effect results in quite distinct phonon energies even between differences of just one charge pair. This is not present in the surface electron recoil spectrum because of the reduced and uneven charge collection associated with surface events.

Now the spectra relevant for electron recoil dark matter, which deposits less energy and hence requires the better resolution of HV detectors to detect, are considered. The background spectra are the same as those in Fig. 3-5, although the range of phonon energy shown is shifted to

lower energies. The bosonic (i.e. dark photon and ALP) spectra consist of those at the masses 6 eV (dashed), 20 eV (dotted), and 60 eV (dash-dotted). This set of spectra is shown in Fig. 3-6

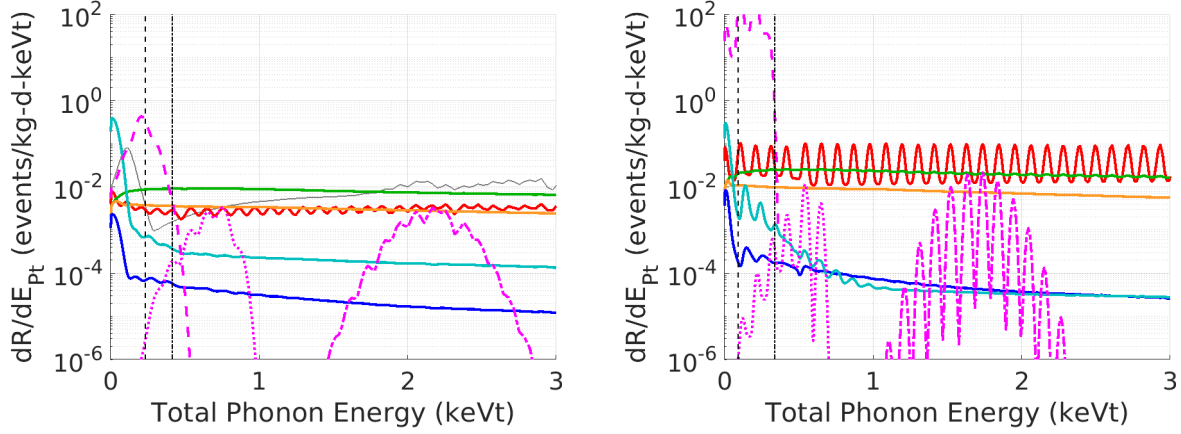


Figure 3-6. Background and DP/ALP spectra for an HV detector.

The linear phonon energy axis more clearly shows the equally separated peaks of the bulk electron recoil spectrum.

The fermionic (i.e. light dark matter) spectra consist of those at the masses 1 MeV (dashed), 3 MeV (dotted), 10 MeV (dash-dotted), and 30 MeV (solid) where a heavy mediator (i.e.  $F_{DM}(q) = 1$ ) is assumed. These spectra, along with the very same background spectra, although now focused on even lower energies, are shown in Fig. 3-7

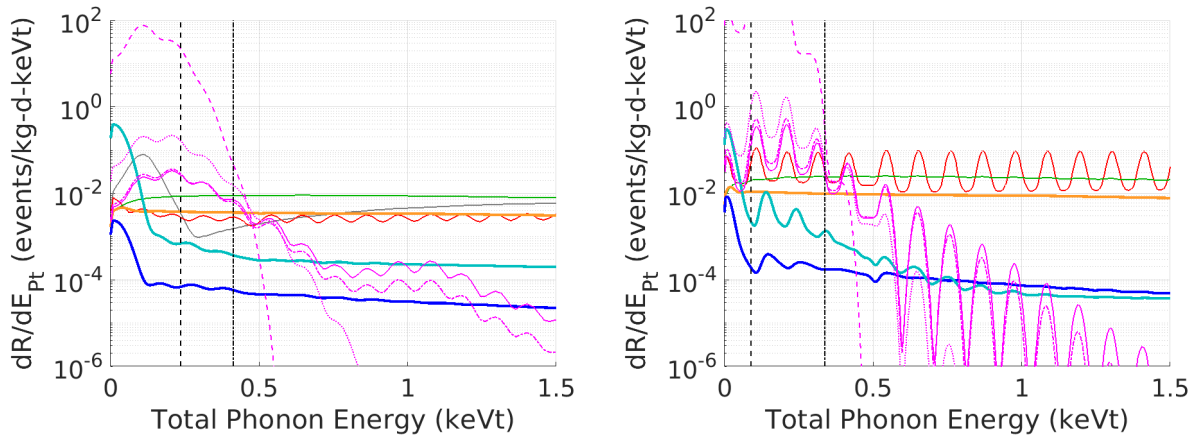


Figure 3-7. Background and LDM spectra for an HV detector.

The light dark matter spectra at the same masses where a light mediator (i.e.

$F_{DM}(q) = 1/q^2$ ) are assumed instead are similar.

## 3.2 Condensed Matter Response Theory

### 3.2.1 Semiconductor Response

Silicon and germanium both have a diamond cubic crystal structure, which is a face-centered cubic structure with four interior atoms bonded equidistantly to the closest corner atom and three closest face atoms with alternating placement. They are both also indirect gap semiconductors. The band gap is the energy separation between the valence band, or most energetic band of bound electrons, and the conduction band, or least energetic band of free electrons. The band gaps of silicon and germanium are 1.12 eV and 0.67 eV respectively. A band gap being indirect means that the top of the valence band and the bottom of the conduction band are not at the same point in k-space.

Silicon and germanium both have their conduction band minima, known as the valleys, at the Brillouin zone boundary. However, for silicon, they are located at its intersection with the x, y, and z axes in all directions, known as the X points, whereas, for germanium, they are located at its intersection with the four diagonals, known as the L points. Around these points are ellipsoidal equipotential surfaces, with electrons tending to move in directions perpendicular to the ellipse's principal axis.

For silicon, all the core electrons have binding energies of  $\gtrsim 100$  eV, whereas, for germanium, despite the  $4p$  subshell being the valence band, the  $3d$  electrons have binding energies of  $\sim 30$  eV. These electrons are relevant for higher energy electron recoils, as they can be freed in addition to the valence electrons.

When a recoil occurs, a certain portion of the recoil energy goes into charge pair production, with the remainder going into phonon production. As explained in the section describing IMPACT, this portion is given by the material's ionization yield  $Y$ . If it is an electron recoil,  $Y = 1$ , while, if it is a nuclear recoil,  $Y(E_R) < 1$ , where  $E_R$  is the recoil energy, and depends on

the material. The standard function for the nuclear recoil yield is given by the Lindhard model:

$$Y = \frac{kg(\epsilon)}{1 + kg(\epsilon)}, \quad (3-21)$$

where

$$\epsilon = 11.5E_R Z^{-7/3} \quad (3-22)$$

$$k = 0.133Z^{2/3}A^{1/2} \quad (3-23)$$

$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon, \quad (3-24)$$

where  $Z$  and  $A$  are the atomic number and atomic mass of the recoiling nucleus respectively [33]. Now, there is initially only one charge pair created, with the recoil energy required for this to occur just being given by the crystal's band gap energy. The remaining energy given to charge pair production is initially imparted as kinetic energy to that charge pair. That energy ends up going into the creation of the remaining charge pairs through secondary recoils. The energy required for an additional charge pair to be created is, on average, the crystal's pair production energy. The pair production energies of silicon and germanium are 3.82 eV and 2.98 eV respectively.

The charge Hamiltonian is:

$$H = \frac{p^2}{2m} + eEx, \quad (3-25)$$

where  $E$  is the applied electric field. Now, charges in a crystal can be treated as free particles by giving them an effective mass  $m^*$ . This treatment can be applied directly for holes since, being in the valence band, they are subject to simple spherical equipotential surface. However, since electrons, being in the conduction band, are subject to the previously mentioned ellipsoidal equipotential surfaces, the treatment for electrons is more complex. This can be alleviated however by applying a coordinate transformation that turns the electron's equipotential surfaces into spheres. This is referred to as a Herring-Vogt transformation and is given by the

matrix:

$$T_{HV} = \begin{pmatrix} \sqrt{\frac{m^*}{m_{\parallel}}} & 0 & 0 \\ 0 & \sqrt{\frac{m^*}{m_{\perp}}} & 0 \\ 0 & 0 & \sqrt{\frac{m^*}{m_{\perp}}} \end{pmatrix} \quad (3-26)$$

where  $m_{\parallel}$  and  $m_{\perp}$  are the effective masses in the parallel and perpendicular direction respectively and  $3/m^* = 1/m_{\parallel} + 2/m_{\perp}$ .

The phonon Hamiltonian is:

$$H = \sum_i \frac{p_i^2}{2m} + \sum_{i \neq j} \frac{m\omega^2}{2} (x_i - x_j)^2, \quad (3-27)$$

where  $m$  is the mass of one of the constituent atoms and  $\omega$  is the frequency of oscillation between the atom and its nearest neighbors [34]. Phonons can correspond to one of two modes of vibration of neighboring atoms, either in phase or out of phase, referred to correspondingly as acoustic and optical phonons respectively. The term acoustic refers to the fact that acoustic-like vibrations that propagate longitudinally are analogous to sound waves in air, while the term optical refers to the fact that, for ionic crystals, individual optical-like vibrations are oscillating dipoles, which have energies similar to that of infrared radiation.

The solutions for acoustic phonons to the resulting equation of motion take the form:

$$\rho\omega^2\epsilon_{\mu} = \sum_{\tau} \left( \sum_{\sigma\nu} c_{\mu\sigma\nu\tau} k_{\sigma} k_{\nu} \right) \epsilon_{\tau}, \quad (3-28)$$

where  $\rho$  is the density of the crystal,  $\epsilon$  is the polarization vector of the phonon, and  $c$  is the elasticity tensor of the crystal [34]. Since silicon and germanium have a cubic crystal structure, the above equation only has three independent components, meaning that it can be reduced to:

$$\rho\omega^2\epsilon = \begin{pmatrix} c_1k_x^2 + c_3(k_y^2 + k_z^2) & (c_2 + c_3)k_xk_y & (c_2 + c_3)k_xk_z \\ (c_2 + c_3)k_yk_x & c_1k_y^2 + c_3(k_x^2 + k_z^2) & (c_2 + c_3)k_yk_z \\ (c_2 + c_3)k_zk_x & (c_2 + c_3)k_zk_y & c_1k_z^2 + c_3(k_x^2 + k_y^2) \end{pmatrix} \epsilon \quad (3-29)$$

where:

$$c_1 = c_{xxxx} = c_{yyyy} = c_{zzzz} \quad (3-30)$$

$$c_2 = c_{xxyy} = c_{yyzz} = c_{zzxx} \quad (3-31)$$

$$c_3 = c_{xyxy} = c_{yzyz} = c_{zxzx}. \quad (3-32)$$

The three eigenvalues of the above matrix allow for three modes of phonon propagation, referred to as longitudinal, fast transverse, and slow transverse. The fact that there are two distinct transverse modes comes from there being two directions perpendicular to that of propagation.

Phonons can decay due to nonlinear terms in the elastic coupling constants. By the isotropic approximation, phonons decay anharmonically, meaning that only longitudinal phonons can decay, and only through the channels  $L \rightarrow L + T$  and  $L \rightarrow T + T$  due to kinematics. The rate of this decay is:

$$\Gamma = Av^5, \quad (3-33)$$

where A is a parameter of the lattice [35].

Phonons can scatter due to defects in the crystal lattice that produced a deformation potential. The rate of this scatter is:

$$\Gamma = Bv^4, \quad (3-34)$$

where B is a constant of the material [35]. Phonons can scatter in one of two ways, either within the same valley or from one valley to another, processes referred to as intravalley and intervalley scattering respectively. Intravalley scattering of acoustic phonons is elastic, while all other phonon scatters are inelastic.

Now, the phonons created during the initial recoil are referred to as prompt (or recoil) phonons. However, if the crystal has a voltage applied across it, another population of phonons will be created through the Neganov-Trofimov-Luke (NTL) effect. The NTL effect is that charges moving faster than the speed of sound of the material they are moving through, which will occur as they accelerate due to the potential difference, will emit phonons much like how Cherenkov

radiation is emitted when charges move faster than the speed of light of the material they are moving through. These phonons are referred to as Luke phonons. An illustration showing the emission of Luke phonons as compared to that of prompt phonons is given in Fig. 3-8 [36].

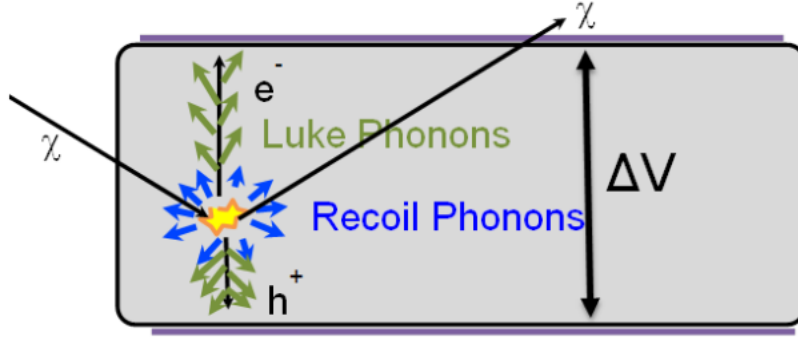


Figure 3-8. An illustration of the emission of prompt (referred to as recoil) and Luke phonons.

Taken together, when a recoil of energy  $E_R$  occurs, the total phonon energy will be:

$$E_P = E_R \left( 1 + Y \frac{eV}{\epsilon_{eh}} \right), \quad (3-35)$$

where  $Y$  is the ionization yield,  $e$  is the electric charge,  $V$  is the bias voltage and  $\epsilon_{eh}$  is the pair production energy. Note that  $YE_R/\epsilon_{eh}$  is just the number of charge pairs.

### 3.2.2 QET Response

A quasiparticle-trap-assisted electrothermal-feedback transition edge sensor (QET) is a TES with an aluminum fin attached. While the temperature is set so that the TES is in its superconducting transition state, the aluminum fin is still well within its superconducting state. The fin collects phonons that reach the surface of the detector, where, if their energy is at least twice the superconducting gap energy, they break Cooper pairs and generate quasiparticles. These quasiparticles can diffuse into the TES proper and generate heat. An illustration of this process is shown in Fig. 3-9 [37].

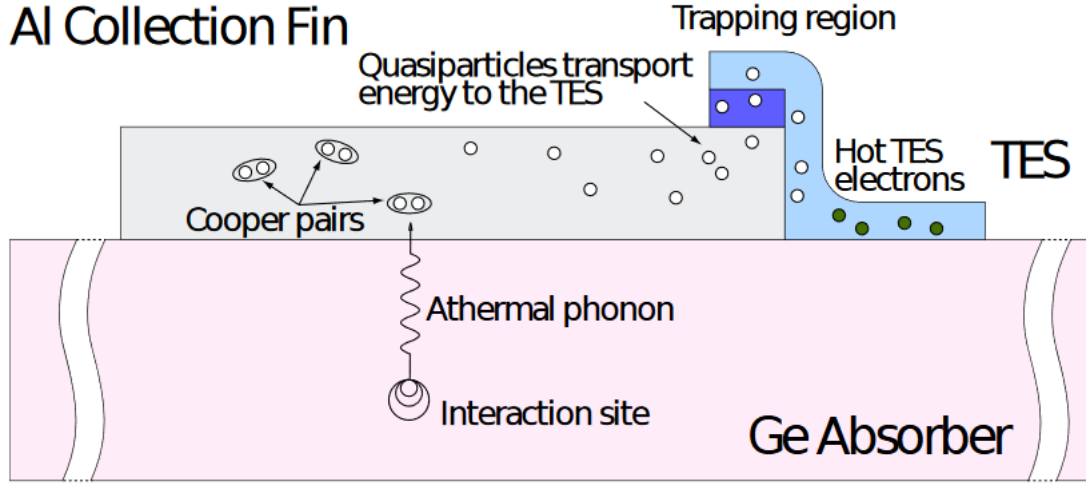


Figure 3-9. An illustration of the response of a QET to an event in a detector (referred to as an absorber).

As with any material, the resistance of a TES increases with temperature. However, because TESs are in a transition state, the way it does so is highly non-trivial. For an individual TES, it can be modelled by the equation:

$$R_i(T_i, I_i) = \frac{R_N}{2} \left[ 1 + \tanh \frac{T_i - T_c \left( 1 - \frac{|I_i|}{I_c} \right)^{2/3}}{T_w} \right], \quad (3-36)$$

where  $R_N$ ,  $T_c$ ,  $I_c$ , and  $T_w$  are the normal resistance, critical temperature, critical current, and transition width of the TES.

The power of the TES comes from its corrective response to such heating. One, they are wired in parallel with a resistor proper referred to as a shunt resistor. When a TES heats up then, less current will run through it and more will run through the shunt resistor. This reduces the Joule heating generated by the TES. And two, they are coupled to a thermal bath corresponding to the cryogenic system. When a TES heats up, the bath will directly cool it back down. Thus, TESs rapidly cool down and return to their steady state after an event. This change in temperature can be expressed by the equation:

$$C\dot{T} = P_{joule} + P_{sub} \quad (3-37)$$

$$C\dot{T} = I_i^2 R_i - \Sigma(T_i^5 - T_{sub}^5), \quad (3-38)$$

where  $C$  is the heat capacity of the TES,  $\Sigma$  is the electron-phonon coupling constant, and  $T_{sub}$  is the temperature of the bath.

Now, in a detector, each phonon channel is actually many QETs wired in parallel. For instance, at IMPACT, the inner phonon channel consisted of 536 QETs, while the outer channel consisted of 504 [38]. With such a layout, each TES receives a different amount of heat from an event, which makes extending the above equations to that many devices quite complex. However, the dynamics of an entire phonon channel can be modelled by the equation:

$$\dot{I}_{TES}L = I_{TES} \left( \frac{R_b R_{sh}}{R_b + R_{sh}} - R_{TES} - R_p \right) + \frac{V_b R_{sh}}{R_b + R_{sh}}, \quad (3-39)$$

where  $I_{TES}$  and  $R_{TES}$  are the overall current and resistance of the channel and  $L$ ,  $R_b$ ,  $R_{sh}$ ,  $R_p$ , and  $V_b$  are the inductance, bias resistance, shunt resistance, parasitic resistance, and bias voltage of the QET circuit.

The inductor is placed after the TES array. When the current through the TESs changes, that alters the magnetic field produced by the inductor. A series array of superconducting quantum interference devices (SQUIDs) placed near the inductor can detect the change in magnetic flux. A SQUID consists of two forked superconductors separated by two thin insulating layers referred to as Josephson junctions. Cooper pairs in each of the superconductors can quantum tunnel through the Josephson junctions to the other. This means that there is a current flowing through the loop, which generates a magnetic field. Due to this design, it can detect changes in current of just one Cooper pair. Thus, even minute changes to the current through the TESs can be translated to the SQUIDs. And the fact that there are many SQUIDs in series amplifies that current.

There is another inductor placed on the opposite side of the SQUIDs that has 1/10 the number of turns of the first inductor. Thus, the change in current through the SQUIDs is further amplified through this sister inductor. The signal is then fed to the remainder of the readout circuit. A diagram of the entire circuit is shown in Fig. 3-10 [39].

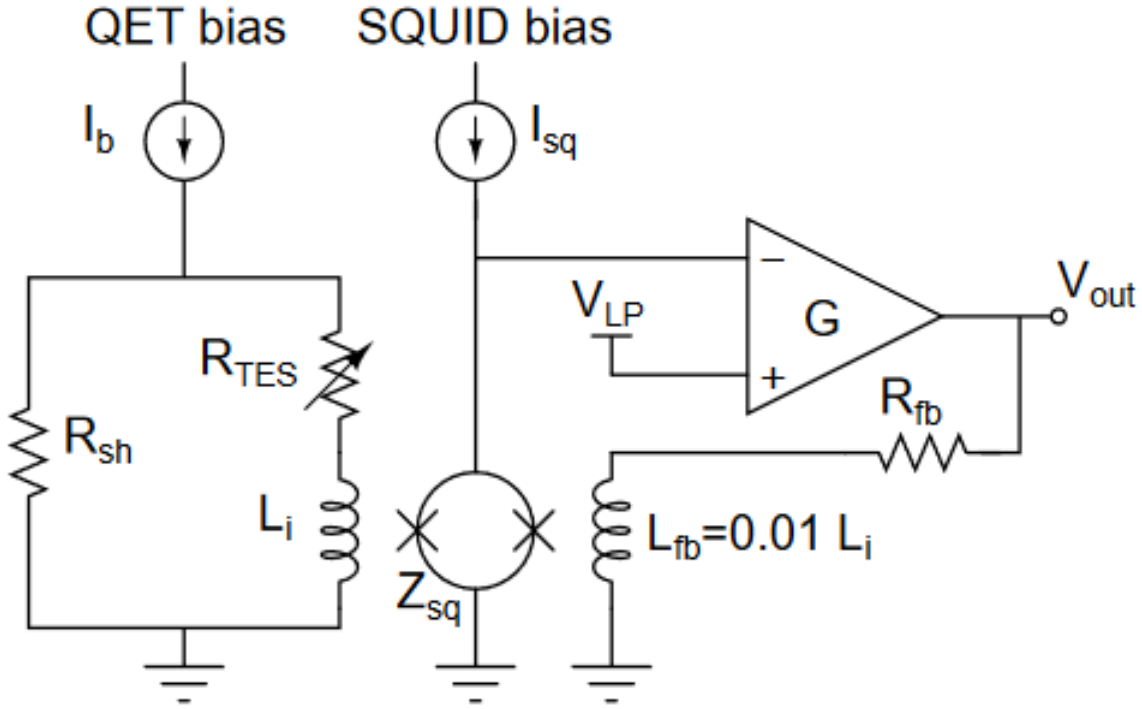


Figure 3-10. A circuit diagram showing a single TES ( $R_{TES}$ ), along with a shunt resistor ( $R_{sh}$ ) and inductor ( $L_i$ ), coupled to a SQUID ( $Z_{sq}$ ) and feedback inductor ( $L_{fb}$ ), with the output fed to a readout device.

The readout itself is the output current. Due to the rapid correction of TESs, it takes the form of a pulse. As an illustration, the averaged response of a set of IMPACT laser events, compared with that of a set of simulated laser events, is shown in Fig. 3-11, with the inner and outer phonon channel IMPACT pulses in solid blue and orange respectively, and the corresponding simulated pulses in dashed. The corrective power of TESs is seen by observing that even real devices return to normal after an event on the order of just one millisecond. Note that the simulation is based on the theory explained both above and below, which is why it produces cleaner data compared to experiment. The inner workings of the simulation will be discussed in the next chapter.

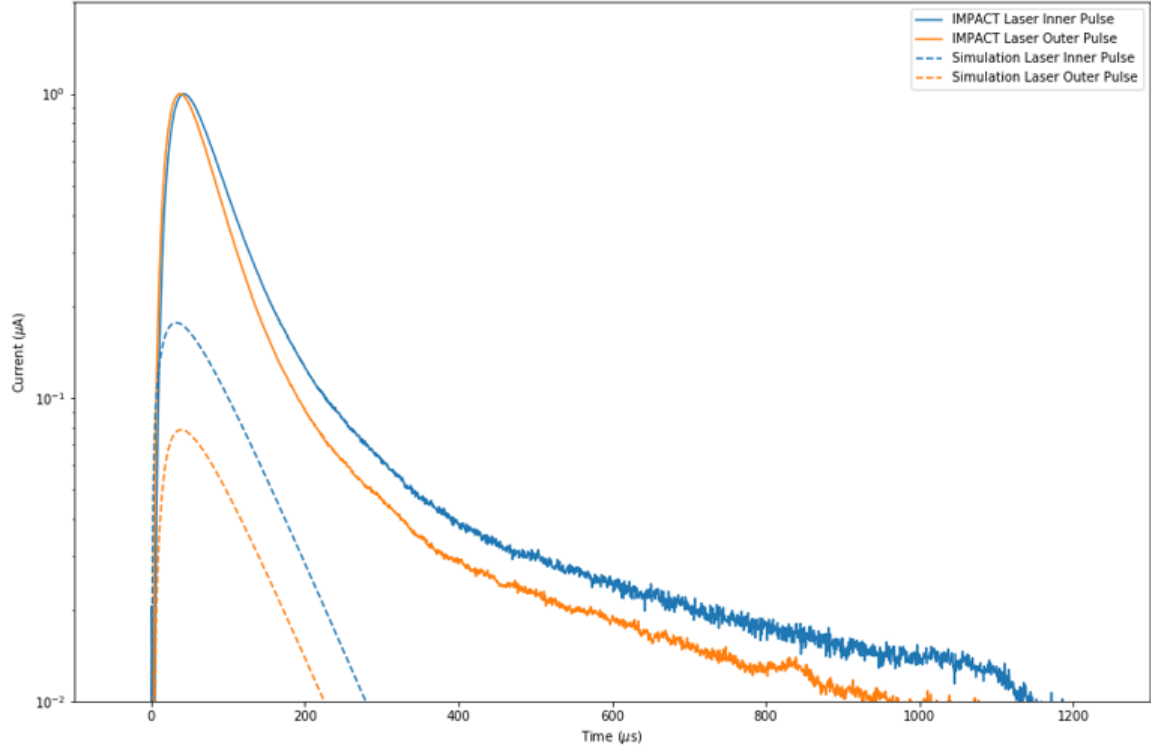


Figure 3-11. A comparison of the IMPACT experiment and simulation TES response to a laser event.

The characteristic rise and fall times of these pulses are functions of various TES parameters. First, define the dimensionless logarithmic temperature sensitivities  $\alpha$  and  $\beta$  as:

$$\alpha = \left. \frac{T_0}{R_0} \frac{\partial R}{\partial T} \right|_{I_0} \quad (3-40)$$

$$\beta = \left. \frac{I_0}{R_0} \frac{\partial R}{\partial I} \right|_{T_0}, \quad (3-41)$$

where  $T_0$ ,  $R_0$ , and  $I_0$  are the steady-state values of temperature, resistance, and current respectively, as well as the additional dimensionless parameter  $\mathcal{L}$  as:

$$\mathcal{L} = \frac{\alpha I_0^2 R_0}{G T_0}, \quad (3-42)$$

where  $G$  is the differential thermal conductance. The expressions for  $C$  and  $G$  are, respectively,

$$C = f_{sc} c_w V_{TES} T_c \quad (3-43)$$

$$G = n \Sigma V_{TES} T^{n-1}, \quad (3-44)$$

where  $f_{sc}$  is a factor that accounts for the increase in the heat capacity of a material in its superconducting phase transition as Cooper pairs breaking apart,  $c_w$  is the specific heat capacity of tungsten,  $n$  is the thermal conduction power law exponent (which, in this case, is 5), and  $\Sigma$  is the electron-phonon coupling constant. In the large heat capacity limit, the expressions for the TES pulse rise and fall times are then, respectively:

$$\tau_{\text{rise}} = \frac{L}{R_{sh} + R_p + (1 + \beta)R_0} \quad (3-45)$$

$$\tau_{\text{fall}} = \frac{C}{G(1 - \mathcal{L})}. \quad (3-46)$$

For HVeV detectors,  $\alpha$  is in the 100-150 range, while  $\beta$  is less than 0.3. Thus, since the resistances are typically well known, the rise time can be used to reconstruct the inductance. However, reconstructing parameters from the fall time is less straightforward. As for the times,  $\tau_{\text{rise}}$  is around a few  $\mu s$ , while  $\tau_{\text{fall}}$  is on the order of 100  $\mu s$ .

Returning to Fig. 3-11, the simulated pulse follows this model. And the rise and first part of the fall of the IMPACT pulse follow it as well. However, after that, it follows a second, shallower exponential, the physics behind which is not well understood.

A type of calibration done on a phonon channel directly is the complex impedance test. This is where a square wave in voltage is applied to the array of TESs in an otherwise steady state. This allows for many of the TES parameters, as well as the overall response, to be checked in a cleaner way than analyzing pulses due to detector events. A set of example complex impedance data taken with the ADR and HVeV detector used at IMPACT but before the experiment proper is shown in Fig. 3-12

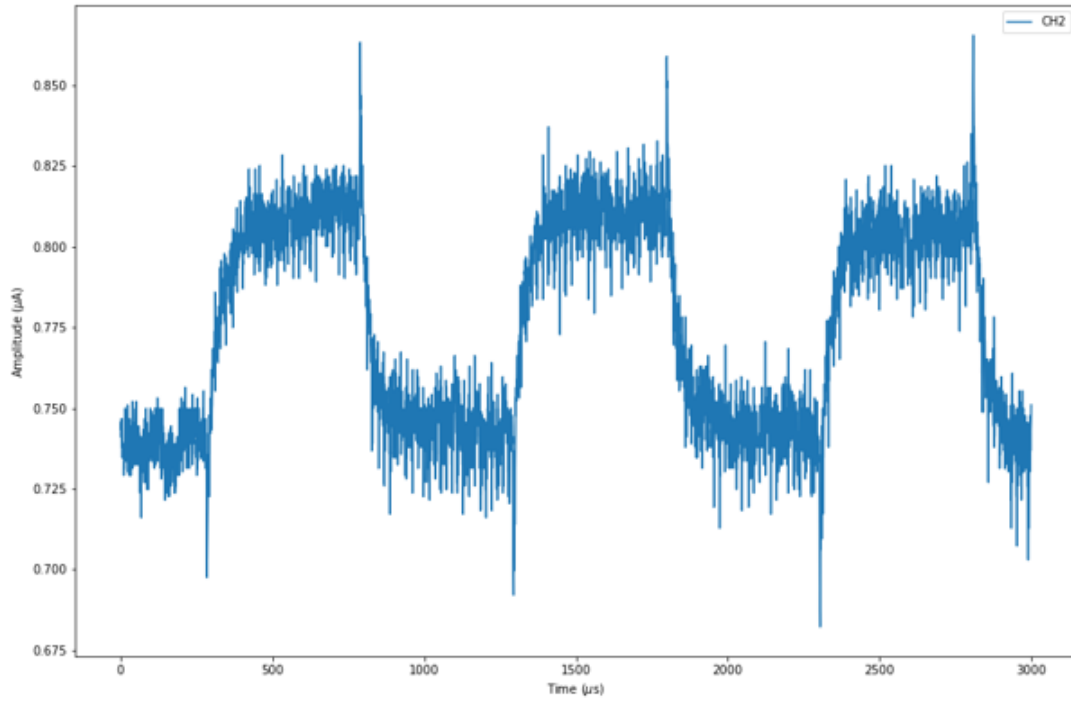


Figure 3-12. A set of complex impedance data taken with the HVeV detector used at IMPACT.

## CHAPTER 4 DETECTOR MONTE CARLO WORK

### 4.1 The Detector Response Code

#### 4.1.1 Software Packages

Modelling the response of SuperCDMS detectors is not a simple matter. Implementing a comprehensive set of particle physics processes, the condensed matter response of semiconductors to those processes, and the TES response to the resulting phonons makes it quite difficult to code a rigorous end-to-end simulation. As a stable base, the software packages SuperCDMS has developed to accomplish this utilize Geant4, which simulates the interactions of particles with matter and is used to model many other experiments, including both ATLAS and CMS at CERN. Now, Geant4 only models the incident and target particles in an interaction, as well as any product particles that would be created in a vacuum.

On top of Geant4, SuperCDMS built SuperSim (SuperCDMS Simulation), which implements the specific detector geometries and configurations, along with relevant background sources and their corresponding interactions. Besides Geant4, SuperSim is the most mature and stable software package SuperCDMS uses in its detector simulation process and has been used to inform data analysis for many years.

To model the condensed matter response, SuperCDMS utilizes G4CMP (Geant4 Condensed Matter Physics), which contains a library of physics processes relevant to semiconductors, as well as sets of material properties for specific semiconductors. In particular, G4CMP models the charge pairs and phonons induced by an interaction. Since G4CMP should be able to model any semiconductor crystal, SuperCDMS built G4DMC (Geant4 Detector Monte Carlo) on top of it, which models the detector specific sensors (i.e. the QETs and HEMTs), including sensor arrangements and electric field configurations. In other words, G4DMC registers charge and phonon collection as detector events. Due to its generality, other experiments use G4CMP for modelling purposes, which is allowed it, and, by extension, G4DMC, to become rather stable more quickly. However, it still has issues with energy accounting, as well as the modelling of events near a surface.

Finally, to model the TES response, SuperCDMS built TESSim (TES Simulation), which takes the output of a G4DMC simulation and converts it into a corresponding TES pulse using a set of differential equations utilizing sets of specific TES parameters. Being the newest of these software packages as well as exclusive to SuperCDMS, it is the least stable of them. For one thing, it has trouble modelling the response of higher energy events. However, it has become the most important of the software packages, since experimental data comes from sensor output like that of current through TESs, not SuperSim- or DMC-level output.

#### **4.1.2 G4DMC Surface Processes**

Given G4DMC's difficulty in simulating events near a surface, a discussion of how G4DMC handles particles that reach a surface is warranted. In general, at a surface, particles can either be absorbed or reflected. What determines which process occurs depends on whether the particle is a charge or phonon.

If the particle is a charge, if the surface is uninstrumented, the track is killed due to increased presence of impurities near surfaces that can act as potential wells and trap charges. If the surface is instrumented, the charge has a hard-coded chance of being absorbed that is informed by the charge recombination rate. If the charge is absorbed, it first loses its kinetic energy as phonons, which models the charge rattling around and losing energy. Then, it falls into the valence band, with half the band gap energy being released as phonons. The remaining half is released when the corresponding opposite charge falls into the valence band as well. In a real crystal, the two charges actually recombine, but, due to the fact that, in Geant4, particle tracks cannot directly interact with one another, such behavior cannot be precisely simulated. Either way though, the same energy gets converted into phonons.

If the charge is reflected, if the charge is a hole, its momentum vector is simply reflected. If the charge is an electron, this cannot always be done, since the fact that an electron's momentum direction is not the same as that of its velocity could lead to the velocity direction pointing it outside the crystal. Instead, the velocity vector is reflected, with the momentum vector being recalculated from that.

If the particle is a phonon, if the surface is a sidewall, it is always reflected due to the fact that there are no sensors on sidewalls. If the surface is a face, it has a chance of being absorbed equal to the product of the probability of a phonon being absorbed by aluminum and the proportion of the face with aluminum coverage from the QETs. If the phonon is absorbed, the portion of its energy to be reintroduced to the crystal is calculated, with the remainder introduced to the TES.

## 4.2 Code Development

G4DMC's other major issue is with energy accounting, or making sure that the total phonon energy is correct. As an example, consider an event where a 100 eV photon is absorbed by an electron in an HVeV detector operated at 0 V. With no Luke amplification, the phonon energy should be just 100 eV. However, G4DMC simulations of such events were only giving phonon energies of  $90.0 \text{ eV} \pm 4.35 \text{ eV}$ . This was found to be the result of G4DMC prematurely killing phonon tracks in QET fins with energy less than twice the band gap of aluminum. This cutoff was not arbitrary, as it represents the threshold below which phonons cannot break Cooper pairs in the aluminum. However, these phonon tracks should either be reintroduced to the crystal or introduced to the TES as heat rather than killed. Fixing that brought the phonon energy up to  $98.0 \text{ eV} \pm 0.50 \text{ eV}$ .

Now consider an event where a 1.95 eV photon is absorbed in an HVeV detector operated at 100 V. Now with Luke amplification, the phonon energy should be 101.95 eV. However, G4DMC simulations of these events were only giving phonon energies of  $93.5 \text{ eV} \pm 0.55 \text{ eV}$ , even after the above code change.

## 4.3 Results

The discrepancy in the total phonon energy for 1.95 eV photon events in an HVeV detector operated at 100 V only amounted to around 10%. However, when the photons are shot at the detector towards its bare face, certain events only have a phonon energy of 1.95 eV, with no apparent Luke amplification taking place. This was found to be the result of electron tracks undergoing intervalley scattering down to the bare face, where they are killed. The electric field

inside the detector is uniform and oriented such that electrons are accelerated towards the instrumented face, but, due to the fact that eV-scale photons have a penetration depth in silicon on the order of just a micrometer, resulting electrons can reach the bare face by scattering processes before the field is able to orient them properly.

Now, unlike the previous discrepancies, this behavior is not a bug. In fact, it is an indication that HVeV detectors treat events near the faces like iZIP and HV detectors do. This has also been seen in IMPACT data. For instance, Fig.4-1 shows an energy histogram of calibration data taken with a  $^{55}\text{Fe}$  source while the detector was operated at 3 V. The low-energy tail can be identified as corresponding to particularly shallow events, where some of the resulting electrons get captured by impurities near the surface.

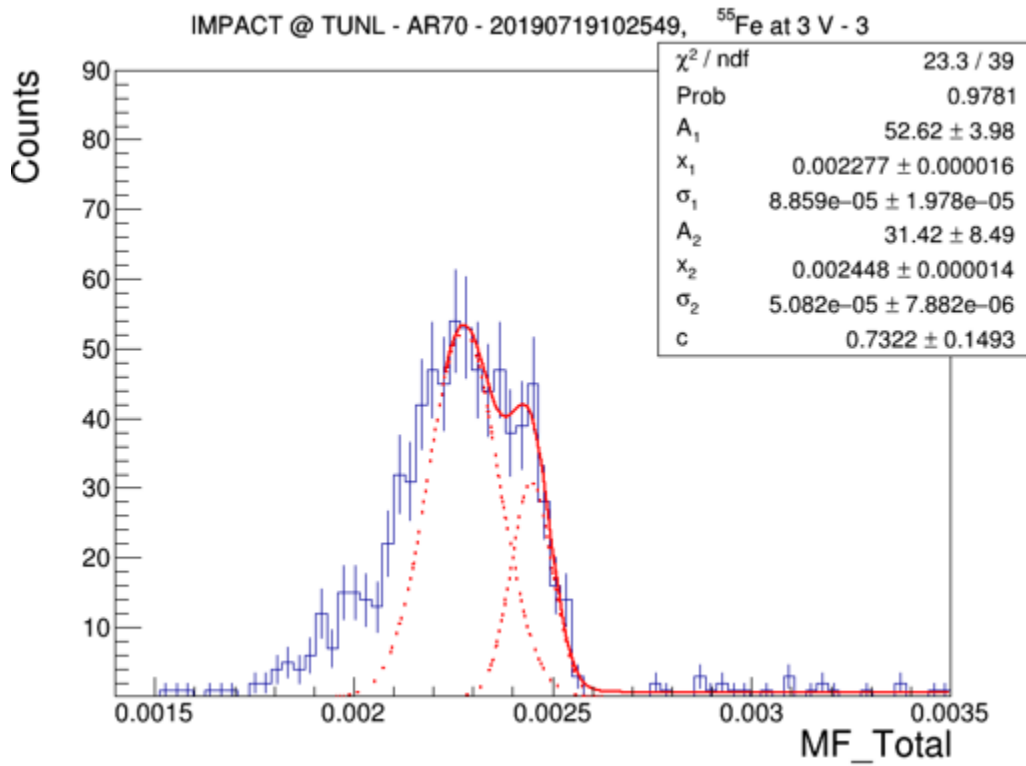


Figure 4-1. An energy histogram of IMPACT  $^{55}\text{Fe}$  data, with two Gaussians (red dotted lines) representing the two distinguishable photon energies. Note the presence of a low-energy tail with the lack of a high-energy tail, which suggests that many events occurred near the surface.

The most important product of DMC simulations however has been an improved

understanding of the TES parameters of the IMPACT experiment. In particular, the overall inductance  $L$ , along with the transition width  $T_w$  and volumetric heat capacity coefficient  $W_V$  of tungsten were not sufficiently nailed down before the experiment's conclusion. To do this, the averaged TES pulse produced during the laser calibration performed at 100 V was compared with the averaged pulse of a simulated set of such events occurring at the very center of the detector biased to the same voltage. The first attempt at this was shown in the previous chapter in Fig. 3-11.

Immediately however, several things were changed in the simulation. First, since the IMPACT pulses are normalized such that they both peak at a current of  $1\mu\text{A}$ , the IMPACT pulses in both channels were renormalized down to the level of the simulation pulse in the corresponding channel. Second, the laser events were known to have a considerable spread in event locations in the xy-plane, so the simulation was changed to have the particles deposited with an xy-circular spread of 3.25 mm, which is half the side length of the inner channel. A Gaussian weighting was then applied during analysis such that events at the very center had a weight of 1, while events the furthest away had a weight of around 0.05. Third, since the IMPACT pulses do not start at exactly  $t = 0$ , which was caused by imperfect time calibration, the simulation pulses were given a time offset of around  $3\mu\text{s}$  to the right. And finally, since the IMPACT pulses have an unexpected double exponential shaped fall, the resulting plots were modified to focus on the first  $250\mu\text{s}$  or so. A second attempt at the comparison was made with these changes applied, and is shown in Fig. 4-2, now with the IMPACT and simulation pulses in blue and orange respectively, and corresponding inner and outer channel pulses in solid and dashed respectively. The importance of these changes is seen in the fact that the two sets of pulses are now essentially in line, which allows for the TES parameters that are fed to the simulation to be tweaked in a much more informative way.

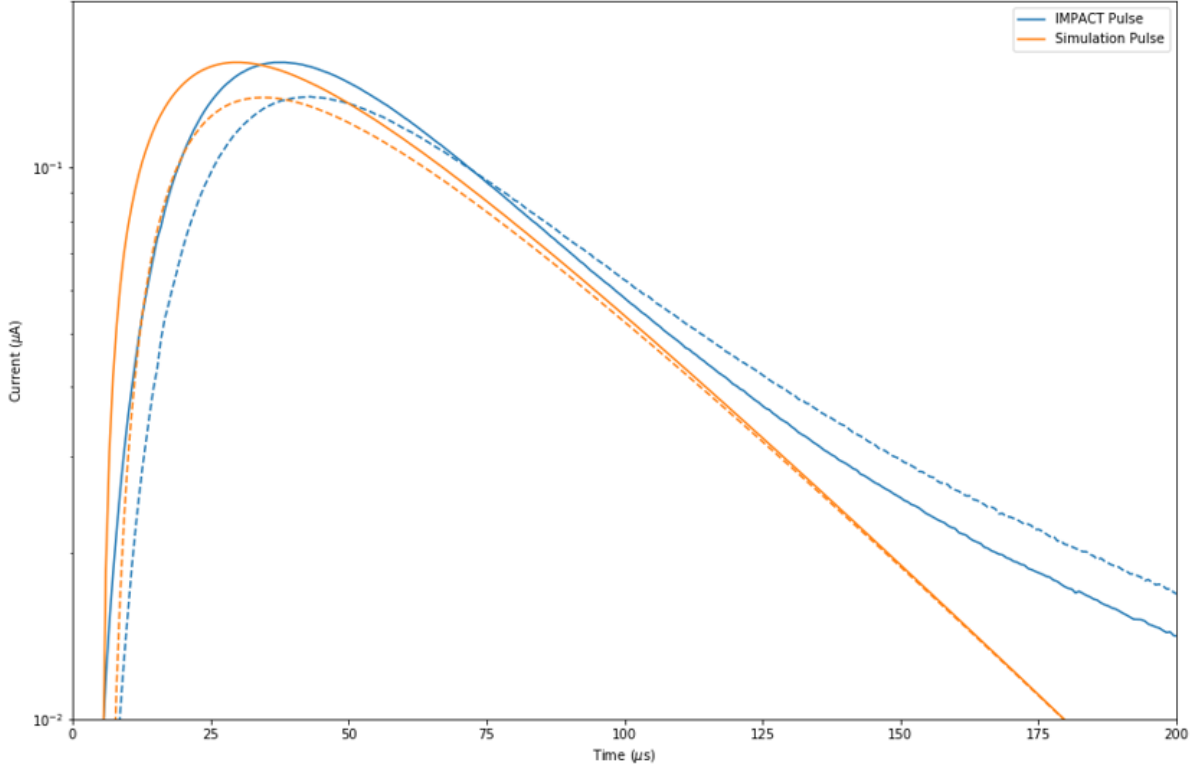


Figure 4-2. A revised comparison of the IMPACT experiment and simulation TES response to a laser event.

From there, the TES parameters could be properly studied. First,  $W_\gamma$  was actually determined from tungsten data sheets. The heat capacity can be expressed as  $C = (\rho/A)\gamma VT$ , where  $\rho$  is the mass density,  $A$  is the atomic weight,  $\gamma$  is the molar specific heat,  $V$  is the volume, and  $T$  is the temperature, which gives that  $W_\gamma = (\rho/A)\gamma$ . It was found that, for tungsten,  $\rho/A = 0.105 \text{ mole cm}^{-3}$  and  $\gamma = 1.3 \text{ mJ mole}^{-1} \text{ K}^{-1}$ , which gives that  $W_\gamma = 137 \text{ J m}^{-3} \text{ K}^{-2}$ , an increase from the original value of  $W_\gamma = 108 \text{ J m}^{-3} \text{ K}^{-2}$ . Next,  $T_w$  was informed by data from the IMPACT TESs that indicated the transition width was quite narrow. In particular, the value was changed to be  $T_w = 0.1 \text{ mK}$ , a decrease from the original value of  $T_w = 0.5 \text{ mK}$ . Finally,  $L$ , being the principal driver of a TES pulse's rise time, was set by choosing a value that, when given to the simulation, generated a pulse whose rise time matched that of the IMPACT pulse. This gave  $L = 4000 \text{ nH}$ , an increase from the original value of  $L = 500 \text{ nH}$ . To confirm their accuracy, a final comparison was made, which is shown in Fig. 4-3.

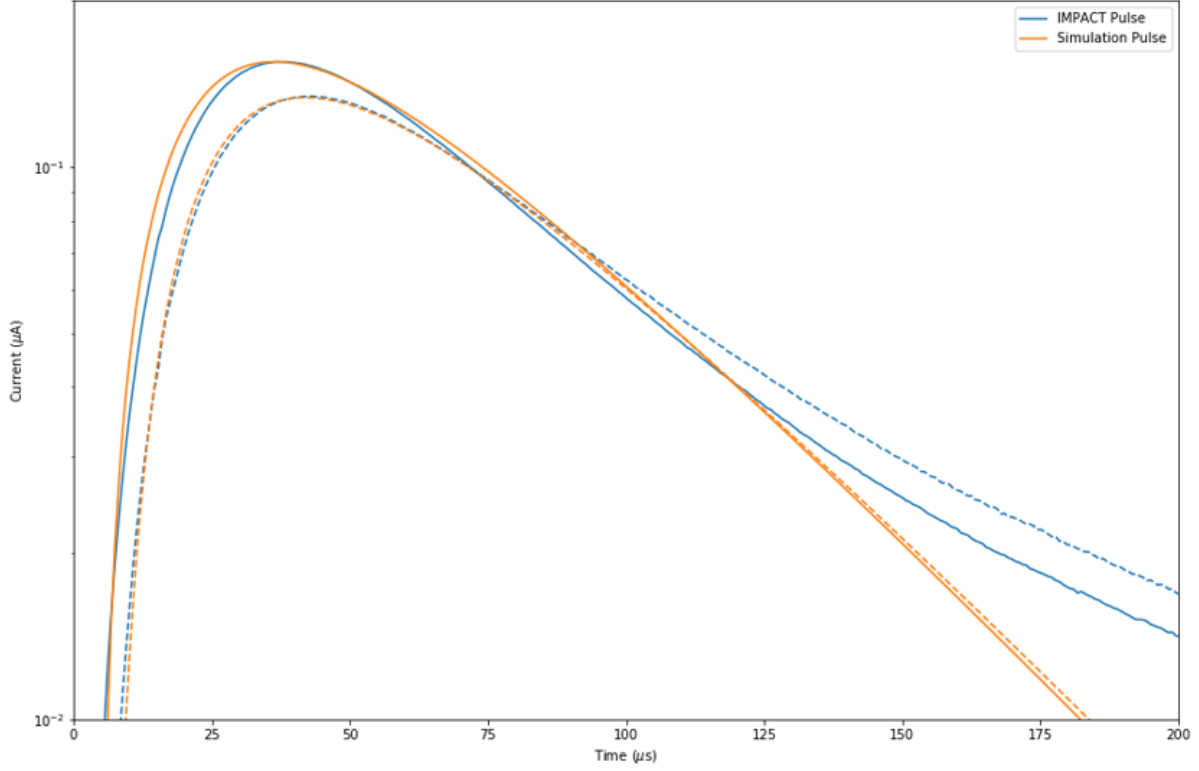


Figure 4-3. The final comparison of the IMPACT experiment and simulation TES response to a laser event.

However, while the settled upon values of  $W_\gamma$  and  $T_w$  are each within their initial ranges of uncertainty, the value of  $L$  is much higher than its expected upper limit of  $L = 1000$  nH. To resolve this, focus shifted to analyzing the IMPACT complex impedance data. Instead of comparing this data to that of a complex impedance simulation, it was run through a parameter fitting script. It works by taking the initial guesses of the Thevenin equivalent resistance  $A$  and the rise time  $\tau_2$  as, respectively:

$$A_0 = \frac{sgamp * R_{sh}}{trace_{max} - trace_{mean}} \quad (4-1)$$

$$\tau_{2,0} = \frac{L_0}{A_0}, \quad (4-2)$$

where  $sgamp$  is the signal generator amplitude,  $trace_{max}$  and  $trace_{mean}$  are the peak and nearest steady-state values of the output current, with the difference between them then being the pulse height, and  $L_0$  is the initial guess of the inductance. These parameters are then iterated over by

fitting them to the three-pole reparameterization model:

$$\frac{dV}{dI} = A(1.0 + 2.0j\pi f\tau_2) + \frac{B}{1.0 + 2.0j\pi f\tau_1 - C/(1.0 + 2.0j\pi f\tau_3)}. \quad (4-3)$$

$L$  is then just the product of  $A$  and  $\tau_2$ .  $A$  tends to be close to  $A_0$ , while  $\tau_2$  is affected by the fit's point-by-point calculation of the rise time. The application of this fit to the complex impedance data shown in Fig. 3-12 is shown in Fig. 4-4, with the data and fit shown in black and mustard respectively, along with a simpler two-pole model fit in green.

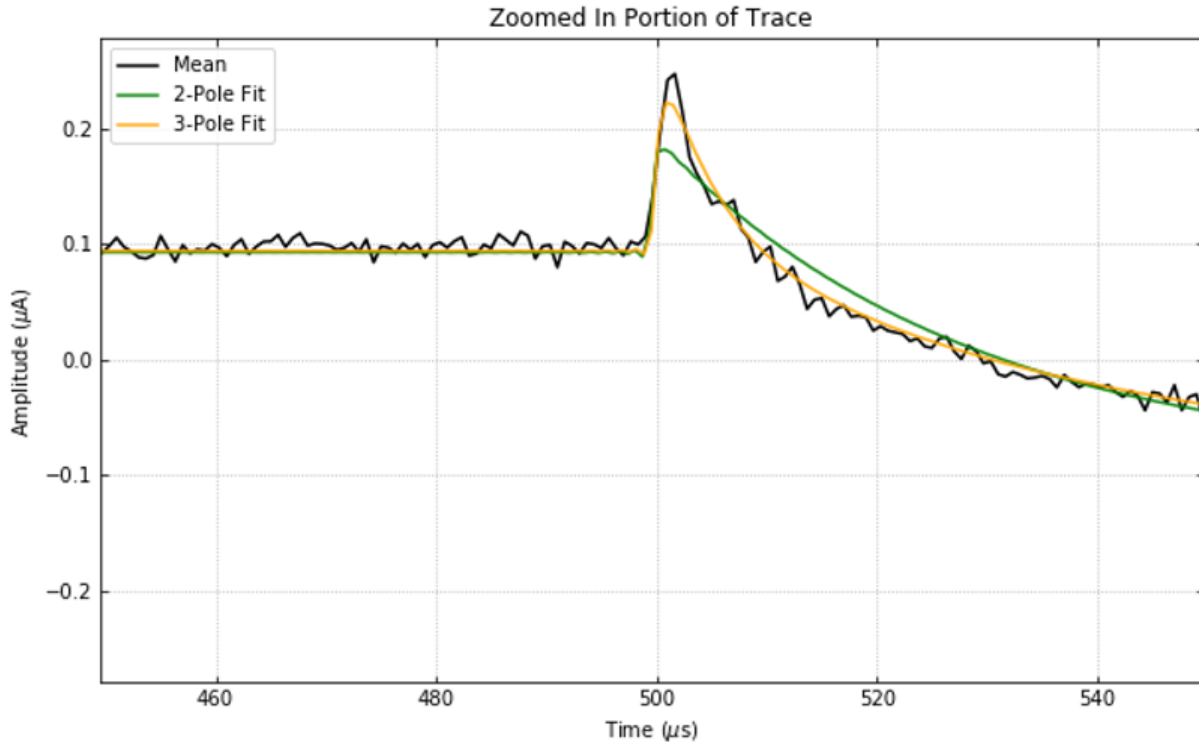


Figure 4-4. The fitting script's match to an input of complex impedance data.

This analysis gave that  $L = 250$  nH, which is more in line with expected values. Such a result contextualizes the purpose of this analysis, as previous experiments with the HVeV detector used at IMPACT had shown that there was a large contribution from a parasitic inductance that brought the total value up to  $L = 950$  nH. Such a result shows that this factor was not present at IMPACT itself.

## CHAPTER 5 SENSITIVITY WORK

### 5.1 The Sensitivity Code

Making sensitivity projections for SuperCDMS is not a simple process. The combination of searching for multiple dark matter candidates over a wide range of masses and cross sections, having a plethora of backgrounds present over the entire range of event energies, and needing to account for various detector effects makes it quite difficult to produce rigorous projections. To that end, SuperCDMS uses two software packages to do so, SensitivityEstimate, which calculates all the backgrounds and generates the corresponding sensitivity projections using the profile-likelihood ratio (PLR) method, while limitcode generates the projections using the optimum interval (OI) method. These two packages will be referred to collectively as the sensitivity code.

#### 5.1.1 Experimental Developments

Now, an obvious purpose of sensitivity work is to generate projections for SuperCDMS SNOLAB detectors. However, another, just as important purpose is to do so for proposals for future detectors or improved background mitigation to help determine their viability. These include incorporating detectors of different sizes or of an entirely new type altogether, improving detector resolutions and leakage background rejection, and altering elements of the experimental design to reduce external backgrounds.

As explained before, the current iterations of iZIP and HV detectors both have dimensions 10 cm x 10 cm x 3.3 cm, referred to as the SNOLAB size. However, as also explained before, reducing the detector size improves the energy resolution. To that end, two smaller detector sizes have been proposed, one of size 3 cm x 3 cm x 1.2 cm, and another of size 1 cm x 1 cm x 0.4 cm, referred to as the 10 cm<sup>3</sup>-size and 1 cm<sup>3</sup>-size respectively.

Two new detector types have also been proposed. One involves making a second type of iZIP detector that has three modifications to the current design meant to improve its phonon energy resolution and is referred to as the phonon iZIP (piZIP) detector. The three changes are reduced detector size, down to the 10 cm<sup>3</sup>-size, reduced critical temperature of the TESs, and

improved transmission between the aluminum fins and tungsten TESs of the QETs. This allows for another, more significant modification, namely the replacement of the charge sensors with more phonon sensors, but with the bias maintained. For GeV-scale WIMPs, the lack of charge sensors will not degrade the overall resolution due to the improvement in the phonon energy resolution allowing for the use of statistical discrimination like that used with HV detectors.

The other proposal involves making a second type of HV detector that is operated at 0 V and referred to simply as the 0V detector. For sub-GeV WIMPs, the lack of charge acceleration is not an issue, as, at such low masses, the WIMP spectra have a very steep drop-off compared to that of backgrounds, making WIMP signals much more easily identifiable, and the recoil energy is near the pair production energy, meaning that there is little to no ionization in the first place.

Another proposal involves three sets of adjustments to the experimental design that build upon each other meant to lower background levels. These will be referred to as the Bkg 1, Bkg 2, and Bkg 3 scenarios, in order of work and cost to implement. The Bkg 1 scenario involves virtually eliminating the U/Th background by replacing Kapton flex electronics cables with ones made of lower activity Kapton and replacing Cirlex detector clamps with ones made of a different lower activity material, along with reducing the  $^{210}\text{Pb}$  background by fabricating detectors one at a time, polishing the crystals, packaging the detectors, and assembling the towers in a low radon environment, and etching the sidewalls of the detector.

The Bkg 2 scenario involves replacing Cirlex detector clamps with ones made of lower activity Cirlex instead (there is currently no procedure for producing lower activity Cirlex like there is for Kapton), further reducing the  $^{210}\text{Pb}$  background by more carefully screening for lower activity copper for the towers, reducing the  $^{60}\text{Co}$  background by electroforming and machining the copper for the towers in an underground environment, and reducing the  $^{32}\text{Si}$  background by screening for lower activity silicon.

The Bkg 3 scenario involves further lowering the activity of the Kapton and Cirlex used in the setup (there is currently no procedure for producing even lower activity Kapton), doing the remaining steps involved in detector creation, including crystal growth and shaping and detector

fabrication and testing, in a low radon environment, along with doing every step in an environment that is also underground so that cosmogenic backgrounds are also reduced, electroforming and machining all the copper in the setup, screening for silicon enriched in  $^{28}\text{Si}$ , and reducing cosmogenic activation backgrounds by storing germanium underground for a longer period of time.

A final proposal involves three sets of improvements to the detector performance that build upon each other meant to improve detector resolutions and reduce detector leakage, charge trapping, and impact ionization rates. These will be referred to as the Det A, Det B, and Det C scenarios, in order of work and cost to implement. However, unlike with the backgrounds, the detector scenarios do not correspond to sets of concrete improvements to the setups, but instead to sets of numerical goals. These goals are listed in Table 5-1 (for phonon resolutions) and Table 5-2 (for charge resolutions). The blank entries are for detector configurations that have neither been fabricated or proposed.

Table 5-1. The phonon energy resolutions (in eV) of each detector scenario

| Detector                | SNOLAB |    | Det A |     | Det B |      | Det C |      |
|-------------------------|--------|----|-------|-----|-------|------|-------|------|
|                         | Si     | Ge | Si    | Ge  | Si    | Ge   | Si    | Ge   |
| 0V 1cm <sup>3</sup>     |        |    | 0.5   |     | 0.13  | 0.28 | 0.013 |      |
| 0V 10cm <sup>3</sup>    |        |    | 2.5   | 4.5 | 0.7   | 1.5  | 0.07  | 0.14 |
| HV 10cm <sup>3</sup>    |        |    | 3.3   | 4.5 |       |      |       |      |
| HV SNOLAB               | 13     | 34 | 12    | 21  | 4     | 6    | 0.6   | 0.7  |
| iZIP 10cm <sup>3</sup>  |        |    | 2.5   | 4.5 | 0.7   | 1.5  |       |      |
| iZIP SNOLAB             | 19     | 33 | 12    | 21  | 3.4   | 6    |       |      |
| piZIP 10cm <sup>3</sup> |        |    | 3.3   | 4.5 | 1.2   | 1.5  | 0.19  | 0.21 |
| piZIP SNOLAB            |        | 12 | 21    | 4   | 6     | 0.6  | 0.7   |      |

Table 5-2. The ionization energy resolutions (in eV<sub>ee</sub>) of each detector scenario

| Detector                | SNOLAB |     | Det A |    | Det B |    | Det C |     |
|-------------------------|--------|-----|-------|----|-------|----|-------|-----|
|                         | Si     | Ge  | Si    | Ge | Si    | Ge | Si    | Ge  |
| iZIP 10cm <sup>3</sup>  |        |     | 60    | 50 | 17    | 17 |       |     |
| iZIP SNOLAB             | 160    | 180 |       |    |       |    |       |     |
| piZIP 10cm <sup>3</sup> |        |     | 8     | 11 | 3     | 4  |       |     |
| piZIP SNOLAB            |        |     | 30    | 53 | 10    | 15 | 1.5   | 1.8 |

### 5.1.2 Ionization Models

The sensitivity code utilizes two ionization models. The first treats the amount of ionization as a function of recoil energy as continuous. In particular, it has the average value:

$$Q(E_R) = \frac{E_R Y(E_R)}{\epsilon_{eh}}. \quad (5-1)$$

It is used for simulating iZIP and piZIP detectors, as the resolution is insufficient to resolve distinct electron-hole pair peaks. The portion of the code that uses this model will be referred to as the continuous code. Even though they do not produce any ionization, 0V detectors are lumped into the continuous code.

The other treats the amount of ionization as discrete. The same equation that the continuous model uses also applies here, just with the amount discretized. There is also a spread applied to the amount to account for the Fano factor. Experiments have shown that  $F = 1$  for all nuclear recoils, while  $F = 0.115$  and  $F = 0.13$  for electron recoils in silicon and germanium respectively [40]. This means that the spread follows a Poisson distribution for nuclear recoils and a binomial distribution for electron recoils. It is used for simulating HV detectors, which are able to produce event spectra with clear electron-hole pair peaks. The portion of the code that uses this model will be referred to as the discrete code. It is independent of the continuous code except for using the same raw background data files and limit calculation scripts.

### 5.1.3 Analysis Cuts

The first cut applied is a data quality (DQ) cut. This simulates the impact of real data quality cuts. It is applied identically for every detector and reduces every rate by 5% across the energy range.

The next set of cuts applied is two fiducial volume (FV) cuts. These define a separation between the detector bulk and surface with the intent of excluding surface events. For continuous scenarios, this just consists of a single boundary, while, for discrete scenarios, the detector is broken into several regions, each with a distinct collection efficiency, and hence is more selective. There are two such cuts, a phonon fiducial volume (PFV) cut and a charge fiducial volume (QFV)

cut, the implementation of which are identical for continuous scenarios. Only iZIP scenarios utilize the QFV cut since only iZIP detectors have charge collection. The percentage by which they reduce rates is determined by a series of functions of event energy, separated by location and event type.

The final cut applied is a yield cut. This allows for electron recoil events to be distinguished from nuclear recoil ones. Like with the QFV cut, only iZIP scenarios can utilize the yield cut. Like with both FV cuts, the percentage by which they reduce rates is determined by a series of functions of event energy.

#### 5.1.4 Limit Calculation Methods

The limit calculation code takes in a total background spectrum and signal model as input. Before any limits are calculated, the spectrum is first prepared by integrating the spectrum over the range of energies to calculate a total background event number  $N_b$ , defining a Poisson distribution with that number as the mean, and performing a Monte Carlo simulation to determine a specific number of event energies  $N_{\text{sim}}$  according to that distribution. Then, the signal model is invoked to calculate a signal event number  $N_s$ . Finally, the set of simulated background events is compared with a set that also includes signal events using one of the limit calculation methods to produce a limit curve.

One method the sensitivity code uses to calculate the sensitivity limits is the optimum interval (OI) method [41]. This method does not take in any knowledge about the specifics of the backgrounds. It takes the total background spectrum and chooses energy ranges where the number of background events is low.

The other method used is the profile likelihood ratio (PLR) method [42]. This method does take in knowledge about the specific backgrounds. It is based off of the likelihood function given by:

$$\mathcal{L} = \frac{1}{N_{\text{sim}}!} e^{-(N_s+N_b)} \prod_{i=1}^N (N_s f_s(E) + N_b f_b(E, \delta)) e^{-(N_b-\mu_b)^2/2\sigma_b^2} e^{-\delta^2/2}, \quad (5-2)$$

where  $\delta$  is a normally distributed morphing parameter,  $\mu_b$  and  $\sigma_b$  are the mean and standard deviation of  $N_b$ , with  $\sigma_b$  taken to be 10%, and  $f_s$  and  $f_b$  are the signal and background probability

density functions, with  $f_b$  being altered by  $\delta$  to incorporate uncertainties in the backgrounds as:

$$f_b(E, \delta) = f_{b,0}(E)(1 + \delta f_{b,\delta}(E)). \quad (5-3)$$

A test statistic is then defined by:

$$\lambda(\sigma_\chi) = \frac{\mathcal{L}(\sigma_\chi, \hat{\theta})}{\mathcal{L}(\hat{\sigma}_\chi, \hat{\theta})} \quad (5-4)$$

that is minimized to set the limit curve.

### 5.1.5 Code Description

When it comes to actually running the code, the starting point is a set of initialization files, each of which corresponds to a unique set of a detector type and size, as well as a background and detector scenario. These are where things like resolution, leakage and background scalings, and exposure, along with algorithms for backgrounds and detector response models, are set. There is also a set of raw backgrounds data files, each of which contains an array of event rates over an array of energies for a particular background. The set of files is called in the raw backgrounds model. With all of that set, the only thing needed to run the code is to pass an array of initialization files to the main script.

When the code is run, a specific initialization file is specified. The values in that file, along with the detector-independent background rate arrays, are passed to what is called a background signal file. These are specific to a particular detector type and size and contain things like detector geometry and otherwise unspecified parameters. There, the background arrays are scaled by the factors in the initialization file and then summed together to produce a combined background spectrum. This array is then passed to the code that directly calculates the sensitivity limits. There, it is first prepared by going through the process described at the beginning of the previous section, then the OI and PLR limits are calculated from the result.

For processing the results, the output of the background modeling is run through a plotting script that plots the total background spectrum, along with a set of individual spectra, separated by event type, while the output of the limit calculations is run through another plotting script that plots the OI and PLR limits, along with a set of comparison curves.

## 5.2 Code Development

The most important update to the code done was a change in the way the Gaussian smearing is calculated. This is done by multiplying each individual background rate array by a matrix. Originally, the matrix was calculated for each background. However, the degree to which a spectrum is smeared is dependent only on the set of energies the spectrum defined over, along with the detector resolution. Now, every raw spectra is measured over the same set of energies and the detector resolution is the same for every event type, so it makes more sense to calculate the matrix just once at the beginning and call it for every multiplication. Since there are many individual backgrounds, implementing this greatly sped up the backgrounds modeling.

In addition to that, the smearing is only done out to four times the phonon energy resolution for a particular energy. This means that the vast majority of entries in the matrix are zeroes. Thus, the bulk of the computation time taken to perform the multiplication is spent doing trivial multiplications by zero. Converting the matrix into a sparse matrix allows all those zeroes to be ignored. Implementing this greatly sped up the backgrounds modeling even further. Combined, these two updates took runs at the best resolution from taking on the order of a month to just a matter of hours.

Another set of updates concerned the leakage rates. One was to the definition of the charge trapping and impact ionization rates. Originally, the two rates were given as probabilities. However, the probabilities were the same for every detector type, which is incorrect because they are dependent on the detector thickness. Instead of fixing that directly, the rates were changed to be given as drift lengths that are only dependent on the nature of charge leakage.

The other was to the scaling of the surface leakage rates. Originally, the rates were specified in units of  $\text{evt/det/s/kg}$ . However, given that surface leakage, being a surface effect, should scale with area instead of mass, this led to a hidden unit error when the leakage spectrum was calculated. This was fixed by simply changing the rates to be specified in units of  $\text{evt/det/s/cm}^2$ . Note that this is not an issue with the bulk or non-Poissonian leakage as they are both bulk effects. In addition, both rates are set to zero for all scenarios due to observations that leakage appears to

be driven by current injected from the electrodes.

A further set of updates was to some of the background scalings. The first was those for radon. For background scenarios 1 and 2, there is assumed to be 1 nBq/cm<sup>2</sup> and 10 nBq/cm<sup>2</sup> of radon activity on the sidewall and faces respectively. Now, in the sensitivity code, radon scalings of 1 mean that there is 25 nBq/cm<sup>2</sup> and 50 nBq/cm<sup>2</sup> of activity on the sidewall and faces respectively. Originally, the scalings were 1/50 and 1/25 for the sidewall and faces respectively, which does not match the expected levels. Changing the scalings to 1/25 and 1/5 for the sidewall and faces respectively fixes the discrepancy.

The other was that for <sup>14</sup>C. For each background scenario, the <sup>14</sup>C and <sup>39</sup>Ar activity is assumed to be the same at 1 nBq/cm<sup>2</sup>. Now, in the sensitivity code, <sup>14</sup>C and <sup>39</sup>Ar scalings of 1 mean that there is 5 nBq/cm<sup>2</sup> and 1 nBq/cm<sup>2</sup> of activity respectively. Originally, noting that the two activity levels should be equal, the scalings were both set to 1, but that ignores the fact that the scalings do not correspond to the same levels. Changing the <sup>14</sup>C scaling to 1/5 fixes the discrepancy.

A final update was to the set of background files. For one thing, to incorporate a downscaling of the experiment from 31 detector towers to 7, the 31-tower model needed to be switched with a 7-tower one. This was necessary because, while the 7-tower model obviously has fewer events, it also has different event rates due to different components of the design being scaled down differently. For another, it was determined that the mu-metal shield's contribution to the neutron background was being underestimated. This comes from the fact that the shield is one of the material sources of <sup>238</sup>U/<sup>232</sup>Th contamination. Fixing both of these things involved importing a new set of raw background files that corresponds to the 7-tower design and has higher neutron event rates, and then pointing every initialization file to that set.

The most important addition to the code was the coding up of iZIP10cm<sup>3</sup> and 0V10cm<sup>3</sup> detectors. For both, this involved writing nine initialization files for each permutation of future background and detector scenarios that specifies the resolutions, as well as a background signal file that specifies the detector geometry. This led to the first projections for iZIP10cm<sup>3</sup> and

0V10cm<sup>3</sup> detectors.

Another addition was a set of scripts that has the background and limit plotting scripts automatically post the plots to a dedicated webpage. This is useful because the standard set of, say, continuous scenarios involves four detector types (iZIP, iZIP10cm<sup>3</sup>, 0V1cm<sup>3</sup>, and 0V10cm<sup>3</sup>), each of two materials (Si and Ge) and three background scenarios (Bkg 1, Bkg 2, and Bkg 3), and the analysis of those scenarios involves two types of background plots (pre-cut and post-cut) and two types of limits (OI and PLR), which, in total, gives 48 background plots and 16 limit plots. And this does not account for any potential interest in variant scenarios. Putting the plots on a webpage allows for easy comparison in any subset of plots. Implementing this involved writing a default HTML file and a script that writes a specific HTML file from the default one, edited to correspond to the subset of scenarios run, and calling the script at the end of the plotting scripts.

## 5.3 Results

### 5.3.1 SuperCDMS SNOLAB Projections

The spectra shown in Fig. 3-4 and Fig. 3-5 are those before the analysis cuts, referred to as the pre-cut spectra. The set of post-cut spectra for iZIP detectors is shown in Fig. 5-1.

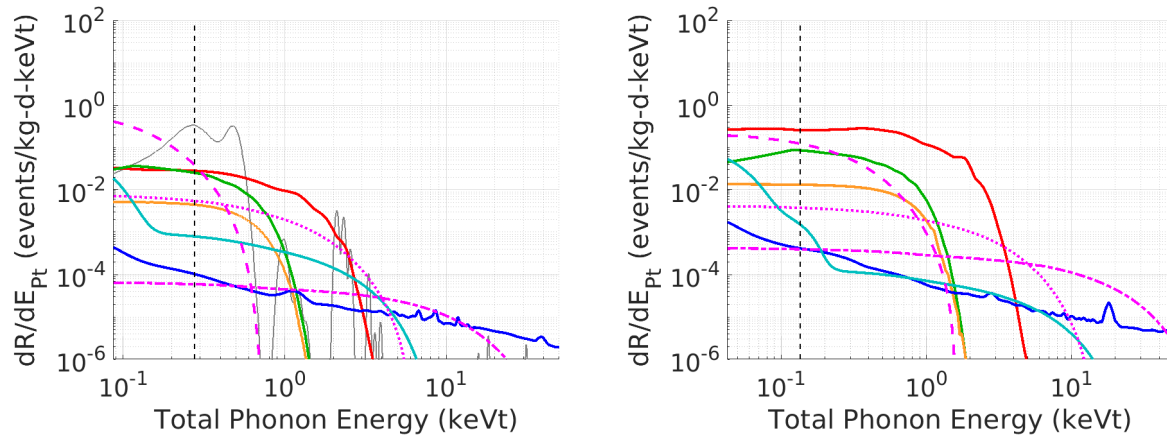


Figure 5-1. Post-cut background and WIMP spectra for an iZIP detector.

Note the effect of the fiducial volume cuts on the surface backgrounds, as well as that of the yield cut on the bulk electron recoil and cosmogenic line backgrounds. The neutron and neutrino backgrounds, which produce bulk nuclear recoil events, are unaffected by the cuts.

The set of post-cut spectra for HV detectors is shown in Fig. 5-2.

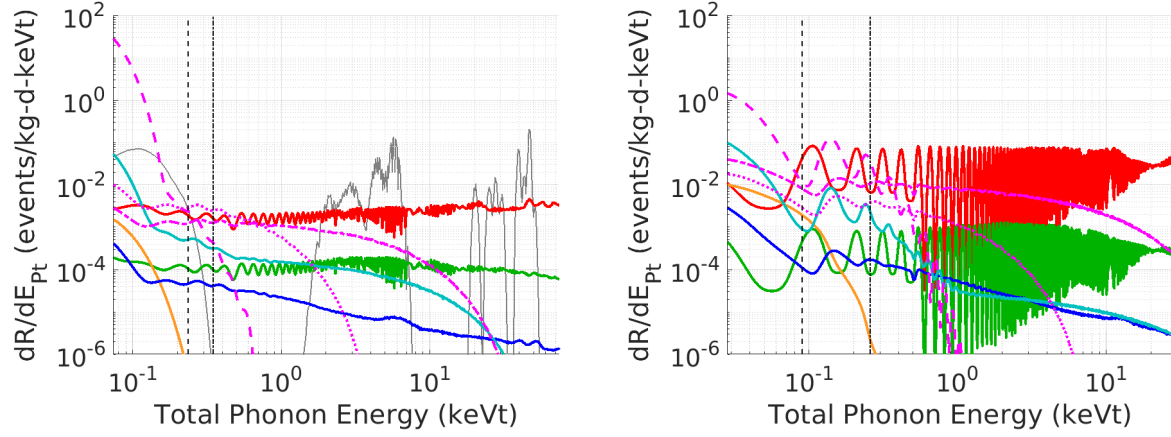


Figure 5-2. Post-cut background and WIMP spectra for an HV detector.

Note the similar effect of the phonon fiducial volume cut on the surface nuclear recoil background. However, its effect on the surface electron recoil background (along with the bulk and cosmogenic line backgrounds) is not as dramatic due to the absence of the charge fiducial volume and yield cuts. The reason there are now peaks in the spectrum is because of the selectivity associated with the discrete fiducial volume cut. The reason the amplitudes of the peaks of the bulk electron recoil spectrum are now larger is because of an artifact in the cut that removes events with incomplete charge collection even if they occur in the bulk.

Given that the electron-hole pair peaks are equally separated, the set of spectra for HV detectors is better plotted with a linear x-axis. This change is shown in Fig. 5-3.

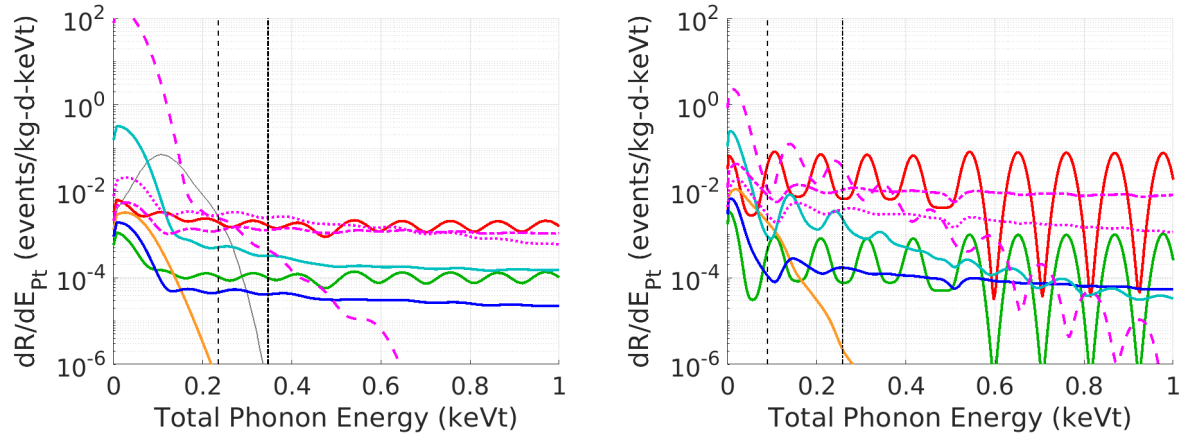


Figure 5-3. Post-cut background and WIMP spectra for an HV detector with a linear phonon energy axis.

A complete set of sensitivity limits for SuperCDMS SNOLAB detectors on nuclear recoil dark matter is shown in Fig. 5-4 [43]. In mustard, cyan, red-brown, and blue are the germanium iZIP, silicon iZIP, germanium HV, and silicon HV limits respectively. Those lines that are dashed and solid are the OI and PLR limits respectively. The thick magenta line is the top of the neutrino fog, while the thin magenta line is the limit where one neutrino event can be expected on average [44]. The neutrino fog is the parameter space where neutrino events, which produce a signal quite similar to dark matter events, obscure such events. The top of the neutrino fog is not a hard limit, as statistical techniques can be used to identify dark matter events almost an order of magnitude below it [45]. The gray shaded region is the parameter space that has been excluded by other experiments. This legend will apply to all other sensitivity limit plots shown except where otherwise specified.

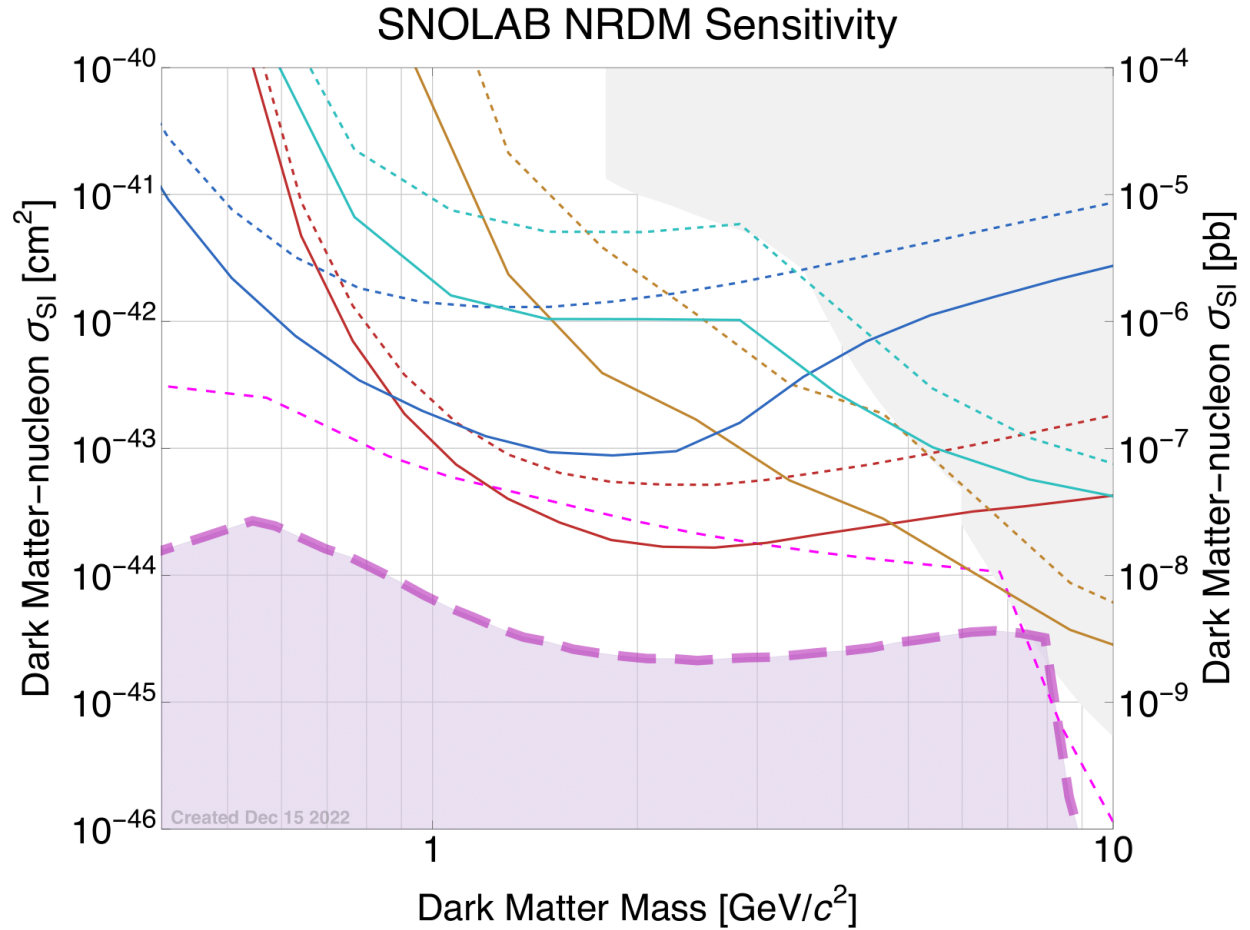


Figure 5-4. SuperCDMS SNOLAB NRDM sensitivity limits.

Note how the HV detectors are more sensitive at lower masses, while the iZIP detectors are more sensitive at higher masses. This is in line with HV detectors being operated at a larger bias and thus producing more signal amplification, but lacking the charge sensors that iZIP detectors have that would allow for the electron recoil event discrimination possible at higher masses. Also note how the Si detectors are more sensitive at lower masses, while the Ge detectors are more sensitive at higher masses. This is in line with Si nuclei being less massive and thus having more noticeable recoils when struck, but Ge nuclei being larger and thus more likely to be struck. Finally, note how the OI limits are more conservative than the PLR limits.

And a complete set of sensitivity limits for SuperCDMS SNOLAB detector on electron recoil dark matter is shown in Fig. 5-5 [43]. The top left plot shows the dark photon limits, with those for silicon and germanium in blue and red respectively. The top right plot shows the ALP

limits, with the same legend, just with the addition of an ALP stellar cooling hint and there now being two gray shaded regions of excluded parameter space, with that due to astrophysical constraints and other experiments in light and dark respectively [46]. The bottom left plot shows the light dark matter with  $F_{DM} = 1$  limits, again with the same legend as the dark photon plot, just with the addition of some specific sharp targets. The bottom right plot shows the light dark matter with  $F_{DM} = 1/q^2$  limits, with the same legend as the previous plot.

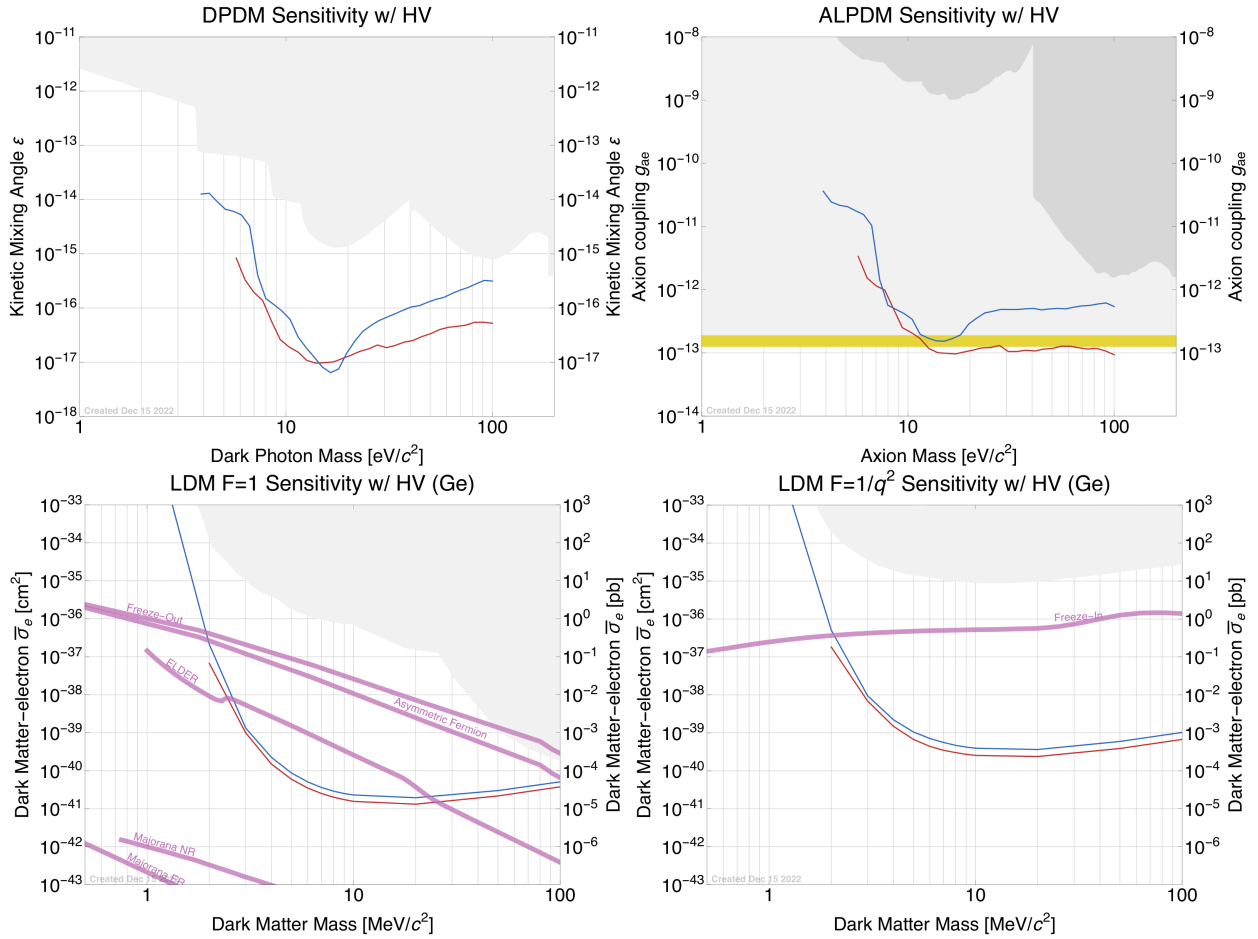


Figure 5-5. SuperCDMS SNOLAB ERDM sensitivity limits.

### 5.3.2 Future Projections

First, consider the possibilities for the detection of WIMPs. The set of spectra for a Si  $0V1\text{cm}^3$  detector in the Bkg 1, Det C scenario, along with a set of limits for various  $0V1\text{cm}^3$  detector scenarios, is shown in Fig. 5-6. In the spectra plot, the WIMP spectra are now at the masses 0.16 GeV (dashed), 0.5 GeV (dotted), and 1.6 GeV (dash-dotted). In the limits plot, in

cyan, blue, and red-brown are the Si 0V1cm<sup>3</sup> detector in the Bkg 1, Det C scenario, the Si 0V10cm<sup>3</sup> detector in the same scenario, and Ge 0V10cm<sup>3</sup> detector in the Bkg 1, Det B scenario (thicker) and Bkg 1, Det C scenario (thinner) limits respectively. The corresponding shaded regions are the discovery potentials. For these, a dark matter model is defined for a representative set of masses, with the cross sections being set by what could be detected over that range at approximately  $3\sigma$ . Detection of dark matter within this model is then simulated with a set of pseudoexperiments by injecting a signal on the basis of that model. The resulting best-fit mass and cross section point closest to that of the injected signal then defines a  $3\sigma$  allowed region. The red points are the injected signals and the contours are the associated allowed regions.

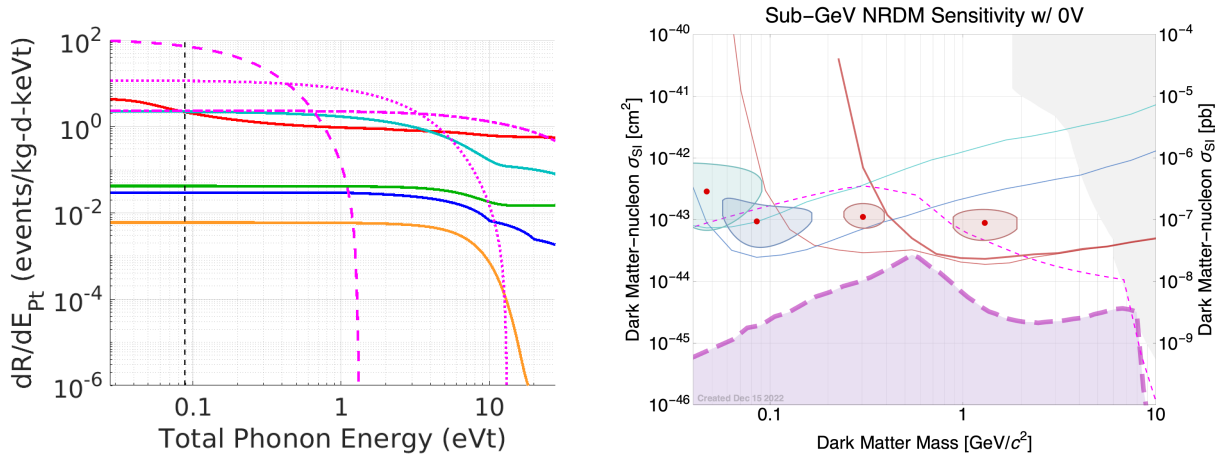


Figure 5-6. Background and WIMP spectra, along with sensitivity limits for 0V detectors.

The spectra plot illustrates the steepness of the WIMP spectra compared to that of the backgrounds in most areas. The resulting background event rejection is good enough that no background reduction beyond the Bkg 1 scenario is required. This will end up holding true for every subsequent detector scenario mentioned. The limits plot shows how Si 0V detectors have a mass reach an order of magnitude lower than any other NRDM detector.

The set of spectra for a Si HV10cm<sup>3</sup> detector in the Bkg 1, Det A scenario, along with a set of limits for various HV10cm<sup>3</sup> detector scenarios, is shown in Fig. 5-7. In the spectra plot, the WIMP spectra are now back at the masses 0.5 GeV (dashed), 1.6 GeV (dotted), and 5 GeV (dash-dotted). In the limits plot, in blue is the Si SNOLAB-sized HV detector in the Bkg 1, Det B

scenario with a six tower payload, in solid red-brown is the Ge SNOLAB-sized HV detector in the Bkg 1, Det B scenario with a two tower payload, and in dashed red-brown is the Ge HV10cm<sup>3</sup> detector in the Bkg 1, Det A scenario with a 20x mass payload. In black is the furthest reach of SuperCDMS SNOLAB.

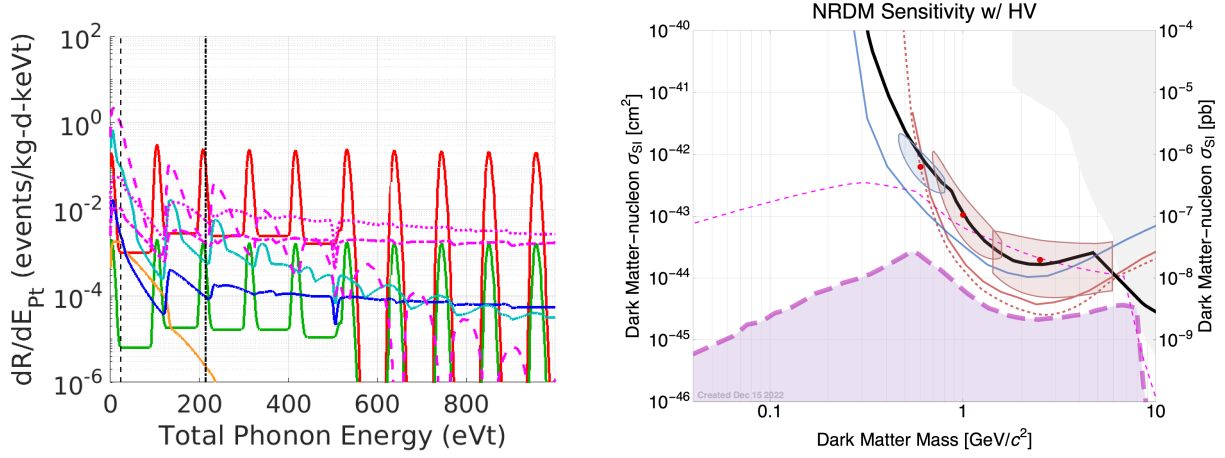


Figure 5-7. Background and WIMP spectra, along with sensitivity limits for future HV detectors.

The spectra and limit plots both illustrate the better resolution of HV10cm<sup>3</sup> detectors compared to that of SNOLAB HV detectors. This is shown in the former in the sharper electron-hole pair peaks in the electron recoil spectra and in the latter in the lower mass and cross section reach. The resolutions are good enough that no detector enhancement beyond the Det B scenario is required. This will end up holding true for every subsequent detector scenario mentioned besides the ERDM 0V case.

The set of spectra for a Si iZIP10cm<sup>3</sup> detector in the Bkg 1, Det B scenario, along with a set of limits for various iZIP10cm<sup>3</sup> detector scenarios, is shown in Fig. 5-8. In the limits plot, in blue and red-brown are the Si (with a six tower payload) and Ge (with a two tower payload) iZIP10cm<sup>3</sup> detectors in the Bkg 1, Det A scenario (thicker) and Bkg 1, Det B scenario (thinner) respectively. In dashed red-brown is the Ge iZIP detector in the Bkg 1, Det B scenario with 20x exposure.

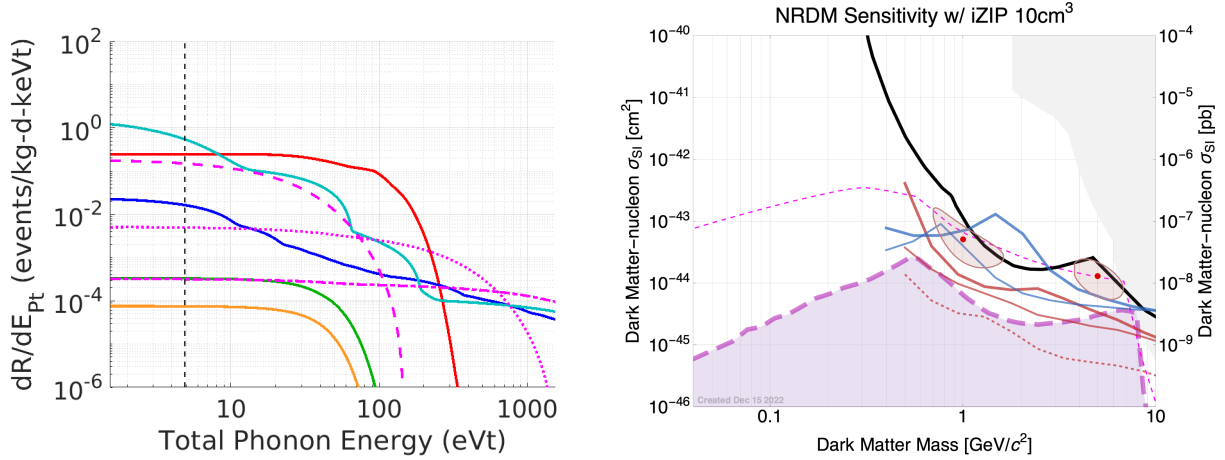


Figure 5-8. Background and WIMP spectra, along with sensitivity limits for future iZIP detectors.

The spectra and limit plots both illustrate the better resolution of iZIP10cm<sup>3</sup> detectors compared to that of SNOLAB iZIP detectors. This is shown in the former in the lower energy cutoff of the two surface backgrounds as well as the bulk electron recoil background and in the latter in the improved mass and cross section reach. Also note how the Ge sensitivity limits are better than those for Si at most dark matter masses.

The set of spectra for a Si piZIP10cm<sup>3</sup> detector in the Bkg 1, Det B scenario, along with a set of limits for various piZIP10cm<sup>3</sup> detector scenarios, is shown in Fig. 5-9. In the limits plot, in blue and red-brown are the Si (with a six tower payload) and Ge (with a two tower payload) piZIP10cm<sup>3</sup> detectors in the Bkg 1, Det A scenario (thicker) and Bkg 1, Det B scenario (thinner) respectively. In dashed red-brown is the Ge piZIP detector in the Bkg 1, Det B scenario with 20x exposure.

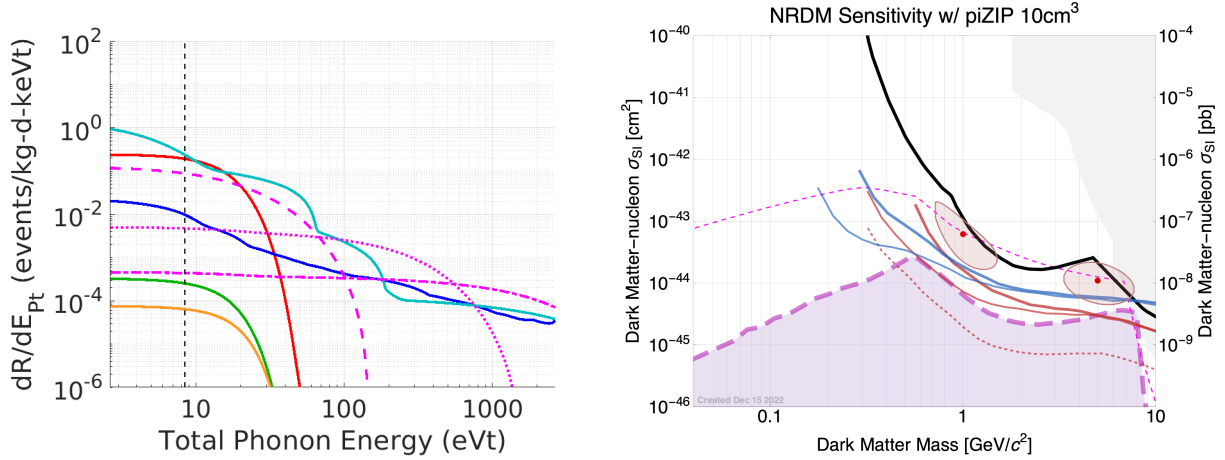


Figure 5-9. Background and WIMP spectra, along with sensitivity limits for piZIP detectors.

The spectra and limit plots both illustrate the better resolution of piZIP detectors compared to that of iZIP detectors of the same size in the same way as that for smaller iZIP detectors compare to that for SNOLAB iZIP detectors. In particular, note the independent order of magnitude lower energy cutoff of the same backgrounds mentioned before. The fact that Ge detectors have an improved reach compared to Si ones also carries over.

Now consider the possibilities for the detection of electron recoil dark matter, first focusing on that of DPDM and ALPDM. The set of spectra for a Ge 0V1cm<sup>3</sup> detector in the Bkg 1, Det C scenario, along with a set of limits for various 0V1cm<sup>3</sup> detector scenarios, is shown in Fig. 5-10. The first limits plot shows those for DPDM, in cyan are the Si 0V1cm<sup>3</sup> detectors in the Bkg 1, Det A (thick) and Bkg 1, Det B (thin) scenarios, in blue is the Si 0V10cm<sup>3</sup> scenario in the Bkg 1, Det C scenario, and in red-brown is the Ge 0V10cm<sup>3</sup> detector in the Bkg 1, Det C scenario. The second limits plot shows those for ALPDM, in solid red-brown are the Ge 0V10cm<sup>3</sup> detectors in the Bkg 1, Det B (thick) and Bkg 1, Det C (thin) scenarios, and in dashed red-brown is the Ge 0V1cm<sup>3</sup> detector in the Bkg 1, Det B, 20x exposure scenario.

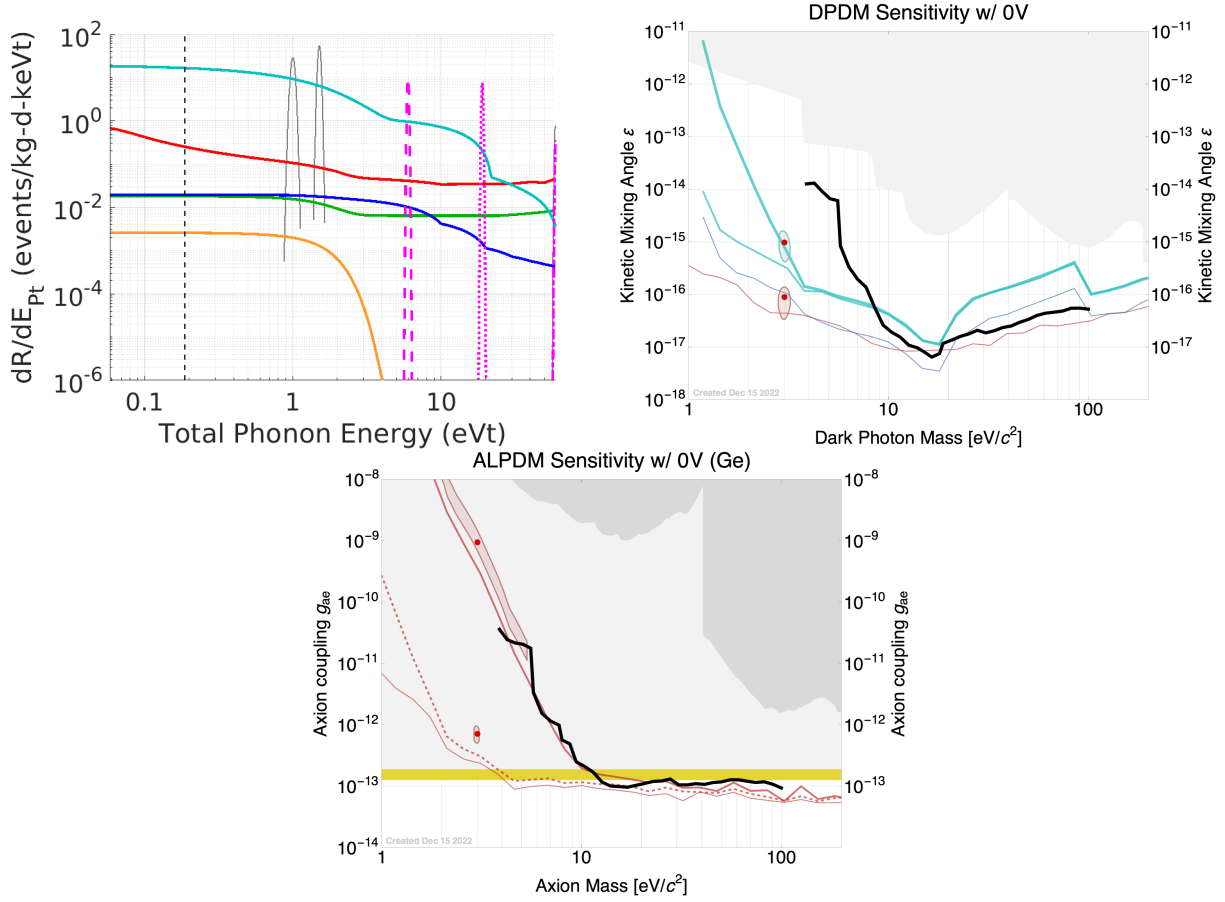


Figure 5-10. Background and DPDM spectra, along with sensitivity limits for 0V detectors.

The dark photon limit plot shows that Ge and Si detectors would probe different regions of parameter space, which arises from the two materials having differing dielectric response functions. The reason that the ALP limit plot does not show any Si limits is because this complementarity does not carry over for ALPs. These two properties will apply for HV detectors as well.

The set of spectra for a Ge HV detector in the Bkg 1, Det C scenario, along with a set of limits for various HV detector scenarios, is shown in Fig. 5-11. The first limits plot shows those for DPDM, in blue and red-brown are the Si and Ge HV detectors in the Bkg 1, Det B (thick) and Bkg 1, Det C (thin) scenarios. The second limits plot shows those for ALPDM, in red-brown are the Ge HV detectors in the Bkg 1, Det B (thick) and Bkg 1, Det C (thin) scenarios.

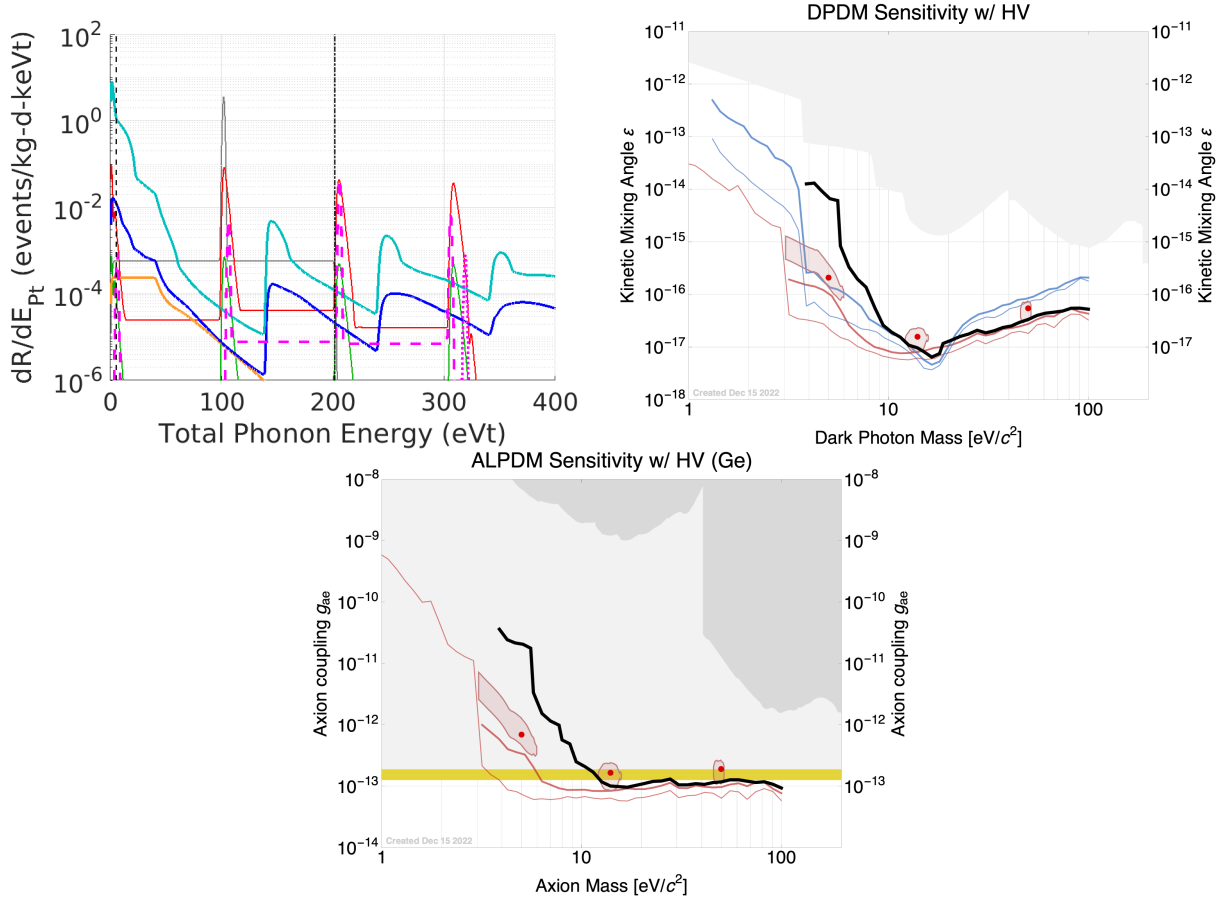


Figure 5-11. Background and DPDM spectra, along with sensitivity limits for HV detectors.

The spectra plot is focused on lower energy recoils, but energies up to about 2.5 keV are relevant, especially for higher mass dark photons. The limit plots show that 0V and HV detectors would probe similar areas of dark photon parameter space, while 0V detectors would be much more capable of detecting low mass ALPs. They do not show any Det A detector enhancement scenarios as their limits are comparable to those of SNOLAB scenarios due to there being no improvement in the charge leakage rates. This will apply for LDM detection as well.

Now focus on the detection of LDM. Note that only the case of a heavy mediator (i.e.  $F_{DM}(q) = 1$ ) is shown. The set of spectra for a Ge 0V1cm<sup>3</sup> detector in the Bkg 1, Det B scenario, along with a set of limits for various 0V1cm<sup>3</sup> detector scenarios, is shown in Fig. 5-12. In the limits plot, in blue are the Si 0V1cm<sup>3</sup> detectors in the Bkg 1, Det A (thick) and Bkg 1, Det B (thin) scenarios, in solid cyan are the same detectors just with 20x exposure, and in dashed cyan is

the Si 0V10cm<sup>3</sup> detector in the Bkg 1, Det C scenario.

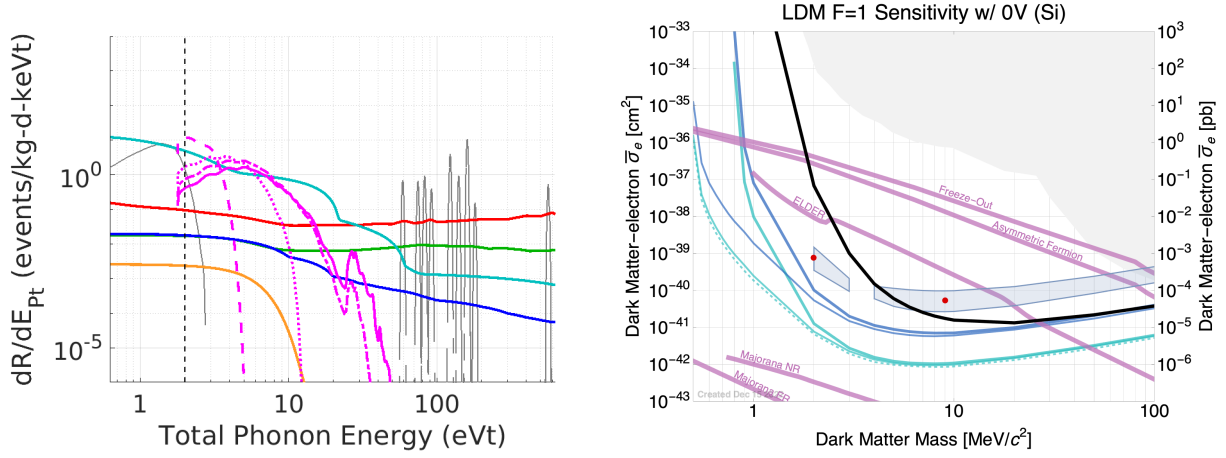


Figure 5-12. Background and LDM spectra, along with sensitivity limits for 0V detectors.

The limit plot shows that a 0V detector would be able to probe parameter space well below that of a SNOLAB HV detector, almost down to the level of the Majorana targets. The reason that no Ge limits are shown is because, for LDM, the analysis threshold is higher for Ge detectors than it is for Si ones. Even though it is not shown, this is especially true for the case of a light mediator (i.e.  $F_{DM}(q) = 1/q^2$ ).

The set of spectra for a Ge HV detector in the Bkg 1, Det C scenario, along with a set of limits for various HV detector scenarios, is shown in Fig. 5-13. In the limits plot, in red-brown are the Ge HV detectors in the Bkg 1, Det B (thick) and Bkg 1, Det C (thin) scenarios.

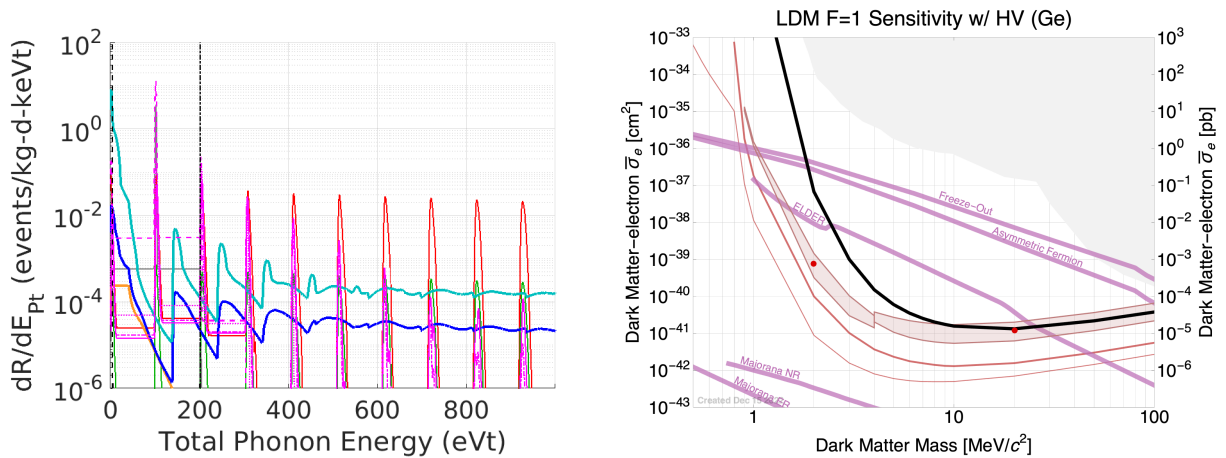


Figure 5-13. Background and LDM spectra, along with sensitivity limits for HV detectors.

The limit plot shows that an HV detector would be able to probe even closer to the motivated Majorana targets. The reason that no Si limits are shown now is because the improvement in the phonon energy resolution associated with HV detectors makes the number of electrons per atom the dominant factor in determining the analysis threshold, regardless of the mass of the mediator.

## CHAPTER 6 FUTURE WORK

### 6.1 Future IMPACT and DMC Work

The results of the first IMPACT run are shown in Fig. 6-1 [47]. They clearly show that the deviation of the ionization yield for silicon from the Lindhard model continues down to recoil energies of just 100 eV, although not as dramatically as prior experiments had suggested.

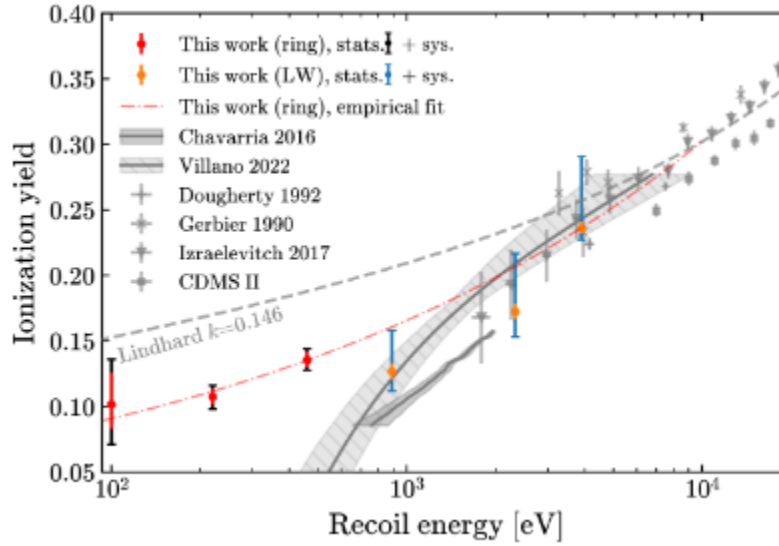


Figure 6-1. The ionization yield for silicon given by the IMPACT experiment (colored points) alongside various other observations (gray points) and the Lindhard model (gray dashed line).

Other IMPACT runs have been proposed to reduce the uncertainties of this data and to determine if there are any dependencies. For instance, a run utilizing the DD neutron generator at NEXUS (Northwestern Experimental Underground Site) has been considered, while a run at the University of Montreal meant to establish if varying the neutron velocity has any effect on the yield has already been performed, with the data in the process of being analyzed.

A run with a germanium HVeV detector would be particularly informative, as measurements have shown that the yield for germanium diverges from the Lindhard model at around the same energy as seen with silicon, as shown in Fig. 6-2 [48]. Such a run would not only further mark the limits of the Lindhard model, but would improve the understanding of the other germanium detectors SuperCDMS uses.

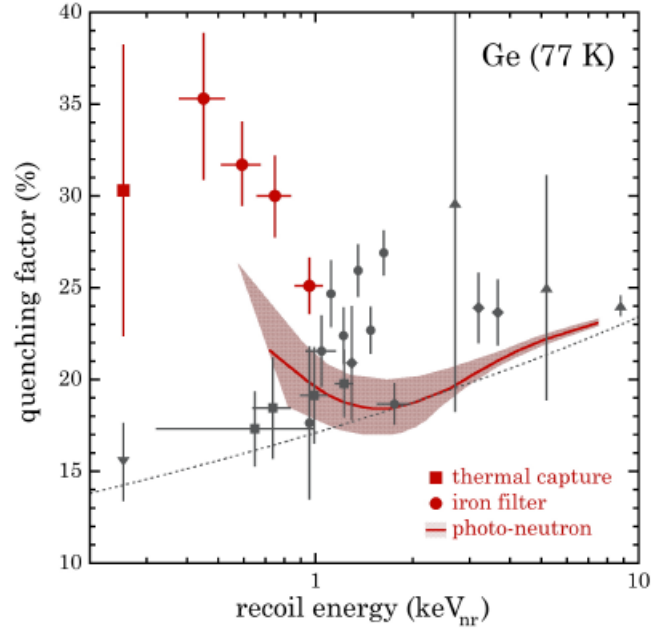


Figure 6-2. The ionization yield for germanium given by the Lindhard model (various observations) as the dashed line (points).

These runs will likely require analysis with G4DMC and TESSim much like the first IMPACT run did. And while, as of right now, it is impossible to tell what the exact analysis tasks will be, it is certain that both software packages are in a better state to accomplish those tasks now than they were at the start of this work.

## 6.2 Future Sensitivity Work

The proposals for the development of SuperCDMS SNOLAB listed and analyzed in the previous chapter all utilize the standard materials of silicon and germanium. However, there are also proposals for the use of entirely new materials. These include diamond and silicon carbide, both of which have larger band gaps, which would greatly reduce the presence of charge leakage in HV detectors,  $\text{Eu}_5\text{In}_2\text{Sb}_6$  [49] and  $\text{La}_3\text{Cd}_2\text{As}_6$ , both of which have very small band gaps, at around 40 meV and 100 meV respectively, which would greatly improve detector resolutions, and the special materials liquid He, GaAs [50],  $\text{Al}_2\text{O}_3$  (sapphire), and  $\text{SiO}_2$  (quartz).

In addition to the use of new materials, there are also novel proposals involving the use of new phonon sensors such as kinetic inductance detectors (KIDs) [51] and Cooper-pair-box (CPB) qubits, as well as the improved mitigation of low-energy backgrounds such as secondary

low-energy photons, which are emitted by Cirlex, and environmental vibrations.

Except for proposals involving secondary low-energy photons and, to a certain extent, GaAs, none of these will be trivial to implement in the sensitivity code. Most of the new material proposals will involve writing new detector response model files that incorporate distinct condensed matter physics, and any involving vibration decoupling will involve writing a new background type as a start. However, making these additions will be important to the long-term use of the code by SuperCDMS.

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## BIOGRAPHICAL SKETCH

As a young child, Harrison Coombes was interested in a broad range of sciences including meteorology, geology, and astronomy. However, with his equally strong interest in math, he eventually settled on physics as the one he wanted to focus on, albeit with a concentration in astrophysics. He was homeschooled for the four years prior to enrolling in a university, although he did enroll in J. Sargeant Reynolds Community College after the first year or so to earn transfer credit. He took his final classes there in 2013.

Next, he enrolled in Auburn University later that same year. While there, he joined the research group of Dr. Greg Hartwell that operates the Compact Toroidal Hybrid device to confine and study plasmas, performing several small tasks including writing code to model the magnetic field of a real solenoid and measuring the flatness of a light source. Later, he switched to work with Dr. Eugene Oks otherwise independently, performing calculations of the electric fields created by ions. This work resulted in a publication. He was able to graduate with a B.S. in physics in 2016 with the credit he had transferred in.

Then, he enrolled in Durham University in Durham, England later that same year. While there, he worked with Dr. David Cerdeno otherwise independently, developing an sneutrino dark matter model governed by the freeze-in mechanism. This work first introduced him to the rigors of dark matter research and resulted in a master's thesis. He graduated with an M.S. in physics in 2017.

Finally, he enrolled in the University of Florida later in the fall of that same year. While there, he joined the research group of Dr. Tarek Saab within the SuperCDMS collaboration, simulating the condensed matter response of the detector used during the IMPACT calibration experiment and performing sensitivity calculations for various detector proposals for the main SuperCDMS experiment. This work resulted in several publications. He also participated in the IMPACT experiment itself as well as multiple collaboration meetings. He graduated with a Ph.D. in physics in the summer of 2023.