Understanding the Response of Small High Voltage Single Crystal Dark Matter Detectors to Photons Using Simulations

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Preliminary Defense

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Outline

- Introduction and Motivation
- Solid State Physics of the Detectors
- HVeV Experiment and Results
- Simulation of HVeV Experiment and Comparison to Data
- Future Plans
- Conclusions

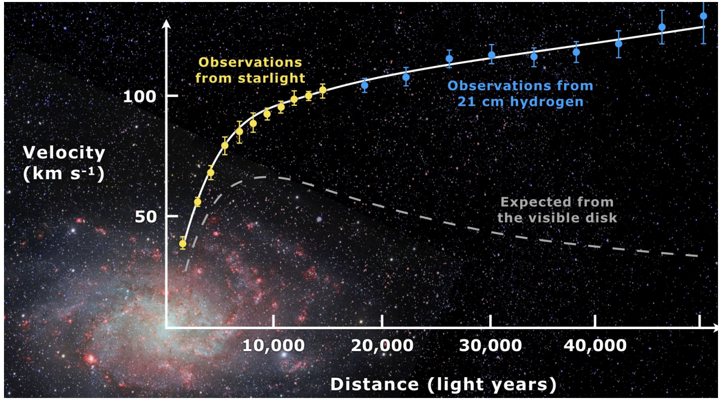
Introduction and Motivation

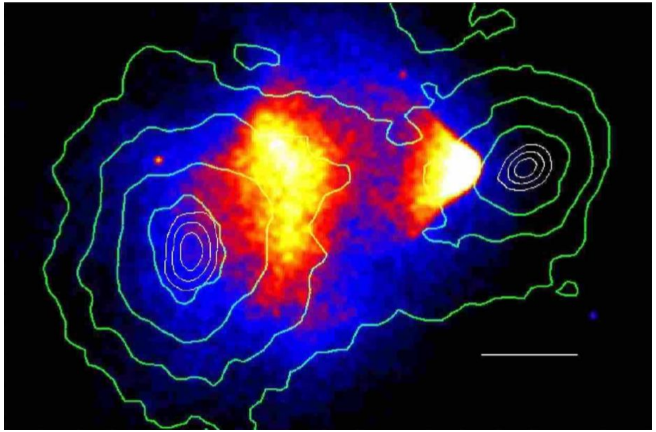
- Dark Matter Evidence, Properties and Detection Method
- Using Semiconductor and Superconductor Technologies for Dark Matter Detection
- Quick Introduction to this Thesis
- The need for Small High-Resolution Athermal Phonon (HVeV) Detectors
- The need for Understanding the Physics of HVeV Detectors with Simulations
- Goals and Structure of This Thesis

Dark Matter Evidence

Numerous observations indicate that the universe mostly consists of unseen massive particles that have no electromagnetic interactions:

- **Galaxy Rotation Curves:**
  Most of the visible mass of the galaxies is concentrated in the center. We would expect rotation velocity to decrease as we get further from the center. This is not consistent with observation.
- **Bullet Cluster:**
  Two galaxy clusters collided. We expect most of the matter in the yellow region where we get the x-rays. This is not consistent with the gravitational lensing map. (green curves)

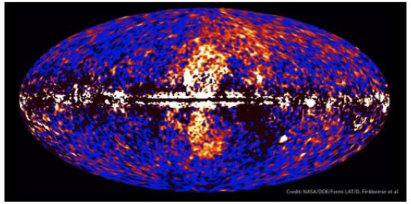




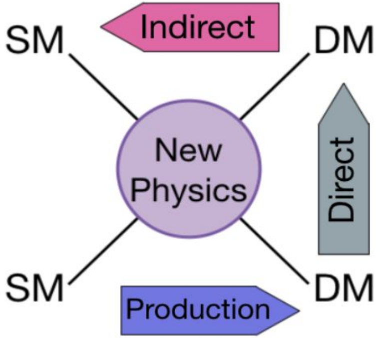
Dark Matter Properties and Detection Methods

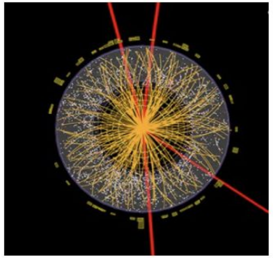
Particle solution does a nice job of explaining the data. Dark matter particles should be:

- Massive
- Neutral and Minimally Interacting
- Stable (Very Long Life-Time)
- Non-Relativistic

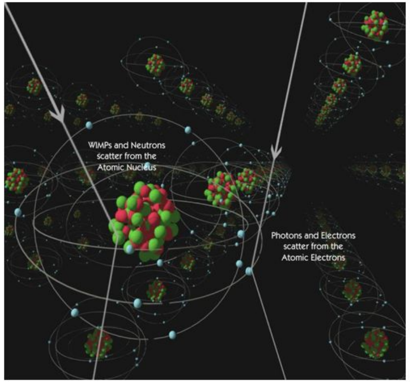


Cosmological Observation





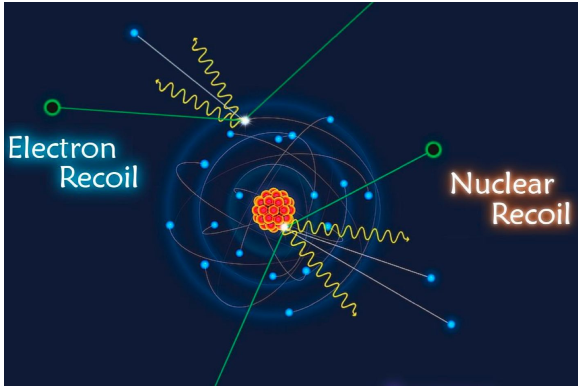
Collider Physics

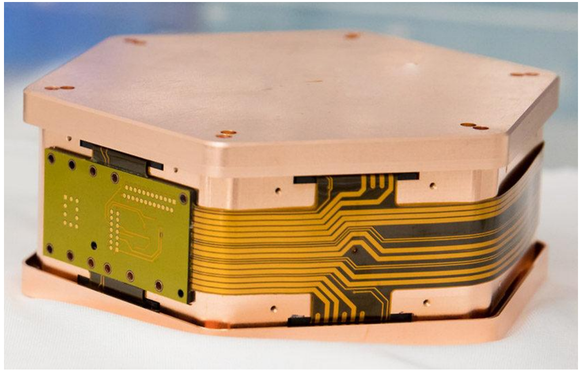


Direct Detection:
SuperCDMS HVeV

Using Semiconductor and Superconductor Technologies for Dark Matter Detection

- Theories predict that dark matter and normal matter interact with each other through nuclear recoil and/or electron recoil at eV to KeV energy scales
- If we make very sensitive detectors, we might be able to observe these interactions experimentally
- Combined Semiconductor and Superconductor technologies are promising avenues for detecting very low energy interactions
- SuperCDMS Experiment uses these technologies to build multiple complementary detectors for its dark matter search
- In this thesis we focus on small high-resolution phonon detector that are called HVeV detectors





Quick Introduction to this Thesis

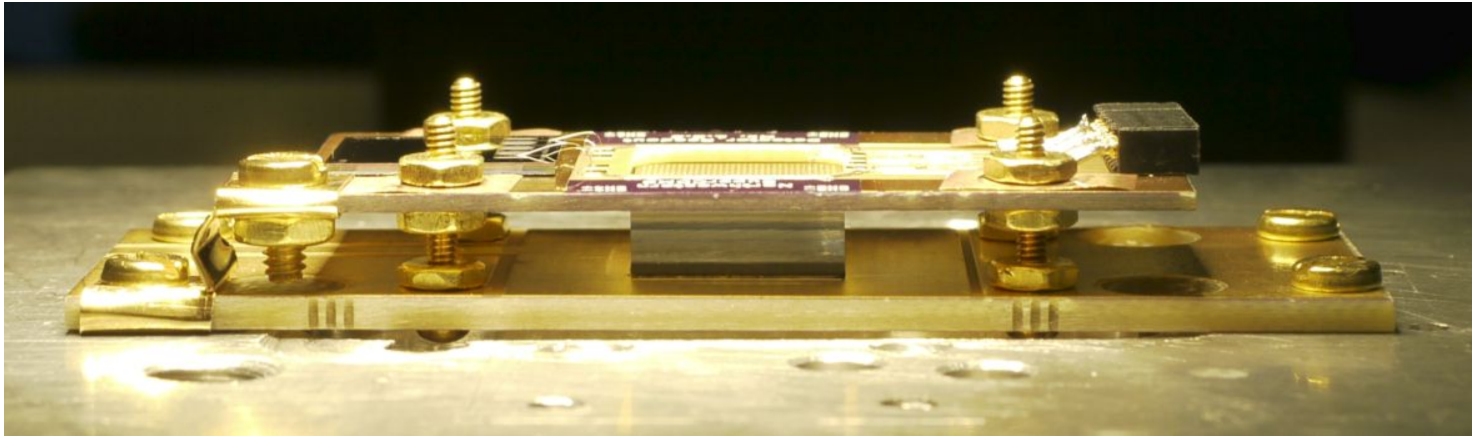
- This thesis is about understanding the next generation of dark matter detectors, which are small, high-energy resolution devices called HVeV (for "High Voltage eV resolution")
- We learned a lot from the CDMS experiment at Soudan, and now we have new detectors which are more powerful
- However, with more sophistication requires more understanding to get out better science results
- There will be two parts:
  - The detector design, experiment and data (which was done before I joined, and is a combination R&D and physics search)
  - The simulations and comparison to data (which is my part)
- We next turn to why we are focusing on the detectors used in this dissertation

The need for Small High-Resolution Athermal Phonon (HVeV) Detectors

- HVeV detectors are very **small** and they are operated under **high voltage** bias
- **Why High Voltage?**
  - We can go to very low thresholds under high voltage. (Will talk about this mechanism more later)
- **Why Small?**
  - We will have much less energy leakage to the side walls in small detectors. (Will become more clear later in the talk)
- **Main Achievements/Objectives of the HVeV Program:**
  - Using such low threshold, this program has been able to exclude more parameter space for lower dark matter masses with above-ground runs
  - HVeV detectors also provide a great opportunity to run tests in preparation for the real experiment with much bigger detectors

The need for Understanding the Physics of HVeV Detectors with Simulations

- The sensitivity of HVeV detectors is limited by the lack of understanding of the physics of the experiment and devices
- Using simulations can play a significant role in enhancing our understanding of the experiment



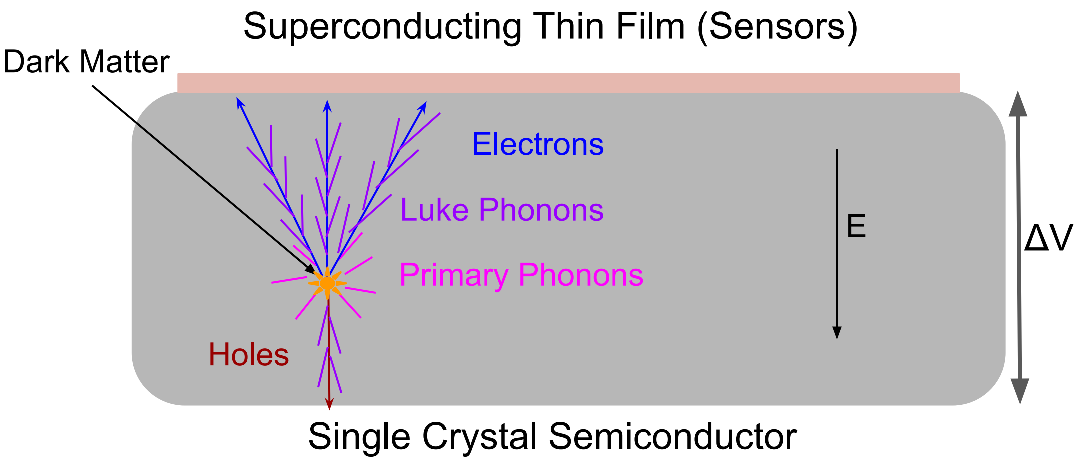
Goals and Structure of This Thesis

- The goal of this thesis is to compare the simulation of HVeV detectors with well understood photon interactions from **laser data** to:
  - Understand the physics of the detectors using simulations
  - Validate and improve the simulation
  - Use the simulation to obtain otherwise inaccessible information about the experiment which can suggest new ways to improve the detectors and/or analyze the data we get from them
- We will talk about:
  - Solid State Physics of the Detectors
  - HVeV Experiment and Results
  - Simulation of HVeV Experiment and Comparison to Data
  - Future Plan and Conclusions

Solid State Physics of the Detectors

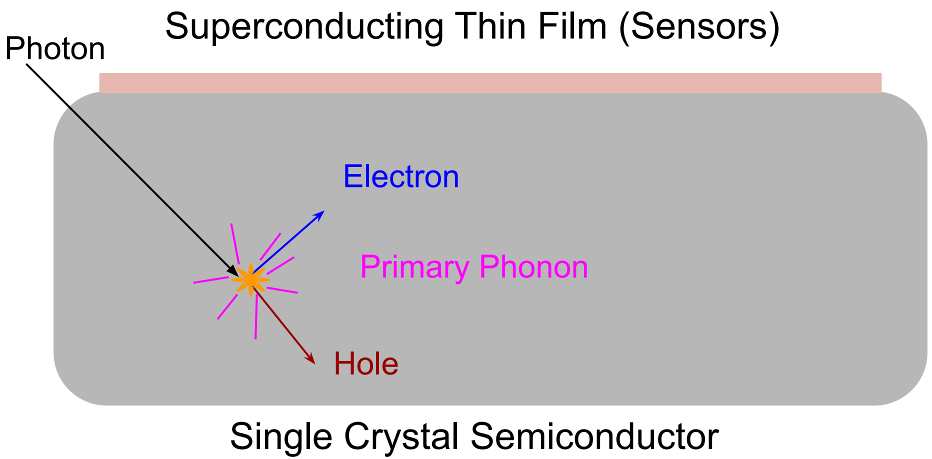
- Overview of the Detector Concept
- Physics of Single Crystal Semiconductors and Lattice Response to Photon Interactions Under Large Voltage Bias
- Physics of Superconducting Sensors

Overview of the Detector Concept



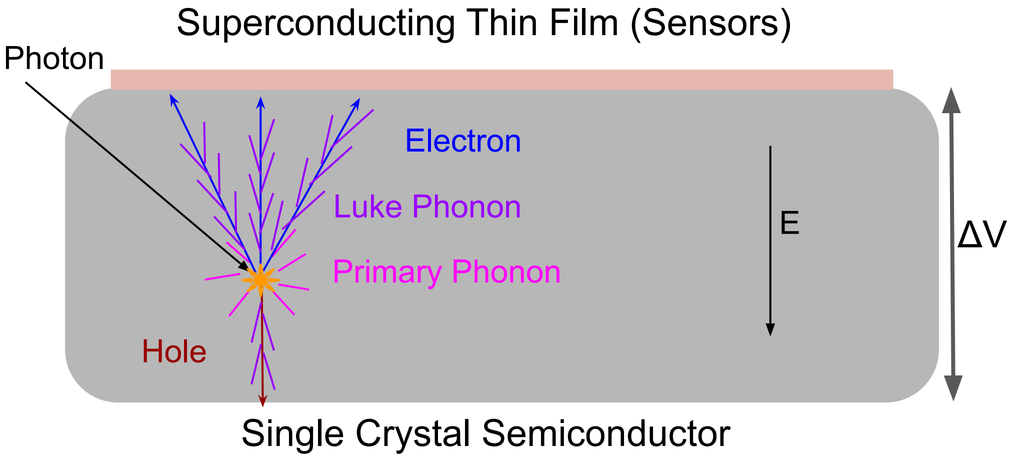
- SuperCDMS detectors are made of single crystal semiconductor and superconducting sensors
- Dark Matter particles will interact with the crystal lattice, energy propagates in the crystal structure and we can measure it using the superconducting sensors
- Now let's talk more about the details of the detector physics if a photon hits the detector. In this thesis, we will look at the laser data i.e, photons hitting the detector

Our Test Experiment: Photons Can Create Primary Phonons and Electron-Hole Pairs



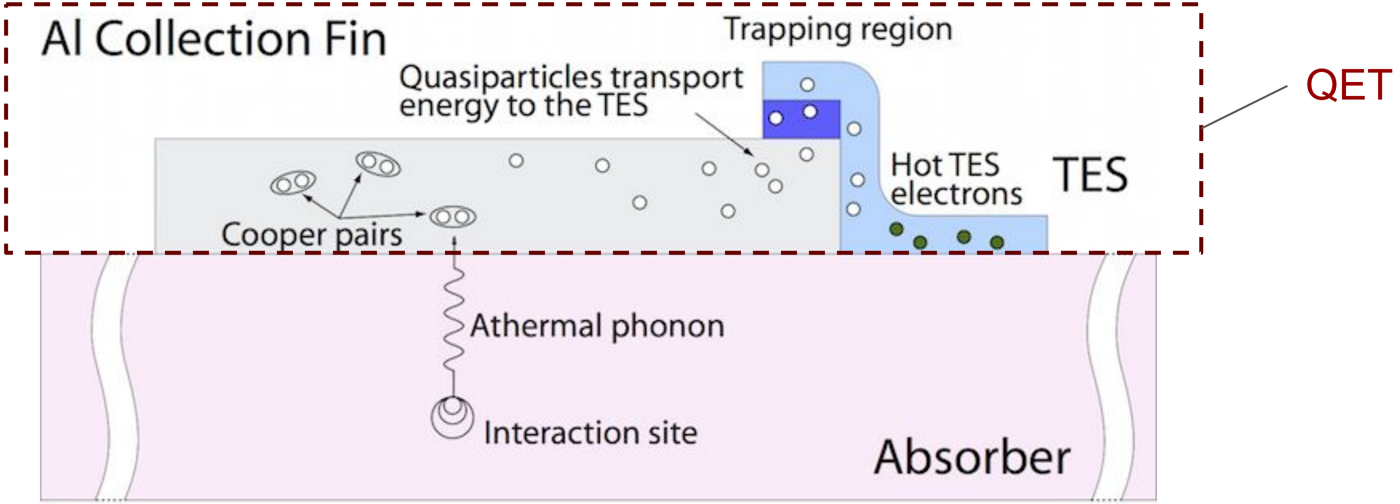
- Photons hitting the crystal (Si) can generate primary phonons (lattice vibration) and send an electron in valence band to the conduction band and make an unoccupied valence state called a hole

Applying Large Voltage Bias and Luke Phonons



- Electrons and holes will travel under the voltage bias and pick up more energy, bang into the lattice which creates more phonons called Luke Phonons. This is why we have a large voltage. More voltage, more Luke phonons
- Electrons travel along valleys (minimum energy potentials)
- Holes go straight in the opposite direction

Superconducting Sensors (QETs)

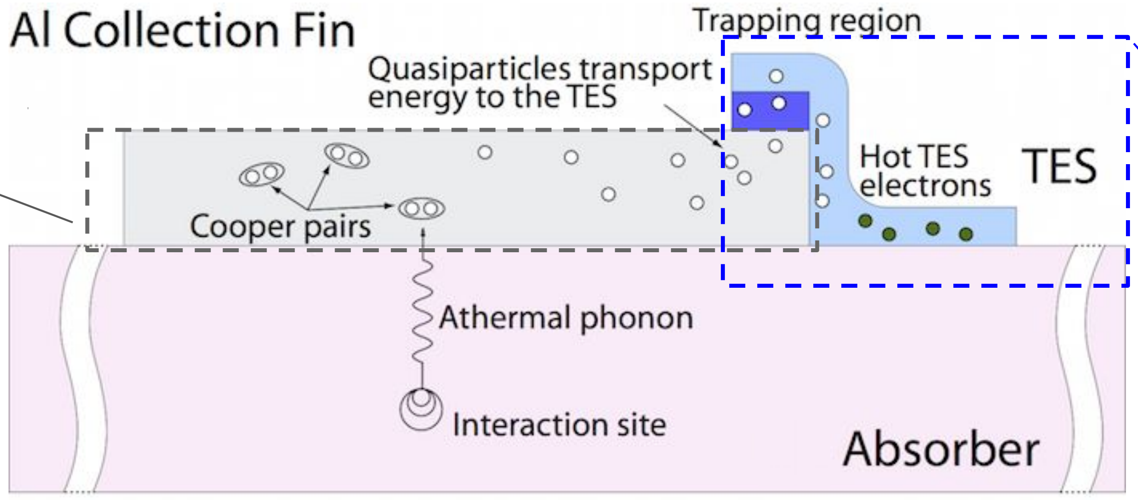


Schematic of one QET from Figueroa Group at Northwestern

Top Surface of the detector crystal is patterned with Quasiparticle-assisted Electrothermal-feedback Transition-Edge Sensor (QETs)

QETs Component: Al fins and Transition Edge Sensors

Al Fin: Superconducting

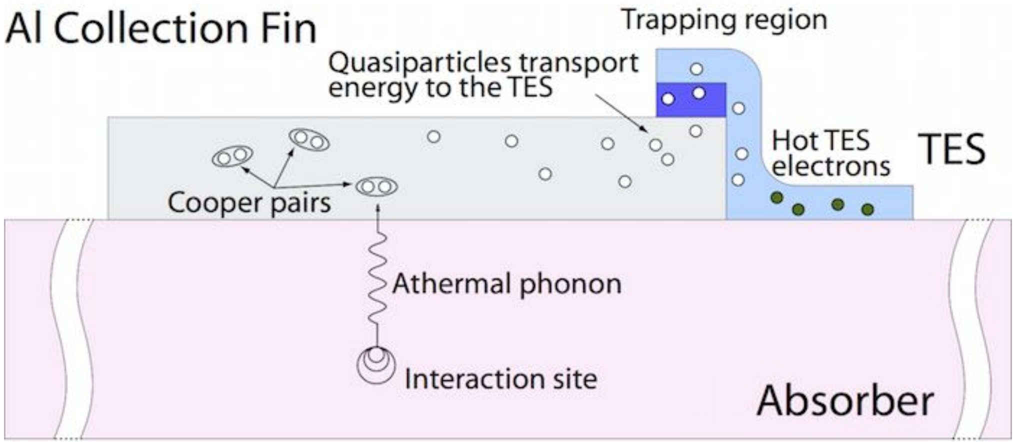


TES: biased with a voltage to be in the middle of the transition

Schematic of one QET from Figueroa Group at Northwestern

Physics of Superconducting Sensors

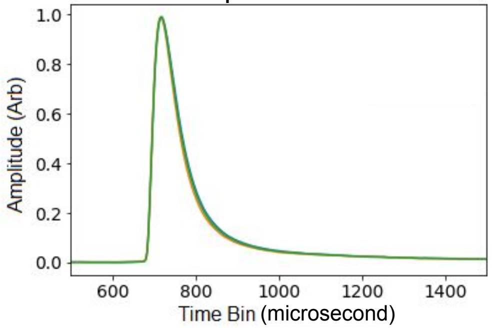
1. Phonons generated from the interaction will get absorbed by the Al, break Cooper pairs and produce quasi-particles



2. The quasi-particles will travel to the TES and transfer their heat to the TES which is at the edge of superconductivity

3. Small changes in the temperature of TES will result in a big change in its resistance, which we can measure from the current

Example TES Pulse



HVeV Experiment and Results

- NEXUS Facility and Experimental Setup
- Detector Geometry
- Laser Calibration System
- Photon Interaction with the Crystal and Collected Phonon Energy
- Charge Trapping and Impact Ionization
- Recoil Energy Spectrum: Main Features and Goals

NEXUS Facility and Experimental Setup

Data Acquisition and
Monitoring System

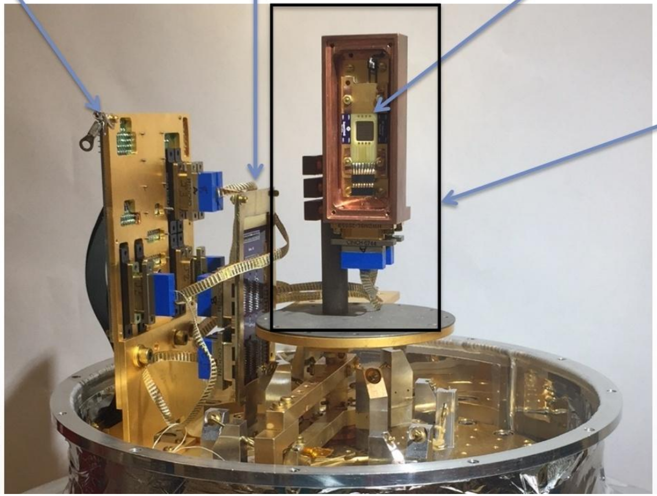
NEXUS Lab Setup

Vericold ADR Fridge

Readout board
SQUIDS
(~1.3K)

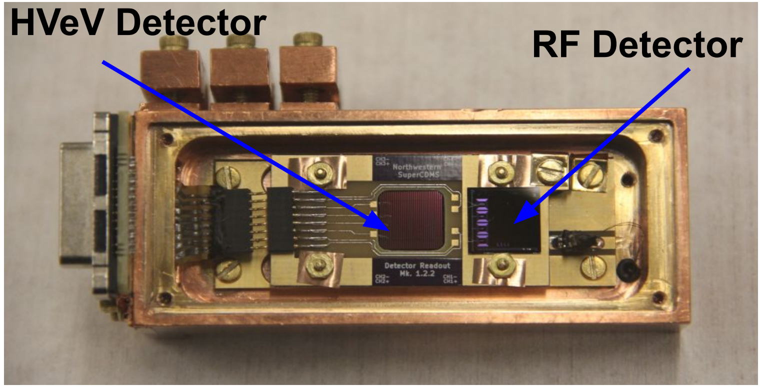
GGG heat sinking
(~300mK)

Detector Box
(~50mK)

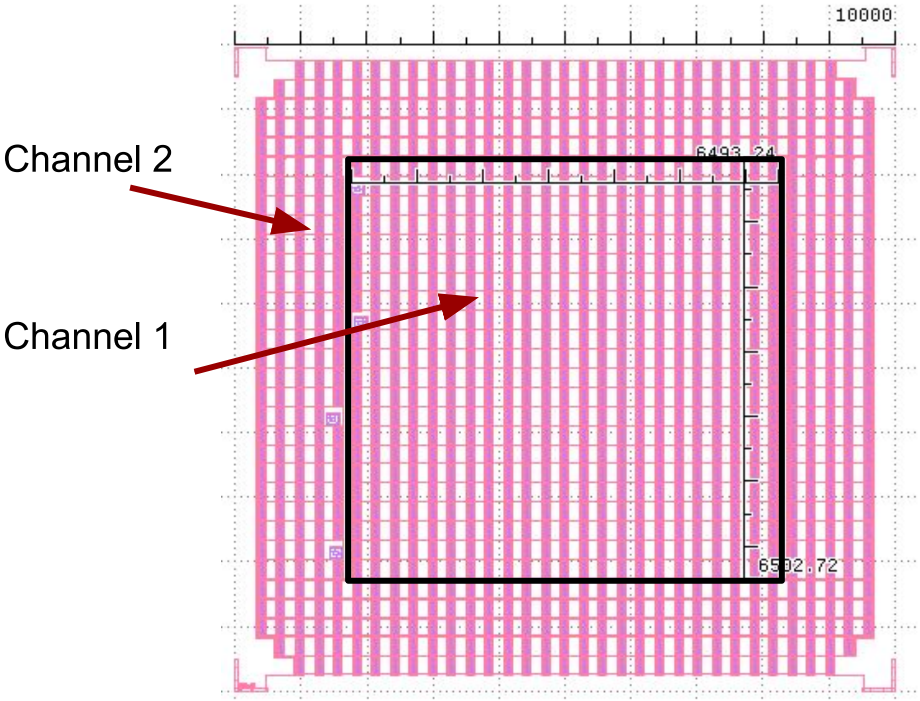


Nb Can
location

Detector Geometry



Si HVeV mounted in the copper holder



- $10{\times}10{\times}4\ mm^3$ silicon chip with a total mass of 0.93 g
- Two QET channels, with critical temperature of 65 mK

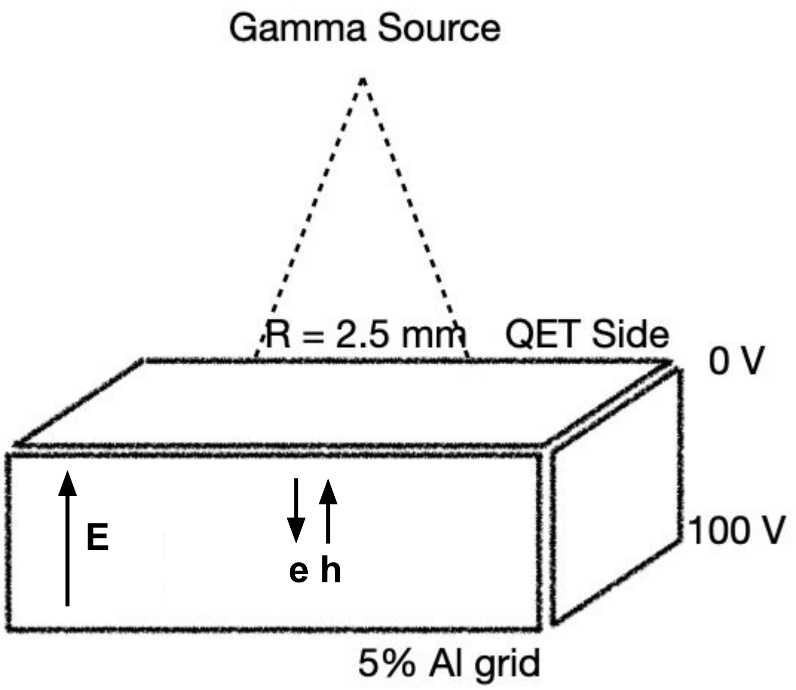
- Channel 1 is 23 x 22 which is 506 QETs
- Channel 2 is five QETs on each side. Total of 538

Laser Calibration Experiment

In this thesis we will focus on the Laser Calibration Runs:

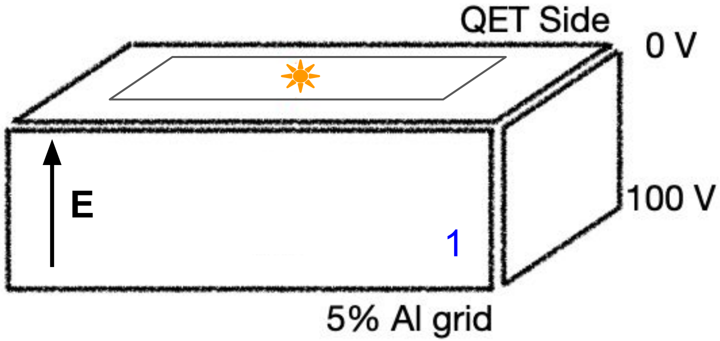
- The laser shoots 1.95 eV photons to the top surface of the detector. Visual spot of R=2.5 mm
- Si band gap is 1.1 eV so 1.95 eV photons can only liberate one eh pair. This makes the calibration data easier to understand
- The number of photons hitting the detector at the same time follows a Poisson distribution with Lambda~1
- The detector is biased at 100 V
- The penetration depth of the photons to the crystal is ~5.3 um and falls exponentially

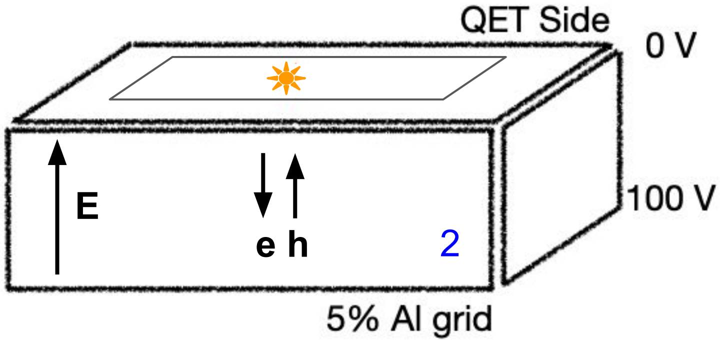
Figures are not to the scale



Collected Phonon Energy: 1 Photon

There are two possible outcomes:





One photon hits the middle of the top surface of the detector and **the generated eh pair recombines or is trapped at the surface immediately.**

Collected Phonon E:

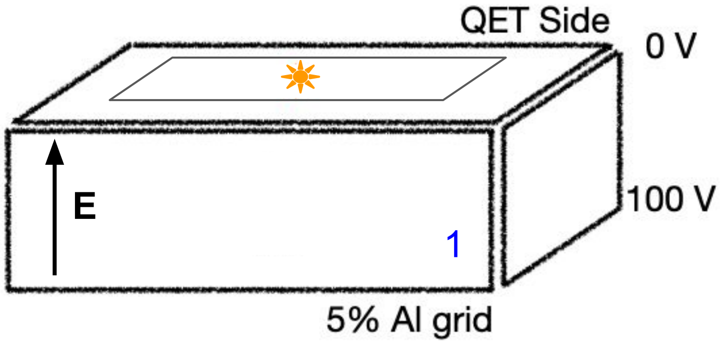
- Initial Photon Energy = 1.95 eV
- Luke Amplification = 0 e * 100 V =0 eV
- **Collected Phonon E = 1.95 eV**
- ~50% probability

One photon hits the middle of the top surface of the detector and generates **one eh pair that goes through full Luke amplification**.

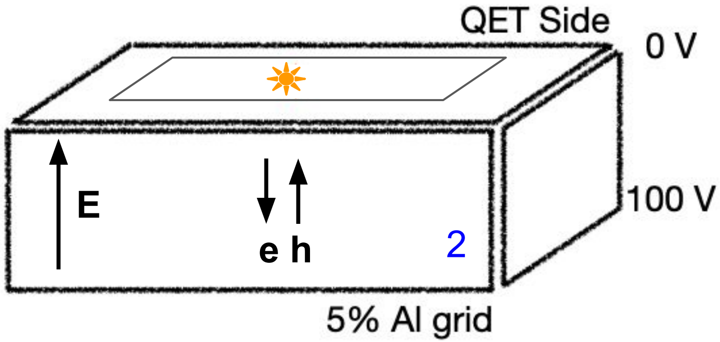
Collected Phonon E:

- Initial Photon Energy = 1.95 eV
- Luke Amplification = 1 e * 100 V =100 eV
- **Collected Phonon E = 101.95 eV**
- ~50% probability

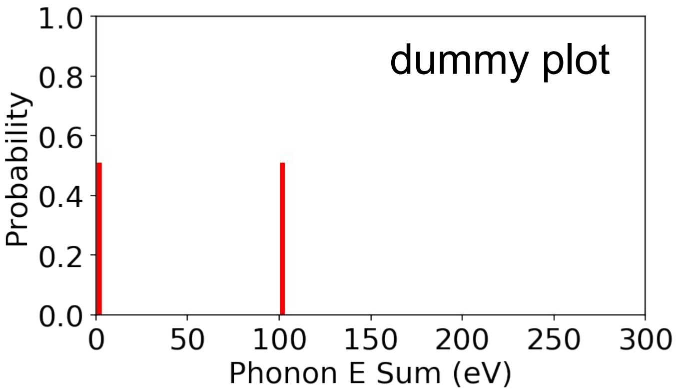
Collected Phonon Energy: 1 Photon



Collected Phonon E = 1.95 eV
Probability = 50%

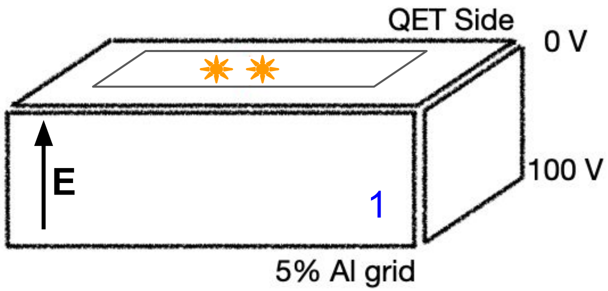


Collected Phonon E = 101.95 eV
Probability = 50%

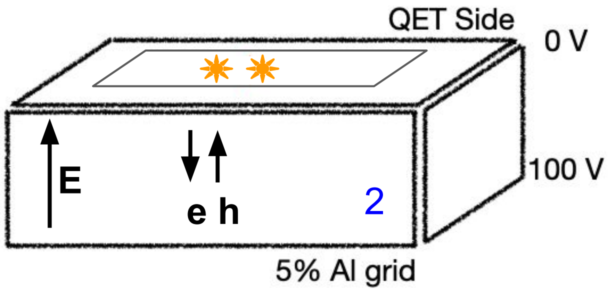


Collected Phonon Energy: 2 Photons

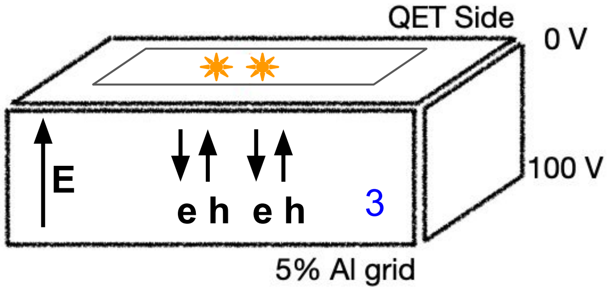
There are three possible outcomes:



Collected Phonon E = 3.9 eV
Probability = 25%



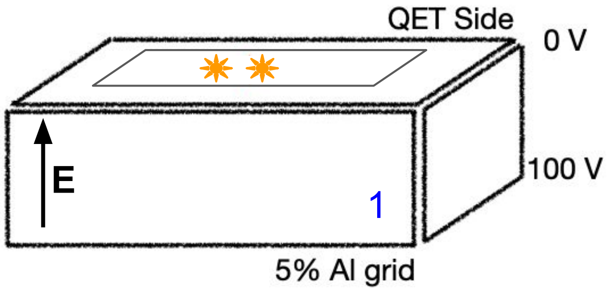
Collected Phonon E = 103.9 eV
Probability = 50%



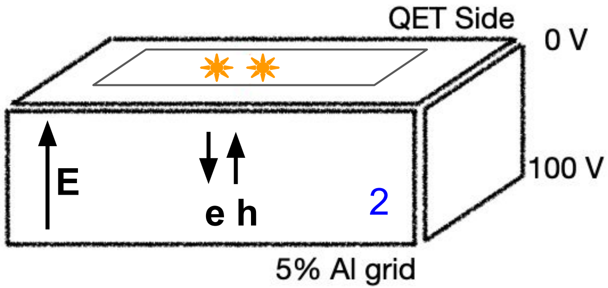
Collected Phonon E = 203.9 eV
Probability = 25%

E= N*1.95 + M*100
N: Number of Photons;
M: Number of ehs fully amplified;
M<=N

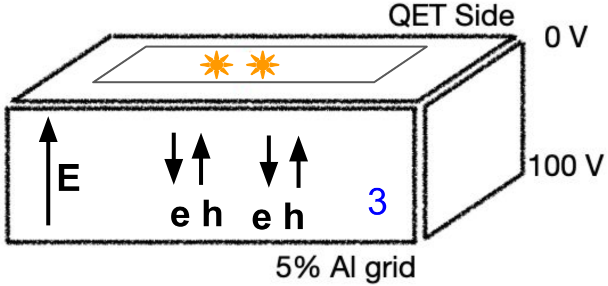
Collected Phonon Energy: 2 Photons



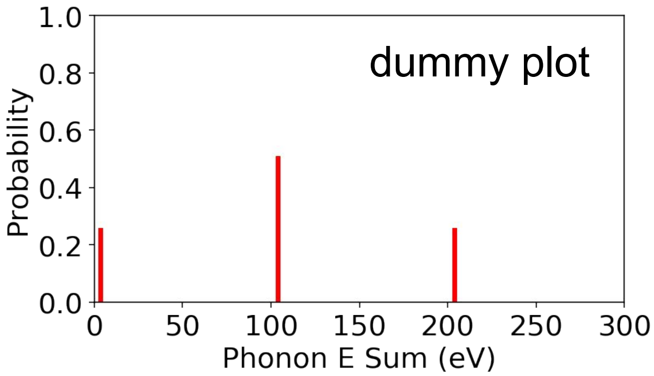
Collected Phonon E = 3.9 eV
Probability = ~25%



Collected Phonon E = 103.9 eV
Probability = ~50%

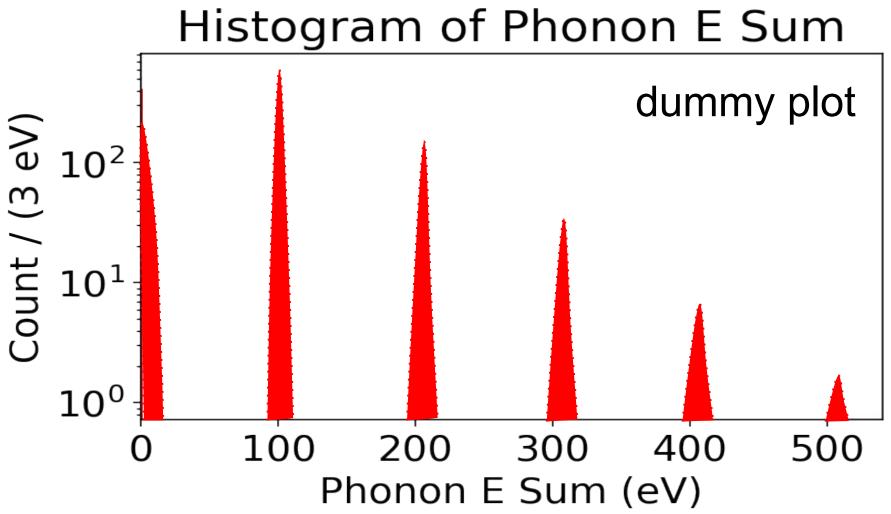


Collected Phonon E = 203.9 eV
Probability = ~25%



Moving to Larger Number of Photons and Adding Detector Resolution Effects

- Now let's assume we have 1500 laser shots
- Each shot has N photons hitting the detector, where N follows a Poisson distribution with Lambda = 1
- The RHS plot is a dummy plot of what we would expect for those 1500 laser shots considering different combinations of N and M and some detector noise



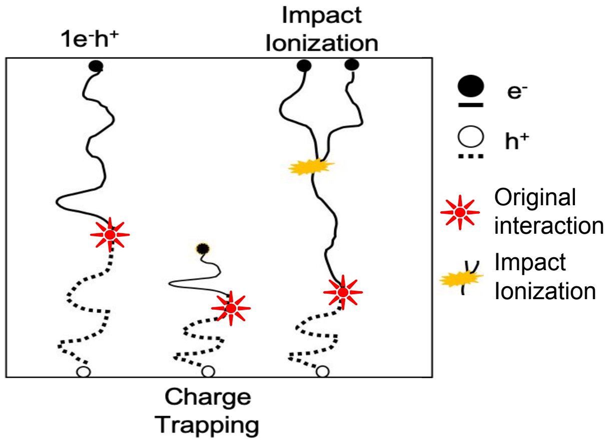
Charge Trapping and Impact Ionization

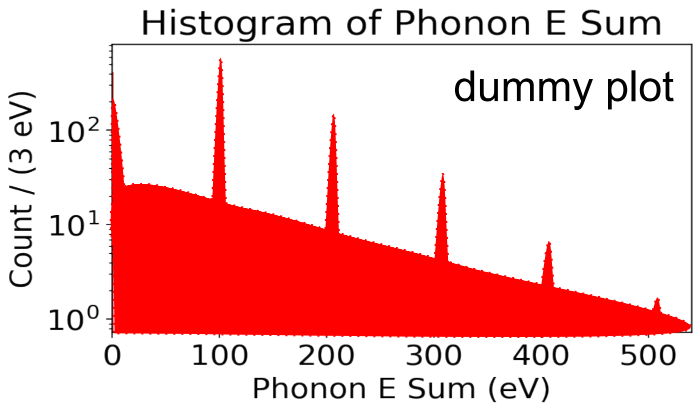
In reality, our crystals are have impurities and we don't get full energy collection all the time.

Charges traveling through the crystal can:

- Get trapped in defects so we lose some of the phonon energy
- Liberate additional charges that are stuck in overcharged impurity regions. These charges are accelerated, creating additional phonons

These processes will lead to partial energy collection which will show up as a background in between the peaks of the spectrum. They depend on the quality of the crystal used.





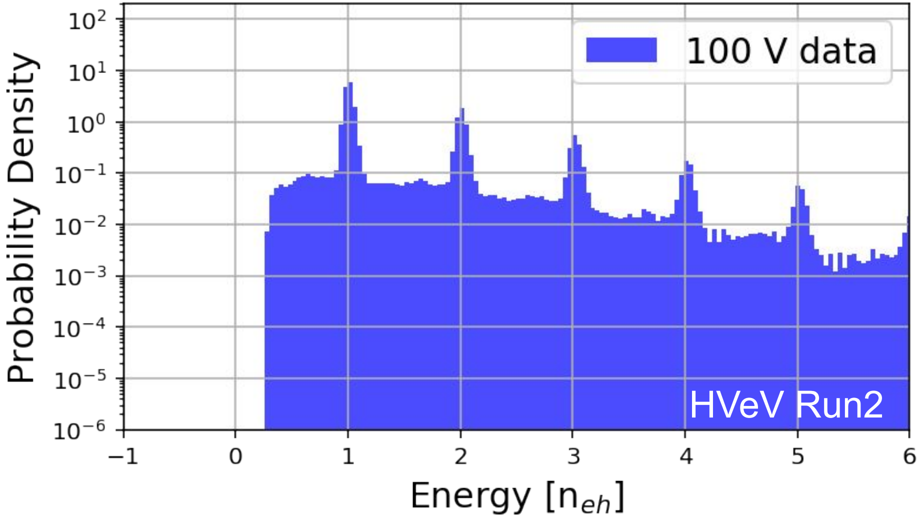
Recoil Energy Spectrum from Real Data: Main Features and Goals

Laser data shows a number of these effects:

- The number of photons hitting the detector follows a Poisson distribution with Lambda~1
- As expected, we see the Gaussian peaks with roughly flat background between the peaks caused by impurities in the crystal (Charge Trapping and Impact Ionization)
- RMS of the first eh pair peak = 3 eV

The goal of the simulation is to understand and reproduce these features:

- **Location of the peaks**
- **RMS of the peaks (Which can hopefully tell us about the detector resolution)**
- **Understand the events between them to understand the detector response**



Notes about this plot:

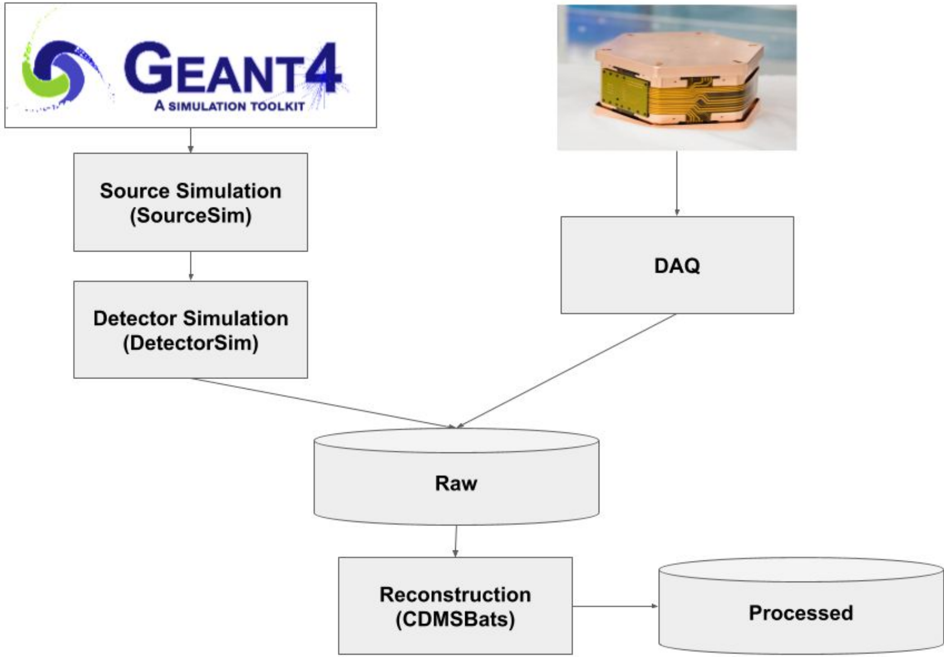
- 0th eh pair peak has been cut out in data by the trigger
- Phonon Energy is scaled to eh energy by dividing to 101.95 eV
- Probability Density is calculated by normalizing the histogram

Simulation of HVeV Experiment and Comparison to Data

- Overview of the Full Simulation
- Overview of Simulation Plan and Three Simulation Samples
    - SourceSim and CrystalSim Results
    - Finding Charge Trapping and Impact Ionization Rates Using a Toy Model and Adding them to the Simulation
- First Results of Comparison of Data to Full Simulation

Overview of the Full Simulation

- We simulate particle interactions using Geant4, and a custom detector simulation which does condensed matter physics (G4CMP)
- SourceSim simulates the laser source
- DetectorSim consists of:
  - CrystalSim
  - TESSim
  - DAQSim and NoiseSim
- After creating the raw data, we can process them by running through Reconstruction
- We can compare processed simulation results and real data

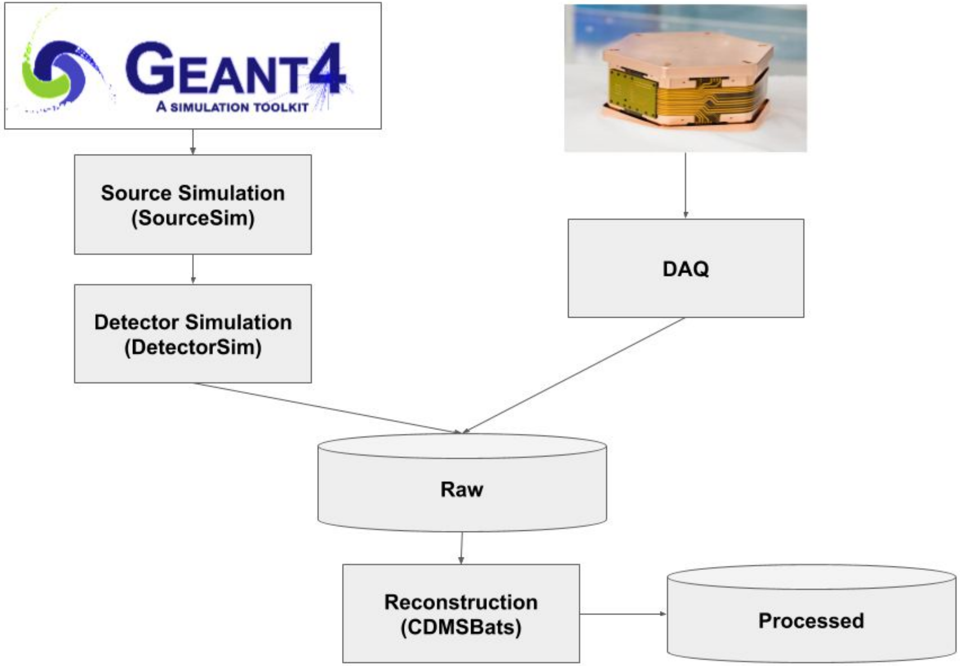


Overview Simulation Plan

In this talk we will show the results of the parts marked with blue:

- Geant4
- SourceSim
- DetectorSim:
  - CrystalSim
  - TESSim
  - DAQSim and NoiseSim
- Reconstruction

Planning to finish TESSim, DAQSim, NoiseSim and Reconstruction for the final Defense



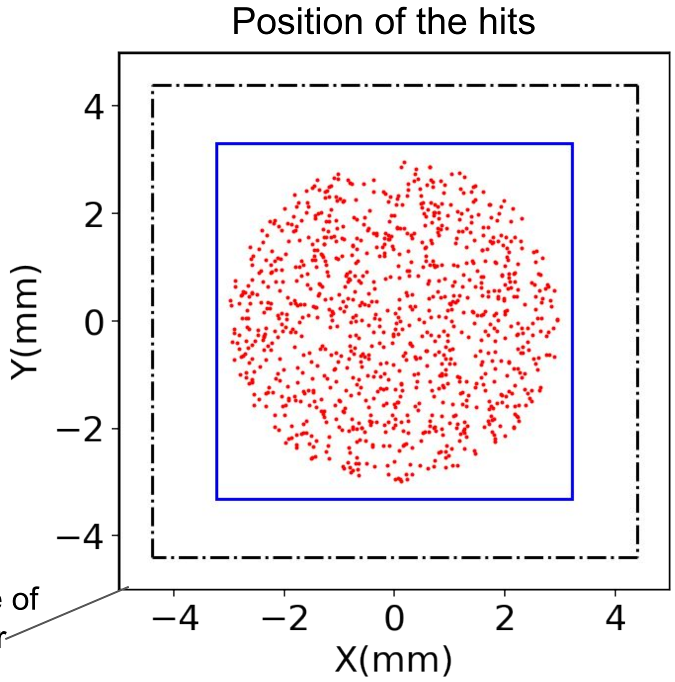
Simulation Information

Simulation Information	
Voltage	100 V Uniform Voltage
Energy	1.95 eV
Position of Energy Deposits	- Top surface of the detector with R < 3 mm - Exponential with SkinDepth of 5.3 um

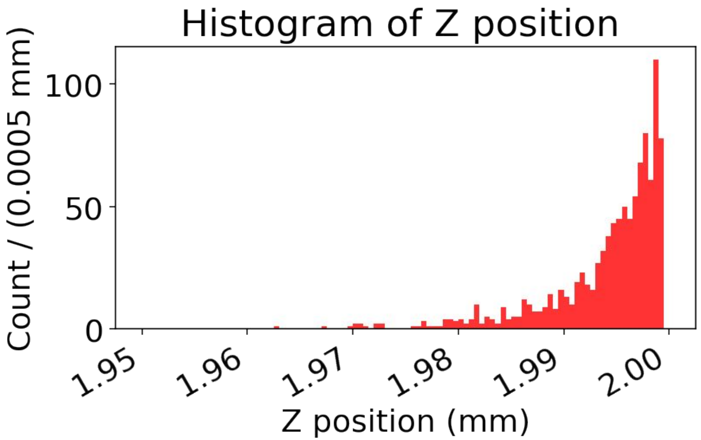
We will start with a simple case and add more effects as we go on.Will show results from three samples:

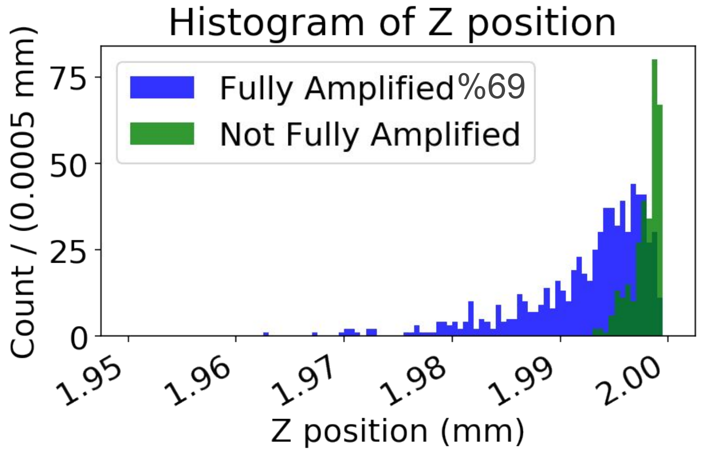
- Sample 1: 1k events where the number of energy deposits is always 1. (N=1)
- Sample 2: 1k events where the number of energy deposits follows a Poisson distribution with Lambda = 1
- Sample 3: 25k events with Lambda = 1 and Charge Trapping and Impact Ionization

Sample 1: SourceSim Results



Top surface of the detector

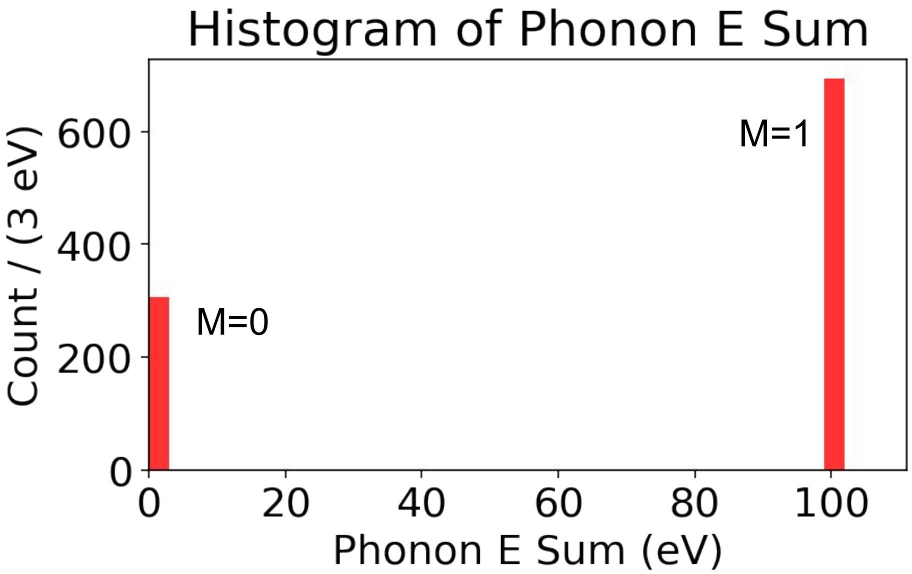




These plots look the same for different samples, so we will not show them for each sample.

Sample 1: CrystalSim Results

- Number of Photons is N=1
- Peaks appear at the right place
- Peaks are very sharp because we don't have the Poisson variation in number of photons and also there is no noise added yet
- There are no events between the peaks because we have not added Charge Trapping and Impact Ionization
- Next Step: Let's look at the sample with Poisson variation



E= N*1.95 + M*100

N: Number of Photons = 1

M: Number of ehs fully amplified= 0 or 1

M<=N

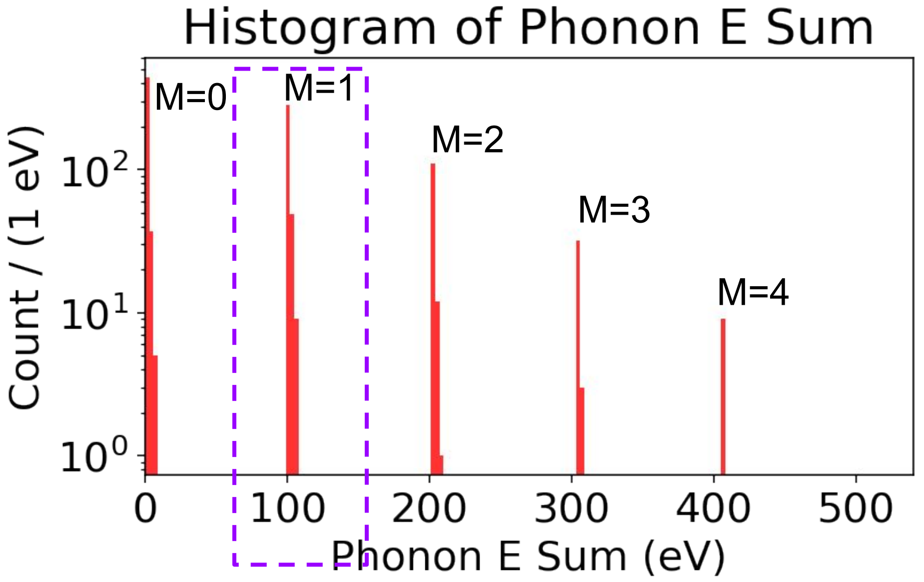
Sample 2: CrystalSim Results

- Lambda = 1

- Now we get the next peaks as we have the Poisson variations in the number of photons hitting the detector at the same time and consequently number of ehs fully amplified

- Variation in the big peaks from the number of fully amplified eh pairs, M, appear at the right place

- Next Step: Let's zoom into the peaks one by one. We start with the peak around 100 eV



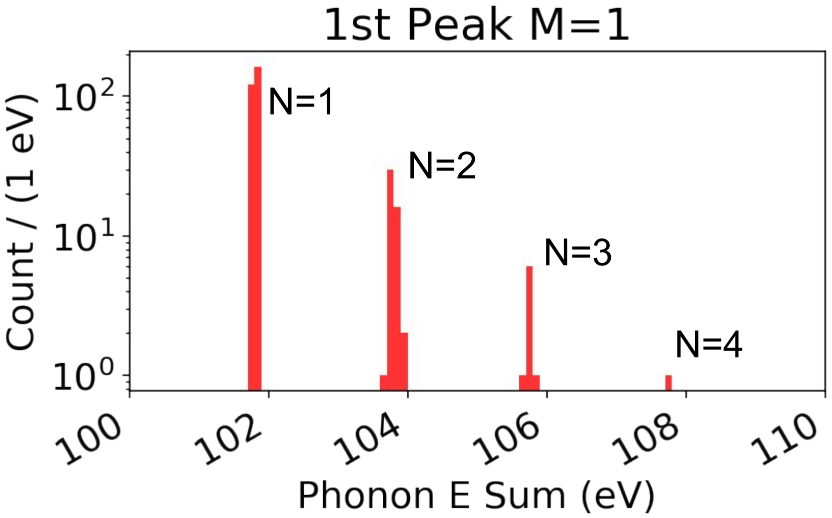
E= N*1.95 + M*100

N: Number of Photons = 0 to 4

M: Number of ehs fully amplified = 0 to 4; M<=N

Sample 2: CrystalSim Results (1st Peak Zoomed-In)

- Zooming into the events around 101.95 eV (the fully amplified energy) we see smaller peaks at 101.95, 103.80 etc. The additional energy is from a photon that deposited energy but the electron/hold pair wasn't amplified.
- Each of these small peaks also has a width, but this is the intrinsic resolution of the detector
- Next Step: Zoom into other electron-hole peaks

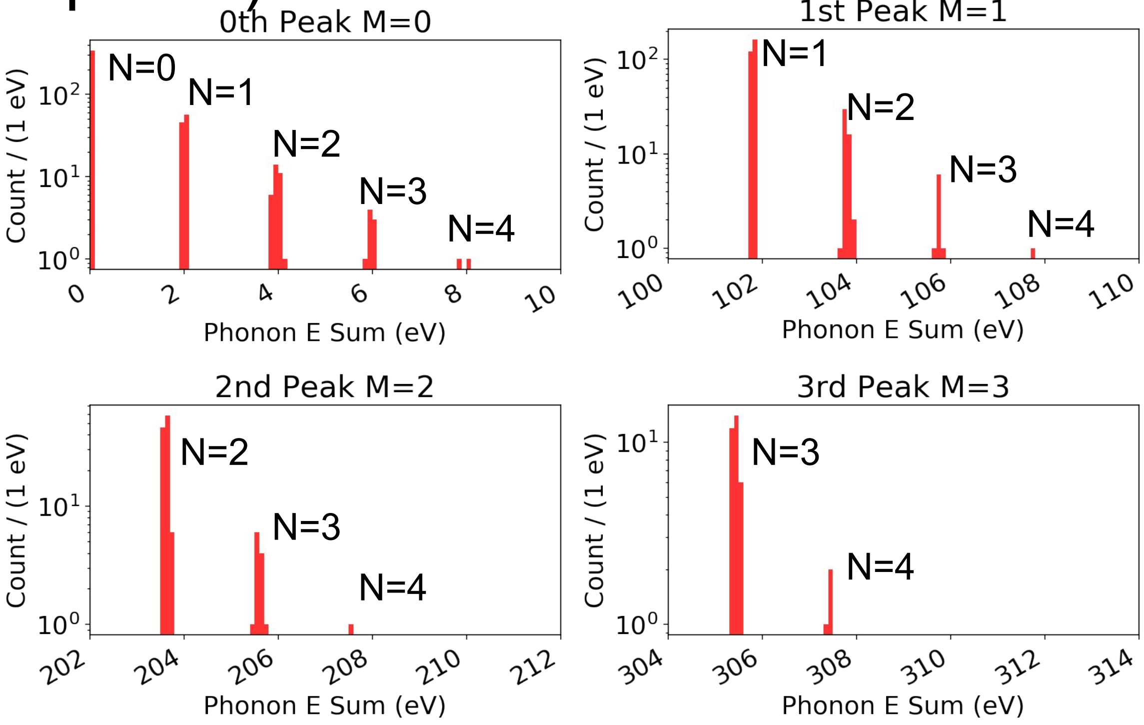


E= N*1.95 + M*100

N: Number of Photons = 0 to 4

M: Number of ehs fully amplified = 1 ; M<=N

Sample 2: CrystalSim Results (Zoomed on the other peaks)



E= N*1.95 + M*100

N: Number of Photons = 0 to 4

M: Number of ehs fully amplified = 0 to 4 ; M<=N

- We see small peaks that are caused by the variation in the number of photons, N. This variation will shift the mean of the peaks and contributes to the RMS
- The variation within the peaks is due to the small detector resolution
- Both effects are expected to be smaller than the resolution due to readout noise
- Next Step: Move to a bigger sample and add Charge Trapping and Impact Ionization

Sample 3: Adding Charge Trapping and Impact Ionization to Understand the Events Between the Peaks

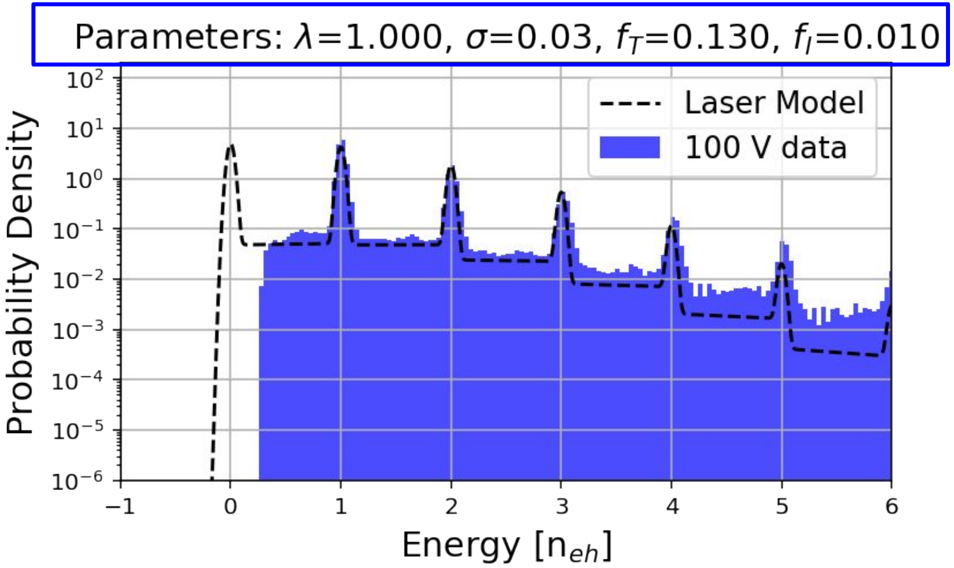
- The rate of Charge Trapping and Impact Ionization depends on the quality of the crystal
- To estimate the parameter values for the simulation we start with an analytical toy model for the data

Finding Important Simulation Parameters Using a Toy Model

This model has free parameters for:

- Lambda of the Poisson Photon Spectrum of the Laser :λ
- Detector Resolution: σ
- Charge Trapping Rate: f_T
- Impact Ionization Rate: f_I

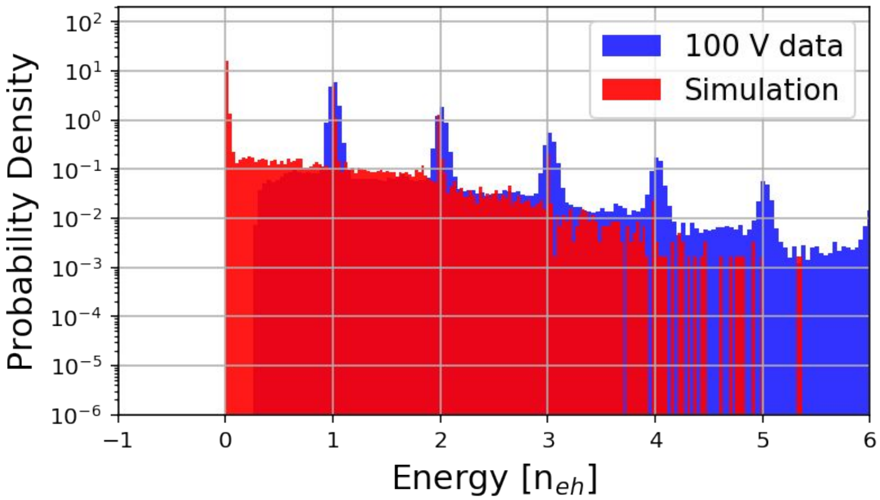
These parameters are calculated by fitting the data to this model. Results are shown in the plot. **Will use these values in our simulations.**



Note: For the first two peaks, this model does a good job of estimating the location of the peaks and the ratio of the peak amplitude to the background. However it is not doing a good job for the higher energy peaks

First Results of Comparison of Data to Full Simulation

- We added Charge Trapping (f_T= 0.13) and Impact Ionization (f_I =0.01) to the simulation. These effects produce the event between the peaks as expected
- Overall shape of the data and simulations are similar. Peaks and backgrounds appear as expected
- The peaks are sharper in the simulation because noise is not yet added



- The events between the peaks will need some tuning as well, but that could also be a noise effect
- No attempt has been made to simulate the trigger for the lowest energies
- Will get the higher peaks when we move to higher statistics simulations

Future Plans

To get a better match between simulation and data, will need to add the following:

- TESSim which simulates the sensors (Ready to be used)
- DAQSim which simulates the electronics readout and noise (Ready except for the NoiseSim compatibility with HVeV detectors)
- Reconstruction which is responsible for processing the raw data (Ready to be used)

When we add noise we will be able to see if we are missing effects, and will be able to determine the detector resolution for dark matter particles

Will be able to tune the amount of CT and II to see if there are other effects

Planning to finish these steps for the final defense so we can validate the full simulation of the HVeV experiment and confirm that the simulation is ready to be used in a dark matter search

Next student in our group will do the Dark Matter search with the simulation when we have the much bigger detectors for the SNOLAB payload

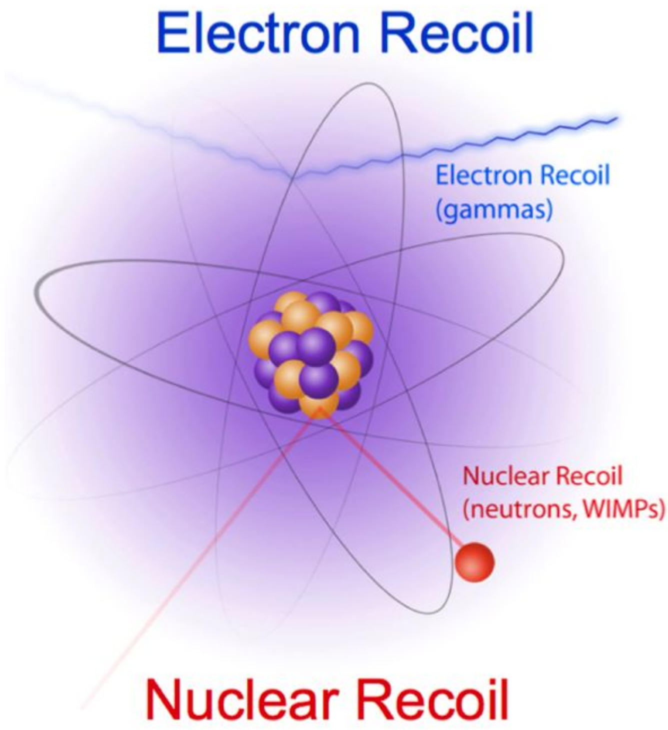
Conclusions

- SuperCDMS effectively uses combined Semiconductor and Superconductor technologies to be one of the most sensitive Dark Matter search experiments
- The sensitivity of the next generation experiment is limited by the lack of understanding of the physics of the detectors. Simulation can play an important role in helping with this problem
- This thesis work is on the full simulation of HVeV detectors, their response in laser experiment, and a comparison to real data to help better inform searches for dark matter
- We have finished the simulation of the laser source and detector crystal. Our results reproduce the main features of the real data
- We are planning to finish this thesis by adding the simulation of the sensors, electronics, noise and run through the data processing algorithm. With a fully validated simulation in hand we will be well suited for a major discovery

Back-up Slides

The need for Small High-Resolution Athermal Phonon (HVeV) Detectors

- We can search for dark matter interaction through Nuclear and Electron Recoil
- If dark matter mass is small compared to the nucleus mass, it will not produce detectable energy through nucleus scattering so we need to focus on electron scatterings for detecting low-mass dark matter
- Electron Recoils produce eV-range energies so we need high resolution eV-scale detectors like HVeV detectors
- Why small? We will have much less energy leakage in small detectors
- These detectors are also used as prototype detectors in preparation for the real experiment



Physics of Single Crystal Semiconductors and Lattice Response to Photon Interactions Under Voltage Bias

Because of the lattice structure, we can approximate the motion of each particle by treating it as a particle in a mean-field:

$$i\hbar\frac{\partial}{\partial t}\psi_0(\mathbf{r},t) = -\frac{\hbar^2}{2m_0}\nabla^2\psi_0(\mathbf{r},t) + U(\mathbf{r},t)\psi_0(\mathbf{r},t)$$

We can divide the potential into the following three potentials:

$$U(\mathbf{r},t) = U_E(\mathbf{r},t) + U_L(\mathbf{r}) + U_S(\mathbf{r},t)$$

External Macroscopic Potential: Voltage bias

Lattice Potential: Gives rise to the band structure

Fluctuation from impurities and defects: Impact Ionization and Charge Trapping

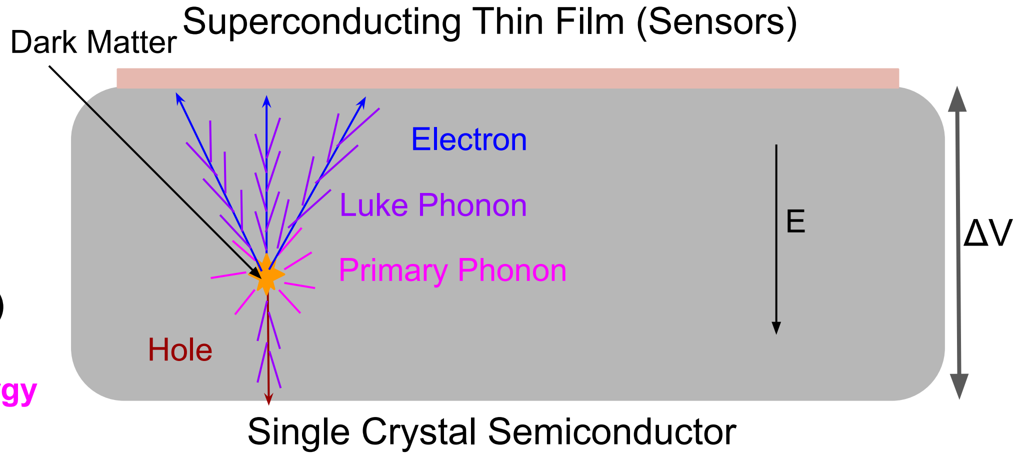
Overview of the Detector Concept

SuperCDMS Detectors are made of Single Crystal Semiconductor and Superconducting Sensors

Dark Matter particles will interact with the lattice and their energy will divide into generating Primary Phonons (lattice vibration) and liberating eh pairs:

Primary Phonon Energy

$$E = E_{ph} + \epsilon_{gap} n_{eh}$$



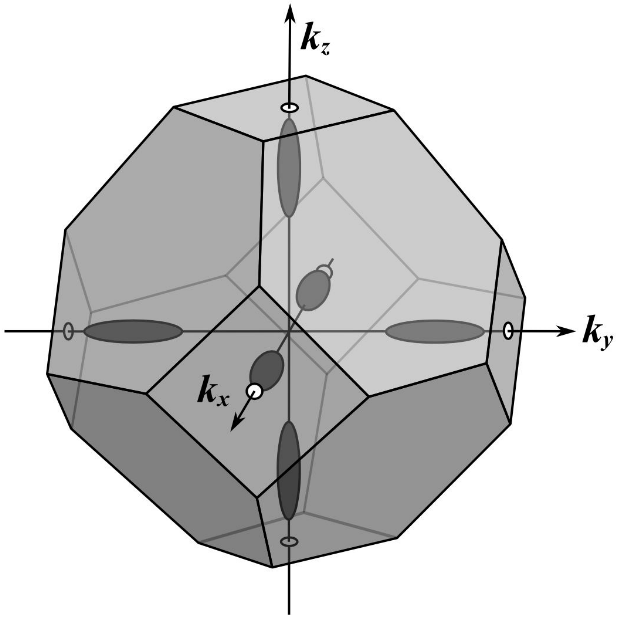
Electron and holes will travel under the voltage bias and produce more phonons called Luke Phonons. We measure the total phonon energy using the sensors and can do a measurement on the recoil energy using:

$$E_{ph} = E_r + n_{eh} V$$

Total Collected Phonon Energy **Recoil Energy**

Silicon Band Structure and Valleys

- Due to the band structure of Si, the electron will travel along the minimum energy potentials that are called valleys. (Shown in the picture)
- Si has an indirect bandgap, which means the minimum potential energy for electron and holes are not aligned in the momentum space so luckily, electron and hole will not annihilate each other



Equal-energy surfaces in the conduction bands of Si

Simulation Information

Version Numbers	
supersim	no-V08-00-03
g4cmp	g4cmp-V07-10-04
geant4	geant4-10-06-patch-02 [MT]

Macro Information	
Number of Events	10K direct deposit laser shots
Voltage	100 V Uniform Voltage
Energy	1.95 eV
Position of Source	Surface Contaminant Limit rho < 3 mm L Limit z > 0 mm L SkinFunction exp SkinDepth 5.3 um
Simulation Parameters	Sample 1 : Number of Laser Photons in Each Shot = 1 Sample 2: Lamba = 1

Simulation Information

Version Numbers	
supersim	no-V08-00-03
g4cmp	g4cmp-V07-10-04
geant4	geant4-10-06-patch-02 [MT]

Macro Information	
Number of Events	25K direct deposit laser shots
Voltage	100 V Uniform Voltage
Energy	1.95 eV
Position of Source	Surface Contaminant Limit rho < 3 mm L Limit z > 0 mm L SkinFunction exp SkinDepth 5.3 um
Simulation Parameters (Chosen based to the results of the signal model)	Poisson with Lambda = 1 Charge Trapping Rate = 0.13 Impact Ionization Rate = 0.01

SourceSim Results