Simulation of CDMSlite Detector's Response to Ge-71 Decay and Comparison to Data

Preliminary Defense, 08/26/2022

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Outline

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  - Search Methods And The SuperCDMS Soudan Experiment
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  - What We Actually See
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  - Overview Of The CDMSlite Detector
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Introduction

- Evidence For Dark Matter And The WIMP Hypothesis
- Search Methods And The SuperCDMS Soudan Experiment
- Event Energy Distribution: WIMPs and the Calibration Source
- What We Actually See
- Overview Of Our Approach

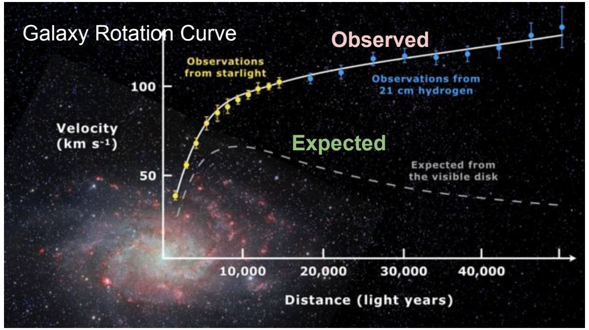
Evidence of Dark Matter’s Existence

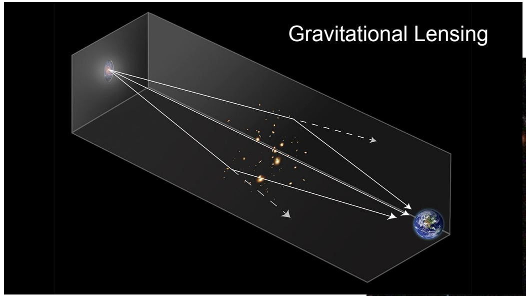
The Observed ≠ The Expected (based on visible matter only)

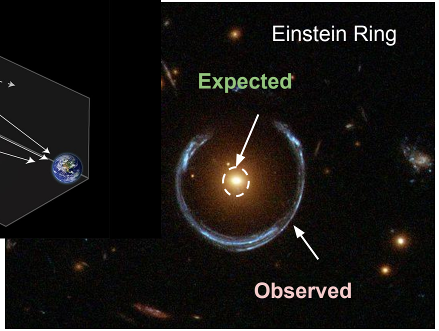
- **Galaxy Rotation Curve**
  - Expected: The rotation velocity decreases at distances farther from the center of a galaxy
  - Observed: Keeps increasing
- **Einstein Ring (Gravitational Lensing*)**
  - Expected: A small ring due to the visible matter (white dashed circle)
  - Observed: Much larger

A large amount of invisible matter

Dark Matter







* The path of light from distant galaxies, as it passes near a closer galaxy, is observed to be bent according to the mass distribution

Dark Matter’s Properties and WIMP Hypothesis

Attempts to find out what dark matter is

- Gravitational Microlensing*,
- Cosmic Microwave Background,
- the Bullet Cluster,
- Simulation of Universe Structure, etc.

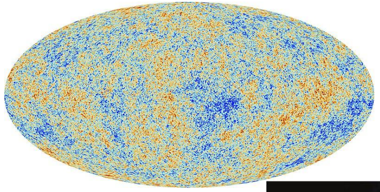
Dark Matter’s Properties

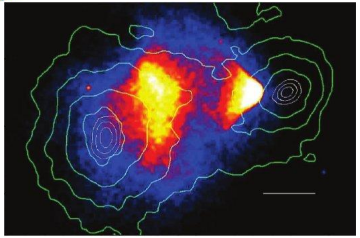
- **Massive**
- **Not a Standard Model Particle**
- **Stable** (long lifetime)
- **Cold** (low velocity, non-relativistic)

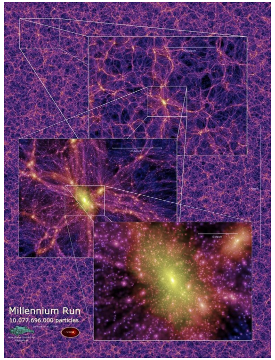
Simple hypothesis

WIMP

(**W**eakly **I**nteracting **M**assive **P**articles)





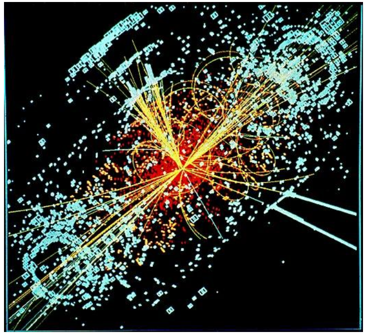


* was to check if the small condensed stars are the dark matter. See the picture of gravitational lensing in the previous page

Search Methods for WIMPs and Direct Detection

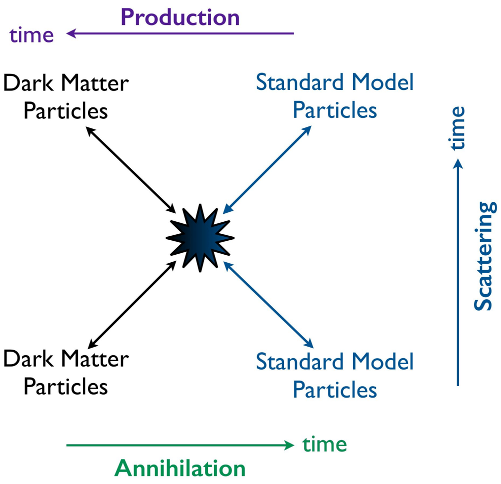
Possible Ways to Observe WIMPs

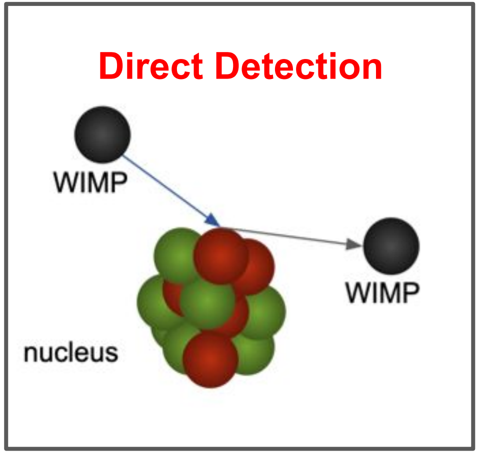
- Production in a Collision
- Indirect Detection (from annihilation)
- **Direct Detection**



Production
LHC

Annihilation
AMS-02

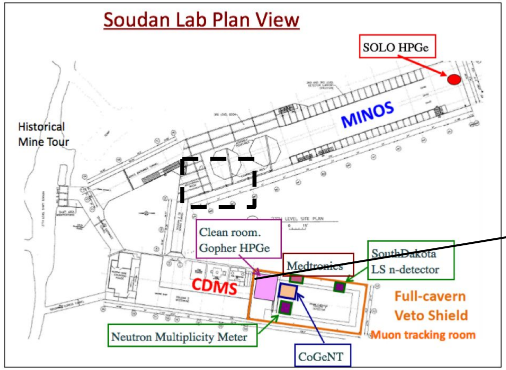


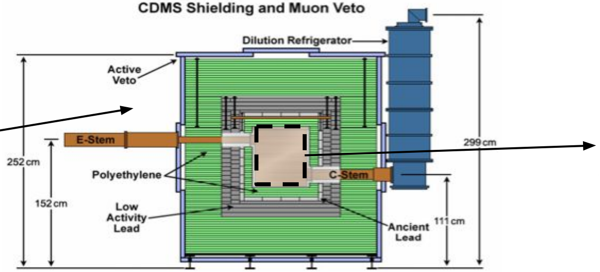


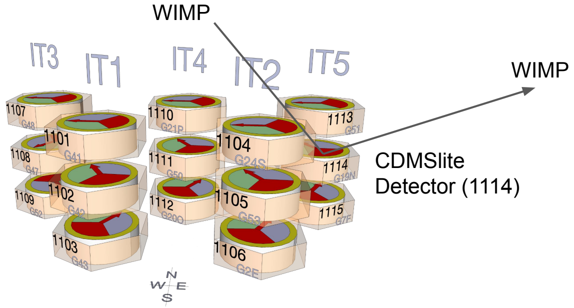
WIMPs might transfer a small amount of energy via nuclear recoil

Overview of SuperCDMS Soudan Experiment & CDMSlite

- Direct Dark Matter search experiment
- Located deep underground in the Soudan Mine in Minnesota
- 15 Germanium Detectors (See the pic below)
- Operated during 2011 to 2015
- Two Operation Modes:
  - iZIP: discriminates between electron and nuclear recoil
  - **CDMSlite**: Single detector (1114) with high voltage across it. No recoil type discrimination, but more sensitive to lower energy interactions
    (more details will be discussed soon)





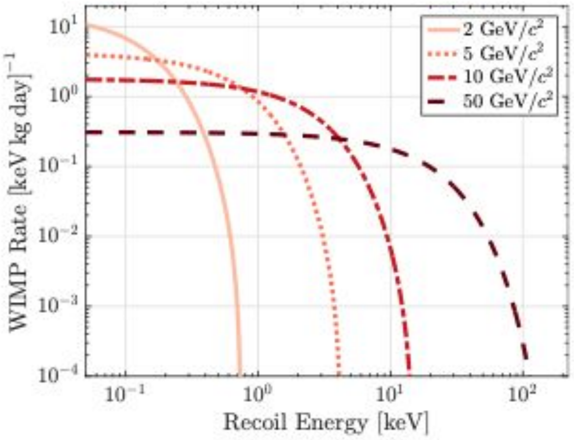


Event Energy Distributions: WIMPs & the Calibration Source

Expectations from WIMPs?

- < ~10 keV
  (deposit energy by low mass WIMP, <10 GeV/c^2)

WIMP Rate vs Recoil Energy



Calibration Source and Expectations from it

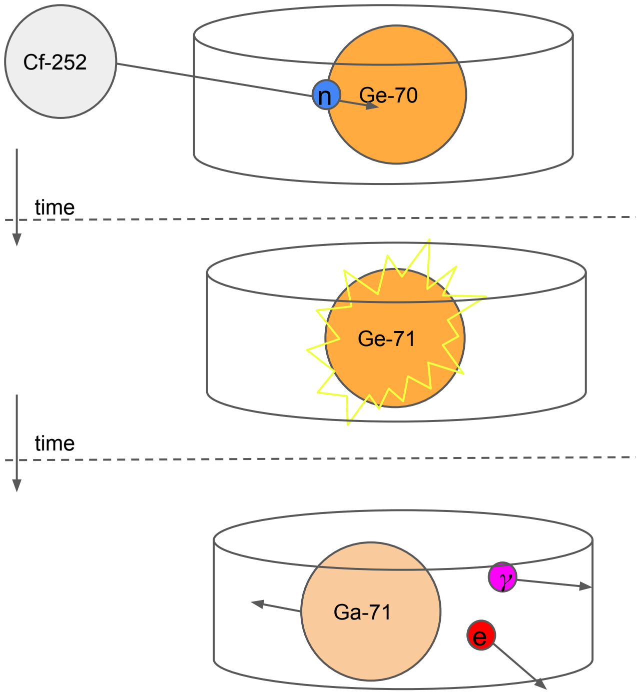
- Ge-71 decay*, mainly 3 peaks
  - ~10 keV
  - ~1 keV
  - ~0.1 keV

* Ge-71 electron capture decay with 100% branching ratio. See this backup page for more details.

Ge-71 Production, Calibration Run and Data Taking

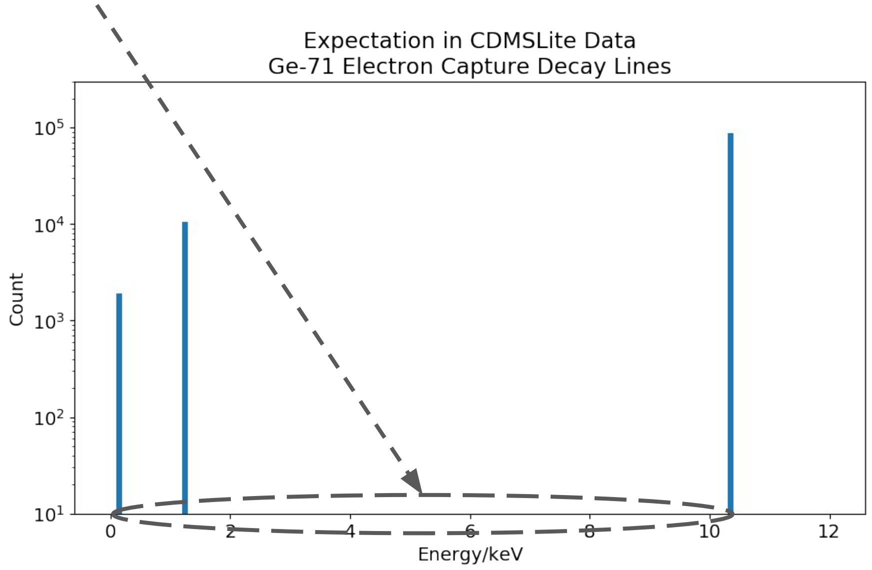
- Ge-71 can be produced by neutron activation
- Calibration Runs
  Put the Cf-252 calibration source near the detector
  - Cf-252 emits neutrons
  - Ge-70 + neutron → Ge-71
  - Ge-71s emit photons and electrons
    (3 specific energies, half life of 11.43 days)
- After calibration runs, data-taking was performed

CDMSlite Calibration and Data-Taking



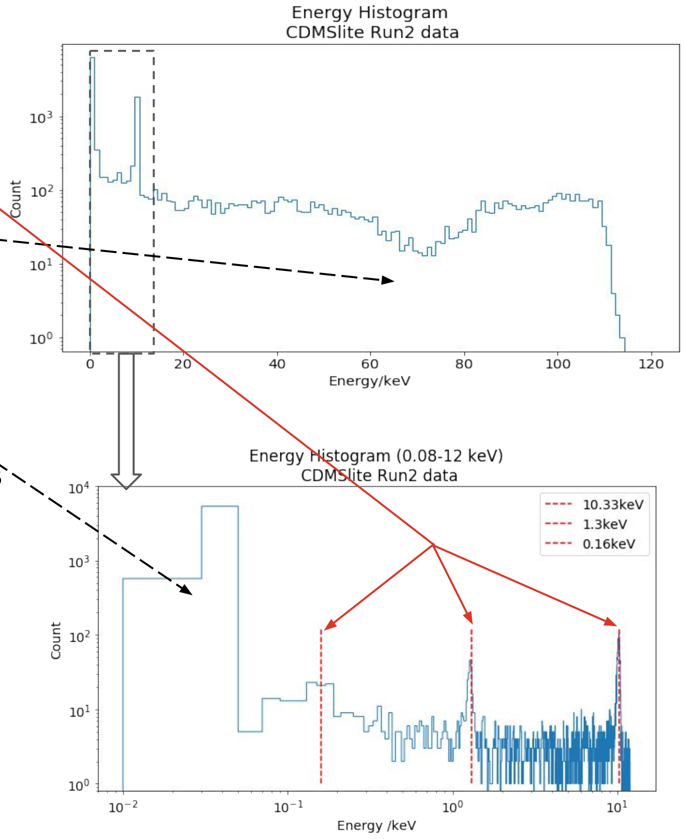
What We Expect to See in CDMSlite Data

- Decay lines from Ge-71 decay: 10.33 keV, 1.3 keV, 0.16 keV
- Events from other sources (not shown in the figure).
  - A lot of noise around zero energy
  - This is where we search for WIMPs



What We Actually See in CDMSlite Data

- Results
  - We see the three peaks corresponding to Ge-71 Decay
  - However, we also see
    - A lot of large energy (>10 keV) events
    - A lot of low energy (<0.1 keV) events
    - A lot of events between peaks
- Data We Focus On and Why
  - **Ge-71 decay events and the events between the peaks** (~0.1 keV, ~10 keV)
  - Not very interested in
    - the large energy events as low-mass WIMPs deposit energies are expected to be <~10 keV
    - the lowest energy events as their measurement is dominated by noise



Observations, Motivation and Goals

Observations

- Data dominated by Ge-71 decay events as expected
- Other events: Bad measurement of Ge-71 decay?

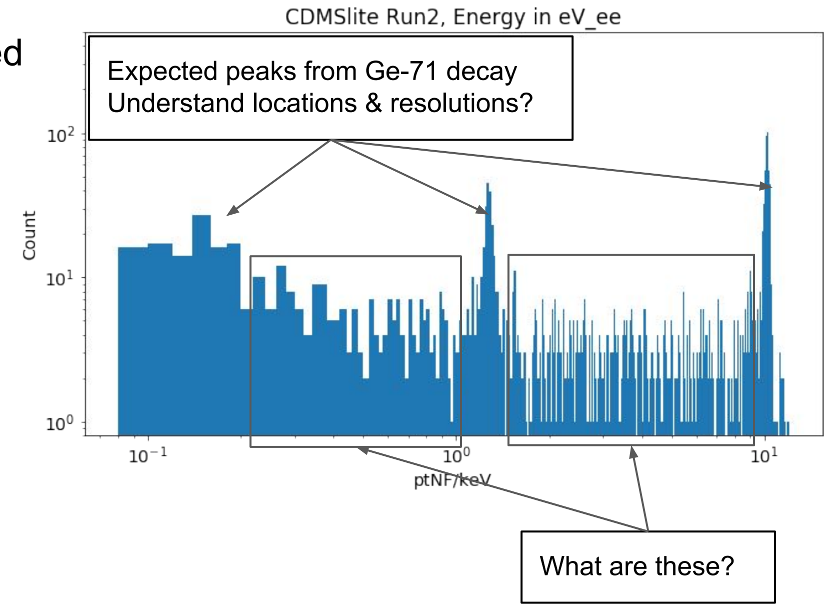
  Some other background? WIMPs*?

Motivation

- Data: powerful but limited by understanding of **CDMSlite Detector's response**

Goal

- To have a better understanding of the detector by **simulation** and comparison to real data

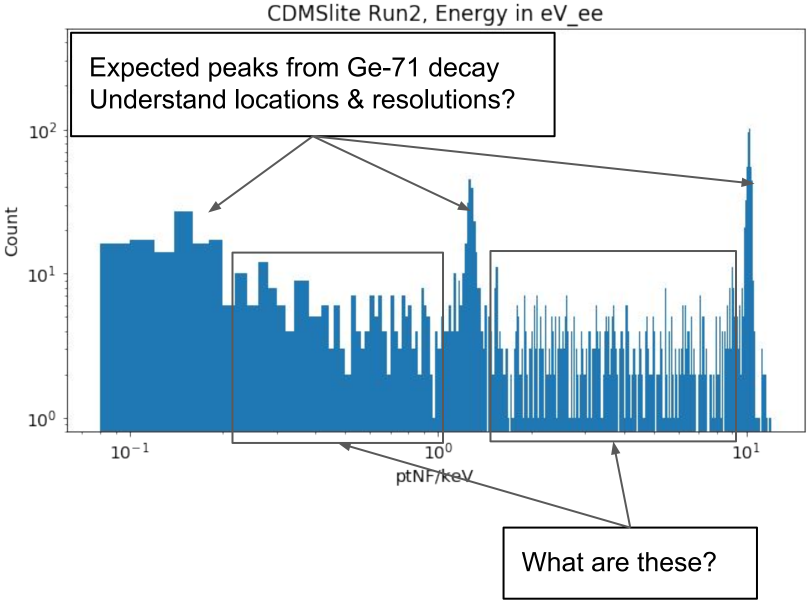


* If we could better understand or reject background, it would be more sensitive to WIMPs

Overview of the Approach

Overview of Approach

- Simulate detector's response to **Ge-71 decay**
  - Does it reproduce the decay lines? Right Energies? Resolution?
  - Will we see the events below the peaks?
- More details
  - Run a series of simulations related to Ge-71 decay
  - Build up the understanding with simulation and compare to data
    (Will not include WIMP study*)



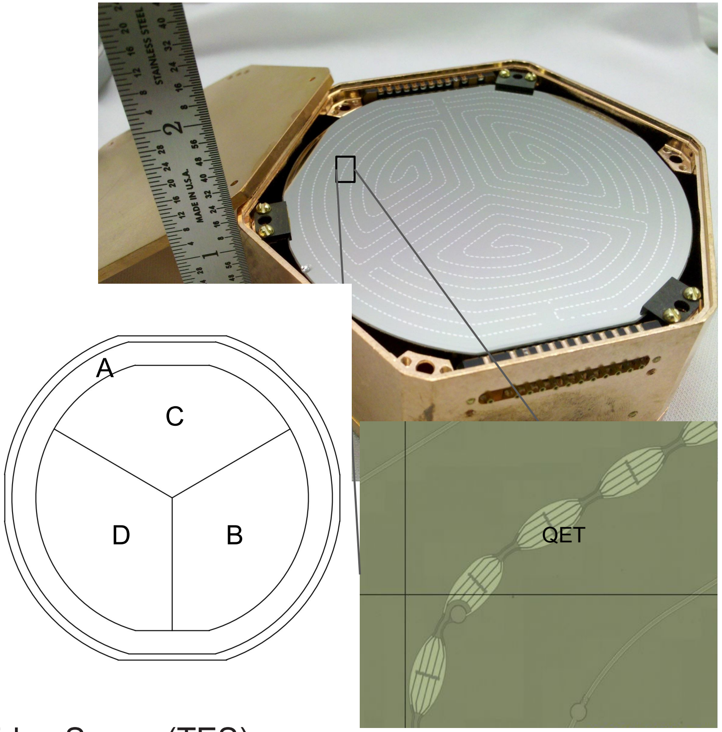
* It would have been more fun and helpful to search for WIMPs, but this has been much bigger/harder than we thought. We are simulating nuclear recoil but not finishing with a search for WIMPs. It will be left for the next generation of students using the next generation of detectors at SNOLAB

CDMSlite Detector

- Overview of the CDMSlite Detector
- Relevant Details about the Detector Technologies
  - Semiconductor - Detector Material (Germanium)
  - Superconductor - Transition Edge Sensor (TES)
- Interactions Inside the Detector

Overview of the CDMSlite Detector

- Material: Germanium
- Roughly cylindrical
- ~76 mm diameter, ~25 mm height, ~600 g mass
- Operated at 70V



Overview of Energy Measurement

(relevant technology details will be shown on the next two pages)

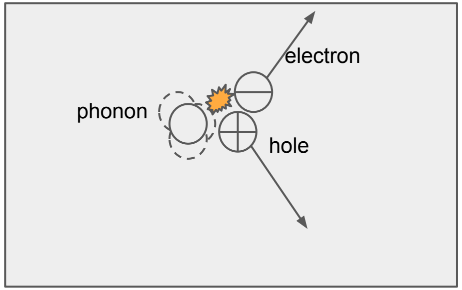
- Four Channels
  - A (the outer channel)
  - B/C/D (the inner channels)
- Each channel instrumented with
  - 400+ QET* units (for energy collection/transportation/readout)
  - Each QET = Several Aluminum Fins + One Transition Edge Sensor(TES)

* **Q**uasiparticle Trap Assisted **E**lectrothermal Feedback **T**ransition Edge Sensor. See some technical details on this backup page.

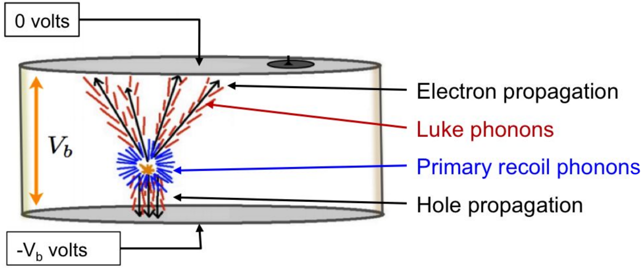
Semiconductor - Detector Material (Germanium)

- An interaction in a semiconductor crystal
  - can ionize electrons

    → produce electron and hole (e-h) pairs
  - can cause lattice vibrations (phonons)

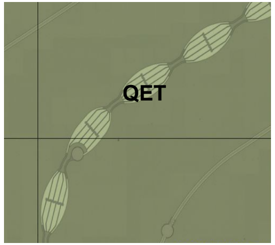


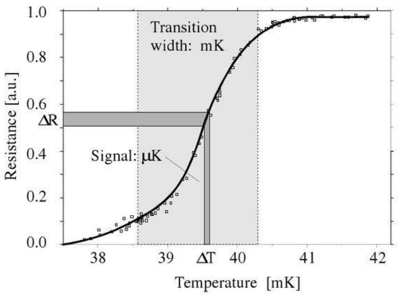
- Neganov-Trofimov-Luke (NTL) Effect:
  When a voltage is set across the crystal, electrons and holes will accelerate and bounce into lattice to produce more phonons (Luke phonons)
  - same energy deposit → more phonons when applying higher voltage
  - → Increase detector's sensitivity to lower energy deposits

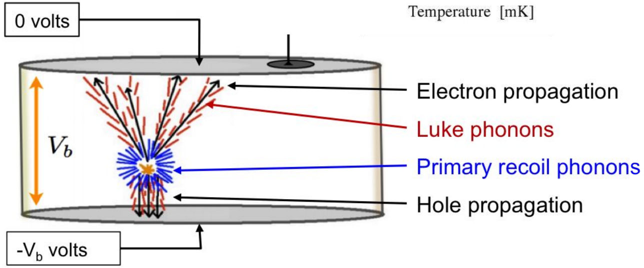


Superconductor - QET

- Phonons arrive at the QET
  - → break cooper pairs in the Aluminum Fins and free a lot of charges
  - → changes temperature of TES
  - → quick change in resistance (at transition edge)
- Put TES in a circuit, phonon energy
  - → change in current
  - → can be read out by electronics

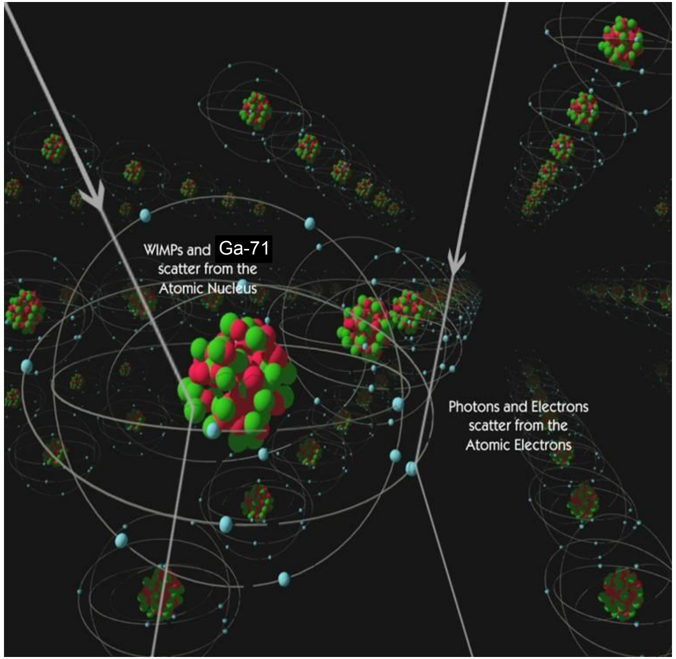






Interactions Inside the Detector

- The crystal contains electrons and nuclei
- They respond differently to
  - WIMPs and particles from Ge-71 Decay
- **Ge-71 decay**
  - Emits photons and electrons
  - The daughter nuclei (Ga-71) recoils



Two Types of Interactions

Photons Electrons	Electron Recoil (ER)
Ga-71 nucleus WIMPs	Nuclear Recoil (NR)

SuperCDMS Simulation and How We Use it

- Overview of Simulation Objectives
- Simulation Infrastructure
- Overview of How We Use SuperCDMS Simulation

Overview of Simulation Objectives

01	How does the CDMSlite Detector respond to the known energies from Ge-71 Decay?	• Do we get back the interaction energy from a known interaction energy deposit? What is the resolution?
02	Does the CDMSlite Detector provide a good measurement of the energy?	• Are there regions of the detector which provide a good measurement and which don't? (Yes) • What causes bad measurements?
03	Can we use full set of energy measurements to help determine if an event is well measured?	• Can we use full set of energy measurements from the four channels to tell us where an interaction occurs, and therefore likely to be well-measured? • Can we model the relationship between energy and position?

Simulation Infrastructure

We designed the infrastructure so that we simulate events that can be analyzed in the same way as real data

Source Simulation (*SourceSim*)

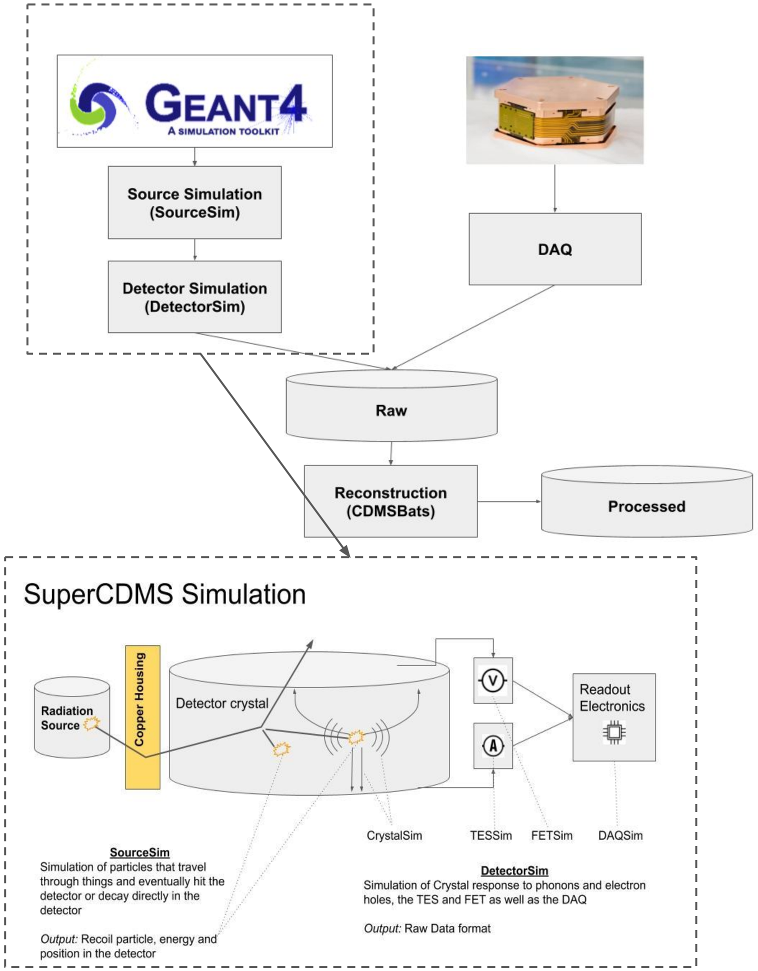
- Source*: ER, NR, Photons, **Ge-71 Decay**
  (More details on the next page)
- Particles traveling through things
- Physics process of interactions and decay
- Output: recoil particles, energies and positions

Detector Simulation (*DetectorSim*)

- **CDMSlite Detector's response**
  (including the detector crystal and QET)
- **Data AcQuisition Simulation** (*DAQSim*)
- Output: Raw Data

Data Reconstruction

- Quantities: energy, etc.



Overview of How We Use SuperCDMS Simulation

Run 3 different types of SourceSim configurations through the same DetectorSim

- SourceSim: **Pure Energy Deposit**, **Photons**, **Ge-71 Decay**
- DetectorSim: CDMSlite Detector

Start with the simplest systems and build up to a full understanding of Ge-71 events

Pure Energy Deposit

- Electron Recoil(ER) and Nuclear Recoil(NR)
- Only a single hit in the detector, the simplest case

Photons

- Majority of the energy released in a Ge-71 decay event
- Interact multiple times inside the detector, each with ER interaction
- Sometime leave the detector

Ge-71 Decay

- Both ER and NR are involved
- Multiple particles are involved, photons, electrons, and a Ga-71 nucleus that recoils

First Steps with Simulated Data and Comparisons to Data

- First Steps With Simulated Data
- Comparing CDMSlite Data To Simulated Data
  - Total Phonon Energy Collected by the Detector
  - Collection Efficiency of the Detector
  - Phonon Energy Sharing inside the Detector

First Steps With Simulated Data

01 Total Phonon Energy Collected by the Detector

- Look at how much energy is collected by the detector
- How much energy do we expect to be collected

02 Collection Efficiency of the Detector

- Compare to the expected energy from simulation to define good and bad measurement
- Determine which region provide a good measurement of energy and which don't
- Determine what causes bad measurement

03 Phonon Energy Sharing inside the Detector

- Look at how much phonon energy is collected in each channel and its dependence on where interactions occur
- Build a model to describe the dependence. It will help us determine whether an event is well measured.

How Much Energy is Collected By The Detector?

Let's see how much phonon energy is collected.

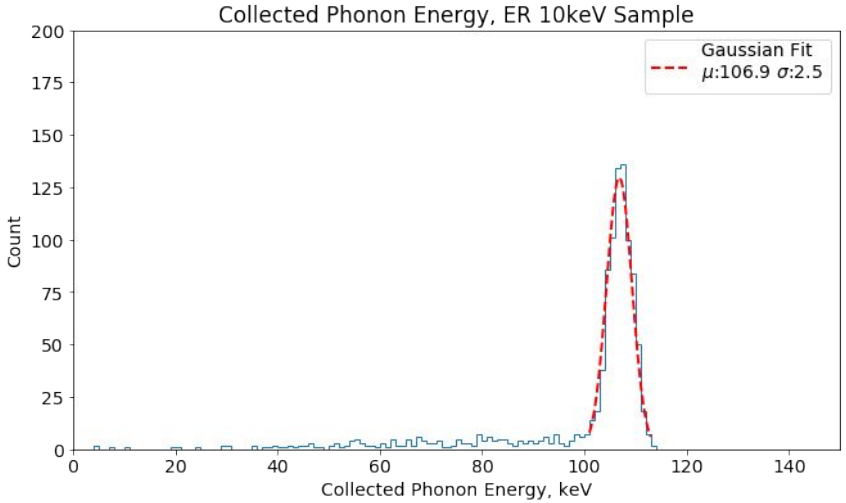
Collected Phonon Energy*: Total phonon energy per event, sum of phonon energies collected by all four channels (A-D)

Starting with ER 10 keV sample

- A single ER deposit of 10 keV in each event
- Uniformly distributed in the detector

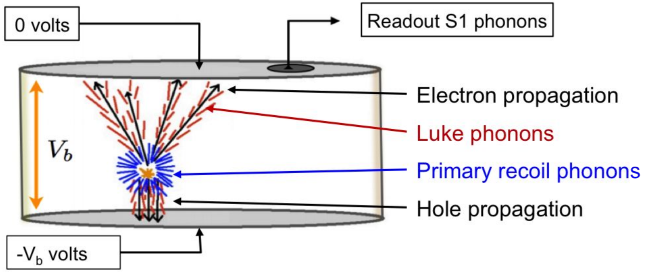
Features

- One peak
  - Peak Location: **106.9** keV
  - Resolution: **±2.5** keV (2.3% of 106.9 keV)
- A long tail on the left side
  - < **~100** keV



* DMC output, treename = 'G4SimDir/g4dmcEvent', branches = 'PhononE'.

How Much Energy Do We Expect To Be Collected?

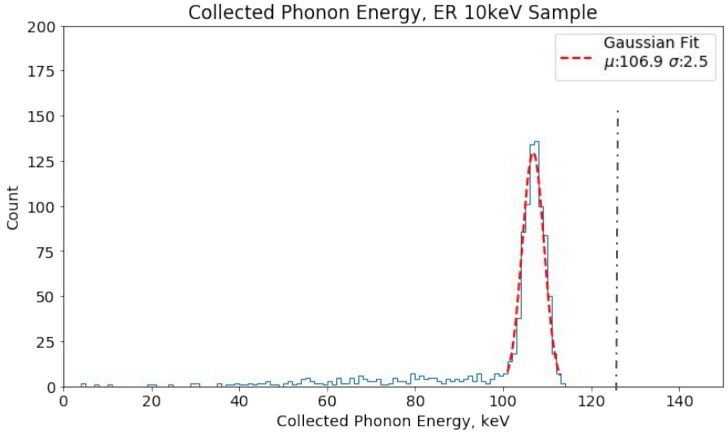


Expected phonon energy

- The total phonon energy per event that we expect the detector to collect

  = Recoil_E×(1+Y_Lindhard×V/ϵ)/2 *

  - 1: from the deposit energy itself
  - Y_Lindhard×V/ϵ: from the voltage/NTL Effect



For ER 10 keV Sample

- Expected**: **123.24 keV**

* Recoil_E is recoil/deposit energy. Y_Lindhard is Lindhard yield, 1 for ER and 0.2-0.3 for NR. V is the bias voltage. ϵ is the energy required to create an e/h pair. It's divided by 2 because only one side of the detector is read out.

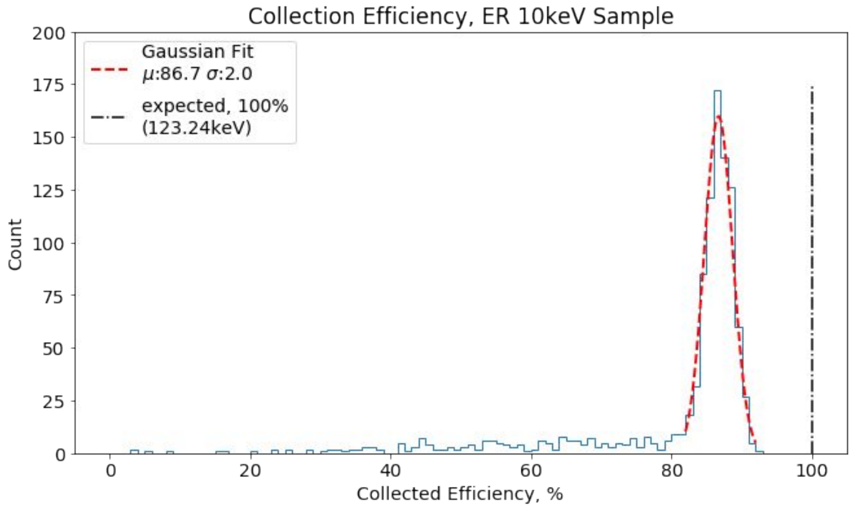
** 10 keV×(1+1×70/2.96)/2 = 123.24 keV

Collection Efficiency And Good/Bad Measurement

Collection Efficiency = (**collected** phonon energy) / (**expected** phonon energy)

Observations and Explanations

- One peak: **86.7**±**2.0%**
  - Don’t expect to collect all the phonons since our detector and TES aren't perfect.
  - **Good Measurement**: we get ~87% of the expected phonons
- A long tail on the left side: < **~80%***
  - **Bad Measurement** due to partial voltage applied in some region of the detector
    (More details will be discussed soon)

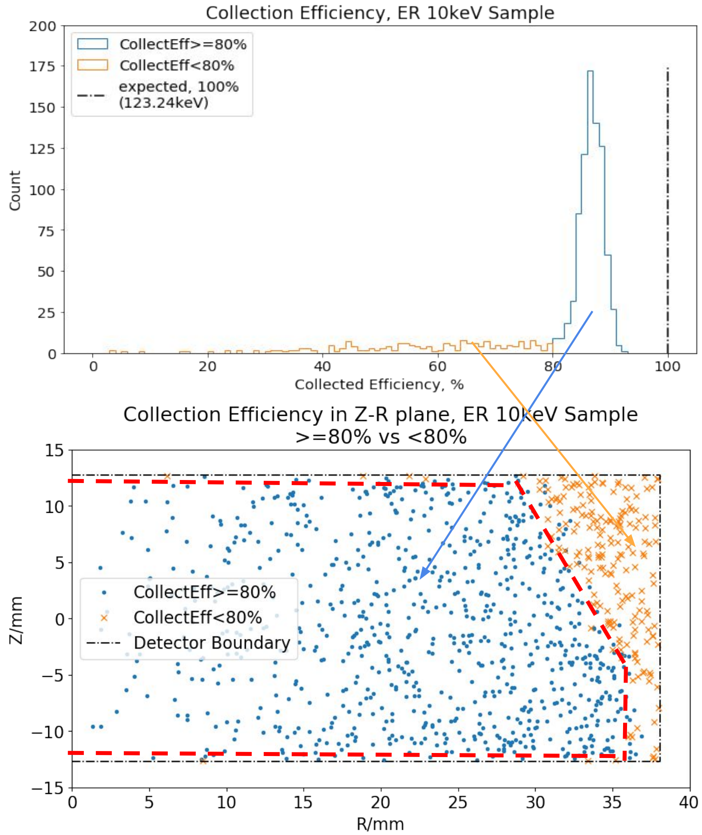


* (peak_location - 3σ) = 86.7% - 3*2.0% = 80.7%

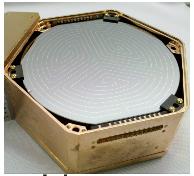
Where Events Occur And Their Collection Efficiency

We know the true position of an interaction in simulation. Let's look at the events with collection efficiency **>=80%** and **<80%**

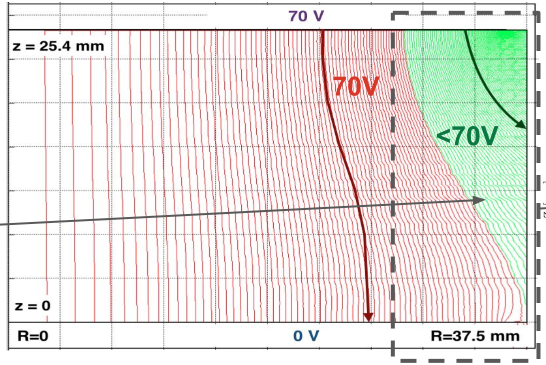
- **>=80%** (good measurement)
  - Most is in the region enclosed by "- - - -"
- **<80%** (bad measurement)
  - (major) A triangle-like region close to the side
  - (minor) Too close to the top/bottom surface



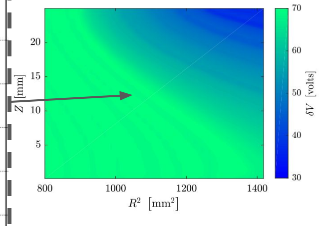
Why Bad Measurement?



- Grounded detector housing
- Not full voltage in region close to side
    - <70V in the region, all Z and R>~30mm

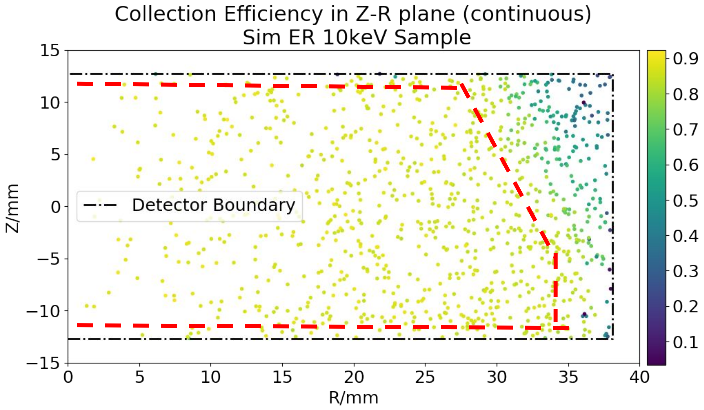


CDMSlite Electric Field Map



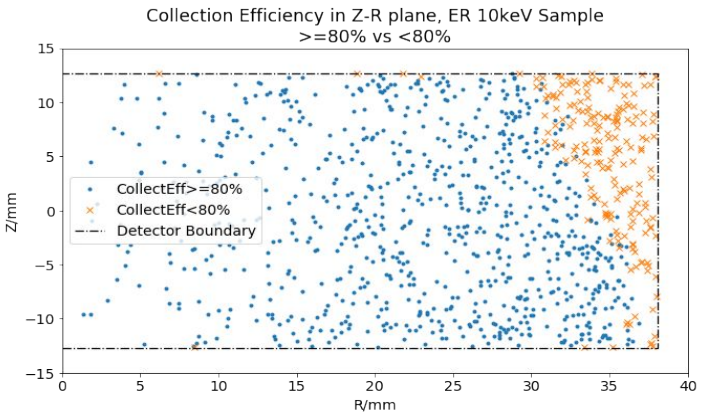
The electric field is included in our simulation

- The collection efficiency plot in Z-R plane shows the same pattern
- Consistent with the field
    - Closer to the top-side corner, lower the voltage and lower the collection efficiency

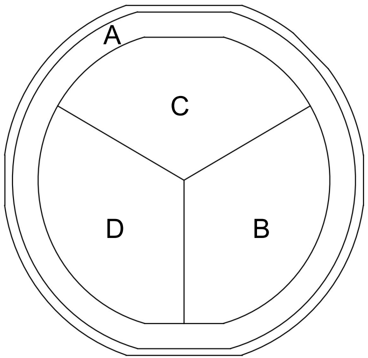


Simulation Data vs Real Data

- Learned from **SIMULATION** Region of Bad Measurement
  - Z near the edges
  - High R (>~30mm)
- We want to reject these events



- In **REAL** data, we don't know the true position of an interaction
- Use the energy collected by the four channels to get position information?
  1st Attempt: energy collected by Channel A
  - High R → More energy in A
  - Low R → Less energy in A



Energy Collection Fraction of Channel A vs Radius

How much phonon energy is collected by Channel A and it's dependence on the radius?

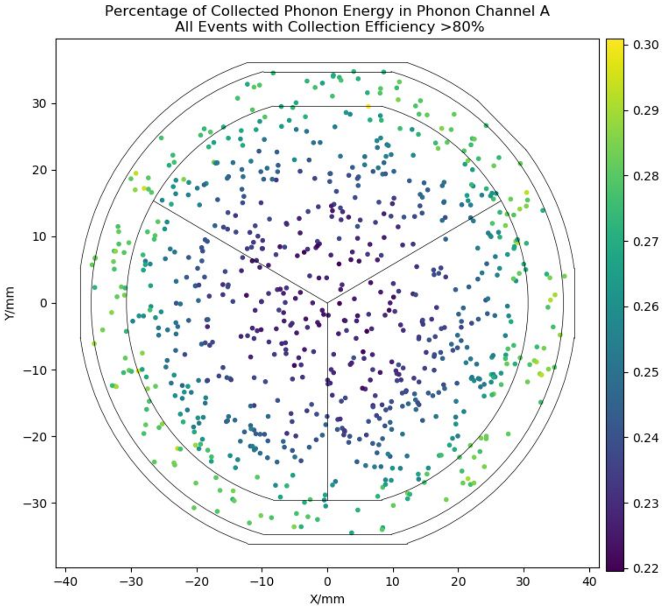
Events: all good measurement events (collection efficiency >=80%)

- Dot: position, where an interaction occurs
- Color: Fraction_A

  (collected phonon energy by A) / Total*

Observation

- Radius ↑, Fraction_A ↑ (more details on the next page)
- Same for all directions
  - Channel A has mostly circular symmetry



* The total phonon energy per event that is collected by the detector in the simulation. Sum of phonon energies collected by channel A,B,C,D of CDMSLite Detector.

Energy Collection Fraction of Channel A vs Radius (cont.)

Observations in the plot of "Fraction_A vs R"

- Bad measurement events

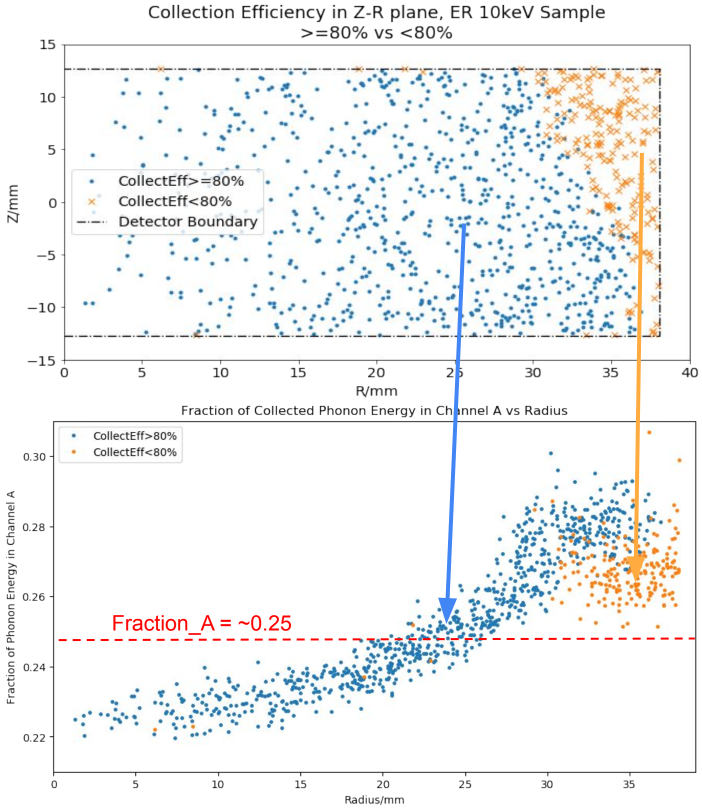
  Fraction_A > **~0.25**

A Simple Solution removes Bad Measurement events

- Fraction_A Cut

  Remove all events with Fraction_A > **~0.25**

  - Unfortunately, a large portion of Good Measurement events are also removed



Fration_A Cut And Data Before/After It

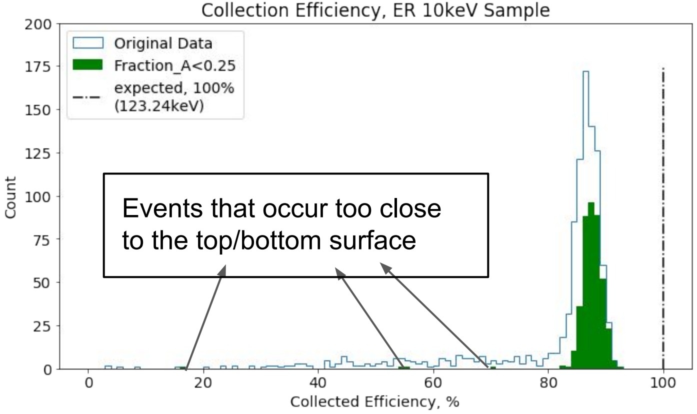
Collection Efficiency plot before/after Fraction_A Cut

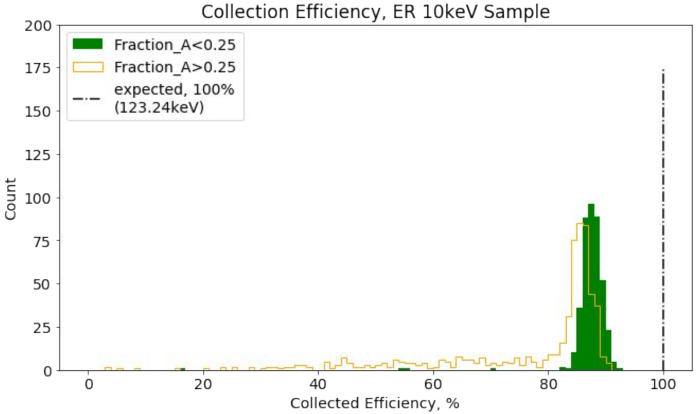
Observations

- The long tail is almost gone
  - except a couple of events
    (that occur close to the top/bottom surface)
- A pretty large portion of good events are also removed. Sensitivity is reduced
- The peak shifts to the right a bit

So

- This simple cut looks promising in simulation
- Next we look at real data to see if the variables look similar





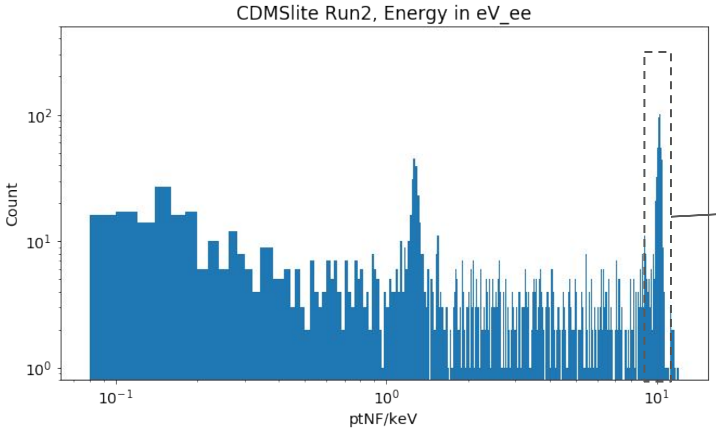
First Comparisons to Data

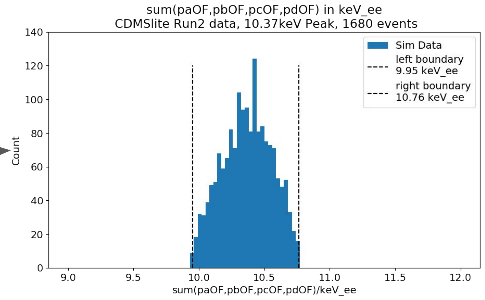
With simulated data (**10 keV** electron recoil), we showed:

- Events with bad measurement are correlated with their positions
- Position information can be used to remove bad measurement events

What does the real data look like?

- We pick the events of **10.3 keV** peak in CDMSlite Data to compare
- Expect them to be photons and electrons and fully measured





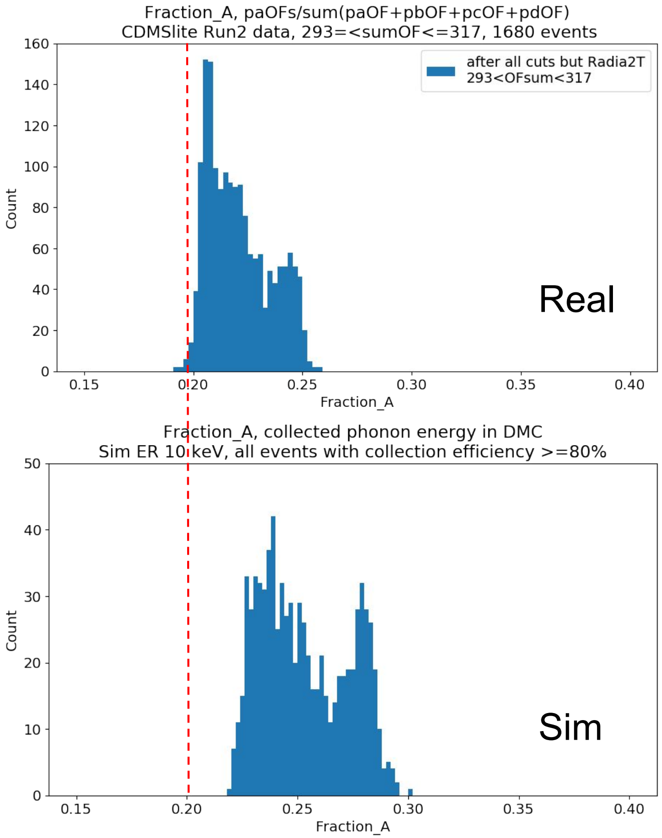
Simulation vs Reality: Fraction_A

Observation

- Real and Sim have a similar shape
  - More on the two ends and less in the middle
  - Real has more events in low region
- Real < Sim, ~0.03
  - Fraction_A(OF) in Reality : 0.19 - 0.26
  - Fraction_A(OF) in Simulation: 0.22 - 0.29

Conclusion

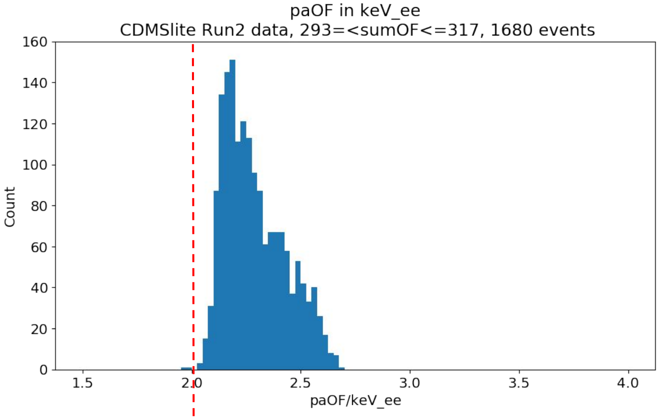
- Fraction_A in Real and Sim have some same qualitative features, but also some quantitative differences

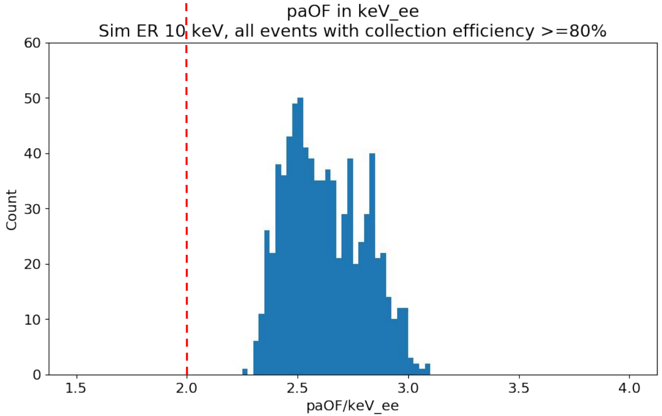


Simulation vs Reality: Equivalent Energy (Channel A)

Since we see the disagreement in Fraction_A, let’s look at the phonon energy itself in the four individual channels to see if they are in agreement.

(Note: both the data and the simulation are scaled to be in the same calibrated unit)





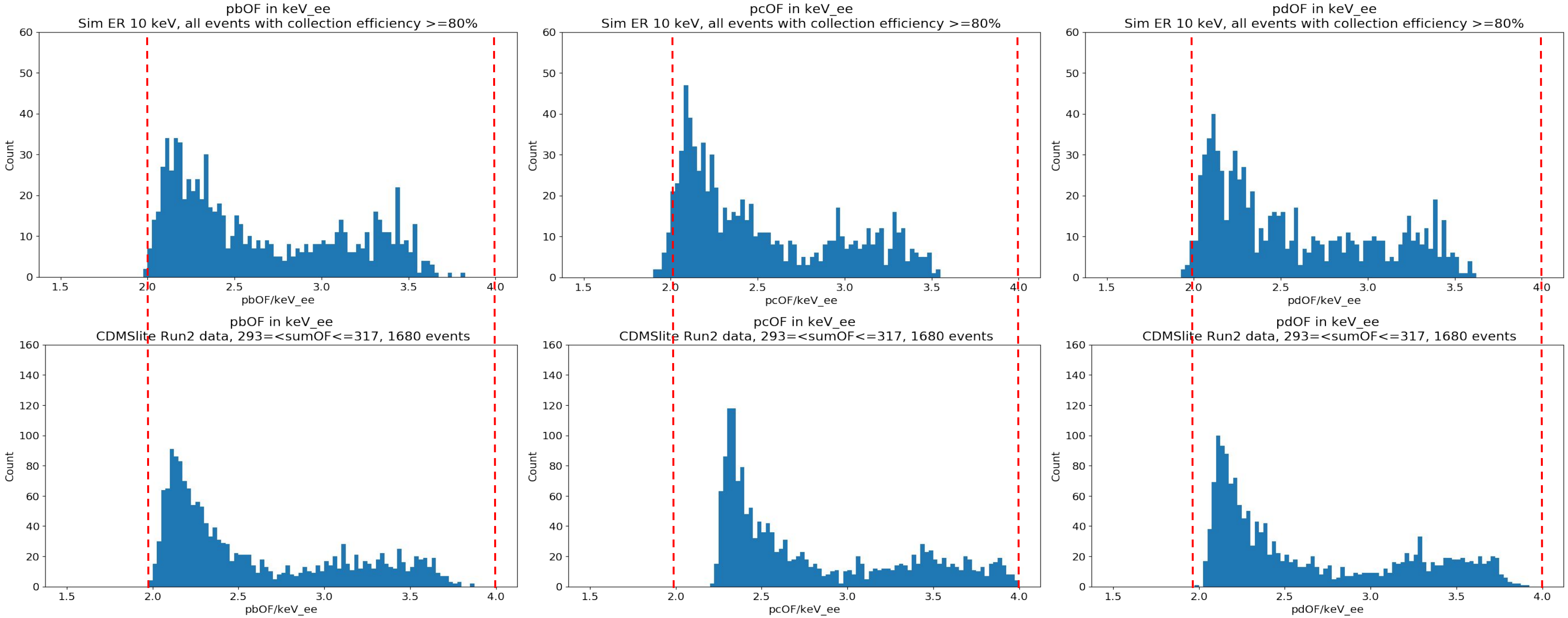
Observation in Channel A

- Real and Sim have the similar shape
- Quantitative differences: Real < Sim, ~0.3 keV_ee
  - PhononEnergy_A in Real   : 2.0 - 2.7 keV_ee
  - PhononEnergy_A in Simulation: 2.3 - 3.1 keV_ee

Simulation vs Reality: Equivalent Energy (Channel B/C/D)

Next let's look at the 3 inner Channels (B, C, D)

- In simulation (top) : Similar as expected as they have the same physics shape (axially symmetric)
- In real data (bottom) : Same shape, but shifted



Simulation vs Reality: Summary and Further Questions

Summary of agreement/disagreement between Real and Sim data

- The fraction and phonon energy distribution for each channel have similar shapes
- In all four cases, there are small but substantive shifts in the energy scale

Questions about phonon energy sharing in Real and Sim data

- Why do they seem to be similar, but not agree quantitatively?

  Calibration issue in the data? Some other effect?

Answering these questions will be the some of the next steps in my thesis

Next Steps and Future Plans After This Thesis

Next Steps for This Thesis

- To include more sophistication in the simulation studies and build up understanding from the analysis as we move from simple ER deposits to the full Ge-71 simulation
- To see if we can use that understanding to develop a better method to remove the bad-measurement events in the real data
- To understand the disagreements between simulation and real data* as well as why the real data looks different from what we would expect, including better calibration for the real data

Future Plans not included in this thesis (Work to be done by other students after I graduate)

- To incorporate the more advanced analysis techniques used in the final analysis that are not well modelled in the simulation currently (e.g. pulse shapes out of the QET/TES)
- To simulate WIMPs and do an optimized search

* There is a known issue. See this backup page.

Conclusion

- The CDMSlite Detector in SuperCDMS Soudan is well designed to search for dark matter. The CDMSlite data is powerful but limited by our understanding of the detector's response
- We have presented a plan to run simulations, analyzed and compared to the real data to make future searches better
- First simulations and preliminary comparisons to data show that:
  - Energy mismeasurements occur when an interaction occurs in a region of the detector that doesn't have the full voltage. We have started simulation-based studies on how to remove those events in real data
  - There is qualitative agreement about the shape of the energy distributions in all four channels between real data and simulated data, but quantitative differences that are likely to be calibration problems
- Next steps include adding more sophistication to the simulations and calibrating the real data
- The path for the rest of the analysis is clear, and will set the stage for discoveries after graduation

BackUp Pages

Reference

Slide 4: Evidence of Dark Matter's Existence

Galaxy Rotation Curve: remade by Mario De Leo (wikipedia) based on Fig 6 in *The extended rotation curve and the dark matter halo of M33*.
Gravitational Lensing: https://webbtelescope.org/contents/media/images/2018/23/4149-Image?news=true
Einstein Rings: *https://apod.nasa.gov/apod/ap111221.html*

Slide 5: Dark Matter's Properties and WIMP Hypothesis

Cosmic Microwave Background, from Planck satellite, https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB. baryonic matter contains <20% of total matter
Bullet Clusters, Fig. 1, A Direct Empirical Proof of the Existence of Dark Matter.
Simulation of Universe Structure, N-Body Simulation, The Millennium Simulation Project, Max-Planck-Institut für Astrophysik, https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/.

Slide 6: Search Methods for WIMPs and Direct Detection

AMS-02: https://www.flickr.com/photos/nasa2explore/32302130661/
LHC: http://cdsweb.cern.ch/record/628469

Slide 7: Overview of SuperCDMS Soudan Experiment & CDMSlite

Soudan Underground Mine (outside): https://www.mprnews.org/story/2010/10/29/mntoday-soudan-underground-mine
Soudan Underground Mine (Level No.27): https://www.ntier.org/resources/elyattractions/
Soudan Lab Plan View: Figure 1 (page 2), https://aip.scitation.org/doi/pdf/10.1063/1.4927978
CDMS Shielding and Muon Veto: Figure 4 (page 4), https://iopscience.iop.org/article/10.1088/1742-6596/606/1/012003/pdf
Detector Towers:(internal link) https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures-913880472

Slide 8: Expected Energies from WIMPs and the Calibration

WIMP Rate vs Recoil Energy. Figure 3.3 (a), Mark David Pepin's Dissertation, *Low-Mass Dark Matter Search Results and Radiogenic Backgrounds for the Cryogenic Dark Matter Search*.

Slide 15: Overview of the CDMSlite Detector

A CDMSlite (also iZIP) detector: (internal link) https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures-Pictures%20for%20Presentations
Electrodes and transition edge sensors: (internal link) https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures-Pictures%20for%20Presentations

Reference

Slide 16: Semiconductor - Detector Material (Germanium)

NTL Effect Diagram: (internal link) https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures--985664779

Slide 17: Superconductor - Transition Edge Sensor (TES)

Electrodes and transition edge sensors: (internal link) https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures-Pictures%20for%20Presentations
Transition Curve: Demers, Hendrix, *Two facets of the x-ray microanalysis at low voltage: the secondary fluorescence x-rays emission and the microcalorimeter energy-dispersive spectrometer*. p. 46 (Figure 2.17). McGill University Link.
NTL Effect Diagram: (internal link) https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures--985664779

Slide 18: Interactions Inside the Detector

scatter diagram: https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams#standardfigures--1153014500

Slide 21: Simulation Infrastructure

Diagrams: (internal link) https://confluence.slac.stanford.edu/display/CDMS/Simulations+Working+Group

Slide 29: Why Bad Measurement?

The photo of the CDMSlite detector: izip fabrication - G51 Mounted, https://confluence.slac.stanford.edu/display/CDMS/Standard+figures%2C+photos+and+diagrams
Right-Top Plot: CDMSlite field map. Zoom-in plots: The field geometry was modeled by finite-element simulation using COSMOL MULTIPHYSICS® software (COMSOL, Inc., Burlington, MA). VI.A.1, *Low-Mass Dark Matter Search with CDMSlite*.

Ge-71 Electron Capture Decay

Ge-70 + n -> Ge-71

Ge-71 + e -> Ga-71

Ga-71 emits photons and electrons and releases its atomic binding energy

- Lower orbit, higher possibility, more energy released
- Consider orbits highlighted with red rectangle

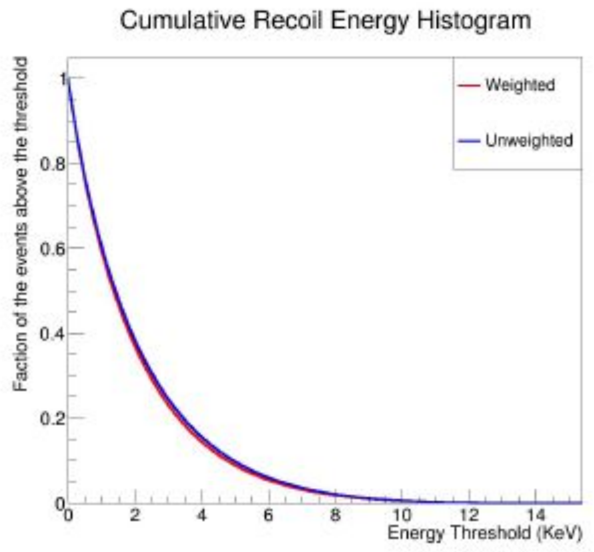
31–Ga	K	2.00	10331.0	13222.0	25.6450	8.63840– 1	8.31930– 1	4649.27	5582.21	99.5174
	L1	2.00	1290.70	2577.90	114.420	6.64890– 3	8.69970+ 0	12.7845	1185.73	92.1847
	L2	2.00	1150.40	2568.50	98.7020	9.11830– 3	7.46030– 1	13.4359	1074.63	62.3345
	L3	4.00	1122.00	2462.50	100.560	8.93490– 3	7.52560– 1	12.3619	1043.22	66.4171
	M1	2.00	157.750	582.900	341.060	3.69570– 5	4.45700+ 0	0.00517	99.2220	58.5229
	M2	2.00	111.010	532.720	349.590	1.28640– 4	3.92590+ 0	0.00408	71.1520	39.8540
	M3	4.00	107.280	512.190	355.030	1.18000– 4	3.71490+ 0	0.00341	61.7004	45.5762
	M4	4.00	27.3700	382.070	403.920	7.64460– 8	1.29660– 2	0.00000	11.7009	15.6691
	M5	6.00	26.8700	377.320	406.630					26.8700
	N1	2.00	11.6900	59.7300	1192.10					11.6900
	N2	0.33	5.00000	27.4800	1774.00					5.00000
	N3	0.67	4.88000	25.9100	1816.10					4.88000

2-3, Part 2 EADL Atomic Subshell Parameters, [Evaluated Atomic Data Library (EADL)]

Detection Efficiency and Ge-71 EC decay

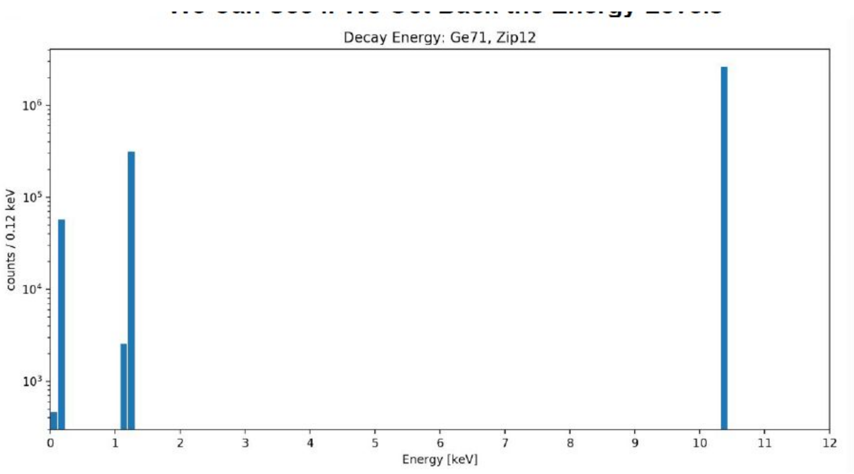
Taken from
https://confluence.slac.stanford.edu/download/attachments/316969774/WimpSim.pdf?version=1&modificationDate=1629132211000&api=v2

Expectation for 10 GeV Wimp



https://confluence.slac.stanford.edu/download/attachments/284335082/Germanium-71.pdf?version=3&modificationDate=1595223635000&api=v2

Expectations for Ge-71

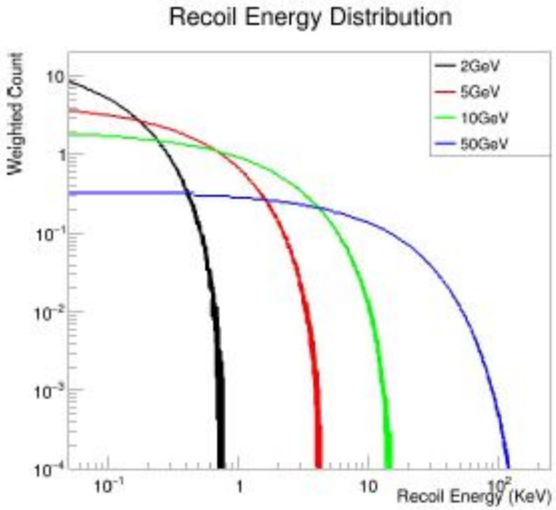


The total energy emitted when a higher-state electron fills an electron hole.
These values all match expectations with EADL binding energies.

What are the expectations for the experiment? Why we are looking in this energy region

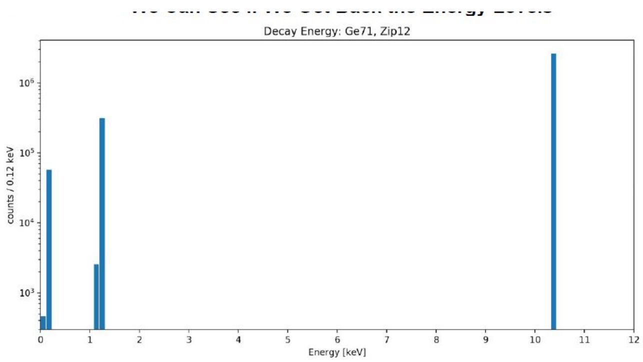
Dark matter particles from the Milky Way

- Low mass WIMP, <10 GeV/c^2
- Hopefully lots of events < 10 kEV



Germanium activation after we take calibration data

→ Mainly 3 peaks from (mostly) photons which help calibrate the detector



The total energy emitted when a higher-state electron fills an electron hole.
These values all match expectations with EADL binding energies.

Some technical info about QET

QET *Quasiparticle Trap Assisted Electrothermal Feedback Transition Edge Sensor* Operating mode in which a TES is fed by Al collector fins. The fins gather athermal phonons from a large area and convert them into quasiparticles. The quasiparticles drift across the fins and become trapped in the TES due to the “one-way” properties of the W-Al interface. The fins thus act like antennas, converting a TES “thermometer” into a fast-responding “microphone”. The “electrothermal feedback” portion of the name refers to the fact that the TES is biased with a constant voltage, which is really not a characteristic of the TES itself. If the TES changes in resistance the electrical power dissipation changes in the opposite way, acting to keep the TES resistance constant at longer time scales. This feedback mechanism mostly determines the fall time of CDMS phonon pulses.

Quoted from [SuperCDMS Glossary]()

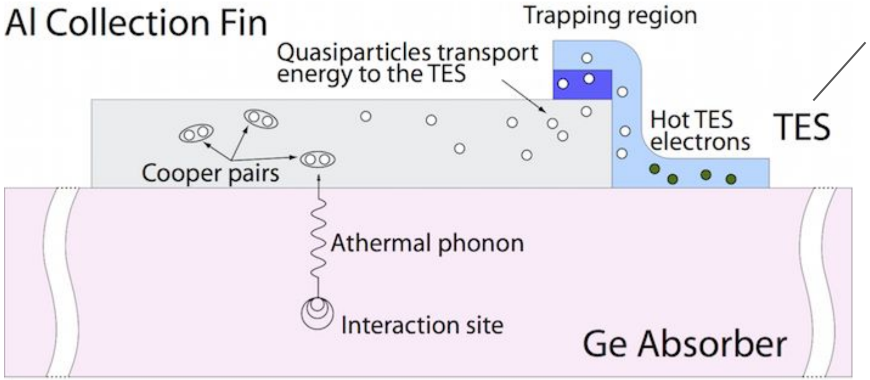


Diagram: https://figueroa.physics.northwestern.edu/research/athermal.html

The TES response changes the current in the channel (each channel is 455 QETs connected in parallel). The current is coupled to a SQUID to get out of the cryostat, and amplified in the front-end electronics. We use the change in current relative to a stable baseline to measure the phonon energy.

Notes about the disagreement between the Sim and Real

A known issue here is that the real detectors have different responses, (due to different Tc, resistance, etc.) on each channel, while your simulation uses an idealized "perfect detector" for everything.

Draft "Story"

- The published CDMSLite analysis used a combination of very powerful cuts, the energy of the events passing all cuts is shown on the right (Take figure from the paper)
- A number of issues left over from the previous analysis
  - When the paper was published we couldn't do a sophisticated simulation the detector response to see how it responded to known sources of events (photons, electrons, WIMPs etc.)
  - A number of cuts were developed using data and designed to get rid of backgrounds of only partially understood origin.
  - The basic assumption was that the data, after Cf calibration runs, would be dominated by Ge activation events and a set of ER events (photons, electrons etc) of unknown energy distribution
  - The assumption was that the detector did not respond well for interactions at large radius, so one of the goals was to develop cuts to get rid of events that had indications that the interaction occurred in the outer radius.
  - Another assumption was that any DM signal would be very low energy so we didn't care about large energy events
  - Another assumption was that we wouldn't be able to get rid of low energy ER events, so we would just set limits on DM by assuming that all the events in the data were background events.
  - Since there was no good simulation of Ge activation, or detector response to Ge activation events, the assumption was that we could/should calibrate the data so that the peaks observed in the data had the expected energies of Ge activation. That we could measure the resolution of the detector to DM events from the measurement of the events in the peak
- Ideally would have:
  - Had a full simulation of all background sources from first principles or measurements in the data
  - We could reproduce all the features of the data in simulation to provide us confidence in our tools
  - We could use the new tools to re-optimize the CDMSLite search for DM
- This thesis is shows a number of steps along the way, but will only complete some of the idealized goals
  - Thing done already:
    - Full simulation of the Ge activation chain
    - Full simulation of the simulation of the electrons and phonons in the crystal (only partially verified)
  - Things not done today:
    - No proper modeling of the TES readout (which means we can't fully simulate the full set of cuts used to see if they were used properly, or if they really did what was claimed)
  - Need to pick a milestone to stop this thesis and hand if off to the next student
    - New data with better detectors coming online soon
    - This student needs to graduate
- The plan is to show what we have learned so it can be handed off
  - Only show results based on pre-TES results and compare to data as best we can