Characterizing Photon and Neutron Responses in CDMS Detectors Using Real and Simulated Cf-252 Data

Josh Winchell

Preliminary Exam

12/14/2020

Outline

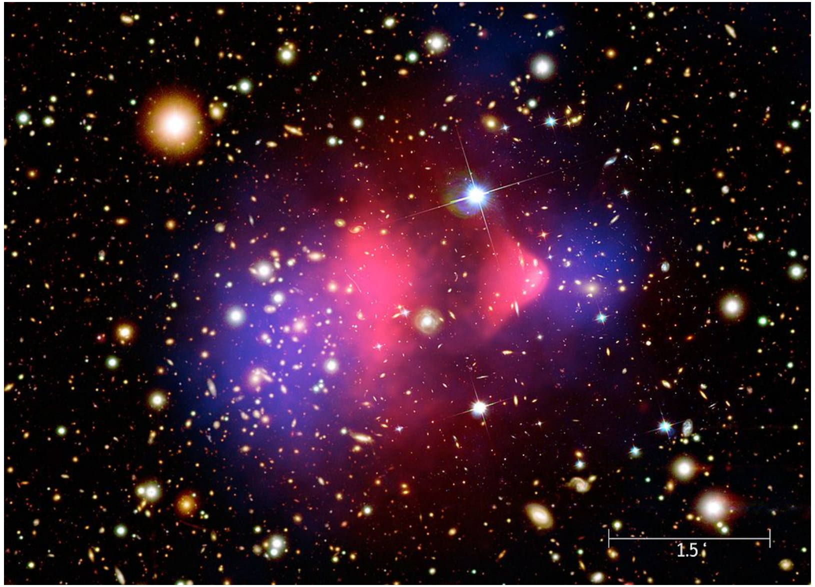
I. Introductory Material
   A. Dark Matter Search with CDMS
   B. CDMS Simulation Chain
   C. Details of this Thesis
II. Experiment Details
III. Real Data and Simulated Data
   A. Cf-252
   B. SourceSim results
   C. Detector response results
IV. Next-Steps and Conclusion

I. **Introductory Material**
   A. **Dark Matter Search with CDMS**
   B. **CDMS Simulation Chain**
   C. **Details of this Thesis**
II. Experiment Details
III. Real Data and Simulated Data
   A. Cf-252
   B. SourceSim results
   C. Detector response results
IV. Next-Steps and Conclusion

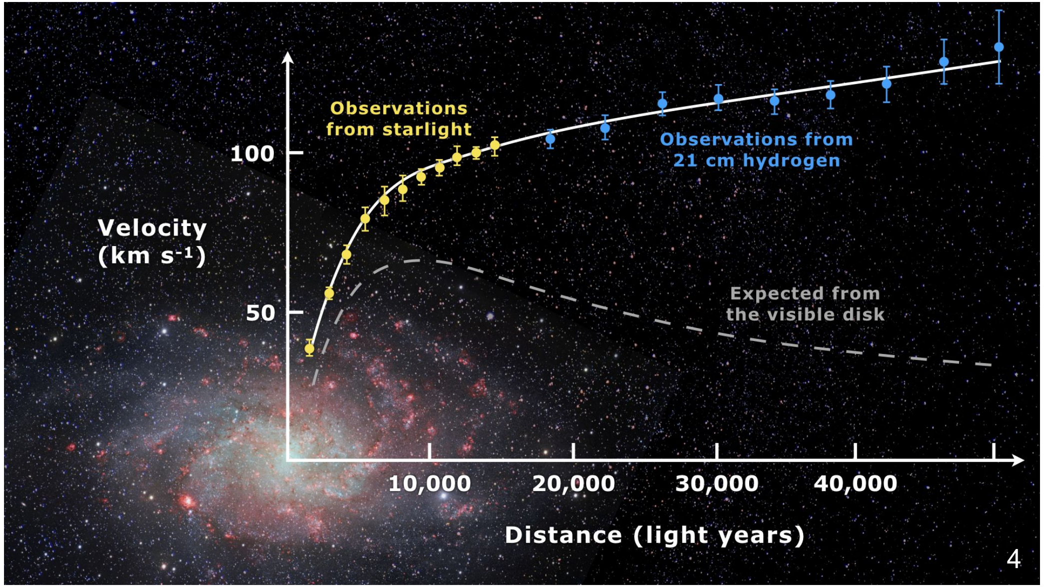
Dark Matter

Multiple observations of the universe suggest the existence of a particle that interacts gravitationally, but not electromagnetically, which we call Dark Matter; for example:

The Bullet Cluster consists of two clusters that collided previously; baryonic interactions (in red, identified by x-rays) are seen to be lagging behind the main center of mass (blue, from gravitational lensing).



Galaxy Rotation Curves are not consistent with the gravity expected from only luminous matter; more distant objects move faster than expected, as if there was something else contributing gravitationally.

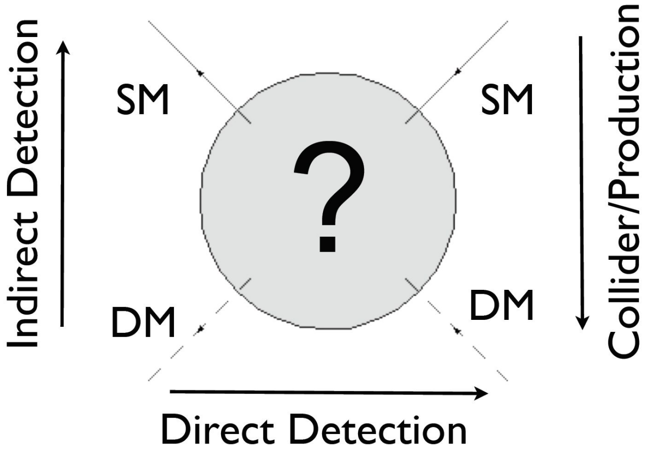


WIMP Dark Matter

A likely candidate for dark matter (‘DM’) is **W**eakly-**I**nteracting **M**assive **P**articles (‘WIMPs’). Such a new particle interacting at the weak scale could solve problems both for particle physics (e.g. the gauge hierarchy problem) and for astrophysics/cosmology (e.g. the observations on the previous slide).

WIMPs would be expected to annihilate to and interact with current **S**tandard **M**odel (‘SM’) particles, meaning we could identify them by:

- Detecting SM particles from ongoing annihilations (indirect detection)
- Producing them in colliders
- Looking for DM/SM scattering (direct detection)

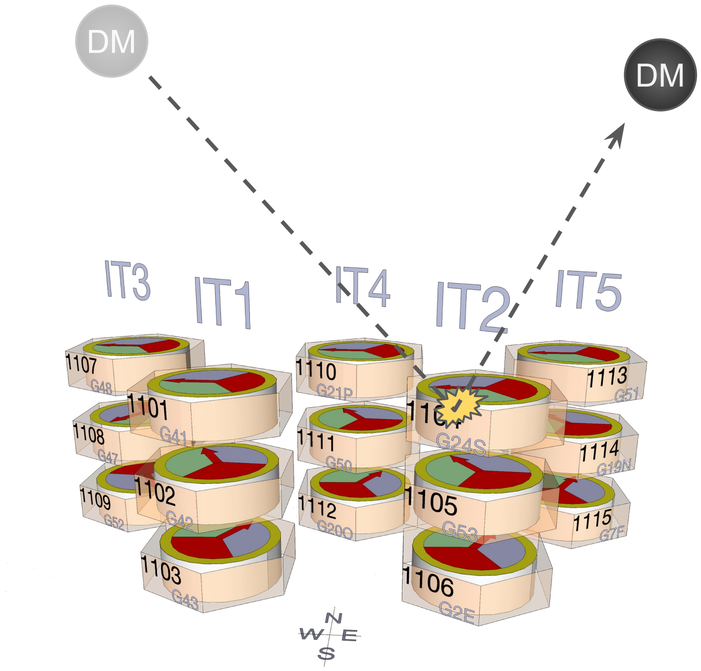


SUPER CDMS

Cryogenic Dark Matter Search

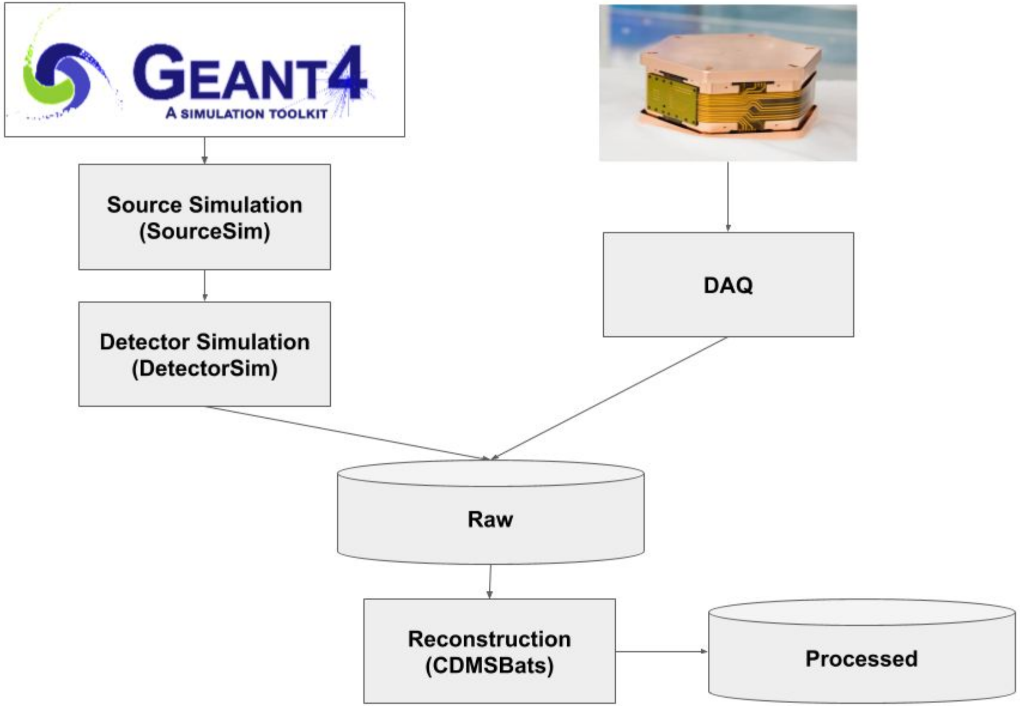
The SuperCDMS experiment aims to identify dark matter by direct detection. Since we expect WIMPs to be able to interact with standard model particles, we expect dark matter to leave some signal in our detectors--specifically by bouncing off a nucleus (‘nuclear recoil’).

The previous CDMS experiment at the Soudan mine in Minnesota (detector layout shown at right) identified new limits on WIMP interaction cross-sections. The next experiment at SNOLAB, Ontario (which will have a greater volume of more sensitive detectors, among other things) aims to improve these further.



CDMS Simulations

To help analyze already-existing data and prepare for future data, we have developed a simulations framework that can model incoming particles, their interactions with the CDMS detectors, and the detector response, at which point we can feed it into the same analysis software used for real data.

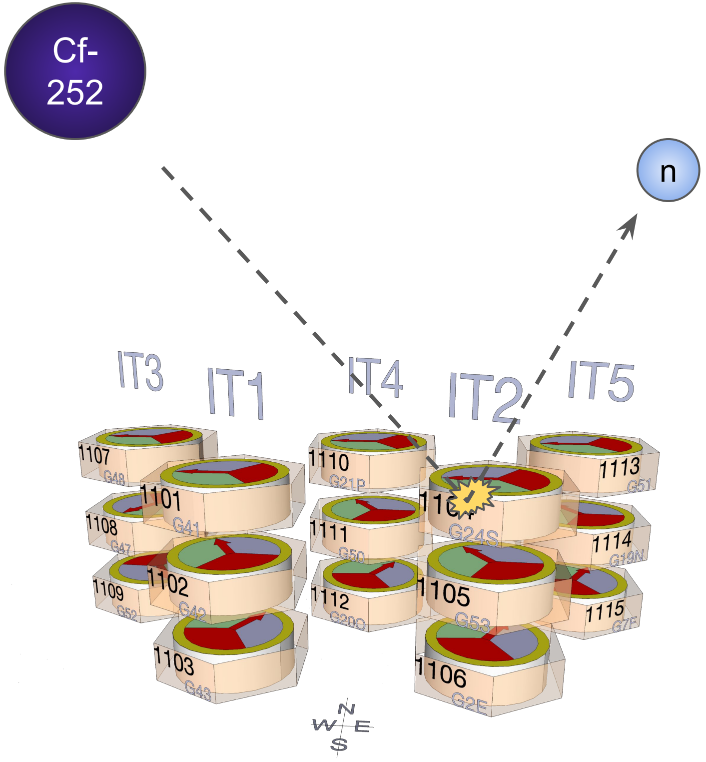


Thesis Details (1/2)

In the experiment, we have to figure out what nuclear recoils look like so that we know what a WIMP signal will look like.

So: a Californium-252 calibration source was placed near the detectors. Cf-252 emits neutrons (primarily--details to follow), which cause nuclear recoils, which shows us what a WIMP interaction might look like in the detector output.

This thesis will focus on this Cf-252 calibration data.



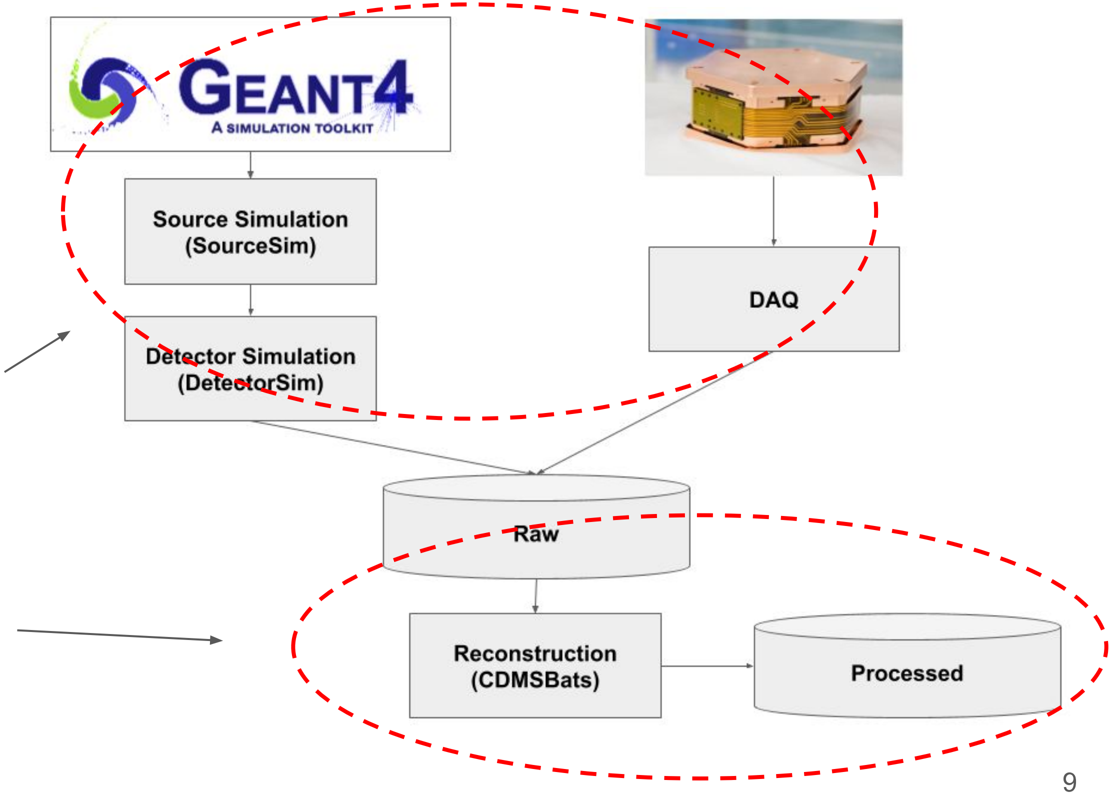
Thesis Details (2/2)

The overarching goal of this work is to better-understand nuclear recoils, since those would be possible indications of WIMP interactions.

We aim to do this with input from both simulated and real Cf-252 data:

1) Study/trace the physical processes modeled in the simulation to better understand the real detector output

2) Validate the final results by checking that the simulation matches real data



I. Introductory Material
   A. Dark Matter Search with CDMS
   B. CDMS Simulation Chain
   C. Details of this Thesis

II. Experiment Details

III. Real Data and Simulated Data
   A. Cf-252
   B. SourceSim results
   C. Detector response results

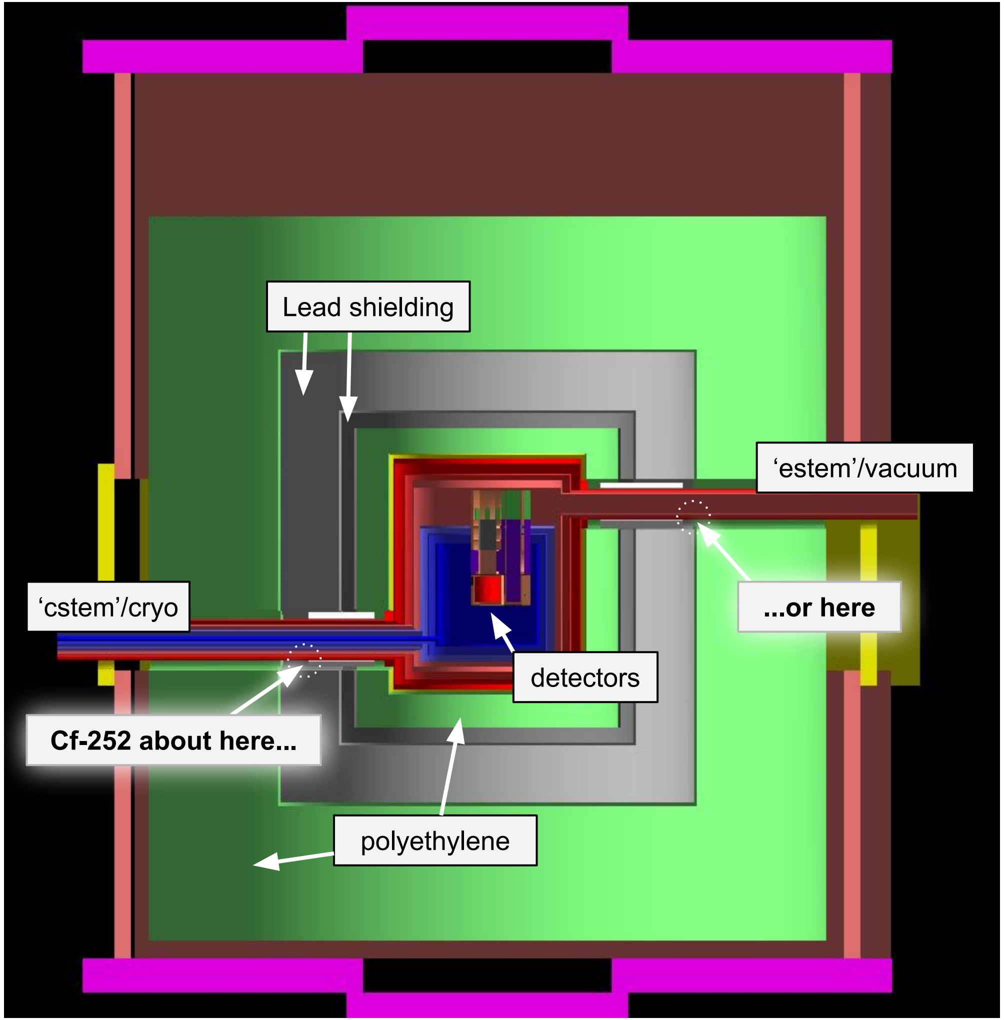
IV. Next-Steps and Conclusion

Experimental Apparatus and Cf-252

The Soudan detectors were shielded within several layers of lead and polyethylene (not to mention about 700m of rock)--plus a veto system--to block as much outside interference as possible.

There are two pipes through the shielding for electronics and cryogenics. Calibration sources could be inserted along the sides of those.

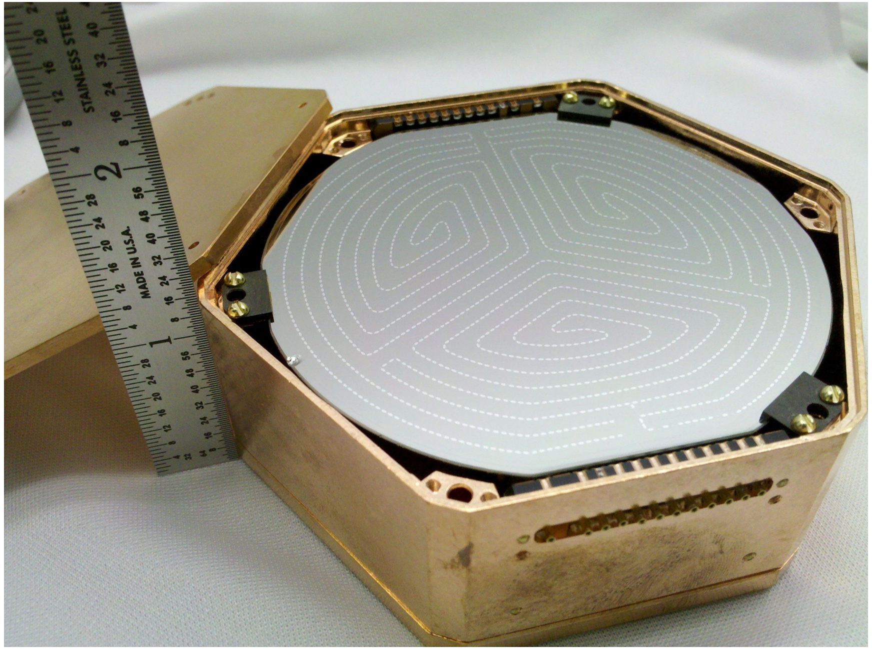
Though Cf-252 primarily lets us calibrate nuclear recoils, its neutrons will cause photons to be released as they interact on the way to the detectors--which can pick up and distinguish energies from both.



iZIP Detectors

In the center of the apparatus were five towers with three detectors each.

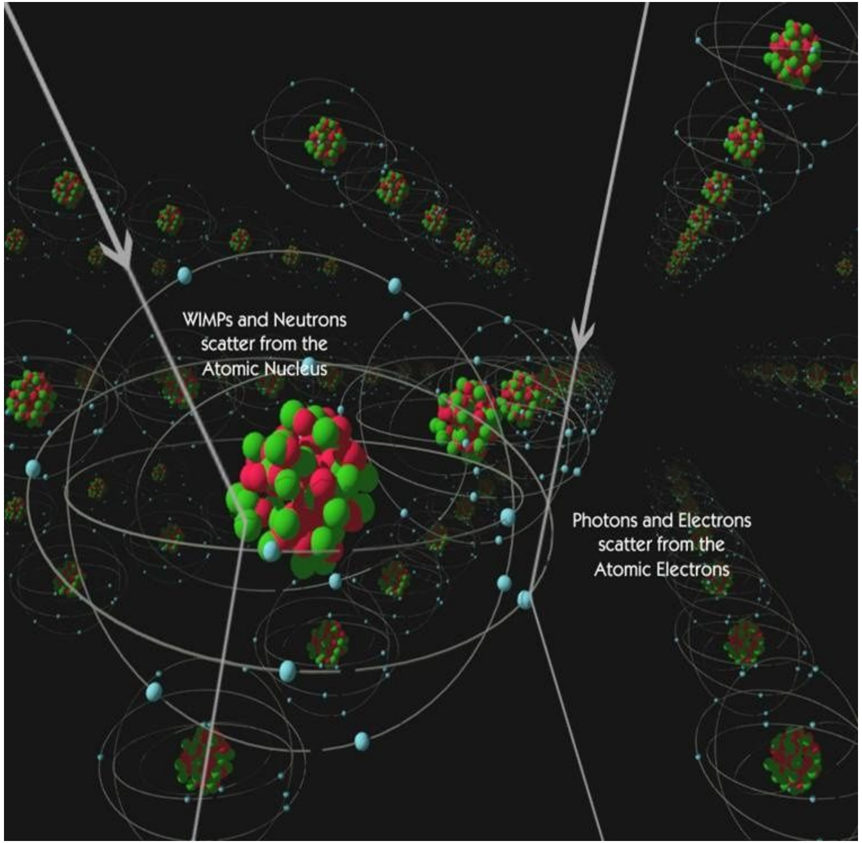
These **I**nterleaved **Z**-sensitive **I**onization and **P**honon (iZip) detectors are able to collect electrons and holes (from photon interactions, say), and phonons (vibrations, as from neutron interactions). Collecting both is important for distinguishing what kinds of particles caused a given interaction.



Nuclear Recoils and Electron Recoils

When particles interact with the iZIPs, they will cause either electron recoils (ERs) or nuclear recoils (NRs).

WIMPS and neutrons will interact as NRs*, which we want to distinguish from ERs.



**How do we distinguish between WIMPs and neutrons?*
Neutron calibration and WIMP-search times are mutually exclusive; during the latter, we expect the shielding to have blocked any source of neutrons.

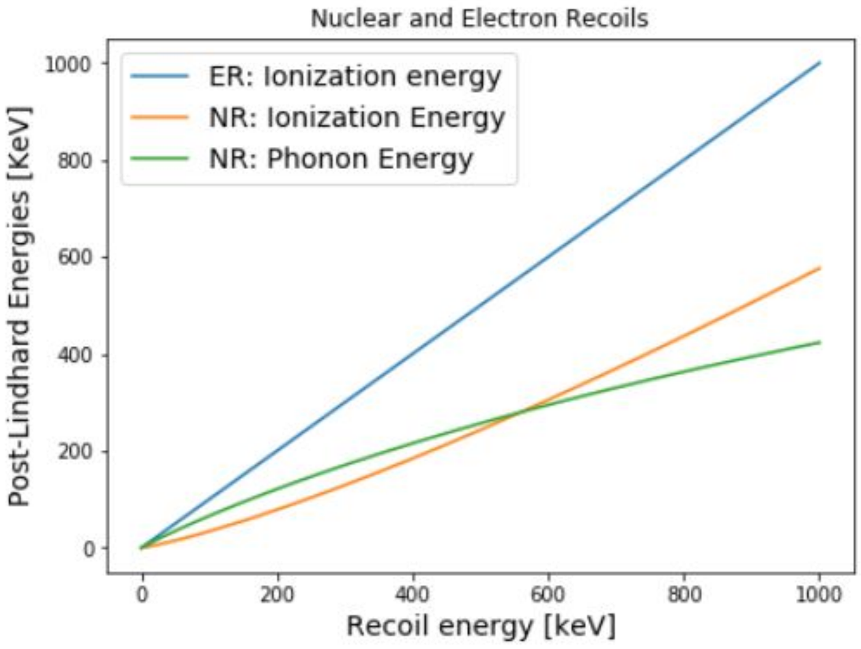
Energies of Recoil Types

IZIPs let us determine whether an interaction was an ER or an NR based on how much of its **recoil energy** becomes **ionization energy.**

- **Recoil energy** is the total energy directly deposited by the incoming particle in part of the detector
- **Ionization energy** is the energy that releases charges (i.e. frees electrons from their orbitals)--*not* phonons

For an **ER**, all of its recoil energy becomes ionization energy.

For an **NR**, only a fraction* of the recoil energy is ionizing; the rest goes into releasing phonons. (Note that this fraction does not change linearly with energy; details later)

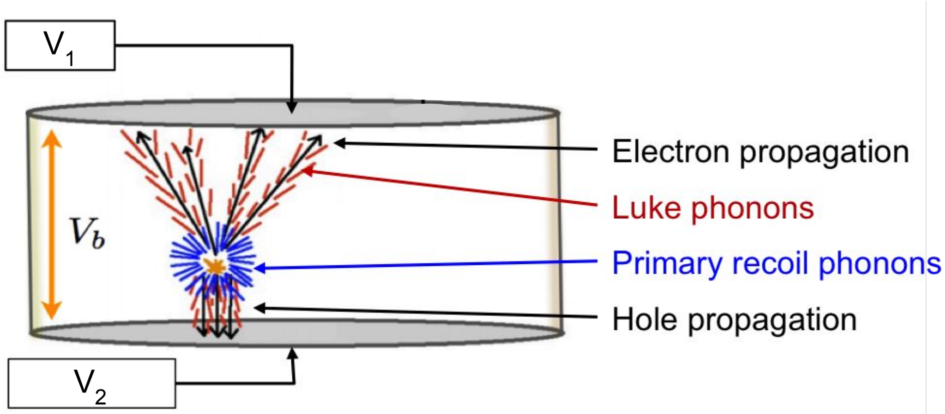


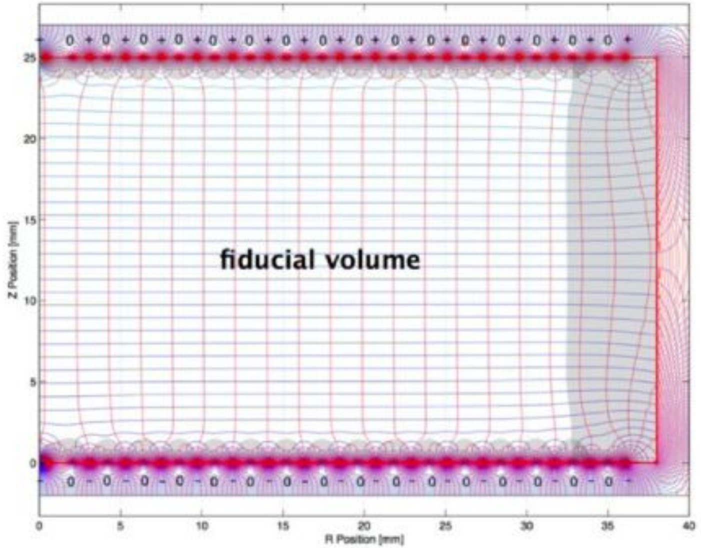
**Called the 'Lindhard Yield'; hence the y-axis label above*

Detector Readout

After the initial recoil, a bias voltage across the detector drifts electrons and holes to be collected at field-effect transistors (FETs) on the iZIP faces. Meanwhile, phonons--either from the initial recoil or created by later charge interactions--are eventually measured with transition edge sensors (TESs).

The ratios of FET and TES readouts on each side give us an idea of where in the detector the recoil occurred, which helps us remove edge events from consideration.



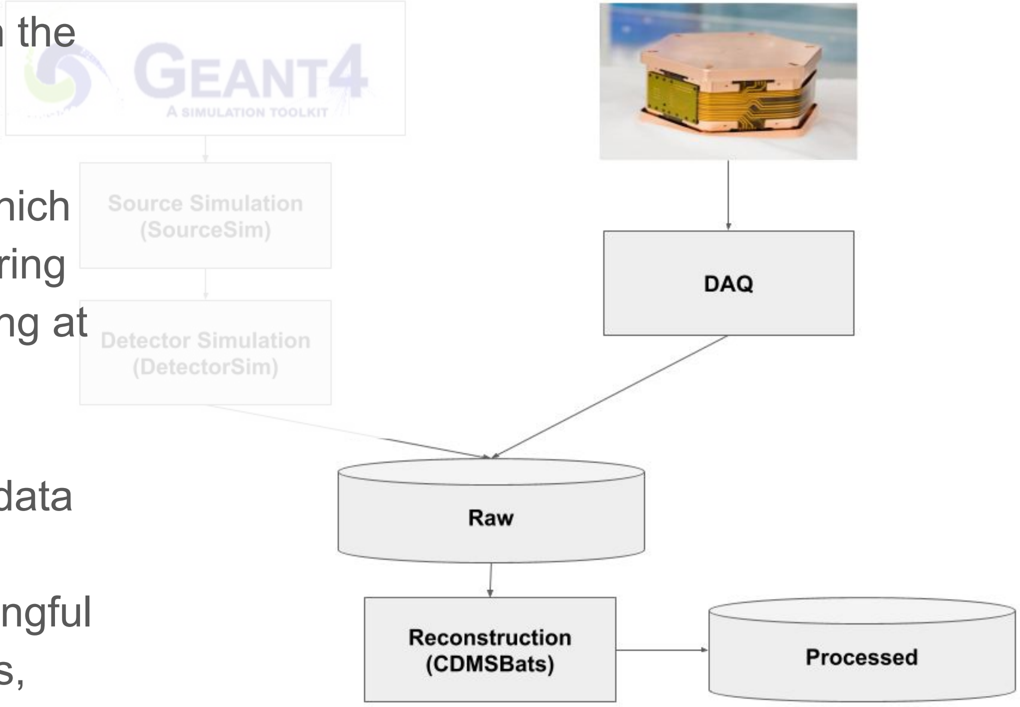


Processing Detector Output

Signals from the TES and FET circuits in the detector are passed on to:

-The **D**ata **A**c**Q**uisition (DAQ) system, which handles triggers and data quality monitoring (i.e. tells us when something worth looking at happened) and sends its raw data to:

-Event Reconstruction, which turns raw data from the DAQ system (in the form of currents, voltages, etc.) into more meaningful physics quantities: timing, recoil energies, charges collected, etc.



I. Introductory Material
   A. Dark Matter Search with CDMS
   B. CDMS Simulation Chain
   C. Details of this Thesis
II. Experiment Details
III. Real Data and Simulated Data
   A. Cf-252
   B. SourceSim results
   C. Detector response results
IV. Next-Steps and Conclusion

The Plan

Recall that we use Cf-252 to provide neutrons and show us what NRs look like in the detector readout. Here we want to make sure we fully understand Cf-252's behavior and resulting data.

We want to check that our simulations can accurately model:

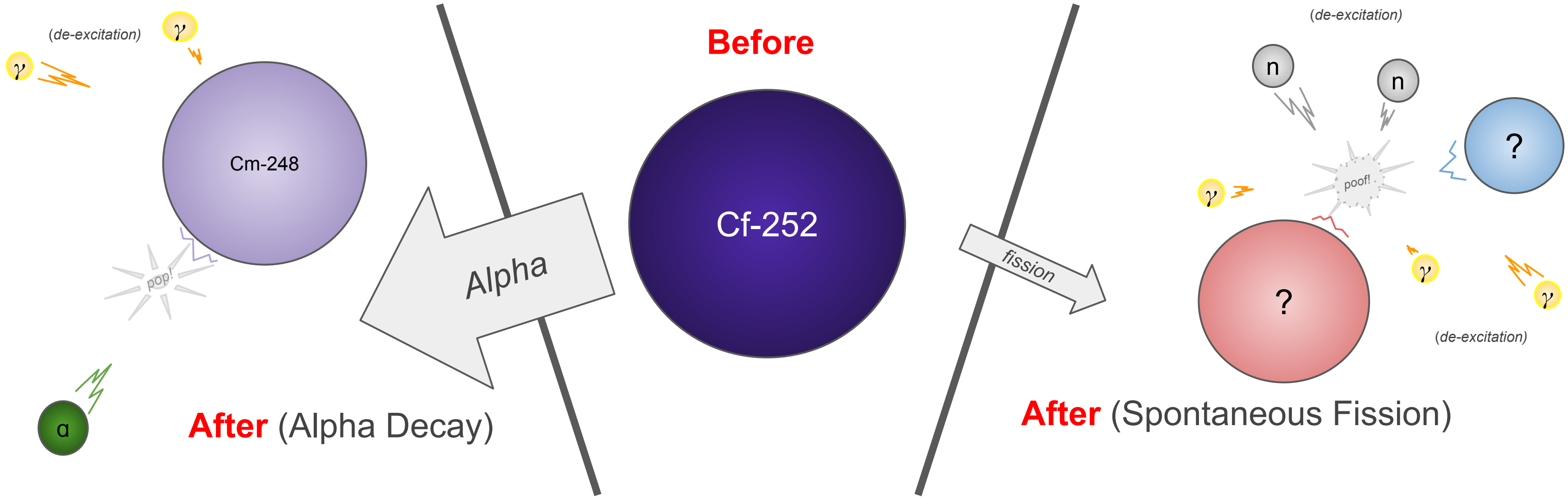
- Cf-252's output spectra reaching the IZIPs
- The IZIPs' responses
- The resulting detector output

...All this such that the final results, when run through the official CDMS event reconstruction software, look like the results from real data.

Californium-252

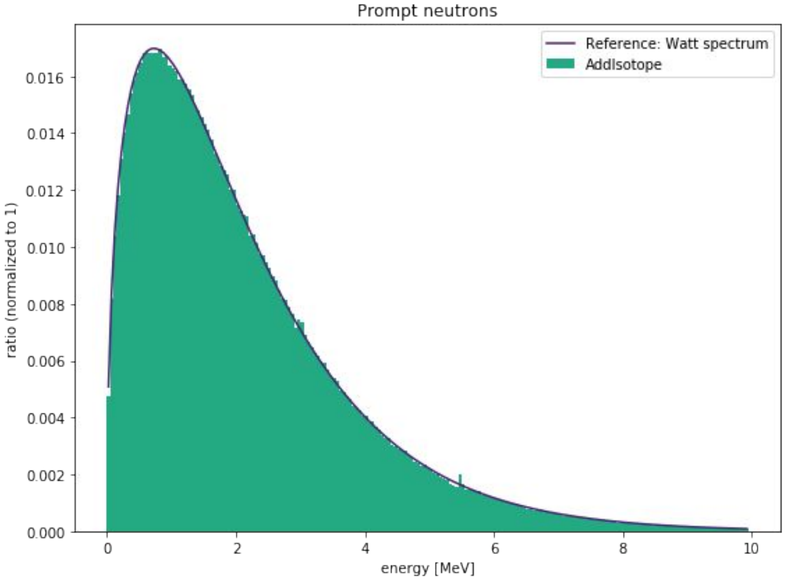
Cf-252 is widely used as a source of neutrons--which are released in spontaneous fission. What other particles it releases--alphas and gammas due to alpha decay or other gammas due to fission--are essentially all blocked in the experiment.

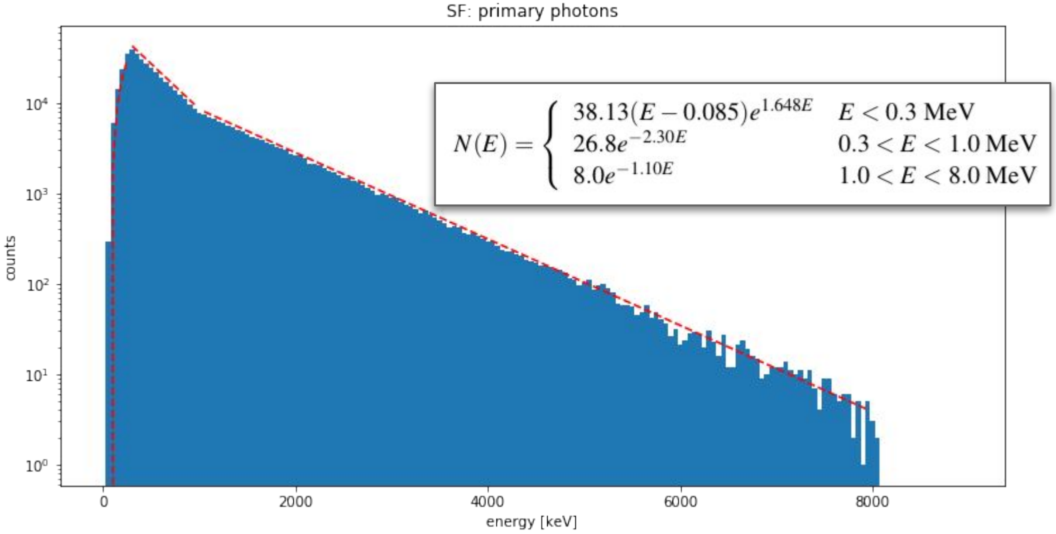
However: on the way to the iZIPs the neutrons will likely bounce around and upset other atoms --which will then emit their own photons or electrons, which could then deposit energy in the iZIPs as well (call these 'secondary').



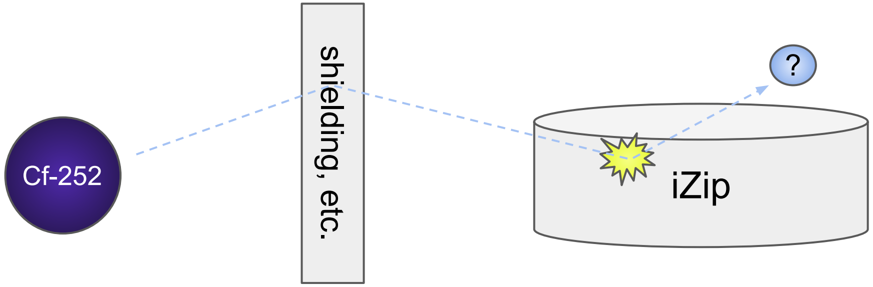
Cf-252 Output Spectra

We’ve validated that the simulation starts with correct Cf-252 behavior.
Though it’s largely only the fission neutrons that interest us, we found that all of the initial decay spectra are modeled well: alpha decay products, fission neutrons, and fission gammas (fission products shown below, for example).





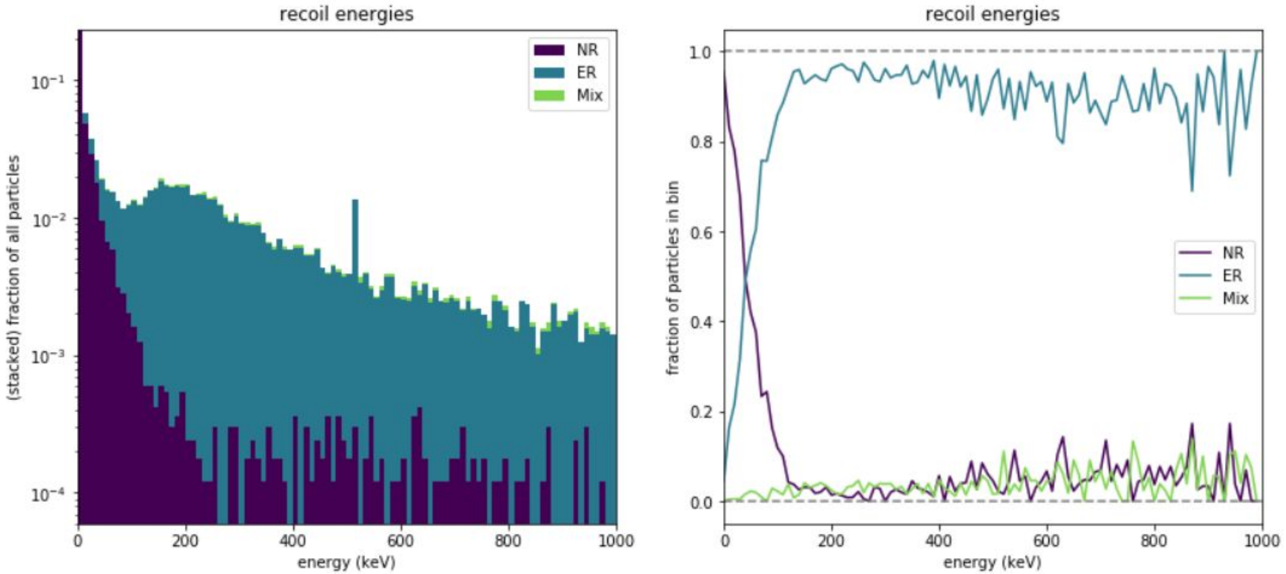
Source to Detector



The first stage of the simulation models particles being emitted from the source, making their way through various experimental components, and depositing energy in the iZIPs

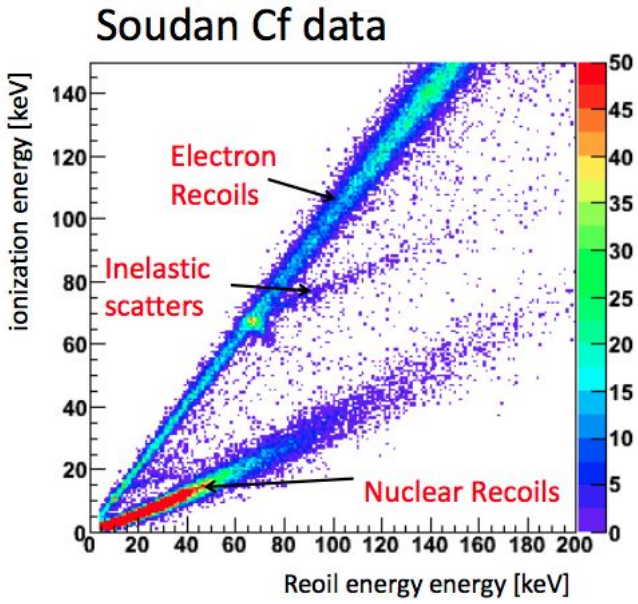
Though we started with neutrons out of Cf-252, we find that it's mostly secondary photons that ultimately deposit energy in the IZIPs.

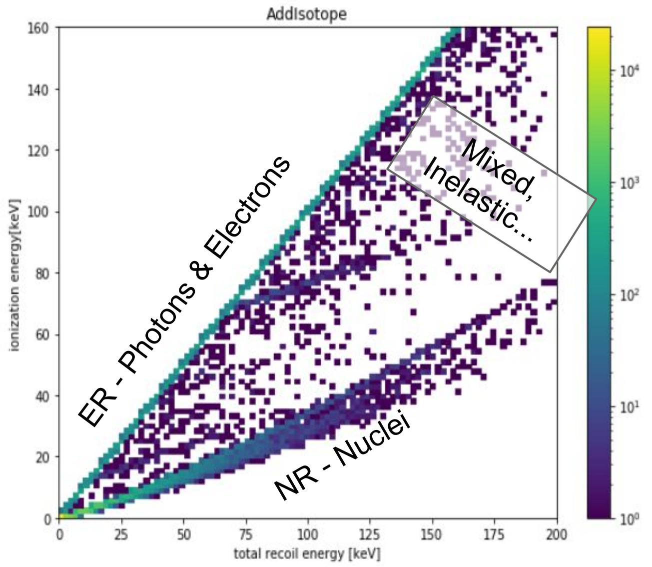
However, the output is more complicated than just basic NRs and ERs.



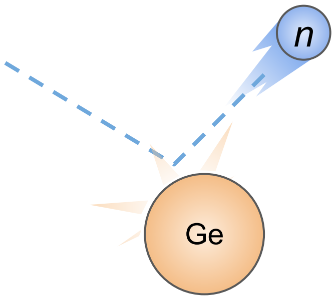
Detector Interactions

The plot to the left shows real Soudan data, which has several distinct features--more than just the upper ER band and the lower NR band. The simulation--on the right-- well-reproduces those features (though detector effects are not yet included--hence less spread in the data). Since this is a simulation, we can check on just how those original neutrons from Cf are causing these different interaction patterns; the following three slides describe these various recoil patterns.

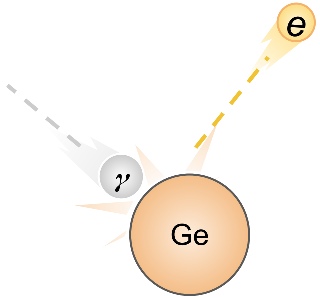




Recoil Types (1/3)



Simple nuclear recoil ('NR')**:** energy depositions due to one neutron bouncing off one nucleus --with no further effects



Electron recoil ('ER')**:** depositions due to only electrons and photons entering the volume and depositing energy.

The deposition types on the following slides will involve both neutrons and photons and/or electrons (hereafter 'γ/e') depositing energy--too quickly for them to be identified as separate events--and so will look like some combination of the above types.

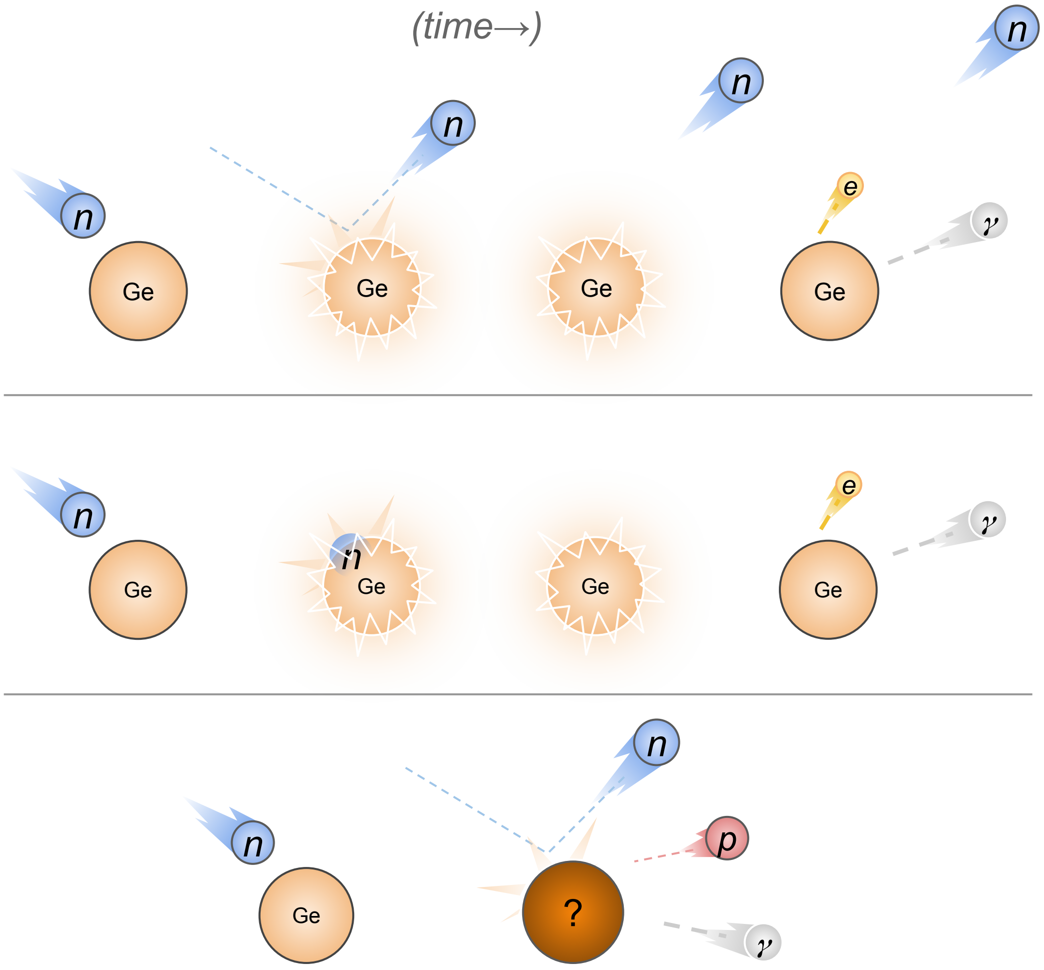
Recoil Types (2/3)

Quasielastic: a neutron bounces off a nucleus in the detector and continues on (leaving the detector)--after which the now-excited nucleus emits photons and/or electrons

Neutron capture (‘nCapture’)**:** similar to quasielastics, except the neutron does not escape after interacting with the nucleus

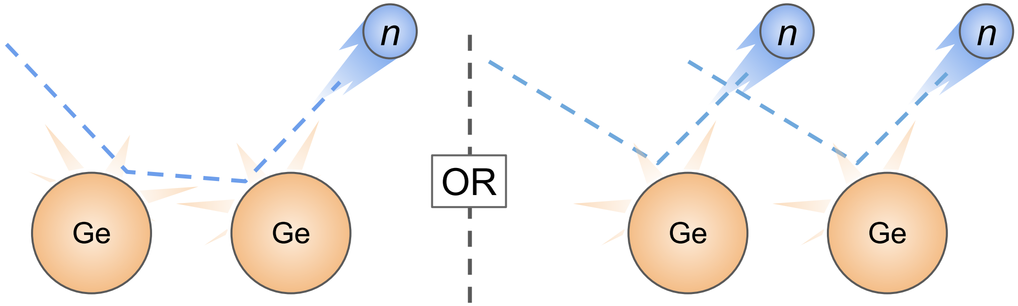
Inelastic: a neutron bounces off a nucleus and knocks out other nucleons (i.e. spallation)

These will all be combinations of γ/e and neutron scatters within the iZip, though they all start with a single incident neutron

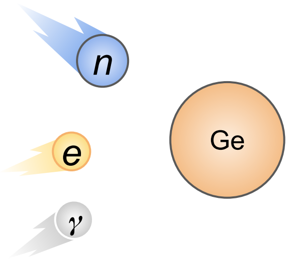


Recoil Types (3/3)

Multi-NR: Either one neutron bounces off multiple nuclei or multiple neutrons cause multiple recoils



Mixed: A neutron and some γ/e enter in quick succession; these will be some combination of the previous deposition types

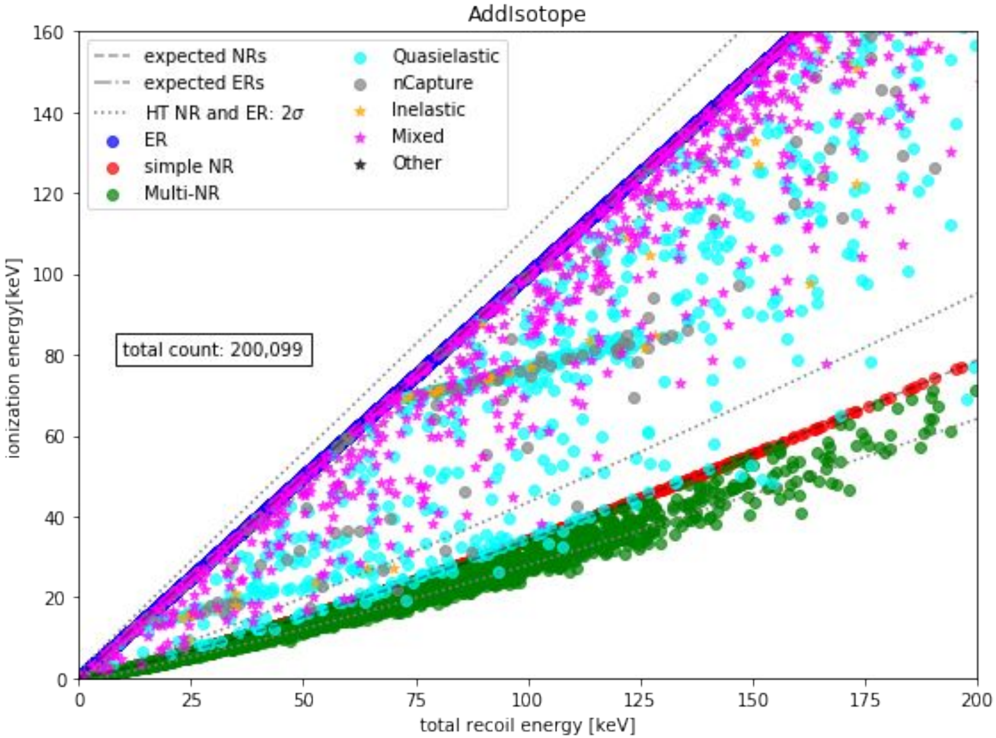


Detector Interactions: Recoil Types

These various recoil types all together create the energy distribution shown previously. Shown here is the same plot, now color-coded by recoil type.

Of particular note:

- Multi-NRs smear the normal NR line down to lower ionization energies
- Other common recoil types (mixed-incident and quasielastic, mostly) similarly smear the ER band



In-progress: DetectorSim and Event Reconstruction

The detector interactions can already be run through the rest of the simulation chain, but we are still analyzing the results.

DetectorSim: Propagates the deposited energies through the crystal and models the readout hardware's response.

To do: validate that the energy depositions' resulting pulses are read out/digitized/scaled correctly.

Reconstruction: With the output of DetectorSim--which looks like the output of a real detector--reconstruct the original energy depositions with the analysis code used in the real experiment.

To do: Check that the final measurements are consistent both with the depositions we started with and also with results from real Cf calibration data.

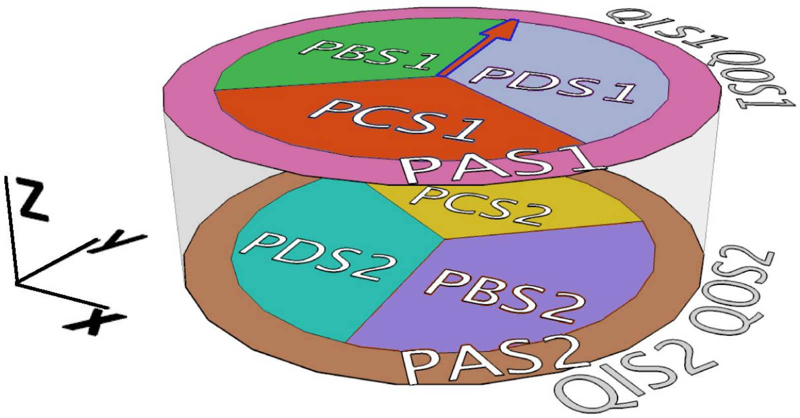
Conclusions

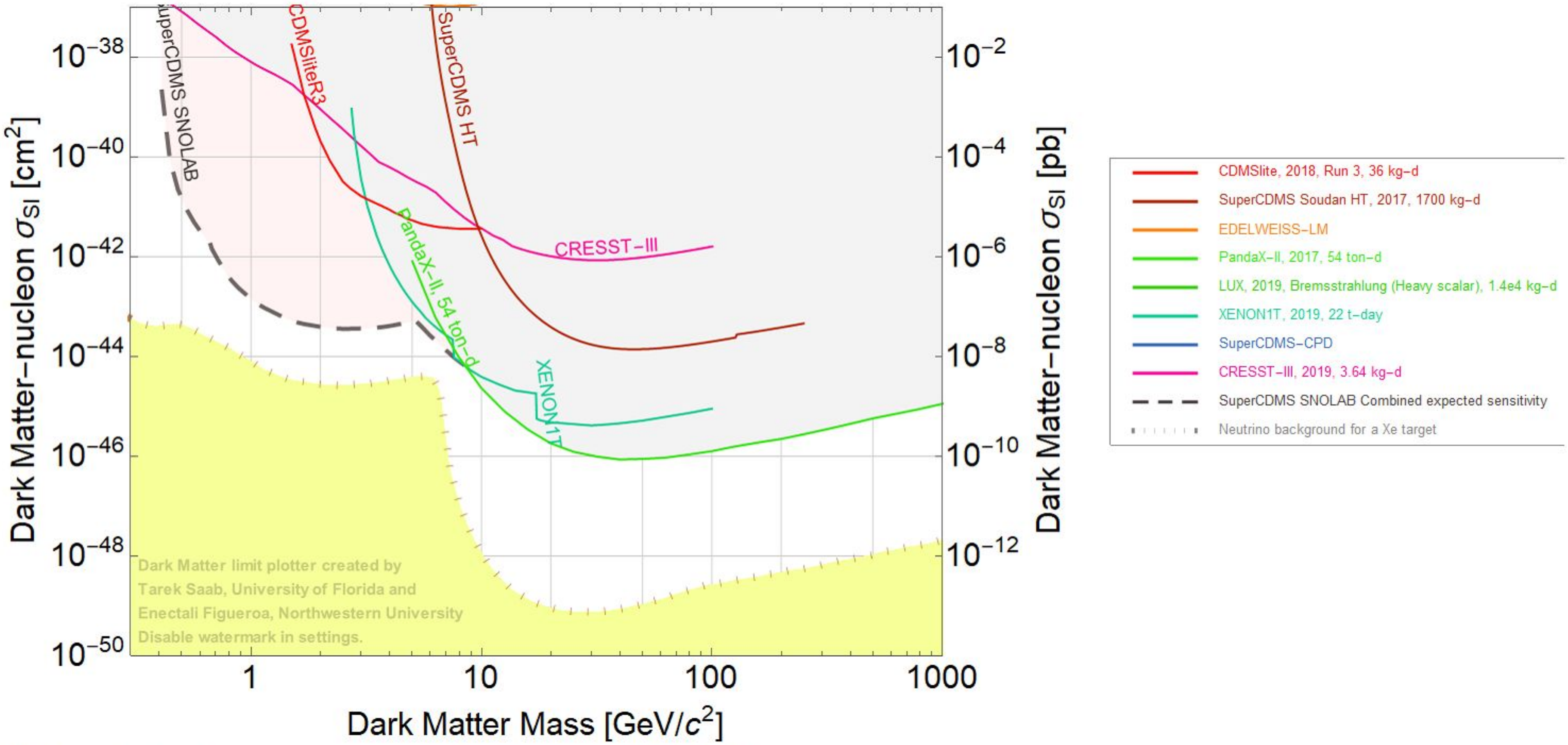
- CDMS has previously achieved world-leading limits on dark matter/WIMPs
- While we set up for SNOLAB we can use real and simulated Soudan data to better understand how WIMPs interact in our detectors
- Simulations of the Cf-252 calibration source match real data in early stages; specifically, the simulated detector response to primary interactions shows the same qualitative features seen in real data
- Later stages are functional but have not been fully analyzed yet: we are still updating and testing the detector readout and event reconstruction software and plan to compare the final simulated results with real Soudan Cf-252 data
- Once we’ve demonstrated that our simulated neutrons produce data just like real neutrons did in Soudan, future students can work on simulating neutrons (and identifying WIMP-like events) at SNOLAB
- So: by providing an understanding of neutrons in CDMS detectors, this thesis may help future collaborators in identifying dark matter signals

Image credits

- Slide 4: Galaxy rotation curve:
  - *By Mario De Leo - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74398525*
- Slide 15: Fiducial volume figure from Matt Pyle’s thesis
- Others public domain or made by/for CDMS

Extras


PBS1
PDS1
PCS1
PAS1
QIS1 QOS1
PCS2
PDS2
PBS2
PAS2
QIS2 QOS2
Z
Y
X

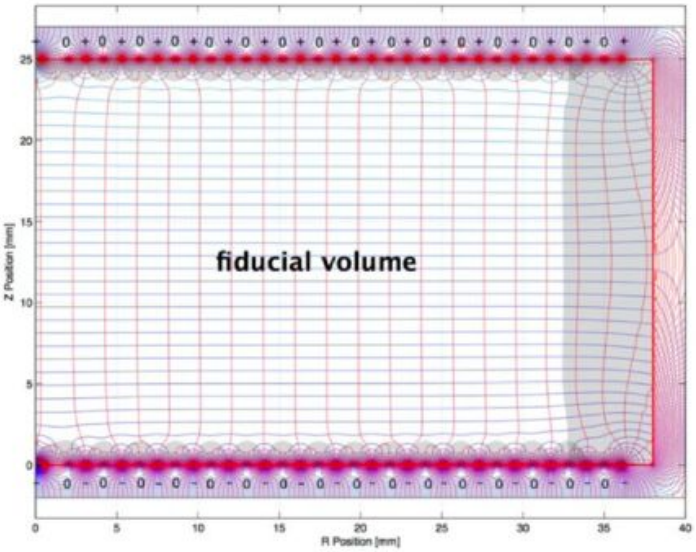


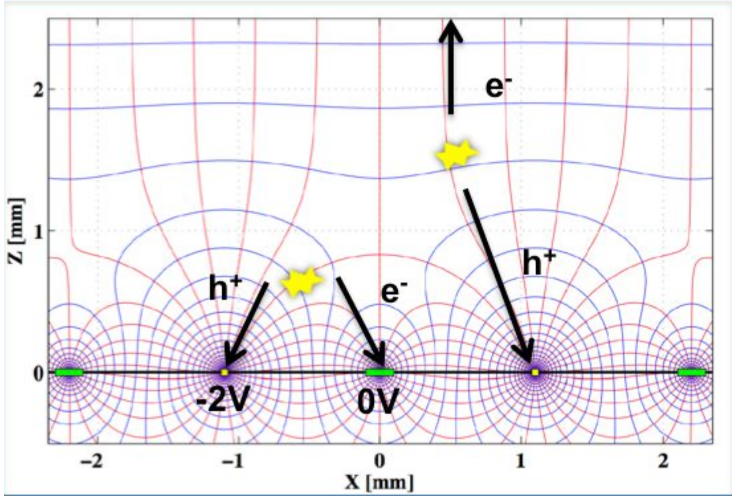
All Nuclear Recoil limits are scaled to a local dark matter density of 0.3 GeV/c^2

Detector Output: Charges

Loose charges are drifted to the edges of the detectors by an overall bias voltage--electrons going to one side and holes to the other. Interleaved ground wires, though, can cause both electrons and holes created nearby to be caught together--which helps us identify edge events.

Charges are read out with field-effect transistors (‘FET’s)

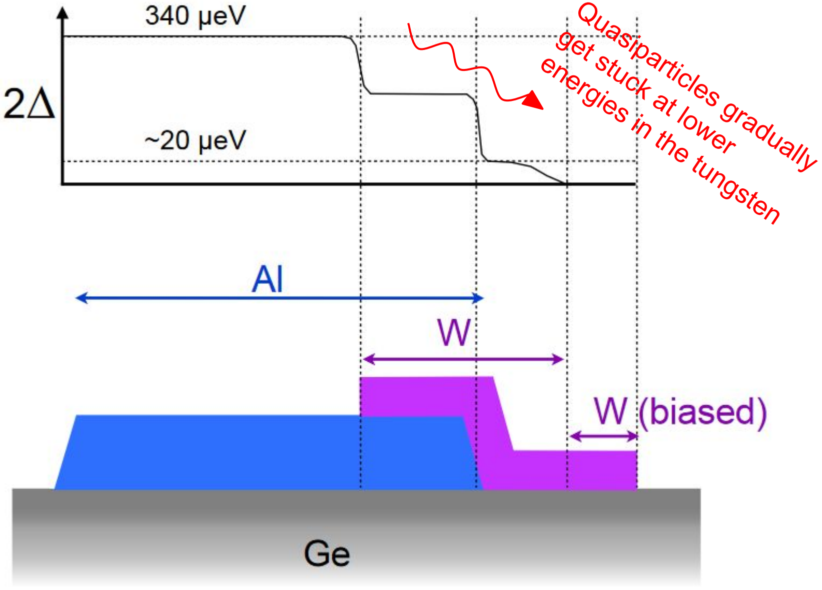


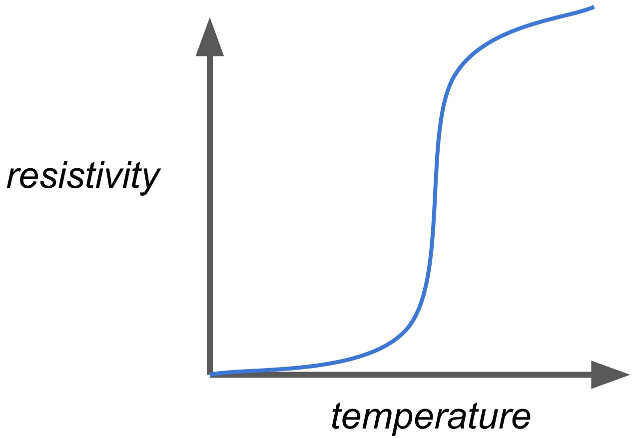


Detector Output: Phonons

Phonons are collected and turned into a signal with an array of transition edge sensors (‘TES’s) [Actually ‘QET’s: Quasiparticle Trap Assisted Electrothermal Feedback TESs].

In short (sort of): Aluminum fins on the detector faces collect phonons, in which Cooper pairs are broken into quasiparticles, which ultimately deposit energy into the TES proper--tungsten held right at its superconducting critical temperature and at a constant voltage. Being right at the transition temperature means that even very small energies can drastically change the resistance--so we would see a significant change in the current flowing through the tungsten, which we can read out.





Cf-252 Decay Chains

Cf-252 has two possible decay chains:

-Alpha decay to Curium-248 (96.91% of the time)

- Produces an alpha particle, a Cm-248 nucleus, and possibly de-excitation photons/electrons
- The nucleus can further decay

-Spontaneous fission (~3.09% of the time) [**'SF'** for brevity]

- Produces photons, neutrons, and fission fragments
- The fragments can further decay