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

PhD Defense
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Overview

- There is reason to believe that an unseen kind of particle exists that comprises most of the matter in the universe; we call this “dark matter.”
- We work with the CDMS Collaboration to try to detect dark matter interactions with ultrasensitive detectors.
- To better understand the behavior of these detectors we use simulations and detailed analyses.
- By comparing real data to simulated data we have identified several ways that simulations and analyses might be improved.

Outline

I. Dark Matter
   A. Motivation
   B. Detection methods
II. The CDMS Experiment and Goals for This Thesis
III. Expected Physics
   A. Prompt Energies
   B. Energy Losses in the Apparatus
   C. Recoil Types
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IV. Simulations
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V. Setup For Understanding Detector Effects
VI. Cf-252 Simulation Results
VII. Real and Simulated Cf-252
VIII. Conclusions

Outline

Dark Matter

Multiple observations of the universe suggest the existence of a particle that interacts gravitationally, but not electromagnetically (so no light for us to see), which we call Dark Matter; for example:

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

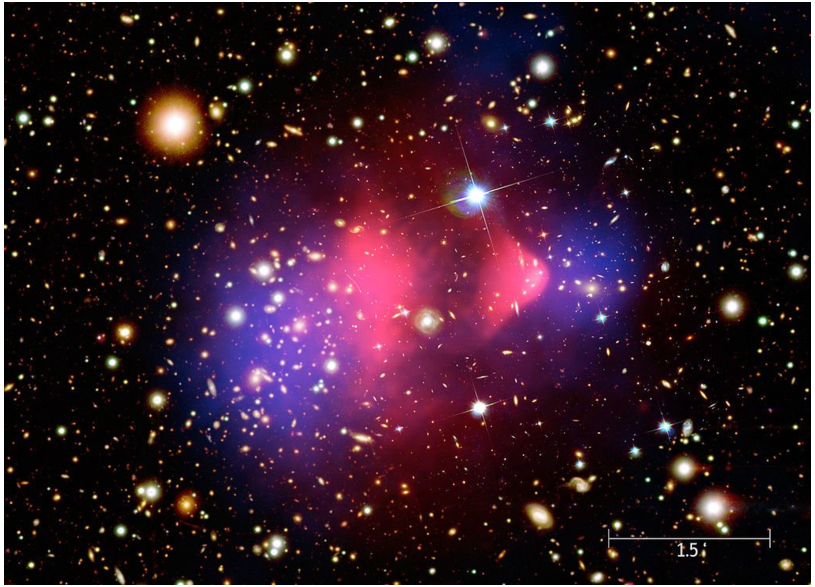


Image from NASA/CXC/M

Galaxy Rotation Curves show higher velocities than are expected from the gravitational forces exerted by the visible matter–as if there's another source of gravity that we can't see.

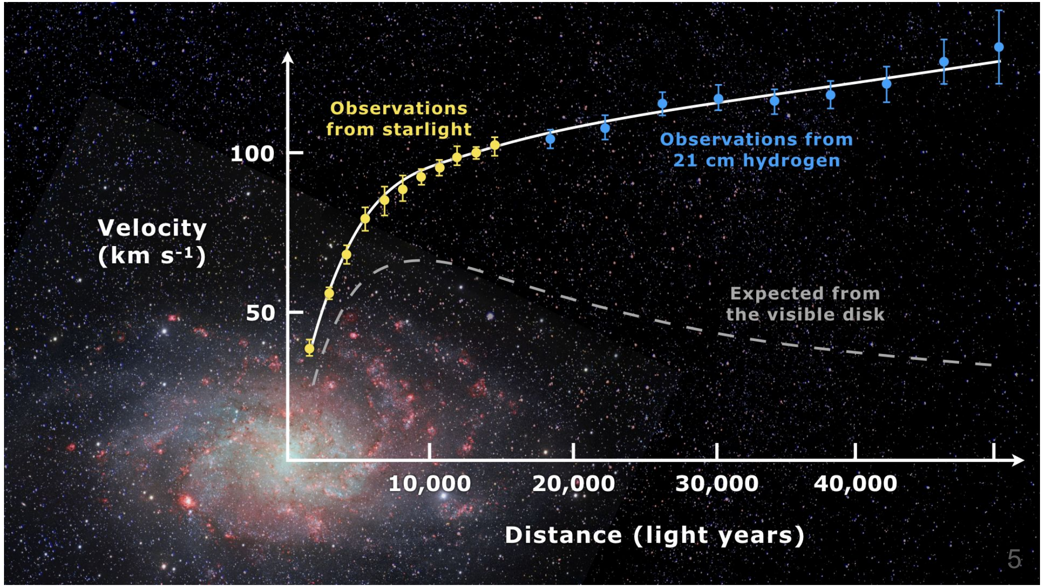


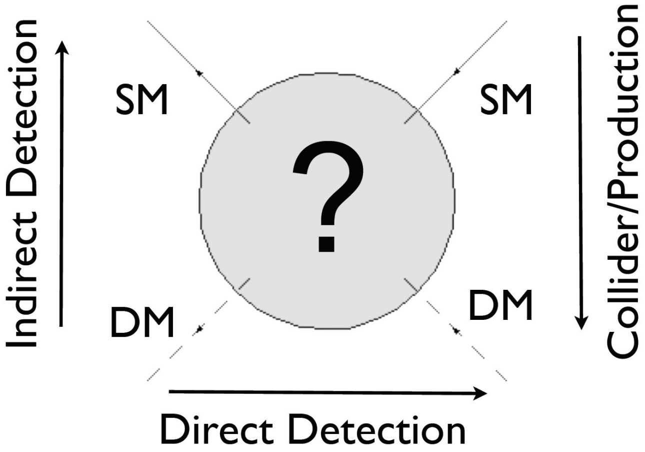
Image by Mario De Leo

WIMP Dark Matter

A likely candidate–the one we focus on–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 and for astrophysics/cosmology.

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 (e.g. the LHC)
- Looking for interactions between DM and SM particles (direct detection)--this is the approach we focus on here!

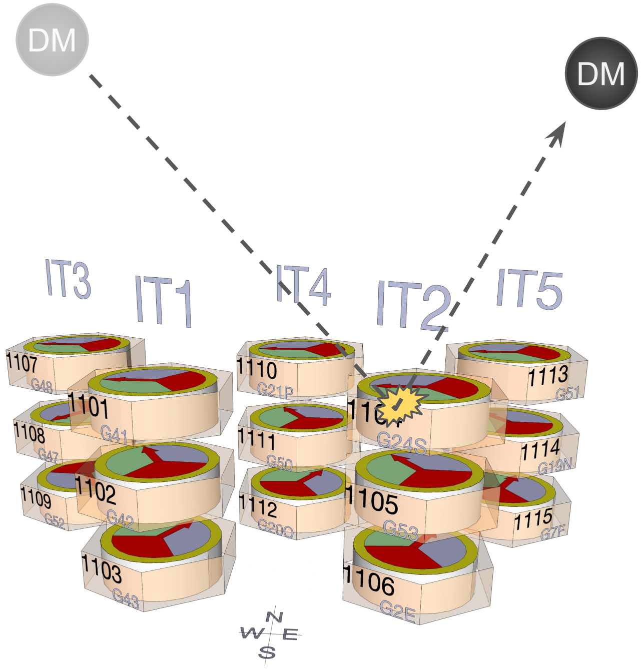


Outline

SUPER CDMS
Cryogenic Dark Matter Search

The SuperCDMS experiment aims to identify dark matter by direct detection. Since we expect WIMPs to be present throughout the Milky Way and able to interact with standard model particles, we expect dark matter to leave some signal in our detectors--specifically by bouncing off a nucleus in a way that most normal matter does not.

The previous CDMS experiment at the Soudan mine in Minnesota (detector layout shown at right) set 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.

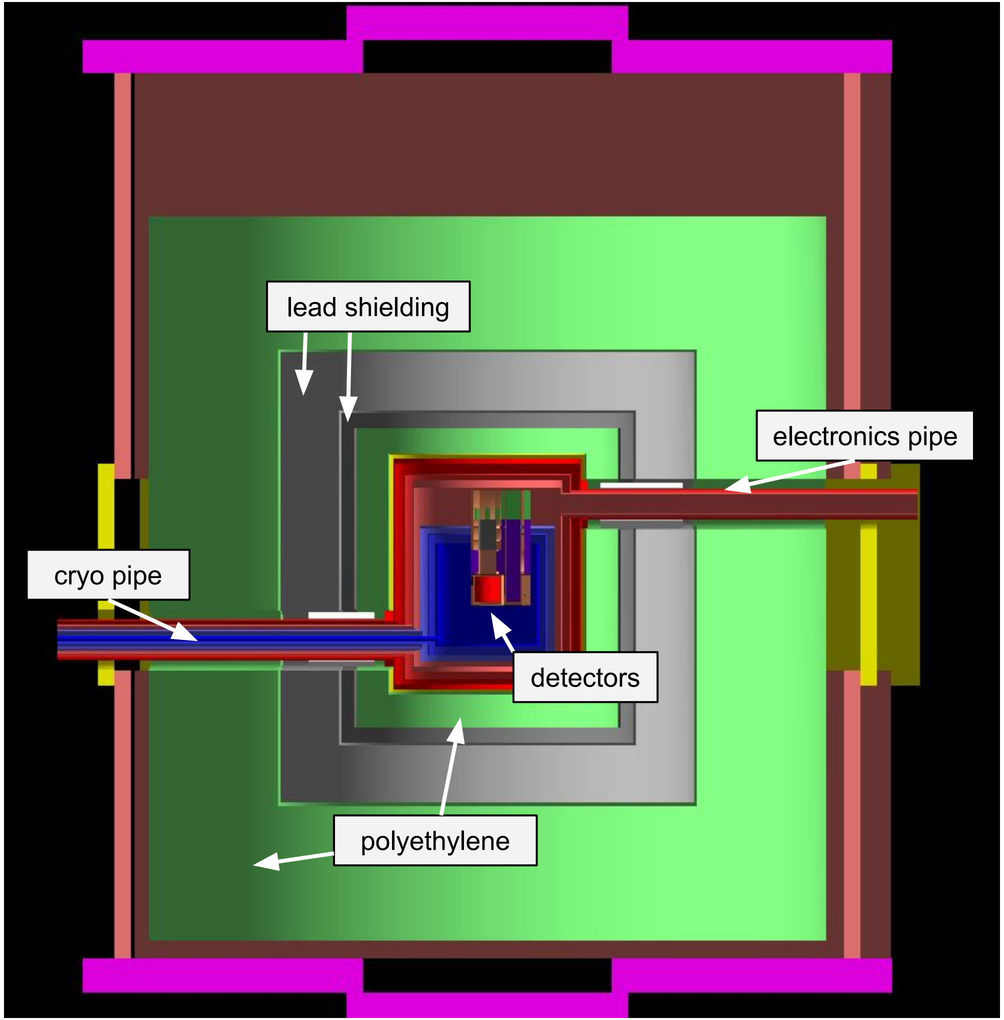


Experimental Apparatus

The figure to the right shows the experimental setup (this particular figure being constructed by our simulations of the real experiment).

The Soudan detectors were shielded within several layers of lead and polyethylene, plus a muon veto system (and about 700m of rock overhead), to block as much outside interference as possible.

There are two pipes through the shielding meant primarily for electronics and cryogenics–but we can also insert radioactive sources here for calibration. We'll be focusing on such calibration sources later.

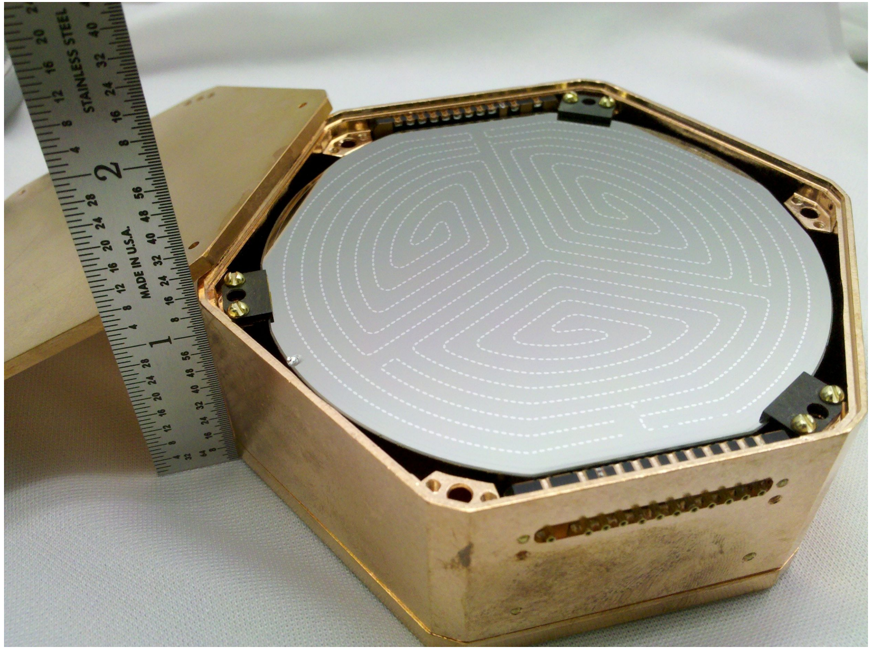


iZIP Detectors

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 (ionization), and phonons, which are vibrations that travel through the detector crystal like particles.

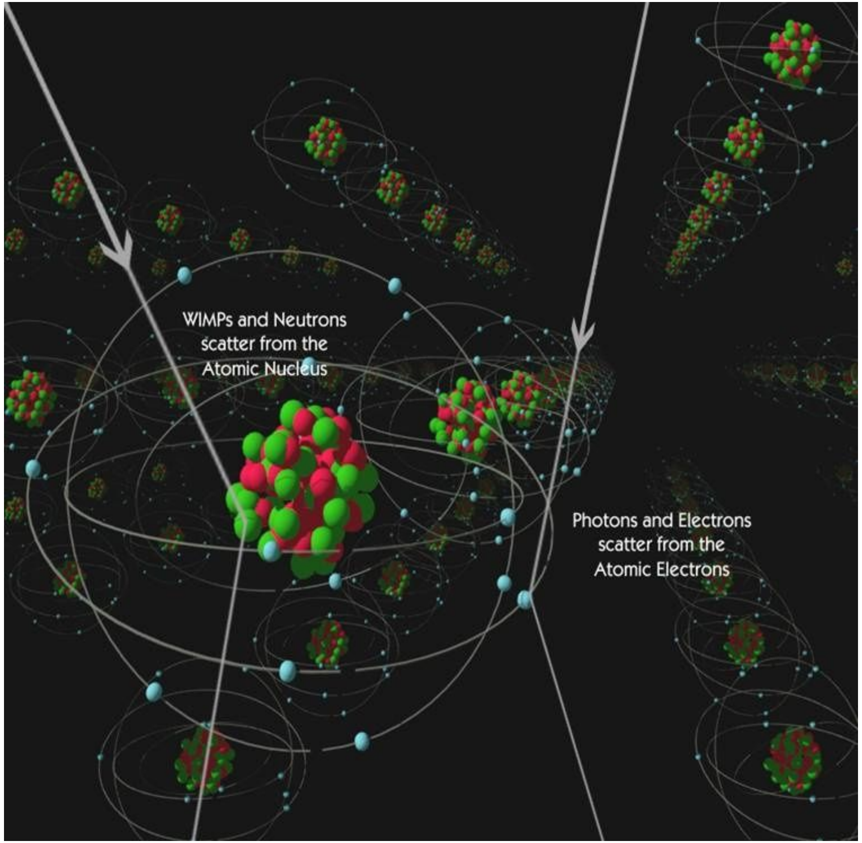
Collecting both ionization and phonons is important because the ratio of the two helps us determine what kinds of particle caused a given interaction.



Nuclear Recoils and Electron Recoils

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

- ERs are caused by charged particles or photons that interact with the electrons of atoms.
- NRs are caused by neutral particles like neutrons or WIMPs that interact with the nucleus of atoms.



If we block all the neutrons, we just need to be able to distinguish ERs from NRs to identify a WIMP signal.

Energies and Yields of Recoil Types

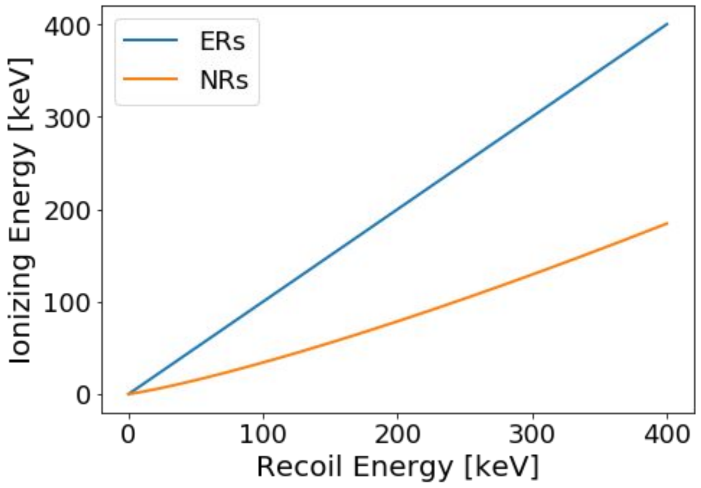
ERs and NRs can be differentiated by their “ionization yield” (or just “yield”), which is the ratio of ionization energy (the energy that knocks out electrons and holes) to the total energy imparted to the given atom (or “recoil energy”).

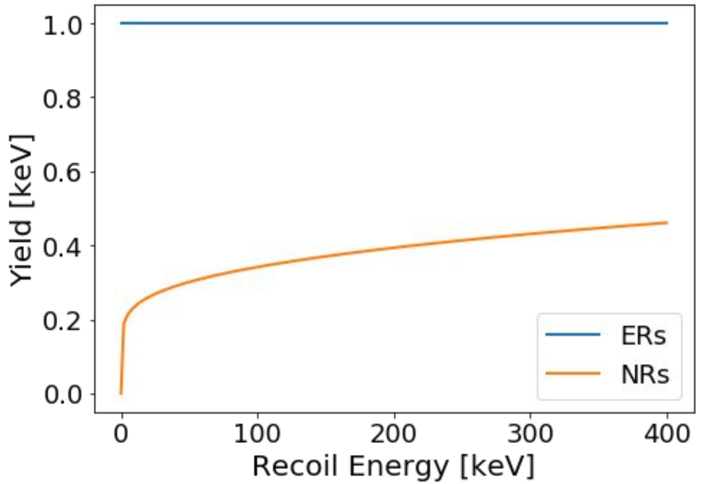
For **ERs**, all recoil energy becomes ionization energy: that is, the yield equals 1 (blue lines at right).

For **NRs**, only a fraction of the recoil energy is ionizing–the rest creates phonons. The yield is a function of the recoil energy, as described by Lindhard (orange lines at right).

To summarize the measurement plan, then:

- We collect charges and phonons (i.e. their energies)
- From those we calculate the yield
- From that we determine if it was an ER or NR
- From that we infer what kind of particle hit the detector



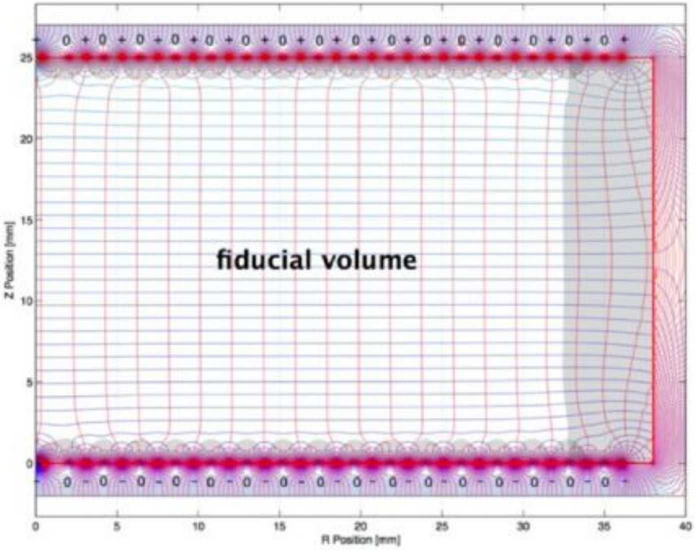


Detector Readout

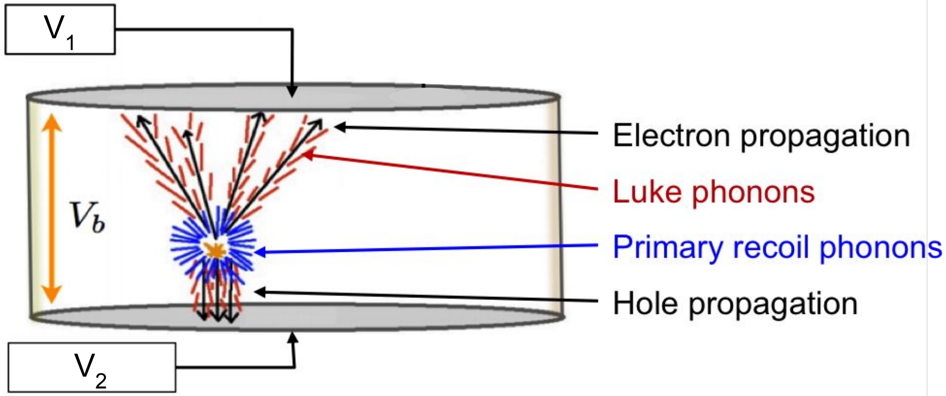
After the initial recoil creates charges and phonons, a bias voltage across the detector drifts electrons and holes to be collected at field-effect transistor (FET) circuits on the iZIP faces–electrons on the top face and holes on the bottom. Meanwhile, phonons reflect around for a while and are eventually collected by transition edge sensors (TESs).

Importantly: charges create *more* phonons, called "NTL phonons" or "Luke phonons," as they travel. The charges gain energy as they drift through the electric field and, once they hit maximum velocity, emit the excess as phonons.

There are multiple FET/TES circuits, and comparing the measurements from each gives us an idea of where in the detector the recoil occurred, which helps us remove edge events–which are often mismeasured–from consideration.



Note that the electrons don't exactly follow the electric field lines at left!



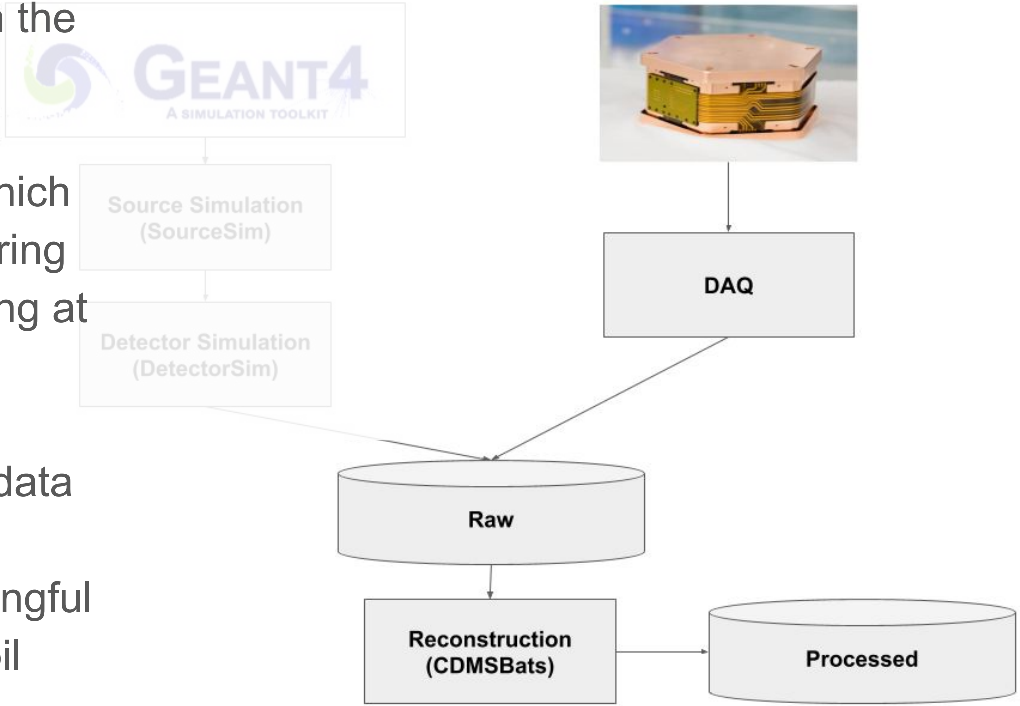
(We'll be identifying a slightly different fiducial region later!)

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 (like estimates of recoil energies, charges collected, timing, etc.).



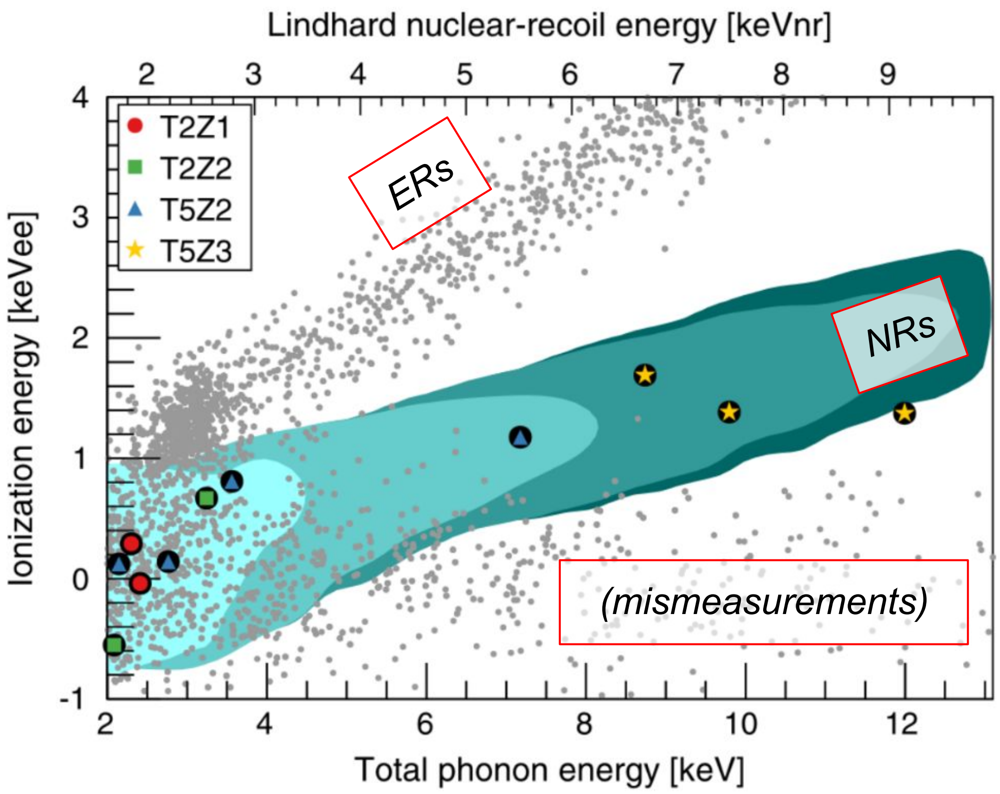
Soudan Results

Shown at right is real data from the Soudan experiment (annotations mine).

This is WIMP-search data: in theory, most everything (backgrounds) should be in the ER. The NR band is subject to a few rare backgrounds, but otherwise we hope to only see WIMPs there.

The ERs show up where expected and there are some events in the NR band… but there are also many mismeasurements.

The highlighted events in the NR bands were determined to be consistent with backgrounds or glitches. Given these and the potential for mismeasurement, how will we be able to identify a WIMP if it shows up?



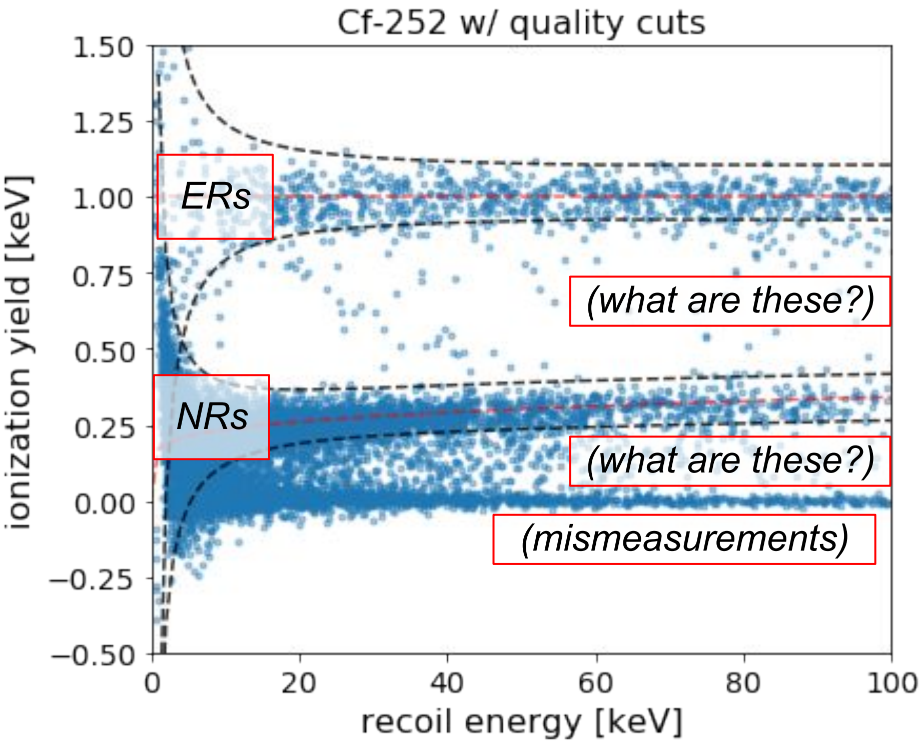
Notes:
- This plot has phonon energy on the x-axis, not recoil energy, as was shown before.
- I'm working with previous data–not doing a new search for Dark Matter myself.

Thesis Goal: Learn About Real Data With Simulated Cf-252

So potential WIMP discoveries depend on a thorough understanding of what's in the NR band. CDMS uses two well-understood calibration sources to help identify energies and events:

- Ba-133, which emits photons of known energies we use for calibration–and also establishes the ER yield band at 1.
- Cf-252, which emits neutrons (and other particles) that provide example ERs and NRs.

We focus on Cf-252 in this work. Its neutrons can not only cause NRs, but also indirectly cause ERs and events that are mixtures of ERs and NRs. Such events make it more difficult to interpret the real detector response–and would be significant backgrounds if they occur during WIMP-searches–but with simulations we can learn a lot about them.



With our Cf-252 simulations we will look at which populations of events are well-measured and what processes contribute to mis-measurements–and how these might be identified in the end results.

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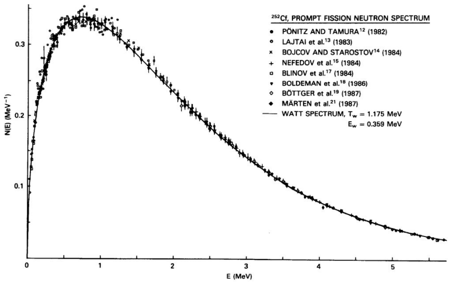
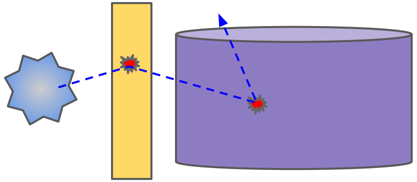
Overview

To understand the processes contributing to our final results, in the following slides we track the yields and energies of particles emitted by Cf-252 across four aspects of particle interactions within the apparatus itself*:

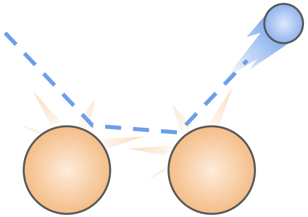
The “prompt” energies of the particles when first emitted



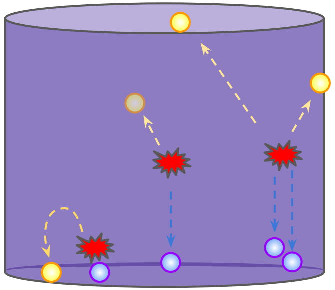
Energy losses due to apparatus components



Complicated energy deposits



Detector mismeasurements



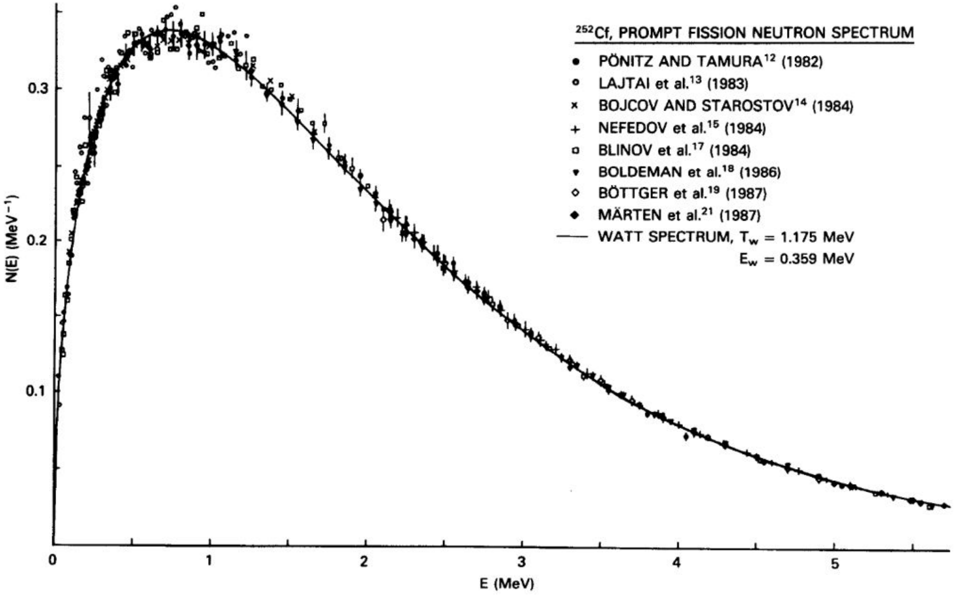
The final energies are also affected by the readout electronics and processing software, but these tend to have lesser impact.

Cf-252 Prompt Neutron Energies

Cf-252 can decay either by alpha decay or spontaneous fission. The former is more likely (about 97% of all decays) but its products are essentially irrelevant (they either never reach the detectors, occur many years later, or aren't useful).

Fission is more interesting, as it's where we get our neutrons. The plot to the right shows the neutron energies emitted from fission events.

We will not ultimately see this exact energy spectrum however…



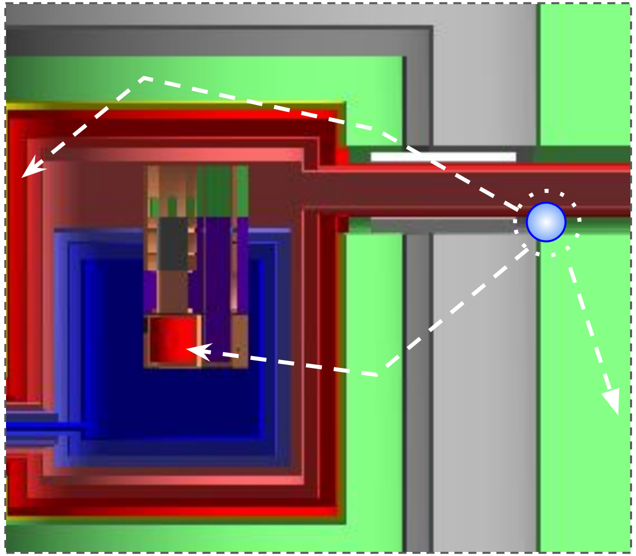
Plot by F. H. Fröhner

Interactions in the Apparatus

The energies and particles involved will change before ever reaching the detector:

- The full energies of the original particles will often not reach the detector:
  - Many particles will simply miss entirely
  - Neutrons in particular will often bounce off other apparatus components, depositing energy where we don't see it

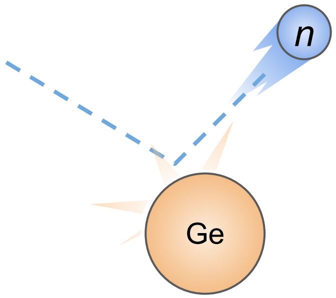
- Neutron interactions in the apparatus can create other particles (mostly photons or electrons, hereafter "γ/e") that may themselves hit the detectors.



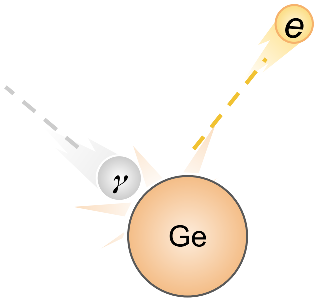
Next is the issue of what these particles do when they actually reach the detector…

Recoil Patterns (1/3)

Once in the detector, if multiple particles deposit energy within a “readout time window” they won’t be individually identifiable–the detector responds to all of them as a whole. In the following few slides we describe the recoil patterns we may have within a given readout window, starting with the simplest two:



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.

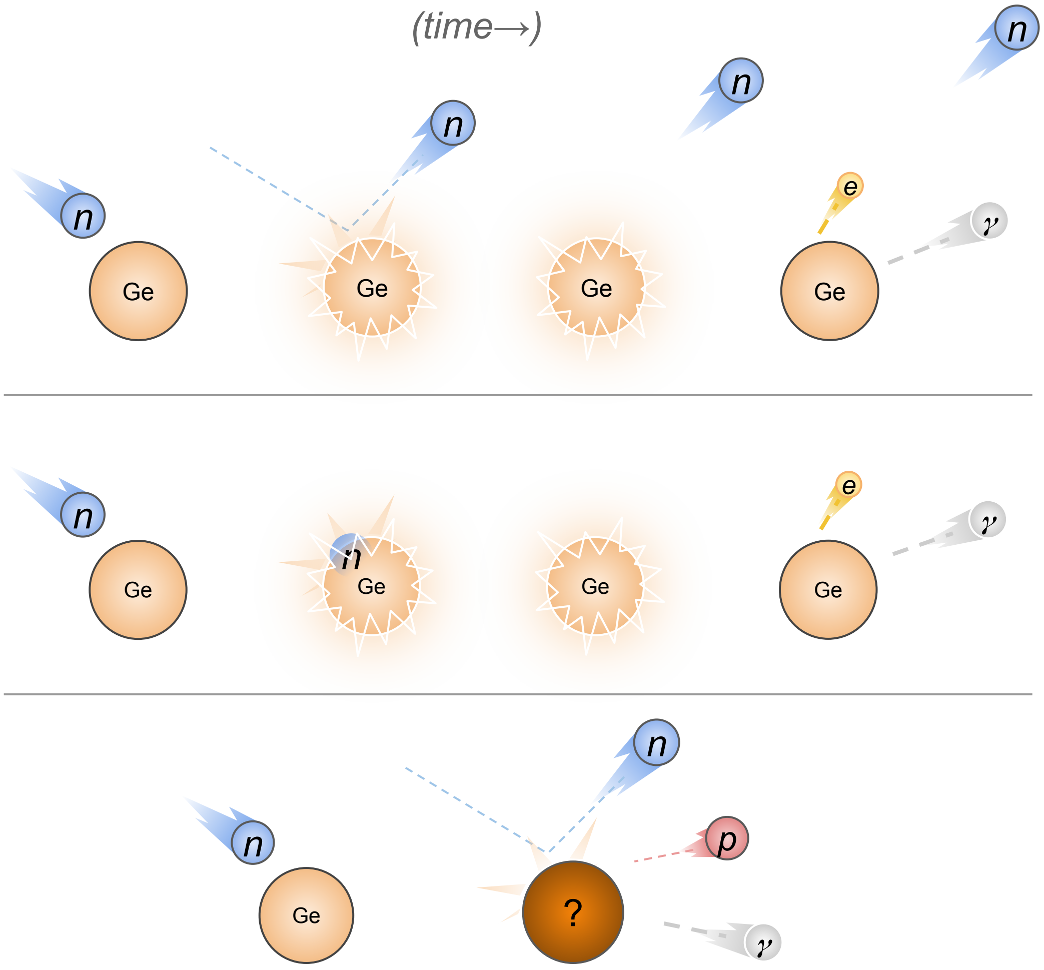
Recoil Patterns (2/3)

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

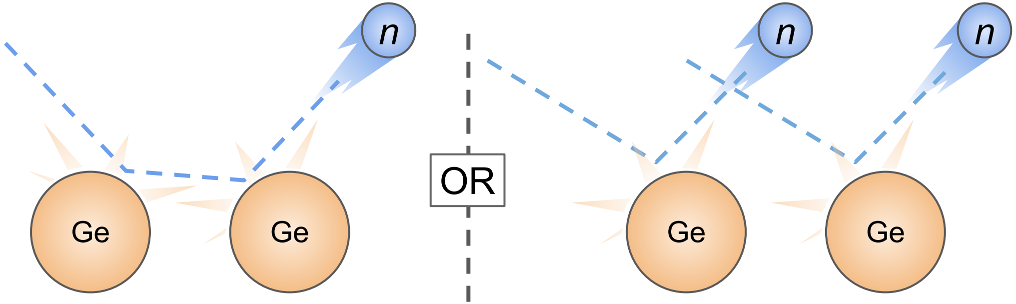
Inelastic: a neutron bounces off a nucleus and knocks out other nucleons (i.e. spallation)

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

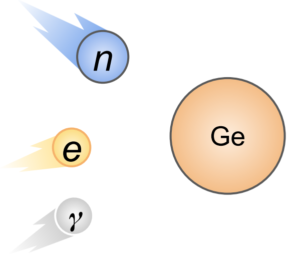


Recoil Patterns (3/3)

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



Recoil Patterns and the Lindhard Model

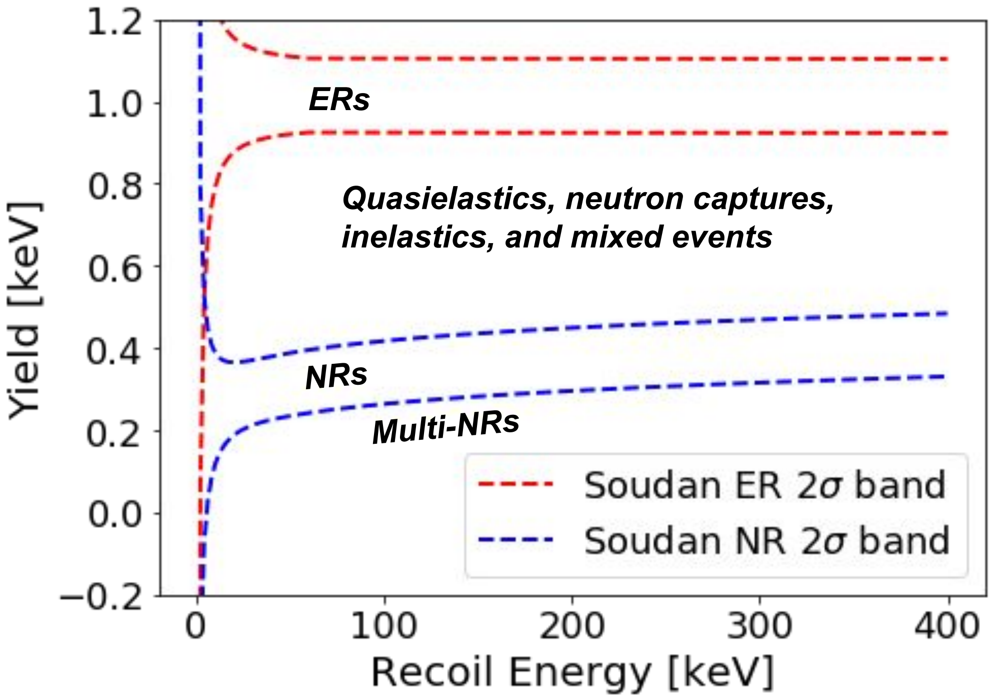
Recall we differentiate ERs and NRs by their ratio of ionizing energy to deposited energy. The recoil types on the previous slides each will show up in different places on a plot of the yields (even without mismeasurements!):

-Normal **ERs** and **NRs** define the two main lines.

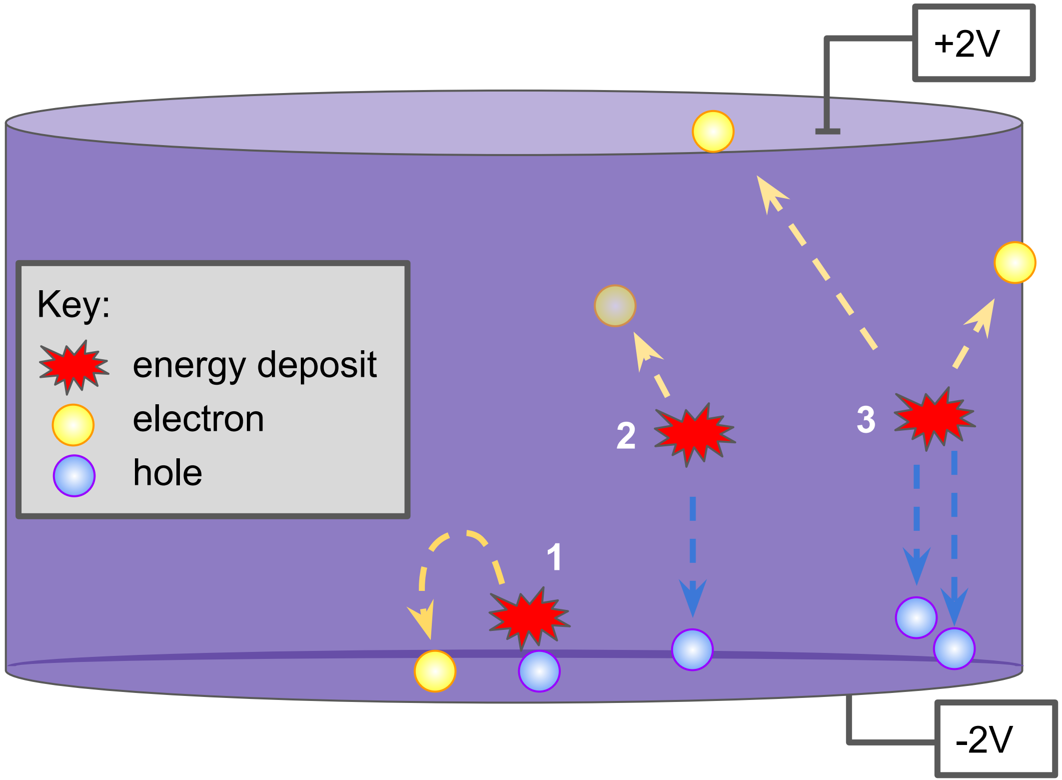
-**Quasielastics, neutron captures, inelastics**, and **mixed events** will be somewhere in-between, since they all involve ERs and NRs together.

-**Multi-NRs** will be *below* the NR line due to how the Lindhard yield scales with energy.

Example: A 50 keV NR has an ionization energy of 15 keV but a 100 keV NR has an ionization energy of 34 keV. So two 50 keV hits will show up 4 keV below a single 100 keV hit!



Detector Mismeasurements (1/3)



After the energy deposits, there is the matter of the charges and phonons released–not all of them will be collected and measured correctly.

To start: not all charges will be collected at the detector face they should. For example:

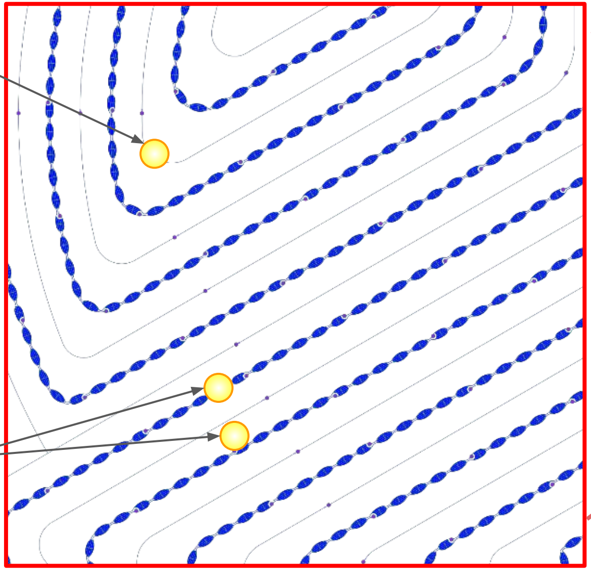
1. Face events, where both electrons and holes are captured by curved fields at the detector faces and cancel one another out.
2. Charge trapping, where charges get stuck in impurities and never reach the detector faces.
3. Edge events, where charges (usually electrons) get stuck on the sidewalls and never reach the detector faces.

Detector Mismeasurements (2/3)

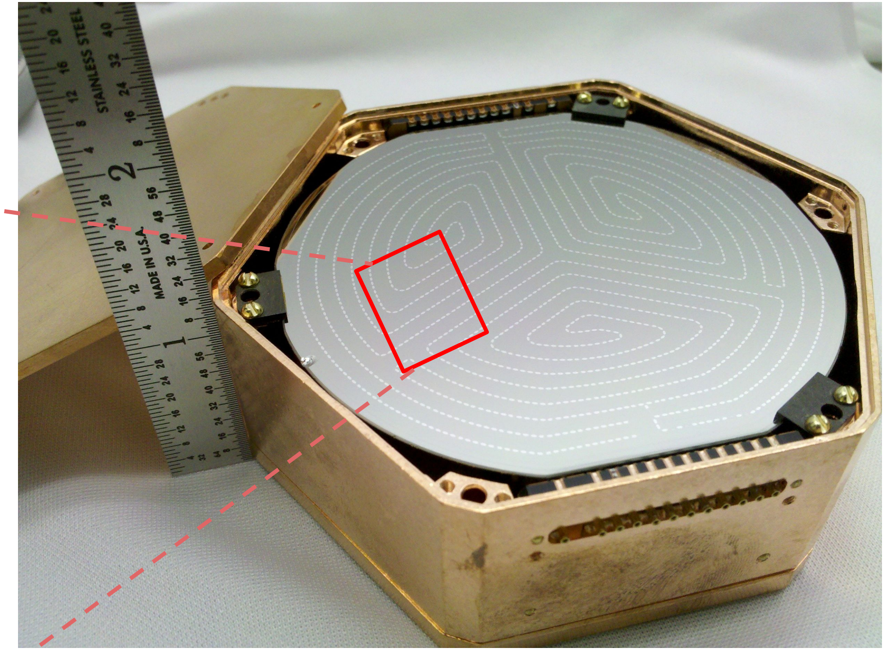
Even charges that reach the faces might not be well-measured. If the electric fields don’t get charges exactly on the electrodes, those charges can be trapped elsewhere and cause a smaller charge signal; they also don’t emit all the NTL phonons we expect, so the phonon system suffers as well.

We refer to these considerations as “off-electrode effects.”*

on-electrode, well-measured

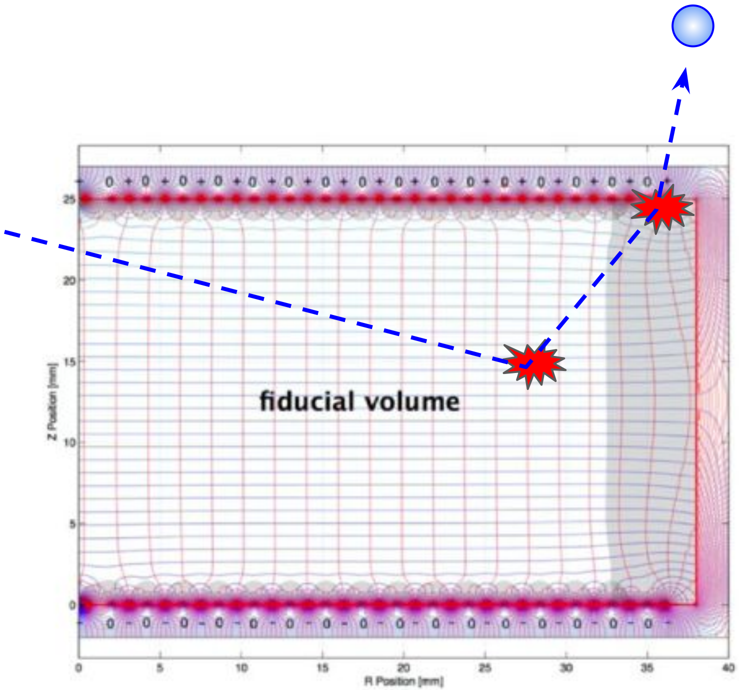


off-electrode, poorly-measured



**Forewarning: in the data we’ll see later, a simulation artifact makes these effects worse than they need to be.*

Detector Mismeasurements (3/3)



The possibility of multi-hit events compound these problems: one hit may be in the center of the detector and be well-measured while another, related hit is at the edge, where it is mismeasured via any of the mechanisms on the previous slides. We call these “semi-fiducial” events.

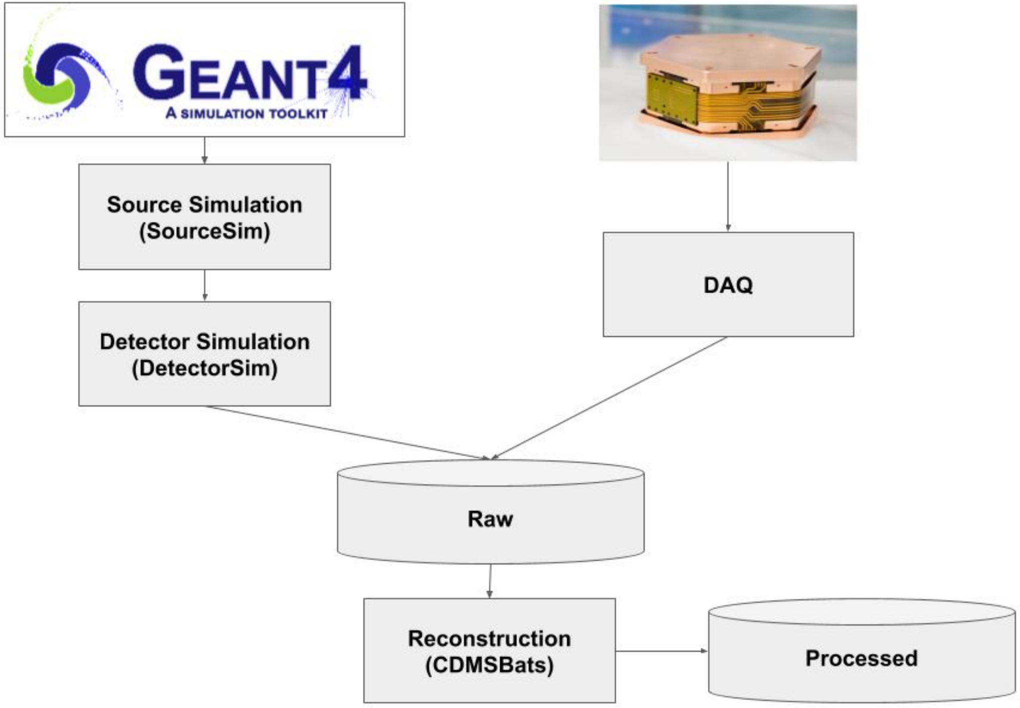
It can be difficult to identify that such an event is actually mismeasured.

(Note that since WIMPs only interact once, the issue here is non-WIMPs that are mismeasured such that they might look like WIMPs.)

Outline

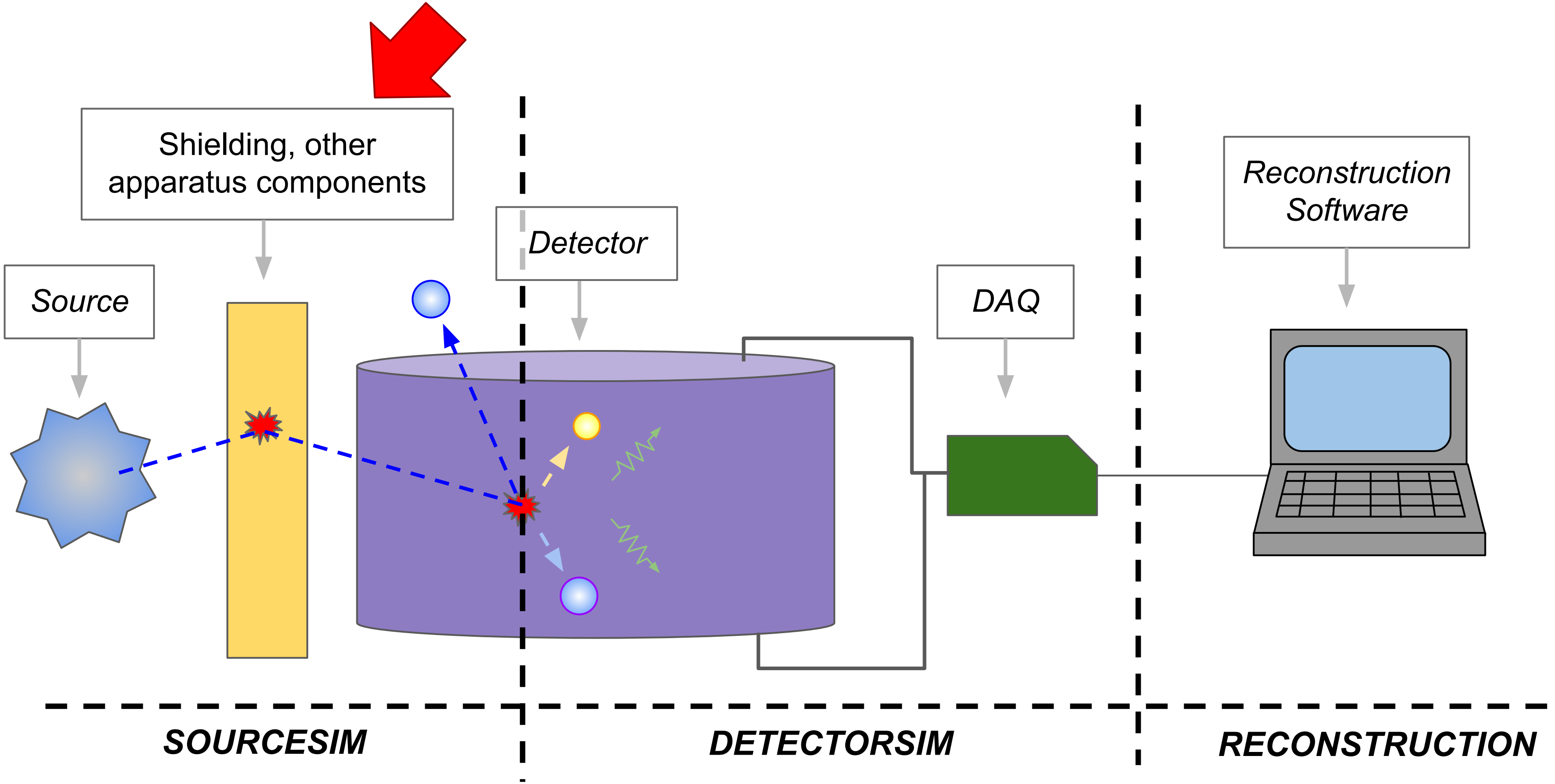
CDMS Simulations

To help analyze/understand 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 reconstruction and analysis software used for real data.



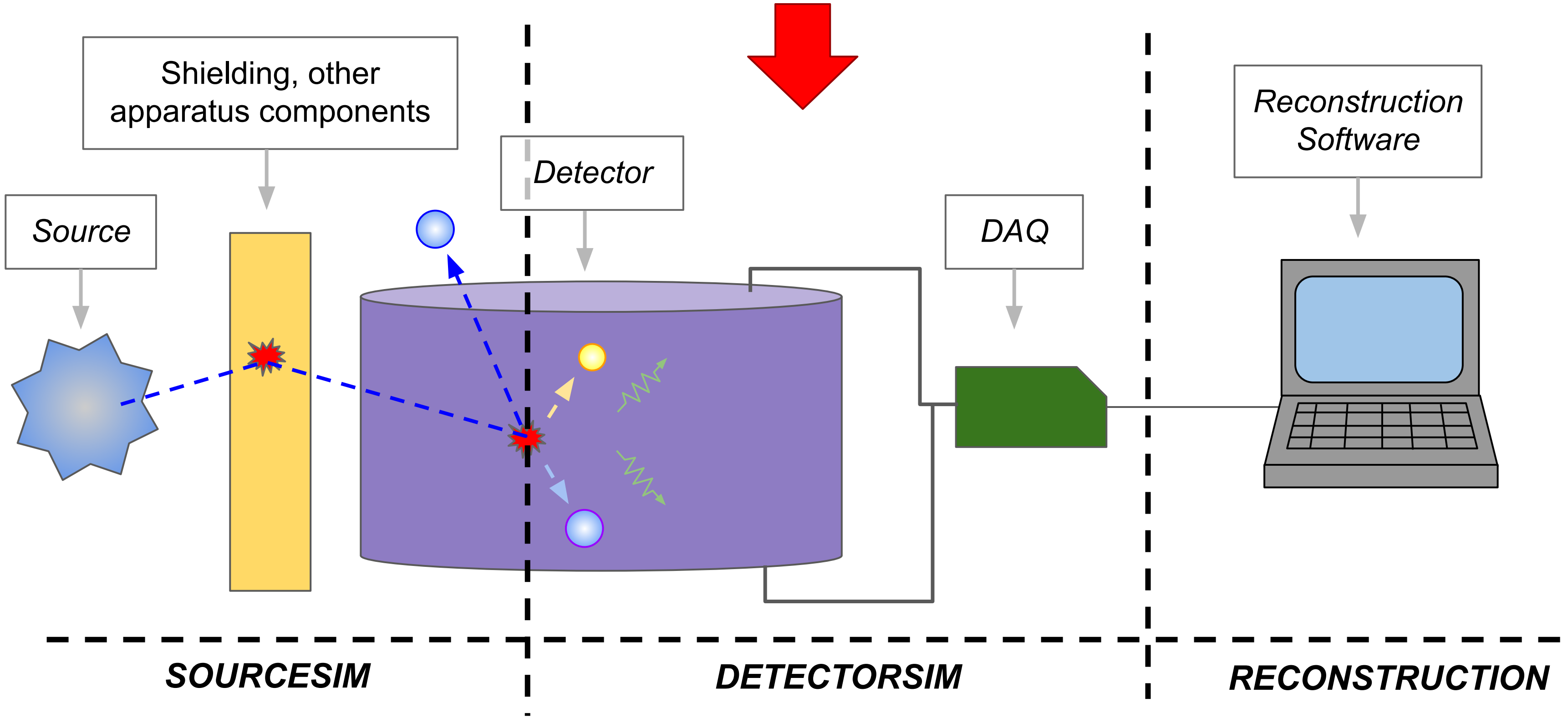
SourceSim

The first stage of the simulation, SourceSim, models incoming particles and their interactions (energy depositions) as they bounce around the geometry of the experimental setup.



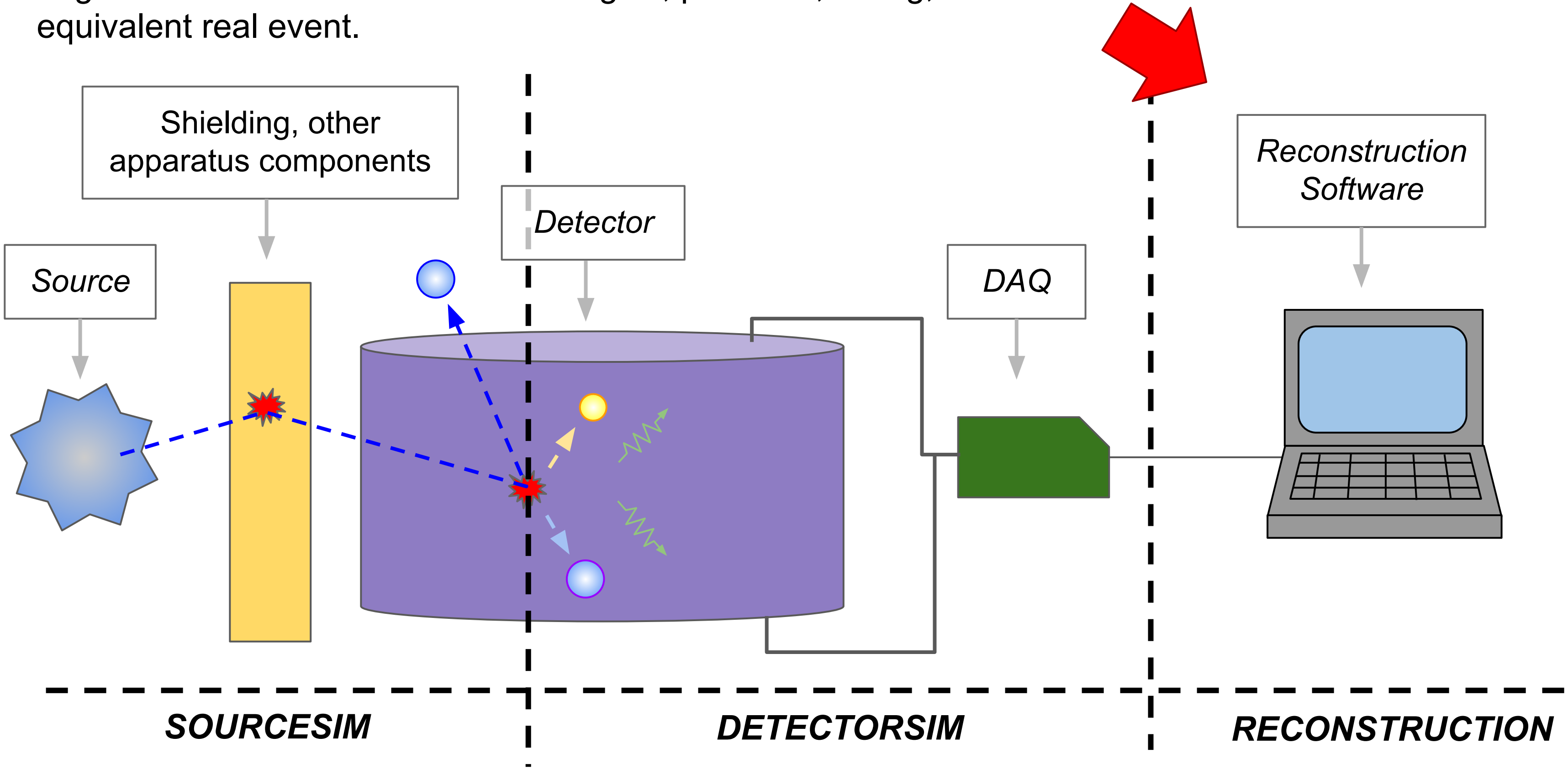
DetectorSim

The next stage, DetectorSim, takes the energy depositions (and types) from SourceSim and models the resulting charge carriers (electrons and holes) and vibrations (phonons) as they propagate to the sensors on the detector faces. It then models the Data Acquisition process to produce a final output file in the same format as would be output by the real DAQ.



Reconstruction

Lastly we run the standard CDMS event reconstruction code, CDMSBats, on the simulated events to get the final determinations of energies, positions, timing, etc. that we would have seen for an equivalent real event.



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Overview of Detector Considerations

In the next section we will look at our simulated Cf-252 data, but first we have some setup to do to explain the detector effects we'll have in mind when looking at Cf-252 data.

In this section we'll do that setup using a set of simpler, idealized samples in which we are able to skip SourceSim and instead directly specify deposited energies, recoil types, and hit locations; since we place all the hits directly in the detector volume–i.e. the "bulk"–we call these "Bulk samples." Since we have such precise control over these samples, they are good for studying specific physical processes in the detectors.

Using these Bulk samples we will:

- Identify "SimFiducial"–a region of the detector where events are reliably well-measured–and "LT Fiducial"–our best approximation of SimFiducial using only real data measurements
- See the effects of "off-electrode" mismeasurements
- See how well energies are collected and how they vary with recoil type
- Estimate which aspects of the simulation chain (and so which components of the real measurement process) contribute most to energy resolution

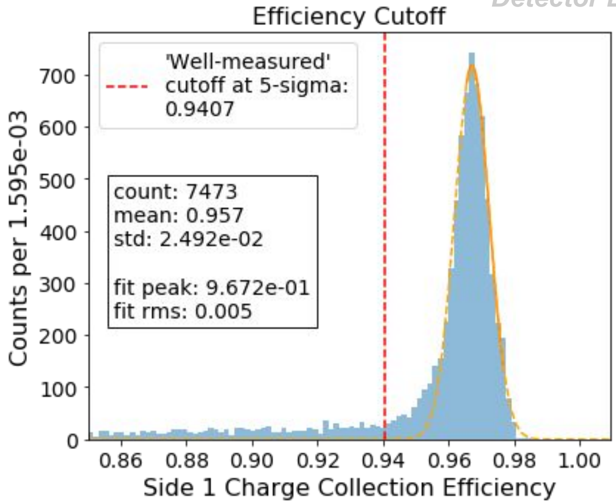
In theory these subjects could have been studied *a priori*, but we've learned the most about them from simulation results.

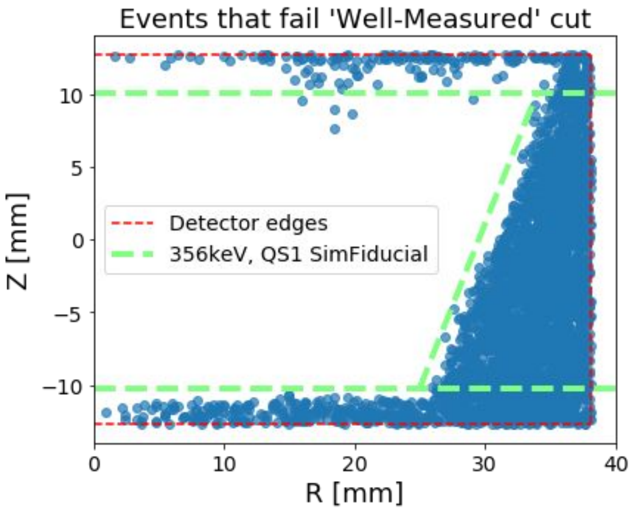
SimFiducial

First we want to determine where, physically, in the detector events are "well-measured." We quantify this with the "collection efficiency," which is the ratio of energy collected by the sensors at the detector faces to the energy originally deposited.

- Top plot: The collection efficiency for electrons being collected on top of the detector*. We see a peak of well-measured events and a tail of poorly-measured events below that.
- Bottom: hit locations in Z/R for "poorly-measured" events. We see they're mostly "edge" and "face" events framing a trapezoidal region of the detector, with only a few events leaking inside the marked boundaries. We call this region "SimFiducial".

**We repeated this process for holes and phonons, but electrons turned out to be the limiting factor.*





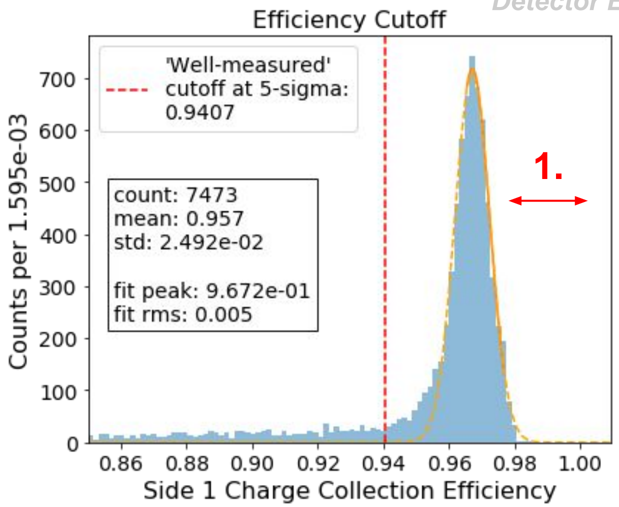
SimFiducial Details

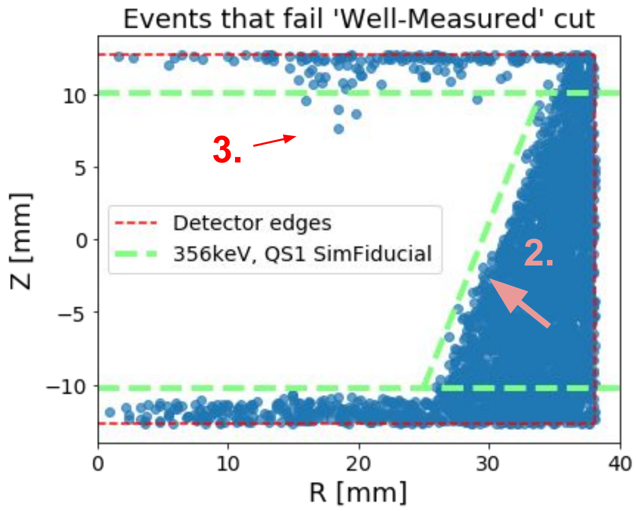
We have three details to explain:

1. The “well-measured” peak is below 1 (i.e. 100% efficiency) due to off-electrode effects: some events have it worse than others (stay tuned) but *all* events lose some energy because of it*.

2. SimFiducial is trapezoidal due to the motion of electrons in a germanium crystal like our detectors. Due to solid-state physics we won’t cover here, electrons (not holes) move diagonally. The radial edge of SimFiducial is sloped because electrons freed past that boundary can move sideways enough to stick on the sidewall (i.e. the angle is due to electron edge events)

3. There are a few poorly-measured events inside our marked SimFiducial region. These also are due to off-electrode effects–and are simply some of the worst-affected.



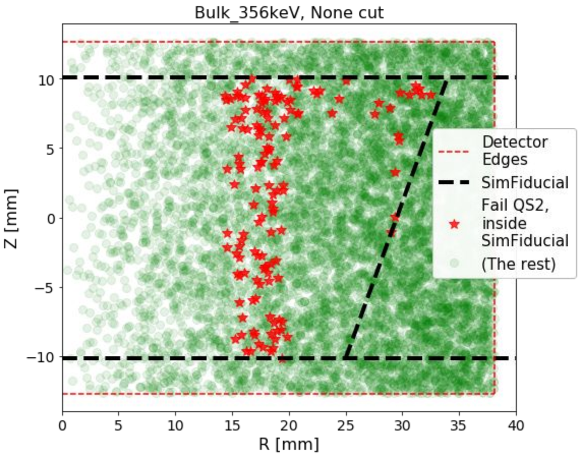


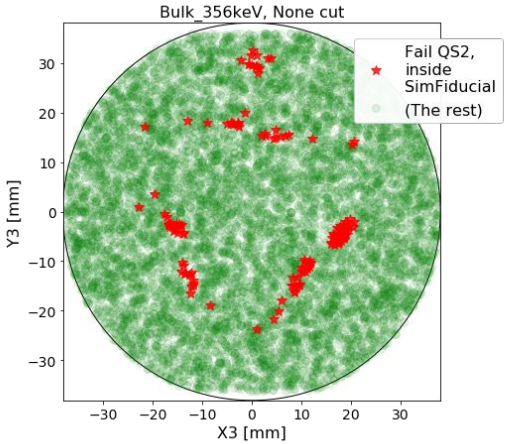
*Though a simulation artifact may be making it worse than it should be for phonons.

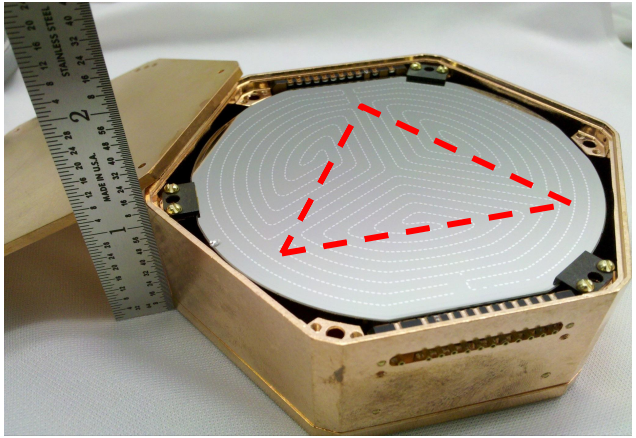
Off-Electrode Effects In SimFiducial

The very worst of the off-electrode effects show up most clearly for holes on the bottom side of the detector, as shown in the left two plots below. We see they favor a particular triangle in X/Y–which corresponds to the highest density of electrode bends on the iZIP5. The worst such events show up here because the electric fields are weaker near the bends, so more charges can miss electrodes.

The frequency of such events and their proximity to the electrode bends is why we didn't just pick a smaller SimFiducial region in the first place.







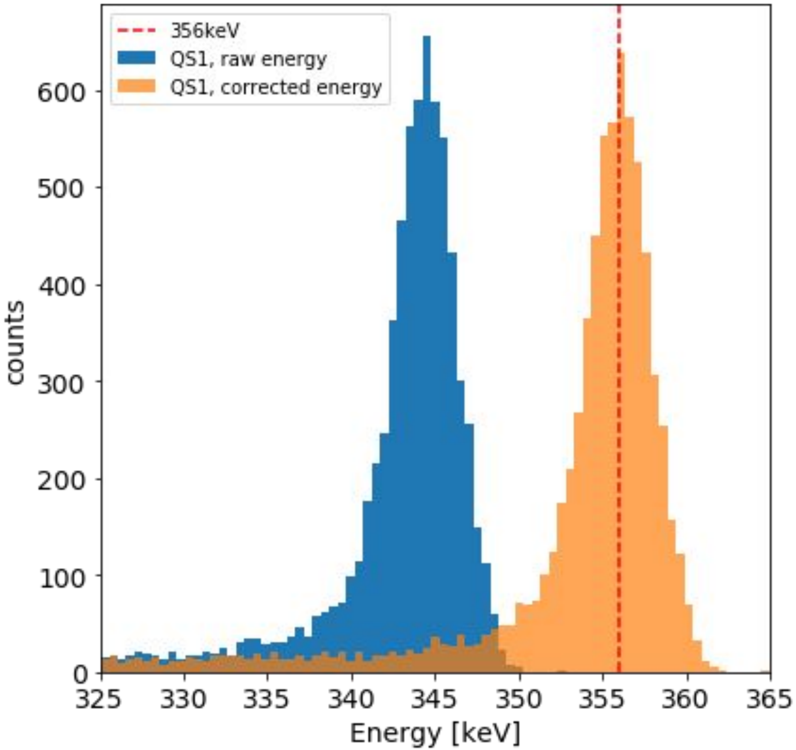
Calibrating Energies with Efficiencies

Since the detectors don't collect energy with 100% efficiency, we have to calibrate the results: by multiplying the collected energies by the value of the collection efficiency peak, we obtain our best-estimates of the true energy.

The plot at the right, for example, shows a sample that only had energy deposits of 356 keV. The best-measured events were centered around 345 keV instead, but we can rescale them back up.

We expect these efficiencies/calibration factors to correspond to a given particle (i.e. electron, hole, or phonon) and detector type, so they should apply across all samples… but we'll see later that phonons have different efficiencies between ERs and NRs.

Bulk Sample: 356 keV ERs



LTFiducial

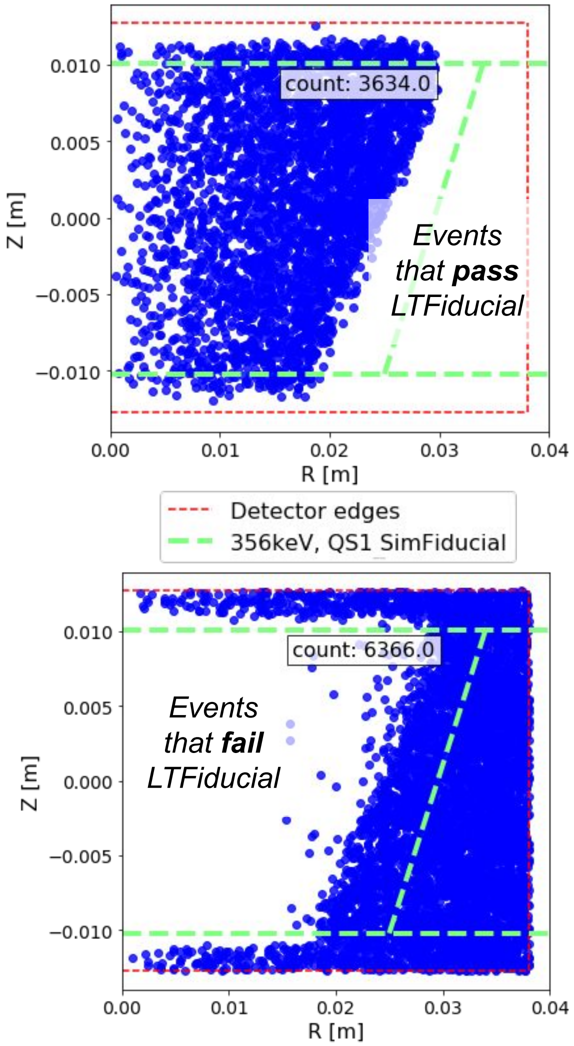
Ideally we would be able to select only events in SimFiducial since those are the most reliable. But real data doesn't have exact position information, so now we switch to a proxy set of cuts used in the real analysis that uses only information available in real data; we call this SimFiducial alternative "LTFiducial."

We set two main requirements for LTFiducial:

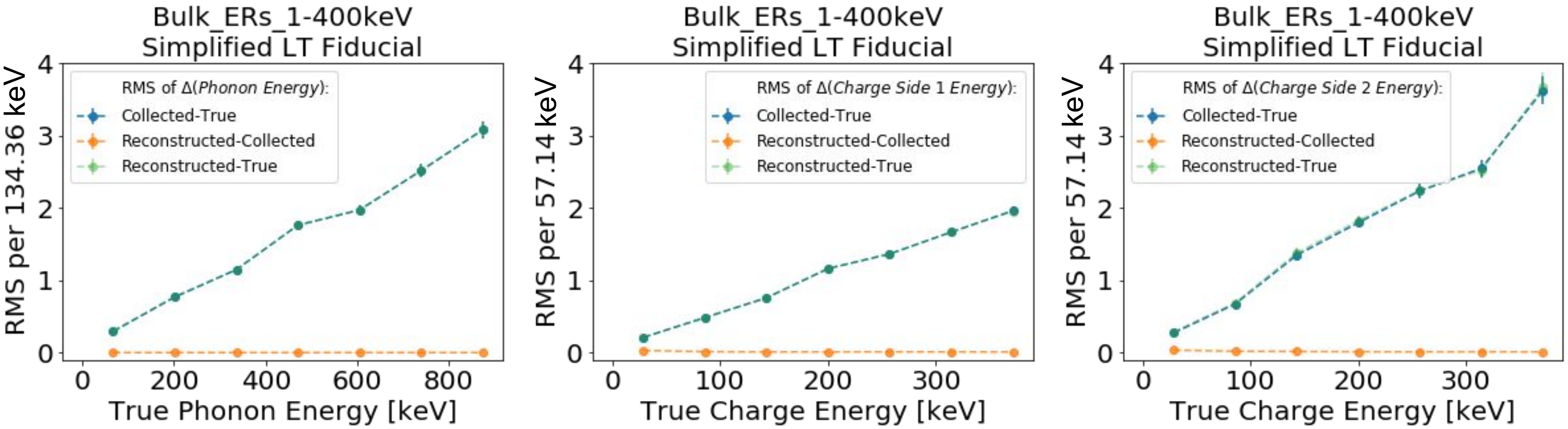
- That very little energy be deposited at high radii.
- That the top and bottom of the detector measure similar charge energies.

These requirements help avoid edge events–where mismeasurements are expected–though they're not as exact as SimFiducial. See at right how there are a few events that pass despite being close to the detector faces, for example.

We see that LTFiducial selects events similar to those in SimFiducial, though it passes fewer events overall (36% compared to 49%--for single-hit events, at least).

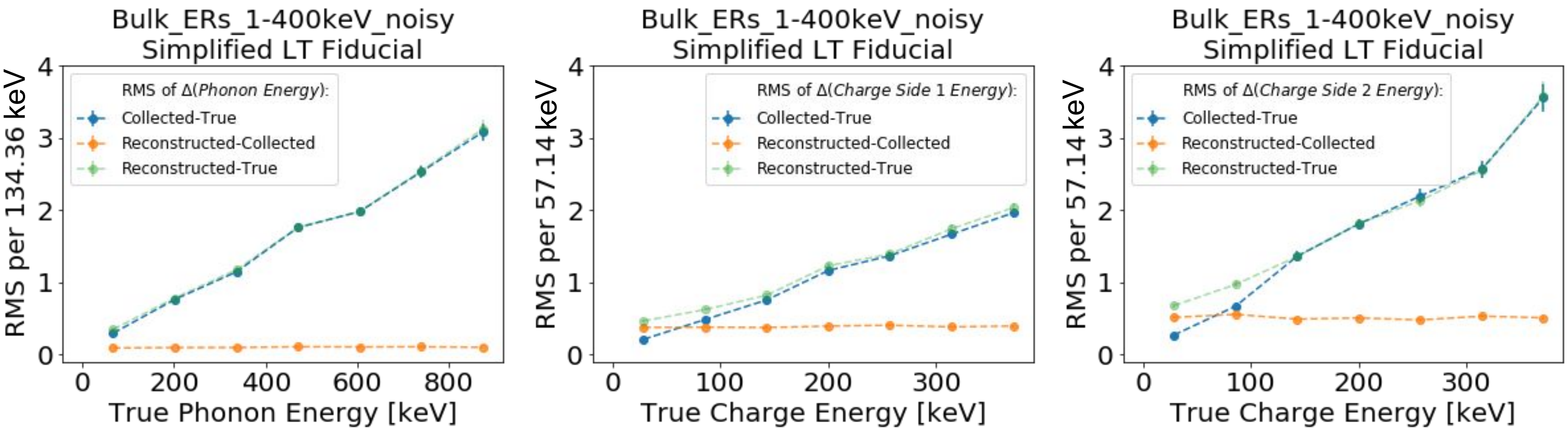


Energy Resolution by Processing Stage



We'll see later that simulated energy resolutions tend to be much better (i.e. smaller) than real-data resolutions. Here, for a simple sample of ERs between 1 and 400 keV–with LT Fiducial requirements–we check what stages of processing contribute the most–and see that the total resolution is overwhelmingly due to SourceSim and DetectorSim processes.

Energy Resolution by Processing Stage (with Noise)



For simulations, we have the option of adding noise (whereas real data always has it). The previous slide was noiseless; here we add noise to the same sample and find that it only has significant impact on the final charge energy resolution at lowest energies. Note that the resolutions between stages add in quadrature.

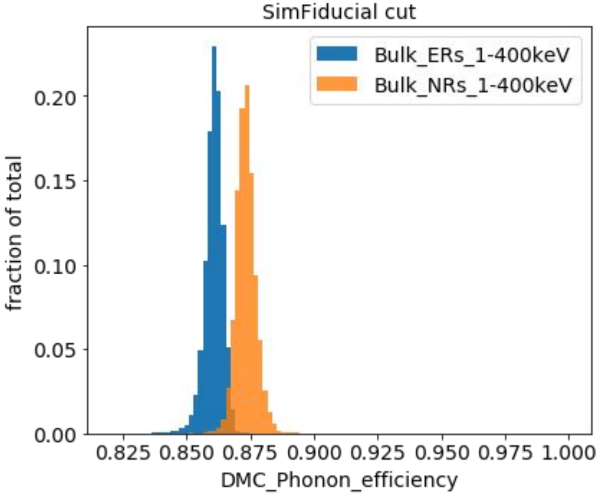
Phonon Efficiency Differences Between ERs and NRs

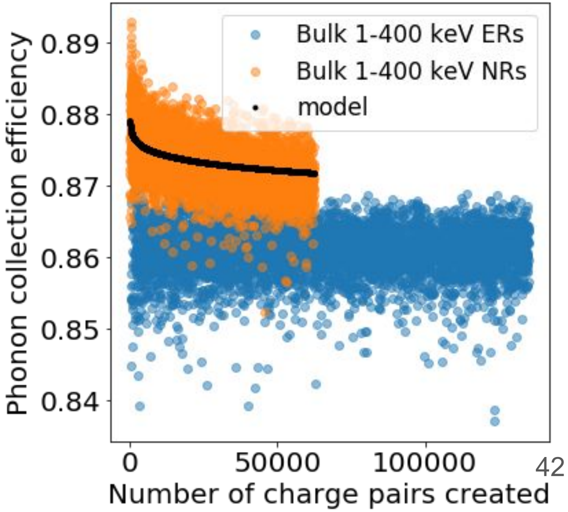
We noted previously that the phonon efficiencies/calibrations change between ER and NR samples. The plots to the right show this: the two plotted samples–one with ERs and the other with NRs–have the same electron and hole collection efficiencies (not shown) but the NR sample has higher phonon efficiencies.

We believe there is a real difference here due to off-electrode effects:

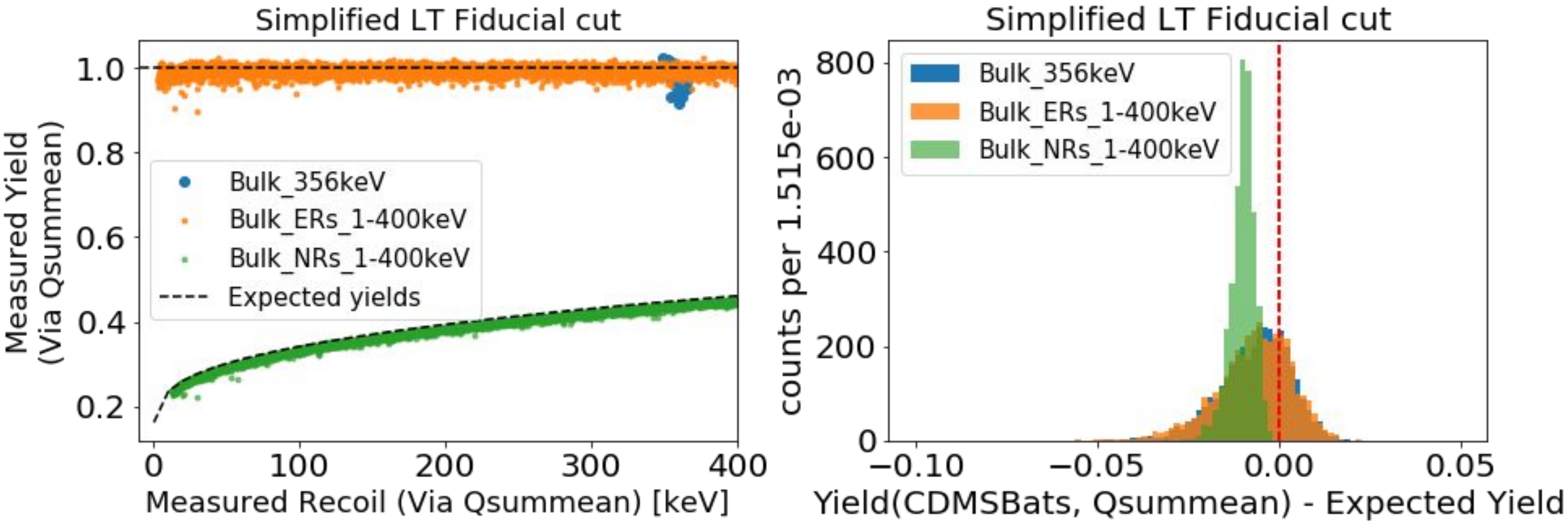
- When charges miss electrodes, they do not emit all the NTL phonons they should.
- But NRs send only some fraction of their energy to the charge system, where it might be "lost" in this manner. Prompt phonons from the original hit are unaffected.
- Therefore the NRs appear to have higher collection efficiencies than ERs–not because NTL and prompt phonons are actually very different, but because some of the former aren't emitted as expected.

…However, the difference between ERs and NRs seen here is exacerbated by a simulation artifact that loses more energy from NTL phonons than prompt phonons (i.e. more from than ERs than NRs).





Yields for Bulk Samples



While we're here, we finish with our Bulk samples by checking their yields as constructed by the final, reconstructed quantities. We see ERs and NRs at the yields we expect them, though they're all slightly low–NRs more so than ERs–which we blame on off-electrode effects.

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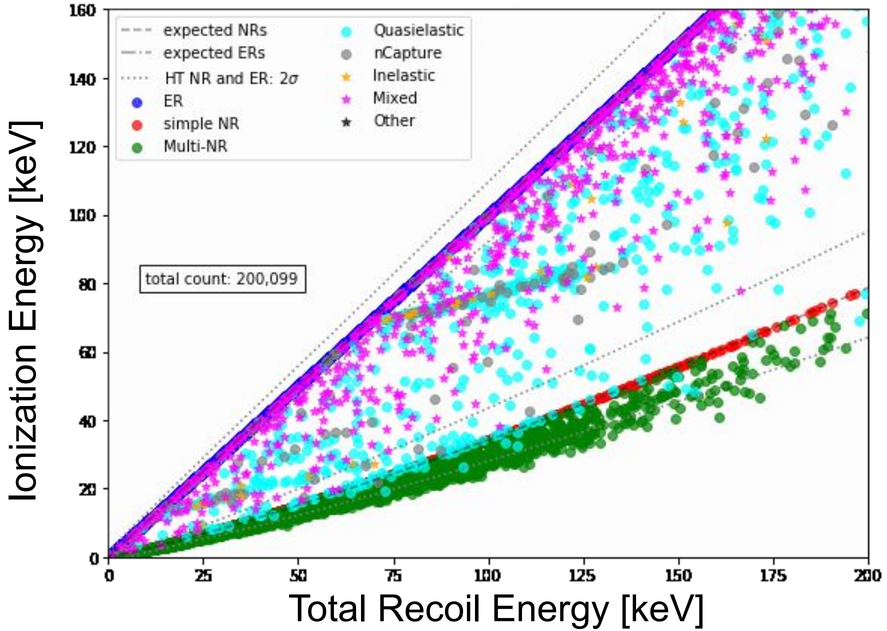
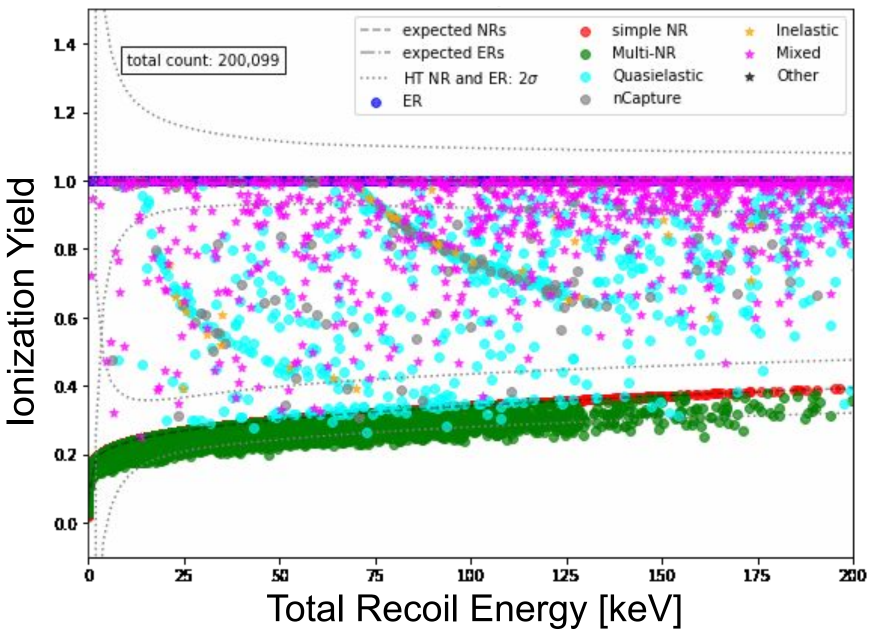
Cf-252 Recoil Type Yields in SourceSim (1/2)





Ultimately we want to check how the reconstructed yields at the end of the simulation chain compare to the yields of real data. But here we first check the yield at the SourceSim stage to see what the complicated recoil types discussed previously “should” look like before any mismeasurements in the detector occur.

We see the ERs and simple NRs right where they should be and the events with both ER and NR effects in-between–and finally the multi-NRs below the NR line, as expected.

Cf-252 Recoil Type Yields in SourceSim (2/2)

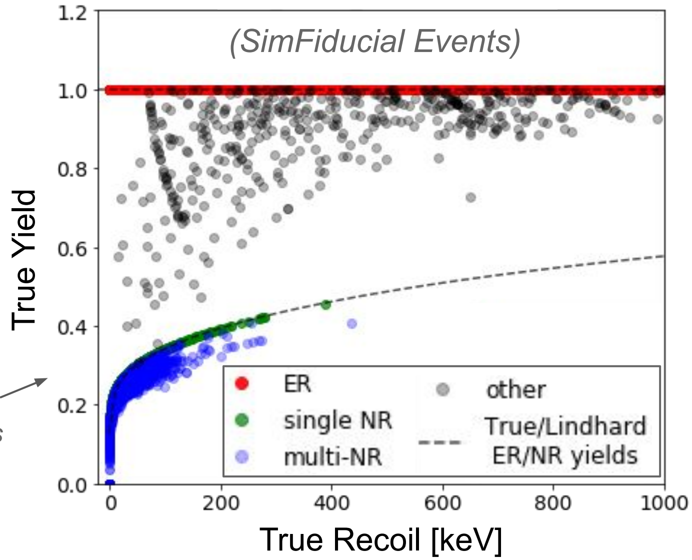
This table quantifies how much of each type of recoil appears significant distance away from the main ER and NR bands.

Again this is all *without mismeasurements*–and we see that a significant proportion–if not a majority–of the more complicated recoil types appear naturally somewhere other than the ER and NR bands.

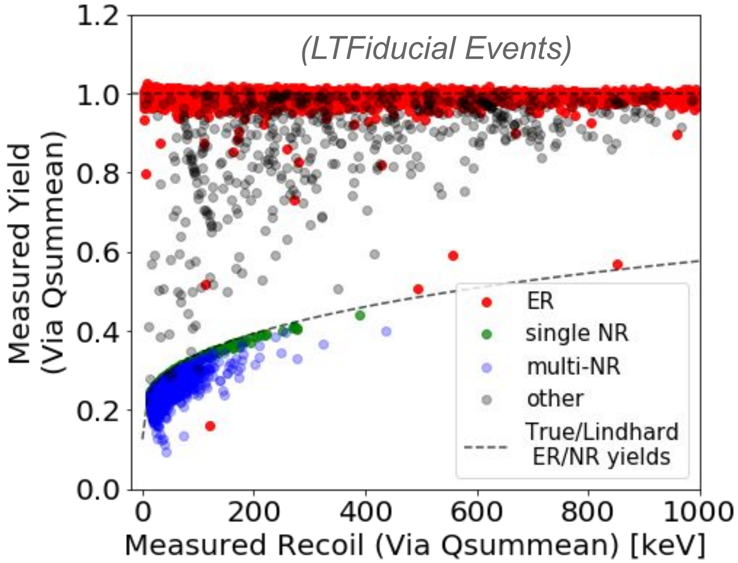
The multi-NRs are notable in particular because so many of them are not on the NR band, but are close enough to obscure its boundary; in real data–where there is no color-coding, they would make the NRs appear systematically low.

Deposition Type	Fraction of depositions [%]	Amount more than 1% away from ER and NR bands [%]
ER	65.53	0
Simple NR	17.00	0
Multi-NR	12.02	97.33 ± 0.64
Quasielastic	1.48	88.16 ± 1.73
nCapture	1.03	19.68 ± 0.98
Inelastic	0.06	97.32 ± 9.32
Mixed	2.89	37.85 ± 0.81
Other	0.0005	0

Cf-252 Recoil Types Yields Before and After Reconstruction



(same kind of data as previous slides, but different Cf-252 sample)



Here we check how the yields change between SourceSim (left) and the final Reconstructed results (right).
We see:

- Detector mismeasurements cause some ERs to drop down close to the NR band (stay tuned)
- Resolutions have generally increased

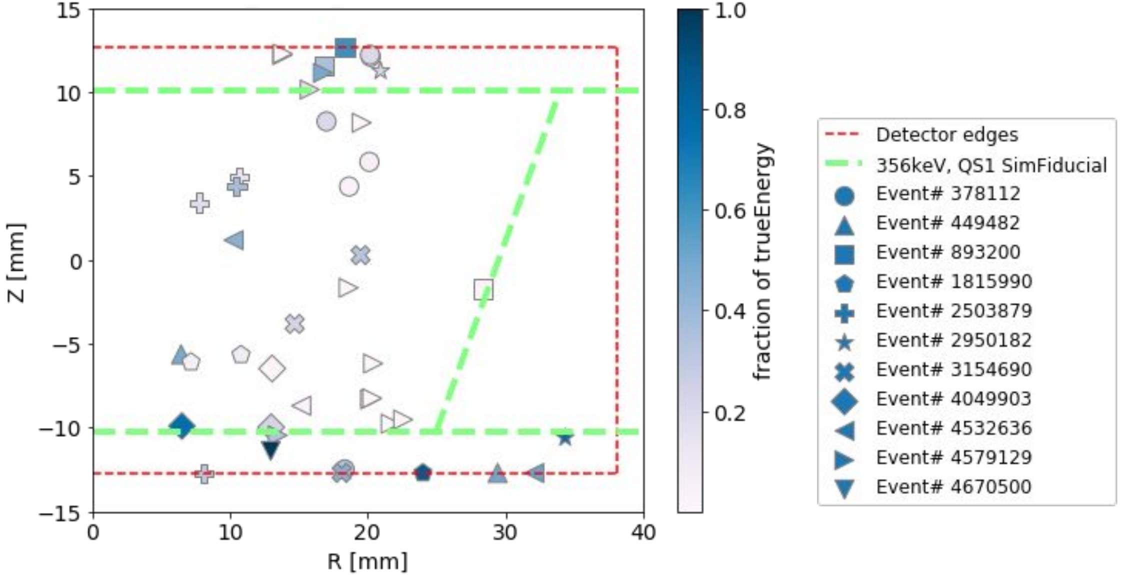
It’s good that the same structures are largely visible, though of course real data won’t have color-coding to help identify them.

Cf-252 Semi-Fiducial Events

Shown here are the hit locations of the events on the previous slide that were worst-measured in the reconstructed data.

We see they're nearly all semi-fiducial events: they have hits outside SimFiducial that are likely mismeasured–but also hits inside SimFiducial that make the event appear well-measured enough to pass LTFiducial (or otherwise are right at the SimFiducial edge).

Worst-mismeasured events of Simulated Cf-252



Conclusions from Cf-252 Simulations

Before comparing this simulated data to real data next, we summarize a few things we learn from simulation:

- Though we'd like events to be either ERs or NRs–and on their respective yield bands–the more complicated recoil types naturally fall in-between those bands. For real data, this means that distinguishing between ERs and NRs and estimating the amount of mismeasurements is difficult.

- It would therefore be helpful (for future analyzers) to determine some new data selection criteria:
  - A cut for multi-hit events (that is, multiple hits within one detector) could remove the most complicated events.
  - A semi-fiducial cut could at least remove most of the worst-mismeasured events.

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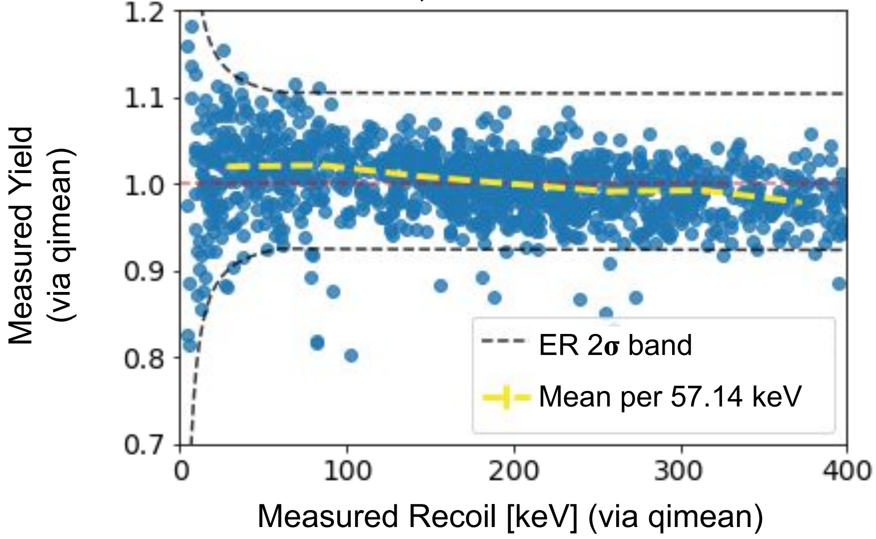
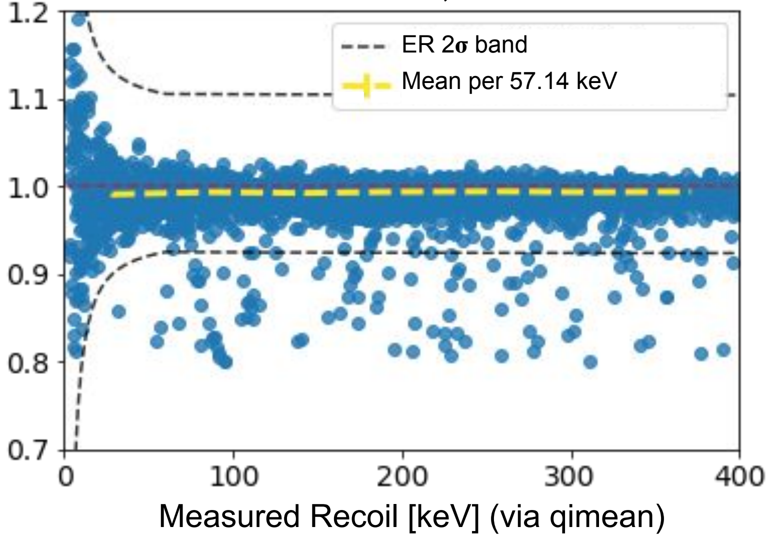
Photon Response in CDMS Detectors: Cf-252 ER Yields

Real Cf-252, EStem + Soudan Cuts



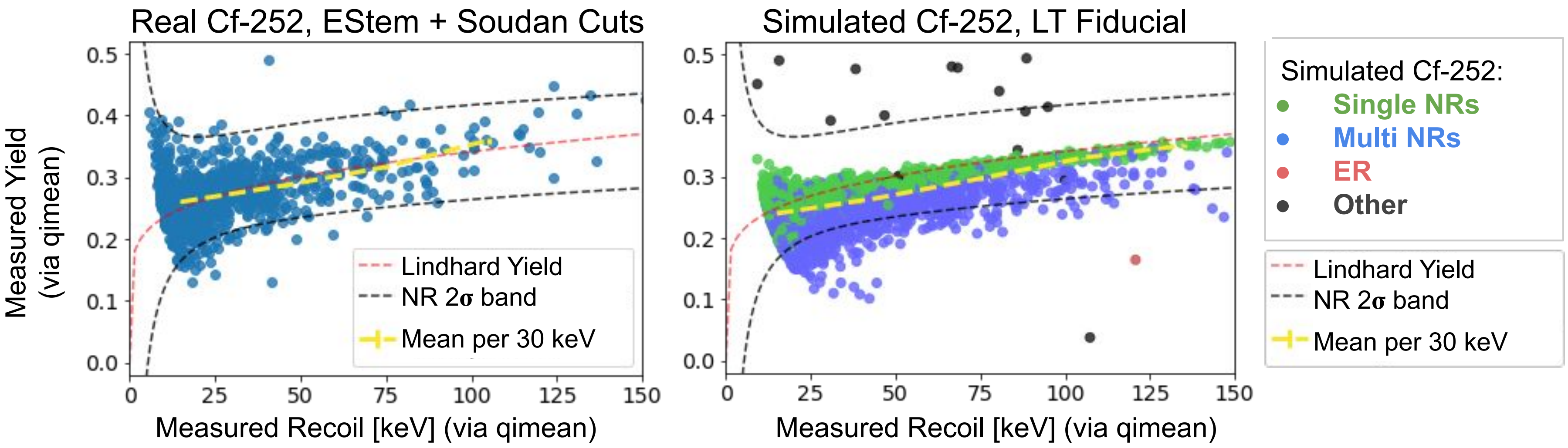
Simulated Cf-252, LT Fiducial



Recall our goal is to see what we can learn about real data (left) from simulated data (right)--and to do this we want to see how well they match first–beginning with the simpler ER band. We see that the samples are similar, but do have slight qualitative differences:

- The real data's yields start slightly high and go low around 200 keV (suggesting some additional calibration is needed) while the simulated yields are more constant, but low (likely due to off-electrode effects).
- The simulated resolution is smaller than that for the real data.

Neutron Response in CDMS Detectors: Cf-252 NR Yields



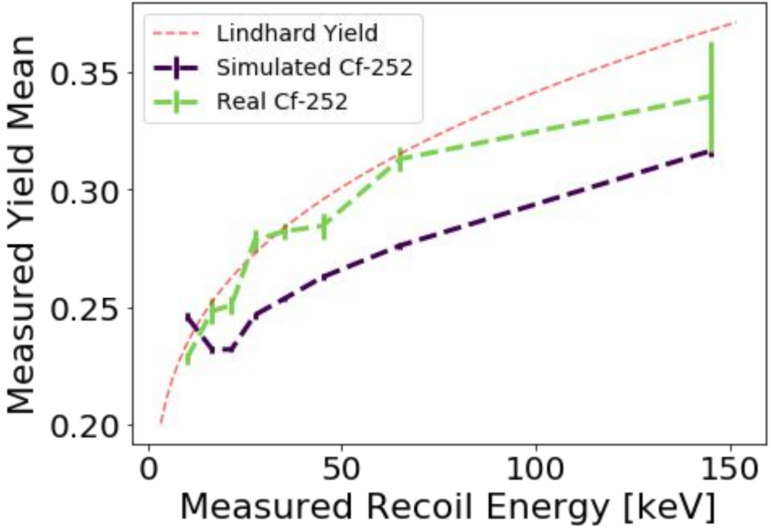
For the the NR band, we focus on recoils below 150 keV since events start getting sparse beyond that.

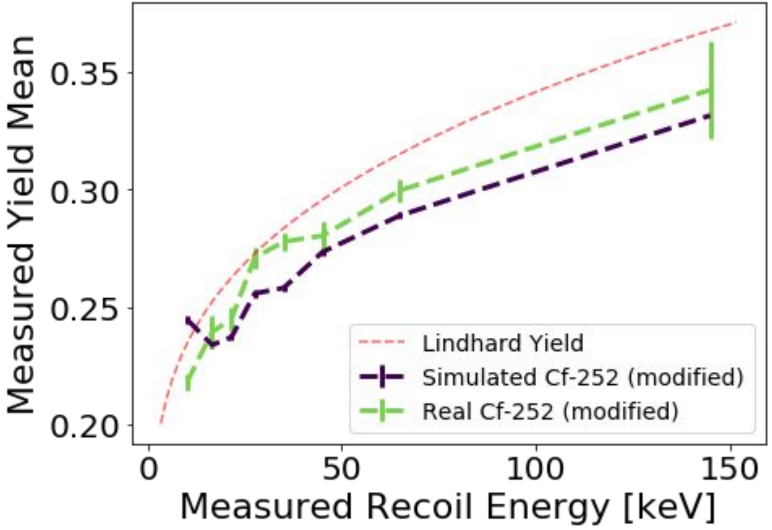
The real data tracks the expected Lindhard Yield fairly well (maybe too well, considering multi-NRs)–but in the simulated data:

- While the single-NR means appear to track the expectation well, the overall yield is pulled down by multi-NR events (which make up roughly 50% of all NR events at all energies and so aren't ignorable).
- The resolution is again smaller as well.

We suspect that outsized off-electrode effects–which throw off NR efficiencies–account for some of these differences as well.

NR Yield Means: Real vs. Simulated



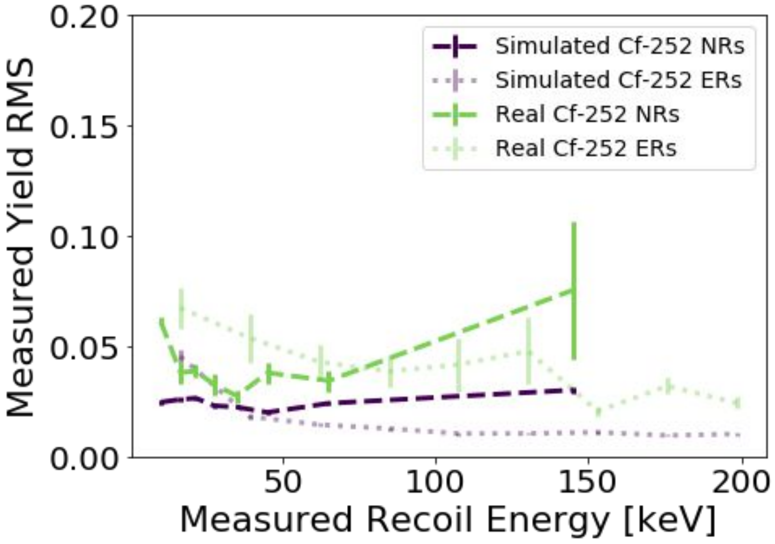


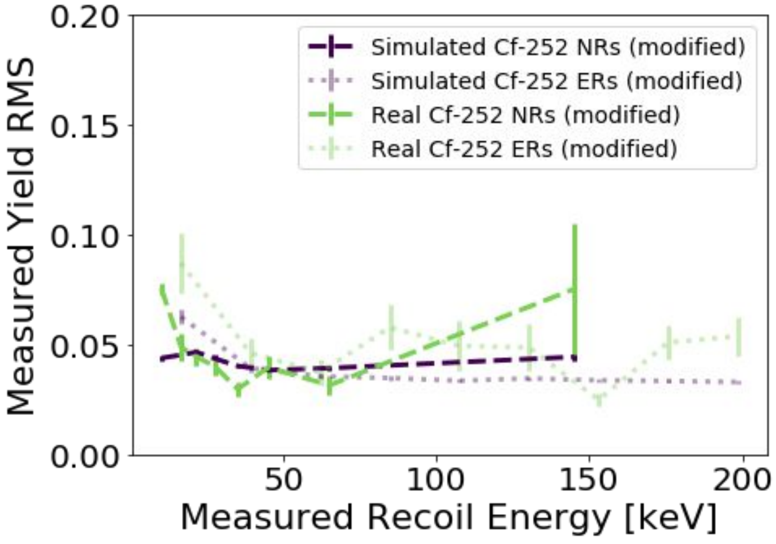
To account (somewhat) for the differences in the means of the NR yields, we note that they become much more similar if we introduce two modifications (original data at left, modified data at right):

- Remove (or mitigate) off-electrode effects in simulated data; recall these both lower our collection efficiencies (and resulting yields) and make ERs and NRs differ more than they likely should*.
- Recalibrate the real data so its ER band is centered at 1 at lower energies (recall it had a slope that probably needs calibrating-out anyways). This drops the yields below the Lindhard Yield, but that is a reasonable place due to multi-NRs.

*There's currently no way to measure the magnitude of off-electrode effects in real data to confirm.

NR Yield Resolutions: Real vs. Simulated





For the resolution differences between real and simulated data, we've found that the difference between real and simulated NRs is about the same as the difference for ERs. Adding 0.0305 in quadrature to both makes the real and simulated data match well for both. Though we don't know exactly what the cause is, this suggests there may be a single simulation change that could fix the resolution for both recoil types at once.

Conclusions From Real and Simulated Cf-252

To summarize:

- In broad strokes, simulated Cf-252 matches real Cf-252 in yield.
- Simulations have lower yield values than real data, but this may be due to off-electrode effects (which may be getting blown out of proportion by a simulation artifact we'll be fixing going forward), but they can be made to agree with relatively simple corrections.
- Simulations also have lower resolutions, but the differences appear to be the same between ERs and NRs, suggesting there could be a single fix for both in simulations.

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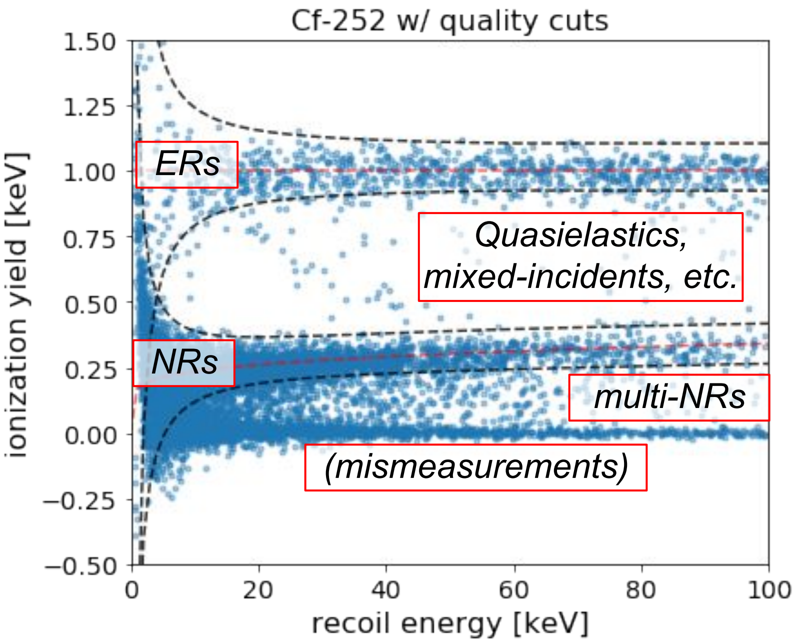
Takeaways (1/2)

Our main takeaways from our Cf-252 studies:

- There are events that look poorly-measured but aren't: quasielastics, neutron captures, etc. that have measured yields between those for plain ERs and NRs. Finding some criteria that could exclude them in real data would be useful for helping pick out plain ERs and NRs–but not help with mismeasurements.

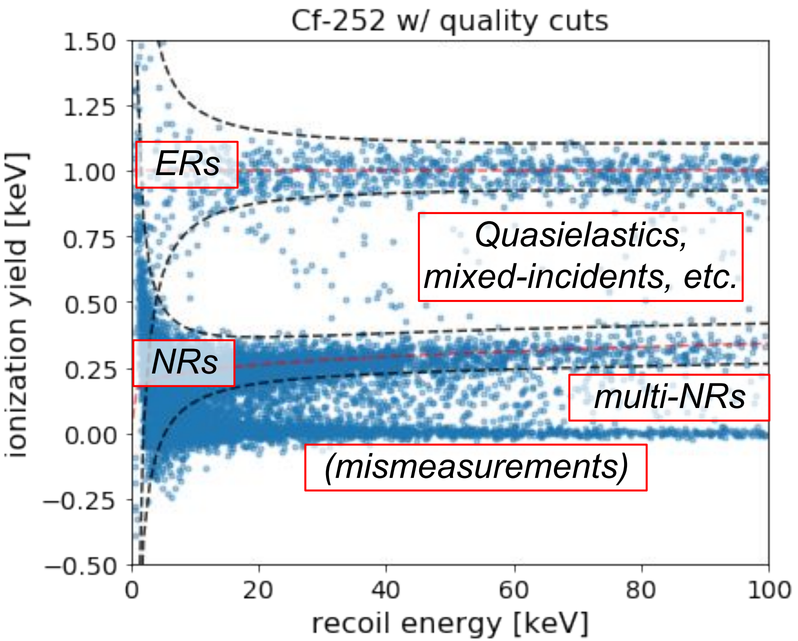
- Conversely, there are events that look well-measured but aren't: semi-fiducial events in which hits inside the detector fiducial region appear to have all their energy collected, but other hits outside the fiducial region lose energy. These include ERs that look like NRs.

- We see off-electrode effects that both drain the energies of all events and make the NR phonon efficiencies differ from the ER phonon efficiencies.



Takeaways (2/2)

- LTFiducial–that is, data selection criteria using only information available in real data–is a good first approximation of SimFiducial, but semi-fiducial events in particular can slip through it.
- Multi-NR events may look like normal NRs, but are consistently low in yield; if we can't differentiate between them, we'll measure NRs low. It's unclear how to account for this in real data.
- Simulations have lower resolutions than real data, but it appears to be the same difference for both ERs and NRs, suggesting there could be a single fix for both.



Next-Steps For Future Scientists

From these results we’ve got several jumping-off points:

- Tune the LTFiducial requirements to get more of the well-measured events at higher radii from SimFiducial, but exclude events close to the detector faces.
- Determine criteria for excluding multi-hit events, since WIMPs will only interact once and multi-hit events can create complications and mismeasurement modes that make distinguishing ERs and NRs harder.
- Study off-electrode effects further, as we don't have a method of measuring them in real data and it’s unclear how much effect they should be having in simulations (in terms of both overall energy loss and making NR efficiencies differ from ER efficiencies).
- (Finish other simulation upgrades not covered here: Cf-252 fission details, inner-workings of the TES/FET circuits, etc.).

Conclusion

- There is good reason to believe there is some kind of invisible particle in the universe accounting for the motion of galaxies–among other things.
- CDMS hopes to detect this particle by seeing it interact directly with extremely sensitive detectors.
- We are building up a simulations framework to better understand the CDMS experiment and detector response.
- Simulating Cf-252 gives us insight into many of the processes that affect how well particle interactions can be distinguished.
- We see good general agreement between simulated data and real data, though with some differences to study.
- We've been able to identify several factors not easily seen or measured in real data (e.g. off-electrode effects, semi-fiducial events) that contribute to mismeasurements.

With simulations providing insight into how detectors respond to particles, we are better prepared to narrow down the potential behavior of dark matter.

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