Texas A&M University
Department of Physics and Astronomy

Simulation of Dark Matter and Standard Model Interactions in the SuperCDMS Soudan Experiment

Final Examination

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Overview

I. Introduction and Motivation: Searching for Dark Matter

II. The *Super Cryogenic Dark Matter Search* Experiment

III. Overview of this Work: Simulations of Dark Matter and Standard Model Interactions in the Detectors

IV. The Simulations Infrastructure

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VI. Fully Simulated Background and Signal Events

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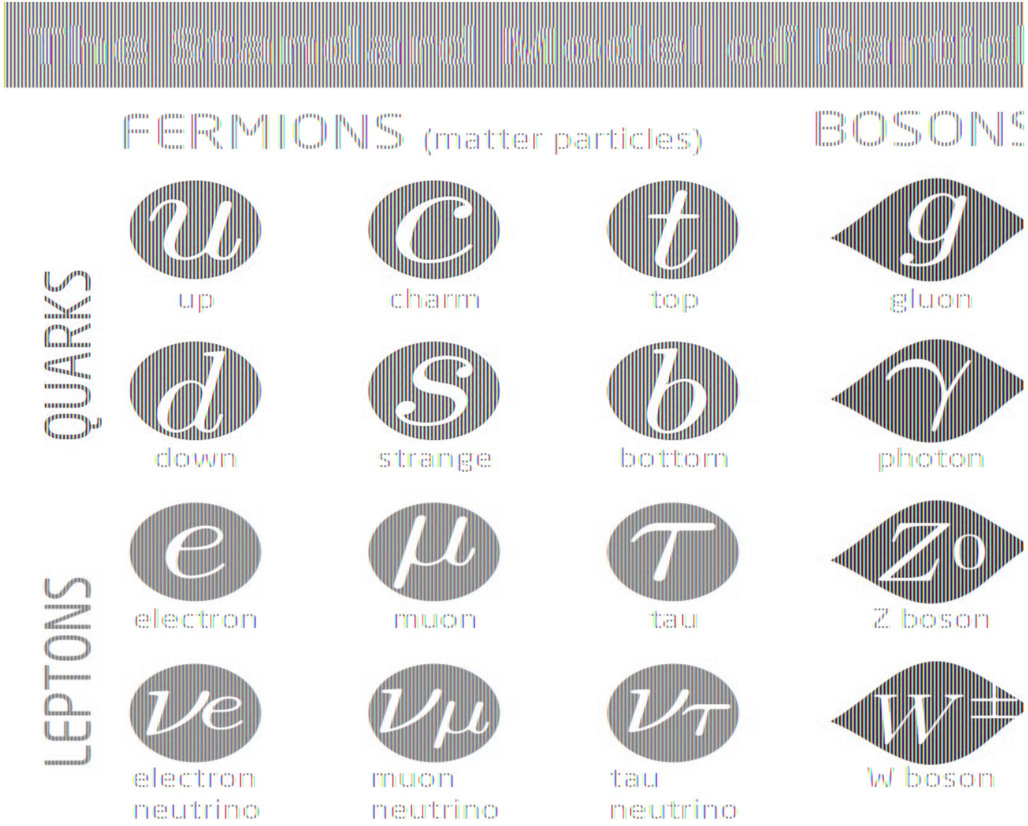
I. Introduction and Motivation: Searching for Dark Matter

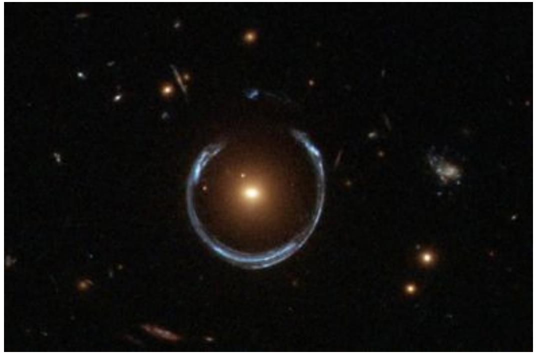
Dark Matter Is Not Explained By The Standard Model

- There is significant evidence for the existence of an unknown substance called dark matter (more on this in next page)
- The Standard Model (SM) is the quantum field theory that describes the known particles and their interactions
- It has been incredibly successful at predicting the existence of many other particles whilst describing the ones known since before the model
- The Standard Model provides no explanation of the dark matter in the universe



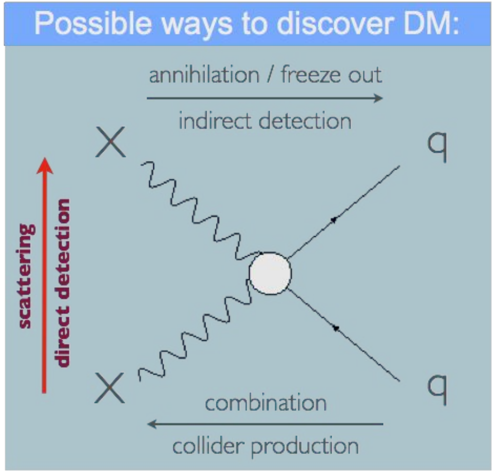
Dark Matter and Existence of WIMPs

- It is observed that Dark Matter is 85% of the gravitational mass of the Universe, yet it has never been directly measured
- Summary of evidence for Dark Matter:
  - Rotational velocity of stars in outer parts of galaxies suggests greater than visible (light-interacting) mass. Dark matter is distributed in a large halo filling each galaxy, including our own Milky Way
  - Gravitational bend (Einstein ring) suggests greater than observed mass
  - Cosmic Background Radiation measurements indicate that there is a large amount of mass in the universe not in atoms (or SM particles)
  - Colliding clusters of galaxies provide evidence that DM is likely to be a particle
- Simplest guess is that DM is a WIMP:
  - Weakly interacting, Massive Particle
  - Neutral, but neutrinos are ruled out
  - Most believe it must be a new type of particle (example theories are Supersymmetry and Dark Sector)



Possible Ways of Detecting WIMPs

- Looking at the non-gravitational WIMP interaction/coupling with the Standard Model
  - Indirect Detection:
    Astronomical observations from WIMP annihilation which will produce "anomalous" high energy SM particles
  - Collider Production:
    High energy collisions of SM particles, producing WIMPs
  - **Direct Detection**:
    Earth is expected to be immersed in the Dark Matter of the Milky Way so it should be flowing through the detectors and hopefully we can detect an interaction. *This work is about searching for WIMPs this way*



- **Current state of the art:**
  - WIMPs haven't been found by any experiment, but many are looking
  - Limits on the likelihood of interaction and its dependence on the WIMP mass keep pushing to better sensitivities
  - The *Cryogenic Dark Matter Search Experiment* **(SuperCDMS)** is particularly competitive at looking for low (keV) energy deposits from a single dark matter interaction

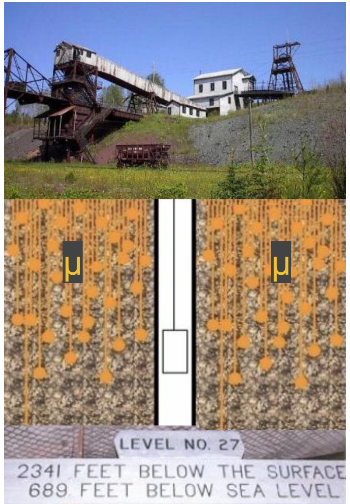
II. The Super Cryogenic Dark Matter Search Experiment

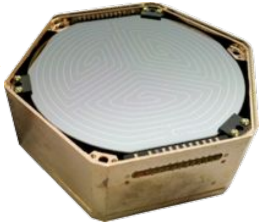
Quick Overview of the SuperCDMS Experiment

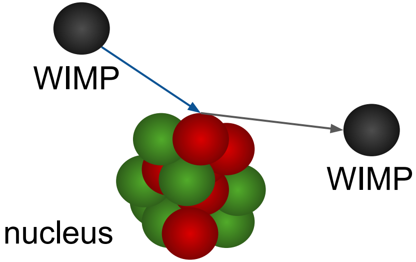
- The *Super Cryogenic Dark Matter Search Experiment* (SuperCDMS) is an experiment looking for dark matter via direct measurement of a dark matter interaction (event) in the detector
- The experiment separates between dark matter interactions (**signal** events) and other interactions (**background** events) from known sources which mimic them
- SuperCDMS is most competitive for low energies, and the challenge is to have selection criteria that choose events (a sample) which balance getting as many signal events as possible with as few background events as possible
- Sophisticated tools are being developed to optimize the signal to background discrimination, and range from high quality detectors to accurate reconstruction algorithms
- Simulations are likely to be the key component for the next generation analyses, given the challenge of discriminating signal from background
- This work is about laying ground for a simulation-based dark matter search analysis with the *SuperCDMS*

The SuperCDMS Experiment

- Earth is moving through the Dark Matter halo of the Milky Way
- We are looking for an interaction between a WIMP and a heavy nucleus in a sensitive detector. A WIMP would interact primarily with the nucleus in the crystal and produce vibrations in it (other models suggest interactions of WIMPs and electrons but are not considered in this talk)
- Detector is deep underground (~2300 feet) to block particles coming from to space that could fake a WIMP interaction
- The experiment is shielded to prevent other types of radioactive decays in the mine producing high energy particles that might reach the detector from entering into our data

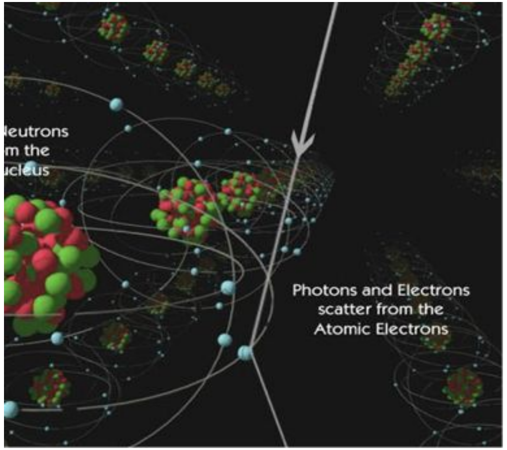


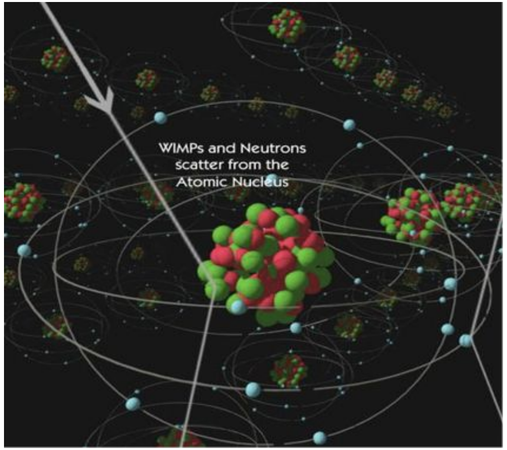




The SuperCDMS Detectors

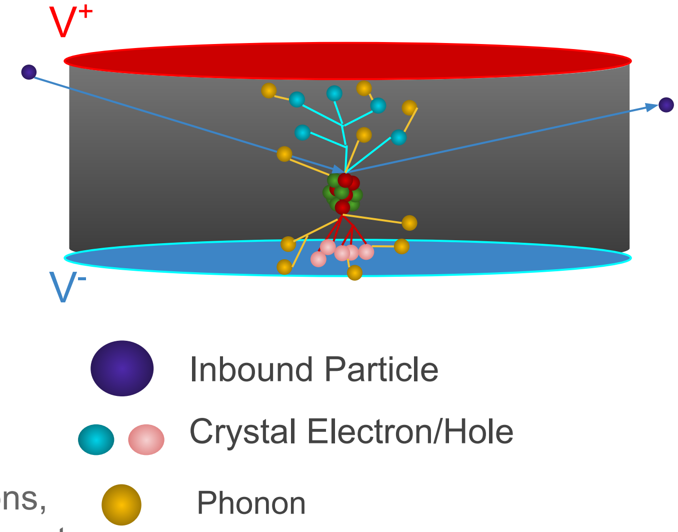
- The Super Cryogenic Dark Matter Search detectors are germanium (and silicon) crystals, with sensitive readout components at the top and bottom
- The cylindrical detector is cooled to superconducting state and a voltage bias is applied across its faces
- An incoming particle can interact:
    - Electromagnetically with electrons in the outer shells, call this **Electron Recoil**
    - Non-electromagnetically off a nucleus in the lattice, call this **Nuclear Recoil**





Measuring Interactions in the Detectors

- When a particle interacts with the detector we have two types of responses:
  - Phonon Energy:
    - Energy deposited directly into the crystal lattice
    - The energy propagates/vibrates through the crystal as phonons
    - Phonons are collected by the dedicated sensors, recording the ***phonon energy***
  - Charge Energy:
    - Electrons can get liberated from the atom which also creates a hole in the lattice (e/h pair)
    - Because of the bias voltage they are accelerated and knock out more electron hole pairs
    - We collect the charge as ***charge energy***



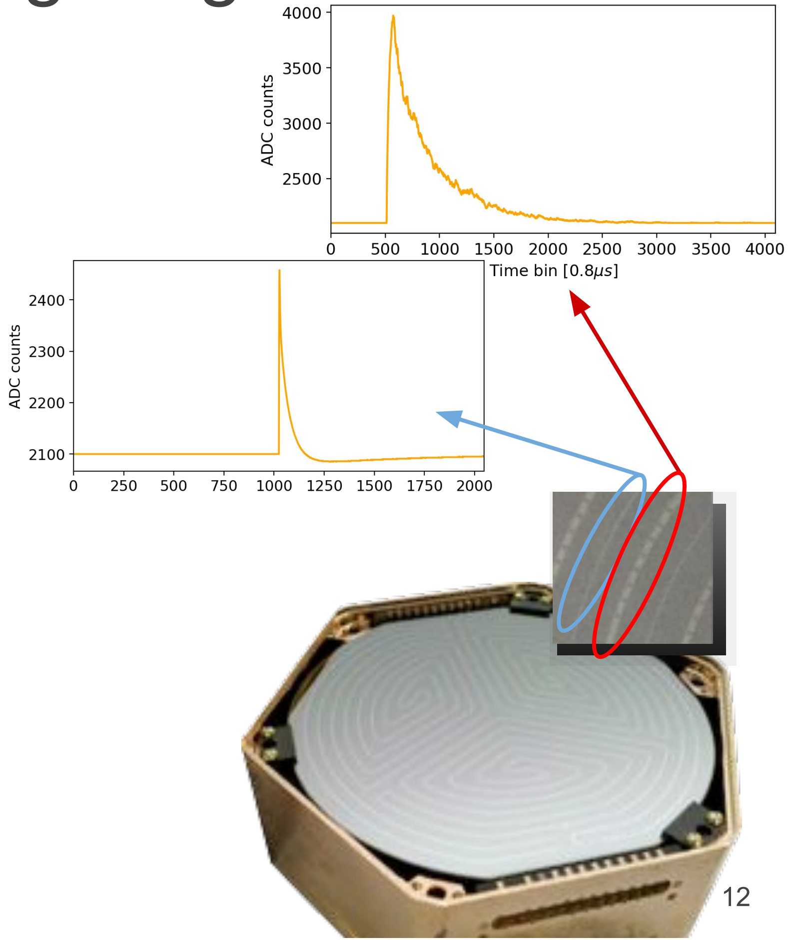
- The accelerating of electron/holes in the bias voltage creates more phonons, which also contributes to the phonon energy, and phonons can also knock out e/h pairs which are accelerated and contribute to the charge energy

- Every particle interaction results in both types of energy deposition, the amount of phonon and charge energy is proportional to the total energy, but the proportions differ due to the primary interaction type (dependent on the particle). More details about both in the next slides

Recording the Phonon and Charge Signal

- Phonon Energy Collection:
  - Phonons are collected via the Transition Edge Sensors (TES*)
- Charge Energy Collection:
  - The electron/holes are collected at the top/bottom charge lines

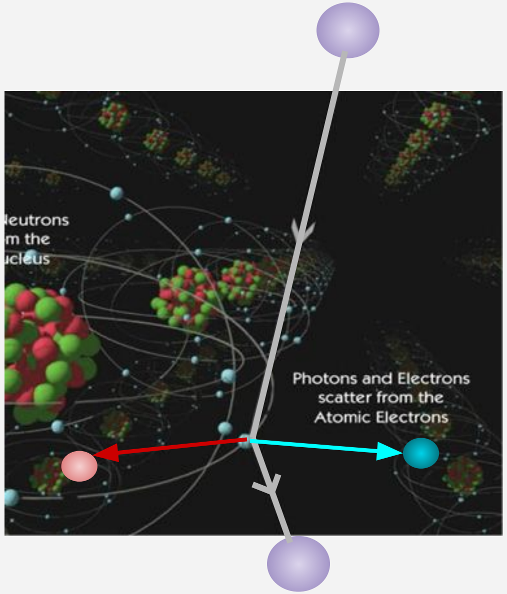
- The analog signal from both components is later digitized and stored for analysis. The amplitude of the signal is a measure of the energy



***TES**: device sustained in a superconducting transition state with very strong dependence of resistance as a function of temperature (i.e. phonons heat up the electron gas and produce a measurable signal)

Details About Electron Recoils

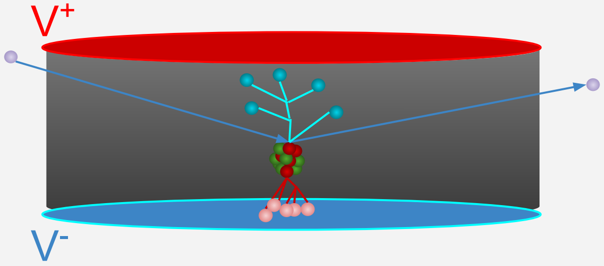
Electromagnetic interaction with an electron in the lattice knocks it out of place
Since it is a crystal lattice a ‘hole’ is also released



Inbound Electron or Photon

Crystal Electron/Hole

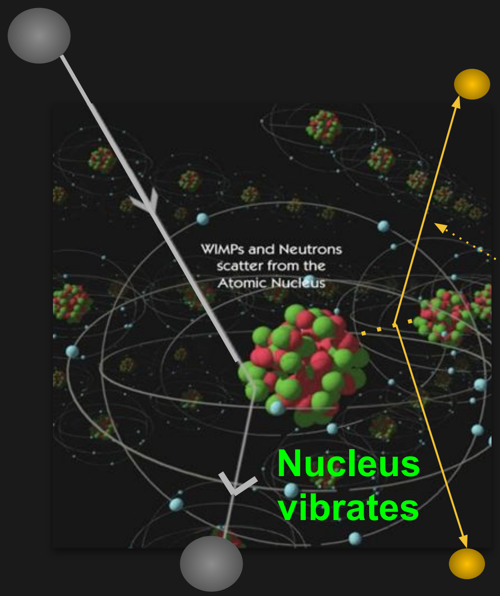
The electron and the hole travel through the lattice, the applied voltage feeds them more energy, up to the charge lines at the top/bottom



Phonons are also created from the accelerated electron/holes, so “phonon energy” is also released

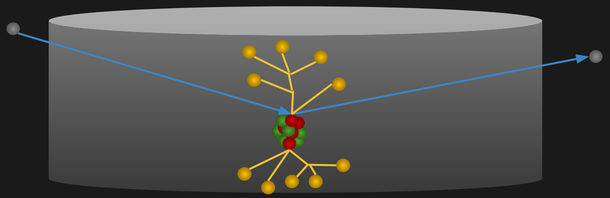
Charge Energy ≃ Phonon Energy

Details about Nuclear Recoils



Phonons: quantized vibrations produced from nuclei oscillations

Produce phonons (quantized vibrations) in the crystal lattice



Only a few electron/holes are released from the primary phonons so there is a small "charge energy" relative to the “phonon energy”

Charge Energy < Phonon Energy

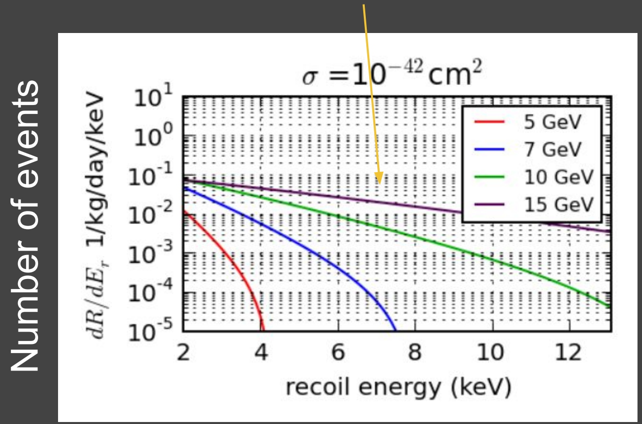
WIMPs (signal) or Neutrons (background)

Phonon

Signal and Background Sources

Signal (WIMP)

- Interaction via nuclear recoil
- Creates a phonon signature, proportional to the amount of energy
- Very few electron/holes released from the primary phonons so, small "charge energy" deposited
- Very few WIMPs are expected to interact in the detector, and those that do are expected to deposit very little energy

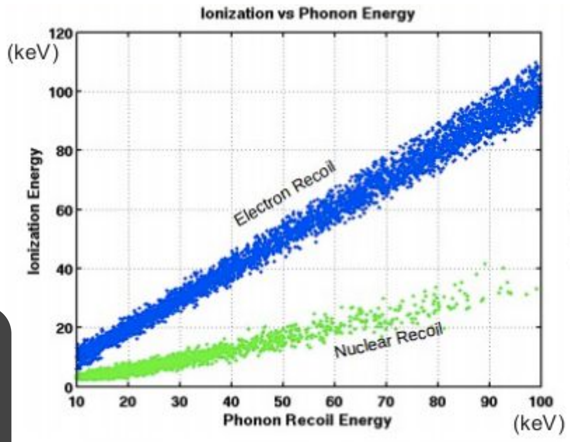


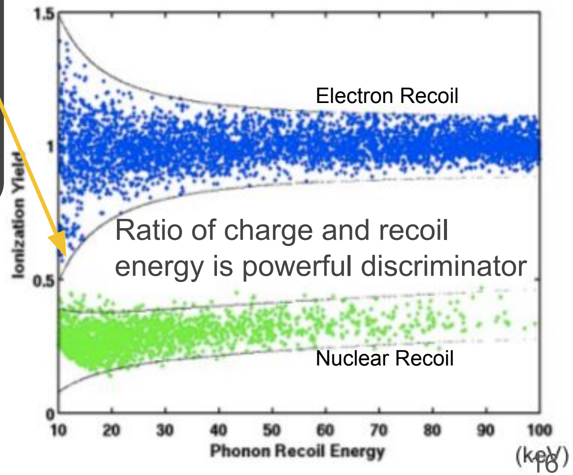
Backgrounds

- From Cosmic Sources:
  - Photons and electrons create electron recoils
  - Neutrons create nuclear recoils
  - Muons create electron recoils
  - Neutrino interaction rates are below sensitivity/threshold
- Radioactive Contaminants that Decay in the Detectors (Radiogenic):
  - Germanium activation: decay of excited Ge nuclei inside the crystal creates electron recoils
  - Lead Implantation: radioactive lead contaminants in the air stick to the Ge crystal surface creating electron and nuclear recoils
- Mismeasured Events:
  - Mixed Events: multiple particle interactions in same “event”
  - Detector/DAQ Malfunction

Discriminating Between Signal and Background Events

- Measure charge and phonon energy for every event, discrimination tool is ratio of both
- Periodically place radioactive sources near the detectors to create Calibration Data to understand this ratio:
  - Electron Recoils (^{133}Ba calibration)
  - Nuclear Recoils (^{252}Cf calibration)
- **Problems:**
  - The cutting edge searches are for low masses where the recoil energies are low, thus the energy resolution is poor (will point out why later in the talk), which makes it challenging to discriminate the recoil type
  - Interactions that occur away from the center of the detector are poorly measured so we don't get a good measurement of both but is difficult to tell when events occur near the sides or top
- Will show that the dominant reason for energy resolution is the noise
- The high quality detector simulation we are developing will help us better understand WHY the energy is under-measured so we can better estimate energy deposited in both systems and/or reject more efficiently events where things are not well measured





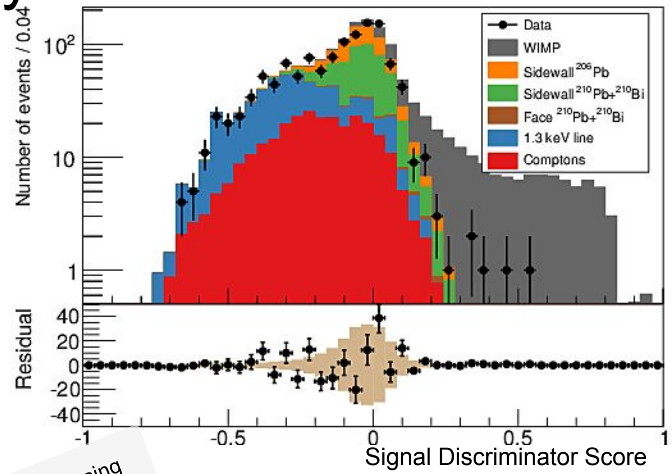
Quick Outline of a WIMP Search Analysis

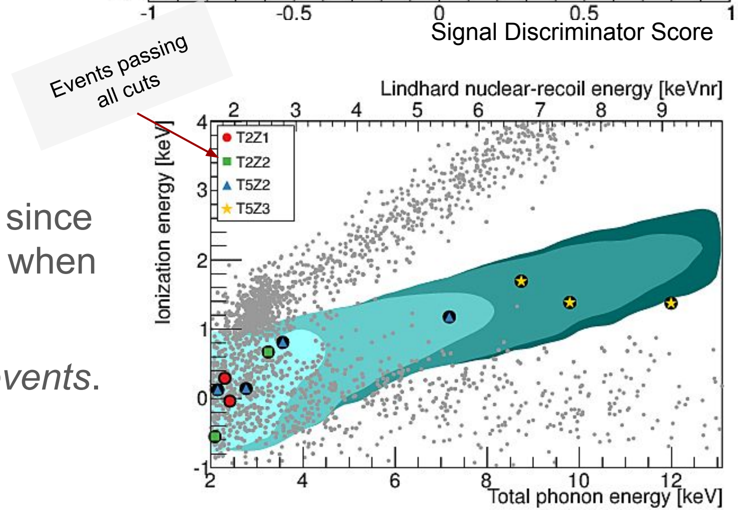
- Basic procedure is to select a sample of events where a significant amount of energy was deposited
- Then select subsample of only wimp-like events, the goal is to simultaneously maximize the number of signal events and minimize the number of background events
- By better understanding what backgrounds and signal look like, we can help create/tune measurement techniques that allow us to better separate the two types
- This begins with making a model of each. Previous analyses used to do that with real data only, from calibration sources, and sometimes aided with stand-alone simulations, but now we want to base the analysis in simulations insight and understanding

Dominant Backgrounds and Previous Analyses

SuperCDMS Collaboration. Phys. Rev. Lett. 112, 241302 (2014)

- Our current background model is based in previous analyses, where the dominant backgrounds were expected to come from 4 types of interactions:
    1. Nuclear Recoils from Lead (^{206}Pb) Contaminants
    2. Electron Recoils from Lead (^{210}Pb, ^{210}Bi) Contaminants
    3. Electron Recoils from Germanium activation (*1.3 keV line*)
    4. Cosmogenic Electrons and Photons (labelled as *Comptons*)





- The challenge is that nuclear recoils are an irreducible background since they look like our signal, and electron recoil can look like our signal when they are mismeasured causing them to look like nuclear recoils
- The final, "optimized selection" resulted in a *handful of WIMP-like events*. They were inspected and determined to be mostly mismeasured or noise-dominated events

III. Overview of this Work: Simulations of Dark Matter and Standard Model Interactions in the Detectors

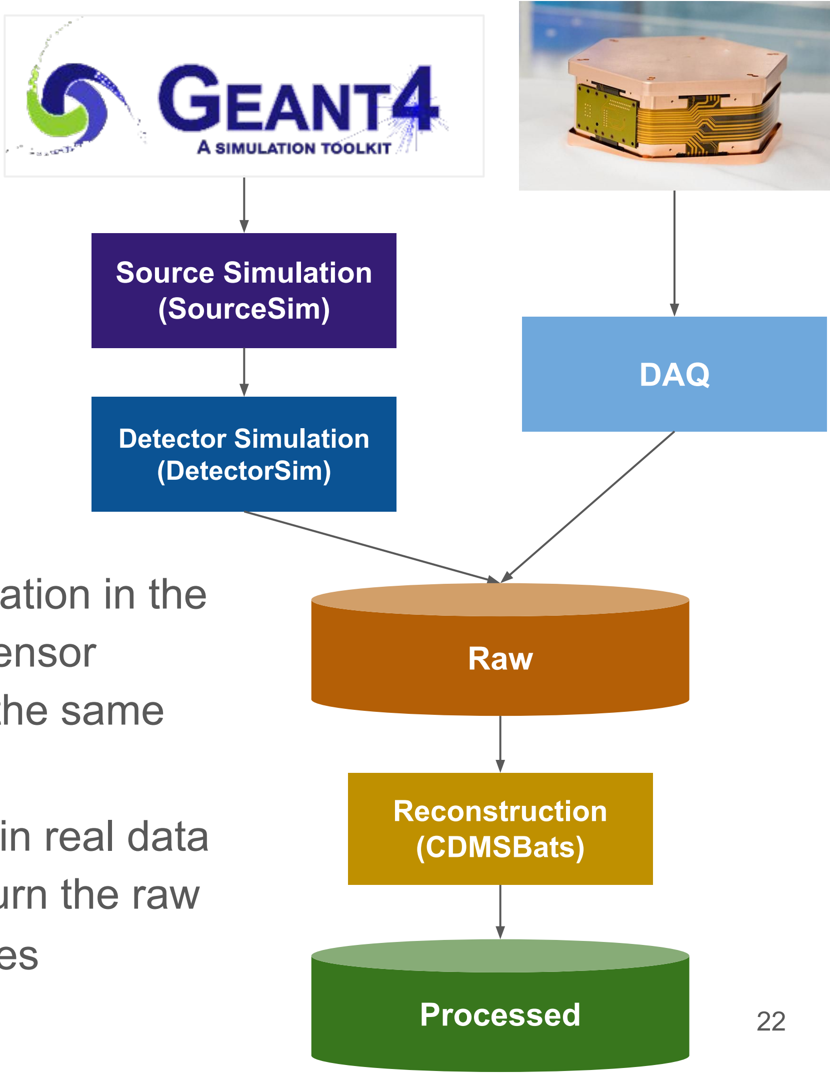
Overview of This Work

- We have created and done preliminary testing of a set of tools for simulating WIMP and SM interactions with the detectors, as well as the detector response and energy readout systems. This lays the groundwork for tuning the simulations to data and doing a simulation-based dark matter search
- Will show some new understanding of interactions in three major topics:
  1. **The Simulations Infrastructure**: we went from isolated pieces of code, to an integrated well-oiled machine that produces huge, version controlled, fully simulated and reconstructed samples of signal and background events
  2. **Simulations of Noise in the Charge System**: the charge noise simulation works as expected, well reproducing real-data noise
  3. **Fully Simulated and Reconstructed Background and Signal Events**:
     - Our studies of these events focus on the readout of the charge system, with and without noise, for both types. We have preliminary comparisons to SM model interactions
     - We have a number of conclusions/results that we will show: intrinsic resolution increases linearly with energy, noise dominates at low energies and is the dominant issue in the resolution of the energy measurement, and second mismeasurement cause is charge loss from near-edge regions in the detector

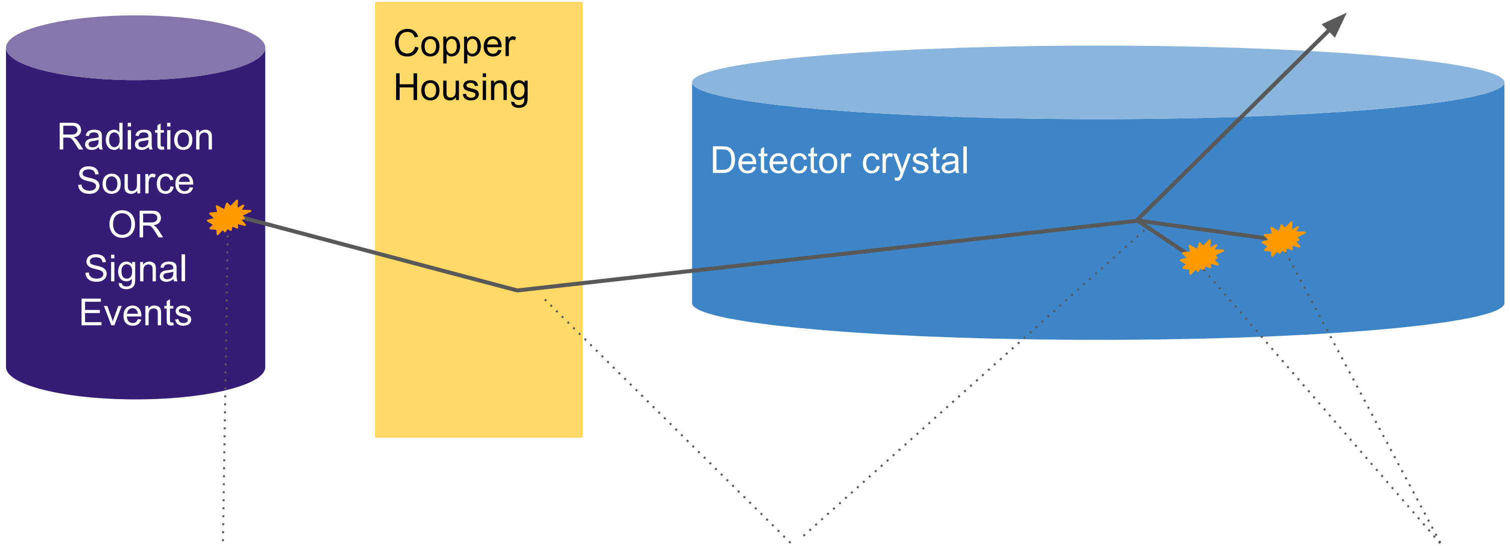
IV. The Simulations Infrastructure

The Simulations Infrastructure Workflow

- The Simulations Infrastructure is composed of 3 basic pieces:
  - **SourceSim**: Simulates particles that enter the experimental apparatus and interact to create an electron or nuclear recoil in the detector crystal
  - **DetectorSim**: Simulates e/h and phonon propagation in the crystal, then simulates the charge and phonon sensor response, adds noise (optionally), and stores in the same format as real data
  - **Event Reconstruction**: same package as used in real data reconstruction, standard analysis algorithms to turn the raw signals into energy and other measurement values



Overview of SourceSim

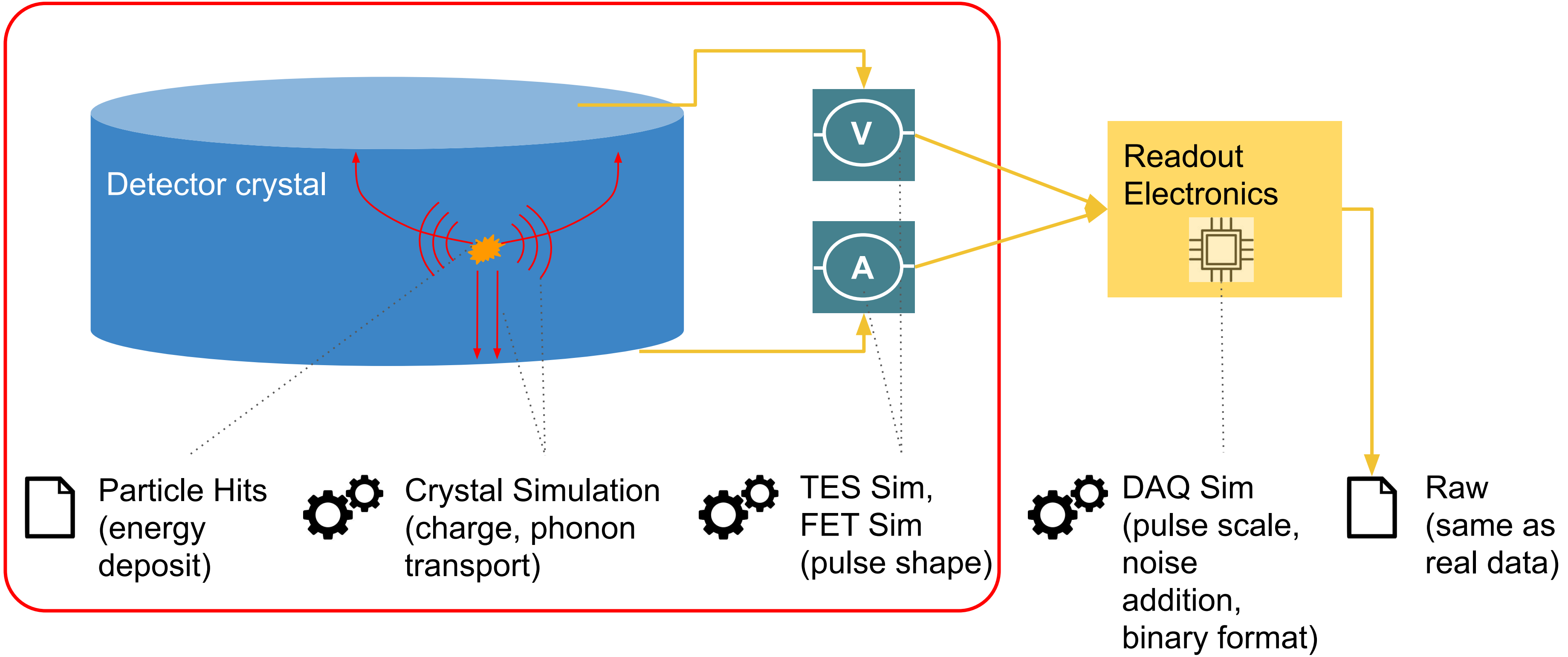


Event Generation (spontaneous events, cosmic background, WIMPs, etc)

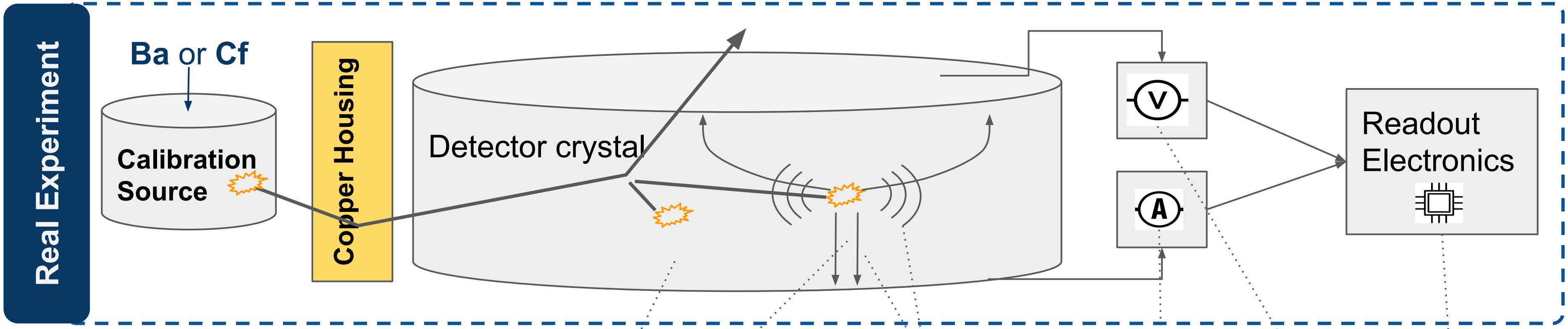
Particle Simulation (transport, scattering, recoil)

Particle Hits (deposited energy into either electron or nuclear recoils, true position, multiple scatters per-event are possible)

Overview of DetectorSim



Simulation Example With A Calibration Sample



Simulations

CrystalSim TESSim FETSim DAQSim

SourceSim

Simulation of particles that travel through things and eventually hit the detector or decay directly in the detector

Output: Recoil particle, energy and position in the detector

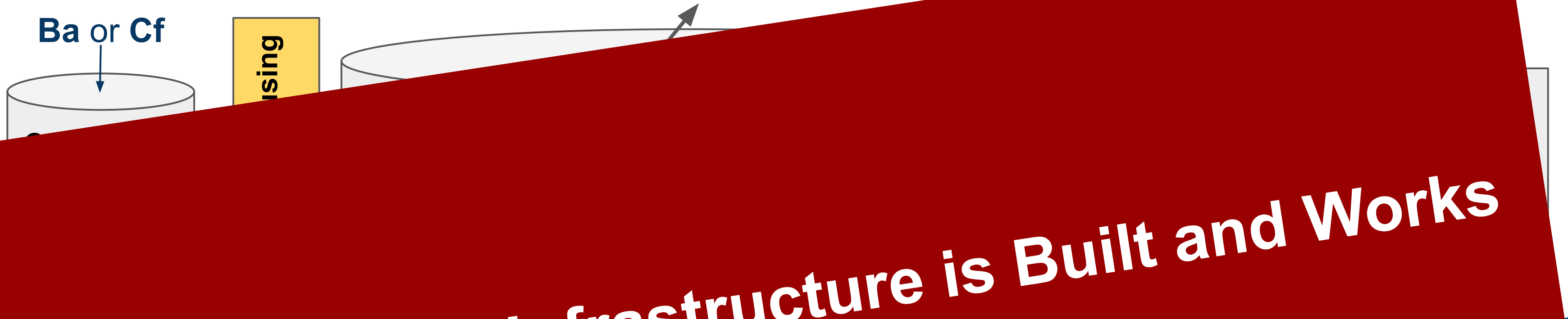
DetectorSim

Simulation of Crystal response to phonons and electron holes, the phonon pulses, charge pulses, as well as the data acquisition (noise and output format)

Output: Raw Data format

Simulation Example With A Calibration Sample

...periment



The Simulations Infrastructure is Built and Works

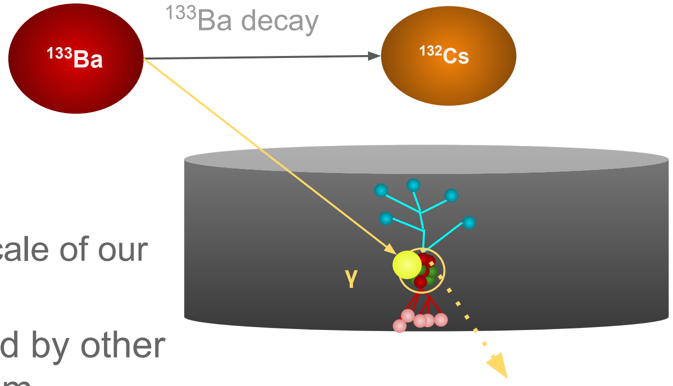
Simulations

... to phonons and electron ... phonon pulses, charge pulses, as well as the data acquisition (noise and output format)

Output: Raw Data format

SourceSim Calibration Example: ^{133}Ba

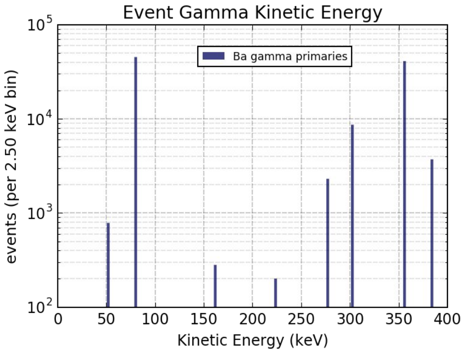
- Barium calibration (in real life, and what is simulated):
  - ^{133}Ba emits photons at discrete energies
  - Place ^{133}Ba near the detector
  - Use these photons to probe electron recoils and set the energy scale of our measured events
- It is expected that some of the photons interact with or get absorbed by other materials before even reaching the detectors so we will not see them
- For the photons that interact we get we get all, or partial, energy deposition in the crystal
- Can compare simulations with data since this Ba is a calibration sample



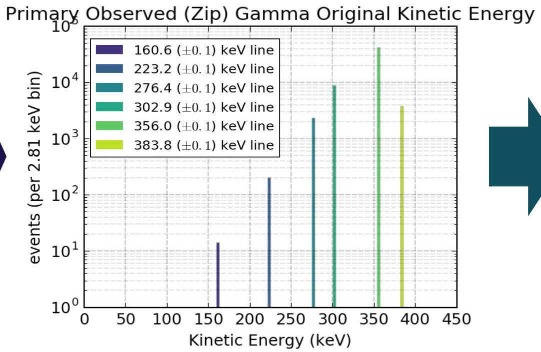
Sometimes scatters and keeps going

Sometimes gets fully absorbed

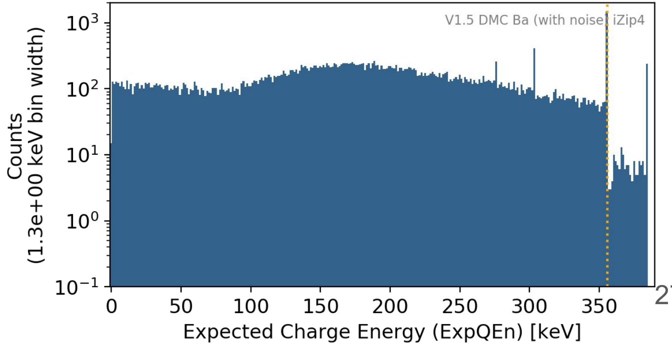
Emitted Primary Photons



Photons that Hit the Detector



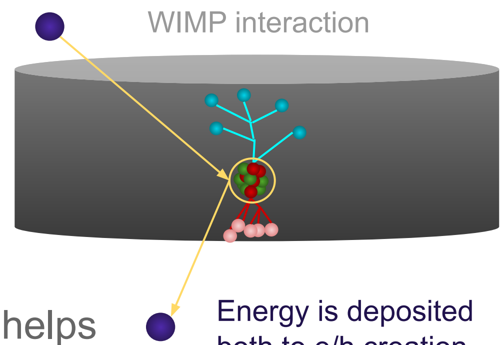
Energy Deposited Into e/h Creation



SourceSim Signal Example: WIMPs

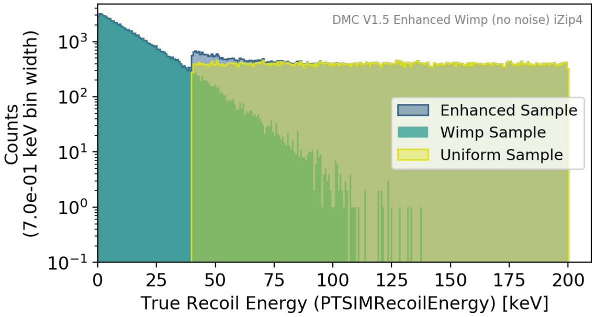
*Mat. Fys. Medd. Dan. Vid. Selsk. 33, no. 10 (1963).

- The WIMP signal is expected to be a single interaction in a nucleus of the crystal (i.e. a Nuclear Recoil)
- To determine the amount of charge energy from nuclear recoils, the simulations use Lindhard Theory*: experimentally motivated theory that estimates fraction recoil energy that is transferred into liberated e/h, or into crystal vibrations (i.e. phonons)
- We complement WIMPs sample with a *Uniform Spectrum* sample, which helps increase statistics of the simulation at higher energies
- Cannot directly compare with data, since we don't have a calibration source for WIMPs (we do have Cf calibrations, but haven't studied those yet)

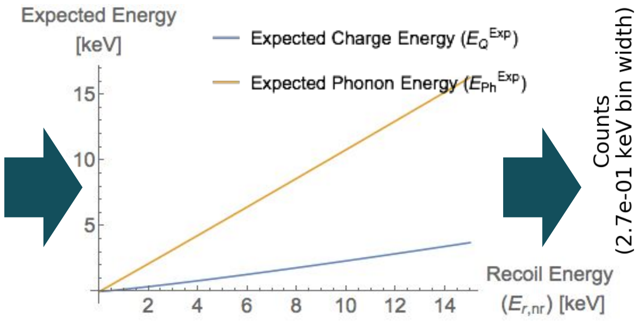


Energy is deposited both to e/h creation and into phonons (per Lindhard Theory)

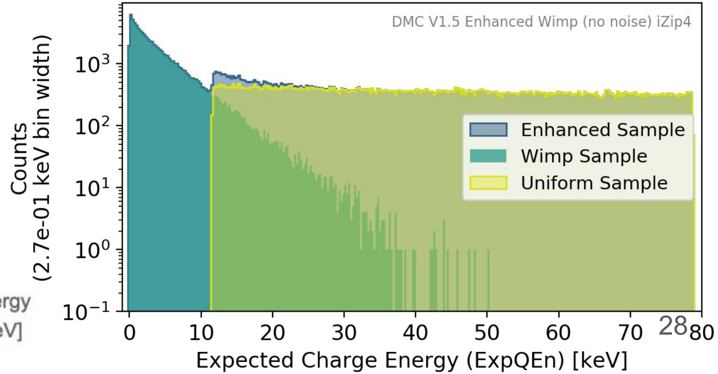
Energy Deposited Into the Detector



Calculate Lindhard Scale Factor

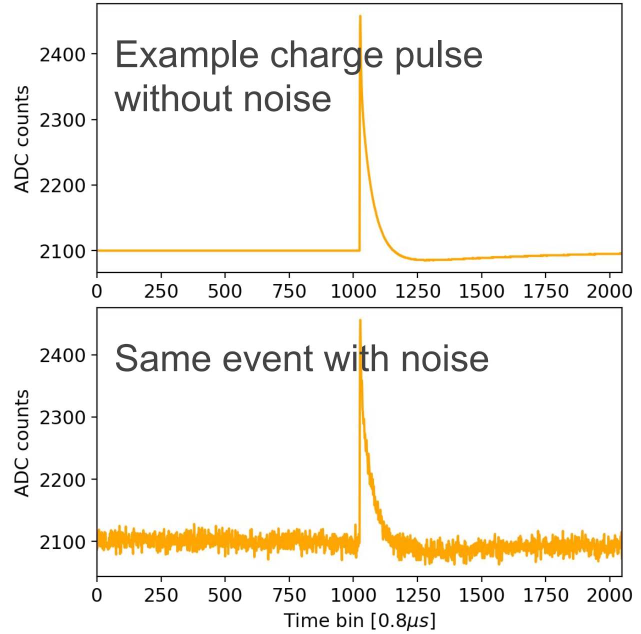


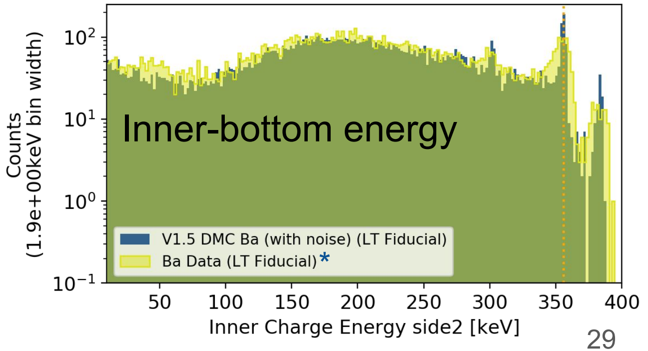
Energy Deposited Into e/h Creation



Reconstruction and Calibration of Simulated ^{133}Ba Data

- The e/h created from the energy deposition in the crystal get pulled by the electric field of the electrodes
- The simulated pulse is the sum of the scaled-up templates (and crosstalk). The amplitudes are proportional to the amount of charge collected by the electrodes
- Noise is added to the simulated event
- Finally, the reconstruction algorithm measures the amplitude and produces the energy estimates
- While sample is overall a good representation of the input and is comparable to data, the peaks in data have MUCH worse resolutions. Tuning is still needed (beyond the scope of this talk). Next is more detail about how we got to this point





*LT Fiducial defined in upcoming slides

Outline of the Simulations Results

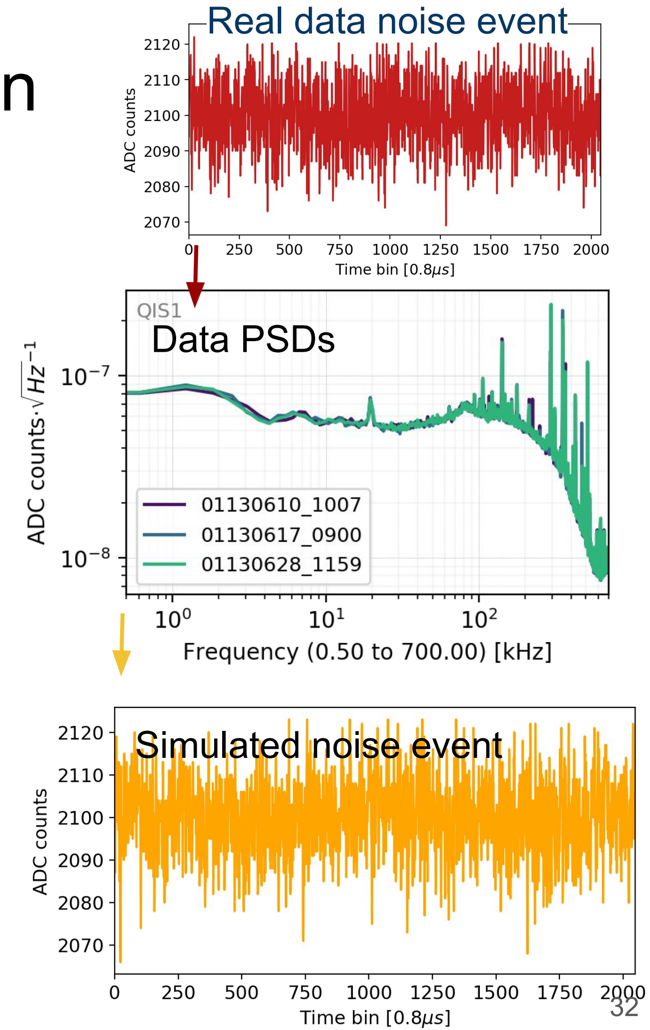
- In this work will show results for charge and charge noise, and data comparisons
- Begin with pure readout noise from the charge system, since will have to add it to charge to compare with data
  - Will show that the simulation works as expected (well reproduces real data Gaussian distributions of energy measurements)
- After that we will study full simulation and reconstruction of charge readout for signal and background events, both with/without noise, and in the full range of energies of interest to SuperCDMS (0-400 keV)
  - First will show with the Barium calibration, that the simulation works as expected, but will need some tuning, and may be missing some effects. The energy response is mostly linear (so the single constant calibration is a good approach), and that the intrinsic detector resolution rises linearly with energy but noise dominates at energies below ~120keV
  - Next will show that the calibration still holds for WIMPs (low energy single scatter nuclear recoils), though there is a limitation at lowest energies (< 2.5 keV)
  - Then will find the well-behaved region of the detector and confirm that poor measurements of the energy are due to incomplete charge collection

V. Simulations of Noise in the Readout System and Energy Measurements

Overview of the Charge Noise Simulation

- During real data taking we periodically read out the detector to take "events" when there are no interactions as a way of measuring the amount of noise in the system (call these ‘randoms’) and since noise isn’t pure white noise, we make a measurement of the power of the noise as a function of frequency
- In the simulations, after the charge pulses are created, noise is added, therefore we can have the same samples with and without noise

- Noise is expected to be normal/Gaussian, so noise events are created from the PSDs from real data by randomly sampling the components of each frequency



Compare Data and Simulation: The Noise Simulation Works as Expected and We Can Measure Resolution in Absence of an Interaction

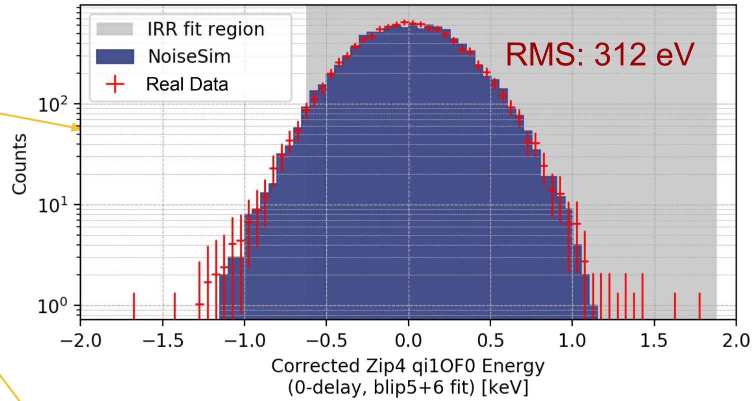
- Can recreate charge measurement observables for each channel separately (see one channel example)
- Top and bottom are independent measurements, so we can combine them (taking the average). Can also recreate these and obtain the same distributions within a few eV of error
- This is the direct/best measurement of the detector resolution in absence of signal

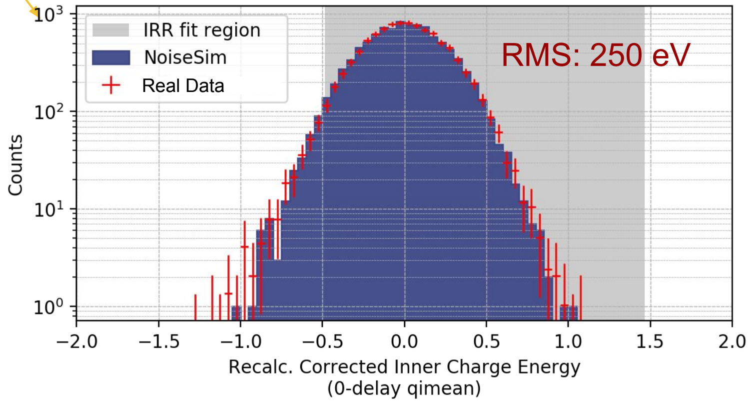
Resolution Due to Noise

Independent channels: 200 to 400 eV (depending on the channel)

Average of inner channels: 250 eV

- The simulation accurately describes our data which is the dominant term in the resolution of our measurement of low energy events

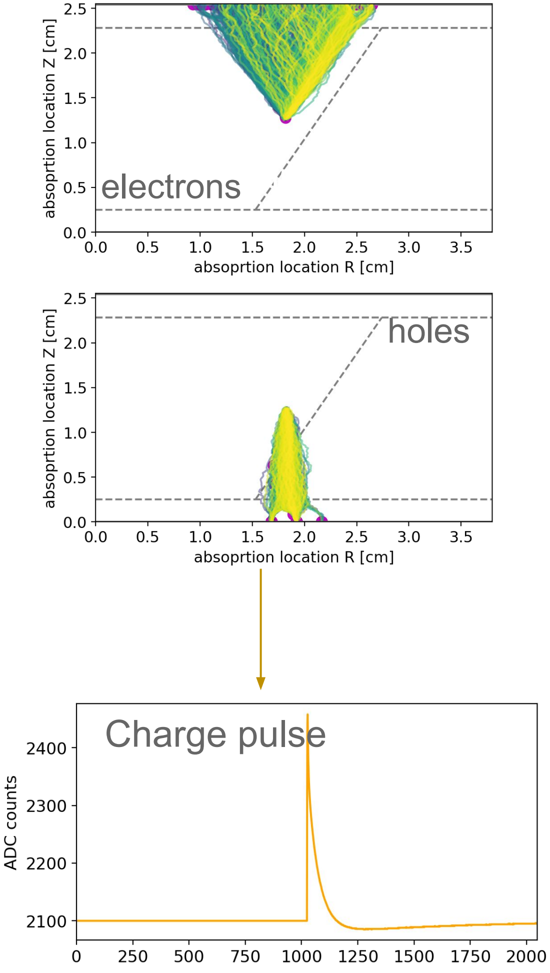




VI. Fully Simulated Background and Signal Events

Overview of the Charge Propagation and Readout Simulation

- The detector simulation begins with looking at the recoil type and the total energy deposited at each position. It then simulates a number of e/h pairs and phonons released by the interaction in the crystal
- Then, the *released* e/h are propagated through the crystal, pulled by the electric field. Electrons propagate restricted to the inter-valleys in the crystal, but holes propagate ballistically
- At the top/bottom of the detector reside the electrodes, the e/h are pulled towards them
- Each e/h will end up in one of the following cases:
  - Reaching an electrode (good charge collection → good measurement)
  - Being trapped in the crystal (partially contributing to the charge collection)
  - Or escaping the crystal (no contribution to charge collection)
- Finally, we simulate the charge readout and data acquisition response, including the addition of templates multiplied by the electrodes collection (including inter-channel crosstalk)

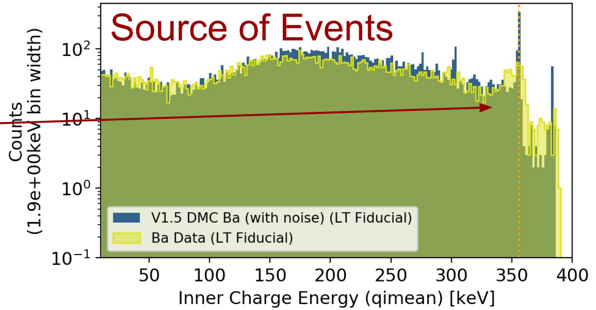


Quick Overview of the Simulation of Charge Collection

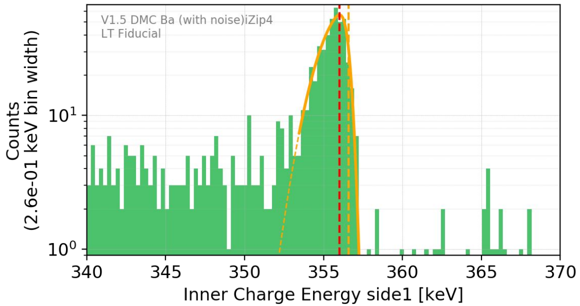
- *Ramo Theory* states that, for an electrode, the total amount of collected/sensed charge is:
    - $Q = \Sigma_i q_i \varphi'_{i\,Ramo}$
        - φ'_{Ramo} is the unitary *Ramo* field. It is 1 at the reference electrode, and grounded at the rest
        - $\varphi'_{i\,Ramo}$ is such field evaluated at q_i's location
- It is expected that electrons go to the top ($V_{Top} > 0$) and holes to the bottom ($V_{Bottom} < 0$)
- Notes:
    - On the top, at an electrode ($V_{Top} > 0$):
        a. If an e is collected → $q_i = -1$ (in units of e) and $\varphi'_{i\,Ramo} = 1$, so $Q_i = -1 \cdot 1 = -1$
        b. If a hole is collected → get $Q_i = +1 \cdot 1 = +1$
        c. So, if I collect 1 of each, $Q_i = 0$
        d. If there are 10 electrons, and I collect them all exactly at the electrode on the top $Q_i = -10$
    - On the bottom, at an electrode ($V_{bot} < 0$):
        a. If a h is collected → $q_i = +1$ (in units of e) and $\varphi'_{i\,Ramo} = 1$, so $Q_i = +1 \cdot 1 = 1$
        b. If I collect the reciprocal 10 holes with perfect efficiency at the bottom $Q_i = +10$
- In our detectors we have 4 channels (electrodes), 2 at the top at +2V, and 2 at the bottom at -2V

Calibration With the Barium Simulation

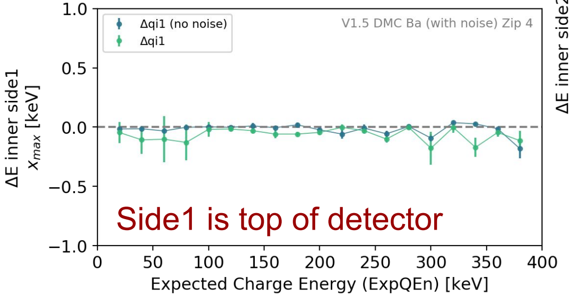
- Recall that 356 keV is clear peak both in data and simulations, and even though we already know the resolution predicted by simulation is MUCH better than real data, can draw basic conclusions from it and create tuning handles for later use

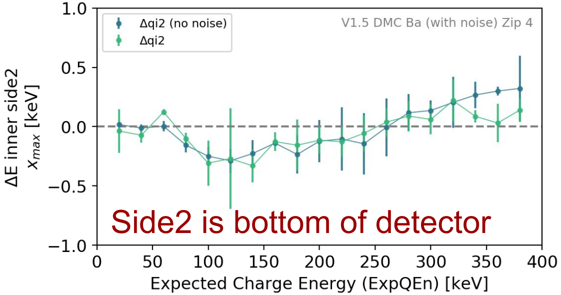


- Consider only events from well-behaved part of the detector (defined in next slide)
- Calibration is set with the 356 keV signature line of barium, so can take well-behaved sample and do a fit to find peak location, then calibrate the sample with a constant factor that sets it to 356.013 keV



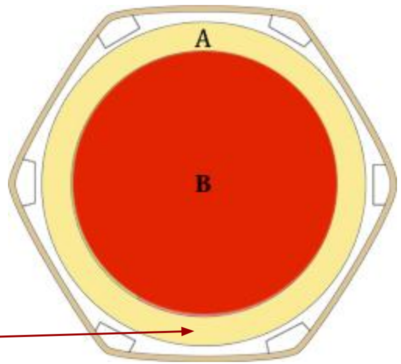
- Since in simulations we have truth information, can then compare observed with expected values as function of energy
    - Channels are linear in energy and well calibrated (centered at zero)
    - Compare noise/without-noise, noise does not change the answer
    - Side1 performs better than Side2





Quick Description of Well-Behaved Criteria: LT Fiducial

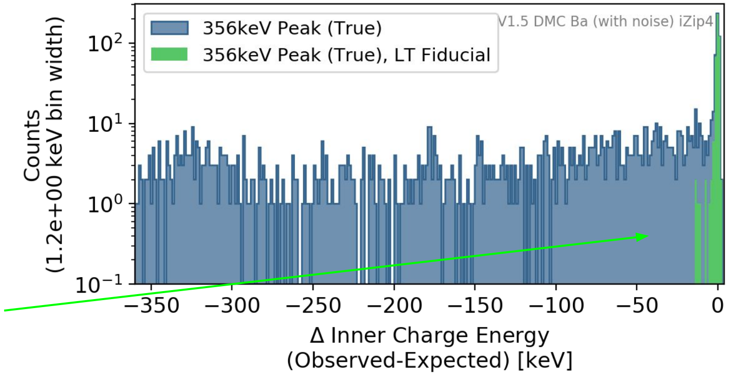
- If a real interaction occurs in certain parts of the detector, not all the charge will be collected by the sensors. Our simulation well reproduces that, so we can have a good modeling of where the detector does a good job and where it doesn't. Can use this to help select well measured events in real analysis



- In previous SuperCDMS analysis 'well-behaved' events, associated with the detector's fiducial volume, have been selected by:
  - Having no energy deposition in outer channels
  - Having roughly symmetric energy measurement in both side's measurements

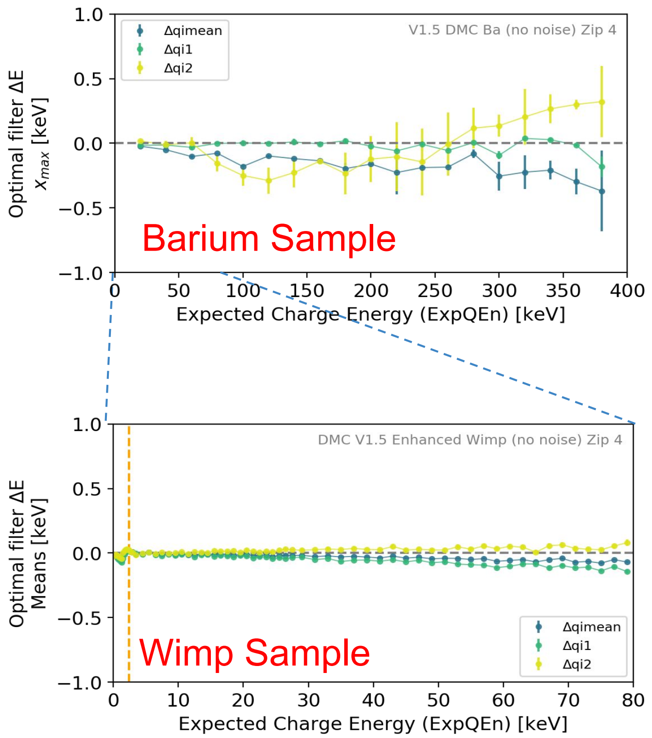
- Consider selecting a sample of 356 keV Peak events (true energy = 356.013±0.100 keV)

- Comprare simulated energy readout readout response energy with truth
  - LT Fiducial does a good job at removing most of the mismeasured events



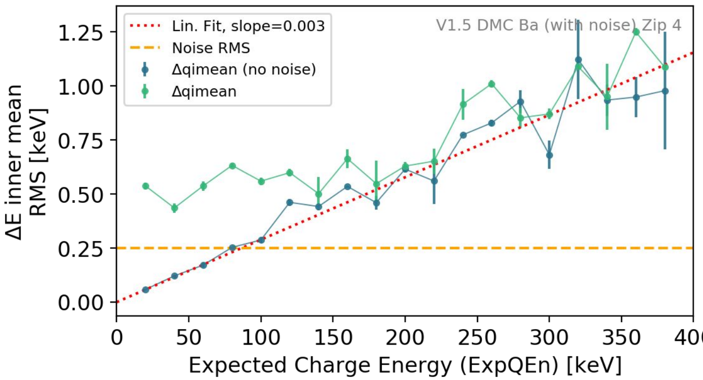
The Charge Simulation Works as Expected

- Consider LT Fiducial selection criteria
- Compare observed energy with the truth/expected energy and see that as function of energy
- Barium sample (full energy range, electron recoils):
  - Both channels are linear in energy, and the difference is centered at zero (i.e. well calibrated)
- Compare with WIMP Sample (low energy, nuclear recoils)
  - Still linear in energy and centered at zero
- Ignoring RMS is not tuned to data, the simulation works as expected, next will see fiducial definition, resolution, and mismeasurement causes



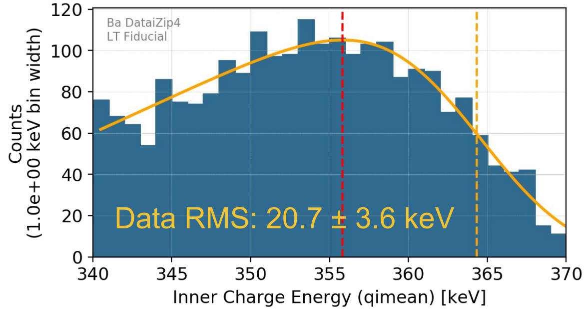
Charge Energy Resolution: Intrinsic Detector Resolution and Noise

- We now have a tool to determine the total resolution, and the contributions from detector effects and noise effects
- Consider LT Fiducial events
- Can now look at RMS, from observed minus expected, as function of energy
- Compare with and without noise to determine the contributions to the resolution
- Noise RMS dominates at low energies
- Intrinsic detector resolution rises with energy and becomes more important at high energies (above ~120 keV)
- This is MUCH better resolution (21X better) than we have in real data but tuning the samples will be needed before use in analysis



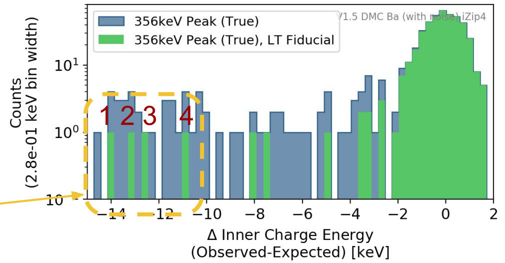
Noise: ~0.300 keV
Detector Resolution: ~0.003 keV • E_{True}

Resolution is Noise in quadrature with Detector Resolution

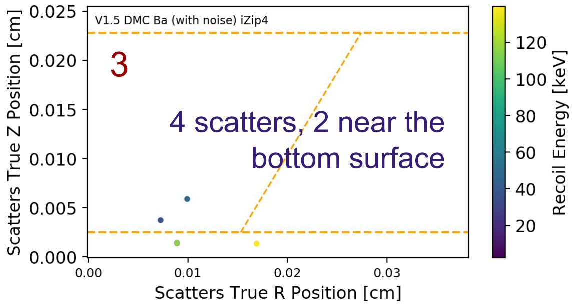


Understanding Causes of Detector Mismeasurement

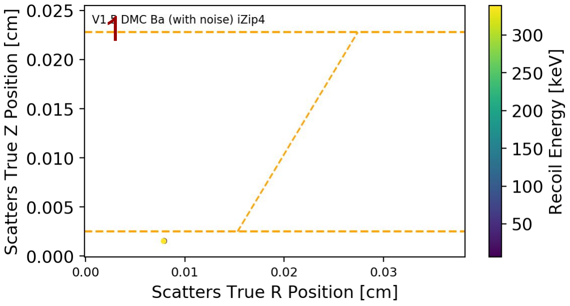
Simulations Indicate that Poor Measurements are Due to Scatters Being Near the Edges of the Detector



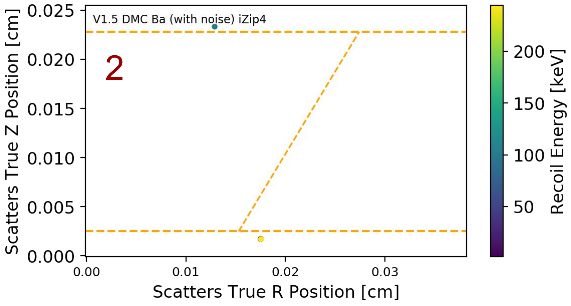
- Again, consider our sample of 356 keV Peak (from true energy), LT Fiducial events, and then select the worst measured ones
- All are related to cases where some (or all) of the scatters are near the detector edges, but both sides were measured low in similar ways: One side because it was far from the original position, and the other because it was close to a top/bottom
- In Barium this is likely to happen because most events have multiple scatters

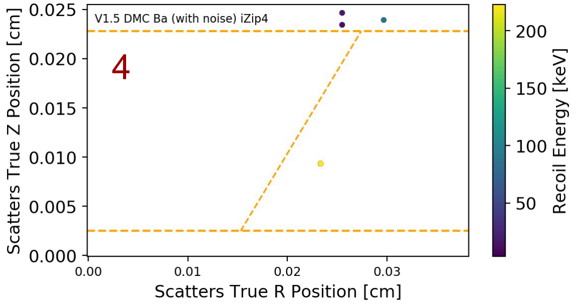


3 scatters, all within 38 μm from each other, and all near the bottom surface



4 scatters, 3 within 4 μm from each other near the bottom surface, 1 near top



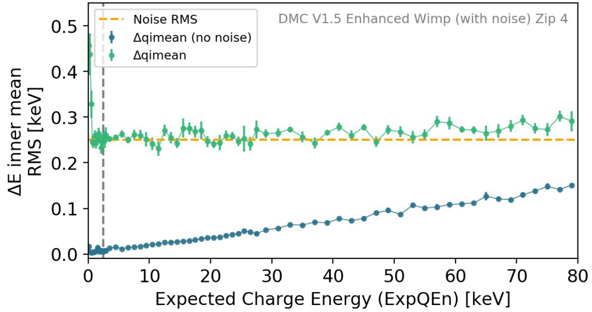


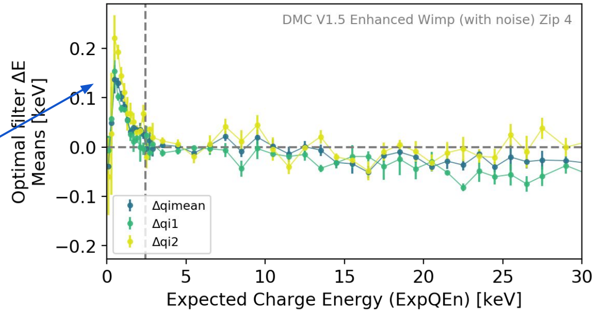
6 scatters, 3 near the top surface, 3 within 30 μm from each other near the sidewall

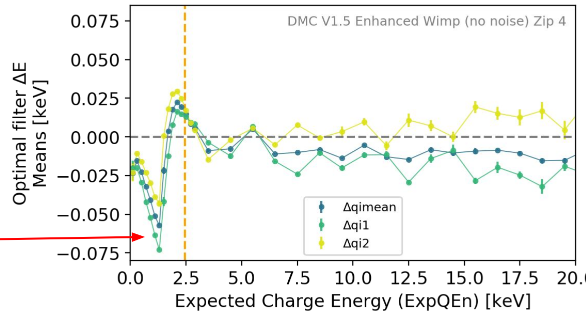
Moving to Understanding the Signal (WIMPs) Simulation

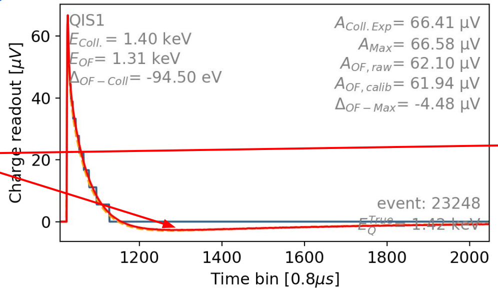
Wimps: Low Energy Single Scatter Nuclear Recoils

- This energy region is where next generation analyses will be focusing on, particularly the lowest energies (< 3keV)
- Consider signal sample: low energy, single scatter, nuclear recoils
- Compare RMS as function of energy, with/without noise: similar answer as barium (high energies), but better intrinsic detector resolution (because of multiple scatter effects in barium)
- Finally compare difference between observed and expected: sample is well behaved, centered at zero above 2.5 keV
- At lowest energies (< 2.5 keV) there are two issues:
  - Noise dominates over the signal and causes large mismeasurement similar to pure-noise measurements
  - The amount of energy collected as a function of time can be so low that it falls below a single ADC count, which causes a digitization misrepresentation. Can see this most easily with no-noise simulations



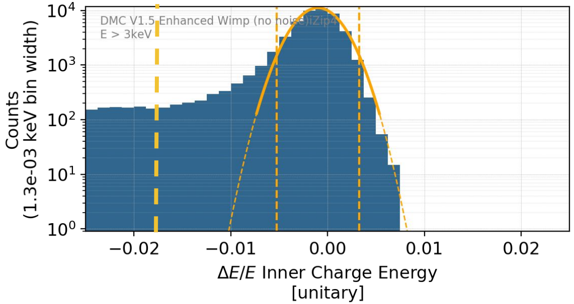


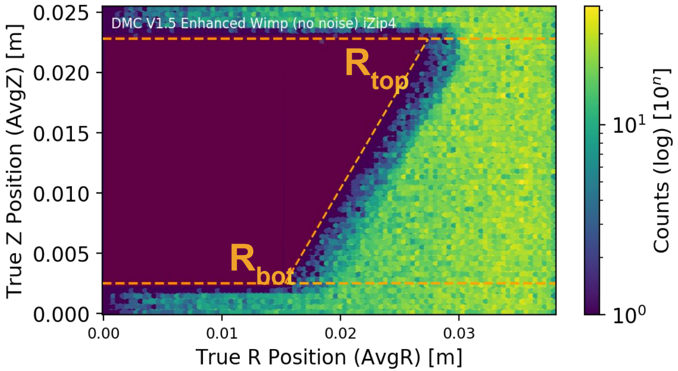


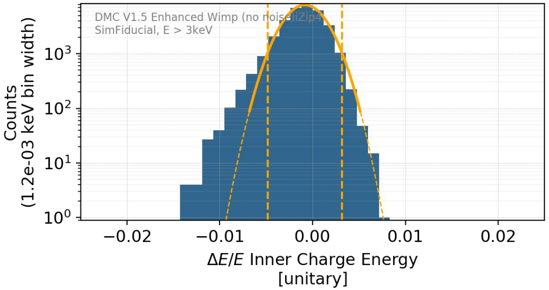


Finding the Well Behaved Part of the Detector: SimFiducial

- **Want to improve the fiducial volume criteria from searches we have done in the past, to improve background/signal separation**
- With the noiseless, single scatter sample, can select mismeasured events: ΔE/E < -0.015
(with E > 3keV due to the lowest energy limitations)
- Then show true position (Z v.s. R) of those
- The well-behaved area is delimited by the location of these events, call this volume: SimFiducial
- Now consider SimFiducial, E > 3keV sample: events are well measured and sample is near perfect Gaussian

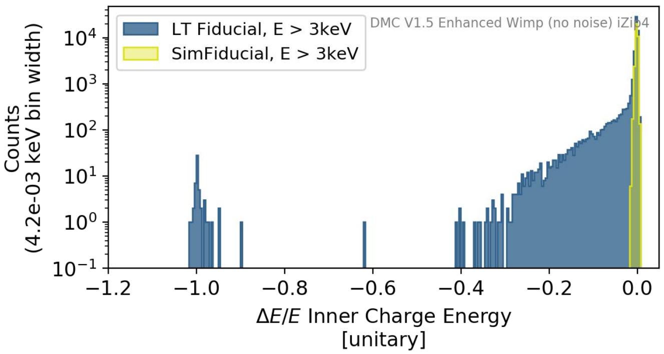


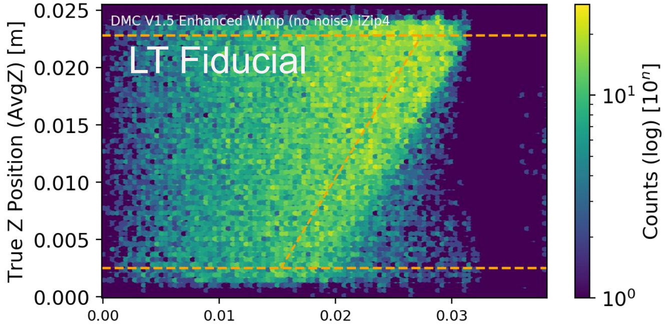


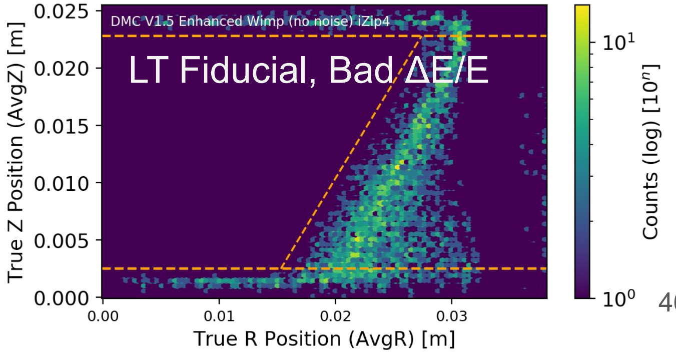


LT Fiducial Comparison

- Recall that LT Fiducial is the selection criteria in previous analyses to select ‘well-behaved’ events
- Consider E_{True} > 3keV subsample (to ignore lowest energies mismeasurement), compare LT Fiducial with SimFiducial
- Long tail in LT Fiducial events → LT Fiducial does not discard ALL events from charge loss regions in the detector
- Show position dependence of LT Fiducial events and from LT Fiducial, Bad ΔE/E (< -0.015). Those events are in a region where SimFiducial would have discarded them
- This suggests that the major cause of LT Fiducial mismeasurement is true position dependence



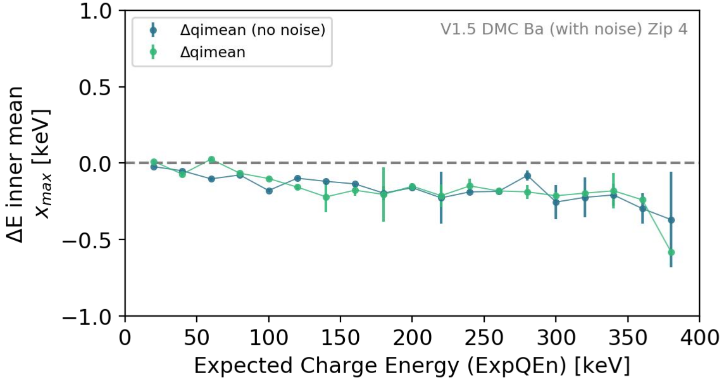


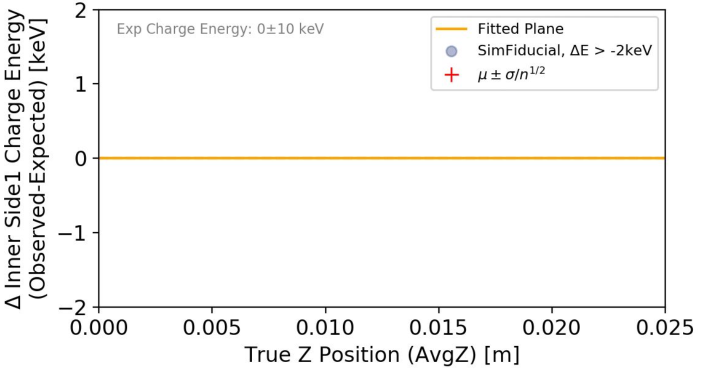


Additional Details that the Charge Simulation Taught Us

Energy Estimate Drops as Function of Energy and Position

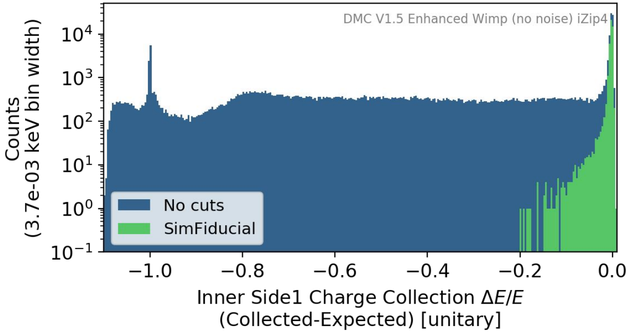
- With the simulation results we have been able to observe additional effects in the data, like for example that the best recoil energy estimate (average of inner channels) drops with energy (at 0.15% rate)
- We learned that even in the well-measured parts of the detector, the measured energy has a dependence on energy and true Z-position of the interaction: a 3D fit as a function of energy and Z-position well describes the profile of the events
- It is possible to use this fit to make corrections in qi1 and qi2 energy measurements and make the average flat, but it is not clear it is applicable or useful in real data, nor how we could extract Z position information from this

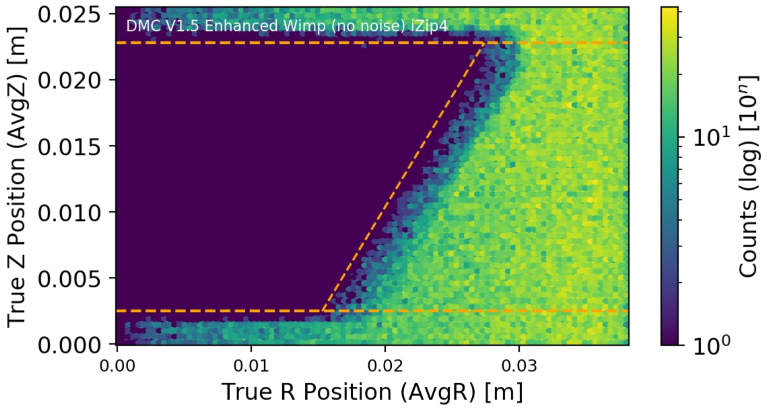




Charge Collection Explains SimFiducial Volume

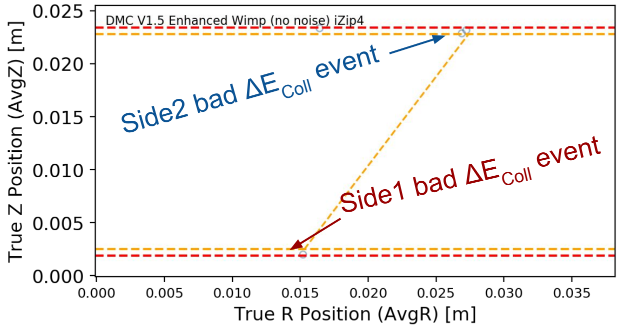
- Charge collection by the electrodes is simulated based on *Ramo Theory*
- With the simulations can look at Charge Collection (result of added Ramo Field values of all charges), and know the energy of the event's pulse without an optimal filter measurement
- Consider Collected Energy ΔE/E
- Charge collection confirms SimFiducial region:
  - Upon selecting E > 1.5keV, $\Delta E_{Coll}/E < -0.02$ SimFiducial volume is the same

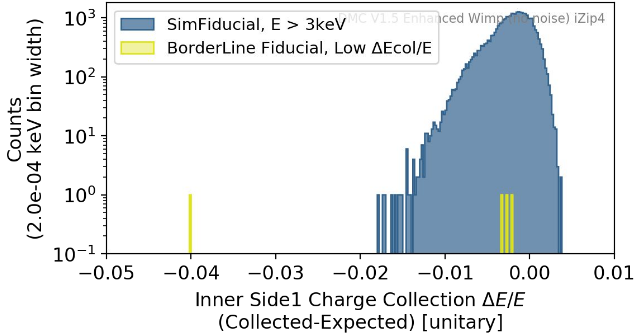


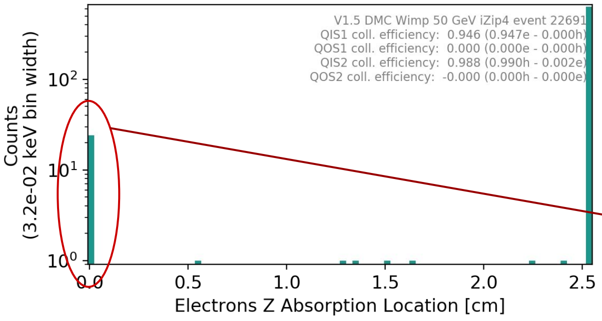


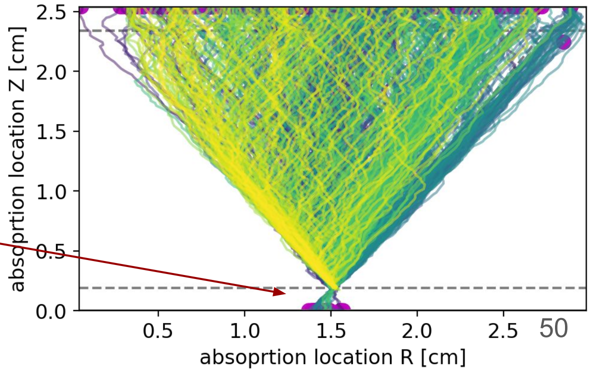
Charge Energy Measurement Is About e/h Being Fully Absorbed at the Electrodes

- Select E >3 keV (avoid events without lowest energy issues)
- Define *Borderline SimFiducial, Bad $\Delta E_{col}/E$* sample:
  - Extend SimFiducial by 0.6 mm in Z_{top} and Z_{bottom}
  - Select E > 3 keV (avoiding mismeasured regions)
  - Select Bad $\Delta E_{Coll}/E < -0.02$ (top or bottom)
- Consider *Borderline SimFiducial, Bad $\Delta E_{col}/E$* events:
  - Only 4 Bad ΔEColl/E events
  - Poor collection on opposite end of their Z-position
- These events have low Ramo-Field values because some of the charges got trapped in the opposite side, thus do not contribute to the charge collection



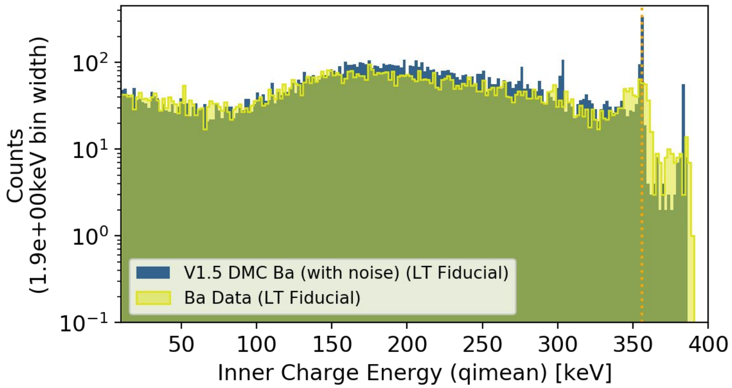


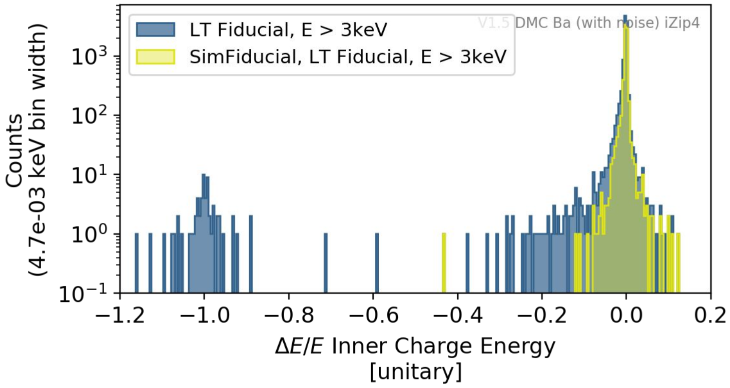




Tuning LT Fiducial Could Have a Big Impact

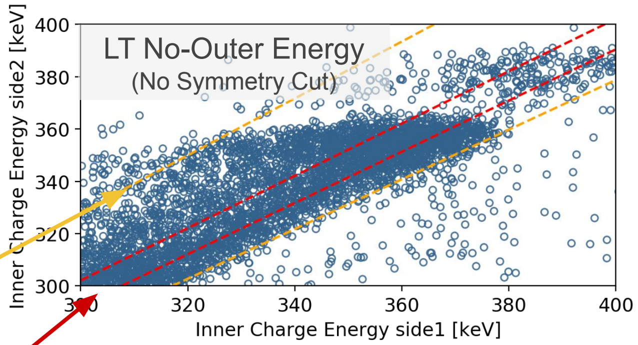
- Consider LT Fiducial Ba, real data and simulation
  - While samples are not too different they do not perfectly line up
  - Resolution is MUCH better in the simulation
- The simulation needs to be tuned for our Ba data
- With a properly tuned simulation we might be able to make additional constraints to the LT Fiducial cut, remove events from the non-SimFiducial region and improve the background discrimination
- We have not completed the study to understand why the 356 keV peak RMS is bigger in data:
  - Perhaps it's about finding a better well-measured criteria
  - Perhaps the simulation needs tuning
  - Perhaps there is a missing effect in the simulation

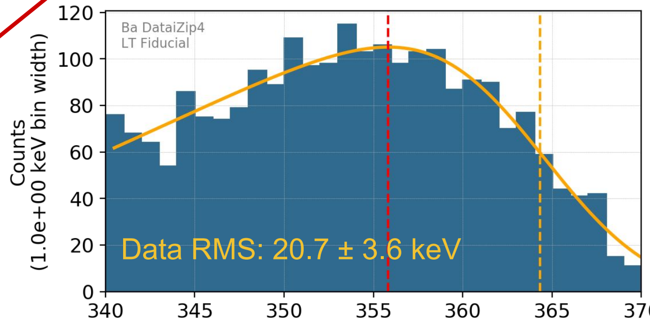


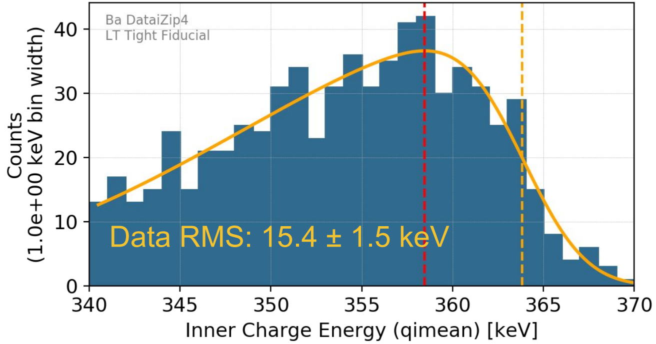


Is LT Fiducial Symmetric Criteria the Causing Larger RMS in Data?

- Quick study to remove events expected to be poorly measured, is that what causes all or part of the larger RMS in data?
- Recall that LT Fiducial is defined with a symmetric measurement of both inner channels (orange dashed)
- To see if RMS in data goes lower, tighten the symmetric band (from orange to red dashed)
- Side1 is MUCH more smeared, this could be an analysis issue to follow up and simulations have helped us find it
- Data RMS goes from 20.7 keV to 15.4 keV (25% better), so it does contribute but is not main cause
- Whilst simulations are too far from real data, they might also provide insight into other quantities to use for better event selection







Next Steps

Next Steps with the Simulations

- The Simulations Infrastructure is now ready for use, and we have done basic tests that tell it works as expected

- Major next step is to tune the simulations for the data: now that we know that they behave as expected but RMS is so different, we can modify the parameters (over 100 of them! E.g. trapping probability, material properties...) to make the answers match the real data characteristics comparing with Ba and Cf calibrations → Want to trust that they well-represent each detector

- Tuning for each detector not only will bring new understanding to the detector itself, but it will allow to make simulation based event selection decisions → Will bring new understanding to the detectors and allow simulation based cuts

- Finally optimizations can be done by using the simulations to feed trustworthy training samples to machine learning methods → Will fully optimize a dark matter search analysis

- The next student will start by repeating all this with phonons

Conclusions

- SuperCDMS is a world leading experiment, with an emphasis on low mass searches for dark matter
  - Requires sensitivity to the smallest energy depositions.
  - Our work to improve this sensitivity, in addition to building better detectors for SNOLAB, is to really understand the detector response.
  - To do this we have moved to a full simulations infrastructure so we can get to fully optimized, simulation-based analyses like the other big search experiments
- We have initiated a powerful and systematic effort to run simulations of the detector, fully process these events as if they were real events, and see if we can use the knowledge from them
- Have shown that Charge Simulations (and Charge Noise Simulations) agree with basic expectations from detector behavior and present no known physics and computational issues
  - Noise simulations well-reproduce real data noise observations
  - Charge observations are linear in energy and calibrations work as expected
  - Intrinsic detector resolution rises linearly with energy and dominates above ~120keV, but noise dominates at low energies. 356keV peak in real data has an RMS ~16x bigger, this is the clear next step for someone to work on!
  - Main source of mismeasurement is position dependence of interaction in the detector
- While my work on simulations is now done, the next steps for the simulations and their use is now established so we an use them to discover dark matter

Thank You!

And special thanks to:

Dave Toback

Jon S. Wilson

Toback Group

Steve Johnson

Guy Almes

Brazos Cluster Team

Ana Arnaus

My wife!

BACKUPS

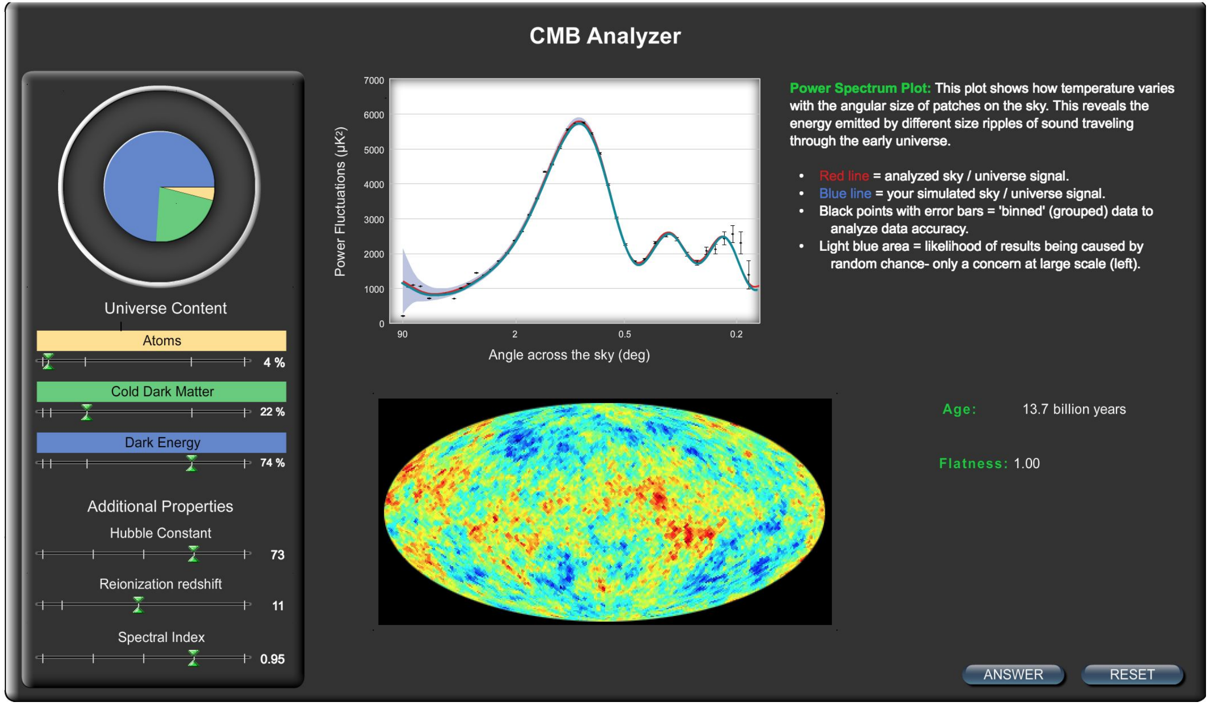
ΛCDM Model
Appendix A

- Observe the temperature variations with the angular size patches in the WMAP

- This tells how patches got disconnected/frozen due to expansion, related to the Ω_{DM} (energy density)

- Best fit is:
  4% Atoms
  22% Dark Matter
  75% Dark Energy

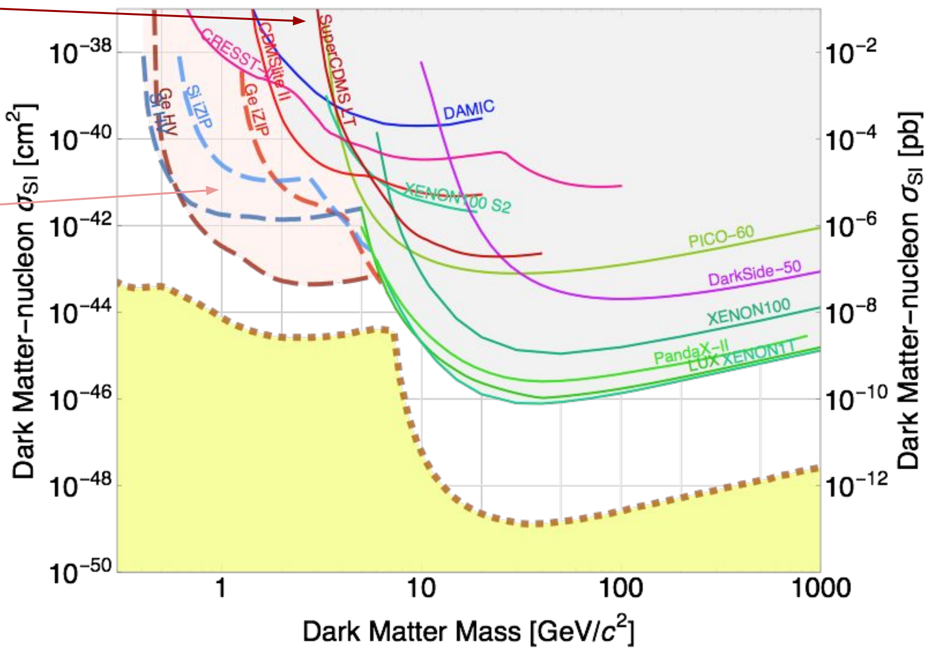
- See NASA's CMB toy plotter: https://lambda.gsfc.nasa.gov/education/cmb_plotter/



WIMP Limits from Multiple Experiments

Appendix B

- The previous version of this analysis is here
- Next-generation estimates (preliminary expected limits) lay all around here
- This analysis lies somewhere in-between
- The goal is to squeeze the most out of our data, while setting path on the upcoming analyses

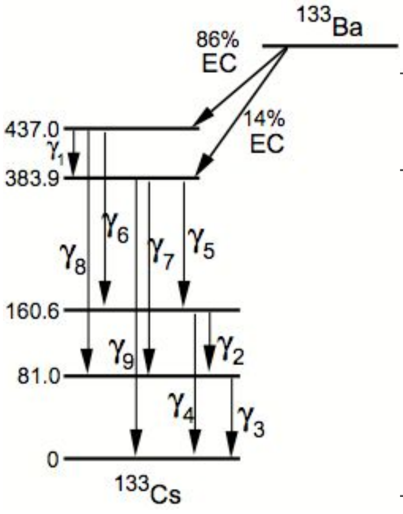


^{133}Ba Decay

- Electron Capture decay

  $p + e^{-} \rightarrow n + \nu_e$

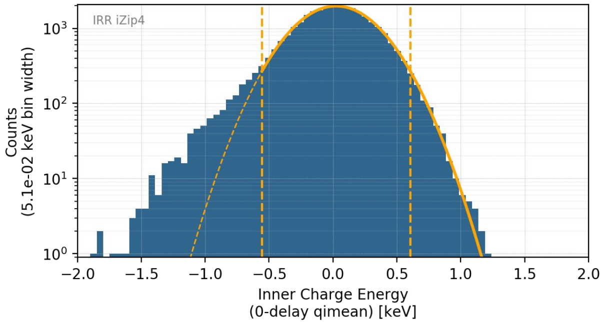
  (+ x-ray from the collapsing e^{-})



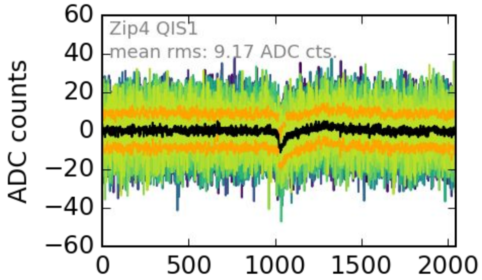
Gamma Emissions

	Energy (keV)	Photons (per 100 disint.)
$\gamma_{4,3}$(Cs)	53,1622 (6)	2,14 (3)
$\gamma_{2,1}$(Cs)	79,6142 (12)	2,65 (5)
$\gamma_{1,0}$(Cs)	80,9979 (11)	32,9 (3)
$\gamma_{2,0}$(Cs)	160,6121 (16)	0,638 (4)
$\gamma_{3,2}$(Cs)	223,2368 (13)	0,453 (3)
$\gamma_{4,2}$(Cs)	276,3989 (12)	7,16 (5)
$\gamma_{3,1}$(Cs)	302,8508 (5)	18,34 (13)
$\gamma_{4,1}$(Cs)	356,0129 (7)	62,05 (19)
$\gamma_{3,0}$(Cs)	383,8485 (12)	8,94 (6)

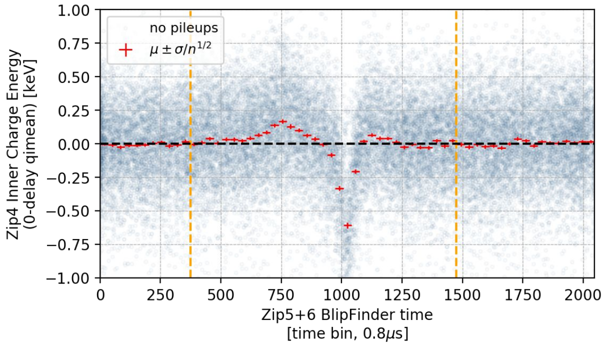
Appendix D
The Simulation Helped Us Discover a New Type of Noise: TowerBlips



- When comparing simulations to data a LHS tail appeared in data (and not in simulations)
- Selecting only left-tail events, a clear *Blip* feature appears, and naturally hurts the WIMP search (a new type of background noise)



- We identified correlations of this *Blip* with all channels in the detector, and further with all detectors in the same tower (i.e. Zip4, 5, and 6)
- We developed a *BlipFinder* tool, that looks for the maximum negative excursion in the optimal filtered event, and reports the amplitude and time of the peak



- The *BlipFinder* tool shows the dependence in the Zip5+6 *Blip time* of the charge energy observation (Zip4), explaining the LHS tail
- With this tool we determined that the *Blip* occurs in all Zips of the same tower ~60% of the time, and ~80% when considering large amplitude *Blips*

TowerBlips Can Be Corrected

- With our TowerBlip Finder, and due to the Zip5 and Zip6 correlation with Zip4, a Blip correction is possible
- Can make a 3D fit of Zip4 observed energy as function of Zip5+6 Blip Time and Amplitude, then use the value of the function to have a predicted energy in Zip4
- The predicted energy can be used as a correction and the LHS tail is gone (except for single-detector Blips)
- The correction matters for the noise sample because it unmasks the pure Gaussian noise distribution (and RMS), we can also find a PSD that is not contaminated by Blips and simulate pure Gaussian noise (without TowerBlips)
- The effect in non-noise measurements appears to be small (~1keV), but could help improve the low energy measurements