Texas A&M University
Department of Physics and Astronomy

Optimized Dark Matter Search using the SuperCDMS Soudan Data and Monte Carlo Simulations

Plan and Outline

Preliminary Exam Presentation

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10/26/2017

Overview

I. Introduction and Motivation: Searching for Dark Matter

II. The *Super Cryogenic Dark Matter Search* Experiment

III. The Detector Monte Carlo (DMC)

IV. Plans for the WIMP Search Analysis

V. Conclusions

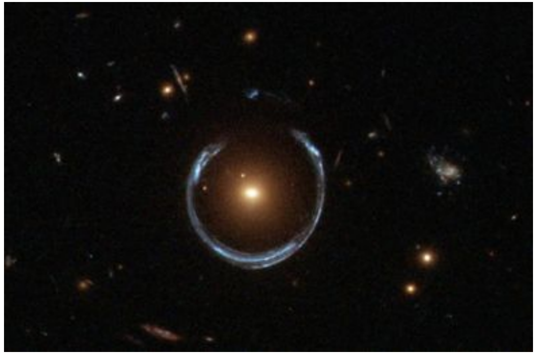
I. Introduction and Motivation: Searching for Dark Matter

Motivation

- It is observed that *Dark Matter* is 85% of the gravitational mass of the Universe, yet it has never been directly measured
- WIMPs are the simplest guess at the particle nature of Dark Matter
- This analysis is a WIMP search with the *Cryogenic Dark Matter Search Experiment (CDMS)*
- Previous versions of this analysis were strong, but the background model/rejection could have been better
- The bulk of the acceptance is in lower energies which are harder to model
- This is a new-generation analysis based on the improved simulations of the CDMS detector
- We are improving the modelling tools and methods to improve the sensitivity
- Now we are making sure we can trust our simulation tools, next we will use them for optimizing the WIMP search

Dark Matter and Existence of WIMPs

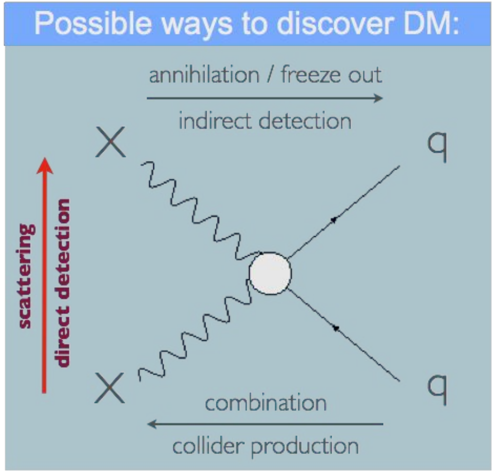
- Dark Matter Exists:
  - Rotational velocity of stars in outer parts of galaxies suggests greater than visible (light-interacting) mass
  - Gravitational bend (Einstein ring) suggests greater than observed mass
  - Cosmic Background Radiation measurements indicate that there is a large amount of mass 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

- Must look at the WIMP interaction/coupling with the Standard Model
    - Indirect Detection:
        Astronomical observations from WIMP annihilation, reconstruction from SM particles
    - Collider Production:
        High energy collisions of SM particles, producing WIMPs
    - Direct Detection:
        WIMP transferring momentum to a SM particle
        This work is about searching for WIMPs this way

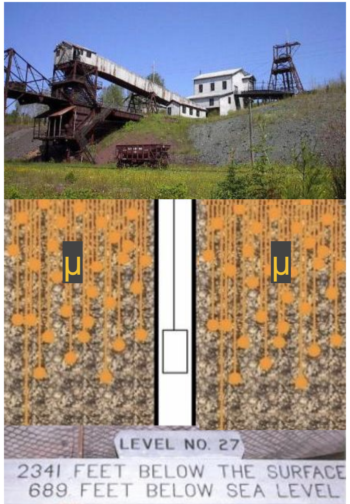


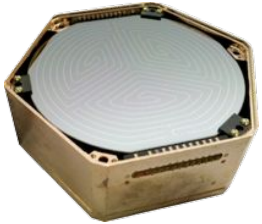
- **Current state of the art:**
    - WIMPs haven't been found by any experiment, but many are looking
    - Limits on the likelihood of interaction and its dependence on the WIMP mass keep pushing to lower sensitivities
    - The *Cryogenic Dark Matter Search Experiment* **(SuperCDMS)** is particularly competitive at the lower mass searches

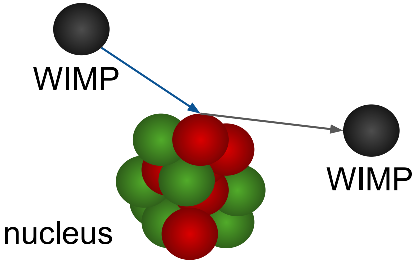
II. The Super Cryogenic Dark Matter Search Experiment

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
- Detector is deep underground (~2300 feet) to keep Cosmic Background from faking a WIMP interaction
- The experiment is shielded to prevent other types of radiogenic sources from entering into our data
- A WIMP would interact primarily with the nucleus in the crystal and produce vibrations in it

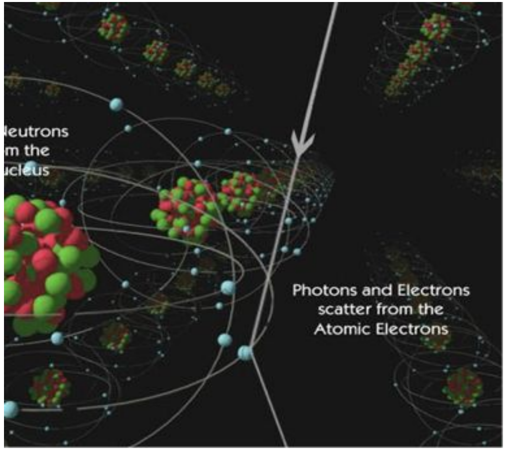


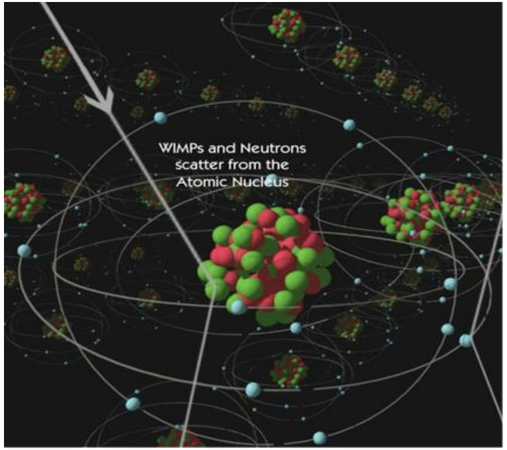




The SuperCDMS Detectors

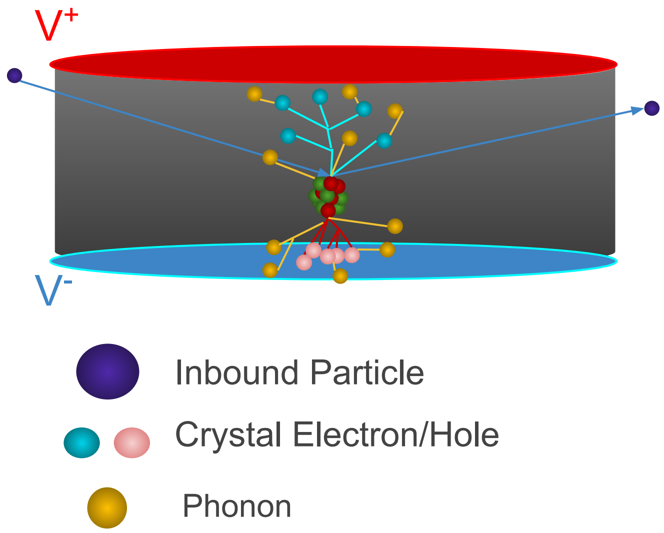
- The Super Cryogenic Dark Matter Search detectors are germanium crystals, with sensitive components at the top and bottom
- The cylindrical detector is cooled to superconducting state and a voltage bias is applied across its faces
- An incoming particle can interact:
  - Electromagnetically with electrons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





Measuring Interactions in the Detectors

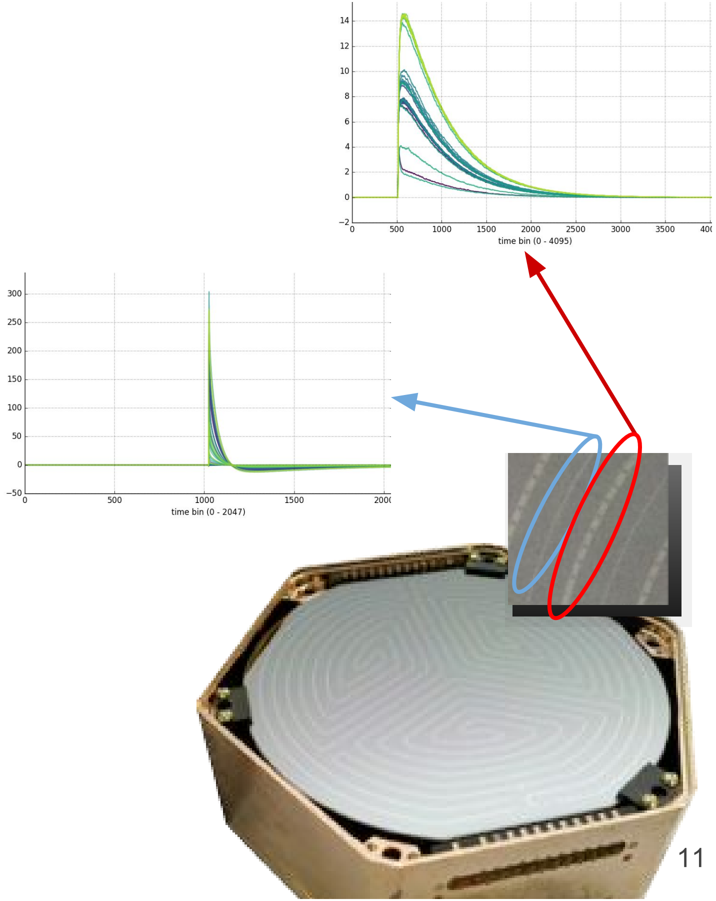
- When a particle interacts with the detector we have two types of responses:
  - Phonon Energy:
    - Energy deposited directly into the crystal lattice
    - The energy propagates/vibrates through the crystal as phonons
    - Phonons are collected by the dedicated sensors, recording the ***phonon energy***
  - Ionization Energy:
    - Electrons getting knocked out of the atoms
    - Because of the bias voltage they are accelerated and knock out more electron hole pairs
    - We collect the charge as ***ionization energy***
    - The electron/holes create more phonons/vibrations



- Every particle interaction results in both types of energy deposition, 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

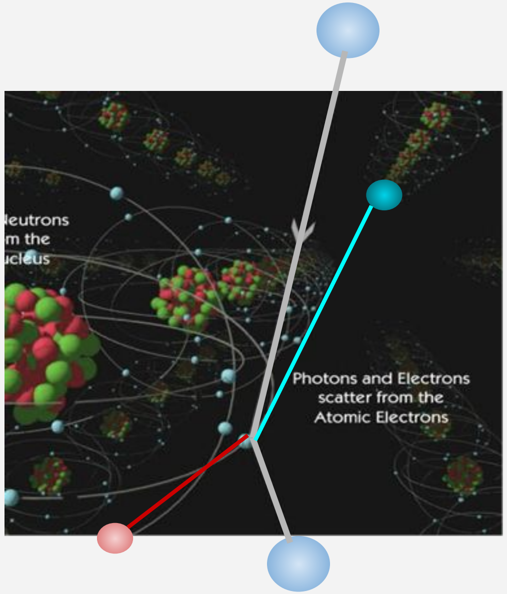
- Phonon Energy Collection:
  - Phonons are collected via the Transition Edge Sensors (TES*)
- Ionization Energy Collection:
  - The electron/holes are collected at the top/bottom charge lines
- The analog signal from both components is later digitized and stored for analysis. The amplitude of the signal 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

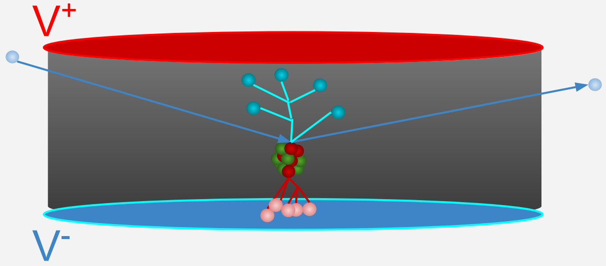
Electromagnetic interaction with electron in the lattice knocks it out of place



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

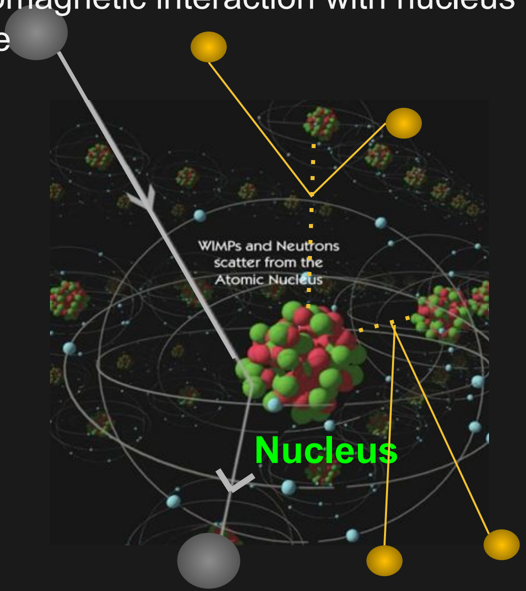


Phonons are also created from the accelerated electron/holes, so “phonon energy” is also released

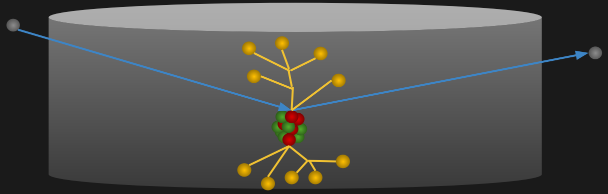
Ionization Energy ≃ Phonon Energy

Details about Nuclear Recoil

Non-electromagnetic interaction with nucleus in the lattice



Produce phonons (quantized vibrations) in the crystal lattice



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

Ionization Energy < Phonon Energy

WIMPs (signal) or Neutrons (background)

Phonon

Signal and Background Sources

Signal (WIMP)

- Interaction via nuclear recoil
- Nuclear recoil creates a phonon signature, proportional to the amount of energy
- Very few electron/holes released from the primary phonons so small "ionization energy" deposited

Backgrounds

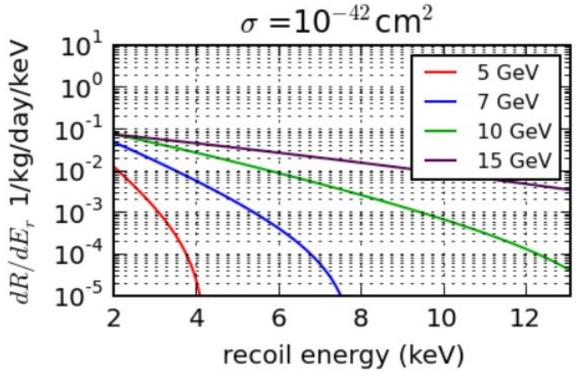
- From Cosmic Rays:
    - Photons and electrons create electron recoils
    - Neutrons create nuclear recoils
    - Muons create electron recoils
    - Neutrino interaction rates are below sensitivity/threshold
- Radioactive Contaminants that Decay in the Detectors (Radiogenic):
    - Germanium activation: creates electron recoils
    - Lead Implantation: creates both electron and nuclear recoils
- Mismeasured Events:
    - Mixed Events: multiple particle interactions in same “event”
    - Detector/DAQ Malfunction

Overview of This Analysis

- We are optimizing the “low mass” WIMP search analysis
  (mass regime between 5 and 15 GeV)

- At low recoil energies (like in this case!) we get poor energy resolution

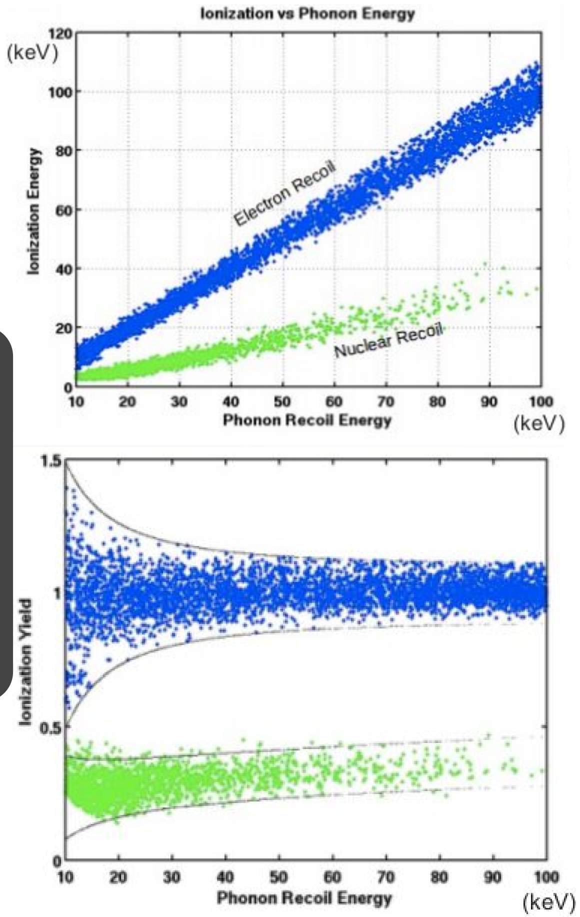
- The challenge is to have a good way of separating backgrounds and signal in this energy range



- We are working in a trustworthy detector simulation (using Monte Carlo methods) to do that:
  - We have developed most of the tools
  - Right now we are working on the validations
  - After that, we will apply to the WIMP search and optimize

Discriminating Between Signal and Background Events

- Measure ionization and phonon energy for every event
- Discrimination tool is ratio of both
- Use *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, 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
  - Difficult to tell when events occur near the sides or top
- The high quality detector simulation we are developing will help us better understand interactions so we can better measure energy deposited in both systems and/or reject more efficiently events where things are not well measured



Quick Outline of the WIMP Search Analysis

1. Construct a background and signal model
2. Develop the tools that simulate the background and signal
3. Validate the tools comparing simulations with calibration data
4. Obtain background estimates
5. Calculate the sensitivity limit
6. Iterate as new improvements/issues are identified

Dominant Backgrounds and Previous Analyses

- Our current background model is based in previous analyses, where the dominant backgrounds were expected to be:

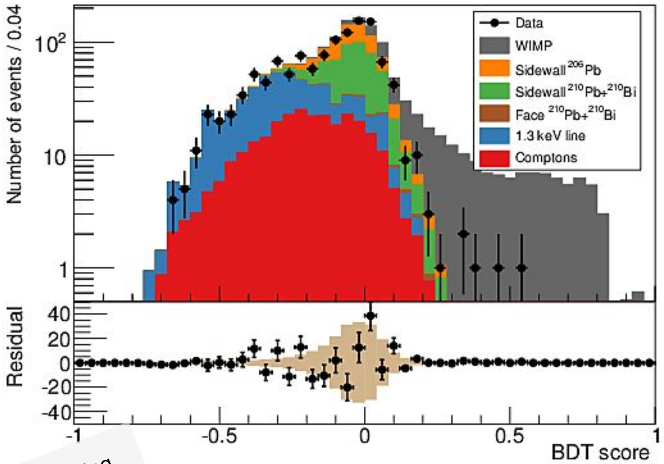
Backgrounds from Real Interactions

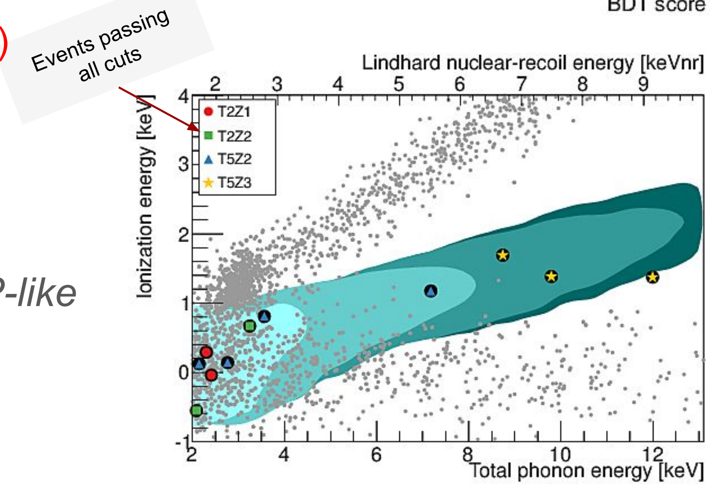
1. Nuclear Recoils from Sidewall ^{206}Pb Contaminants
2. Electron Recoils from Sidewall/Face ^{210}Pb, ^{210}Bi Contaminants
3. Electron Recoils from Germanium activation (*1.3 keV line*)
4. Cosmogenic Electrons and Photons (labelled as *Comptons*)

Backgrounds from Pathologies in the Experiment

- These were not included, will now be added

- The final, “optimized selection” resulted in a *handful of WIMP-like events*. They were inspected and determined to be mostly mismeasured or faulty events





Optimized WIMP Search Analysis Goals

Goal 1. Improve the background rejection from known interactions that are poorly measured

- Using the high quality Detector Monte Carlo to get a better background model

Goal 2. Take into account the “mismeasured events” as a background:

- By gaining knowledge of the detector’s response through the Detector Monte Carlo we might be able to better identify the mismeasured events
- We might be able to simulate these events as well

- In this talk we show how we will focus on ***Goal 1*** since ***Goal 2*** is likely to be easy, and not as important for the future

III. The Detector Monte Carlo (DMC)

The Tool that Simulates the Backgrounds

- The *Detector Monte Carlo (DMC)* is the tool that simulates both the signal and backgrounds
- Once fully validated it will:
  - Improve our understanding of the detectors' response
  - Improve our background model
  - Allow us to better reject backgrounds while retaining more signal
- The analysis relies on the ability to discriminate the background efficiently, which is particularly complicated at low energies. The improved background model/rejection will help us recover previously lost events/signal
- The first step towards such an *optimal* analysis is a DMC we can trust, which is what I have been working on!

Overview of the Detector Monte Carlo

- The DMC produces a full simulation of events in the detectors
- First it simulates the particle-level interactions of inbound particles with electrons or the nuclei in the detectors
- Then it simulates the electron/hole and phonon propagation in the crystal lattice, up to the phonon and charge sensors
- Next it simulates the sensor response to produce the charge and phonon signals
- Finally it executes the same *data analysis software* to get the same analysis tools and output as real experimental data

Plan for Validating the DMC

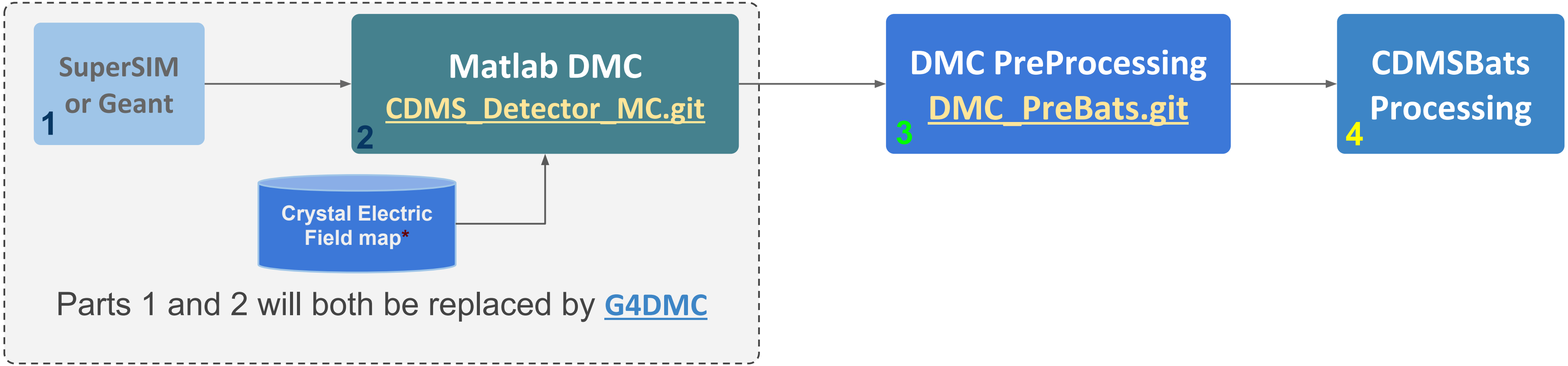
- We are now able to validate the *physics* of the code (now that the code works!)

I. Start with calibration samples, because those we understand
   - ^{133}Ba (electron recoil source) first, ^{252}Cf (nuclear recoils) later

II. Look at the locations and resolution of expected features in the energy spectrum

III. Next understand the variations of variables as a function of energy and position
   - First we'll compare the DMC relative to itself identifying a golden portion of a detector and variations around it
   - Next we'll do the same with data
   - Finally we'll have common ground to compare data with DMC
   - Ideally this will help us understand if some of the variations around the golden portion can be corrected or should be thrown away

Technical details about the DMC Generation Tools



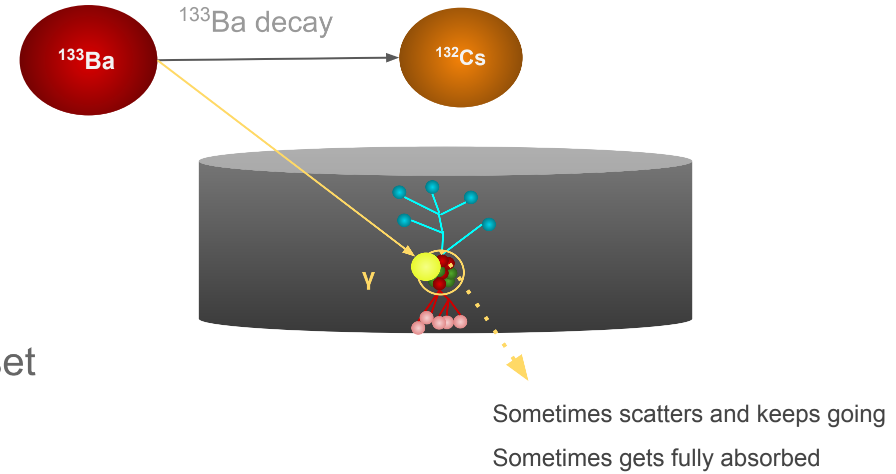
1. SuperSIM: Geant 4 based package for particle generation, scattering, and interactions with the detectors
2. Matlab DMC:
   a. Simulates charge (electron/holes) and phonon propagation in the crystal
   b. Uses the e^-/h^+ and phonons at the crystal edges to simulate the absorption and creates the event read-out
3. DMC PreProcessing: turns the simulated events into a format usable for processing like real data
4. CDMSBats Processing: the same data processing as done with real data (with a few DMC specific additions)

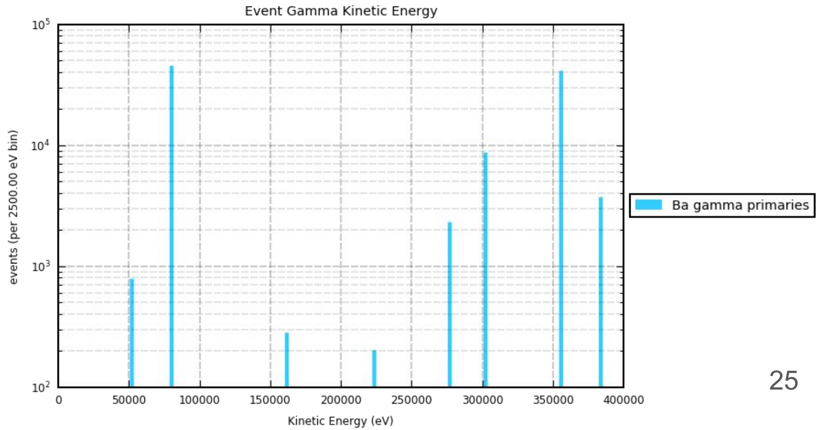
* Note: the crystal electric field map is a solution from a commercial finite element analysis package (COMSOL)

Example: Validation with ^{133}Ba Calibration

Calibration Setup

- ^{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 or get absorbed by with other materials before even reaching the detectors so we will not see them

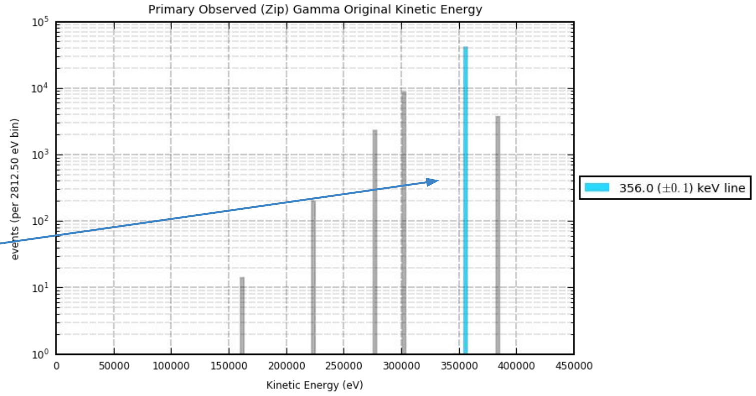




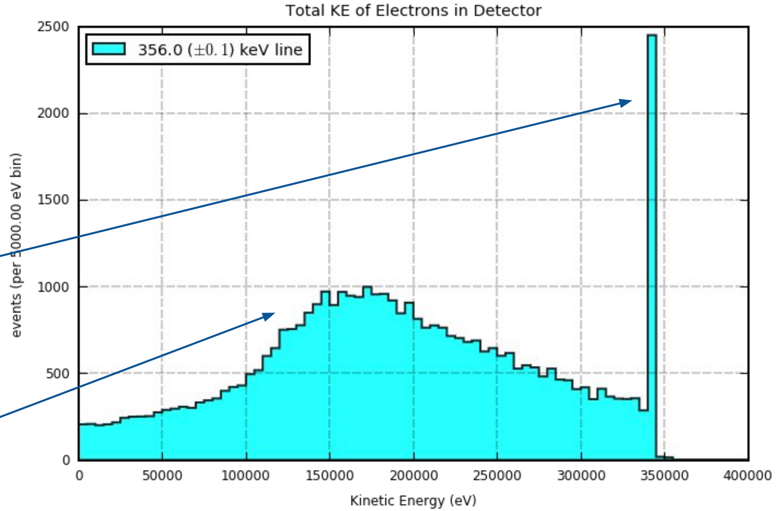
Simplifying the ^{133}Ba Simulation
(selecting just 356 keV gammas)

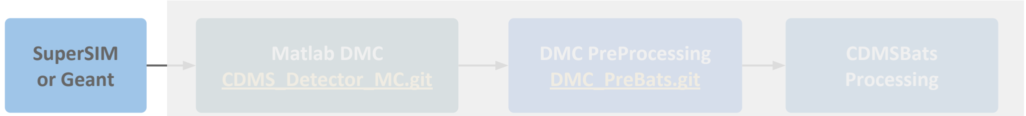
Before DMC: SuperSIM

- Take for example the 356 keV events only



- The DMC first stage, SuperSIM, takes the inbound gammas, and simulates the electron recoils in the crystal
- The energy deposited by electron recoils in the detector shows:
  - A delta-like function very close to full energy deposition
  - A Compton-scattering spectrum for the events that bounced around without being fully stopped

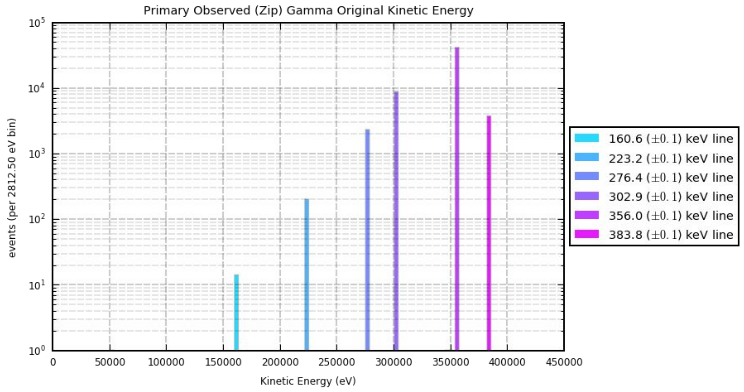


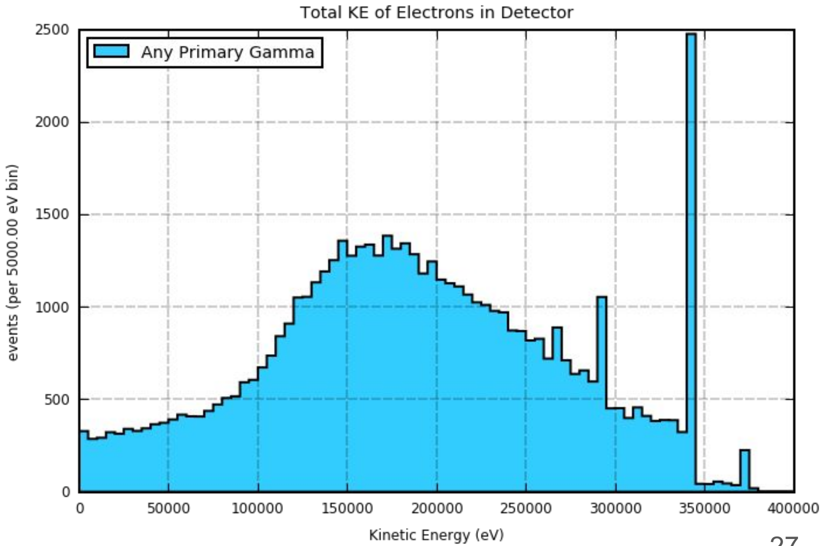


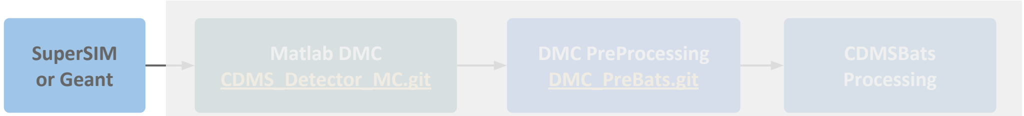
The Full ^{133}Ba Simulation

Before DMC: SuperSIM

- Now extend to the full set of ^{133}Ba primary gammas
- Notice lower energies are not observed because they are blocked by the detector housing and surrounding material
- The ^{133}Ba electron recoil spectrum becomes more complicated, with all the Compton edges added together
- Next consider how our detector reacts to measure each event



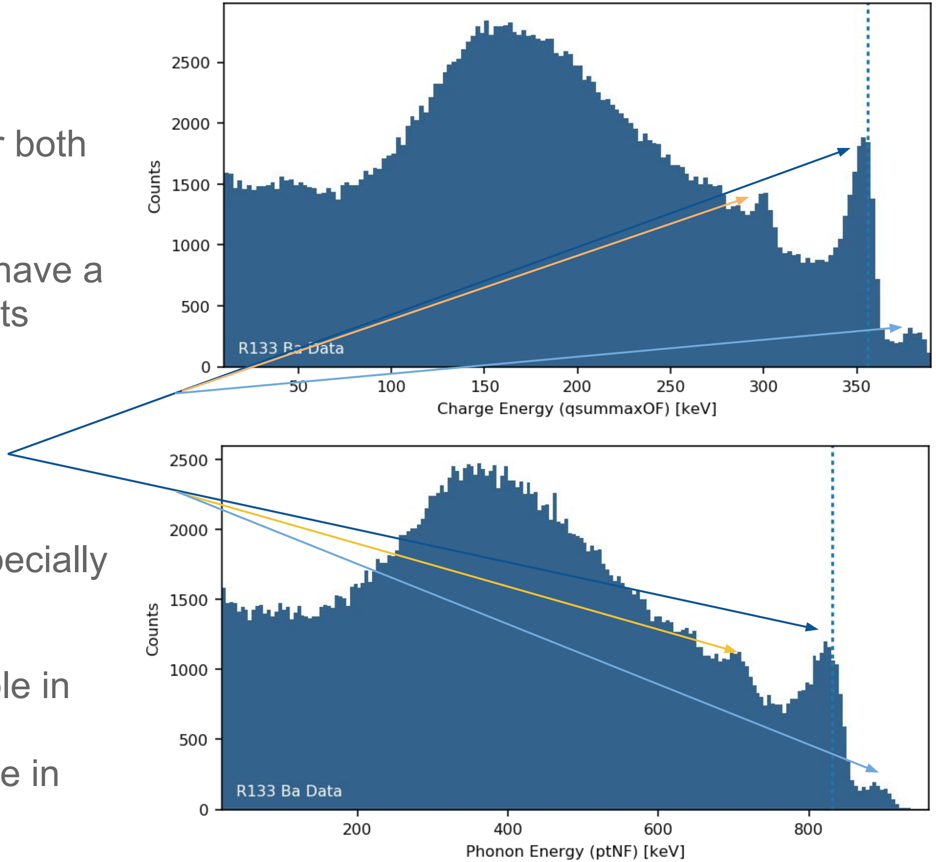


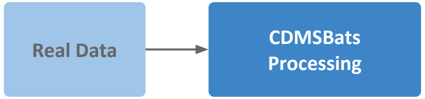


Real ^{133}Ba Calibration Data

How Real Calibration Data Looks Like

- Consider the experimental measurements we get for both *ionization energy* and *phonon energy*
- Note that the lines are no longer delta functions but have a range of energy because of detector resolution effects
- At least three of the ^{133}Ba lines are easily noticeable
- They are located at the expected locations
- Resolution effects: the distributions get smeared especially towards lower energies
- Our way of validating is running the equivalent sample in the DMC Generation tools, and comparing our fully simulated and reconstructed results with what we see in data

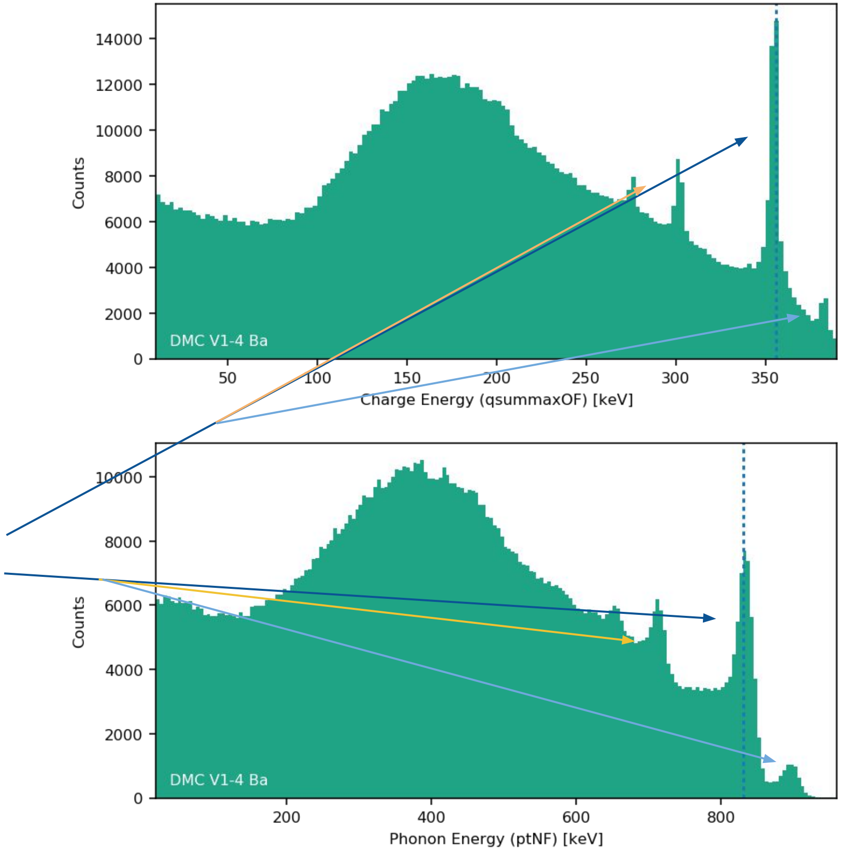




Next Piece of ^{133}Ba Simulation Picture

After SuperSIM: DMC and Processing

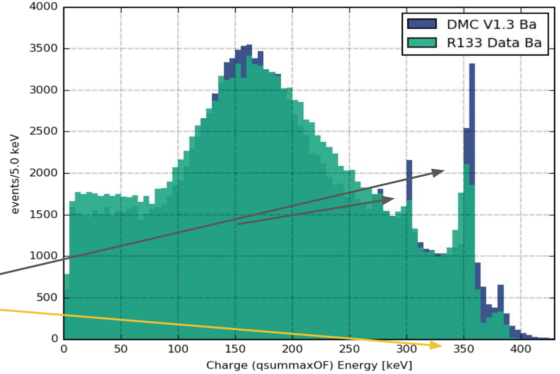
- Now:
    1. Run DMC (from crystal propagation through pulse simulation)
    2. Run official production code just as real data
- We also have ionization energy and phonon energy
- Peaks are still at the right location, and with correct number of events at each (i.e. proportions)
- Also get resolution effects from detector physics!

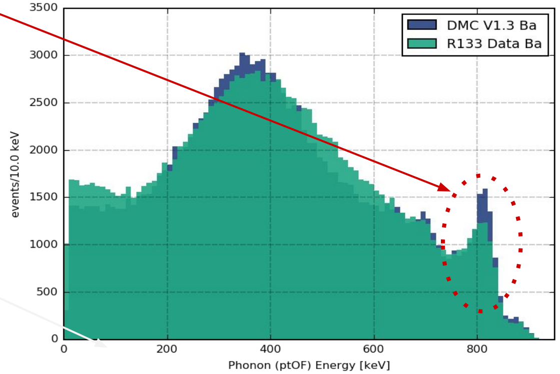


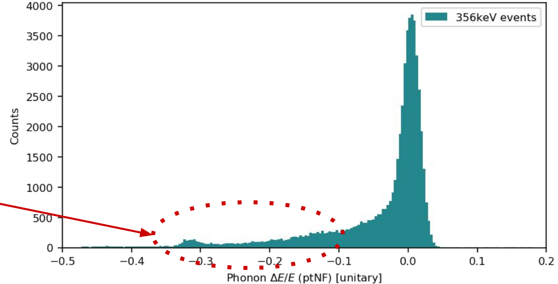
SuperSIM or Geant → Matlab DMC CDMS_Detector_MC.git → DMC PreProcessing DMC_PreBats.git → CDMSBats Processing

Current Status of the DMC Validation

- The DMC is well behaved:
  - We see the peaks in the right places
  - The number of events in each peak is similar
  - The width (resolution) is better in our simulation than it is in data (working on understanding this)
- Need to dig deeper into the variations, looking closely at:
  - Pulse shape
  - Energy estimates and goodness of fit
  - Energy yield
  - Dependence of all v.s. energy
  - Dependence of all v.s. Position
- We are working in understanding the measurement effects
  (example: 356 keV events, the relative error of the energy)







Milestones of the DMC

- One line summary: *We have taken the simulation software from something that didn't work to something that is starting to approximate reality*

- We have come a long way developing and validating the tools:
  - It didn't do the calculations correctly, we fixed energy conservation and other problems like crashes
  - Went from 20% event crashes a few years ago all the way to near-zero (the remainder occur at energies we don't care about but we are still investigating if they matter)
  - Processing time of single event went from ~2hrs to ~15mins
  - Matlab TES Sim has been replaced by the TES ODE, based in an *ordinary differential equation solver* which takes into account thermo-electrical saturation (developed primarily by Jon Wilson)

- We have developed the set of tools and conventions to make the code reproducible, tagged, and version-controlled

- We developed the tools that stream-line the DMC event production: from adding new samples to storing the data in the online catalog (over 6M events generated with the Brazos Cluster, across multiple samples now!)

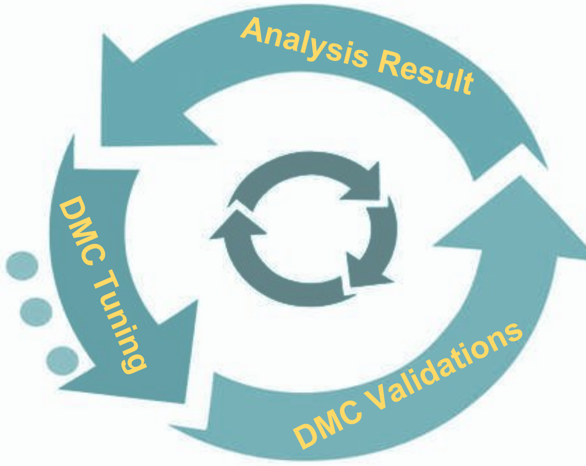
Current Status of the DMC

- With a fully functional, well-oiled production, now that we *can see* the changes at each stage, our work is focused in understanding how the simulations compare to data
- Now that we can easily see what the simulation does at each stage, we can study what is still broken, what effects are needed to be added, and what detector model parameters need to be tuned
- With a well set up set of tools we have moved CDMS to the next generation of analysis style, to become more like the advanced analysis techniques employed by much larger and sophisticated experiments like the LHC
- This setup is not just for the old data, but to make things well set up for the new data taking run to start in a few years (*SuperCDMS SNOLAB*) with more, and better detectors (more on this soon!).

IV. Plans for the WIMP Search Analysis

Plans and Next Steps for the Analysis

- Will cycle the validation → tuning of the DMC until it's good enough for this analysis
- First step is to know how to see if the DMC is good enough, so:
  - With a first-version DMC get the analysis going to the end to see what limits (or background estimates) we get, and explore how next-effects matter
  - Then iterate as needed until next-effects are not meaningful to the final answer (systematics)
- With the satisfying DMC we can explore *optimization* mechanisms:
  - We will obtain an improved result using the same tool as previous analysis
  - We might try something else, like a NeuralNET if appropriate
- Finally, open the box, look for WIMPs, and make a discovery or set one of the world's best limits!



Conclusions

- We are searching for WIMPs with the SuperCDMS detectors
- Previous versions of the analysis were strong, but left backgrounds that could have been rejected
- To improve the sensitivity we want to go to lower energy
- Lower energy with the detector is harder to understand so 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 to better optimize the sensitivity
- Tools are in progress and we will start the iterative process of validating the tools, updating the analysis and figuring out the dominant remaining backgrounds until we are fully optimized
- While we may not discover DM in this data set, we hope to set the world's best limits at low mass and design the algorithms for best practice for the upcoming data taking at SNOLAB which should have more and better detectors!

Thank You!

And special thanks to:

Dave Toback

Jon S. Wilson

Toback Group

Steve Johnson

Guy Almes

Brazos Cluster Team

BACKUPS

ΛCDM Model

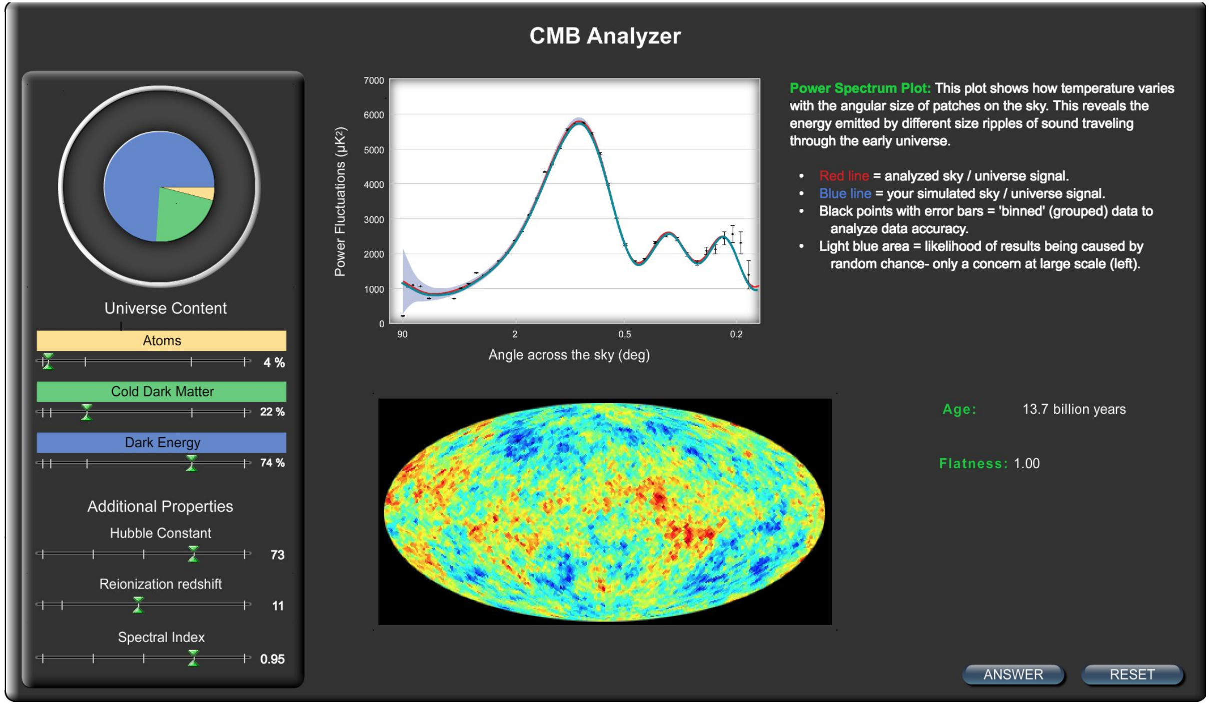
Appendix A

- 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

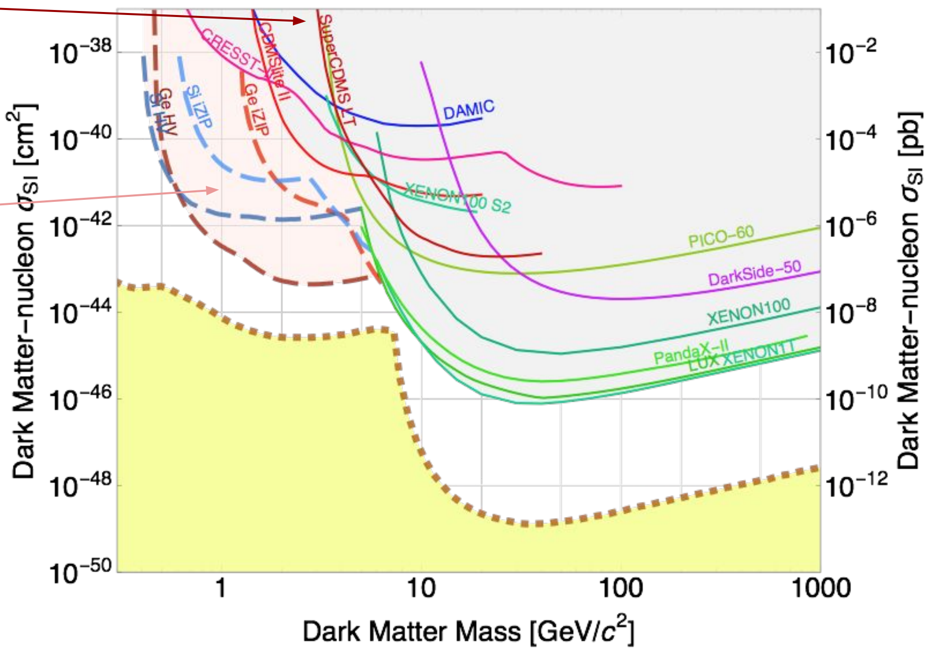
- See NASA's CMB toy plotter: https://lambda.gsfc.nasa.gov/education/cmb_plotter/



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

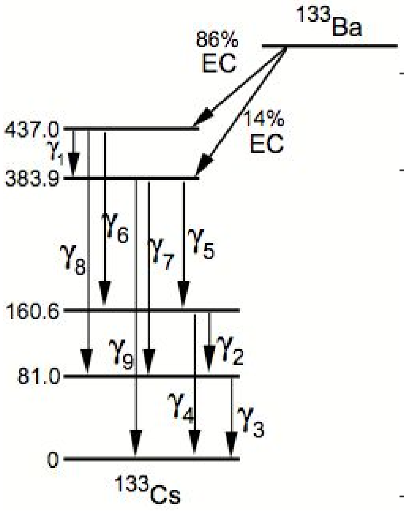


^{133}Ba Decay

- Electron Capture decay

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

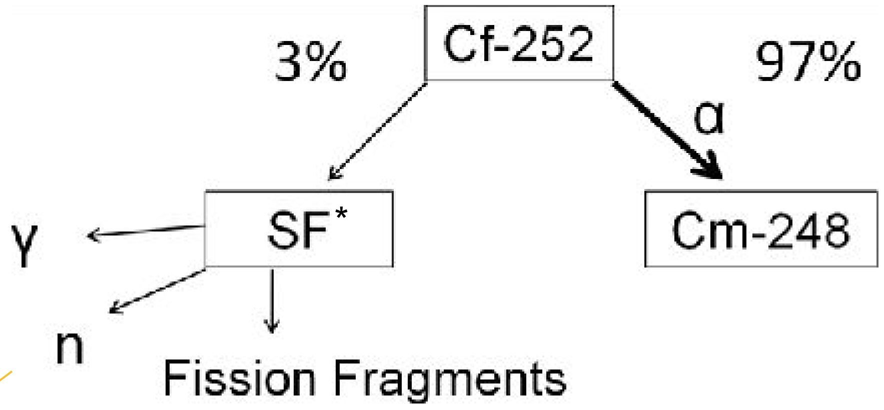
  (+ x-ray from the collapsing e^-)



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)

^{252}Cf Decay



* SF: Spontaneous Fission

- The neutrons make it to our detector and produce nuclear recoils

- This doesn't leave the source, so doesn't make it to our detector!

Appendix E

^{206}Pb, ^{210}Pb, and ^{210}Bi

- From the Uranium/Radon decay series
- ^{206}Pb
  - Last state in the decay chain
  - It is stable, so nothing really comes our of it
  - In our simulations this is really about the knocked-out particles that punched through into the detector:
    - Actual ^{206}Pb nuclei that reached the detector
    - Copper fragments from the housing
- ^{210}Pb and ^{210}Bi
  - Mostly all β^- decay, so just electrons (and photons) make it to our detectors