

# The Search for Dark Matter: Next-Generation Simulation Tools for the CDMS Experiment

Master's Defense  
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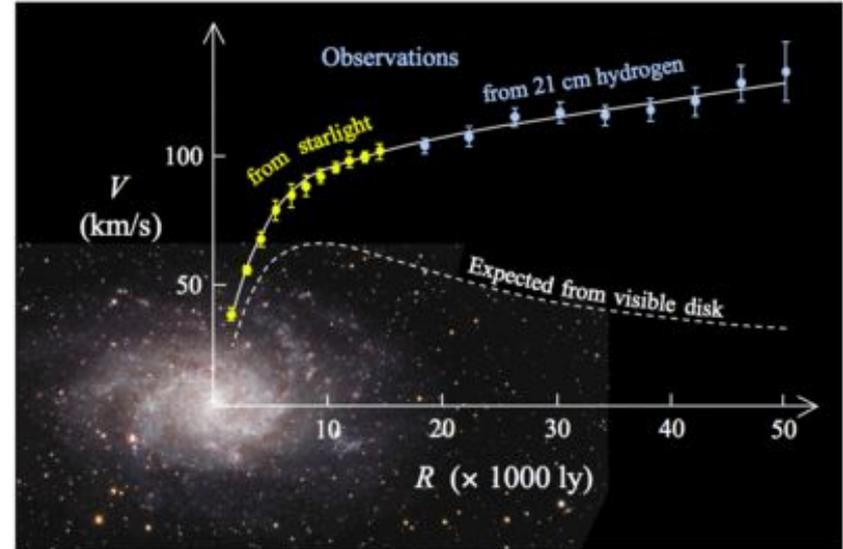
# Introduction to Dark Matter

1. Some evidence for Dark Matter in the universe
2. A cosmic Dark Matter observation

# Some evidence for Dark Matter in the universe

Stars in galaxies and clusters of galaxies don't appear to move as predicted by Newton's laws. They orbit too rapidly, as though unseen mass, or "dark matter", were present.

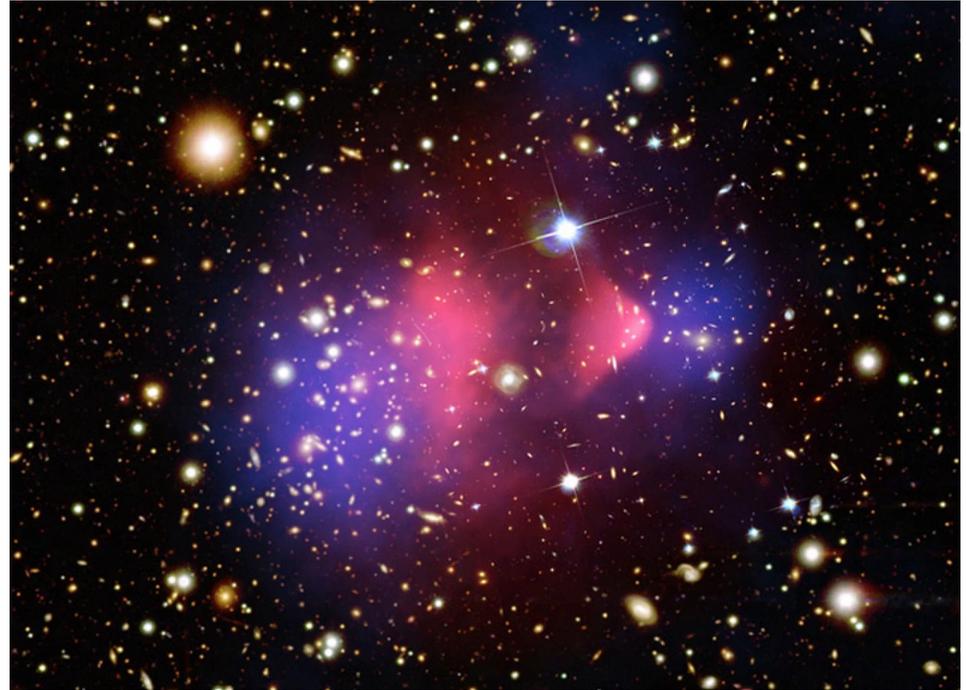
One possible explanation: *weakly* interacting massive particles "WIMPs" are present throughout the universe, which participate in gravity, but not much else.



Data for the image are from Corbelli, E.; Salucci, P. (2000). "The extended rotation curve and the dark matter halo of M33". *Monthly Notices of the Royal Astronomical Society*. **311** (2): 441–447. [arXiv:astro-ph/9909252](https://arxiv.org/abs/astro-ph/9909252). [Bibcode:2000MNRAS.311..441C . doi:10.1046/j.1365-8711.2000.03075.x](https://doi.org/10.1046/j.1365-8711.2000.03075.x).

# A Dark Matter collider observation

- The Bullet cluster is the aftermath of a collision between two galaxy clusters
- Interstellar dust and gases (red)
  - Heated by inelastic collisions
  - Slows down
- Gravitational lensing (blue)
- Dark matter
  - Did not slow down!
  - Dark matter is particle-like and weakly interacting



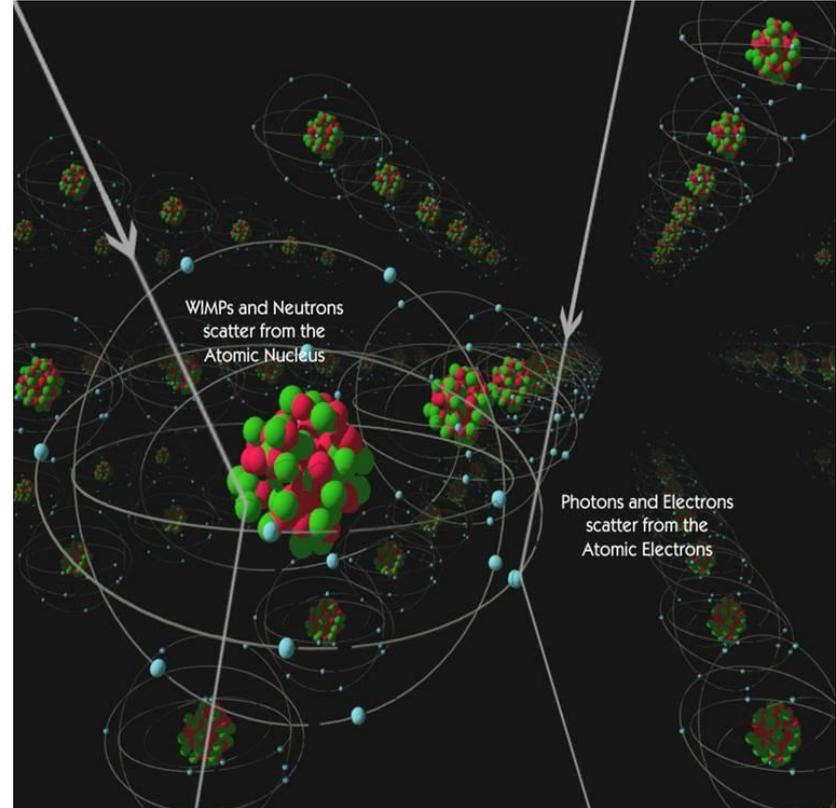
Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.;  
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;  
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al

# The Cryogenic Dark Matter Search (CDMS)

1. We try to directly detect Dark Matter
2. Nuclear recoils in a detector
3. Introducing: the detector
4. Managing background signals
5. Recording data

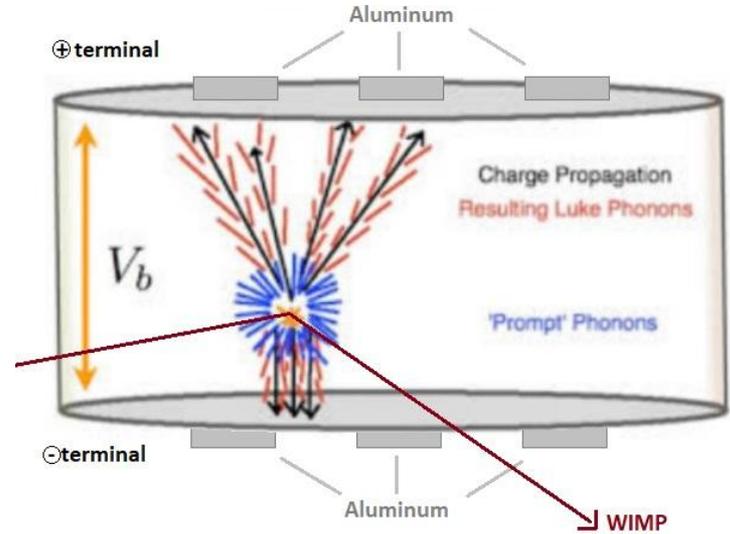
# We try to directly detect Dark Matter

- WIMPs, neutrons scatter from the atomic nucleus
- Photons, electrons scatter from an atomic electron
- Our background is overwhelmingly of the second type
- Experiment designed to separate the two types



# Energetic recoils in a detector

- Do an experiment looking for particle interactions in a crystal
- Particle transfers kinetic energy to atoms
- Crystal converts recoil energy to phonons, electron-hole charge pairs
- Phonons collected by aluminum fins
- Charges drawn to voltage-biased terminals
- Charges accelerate, creating more charge pairs and phonons (also collected)

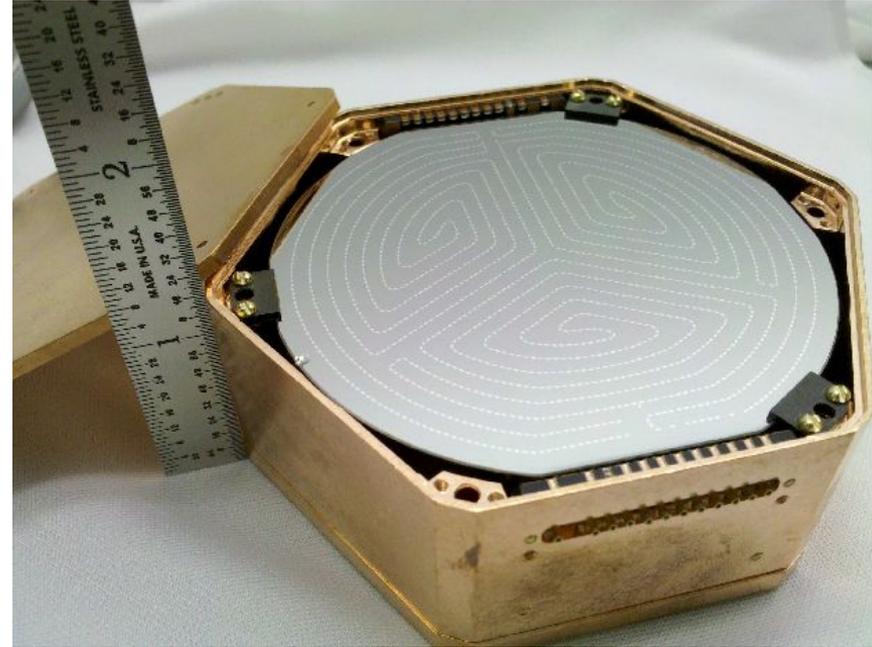


# Introducing the Detector

## Cryogenic Dark Matter Search (CDMS)

Detector contains:

- Crystal the size of a hockey puck
  - germanium or silicon
- Superconducting phonon sensors
  - aluminum and tungsten
- Copper housing
- Actual temperature 40mK

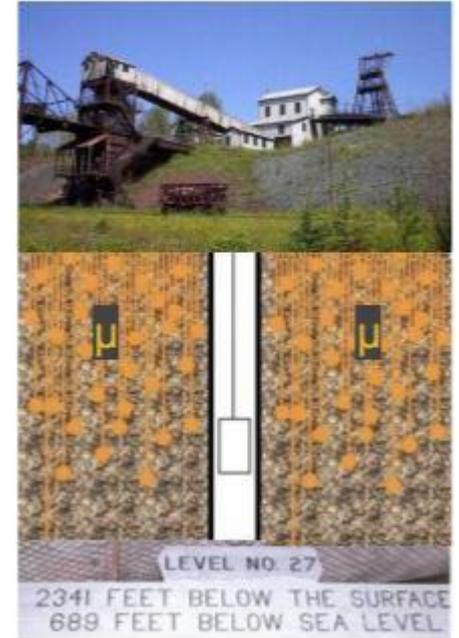


A CDMS “iZIP” detector with photolithographically defined phonon sensors.

# Managing background signals

Important background sources:

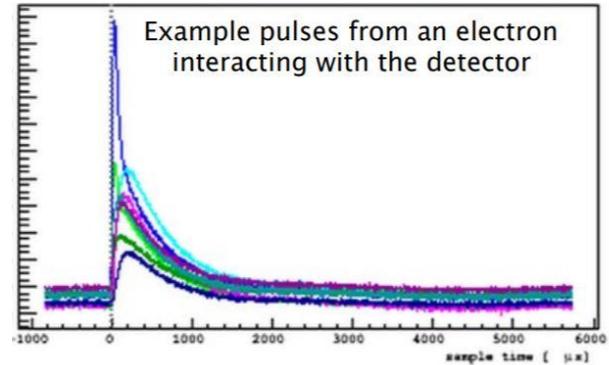
1. Cosmogenics (e.g. muons from cosmic rays)
  2. Environment (e.g. cavern walls are radioactive)
  3. Contaminants (e.g. radon gas in the nitrogen lines)
- Muons penetrate multiple meters of normal matter
  - Experiment was installed deep in an inactive mine in Soudan, Minnesota
  - A future experiment is located in an even deeper mine in Sudbury, Ontario (aka SNOLAB)



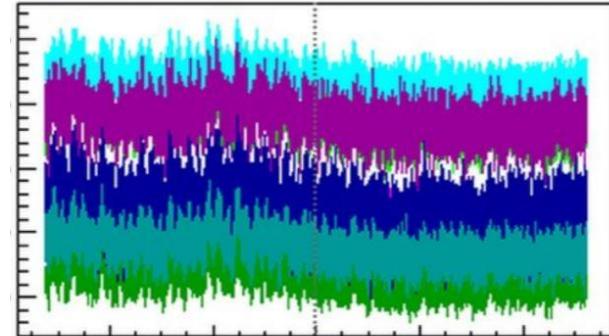
Muons blocked by Soudan low background counting facility

# Recording Data

- Detector reads out current through each of its phonon and charge sensors
- Data is recorded in fixed-width time intervals (about 7 ms)
- Later, data processing reconstructs each event's initial energy
- The Soudan experiment read out millions of events from 2012-2015
- The SNOLAB experiment scheduled to begin 2019/2020



Pure Noise, when no Particle is Interacting



*Will want to simulate all this to make sure we understand all the processes*

# Separating Background and Signal events

1. Searching for rare events
2. Understanding the detector response
3. Separating events by recoil type
4. Simulation can help design the Analysis

# Searching for rare events

The goal of Analysis is to recognize a few signal events, either individually or in ensemble, from among the millions of non-signal events recorded in detector experiments.

One challenge is that background sources can produce the same detector readout information as a true dark matter interaction

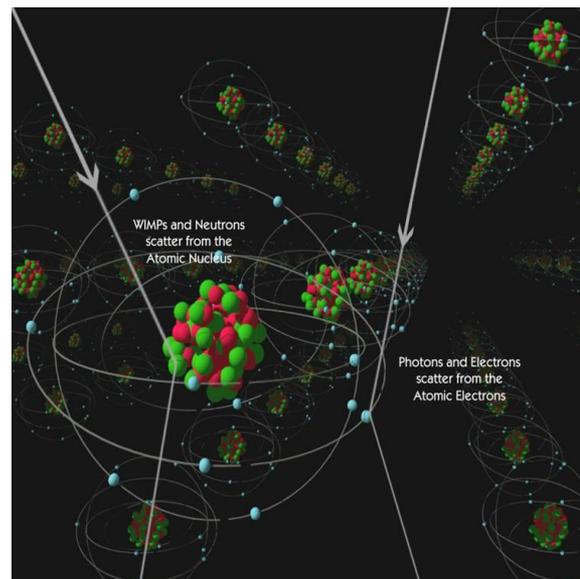


# Understanding the detector response

- Need to understand how the detector responds to photons and neutrons

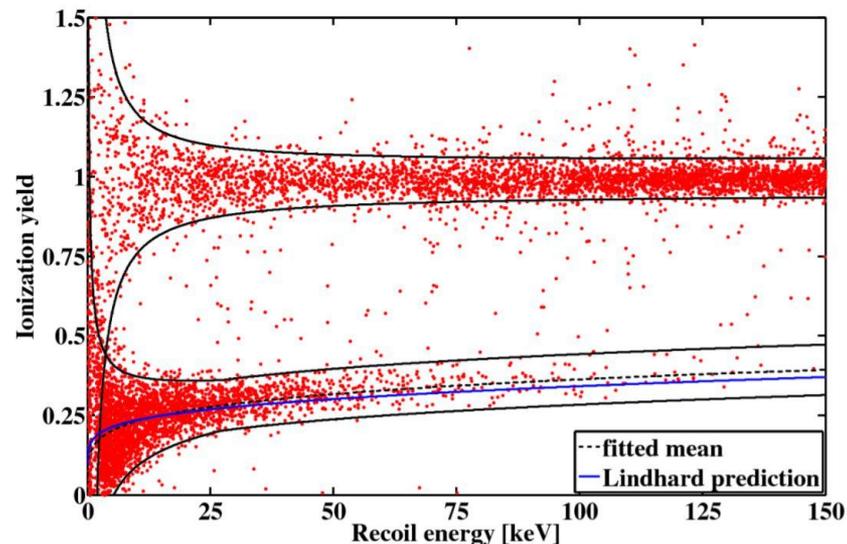
Expose detector to two calibration sources:

- Radioactive californium-252
  - emits neutrons
  - nuclear recoil in the detector
  - similar to a dark matter signal
- Radioactive barium-133
  - emits photons
  - electron recoil in the detector
  - similar to most background sources



# Separating events by recoil type

- Recognize events by their properties
  - “ionization yield”: ratio of energy in charge sensors, phonon sensors
  - Electron recoil (higher yield branch)
  - Nuclear recoil (lower yield branch)
- 
- Will want our simulations to be able to reproduce this (in-progress)

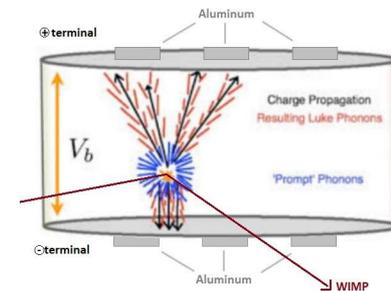


Taken from  
Ahmed, Z. et al, “Search for inelastic dark matter with the CDMS II experiment.”  
Phys.Rev. D83, 2011

# Simulation can help design the Analysis

Simulation allows us to practice analysis techniques when the answer is known.

- Can we design a set of cuts to separate the background from the signal?
  - Separating background from signal is easier when the answer is known
- How accurate is event identification?
  - Simulate WIMPs at different energy scales and try analysis on each
  - Determine empirically the limits of accurate identification



*Simulate all of this!*

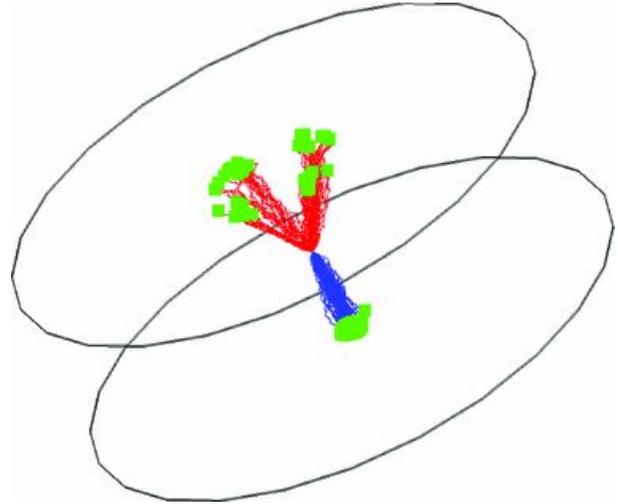
# Next-Generation Simulation Tools

1. Introducing: the simulation
2. Introducing: the structure
3. Organizing the Structure for Simulation
4. Version control of large-scale Simulations
5. Permanent storage

# Introducing the simulation

A great deal of effort has been put into a reliable, accurate simulation of the detector. It is a mix of particle physics and condensed matter physics.

1. Simulate particles traveling in a material
2. Particles interact, create recoil in detector
3. Simulate detector response to a recoil
4. Add experimental readout noise
5. Process just like real data  
(Reconstruct each event's initial energy)



Geant4 Simulations of the SuperCDMS iZIP Detector  
Charge Carrier Propagation and FET Readout  
Agnese, R., Brandt, D., Asai, M. et al. J Low Temp  
Phys (2014) 176: 930.  
<https://doi.org/10.1007/s10909-014-1182-9>

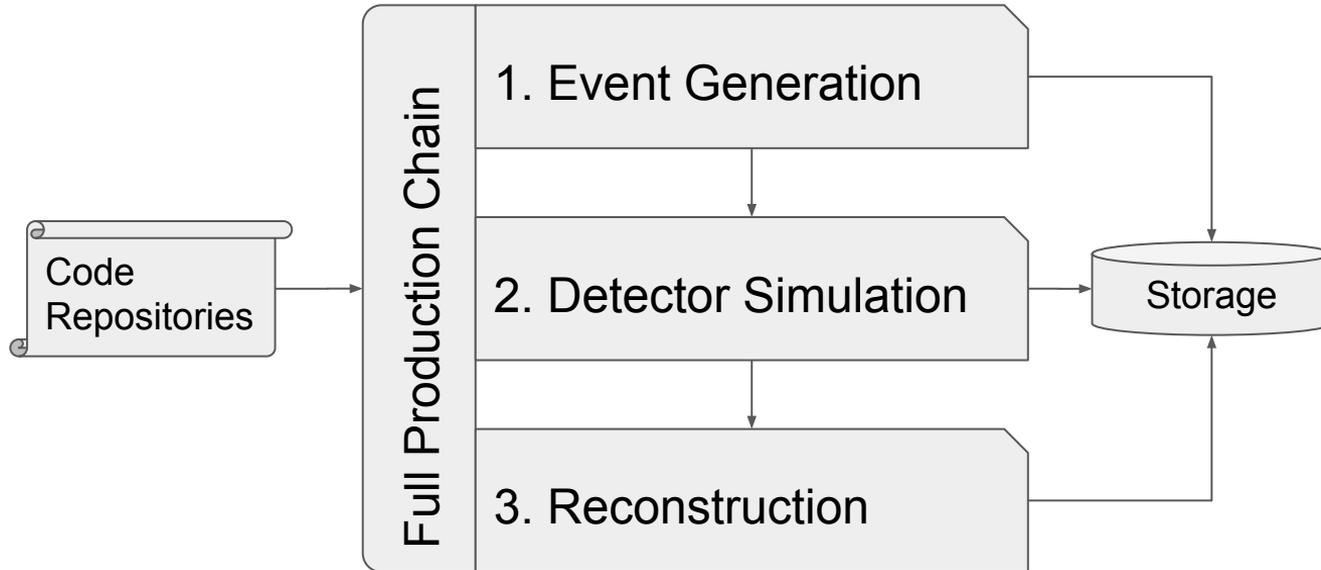
# Introducing the structure

We have been working to build and maintain a powerful software infrastructure for producing the needed simulations datasets.

- *Primary goal:* Easy reproducibility of all simulated datasets.
- Simple and Organized code structure and workspace directories
- Version control and collaborative sharing of code pieces
- Standardized, user-friendly tools for frequently executed tasks
- Straightforward to move to complete automation
- Robust bookkeeping for use by analyzers, label datasets by code version
- Clear path to adoption for SNOLAB use

# Organizing the Structure for Simulation

Many pieces of code need to work together to define, produce, and store the simulations.



# Permanent storage

Simulation proceeds in steps, and output can be saved at any of several intermediate steps for permanent storage. Currently, permanent storage means disks at SLAC. Transfer tools move data to/from TAMU.

All of the stored files are listed in the SLAC Data Catalog, which is a web interface for searching and retrieving files. Datasets are labeled by code versions and parameters used to create them.



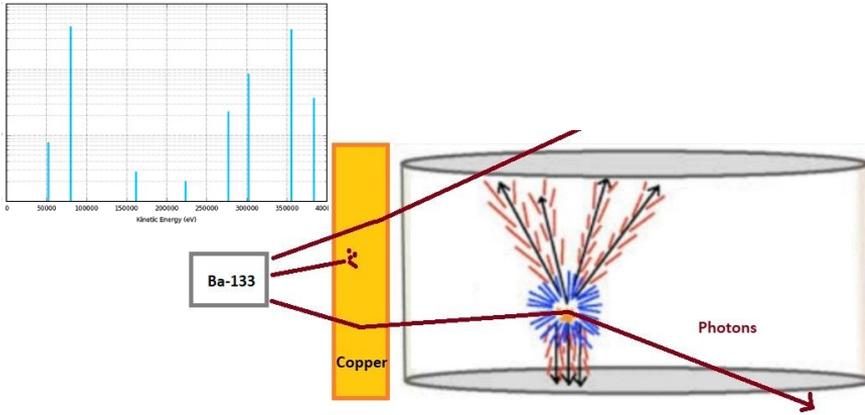
The screenshot shows a web browser window with the address bar containing the URL `srs.slac.stanford.edu/DataCatalog/?experiment=CDMS`. The page header includes a "Tools" link. The main content area features the "CDMS Data Catalog" logo, which consists of a circular image of a galaxy with the text "Super" and "CDMS" overlaid, followed by the text "CDMS Data Catalog". To the right of the logo, the page displays "Version: 1.13-SNAPSHOT" and "Login | Jira". Below this, a list of project links is shown: "Project: CDMS | CTA | EXO | SID | HPS | LSST-CAMERA | LSST-DESC | LSST-DM | SLAC-PAC-LSST | SRS | SSRL". At the bottom, the mode is set to "Prod" with other options "Dev" and "Test" available. A navigation bar at the very bottom includes links for "View: [ Tree . Data Types . File Formats . Messages . Admin . Problems ]".

# Example Simulations And Results

1. Example simulation: barium-133
2. Results of Simulation

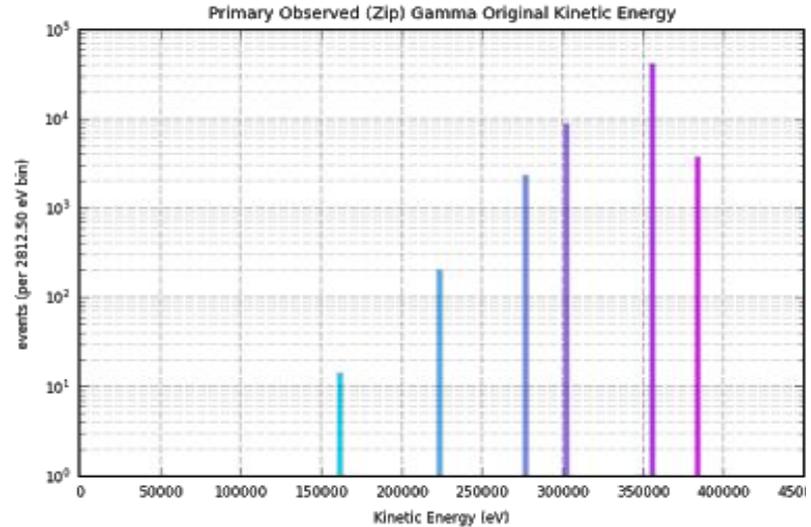
# Example Simulation: Step 1: Particle Simulation

Simulated **particle** energy spectrum for the barium-133 calibration source.



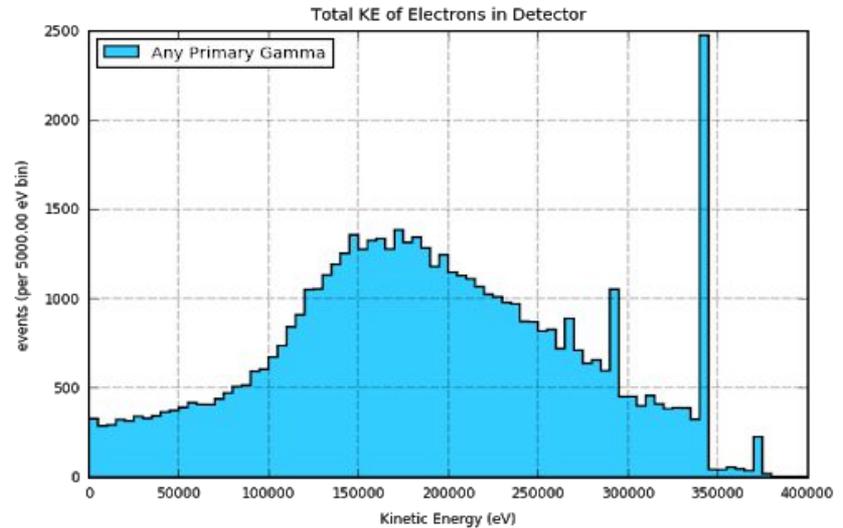
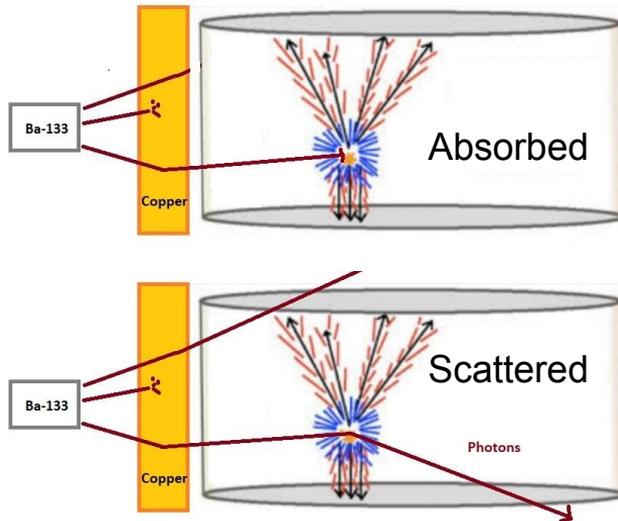
Left: photons emitted by a barium source  
(spectrum given in figure)

Right: simulated photons incident upon detector crystal,  
(the lowest-energy photons did not reach the detector)



# Example Simulation: Step 2: Recoil Simulation

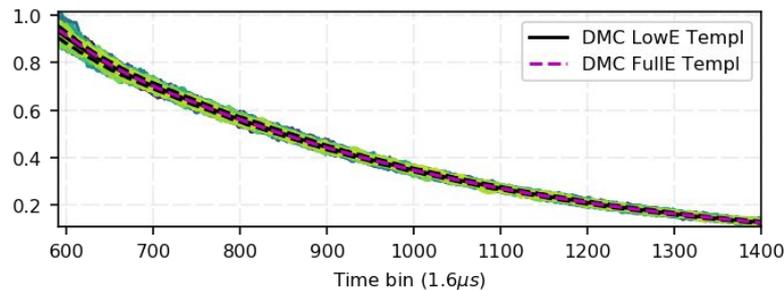
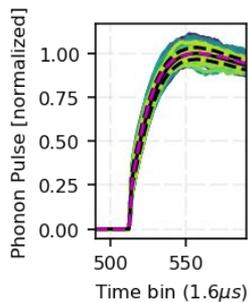
- Simulated **recoil** energy spectrum for the barium-133 calibration source.
- Recoil created in detector by photons (broadening is due to compton scattering)



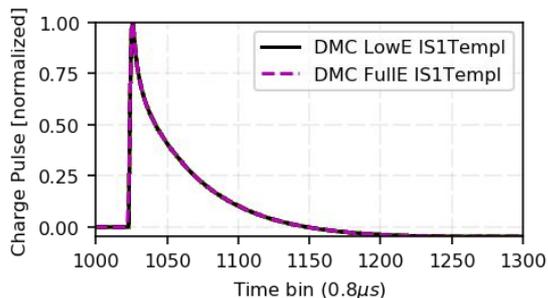
# Example Simulation: Step 3: Detector Simulation

Simulated **detector readout** for the barium-133 calibration source.

Top: typical  
phonon pulses

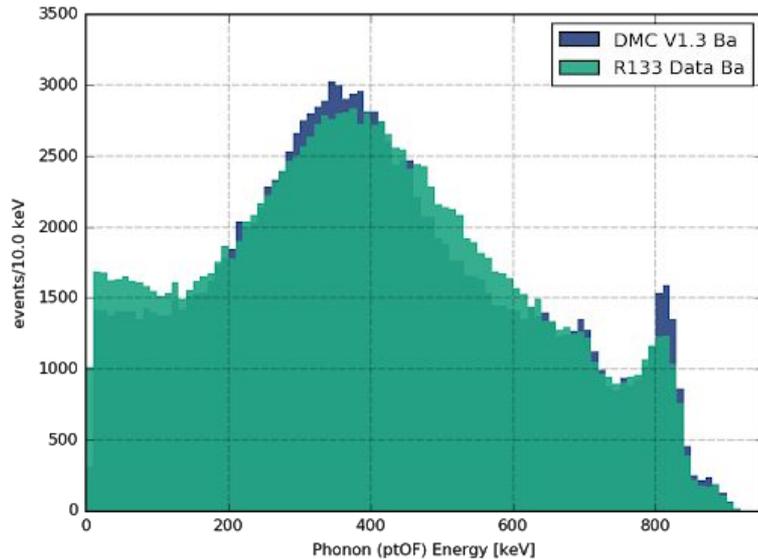


Bottom: typical  
charge pulses

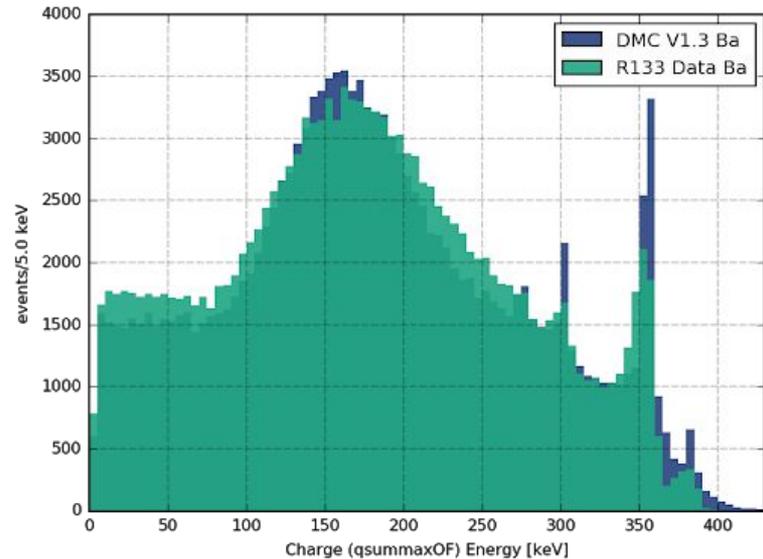


# Example Simulation: Steps 4-5: Fully Processed

**Reconstructed** energy spectrum for the simulated barium-133 (blue), overlaid with same energy spectrum from Soudan experiment (green).



Left: phonon sensor reconstructed energy



Right: charge sensor reconstructed energy

# Results of Simulation

We have already simulated many other backgrounds, calibration source samples, and wimps, and they have been used to develop our understanding.

Analysis	Number of fully simulated events	Purpose	Status
High Threshold	2,380,000	Searching for high-mass WIMPs	Complete
Low Threshold	480,000	Searching for low-mass WIMPs	1st Complete 2nd in progress
CDMSlite	1,320,000	Searching for low-mass WIMPs	In progress

# Plans for the Future and Conclusion

1. Software Development
2. Plans for Future Simulations
3. Plans for the Analysis of Real Data
4. Conclusion

# Software Development

Two major changes to the code pieces are in progress that require attention for the purpose of organizing the structure.

1. Detector simulation code will be replaced
  - New version written in Geant4 (by Cern)
2. Output formatting code will be replaced
  - New version outputs event metadata, and mimics the file format of real experiment data.

Job submission scripts for the Brazos cluster will need to be updated to work with the new structure.

# Plans for future simulations

- Update Soudan simulations
  - Next production batch ~2 million events
  - Begin production in April 2018
  - Complete production in June 2018
- Simulation of SNOLAB detectors when the new Geant4 version is complete

# Plans for the Analysis of Real Data

- The Soudan experiment analysis will be repeated using improved techniques informed by our simulations.
  - Data selection cuts will be optimized using simulated data.
- The structure for large-scale simulations (in development) will be needed to quickly optimize cuts for SNOLAB data.
  - Analysis techniques informed by the simulations will reveal key insights about potential WIMPs at SNOLAB.

# Conclusion

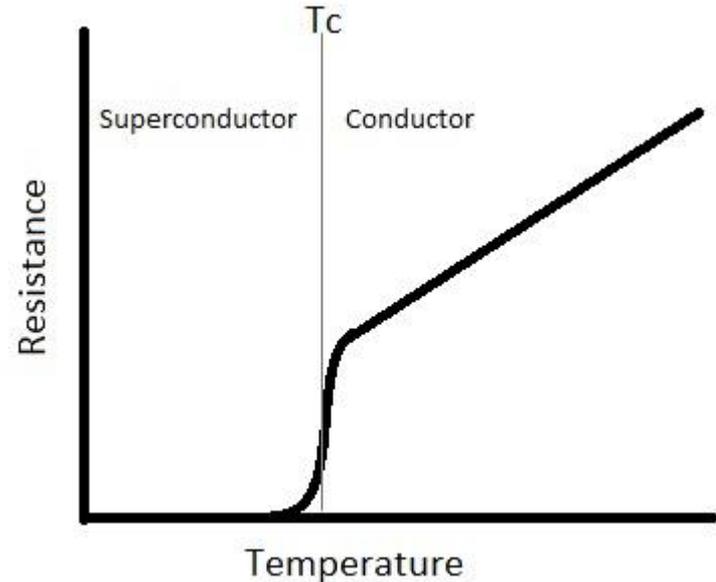
- It is an exciting time to be searching for Dark Matter
- Accurate and rapid simulations are moving to become a central part of next-generation searches
- The structure for large-scale simulations is nearing completion
- Will be useful for both re-analyzing the Soudan data, and as a way of preparing for data from SNOLAB
- The world's first true Dark Matter discovery may be right around the corner!

# Backup slides

# Very sensitive “Transition Edge” Detector

The phonon sensors need to be very sensitive to small amounts of energy from the absorbed germanium crystal phonons.

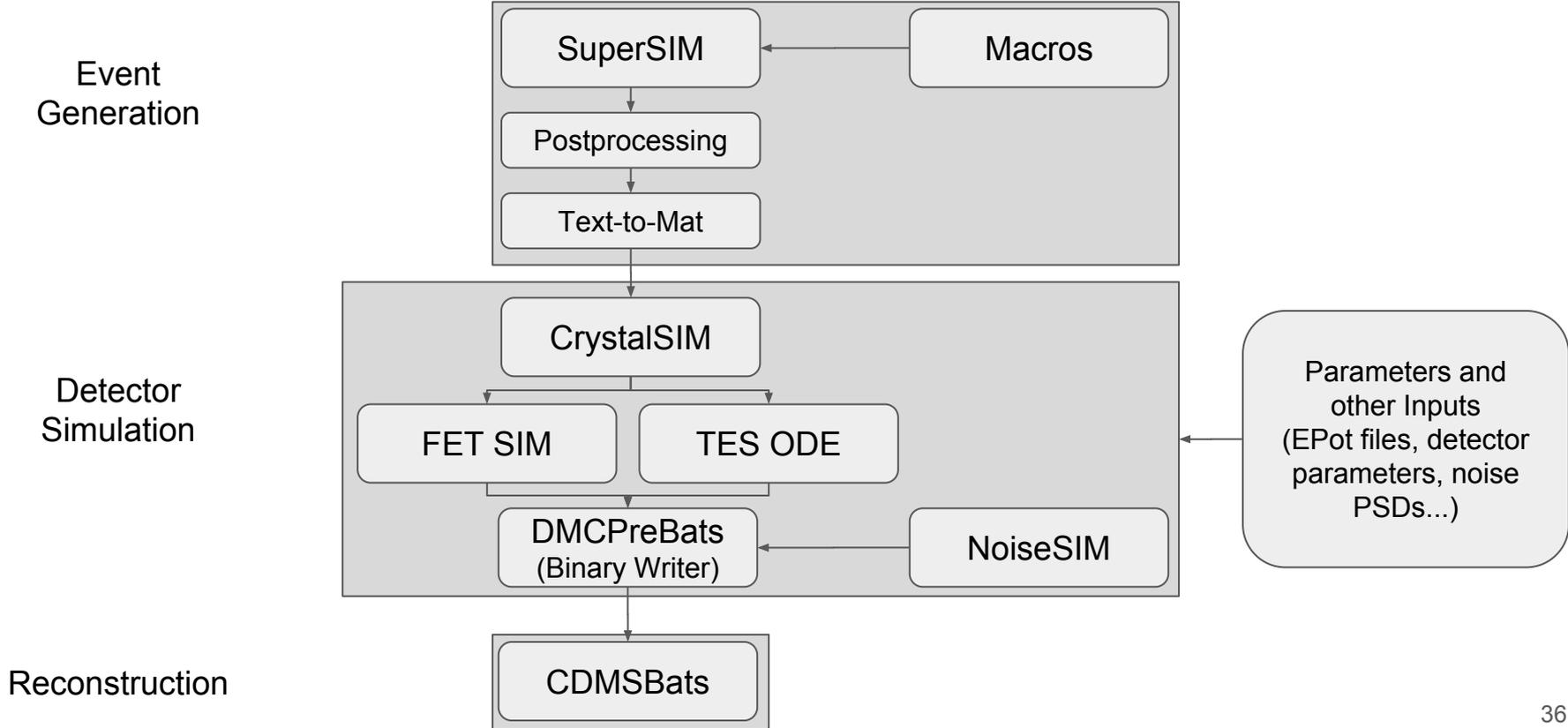
A metal near its superconducting temperature is very sensitive to small changes. A steady current through the superconductor will decrease rapidly if its temperature increases due to a small energy deposit.



# What we Simulate

- Primary calibration sources: Cf and Ba, to calibrate the other simulations
- WIMPs, to explore the differences with neutron recoil
- Key contaminants: Pb from atmospheric Rn, radioactive Ge from cosmic rays
- Alternative calibration sources: photoneutron Y and Sb

# Diagram of Code Pieces



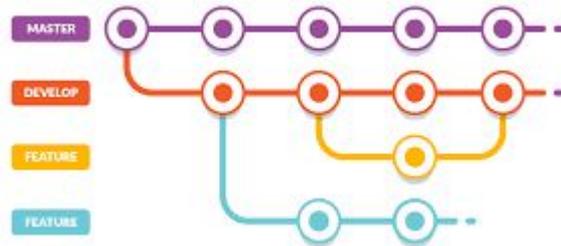
# Version control of large-scale Simulations

Creation of large scale simulations proceeds in batches called “Production”.

- A production is a generation of all the requested datasets
- A production uses the same code and parameters for all datasets Changes to simulation code and parameters motivates new productions

Each production should be independently reproducible.

- Code used must be saved in repositories, version tags recorded in a table
- Other inputs must be permanently stored



# My contribution to the Structure

To achieve the goals of the project, effort is directed into several important tasks.

- Organize code, dataset, and workspace directories
- Maintain version control and collaborative sharing of code pieces
- Track versions of code pieces used to produce and label datasets
- Ensure safe permanent storage and online availability of published datasets
- Create user-friendly tools to standardize frequently executed tasks
- Collect status updates from collaborators and present summary at meetings

# Software Development

Tools	Function	Comments, Code Status	Who
Event Generation: SuperSIM Job Scripts	Split into jobs, submit, and manage output	Functional, not in Git	MK+JW+Others?
Detector Simulation: DMC Job Scripts	Distribute into jobs, submit, and manage output	<ul style="list-style-type: none"> <li>• MATLAB Version: In git, tagged. Changes needed for Binary Writer.</li> <li>• G4DMC Version: Not started</li> </ul>	JM+RL
Reconstruction: CDMSBats Job Scripts	Collect into jobs, submit, and merge output	In git, tagged. Changes needed for Binary Writer.	JM+RL+XZ
Globus Transfer Tool	Move monte carlo data to permanent storage	Functional, not automated	JM+RL
Catalog Scripts	Add new data files to the Catalog, organize Metadata	Currently done by hand. Moving to script	RL+CC?

# Plans for Validation of Simulation results

Validation occurs in two ways

1. After a code version change, comparing to output of previous version
2. Comparing simulation output to calibration samples from the experiment

# WIMP sensitivity

Wimp sensitivity by detector.  
Neutrino background defines a  
Practical floor to the search.

