Tuning SuperCDMS Simulation for Dark Matter Searches Using CDMSLite Data

Dylan Monteiro

Masters Defense Talk 7/23/2025

Physics and Astronomy

Outline

Physics and Astronomy

1. Motivation to Search for Dark Matter with the SuperCDMS Experiment
2. Motivation for SuperCDMS Simulation and Tuning
3. Tuning and Validation of Simulations
4. Results
5. Next Steps and Conclusions

Motivation to Search for Dark Matter with the SuperCDMS Experiment

SUPER CDMS

Physics and Astronomy

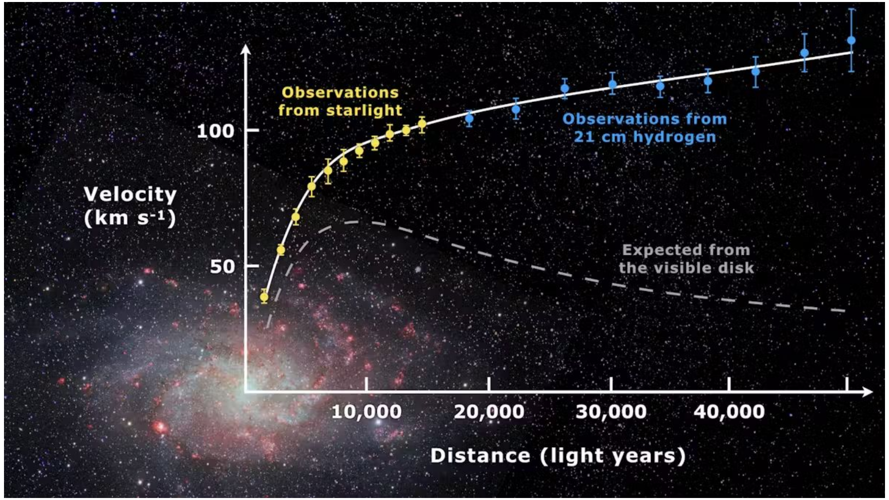
Why care about dark matter?

Astronomical observations cannot be explained by general relativity using known standard model particles. This suggests:

Neutral, Beyond Standard Model (BSM) matter contributes to majority of mass in the universe.

Particle dark matter hypothesis can explain data in:

- Galactic rotational velocities
- Cosmic Microwave Background
- Gravitational lensing observations



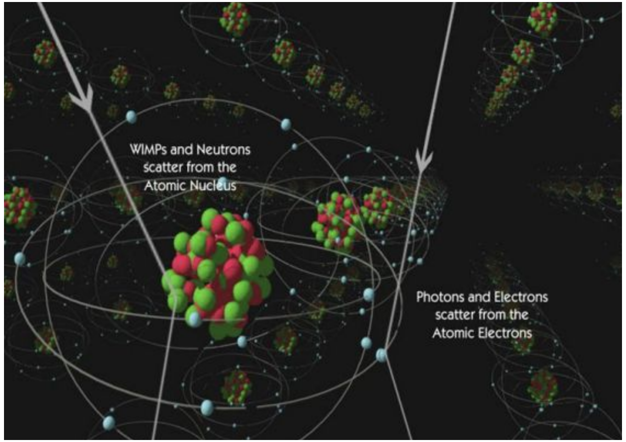
Motivation for SuperCDMS

Physics and Astronomy

Direct detection experiment: Has possibility to observe dark matter particle scattering off of electrons/nuclei through several mechanisms.

Why use the Super Cryogenic Dark Matter Search (SuperCDMS)?

- Sensitive to < 10 GeV/c^2 Weakly Interacting Massive Particles (WIMPs), in unsearched regions of parameter space.
- Also sensitive to many different possible DM candidate models and BSM matter.
- Leverages experience from previous iterations: SuperCDMS @ Soudan, CDMSLite, CDMS II, etc…



SuperCDMS Experimental Design

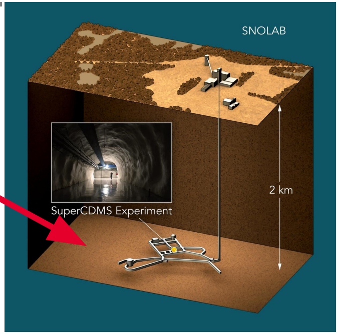
Physics and Astronomy

Method of Detection: Measures ionization and vibrational energy (phonons) produced by scattering events within cryogenically cooled, semiconductor targets.

Background Suppression:

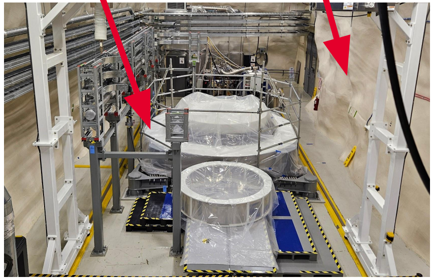
- Located underground to reduce cosmic radiation.
- Shielded with lead, polyethylene, and water to reduce environmental radiation.
- Clean room and active measures during fabrication to reduce radioactive contamination.

Upcoming experiment at SNOLAB will have better detector performance and background suppression than previous iterations.



Polyethylene shielding

Cavern Walls



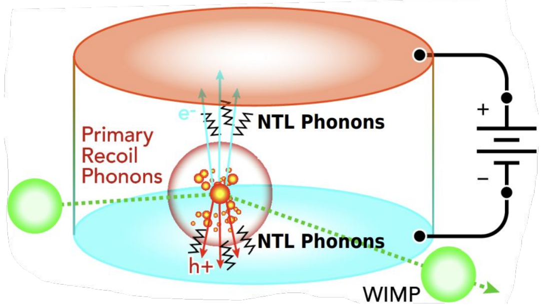
SuperCDMS Detector Design

SUPER CDMS

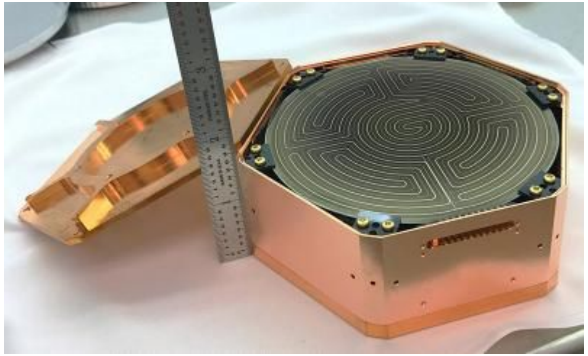
Physics and Astronomy

Features:

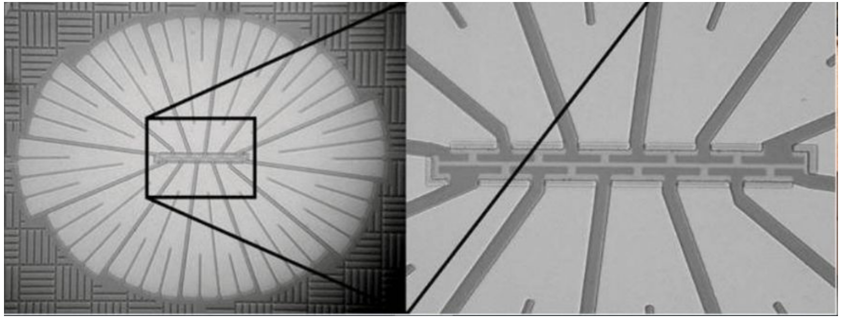
- **Ultra-high purity semiconductor (Si/Ge) target** where interactions produce charges and phonons.
- **Transition-Edge-Sensors (TES)** for phonon measurement patterned photolithographically onto crystal.
- **Charge-collecting electrodes,** biased across detector to amplify phonon gain and measure ionization yield.



Event in Detector, B. Krosigk 2018



SuperCDMS Single Detector



(Left) Microscopic View of Phonon-Absorbing Aluminum Sensors
(Right) Close up of TES

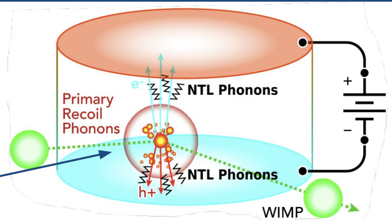
Detector Response from Interaction to Signal

Sequence of energy transfer:

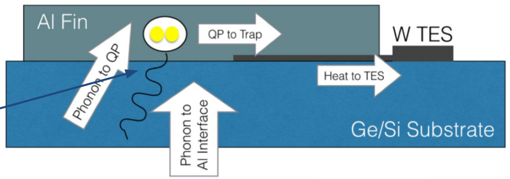
1. Scattering processes deposit energy into the crystal, ionizing electrons which are accelerated to the surface, creating extra phonons as they interact with the lattice.

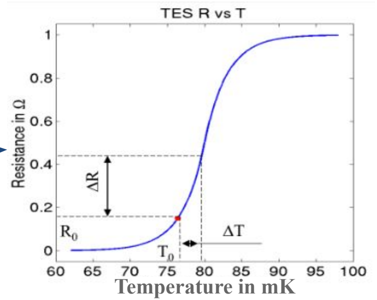
2. Phonons absorbed by aluminum sensors at surface break Cooper pairs, which migrate to TES and raise the temperature.

3. Temperature change causes dramatic spike in resistance along superconducting transition. This appears as a current pulse in our readout channels.



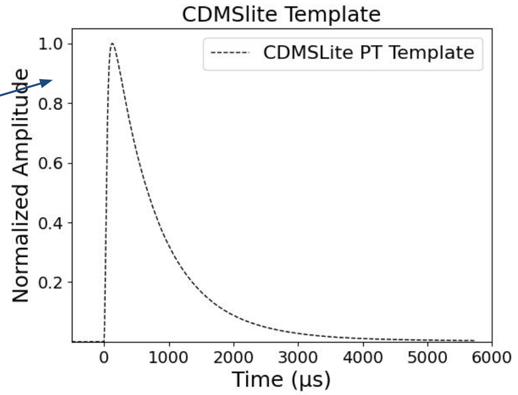
Event in Detector, B. Krosigk 2018





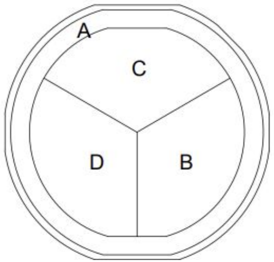
Expected Pulse

- There are multiple readout channels in CDMS detectors; summing over all channel pulses produces **Phonon Total (PT)** pulse.
- Understanding the physical mechanisms that produce this pulse shape will help us:
  - More effectively reject background during data analysis.
  - Distinguish between different interaction types.
  - Improve energy and position reconstruction.



Real data “template” constructed by averaging over select set of high quality pulses.

Top View: CDMSLite Channel Layout



Motivation for Simulation and Tuning

Physics and
Astronomy

Why Simulate the Experiment?

Physics and Astronomy

Big Picture: Improve the sensitivity of dark matter searches.

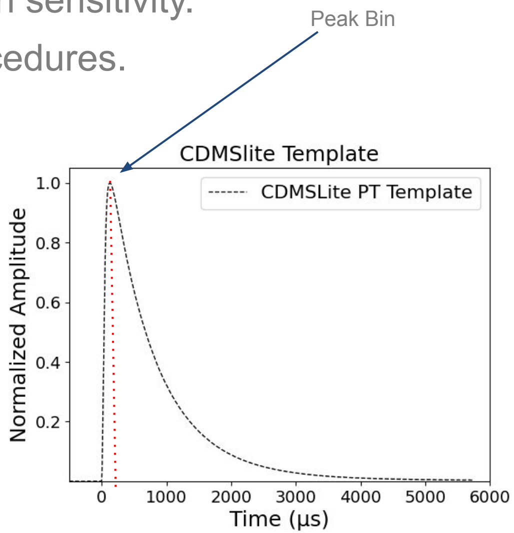
Simulations help by…

- Predicting detector response for both signal and background events.
- Developing analysis selection and search methods to optimize search sensitivity.
- Predicting which methods will improve calibration and resolution procedures.

Goal of this work:

Using historical experimental data (2018 CDMSLite), improve the physical credibility of simulation for future use in SuperCDMS analysis.

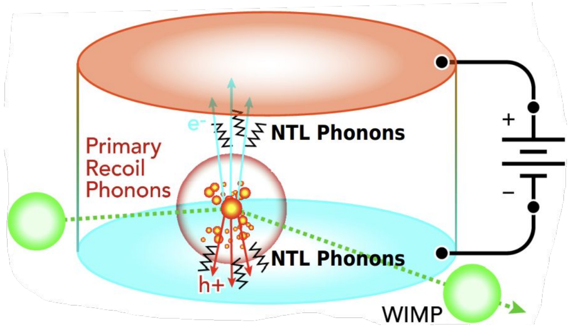
Two examples: by ensuring simulation reproduces average pulse shape as well as producing correct peak time (Peak Bin).

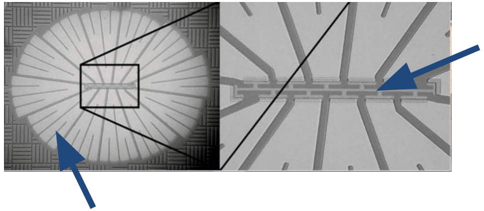


Physics Modeling in Detector Simulations

- Using a combination of Monte Carlo techniques and Diff. Eq. solvers, millions of microscopic interactions are modeled to reproduce macroscopic observables.
- Probability coefficients and physical quantities are used to solve sets of parameterized equations for multiple processes, each with multiple parameters.
- Not all parameters can be derived from first principles, many need to be determined phenomenologically.

Major focus of this work: Find the best parameter values by comparing simulation output to experimental data.





Probability to absorb phonons at aluminum (left) vs directly on TES (right) are free parameters not easily derived.

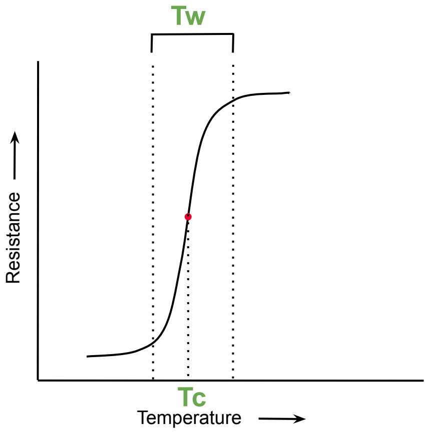
Parameter Descriptions

Physics and Astronomy

Phonon Sensor Diagram

Relevant parameters to this work:

- **Tsubst:** Substrate temperature
- **PhononAbsQETs:** Probability to absorb phonon at aluminum
- **TESsubgapAbs:** Probability to absorb phonon at tungsten TES
- **Tc:** Superconducting transition temperature
- **Tw:** Superconducting transition width



TES Superconducting Resistance Curve

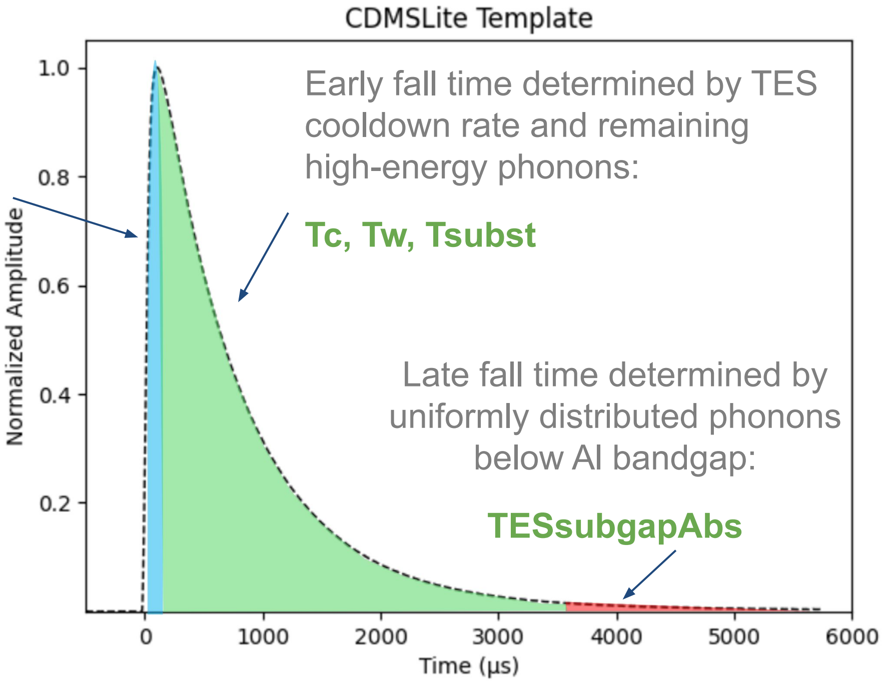
Expected Parameter Impact to Pulse Shape

Relevant parameters to this work:

- **Tc:** Superconducting transition temperature
- **Tw:** Superconducting transition width
- **Tsubst:** Substrate temperature
- **PhononAbsQETs:** Probability to absorb phonon at aluminum
- **TESsubgapAbs:** Probability to absorb phonon at tungsten TES

Rise time and peak shape from initial absorption of phonons at Al phonon sensors:

PhononAbsQETs



Tuning Motivation

Need to be confident that simulation accurately predicts Standard Model response before using it in dark matter search analyses.

However, when considering event samples from calibration data, the simulation currently **fails several validation checks**:

Perhaps better parameter values could be the solution?

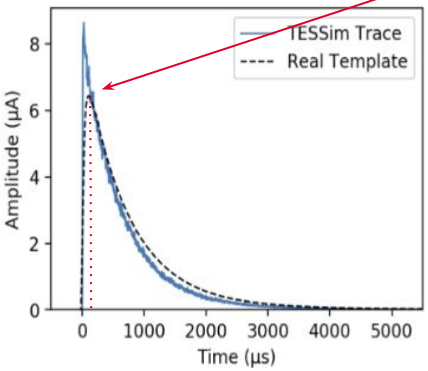
Simulation Tuning: Methodically varying parameters to find the values which result in the best match of simulation to experimental data.

*This will be an iterative process whenever physics modeling is changed within simulation.

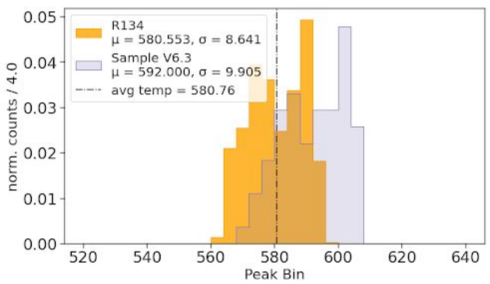
Examples of Failed Validation

Peak Bin = Time bin of maximum pulse strength
R134 = 2018 CDMSLite real datarun 134
Sample V6 = Simulated CDMSlite response

Simulation vs Real Data Pulses



Simulation vs Real Data Peak Bin



R. Bhattacharyya, 2025

Tuning Goals for This Work

Physics and Astronomy

1. **Determine a reliable procedure** for simulation parameter tuning.
2. **Build a software framework** to automate that tuning procedure.
3. **Find first approximation for best parameter values** by tuning simulation to reproduce average pulse shape.
4. **Verify results** by revisiting validation checks.
5. Use results to investigate what **physics modeling improvements** may be necessary in simulation.

Tuning and Validation of Simulations

Physics and
Astronomy

How to Define Optimal

Physics and Astronomy

While we want the simulation to reproduce all variations in the data, we will start with a single variable for a single distribution:

Chi^2 (χ^2): The sum of squared residuals between average simulation pulse and average data pulse, which is used to quantify "optimal" parameters.

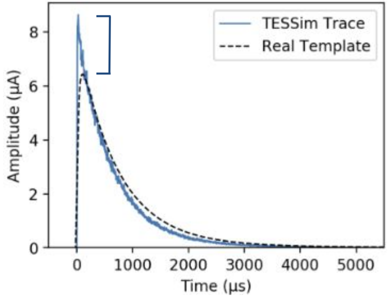
$$\chi^2 = \sum_i \frac{|\tilde{v}(f_i) - A\,\tilde{s}(f_i)|^2}{J(f_i)}$$

(S. Golwala, 2000)

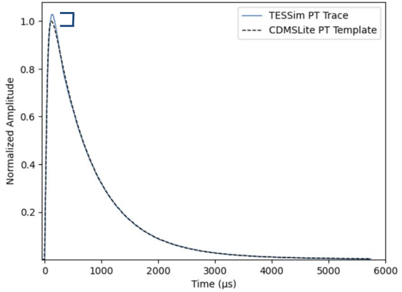
$\tilde{v}(f_i)$ = Simulated pulse
$\tilde{s}(f_i)$ = Normalized pulse shape from real data
A = Scaling amplitude
$J(f_i)$ = Noise power spectral density
f_i = i'th frequency bin

χ^2 = 0 would imply a perfect match.

High χ^2 Pulse



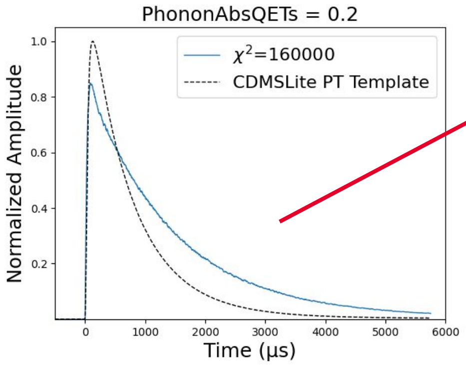
Low χ^2 Pulse

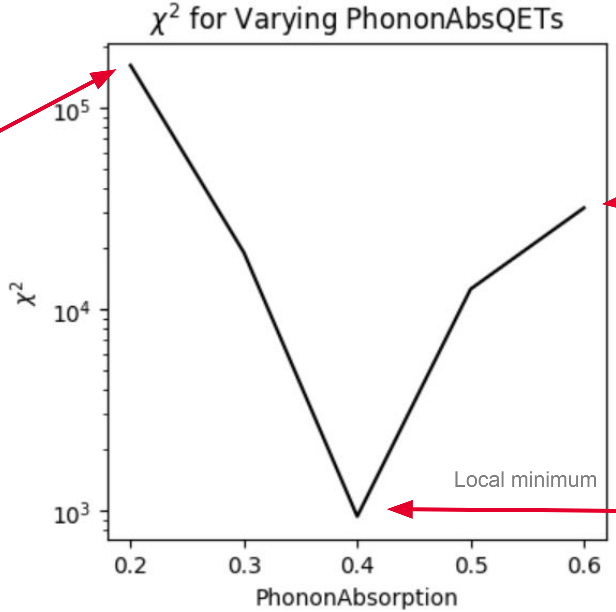


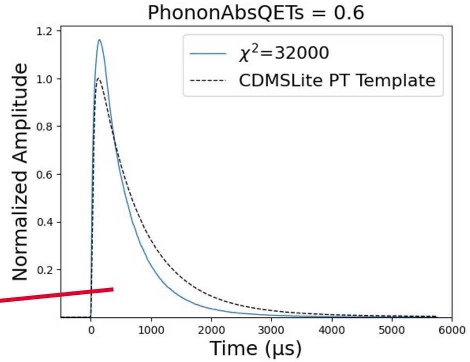
One-Dimensional χ^2 Minimization

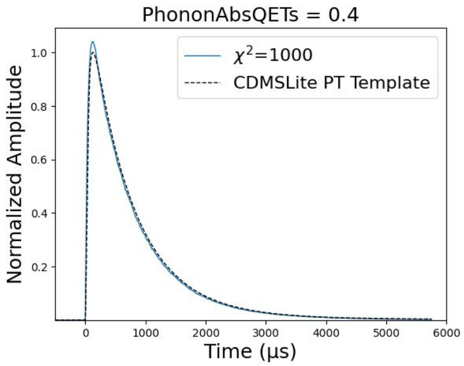
Physics and Astronomy

Finding lowest χ^2 for a single parameter isn't too difficult.
Can see how lowest χ^2 corresponds to the best pulse shape match between simulation and real data.









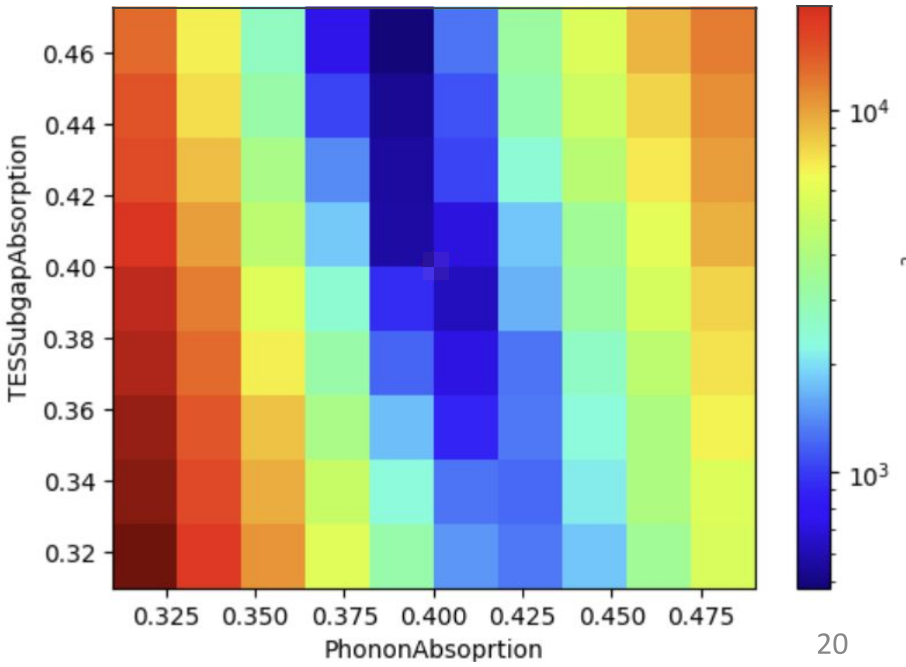
Multi-Dimensional χ^2 Minimization

Physics and Astronomy

When minimizing χ^2 over multiple parameters, correlation and degeneracies are revealed.

This motivates the creation of a more sophisticated minimization algorithm for any set of N parameters.

χ^2 Minimum in 2D Region



Optimization Algorithm Design

To do tuning in multiple dimensions we use an automated, recursive gradient descent algorithm to minimize the χ^2.

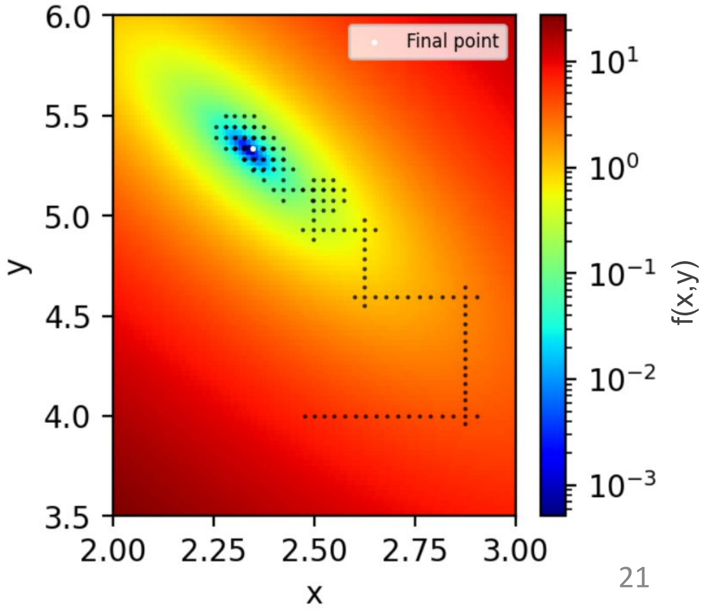
This allows:

- Improved automation to reduce time spent by researchers.
- Systematic reproducibility to validate results.

Algorithm structure:

- N-dimensional for any set of simulation parameters.
- Descends each axis until finding local minimum, then switches to new axis.
- Recursively interfaces with simulation package to run jobs, analyze data, and descend gradient.

Descent path on “dummy” 2D test data



Tuning Procedure

Physics and Astronomy

Using the previously described tool, we now move to find best-fit parameters for 2018 CDMS Low Ionization Threshold Experiment (CDMSLite) data.

Goals:

- Determine which parameter values achieve best possible fit to data.
- Learn more about the effect of specific parameters and event generation on pulse shape.

Steps to achieve this:

1. Simulate a set of events across entire detector volume with best guess “seed” parameters.
2. Calculate average pulse and χ^2 relative to CDMSLite average
3. Determine next step in parameter space using descent algorithm.
4. Repeat until a χ^2 minimum is found.

Results

Physics and Astronomy

Result: Before and After Tuning for Average Shape

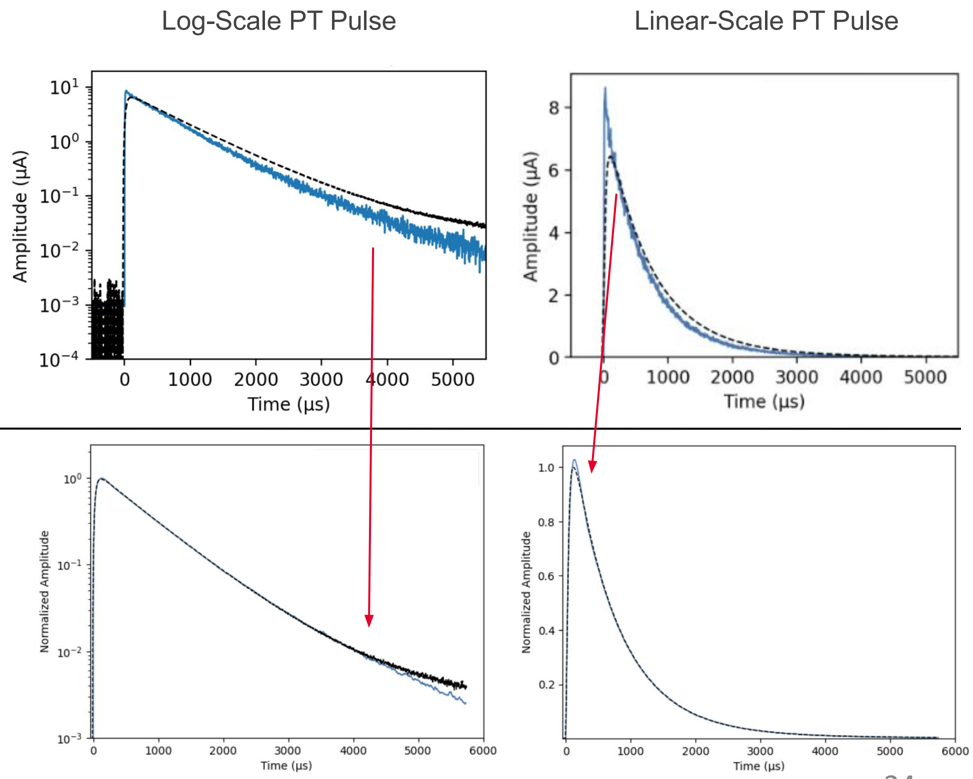
Physics and Astronomy

— Simulated PT Pulse
- - - - Real CDMSlite Template

Pre-Tuning Shapes

Post-Tuning Shapes

After tuning, the simulation demonstrates better match to data. However there are still differences at the peak and tail-ends of pulse.



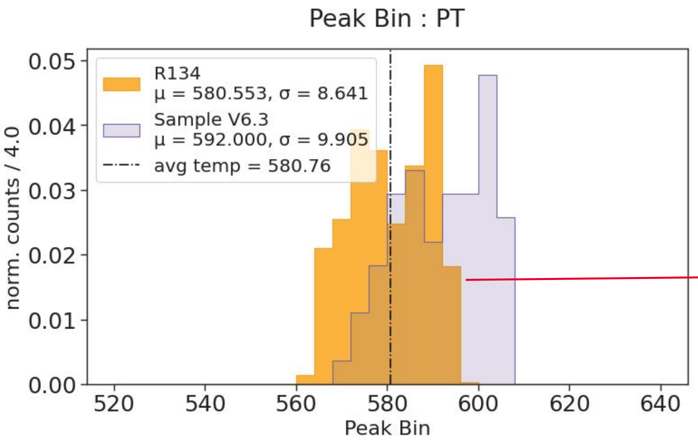
Result: Event-by-event Sample Variation

Physics and Astronomy

We have shown that tuning improved the simulation’s average pulse shape. Next step is to investigate event-by-event variation: The mean and RMS of Peak Bin distributions cleary are better matched…

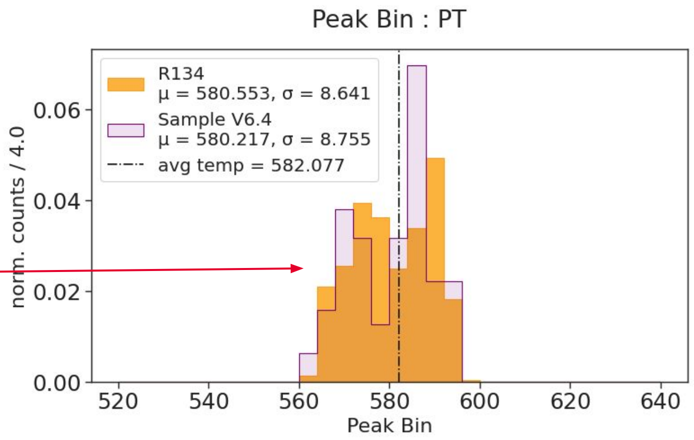
Peak Bin = Time bin of maximum pulse strength
R134 = 2018 CDMSLite real datarun 134
Sample V6 = Simulated CDMSlite response

Pre-Tuning Distributions



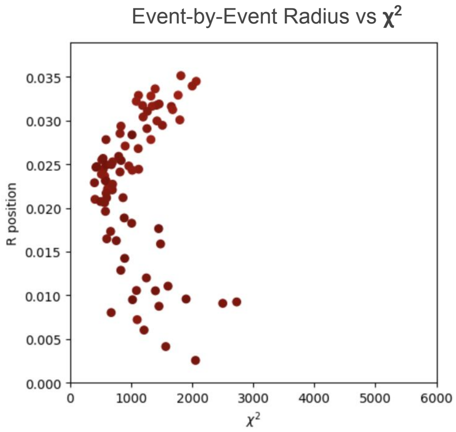
R. Bhattacharyya, 2025

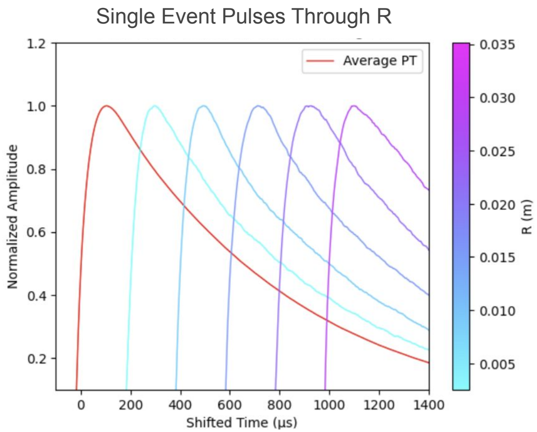
Post-Tuning Distributions



R. Bhattacharyya, 2025

Next Steps, Position Dependence?





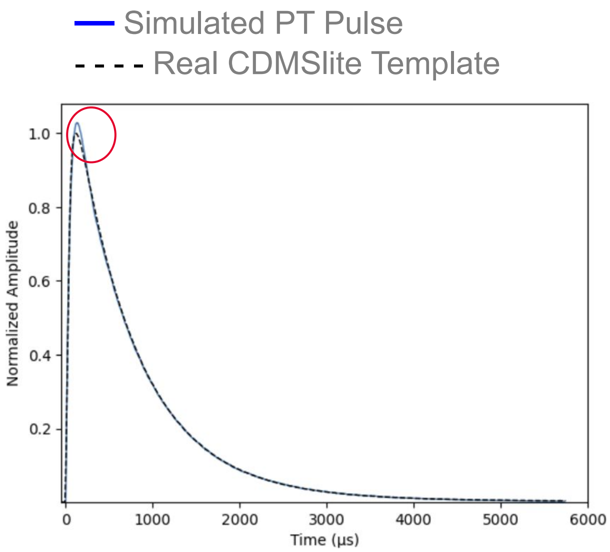
What can we learn about the detector response by looking at the position dependence of χ^2 through different event-by-event radii from the center of detector?

- Best fit (lowest χ^2) occurs around radius 25 mm. This isn't surprising as it is the average R of a uniformly distributed sample across a cylinder with our detector radius.
- It is not obvious why the pulse shape varies so much as a function of position. More work is needed to understand this dependence.

Future Work

Physics and Astronomy

- Simulation still does not match data. Need to understand cause of positional variation in pulse shape.
- Possible avenues to investigate this positional variation:
    - New physics modeling: specular surface reflection, surface downconversion.
    - Tuning campaign with different parameters, eg. anharmonic decay
- After confidence in simulation is achieved, tuning campaign for the new SuperCDMS detectors will be needed.
- After all tuning and validation is complete, simulation-informed analysis of new SuperCDMS data (expected 2026) can occur.



Conclusions

Physics and Astronomy

- **We have presented our formalism** to iteratively tune the simulation to reproduce the average shape of experimental data.
- **This optimization procedure has been constructed and validated** in a software package called Autotune to significantly automate the tuning process and handle correlated parameters.
- Average pulse shape and certain pulse shape variations **demonstrate a noticeable improvement** in reproducing experimental data after tuning.
- Discrepancies in simulation output make it clear that our **next steps are now to understand the cause of position-dependent pulse shapes**, and to use that knowledge to improve simulation modeling.

This progress represents a significant step forward in our simulations program, which may provide the linchpin for a dark matter discovery in future simulation-informed analysis.

Backup

Physics and Astronomy

Backup

Physics and Astronomy

Models SuperCDMS is sensitive to:

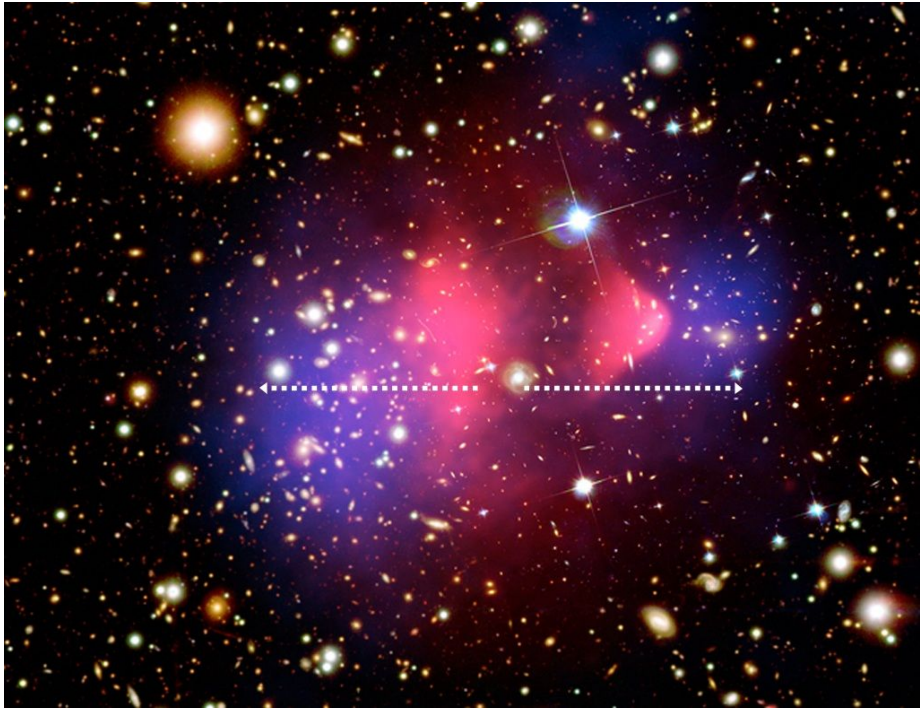
- Weakly Interacting Massive Particles (WIMPS)
- Asymmetric dark matter
- Dark photons
- Axions
- Lightly Ionizing Particles (LIPs)
- Coherent Neutrino Scattering

Backup: Bullet Cluster
Counter-argument to modified gravity

Blue = Gravitational lensing mass distribution

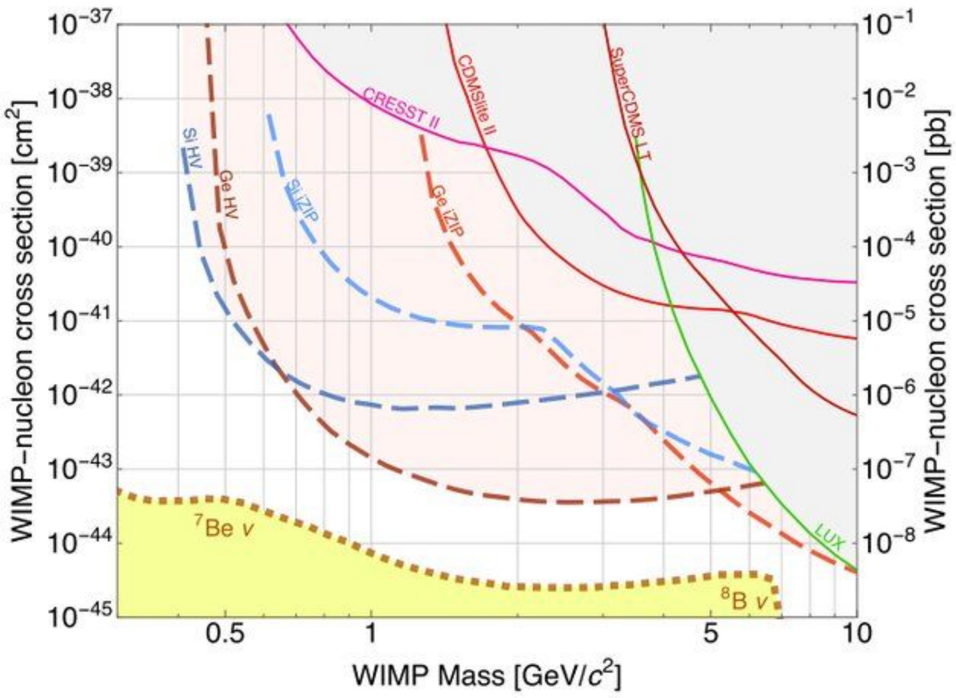
Red = Xray-based mass distribution

Only way modified gravity works here is if non-local fields exist.



Backup Sensitivity

Physics and Astronomy

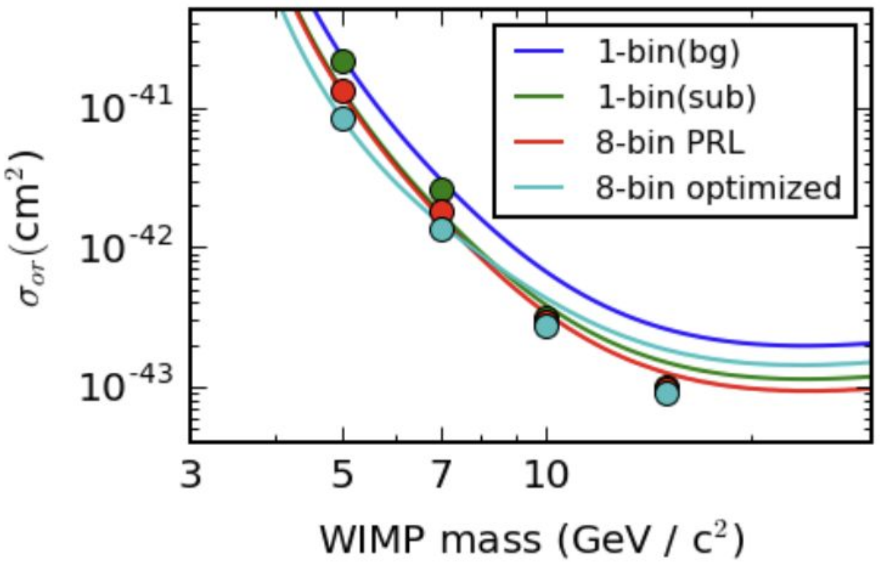


R. Agnese et al., "Projected Sensitivity of the SuperCDMS SNOLAB experiment", 2016 [arXiv:1610.00006]

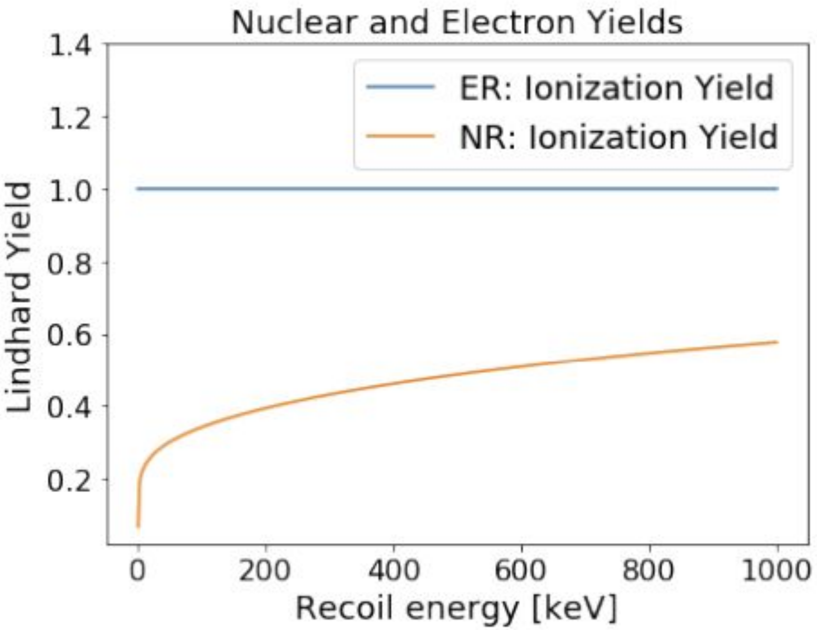
Backup: Simulation Improved Sensitivity

Watson Undergraduate TAMU thesis 2016

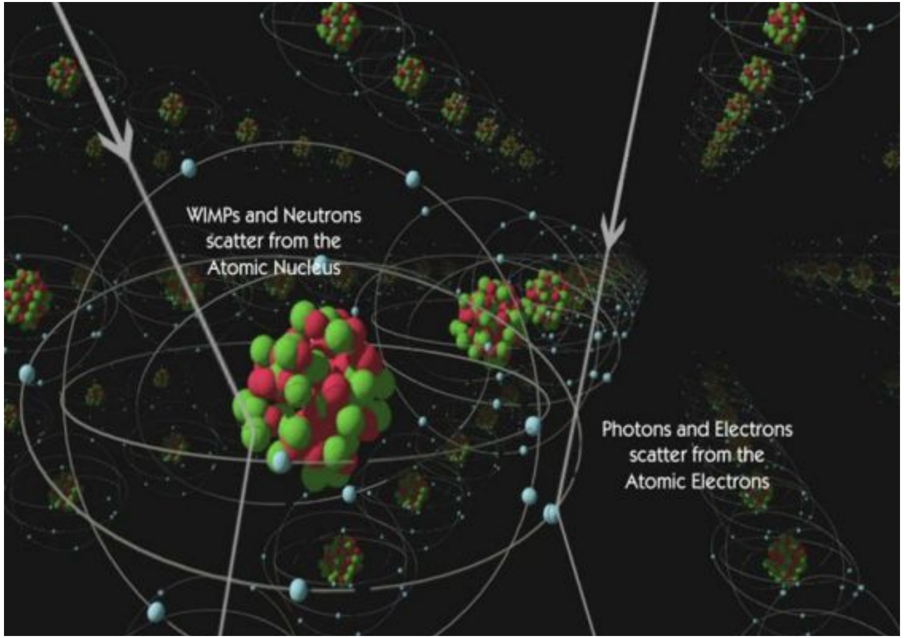
Optimized = Including simulated background hits in detectors



Backup: ER vs NR and Lindhard

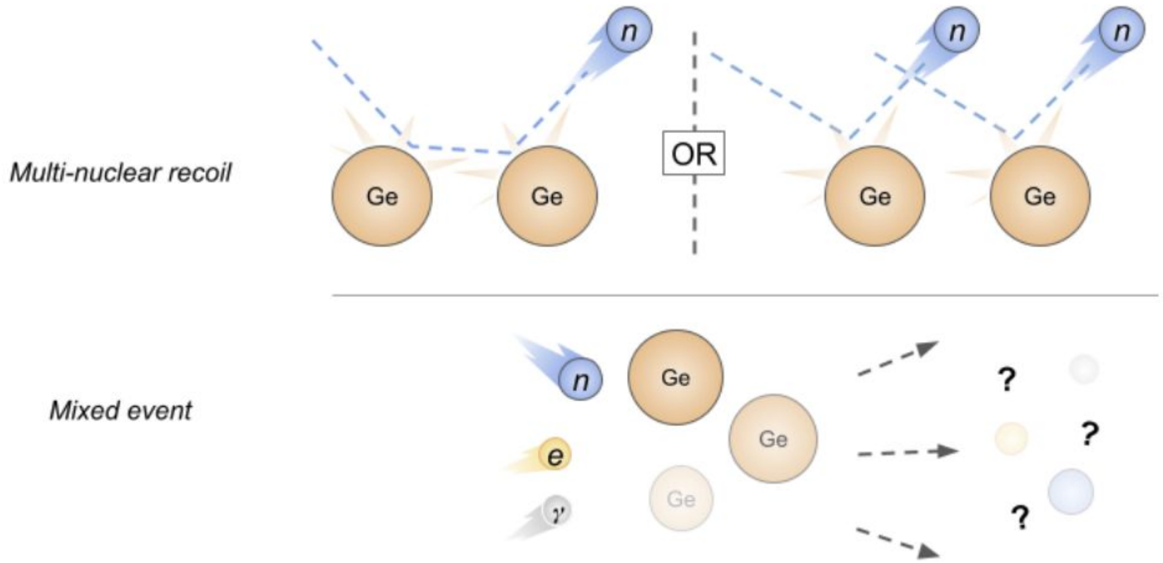


J. Winchell Thesis 2023



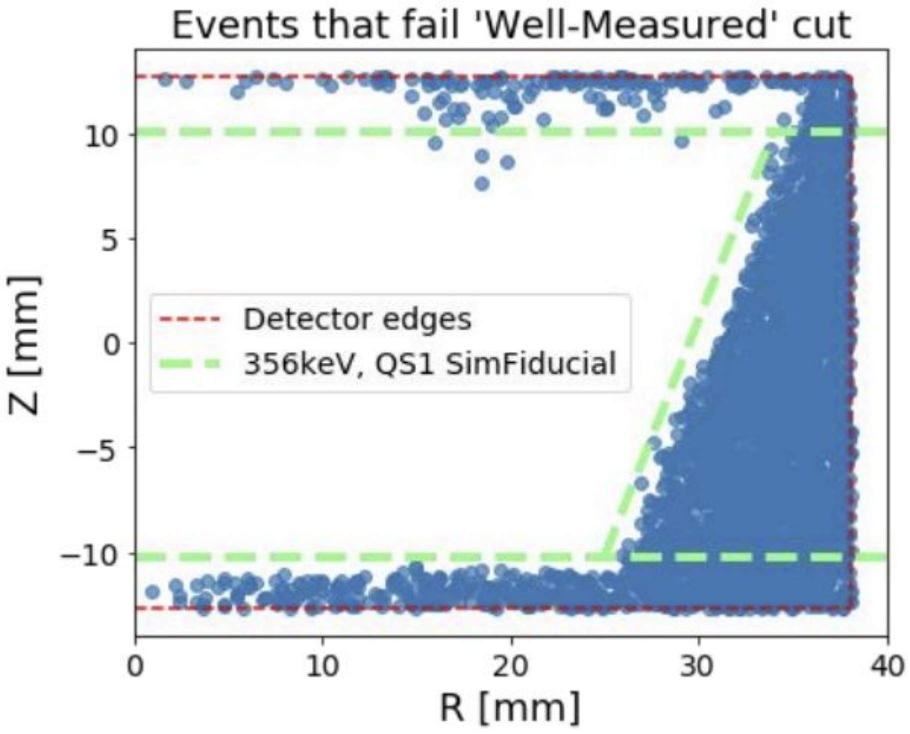
Backup: Multiple-Scatter Events

Physics and Astronomy



J. Winchell Thesis 2023

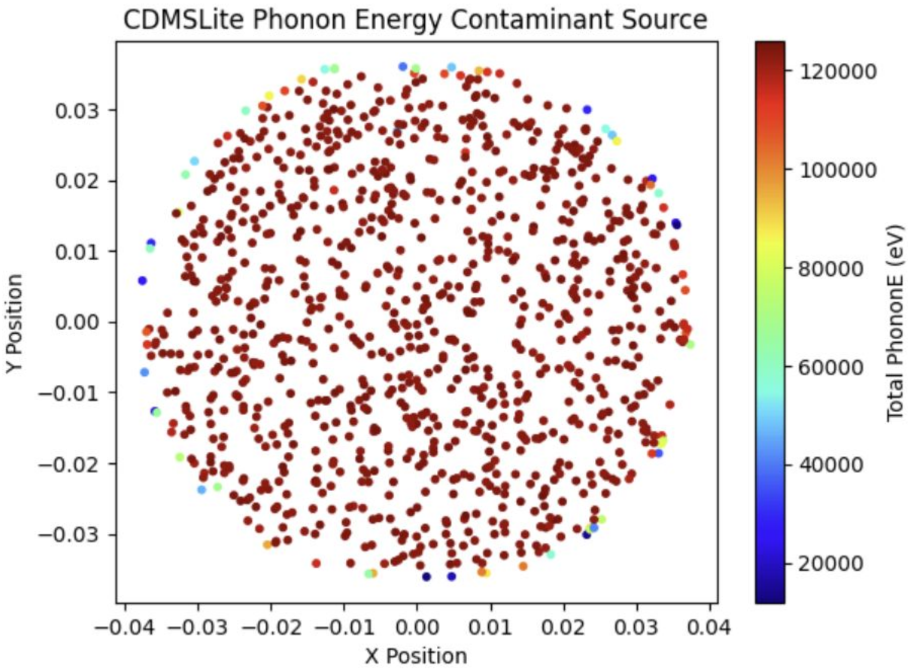
Backup: Fiducial Cut



J. Winchell Thesis 2023

Backup: Simulation Statistics on Event Position

Physics and Astronomy

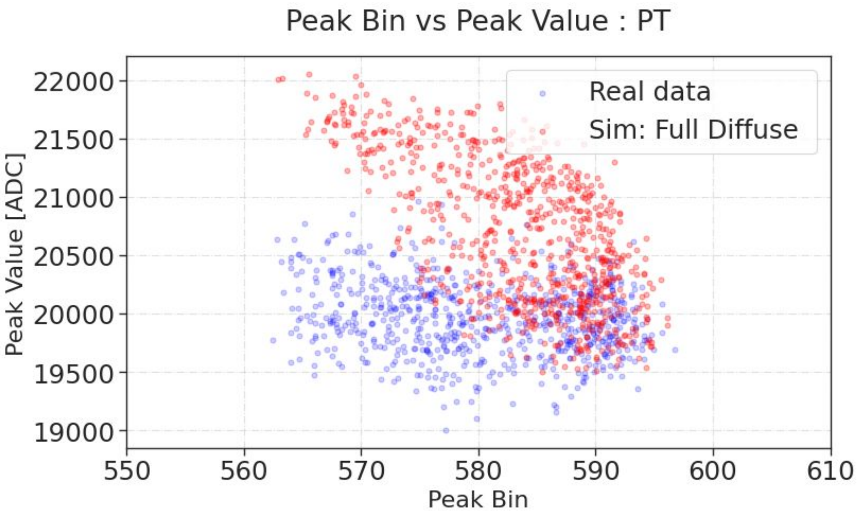


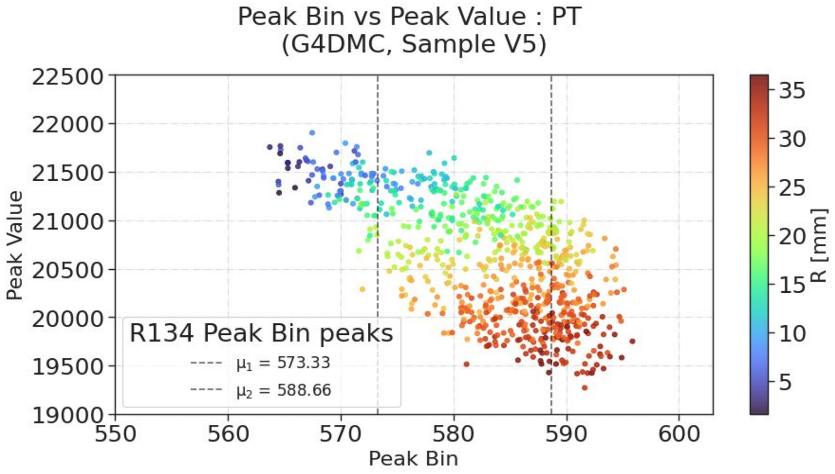
$$< r > = \frac{1}{\pi R^2} \int_0^R r * (2\pi r) dr = \frac{2}{3} R$$

CDMSLite detectors have 38mm radius → <r> = 25mm

Backup: Positional Variation and Failed Validation

Simulation

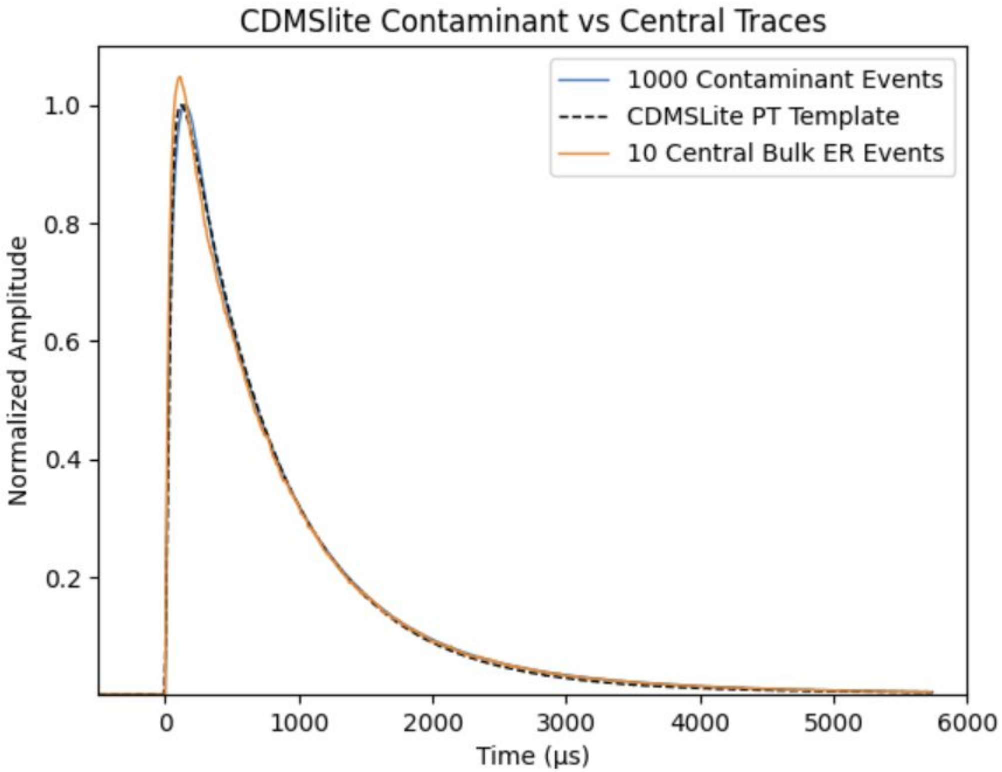




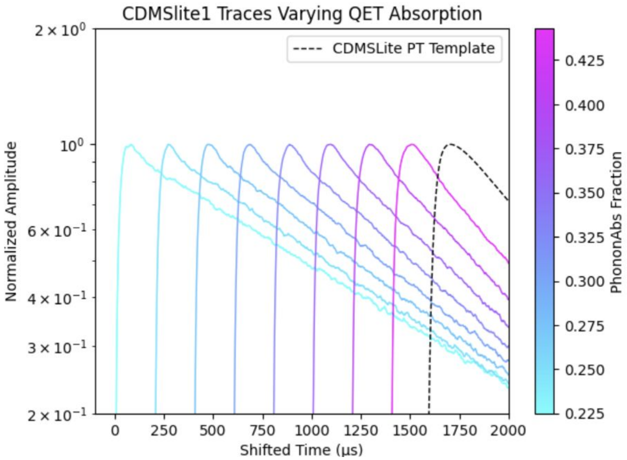
Backups: Uniform vs Single Event Position

Physics and Astronomy

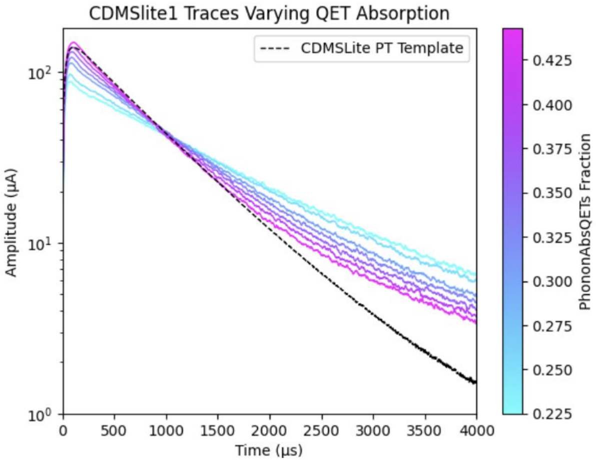
- **Contaminant** = Simulated events occur uniformly through volume
- **Central** = Simulated events occur in exact center of detector crystal
- Including larger radius events in average broadens pulse peak.
    - This effect is an open research question we are investigating.



Backups: Absorption Probability Effect on Pulse



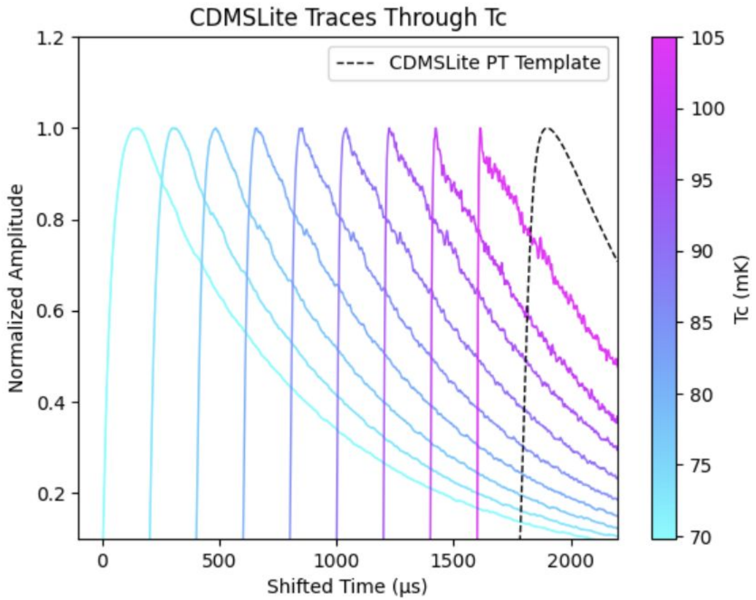
*PT traces have been normalized and shifted in time arbitrarily for visualization purposes



Increasing absorption probability causes:	Broadening of pulse at peak times.	Faster TES cooldown after peak times.
Possibly due to:	Hotter temperatures result in smaller superconducting response.	More phonons absorbed at peak means less remaining afterwards, allowing faster cooling.

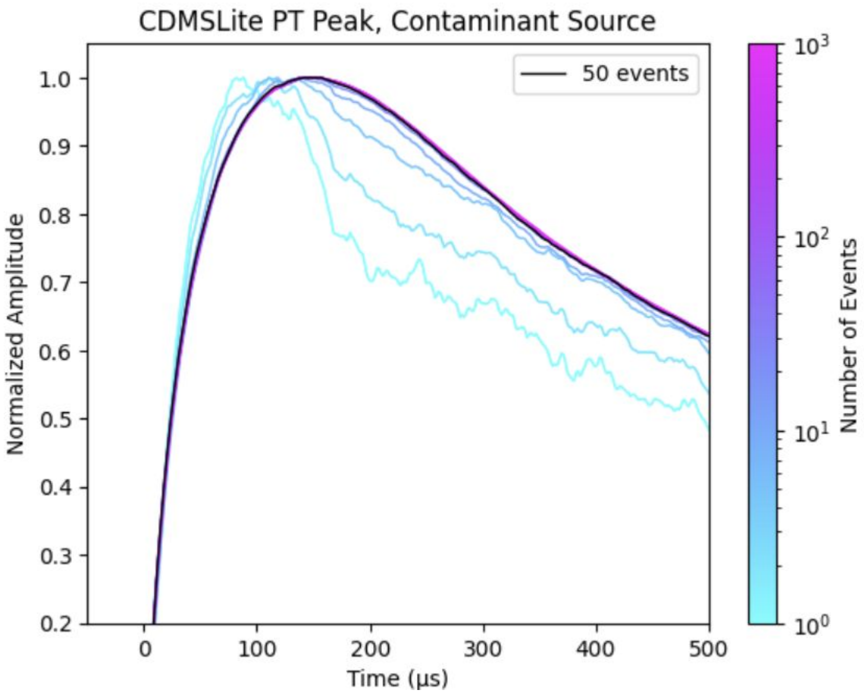
Backup: Transition Temp Effect on Pulse

Physics and Astronomy



*PT traces have been normalized and shifted in time arbitrarily for visualization purposes

Backup: Simulation Statistics on Pulse Shape



Backup

Physics and Astronomy

How to reject backgrounds in real data

Background spectrum