New Results From the CDMS low ionization threshold experiment (CDMSlite)

TAUP 2015

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For the SuperCDMS Collaboration

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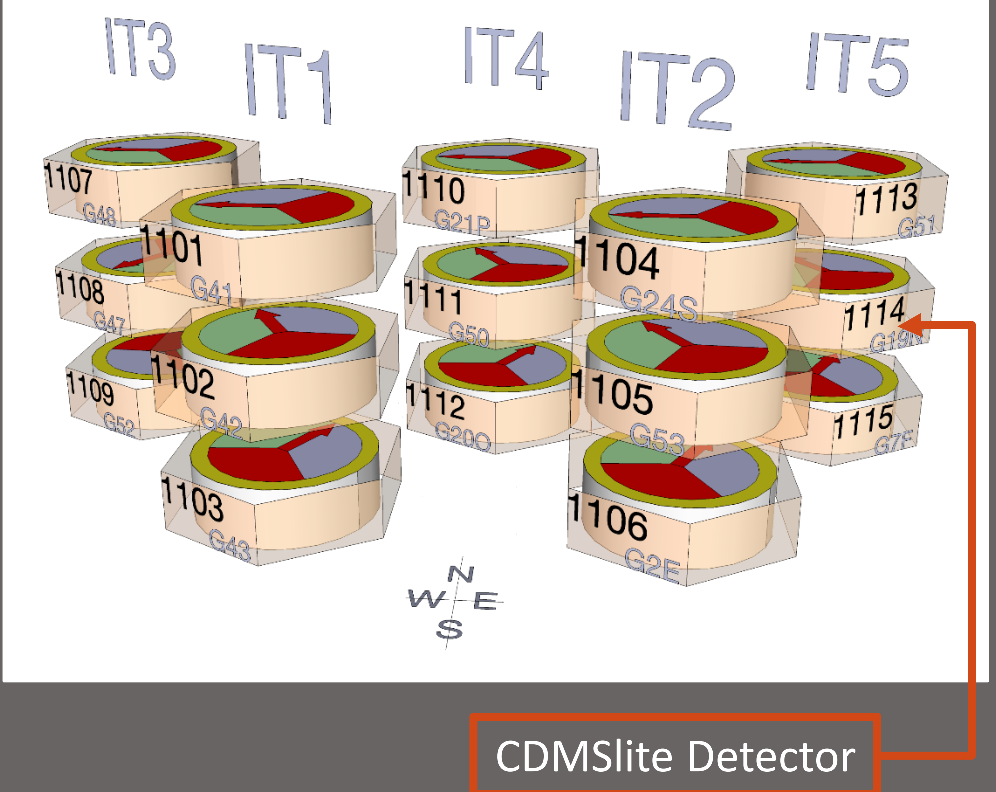
CDMSlite Overview

- Part of SuperCDMS in the Soudan Underground Laboratory[1]
- Operate single SuperCDMS iZIP detector (~0.6 kg) at relatively high (~70 V) bias potential
- Lower thresholds (no nuclear/electron recoil discrimination)

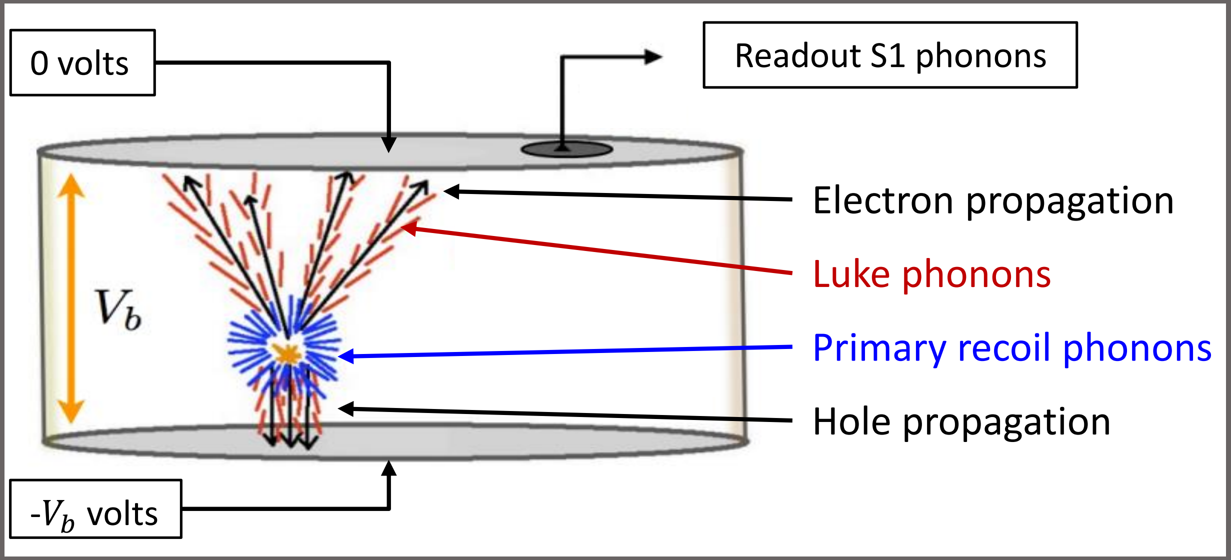
SuperCDMS Soudan Detector Array



[1] SuperCDMS Talks: P. Redl, Tuesday 17:20
R. Calkins, Thursday 15:30

CDMSlite Mode Detector Operation

- Drifting charges produce large phonon signal proportional to ionization (Neganov-Luke Effect)
- When $V_b \gg \epsilon_\gamma$ Luke phonons dominate signal
- Read out ionization energy via phonons



$$E_t = E_r + E_L = E_r\left(1 + Y(E_r)\frac{eV_b}{\epsilon_\gamma}\right)$$

Total phonon Energy

Primary Recoil Energy

Luke Phonon Energy

$Y(E_r)$: Ionization Yield ($Y \equiv 1$ for ER)

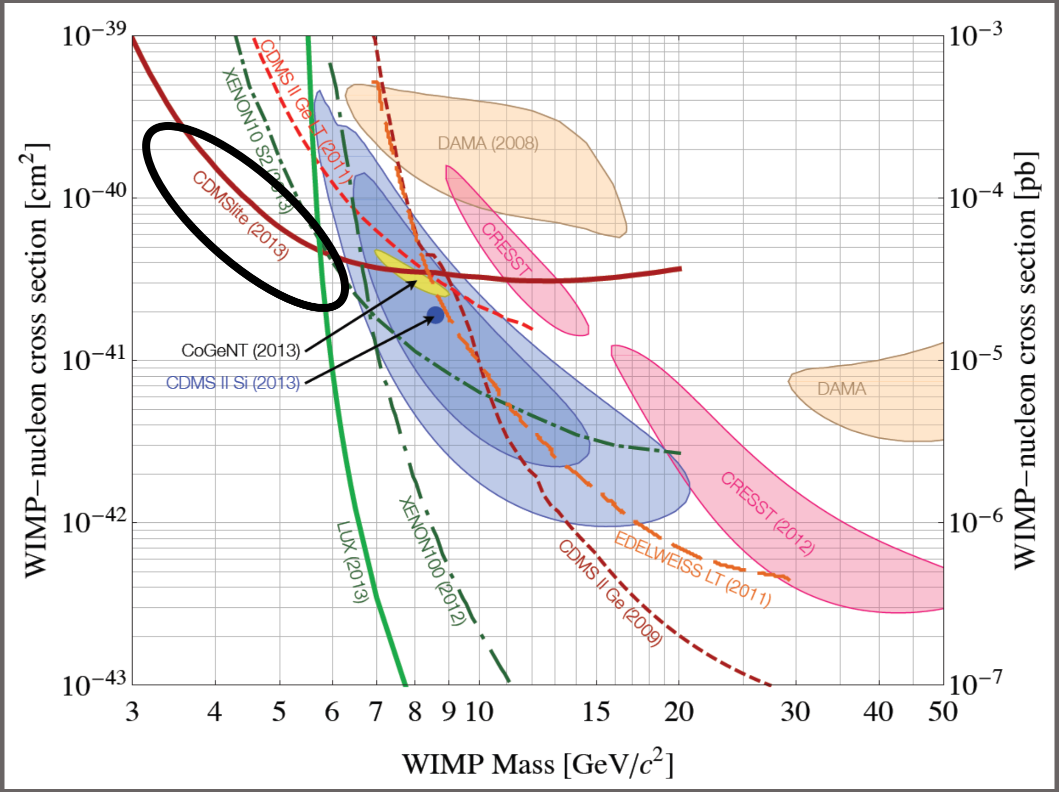
e : Elementary Charge

V_b : Bias Potential

ϵ_γ : Average energy for an ER to create an e/h pair in Ge

Run 1 Reminder/Run 2 Details

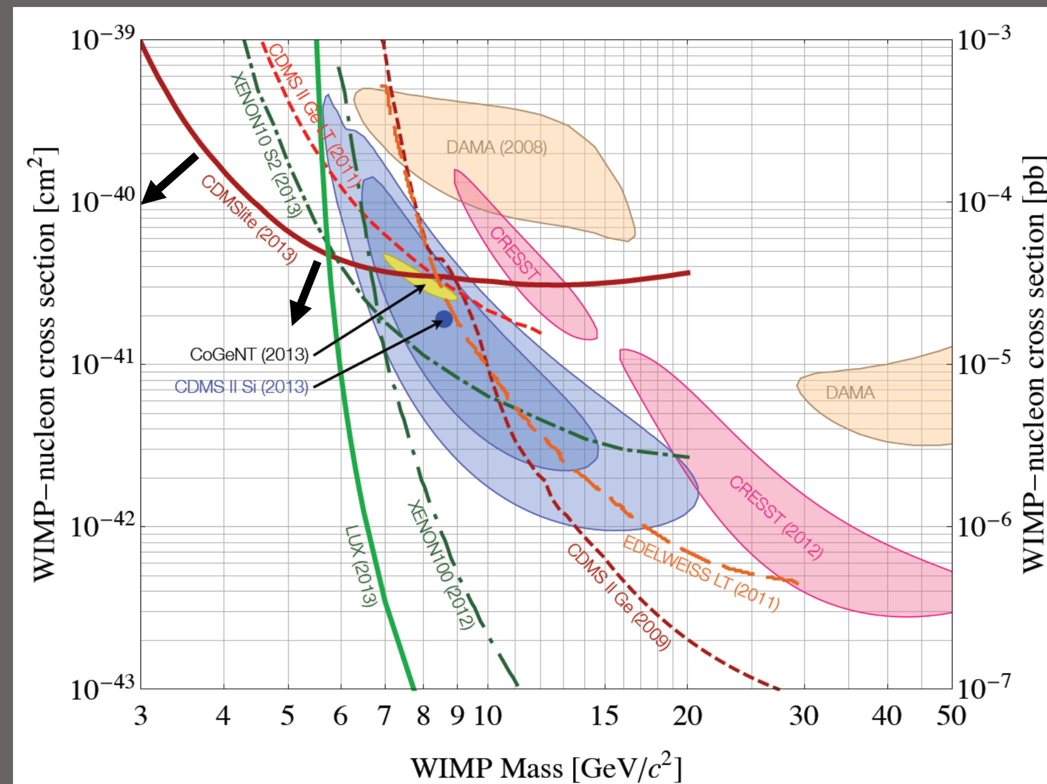
- First CDMSlite Run in 2013[2]
  - Single iZIP detector
  - −69 V bias potential
  - 6.5 kg-d exposure
  - 170 eV Ionization Threshold
  - Leading Limits (at the time) for $m_\chi \lesssim 5.5$ GeV/c^2
- Motivated a second run
  - Same detector
  - −70 V bias potential
  - February–November 2014 (70.10 kg-d)
  - Warm-up to room temperature in August for cryogenic maintenance
  - Period 1/2 for before/after warm-up (59.32/10.78 kg-d)
  - Several other improvements



[2] R. Agnese *et al.* (SuperCDMS collaboration) Phys. Rev. Lett. 112, 04130

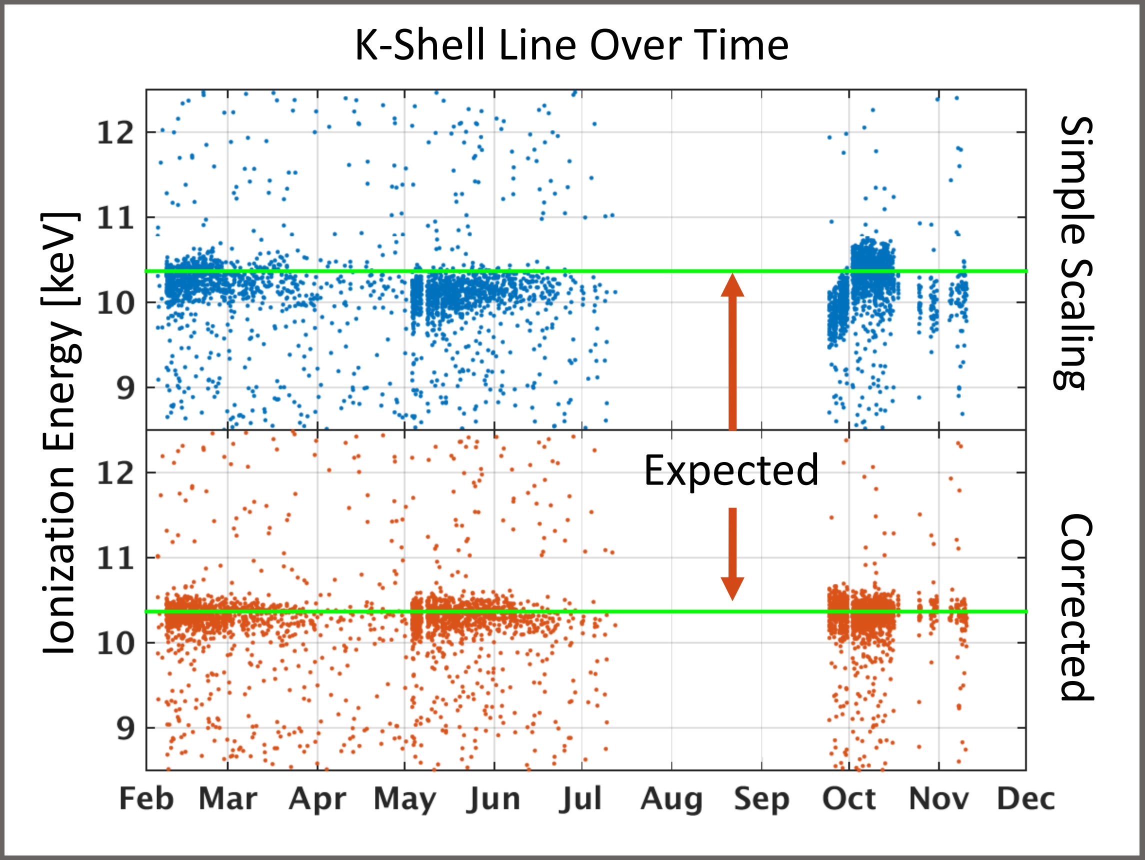
Improvements Over First Run

- Operational improvements
  - Mitigate transient detector leakage current
  - Reduce variation in bias potential by improving electronics board: clean, seal again humidity, place in N_2 gas.
  - Install vibration sensors on cryocooler to monitor low-frequency (LF) noise
- Analysis improvements
  - Better energy calibration
  - Better LF noise rejection
    - Lower threshold
  - New radial fiducial volume cut



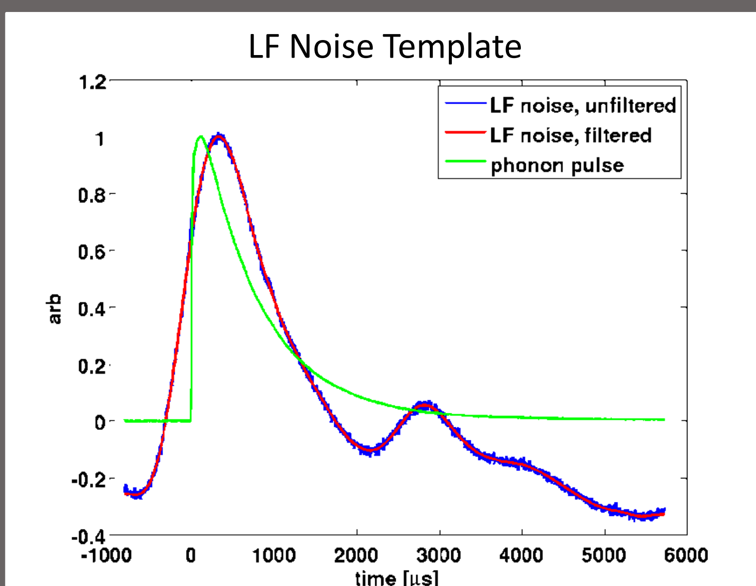
Run 2 Ionization Energy Scale Calibration

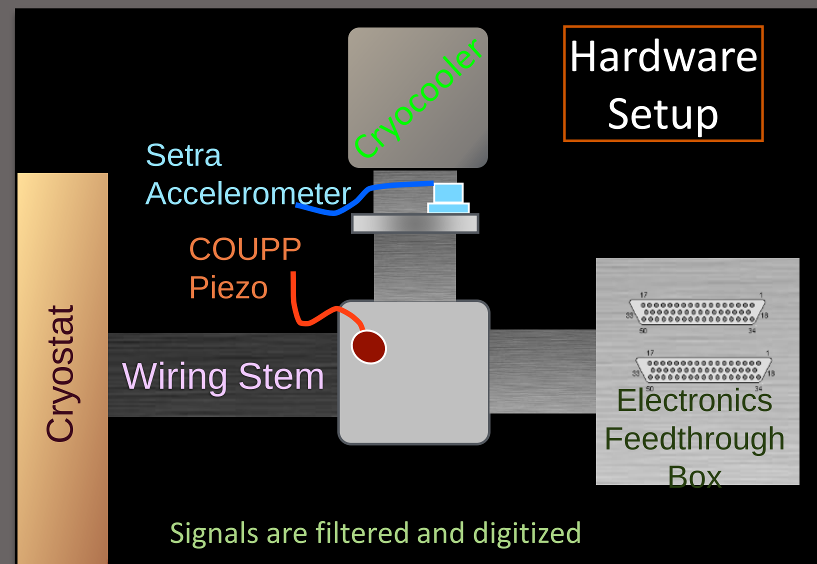
- ^{252}Cf Neutron Source
  - neutron-capture generates ^{71}Ge
  - Electron-capture decay
  - 10.37 keV (K-shell), 1.30 keV (L-shell), 0.16 keV (M-shell)
  - M-shell new for this analysis
- Use known recoil energy and high statistics of K-shell capture line to calibrate total phonon energy scale
- Changes in environmental or operational conditions can cause variation in bias potential
- Correct for:
  - Base temperature Changes
  - Parasitic resistances
  - Discrete period shifts
  - Position dependence



Low Frequency Noise Monitoring

- Mechanical action of cryocooler correlated with low-frequency noise
- Previous SuperCDMS studies discriminated purely on pulse shape
- Vibration sensors installed on cryocooler
- Monitors give event-by-event readout

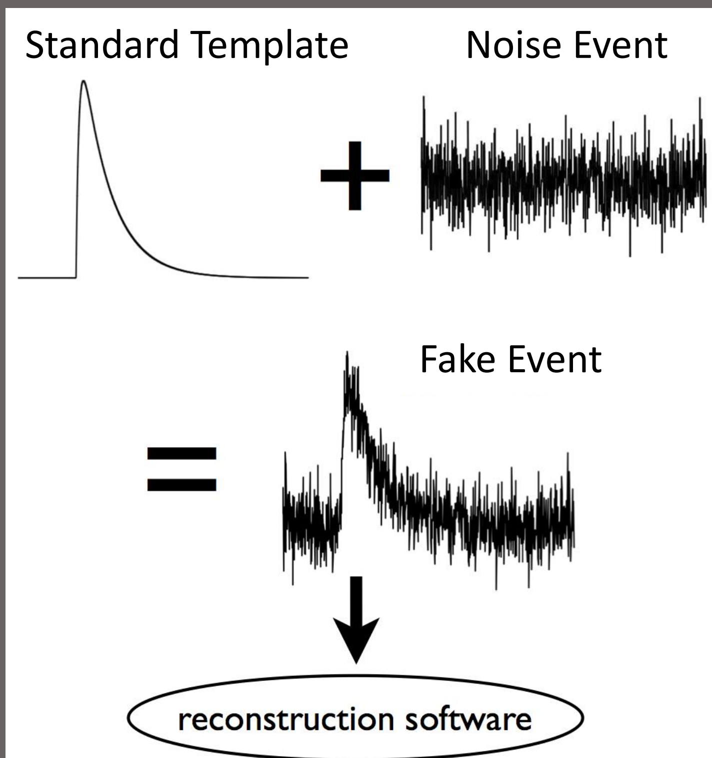


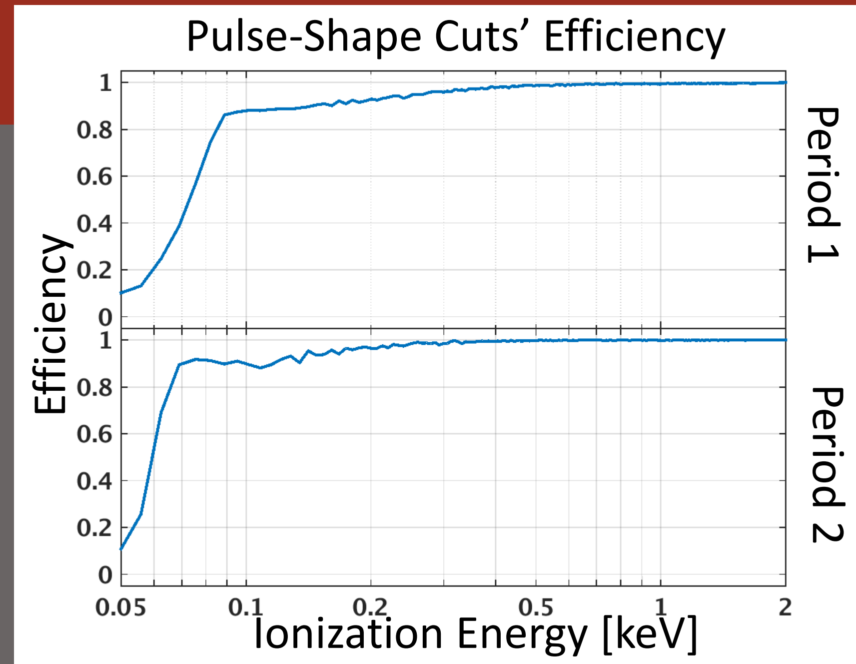


- Use monitor information to identify calendar times of higher LF noise rate
  - Use to inform pulse-shape cut
  - Tighter cut in higher rate periods
- Cryocooler degraded during first data period
  - Warm-up for maintenance

Pulse-shape Efficiency

- Generate simulated pulses and processes as usual



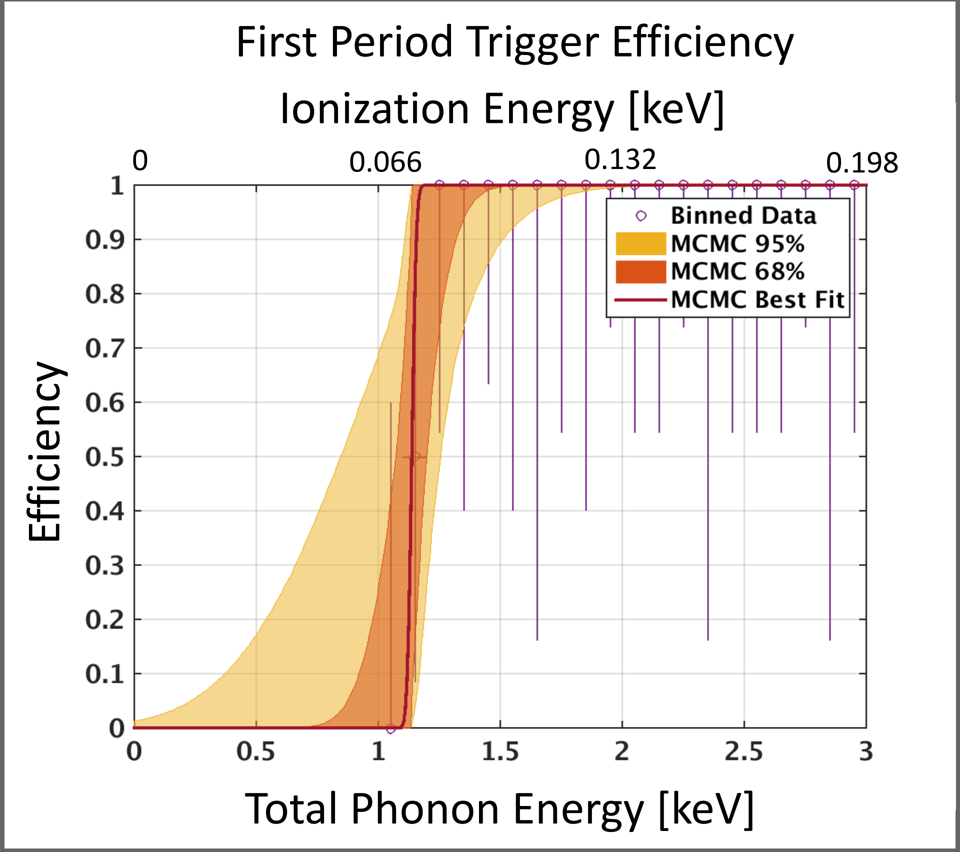


- Efficiency of: LF noise, glitch, standard-event pulse-shape cuts
- Sharp drop at ~80 eV due to LF noise energy assignment in reconstruction

Hardware Trigger Threshold

- Method
  - Use high statistics Cf calibration data
  - On good multiple scattering events, find probability that CDMSlite detector triggered given that another detector has triggered
  - Fit to error function using Markov-chain Monte Carlo
- Better LF noise rejection with noise monitor information
- Post maintenance period had lower LF noise rate and a physically lower threshold
- Lowered thresholds from 170 eV to <75 eV ionization energy

50% Efficiency at 75^{+4}_{-5} eV Ionization Energy



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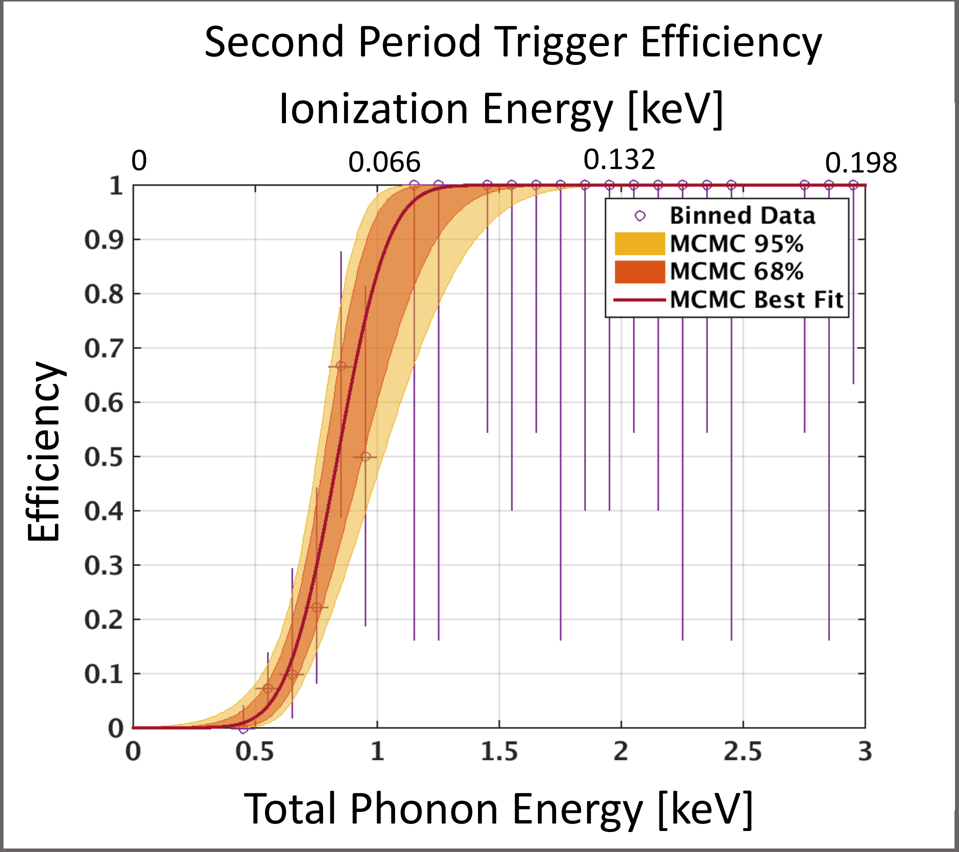
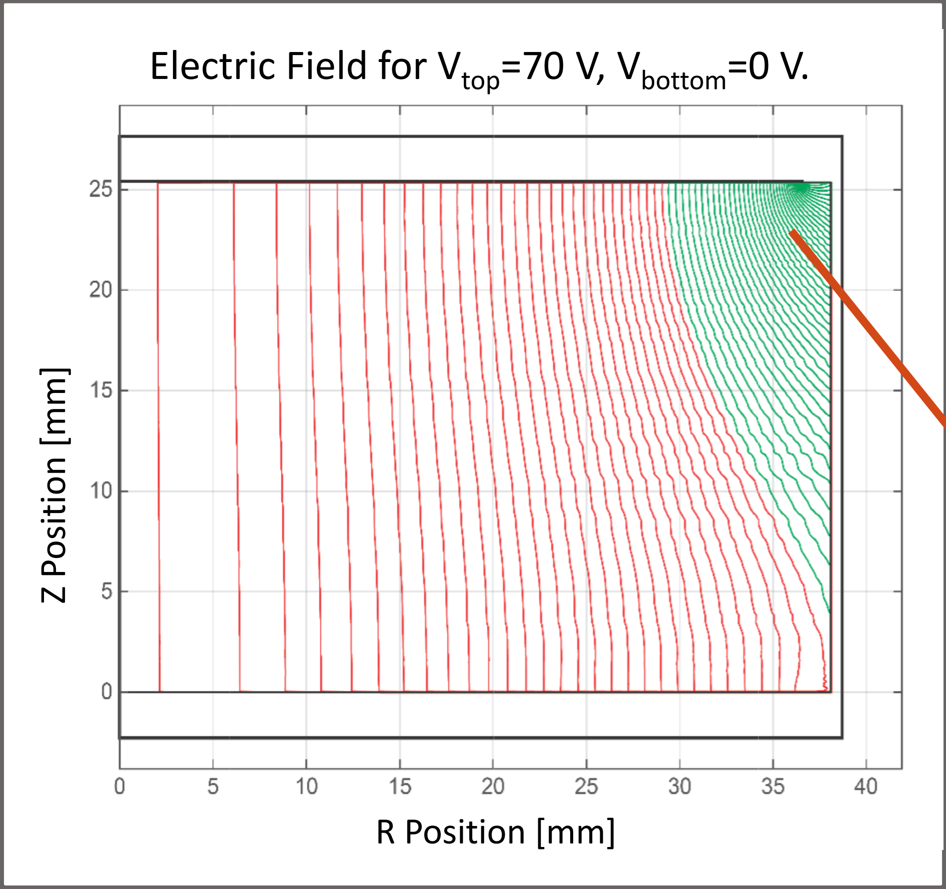
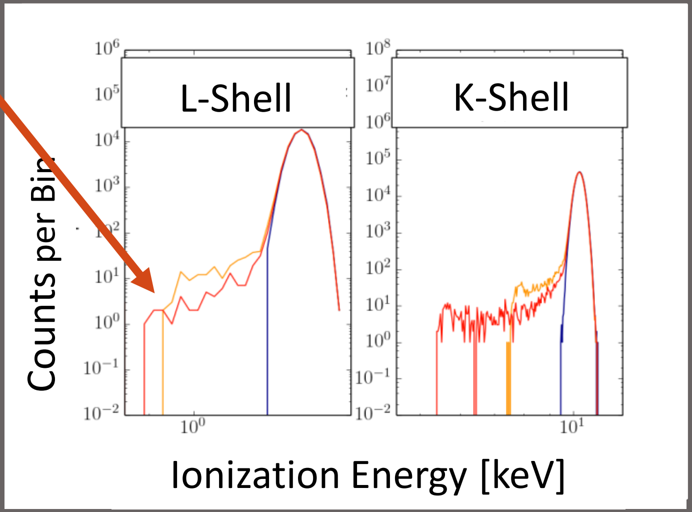
50% Efficiency at 56^{+6}_{-4} eV Ionization Energy



Fiducial Volume Motivation

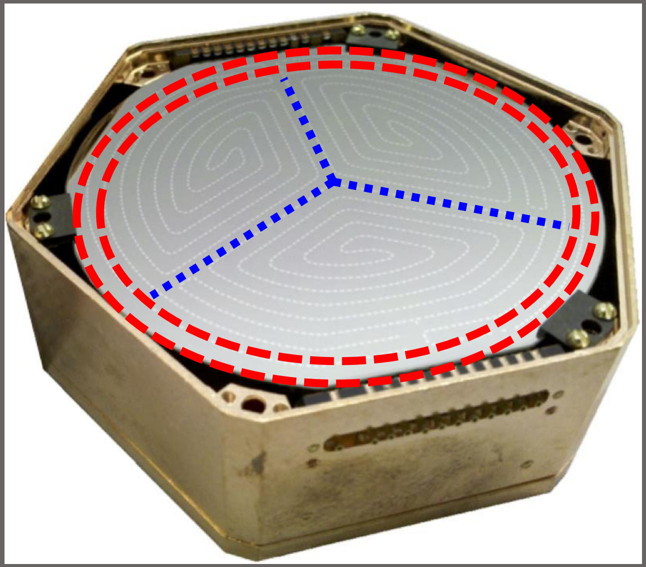


- Gap between edge of crystal and grounded copper housing
  - Full V_b not contained in crystal
- e/h pairs created at large radii traverse $V < V_b$
  - Reduces Neganov-Luke Amplification
- Adds low energy skew to spectrum!

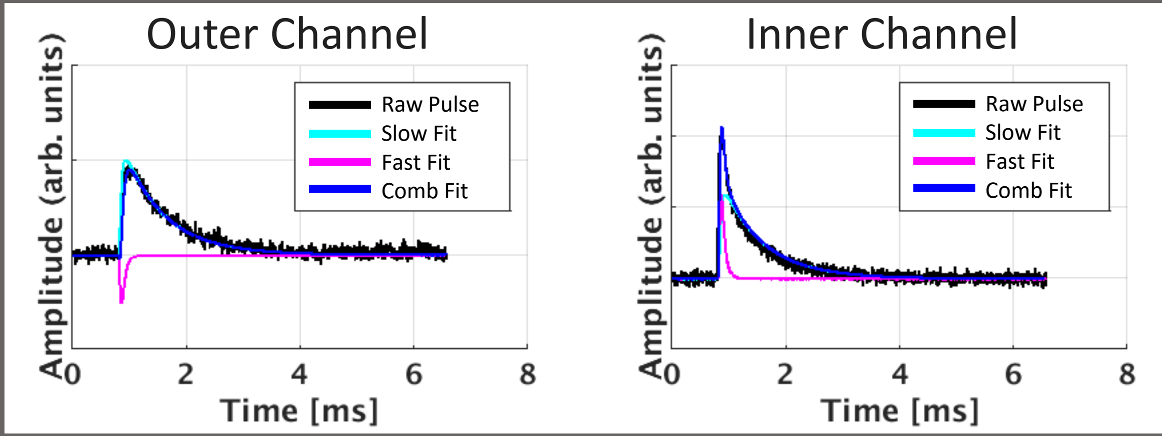


Building a Radial Estimator

- Four phonon sensors on detector face



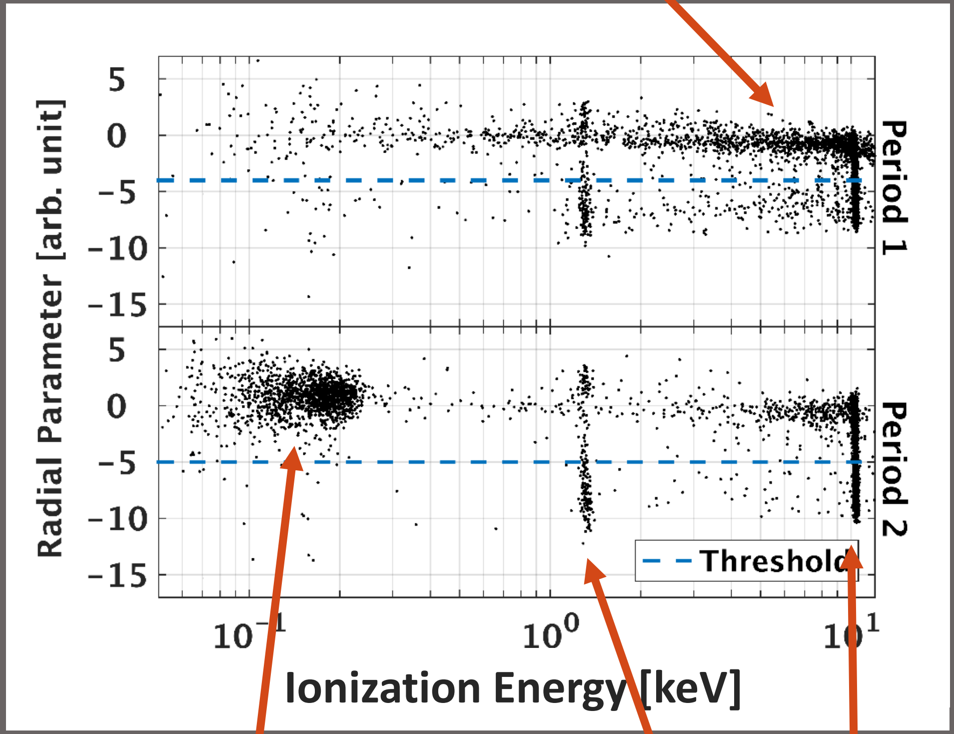
- Fit pulse in each to a linear combination of two templates:
  - Fast: Position information
  - Slow: Energy information
- Compare fast component of outer and inner channels to derive empirical radial parameter



Radial Fiducial Cut

- >90% of reduced amplification events are removed by the cut
  - Skew events
- Vertical clusters are ^{71}Ge activation peaks
- 2 differences in periods
  - Differences in operational conditions make period 2 be shifted downwards
  - Appearance of unknown background below ~250 eV at higher radius, tight x-y cluster, in period 2.
- Tighter cut threshold in period 2

Reduced amplification events,
Sidewall surface events



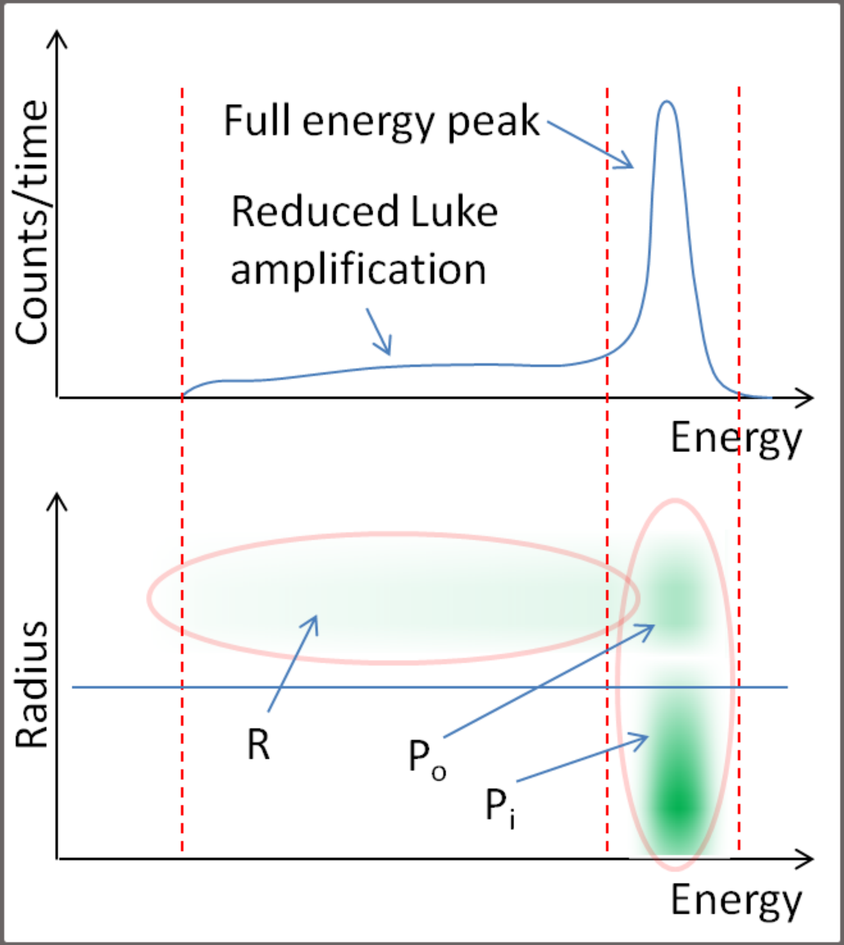
Unexpected Background

^{71}Ge Activation Peaks

Radial Fiducial Cut Efficiency

- Want fraction of events passing cut

$$Eff = \frac{P_i}{P_i + P_o + R} = \frac{P_i + P_o}{P_i + P_o + R} \cdot \frac{P_i}{P_i + P_o}$$



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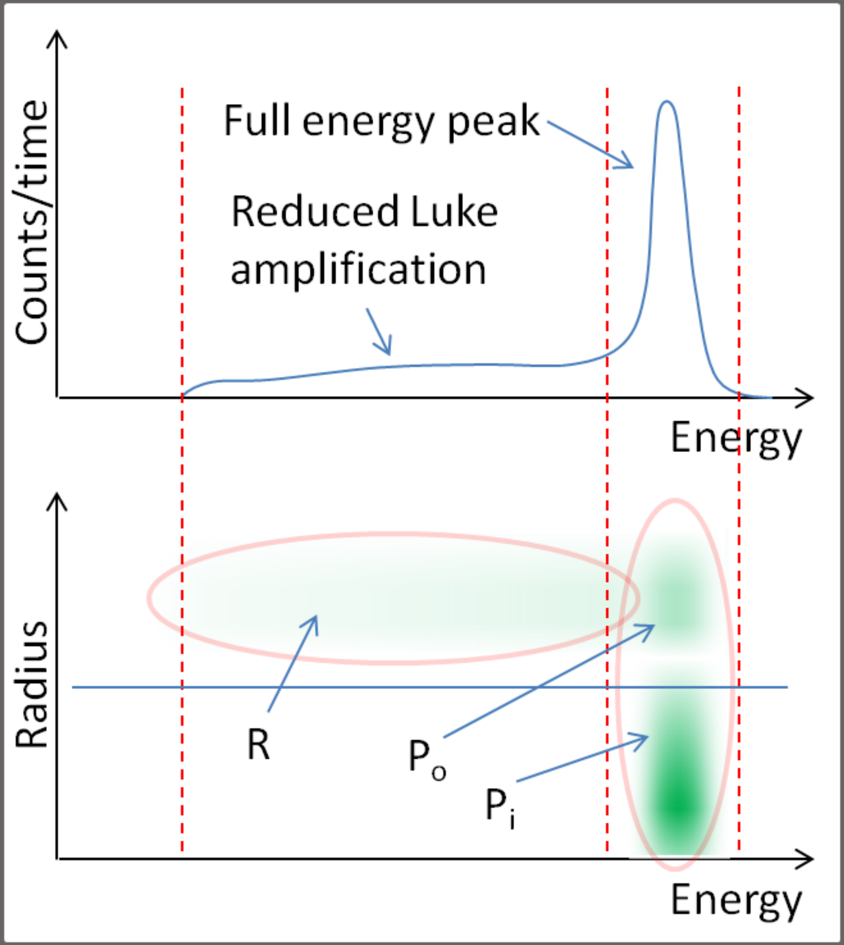
- First, find Percentage of events at full amplification:
  - Geometrical Effect
  - Energy independent – use capture peaks
  - Break radial-energy plane into sections
  - Fit for component decaying with $\tau_{1/2}$ of ^{71}Ge activation peaks and component constant in time
  - 86.4$\pm$0.9% of Events appear at full amplification



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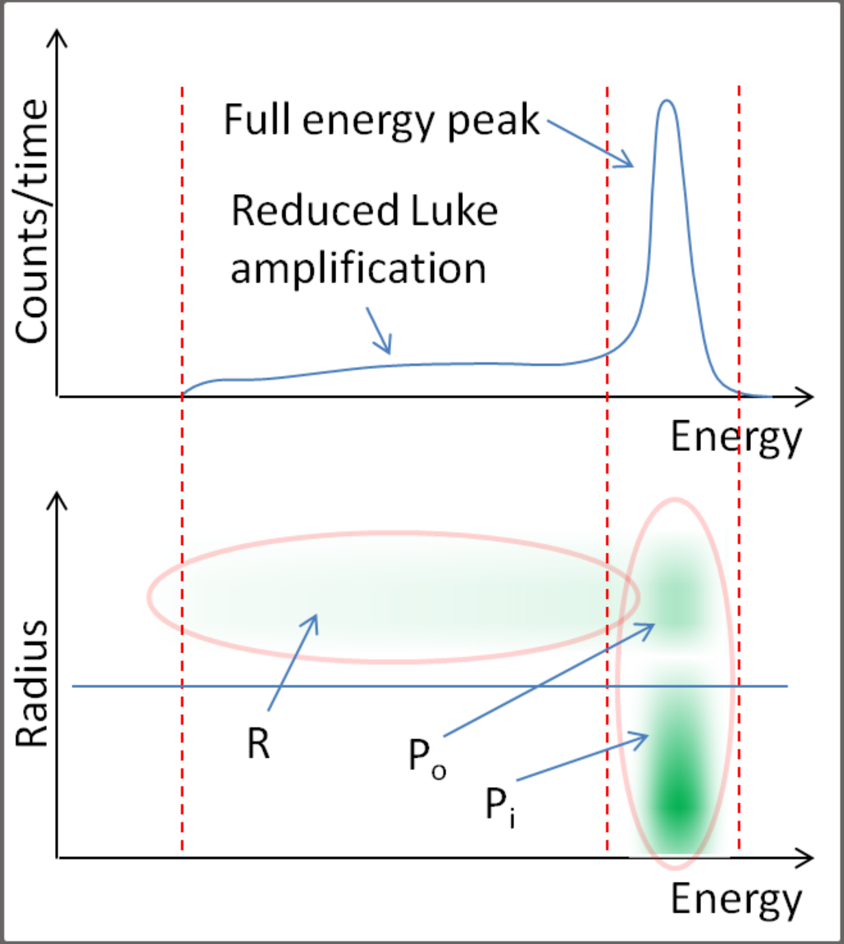
- Second, find percentage with full amplification that is still removed:
  - Energy dependent – use pulse simulation
  - Take fast/slow templates from L-shell events
  - Add noise pulse
  - Scale to lower energies
  - ~40-50% removed, based on energy and period of run



Radial Fiducial Cut Efficiency

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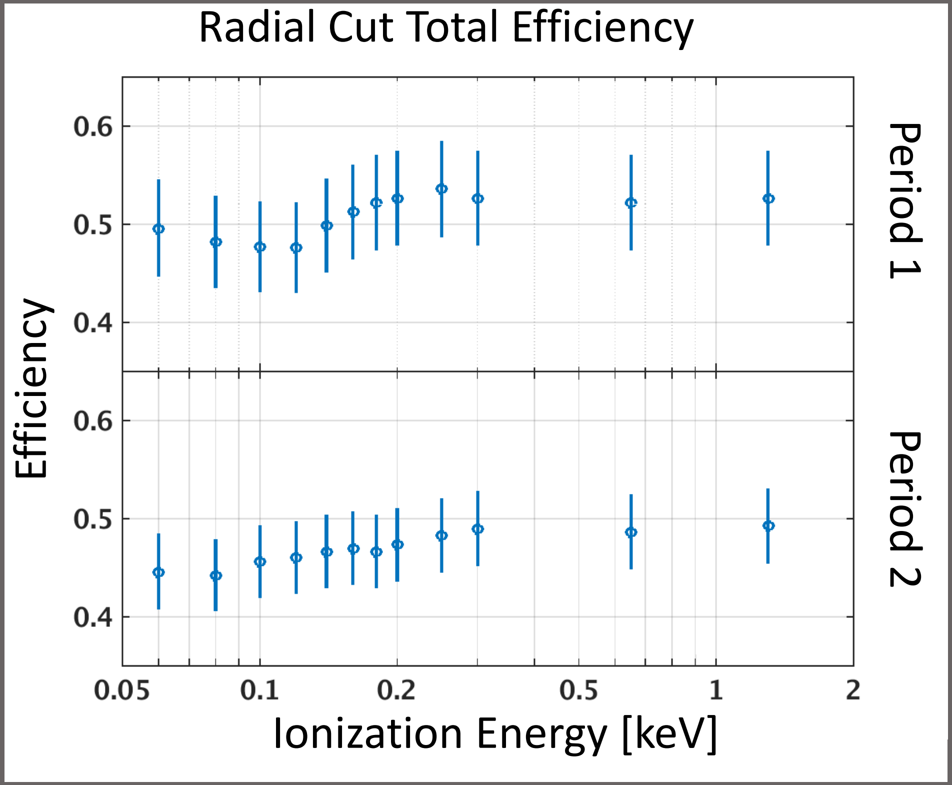
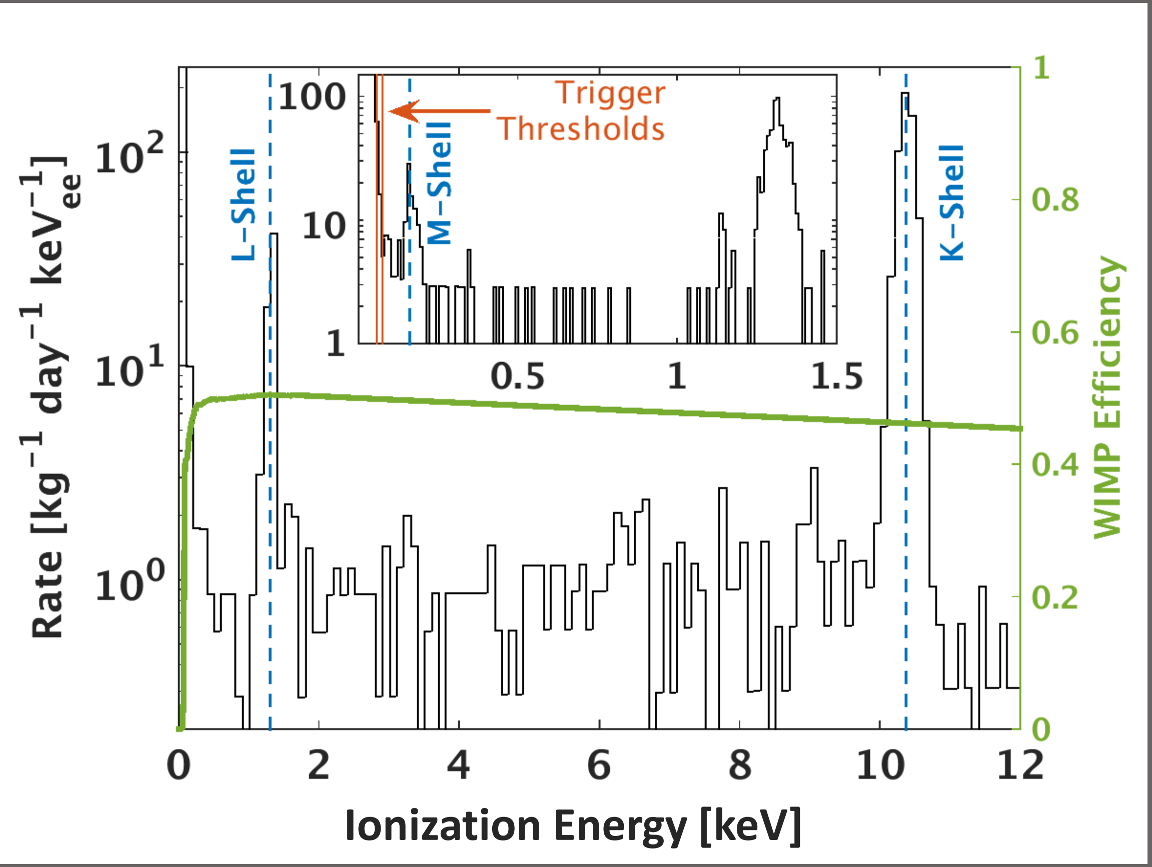
$$Eff = \frac{P_i}{\underline{P_i + P_o + R}} = \frac{P_i + P_o}{P_i + P_o + R} \cdot \frac{P_i}{P_i + P_o}$$

- Total radial efficiency: ~45-55%
  - $\pm$~5% Uncertainty



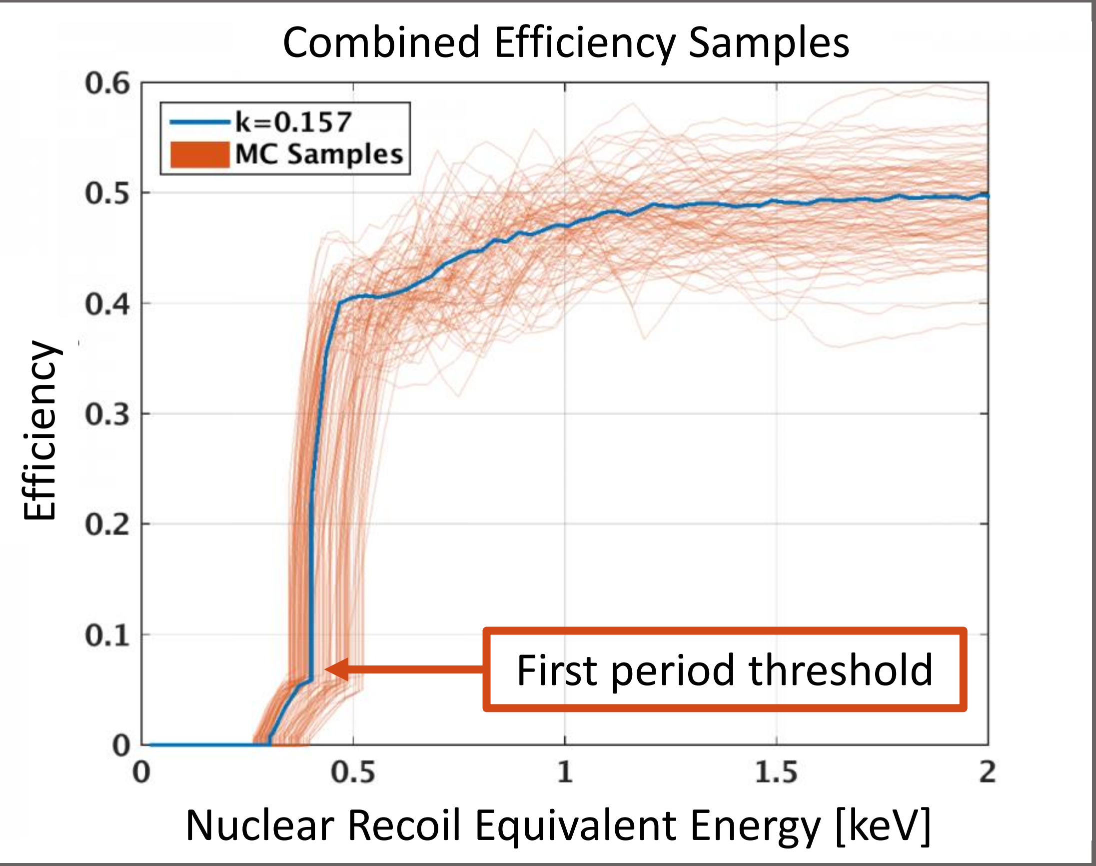
CDMSlite Run 2 Energy Spectrum

- Corrected for all efficiencies
  - Except Trigger (to show noise)
- ^{71}Ge Activation Peaks
  - 10.37, 1.30, 0.160 keV
- ~1 count/(keV-kg-d) between K and L peaks
- 50% Trigger Efficiency Points
  - 75^{+4}_{-5} and 56^{+6}_{-4} eV ionization energy



Setting the Limit

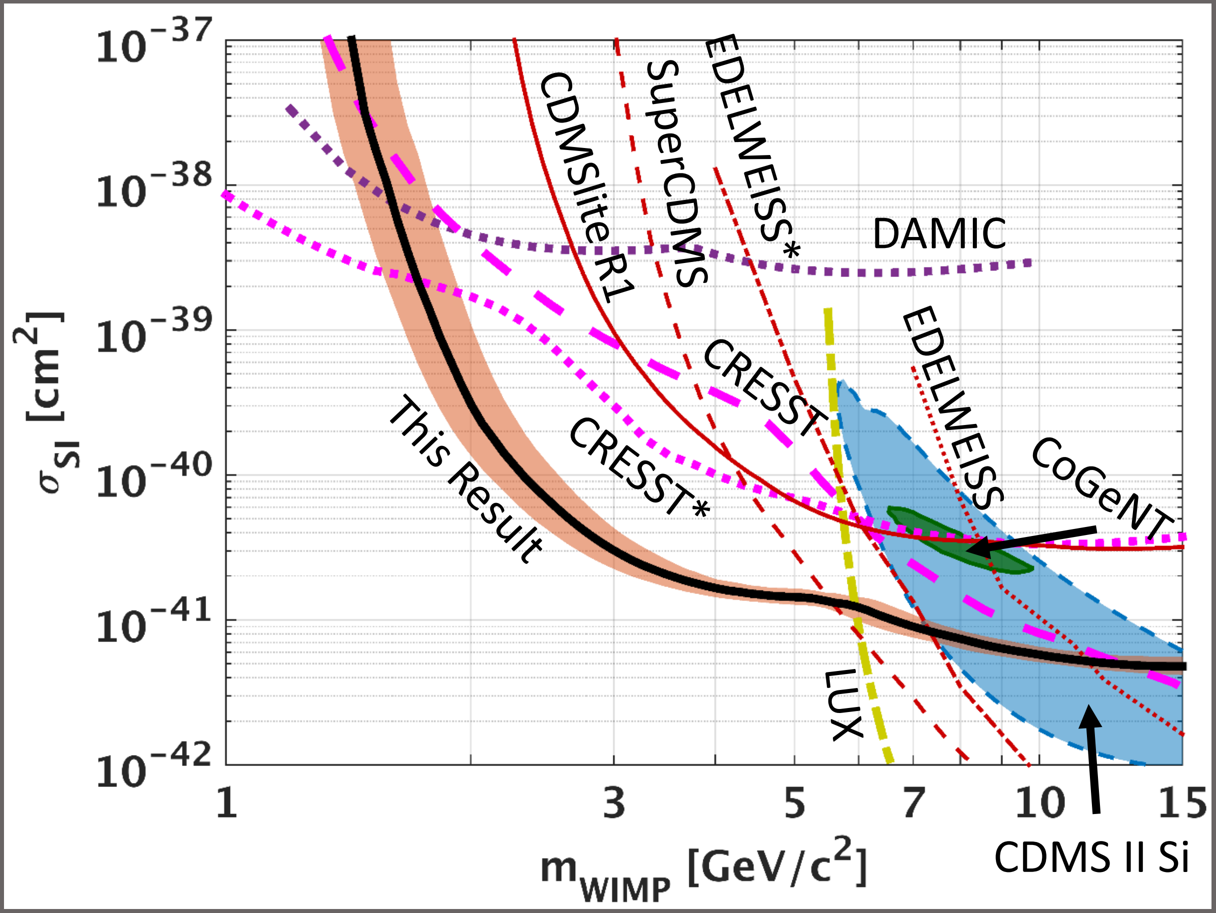
- Use Optimum Interval with no background subtraction[3]
- Convert to nuclear recoil equivalent energy using Lindhard model
  - $Y(E_{nr}) = \frac{k\ g(\varepsilon)}{1+k\ g(\varepsilon)}$
  - For Ge, $k = 0.157$
    - Scan over $k = 0.1 \rightarrow 0.2$
- Scan over uncertainty distributions 1000 times
  - Uncertainty in efficiencies
  - Uncertainty in Conversion to nuclear recoil energy



[3] S. Yellin, Phys. Rev. D 66, 032005 (2002).

CDMSlite Run 2 WIMP Limit

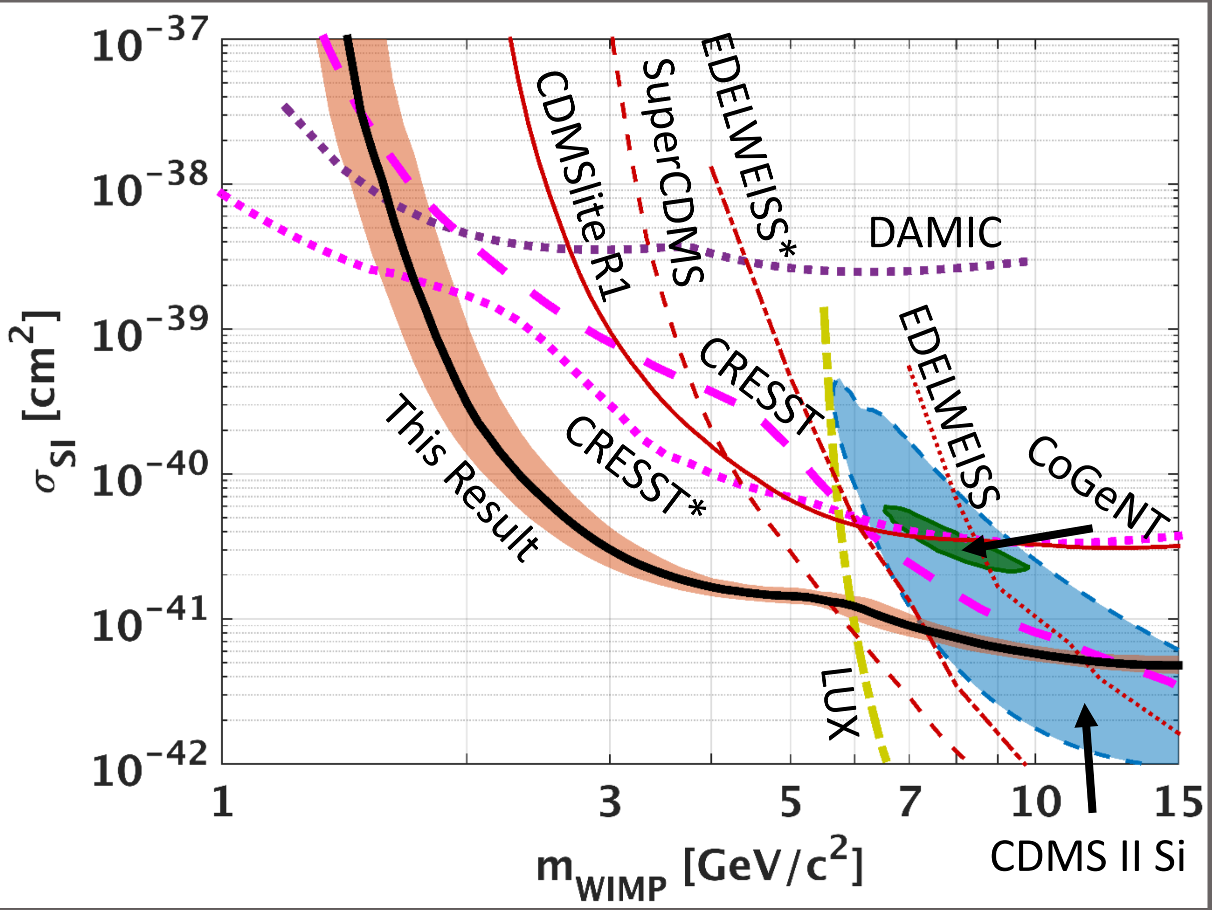
- Median (90% C.L.) and 95% interval from 1000 samples
- Excludes new parameter space for $m_\chi \in 1.6 - 5.6$ GeV/c^2
- Improved over Run 1
  - 33.3x at 3 GeV/c^2
  - 4.3x lower at 5 GeV/c^2
  - Lower Thresholds
  - Reduced backgrounds
- Bump at ~6 GeV/c^2 due to M-shell peak at 160 eV ionization energy



*Preliminary Shown at this conference

Conclusions

- CDMSlite Run 2
  - 70.10 kg-d exposure
  - −70 V bias potential
  - 56/75 eV Ionization Trigger Thresholds
  - Lower Background from fiducial volume cut
- Run 3 at Soudan under analysis
  - Modest improvement expected
- Expect large Improvements for SuperCDMS SNOLAB
  - 2 eV ionization threshold
    - 100 V bias potential
    - Lower detector T_c for improved phonon resolution ($\propto T_c^3$)
  - 20 events keV^{-1} kg^{-1} yr^{-1} Background
    - Material screening and quality control



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Thank you
The SuperCDMS Soudan Collaboration

California Inst. of Tech. | CNRS-LPN* | Durham University | FNAL | NIST*
Northwestern | PNNL | Queen's University | SLAC | Southern Methodist U.
Santa Clara University | South Dakota SM&T | Stanford University | Texas A&M University | U. British Columbia
U. California, Berkeley | U. Colorado Denver | U. Evansville | U. Florida | U. Minnesota | U. South Dakota

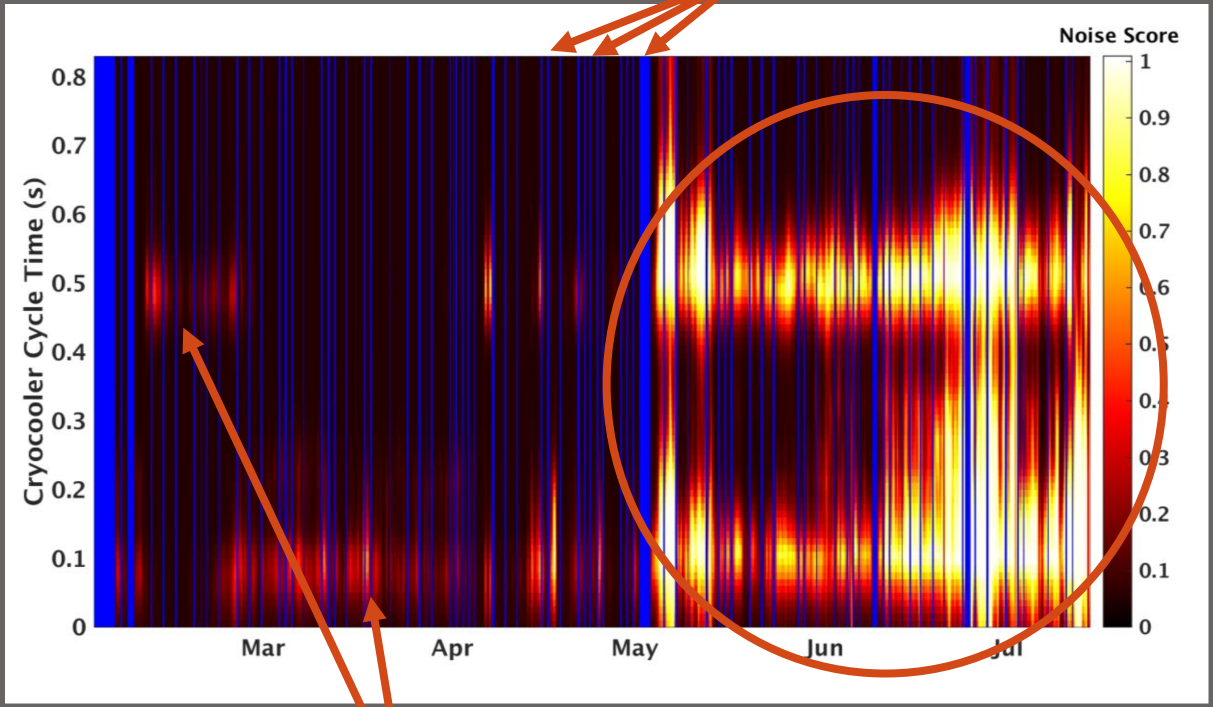
* Associate members

Back-up Slides

Cryocooler Noise Score

- Construct a correlated noise score to track low frequency noise.
  - 1 → Large LF Activity
  - 0 → Small LF Activity
- Looks for events in specific energy range and close in time (cryocooler cycle and calendar)
- Tighter pulse-shape cut for periods of larger LF activity

Blue≡Dead time (Calibration Data)

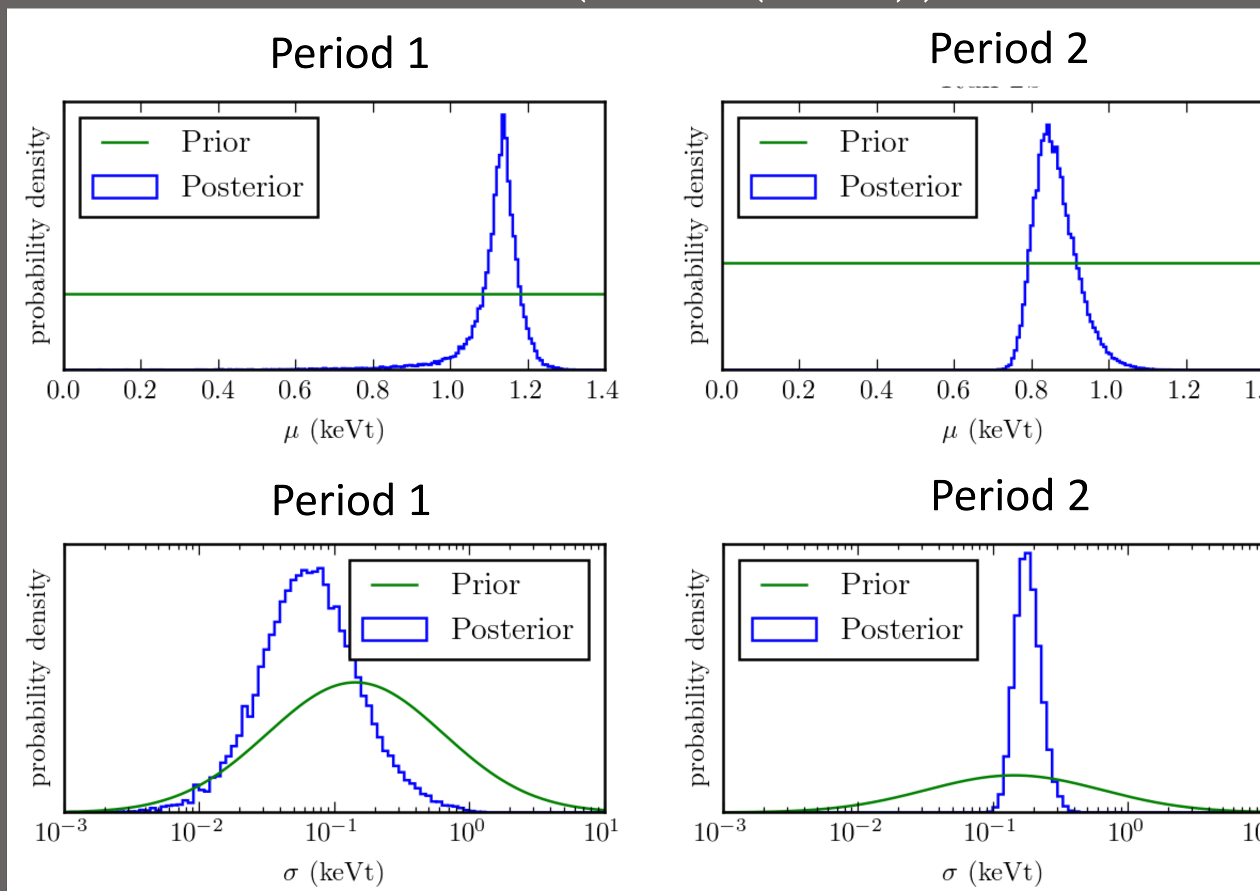


Degradation Evident

Usual LF noise timing

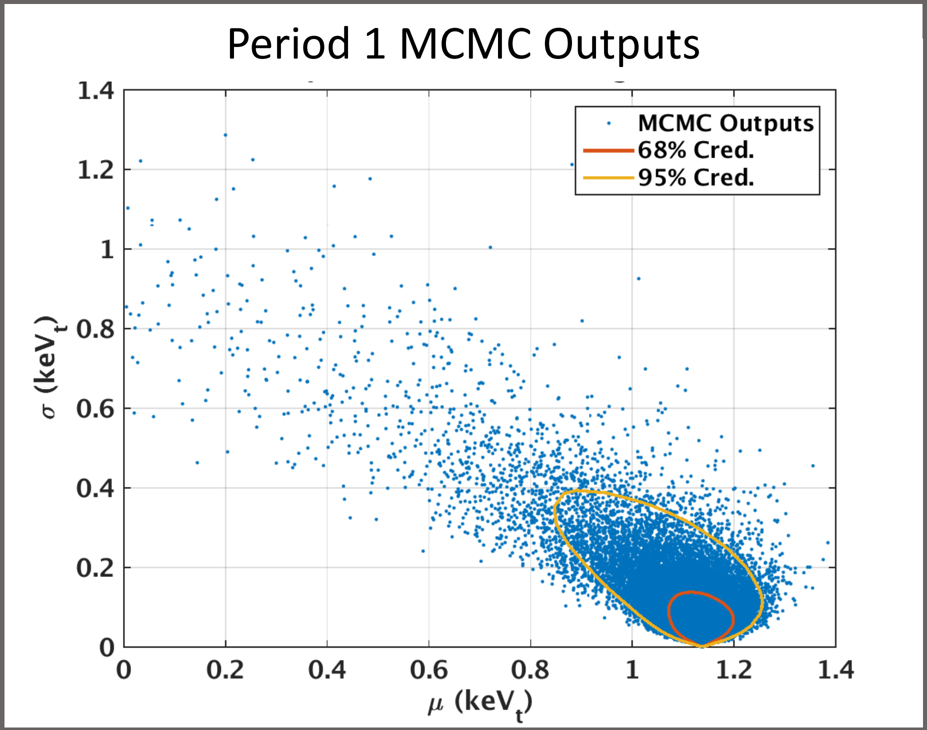
Trigger Efficiency MCMC – Marginal Distributions

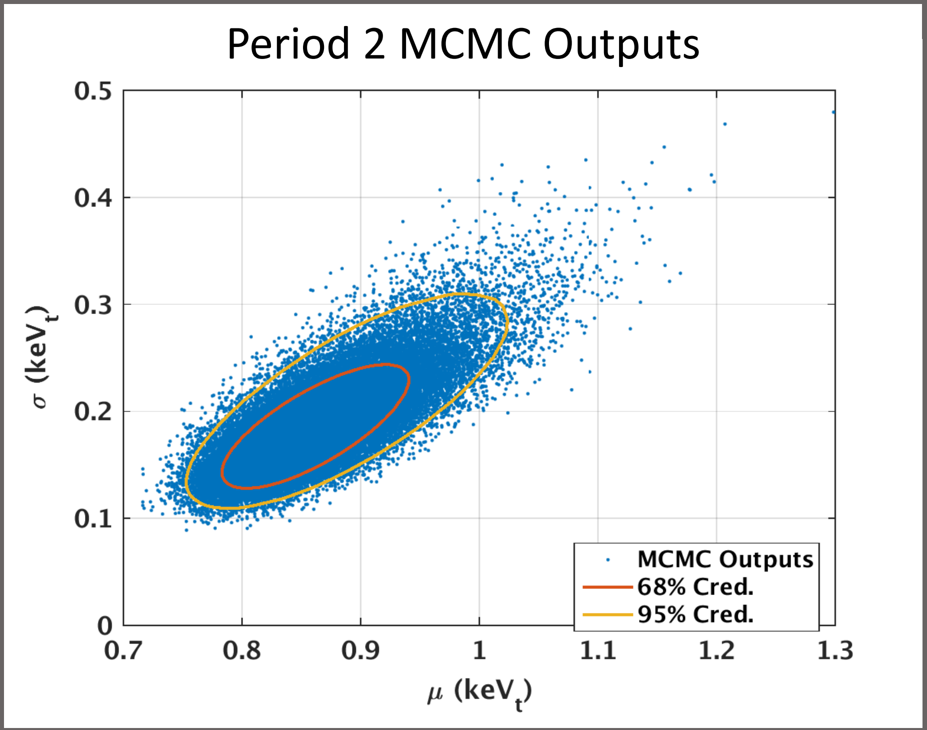
$$f(E_t) = 0.5\left(1 + \mathrm{erf}\left(\frac{E_t - \mu}{\sqrt{2}\sigma}\right)\right)$$



Trigger Efficiency MCMC – 2D Distributions

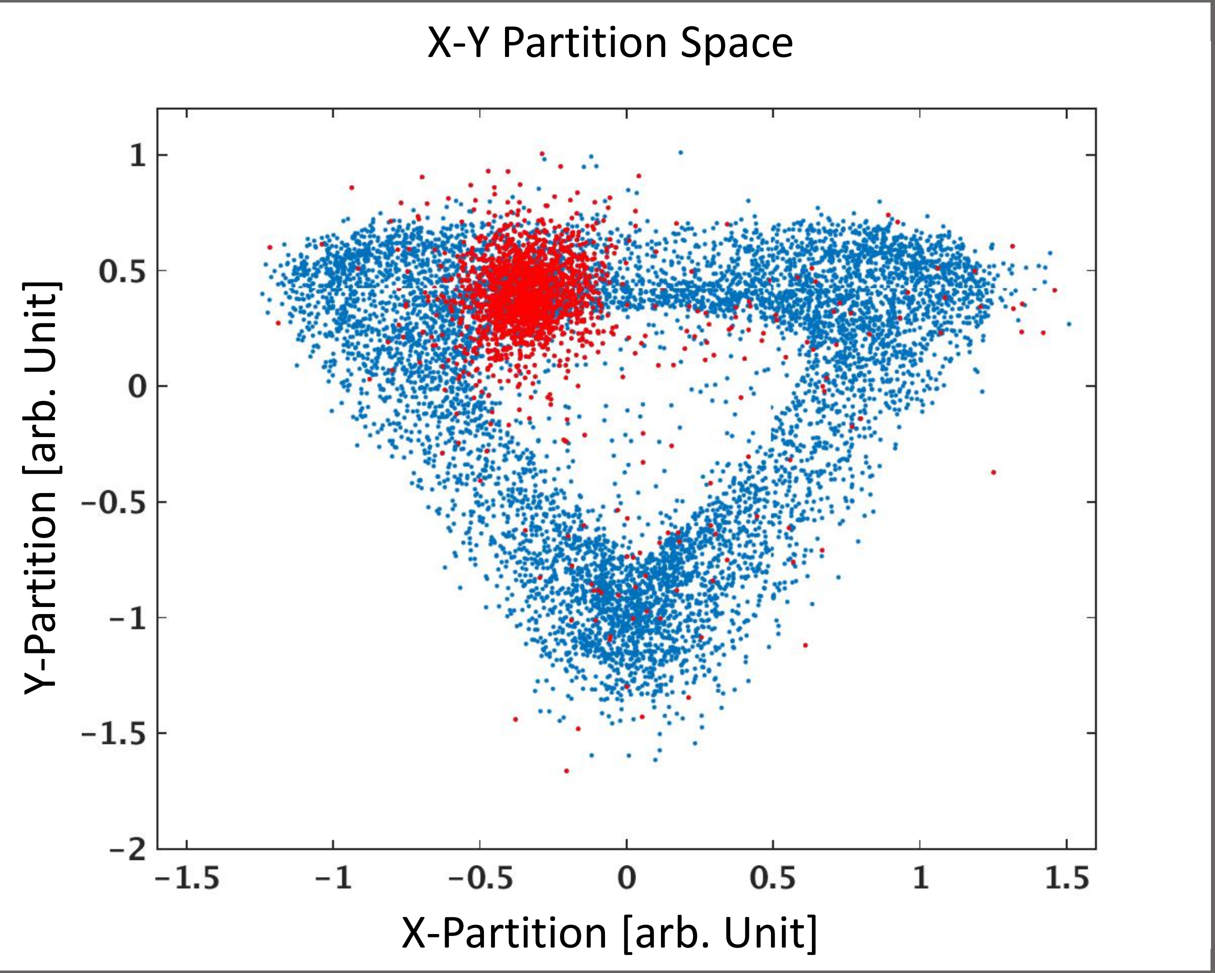
$$f(E_t) = 0.5\left(1 + \operatorname{erf}\left(\frac{E_t - \mu}{\sqrt{2}\sigma}\right)\right)$$



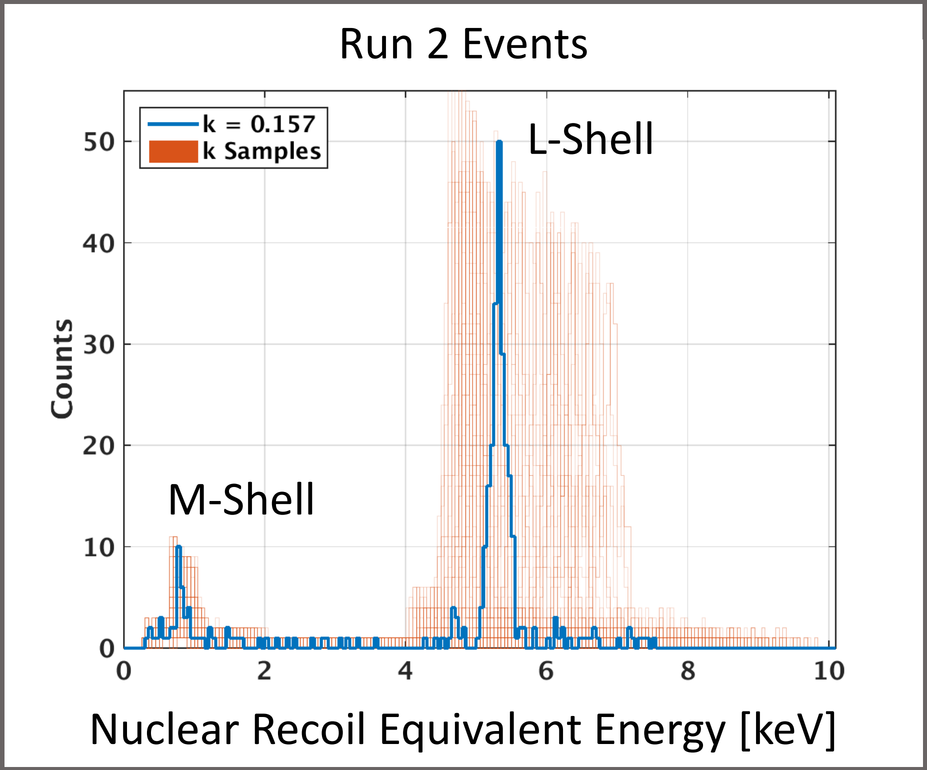


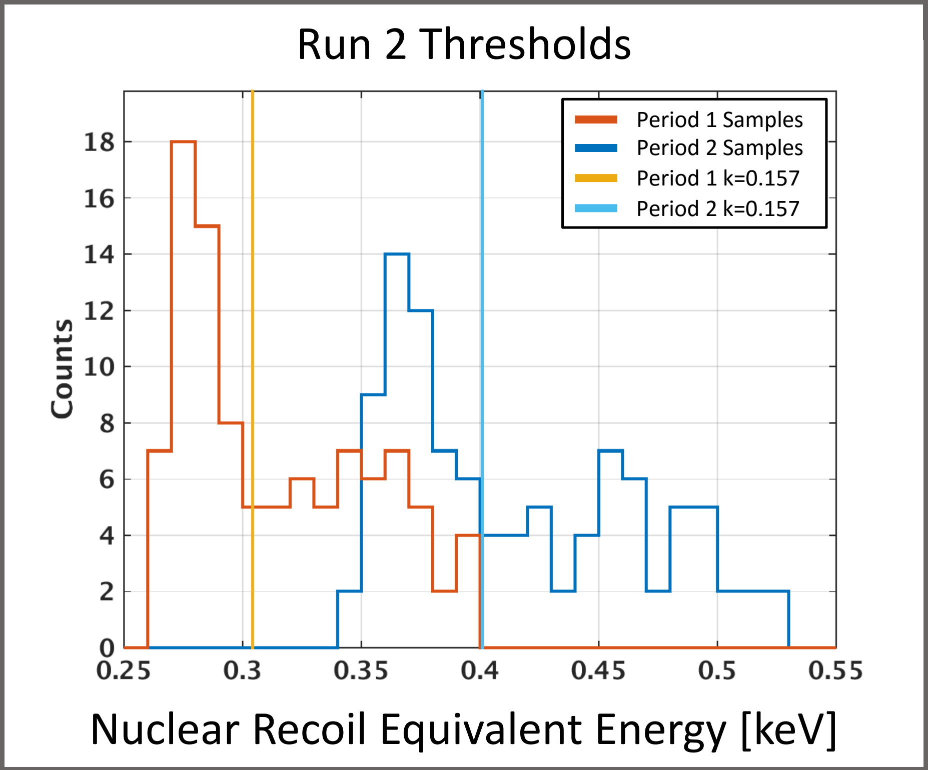
Unexpected Background

- X-Y Position based on fast/slow template fitting
- Red events are between 100 and 200 eV ionization energy
- Clear position clustering in x-y space



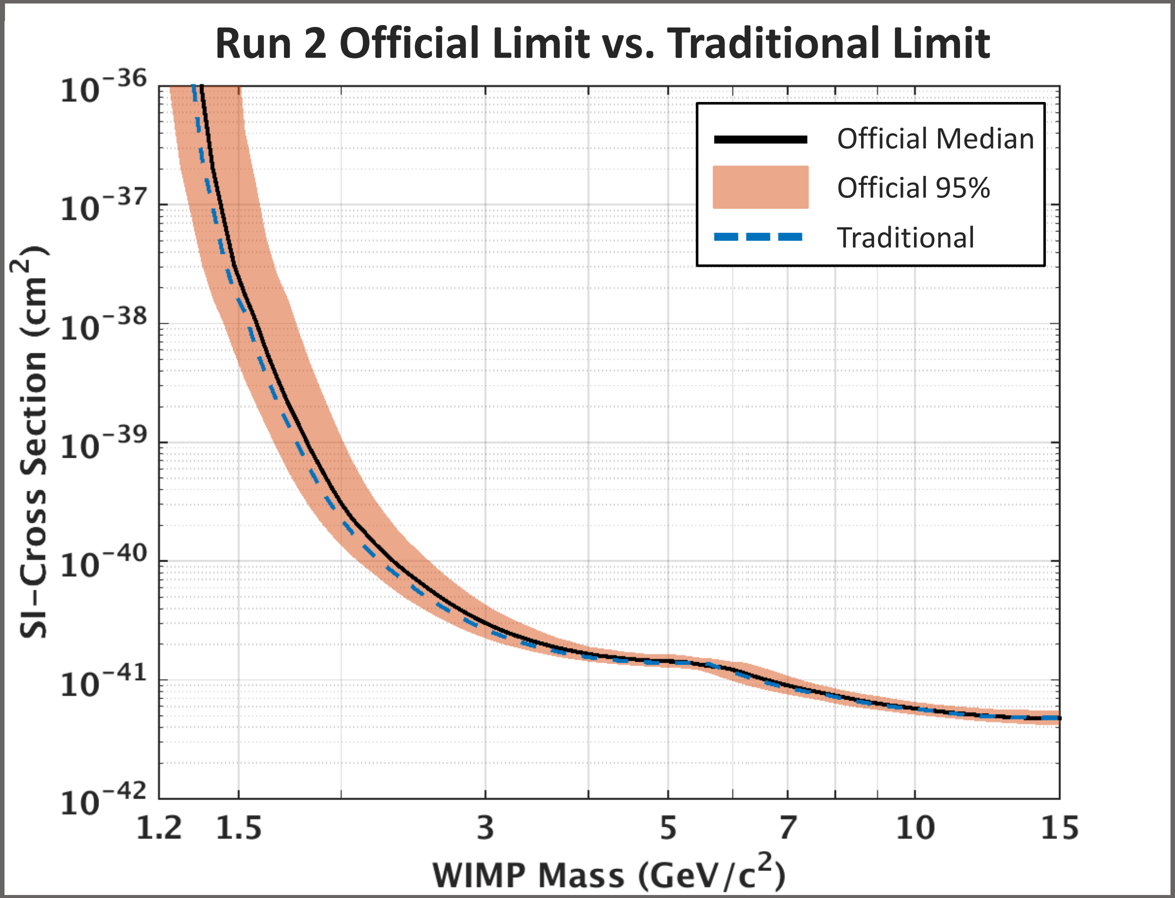
Sampling Lindhard Models





Limit Comparison: Sampling vs. Traditional

- Median and 95% Interval from official limit
- Traditional Limit:
  - Mean value for single efficiency
  - Standard Lindhard model
    - $k = 0.157$
- Consistent and within uncertainty



Limit Comparison: Tight vs. Loose Radial

- Median and 95% Interval from official limit
- Loose limit
  - Set Radial cut at same threshold in both run periods.
  - Loosen second period to value of first period
  - Introduces more background from 250 eV ionization population
- Slightly weaker limit, ~9%
  - Within uncertainty