CDMSlite

CDMS **L**ow **I**onization **T**hreshold **E**xperiment

Running the SuperCDMS Soudan iZIPs in voltage-assisted calorimetric ionization mode

Priscilla Cushman
University of Minnesota

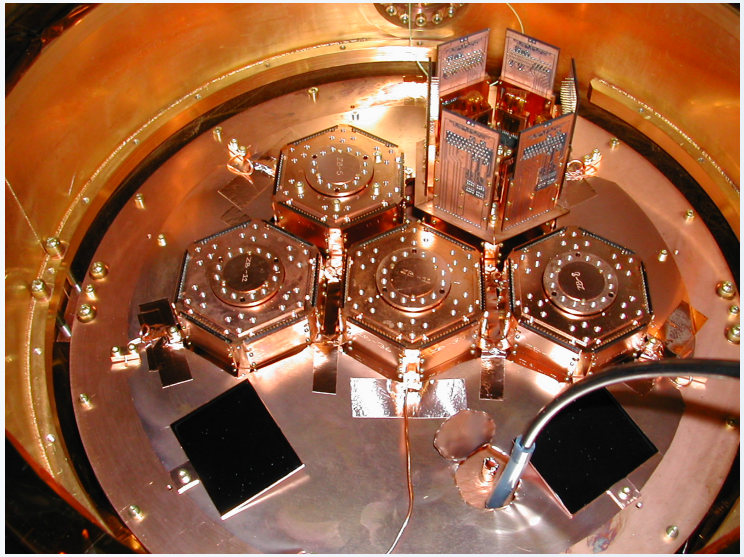
SuperCDMS at Soudan

Santa Clara University · South Dakota SM&T · Stanford University · Texas A&M University · U. British Columbia · California Inst. of Tech. · CNRS-LPN · Durham University · FNAL · NISER · NIST

U. California, Berkeley · U. Colorado Denver · U. Evansville · U. Florida · U. Minnesota · U. South Dakota · Northwestern · PNNL · Queen's University · SLAC · Southern Methodist U.

interleaved
Z-sensitive
Ionization and
Phonon-mediated detectors

2.5 cm thick
3"diameter
620 g Germanium



SuperCDMS at Soudan

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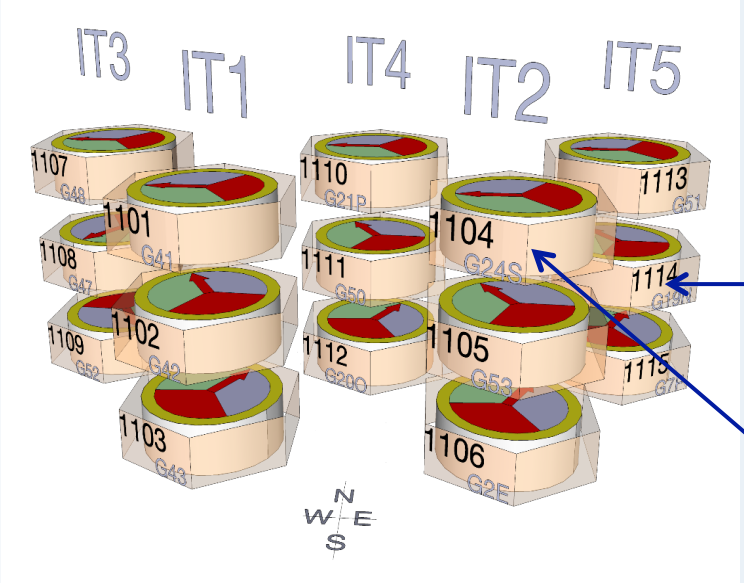
interleaved
Z-sensitive
Ionization and
Phonon-mediated detectors

2.5 cm thick
3”diameter
620 g Germanium

CDMSlite:
one iZIP in HV mode

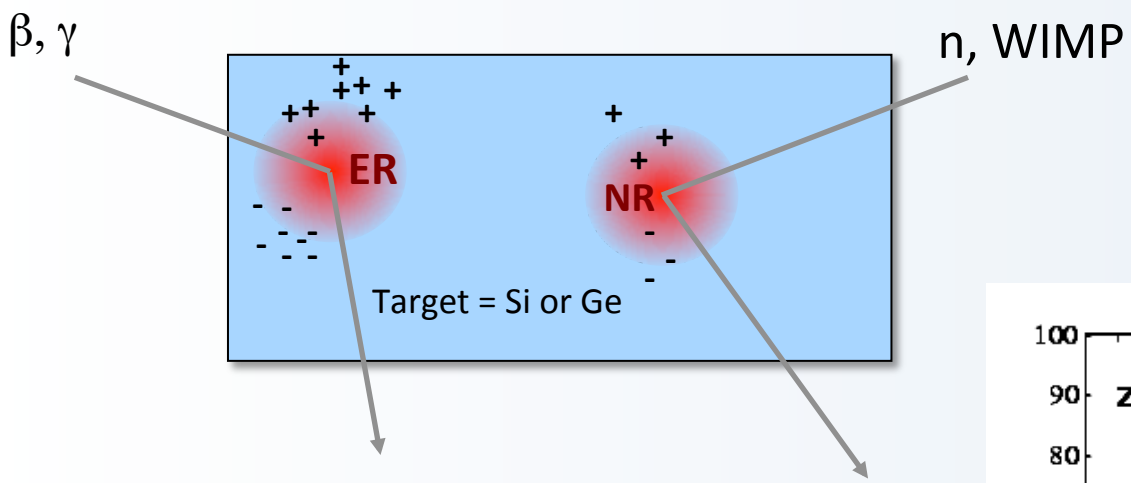
Run 1	Aug – Sept 2012
Run 2a	Feb – July 2014
Run 2b	Sept – Nov 2014
Run 3	Feb – May 2015



CDMSlite iZIP (Run 1-2)

CDMSlite iZIP (Run 3)

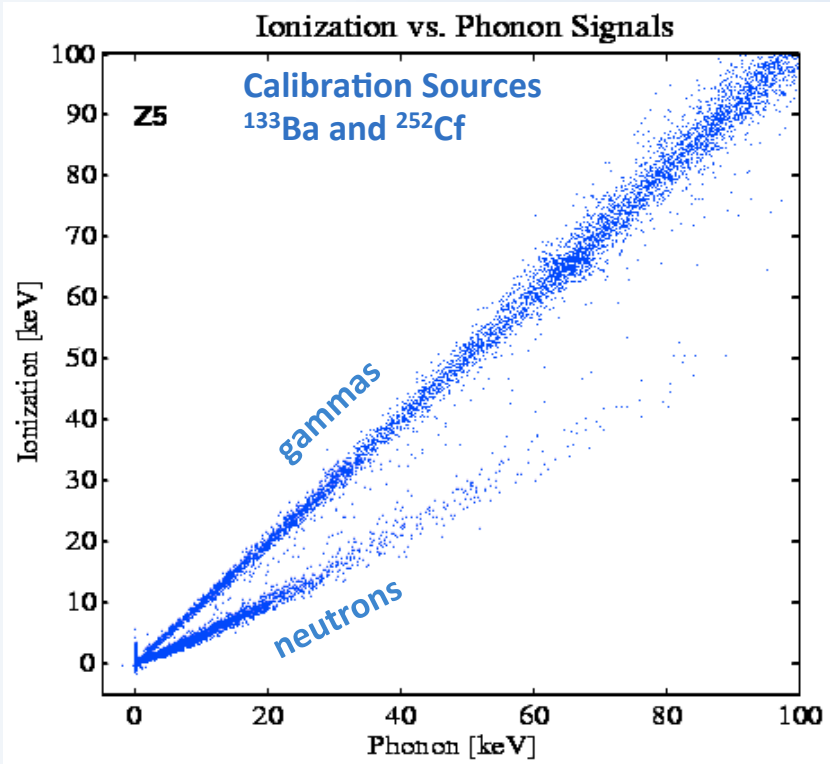
SuperCDMS iZIP technology



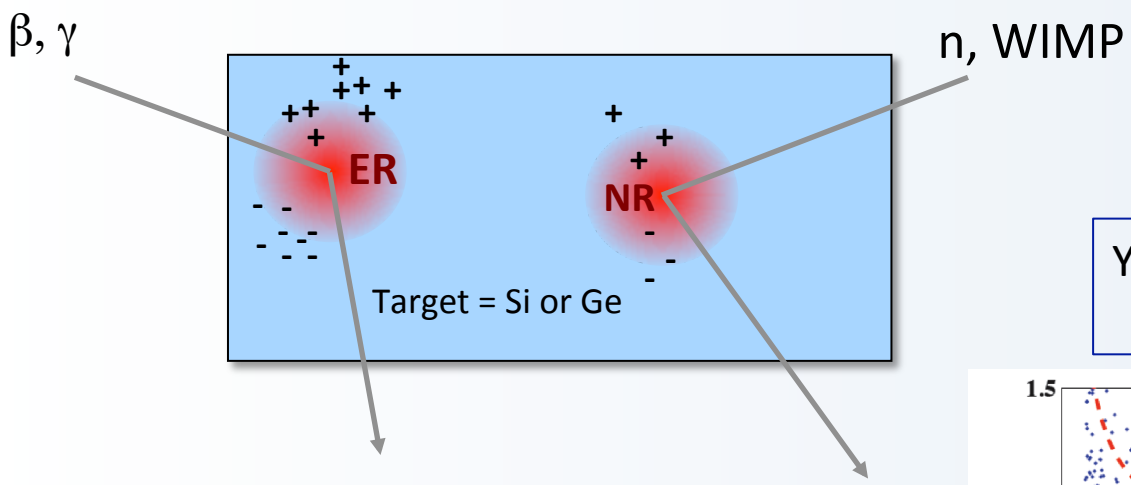
Phonon signal measures energy deposition

Ionization quenched for nuclear recoils

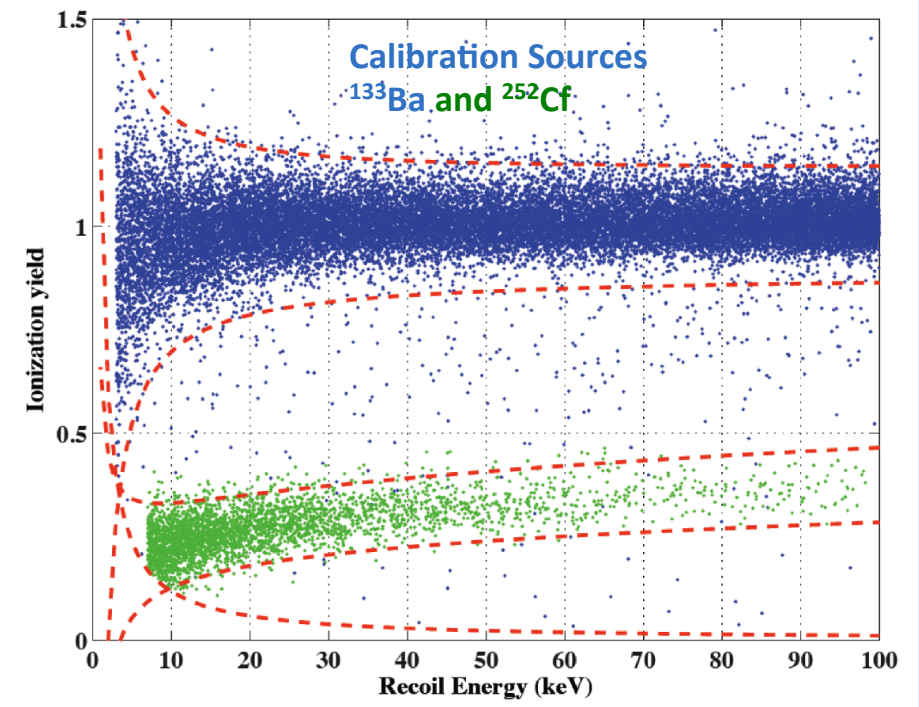
Excellent (>10^5) rejection of electron recoil background



SuperCDMS iZIP technology



$$\text{Yield} = Y(E_r) = \frac{\text{Ionization Energy}}{\text{Recoil Energy}}$$



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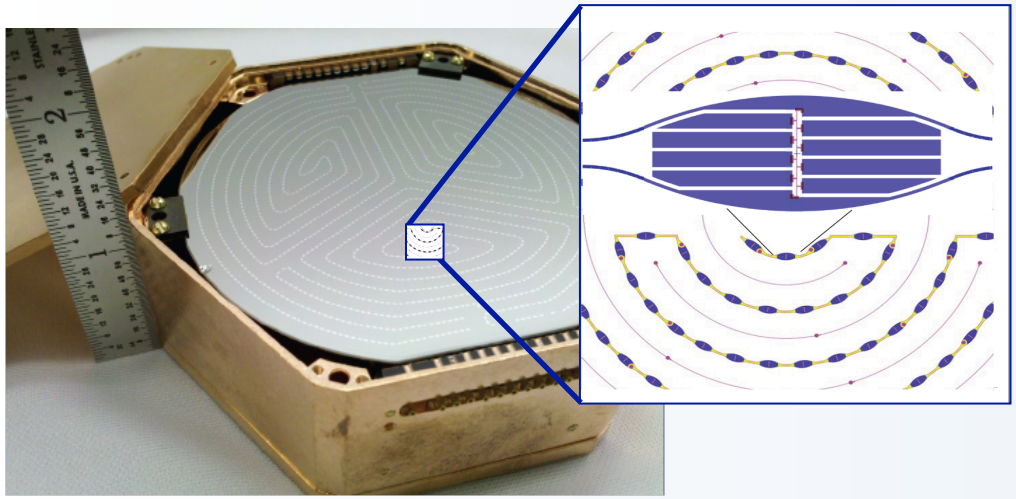
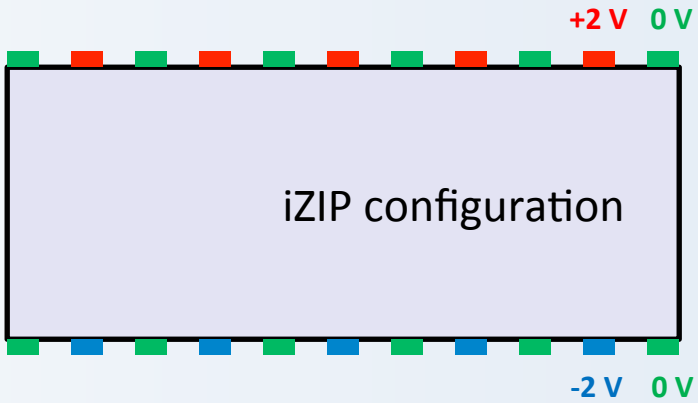
SuperCDMS iZIP



Phonon and ionization signals read out from both sides

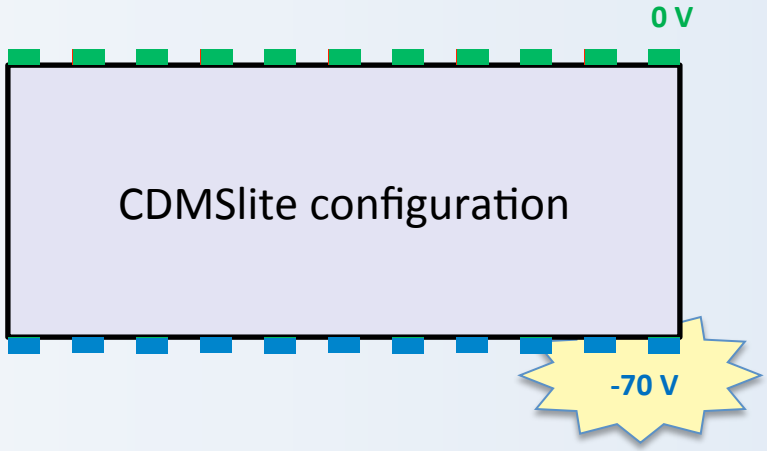


SuperCDMS iZIP → lite

For sensitivity to the lowest mass WIMPs, we need to lower our threshold.

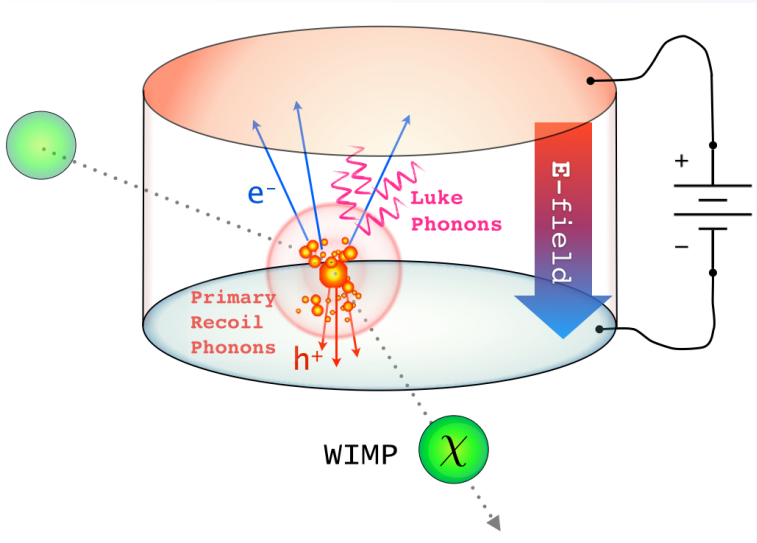
This can be done by running at much higher voltages, but without ER/NR discrimination

Read out phonon sensors on grounded side



Trade-offs

As e-h pairs move through crystal they create Luke Phonons



Total Phonon Energy = E(Recoil) + E(Luke)

$$E_{tot} = E_r + E_L = E_r + N_{e-h} e V_b = E_r \left(1 + Y(E_r)\frac{eV_b}{\varepsilon_\gamma}\right)$$

ε_γ ~ 3 eV: Avg E needed by ER to create an e-h pair

Electron Recoils: $Y \equiv 1$

Nuclear Recoils: $Y(E_r) \approx 1/3$

CDMSlite $V_b >> \varepsilon_\gamma$

$$E_{tot} = E_r\left(1 + g(V_b)\right)$$

Luke phonons dominate

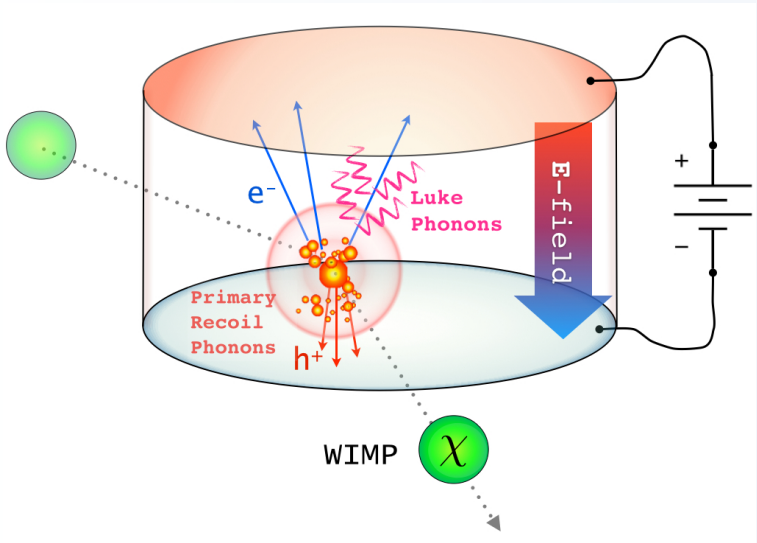
ER:NR Discrimination Mode V_b =4 V

$$Y(E_r) = \frac{E_Q}{E_r} = \frac{E_Q}{E_{tot} - N_{eh} e V_b}$$

Keep E_L small, measure E_Q (^{133}Ba) and the Yield Band centroid (^{252}CF) to find the NR scale

Trade-offs

As e-h pairs move through crystal they create Luke Phonons



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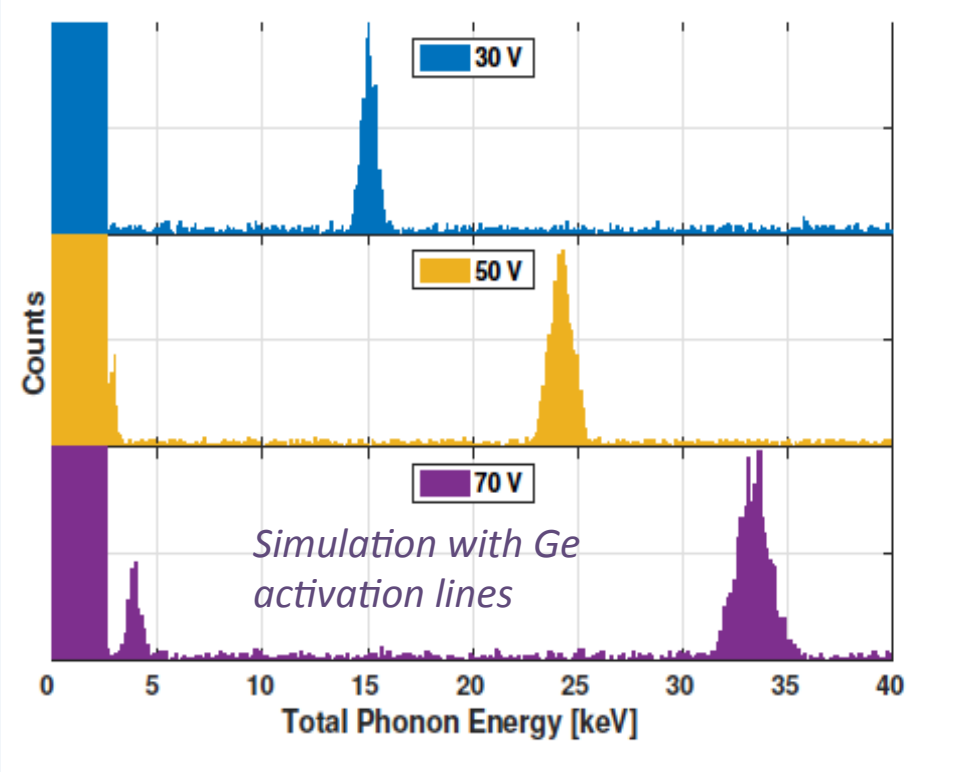


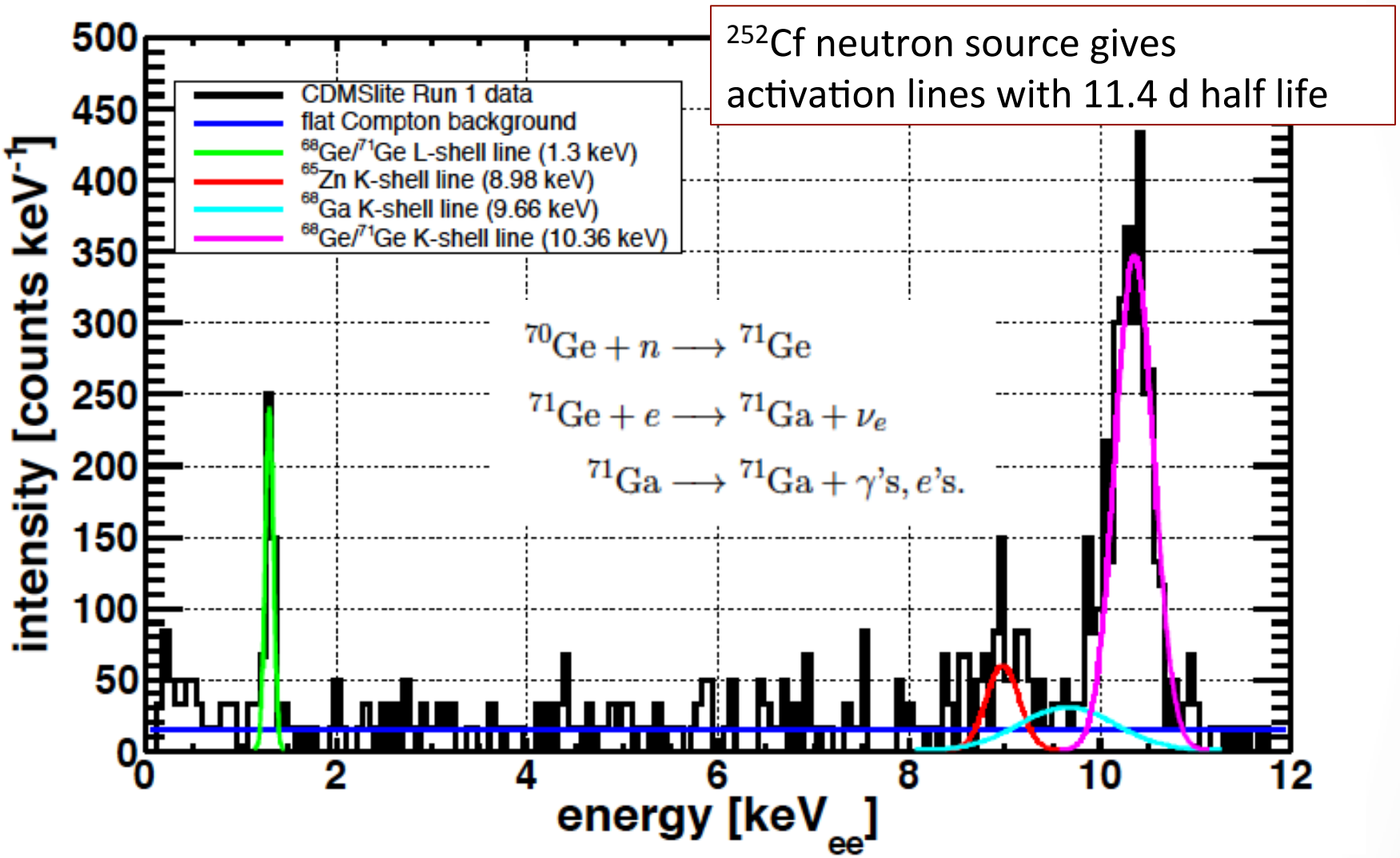
CDMSlite $V_b >> \varepsilon_\gamma$

$$E_{tot} = E_r\left(1 + g_L(V_b)\right)$$

Luke phonons dominate

Amplification = 24 at V_b = 70 V
But only x 12 for one-sided readout

Run 1: First look at our low energy spectral features

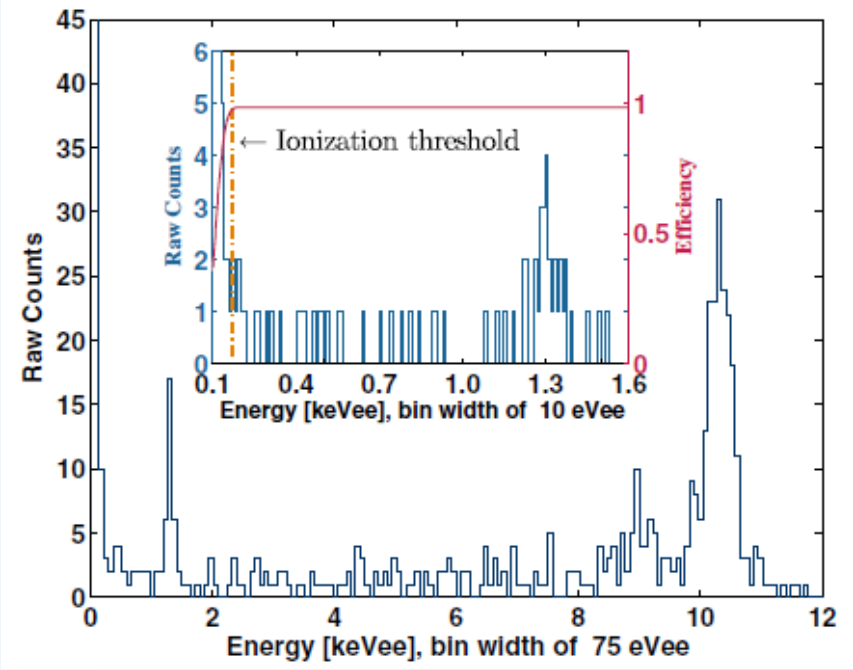


CDMSlite Run 1

Proof of Principle (2013)

R. Agnese et al. Phys. Rev. Lett. 112, 04130

- - 69 V bias on one detector.
- 6.5 kg-d, ~170 eV_{ee} ionization threshold



CDMSlite Run 1

Proof of Principle (2013)

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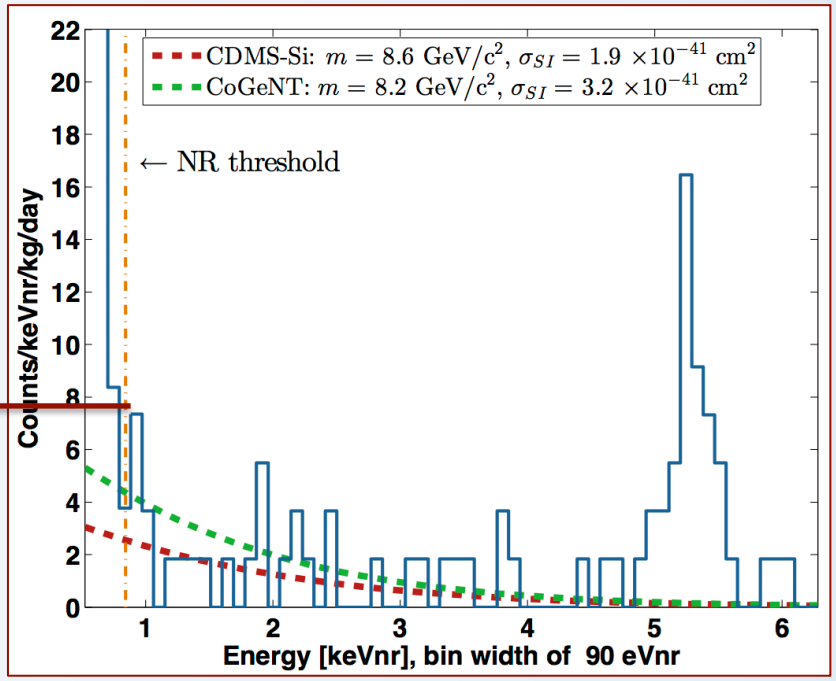
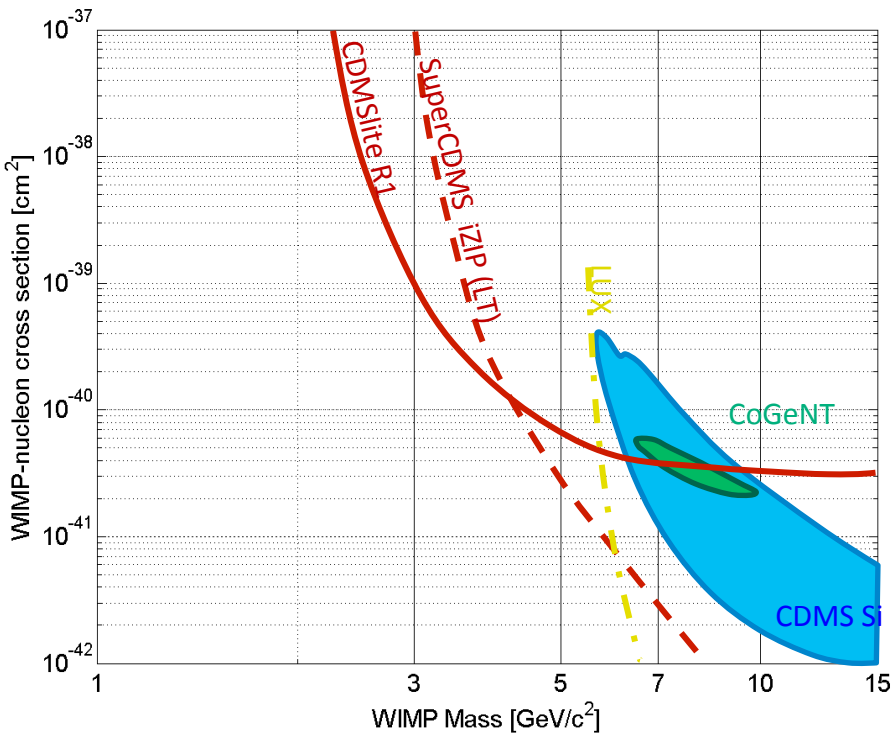
- - 69 V bias on one detector.
- 6.5 kg-d, ~170 eV_{ee} ionization threshold corresponding to ~ 841 eV_{nr}

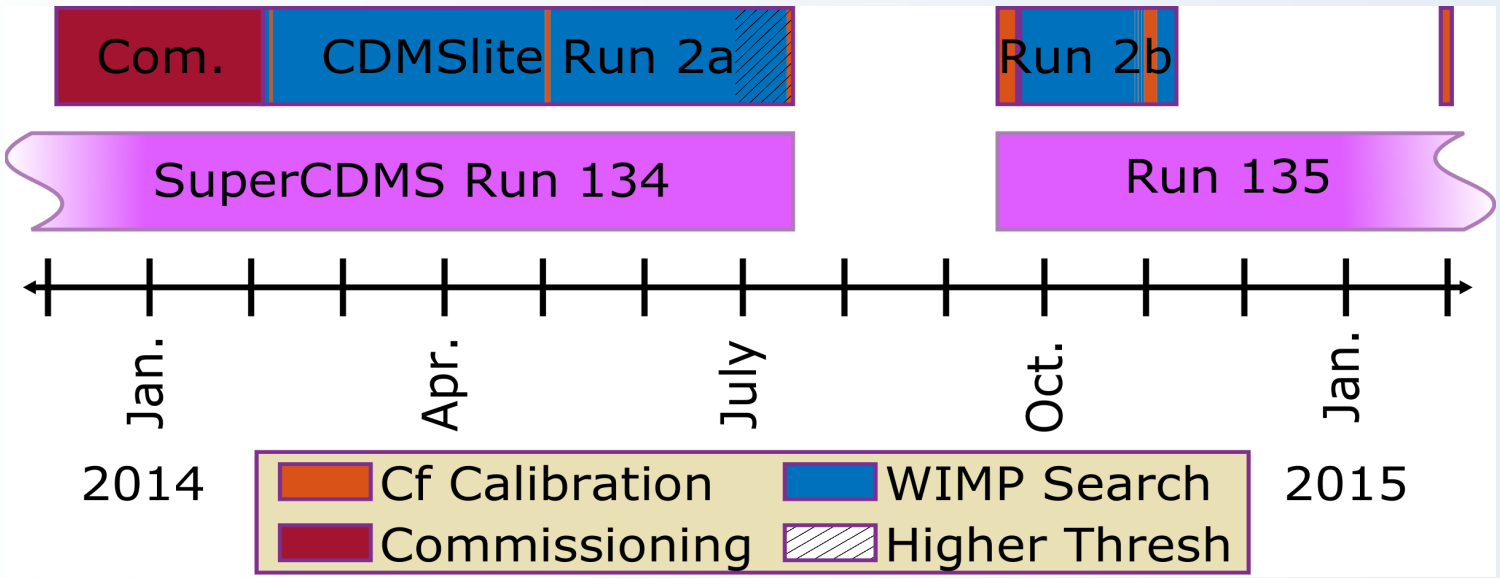




Convert to nuclear recoil equivalent energy using Lindhard model

- $Y(E_{nr}) = \frac{k\, g(\varepsilon)}{1+k\, g(\varepsilon)}$
- For Ge, $k = 0.157$

CDMSlite Run 2



Operational Improvements

10 times more exposure!

Detector pre-biasing (10 min @ 80 V)

Install vibration sensors on cryocooler

Mitigate transient detector leakage current

Seal and "de-humidify" HV distribution board

Analysis Improvements

Better energy calibration

Correct for base temperature variation

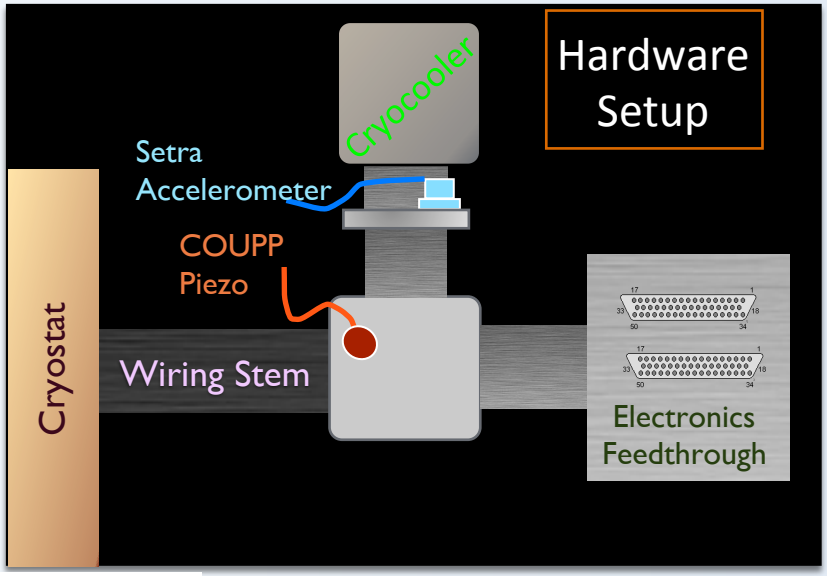
Better low freq. noise rejection

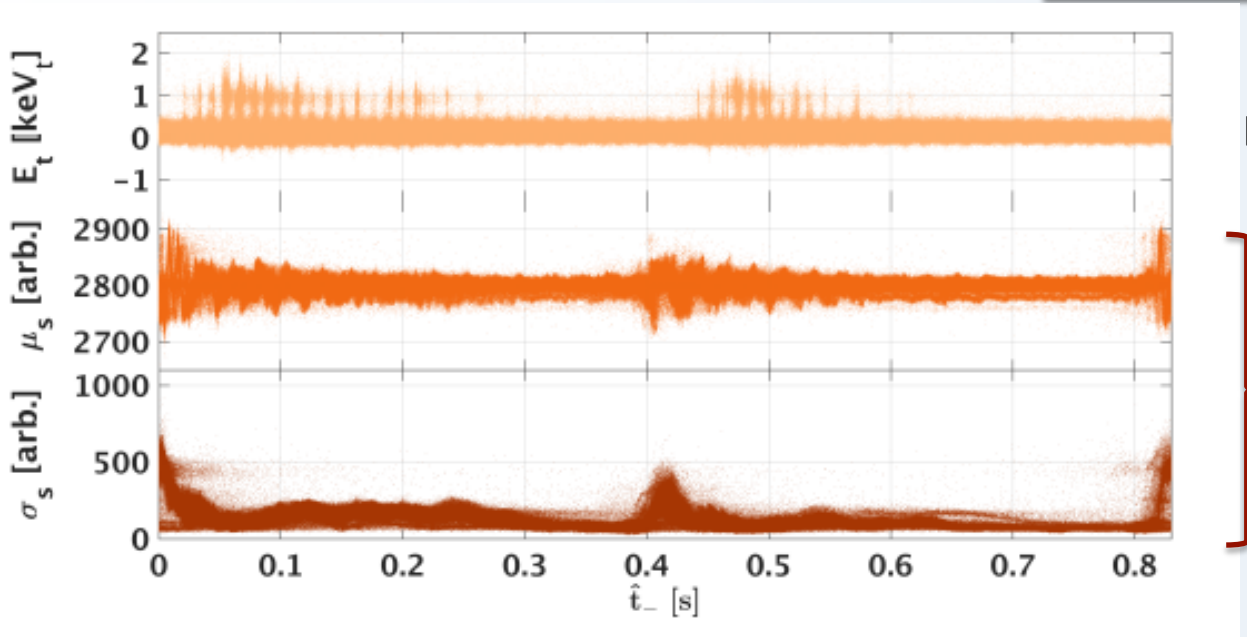
➔ lower threshold

New radial fiducial volume cut

Low Frequency Noise monitoring

- Sensors installed on cryocooler
  signals filtered, digitized, and time-stamped
- Sensor data and derived triggers recorded in the
  experimental data stream (evt by evt)
- Discovered clear LF noise correlation with the
  830 ms cryocoler cycle
  and a secondary mid-cycle thump



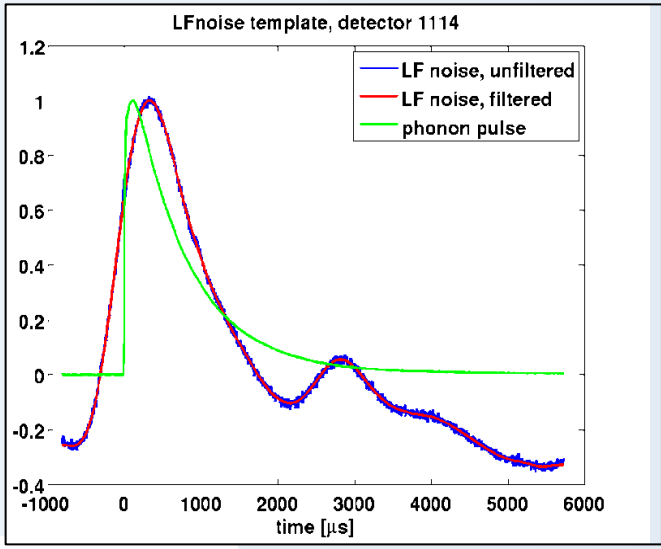


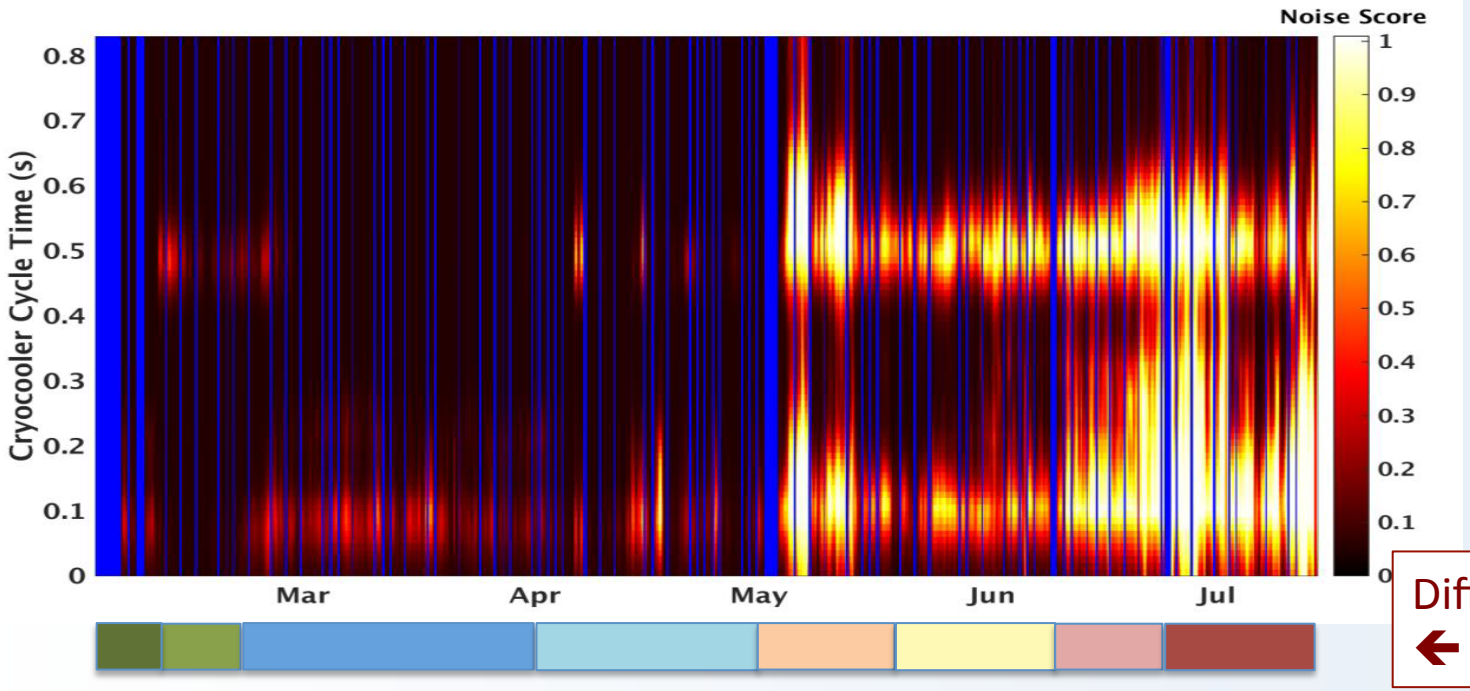
Low energy phonon pulses

Mean and std of ADC from digitized Setra trace

Low Frequency Noise Pulse Shape Cut

- For each pulse, fit to a LF pulse template.
- Compare to a good pulse template fit by forming $\Delta\chi^2$
- Create a correlated noise score based on the sensor data
  Define time blocks with similar cryocooler noise
- Tailor the pulse shape cuts to each period





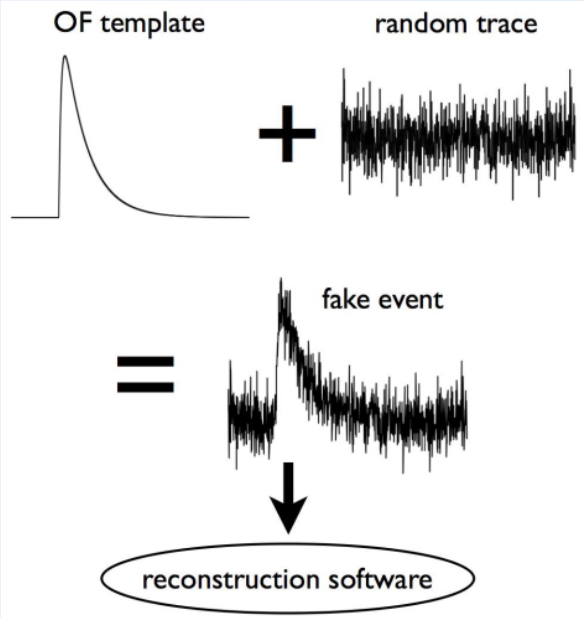
Different template
← time blocks

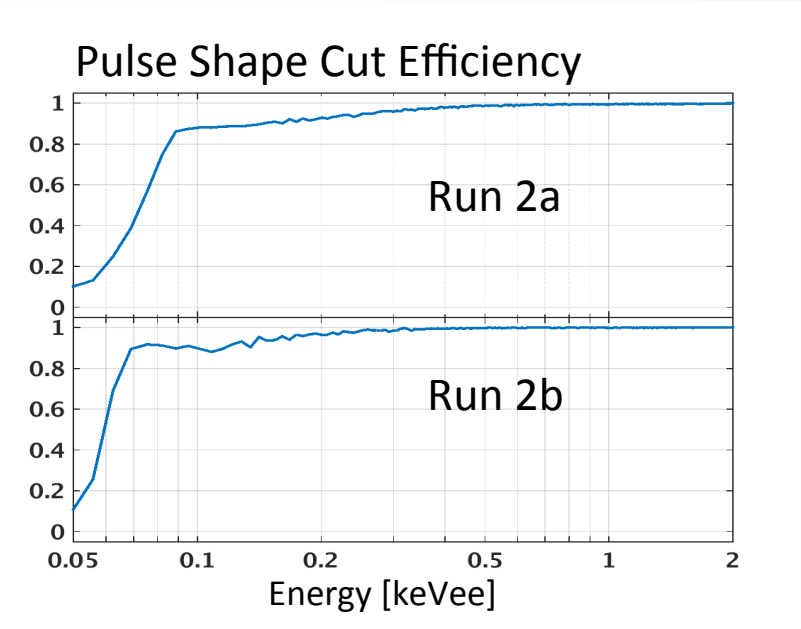
Pulse Shape Cut Efficiencies

- Measure efficiency via simulation:
  - Scale template pulse to low energy
  - Add real noise

    comes from randoms within and at end of run

    provides appropriate run-by-run noise environment
- Determine fraction that passes cuts





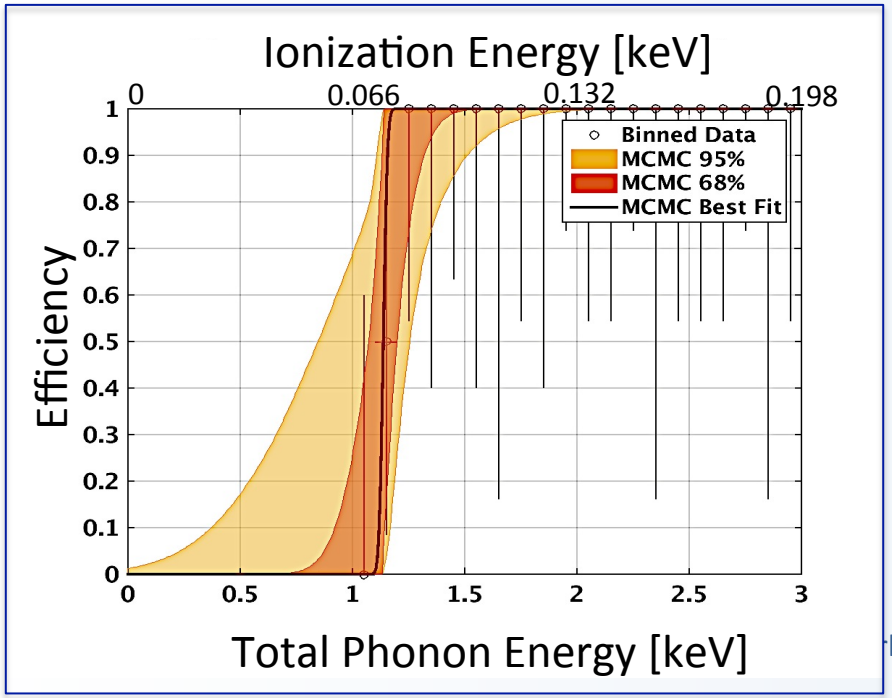
Low Frequency Noise monitoring – Run 2b

- Warm up and repair cryocooler, Ice box remains closed
- Vibration significantly reduced, lower hardware threshold.

Hardware threshold determination: Use multiple scattering evts from Cf calib
Find probability that CDMSlite detector triggered, given another detector did.
Fit to err function using Markov chain MC.

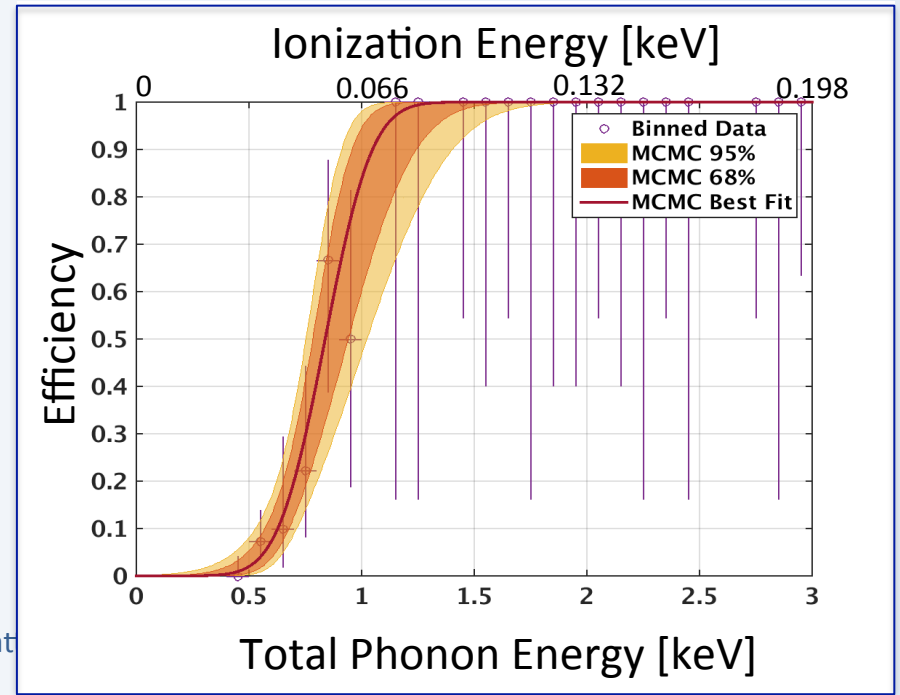
Run 2a (59.32 kg-d)

50% efficiency at $75 \pm^{4}_{5}$ eV_{ee}



Run 2b (10.78 kg-d)

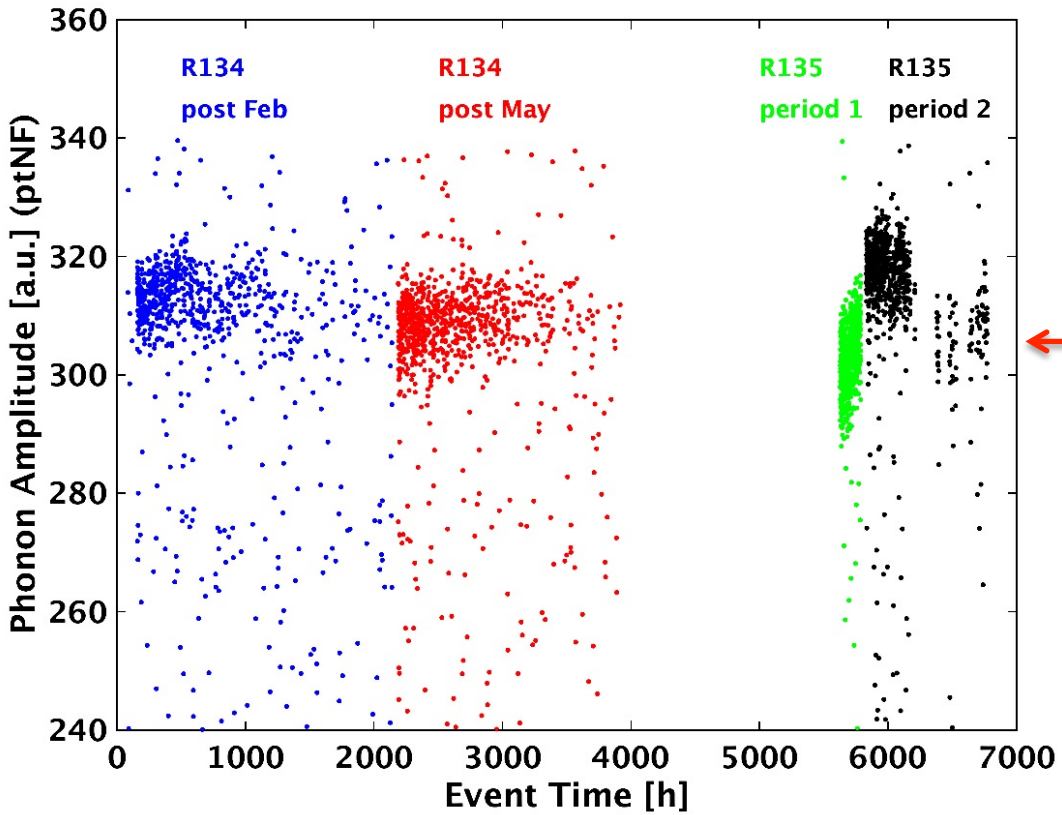
50% efficiency at $56 \pm^{6}_{4}$ eV_{ee}



Energy Scale Calibration

Use high-statistics K-shell to calibrate energy scale

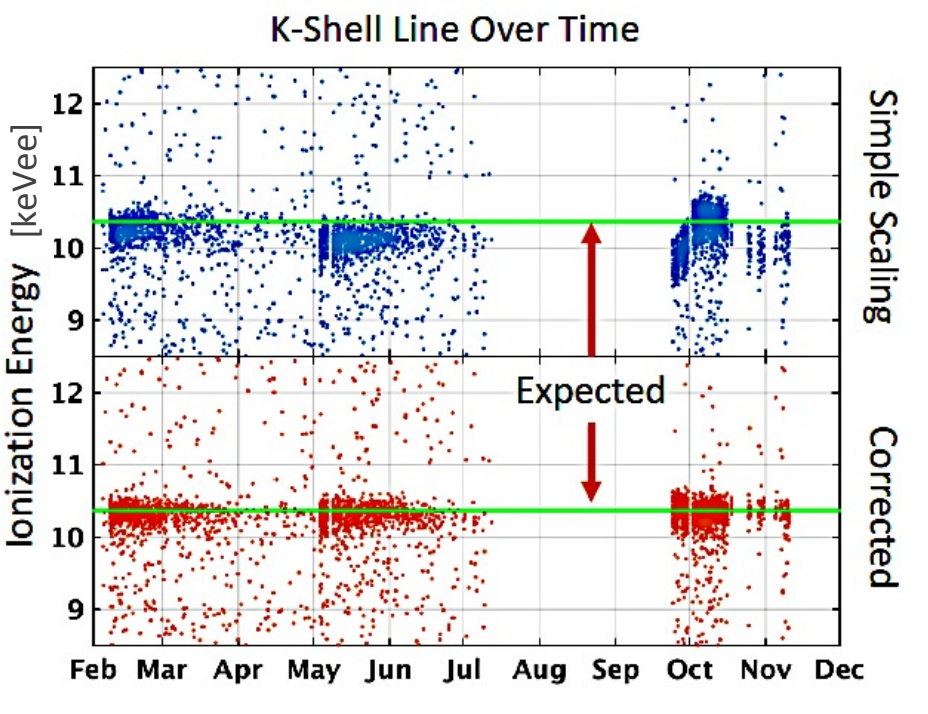
^{252}Cf neutron source
n-capture ➔ ^{71}Ge
e-capture decay: K-shell 10.37 keV
L-shell 1.30 keV
M-shell 0.16 keV



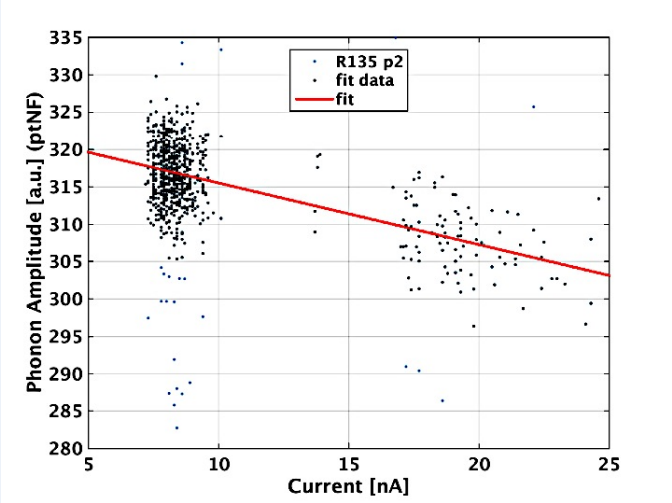
K-Shell

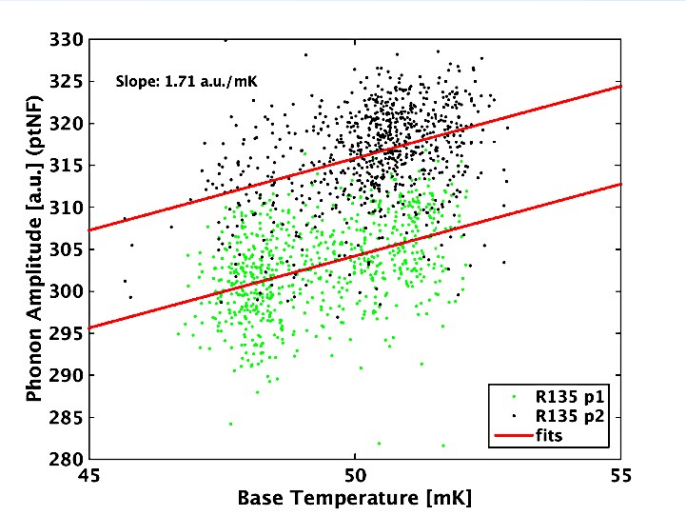
Energy Scale Calibration

- Clean and seal HV distribution board, operate under N_2
- Correct for changing parasitic resistance with new current readout
- Correct for change in base temperature
- Discrete period shifts, position dependence.



$$E_{tot}[keV_t] = E_r[keV_{ee}]\left(1 + g_L(V_b)\right)$$



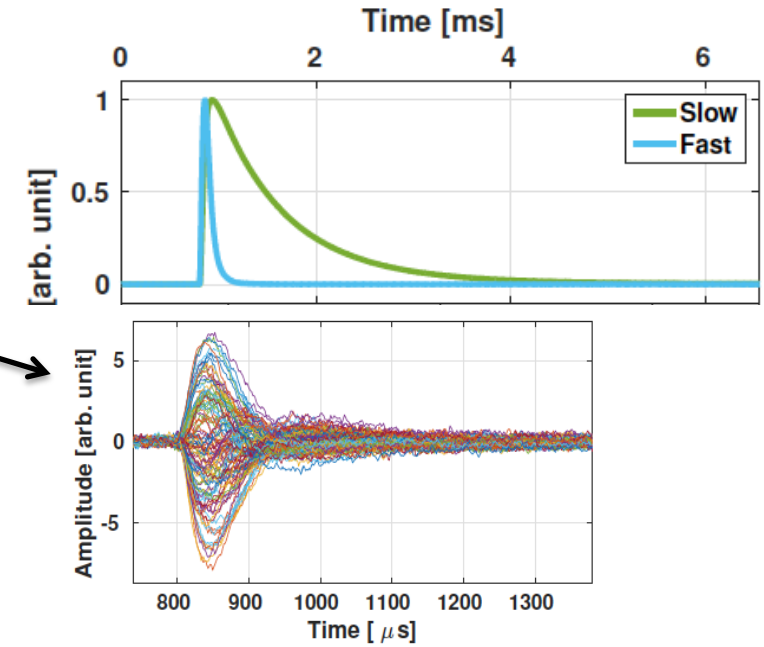


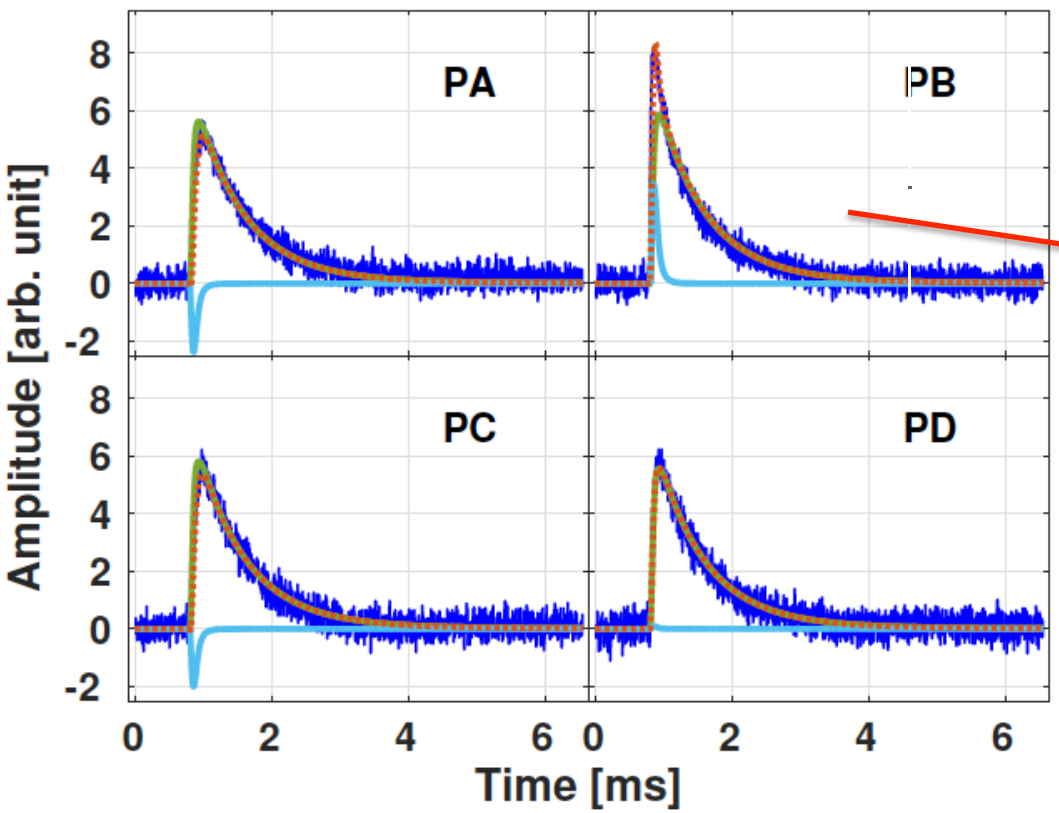
Two-Template Phonon Pulse Fitting

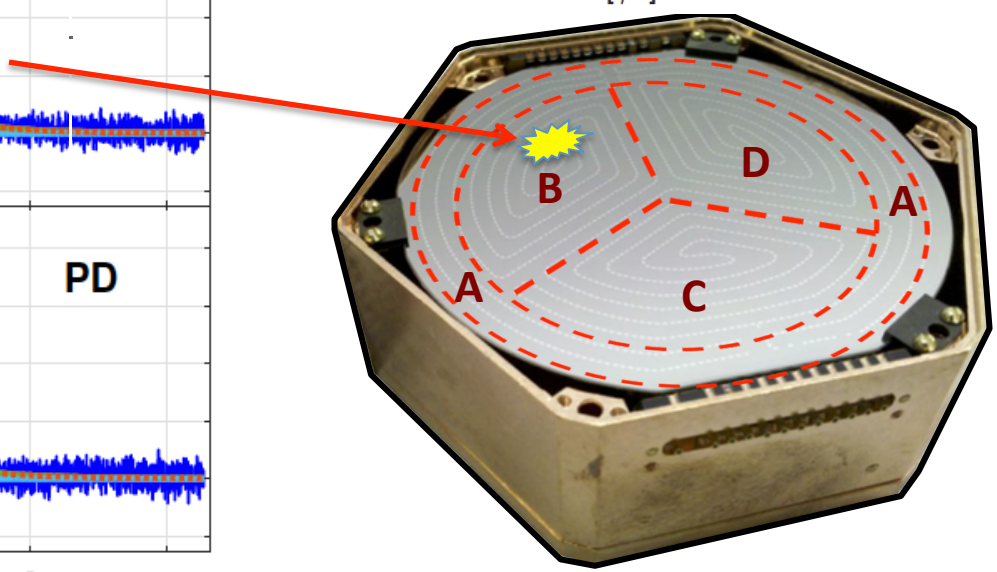
Initial absorption of phonons is localized.

Thus the fast component encodes for position

The fast template is formed from the residuals of the standard averaged template.



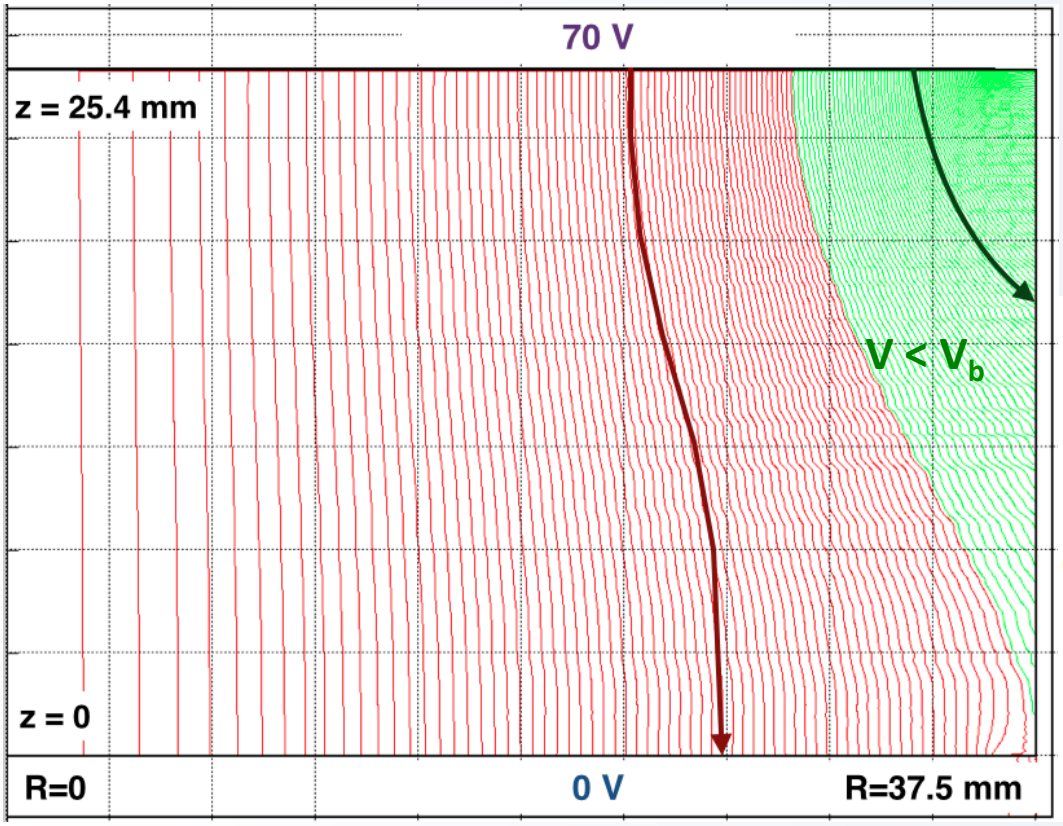




Poor E-field uniformity near the outer radius

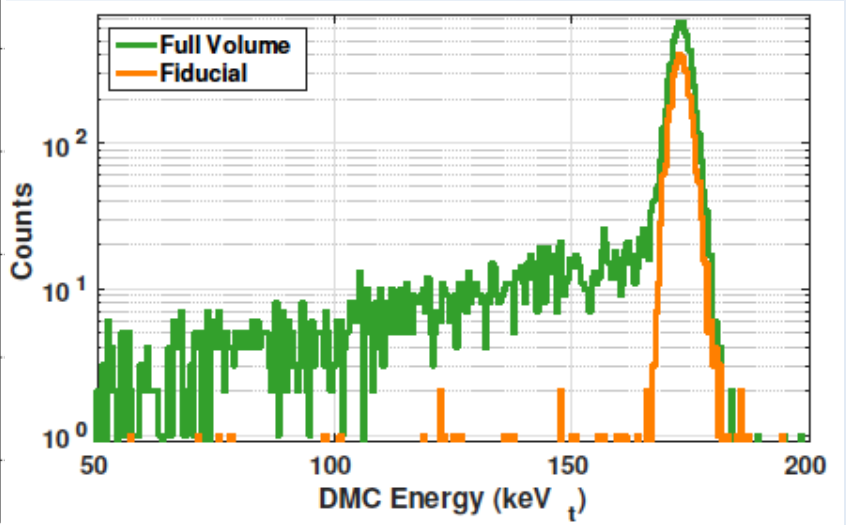
grounded sidewall and one-sided readout

e-h pairs created at large radii traverse $V < V_b$ ➔ reduced Luke Amplification



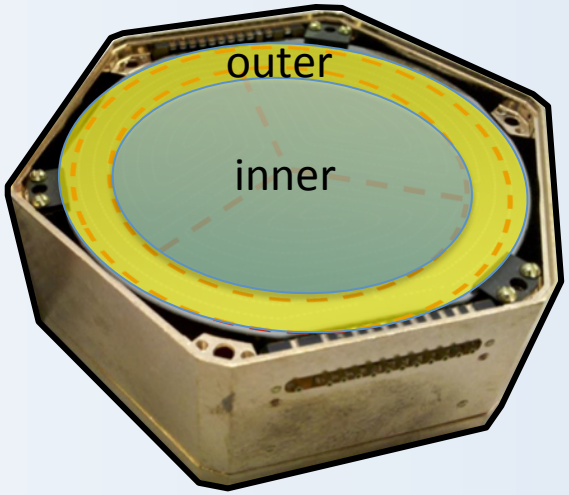
K-shell peak from Detector MC
Fiducial cut on the radial partition

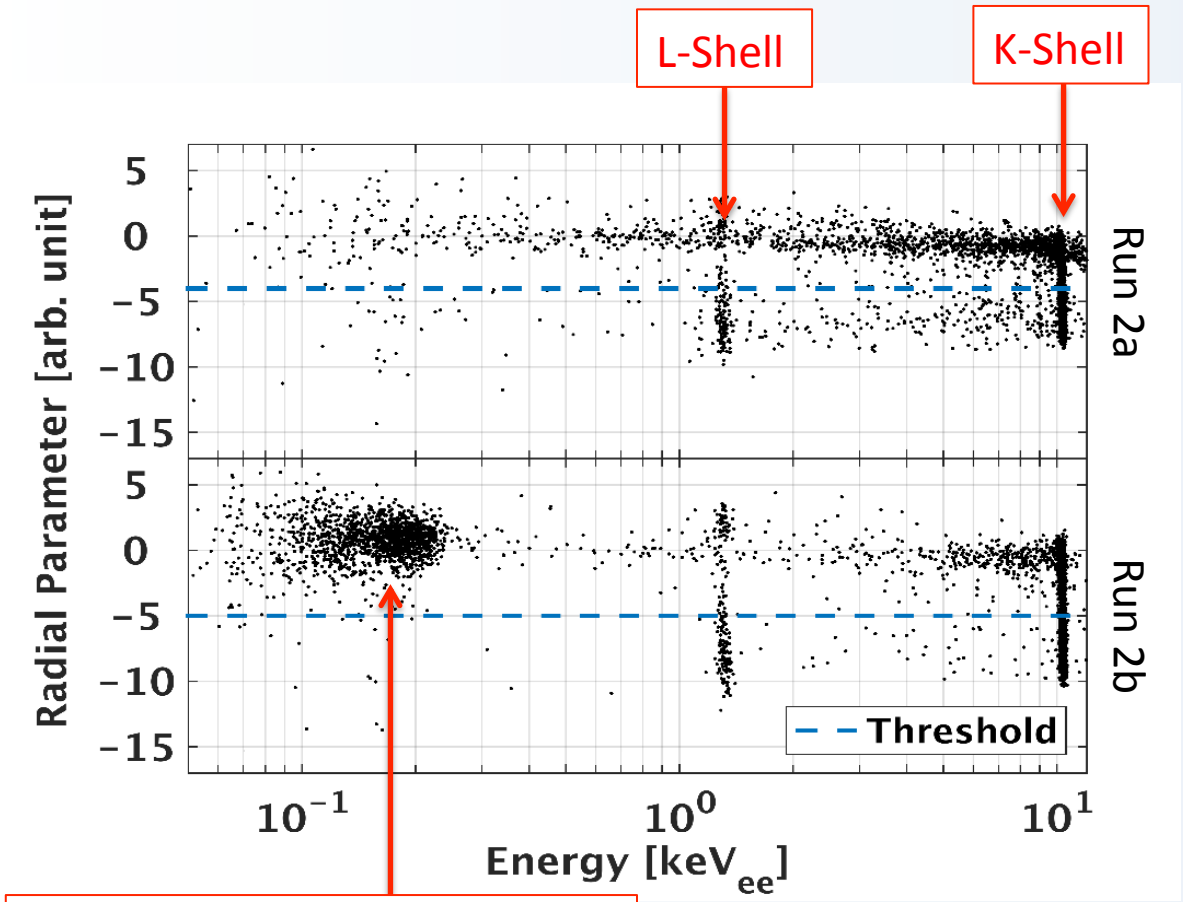
$$R = \frac{\text{Outer channel}}{\text{All channels}} < 0.2$$



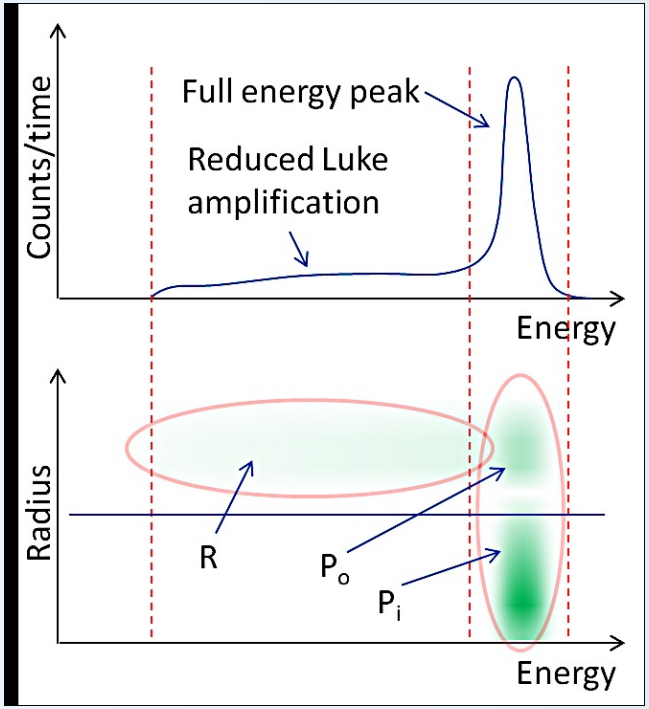
Fiducial Cut using 2-template fit

Use two-template fit to derive an empirical radial parameter from comparison of inner and outer channels.





Localized bkg near connector

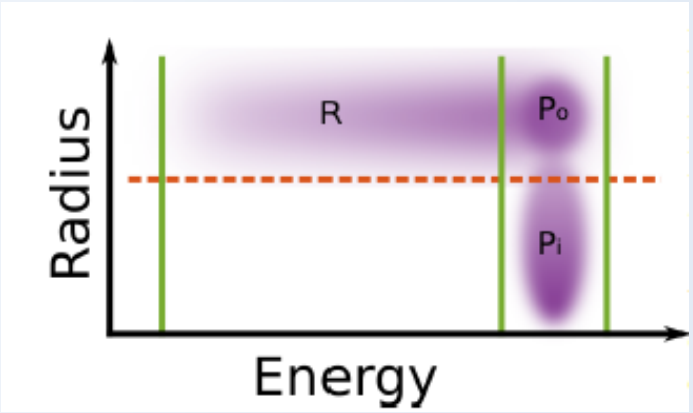


Efficiency of fiducial cut

$$\varepsilon = \frac{P_i}{R + P_i + P_o} = \frac{P}{R+P} \cdot \frac{P_i}{P} = \varepsilon_E \varepsilon_P$$

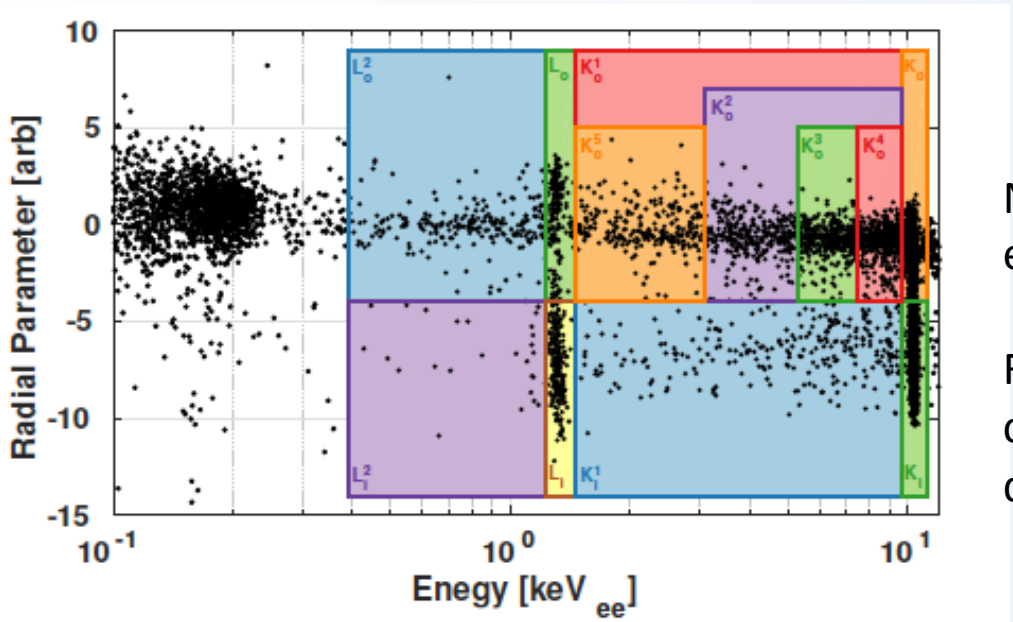
86% have full energy

55-60% peak evts pass radial cut



Measure efficiency at lower energy with energy-scaled pulse simulation

L-Shell pulse templates + noise



It's Complicated!

Needed to disentangle L and K shells from each other and from the Compton bkgd!

Fits to the exp. decay of lines after each Cf calibration, and relative strengths of K vs L determine shell strength in each bin

Efficiency of fiducial cut

$$\varepsilon = \frac{P_i}{R + P_i + P_o} = \frac{P}{R+P} \cdot \frac{P_i}{P} = \varepsilon_E \varepsilon_P$$

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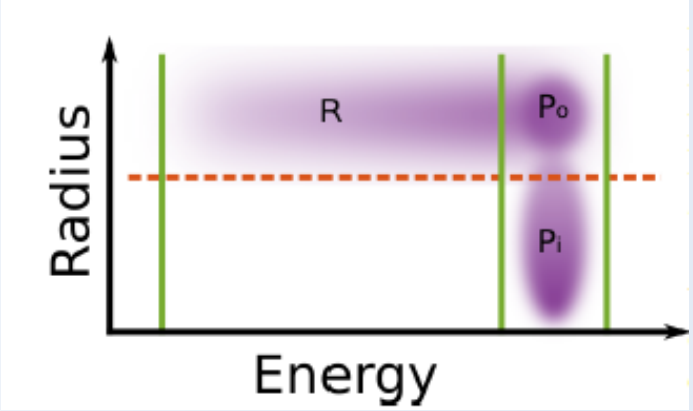

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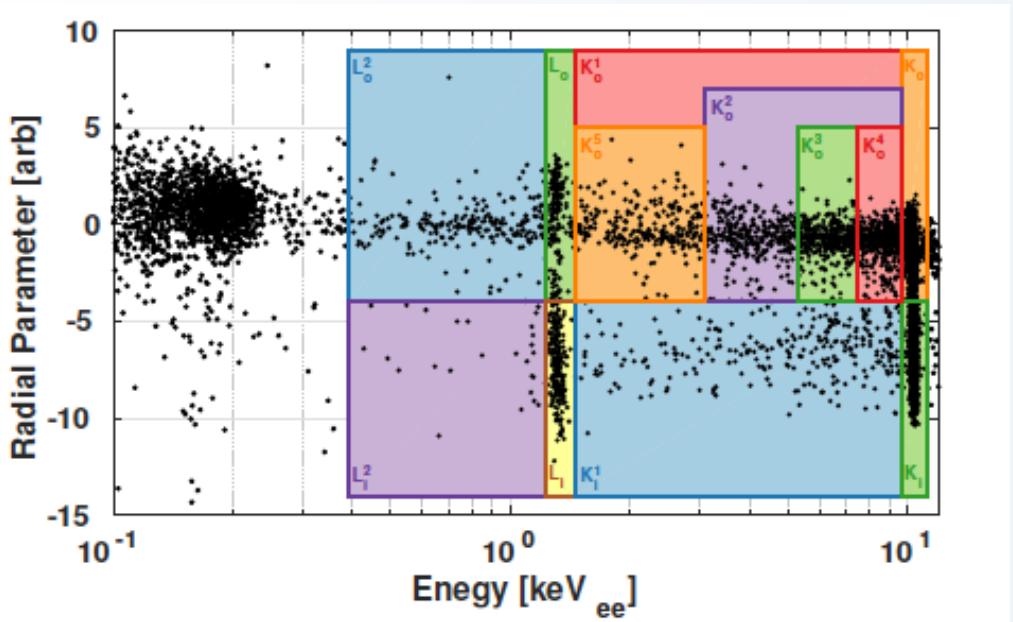
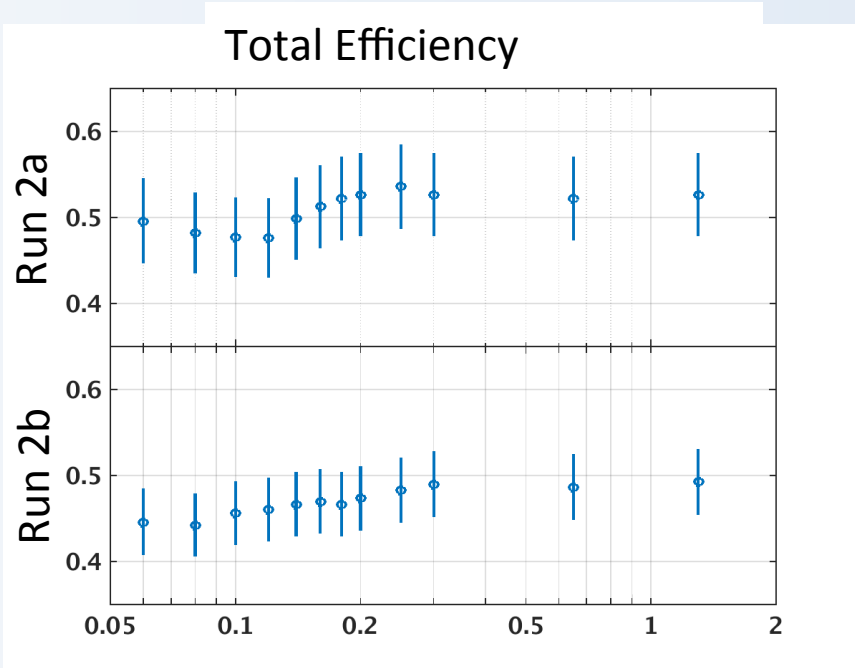
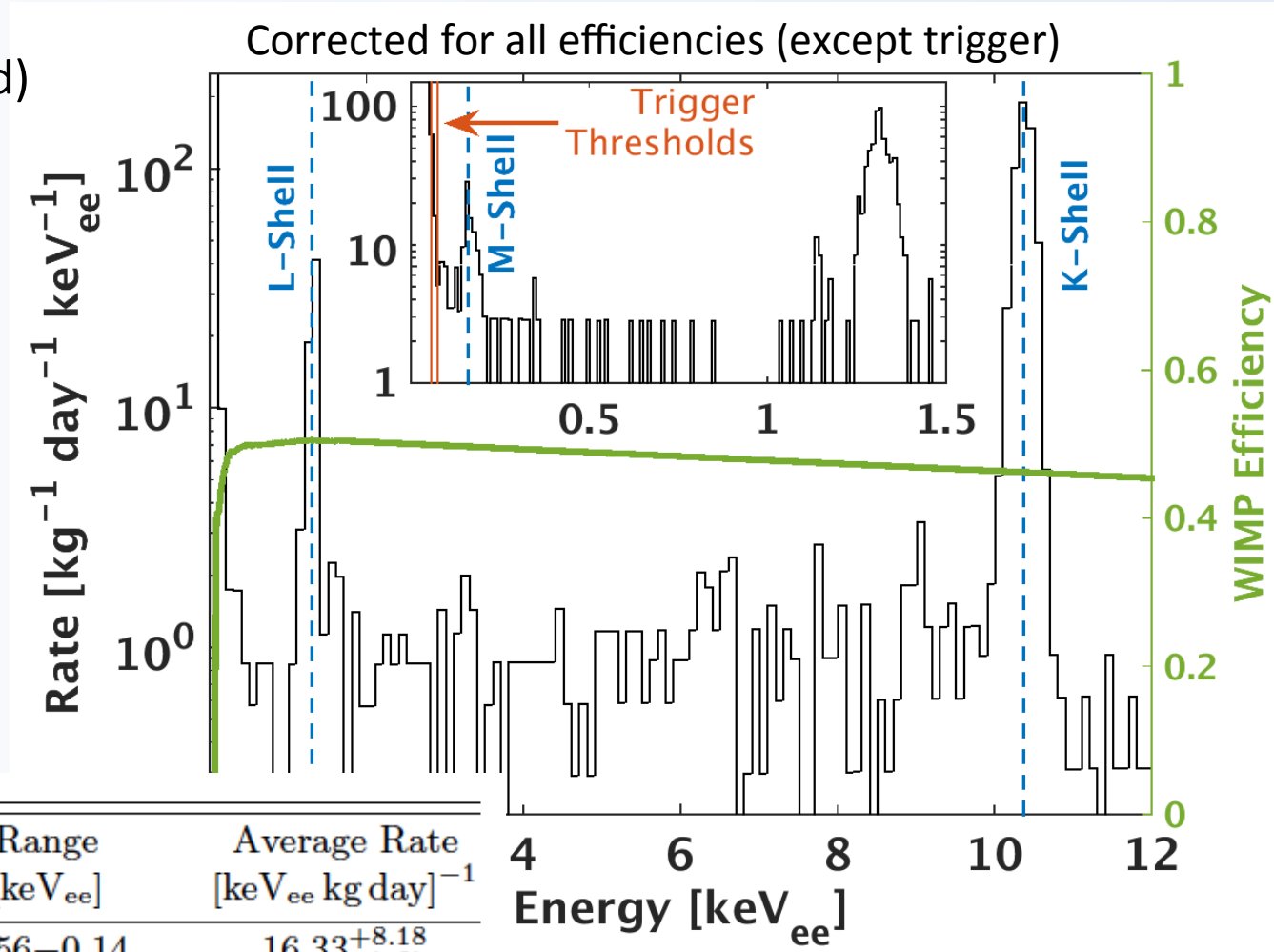




Run 2 Energy Spectrum

- Reached an energy threshold of 56 eV_{ee} for electron recoils
- Bkgd ~ 1 ct/(keV-kg-d) between K and L
- All three activation peaks can be seen

M: 0.16 keV
L: 1.30 keV
K: 10.37 keV



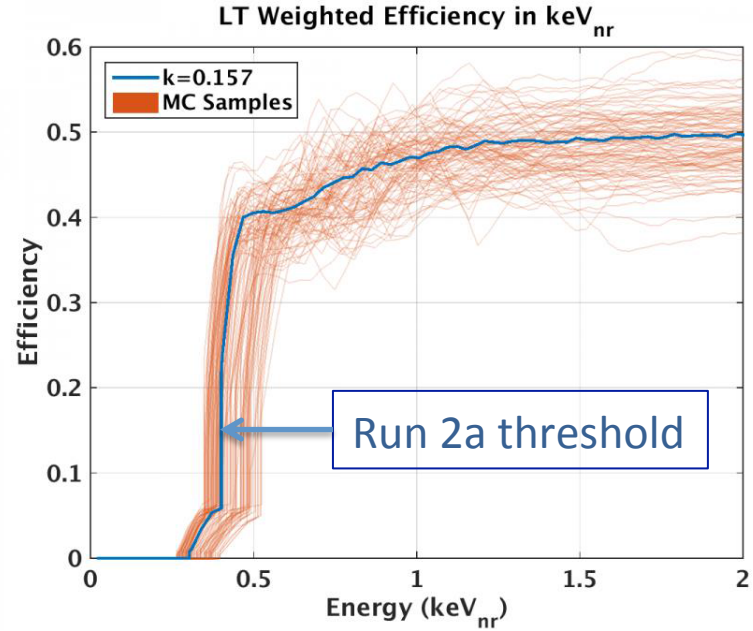
Energy [keV_{ee}]	Resolution [σ/μ, %]	Range [keV_{ee}]	Average Rate [keV_{ee} kg day]$^{-1}$
		0.056–0.14	$16.33^{+8.18}_{-7.97}$
0.16	11.4±2.8	0.2–1.2	1.09±0.18
1.30	2.36±0.15	1.4–10	1.00±0.06
10.37	0.974±0.009	11–20	0.30±0.03

Setting the Limit

Use Optimum Interval with no background subtraction

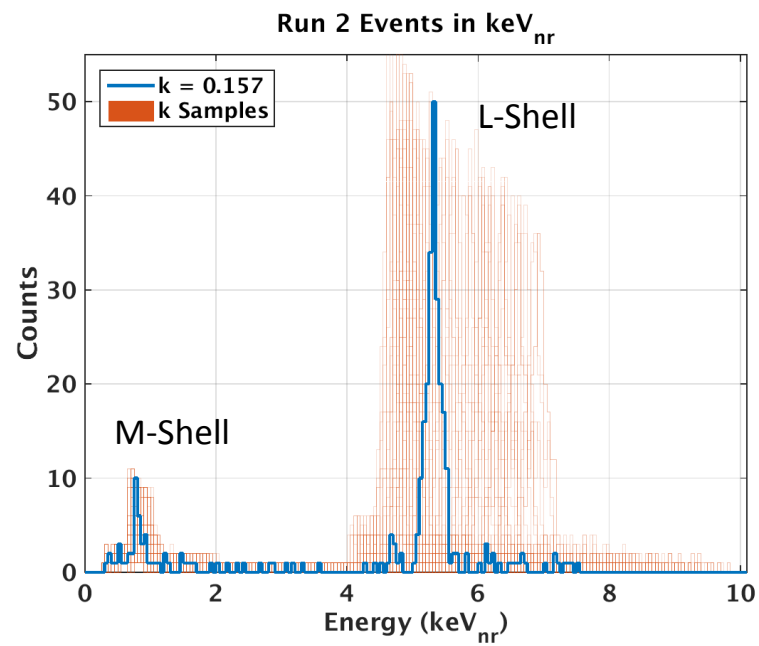
Convert to nuclear recoil equivalent energy using Lindhard Model

$$Y\left(E_{nr}\right) = \frac{kg(\varepsilon)}{1 + kg(\varepsilon)}$$

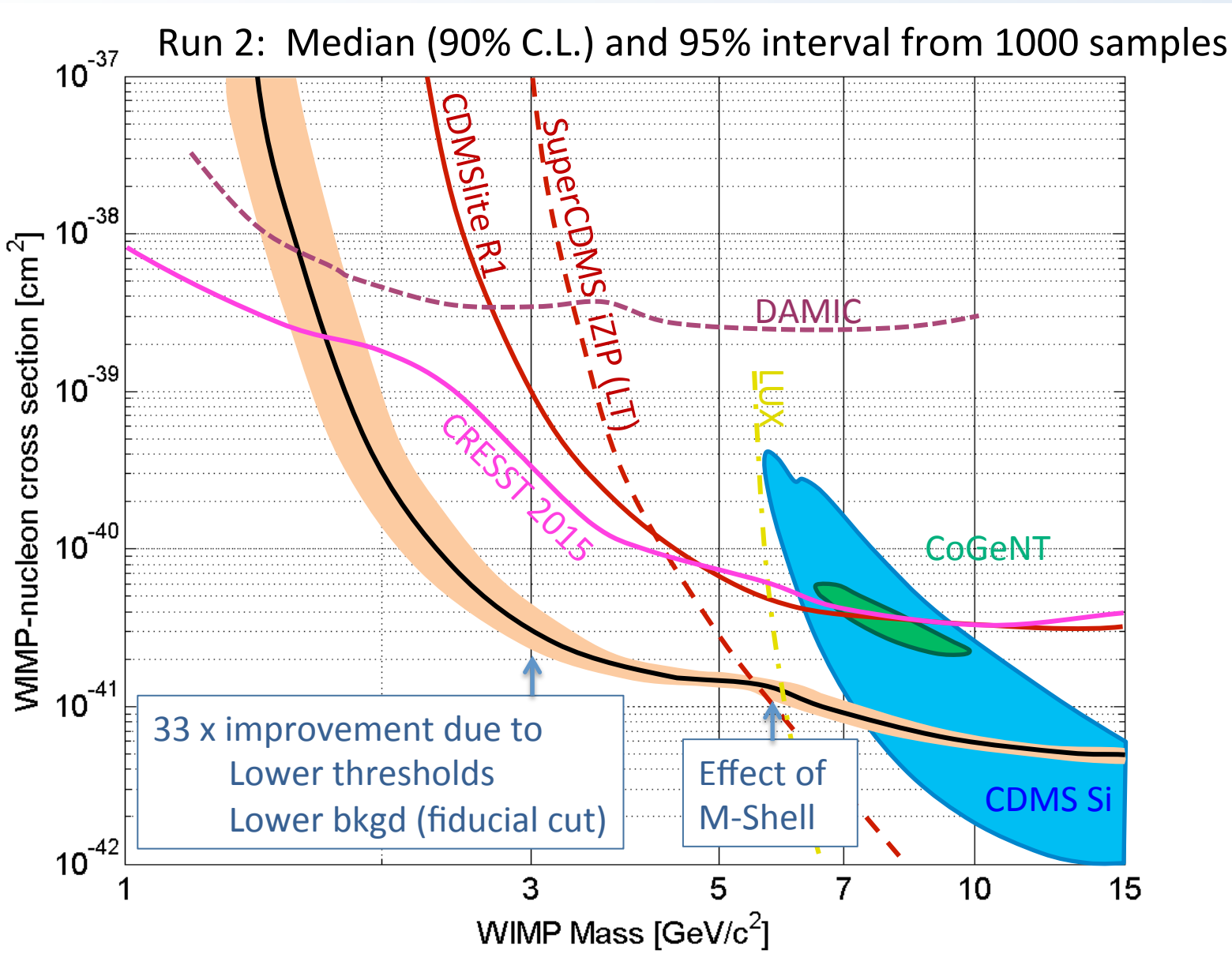


Redo 1000 times with input parameters drawn from the full uncertainty distributions.
The median is the final result
Uncertainty is given by distribution

Nuclear recoil model is also treated same way
k scanned from 0.1 ➔ 0.2



CDMSlite Limit Curve



Published Wednesday: R. Agnese et al. (SuperCDMS Collaboration) Phys. Rev. Lett. **116**, 071301

CDMSlite Run 3

The Run

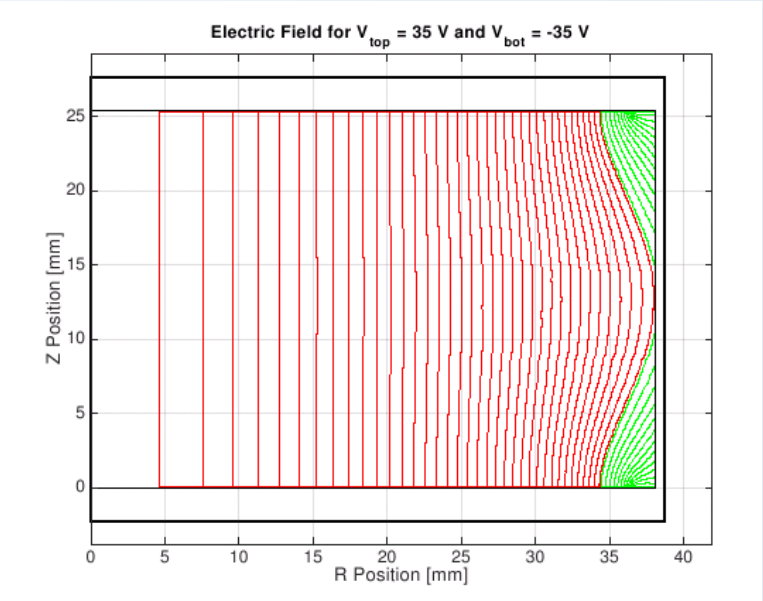
- Different detector: 75 Volts across T2Z1
- Potentially lowest threshold yet
  - *Lower hardware threshold*
  - *Lower LF noise*
- But not larger exposure. (40 kg-d)

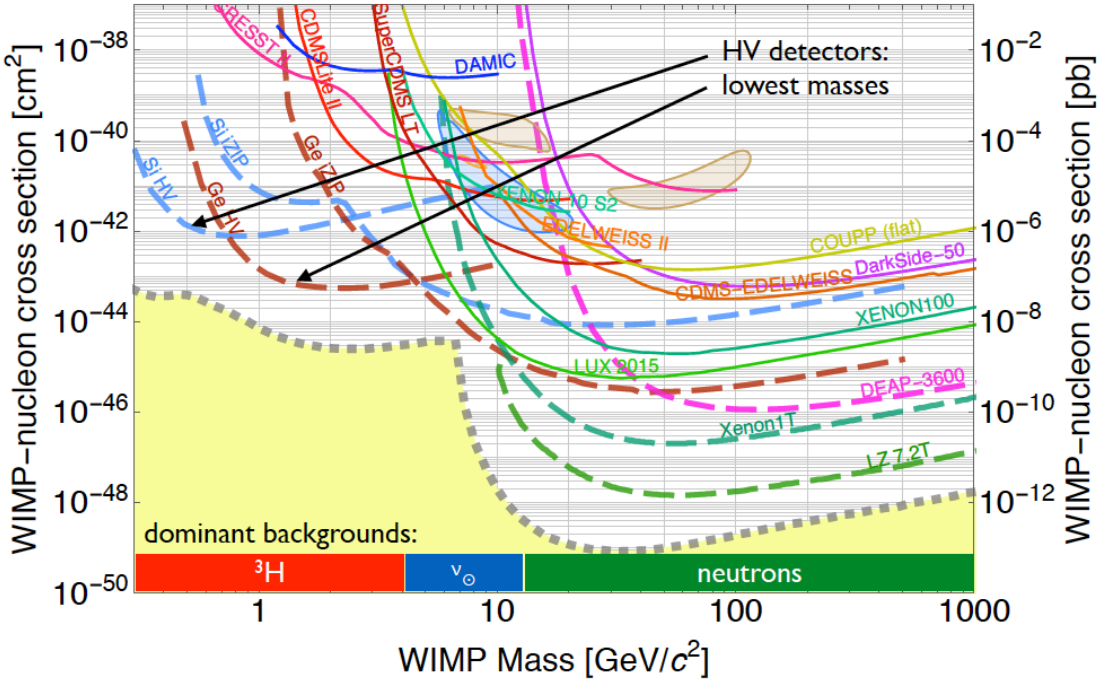
Tasks

- Develop low-energy background modeling
  - *GEANT4 physics processes (e.g. Comptons, Monash Model, tritium)*
  - *Detector MC (E-field, radial cuts, phonon physics)*
- Understand Luke Gain scaling. Study bias scans, fold in test facility data
- Improve the 2-template fit and radial parameter
- Apply "salting" technique for unbiased analysis (Practice with the Run 2 data)
- Prepare analysis techniques for SNOLAB

SNOLAB HV Detectors (see Sunil's talk)

- Improvements for SuperCDMS SNOLAB include:
  - larger detectors
  - improved phonon sensors
  - double sided readout
  - increased HV and improved resolution
  - thresholds in the eV_{ee} range

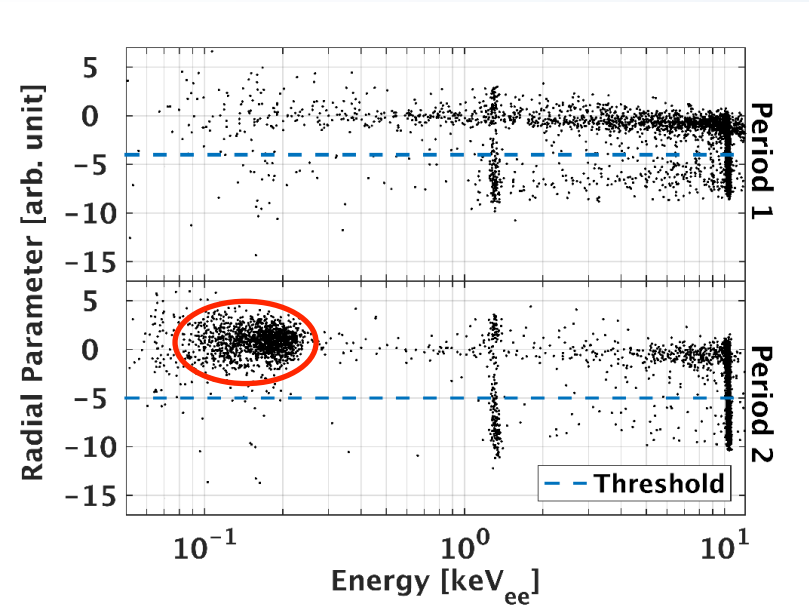


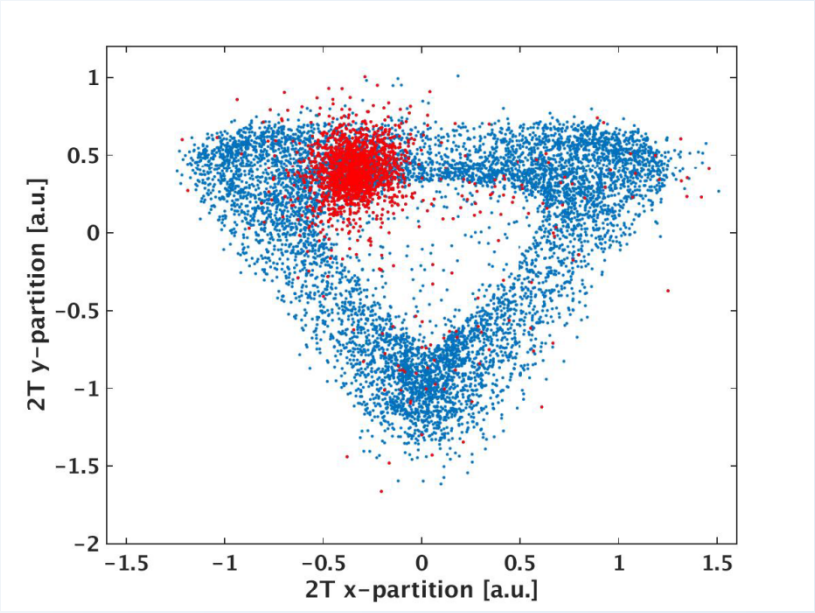


Backup Slides

Mystery Spot

- A localized background which appeared in Run 2b at low energy
- Possibly connected to electrical anomalies near the DIBs
  similar effects observed in the past
- Mostly removed by fiducial volume cut
- Currently doing forensics on detector





$\Delta\chi^2 = \chi^2(OF) - \chi^2(LF)$