University of Minnesota

Results from the Cryogenic Dark Matter Search experiment

Oleg Kamaev
University of Minnesota
for the CDMS Collaboration

2009 Meeting of the Division of Particles and Fields of the American Physical Society

July 26-31, Detroit, MI

UNIVERSITY OF MINNESOTA

CDMS-II Collaboration

Caltech
Z. Ahmed, J. Filippini, S. R. Golwala, D. Moore, R.W. Ogburn

Case Western Reserve University
D. S. Akerib, K. Clark, C. N. Bailey, D. R. Grant, R. Hennings-Yeomans, M.R. Dragowsky

Fermilab
D. A. Bauer, F. DeJongh J. Hall, L. Hsu, D. Holmgren, E. Ramberg, J. Yoo

MIT
E. Figueroa-Feliciano, S. Hertel, S. Leman, K. McCarthy

NIST
K. Irwin

Queens University
W. Rau

Santa Clara University
B. A. Young

Stanford University
P.L. Brink, B. Cabrera, J. Cooley, M. Pyle, S. Yellin

Syracuse University
R.W. Schnee, M. Kos, J. M. Kiveni

Texas A&M
R. Mahapatra

University of California, Berkeley
M. Daal,, N. Mirabolfathi, B. Sadoulet, D. Seitz, B. Serfass, D. Seitz, K. Sundqvist

University of California, Santa Barbara
R. Bunker, D. O. Caldwell, H. Nelson, J. Sanders

University of Colorado at Denver
M. E. Huber

University of Florida
T. Saab, D. Balakishiyeva

University of Minnesota
P. Cushman, L. Dong, M. Fritts, V. Mandic, X. Qiu, O. Kamaev, A. Reisetter

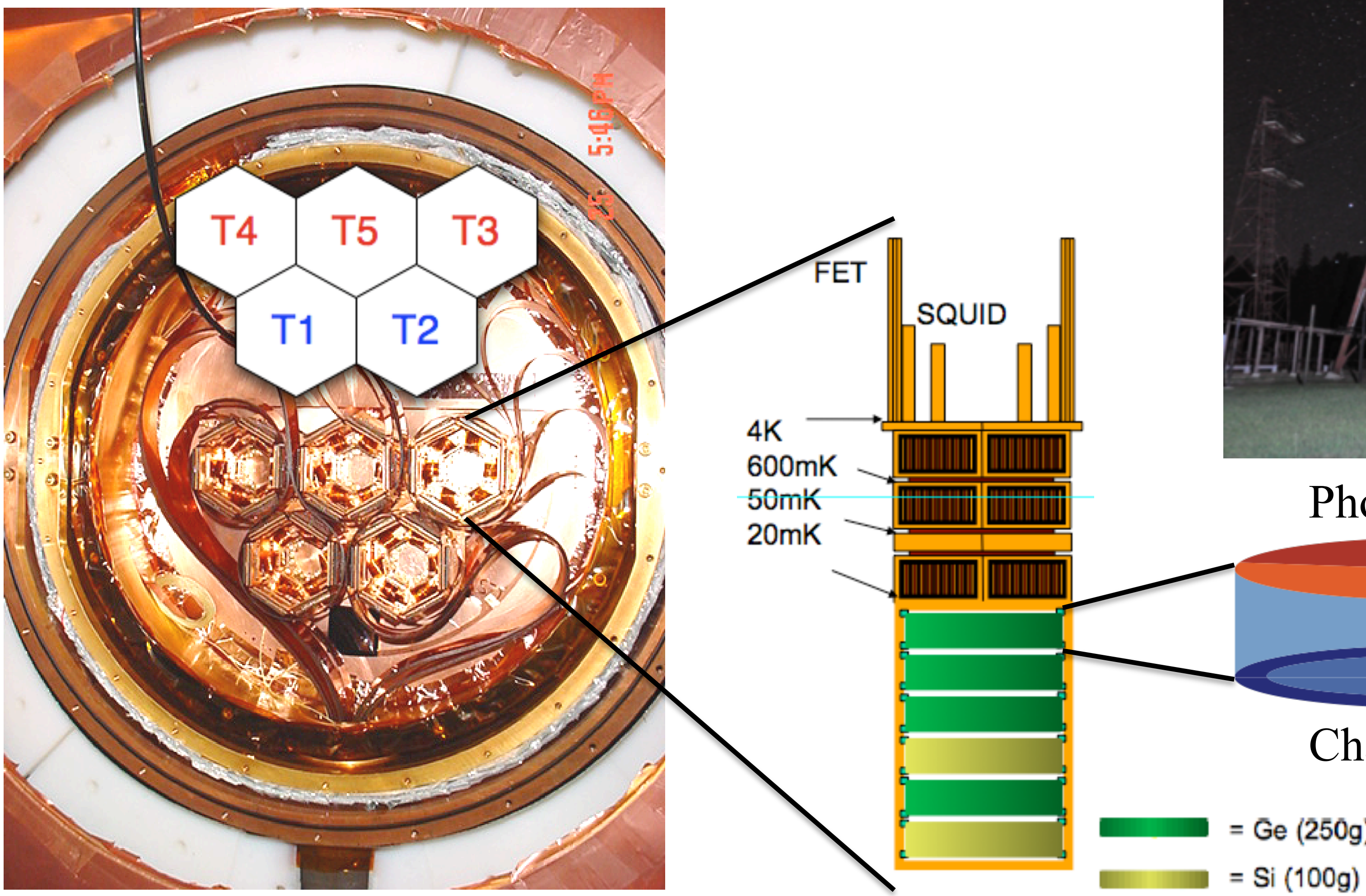
University of Zurich
S. Arrenberg, T. Bruch, L. Baudis, M. Tarka

CDMS Experiment

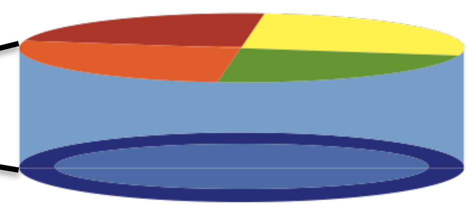
- Located at Soudan Undeground Lab at 2090 m.w.e. depth;

CDMS Experiment

- Located at Soudan Undeground Lab at 2090 m.w.e. depth;
- 5 Towers of 6 detectors (Ge/Si) operated at ~40 mK;



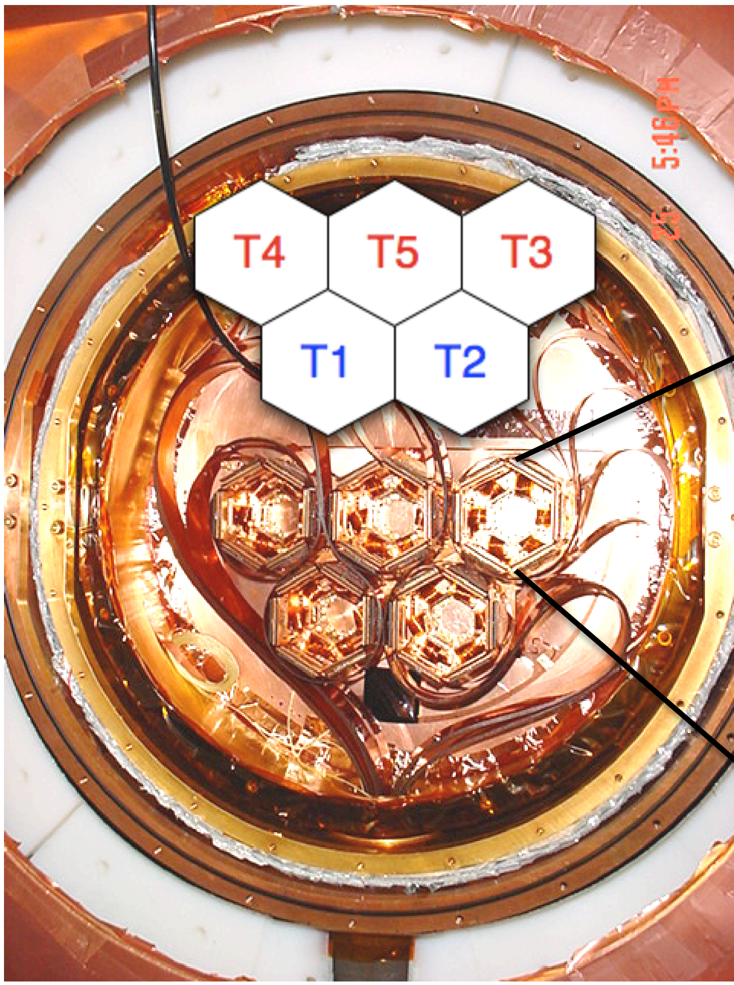
Phonon side

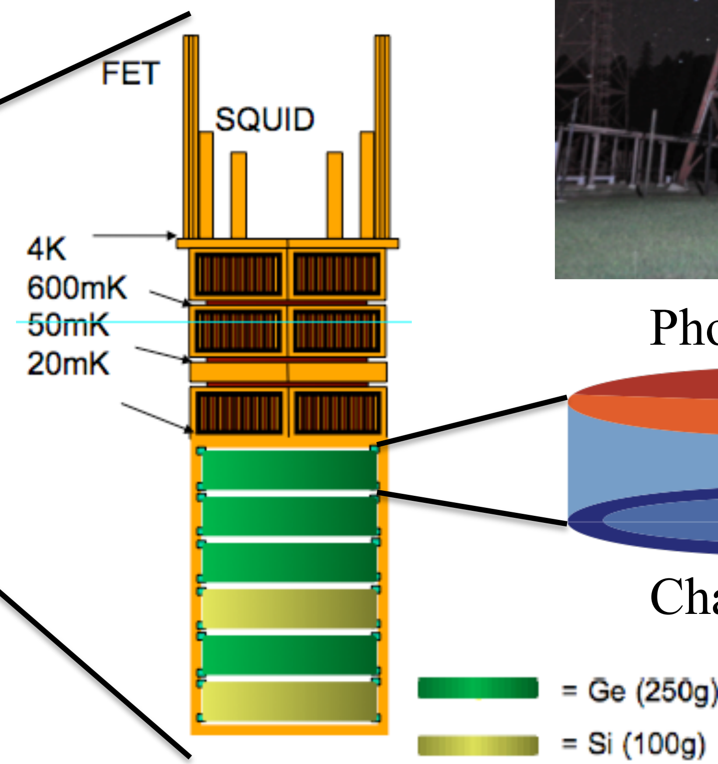


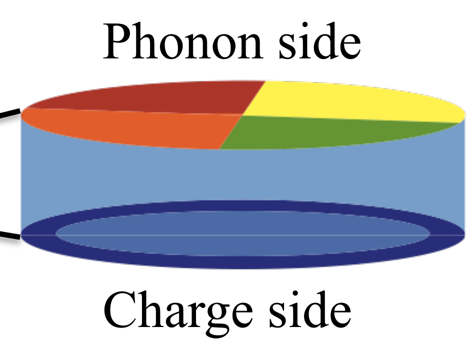
Charge side

CDMS Experiment

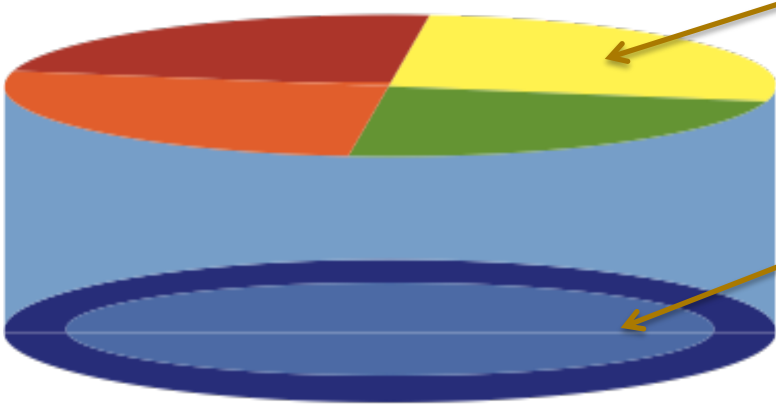
- Located at Soudan Undeground Lab at 2090 m.w.e. depth;
- 5 Towers of 6 detectors (Ge/Si) operated at ~40 mK;
- Active/passive shielding against muons and environmental radioactivity.





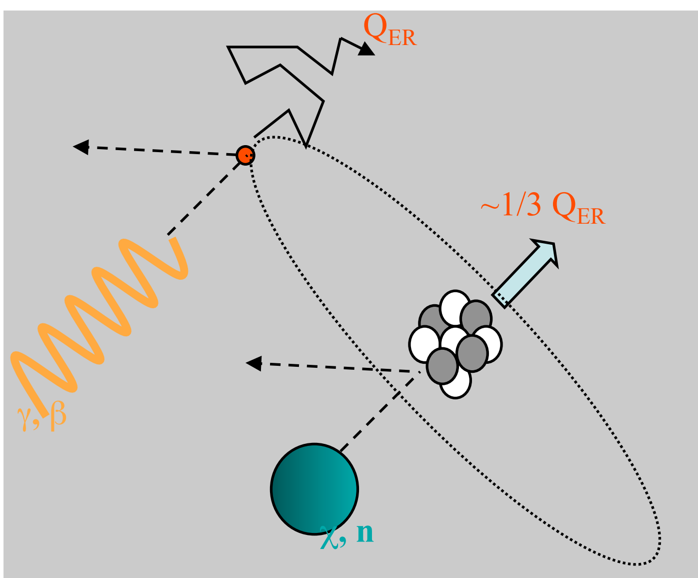


Z-sensitive Ionization Phonon Detector (ZIP)

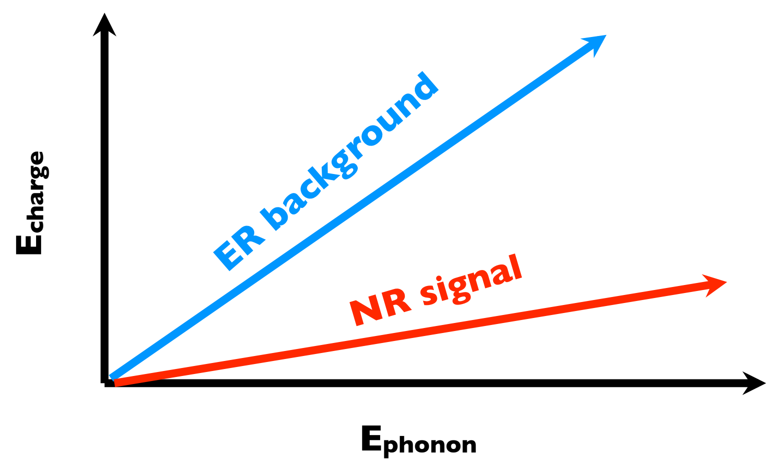


Phonon side:
- 4 quadrants of phonon sensors
- provide phonon energy and position info

Charge side:
- 2 concentric electrodes (inner and outer)
- provide ionization energy and veto



Nuclear/ Electron recoil discrimination:

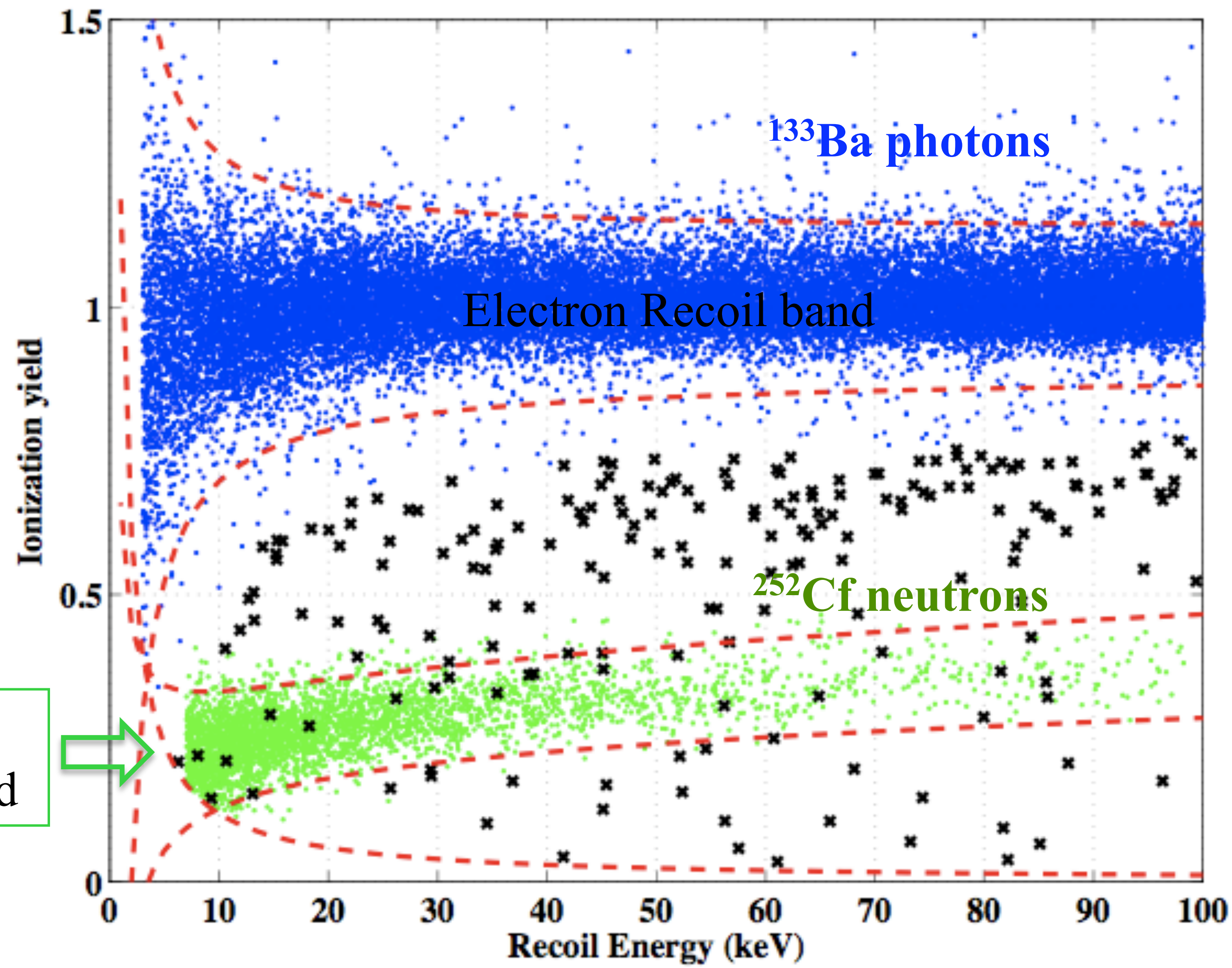


Signature of Nuclear Recoil: reduced ionization relative to phonon signal.

Yield Discrimination

Ionization Yield:

$$y = \frac{E_{charge}}{E_{phonon}}$$



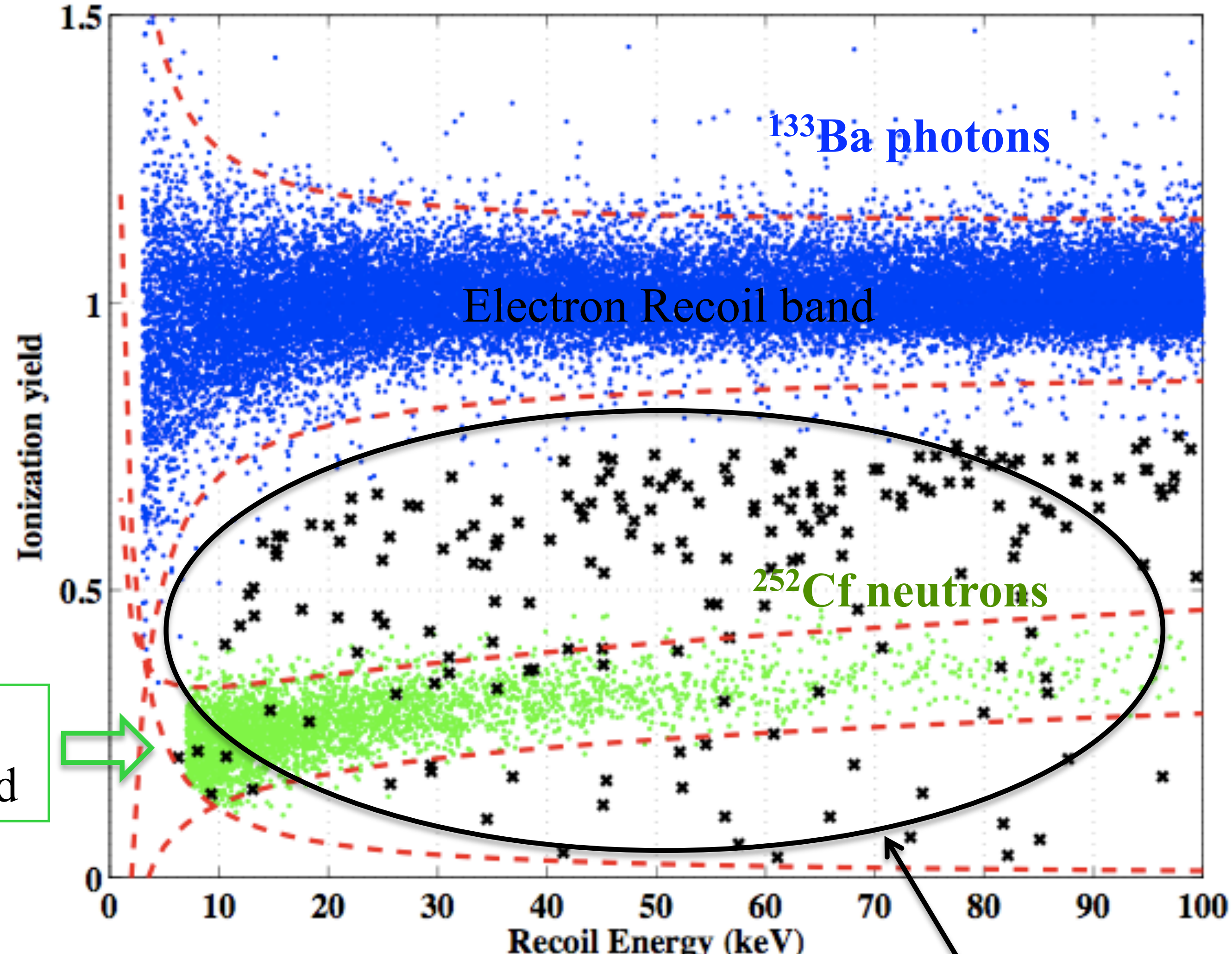
Signal region:
2σ Nuclear Recoil band

Primary electron recoil rejection >10,000:1

Yield Discrimination

Ionization Yield:

$$y = \frac{E_{charge}}{E_{phonon}}$$

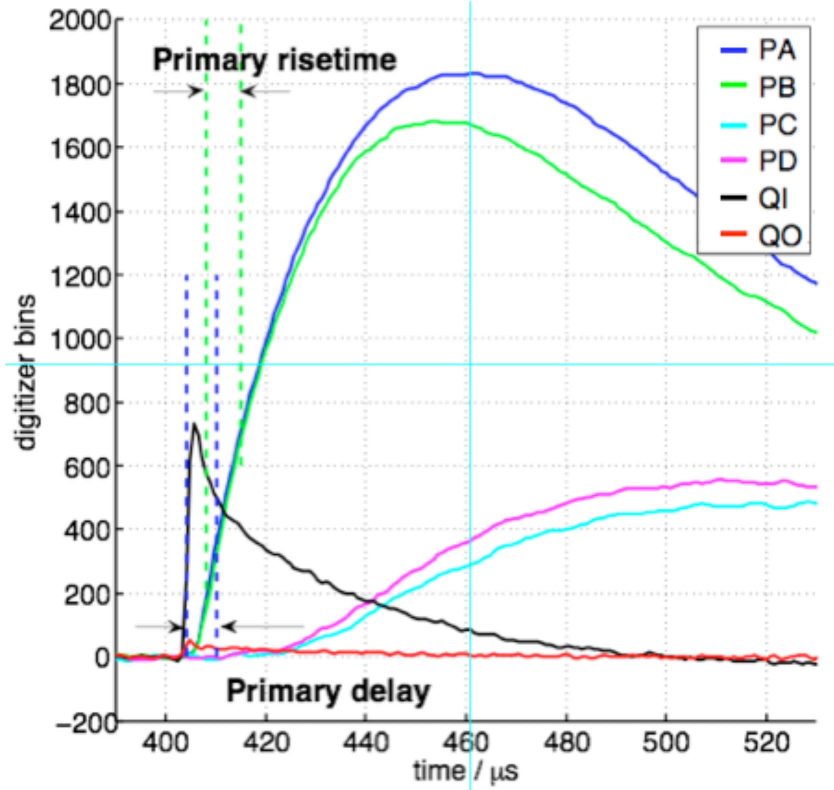


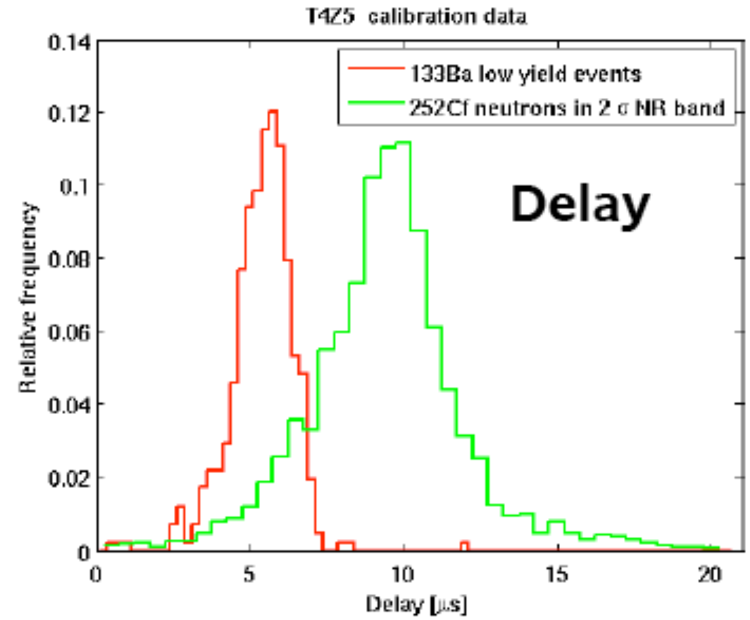
Signal region:
2σ Nuclear Recoil band

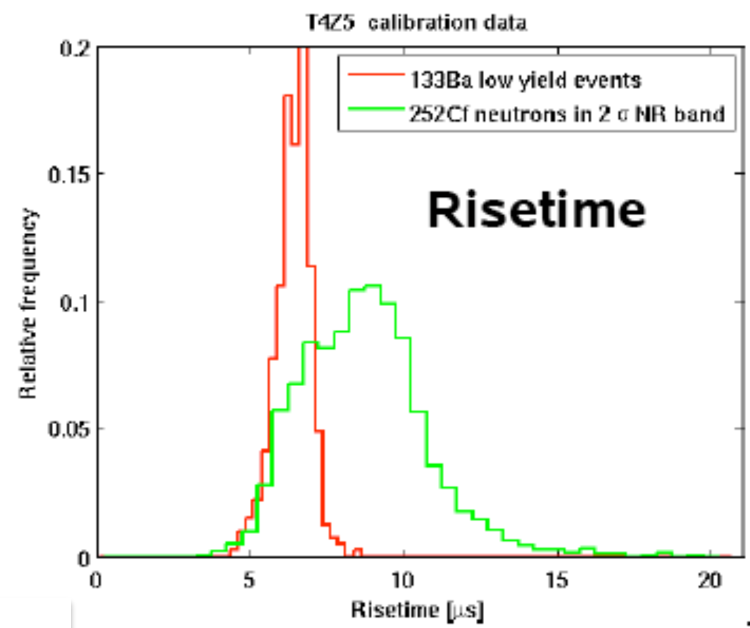
Low yield electron recoil surface events.

Primary electron recoil rejection >10,000:1

Surface Events Discrimination

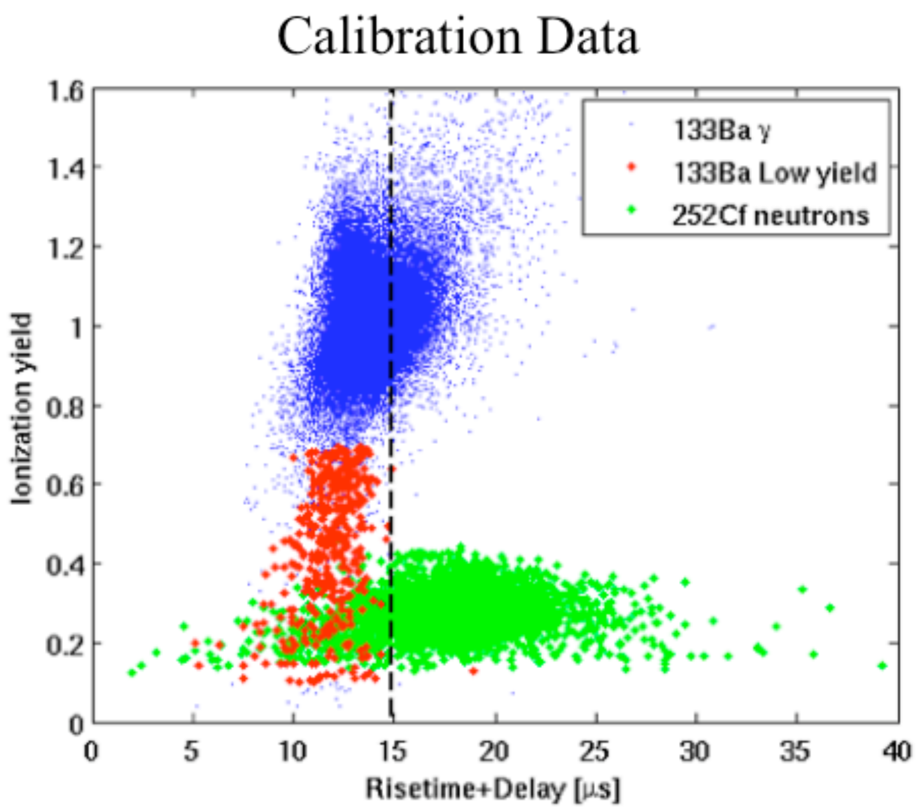


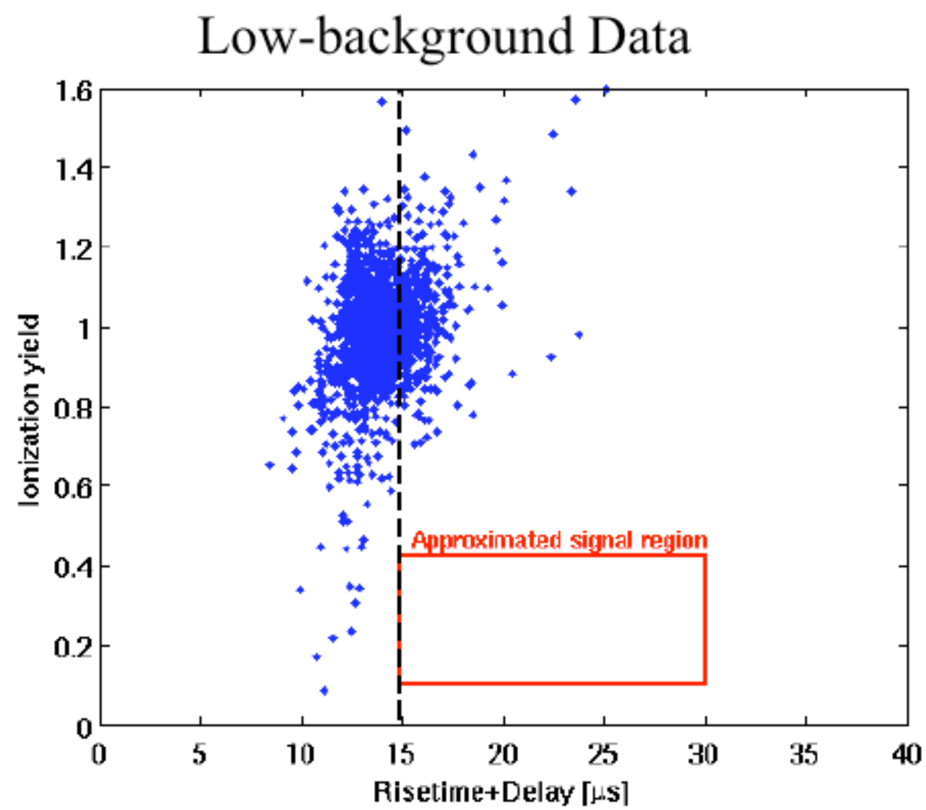




- Pulses from surface events can be distinguished from bulk NR event pulses;
- Timing is a powerful discriminator against surface events.

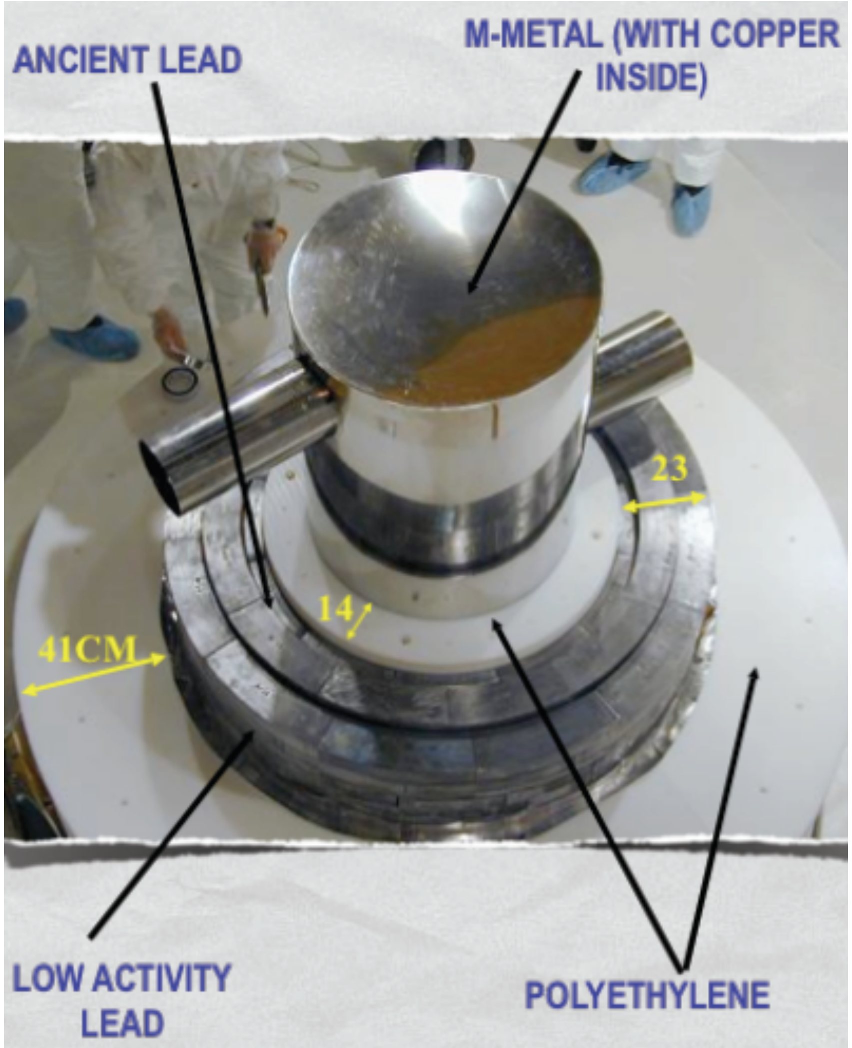
Surface Events Discrimination





- Yield & Timing reject surface event
- Surface event rejection from timing ~200:1
- Cut set to allow ~0.5 events total leakage to WIMP candidates

CDMS Shielding



Passive shielding:
- Pb: shielding from γ's
- Polyethylene: moderate neutrons from fission and from (α,n) interactions from U/Th decays
- Copper: shielding from γ's.

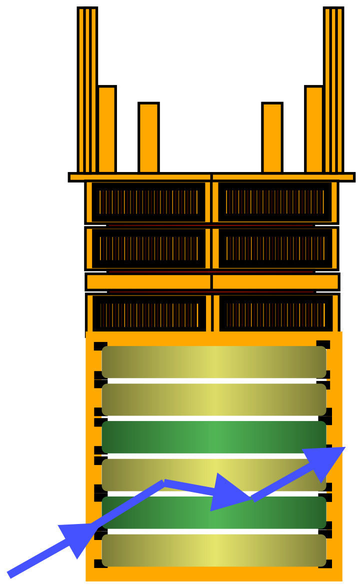
Active shielding:
- Muon veto to reject events from cosmic rays.

Event Selection

- Muon-veto anticoincident events

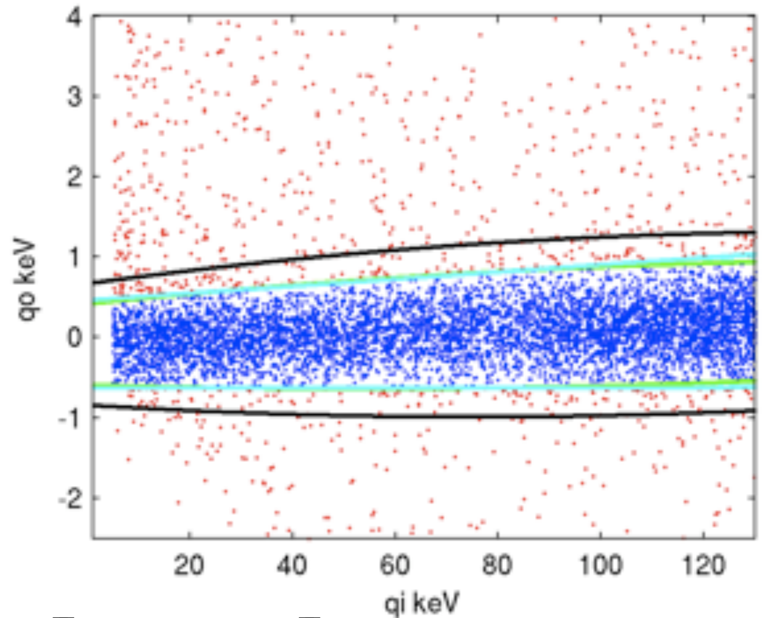
Event Selection

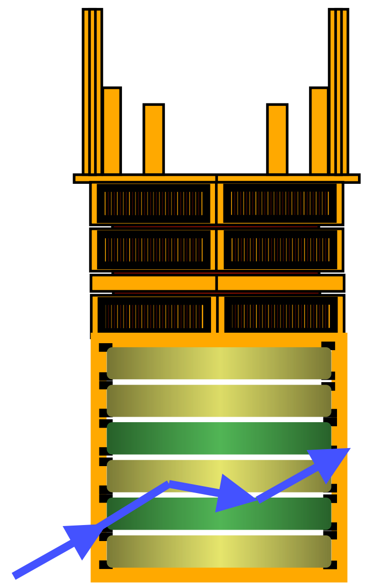
- Muon-veto anticoincident events
- Single scatter events (all 30 detectors)

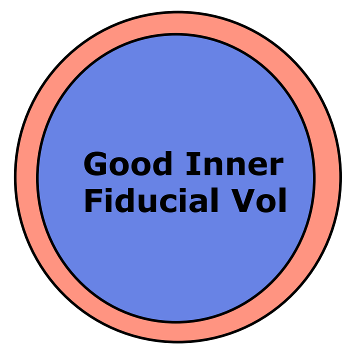


Event Selection

- Muon-veto anticoincident events
- Single scatter events (all 30 detectors)
- Within fiducial volume

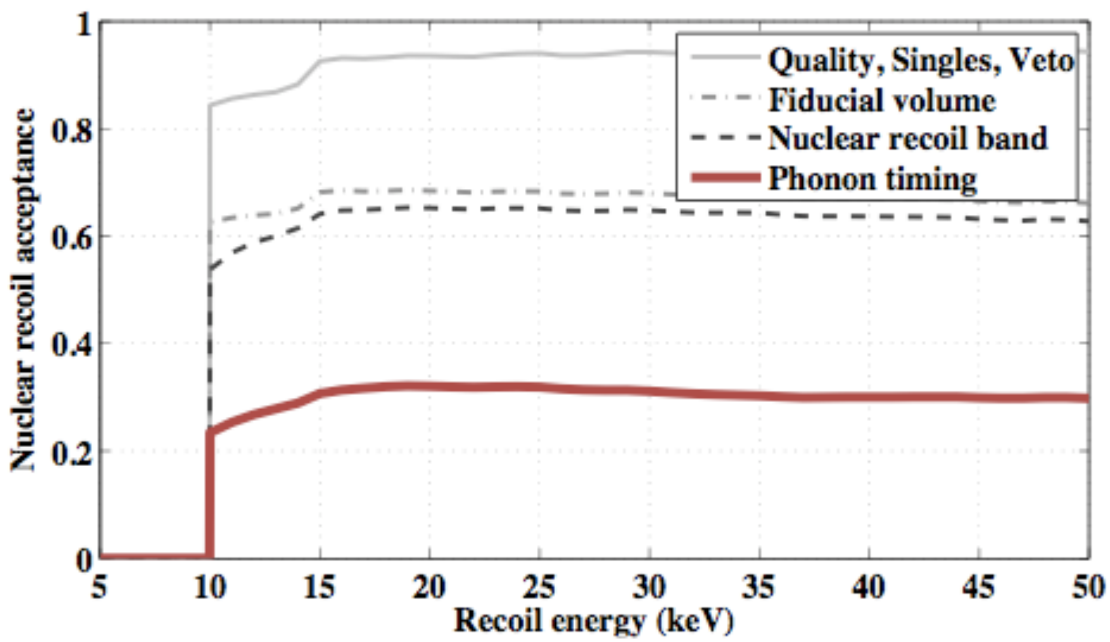


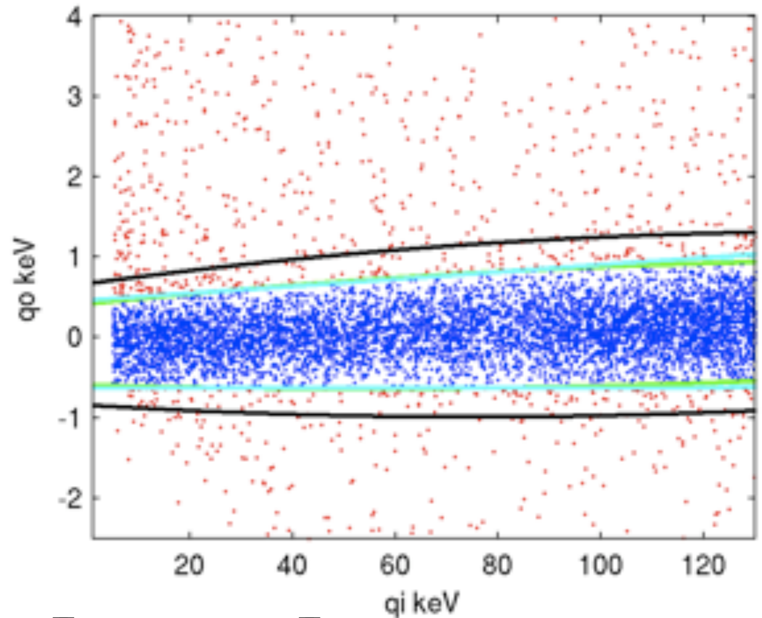


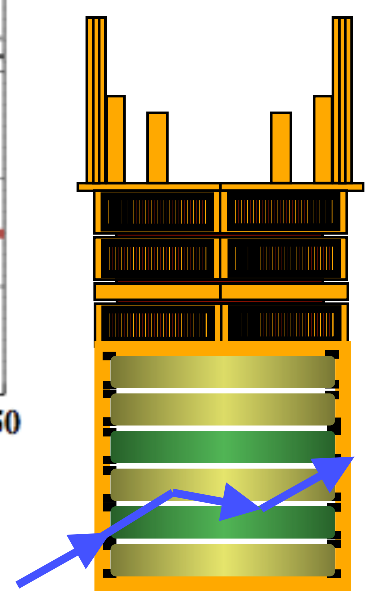


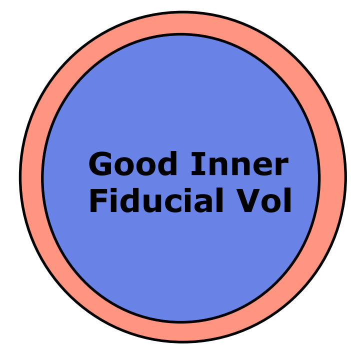
Event Selection

- Muon-veto anticoincident events
- Single scatter events (all 30 detectors)
- Within fiducial volume
- Satisfy data quality & noise rejection cuts
- Satisfy NR yield & phonon timing cuts



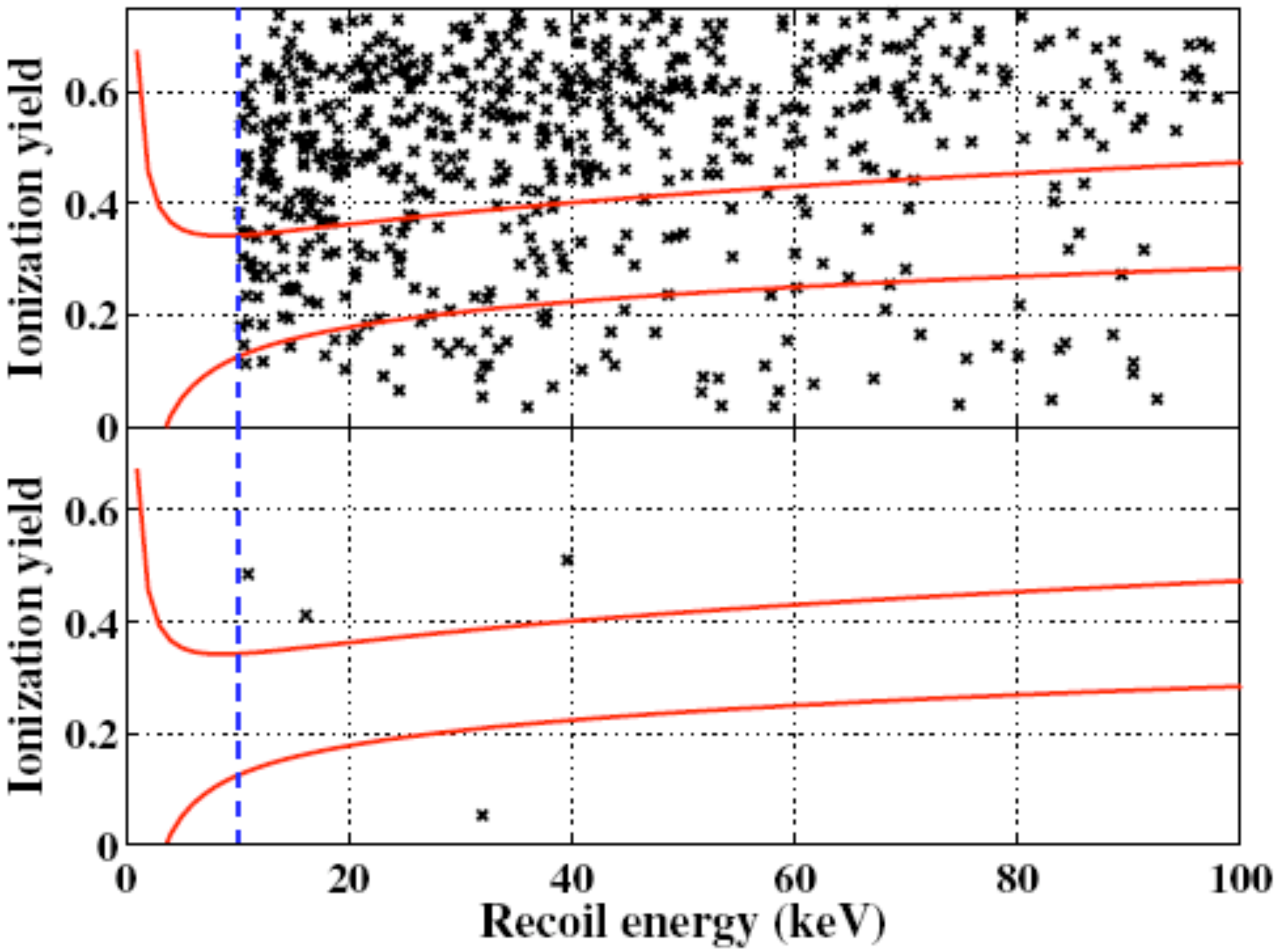






CDMS-II Results

No events observed!



PRL 102, 011301 (2009)

CDMS-II Results

Exposure:

- 398 raw kg-day
- 121 kg-day WIMP equiv. @ 60 GeV

Surface Background:

- estimated number of background events to pass surface cut in Ge:

$$0.6^{+0.5}_{-0.3}\text{(stat.)}^{+0.3}_{-0.2}\text{(syst.)}$$

Neutron Background:

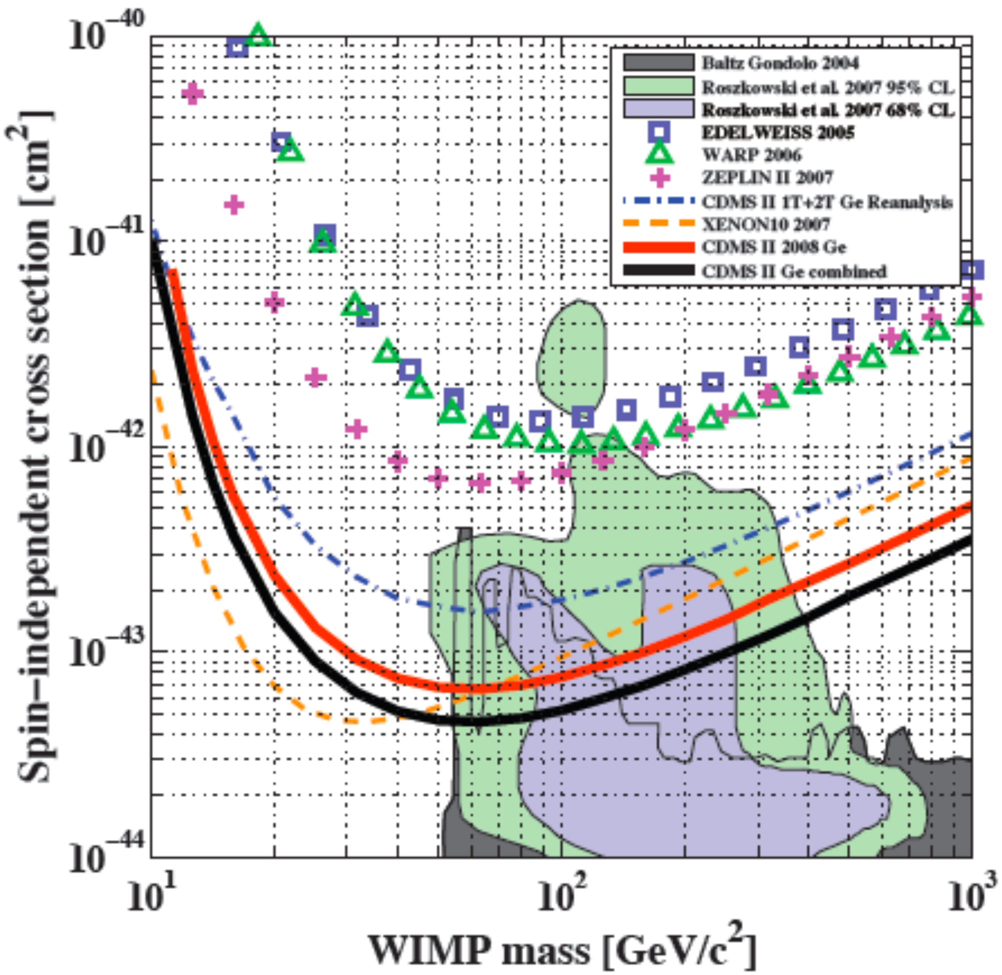
- Poly Cu (α,n) <0.03
- Pb (fission) <0.1
- Cosmogenic <0.1 (MC 0.03-0.05)

Result:

6.6×10^{-44} cm^2 @ 60 GeV

4.6×10^{-44} cm^2 @ 60 GeV

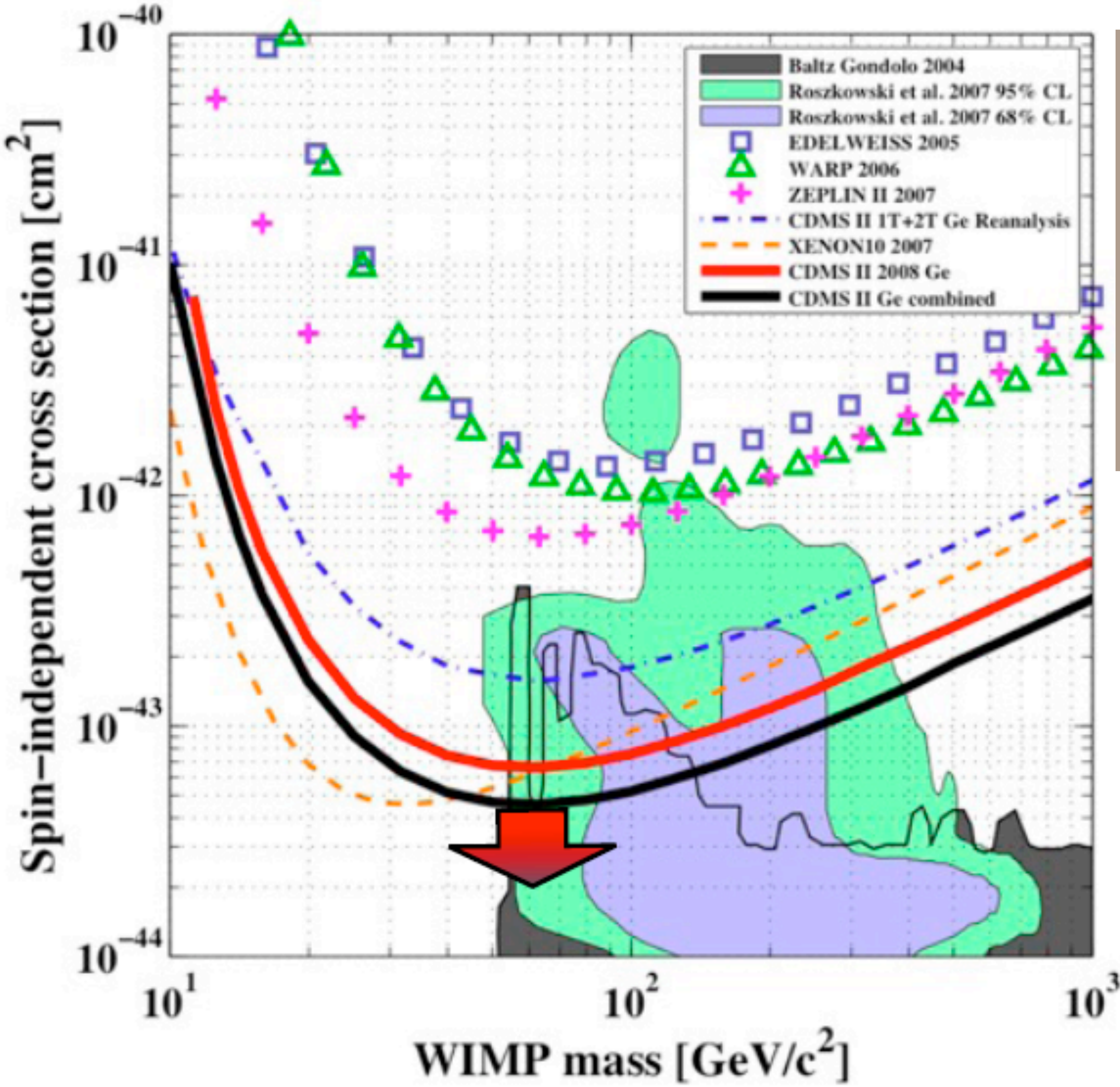
(combined with previous CDMS data)

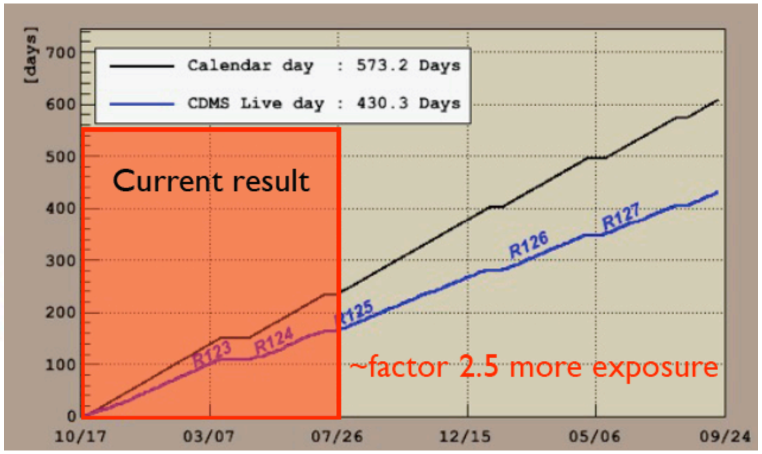


PRL 102, 011301 (2009)

Completing 5-Tower Data Run
[CDMS 2009 analysis]

Completing 5-Tower Data Run





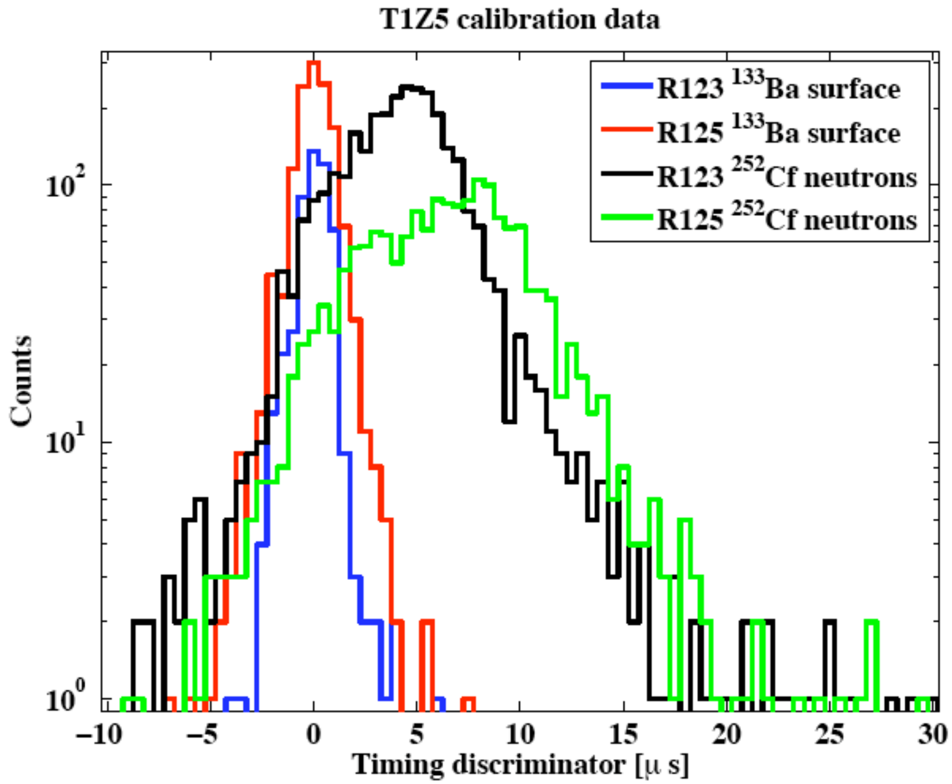
Raw exposure:

- Run 118-119 = ~120 kg-d
- Run 123-124 = ~400 kg-d
- Run 125-128 = ~750 kg-d

~2.5 times more total exposure!

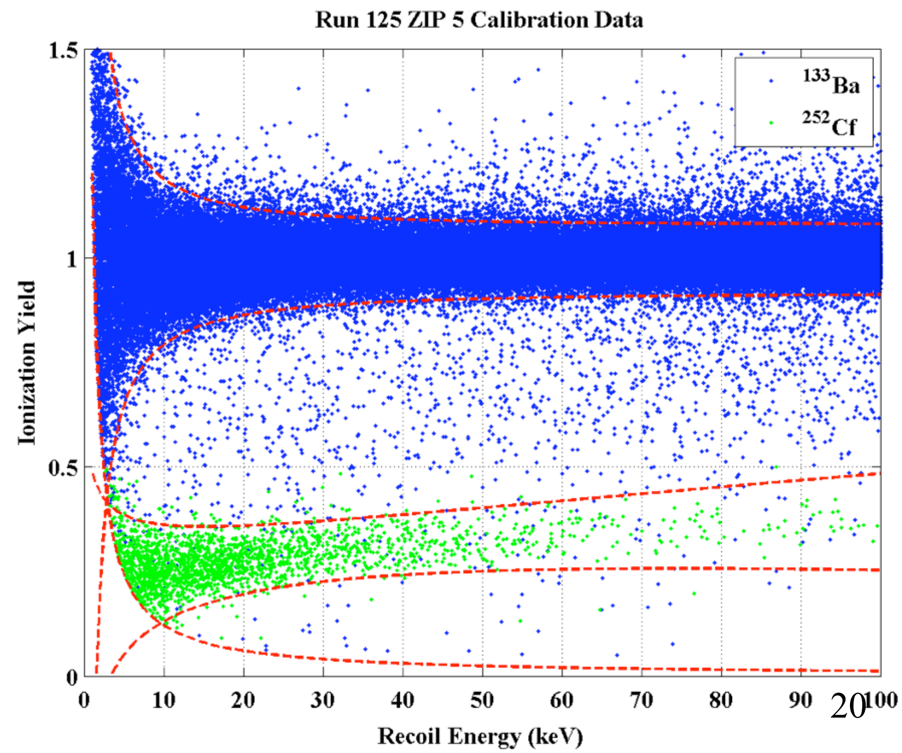
Run 125-128 results [CDMS 2009 analysis] are expected in August 2009.

CDMS 2009 Preview

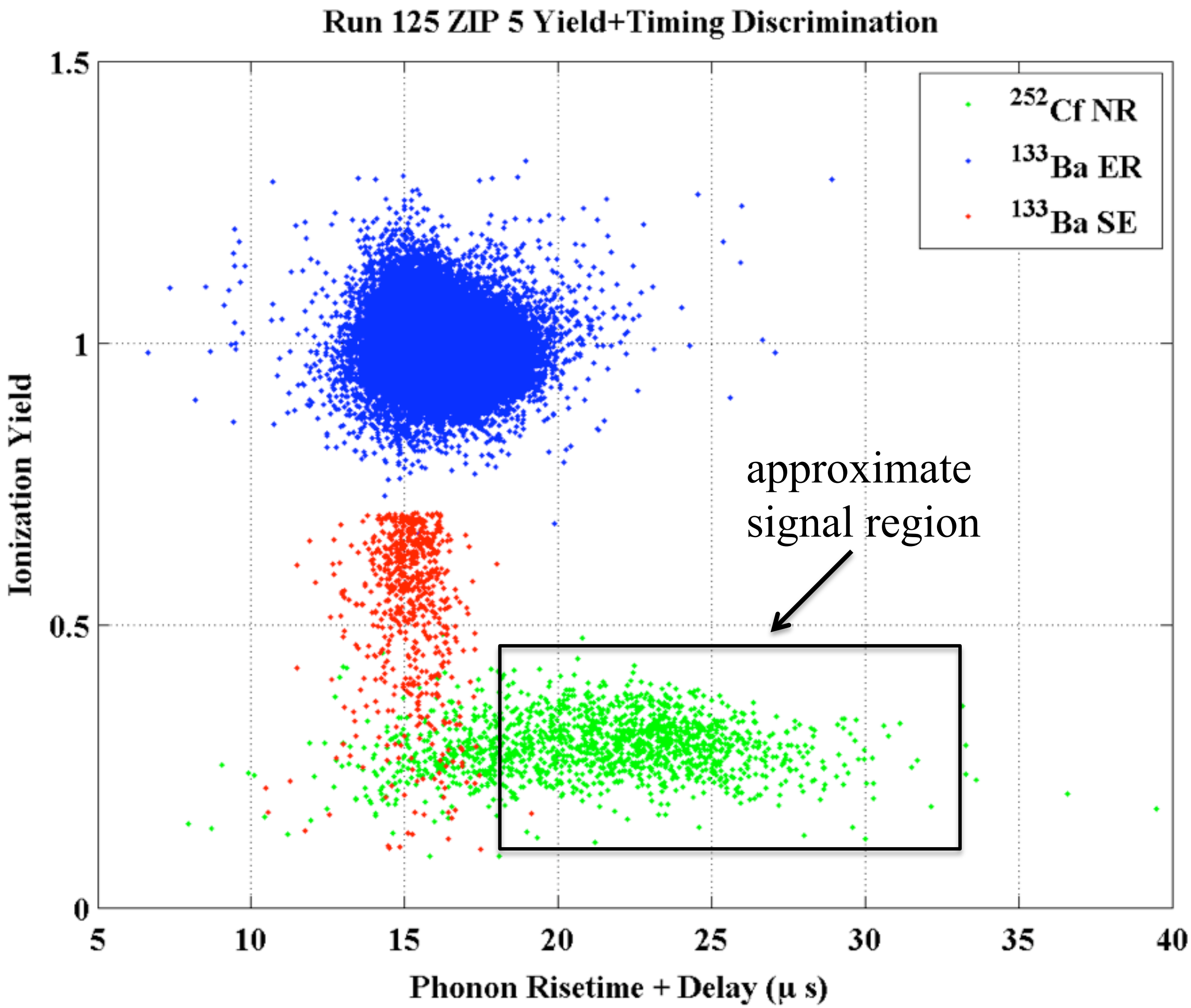


Timing discrimination of surface events looks promising.

Yield discrimination of Nuclear Recoil events



CDMS 2009 Preview

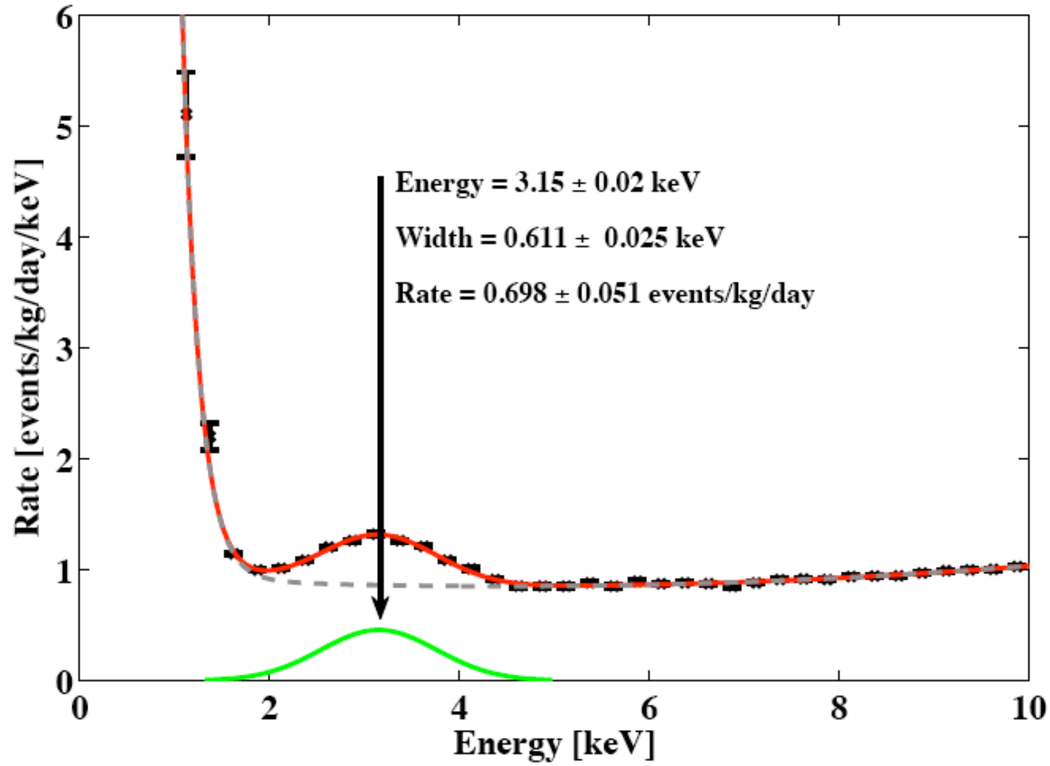


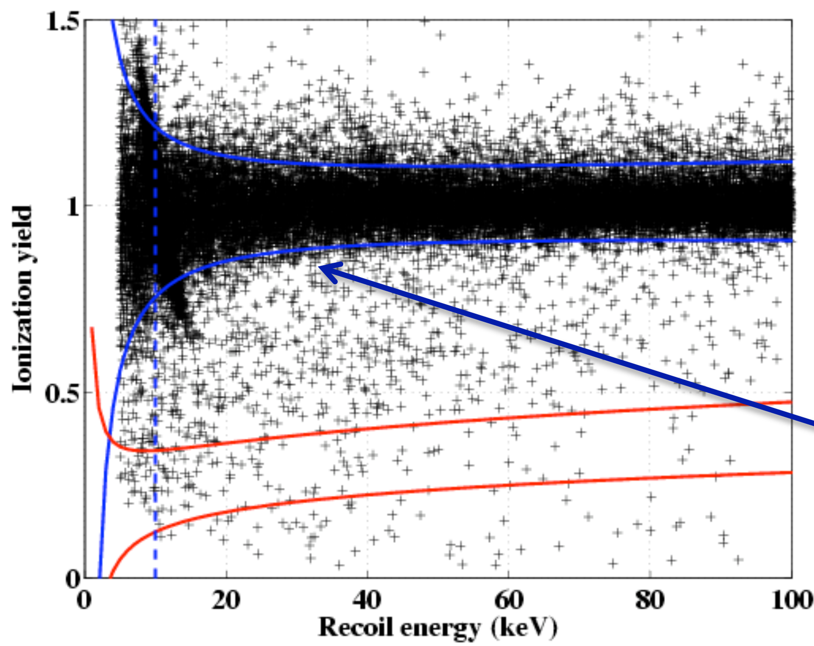
More Physics with CDMS data:
Low-energy Electron Recoil spectrum analysis

Low-energy ER spectrum

Ignited by DAMA signal:

- Excess in detected rate in the low energy spectrum;
- Modulation signal centered at ~3 keV peak;
- Not from WIMPs that'd interact via Nuclear Recoils;
- May be it's an X-ray from DM interaction…



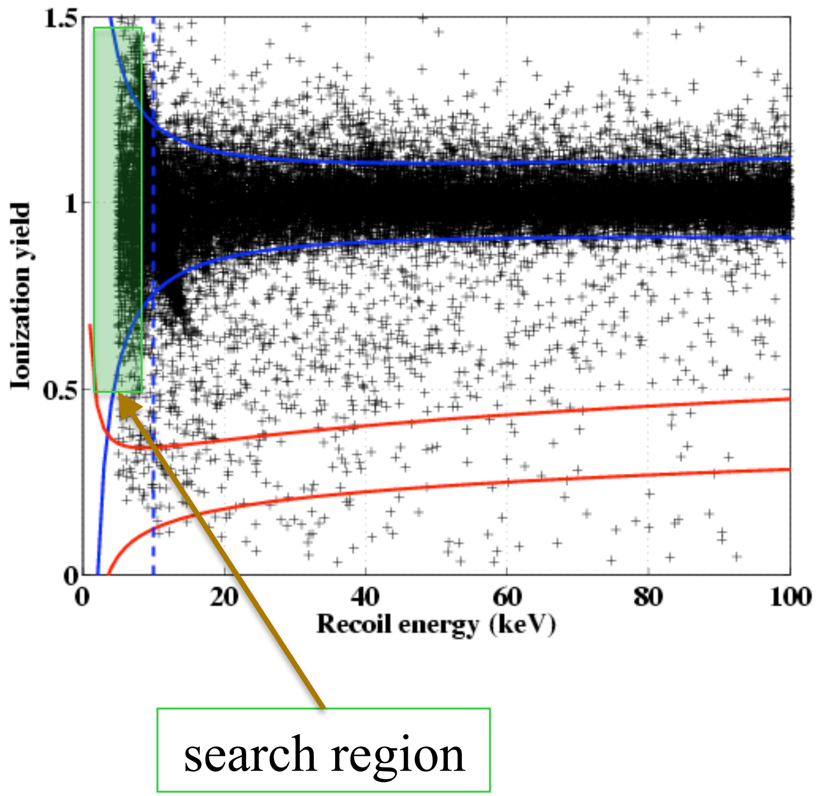


Signal from electromagnetic DM interaction should be detectable by CDMS.

Let's look at Electron Recoil band.

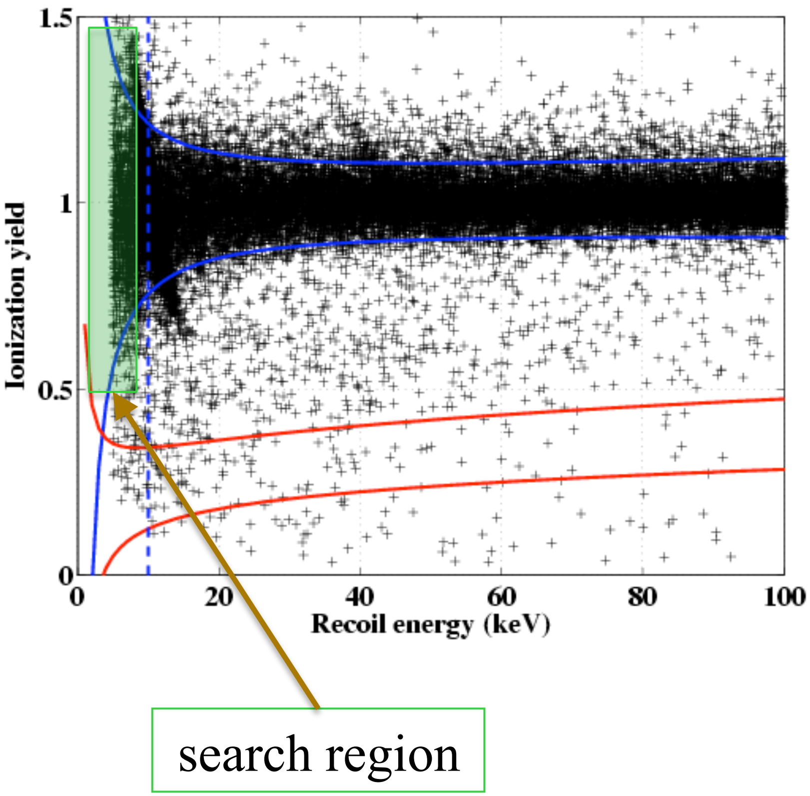
Low-energy ER: Event Selection

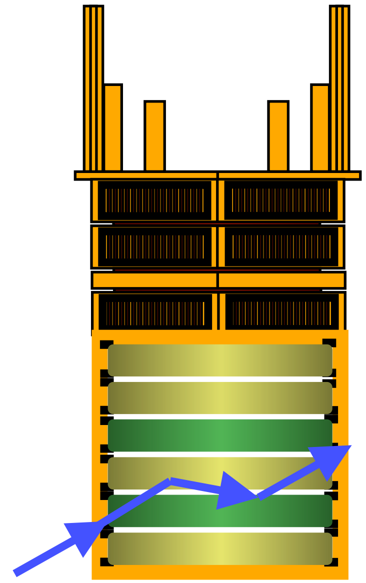
- Low energy electron recoil events



Low-energy ER: Event Selection

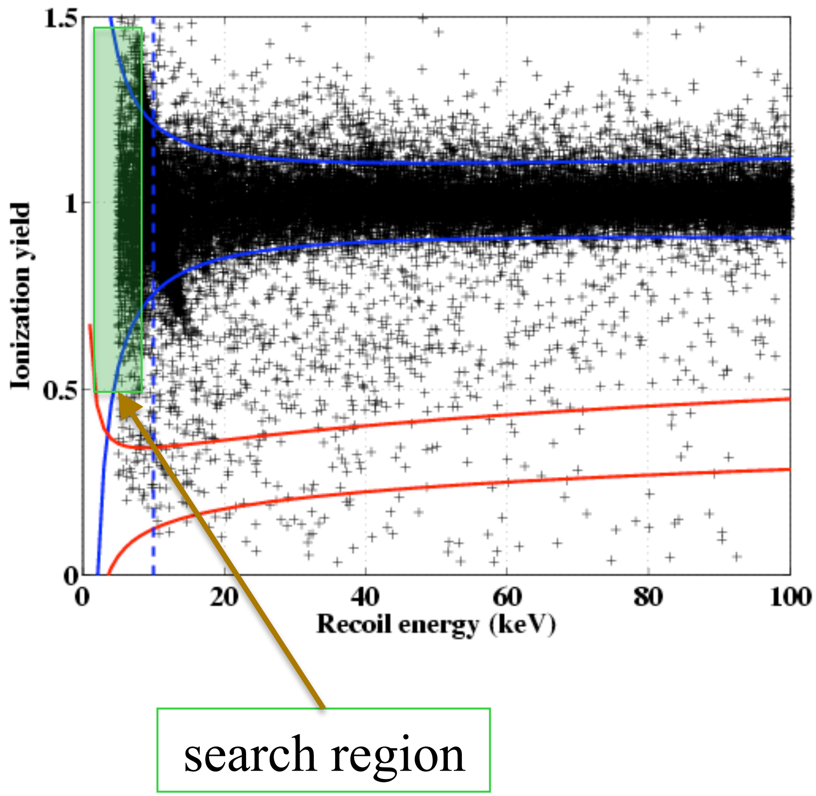
- Low energy electron recoil events
- Single scatter events (all 30 detectors)

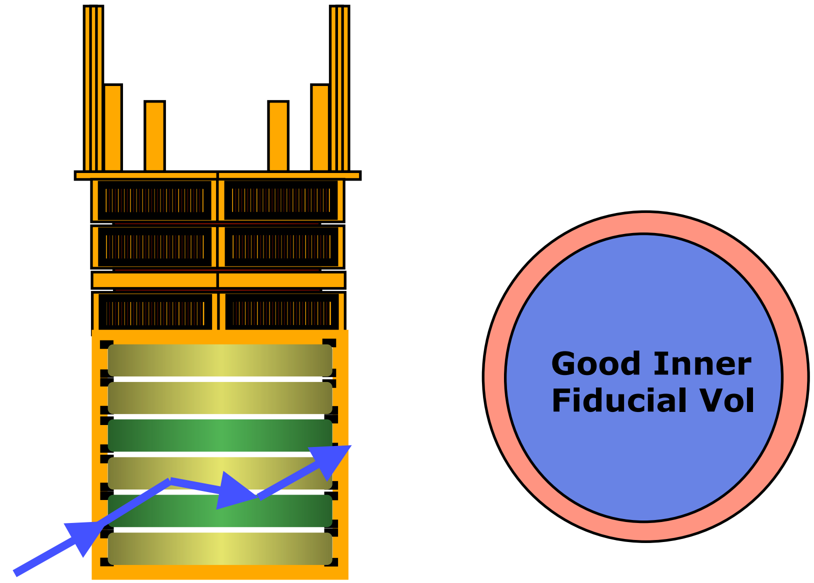


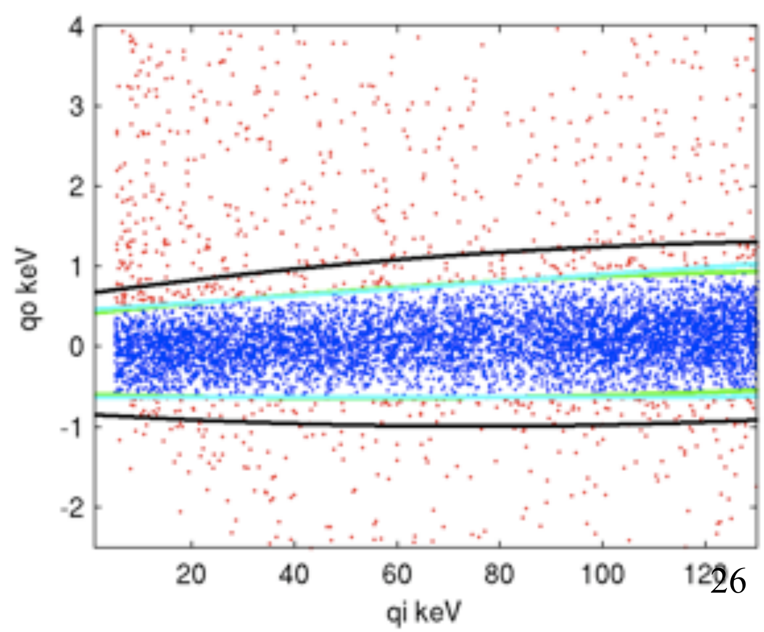


Low-energy ER: Event Selection

- Low energy electron recoil events
- Single scatter events (all 30 detectors)
- Within fiducial volume

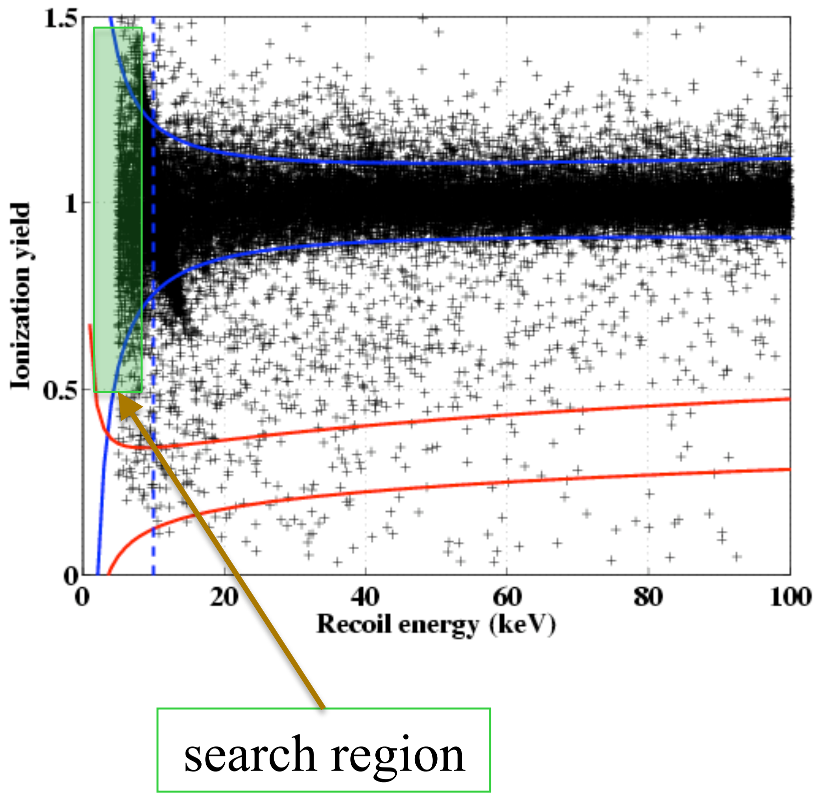


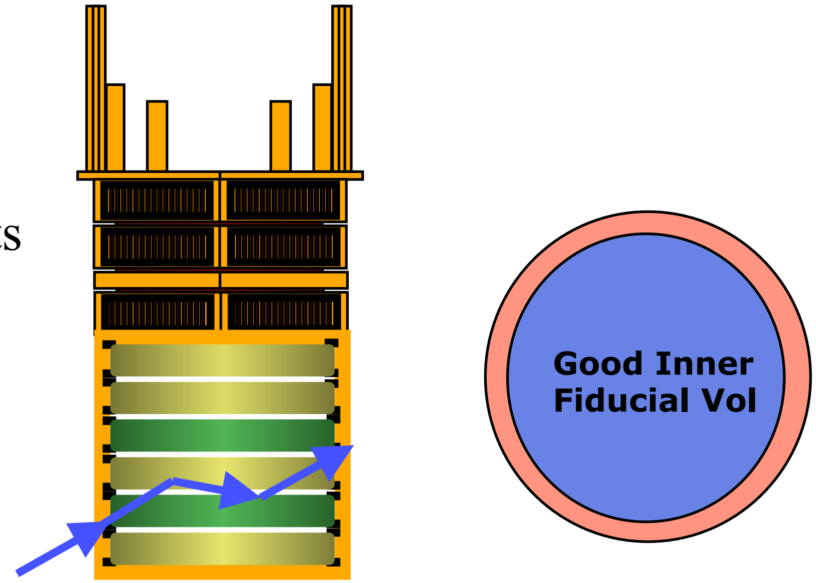


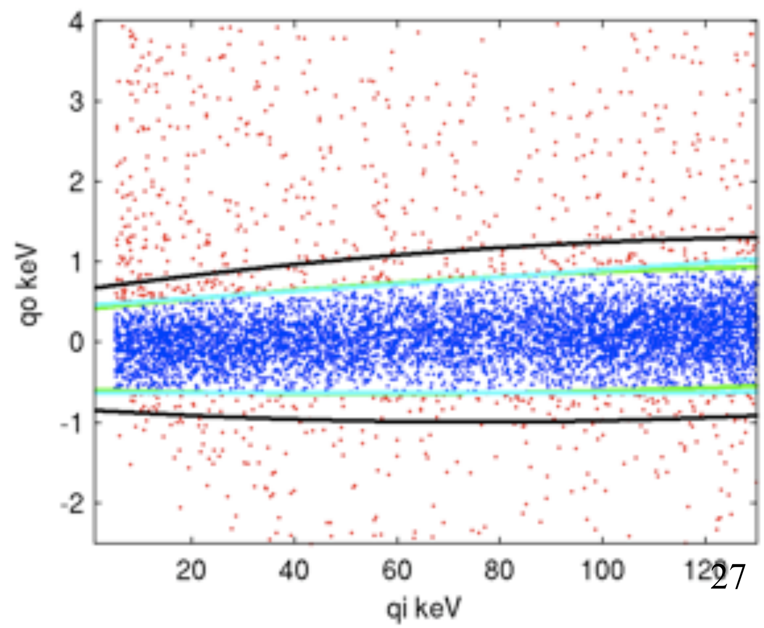


Low-energy ER: Event Selection

- Low energy electron recoil events
- Single scatter events (all 30 detectors)
- Within fiducial volume
- Satisfy data quality and noise rejection cuts

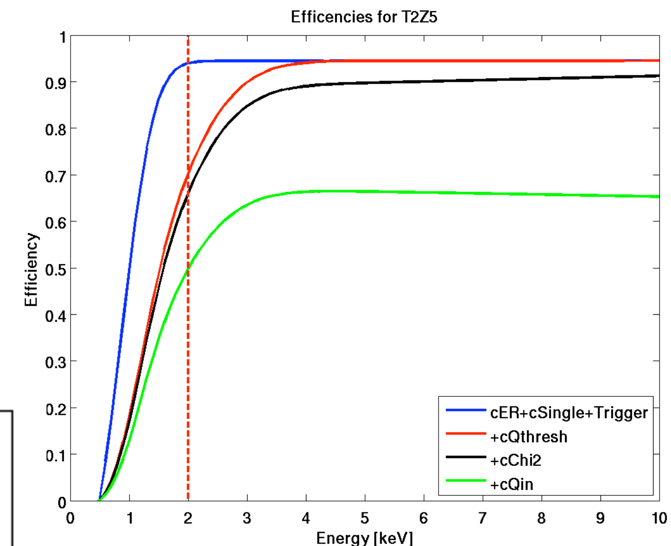




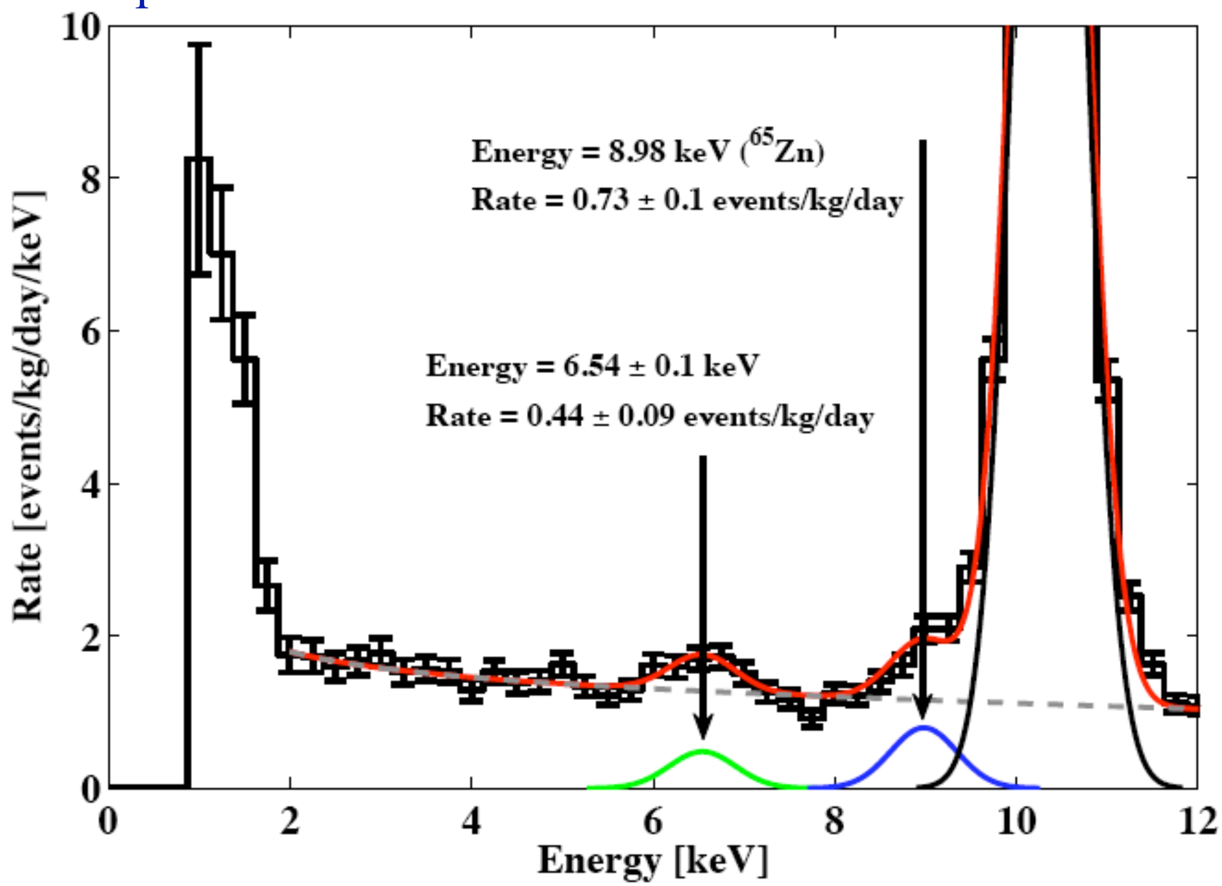


Low-energy ER: Background Rate

- Detection efficiency is 30% ~ 70% and depends on detector;
- Exposure: 443.2 kg-days before cuts.



Efficiency corrected coadded low-energy spectrum:

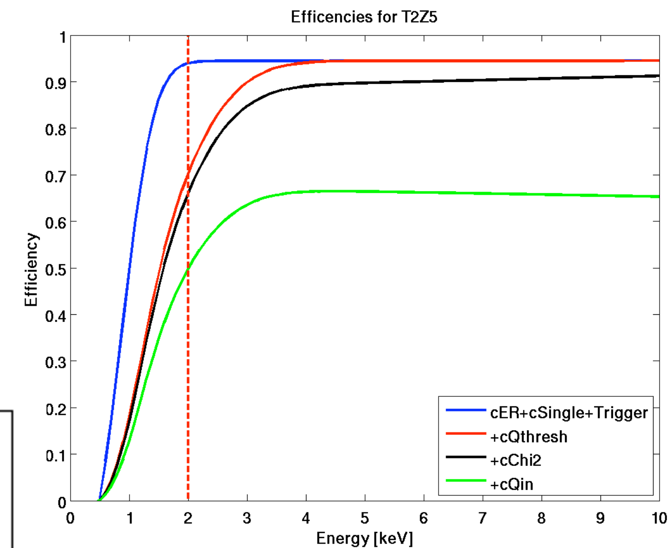


No excess in the counting rate above background!

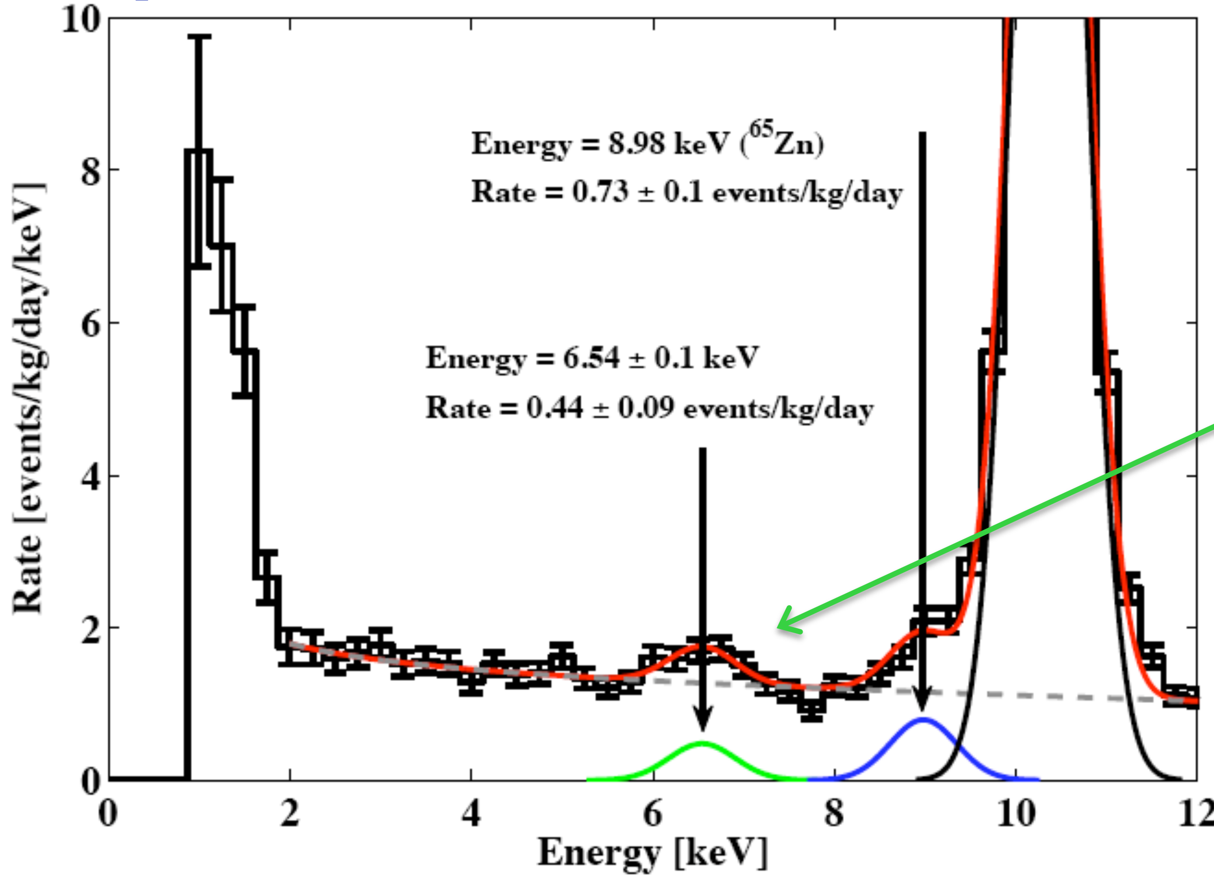
Background rate is ~1.5 counts/kg/day/keV

Low-energy ER: Background Rate

- Detection efficiency is 30% ~ 70% and depends on detector;
- Exposure: 443.2 kg-days before cuts.



Efficiency corrected coadded low-energy spectrum:



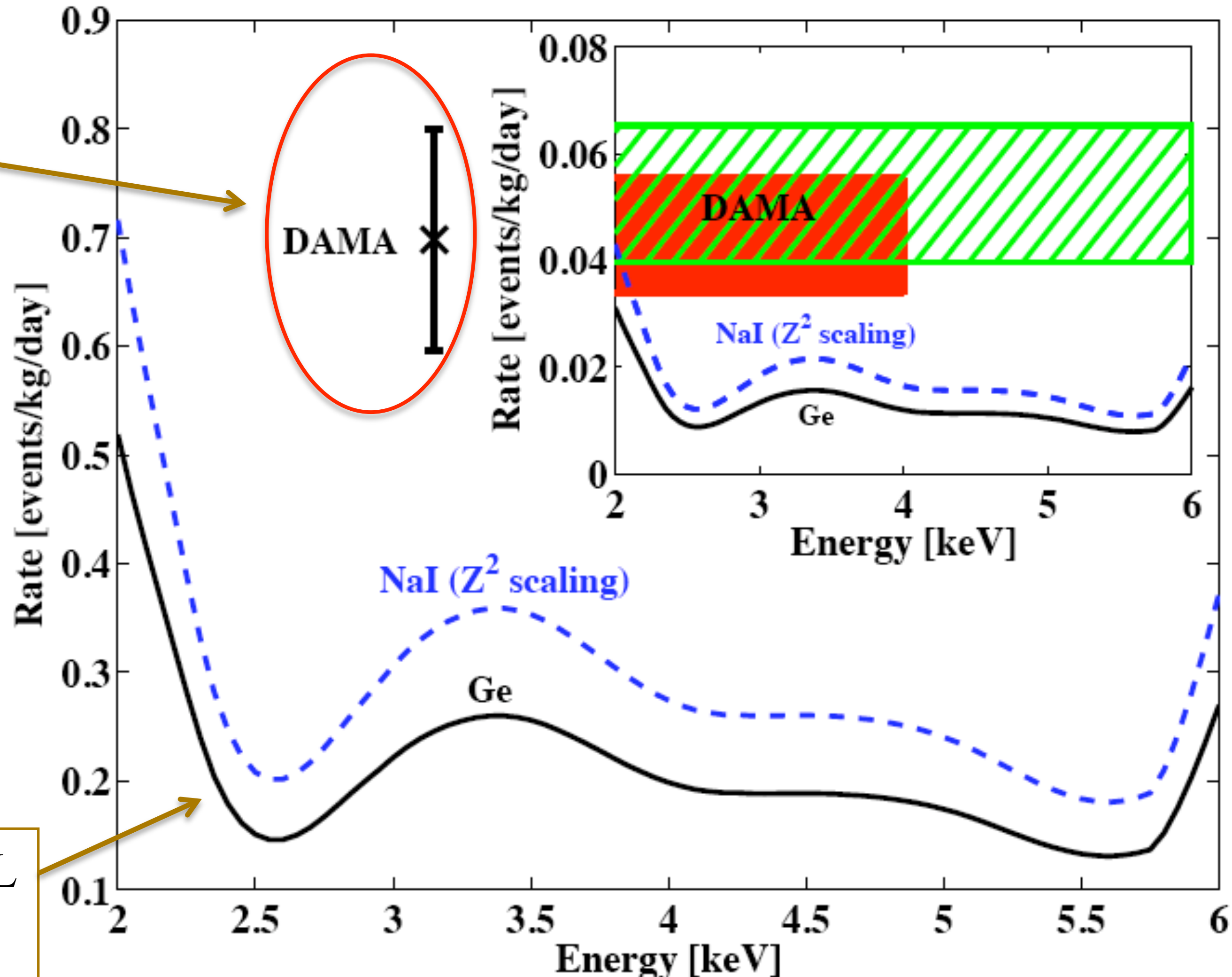
Most likely due to de-excitation of ^{55}Mn (6.54 keV line), which was caused by EC decay of ^{55}Fe (from cosmogenic activation of Ge).

Background rate is ~1.5 counts/kg/day/keV

Low-energy ER: Comparison with DAMA

Total rate above background from DAMA

Upper limit @ 90% CL on event rate excess above background



arXiv:0907.1438

More Physics with CDMS data:
Axion Search

Axio-electric coupling

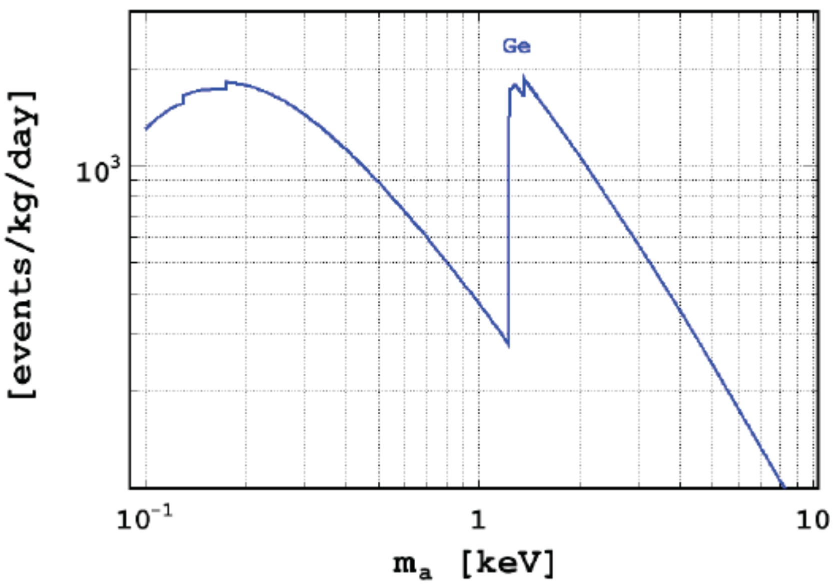
- For low mass axion (~keV) pair production is kinematically forbidden. Thus, it is absorbed by a bound electron, which is then ejected from the atom, similar to photoelectric effect;
- Interaction rate of axion-like dark pseudoscalar in the local halo:

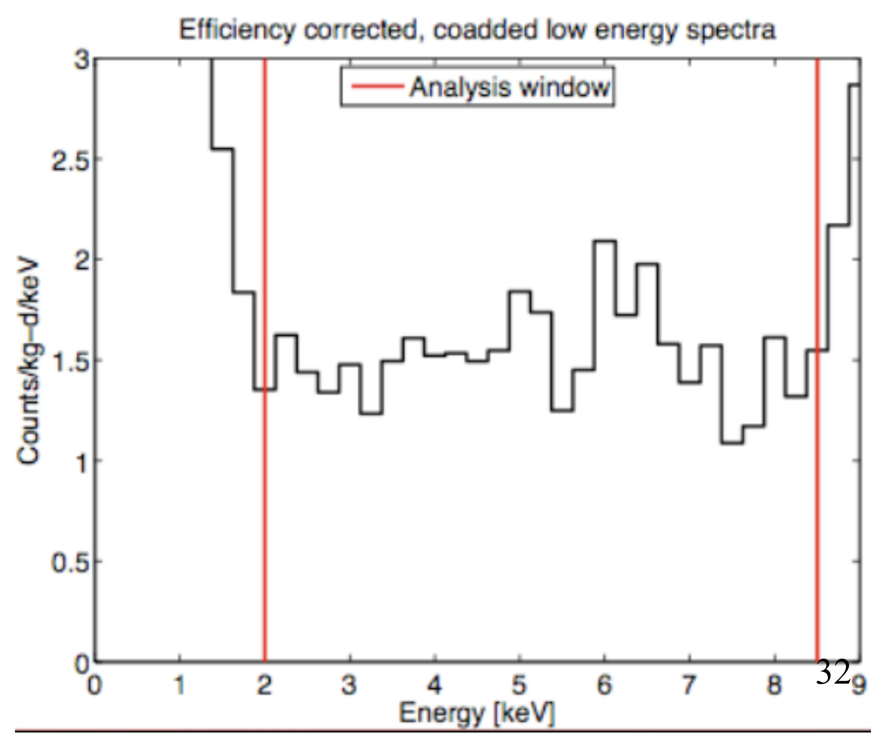
$$\mathrm{R}\ [\mathrm{cpd\ kg}^{-1}] = 1.2 \times 10^{43} A^{-1} g_{a\bar{e}e}^{2} m_a \sigma_{p.e}$$

where A atomic mass number.

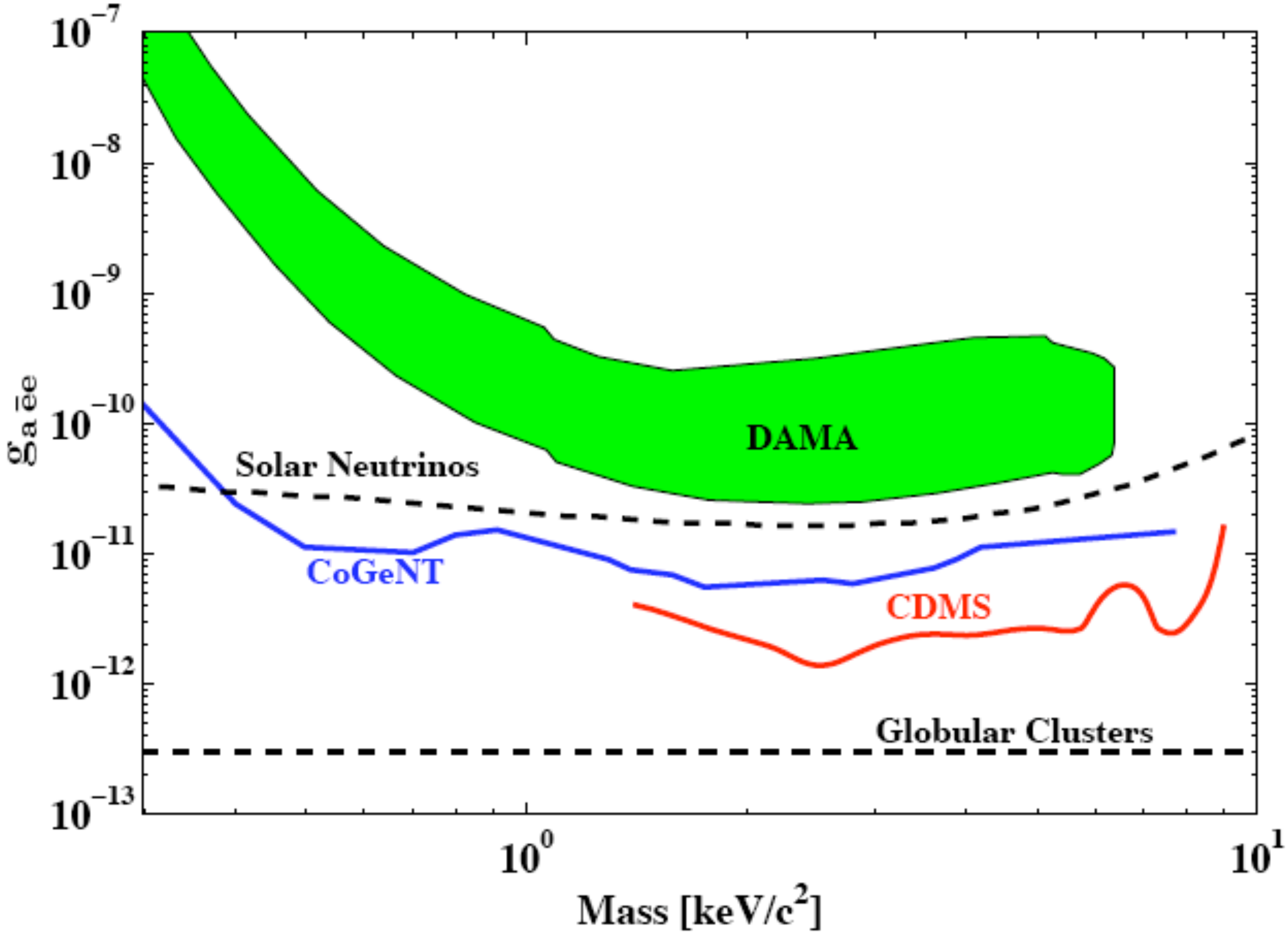
- Observable from interactions: peak at energy m_a in ER spectrum.

Expected event rate for Ge by the axio-electric coupling (g_{aee}=10^{-10})





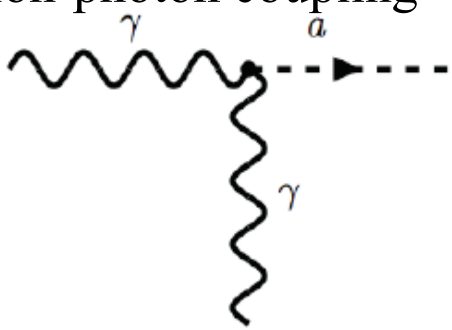
Axio-electric coupling



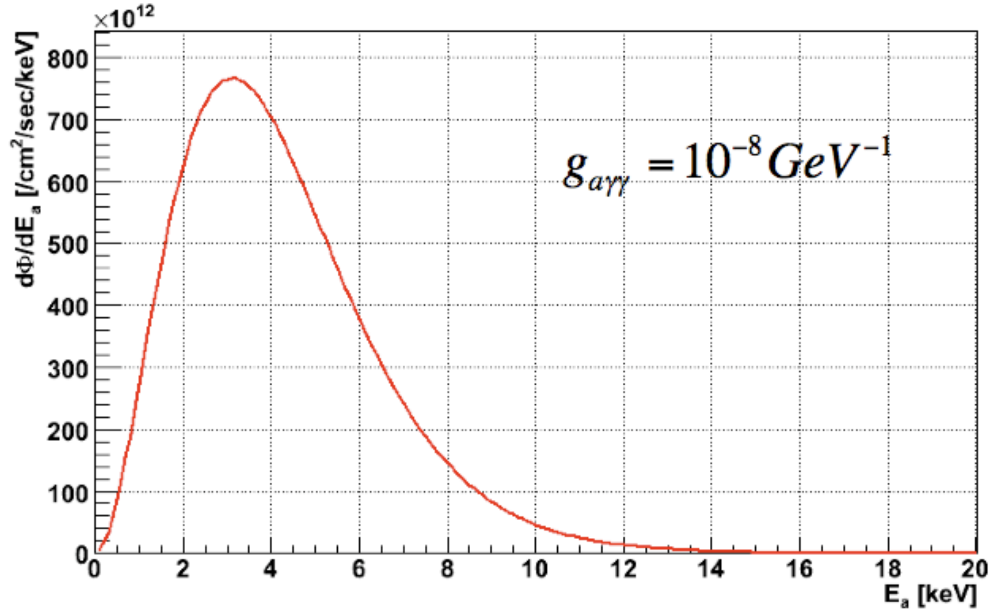
arXiv:0902.4693

Solar Axions Search

• Axion-photon coupling



• Spectrum of the solar axion flux at Earth for a given coupling



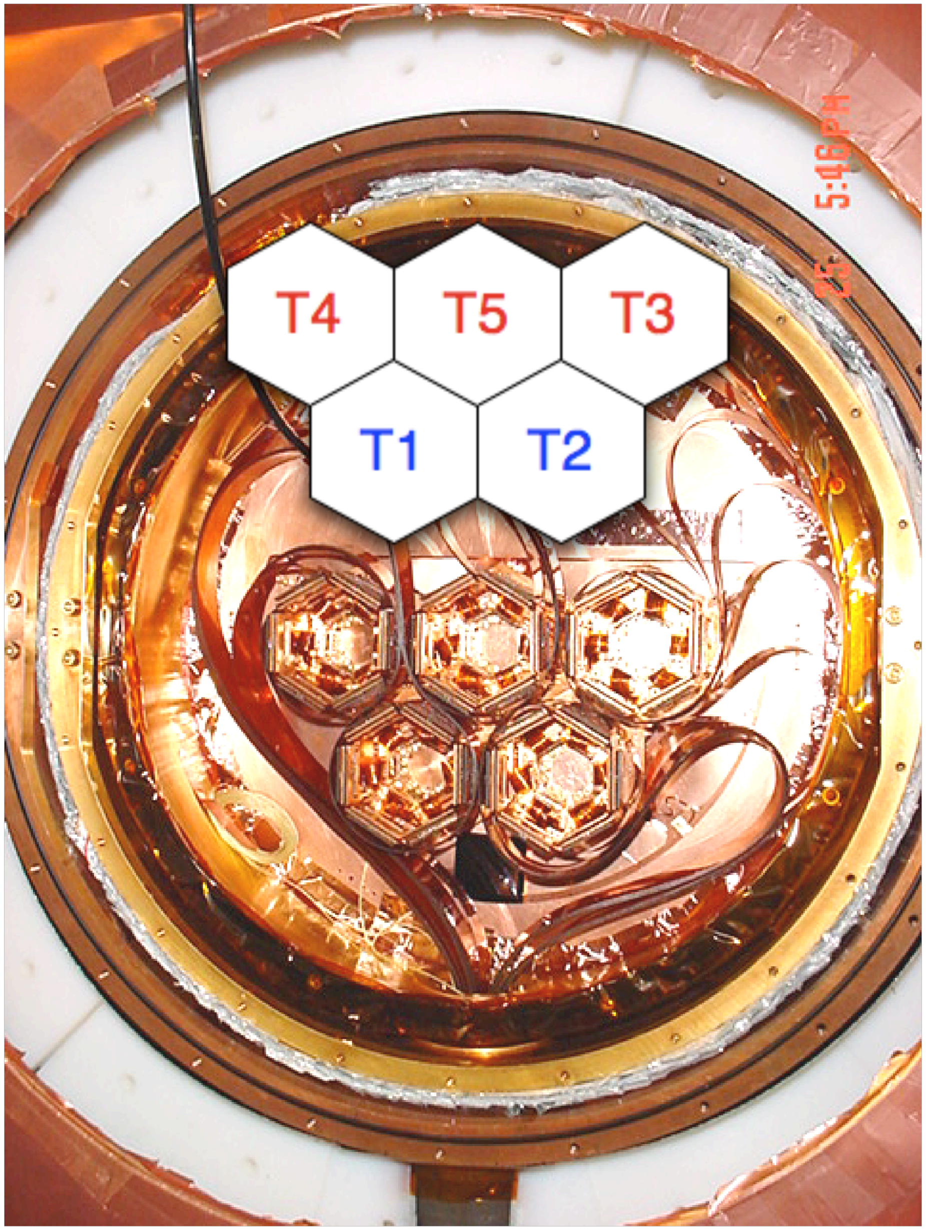
Coherent Primakoff conversion:

• Light axions will experience Bragg scattering in a crystal (momentum transferred = reciprocal lattice vector);

• Bragg condition implies that axion energy $E_a = \hbar c \frac{|\vec{G}|^2}{2\hat{u}\cdot\vec{G}}$ where u is the direction of the Sun

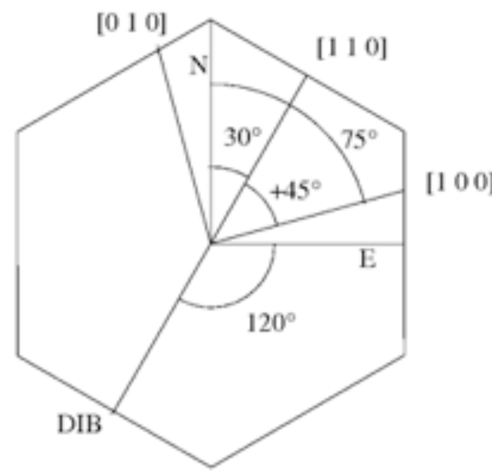
• Correlation of the expected rate with the position of the Sun is a signature of the axion signal.

Solar Axions: Detectors Stacking

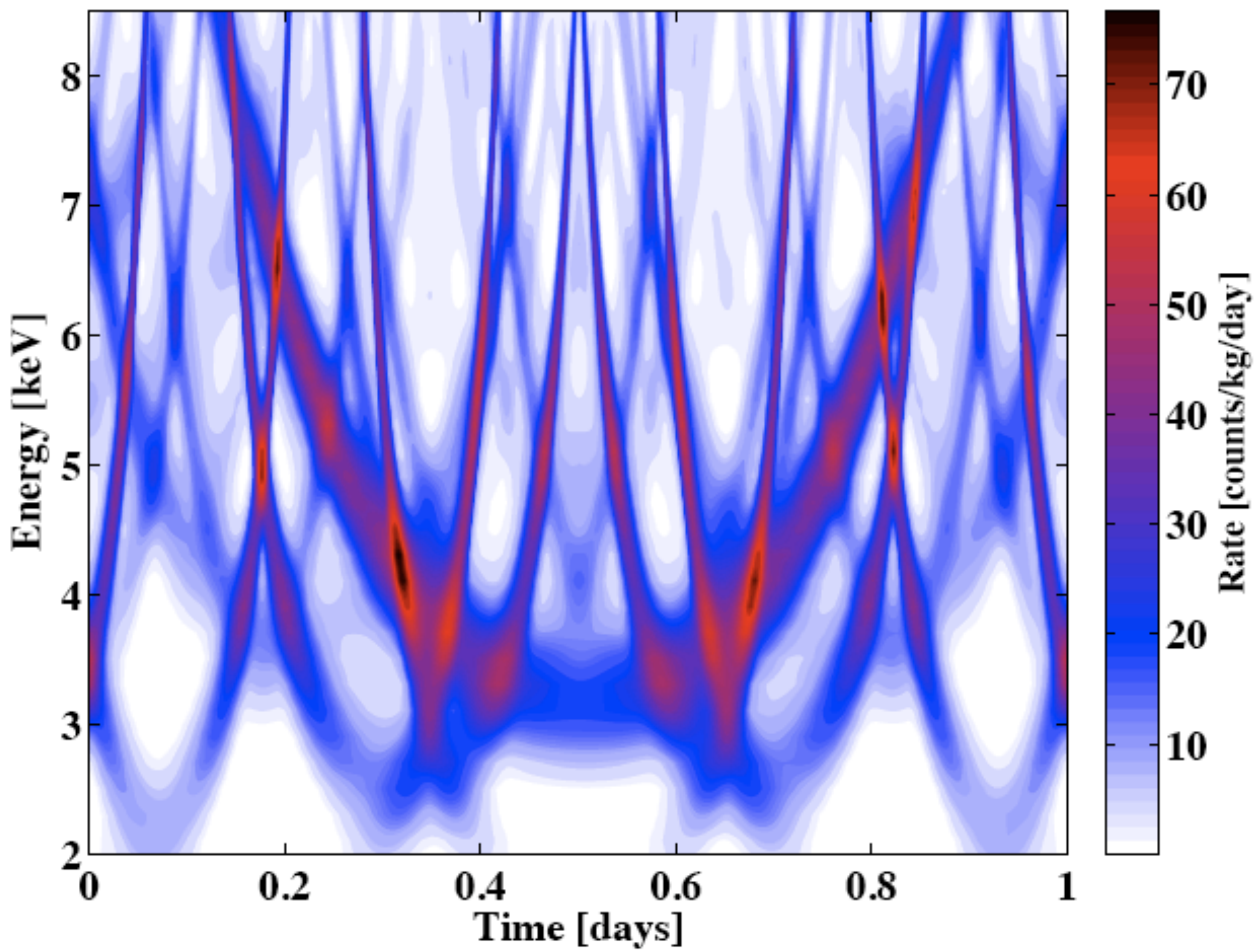


- 30 Ge and Si detectors form 5 towers with 6 detectors in each;
- Each detector in a tower is rotated by 60^0 with respect to the former;
- Crystal's alignment, relative to true north, is known to $0.86^0 \pm 3^0$.

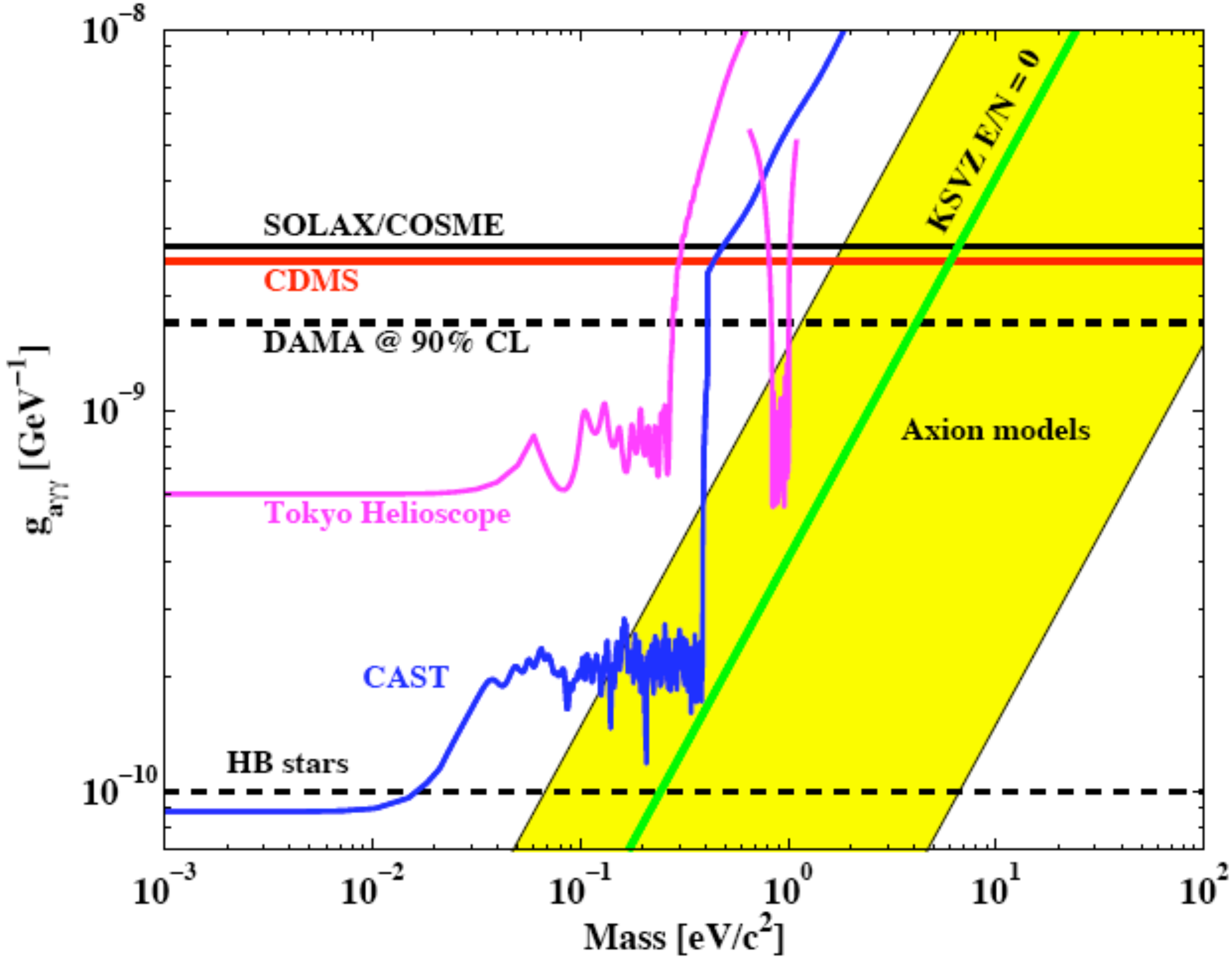
	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24



Expected Solar Axion Event Rate



Solar Axion Limit



arXiv:0902.4693

Summary

- CDMS has a world-leading limit on WIMP nucleon spin-independent cross-section: [PRL 102, 011301 (2009)]
  4.6×10^{-44} cm^2 @ 90% CL for 60 GeV WIMP;

- World-best sensitivity for WIMPs above 44 GeV;

- World-leading experimental limit on the axio-electric coupling: [arXiv:0902.4693]
  1.4×10^{-12} @ 90% CL for 2.5 keV axion;
- Upper limit on the axion-photon coupling:
  2.4×10^{-9} GeV^{-1} @ 95% CL;

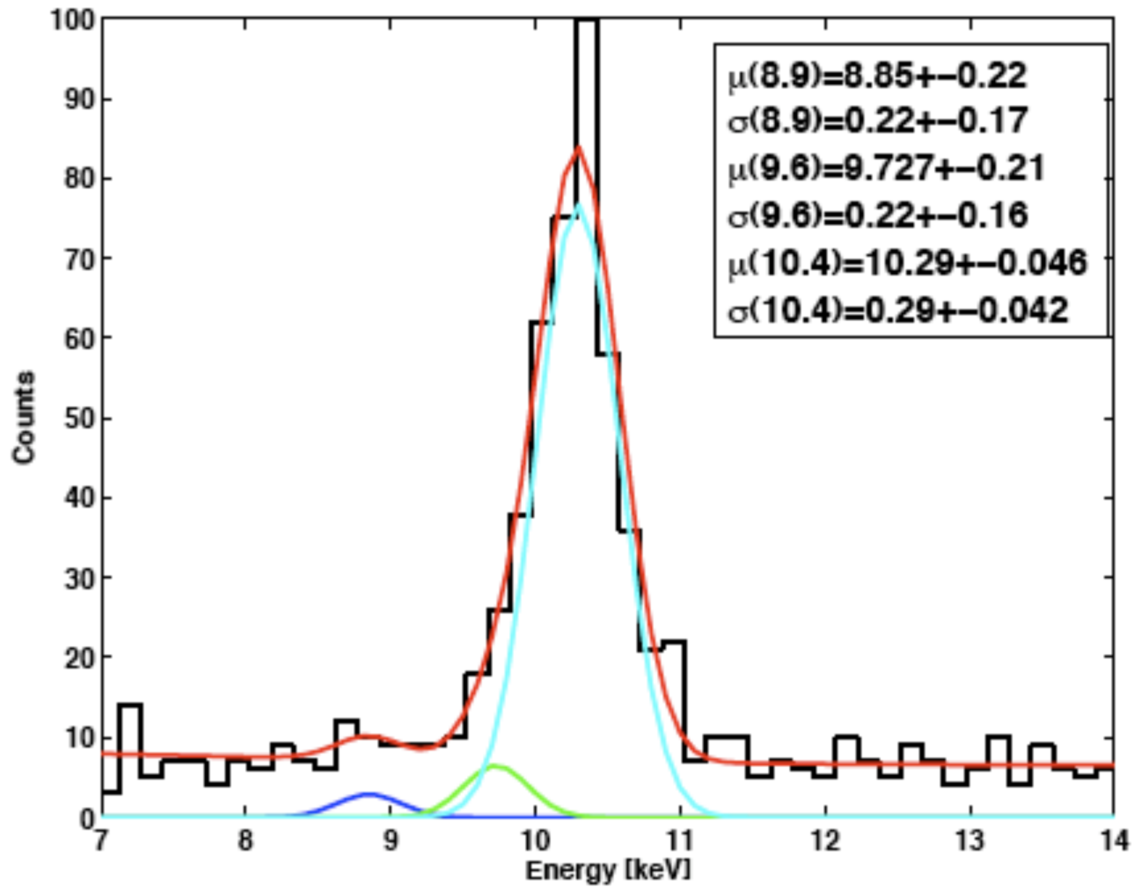
- No excess in the counting rate above background in 2-8.5 keV electron recoil spectrum; [arXiv:0907.1438]

- Analysis of 750 kg-day 5-tower data is ongoing and results are expected by end of summer.

Backup Slides

Calibration and Energy Resolution

- ^{133}Ba (gammas) and ^{252}Cf (neutrons) sources were used for calibration
- Neutron capture on ^{70}Ge ➔ ^{71}Ge; electron capture decay of ^{71}Ge ➔ 10.36 keV electron recoil events
- Resolution as F(energy) obtained by extrapolation to the zero-energy noise blob



Low-energy ER: Unbinned Likelihood Fit

Event rate:

$$R(E,d) = B(E,d) + A(E,d)$$

where

- *A(E,d)* is a Gaussian smeared by detector's resolution

$$A(E,d) = \varepsilon(E,d) \cdot \frac{\lambda_0}{\sqrt{2\pi}\sigma_0(d)} e^{-\left(\frac{E-E_0}{\sqrt{2}\sigma_0(d)}\right)^2}$$

- background

$$\begin{aligned} B(E,d) &= \varepsilon(E,d) \cdot \left[C(d) + D(d)E + \frac{H(d)}{E}\right] \\ &+ \eta \cdot \varepsilon(E,d) \cdot \frac{\lambda_{6.54}}{\sqrt{2\pi}\sigma_{6.54}(d)} e^{-\left(\frac{E-6.54}{\sqrt{2}\sigma_{6.54}(d)}\right)^2} \end{aligned}$$

Find the best λ_0 to maximize the function

$$\log(\mathcal{L}) = -R_T + \sum_{i,j} \log R(E_i, d_j)$$

Axio-electric: Unbinned Likelihood Fit

Event rate:

$$R(E,t,d) = \lambda A(E,t,d) + B(E,d)$$

where

- *A(E,t,d)* is a Gaussian smeared by detector's resolution
- *λ* is the scale factor
- background $B(E,d) \;\equiv\; \varepsilon(E,d)\left[C(d) + D(d)E + H(d)/E\right] + \varepsilon(E,d)\frac{\lambda_{6.54}}{\sqrt{2\pi}\sigma_{6.54}} e^{\left(-\frac{(E-6.54)^2}{2\sigma_{6.54}^2}\right)}$

Find the best *λ* to maximize the function

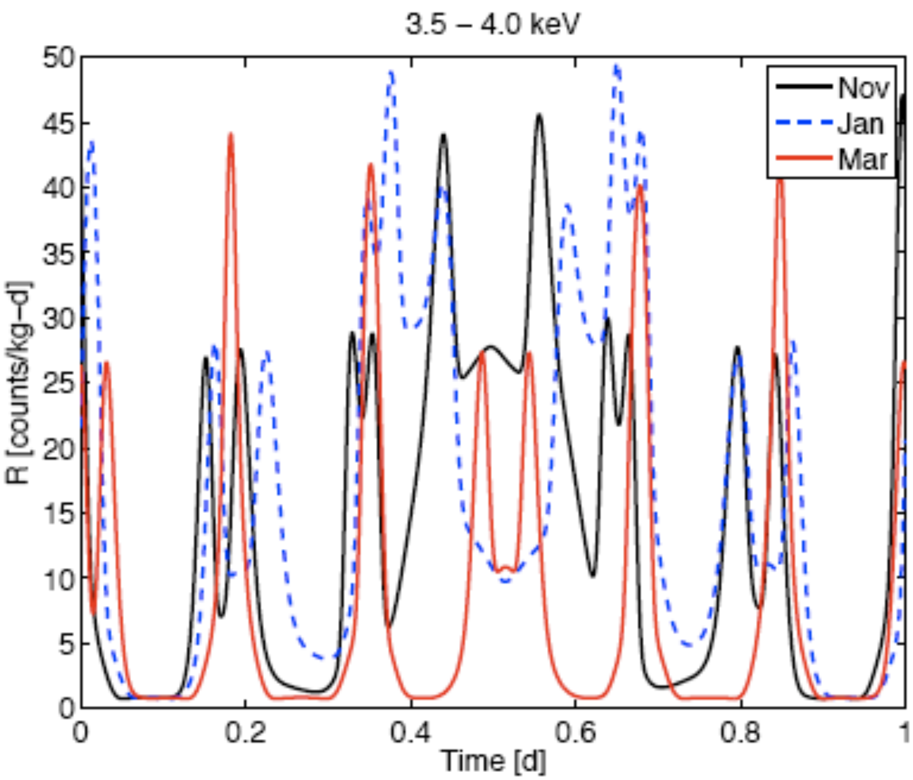
$$log(\mathcal{L}) = -R_T + \sum_i log(R(E_i,t_i,d_i))$$

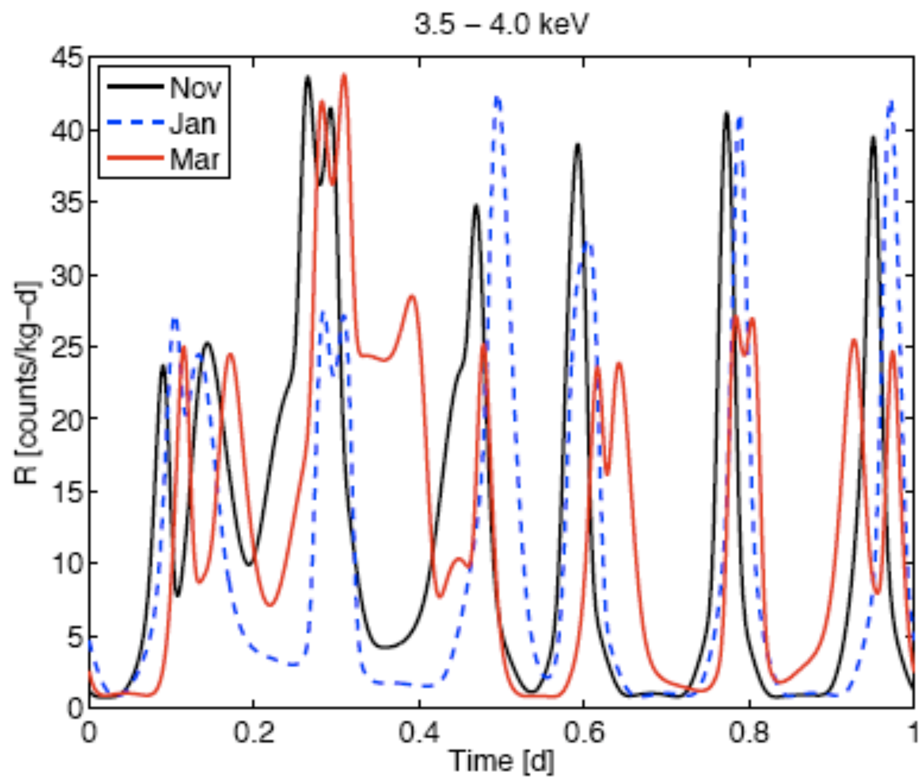
Expected Solar Axion Event Rate

- Expected solar axion signal, two detectors with different azimuth angle to true north are shown

- Strong daytime variation, different in differently oriented detectors, helps to discriminate against background.

[T1G1]	[T2S1]	[T3S1]	[T4S1]	[T5G1]
[T1G2]	[T2S2]	[T3G2]	[T4G2]	[T5G2]
[T1G3]	[T2G3]	[T3S3]	[T4S3]	[T5S3]
[T1S4]	[T2S4]	[T3G4]	[T4G4]	[T5G4]
[T1G5]	[T2G5]	[T3G5]	[T4G5]	[T5G5]
[T1S6]	[T2S6]	[T3G6]	[T4G6]	[T5G6]





Solar Axions: Unbinned Likelihood Fit

Event rate:

$$R(E,t,d) = \lambda A(E,t,d) + B(E,d)$$

where

- $A(E,t,d)$ is expected event rate for $g_{a\gamma\gamma}=10^{-8}$ GeV^{-1}
- λ is the scale factor
- background $B(E,d) \equiv \varepsilon(E,d)\left[C(d) + D(d)E + H(d)/E\right] + \varepsilon(E,d)\frac{\lambda_{6.54}}{\sqrt{2\pi}\sigma_{6.54}} e^{\left(-\frac{(E-6.54)^2}{2\sigma_{6.54}^2}\right)}$

Find the best λ to maximize the function

$$log(\mathcal{L}) = -R_T + \sum_i log(R(E_i,t_i,d_i))$$

Unbinned Likelihood Fitting

What is Unbinned Generalized LogLikelihood Fitting Method?

Suppose that: $f(x;\vec{p})$ - fitting function, where $\vec{p}$ - vector of fitting parameters.

Integral over fitting range is $N(\vec{p}) = \int_{x_1}^{x_2} f(x;\vec{p})dx$.

Likelihood is $L(\vec{p}) = \prod_{i=1}^{n} \frac{f(x_i;\vec{p})}{N(\vec{p})}$, where n - total # of observed events.

Now we add probability for observing n events, when the number of observed events is Poisson with mean $N(\vec{p})$.

Generalized Likelihood is $L(\vec{p}) = \frac{N^n(\vec{p})e^{-N(\vec{p})}}{n!} \prod_{i=1}^{n} \frac{f(x_i;\vec{p})}{N(\vec{p})}$.

After algebra and removing terms that doesn't affect location of minimum:

$-\ln L(\vec{p}) = \int_{x_1}^{x_2} f(x;\vec{p})dx - \sum_{i=1}^{n} \ln f(x_i;\vec{p})$ --- We minimize this in MINUIT.