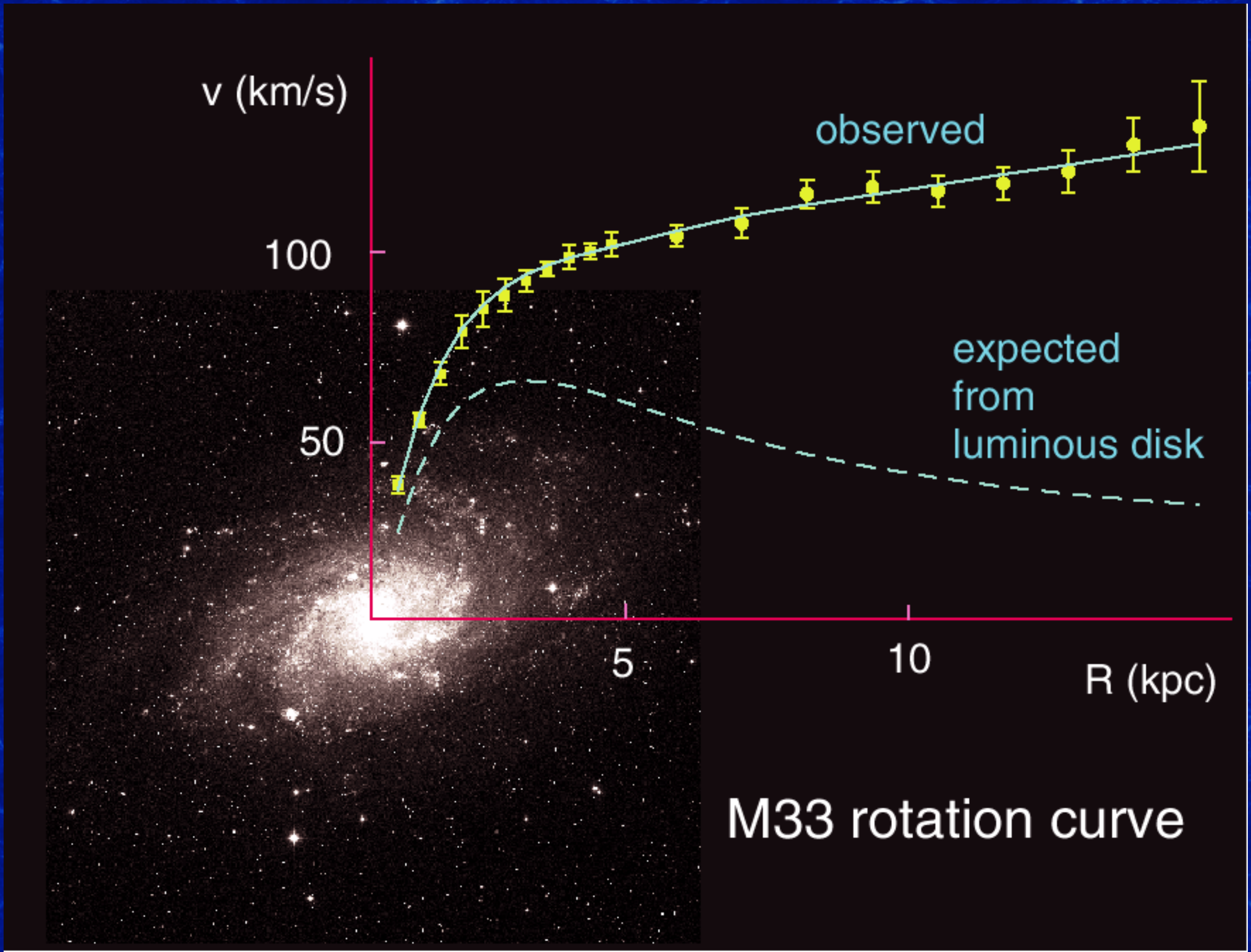
How to Discover WIMP Dark Matter

Jeter Hall

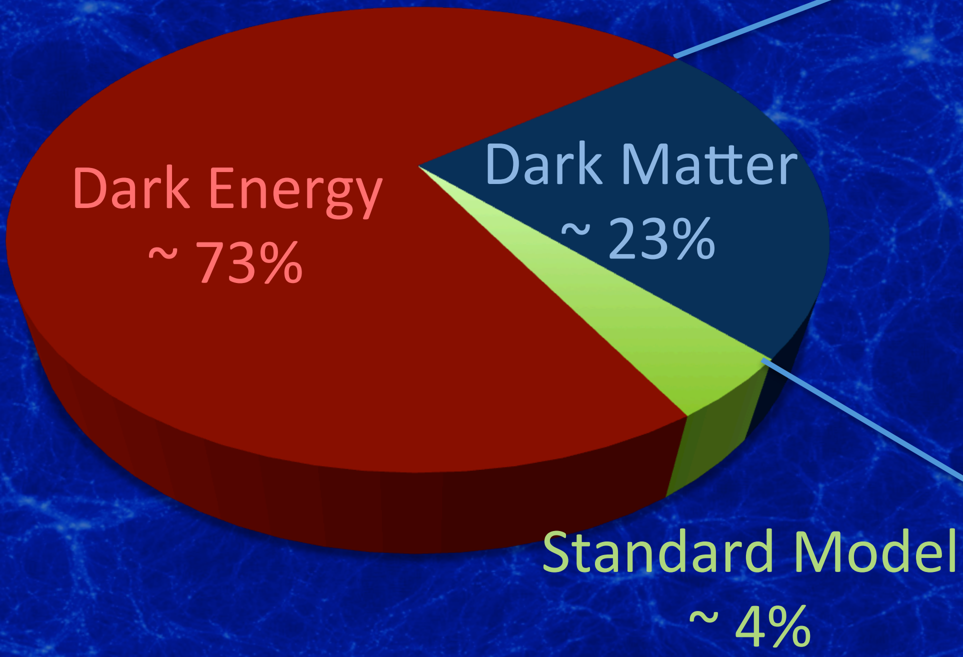
Fermi National Accelerator Laboratory

The Dark Matter Problem



L. Bergstrom Rept.Prog.Phys. 63, 793 (2000)

Composition of the Universe



<u>Dark</u>
Gravitational evidence only

<u>Cold</u>
Large scale structure

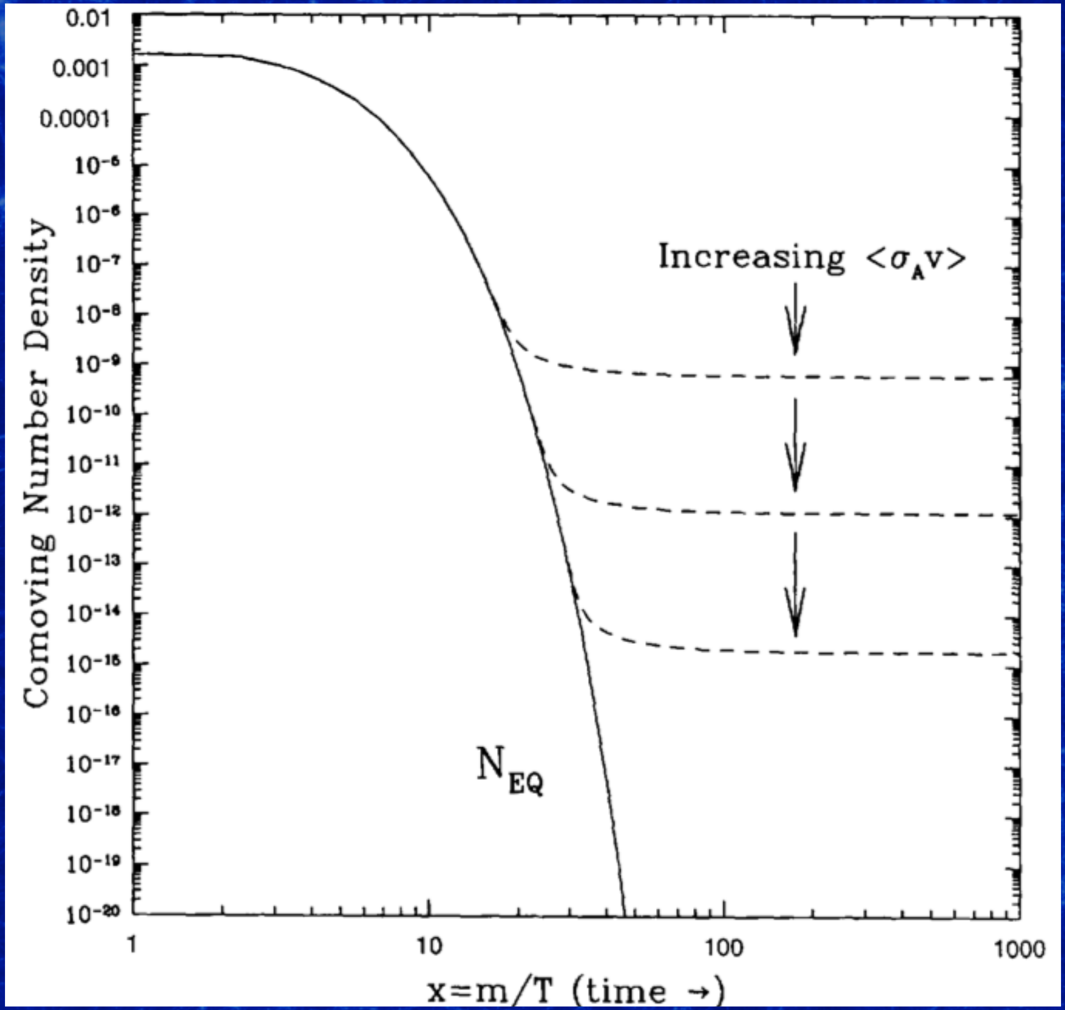
<u>Non-baryonic</u>
Big Bang nucleosynthesis
Cosmic microwave background
Structure formation

- Dark matter and dark energy are pillars of modern cosmology

Thermal Relics

- Weak scale mass and annihilation cross-section yield a thermal relic density similar to the observed DM density

Equilibrium Annihilation Freeze-out



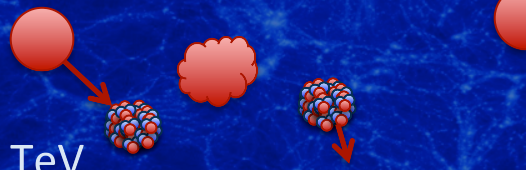
Searching for WIMPs


WIMP Production


WIMP Indirect Detection

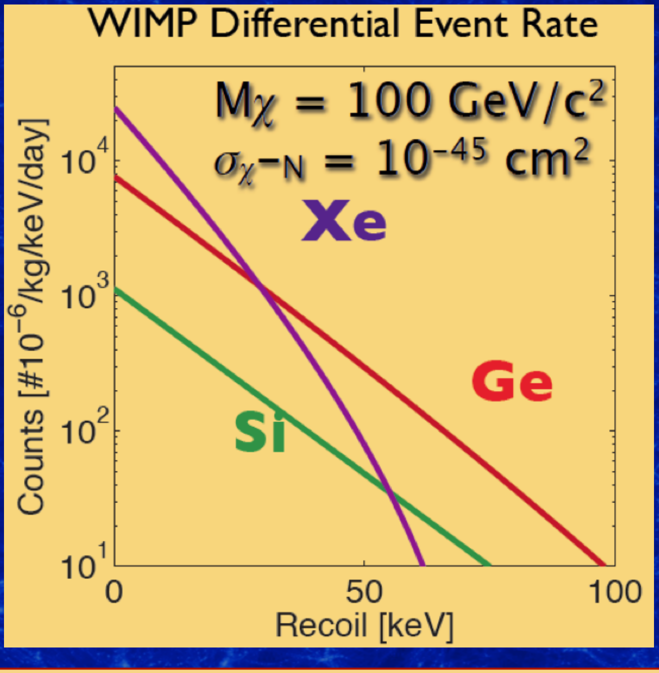

WIMP Direct Detection

Direct Detection of Dark Matter



1 GeV – 10 TeV
$\sigma_{SI} < 10^{-44}$ cm^2
$\sigma_{SD} < 10^{-36}$ cm^2

- Searching for WIMP-Nucleus elastic scattering
- In a sea of background radiation
  - Low background frontier
- Understanding and controlling backgrounds is the key to discovery
  - Assay and Materials Selection
  - Shielding
  - Discrimination



$$\frac{dR}{dE_r} = n\left\langle v\,\frac{d\sigma(v,A,N,S,?)}{dE_r}\right\rangle = \frac{R_0}{E_0 k}\, e^{-E_r/E_0 k} \propto \int_{v_{\min}}^{v_{esc}} d^3v\, \frac{d\sigma}{dE_r}\, v f(v)$$

CDMS

The Cryogenic Dark Matter Search

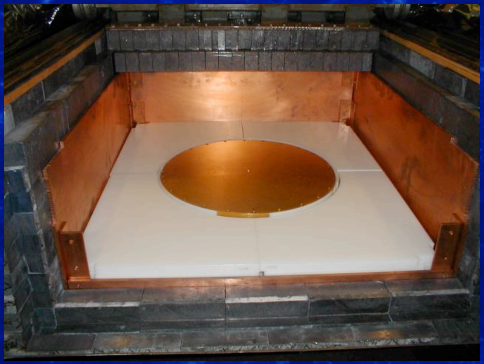
California Institute of Technology
Case Western Reserve University
Fermi National Accelerator Laboratory
Massachusetts Institute of Technology
NIST *
Queen’s University*
Santa Clara University
Southern Methodist University*
SLAC/KIPAC *

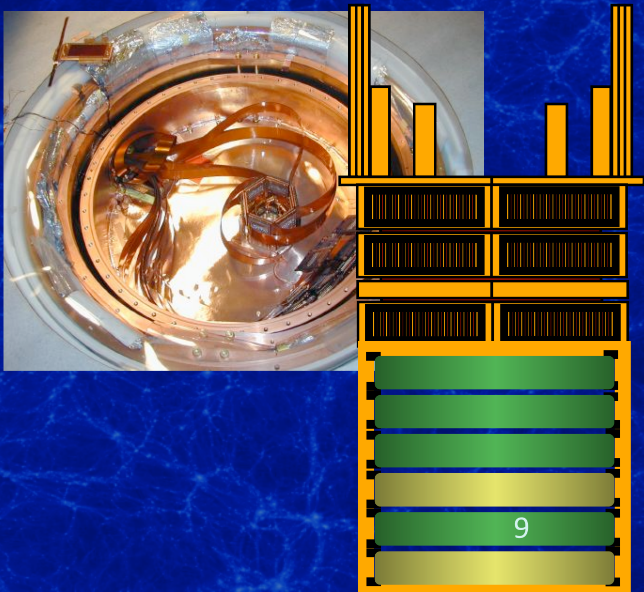
Stanford University
Syracuse University
Texas A&M
University of California, Berkeley
University of California, Santa Barbara
University of Colorado Denver
University of Florida
University of Minnesota
University of Zurich

20 institutions, 30 Faculty and Scientists, 70 Students and Postdocs

** new collaborators or new institutions in SuperCDMS*

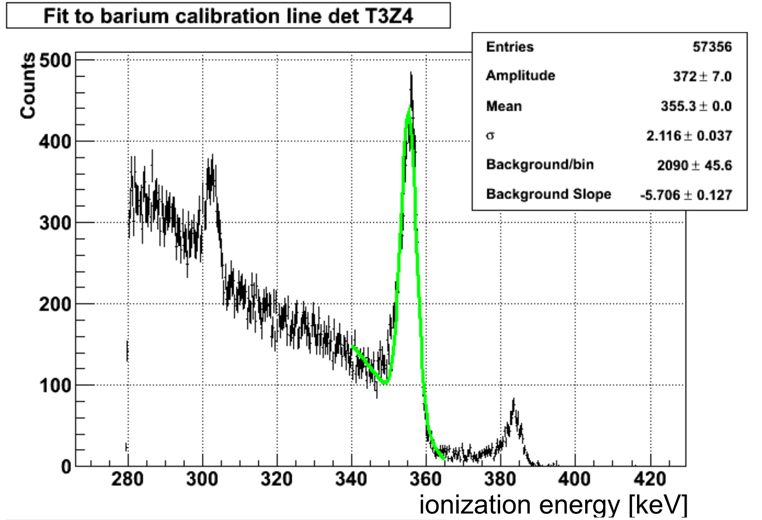
Shielding and Materials Selection

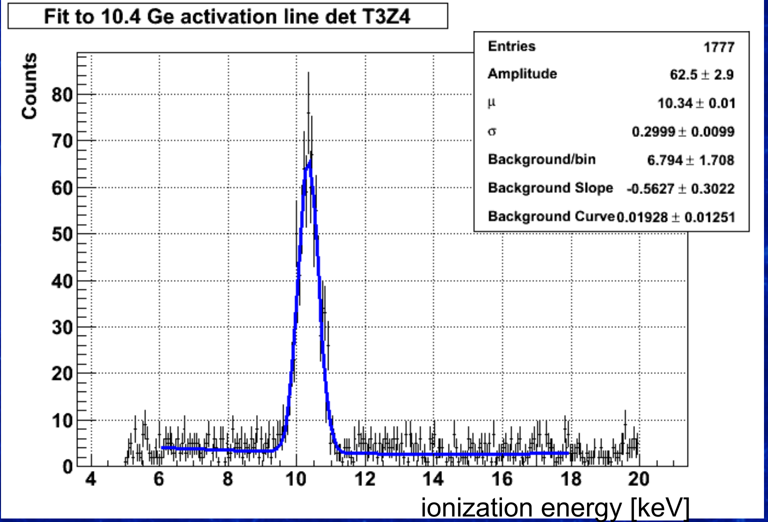


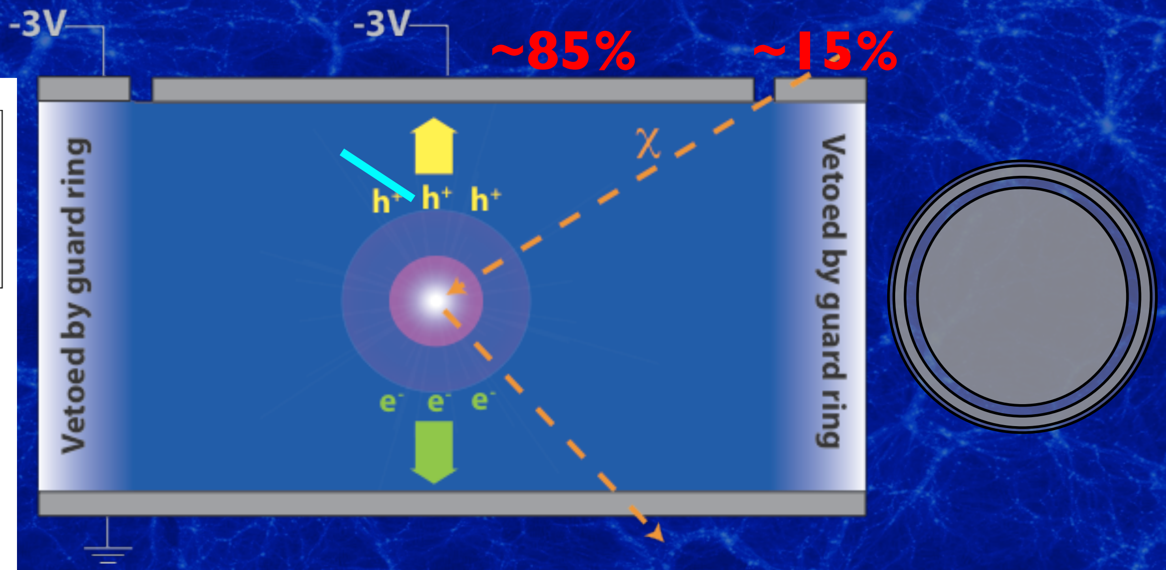


- 2000 m.w.e. (0.5 mile) rock overburden
- Plastic scintillator active veto
- 20 cm lead
- 50 cm polyethylene
- Copper cryostat
- 1 mm silicon endcaps
- Gaps between detectors minimized
- Rigorous cleanliness

Ionization Measurement







Complete collection at **3V/cm** (after trap neutralization)

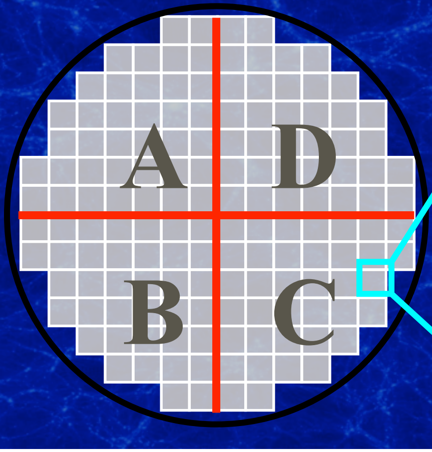
Low-noise JFET amp at 140 K: Zero-energy resolution **~100 e** (~0.5% @ 511 keV)

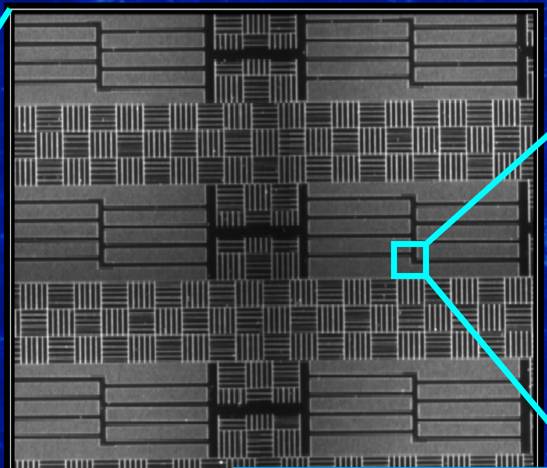
$$\text{Charge} = E_{\text{ionization}}/\varepsilon$$

$$\varepsilon_{Si} = 4\ \text{eV}$$

$$\varepsilon_{Ge} = 3\ \text{eV}$$

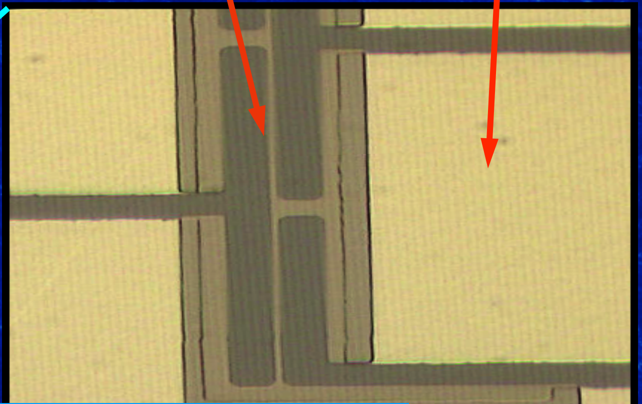
Phonon Measurement

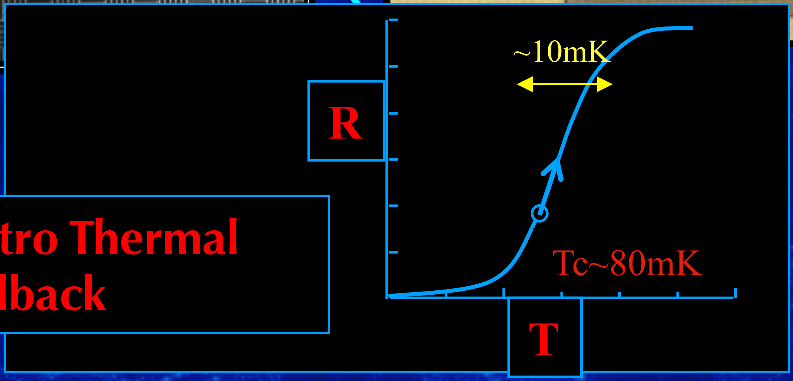




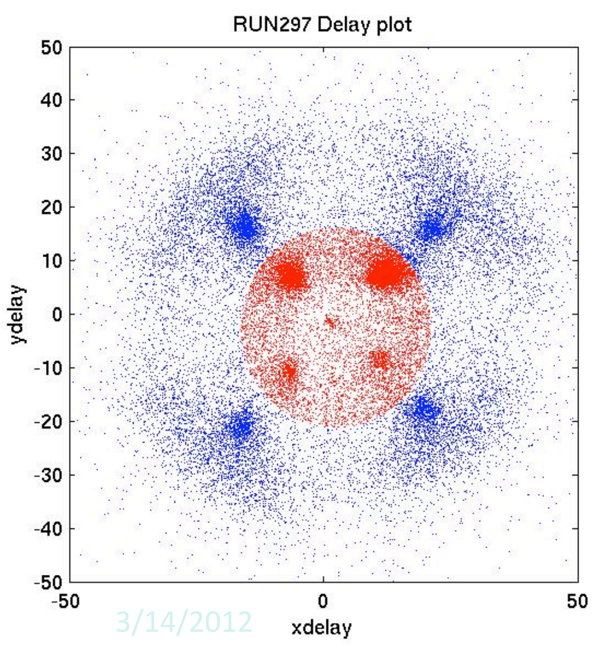
380μ x 60μ aluminum fins

1 μ tungsten





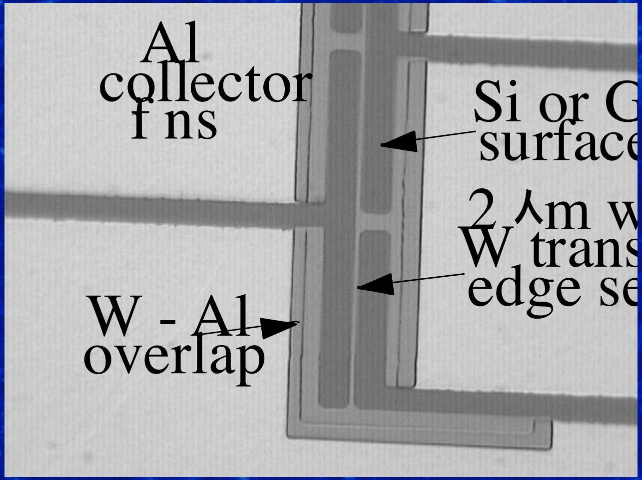
Electro Thermal Feedback

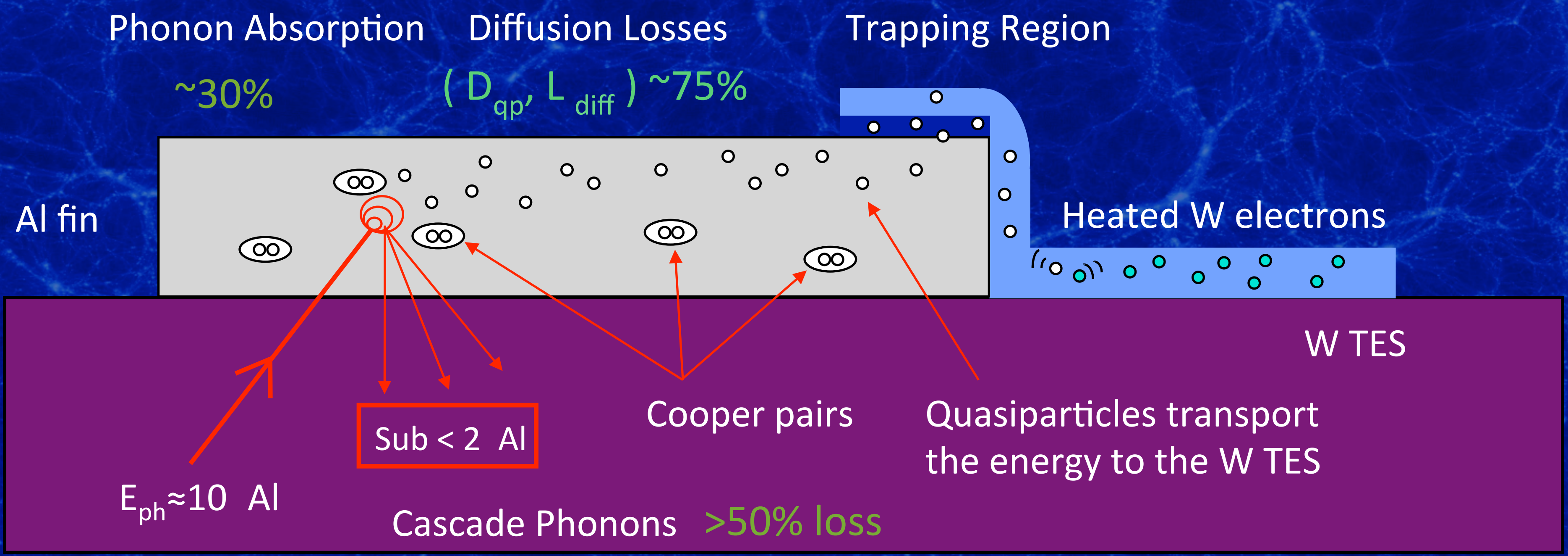


$$E_{phonon} = E_{recoil} + V \times E_{ionization}/\varepsilon$$

Athermal Phonon Sensors

- High-energy phonons (~400 GHz) from particle recoil break Cooper pairs in superconducting Al (Tc = 1 K). The Al film acts as a ‘phonon filter’ against other heating mechanisms.
- Resultant quasiparticles diffuse towards the tungsten trap where electron scattering heats up the W tungsten transition edge sensors (Tc ~ 70 mK)





Phonon Absorption

~30%

Diffusion Losses

(D_{qp}, L_{diff}) ~75%

Trapping Region

Al fin

Heated W electrons

W TES

E_{ph}≈10 Al

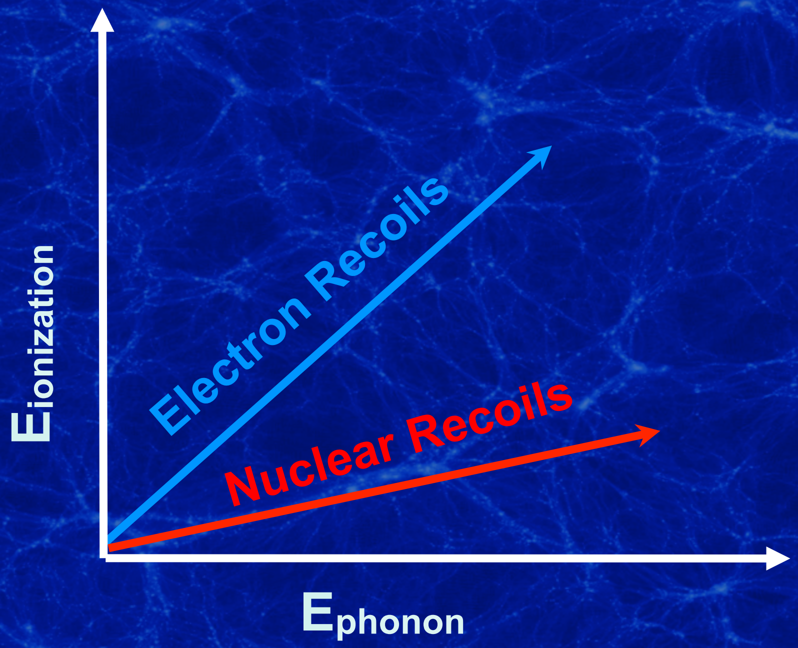
Sub < 2 Al

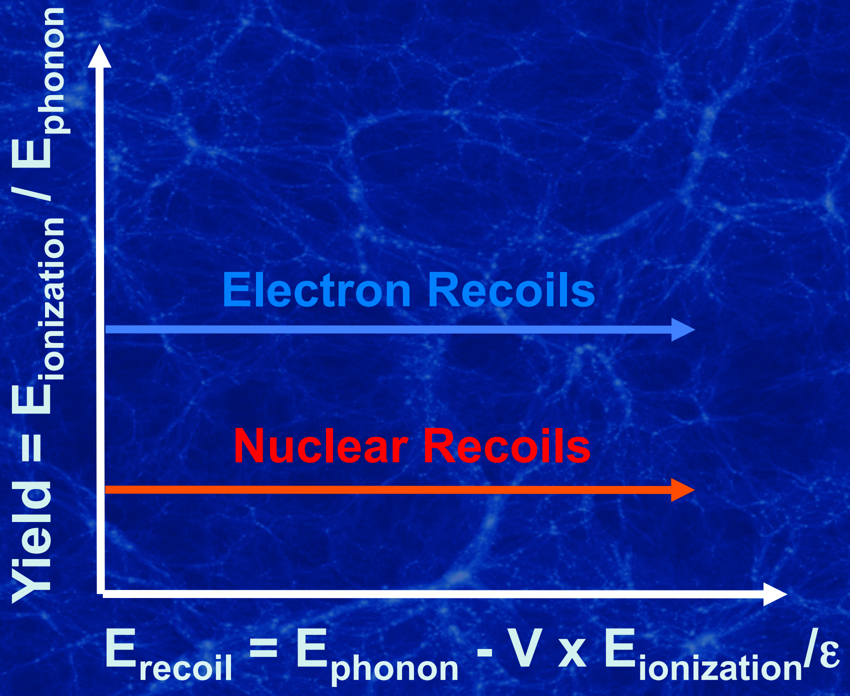
Cooper pairs

Quasiparticles transport the energy to the W TES

Cascade Phonons >50% loss

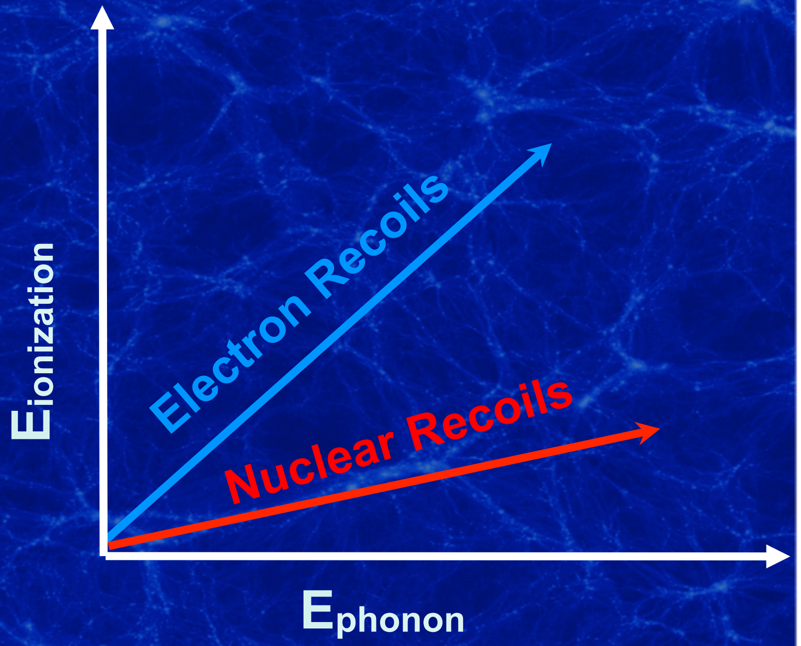
Ionization Yield and Recoil Energy

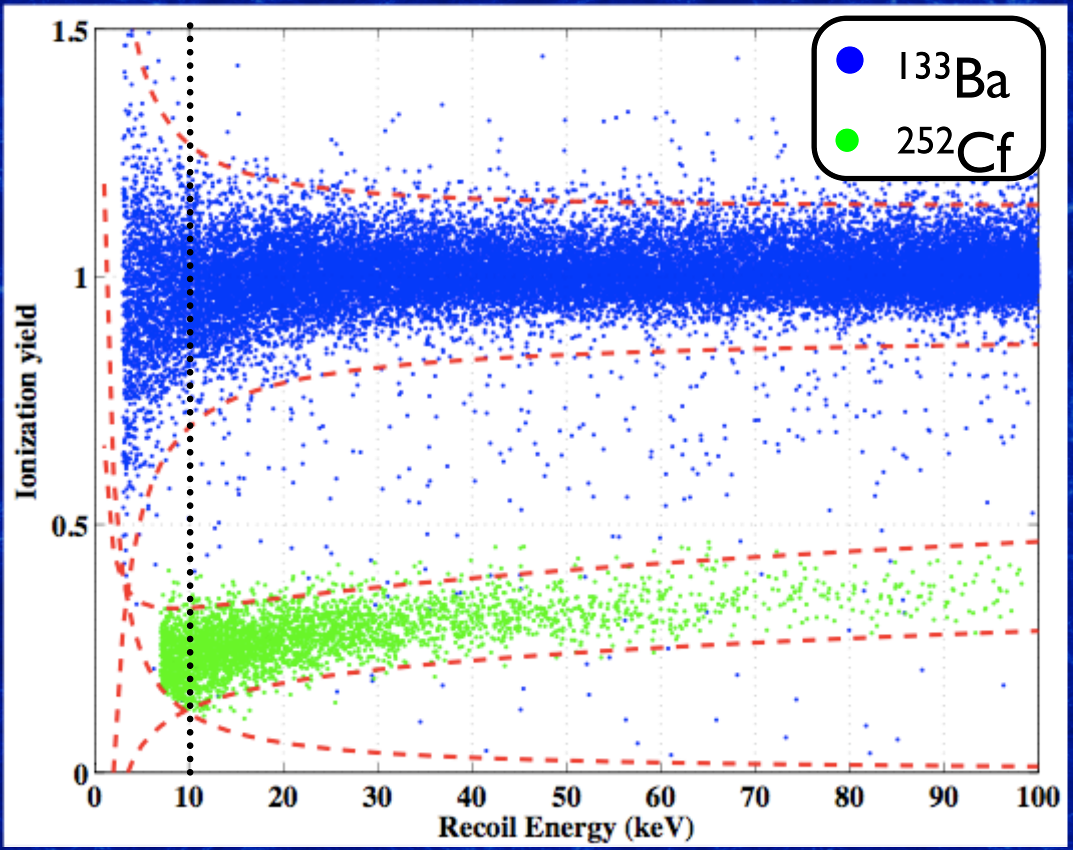




$$E_{recoil} = E_{phonon} - V \times E_{ionization}/\varepsilon$$

Ionization Yield and Recoil Energy

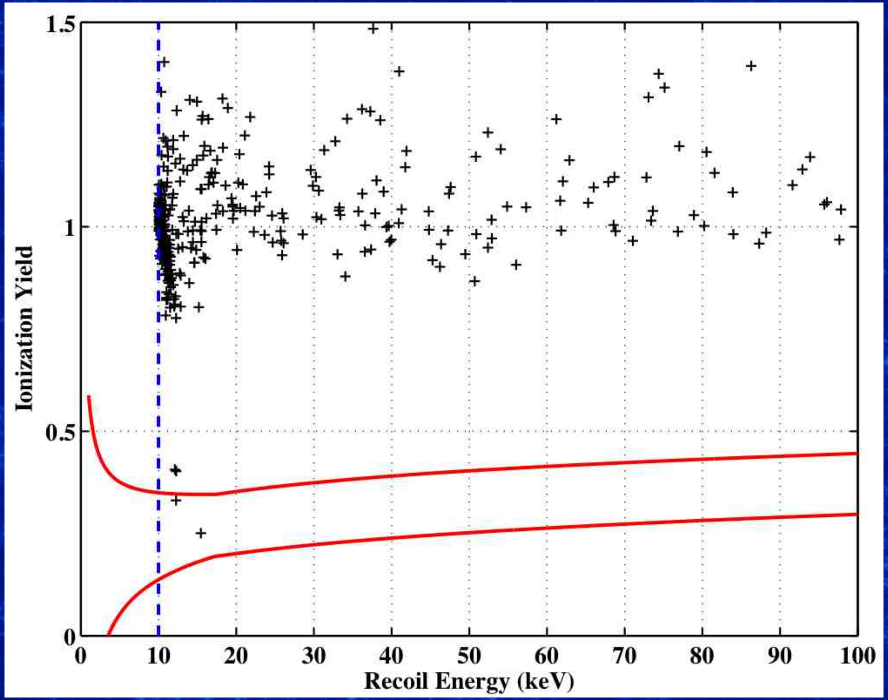




Better than 1:10^4 event by event gamma discrimination based on yield

Example WIMP Search Results (315 kg day)

- 2 events passing all cuts after an exposure of ~2 years
- Background estimate of 0.9 ± 0.1 (stat) ± 0.2 (sys) events
  - 0.8 surface events with poor charge collection
  - 0.1 neutrons scatters
- Exceptional discovery potential
- Limits of CDMS-II technology



CDMS progress

1 kg Ge

0 ev, 52.6 kg.days
10/2003 to 01/2004

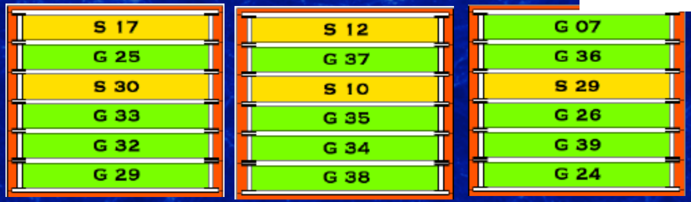
Phys. Rev. Lett. **93, 211301 (2004)**

1.5 kg Ge

1 ev, 93.1 kg.days
03/2003 to 08/2004

Phys. Rev. Lett. **96, 011302 (2006)**

4.5 kg Ge

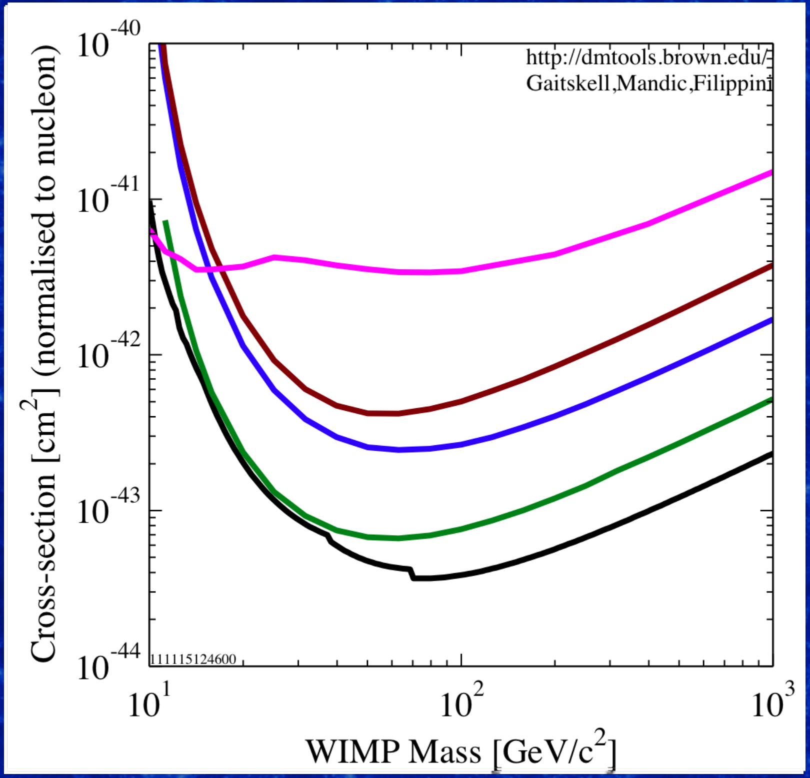


0 ev, 397 kg.days
10/2006 to 03/2007

2 ev, 1200 kg.days
04/2006 to 10/2008

Science **327, p. 1619,** **arXiv:0912.3592**

Phys. Rev. Lett. **102, 011301 (2009)**



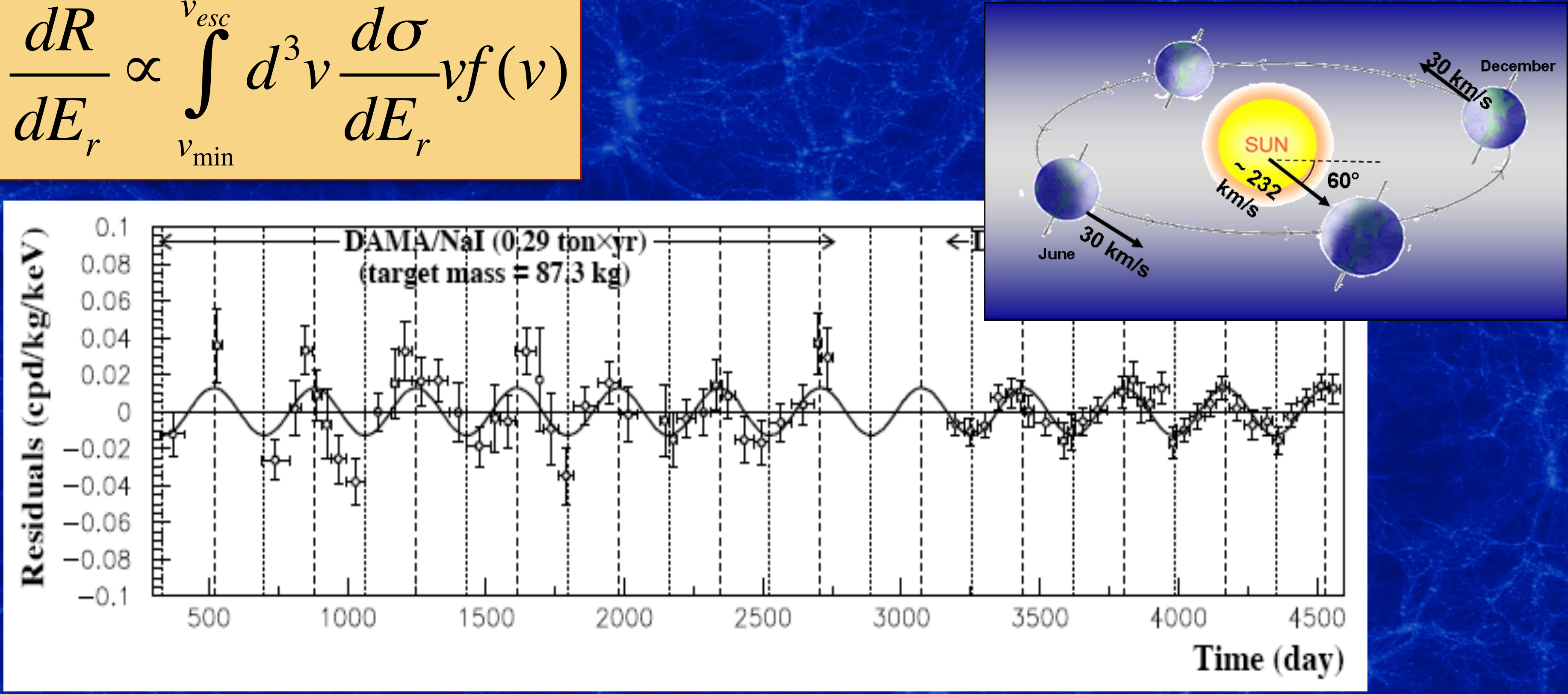
CDMS backgrounds under control:
So far independent of the exposure!

But ZIPs seem to have reached their rejection limit and can't offer better sensitivities.

Light Dark Matter

DAMA Annual Modulation

$$\frac{dR}{dE_r} \propto \int_{v_{\min}}^{v_{esc}} d^3v \, \frac{d\sigma}{dE_r} v f(v)$$

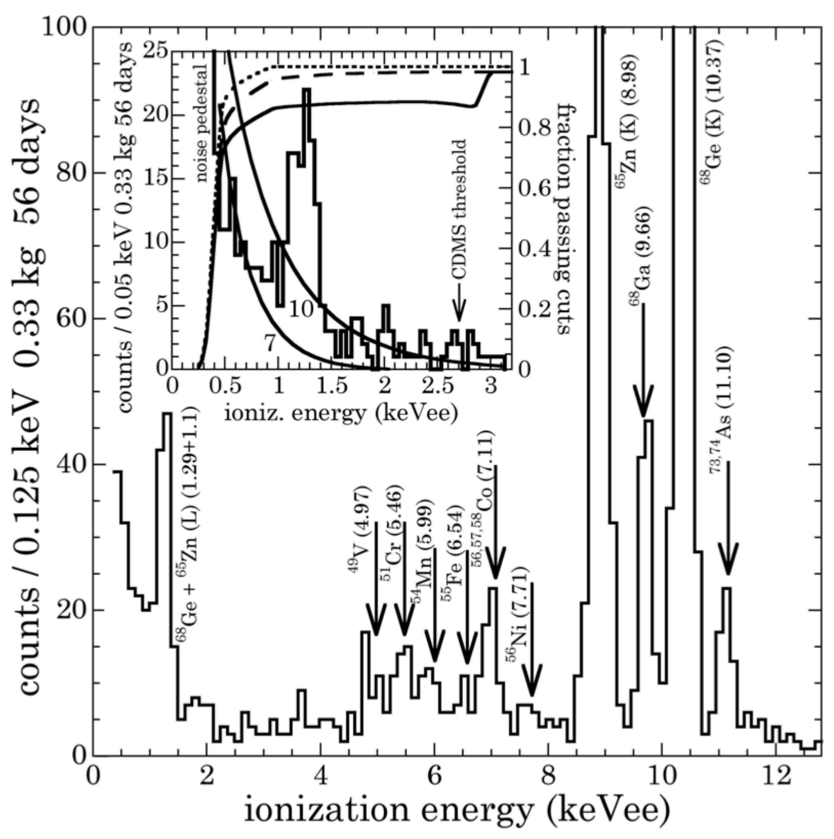


Bernabei et al., Eur. Phys. J. C ***56*** *333 (2008)*

- DAMA annual modulation search has measured an 8 sigma effect over ten years consistent with the dark matter hypothesis
- New theories in 2008 suggested that light (<10 GeV) WIMPs may be an interpretation

CoGeNT Low Energy Excess

- High purity Ge ionization detector optimized for low noise
- Low energy (<2 keVee) excess of events
- Spectrum ‘consistent with dark matter elastic scatters’, ie it is roughly exponential



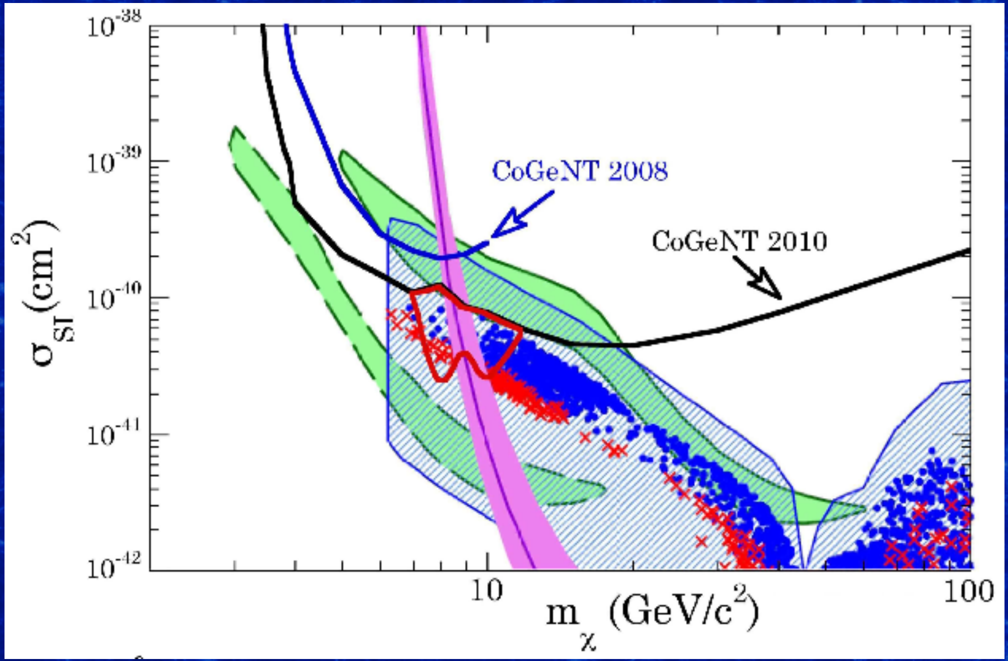
Aalseth et al., PRL 106, 131301 (2011)

Physics search outcomes

- Positive evidence
  - There is a significant excess of signal events. Measurements of the signal properties ensue.
- No evidence
  - There is no significant excess of signal events. Limit the new physics. The sensitivity is expected to increase like $(MT)^{\gamma}$ where γ=0.5-1.
- Ambiguous
  - The systematic error on the background is unknown, so it isn't clear if there is a signficant excess. Take the events as 'signal' and derive one sided limits. The sensitivity is not expected to increase until the backgrounds are understood.
  - You should not interpret this as the 'positive evidence' case.

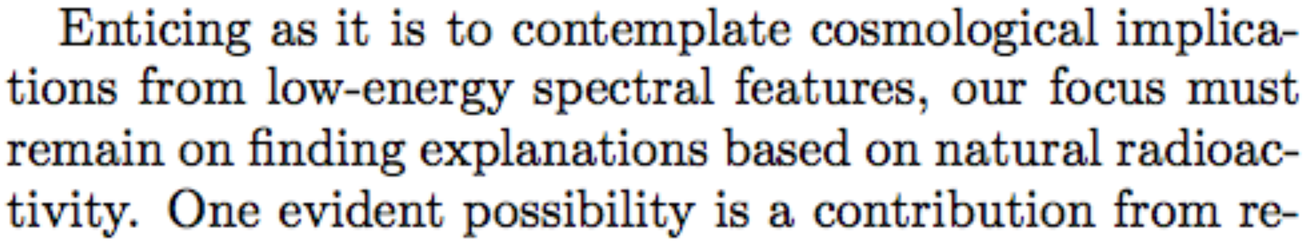
How not to detect dark matter

- CoGeNT does not understand their backgrounds in the region of interest



Aalseth et al., PRL 106, 131301 (2011)

- Therefore,

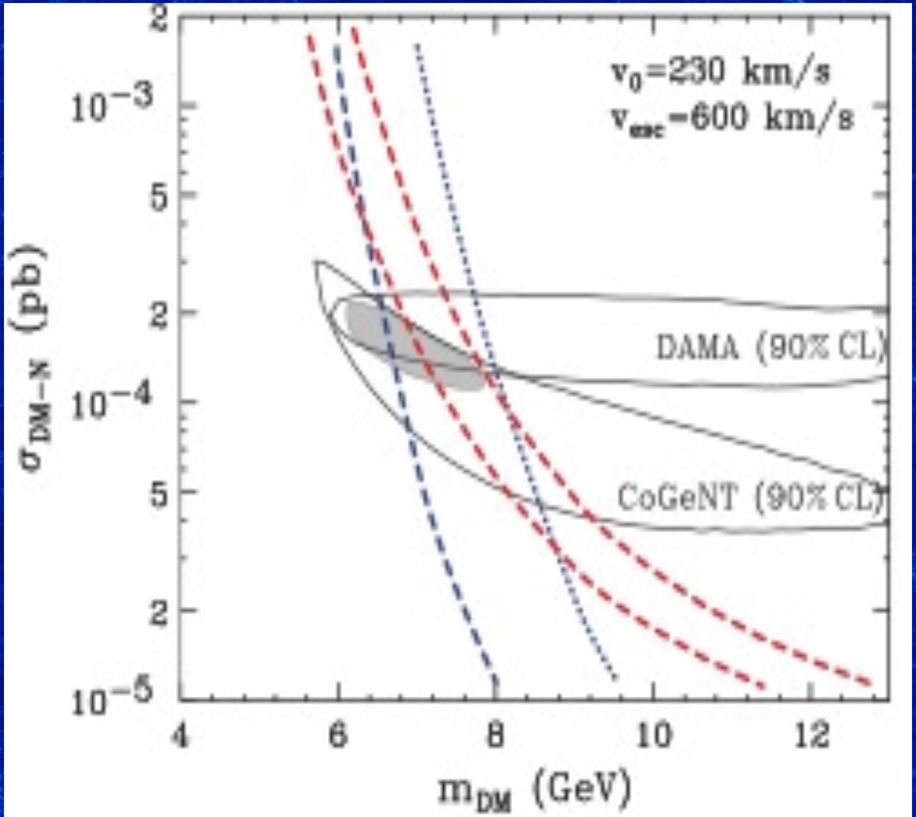


Enticing as it is to contemplate cosmological implications from low-energy spectral features, our focus must remain on finding explanations based on natural radioactivity. One evident possibility is a contribution from re-

Aalseth et al., PRL 106, 131301 (2011)

Light Dark Matter

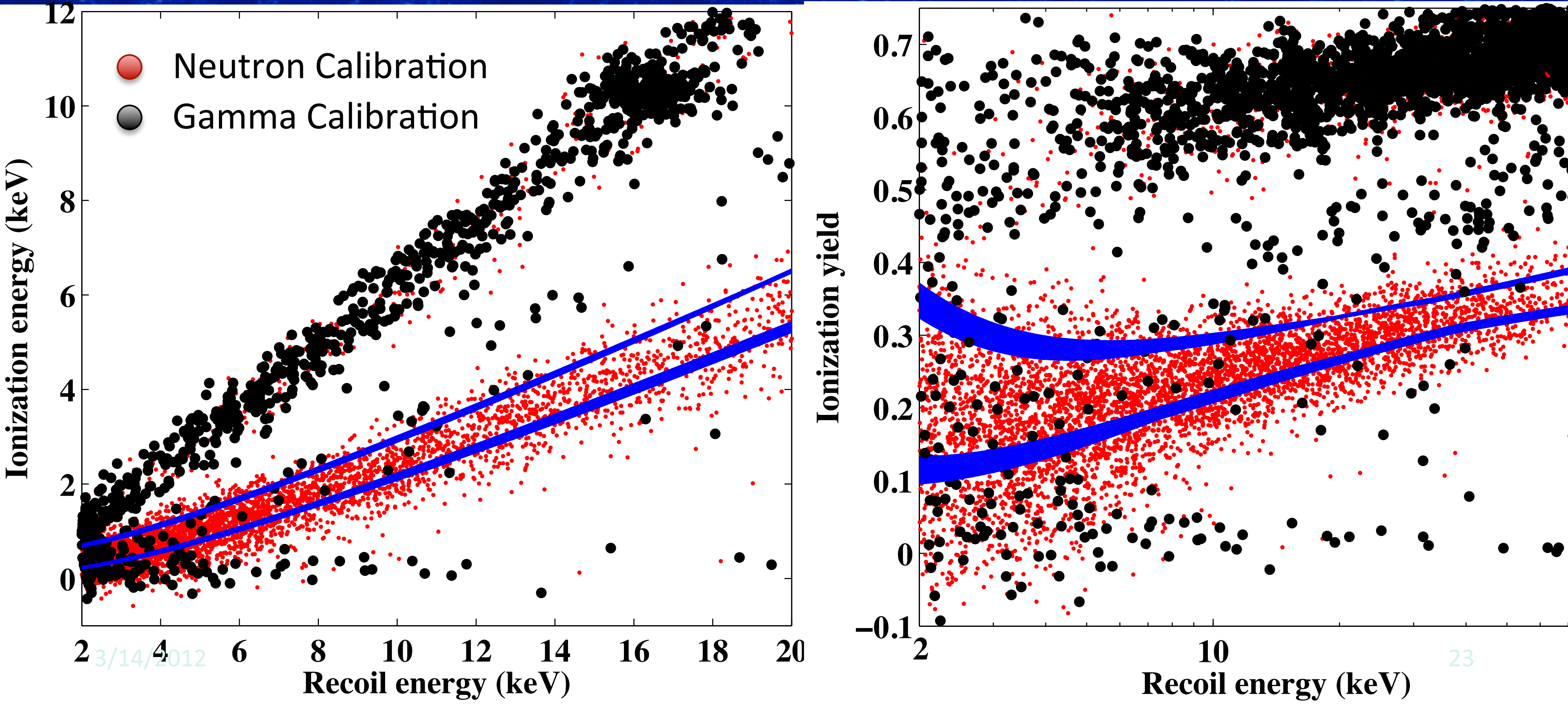
- Recent results from DAMA/LIBRA, CoGeNT and others have been interpreted as possible evidence for elastic scatters from WIMPs with m_x~7 GeV and σ_{SI}~1x10^{-40} cm^2
- Previous CDMS Ge results not sensitive to these models since thresholds were ~10 keV (to maintain expected backgrounds <1 event)
- CDMS can lower thresholds significantly at cost of higher backgrounds



Hooper, Collar, Hall, McKinsey, and Kelso, Phys. Rev. D ***82****, 123509 (2010)*

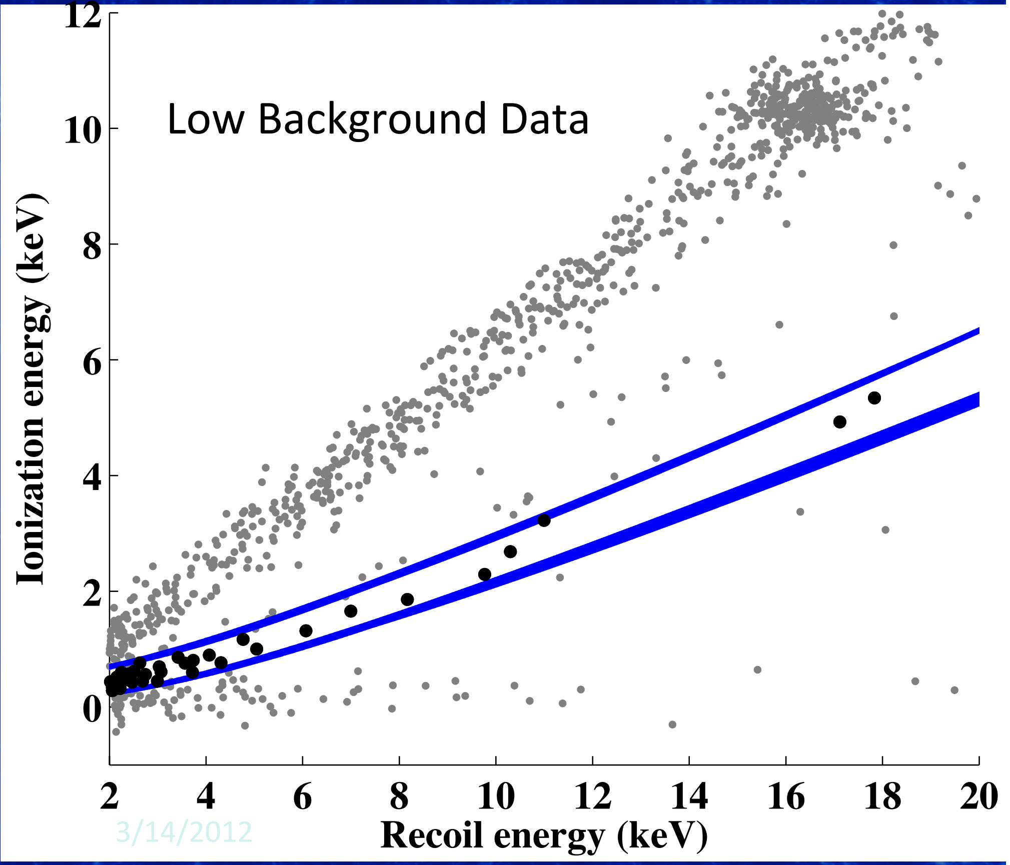
Low Energy Events in CDMS

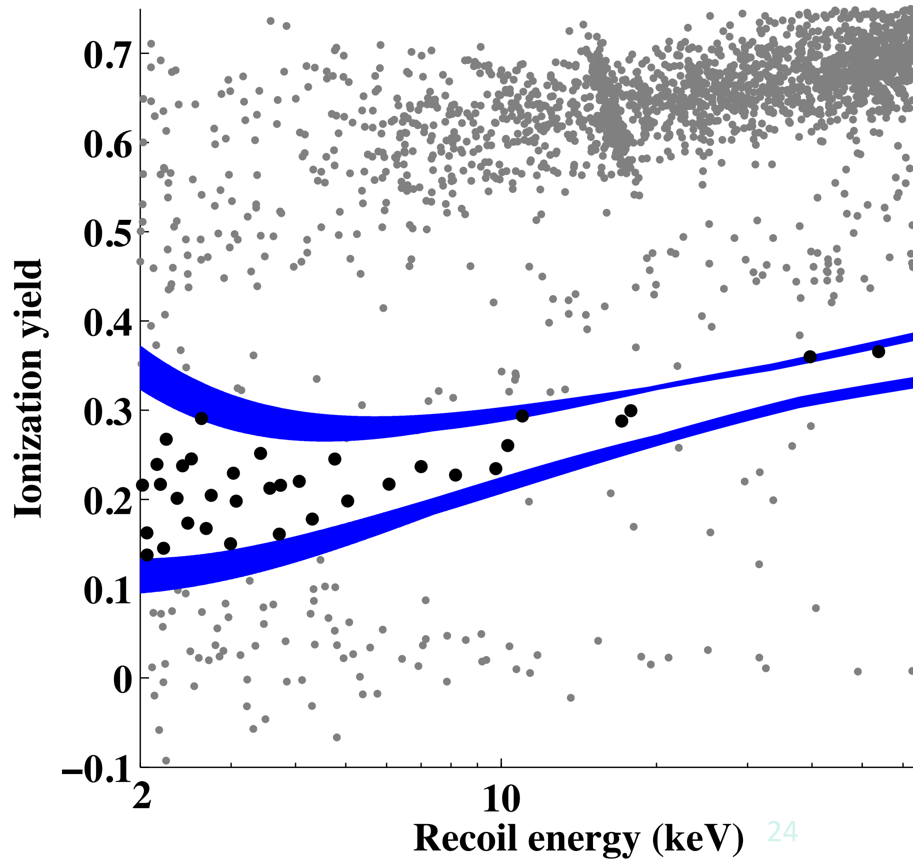
- At low energies the discrimination between nuclear and electron recoil worsens
- Still effective at reducing backgrounds, but not eliminating them
- Analysis not ‘discovery’ only used to setting limits



Low Energy Events in CDMS

- Many more background events accepted at low energies



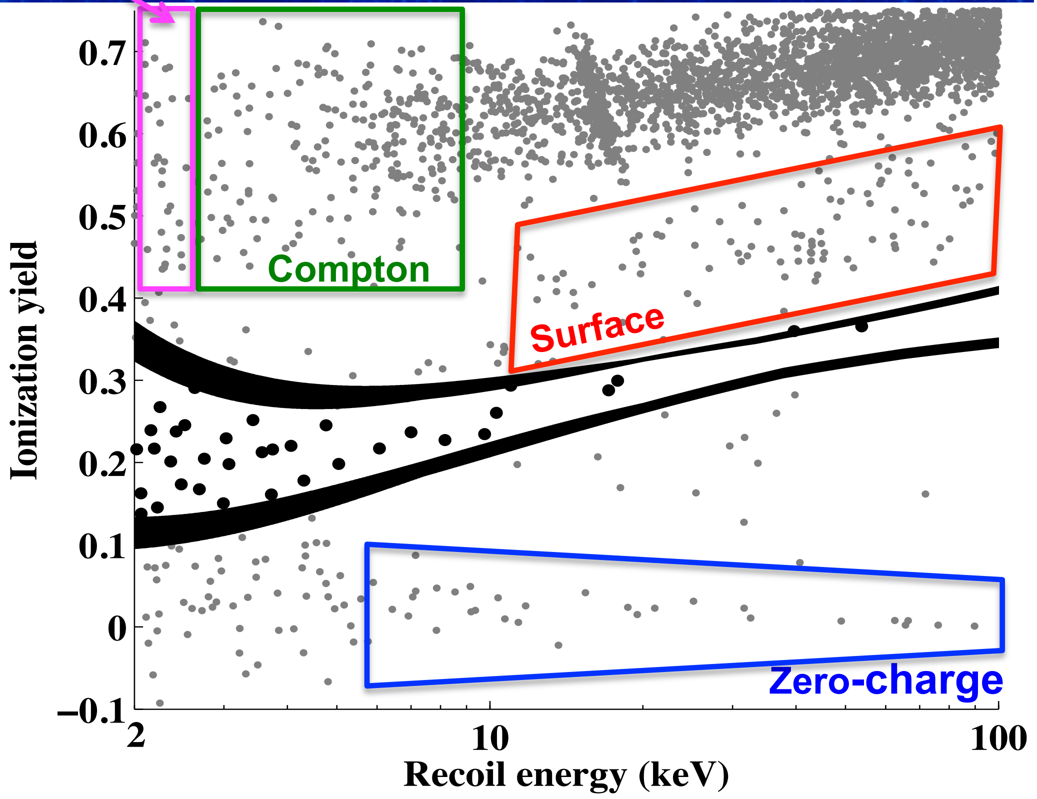


Low Energy Events in CDMS

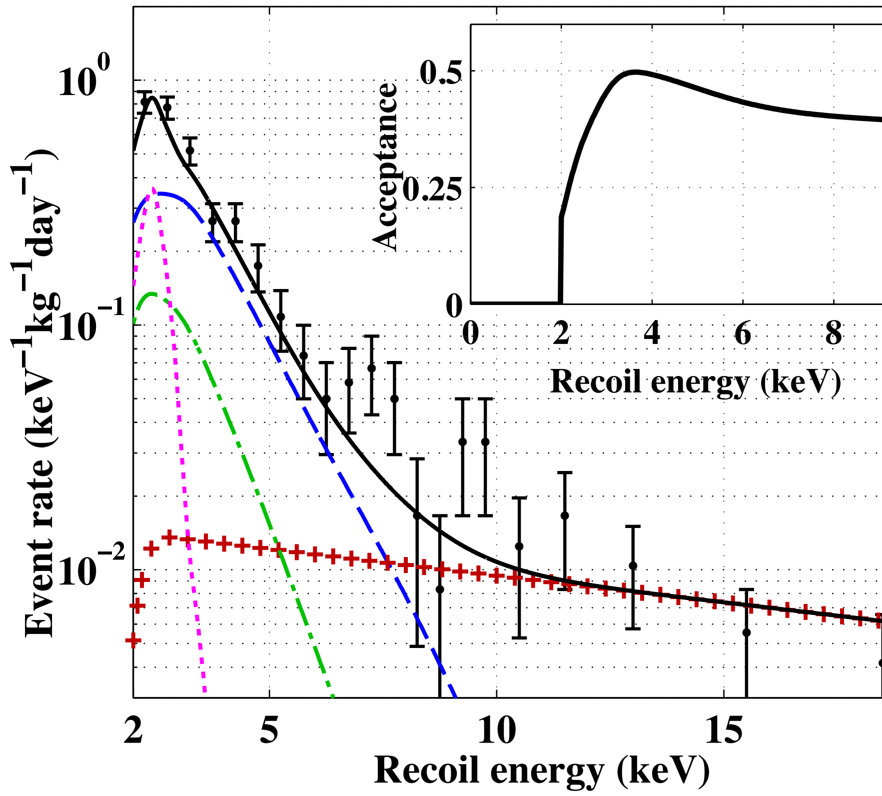
- Extrapolation of backgrounds plausibly explains events in signal region

1.3 keV line

Sidebands for background estimate:

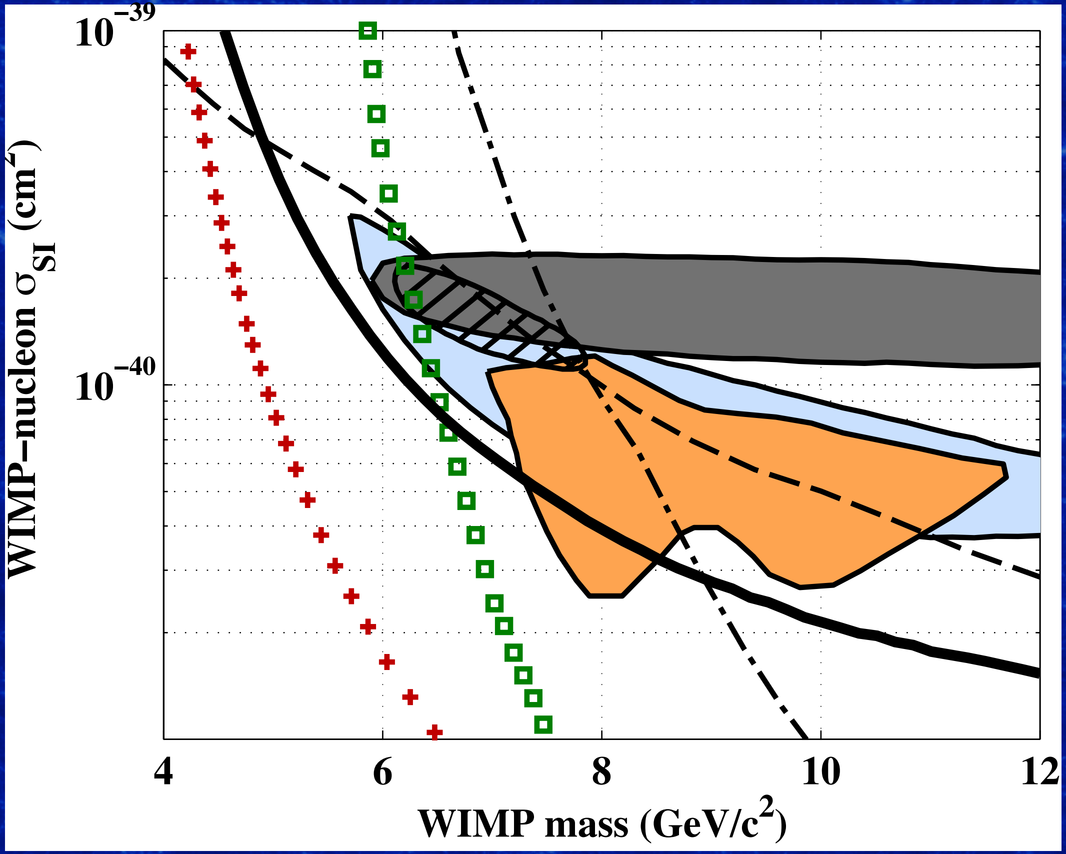


Expected background spectra:



Low Energy Results from CDMS

- CDMS-II data excludes the low mass interpretation of CoGeNT/DAMA



Ahmed et al., PRL **106**, 131302 (2011)

Low Energy Results from CDMS

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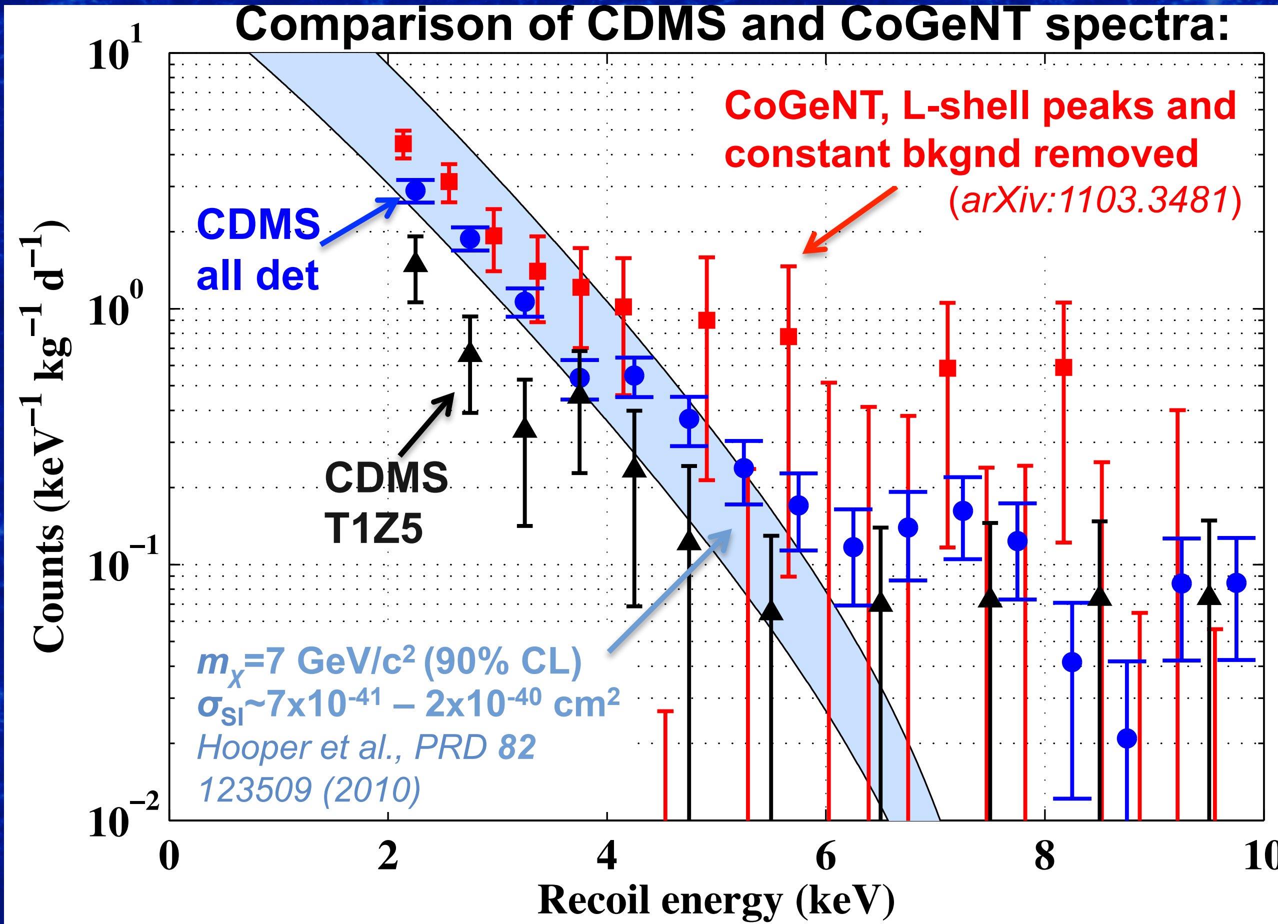
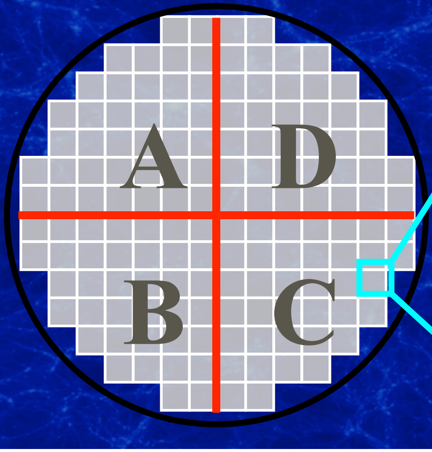
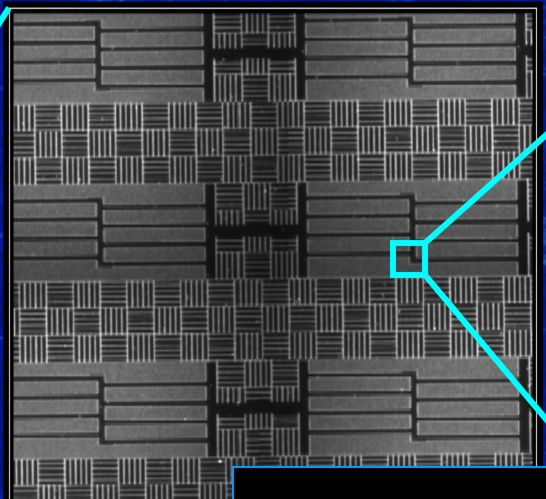


Ahmed et al., PRL **106**, 131302 (2011)

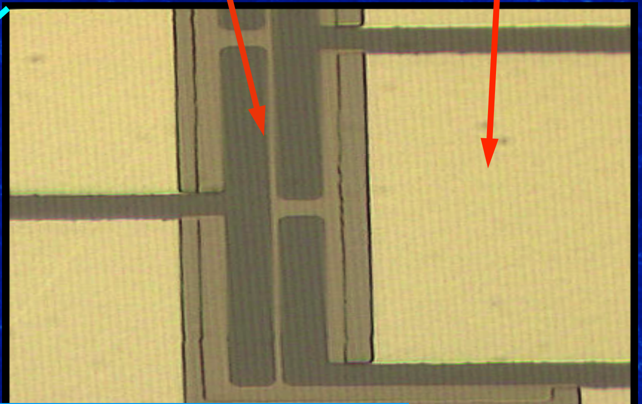
Bolometric Ionization Amplification

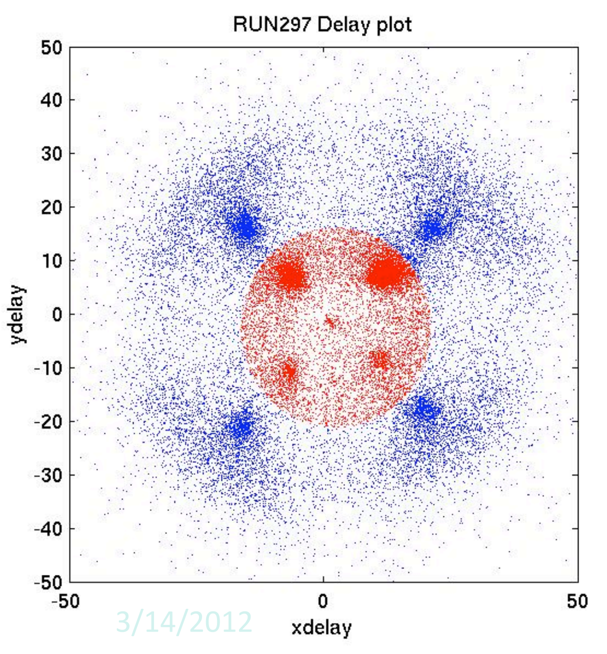


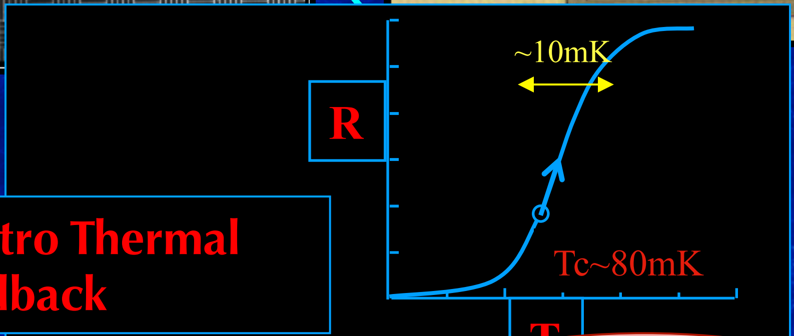


380μ x 60μ aluminum fins

1 μ tungsten







Electro Thermal Feedback

$$E_{\text{phonon}} = E_{\text{rec}} + V \times E_{\text{ionization}}/\varepsilon$$

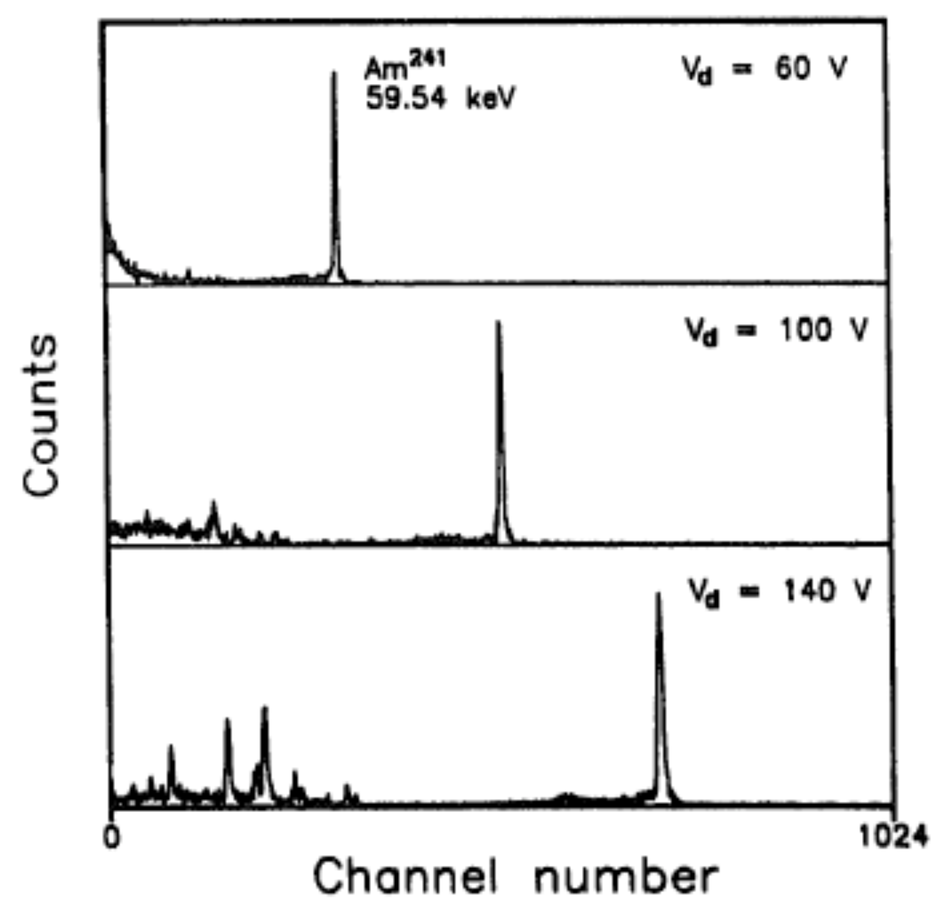
Neganov-Luke Amplification

- First Suggestion
  - B. Neganov and V. Trofimov, Otkryt. Izobret. 146, 215 (1985)
  - P.N. Luke, J.Appl.Phys 64, 12 (1988)
  - P.N. Luke et al., NIM A289, 406 (1990)
- Investigation for dark matter
  - N.J.C. Spooner et al., Phys. Lett. B278, 382 (1992)
- Photon detection for CRESST
  - M. Stark et al., NIM A545, 738 (2005)
- Using CDMS detectors for coherent neutrino elastic scattering
  - D.S. Akerib et al., NIM A520, 163 (2004)

Luke Amplification

Exponential is the most generic spectrum, especially near the electronic noise of detectors

Good signal to noise is an important ingredient for understanding a dark matter signal

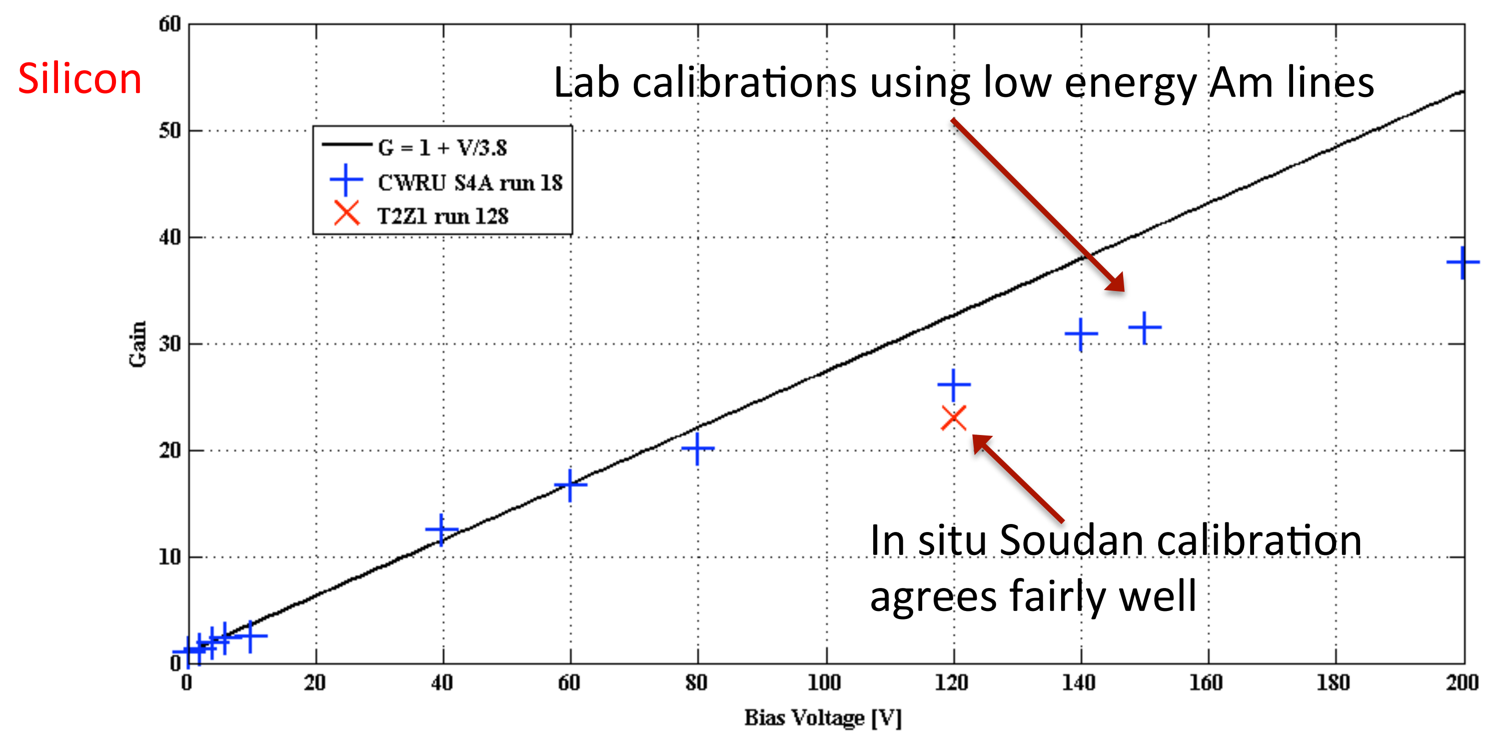


P.N. Luke et al., NIM A289, 406 (1990)

Turning it up to 11

- CDMS electronics max bias is 10V, Luke gain of 2
- Parasitic investigation during CDMS
  - CDMS low ionization threshold experiment (CDMSlite)

Luke Gains - Si

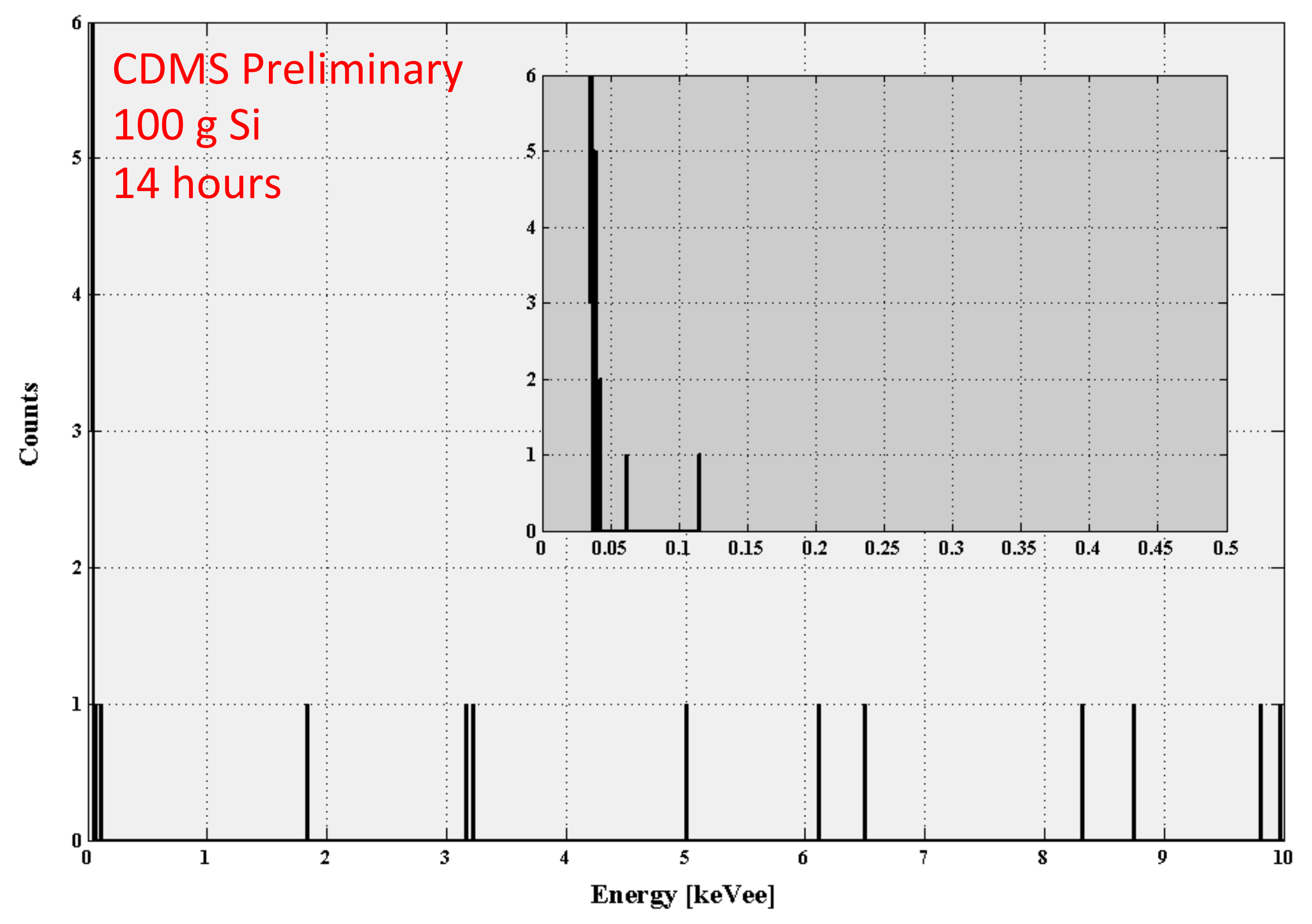


Lab calibrations using low energy Am lines

In situ Soudan calibration agrees fairly well

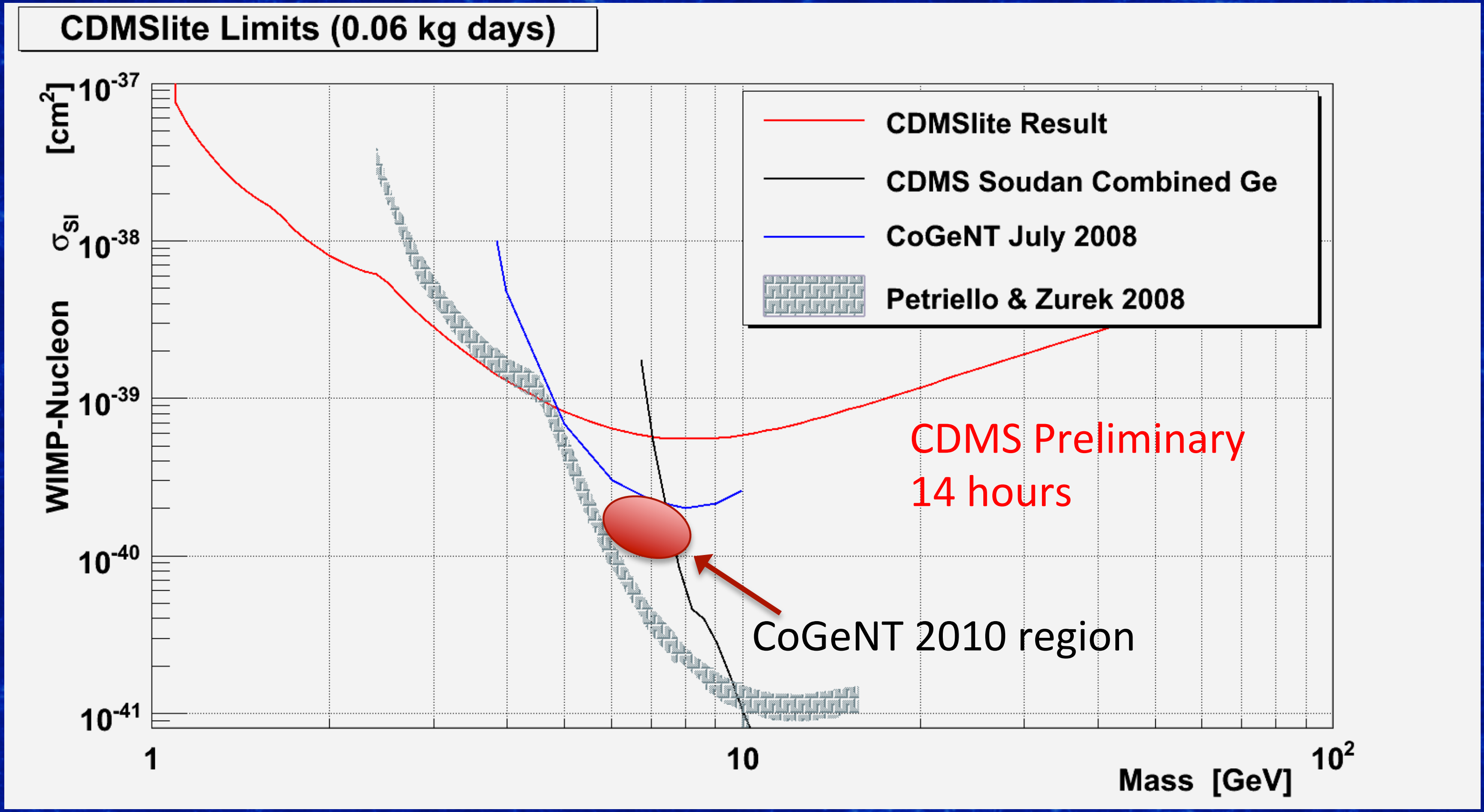
- Gain deviates from theory, coincident with turn on of field emission (increase in noise)

CDMS Luke amplification



- Signal gain of 22 with ~50% increase in noise
- 50 eV threshold in Soudan (12 eh pairs)

CDMS Luke amplification



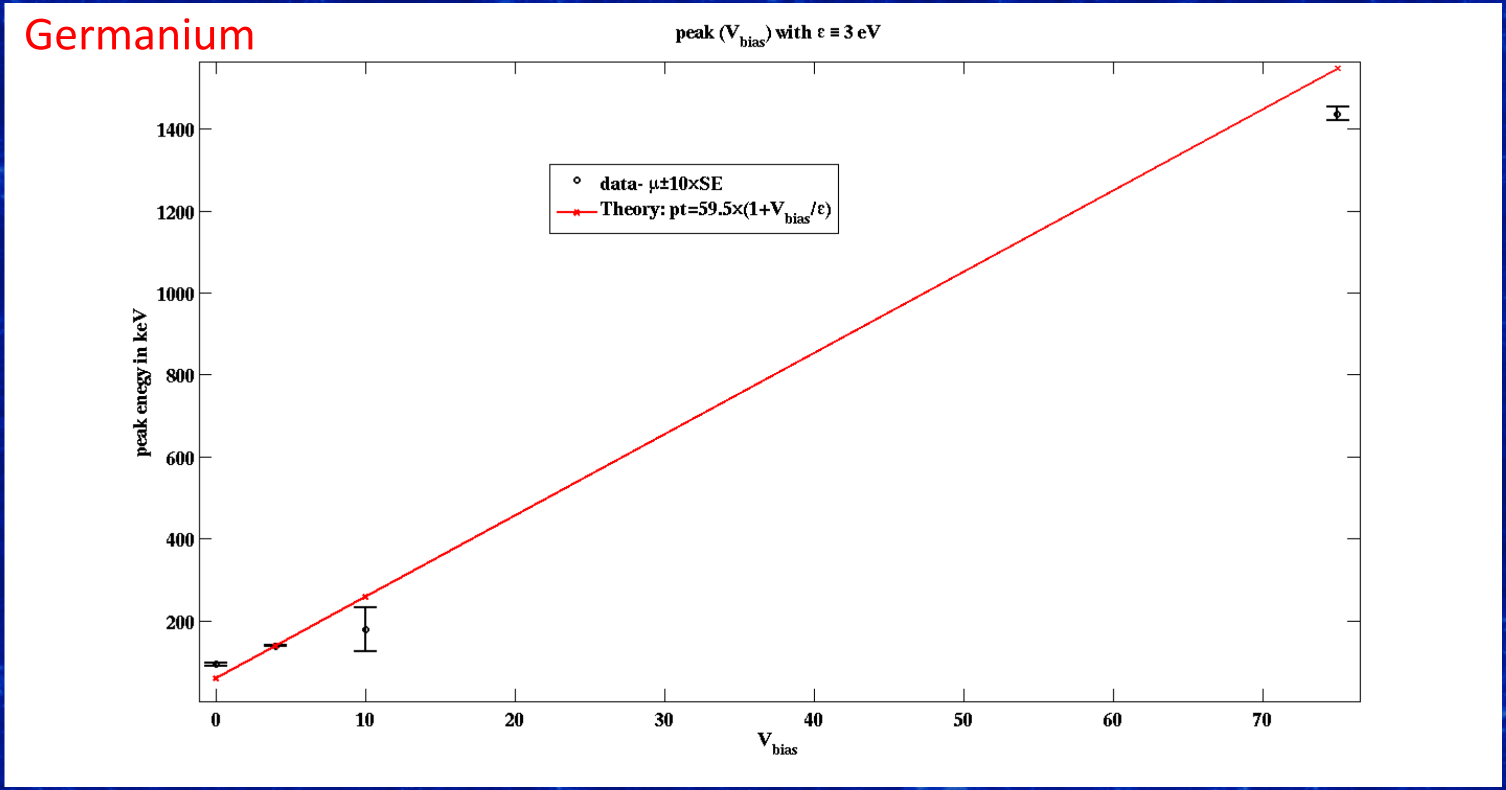
- Not quite at CoGeNT sensitivities (only 14 hrs)
- Much less dependent on systematic issues

Future Prospects

SuperCDMS Luke Amplification Advantages

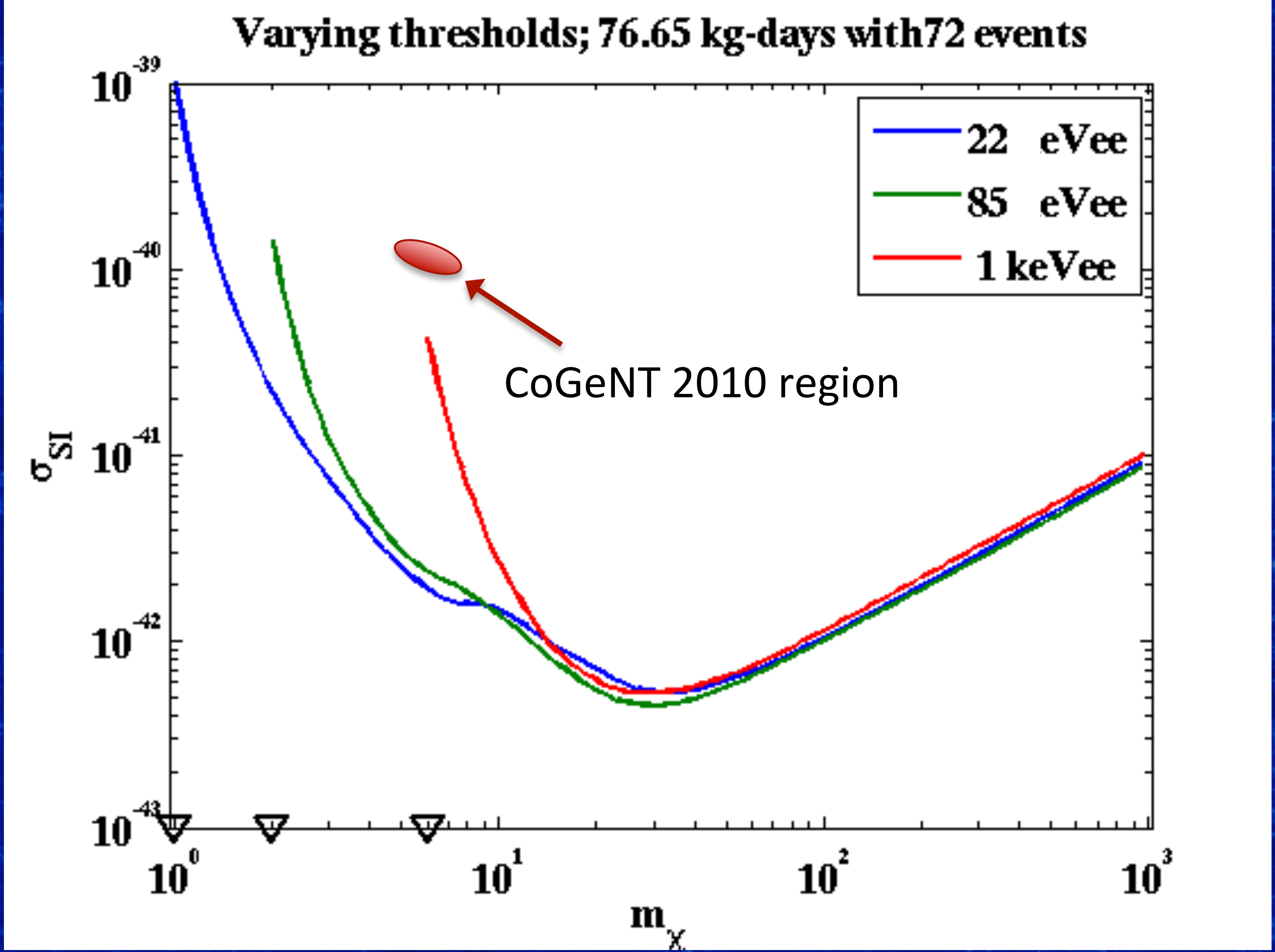
- Better linearity
- Germanium has low energy lines for calibration
- 2.5X Thicker = 2.5X less E
  - Field emission at higher V
  - Breakdown at higher V

Luke Gains - Ge



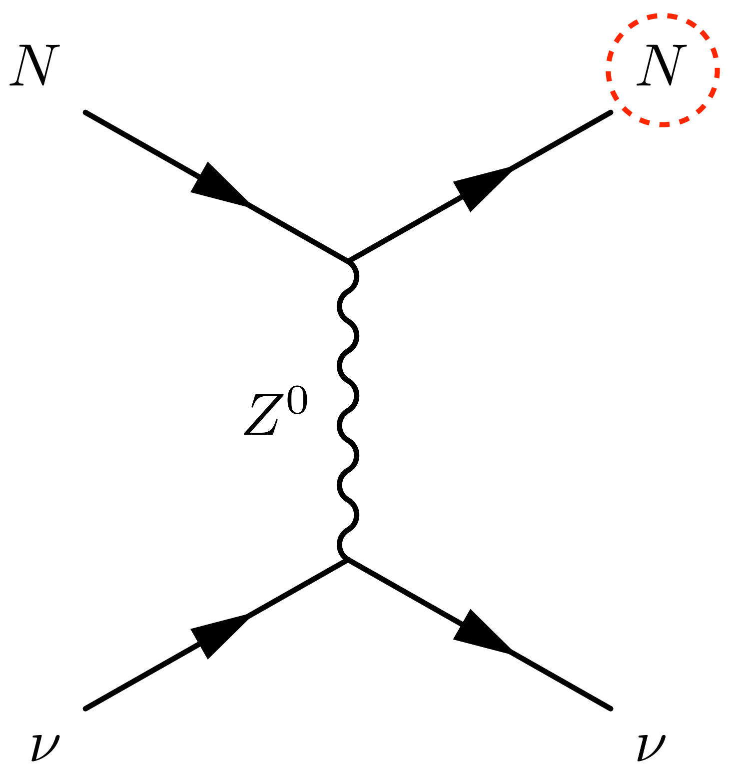
- Gain is closer to the theoretical expectation in Germanium
  - Evidence that higher gains are possible with 2.5X thicker SuperCDMS detectors
- Significant detector to detector variations seen
  - Sensitive to, or measuring, substrate properties

Projected Sensitivity



- Projections are promising, sensitivity to ~1 GeV WIMP mass
- Less dependent on systematic issues in CoGeNT region

Coherent Neutrino Scattering

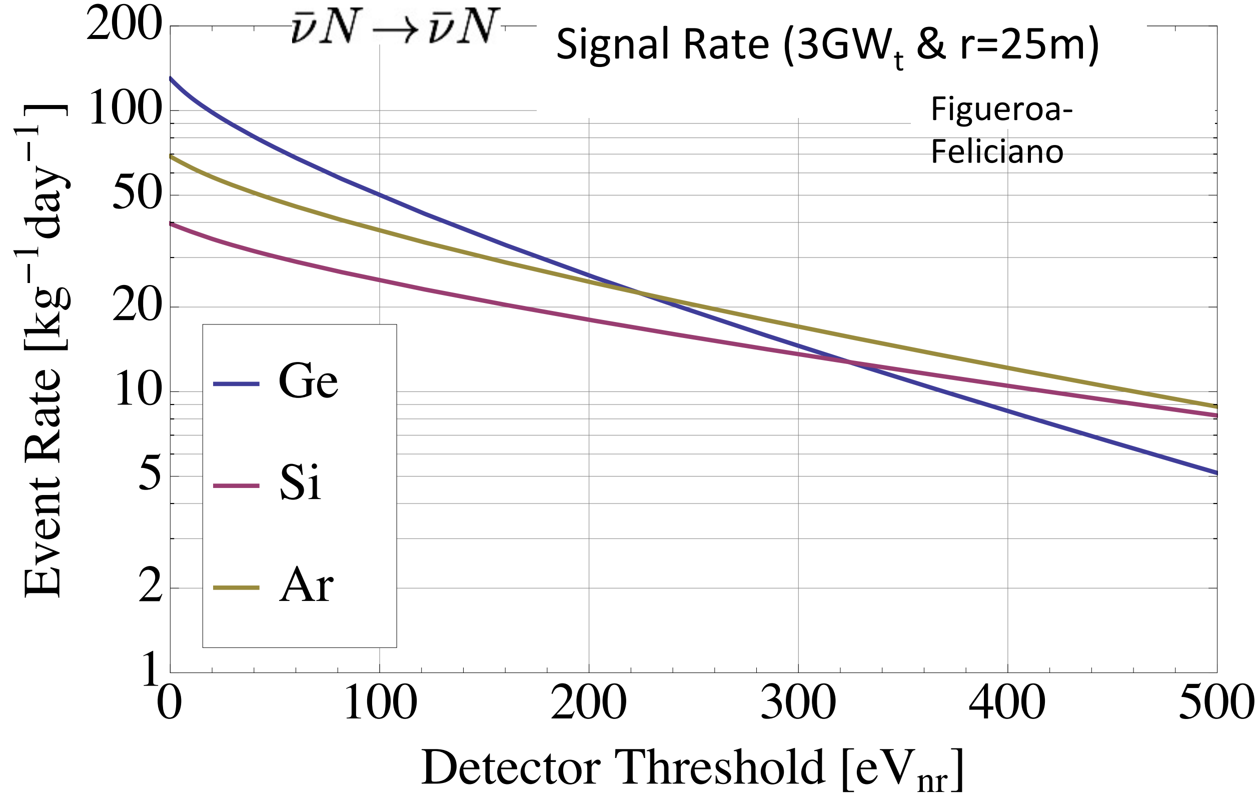


$$\sigma_{\nu N\rightarrow\nu N} \simeq \frac{G_F^2}{4\pi}N^2E_\nu^2$$

	E_ν=3MeV
Ge	6.0x10^{-41}cm^2
Ar	1.8x10^{-41}cm^2
Si	7.4x10^{-42}cm^2

- Largest standard model neutrino cross-section
- Independent of flavor – unique sterile neutrino searches possible

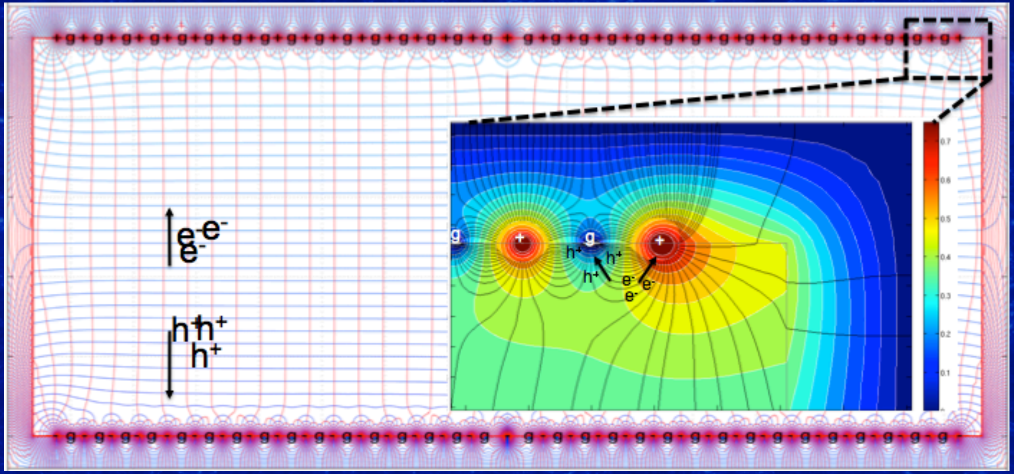
Coherent Neutrino Scattering

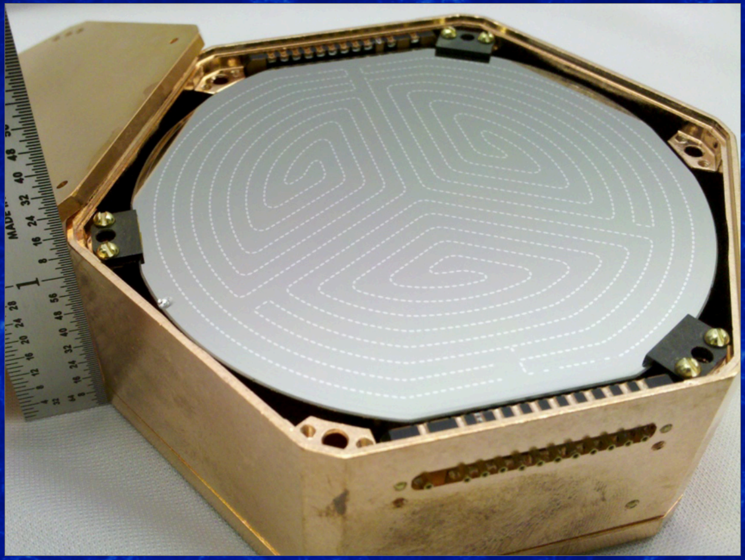


- Reactor neutrino detection requires extremely low thresholds (Si: 130eV$_{nr}$, Ge: 40eV$_{nr}$)
- Cross-section has never been measured

SuperCDMS Technology Breakthrough

- New symmetric detectors (iZIP) have demonstrated a background rejection improvement of more than an order of magnitude (ton scale CDMS style experiment now feasible)
- Trial run in Soudan facility with a 10 kg payload (X5 sensitivity)

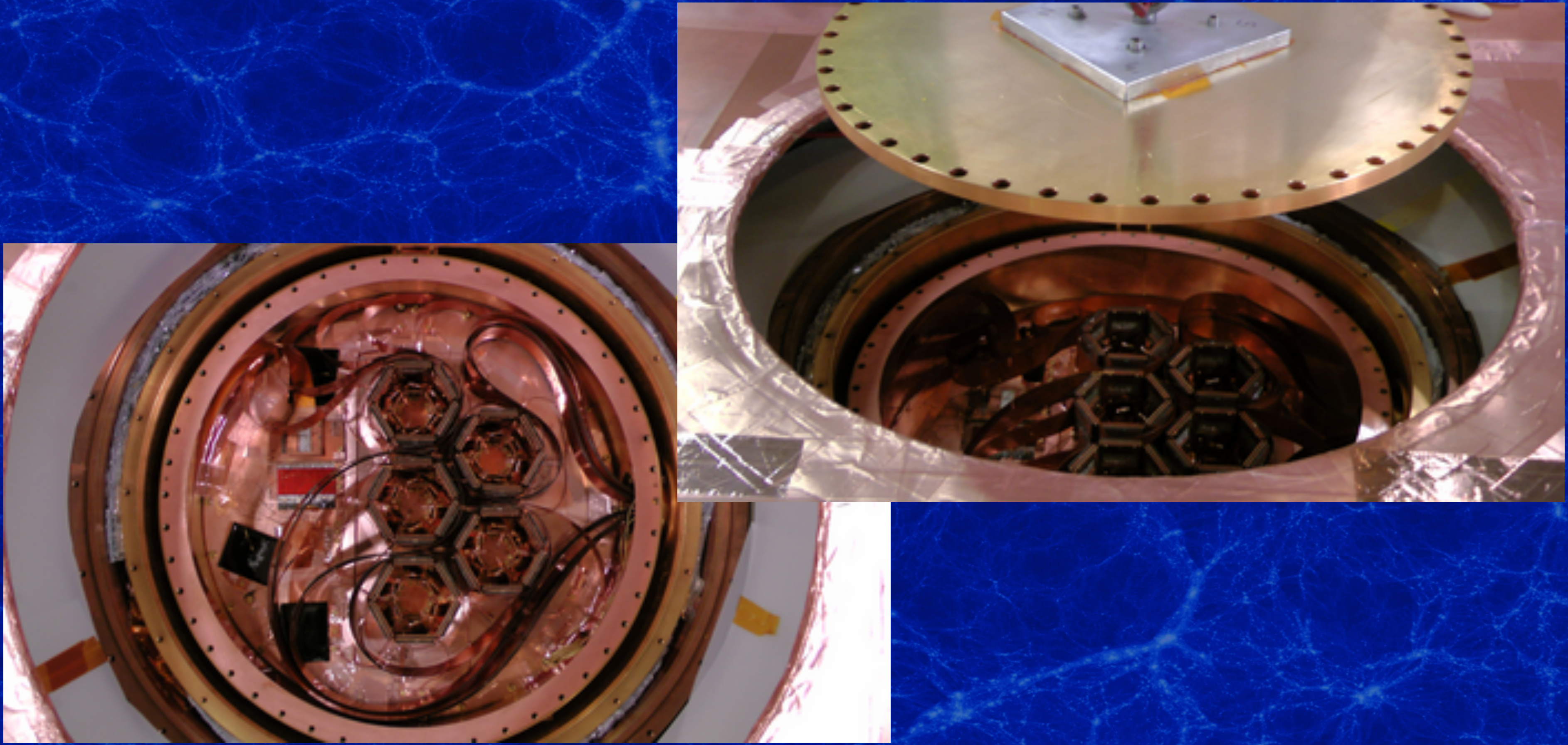




SuperCDMS Delay

- Shaft fire in Spring 2011
- Impact minimal but some engineering work delayed

SuperCDMS Status



- 10 kg of Ge detectors now at 50 mK (as of Nov 30)
- Expect 4X the sensitivity to WIMP dark matter

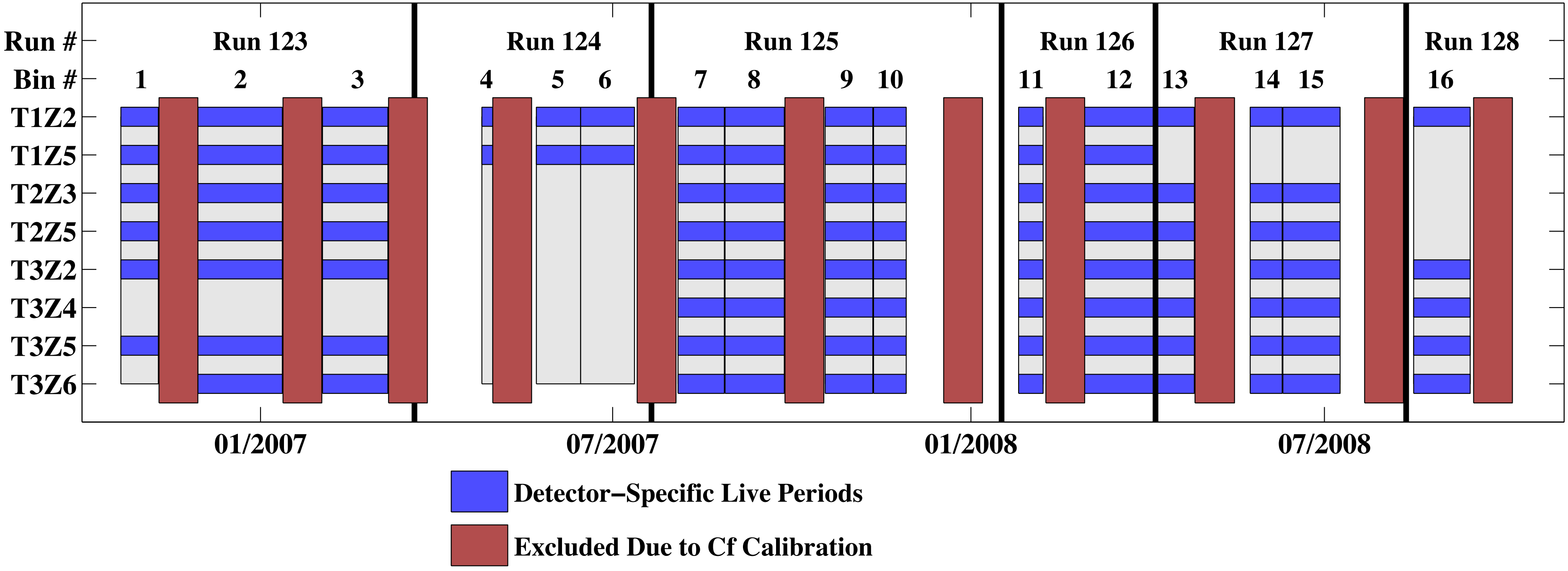
Conclusions

- WIMP discovery is best done in the low background (high S/N) regime
- CDMS is the leader in low background WIMP searches
- New CDMS technologies are successfully pushing in two directions, lower backgrounds and lower energy thresholds

Backup

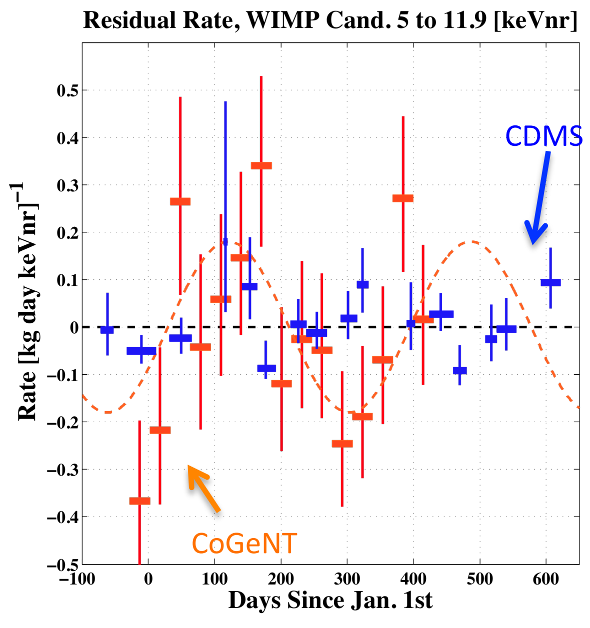
CDMS-II Annual Modulation Search

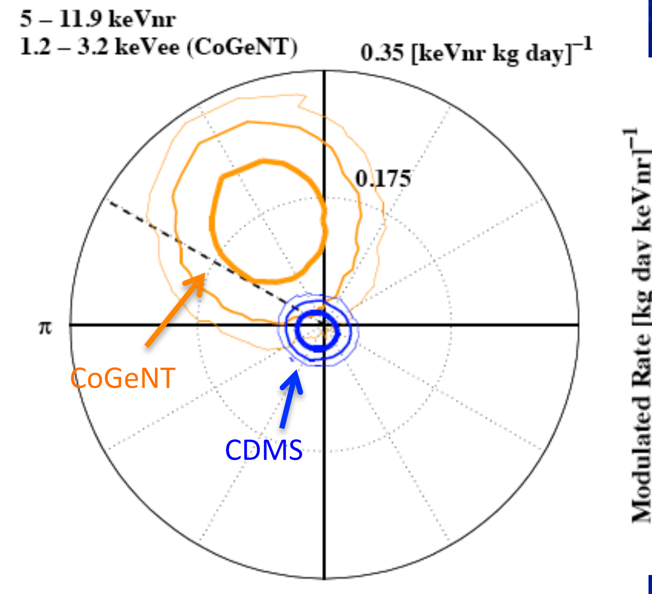
- CDMS II accumulated data for nearly two annual cycles, Oct. 2006-Sept. 2008
- Use the energy interval 5-12 keV_{nr}
  - 100% trigger efficiency at 5 kev_{nr}
  - 12 kev_{nr} matches the highest energy of the CoGeNT low gain channel



CDMS-II Annual Modulation Search

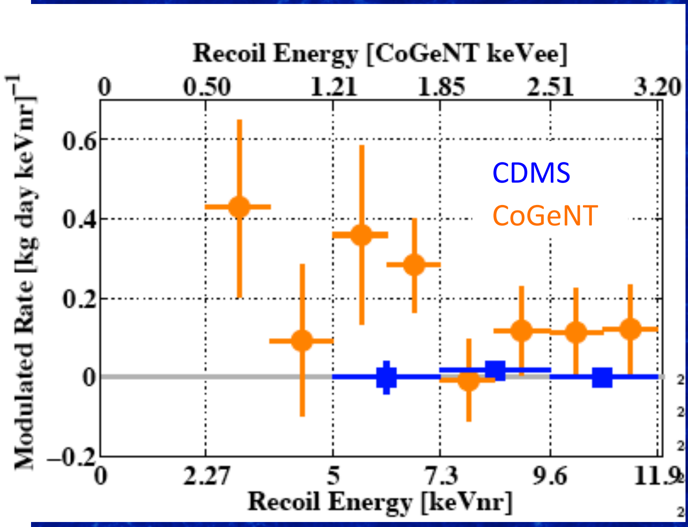
- No significant annual modulation
- Results incompatible with CoGeNT modulation at the >95% CL in the energy range 5-12 keV_{nr}





Contours: 68%, 95%, 99%

PRELIMINARY



Ahmed et al., arXiv:1203.1309, submitted to PRL

Summary

- Searching for dark matter requires careful accounting and shielding of all natural radioactivity
- Sensitivity to weakly interacting massive particles is rapidly increasing (~order of magnitude every 3 years) with a variety of experimental techniques
- We could be on the verge of discovering the nature of the dark matter

Xenon-100 Results