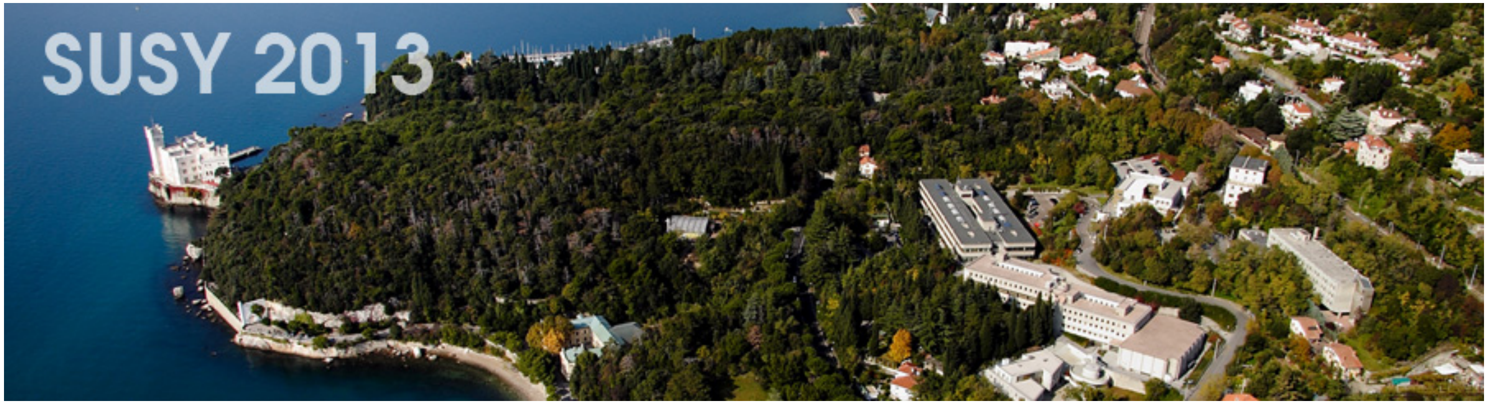

CDMS II Results and Supersymmetry

A.N. Villano (University of Minnesota)

(for the CDMS collaboration)

SuperCDMS Collaboration

SuperCDMS Collaboration

California Inst. of Tech.
B. Cornell, S.R. Golwala,
D.C. Moore, R.H. Nelson

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D. Holmgren, L. Hsu, B. Loer,

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E. Figueroa-Feliciano, S.A. Hertel,
K.A. McCarthy

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J. Hall

Queen's University
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S.M. Oser, H. Tanaka

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B. Sadoulet, B. Serfass, D. Speller

U. of Colorado, Denver
M.E. Huber

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A. Reisetter

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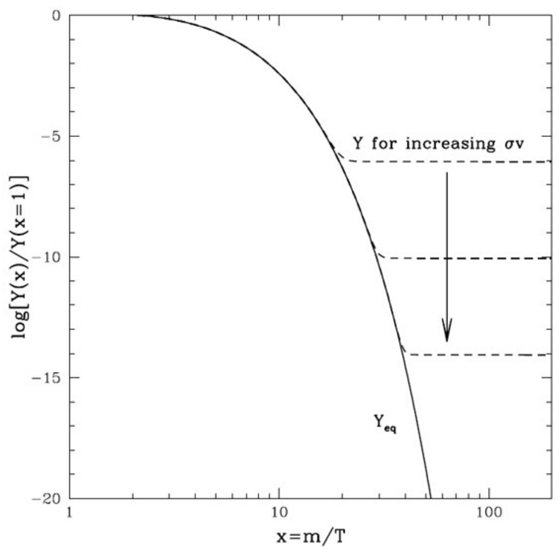
T. Saab, B. Welliver

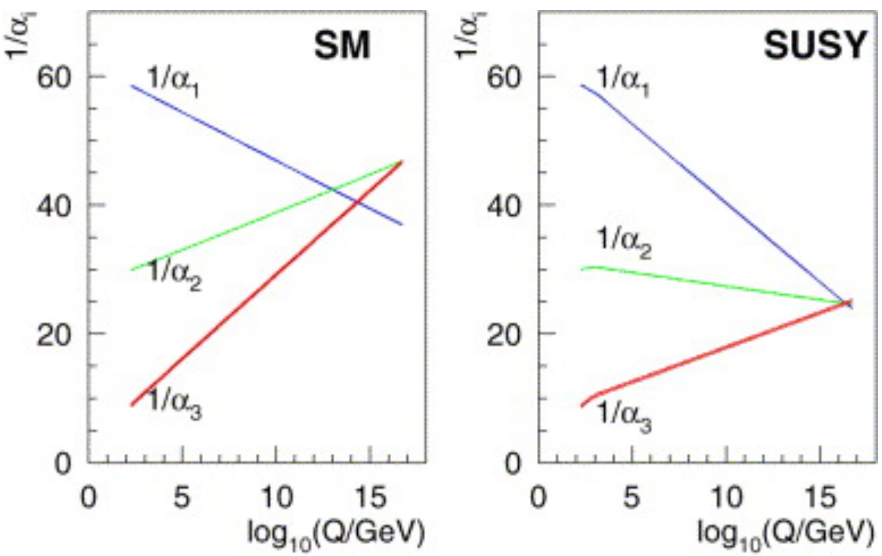
University of Minnesota
H. Chagani, P. Cushman, S. Fallows,
M. Fritts, T. Hofer, A. Kennedy,
K. Koch, V. Mandic, M. Pepin,
A.N. Villano, J. Zhang

*Emeritus Professor at U.C. Santa Barbara

Particle Dark Matter



E. Kolb, M. Turner. "The Early Universe"
Perseus Books (1990)

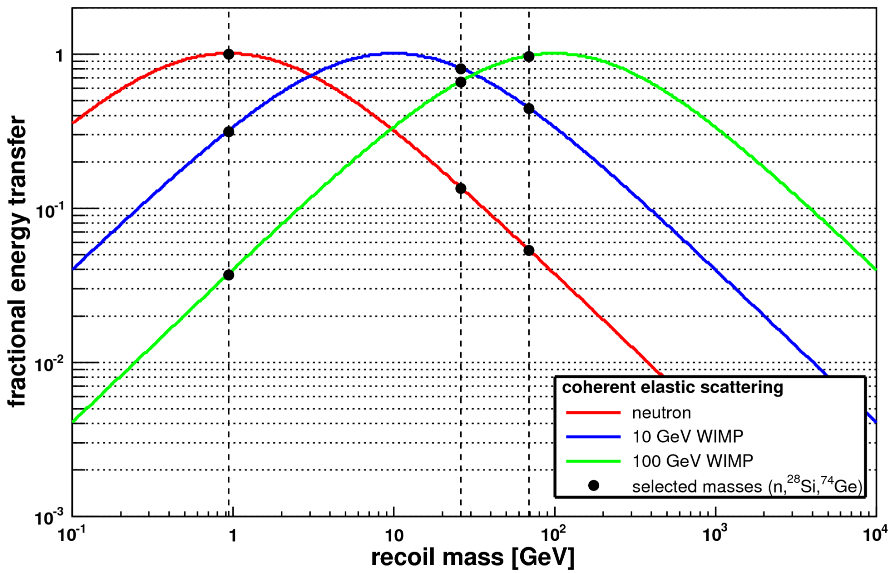


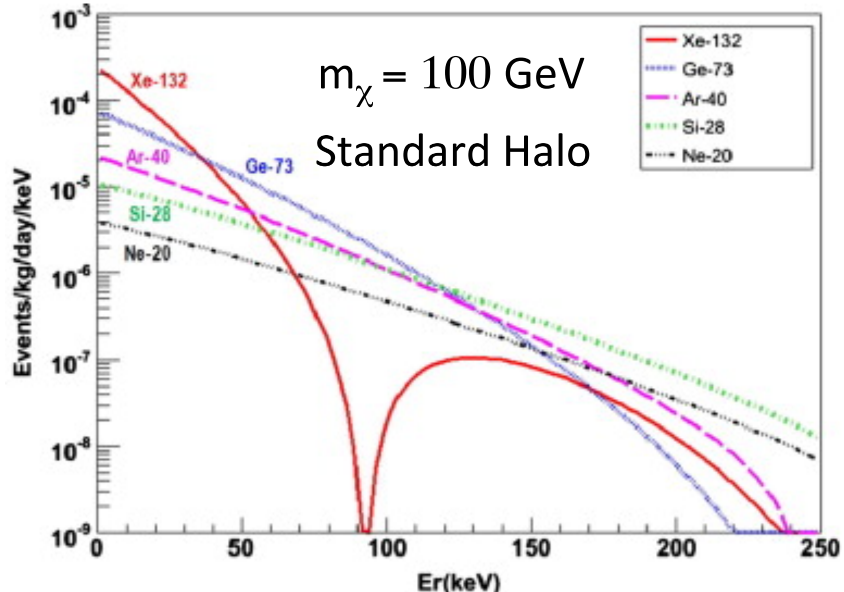
W. de Boer et al., Phys. Lett. B636, 13 (2006)

Galaxy rotation curves and cluster motions point to missing mass, it is noted that a cold thermal relic can be produced in the early universe (left) and the MSSM (right) gives a concrete candidate: χ^0

1. Natural relic cold dark matter (CDM) candidate
2. The particle can naturally be created thermally with 2 GeV/c^2 < m_χ < 10 TeV/c^2
3. New particles soften Higgs mass fine-tuning (hierarchy problem)
4. Running couplings more appropriate for unification

Coupling to Detectors



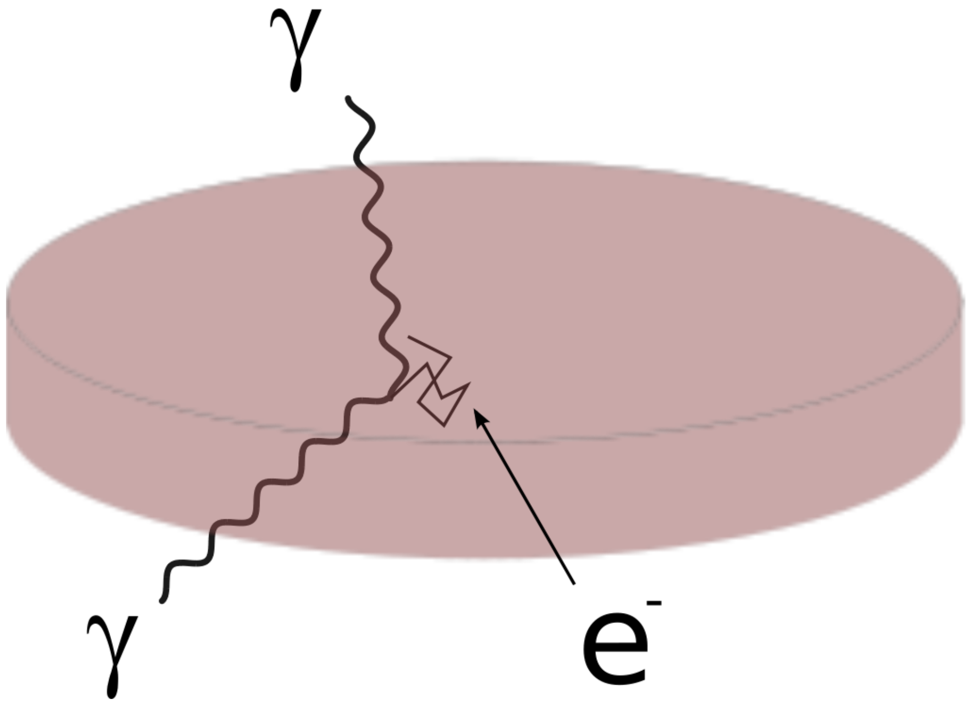


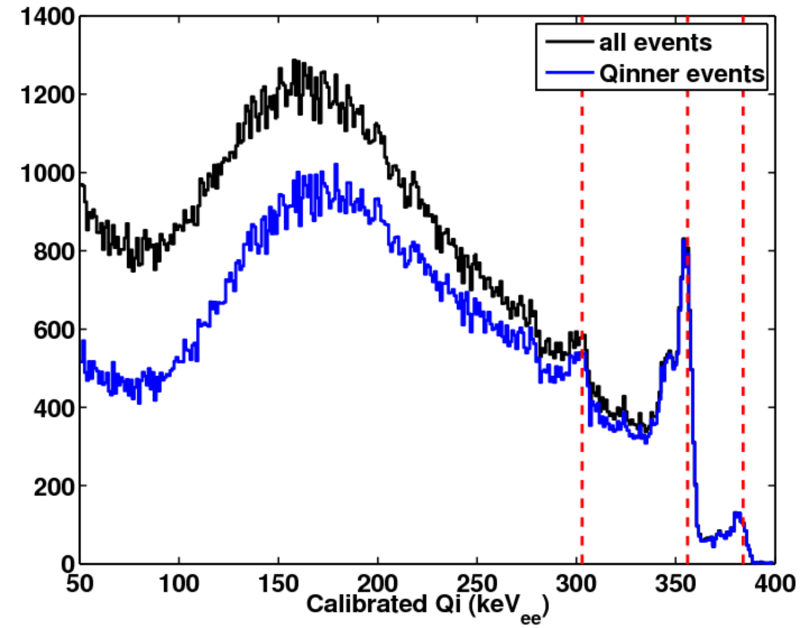
K. Arisaka et al., Astropart. Phys 31, 63 (2009)

- Functions f_p and f_n are thought to be roughly equal so A^2 enhancement
- Si gets a kinematic enhancement over Ge for given halo model
- Cross section very small relative to other particle processes (below 10^{-39} cm^2 for WIMP masses above 7 – 10 GeV/c^2), so only single scatters in detector

$$\sigma^0_{SI} = \frac{4}{\pi}\mu^2_{\chi N}[Zf_p + (A-Z)f_n]^2$$

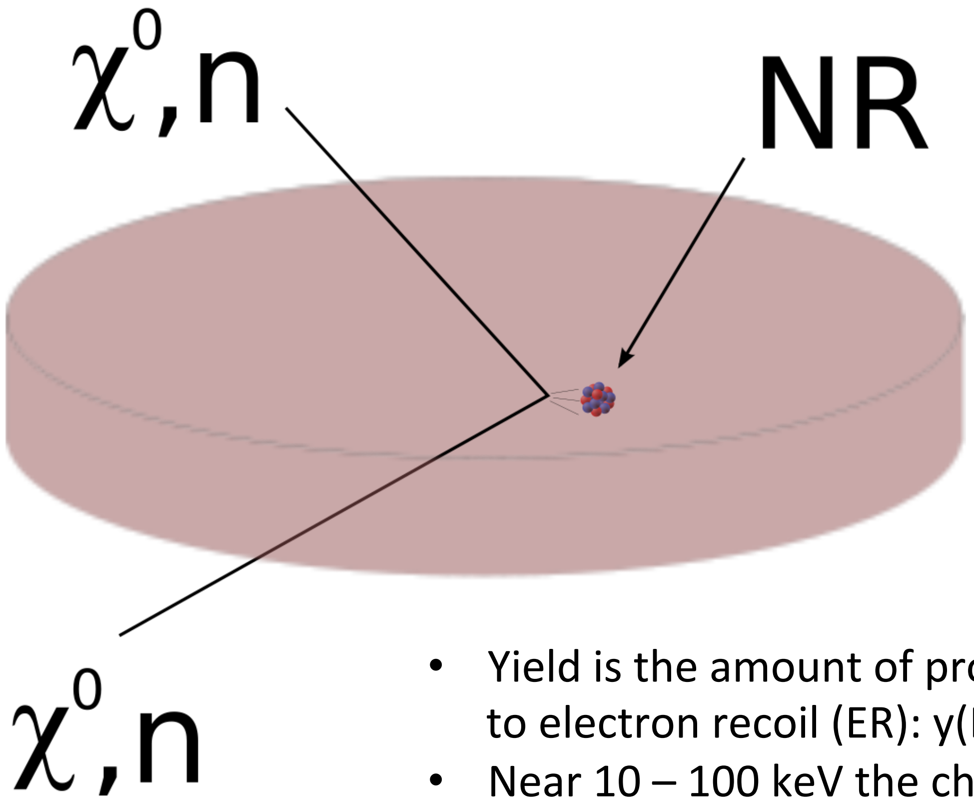
Expected Events: Electron Recoils (ERs)



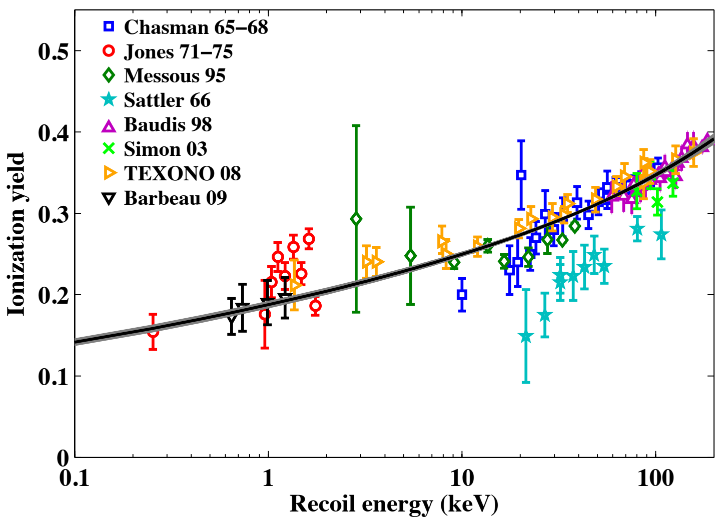


- ERs charge calibrated via ^{133}Ba line (right)
- The yield for ERs is around unity: longer deposition length allows charge production not to "saturate"
- Gammas and electrons will deposit energy via ERs

Expected Events: Nuclear Recoils (NRs)

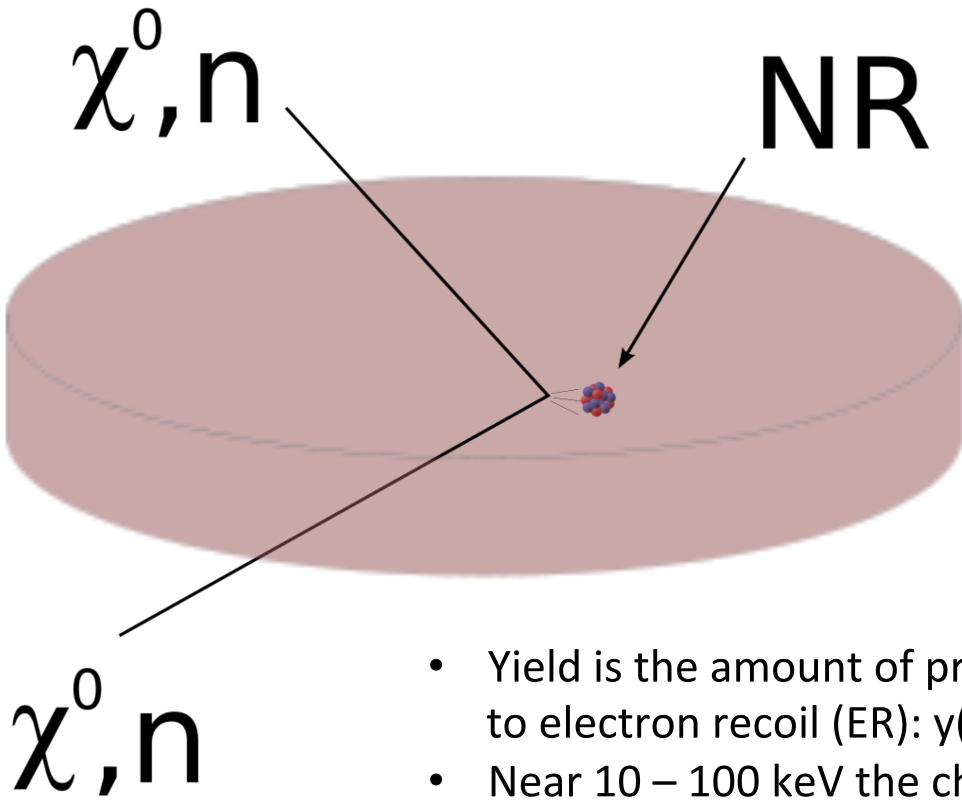


Lindhard Model:



- Yield is the amount of produced charge calculated relative to electron recoil (ER): $y(E_R)$
- Near 10 – 100 keV the charge "quenching" is about 20%
- WIMPs will deposit their energy via NR
- Event-by-event measurement of yield can be used to discriminate NRs from ERs
- Neutrons, however, produce NR-like events

Expected Events: Nuclear Recoils (NRs)



Lindhard Model:

$$\epsilon = 11.5 E_R(keV) Z^{-\frac{7}{3}}$$

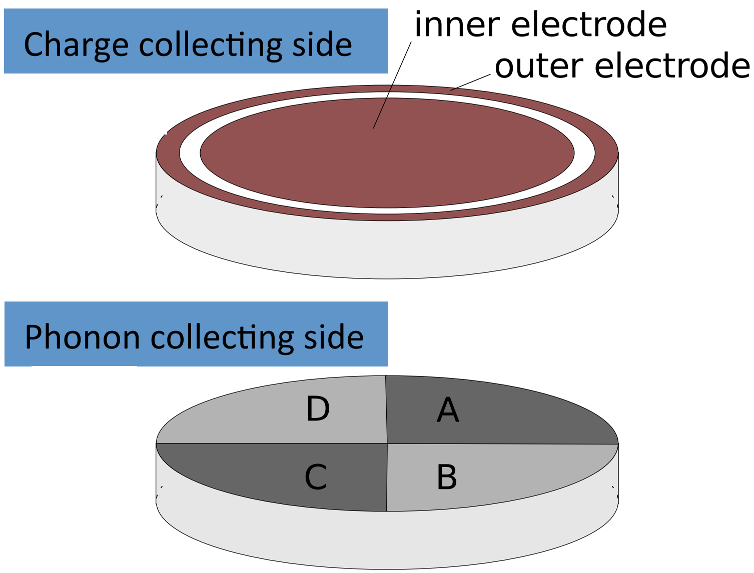
$$k = 0.133 Z^{\frac{2}{3}} A^{-\frac{1}{3}}$$

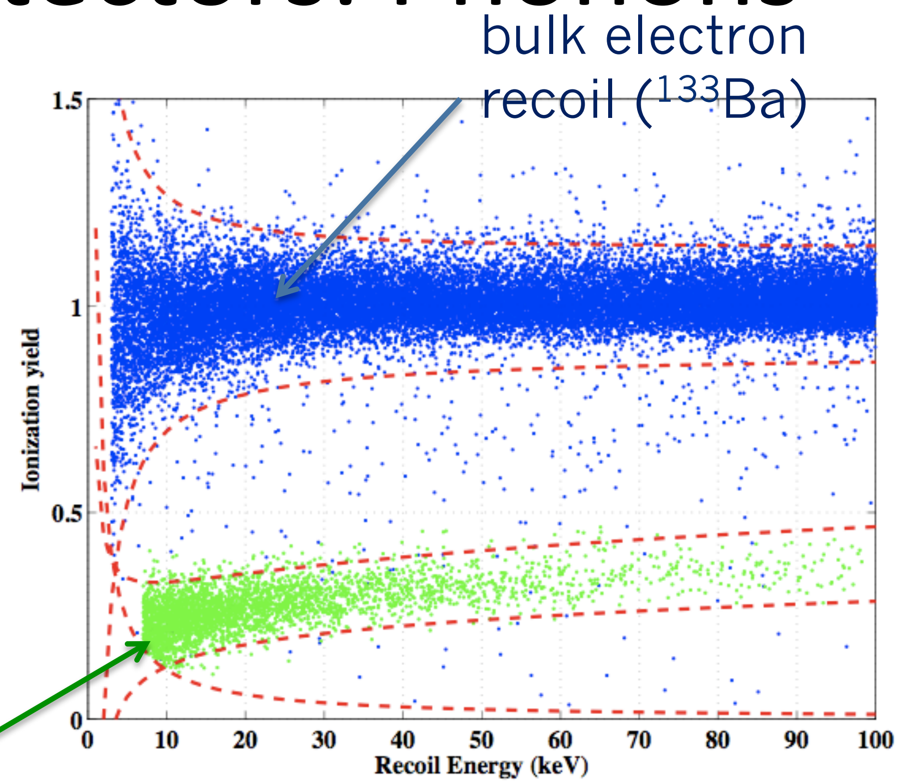
$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$y(E_R) = \frac{k g(\epsilon)}{1 + k g(\epsilon)}$$

- Yield is the amount of produced charge calculated relative to electron recoil (ER): $y(E_R)$
- Near 10 – 100 keV the charge “quenching” is about 20%
- WIMPs will deposit their energy via NR
- Event-by-event measurement of yield can be used to discriminate NRs from ERs
- Neutrons, however, produce NR-like events

CDMS II Style Detectors: Phonons



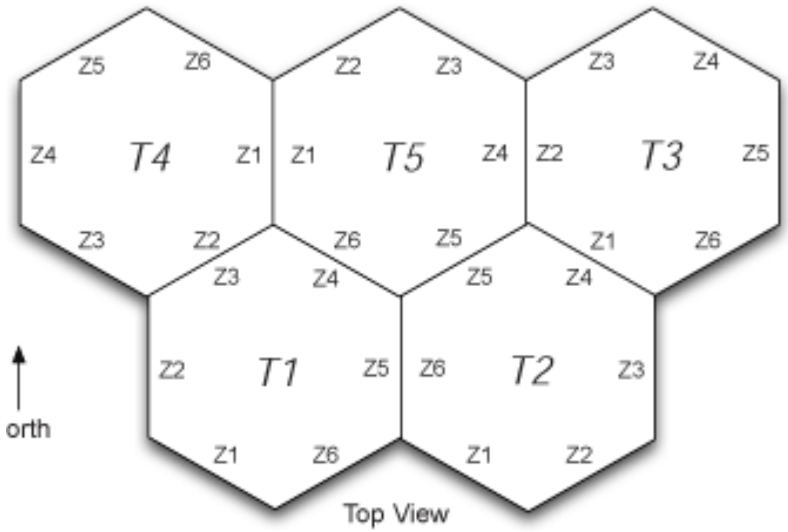


- Phonons give great absolute energy scale!
- Charge gives a great measurement of yield!
- Can separate ER/NR very well above 10 keV
- 2σ bands for ER and NR shown above
- ER are (mostly) eliminated as background above 10 keV, neutron-induced events remain

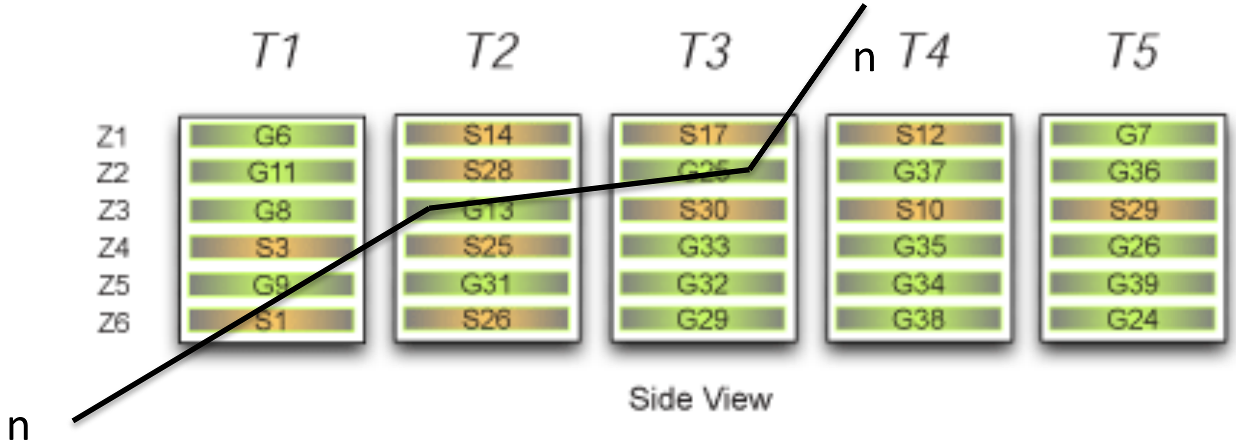
ZIP = **Z**-sensitive **I**onization and **P**honon

These detectors are now sometimes called "oZIPs" for "old" or "original" ZIPs to distinguish from newer detectors

Eliminate Neutrons: Segmented Detector

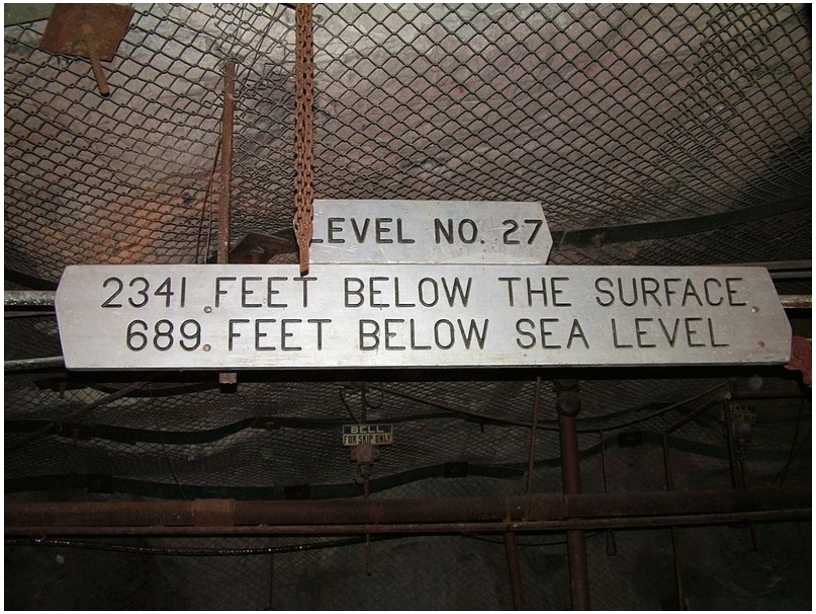


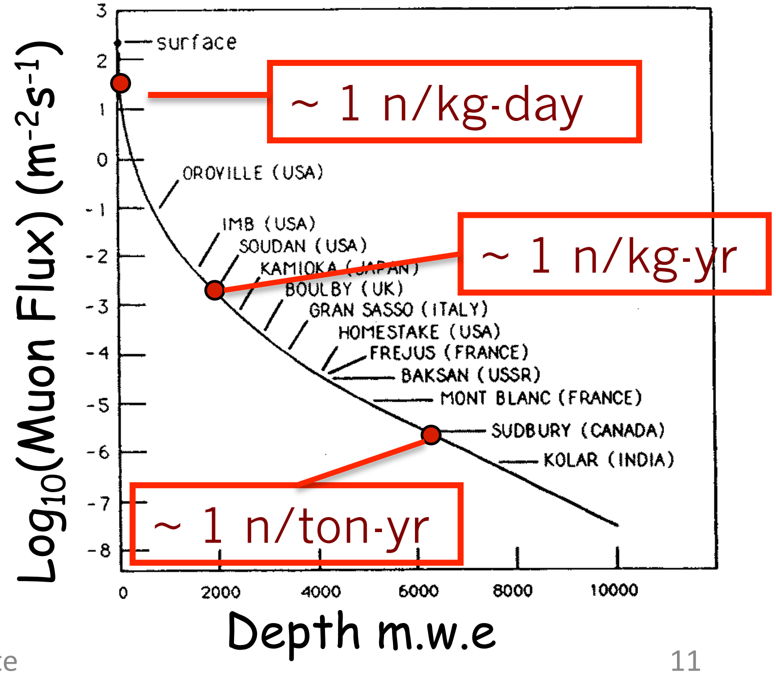
- CDMS has always been highly segmented
- Hexagonal housings hold cylindrical ~ 1cm thick detectors (left)
- For CDMS II Soudan largest exposure periods had 5 towers (below)
- Multiple scattering of neutrons result in events with multiple hits in the detectors (below), these are rejected since the WIMP cross section makes it extremely unlikely for it to scatter more than once



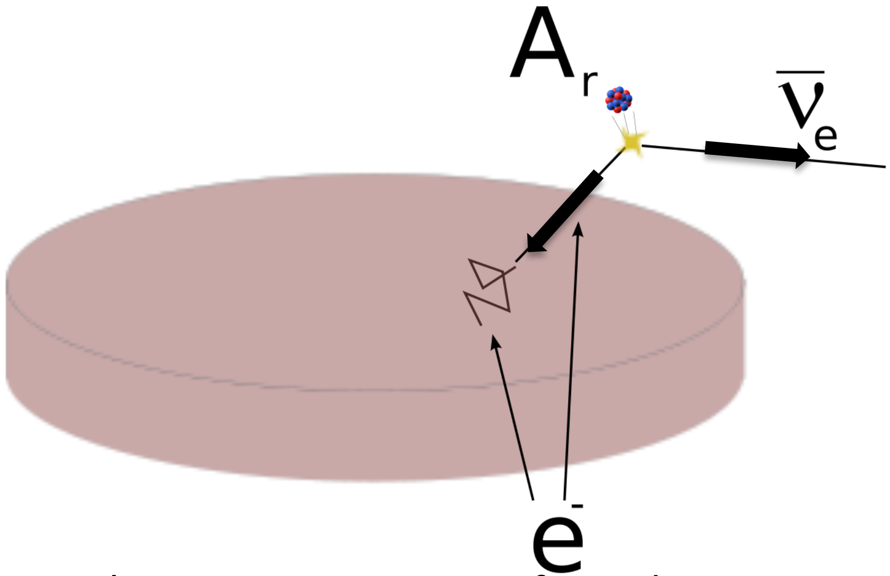
Eliminate Neutrons: Go Underground

Experiment	Net Exposure	Cosmo neutrons	Shield neutrons	Surface events	Fiducial Volume
CDMS-I SUF	28 kg-d	18	---	2	---
CDMS-II Soudan	1 kg-y	.01	.07	1.2	37%
SuperCDMS Soudan	6 kg-y	.07	.24	.005	68%
SuperCDMS SNOLAB	385 kg-y	.03	.1	<.24	73%

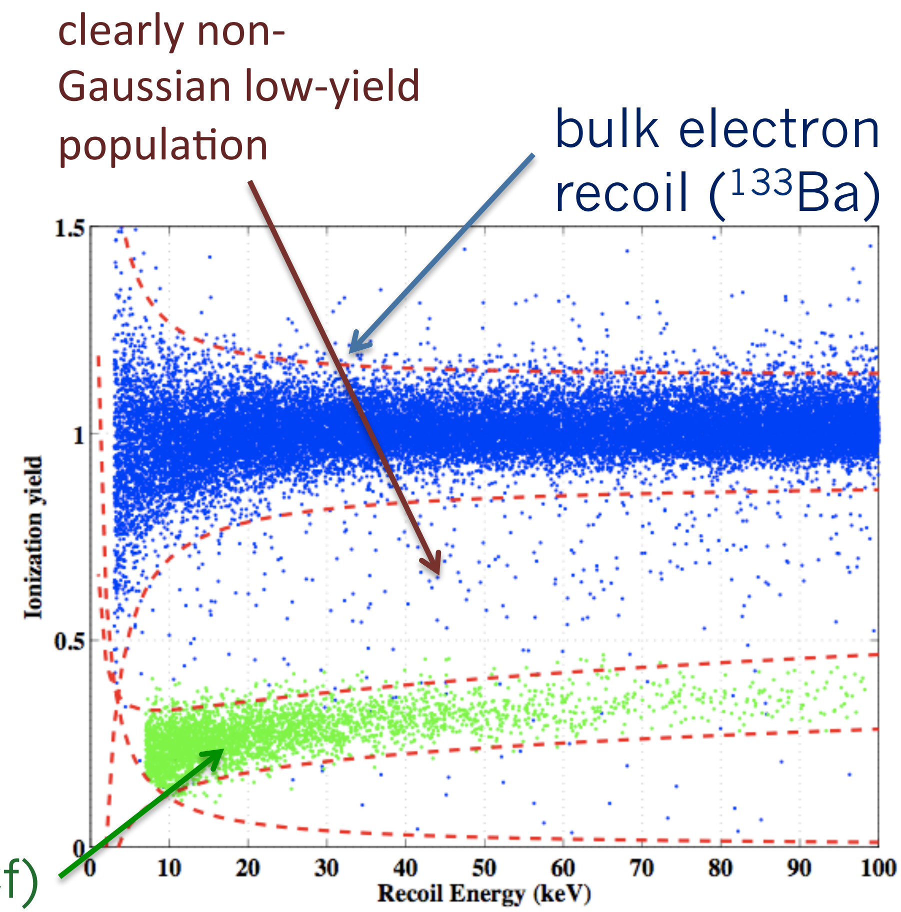




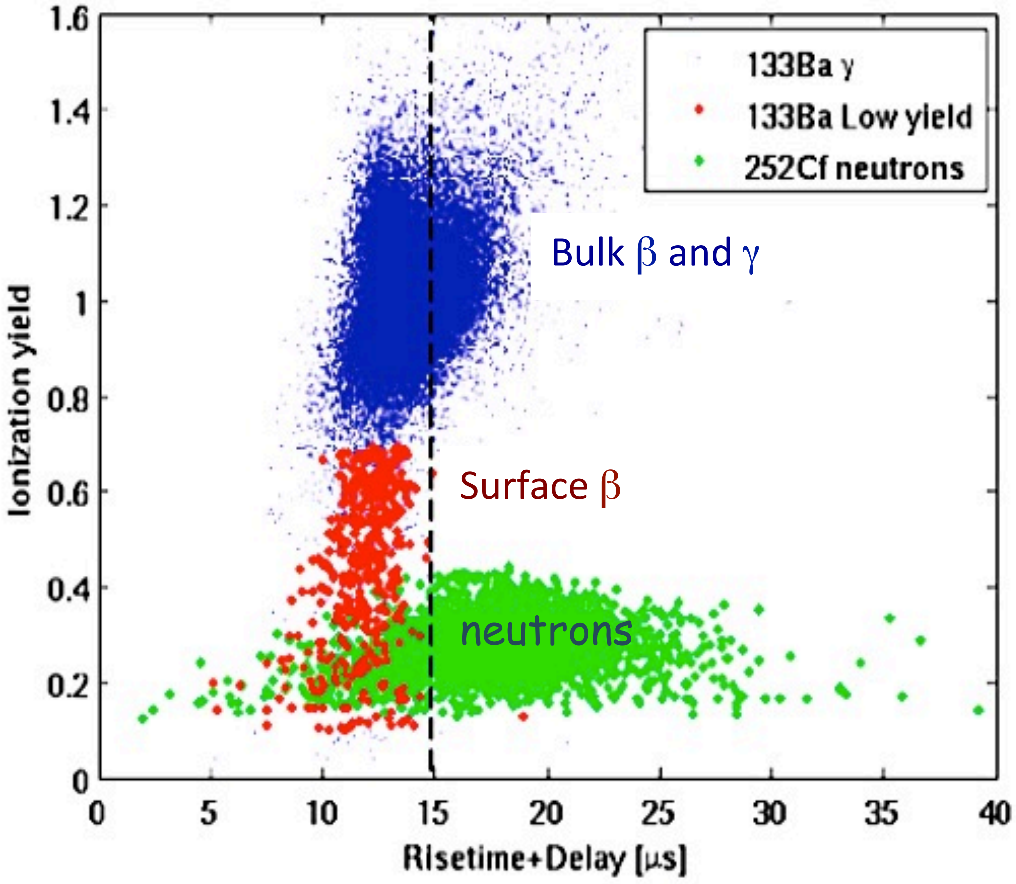
Surface Events (SEs): A Problem?



- Electrons streaming in from decays near a detector interact near detector surface
- ERs occurring in the 10 micron dead layer result in incomplete charge collection
- These events show reduced yield and can appear in the NR band (right)



Surface Events (SEs): A Problem?



- CDMS II detectors can use phonon pulse properties to distinguish surface events
- Lose some efficiency but cuts can be highly effective (left)
- The events are sometimes referred to as β generically, which usually means any events coming under the 2σ ER band line
- The procedure used is sometimes called a "timing-cut" because phonon delay and risetime variables help distinguish NRs from SEs (left)

Exposures at Soudan

run	num. towers	detector types	Ge dets	Si dets	Publications (pre-2010)
118	1	oZIP (6)	4	2	PRD **72**, 052009 (2005)
119	2	oZIP (12)	6	6	PRL **96**, 011302 (2006) PRD **73**, 011102 (2006)
123	5	oZIP (30)	19	11	PRL **102**, 011301 (2009)
124	5	oZIP (30)	19	11	PRL **102**, 011301 (2009)
125	5	oZIP (30)	19	11	Science **327**,1619(2010)
126	5	oZIP (30)	19	11	Science **327**,1619(2010)
127	5	oZIP (30)	19	11	Science **327**,1619(2010)
128	5	oZIP (30)	19	11	Science **327**,1619(2010)
132	3	oZIP (4), mZIP (10), iZIP (3)	17	0	(engineering)
133	5	iZIP (15)	15	0	(3 publications fall `13 – spring `14)

This Work: "c58" (runs 125–128)

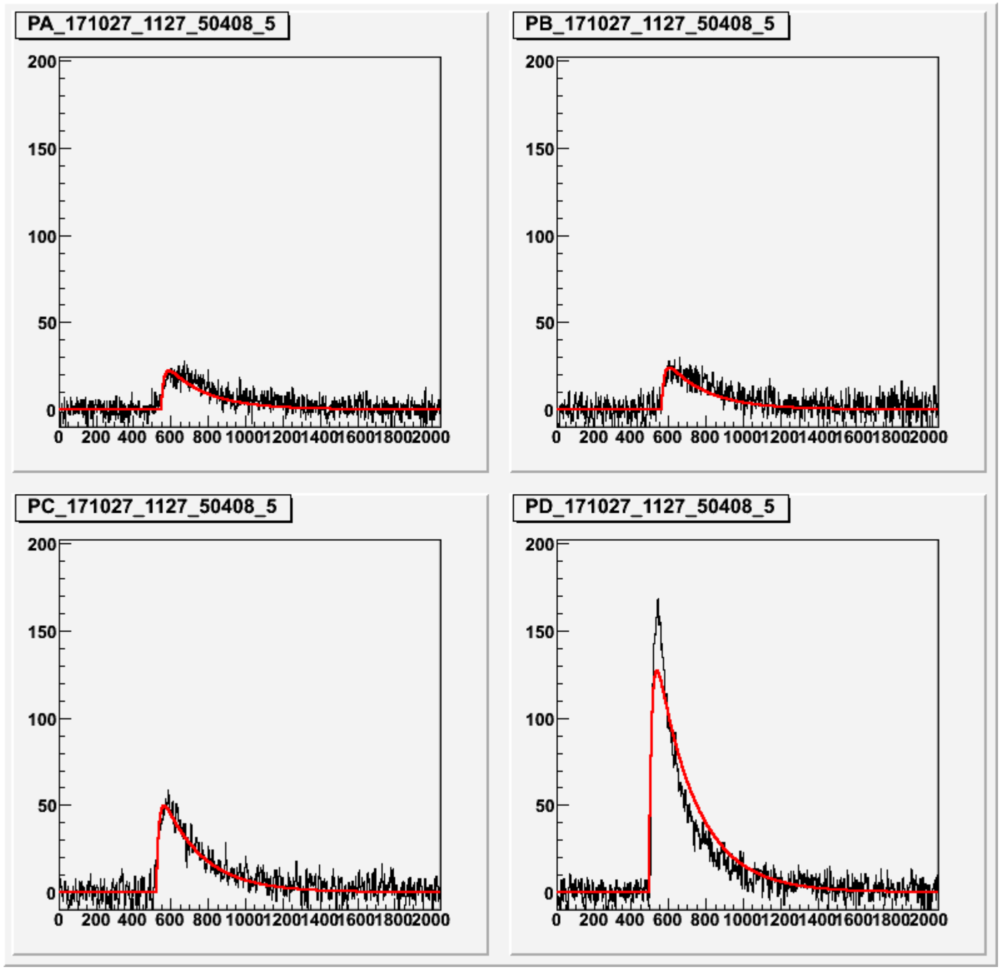
Optimal Filter

Single Template Optimal Filter

- Pulse templates are fit to digitized pulses in frequency space using an "Optimal Filter" (OF) algorithm
- The OF yields energy and start time measurements
- Some examples of single-template OF fits show the basics of the procedure (right)

Cross-talk Optimal Filter

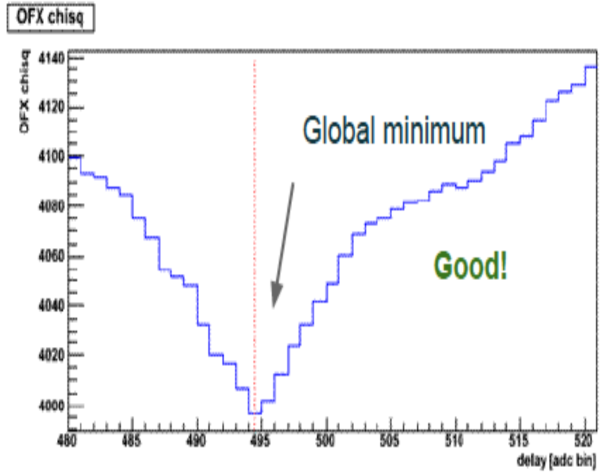
- Charge channels are known to have capacitive coupling
- Use "cross-talk" OF to correct for the effect, but finding best fit value more difficult (next slide)

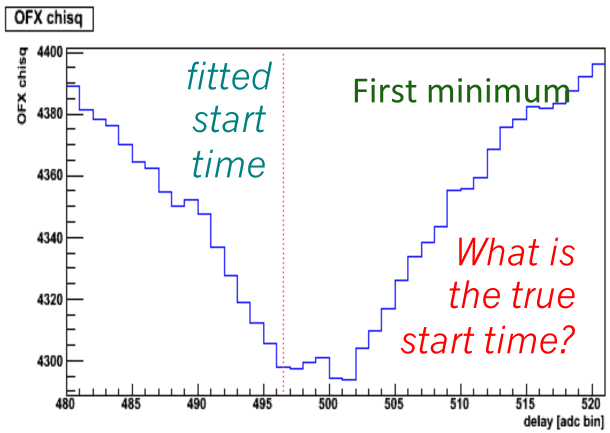


Post – 2010 Re-processing

Germanium Data

- Charge pulses are fit with cross-talk OF (two channels simultaneously)
- The charge start time is used to construct the phonon delay and hence affects the timing cut
- Most of the time the procedure used gives global minimum in χ^2 (right, top)
- Prior to 2010, the algorithm sometimes fit at a local minimum, for the current data this was fixed (right, bottom)

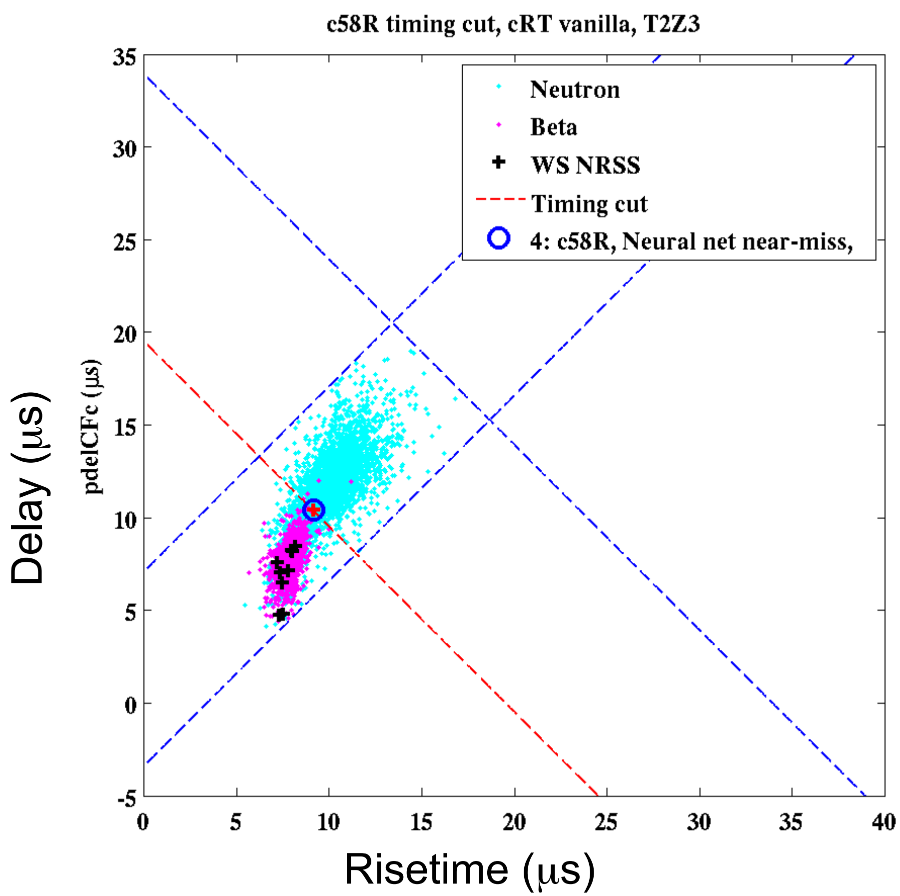




Silicon Data

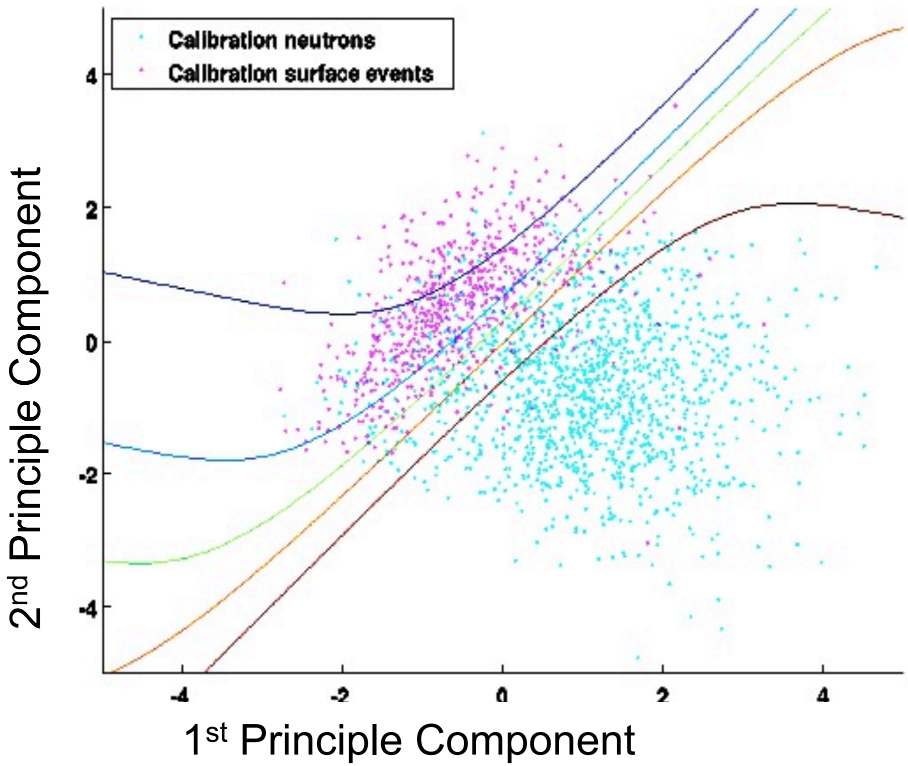
- Si data from the CDMS II runs 125-128 had not been analyzed so did position correction
- Also used the improved charge algorithm (right)

CDMS II Ge/Si Timing Methods: Classic



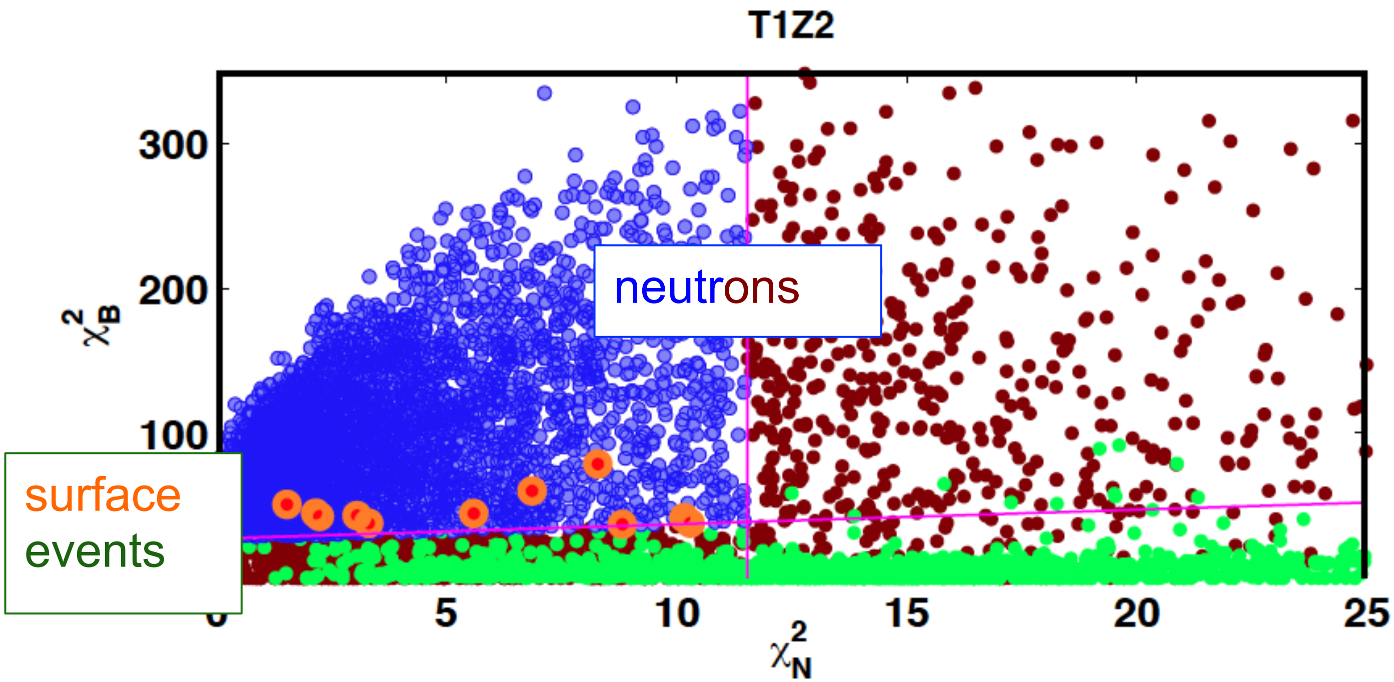
- Use a linear combination of phonon delay and risetime
- Standard cut used in previous CDMS II analysis
- Provides consistency check for 2010 result, and direct comparison with charge OF upgrade

CDMS II Ge/Si Timing Methods: Neural Network (NN)



- Use more than 2 timing parameters and choose the 2 with the best discrimination power using a generalized rotation, these are the "principal components"
- The neural network (NN) procedure selects between SEs and NRs by using a training set
- The NN output is a single discrimination parameter which returns a value in the range [0,1]: 0 for SEs, 1 for NRs
- The contours of this variable in the principal component plane can help visualize the cut (left)

CDMS II Ge/Si Timing Methods: χ^2



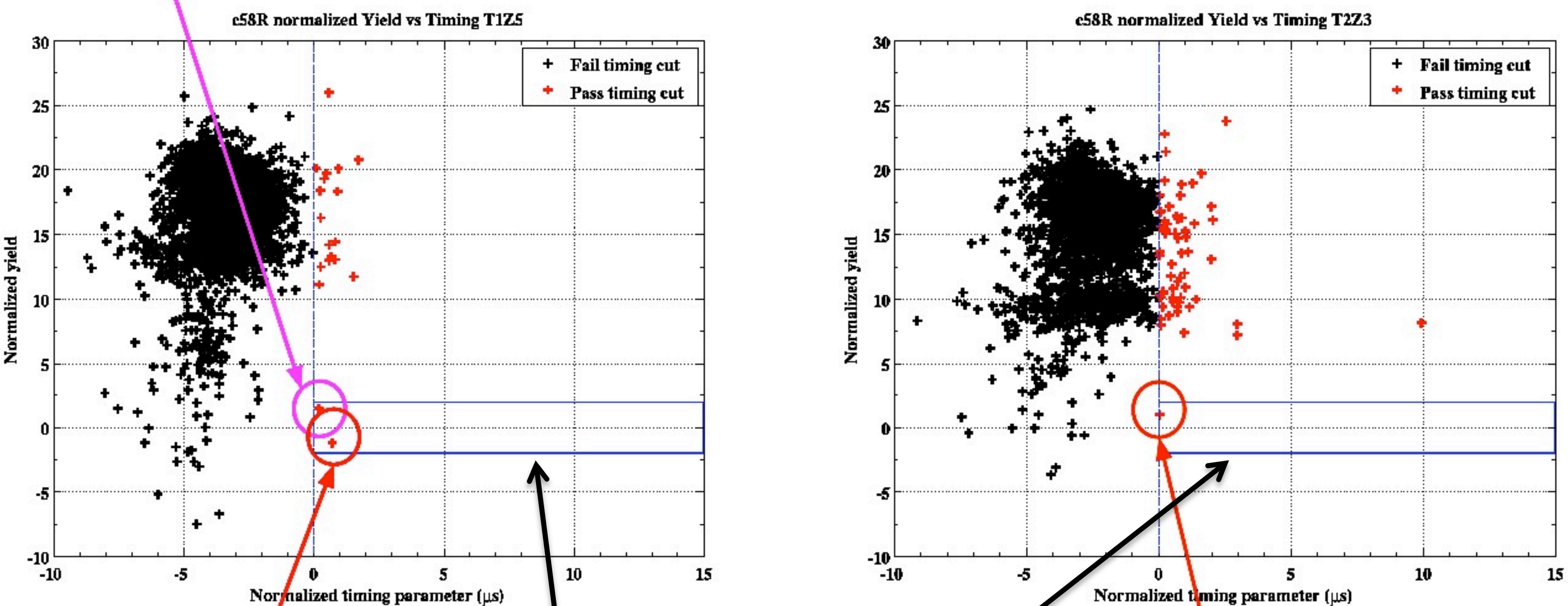
- 5D-χ^2 uses 5 different timing parameters and defines statistics to determine how neutron-like an event is (χ^2_N) and how beta-like an event is (χ^2_B)
- The cut is then set in the χ^2_N - χ^2_B plane (above)
- The neutron consistency cut is set to pass 90% of the neutrons in the control sample (^{252}Cf data) (vertical line, above)
- The near horizontal line requires ($\chi^2_N - \chi^2_B$) > η, where η is the value which parameterizes the cut

CDMS II Re-Analysis Ge Candidates

Timing vs. Yield Display of Ge Candidates for c58 Re-Analysis

Second candidate event from **2010** publication was well outside signal region for all analyses

27 Oct 2007
12.30 keV
NN + Classic + **2010**

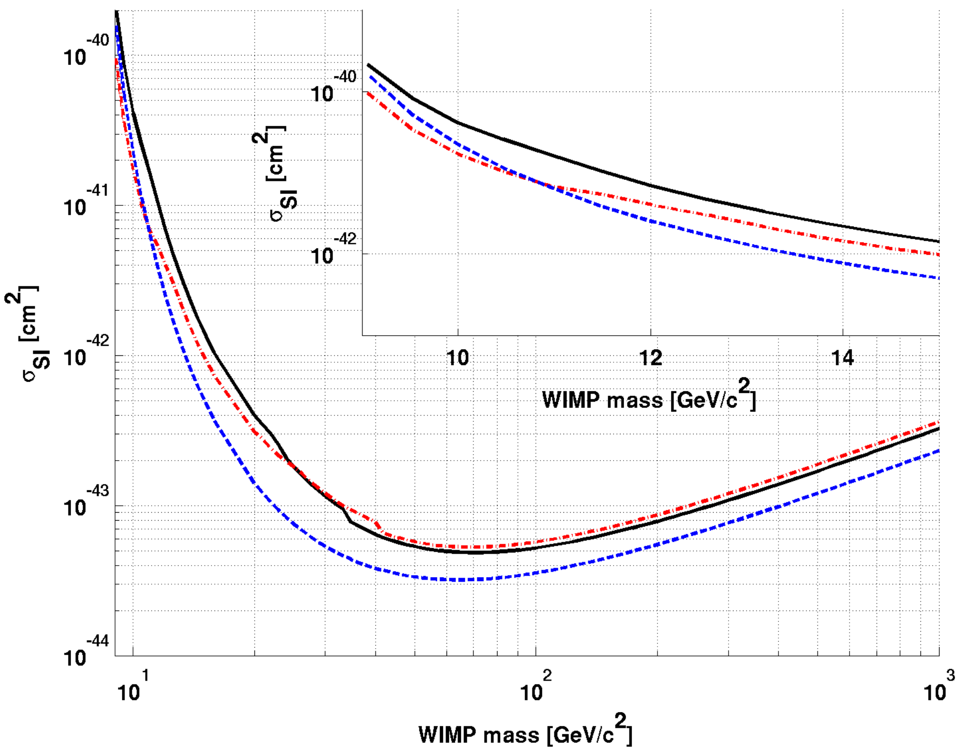


1 Feb 2008
13.44 keV
NN + Classic

"classic" signal box

30 May 2008
10.81 keV
Classic

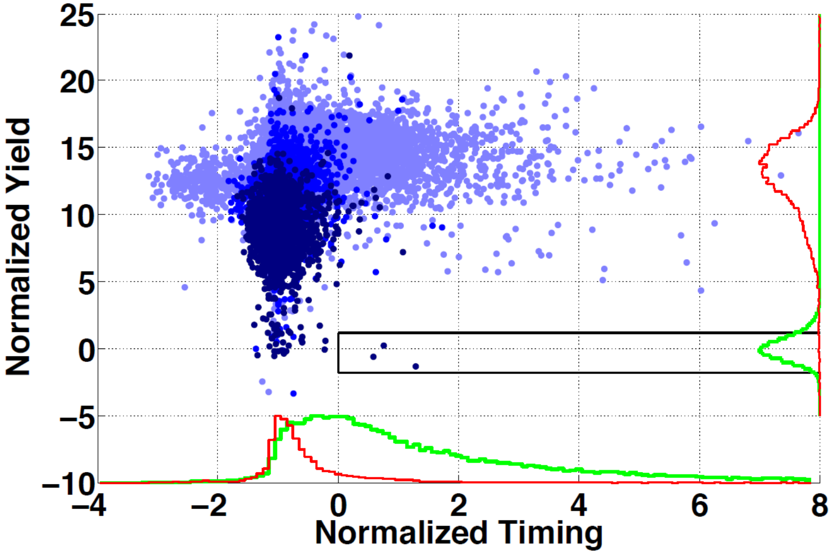
Ge Data Re-processing Results

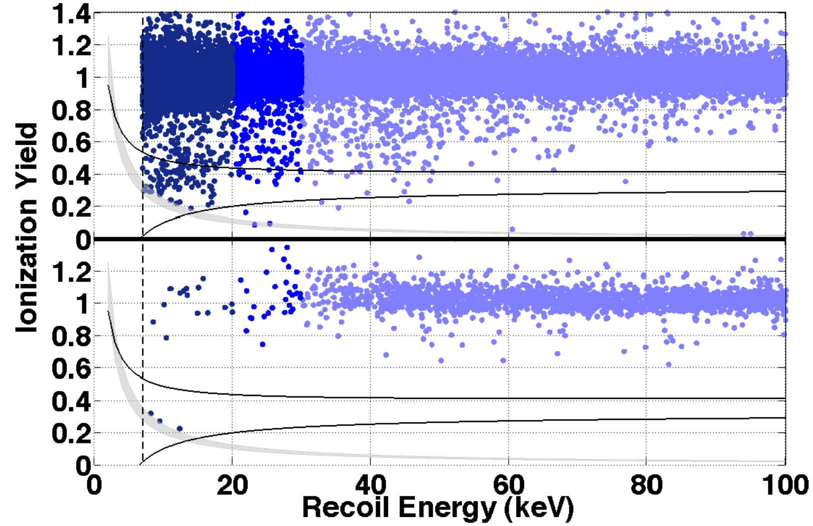


S. Yellin, Phys. Rev. **D66**, 032005 (2002)

- (black, solid) 90% C.L. limit using the classic cut
- (red, dashed) 90% C.L. limit using the NN cut
- (blue, dashed) 90% C.L. limit using the 5D-χ^2
- The 5D-χ^2 method is dominant at high WIMP mass, but the NN cut is stronger below 11 GeV/c^2
- All the cut-setting methods use Yellin's "optimum interval" method after cut optimization
- The optimum interval method allows extractions of limits without systematics due to poor knowledge of backgrounds

CDMS II Si Candidates

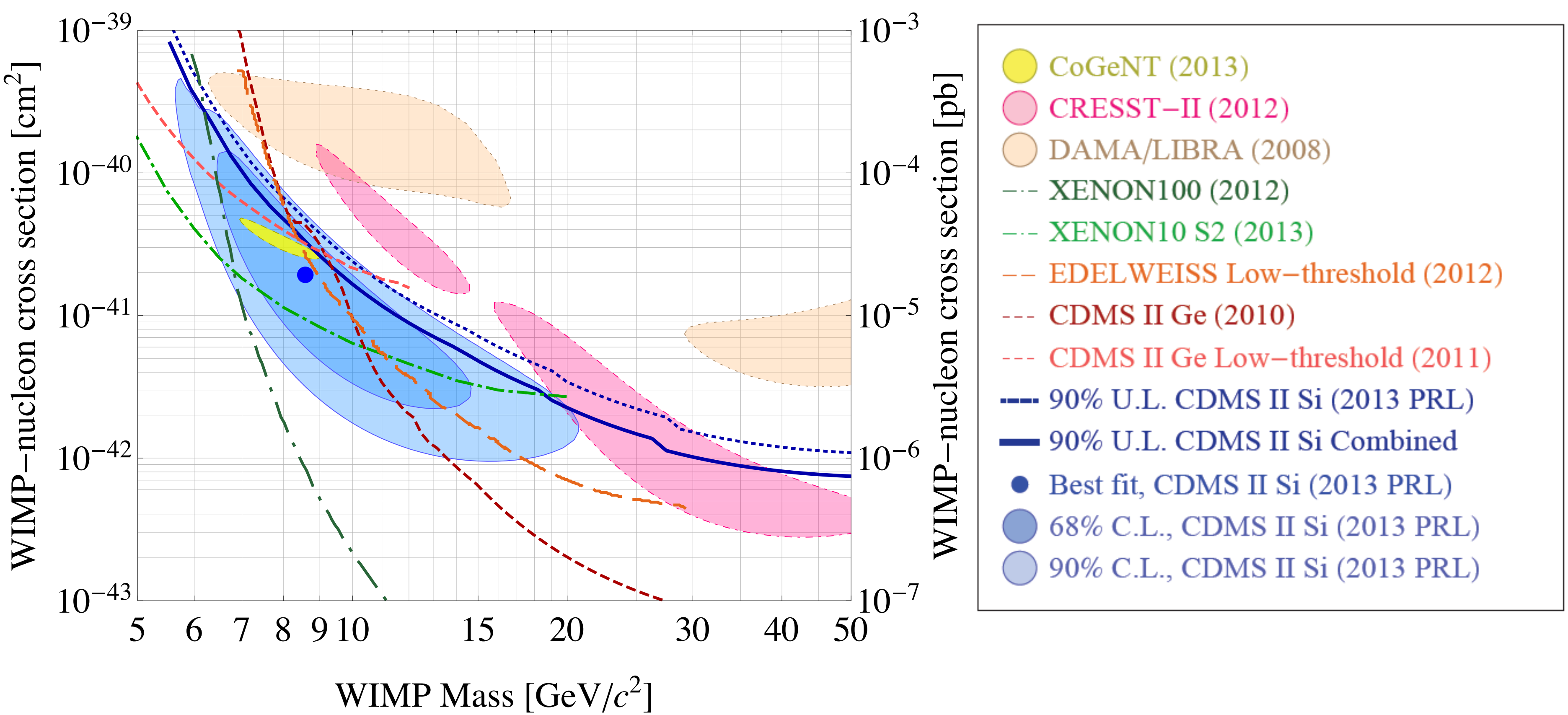




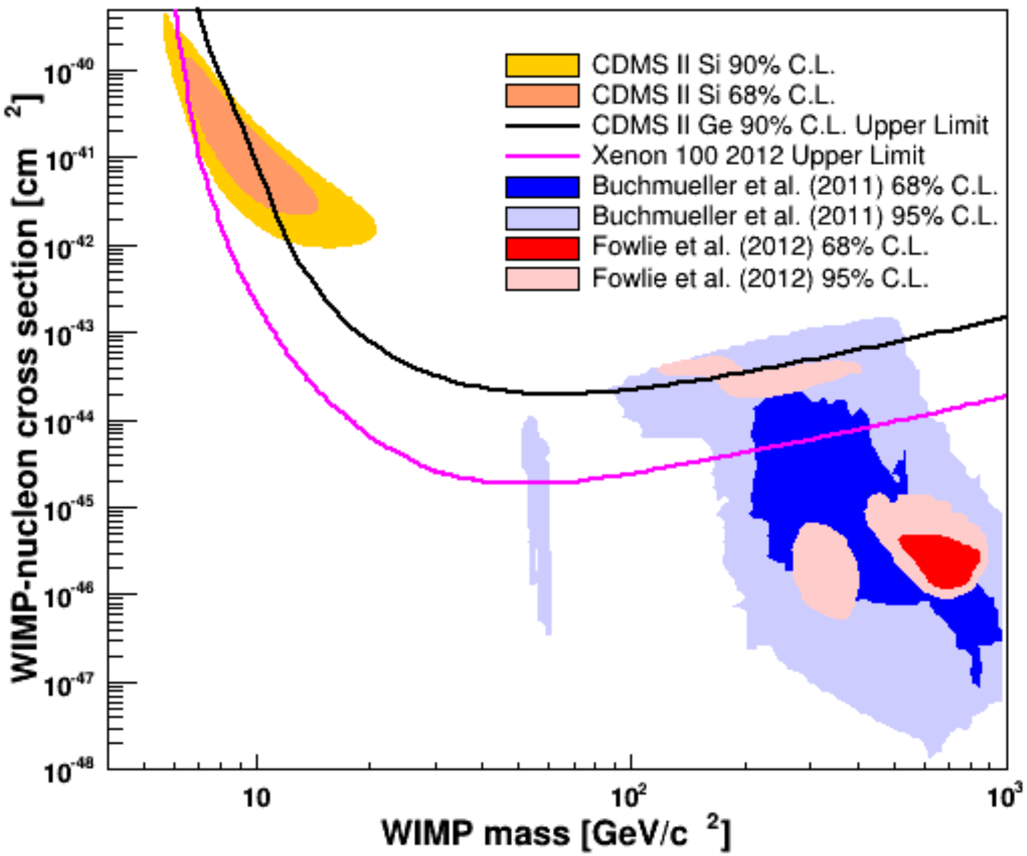
- 2D-χ^2 uses 2 different timing parameters and defines statistics to determine how neutron-like an event is (χ^2_N) and how beta-like an event is (χ^2_B)
- Similar to the 5D version but only uses the phonon delay and risetime which are used in the classic method as well
- Discovered 3 candidate events

R. Agnese et al., Phys. Rev. Lett. **In press** (2013): arXiv:1304.4279

Ge/Si Re-analysis Limits



Comparison to cMSSM (2011-2013)

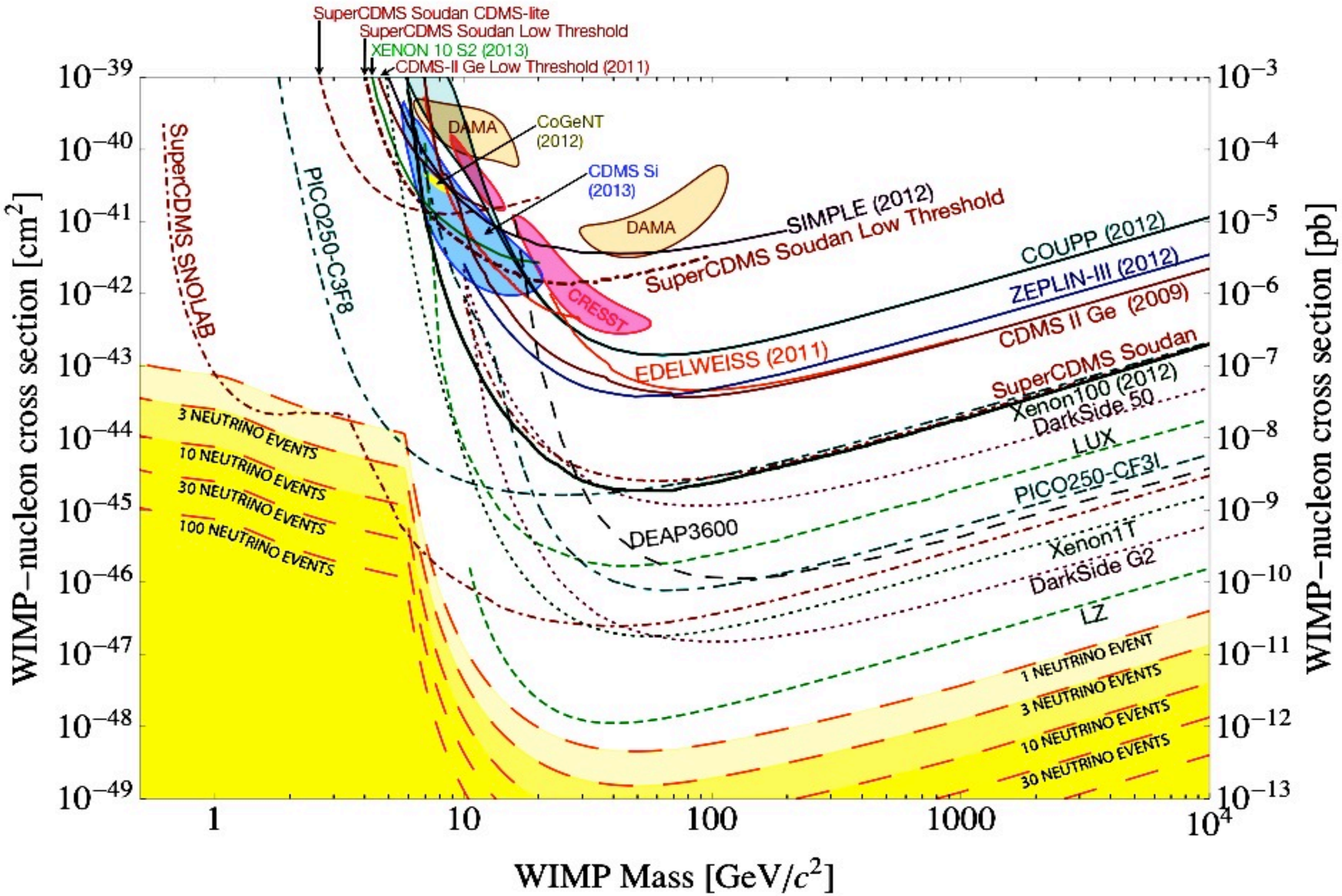


- With new LHC Higgs mass constraints the cMSSM moves neutralinos to heavier masses and lower cross sections
- Several collaborations (CDMS, CoGeNT, CRESST etc.) see "hints" of signals at lower masses
- This conference has shown that LHC results seem to push the cMSSM to the limits, what are the boundaries for SUSY in general on the standard WIMP phase space (left)?

Buchmueller et al., (2011) arXiv:1110.3568

Fowlie et al., Phys. Rev., **D86**, 075010 (2012)

Projections for the Future



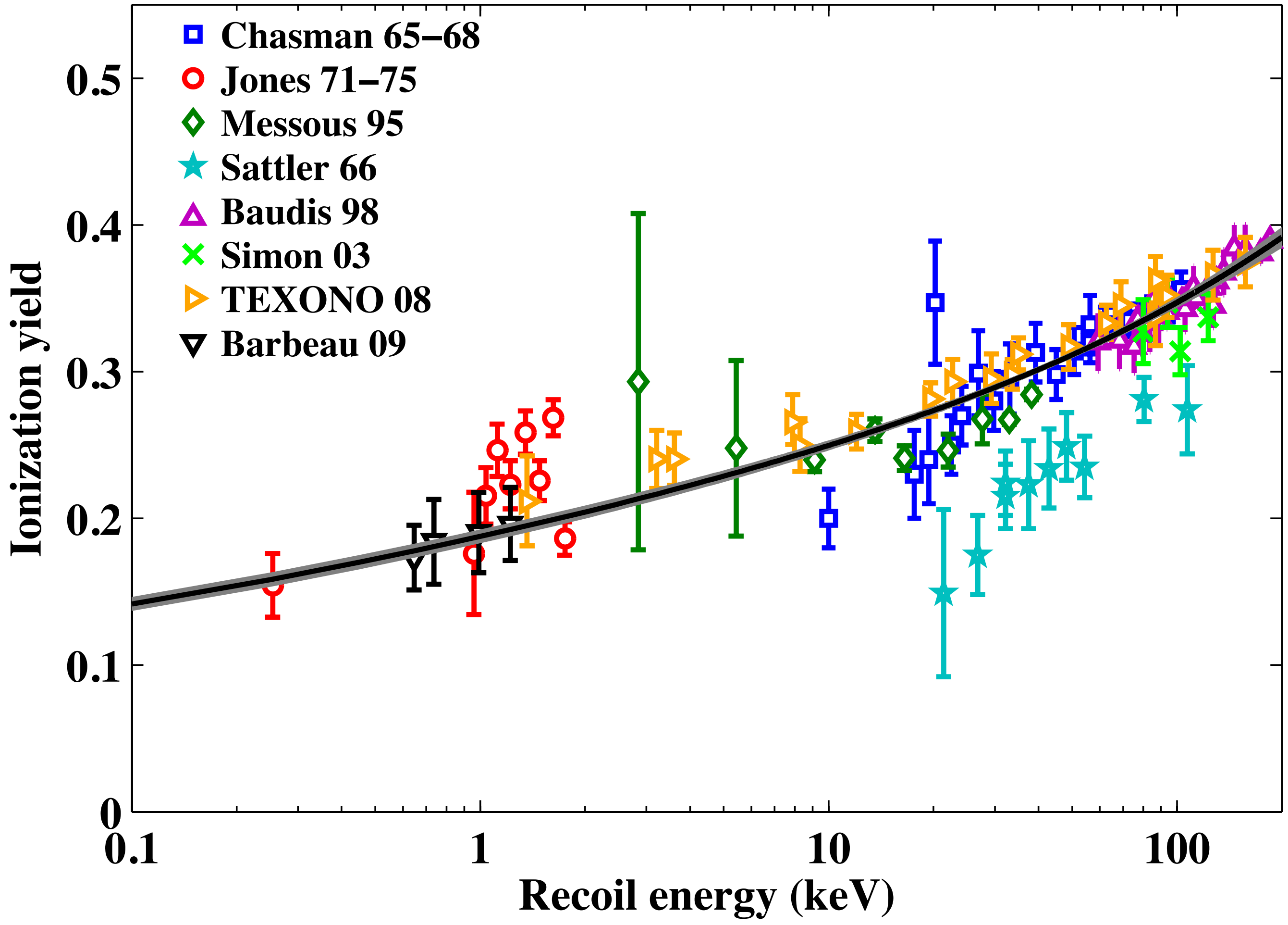
J. Billard et al., arXiv:1307.5458

Summary

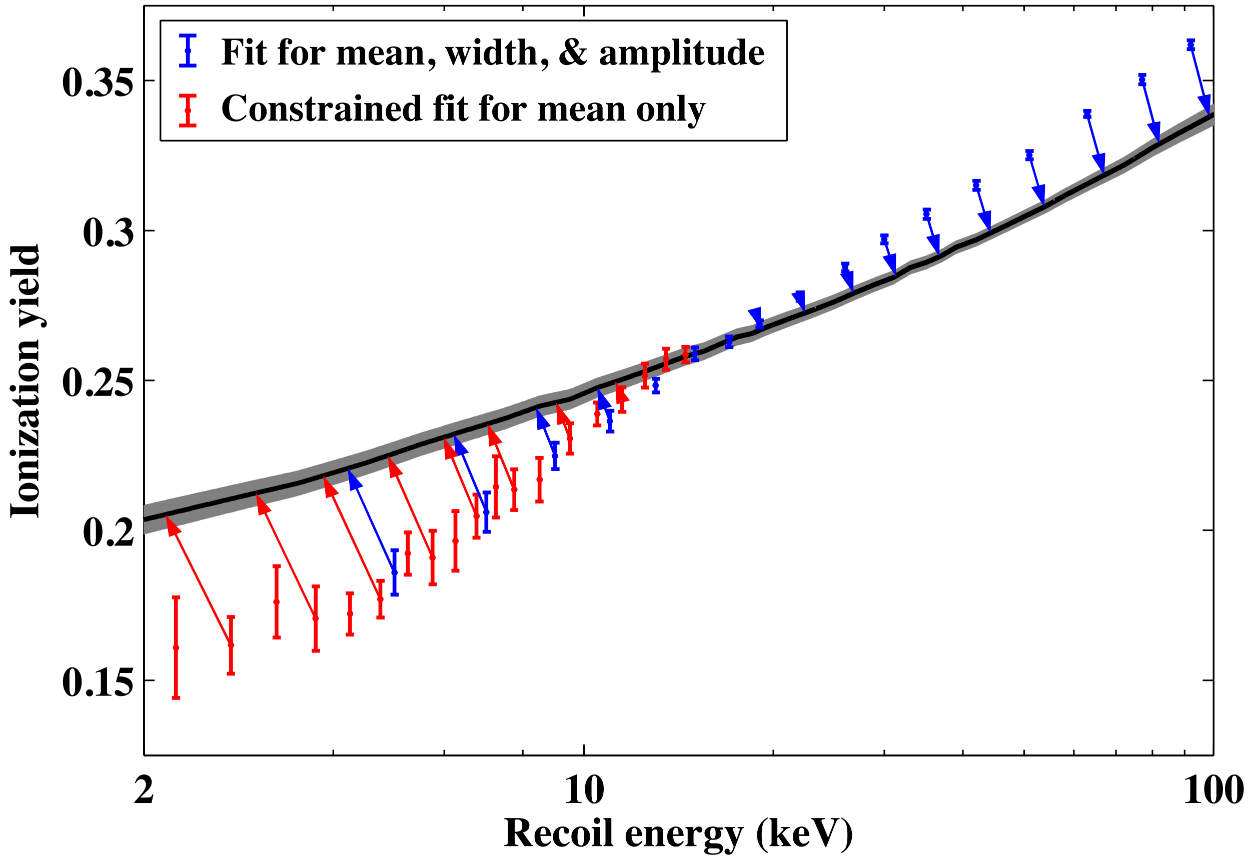
- New analysis methods have been employed on the Ge/Si data from the CDMS II
  - Ge data produced 0, 2, 3 candidates for 5D-χ^2, NN and classic timing methods
  - Ge limit the strongest 10 keV threshold limit produced by CDMS
  - Si data produced 3 candidate events using a χ^2 analysis
  - A likelihood analysis of this data favored a region around m_χ = 8.6 GeV/c^2 and σ_n = 1.9×10^{-41} cm^2
- While SUSY still remains a very interesting candidate theory WIMP masses have been pushed higher and to lower cross section by Higgs mass ~ 126 GeV/c^2 – direct detection should push to improve in both the high and low mass ranges!
- A myriad of theoretical models exist which can produce lighter DM but how are they linked to SUSY, do we need to move beyond minimal models like the cMSSM?
- SuperCDMS is continuing to push to lower threshold in both the new SuperCDMS-Soudan data set (run 133) and the CDMS II Ge set, exploring consistency at low WIMP mass is key

Backup Slides

Energy Scale Measurement: Ge

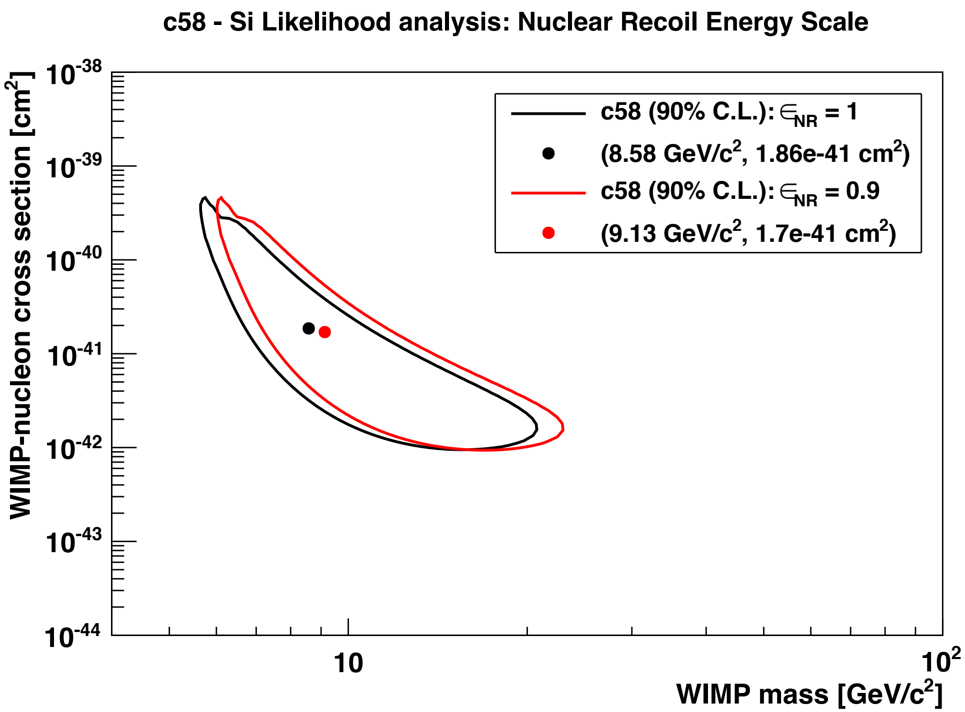


Energy Scale Measurement: Ge



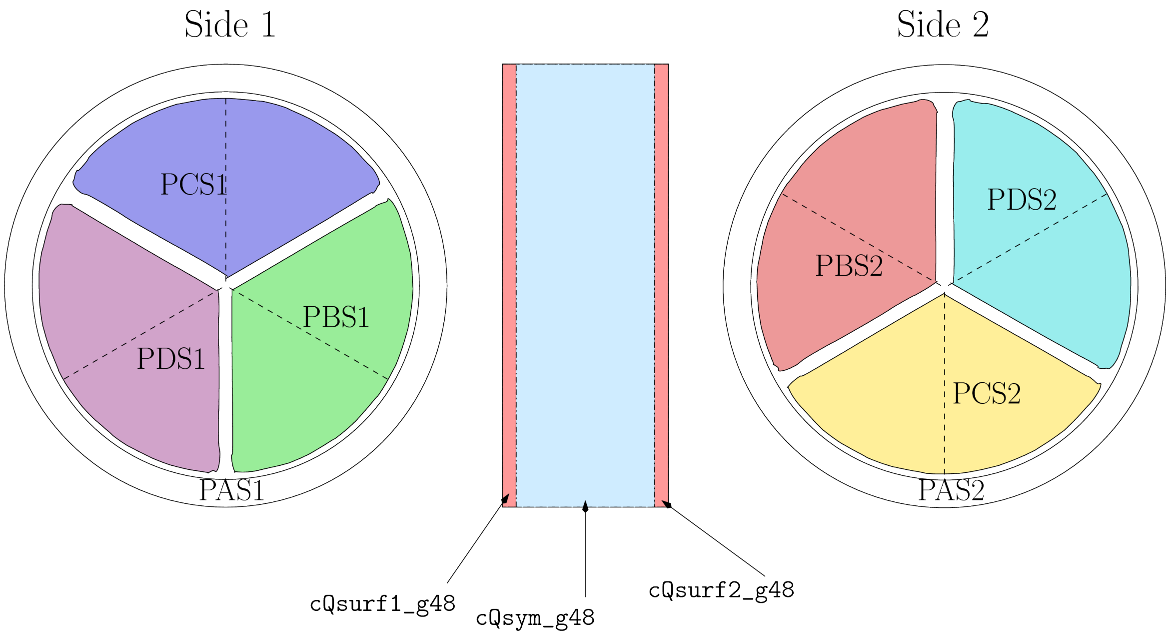
- CDMS Germanium measurements show over-measured energies below 15 keV and under-measured above w.r.t. measurements of yield (previous slide)
- Re-scaling the energies to best-fit values improves the Ge limits at low mass for 10 keV threshold modestly

Energy Scale: Effect on Results



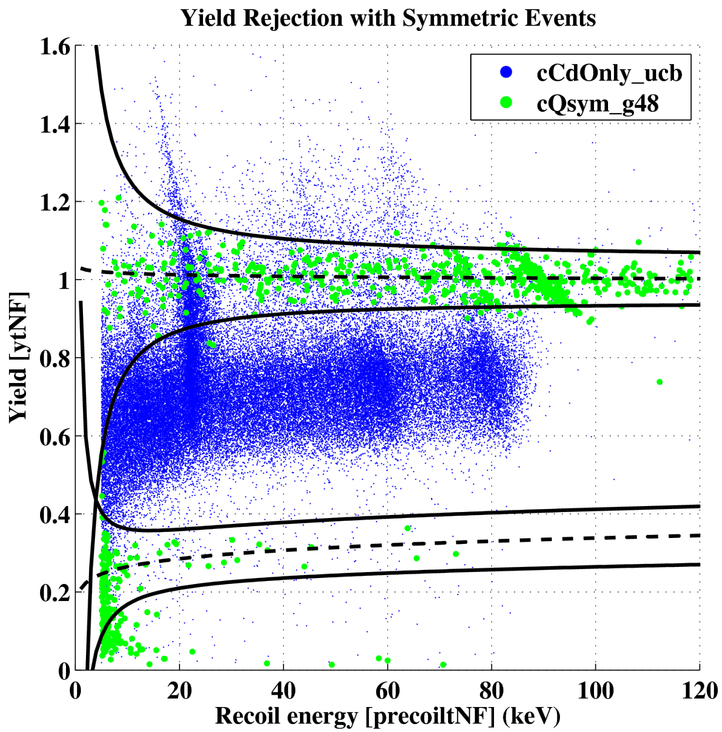
- Similar studies were undertaken on Si data
- The result of rescaling the energies to the best fit values is a slight shift (left) of the contours and best-fit values

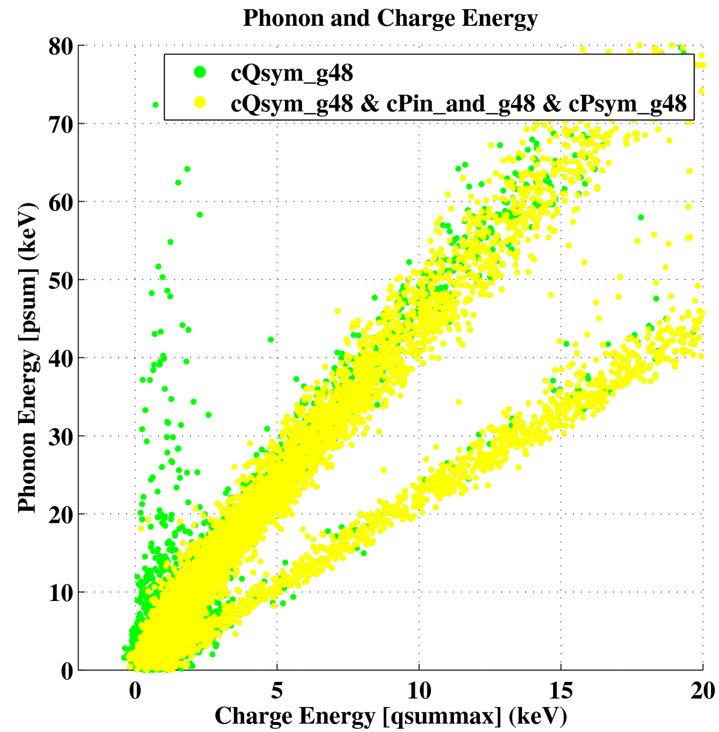
SuperCDMS Style Detectors



- The SuperCDMS detectors are of the iZIP type (above) and include dual-sided readout for both charge and phonons
- This is accomplished with an "interdigitated" design for electrodes and TES depositons – interdigitated z-sensitive ionization and phonon (iZIP) detectors
- The channel layout is shown above, the red shaded areas in the middle are a cartoon of the excluded "surface" regions by the charge asymmetry restriction (next slide), they are not to scale

Surface Event Discrimination (iZIP)





- The interleaved design and dual-sided charge readout gives very asymmetric charge signal for SEs
- Reduction by at least a factor of 1.7×10^{-5} on SE backgrounds

R. Agnese et al., Phys. Rev. Lett. **In press** (2013): arXiv:1305.2405