Recent Results from CDMS Experiment

Caltech – 01/06/2004

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Overview

- Dark Matter: Evidence and Candidates
- CDMS Experiment: Setup and Detectors
- Run Overview
- Background Discrimination
- Results: Neutrons vs WIMPs
- Soudan Status
- Conclusion

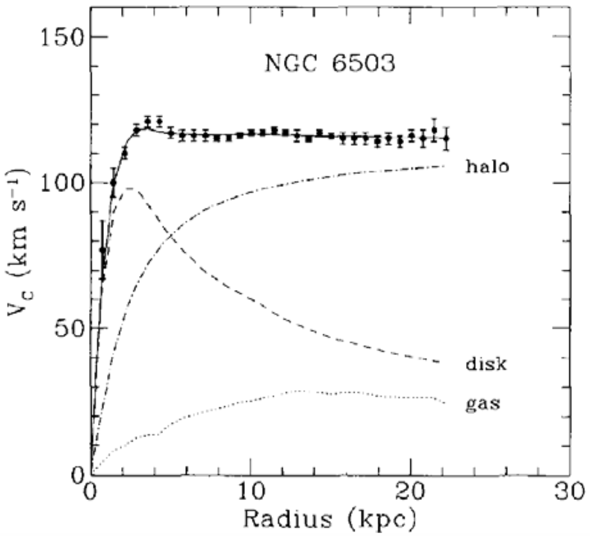
Evidence for Dark Matter

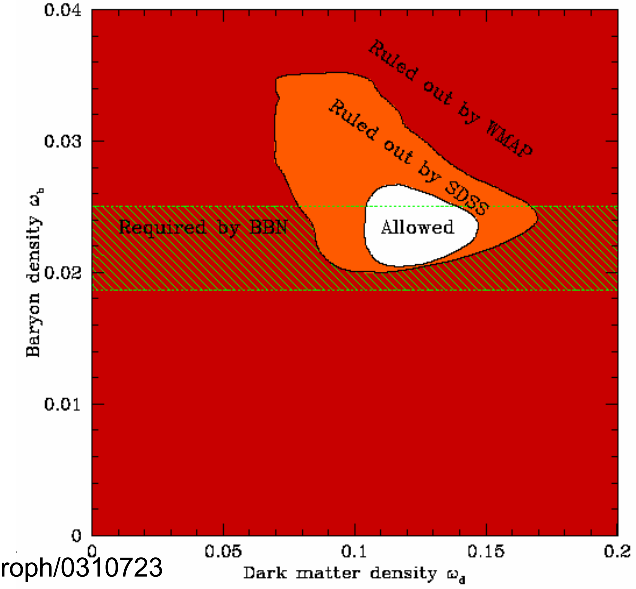
- First evidence by Zwicki in 1933.
- Much observational evidence:
  - Rotational curves of spiral galaxies
  - Dispersion velocities in elliptical galaxies
  - Dispersion velocities in clusters of galaxies
  - X-rays originated from clusters of galaxies
  - Gravitational lensing by galaxy clusters
- More recently:
  - CMB (WMAP, BOOMERANG, MAXIMA, DASI…)
  - Large Scale Structure Formation (2dFGRS, SDSS…)
  - Light Nuclei abundances
  - SN Ia redshifts
- ⇒ Estimated parameters of the Standard Model of Cosmology :

$$\Omega_{dm} \sim 0.25$$

- **What is it?**

Rotational Curve of NGC6503





Tegmark et al,astroph/0310723

Candidates

- Baryonic - **Ma**ssive **C**ompact **H**alo **O**bjects (MACHOs):
  - Hypothesis: ionized gas (observed at z~3) cooled and formed compact objects.
  - MACHO and EROS used gravitational microlensing to search for these dark massive objects.
  - Result: objects with mass $10^{-7}\ M_S < m < 10^{-3}\ M_S$ make up **<25%** of the dark matter halo for most halo models.

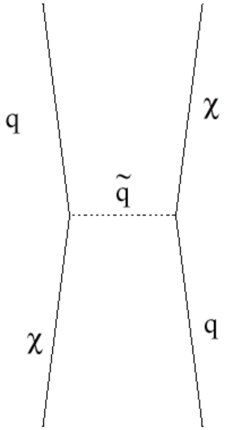
- Neutrinos:
  - Neutrino oscillation (SuperKamiokande, SNO …) indicates that neutrinos are massive.
  - Can constrain neutrino mass: $0.04\ \text{eV} < m_\nu < 0.6\ \text{eV}$ (from atmospheric neutrino oscillations, WMAP and SDSS data; Tegmark et al, astroph/0310723).
  - Neutrinos alone cannot explain the observed large structure (due to neutrino streaming) $\Rightarrow$ **$\Omega_\nu < 0.03$.**

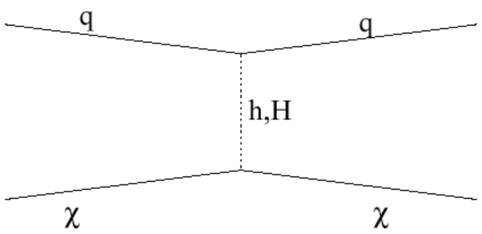
- Axions:
  - Peccei and Quinn: solution to the strong CP problem.
  - SN1987A observation: $10^{-6} < m_a < 10^{-2}$ eV.
  - Axions couple to magnetic field ⇒ search using microwave cavity in a strong magnetic field.
  - Can probe only a portion of the allowed mass range.

Weakly Interactive Massive Particles (WIMPs)

- Sufficiently massive that they could account for the missing mass.
- Rarely interacting with ordinary matter (which is why they have not been observed yet).
- Supersymmetry offers a natural WIMP candidate:
  - For every particle, there is a super-partner particle with spin different by ½.
  - The lightest super-partner (LSP) stable and weakly interacting with ordinary matter ⇒ **natural WIMP candidate!**
  - In most cases, the LSP is a neutralino - a superposition of superpartners of B, W, and two neutral, parity even Higgs fields.

$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$





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CDMS Collaboration

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M. E. Huber

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CDMS Experiment

- Cryogenic Dark Matter Search (CDMS) Experiment is designed to search for Dark Matter in the form of WIMPs

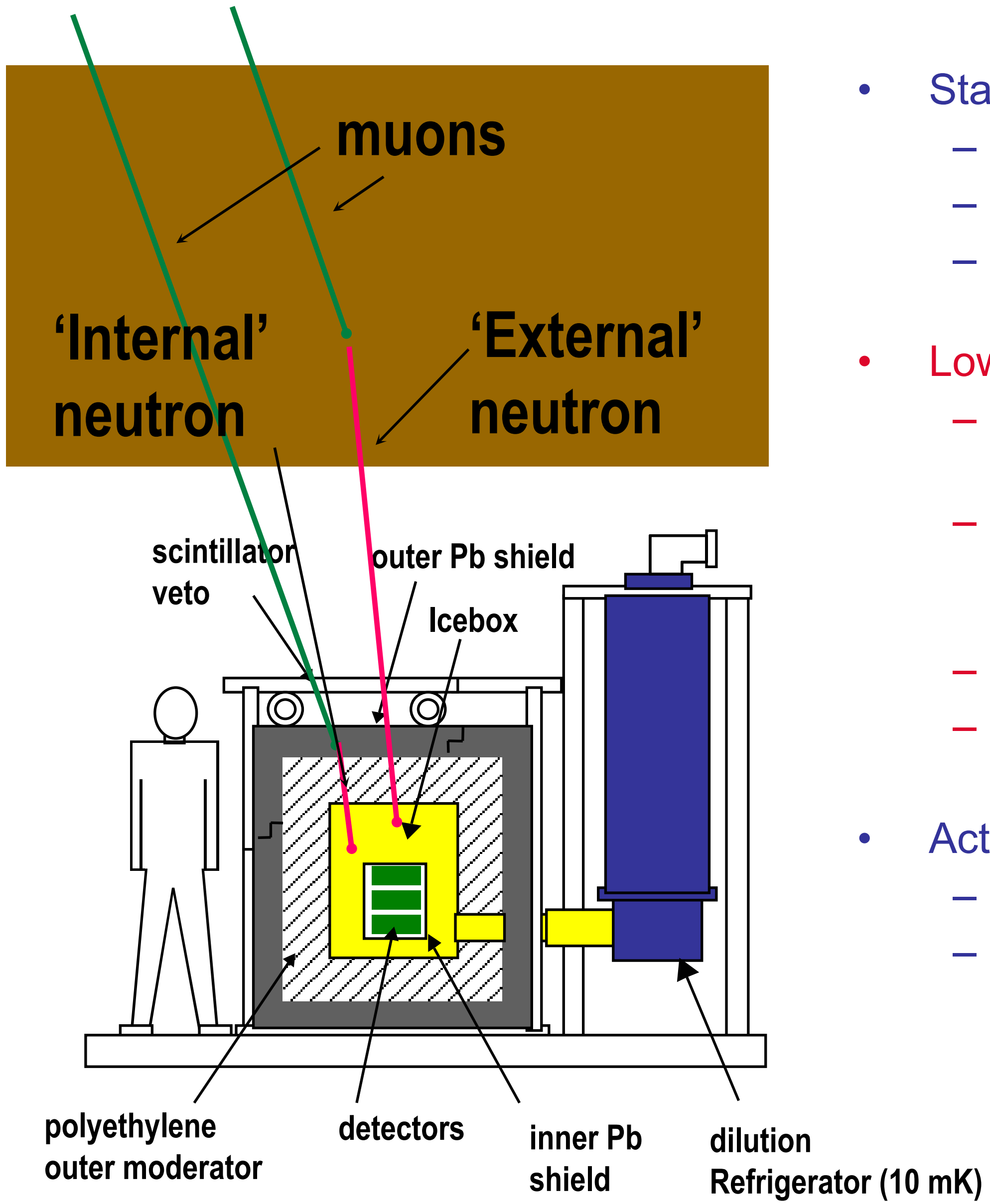
- Expect very small signal (if any!) ⇒ Main objective is understanding and suppression of various types of backgrounds.

- Background suppression:
  - Underground
  - Shields (Pb, polyethylene, muon scintillator veto)

- Ge and Si based detectors with two-fold interaction signature allow effective suppression of the dominant gamma background:
  - Ionization signal
  - Athermal phonon signal
  - Can distinguish electron recoils (gammas, betas) from nuclear recoils (neutrons, WIMPs)

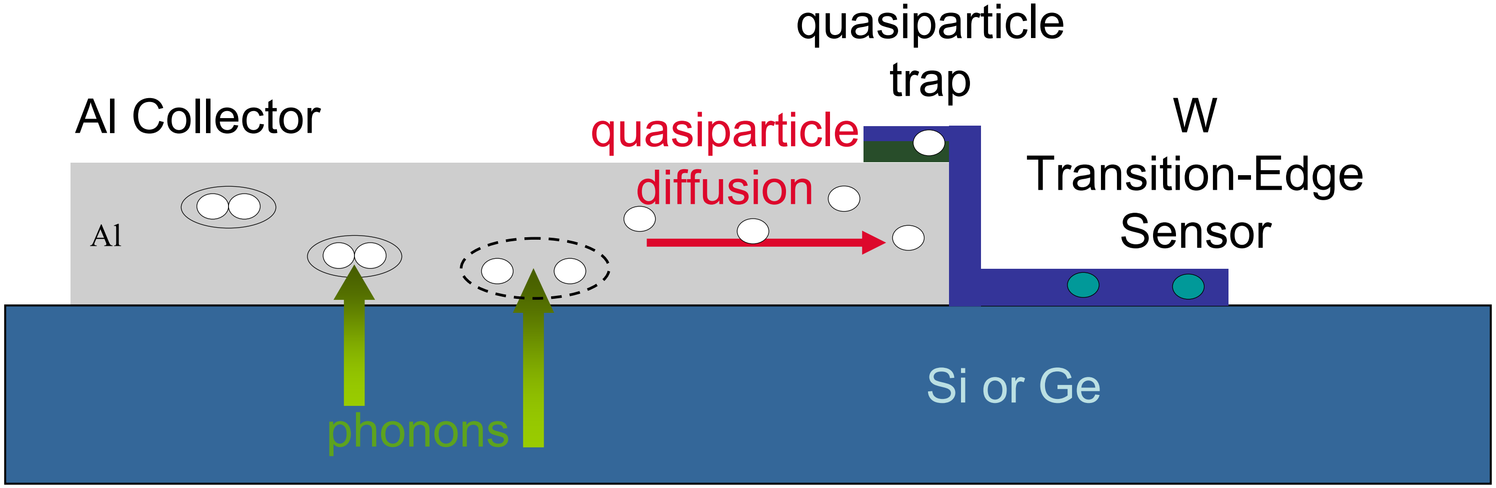
- Remaining neutron background:
  - Relative event rates: Ge vs Si, singles vs multiples

Stanford Underground Facility (SUF)



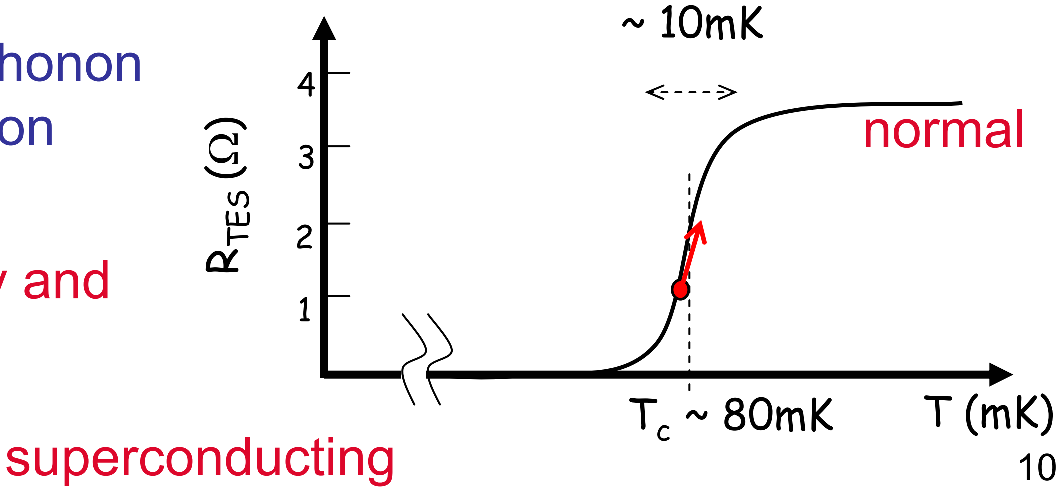
- Stanford Underground Facility
  - 17 mwe of rock
  - Hadronic component down by 1000
  - Muon flux down by ~5
- Low Background Environment
  - 15 cm Pb reduces photon flux by factor >1000
  - 25 cm polyethylene reduces muon-induced neutron flux from rock and lead by factor >100
  - Radiopure cold volume (10 kg)
  - Additional internal (ancient) lead shielding
- Active Scintillator Muon Veto
  - Muon veto >99.9% efficient
  - Reject ~20 "internal" neutrons/ day produced by muons within shield

ZIP Detectors (1)



W Transition-Edge Sensor:
a really good thermometer

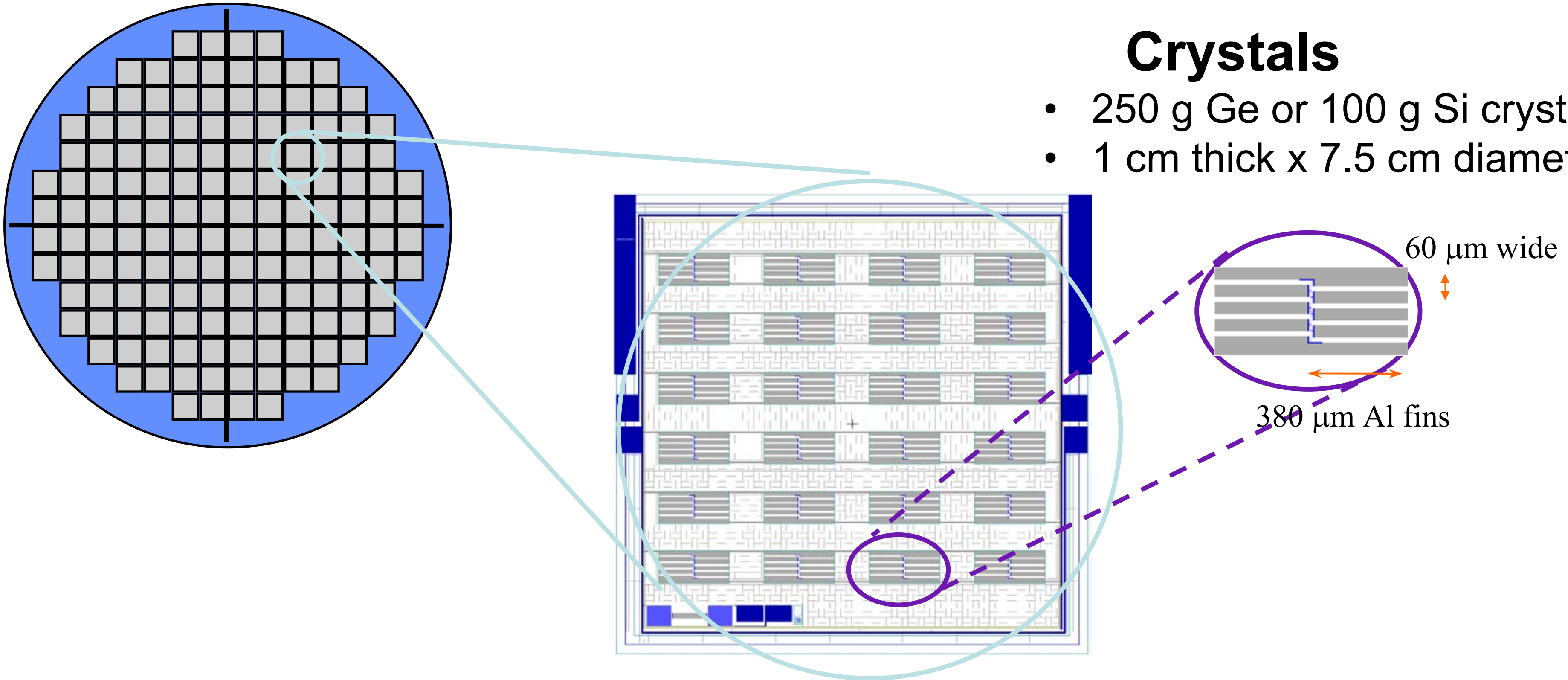
- Measurement of athermal phonon signals maximizes information
- Fast pulse, excellent energy and timing resolution



ZIP Detectors (2)

Crystals

- 250 g Ge or 100 g Si crystal
- 1 cm thick x 7.5 cm diameter



Phonon Sensors

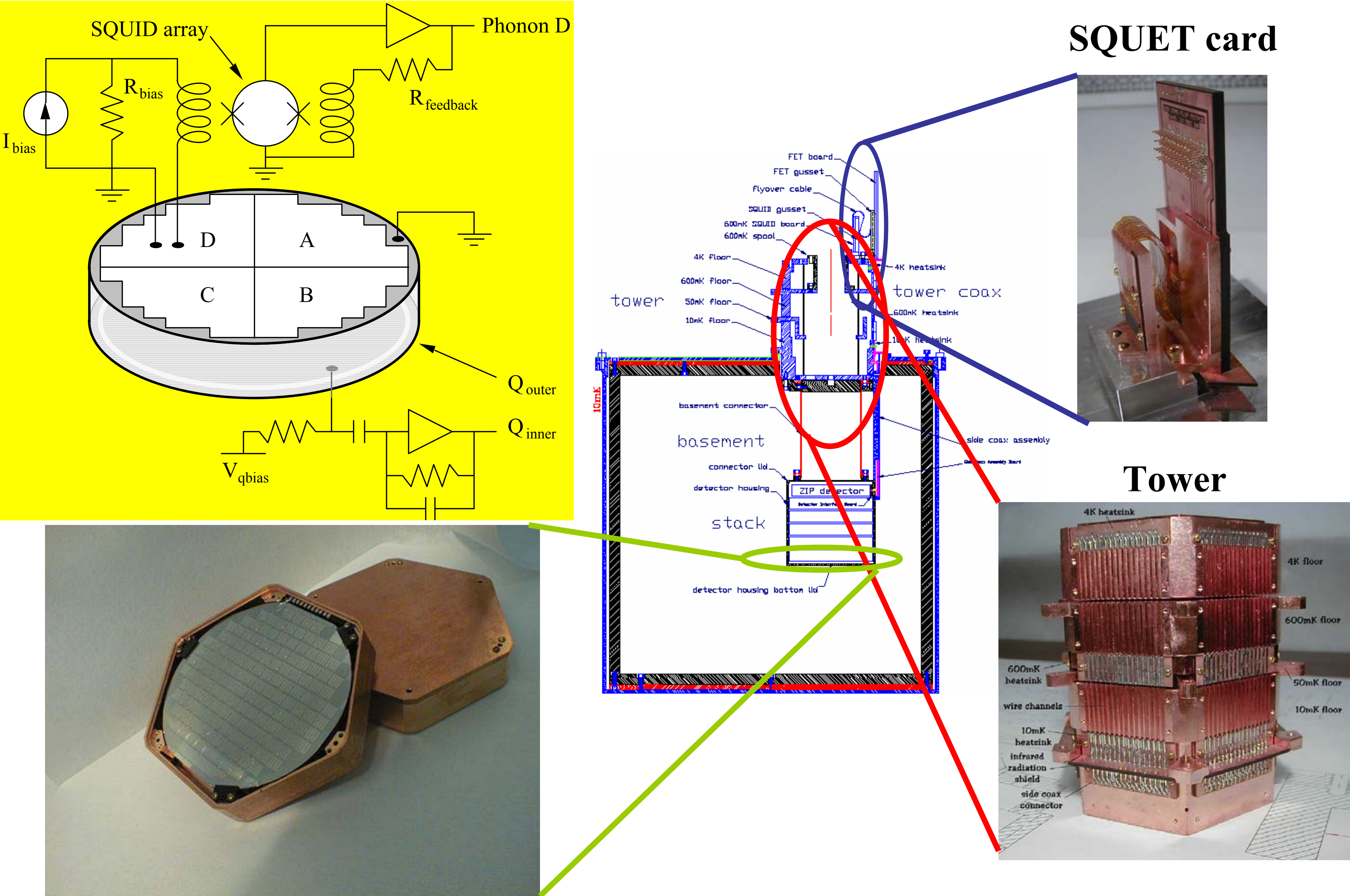
- Photolithographic patterning
- 4 quadrants
- 37 cells per quadrant
- 6x4 array of W transition-edge sensors per cell
- Each W sensor “fed” by 8 Al fins

⇒ ~1000 TES per quadrant!

Charge Sensors

- Electrons and holes created in an interaction.
- Electric field through the crystal separates electrons and holes.
- 2 electrodes (+ ground).
- Allows rejection of events near outer edge.

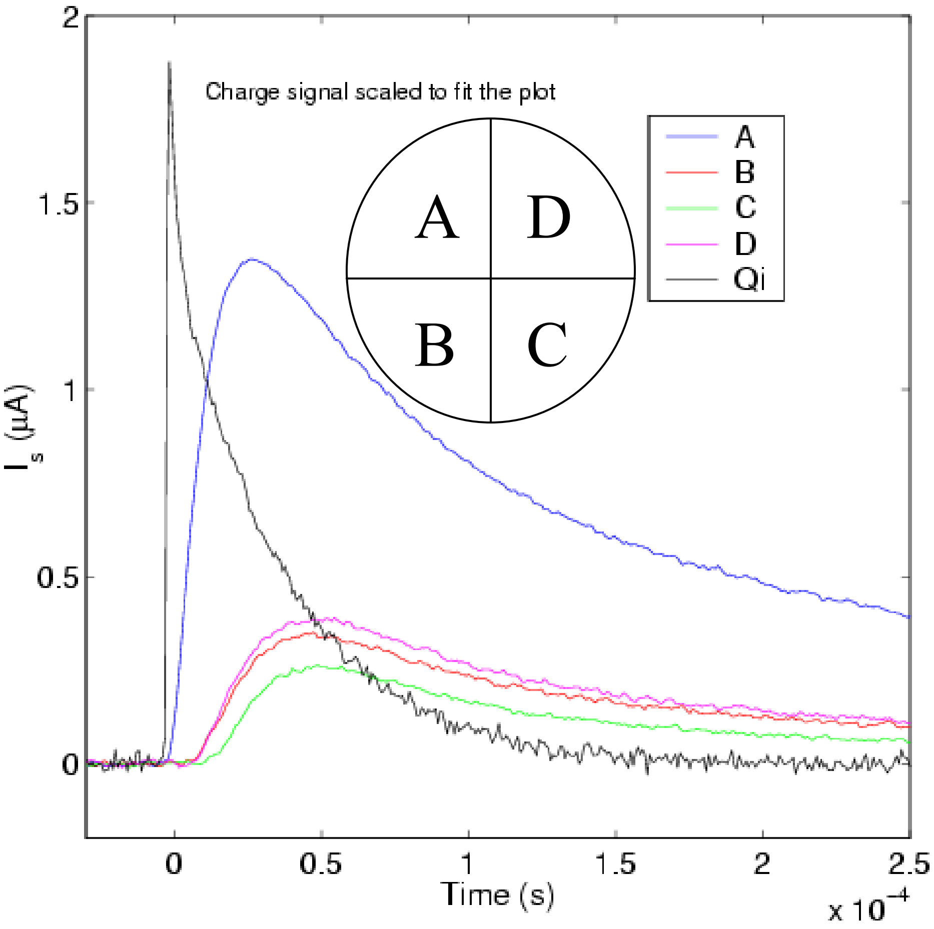
Detector Readout



SQUET card

Tower

Ionization and Phonon Signals



- Ionization:
  - Fast: 1 μs rise-time, 40 μs fall-time.
  - Good measure of the Event Time.

- Phonons:
  - Start times depend on event position.
  - Rise time depends on interaction depth.

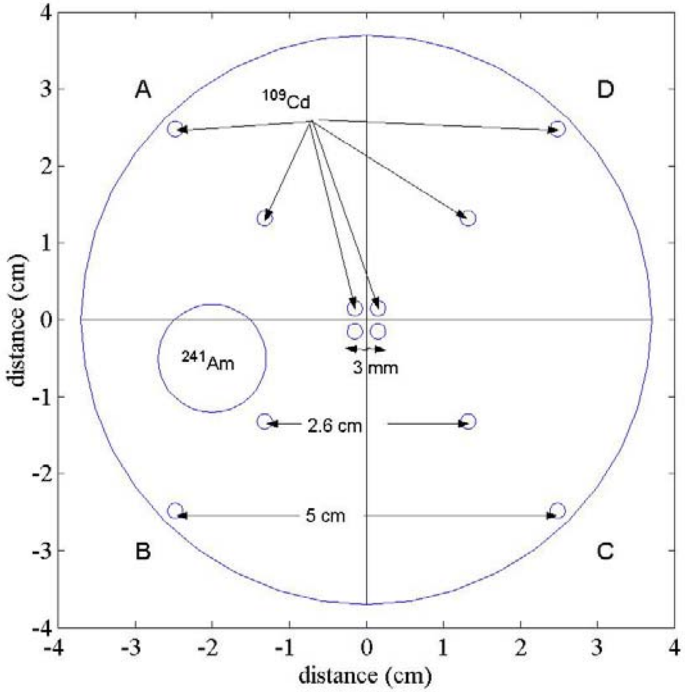
- Ionization and Phonon signal amplitudes reveal the recoil energy.

- Timing **and** amplitude of the phonon signals can be used to reconstruct event position.

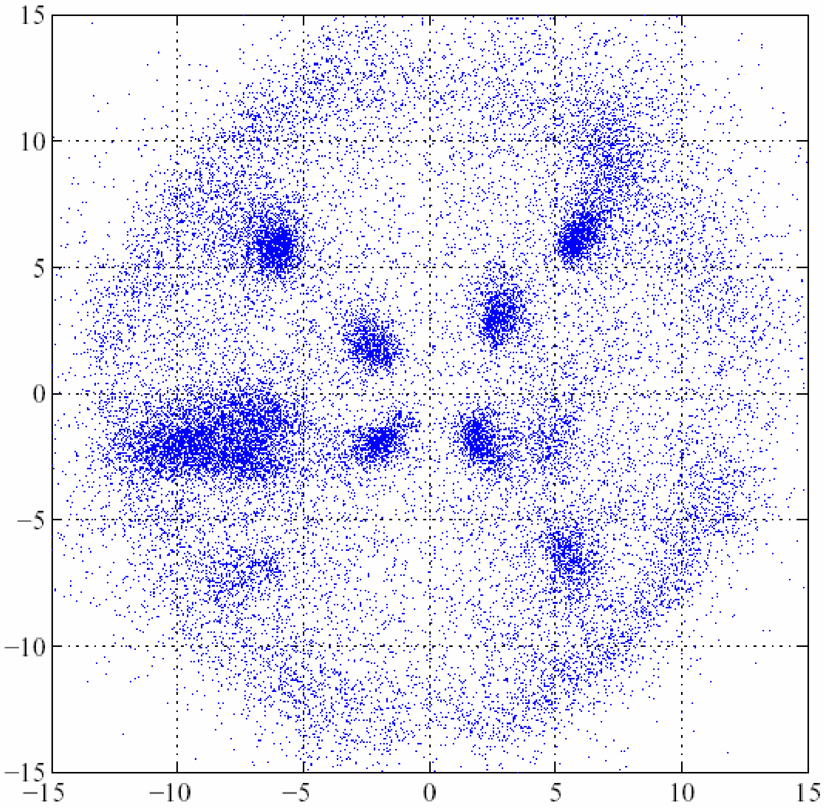
- Allows position correction of any non-uniformities (T_c gradient).

Position Reconstruction

- Calibration run performed at the UCB Test Facility.
- Exposed one detector to a large-surface ^{109}Cd source, behind a Pb collimator.
- Used phonon amplitude and timing information to reconstruct positions of collimator holes.



Position reconstructed using phonon start-times.



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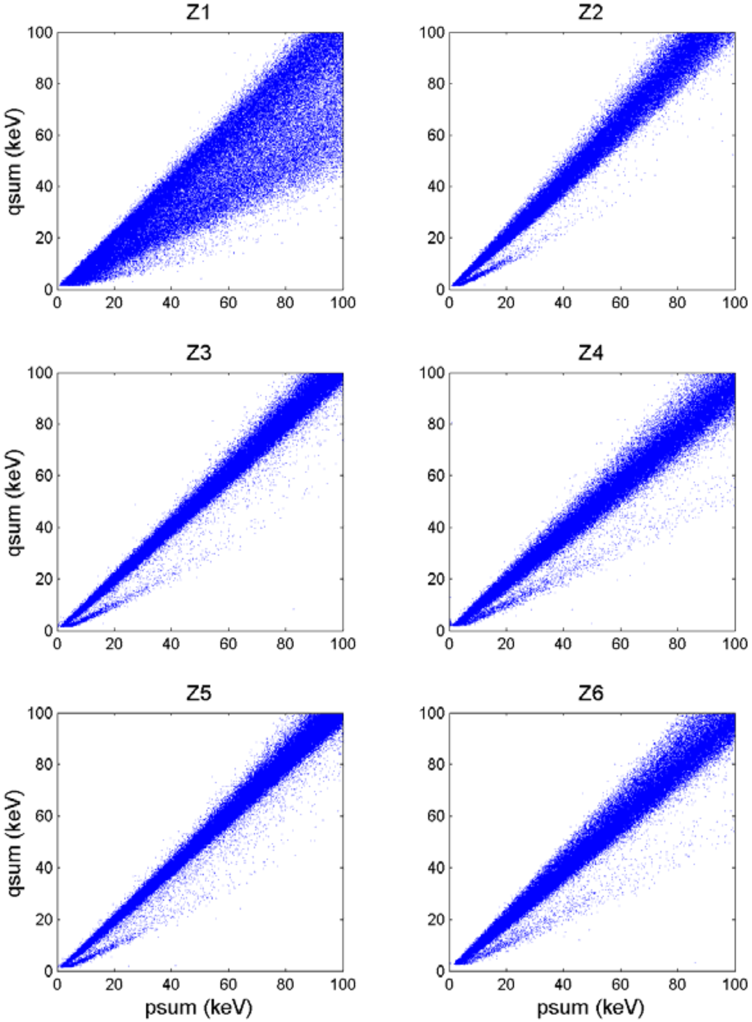
Run Overview

- Previous Results: CDMS I
  - 1998-1999 run of 3 Ge BLIPs = **15.8 kg days** after cuts
  - **23 singles & 4 multiple** nuclear-recoils, most (or all) neutrons
  - Final results: Phys. Rev. D66, 122003 (2002), astro-ph/0203500
  - Conflict with DAMA, agreement with Edelweiss and Zeplin I.
- Recent Results: Preparations for CDMS II at deep site
  - Run first tower at SUF: 4 Ge and 2 Si ZIPs
  - Run ‘b’ at SUF uninterrupted from November ‘01 to June ‘02.
  - 66 livedays at **3 V** bias = **28 kg days** after cuts.
  - 52 livedays at **6 V** bias = **21 kg days** after cuts.
- Goals Achieved:
  - **Confirmed CDMS I results**, hep-ex/0306001 (to appear in Phys. Rev. D)
  - Establish the **contamination levels** of the detectors before their installation at Soudan: **acceptable**.
  - **Measured gamma and beta rejection efficiencies: better than proposal.**
  - Measured the muon anti-coincident flux at SUF simultaneously with Si & Ge ZIPs.
  - Tested and confirmed Monte Carlo predictions of neutron rate suppression due to addition of internal polyethylene.
- Towers 1 and 2 now installed at Deep site facility, Soudan, Minnesota.

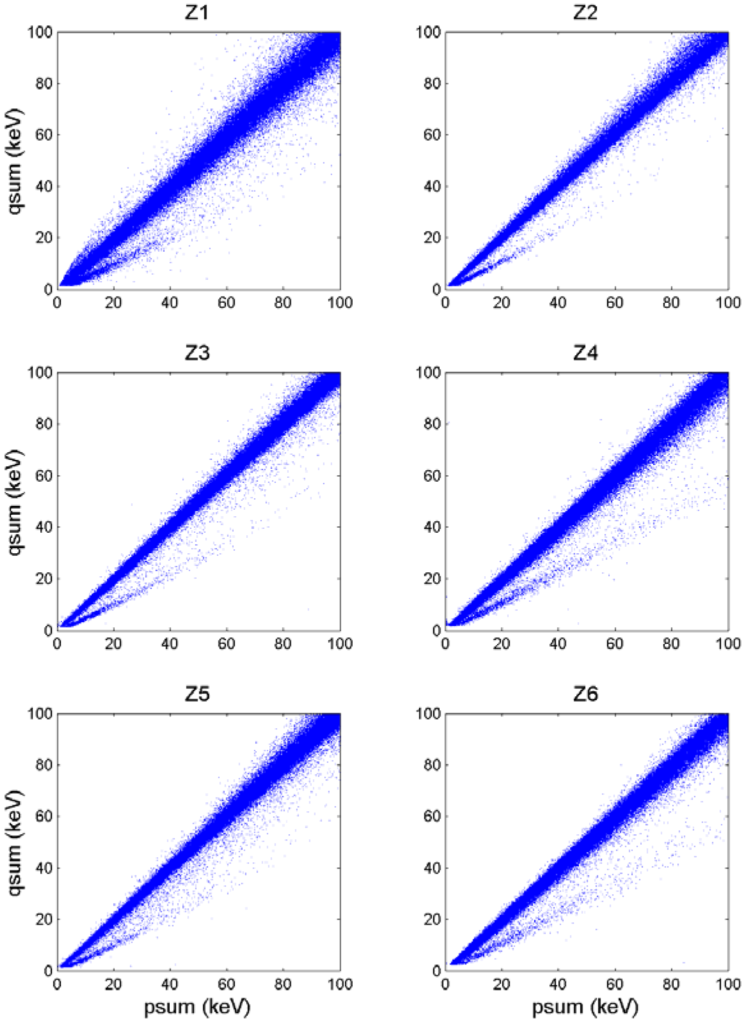
Detector Performance

Calibration Data

Before Position Correction



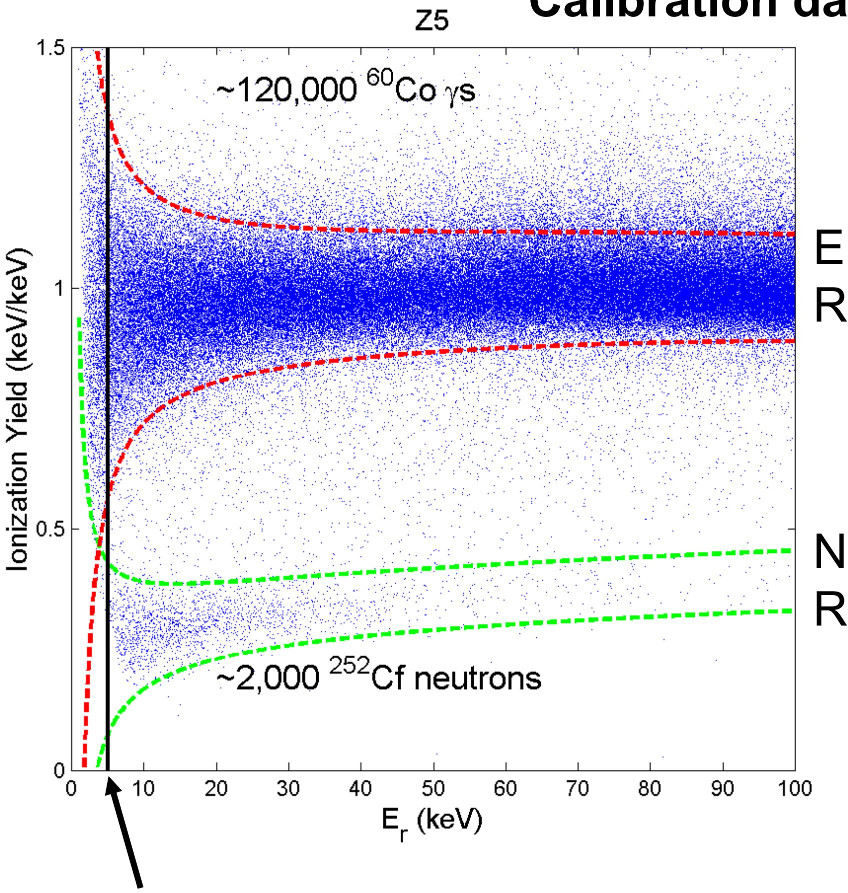
After Position Correction



Electron Recoil Discrimination

- Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil
- Most background sources (gammas, betas, alphas) produce electron recoils
- WIMPs (and neutrons) produce nuclear recoils
- **γ rejection > 99.98%** - More than 5x better than CDMS II proposal

Calibration data



Electron Recoils

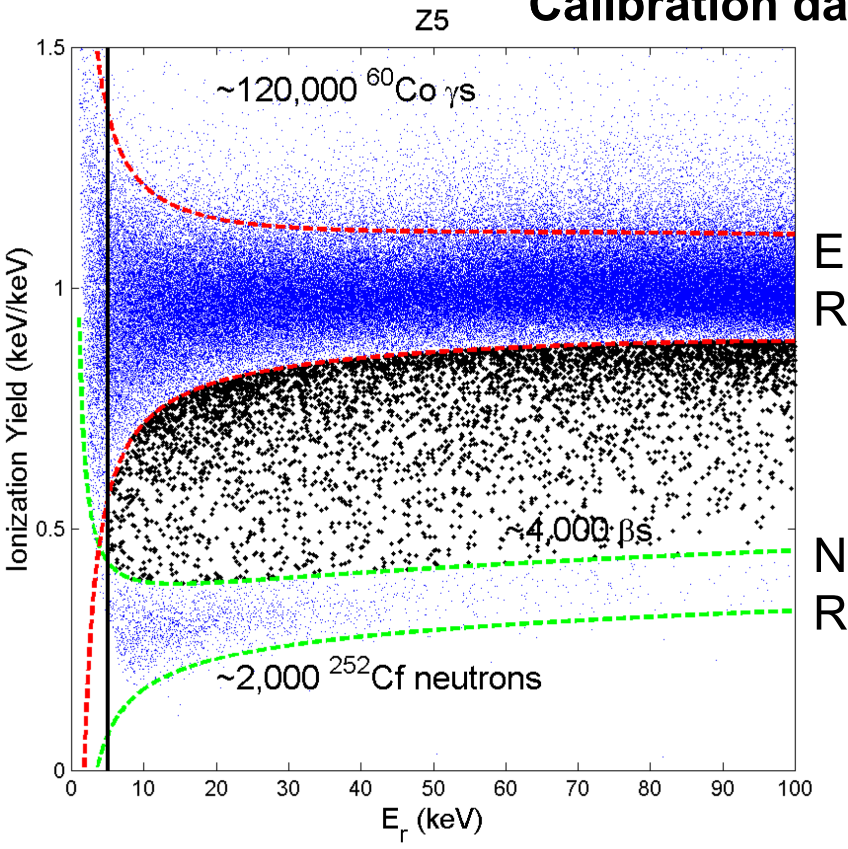
Nuclear Recoils

5 keV

Electron Recoil Discrimination

- Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil
- Most background sources (gammas, betas, alphas) produce electron recoils
- WIMPs (and neutrons) produce nuclear recoils
- γ **rejection > 99.98%** - More than 5x better than CDMS II proposal
- Surface electron recoil events can mimic nuclear recoil events!

Calibration data



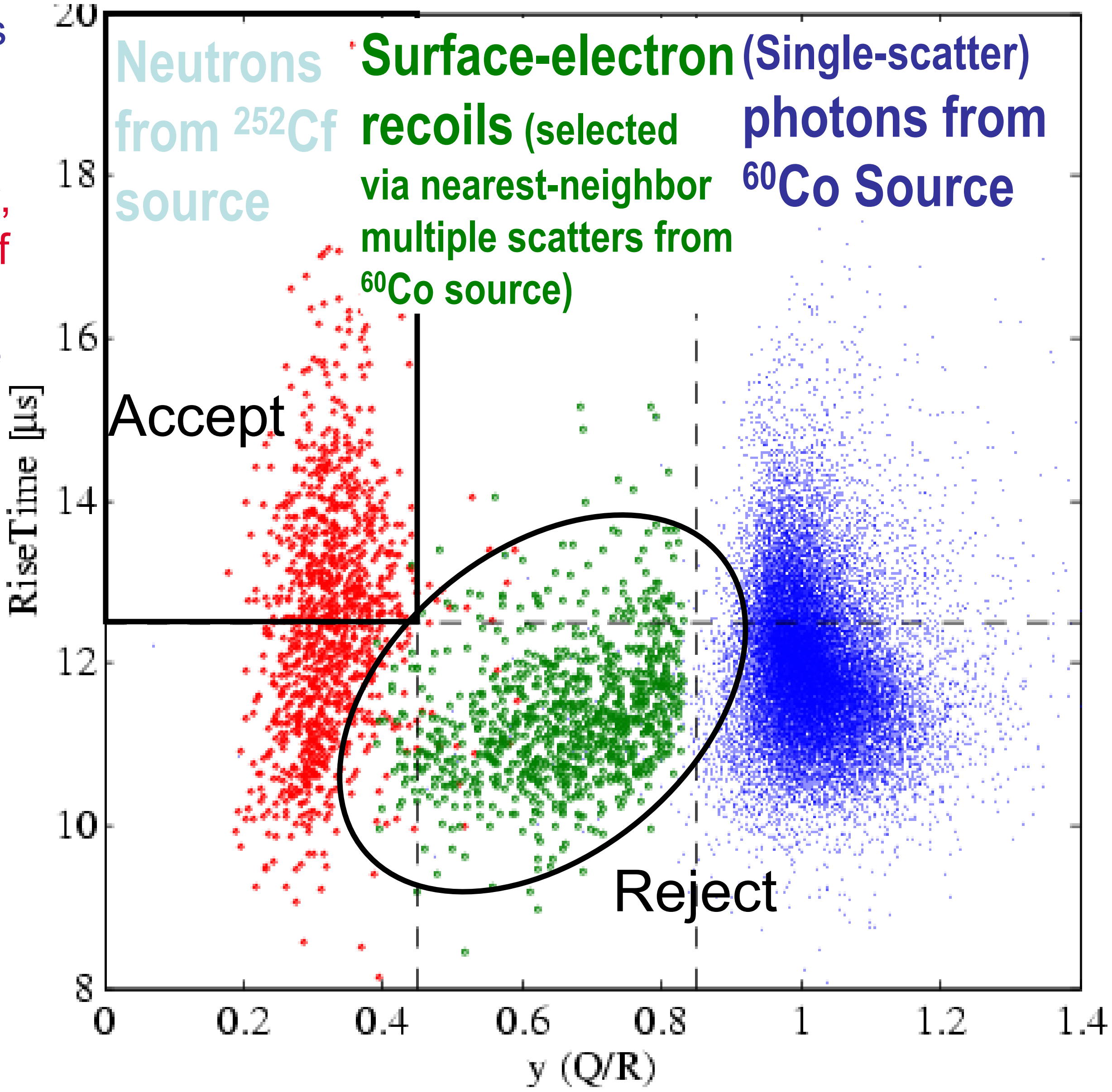
Electron Recoils

Nuclear Recoils

- Detectors provide near-perfect event-by-event discrimination against otherwise dominant electron-recoil backgrounds

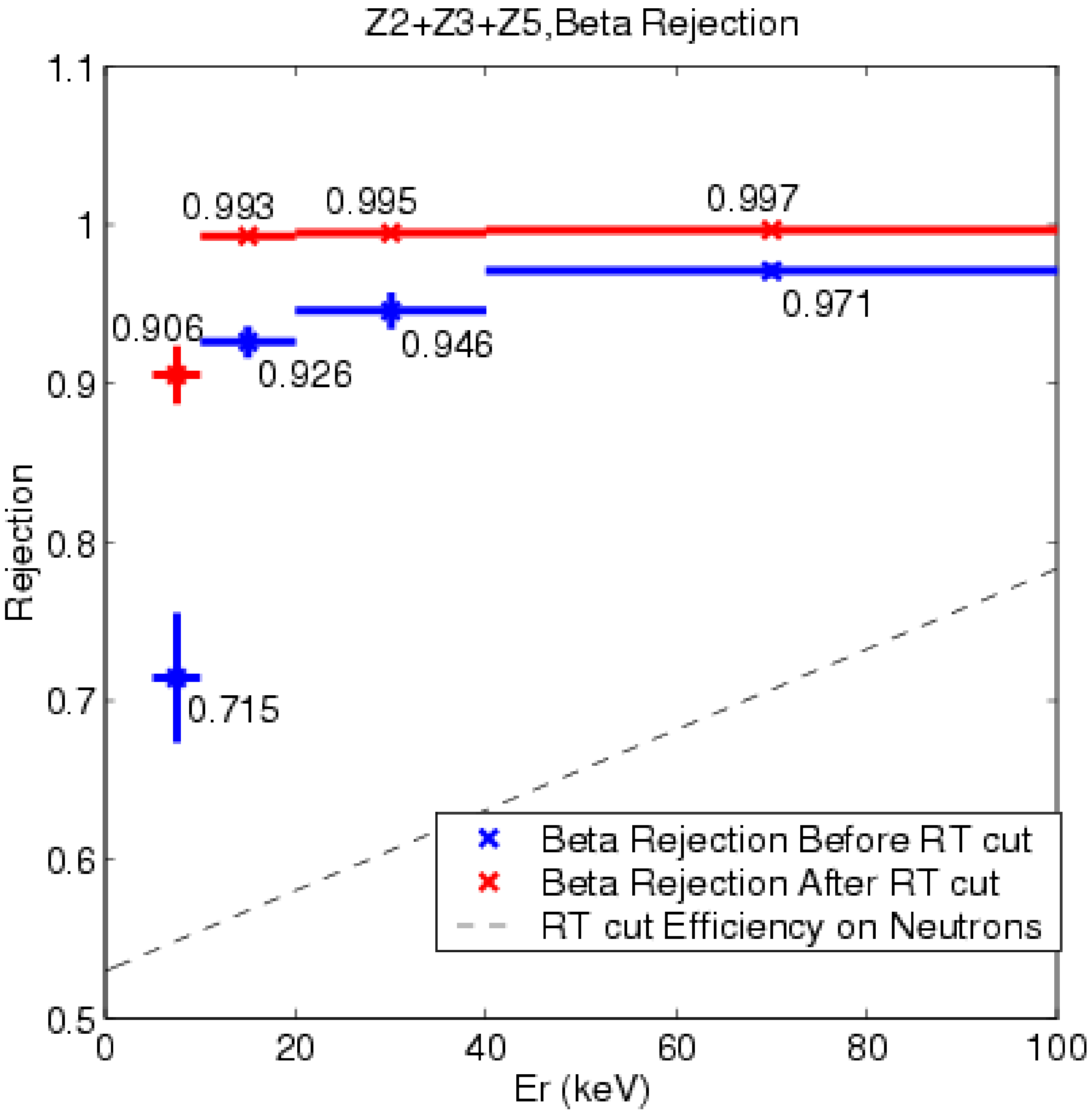
Rejecting Surface Events

- Events near crystal surfaces produce different frequency spectrum of phonons
- These phonons travel faster, result in a shorter risetime of the phonon pulse
- Risetime cut helps eliminate the otherwise troublesome background surface events



Rejecting Surface Events

- Events near crystal surfaces produce different frequency spectrum of phonons
- These phonons travel faster, result in a shorter risetime of the phonon pulse
- Risetime cut helps eliminate the otherwise troublesome background surface events
- **Rejection** of surface electron recoils based on ionization yield alone is **>90% above 10 keV**
- Rejection of electrons recoils based on risetime of phonon pulses is >90% while **keeping >55% of the neutrons**
- Overall **rejection of beta** electrons appears **>99%**, twice as good as in CDMS II proposal



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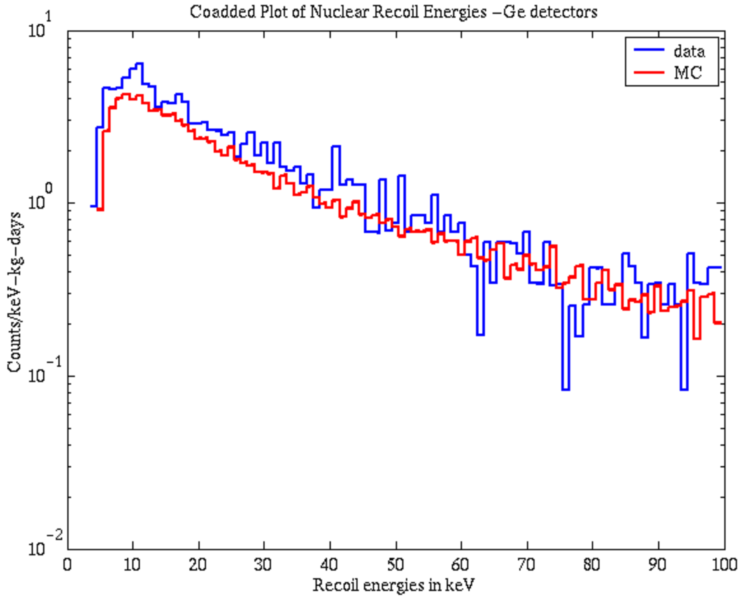
Neutron Rates

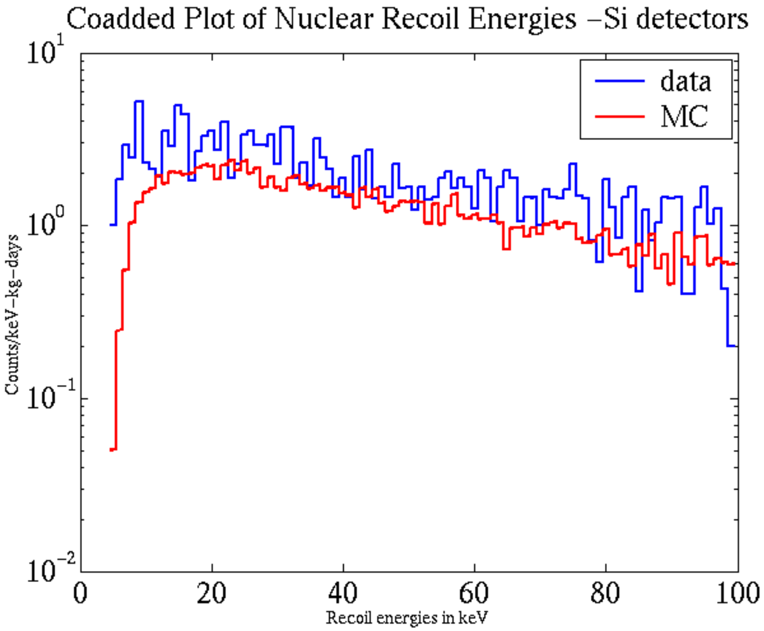
After Run 19, internal polyethylene added.

External, muon-anticoincident neutron rate dropped by a factor of 3.

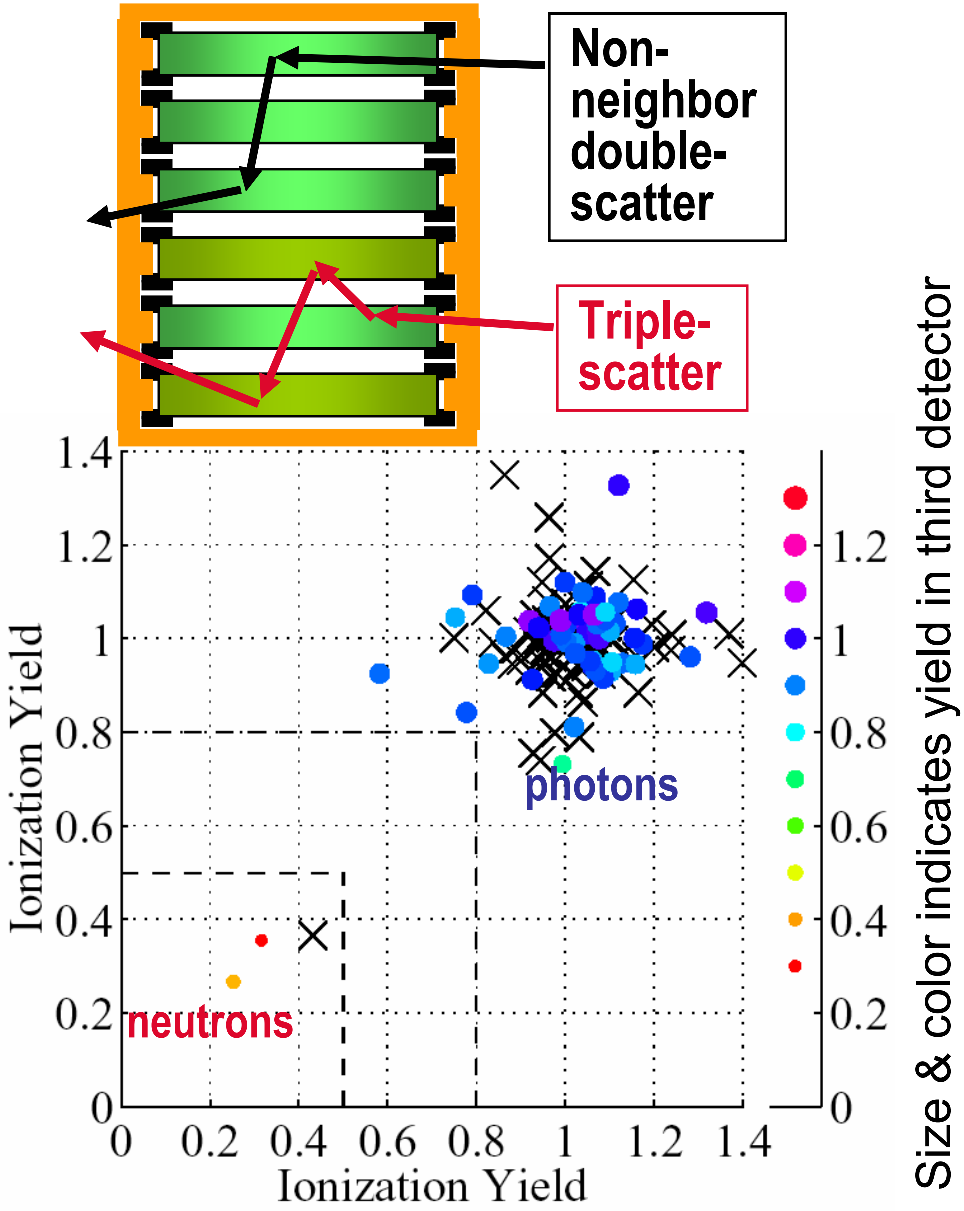
Internal, muon-coincident neutron rate dropped by a factor of 2.3 - as predicted by the Monte Carlos!

- ◆Based on Run 19's 23 singles, 4 multiples in 15.8 kg days, expect ~17 Ge singles, ~3 Si Z4 singles, ~7 multiples in 28 kg days of Run 21.
- ◆We see 20 Ge singles, 2 Si Z4 singles, 8 multiples in 28 kg days of 3 V bias data set of SUF Run 21.



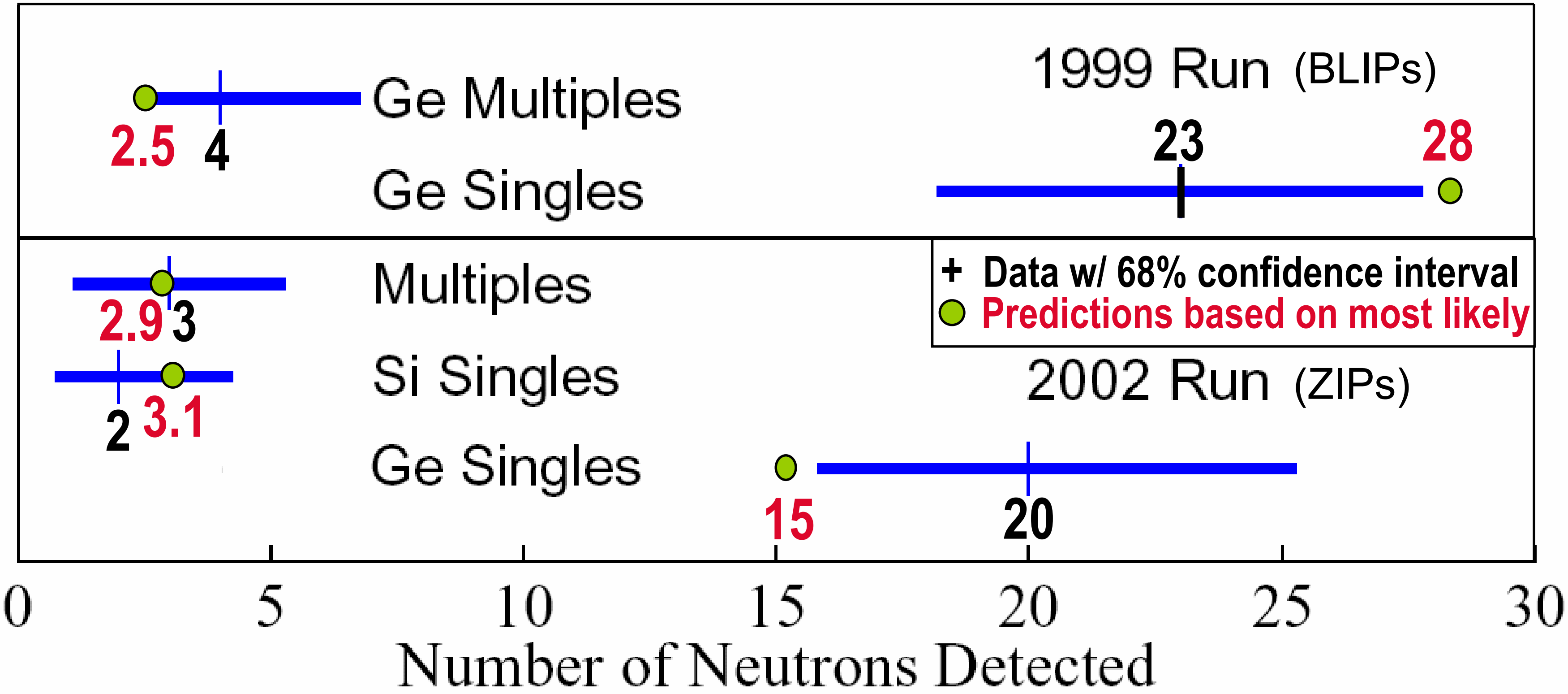


Neutron Multiple Scatters



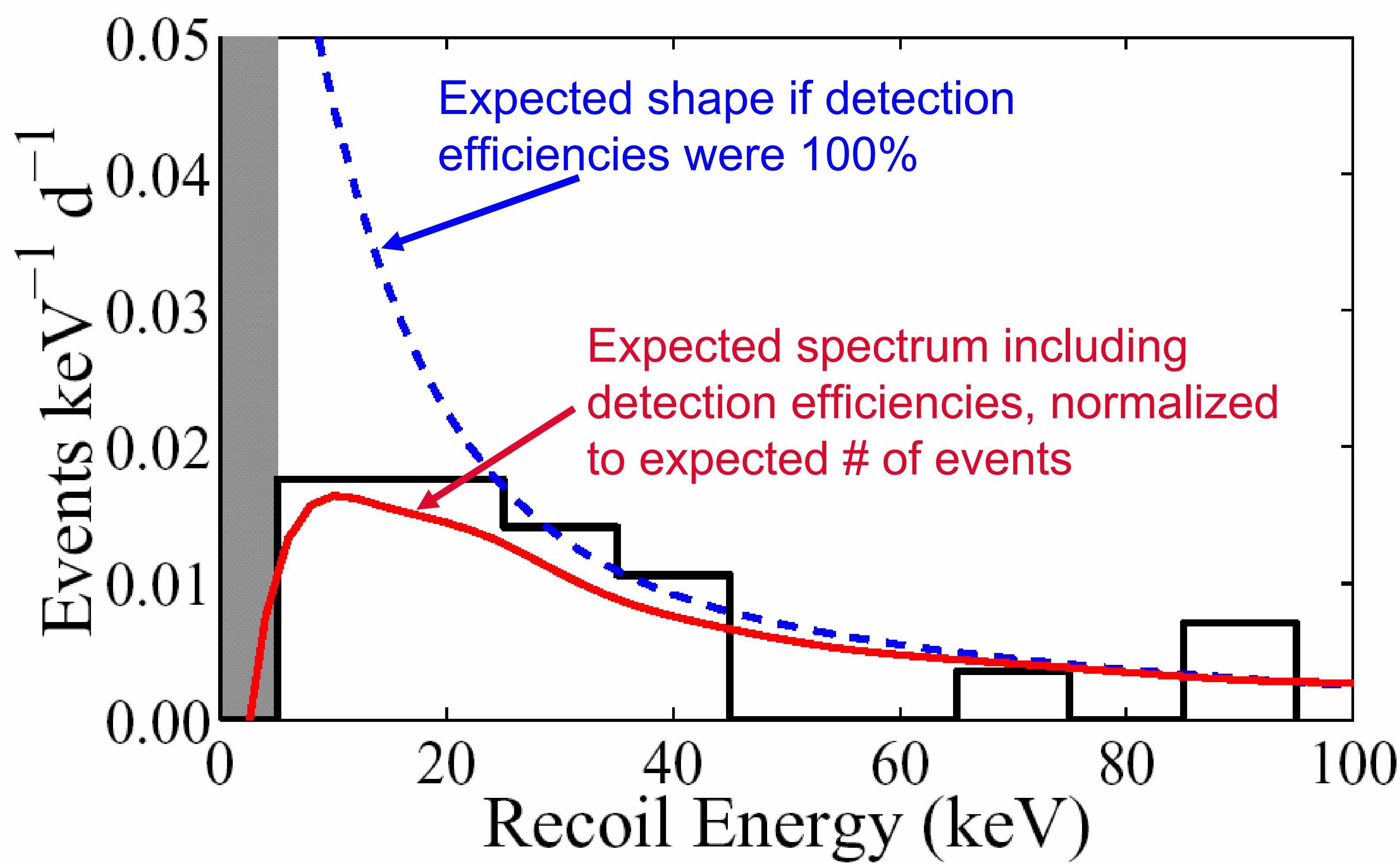
- **2 triple-scatter** (filled circles) and **1 non-nearest-neighbor double-scatter** (×) NR candidates 5-100 keV
  - – Ignore nearest-neighbor doubles because possible contamination by surface electrons
- Expect **~16** single-scatter neutrons per 3 multiple scatters
  - – Implies many (or all) of **20** single-scatter WIMP candidates are neutrons

Consistency of Neutron Hypothesis



- **Most likely neutron background** from simultaneous fit to 1999 and 2002 data (including factor 2.3 from additional polyethylene) provides **good agreement with data**.
- Likelihood ratio test: expect worse agreement **30%** of the time

Nuclear Recoil Energy Spectrum

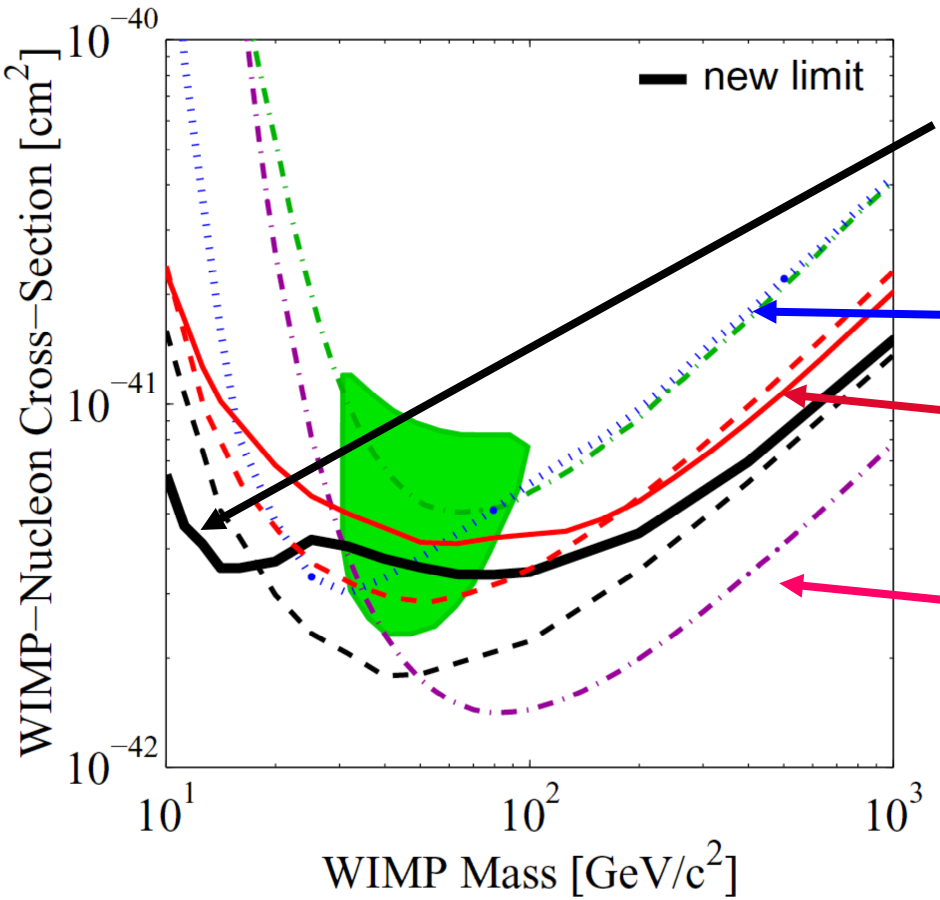


Expected shape if detection efficiencies were 100%

Expected spectrum including detection efficiencies, normalized to expected # of events

- Energy spectrum agrees with expected neutron spectrum
  - Kolmogorov-Smirnof test indicates we should expect worse agreement **32%** of time

3 V bias SUF WIMP limit



New CDMS II 3 V bias SUF Run 21 limit, with neutron subtraction

SUF Run 19 limit

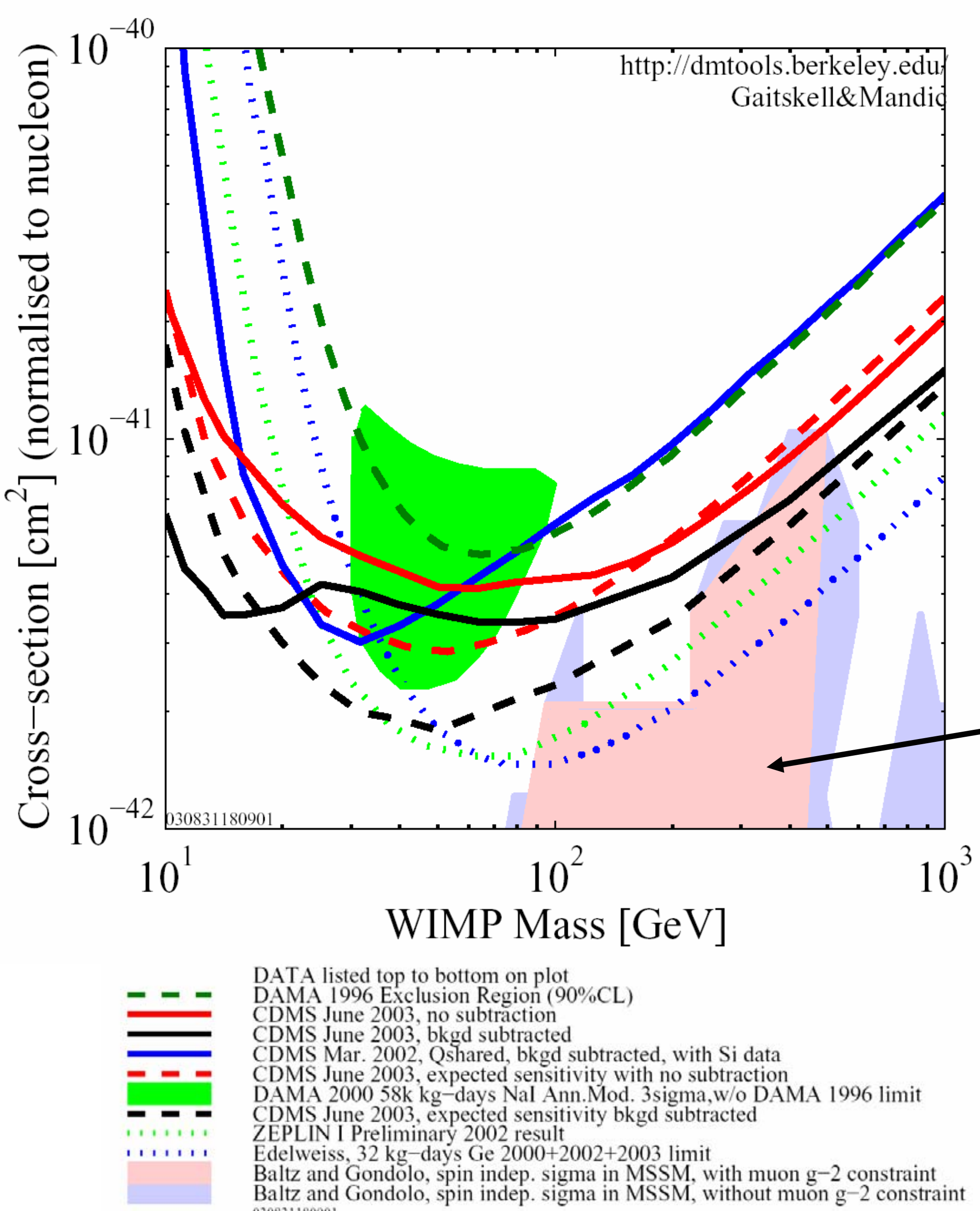
SUF Run 21 no neutron subtraction

Edelweiss 2002

- Exclude DAMA most likely points (x,o) at >90% even without neutron subtraction.

Expected sensitivities calculated from expected neutron background of 3.3 multiple-scatters, 18 single scatters in Ge, and an expected background in Si of 0.8 electrons and 3.6 neutrons.

Exclusion Limit Curves

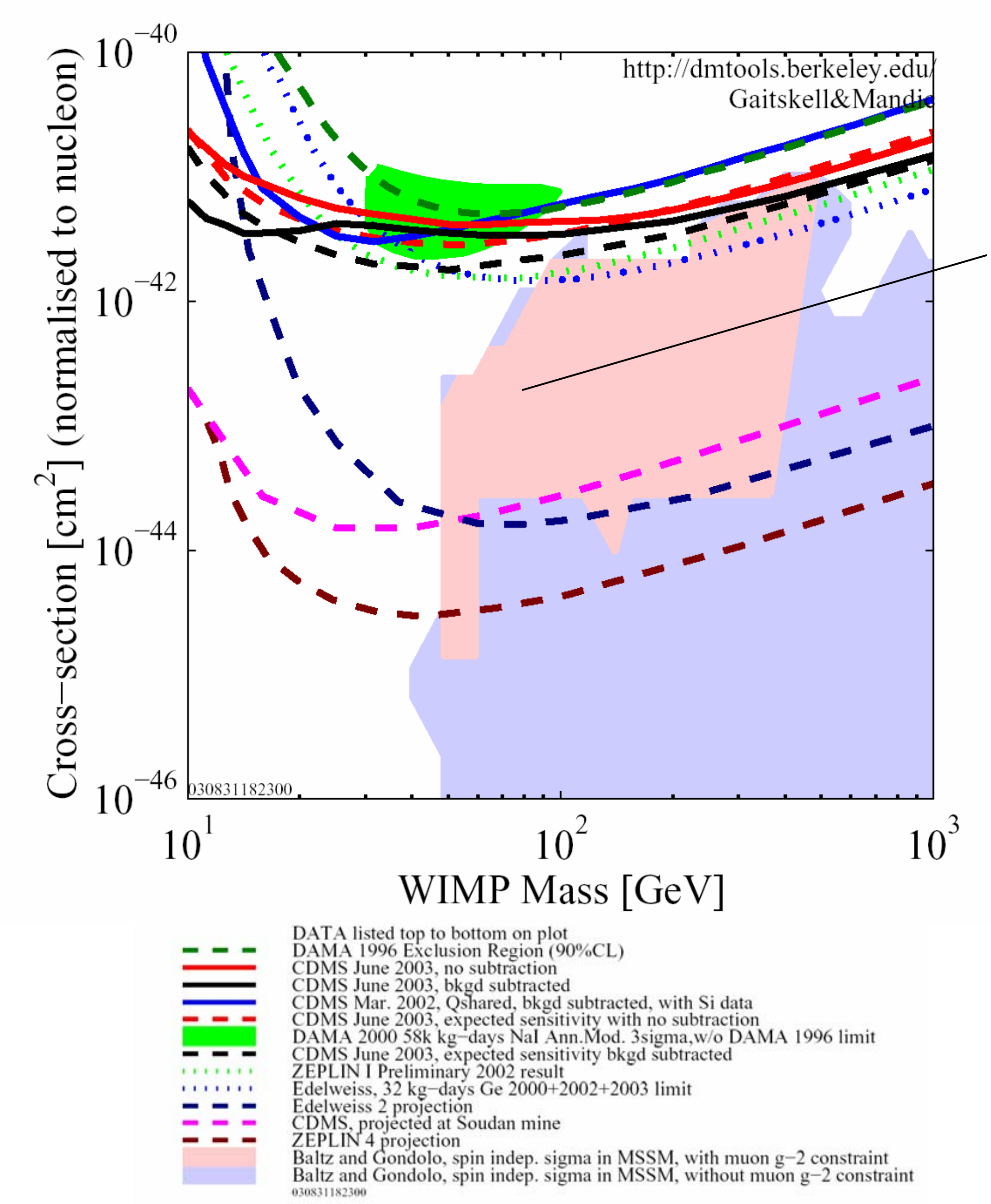


Starting to enter theoretically allowed range!

Very exciting time!

Theoretically Allowed Range in MSSM

Projected Limits



Expectation for the first Soudan run

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Soudan

- 780 m.w.e. deep site, in an old iron mine. Sharing the cavern with MINOS and Soudan II experiments.

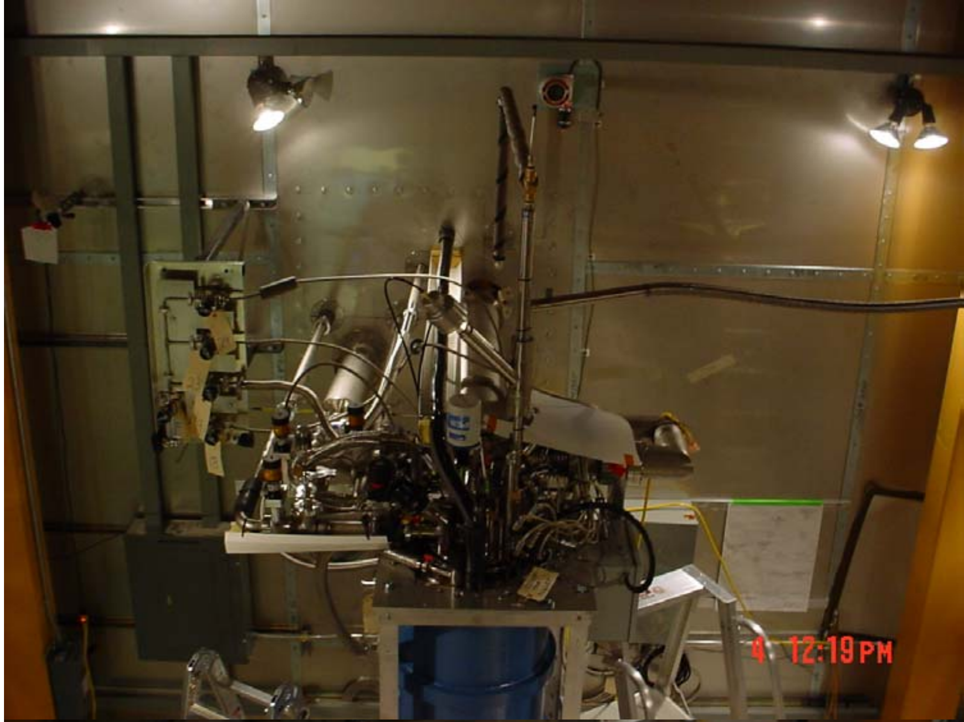
- Limited access: much of the experiment must be automated!

- A series of cryogenic problems mostly resolved.

- Jan-Mar 2003: installed two towers (12 detectors) with corresponding readout hardware.

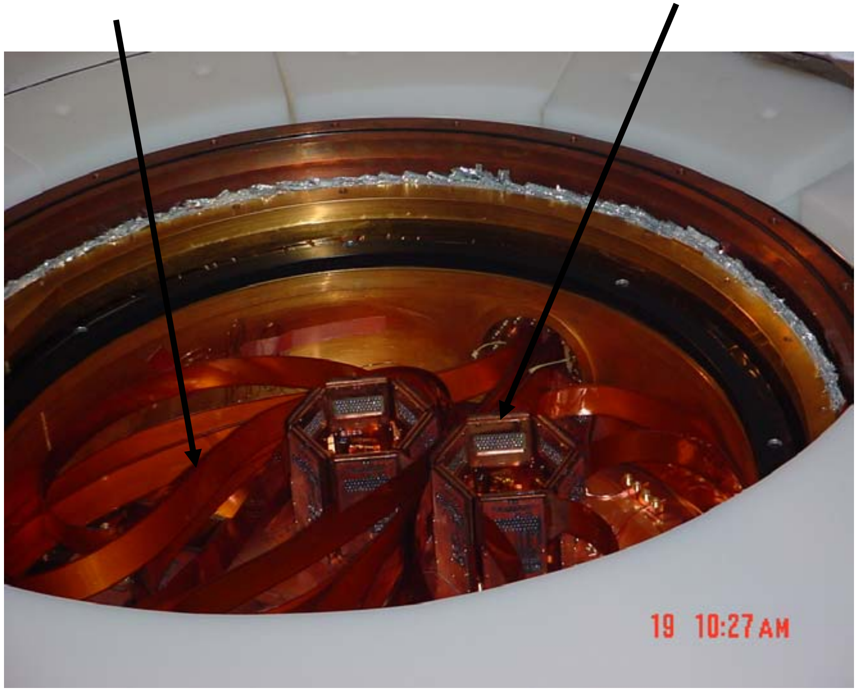
- Much work on electronic noise suppression, automation of the cryogenic system, data acquisition etc.

- Oct-present: started low background running, with occasional calibration runs.



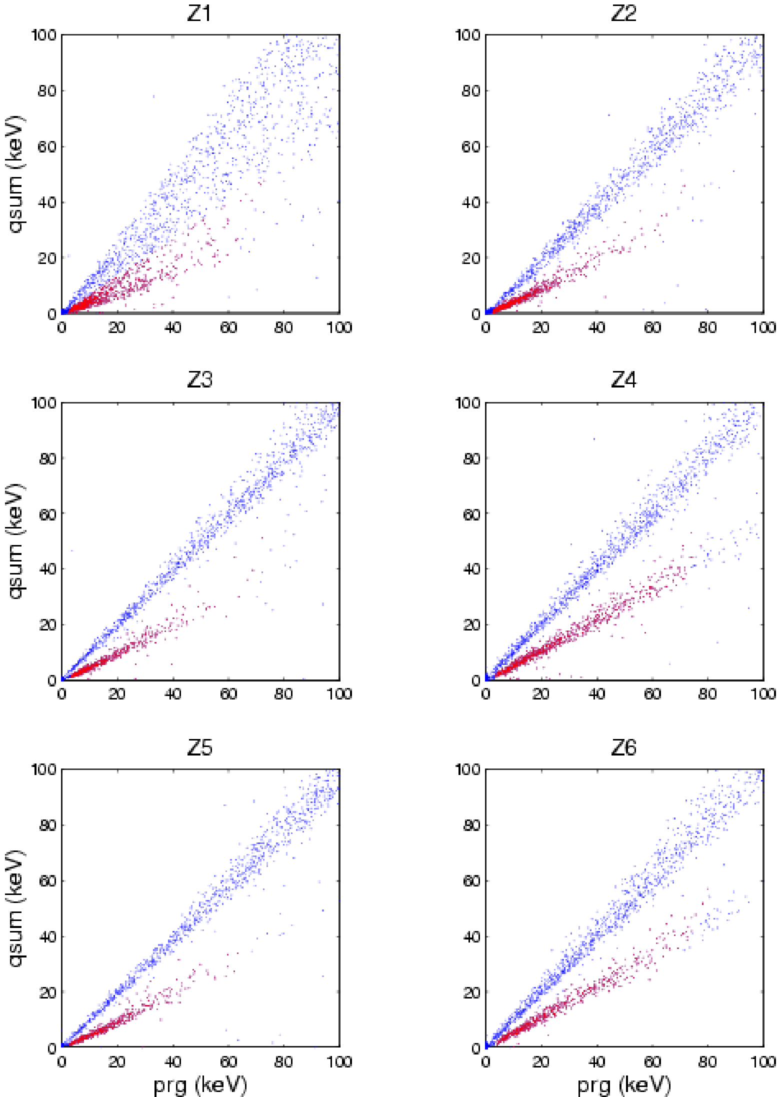
First Data Being Analyzed!

First Two Towers Installed


Striplines

SQUETs

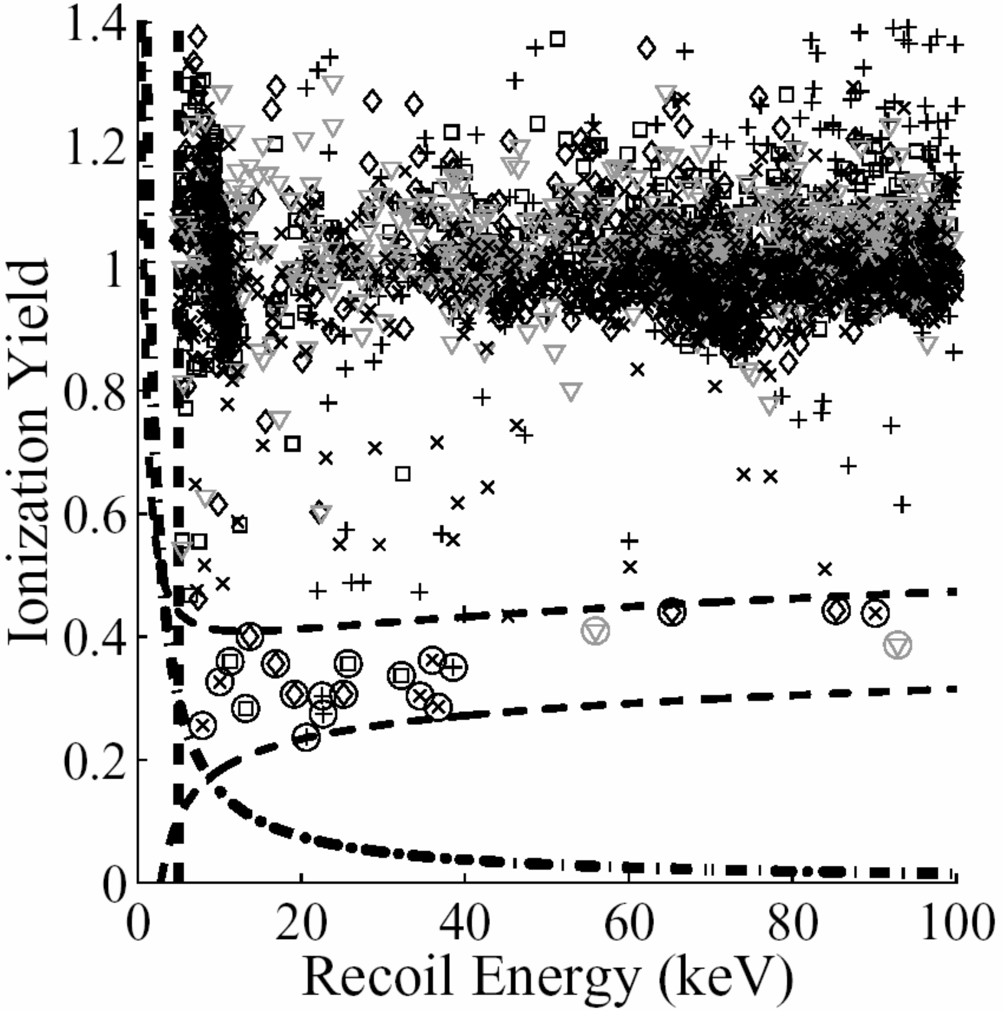
Neutron Calibration



Conclusions

- First tower of 6 ZIP detectors exceeds performance expectations.
- Confirmed previous CDMS results (based on BLIP detectors).
- Best upper limits of any experiment for the mass range 10 to 35 GeV for scalar-interacting ($\sigma \sim A^2$) WIMPs.
- CDMS data are incompatible with DAMA signal at high confidence.
- Sensitivity limited by external neutron background from muons interacting in surrounding rock.
- Reduction of neutron background by factor of 2.3 due to installation of internal moderator in agreement with Monte Carlo predictions.
- Construction completed at deep site in Soudan, Minnesota. Towers 1 & 2 now installed at Soudan, first data taken.

2002 Run Single Scatter Nuclear Recoil Spectrum

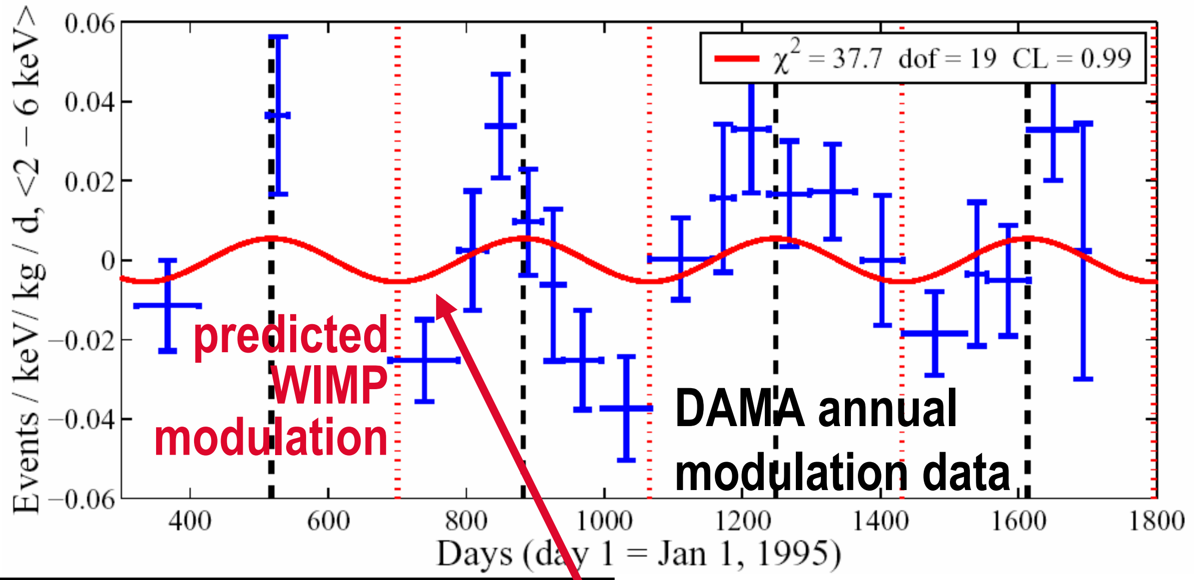


Combined 4 Ge detectors (x, ◊, □, +) and 1 Si detector (∇)

Estmated contamination from surface electron recoils:

- Ge: 1.2 ± 0.3 events
- Si: 0.8 ± 0.6 events

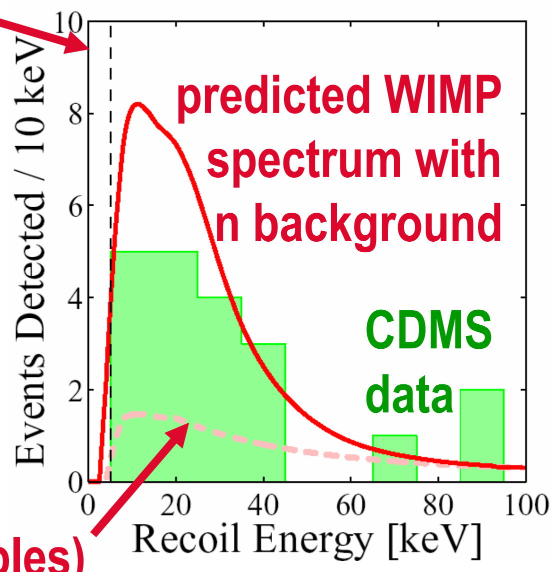
Incompatibility with DAMA



predicted WIMP modulation

DAMA annual modulation data

Best simultaneous fit to CDMS and DAMA predicts too little annual modulation in DAMA, too many events in CDMS (even for small neutron background)



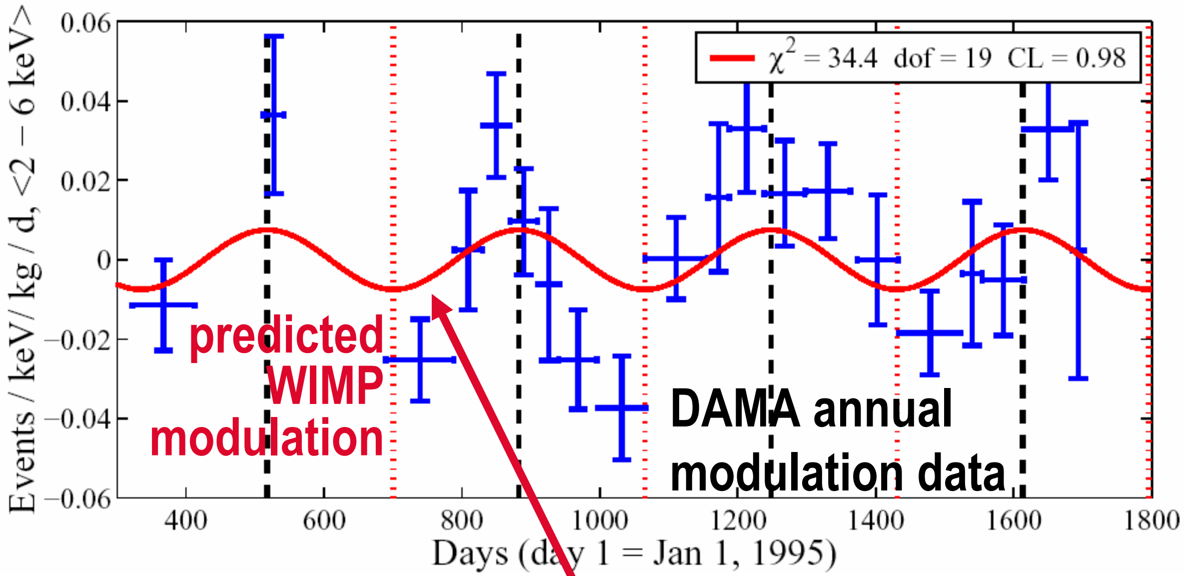
predicted WIMP spectrum with n background

CDMS data

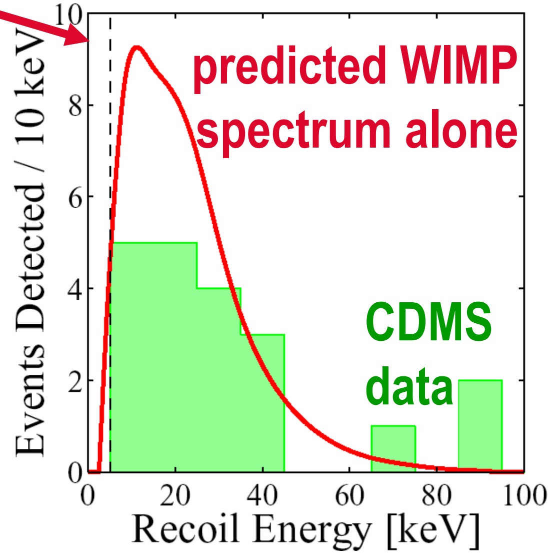
n background (1.4 multiples)

- Test under assumptions of
  - “standard” halo
  - standard WIMP interactions
- CDMS results incompatible with DAMA model-independent annual-modulation data (left) at > **99.98%** CL

Incompatibility with DAMA



Best simultaneous fit to CDMS and DAMA predicts too little annual modulation in DAMA, too many events in CDMS (even for no neutron background)



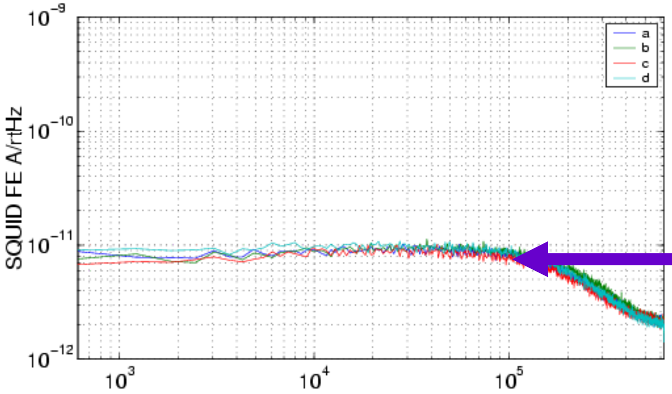
- Test under assumptions of
  - “standard” halo
  - standard WIMP interactions
- CDMS results incompatible with DAMA model-independent annual-modulation data (left) at > **99.8%** CL even if all low-energy events are WIMPs

Performance of the Readout Systems

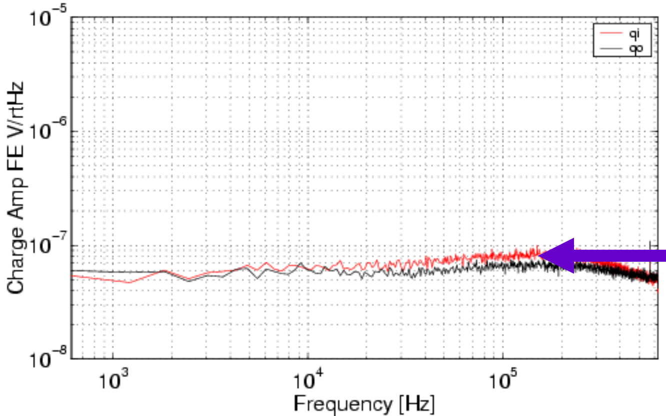
- The readout systems behave exactly as expected.
- We present the observed noise spectra for all 4 phonon channels and both charge channels of one of our Si detectors.

The given noise levels determine the lowest observable signals. We present the energy distribution (in charge and phonons) of no-signal data traces for the six detectors currently running at SUF.

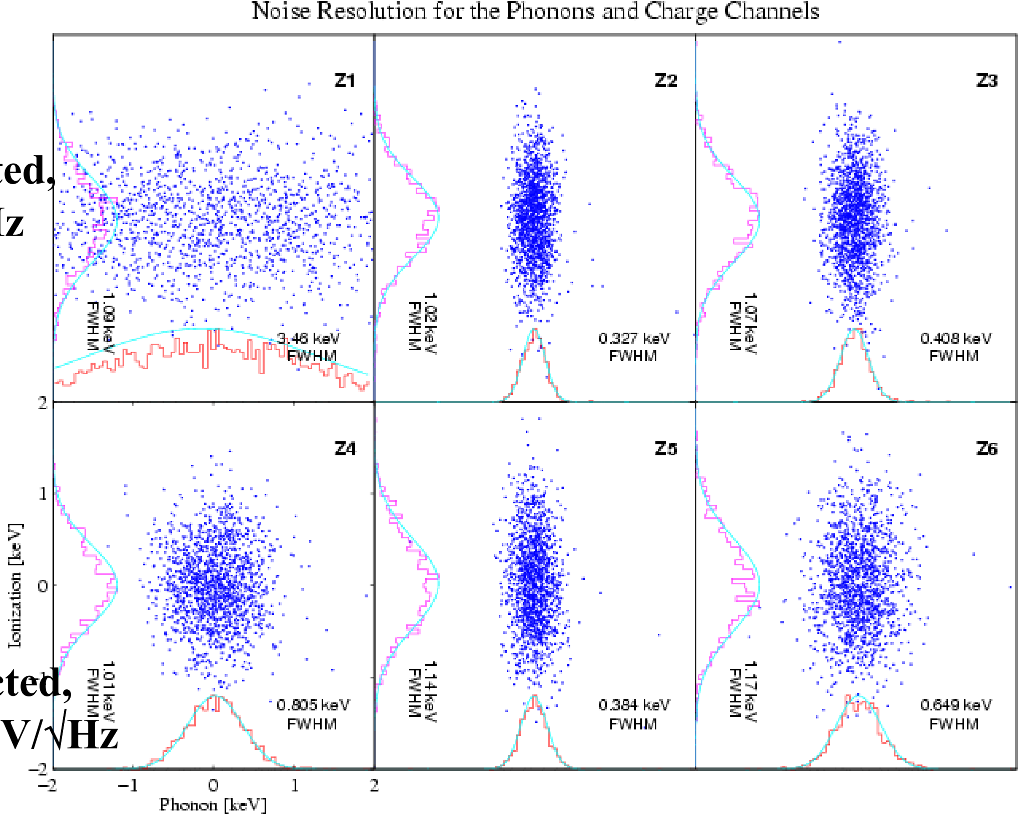
We can trigger on **sub-keV** phonon signal.



As expected, 10 pA/√Hz

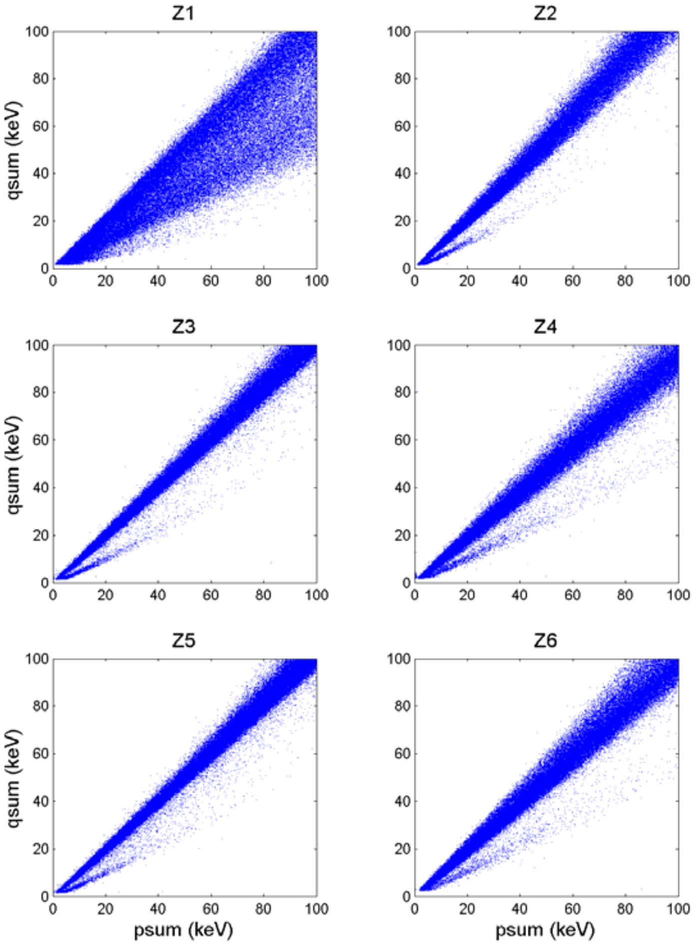


As expected, 70-100 nV/√Hz

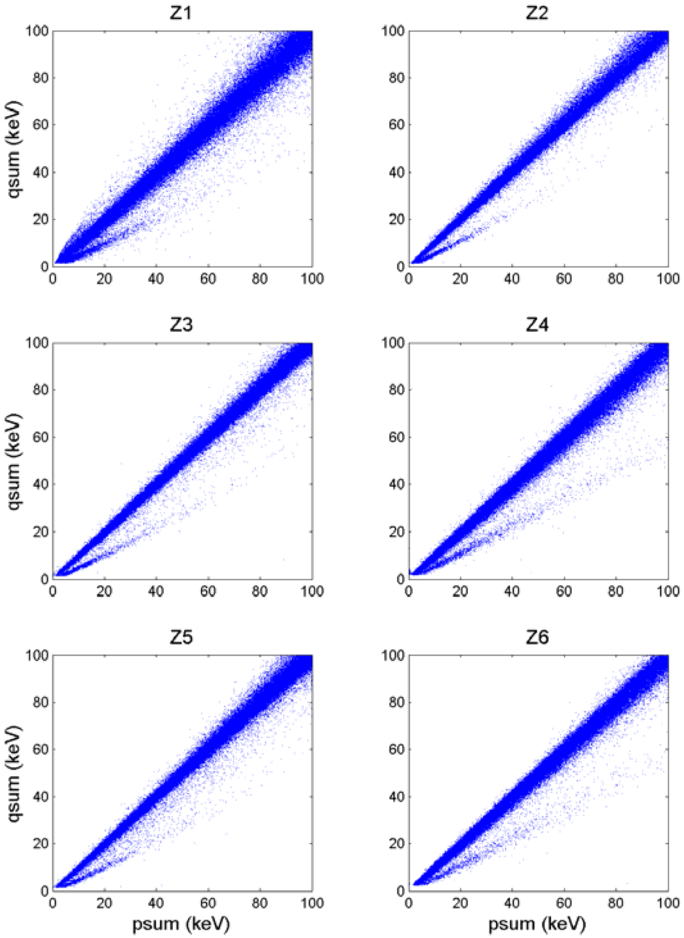

Noise Resolution for the Phonons and Charge Channels

Position Correction of Phonon Signal

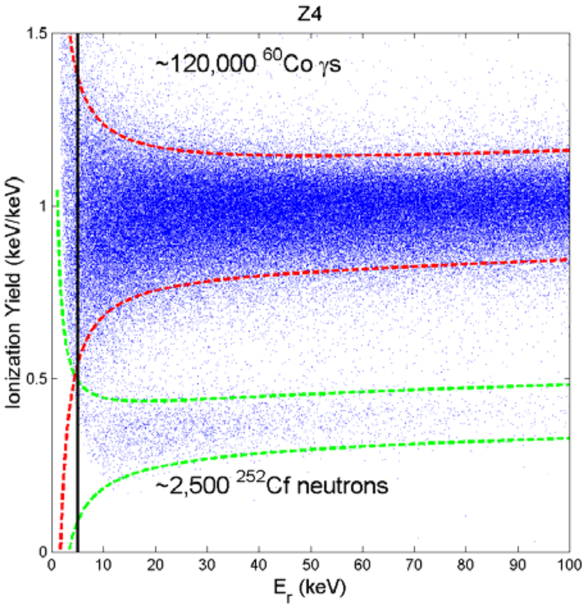
Before

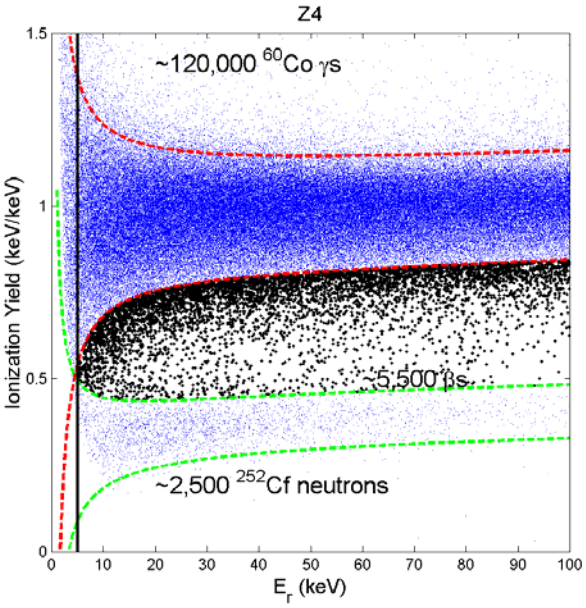


After



Z4 Charge-Phonon Plots

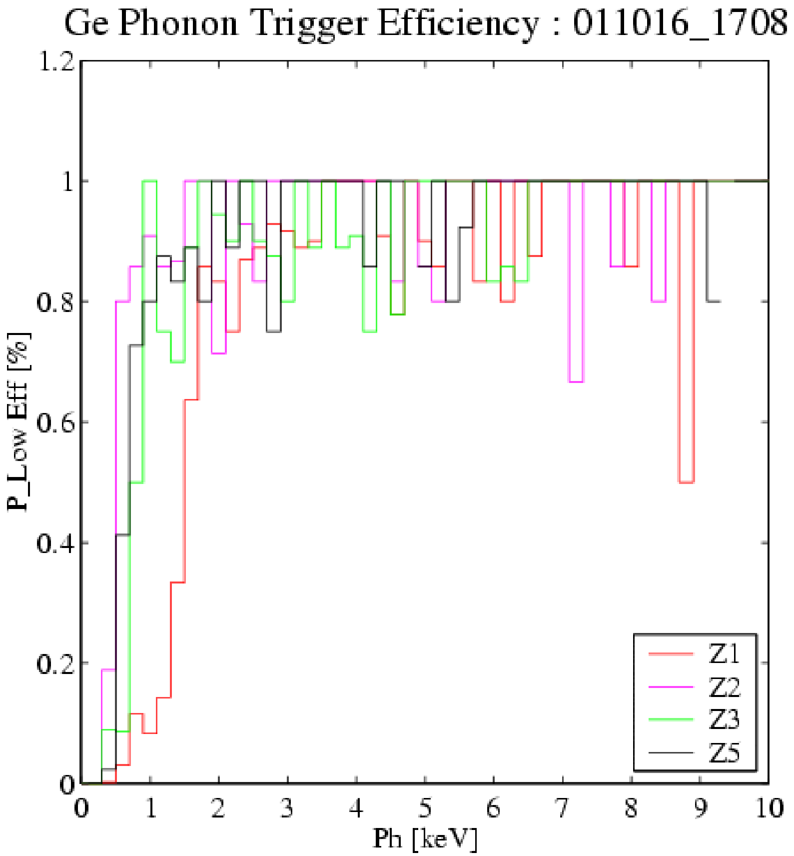




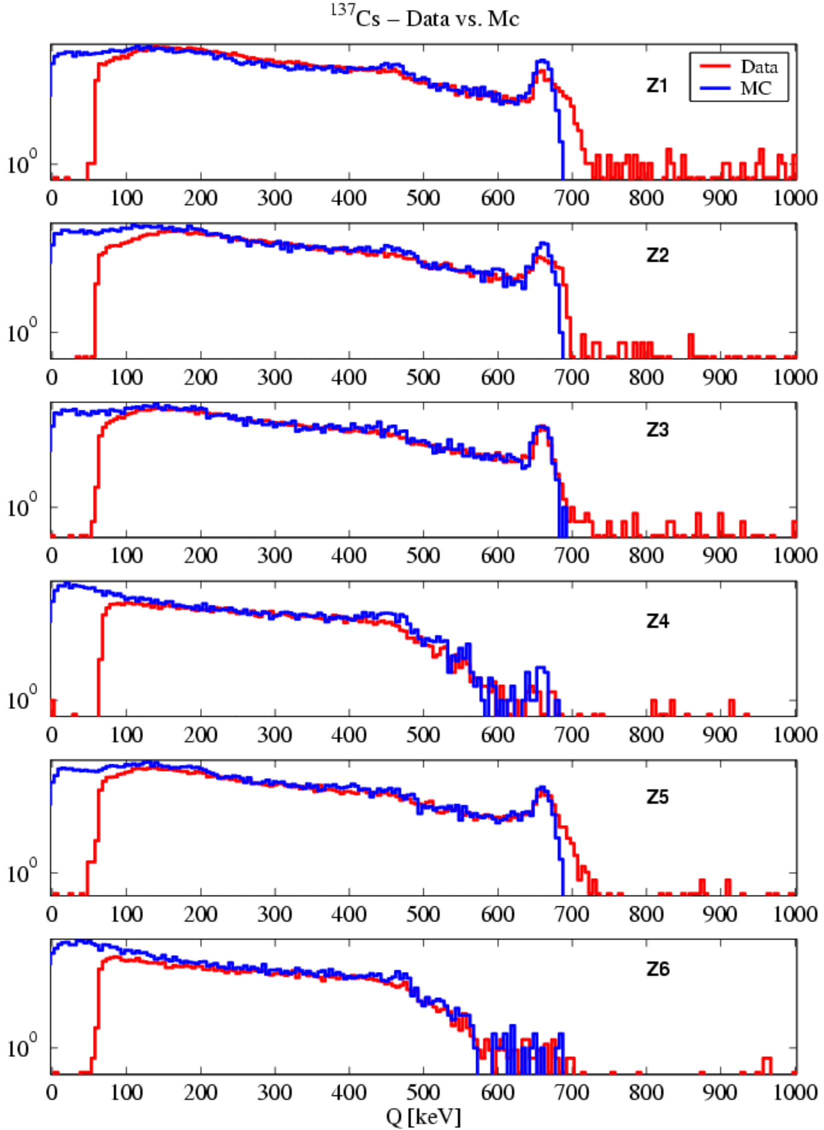
Energy Calibration – ^{137}Cs Source

Triggering on phonon channels:

- 1-2 keV in Ge detectors (for gammas)
- 2-3 keV in Si detectors (for gammas)

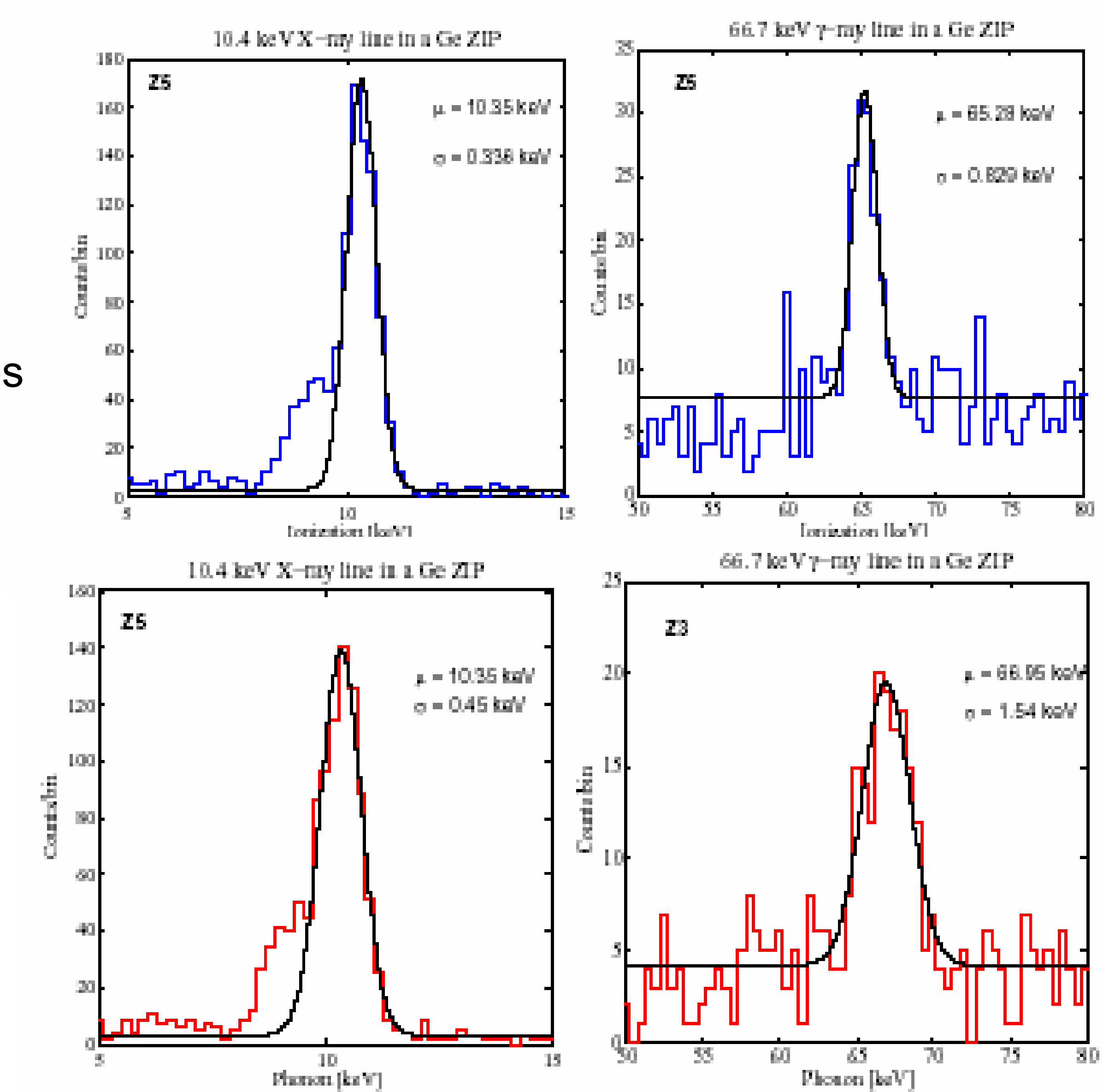


Calibrating charge channels with 662 keV line of Cs-137 gamma source:



Energy Calibration – Ge activation

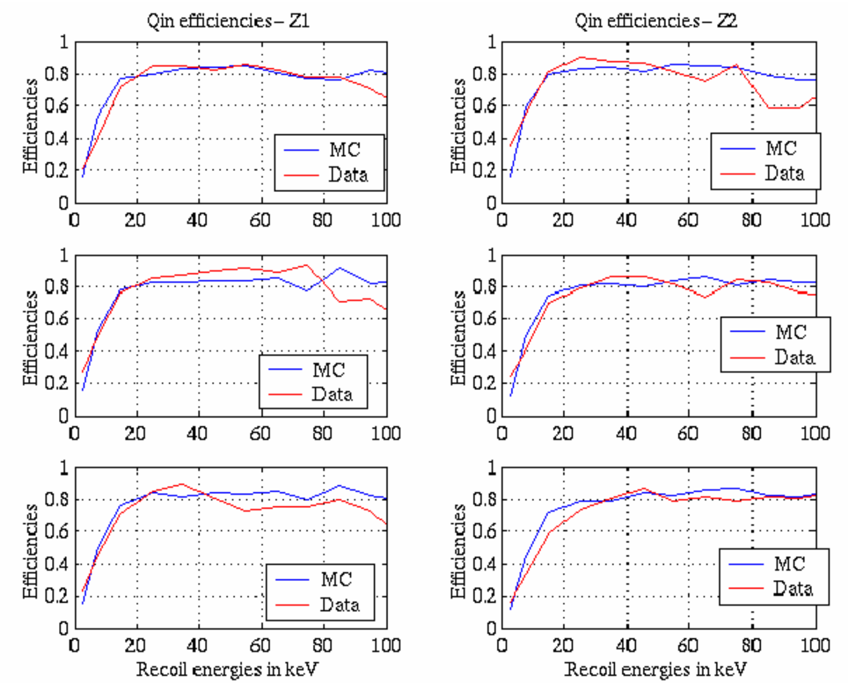
Neutron activation of ^{70}Ge produces ^{71}Ga and a 10.4 keV photon (11 days half-life)



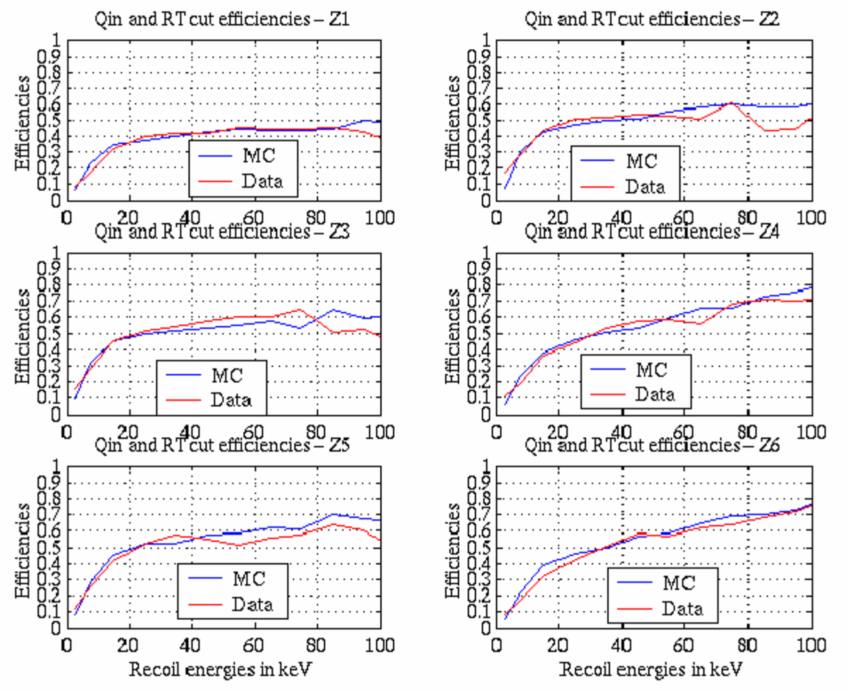
Neutron activation of ^{72}Ge produces ^{73}Ge and a 66.7 keV photon (1/2 second half-life)

Cut Efficiencies

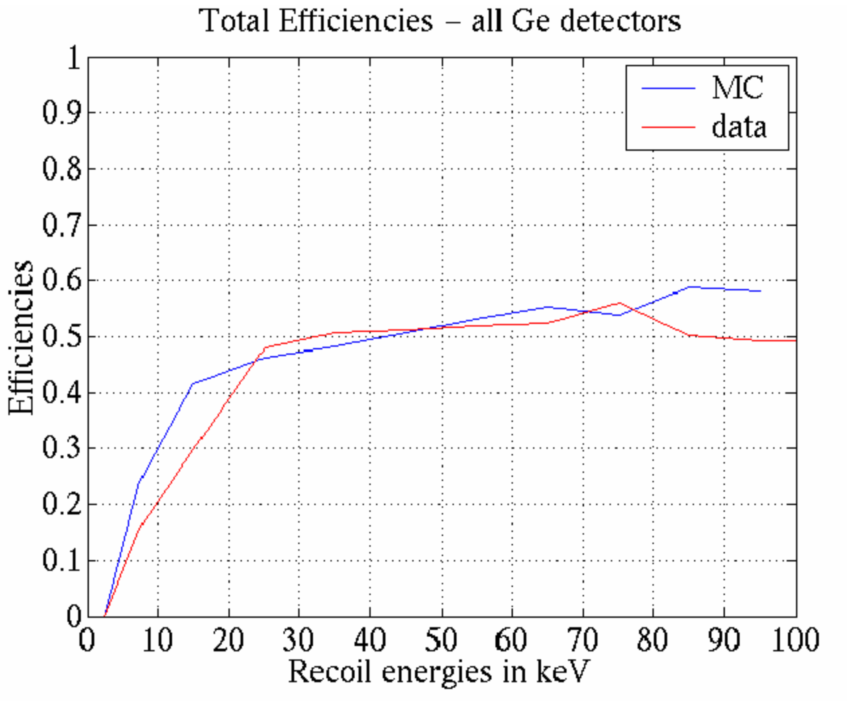
Qpart only

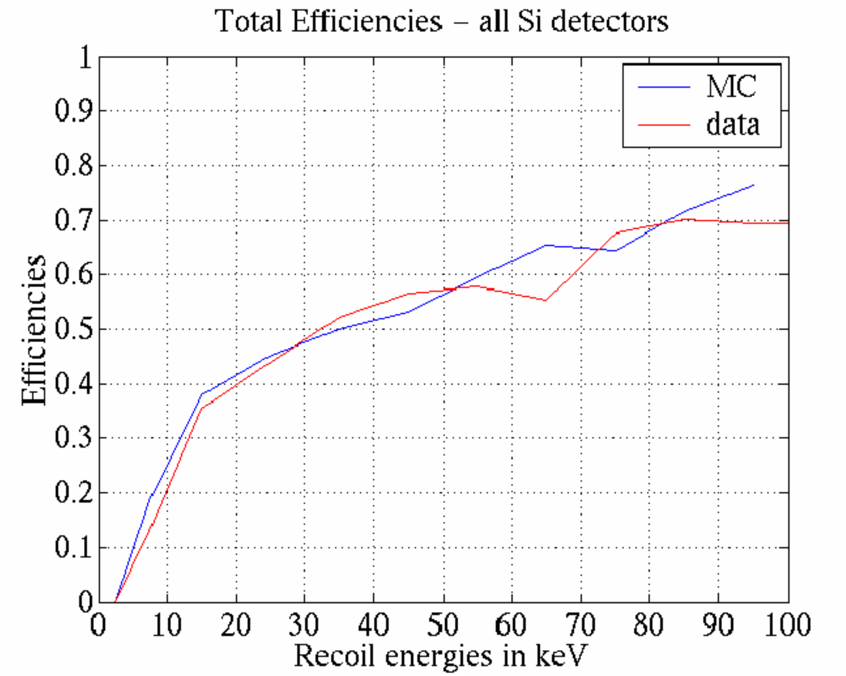


Qpart and Phonon risetime

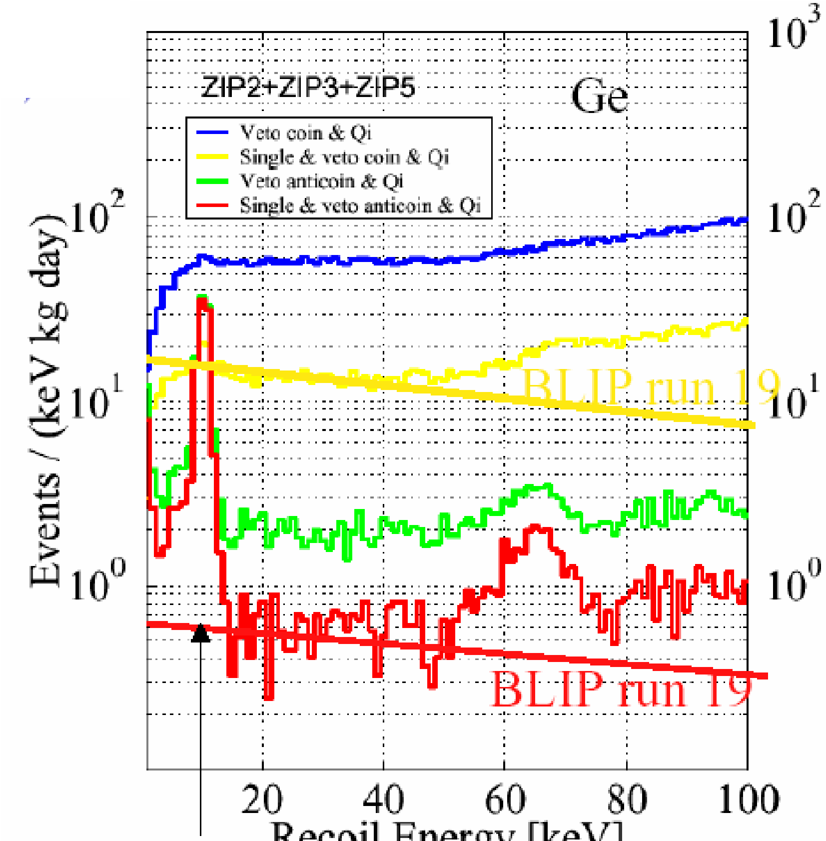


Total Cut Efficiencies





Gamma Spectrum



Ga peak
from ^{71}Ge: decays