



WIMP Hunting with the Cryogenic Dark Matter Search

Jeff Filippini

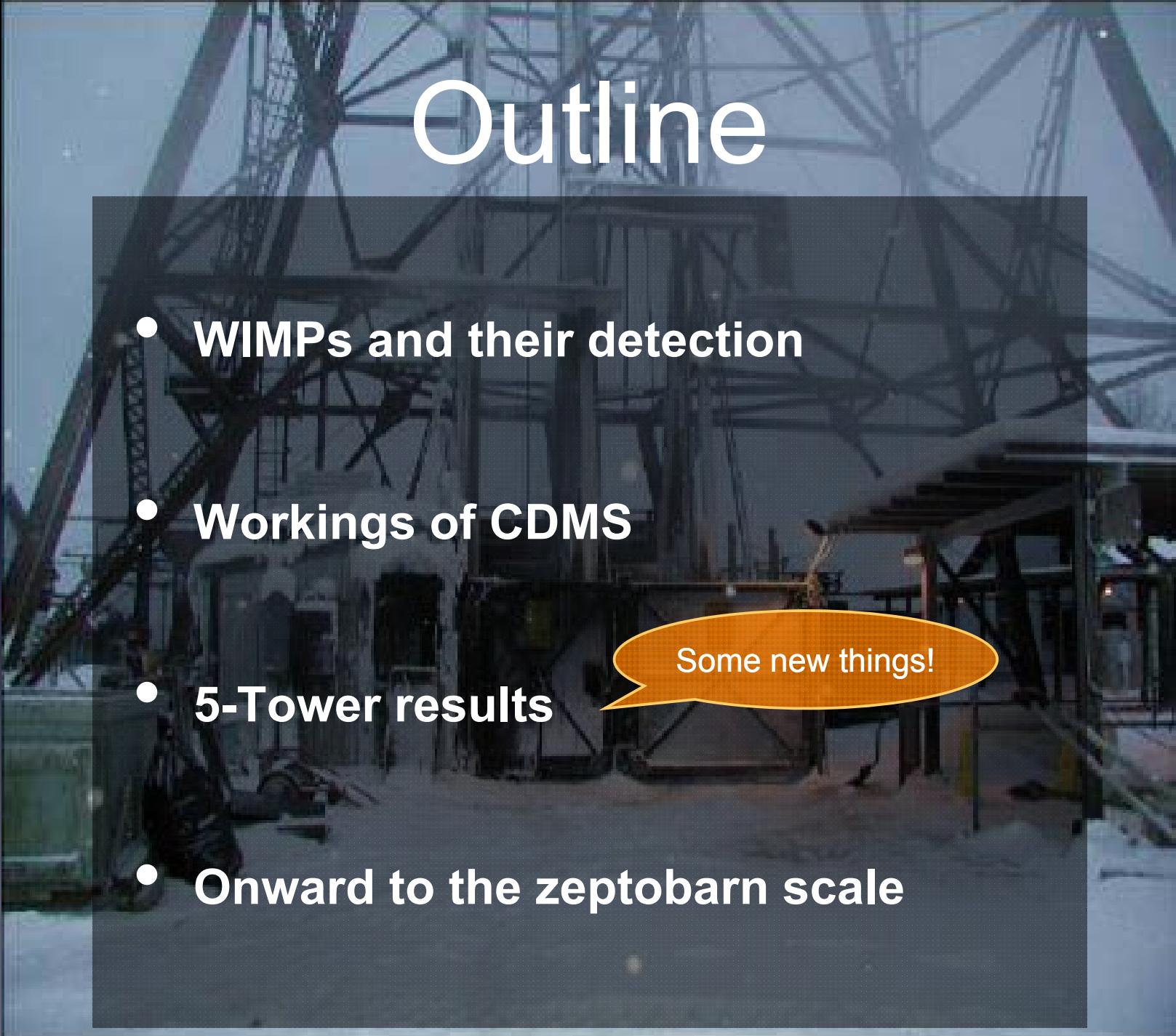
California Institute of Technology
for the CDMS Collaboration

*Les Rencontres de Physique de la Vallée d'Aosta - March 2,
2009*

Outline

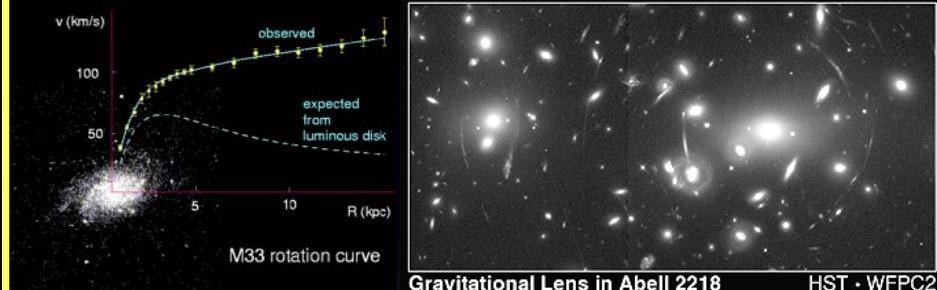
- WIMPs and their detection
- Workings of CDMS
- 5-Tower results
- Onward to the zeptobarn scale

Some new things!

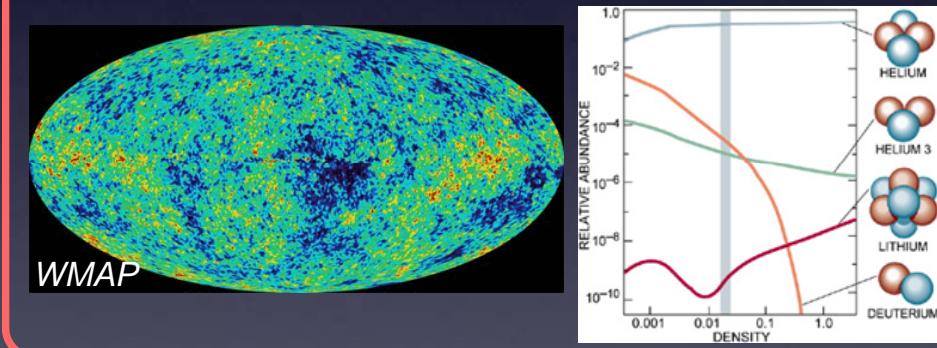


Contemplating the Darkness

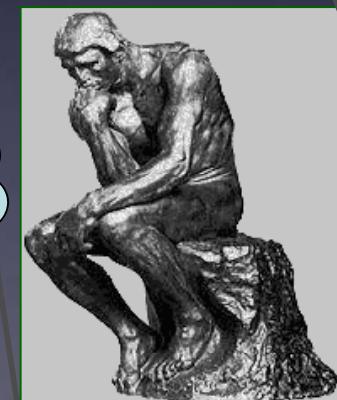
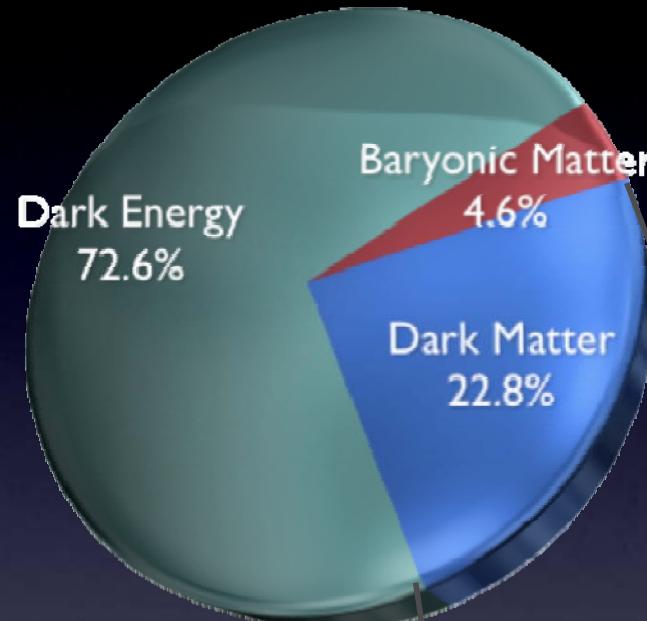
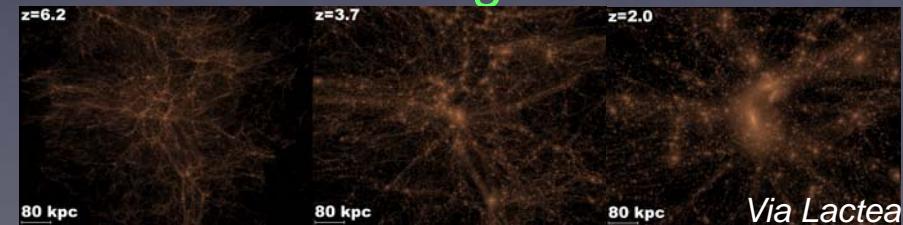
The Modern Universe



The Ancient Universe



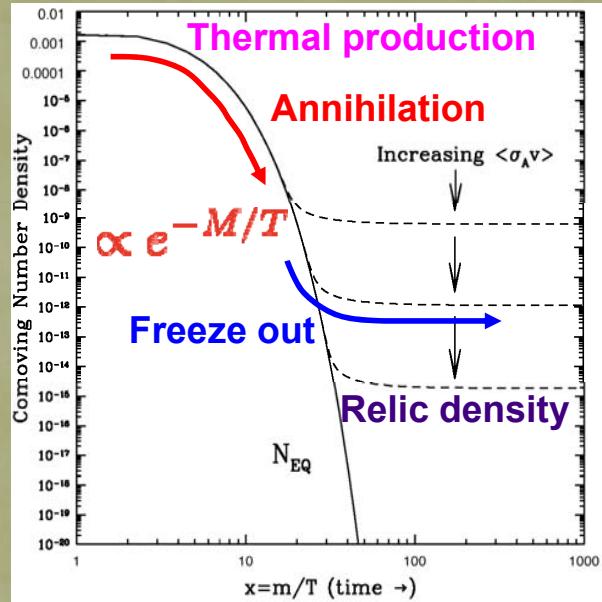
The Evolving Universe



... but what is this stuff?

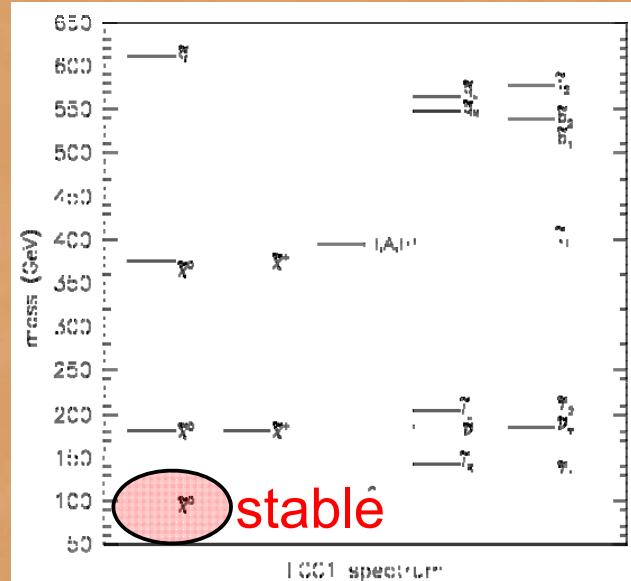
The Strength of WIMPs

Cosmology



$$\Omega_\chi \approx \frac{10^{-27} \text{ cm}^3 \text{s}^{-1}}{\langle \sigma_{\chi\chi} v \rangle}$$

Particle Physics



Baltz et al., PRD 74, 103521 (2006)

$$\Omega_\chi \approx 1 \Rightarrow \begin{cases} \sigma_{\chi\chi} \approx 0.1 \text{ pb } (10^{-37} \text{ cm}^2) \\ \sigma_{\chi\chi} \approx \frac{\alpha^2}{M_\chi^2} \Rightarrow M_\chi \approx 100 \text{ GeV/c}^2 \end{cases}$$

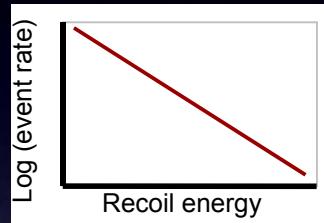
Weakly Interacting Massive Particles:

Heavy, stable particles produced thermally in the early universe

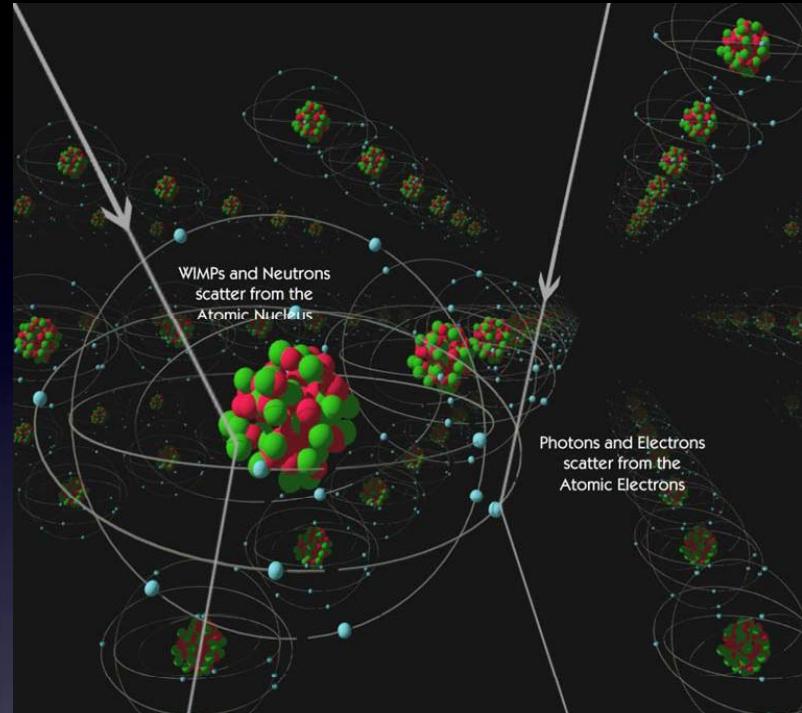
Direct Detection of WIMPs

$v_{\text{galactic}} \sim 10^{-3} c$ → coherent A^2
enhancement of scalar (spin-independent) scattering

Simple “spherical cow” halo: $v_0 = 270$ km/s, $v_{\text{esc}} = 650$ km/s



Exponential spectrum of $\langle E \rangle \sim 30$ keV nuclear recoils, $\ll 1/\text{kg-day}$



Challenges

- very **low energy** thresholds (~ 10 keV)
- Rigid **background control** (cosmogenic, radioactive)
 - Cleanliness
 - Shielding (passive, active, deep site)
 - Discrimination power
- Large **exposures** (large active mass, long-term stability)

CDMS: The Big Picture



CDMS in a nutshell: Event by event discrimination between nuclear and electron recoils using low-temperature detectors with no background subtraction

Low-temperature detectors

- Millikelvin temperatures → phonon sensitivity
- Ionization: dE/dx discrimination

“Zero-background” operation

- Keep expected background $< \sim 1$ event
- No background subtraction → sensitivity $\sim MT$





The CDMS Collaboration



California Institute of Technology

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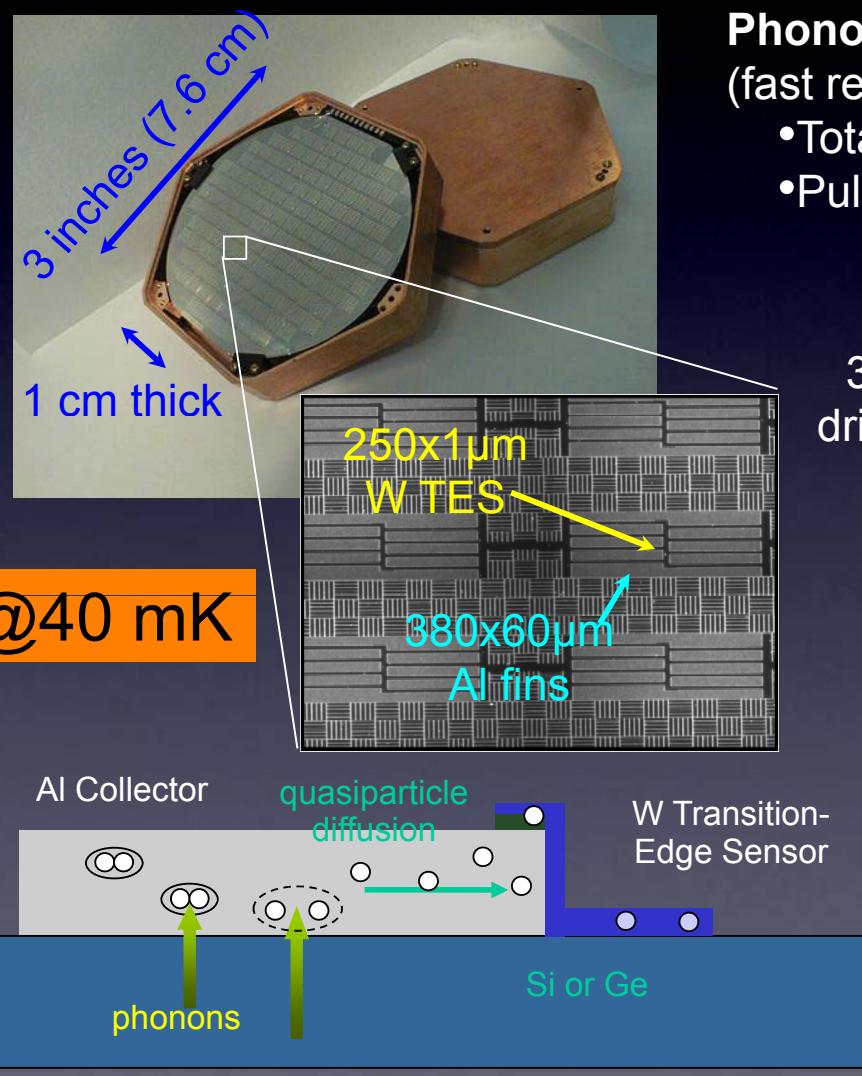
J. Beaty, **P. Cushman**, L. Duong, M. Fritts,
V. Mandic, X. Qiu, A. Reisetter

University of Zurich

S. Arrenberg, **L. Baudis**, T. Bruch, M. Tarka

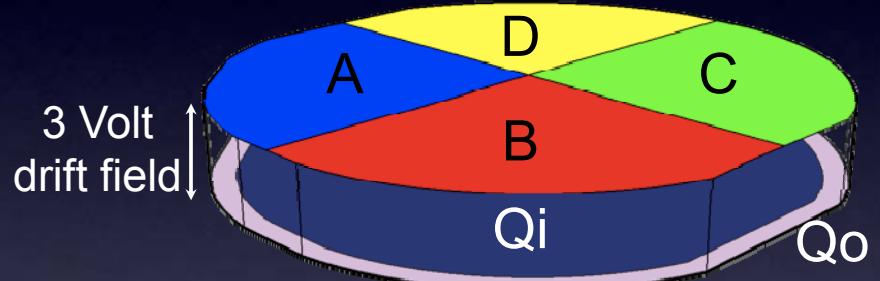
(Authors as of Feb. 2009)

ZIP Detectors (Z-sensitive Ionization and Phonon)

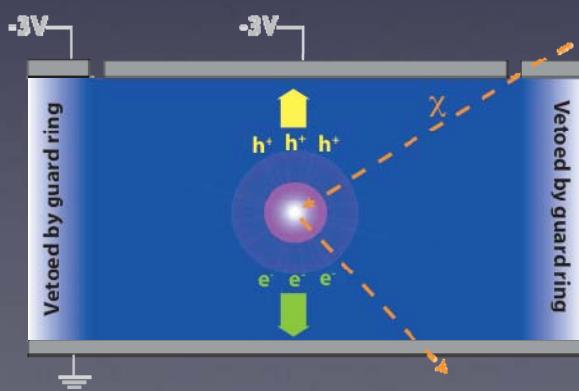


Phonon: 4 quadrants of athermal phonon sensors
(fast response: $\sim 5\mu\text{s}$ risetime)

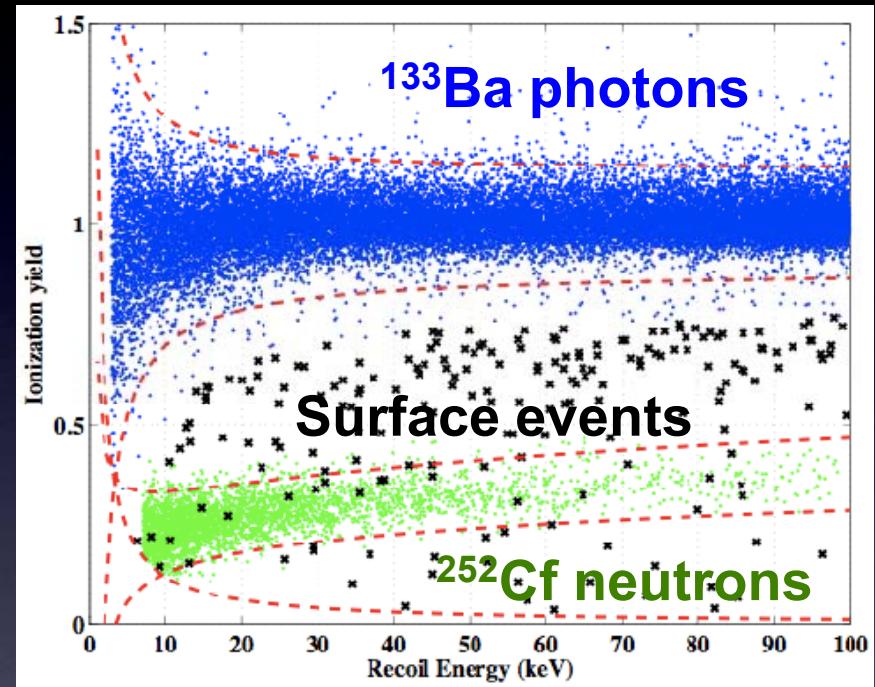
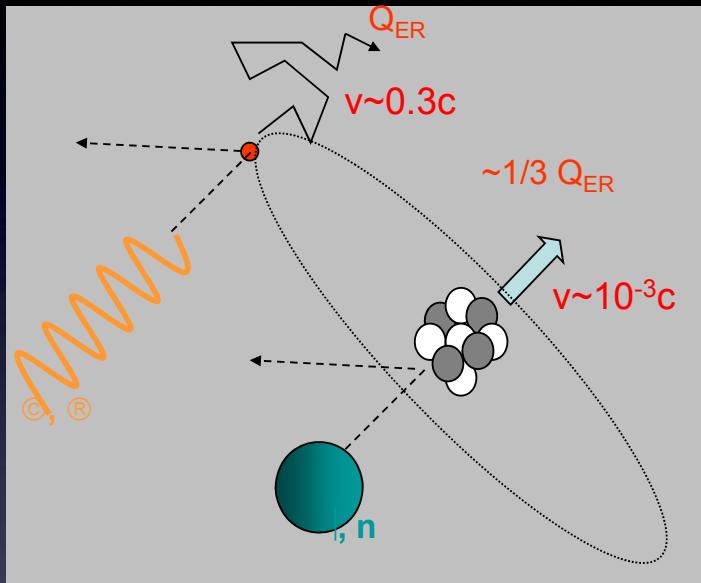
- Total amplitude \rightarrow **energy** ($\sigma \sim 200 \text{ eV} @ 0 \text{ keV}$)
- Pulse shape + distribution \rightarrow **position**



Charge: 2 concentric electrodes
• Inner \rightarrow **ionization** ($\sigma \sim 250 \text{ eV} @ 0 \text{ keV}$)
• Outer \rightarrow **fiducial volume selection**



Bulk Electron Recoils: Yield

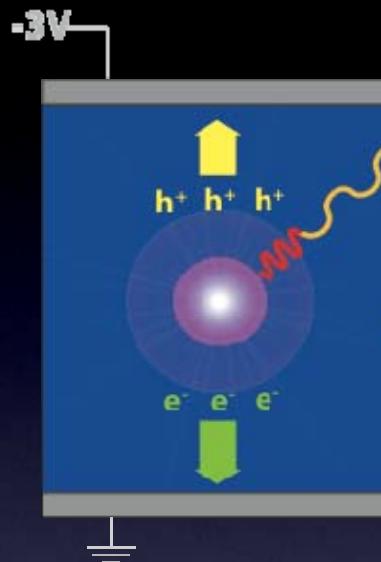


- Ionization yield: $y \equiv \frac{Q}{E_{recoil}}$
- Reject *bulk* electron recoils $\sim 10^6:1$

Distinguishable @ ~3 keV

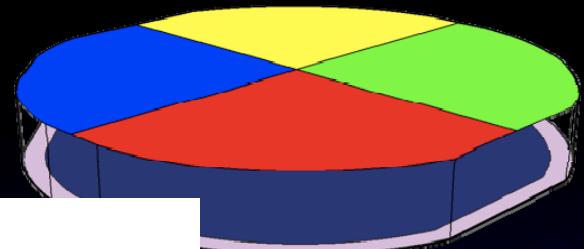
Reduced charge from **surface electron recoils** (e.g. betas)

Surface Electron Recoils: Timing



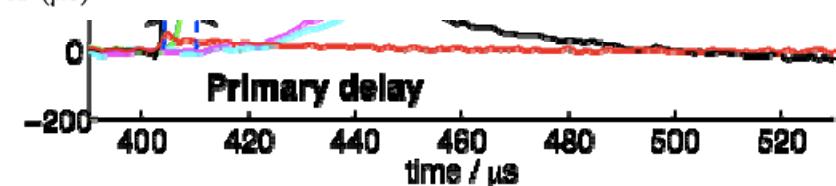
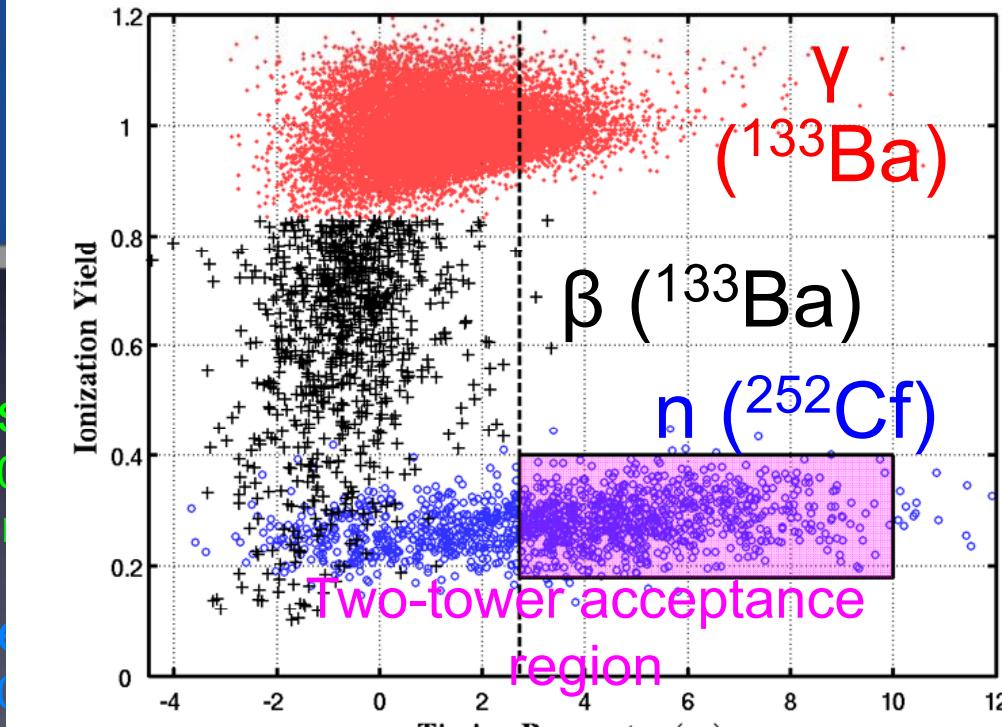
carrier back-diffusion

~10μm “dead layer”



- Primary rise
(time from 10% to 90% amplitude for)
- Primary decay
(time from 20% to 80% of phonon amplitude)

*Surface event rejection
(also ~~rejects~~ against
alphas)*



Neutrons: Soudan Underground Lab



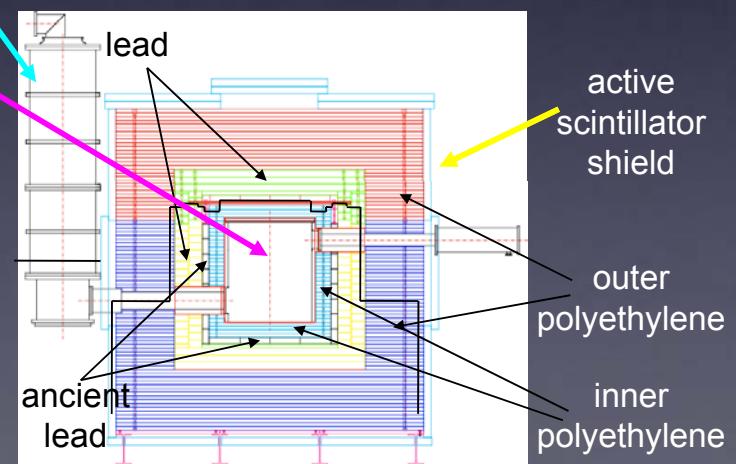
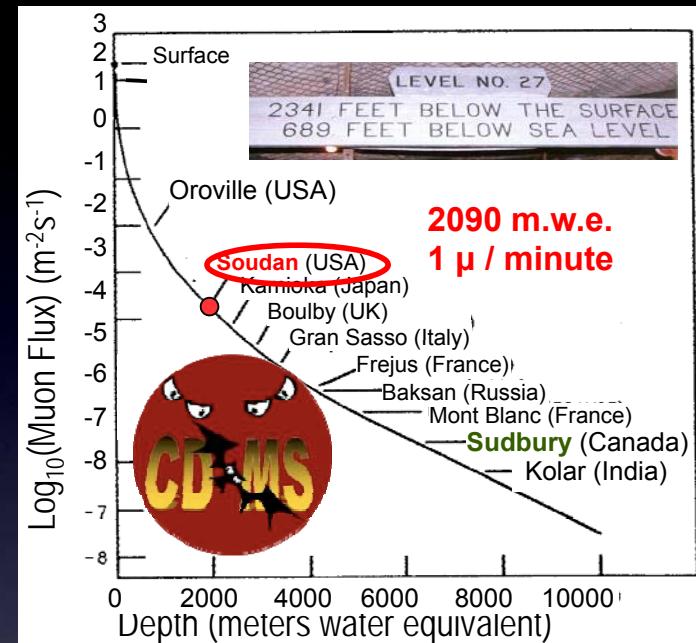
Oxford
Instruments
400 μ W
dilution
refrigerator

1 m³ @40 mK!

Neutron-induced nuclear recoils

- Cosmogenic: Depth, scintillator shield
- Radiogenic: Polyethylene, clean materials

~0.05 unvetoed neutrons
per kg-year (Monte Carlo)

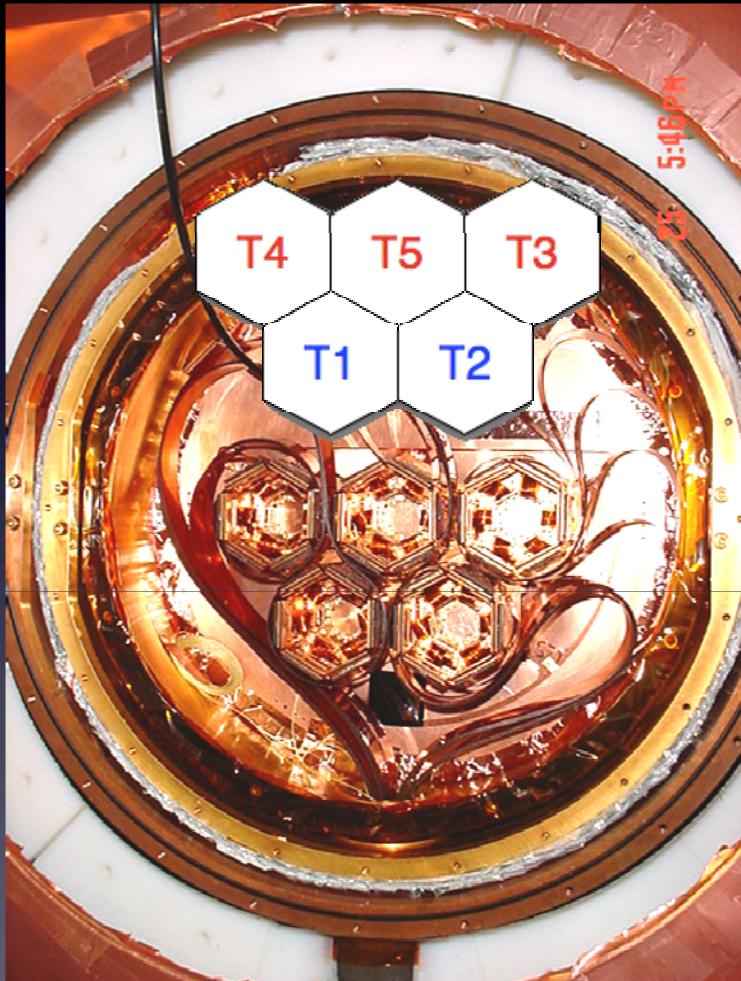


First Five Tower Runs

(2006-7) ³⁰Ps (5 Towers) in Soudan

icebox:

4.75 kg Ge 1.1 kg Si



	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

Side View

contamination

- Increased DAQ throughput for calibration
- Cryocooler for increased LHe hold time

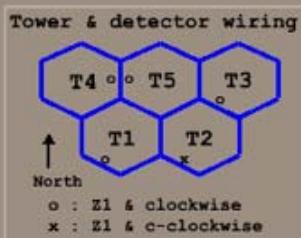
First two runs analyzed thus far:

- Run 123 (21Oct06-21Mar07): ~108 live days (**430 kg-d** Ge raw)
- Run 124 (20Apr07-16Jul07): ~56 live days, (**224 kg-d** Ge raw)

CDMS Event Display [5-Tower]

Fri Nov 2 23:45:38 2007
For Trigger & WIMP Search

Series Number = 1711022042
Event Number = 230095
Time since Lev^t (ms) = 16930
Live Time since Lev^t (ms) = 16899



Ampl vs [us]

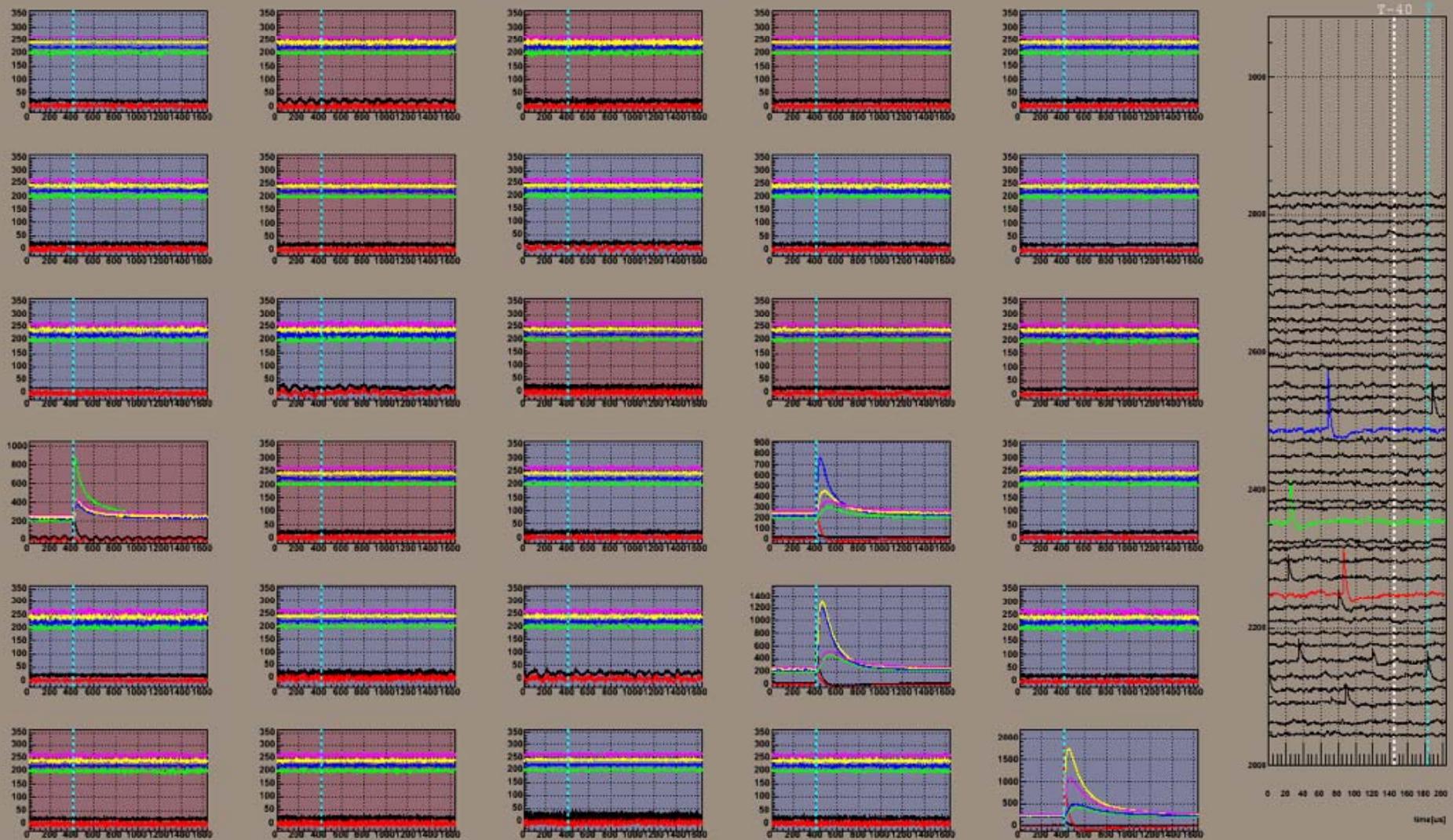
260 ----- Pd
240 ----- Pc
220 ----- Pb
200 ----- Pw
20 ----- Qo
0 ----- Qi

TrigInfo : Q P QdP RANDOM

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

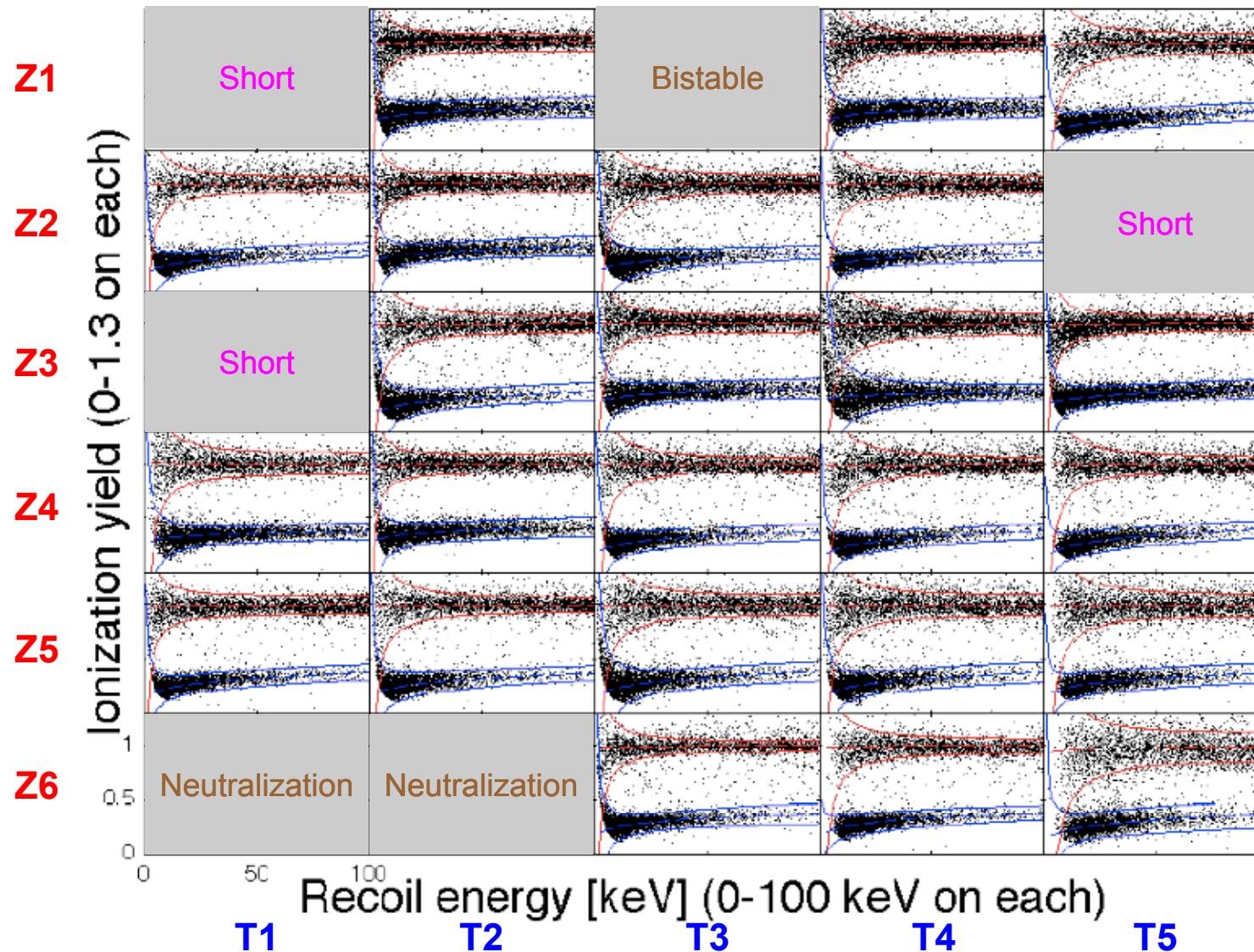
VETO Map (ColCode > 50 VADC)

Tne	Tte	Tse			
C-stem	Tnw	Tsw	E-stem		
S3e	S3n	S3nw	S3w	S3s	S3se
S2e	S2n	S2nw	S2w	S2s	S2se
S1e	S1n	S1nw	S1w	S1s	S1se
Bnw	Bw	Baw			
Bn	Bne	Bae	Bs		



Five Tower Yield Bands

Run 123 Neutron Calibration

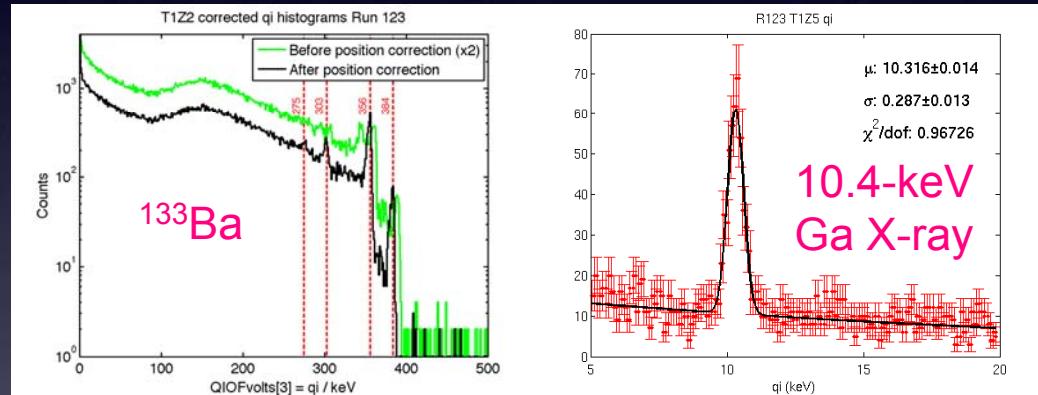


First 5-Tower Analysis

Blind analysis (2007)

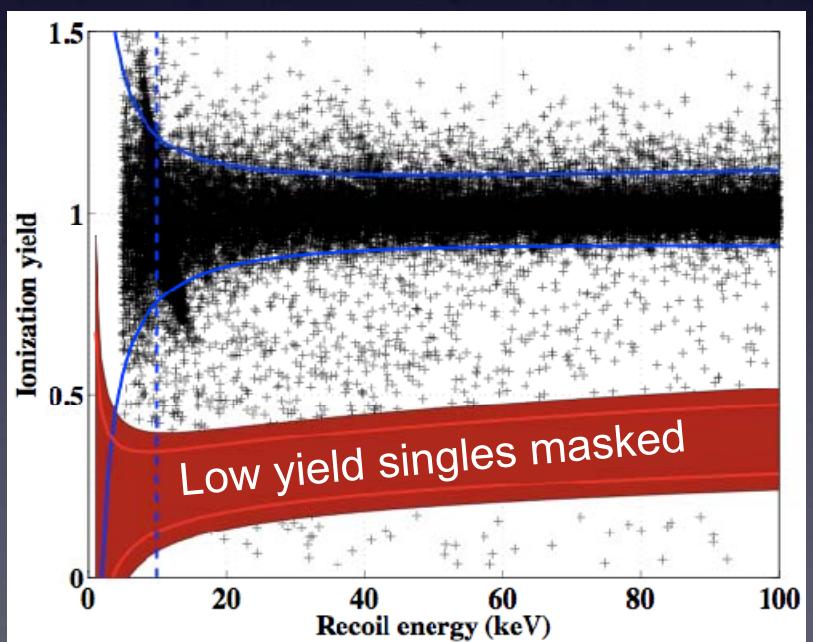
Reduction

- Pulse identification
- Position correction
- Calibration (^{133}Ba , ^{252}Cf)



Data quality

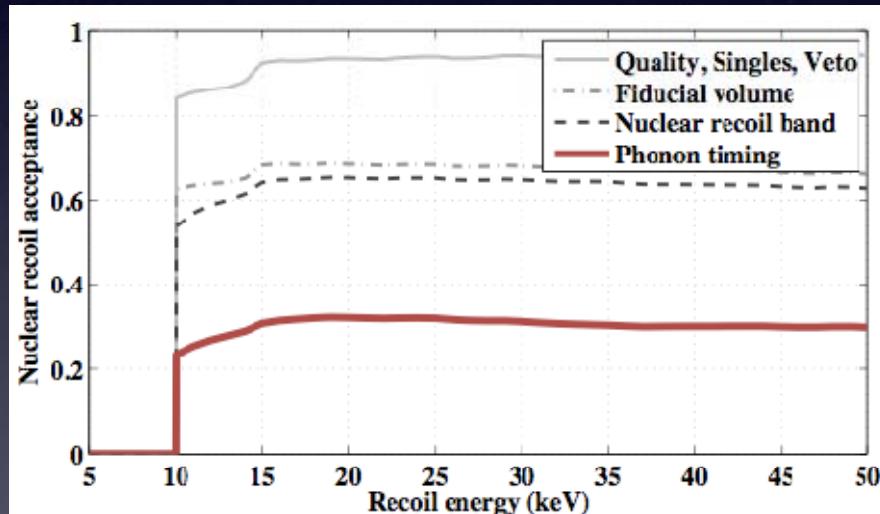
- Data quality cuts
 - Periods of poor noise, neutralization
 - Malformed detector regions
 - Reconstruction failures



Blind Analysis Summary (Ge)

Physics

- Veto-anticoincidence cut
- Single-scatter cut
- Q_{inner} (fiducial volume) cut
- Ionization yield cut
- Phonon timing cut



397 raw kg-d Ge
(121 kg-d WIMP
equiv. @ 60 GeV/c²)

Surface background

Leakage computation based on
low-yield multiple-scatters

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

Neutron background

Poly, Cu (α, n): <0.03

Pb (fission): <0.1

Cosmogenic: <0.1 (MC 0.03-0.05)

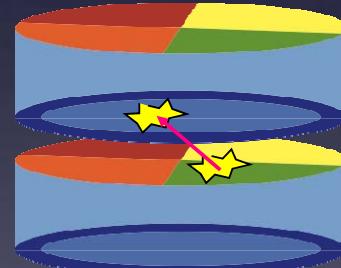
8 vetoed neutron multiples seen

0 vetoed singles seen

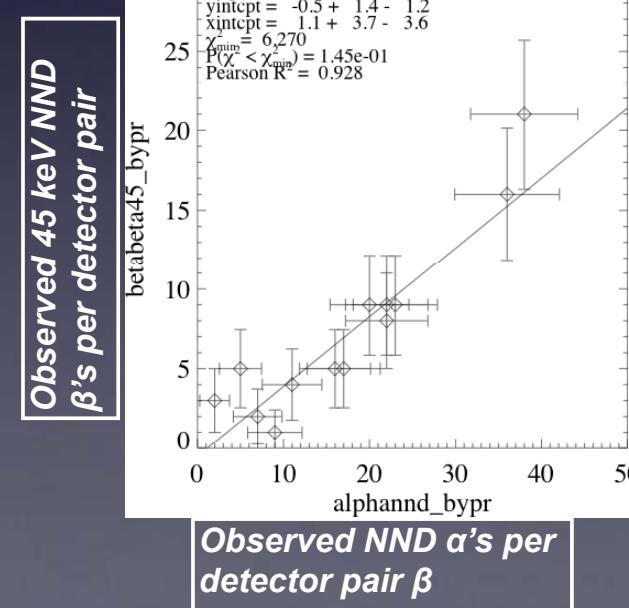
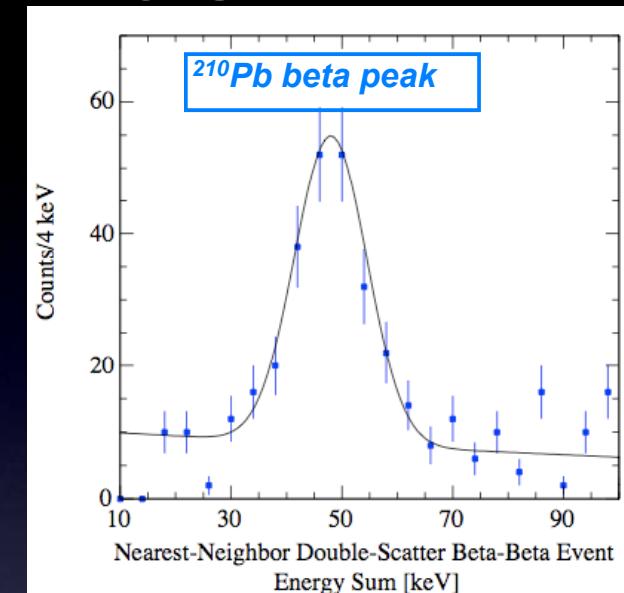
Backgrounds

Ongoing simulation and assay work to understand surface event sources
($\sim 0.6/\text{det/day}$, $0.03 \text{ singles/det/day}$)

Recent success with correlating α and β rates, nearest neighbor double scatters (NNDs)



~75% of our contamination is ^{210}Pb (Rn daughters)
=> Already reduced by improved handling



Opening the Box

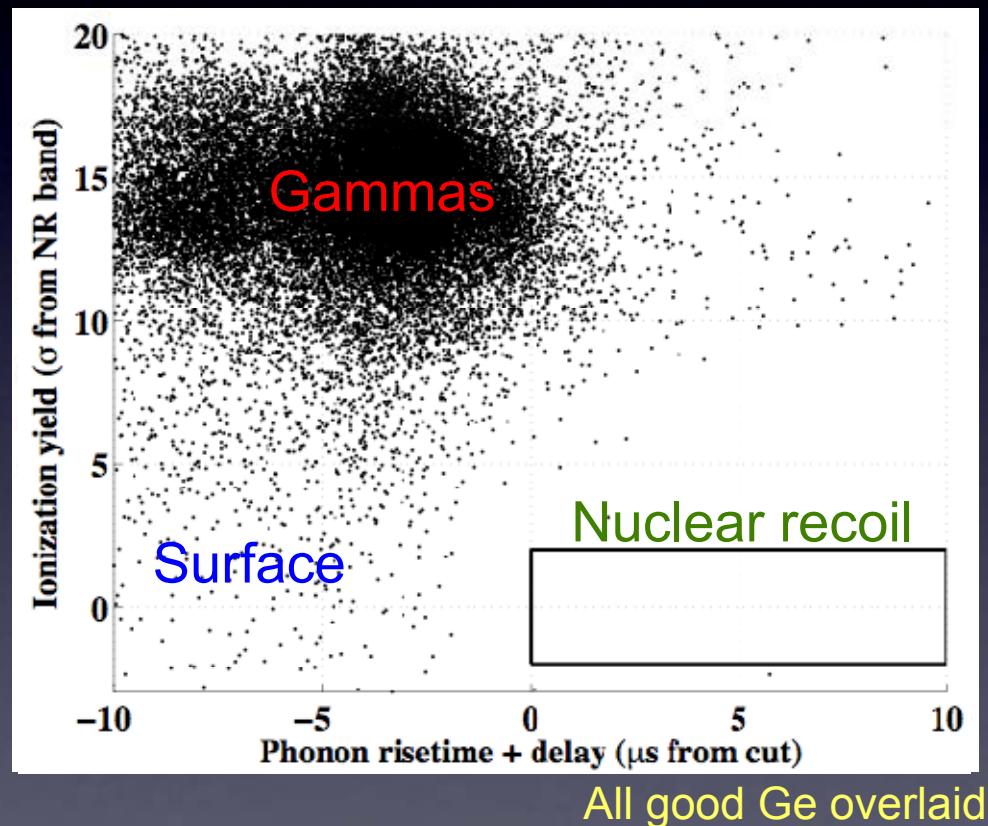
Box opened **February 4, 2008**, for 15 Ge ZIPs

(Remaining 8 Si and 1 Ge held for further leakage characterization)

3 σ region masked
=> Hide unvetoed
singles

Lift the mask, see 97
singles *failing* timing
cut

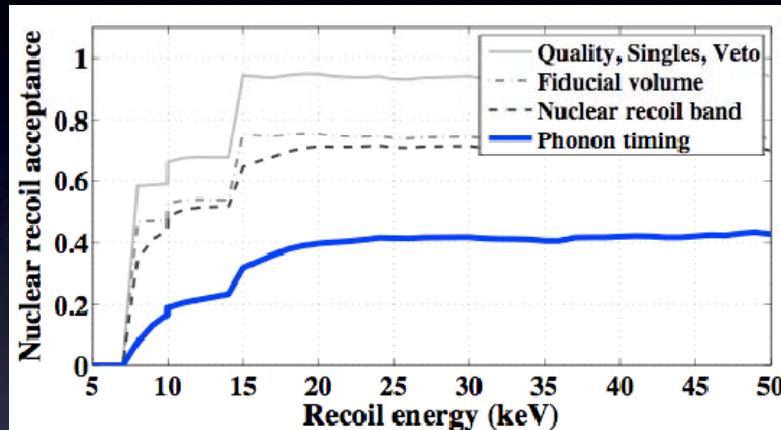
Apply the timing cut,
count the ~~candidates~~



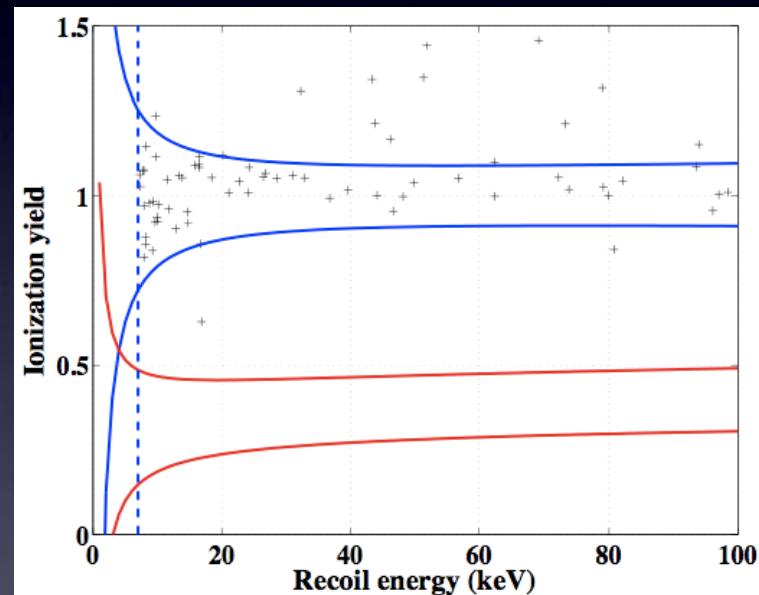
No events observed

Si ZIP Analysis

Box opened **December 3, 2008**, for **6 inner Si ZIPs**
(Remaining 2 Si at Tower ends dropped for poor background)



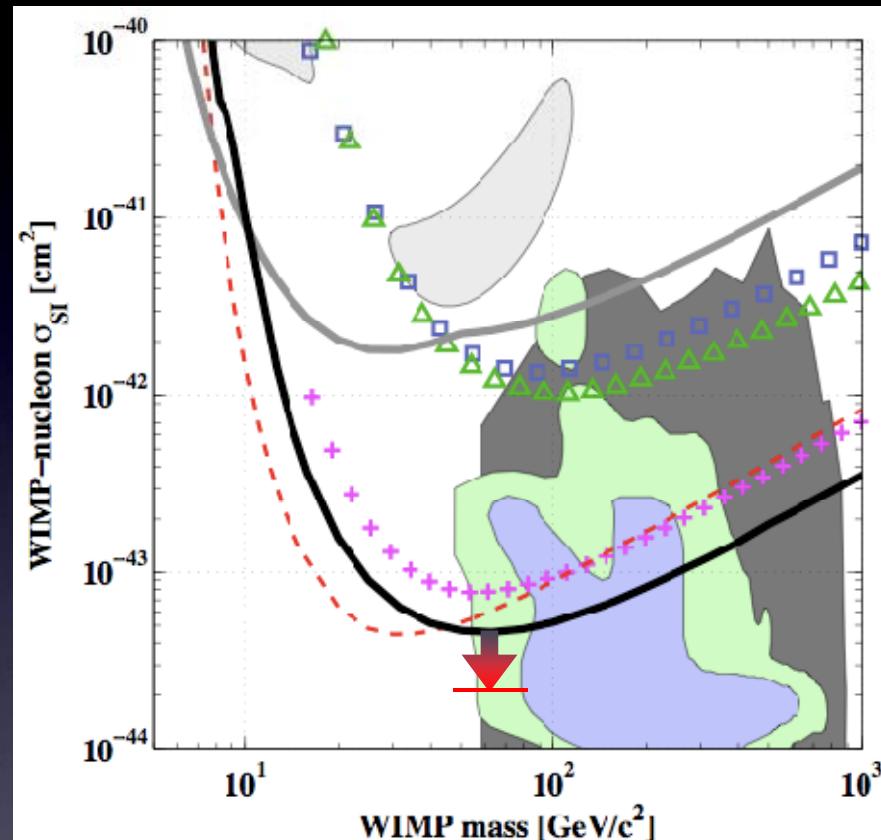
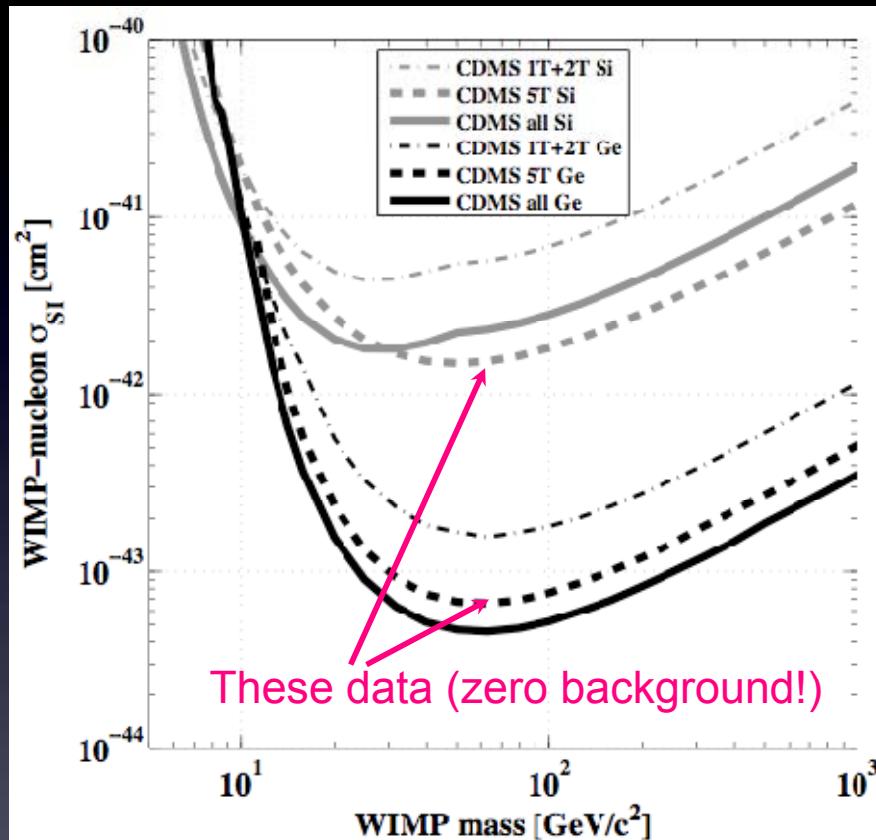
53.5 raw kg-d Si
17.9 kg-d WIMP equiv. @ 60
GeV/c²



Surface background
 $1.1^{+0.9}_{-0.6}(\text{stat.}) \pm 0.1(\text{syst.})$

No events observed

5-Tower WIMP Limits



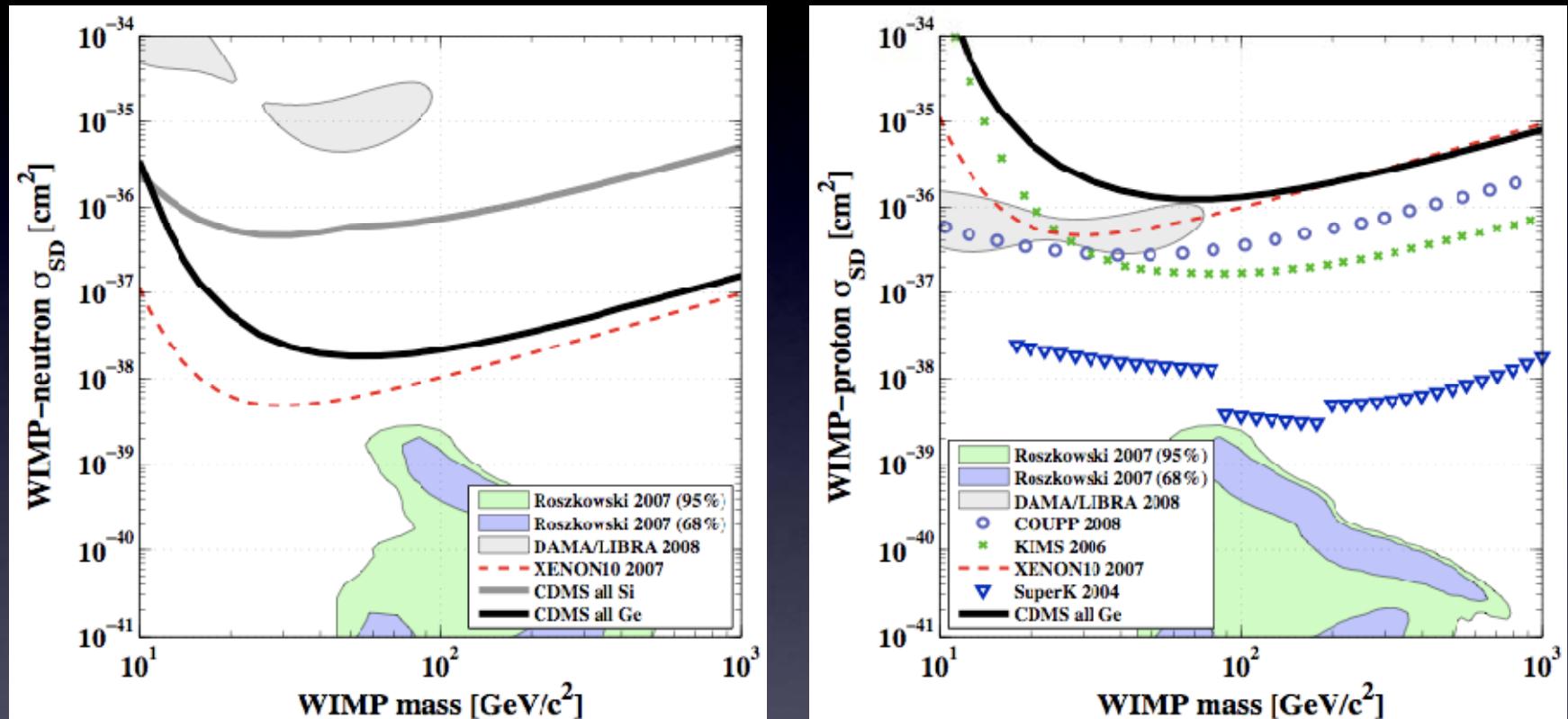
Strongest limits on spin-independent WIMP scattering above $\sim M_Z/2$:

$$\sigma_{SI} < 4.6 \times 10^{-44} \text{ cm}^2 \text{ @ } 60 \text{ GeV}/c^2 \text{ (90% CL)}$$

46 zeptobarns

Phys. Rev. Lett. **102**, 011301
(2009); arXiv:0802.3530

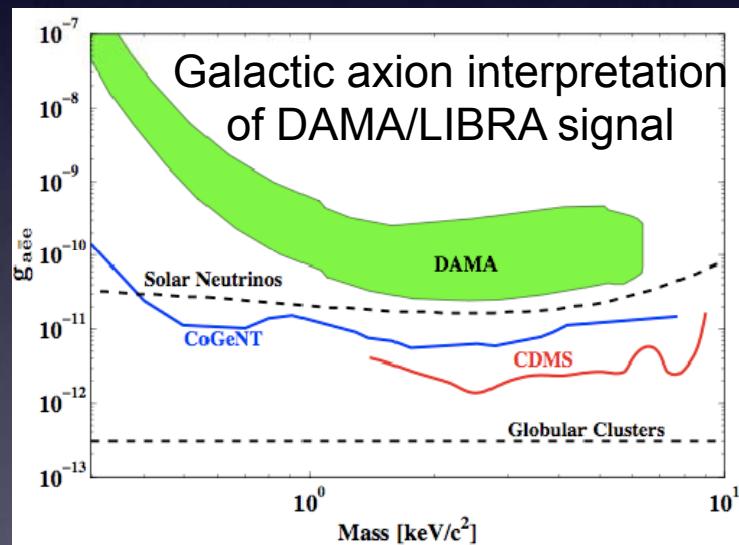
Spin-Dependent WIMP Limits



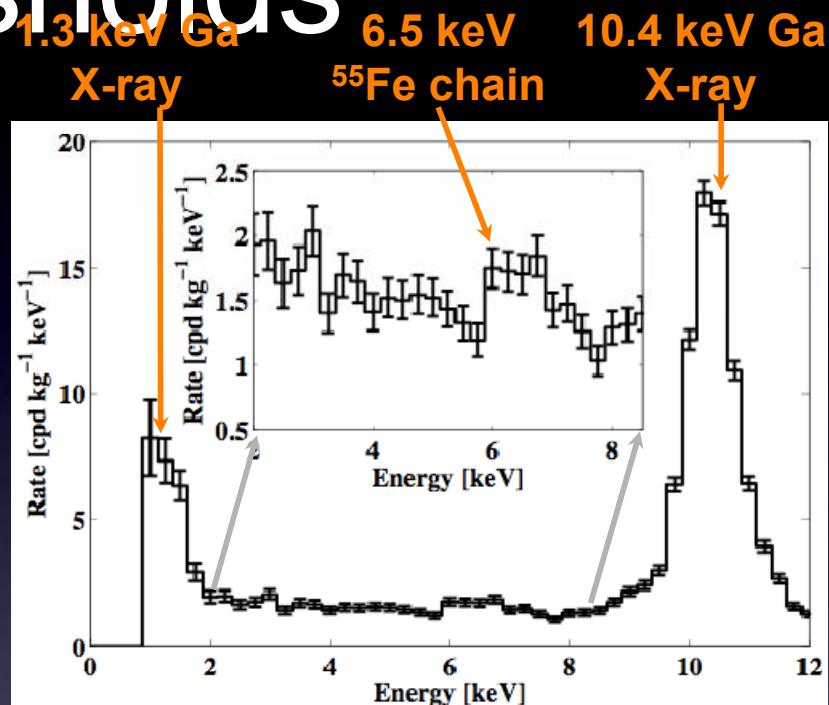
^{73}Ge (7.73%) and ^{29}Si (4.68%) give sensitivity to spin-dependent (axial) WIMP interactions

CDMS at Low Thresholds

- Probe low energy CDMS electron spectrum, e.g. for
- $a \rightarrow \gamma$ for solar axions
- $a \rightarrow e^+e^-$ from galactic axions



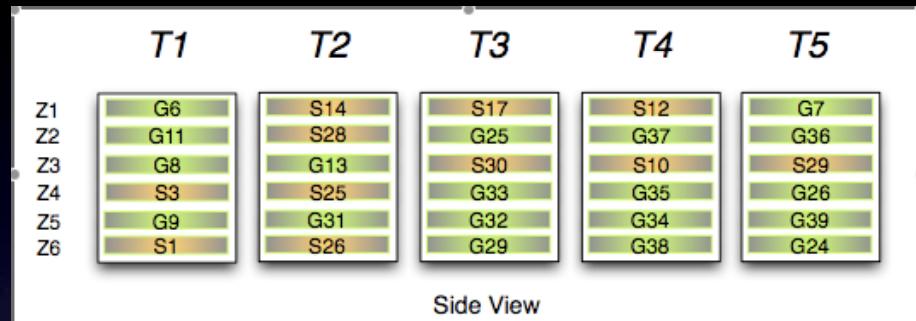
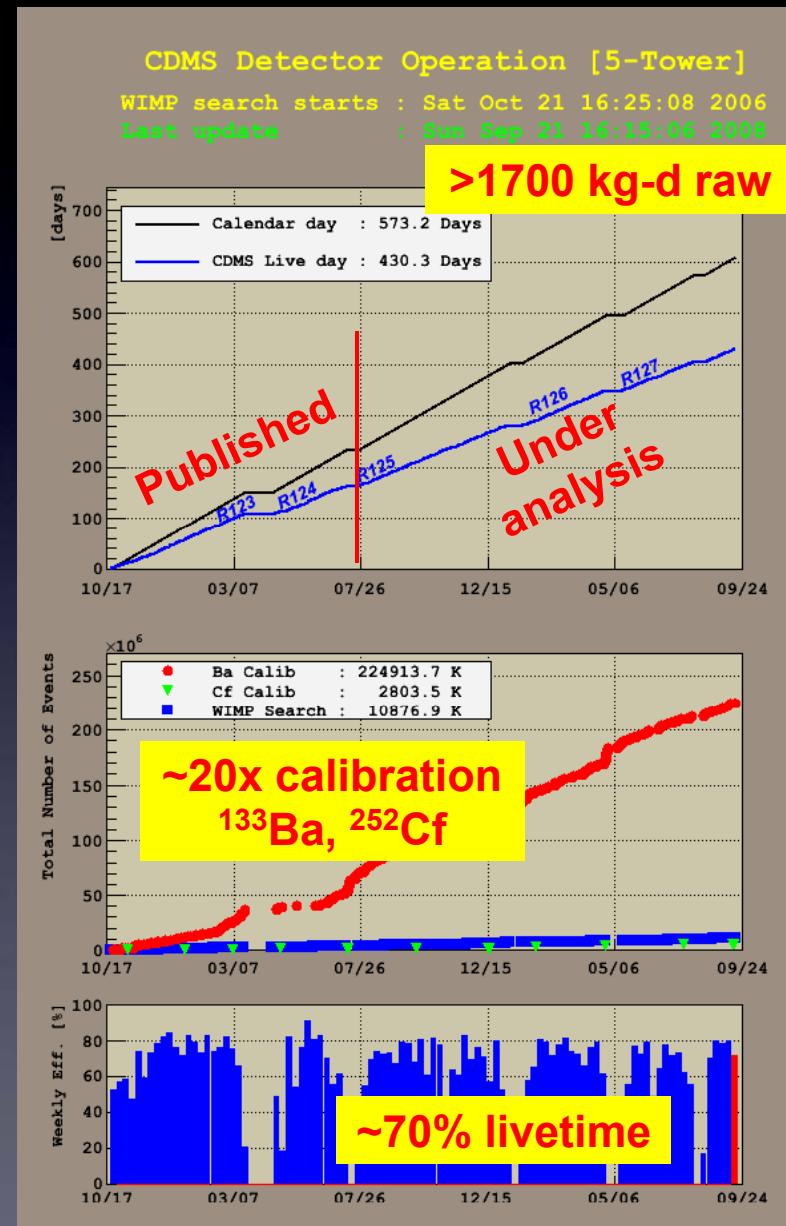
arXiv:0902.4693 (submitted)



Stay tuned for upcoming results on:

- *Upper limits on low-mass WIMPs ($\sim\text{GeV}$) from low-energy nuclear recoils*
- *Generic searches for anomalous electron recoil backgrounds*

Five Tower Status



Ongoing data run (all exposures before cuts):

- Run 123 (21Oct06-21Mar07): **430 kg-d Ge**
- Run 124 (20Apr07-16Jul07): **224 kg-d Ge**
- Run 125 (21Jul07-09Jan08): **466 kg-d Ge**
- Run 126 (17Jan08-28Apr08): **273 kg-d Ge**
- Run 127 (05May08-01Aug08): **221 kg-d Ge**
- Run 128 (12Aug08-18Sep08): **108 kg-d Ge**
- Run 129 (19Nov08-date): **ends ~next week**

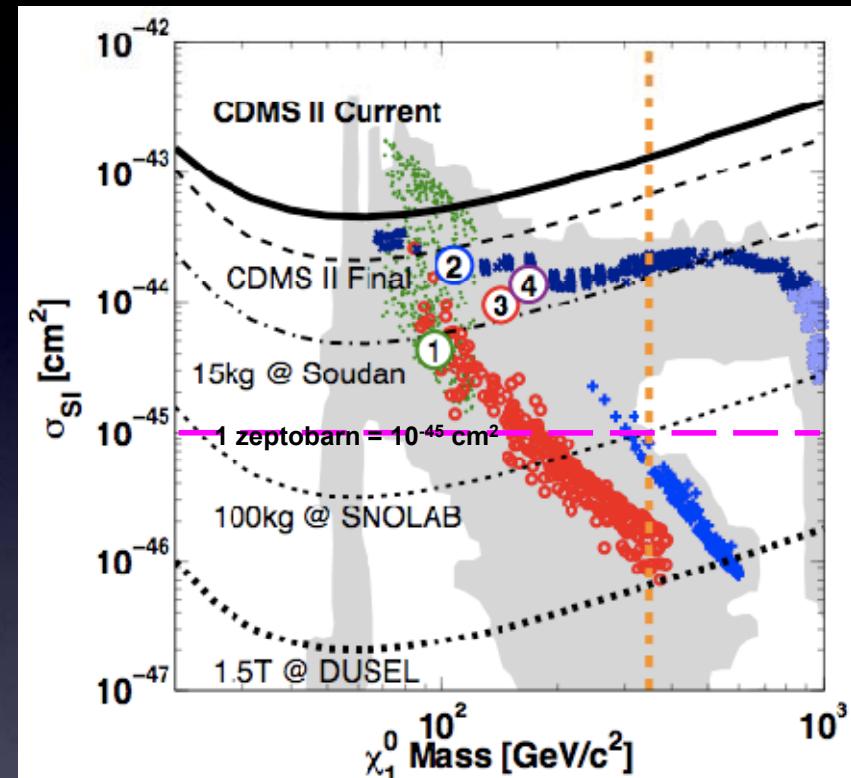
**>3x data under analysis
for Summer 2009!**

What's Next?: Beyond CDMS II

- **SuperCDMS**: 2 SuperTowers to Soudan (starting April 2008), later SNOLAB
 - 2.5x less surface per mass
 - Cleaner surfaces (less Rn)
 - More efficient photolithography



- **GeODM (Germanium Observatory for Dark Matter)**: development for ton-scale experiment at deeper location (SNOLAB, DUSEL)
 - Multiplexed sensor readout
 - Multi-kg detectors with cheaper dislocation-free substrates
 - Kinetic inductance phonon sensors

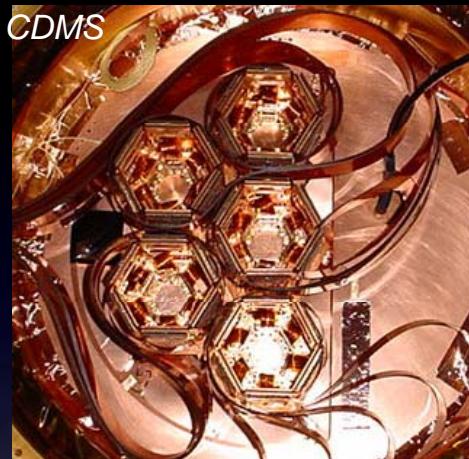


CMSSM: bulk, focus point,
coannihilation, A^0 funnel

For references, see <http://dmtools.berkeley.edu>
(Gaitskell, Mandic, Filippini)

Unmasking WIMPs

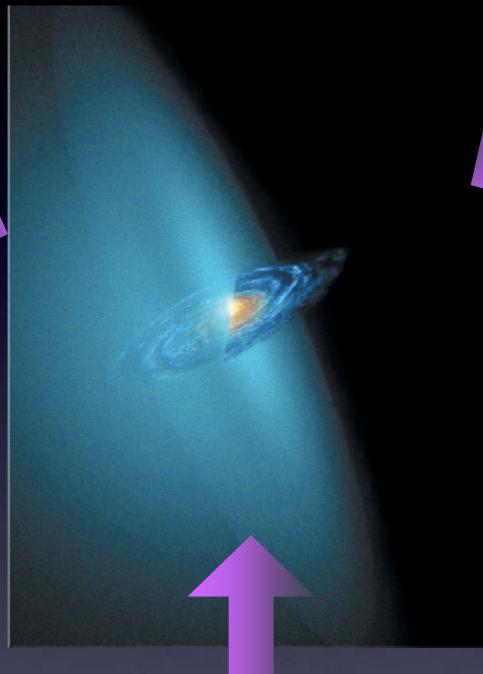
Tevatron



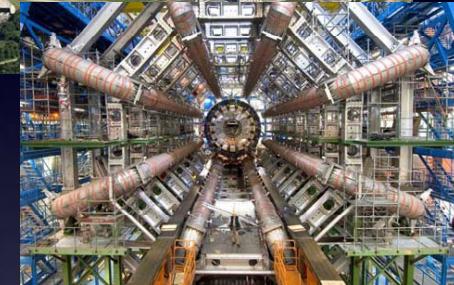
WIMP scattering on Earth

Are WIMP scattering and annihilation related?

Are the main WIMP annihilation processes active today?



LHC



WIMP production on Earth

Are there new charged/colored particles at the TeV scale?

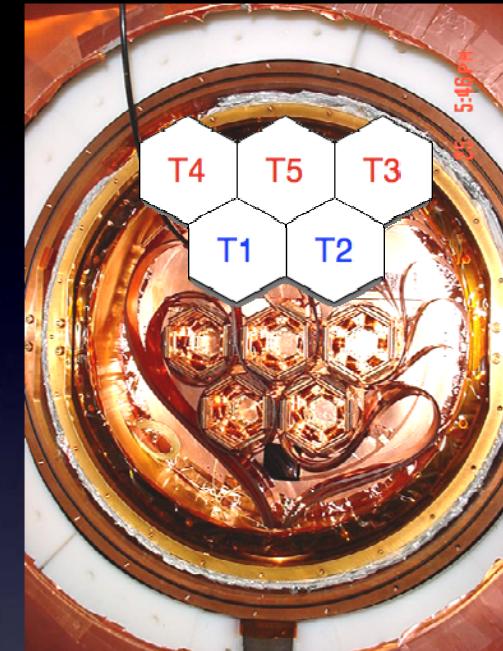


WIMP annihilation in the cosmos



Conclusions

- CDMS has maintained “zero background” operation down to $4.6 \times 10^{-44} \text{ cm}^2$ (46 zeptobarns)
- The 5-Tower run of CDMS II is ongoing, pushing to 10^{-44} cm^2
- SuperCDMS in production for operation at the zeptobarn scale
- Ongoing detector development toward ton-scale arrays
- The next few years will be an exciting time for WIMPs!



“Just in Case” Slides

Background Control I

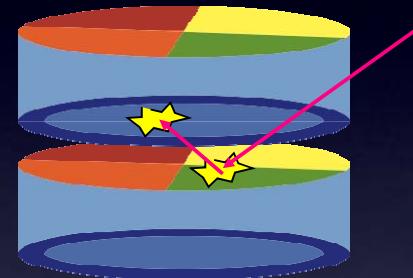
Rate Reduction

- Passive Pb, poly **shielding**
- **Low-activity Cu** environment
- 2700 mwe depth



Multiplicity

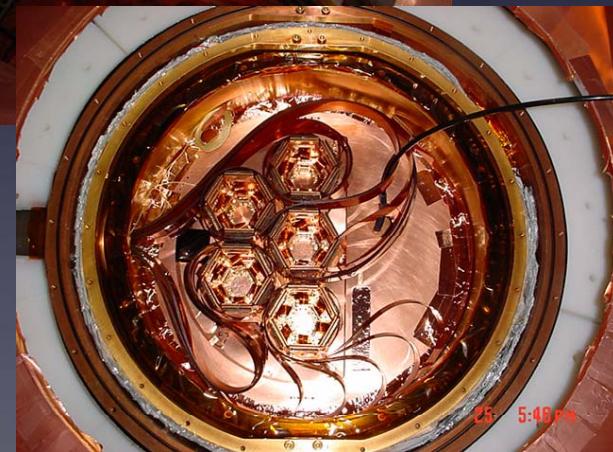
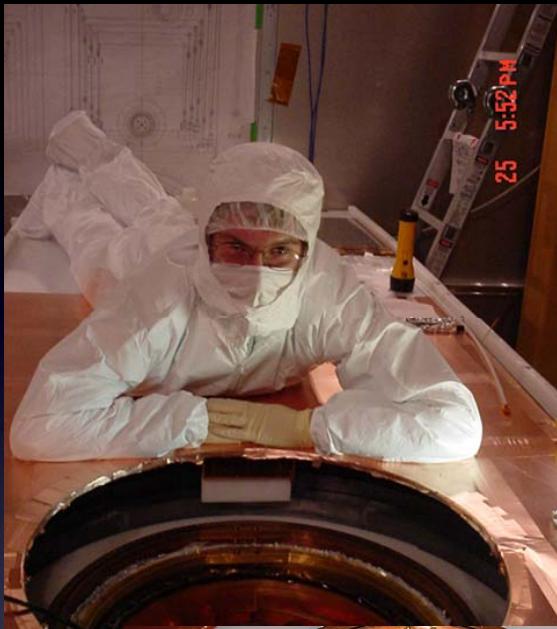
- Signal above 4σ noise in one and only **one** detector



- No signal in surrounding scintillator shield



Soudan Commissioning



- January 2005: Installation and checkout of cold hardware, heat shielding
- Spring 2005: *Dilution unit plugged, disassembled and reassembled fridge*
- Summer 2005: *Inadequate cooling*
- Fall 2005: Improve cryocooler coupling
- Winter 2006: *Inadequate cooling*
- Spring 2006: Improve thermal contacts, reinstall detectors and hardware
- Summer 2006: Detector tuning
- October 2006: **WIMP search begins**

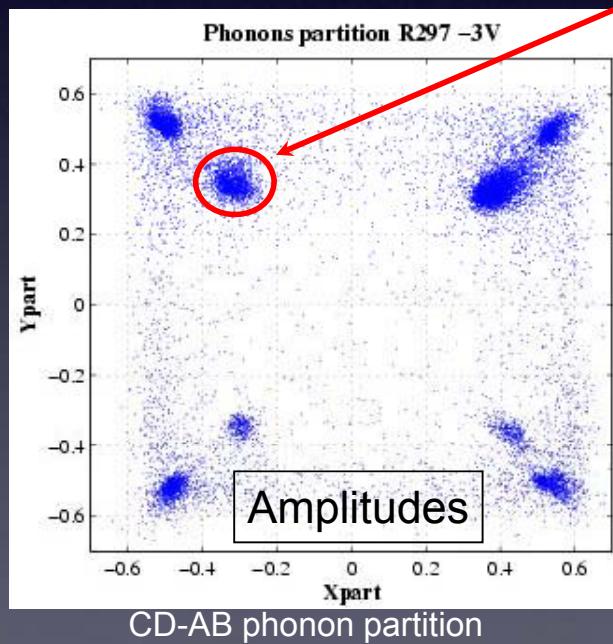
Position Reconstruction



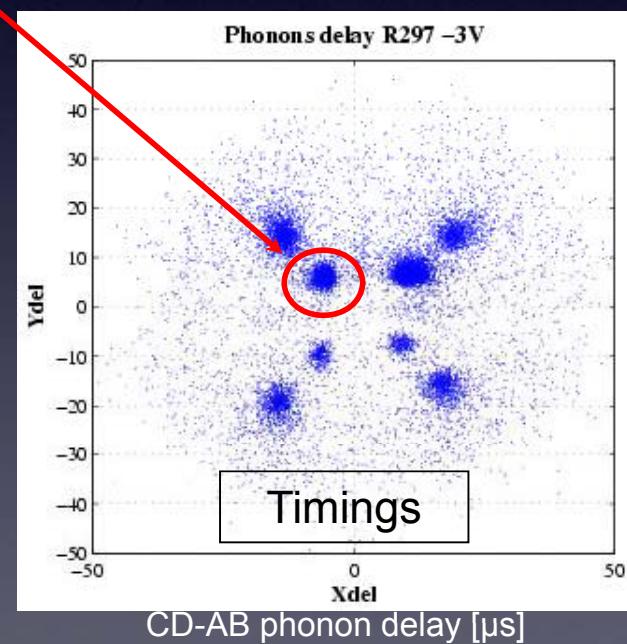
Crucial to **correct for position dependencies** of athermal phonon signals

Collimated ^{109}Cd sources (β , 22 keV γ)

AC-BC phonon partition



AC-BC phonon delay [μs]



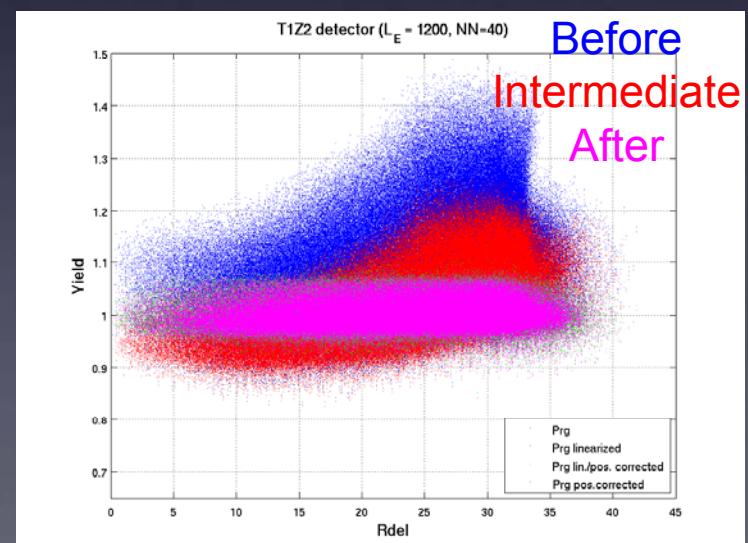
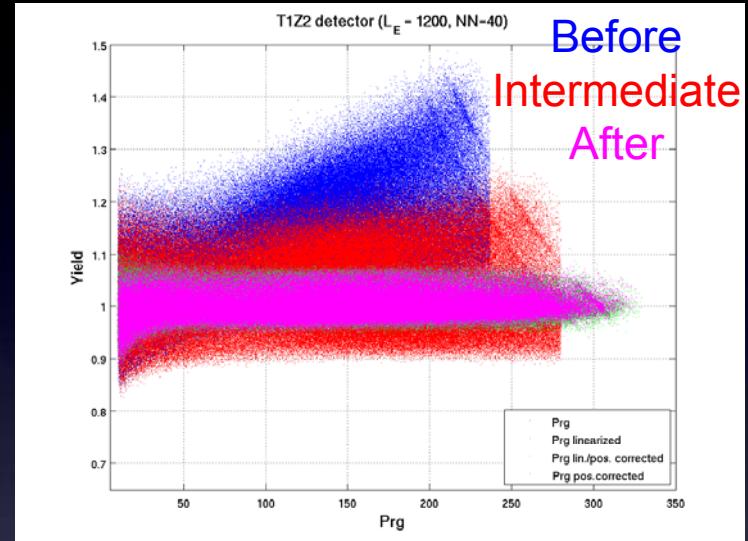
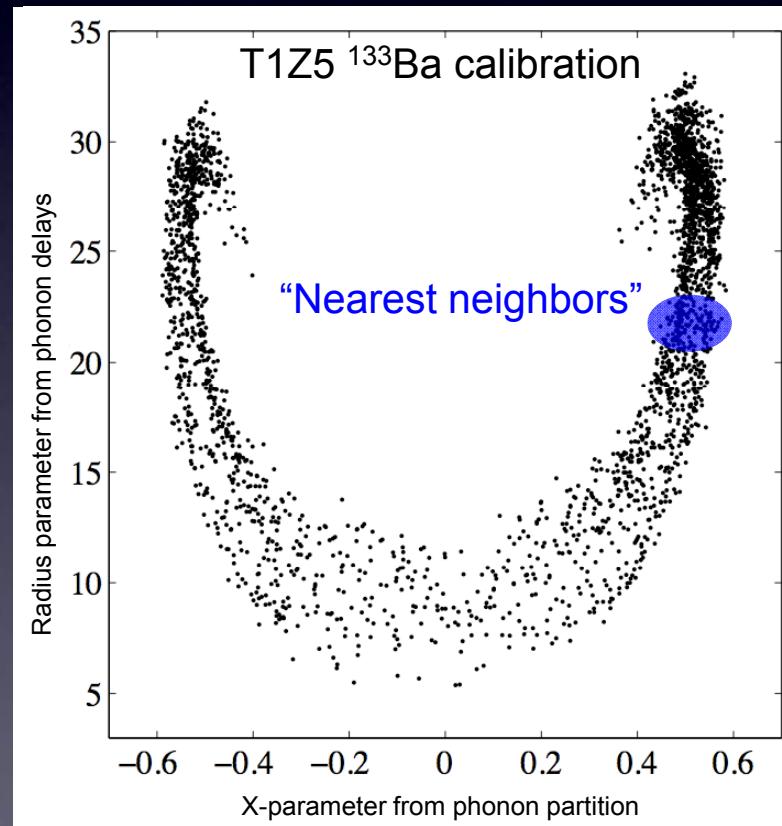
CD-AB phonon partition

CD-AB phonon delay [μs]

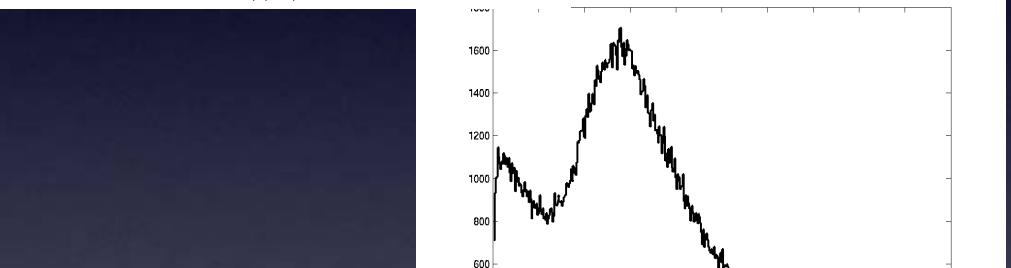
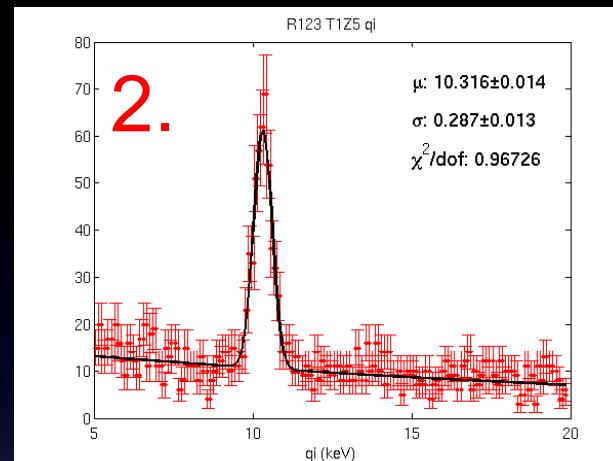
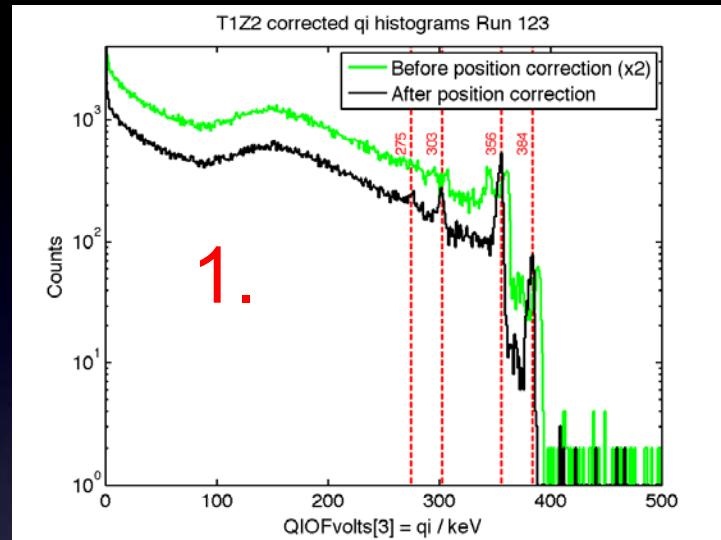
*Data from UC Berkeley calibration of T2Z5, née G31
V. Mandic et al., NIM A 520, 171 (2004)*

Position Correction

Correct events by comparisons to neighbors in phonon partition, phonon delay and energy



Energy Calibration

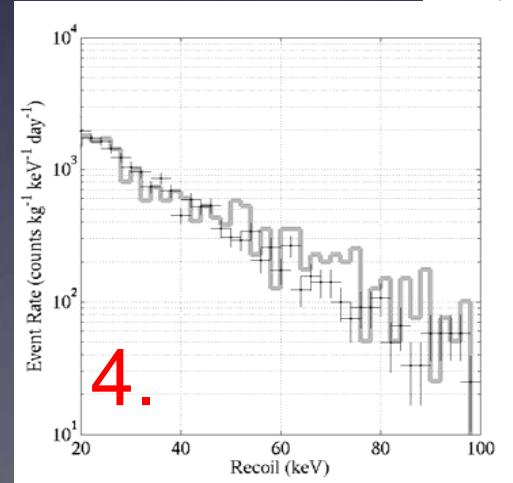


1. Charge calibration with ^{133}Ba

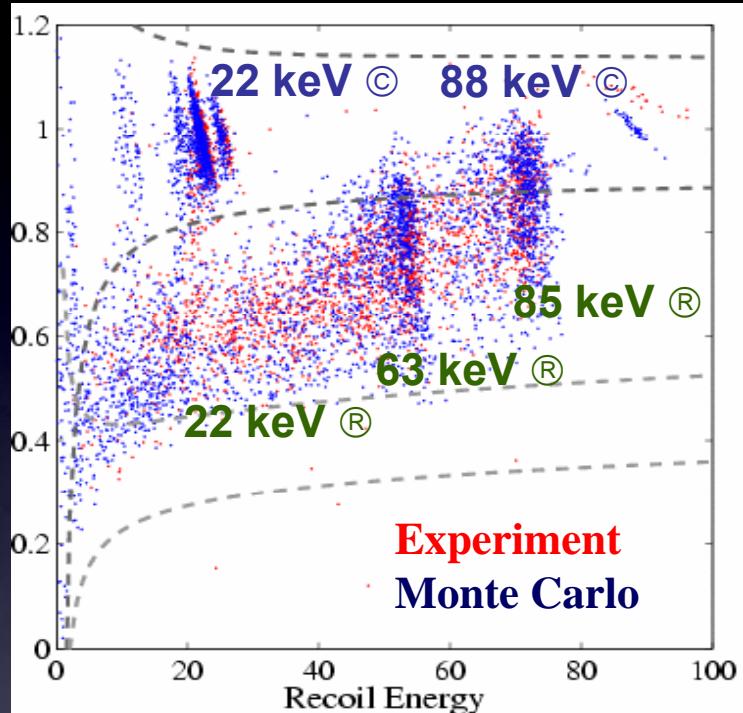
2. Confirm with 10.4 keV line

3. Calibrate phonons against charge

4. Nuclear recoils consistent with unquenched Monte Carlo (+'s)



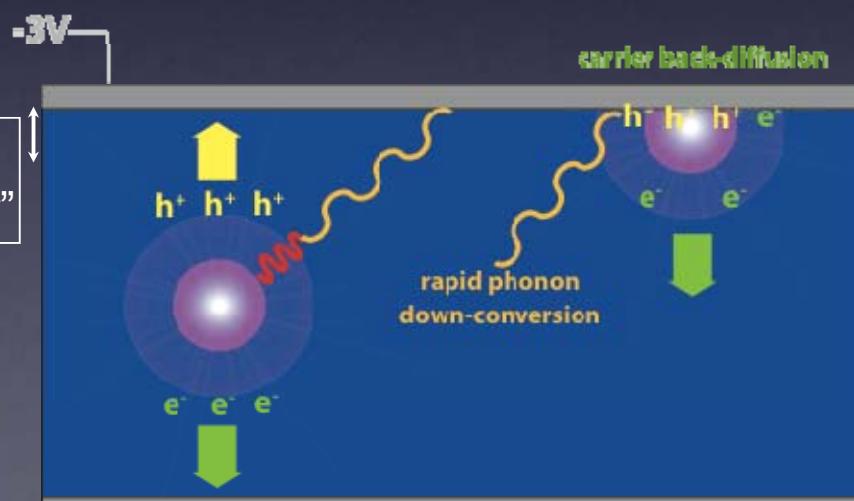
Near-Surface Events



*Data from UC Berkeley calibration of
T2Z5, née G31
V. Mandic et al., NIM A 520, 171
(2004)*

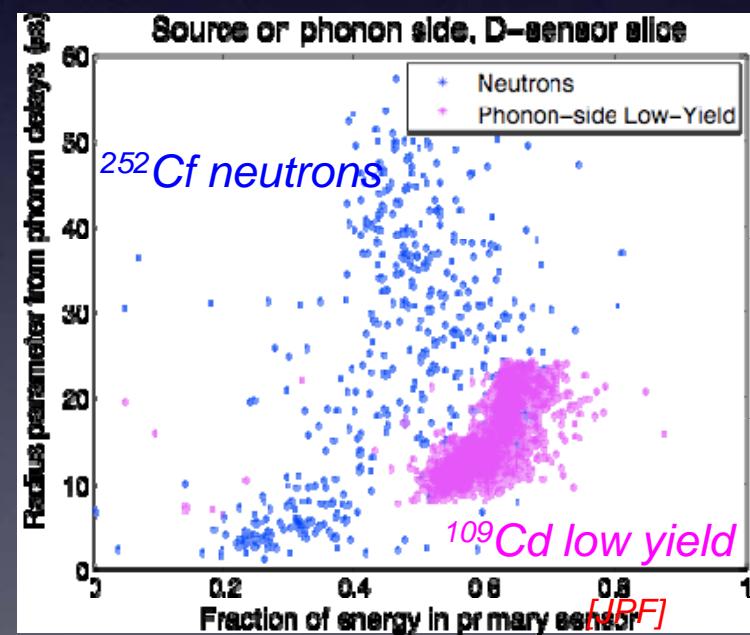
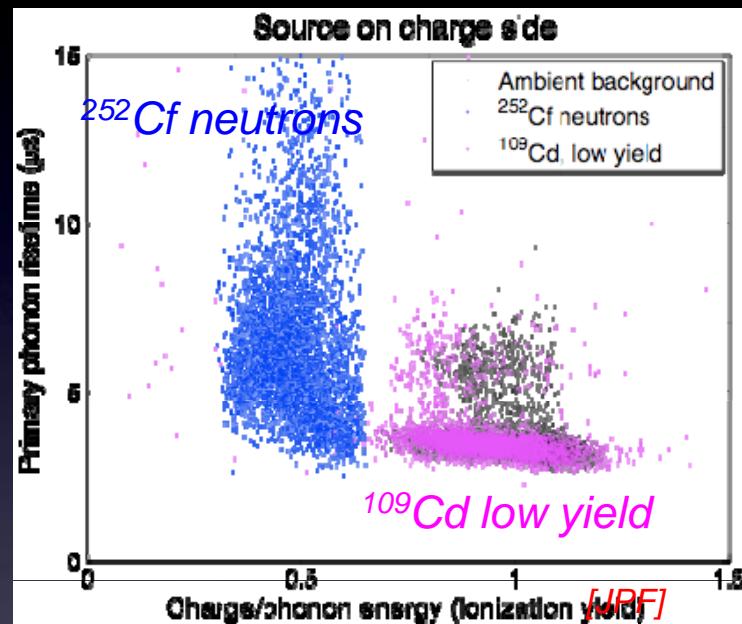
Reduced charge yield from surface events (e.g. K-40, Rn chain) from carrier back-diffusion can mimic signal

Greatly improved by α Si contact (Shutt et al.), still **dominant background** for CDMS



First Characterizations

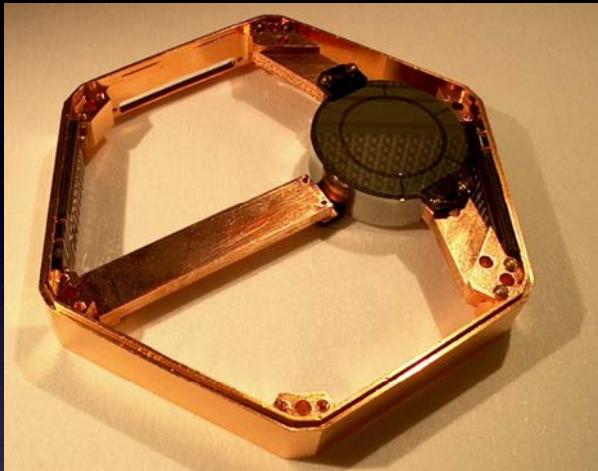
Cd-109 calibration of “G3D” at UC Berkeley (July 2007 - ongoing)



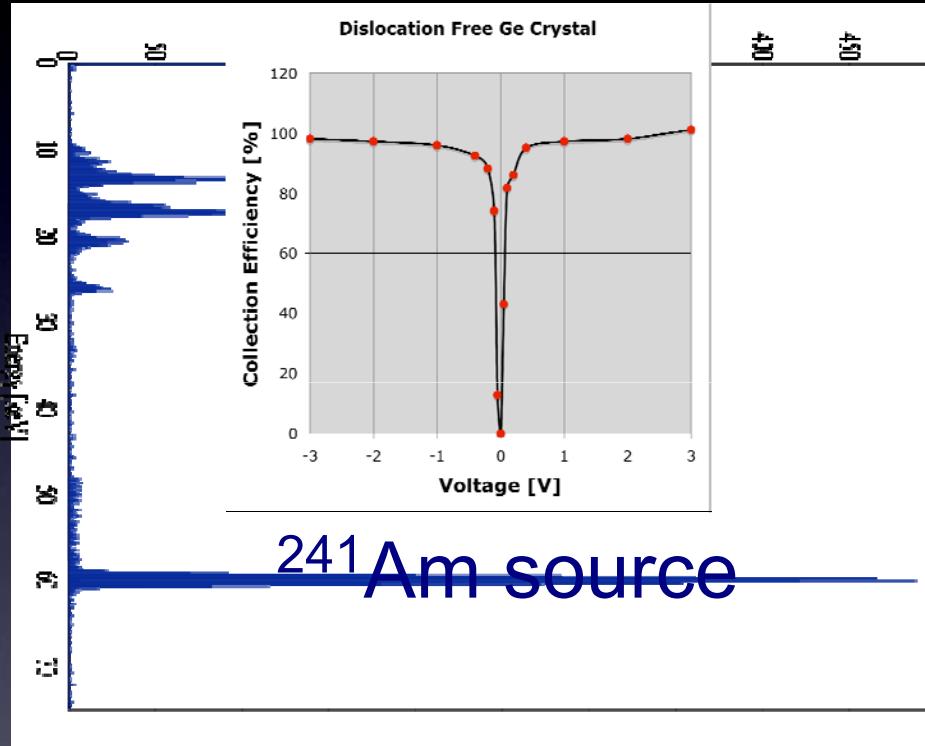
- Strong yield and timing discrimination on charge face
- Greatly enhanced phonon partition discrimination on phonon face

Path to Large Crystals?

Charge collection in dislocation-free Ge (Berkeley, February 2008)



- 3cm x 1cm sample of II-grown dislocation-free Ge (E.E. Haller)
- Unusable @77K, but can be neutralized at <100mK
- Excellent charge collection @ low voltages
- Available in >6" diameters (standard detector grade Ge limited to 3-4")



3"x1cm: 250g (CDMS II)

6"x2": 5kg?

WIMPs at a Zeptobarn

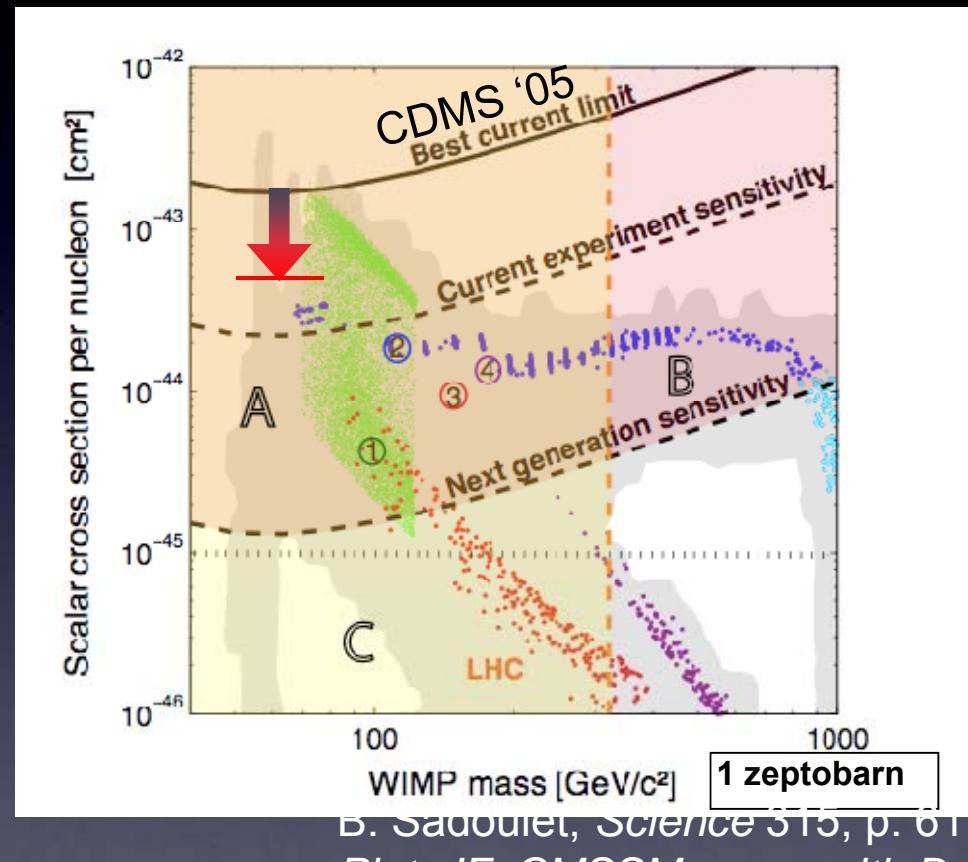
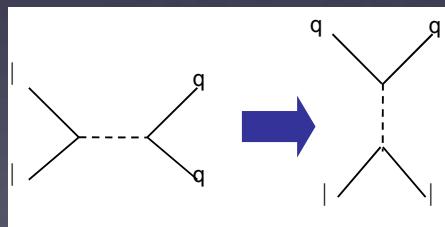
Bulk region

- Natural weak scale from light SUSY
- G-2 favored, FCNC disfavored

Focus point

- Natural weak scale from RGE focusing
- Decoupled scalars \Rightarrow low FCNCs

Crossing symmetry!



D. Soudani, Science 315, p. 61 (2007)
Plot: JF; CMSSM scans with DarkSUSY

“Zeptobarn-class” direct detection has substantial discovery potential and complementarity with the LHC

Higgs funnel

- Broad resonance ($M_A \sim 2 M_X$) speeds annihilation

Coannihilation Tail

- Near-degeneracy between LSP and NLSP

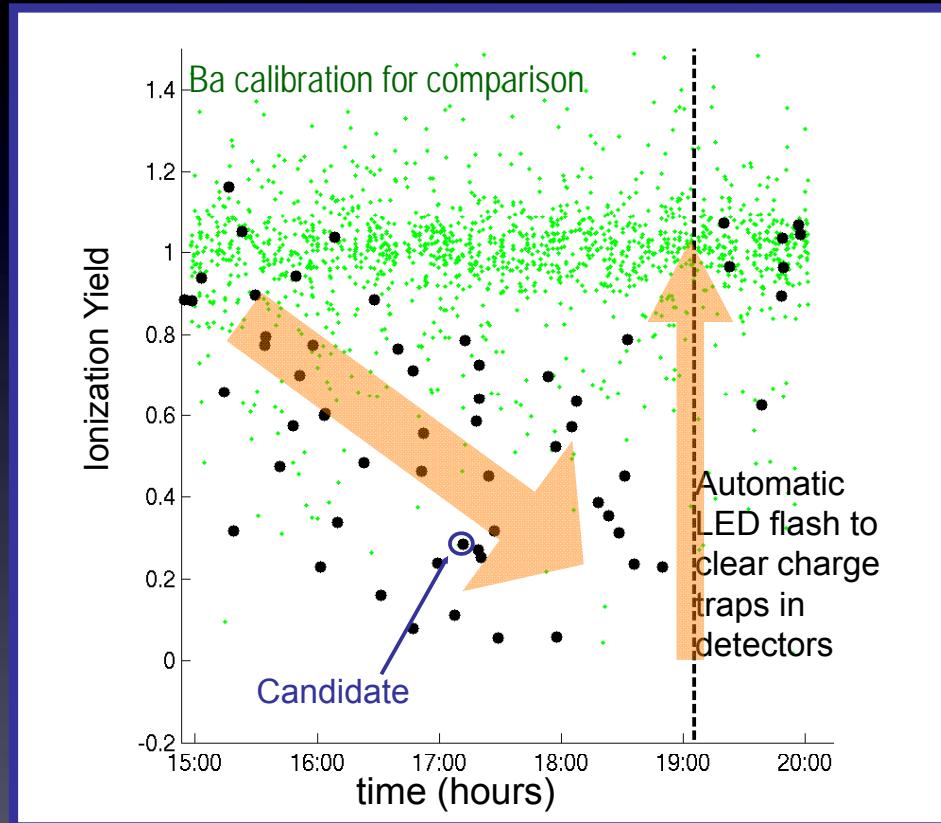
“Spectral coincidences”

Got WIMPs?

Automatic LED flash every 4 hours to discharge trapping sites

This candidate from a run with poor neutralization!

- Consistent with background in any case
- **Included in limit calculation** (worsens upper limit)
- **Improved screening** for current run



Data selection failure, NOT a WIMP candidate