WIMP Hunting with the Cryogenic Dark Matter Search

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Virtual Institute of Astroparticle Physics - April 18, 2008

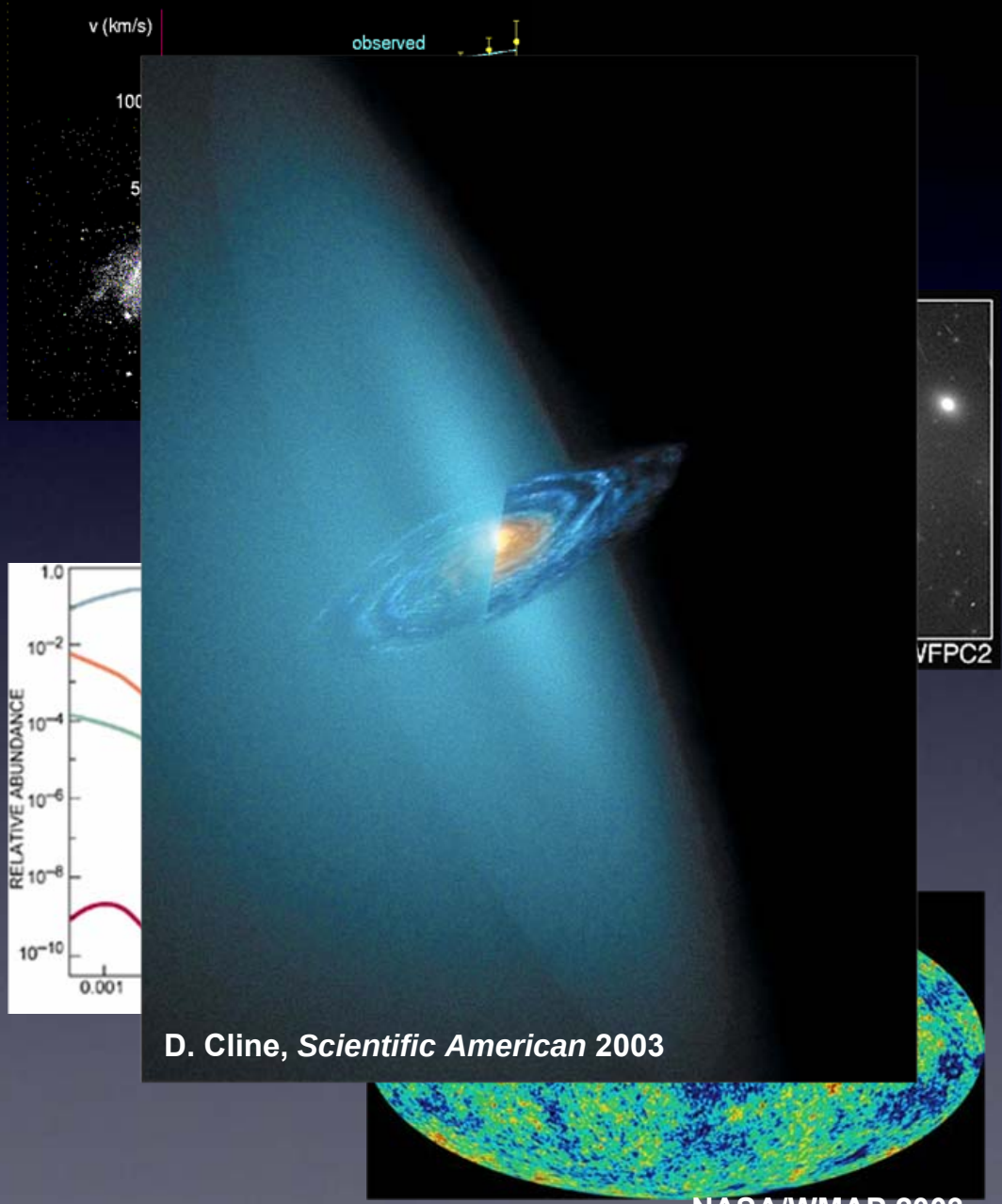
Outline

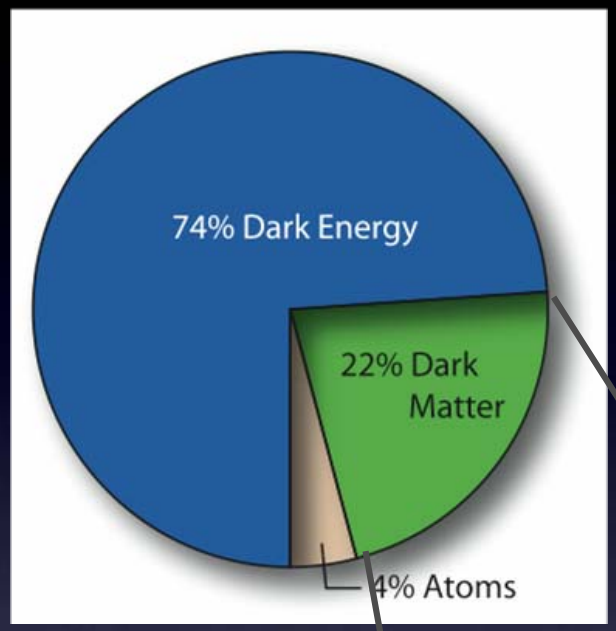
- WIMPs and their detection
- Workings of CDMS
- First 5-Tower analysis

New results!

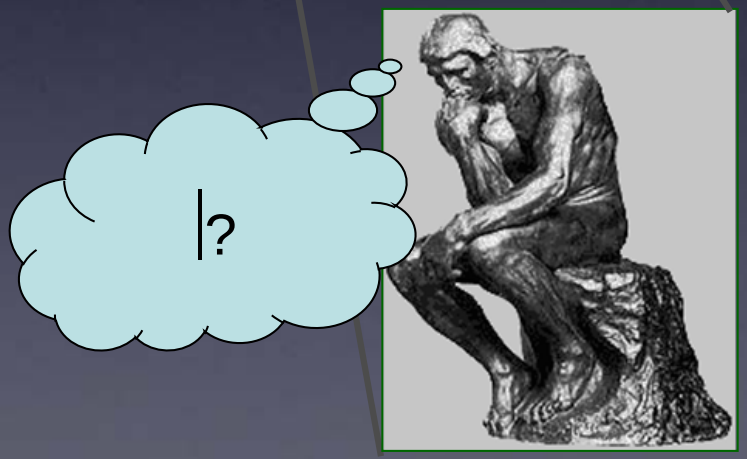
- The future at the zeptobarn scale

The Missing Mass





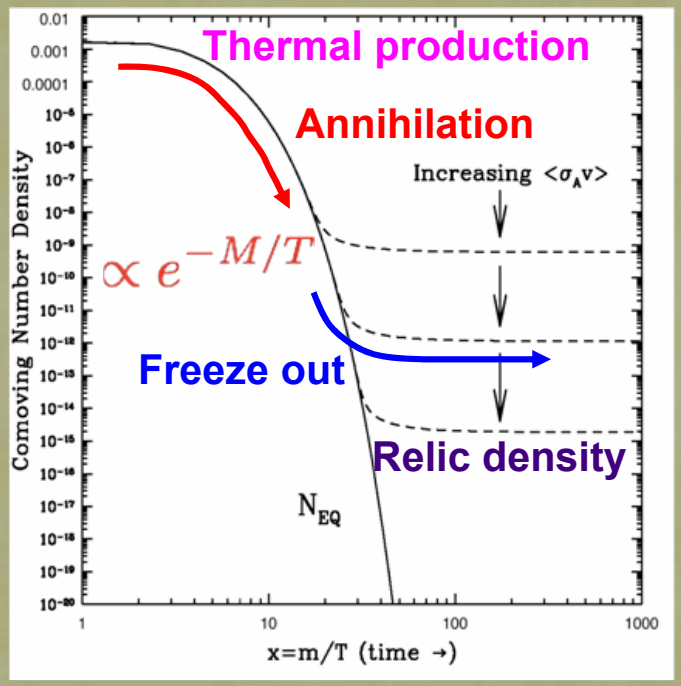
NASA/WMAP Science Team 2006



But what is this stuff?

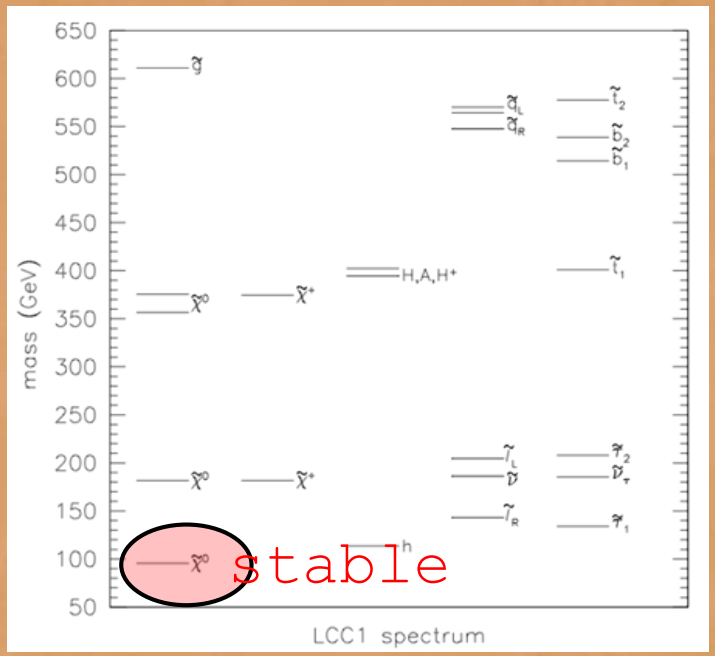
The Strength of WIMPs

Cosmology



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

Particle Physics



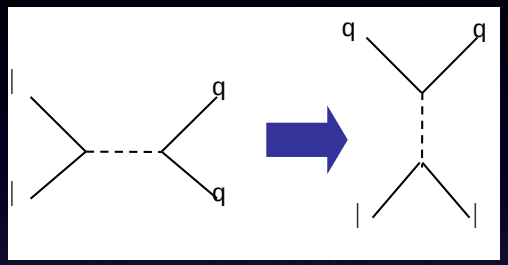
Baltz et al., PRD **74**, 103521 (2006)

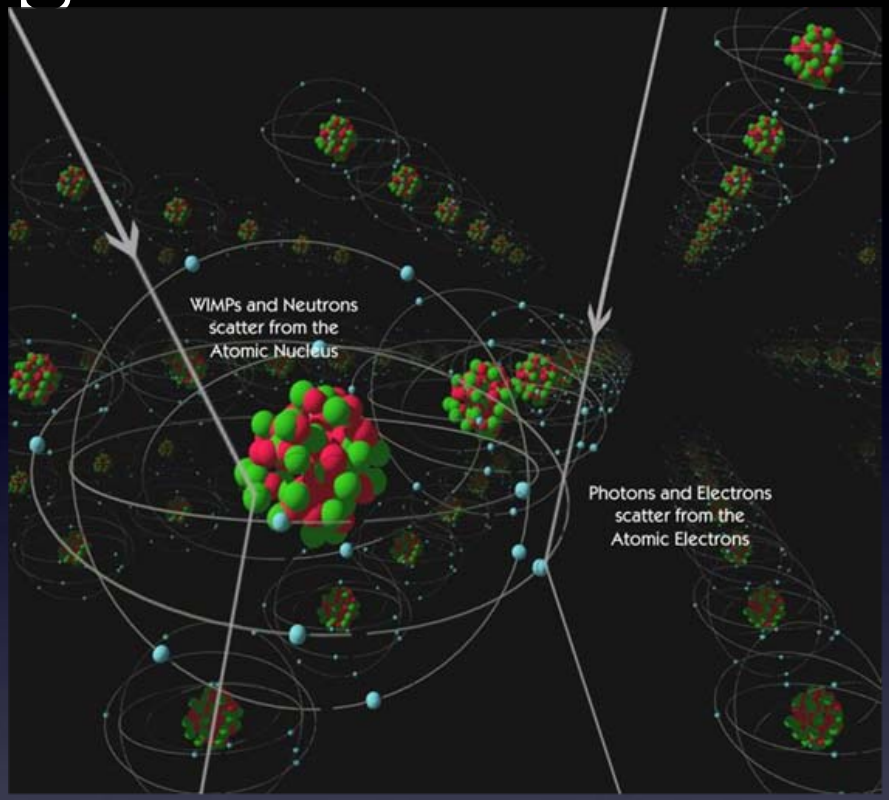
$$\Omega_\chi \approx 1 \Rightarrow \left\{ \begin{array}{l} \sigma_{\chi\chi} \approx 0.1\,\mathrm{pb}\ \ (10^{-37}\ \mathrm{cm}^2) \\ \sigma_{\chi\chi} \approx \dfrac{\alpha^2}{M_\chi^2} \Rightarrow M_\chi \approx 100\ \mathrm{GeV/c}^2 \end{array} \right\}$$

Strong theory motivation for **Weakly Interacting Massive Particles**

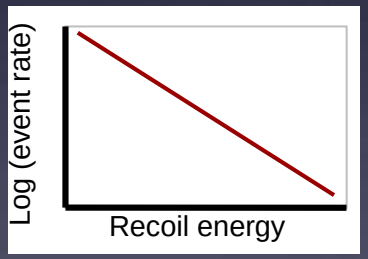
Direct Detection of WIMPs

Crossing symmetry => detectability?





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



Simple "spherical cow" halo: v_0=270 km/s, v_{esc}=650 km/s

Exponential spectrum of <E>~30 keV nuclear recoils, <<1/kg-day

Also: diurnal direction modulation, annual spectrum modulation

Detection Challenges

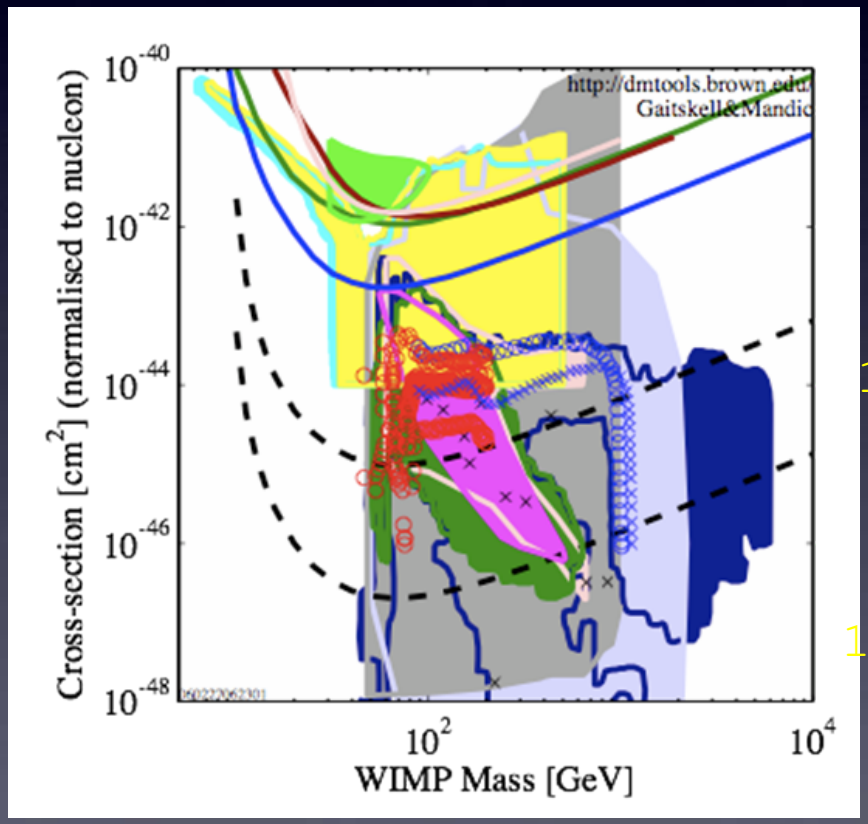
- Very **low energy** thresholds (~10 keV)

- Rigid **background control** (cosmogenic, radioactive)
  - Cleanliness
  - Shielding (passive active)
  - Discrimination power

- Substantial **depth**
  - Neutrons (muon induced, etc.) look like WIMPs

- **Large exposures** (large masses, long-term stability)

Exponential spectrum of <E>~30 keV nuclear recoils, <<1/kg-day



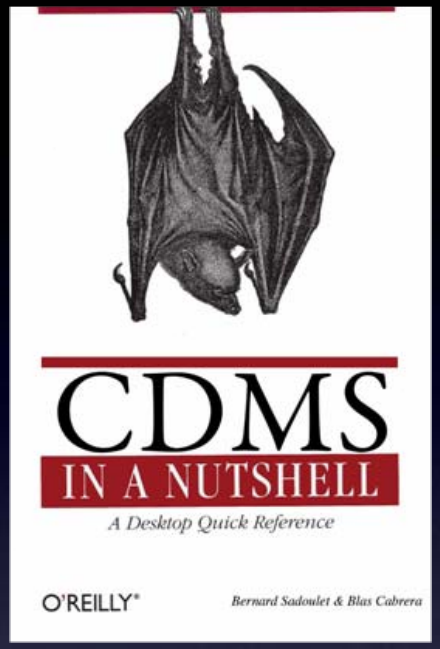
1/kg-d

1/kg-y

10/ton-y

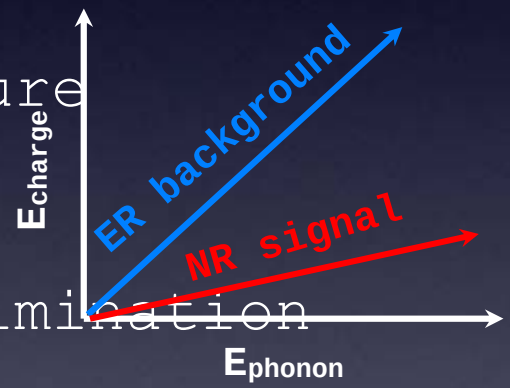
CDMS: The Big Picture

Use a combination of **discrimination** and **shielding** to maintain a **"zero background"** search for **nuclear recoils** with **low temperature** semiconductor detectors



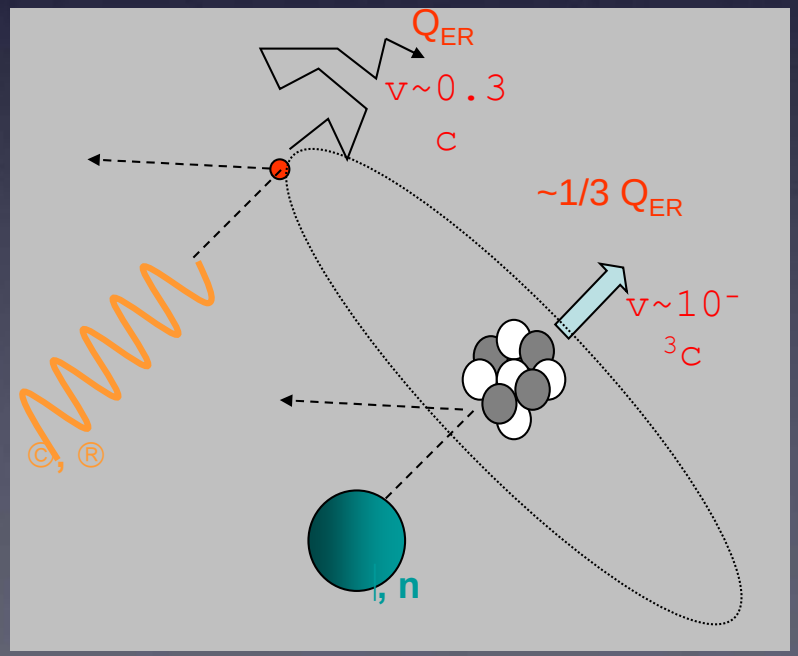
Discrimination

- Phonons
  - energy measure
  - pulse shape
- Ionization
  - dE/dx discrimination



Shielding

- Passive (Pb, poly, *depth*)
- Active (muon veto shield)



The CDMS Collaboration

Brown University
M. Attisha, **R. Gaitskell**

Caltech
Z. Ahmed, **S. Golwala**, D. Moore

Case Western Reserve University
D. Akerib, C. Bailey, D. Grant, R. Hennings-Yeomans, M. Dragowsky, G. Wang

Fermilab
D. Bauer, F. DeJongh, J. Hall, D. Holmgren, E. Ramberg, R. Schmitt, J. Yoo

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

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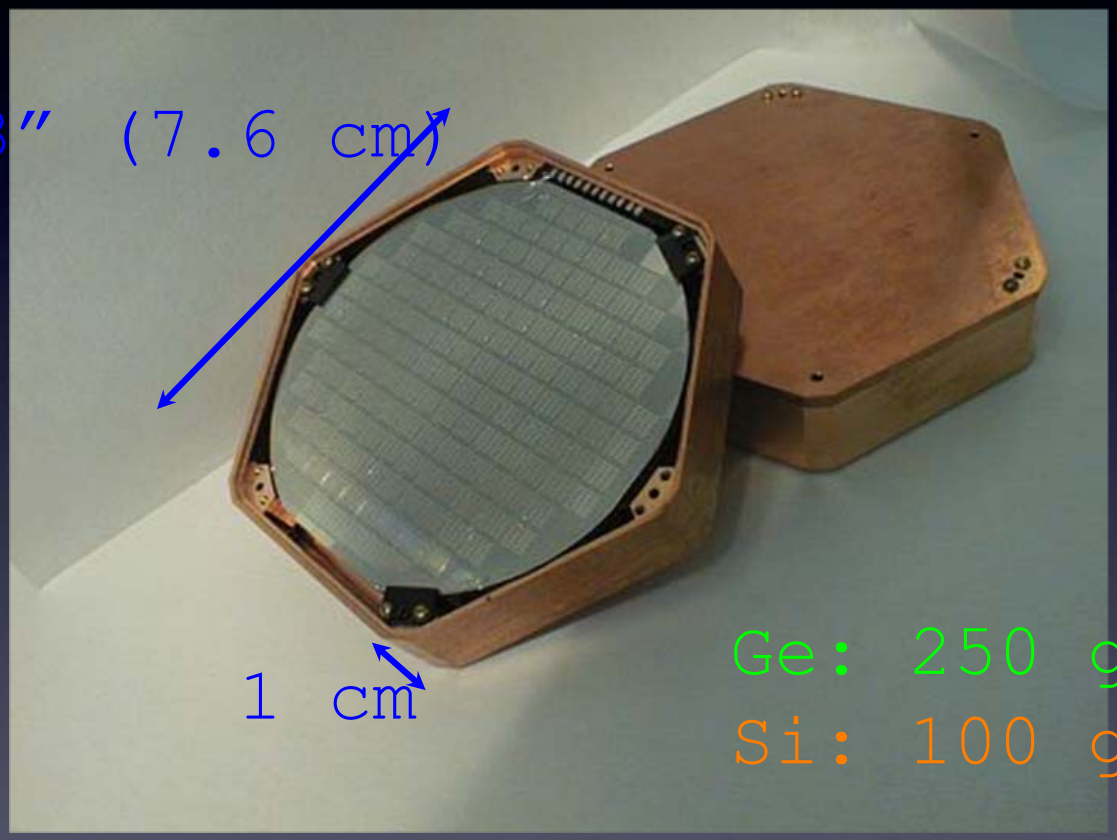
J. Beaty, **P. Cushman**, L. Duong, M. Fritts, **V. Mandic**, X. Qiu, A. Reisetter

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

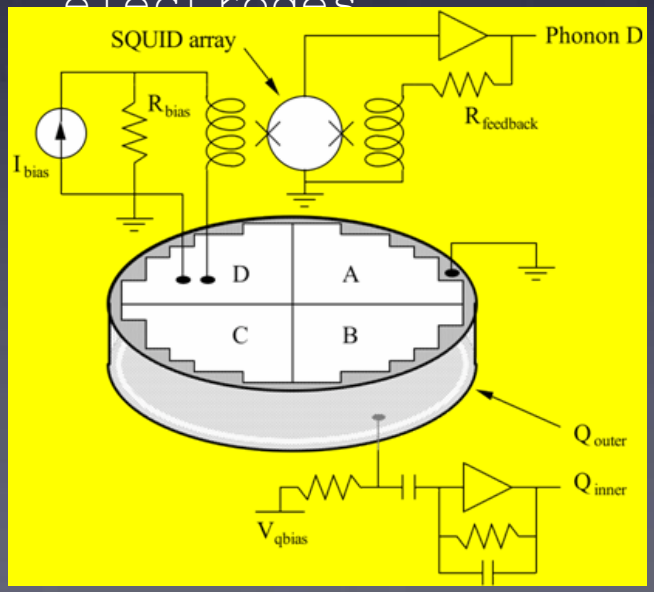
ZIP Detectors
(Z-sensitive Ionization and Phonon)



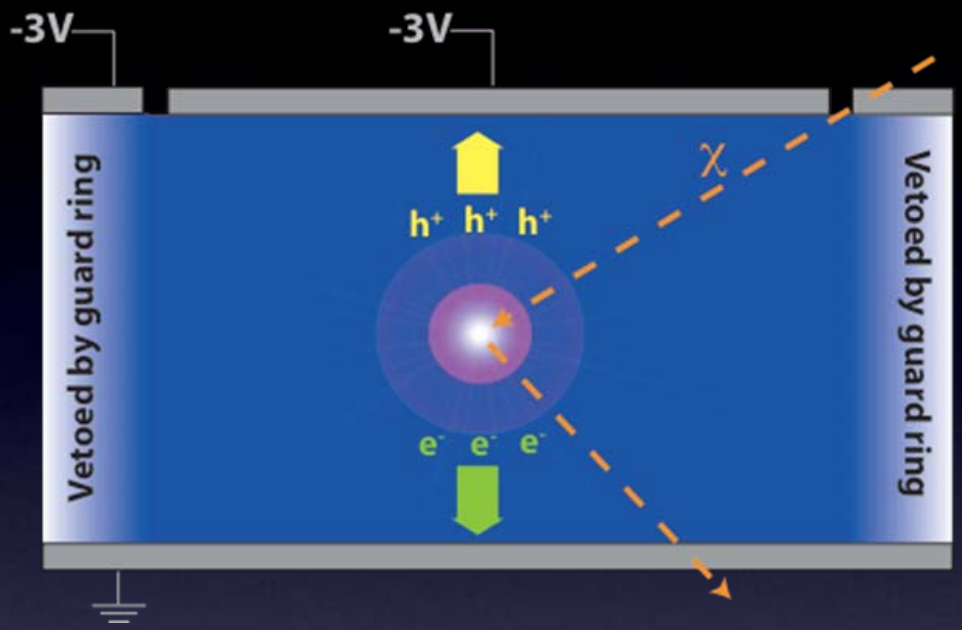
Operated at **~40 milliKelvin** for good phonon signal-to-noise

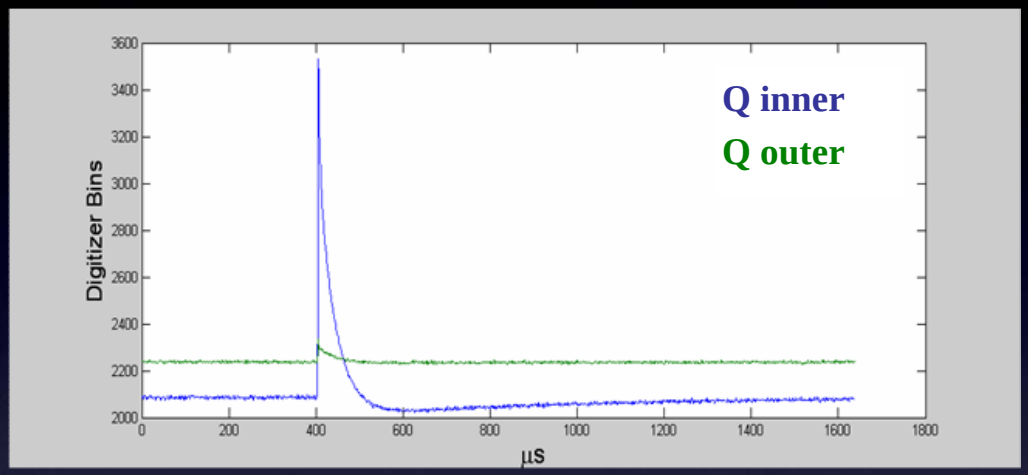
Phonon side: 4 quadrants of athermal phonon sensors
=> ***energy measurement***

Charge side: 2 concentric electrodes



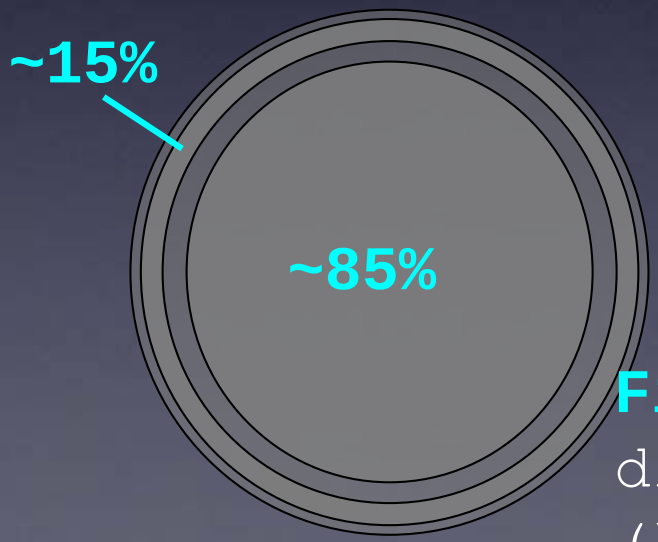
ZIP Detectors: Ionization





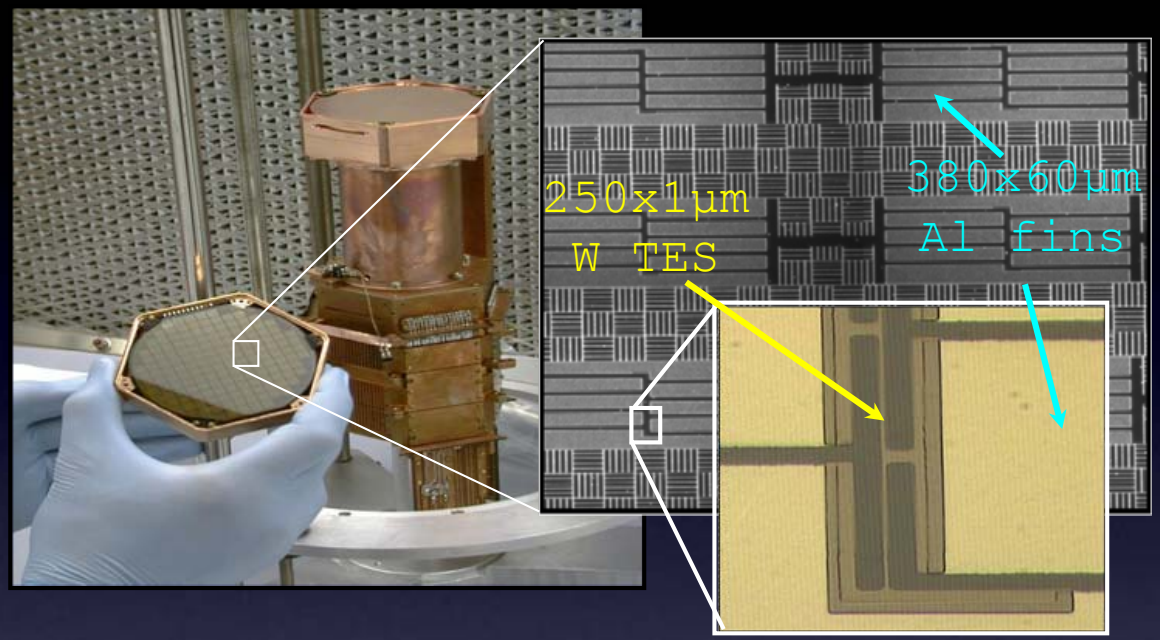
Essentially complete collection at **3V/cm** (after trap neutralization)

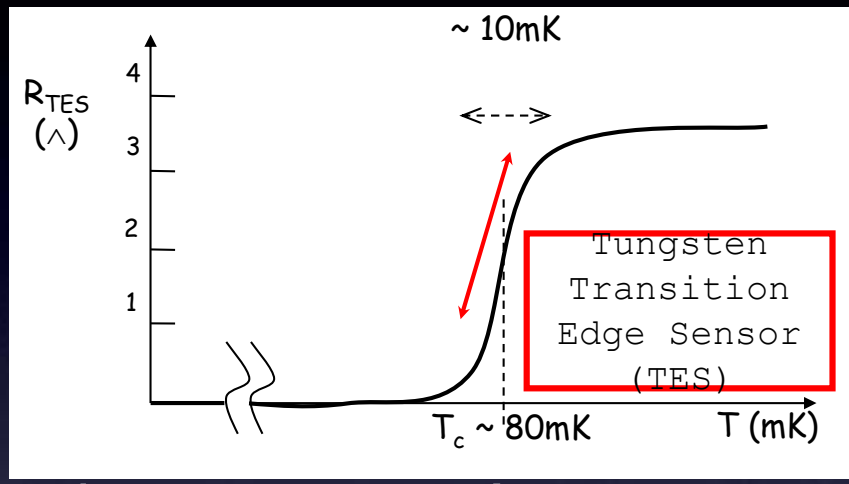
Low-noise JFET amp at 140 K: Zero-energy resolution **~250 eV** (~3 keV @ 511 keV)



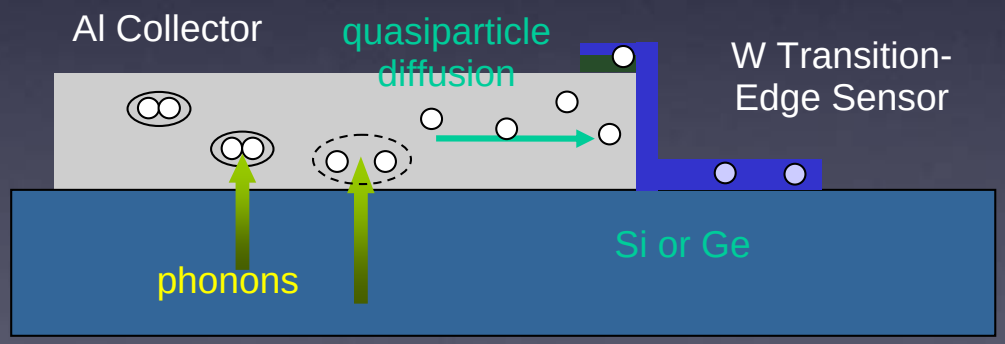
Fiducial volume cut from divided electrode (“**guard ring**”)

ZIP Detectors: Phonons





4 SQUID readout channels, each 1036 W TESs in parallel



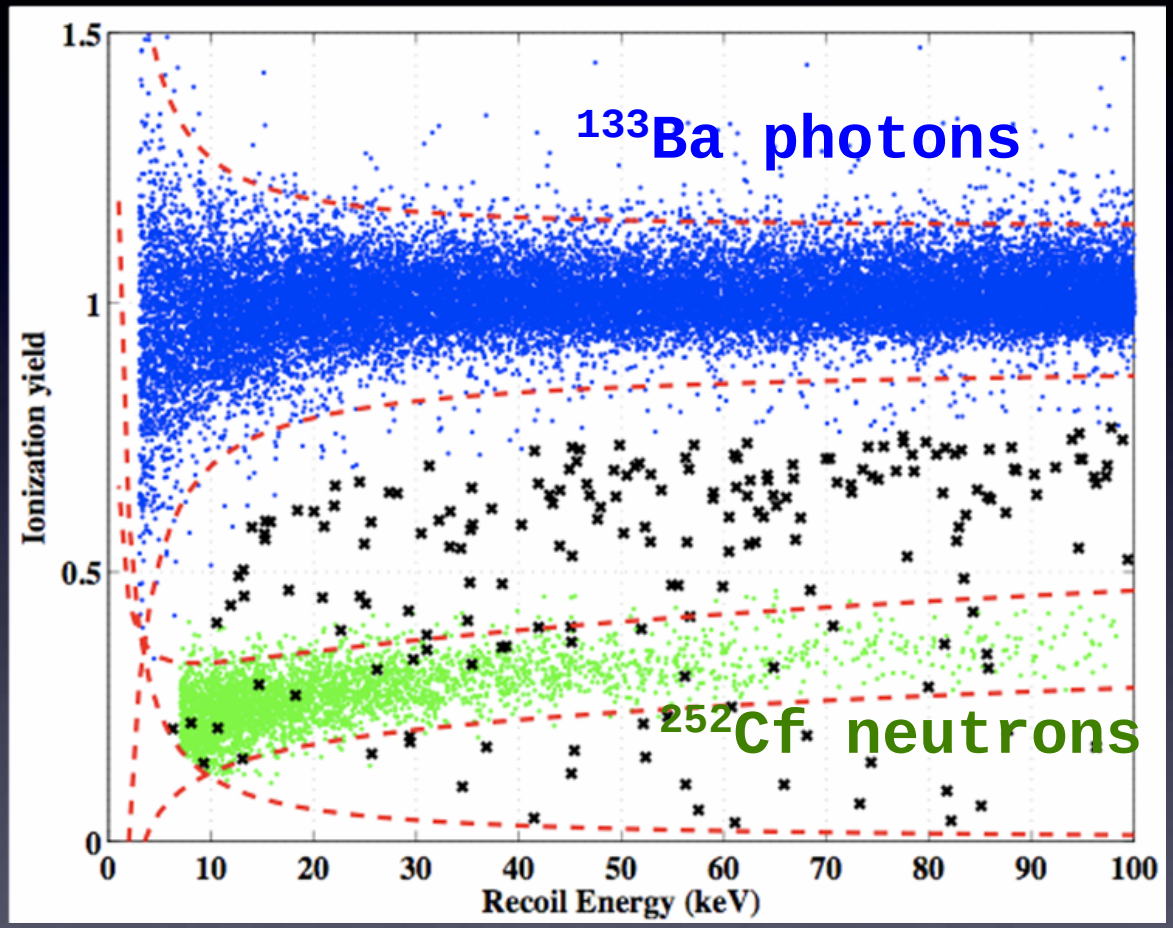
≈

Fast response: ~5 μs risetime

Zero-energy resolution ~**100 eV** in each channel, total **~5%** at higher energies (after position correction)

Yield Discrimination

$$y \equiv \frac{Q}{E_{recoil}}$$

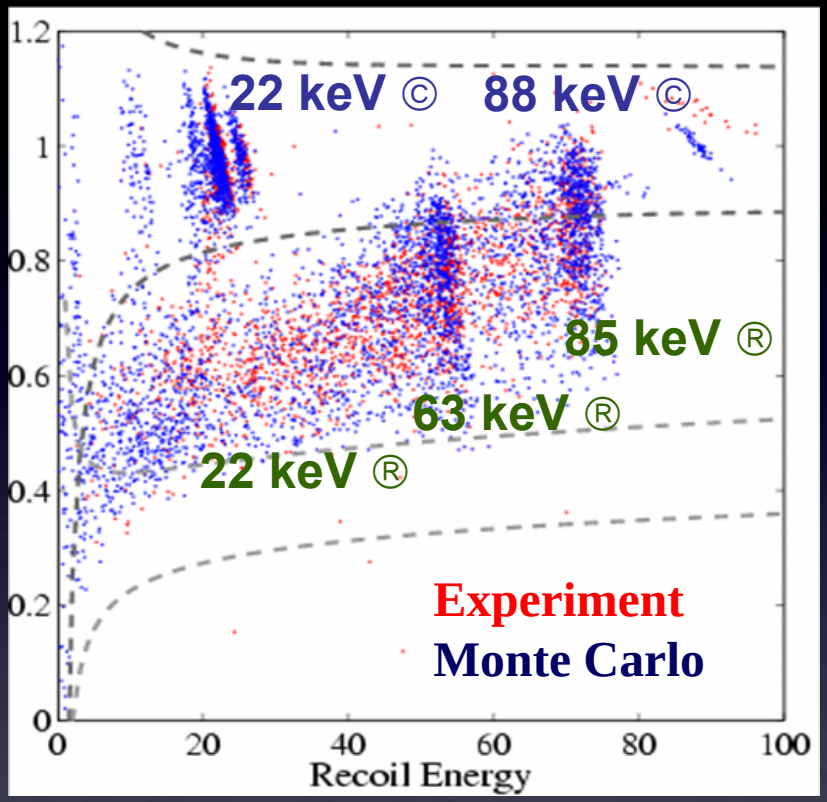


Primary electron recoil rejection **>10,000:1**

Good agreement with Lindhard theory

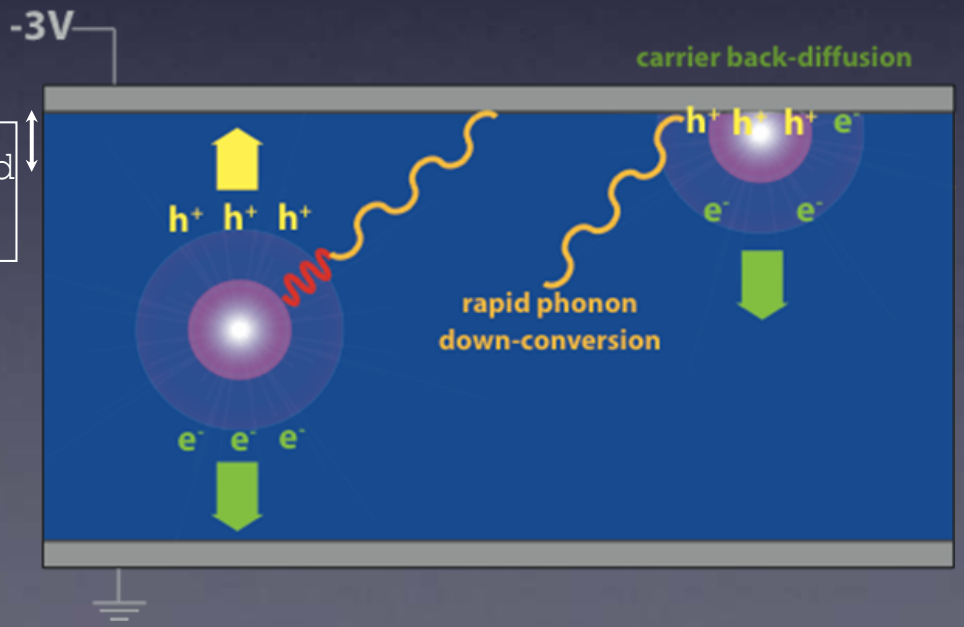
Distinguishable @ ~3 keV

Near-Surface Events



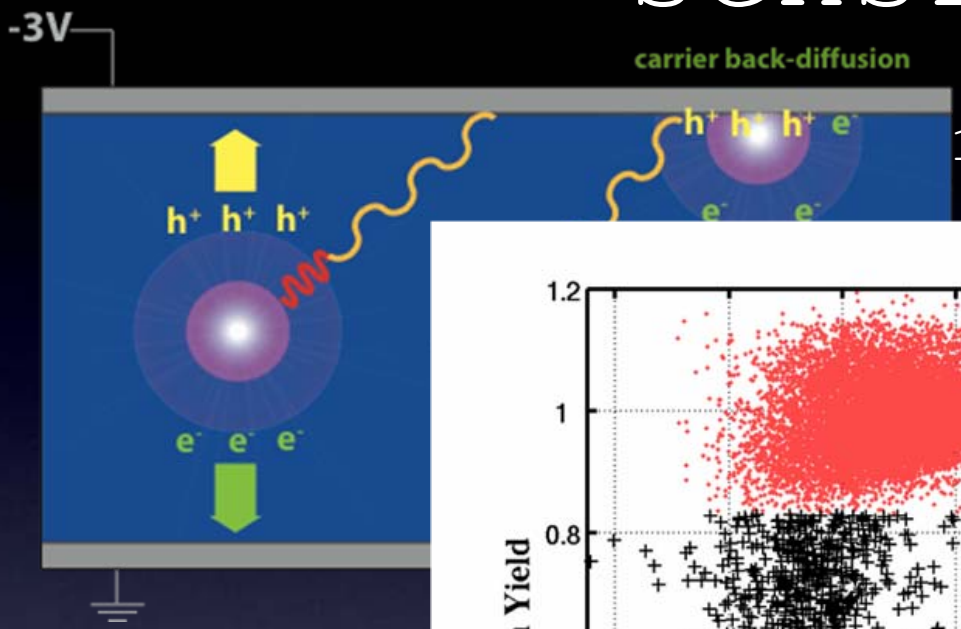
Reduced charge yield from surface events (e.g. K-40, Rn chain) from carrier back-diffusion can mimic signal

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

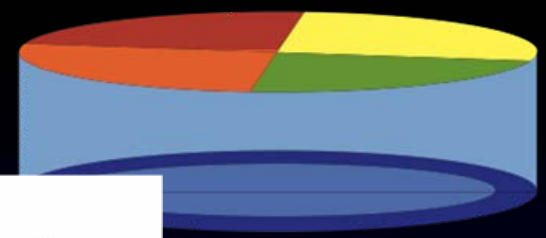


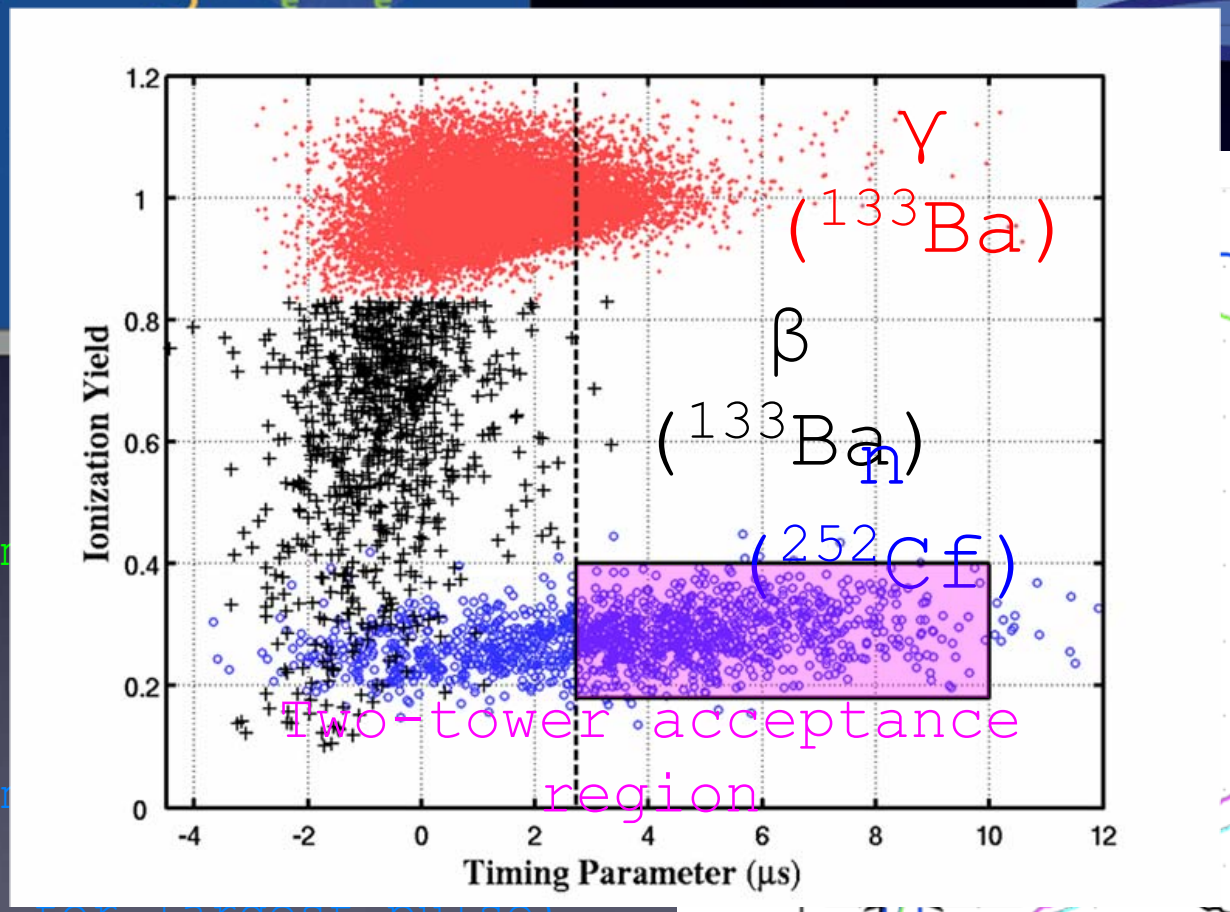
Data from UC Berkeley calibration of ***T2Z5****, née* ***G31***
V. Mandic et al., NIM A ***520****, 171 (2004)*

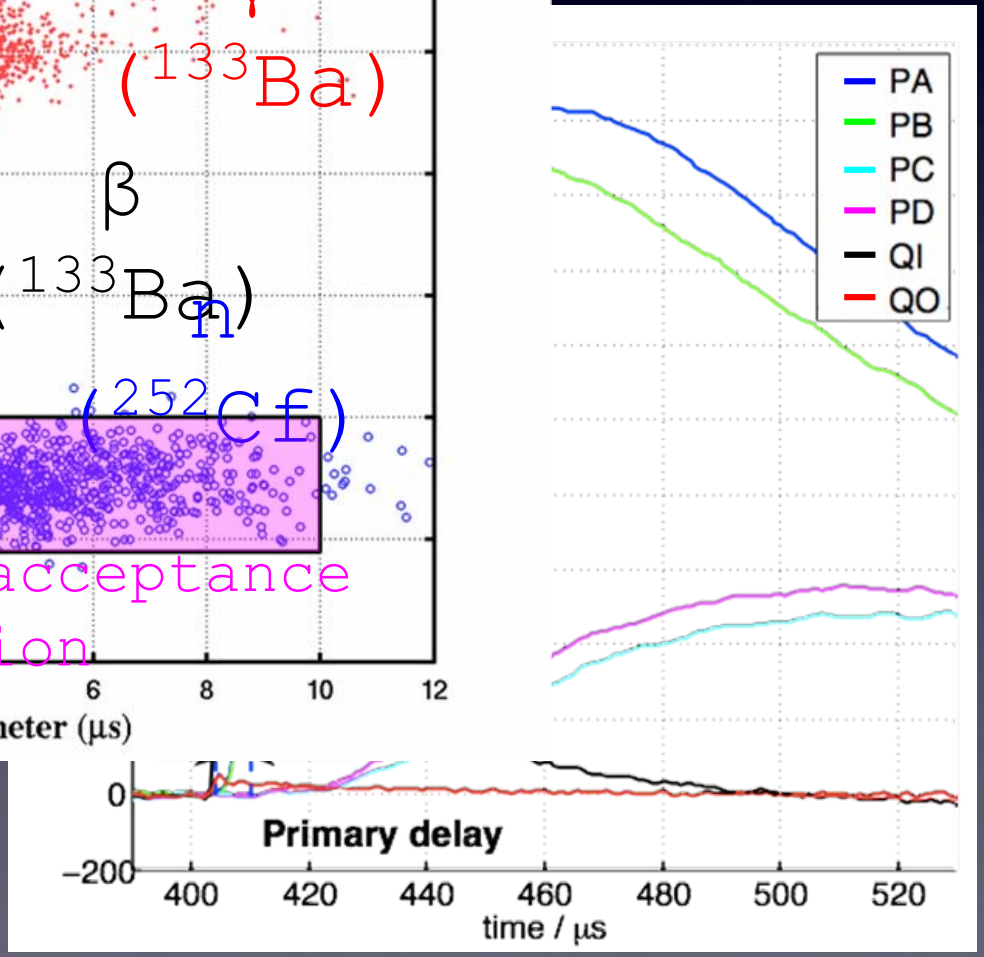
ZIP Detectors: Z-sensitivity



10μm "dead layer"



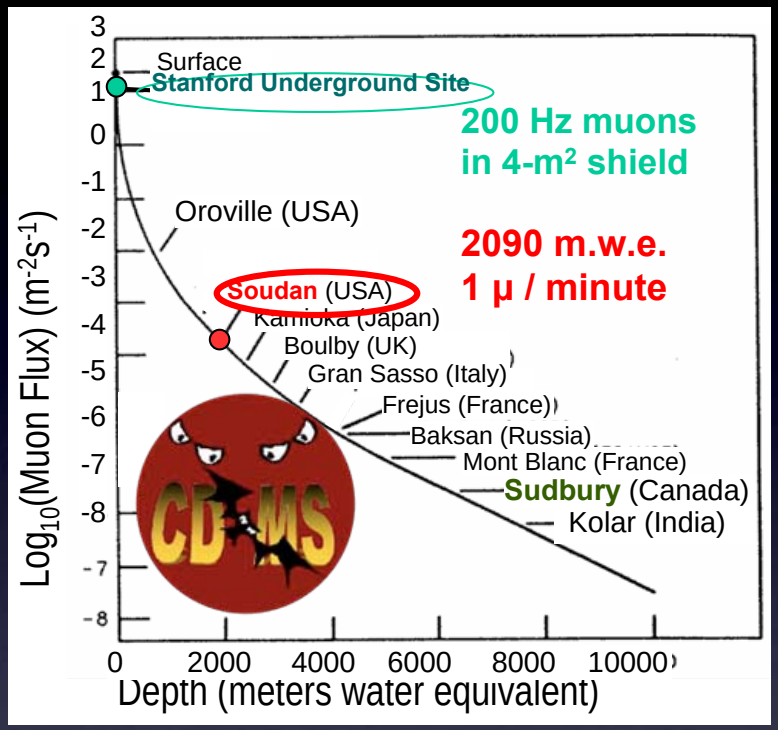




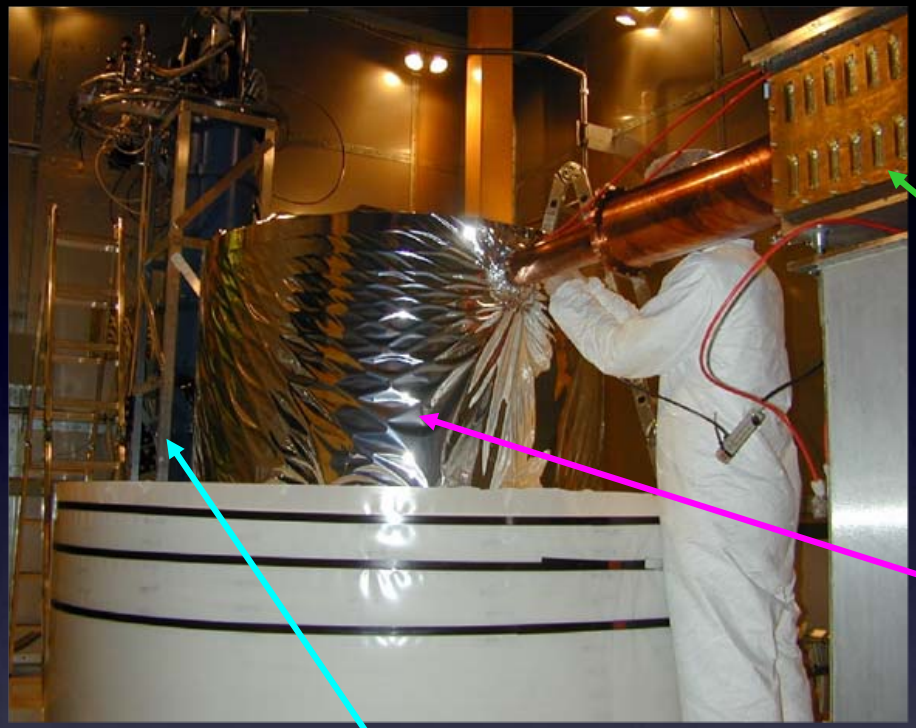
- Primary
  (time fro
  amplitude
- Primary
  (time fro
  amplitude
  amplitude for largest pulse)

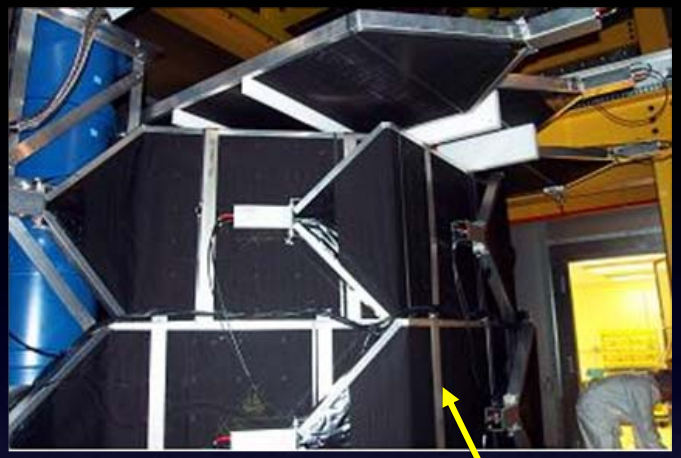
Surface event rejection ***> 100:1***

Soudan Underground Lab



Soudan Installation





vacuum-sealed electronic connector box ("E-box")

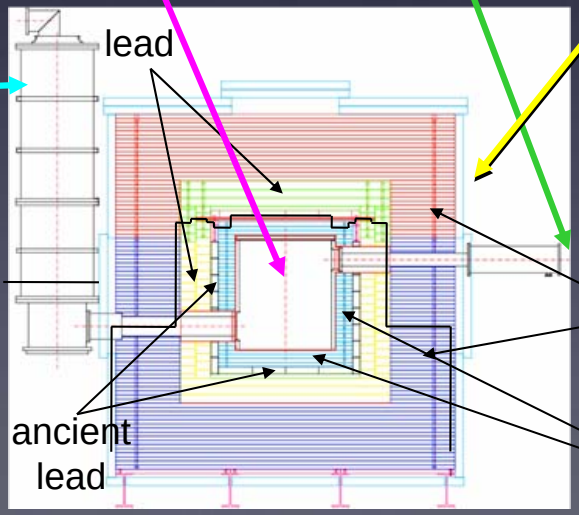
Plastic scintillator

detector cold volume ("icebox")

RF shielded class 10,000 clean room

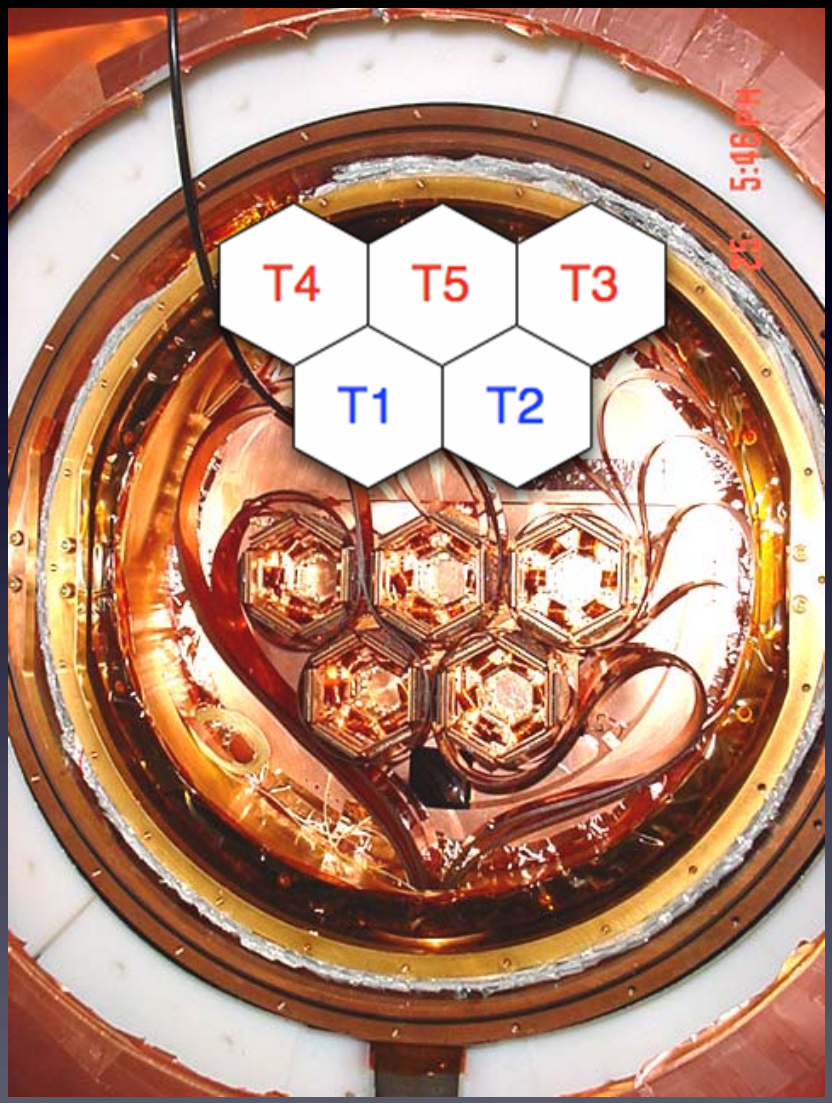
Oxford Instruments 400µW dilution refrigerator

1 m^3 @40 mK!

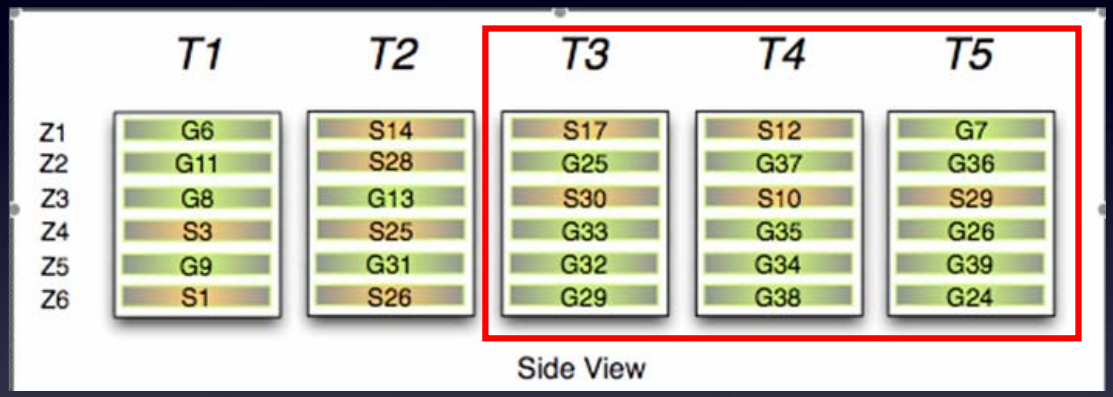


~0.05 unvetoed neutrons per kg-y (Monte Carlo)

Five Tower Runs (2006-8)



30 ZIPs (5 Towers) installed in Soudan icebox: 4.75 kg Ge, 1.1 kg Si



Significant improvements in new detectors:

- Grounded outer grid eliminates low-yield events from **detector-detector crosstalk**
- Somewhat reduced **surface contamination** (vs. T2)
- SHI Gifford-McMahon **cryocooler** for improved LHe hold time

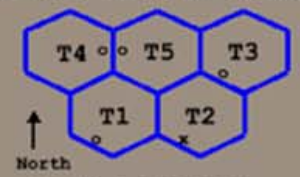
CDMS Event Display [5-Tower]

Fri Nov 2 23:45:38 2007

Per Trigger & WIMP Search

Series Number	=	1711022042
Event Number	=	230095
Time since Levt (ms)	=	16930
Live Time since Levt (ms)	=	16899

Tower & detector wiring



o : Z1 & clockwise

x : Z1 & c-clockwise

Ampl vs [us]

260 -------- Pd
240 -------- Pc
220 -------- Pb
200 -------- Pa

20 -------- Qo
0 -------- Qi

TrigInfo : Q P Q&P RANDOM

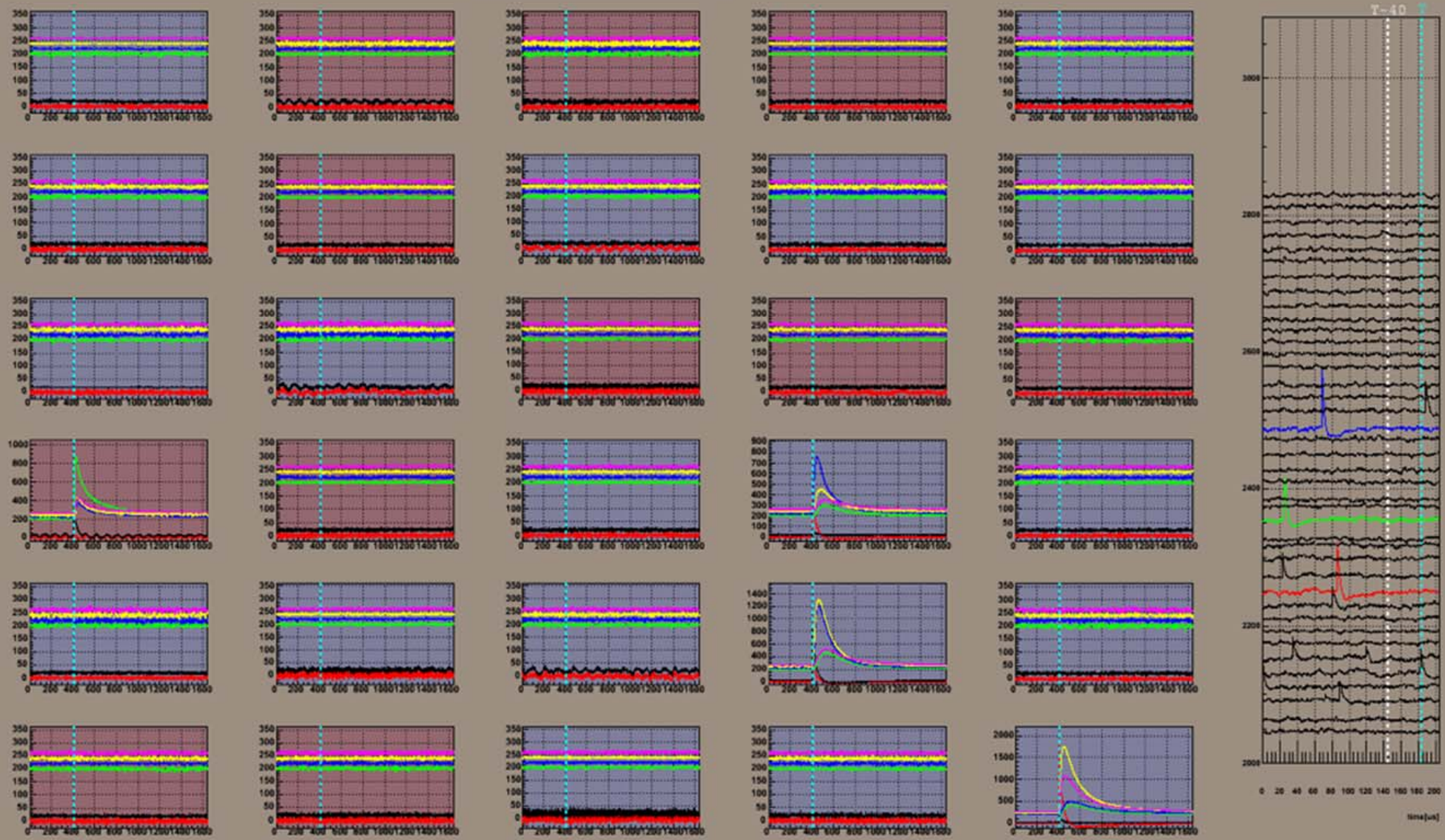
T1G1	T2S1	T3S1	T4S1	T5G1
T1G2	T2S2	T3G2	T4G2	T5G2
T1G3	T2G3	T3S3	T4S3	T5S3
T1S4	T2S4	T3G4	T4G4	T5G4
T1G5	T2G5	T3G5	T4G5	T5G5
T1S6	T2S6	T3G6	T4G6	T5G6

VETO Map (ColCode > 50 VADC)

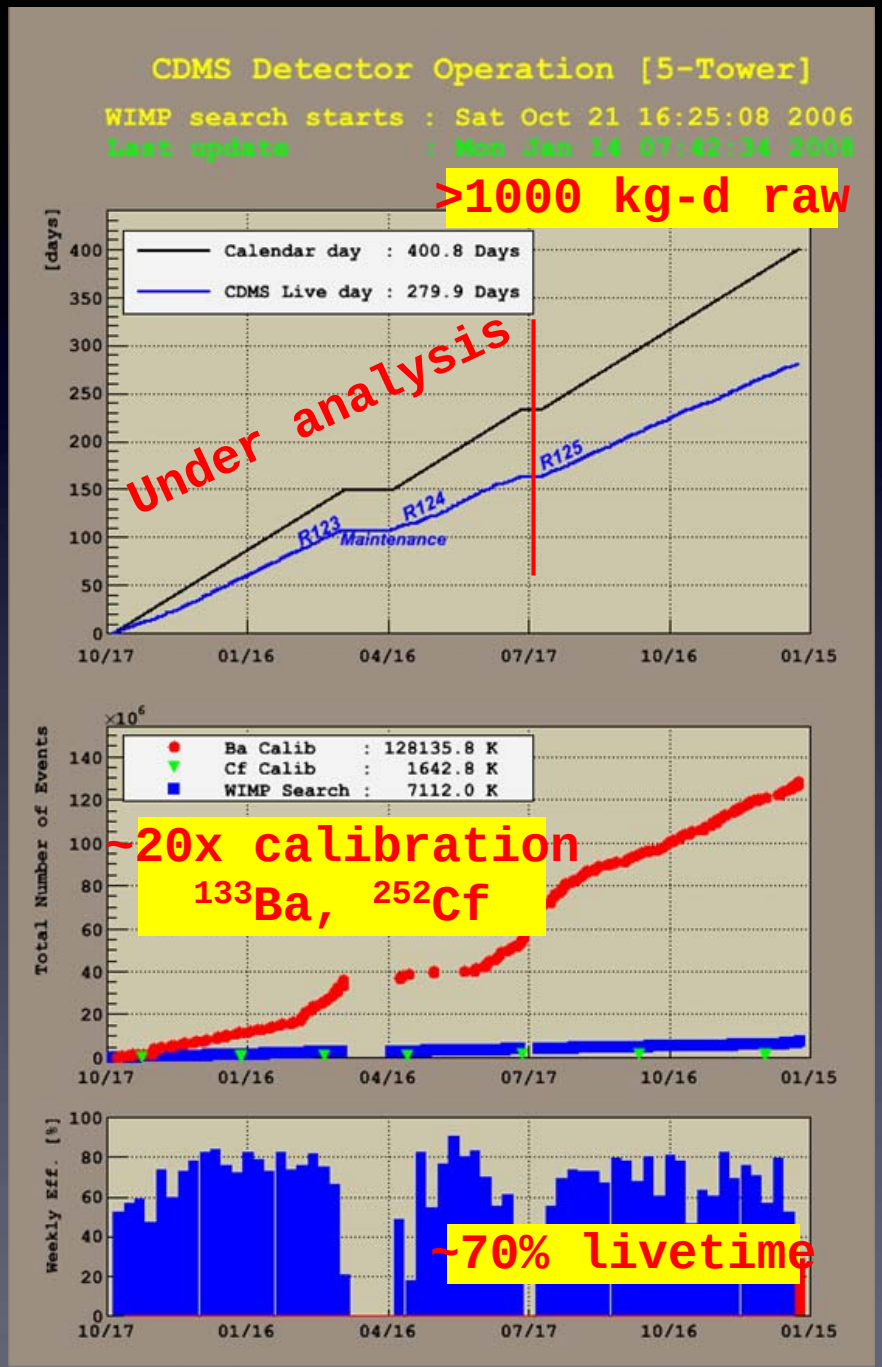
Tne Te Tse
C-stem Tnw Tw Tsw E-stem

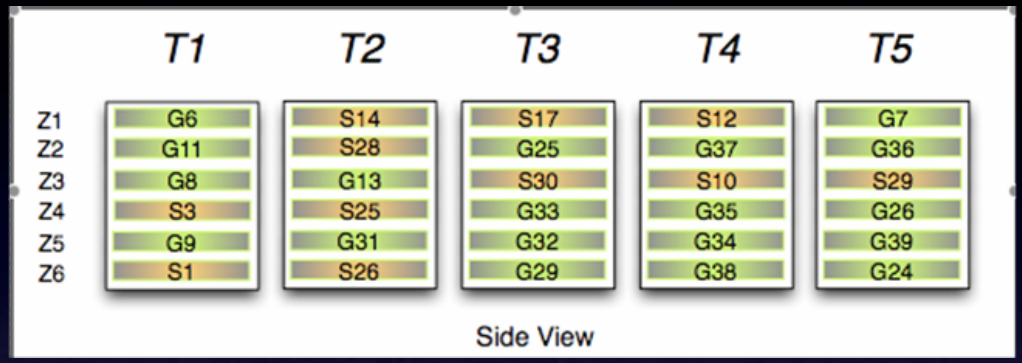
S3e S3n S3nw S3w S3sw S3s S3se
S2e S2ne S2n S2nw S2w S2sw S2s S2se
S1e S1ne S1n S1nw S1w S1sw S1s S1se

Bnw Bw Bsw
Bn Bne Be Bse Bs



Five Tower Status





Four successful data runs so far, first two analyzed (all exposures before cuts):

- Run 123 (21Oct06-21Mar07): **430 kg-d** Ge
- Run 124 (20Apr07-16Jul07): **224 kg-d** Ge
- Run 125 (21Jul07-09Jan08): **465 kg-d** Ge
- Run 126 (17Jan08-date): **ongoing**

>10x the 2-Tower exposure so far!

First 5-Tower Analysis

Blind analysis (2007)

Reduction

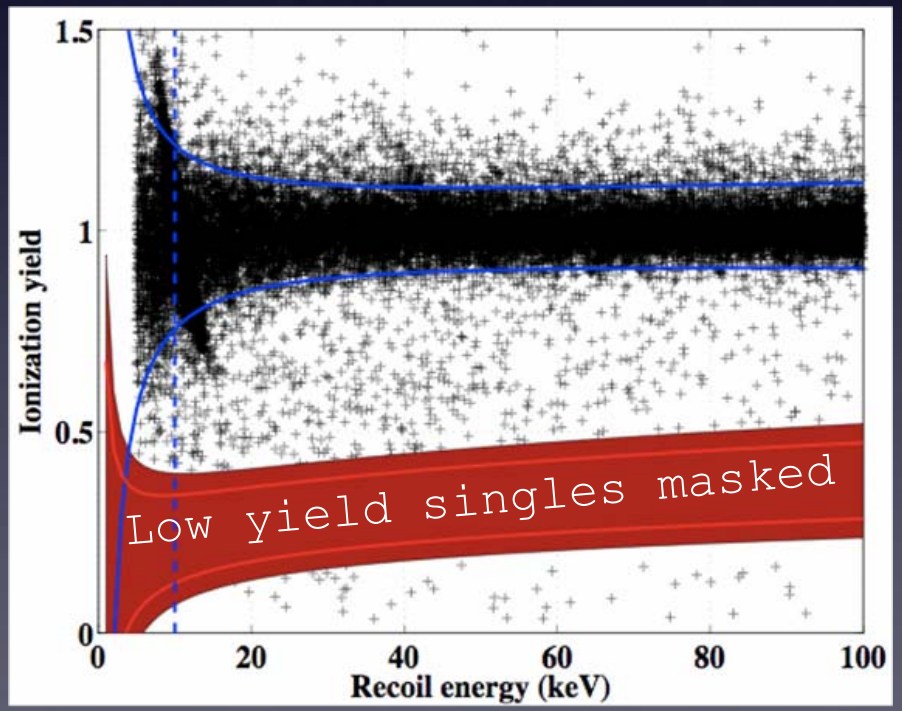
- Data processing
- Position correction
- Calibration

Data quality

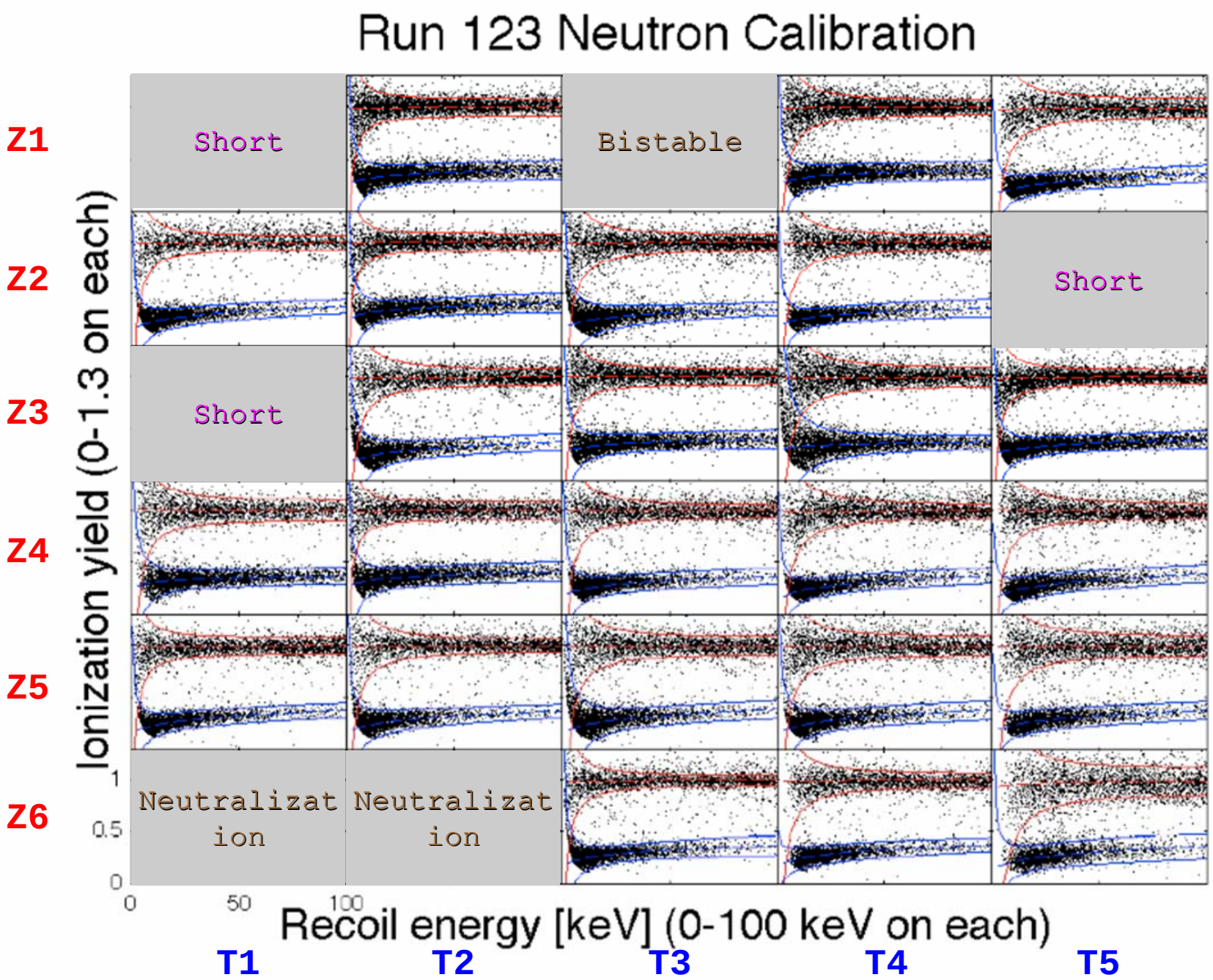
- Data quality cuts
  - Periods of poor noise, neutralization
  - Malformed detector regions
  - Reconstruction failures

Physics

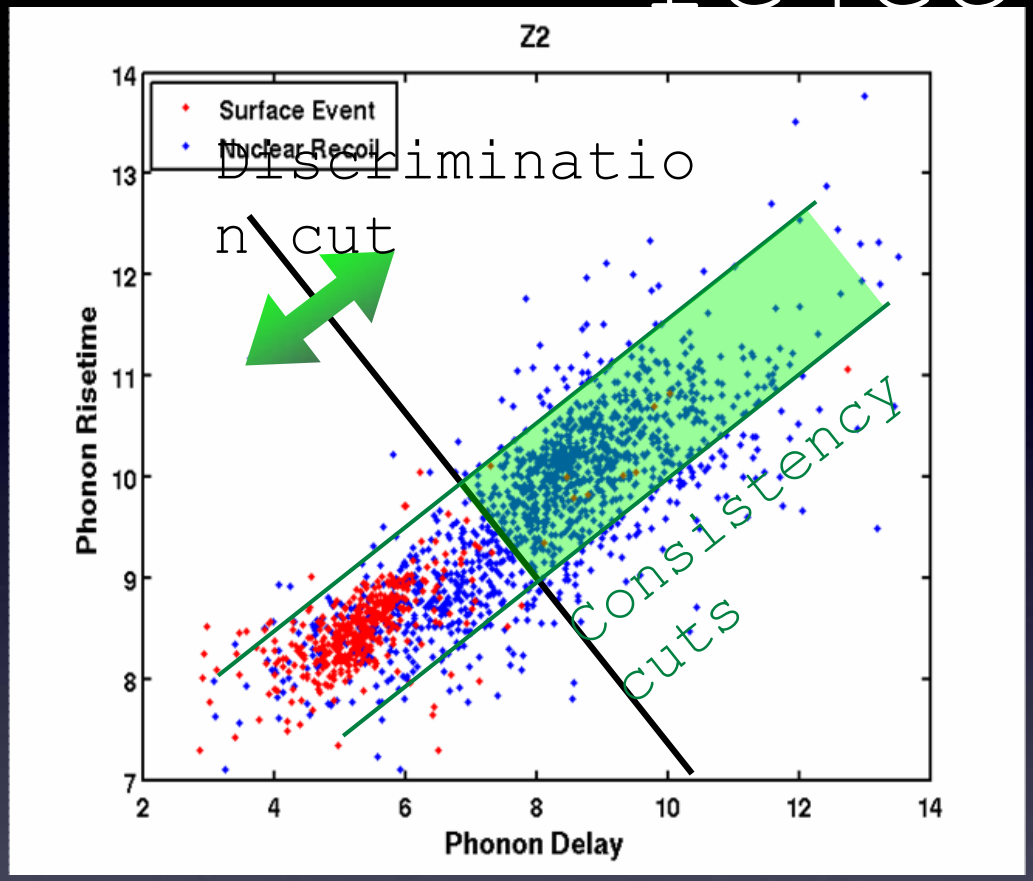
- Veto-anticoincidence cut
- Single-scatter cut
- Q_{inner} (fiducial volume) cut
- Ionization yield cut
- Phonon timing cut

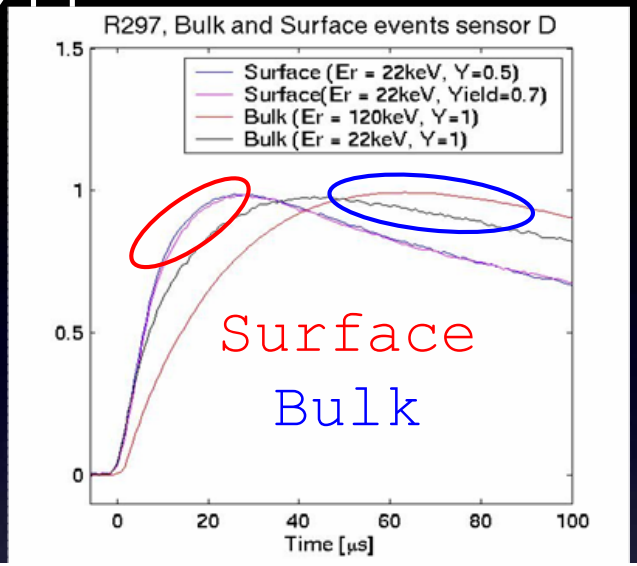


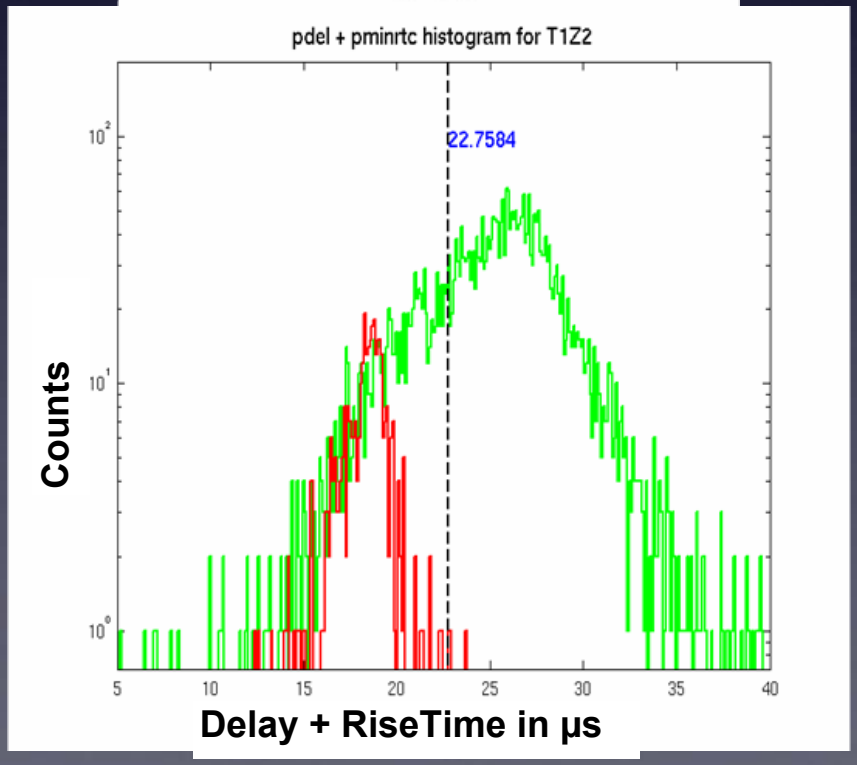
Five Tower Yield Bands



Surface event rejection







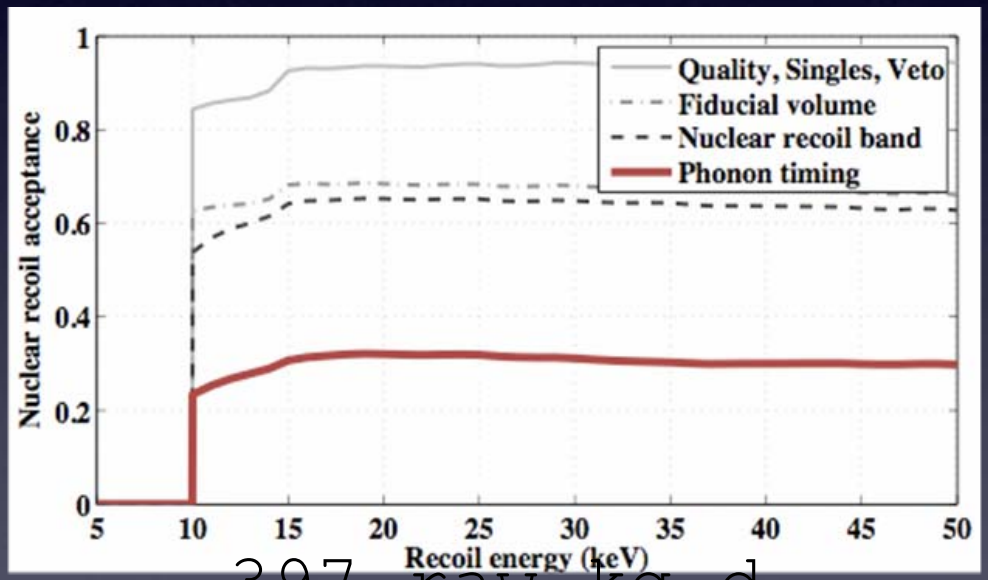
Simple timing cut rejects surface electron recoils ~200:1

Discrimination cut chosen for **~0.5 event** at required exposure

Blind Analysis Summary

Physics

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



397 raw kg-d
121 kg-d WIMP equiv. @ 60 GeV/c^2

Surface background

Leakage computation based on signal region multiple scatters

0.6 ± 0.5 (stat.)

Further estimates with better stats, separate treatment of faces.

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

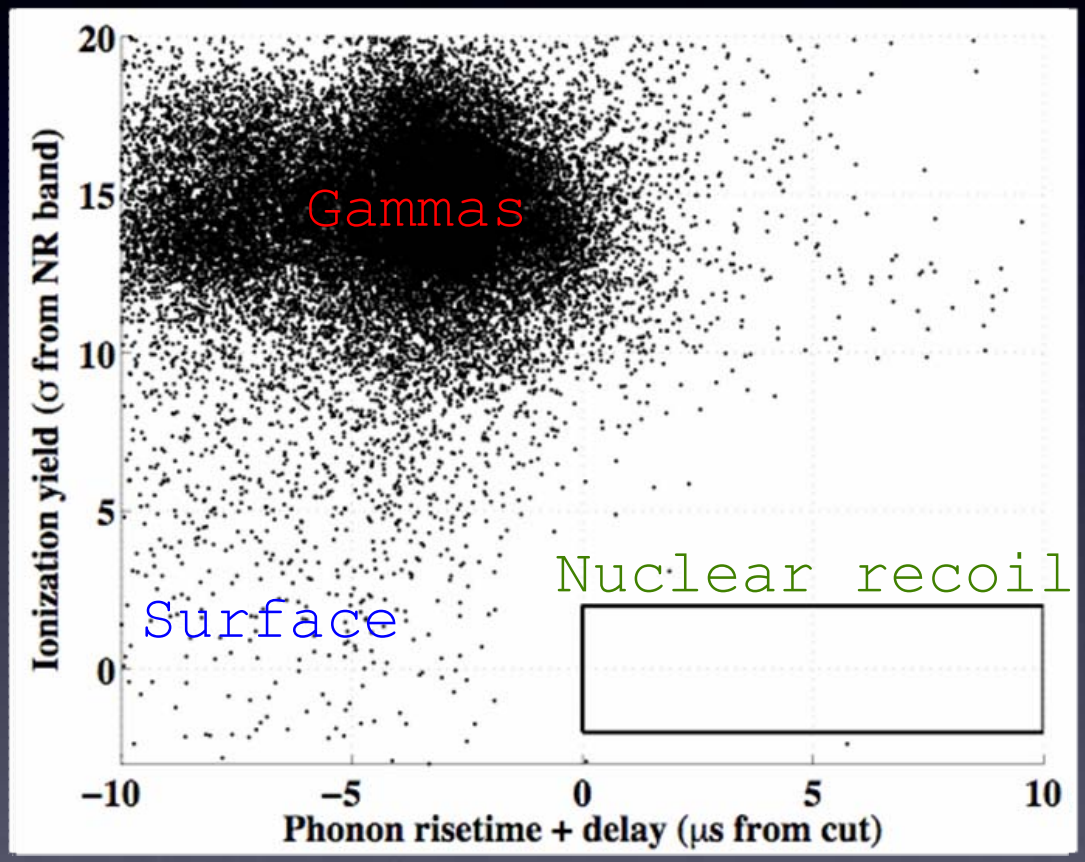
Opening the Box

Box opened **Monday, February 4** for **15 Ge ZIPs**
Remaining 8 Si and 1 Ge undergoing further leakage characterization

3σ region masked => Hide unvetoed singles

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

Apply the timing cut, count the candidates



No events observed

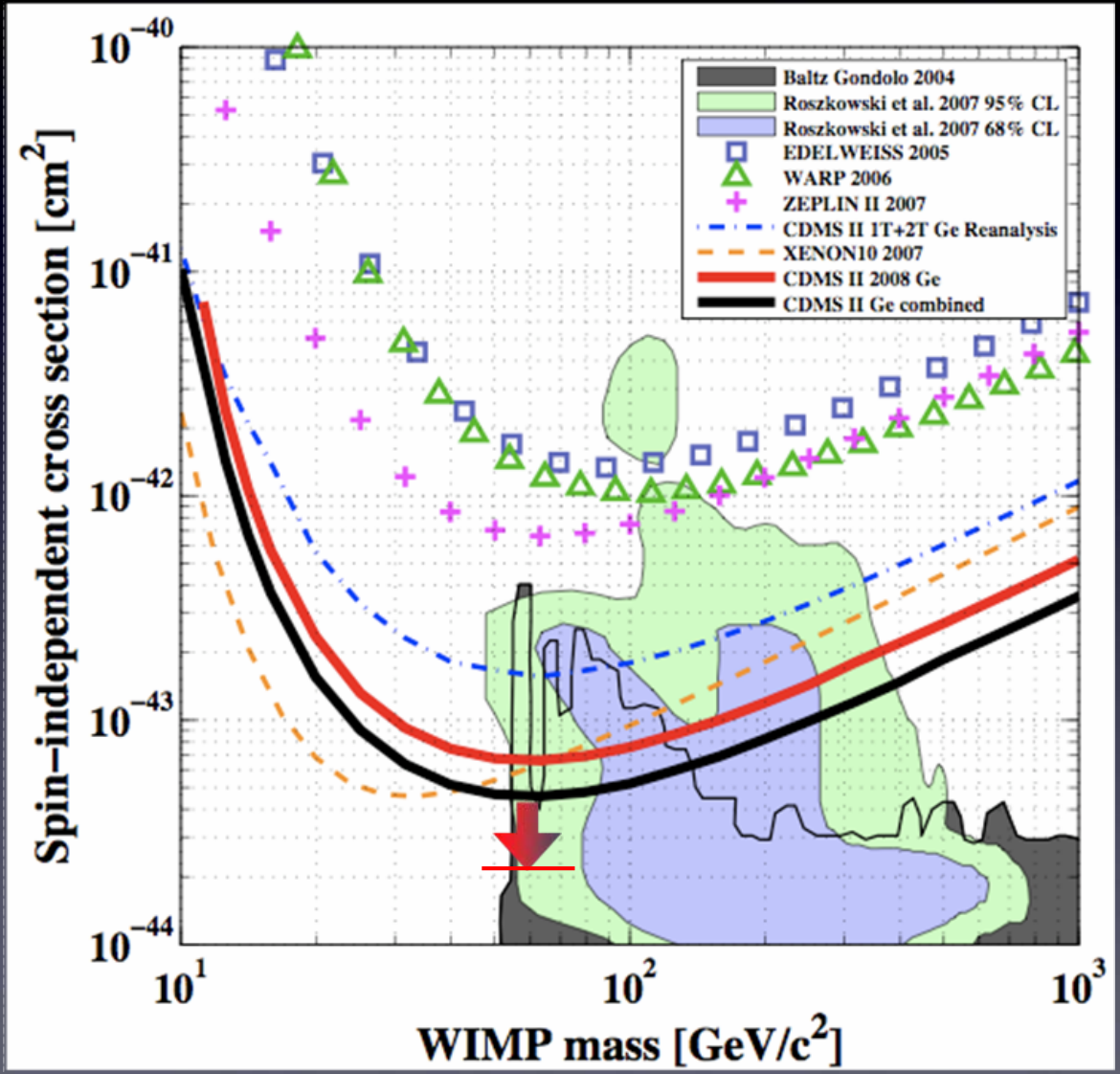
Current WIMP Limits

Strongest SI limits above ~$M_Z/2$

>2x data in hand, run continues!

Ongoing detector characterization and

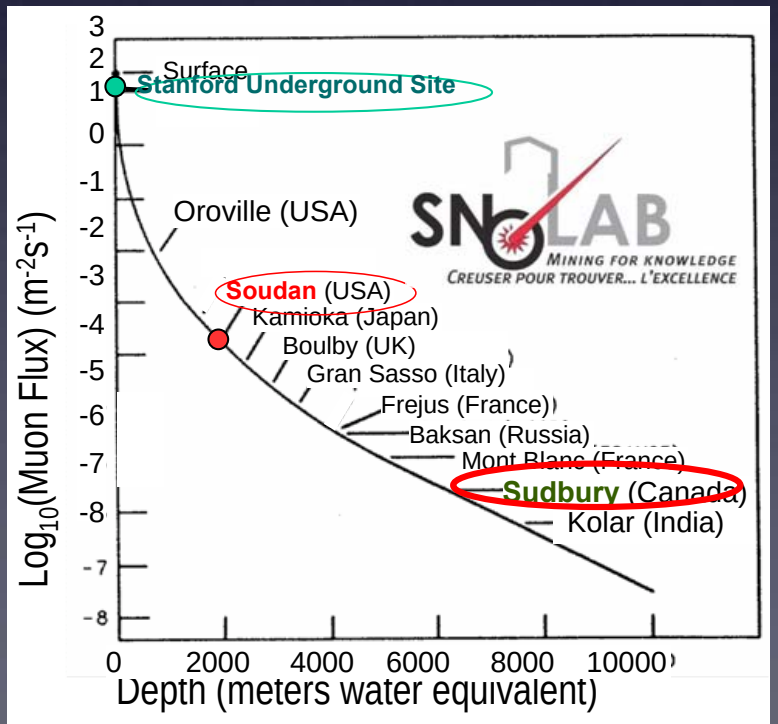
Preprint at:
- http://cdms.berkeley.edu
- arXiv:0802.3530

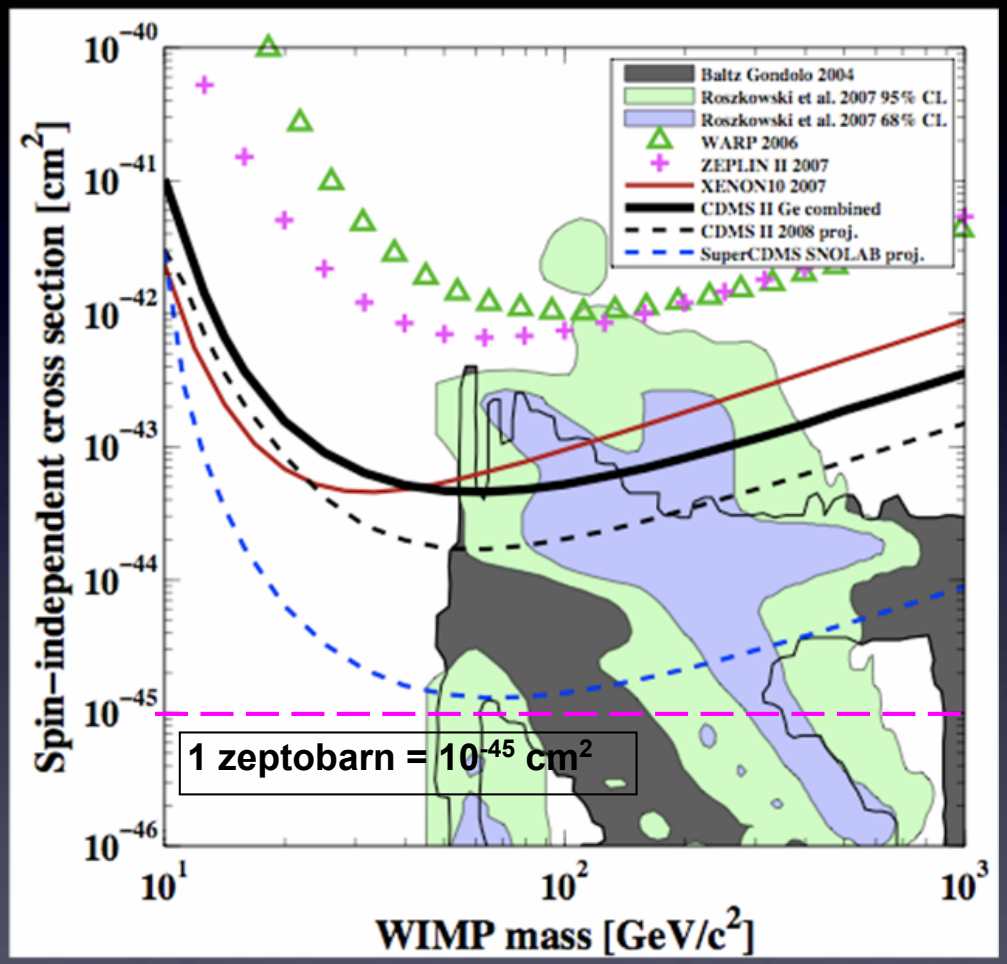


What's Next?: SuperCDMS

25 kg experiment to explore the zeptobarn scale, funded by NSF/DOE to run two SuperTowers at Soudan, then move to **SNOLAB**

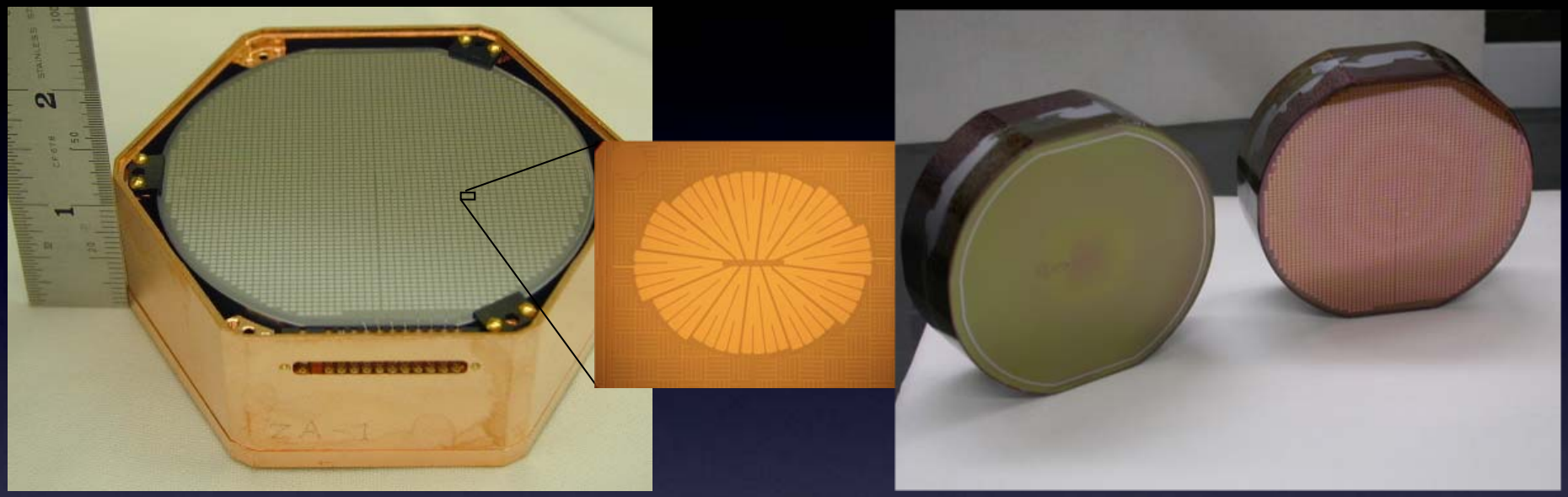
- **7 SuperTowers** of thick Ge ZIPs
- Improved surface handling
- Improved analysis (some already in hand!)
- Improved detector performance





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

SuperCDMS ZIPs

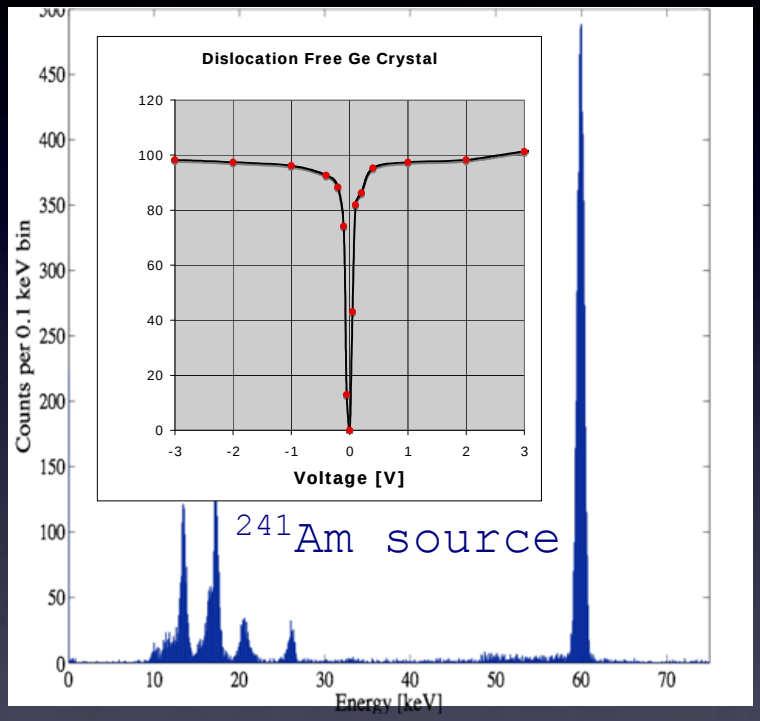


- 2.5x detector mass (7.6 cm x **2.54 cm**, 600g)
  => *better volume/surface, faster manufacture*
- Single mask lithography
  => *more reliable manufacture, less testing time*
- Improved active Al coverage
  => *better "antennas" for phonon collection*

Also in development: new sensor configurations, double sided phonon sensors, electric field shaping, dislocation-free substrates, kinetic inductance technology, ...

Paths to Large Crystals

Dislocation-Free Ge
(Berkeley - Feb. 2008)



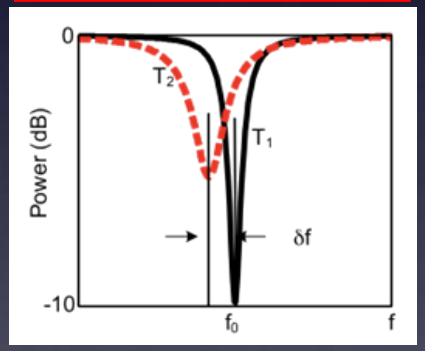
- 3cm x 1cm sample of H-grown dislocation-free Ge (E.E. Haller)
- Unusable @77K, but excellent charge collection at <100mK
- *Available in >6" diameters (standard detector grade Ge limited to 3-4")*

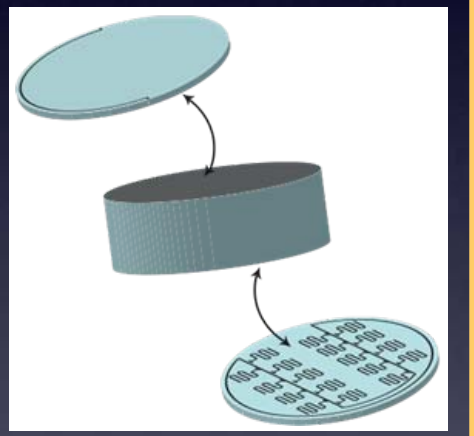
Kinetic Inductance
(Berkeley/Caltech - ongoing)

- Promising tests of kinetic inductance detectors (KIDs) for large phonon readout
- Frequency-domain multiplexing, ease of manufacture

•Superconductor:

$L = L_m + L_{ki}(n_{qp})$





3"x1cm: 250g (CDMS II)

6"x2": 5kg?

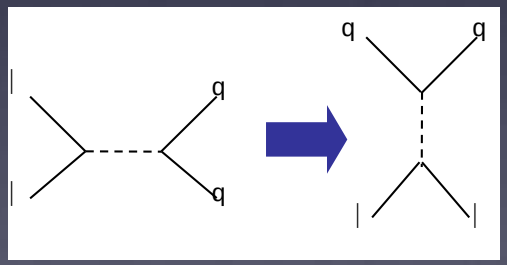
WIMPs at a Zeptobarn

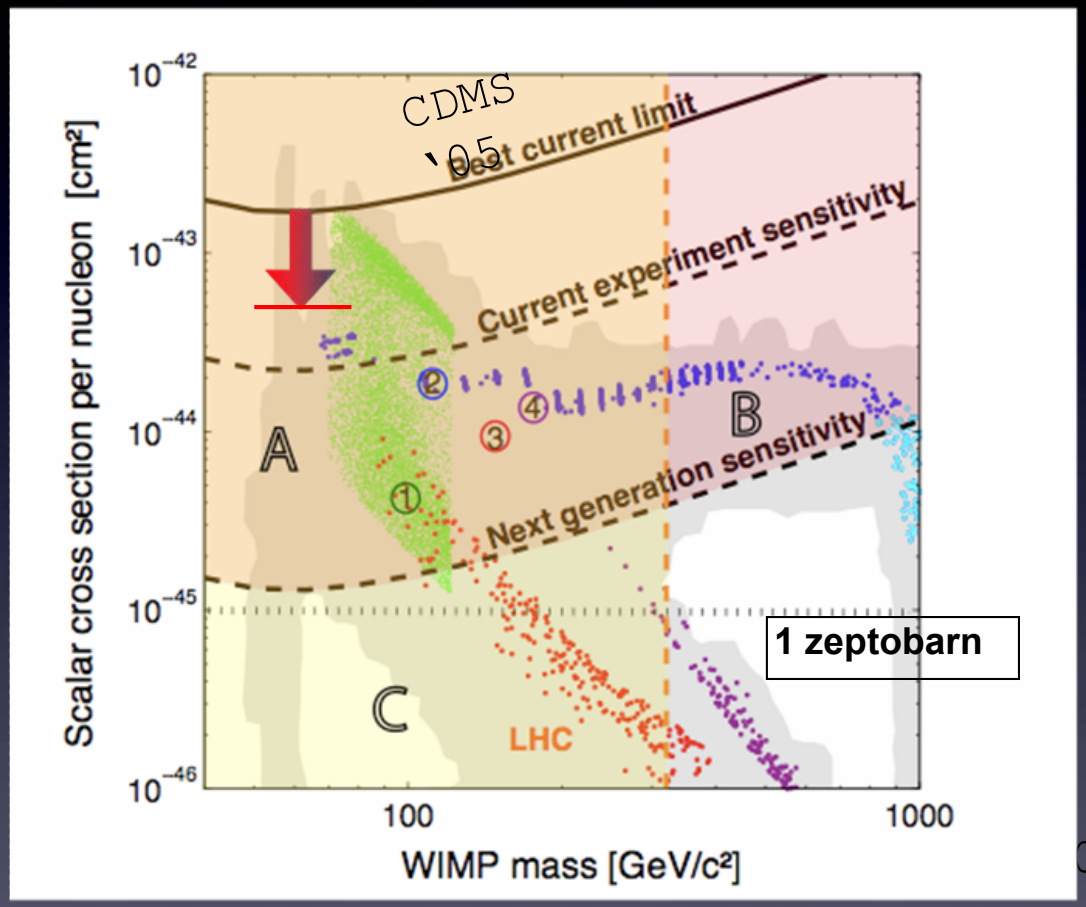
- Natural weak scale from light SUSY
- G-2 favored, FCNC

Focus point

- Natural weak scale from RGE focusing
- Decoupled scalars => low FCNCs

Crossing symmetry!





Higgs funnel

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

Coannihilation Tail

- Near-degeneracy between LSP and NLSP

"Spectral coincidences"

B. Sadoulet, *Science* 315, p. 61 (2007)

Plot: JF; CMSSM scans with DarkSUSY 4.1

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

WIMP Complementarity

Are WIMP scattering and annihilation related?

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

Are the main WIMP annihilation processes active today?

Conclusions

- CDMS has maintained "zero background" operation down to 4.6×10^{-44} cm^2 (46 zeptobarn)
  (preprint at arXiv:0802.3530)
- The 5-Tower run of CDMS II is ongoing, pushing to 10^{-44} cm^2 (10 zeptobarn)
- SuperCDMS under development for background-free operation at the zeptobarn scale
- The next few years will be an exciting time for WIMP dark matter!