RECOILING AGAINST THE DARK UNIVERSE: CDMS and the Hunt for Dark Matter

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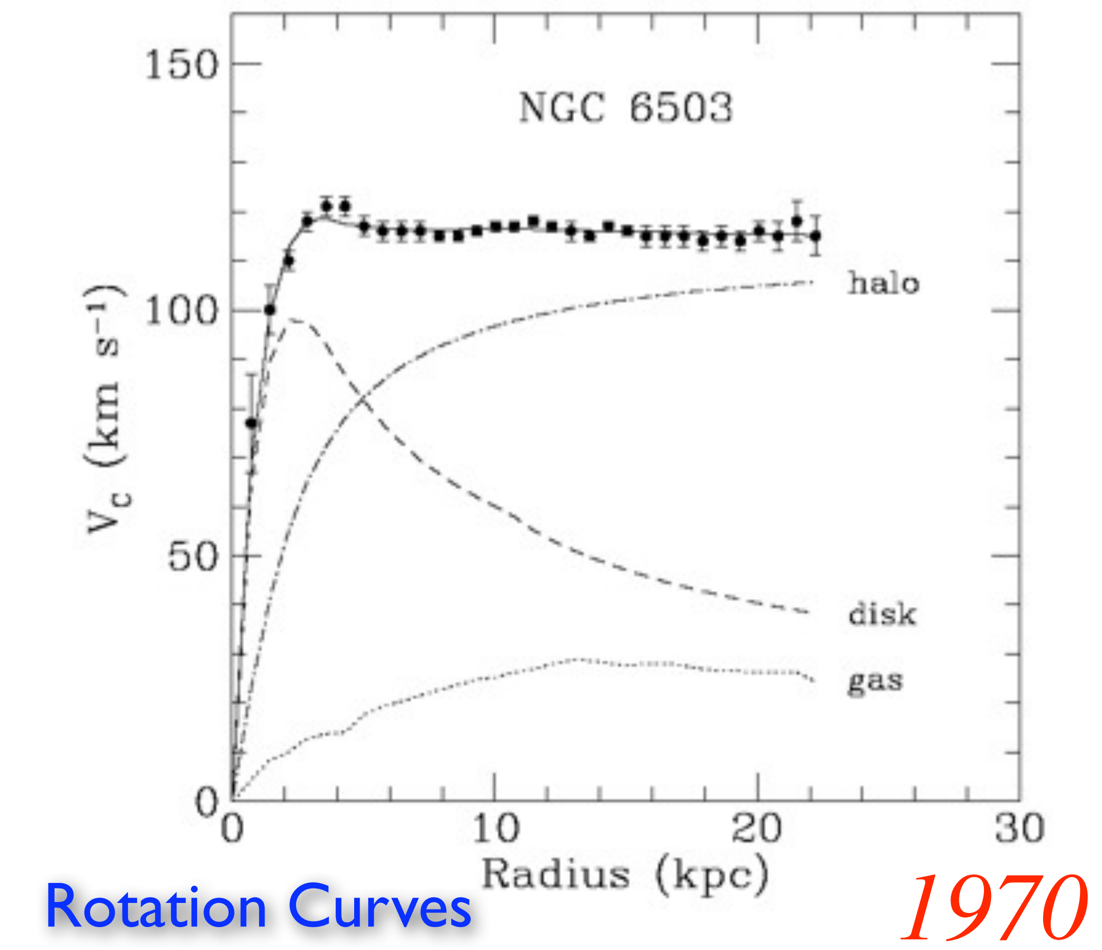
CDMS Analysis Coordinator

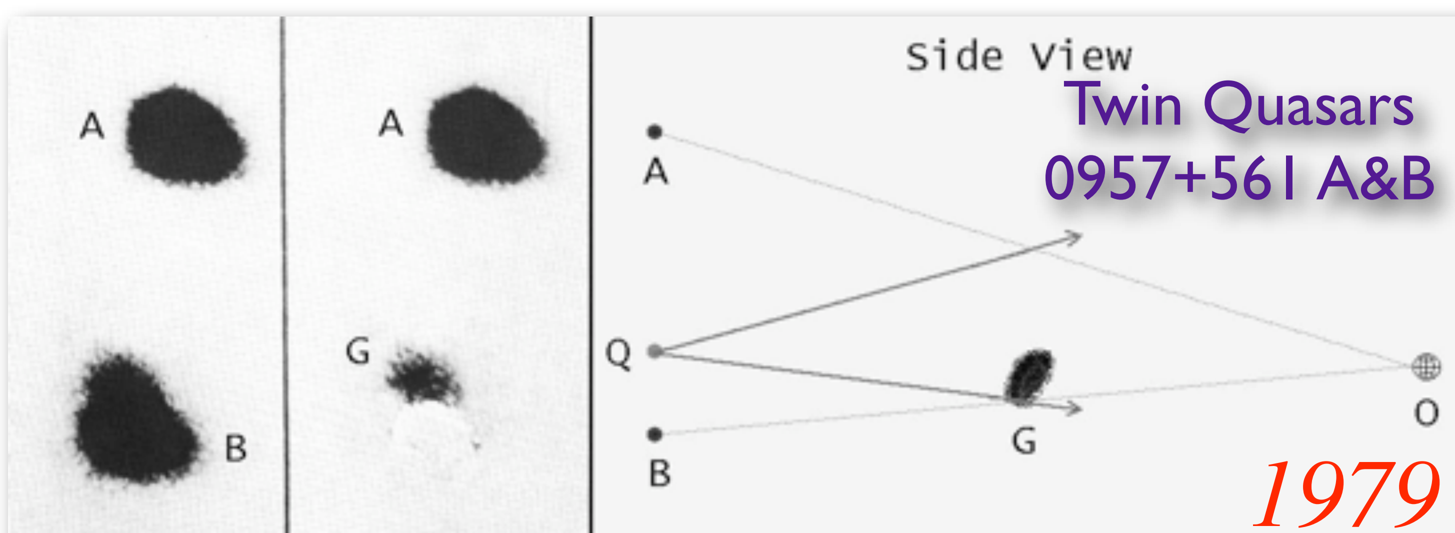
Overview

- What we know and what we don’t know about dark matter
- CDMS-II experiment
  - detection principle
  - results from 5 - tower run
  - current status
- The future
  - SuperCDMS
  - backgrounds

Introduction to Dark Matter

The Evidence for Dark Matter





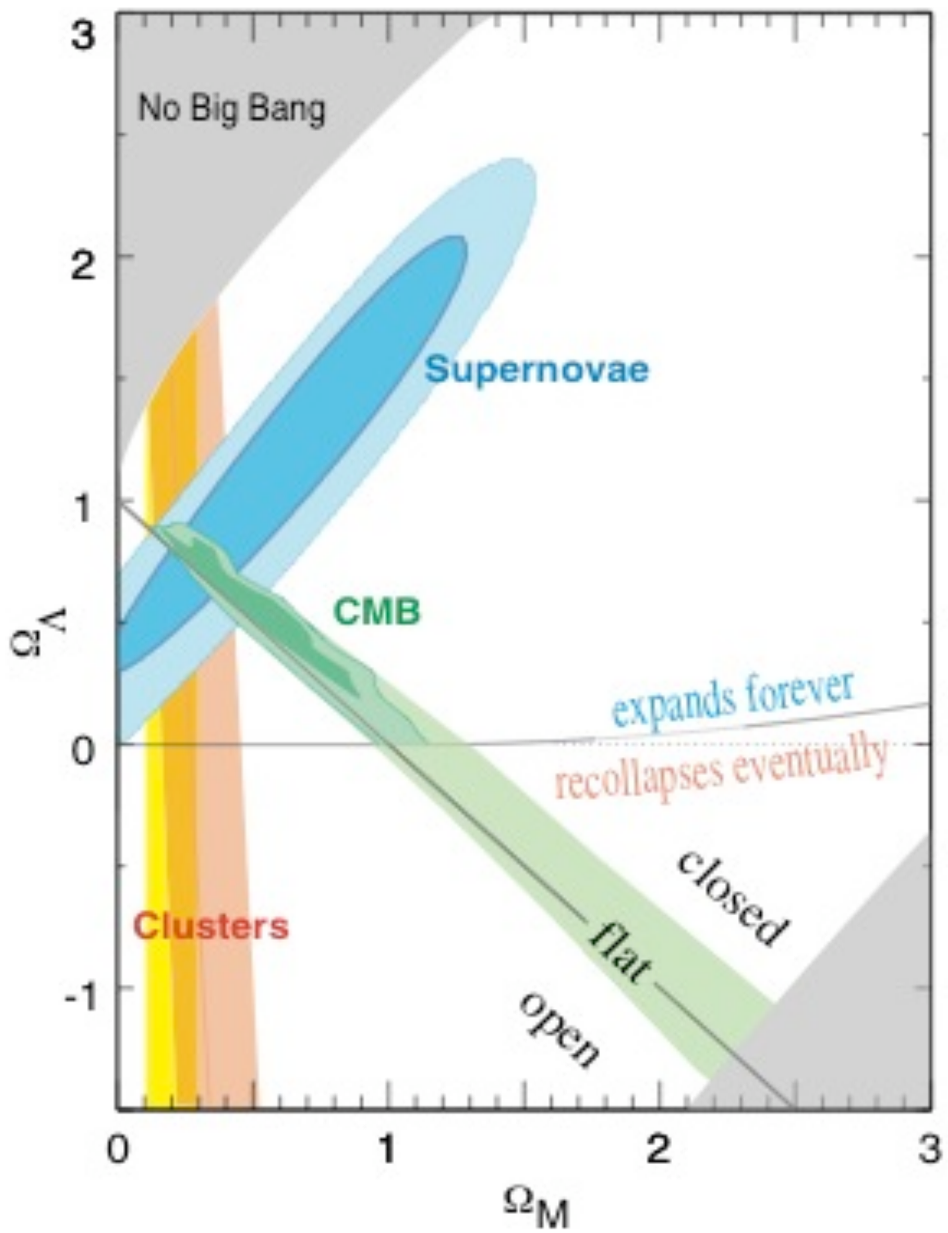
The Bullet Cluster

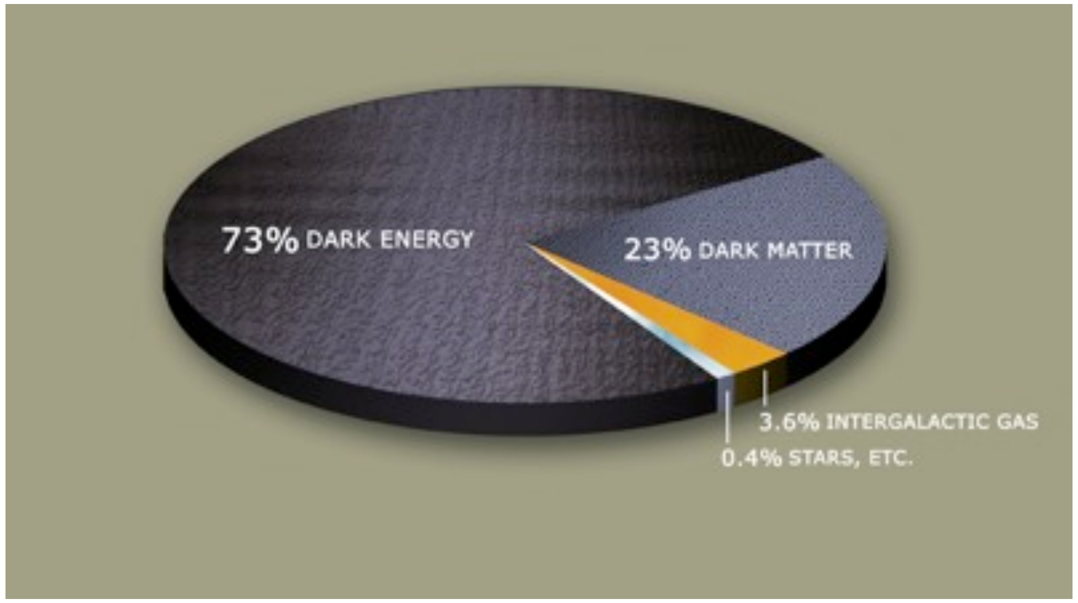
- Observations of the **Bullet Cluster** in the **optical** and **x-ray** fields combined with **gravitational lensing** provide compelling evidence that the dark matter is particles.
- Gravitational lensing tells us mass location
  - **No dark matter = lensing strongest near gas**
  - **Dark matter = lensing strongest near stars**

Clowe et al., ApJ, 648, 109

blue = lensing
red = x-rays

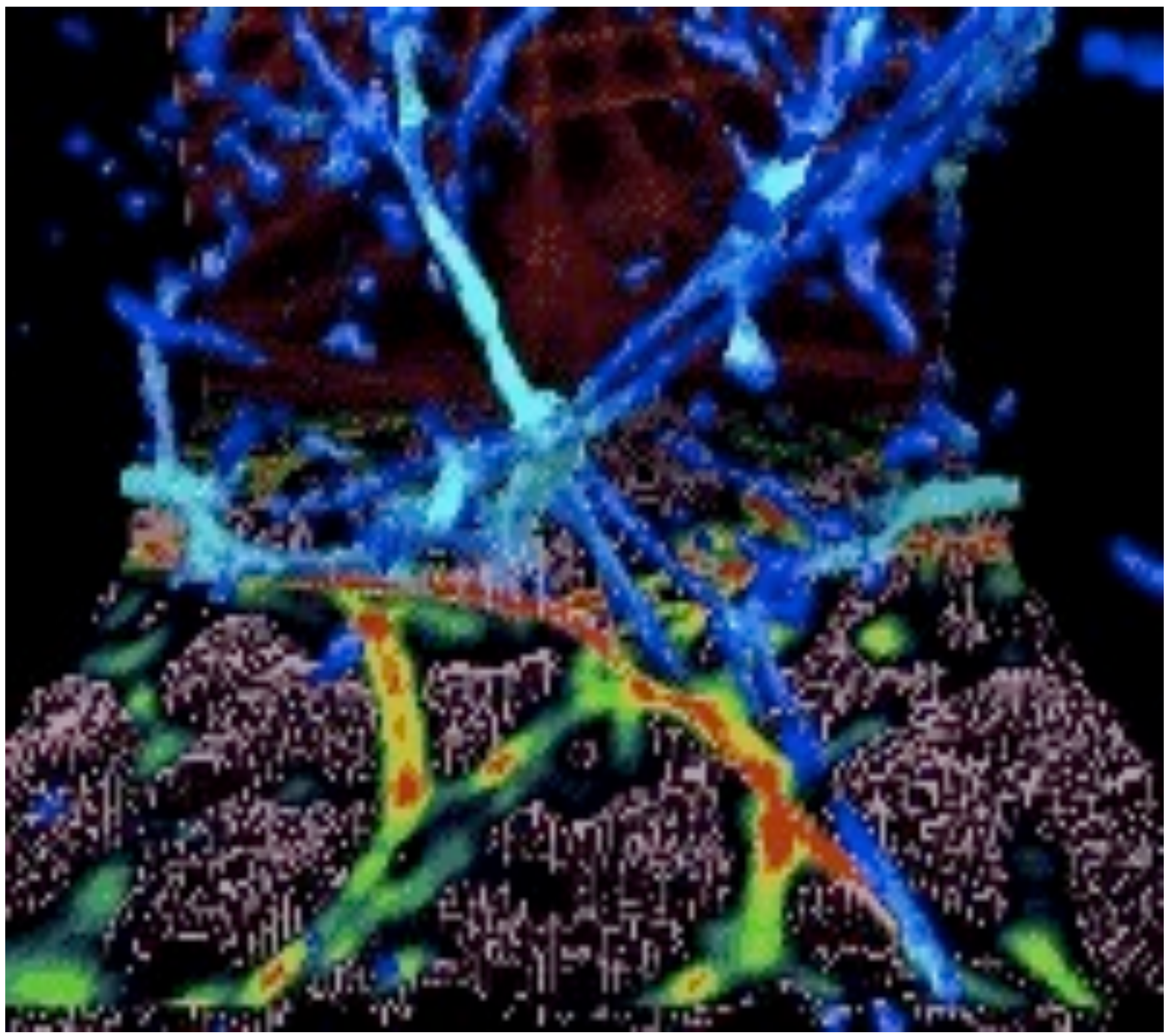
The Cosmic Pie





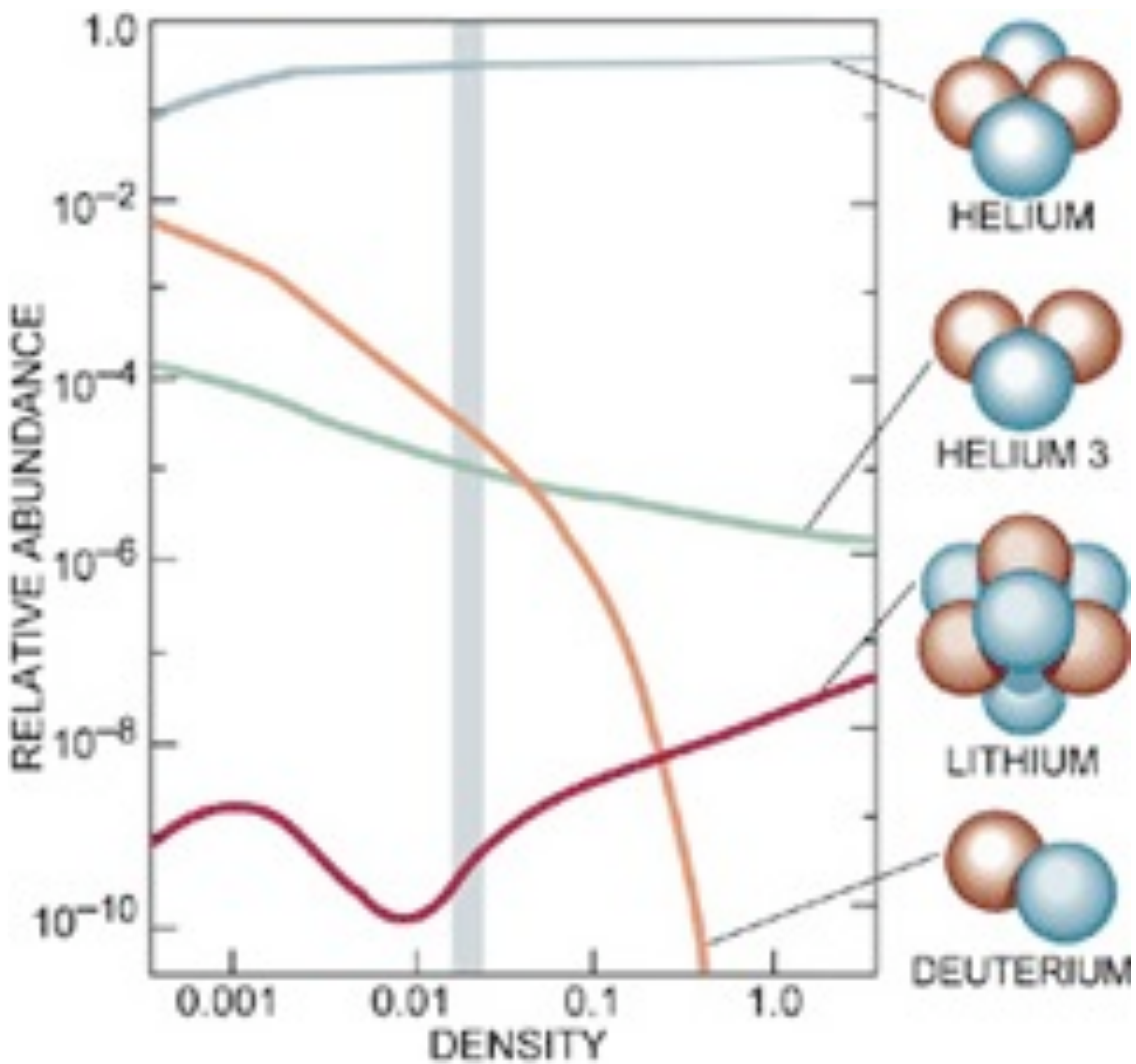
- Measurements from CMB + supernovae + LSS indicate that **~23% of our Universe is composed of dark matter**.

What Could Dark Matter Be?



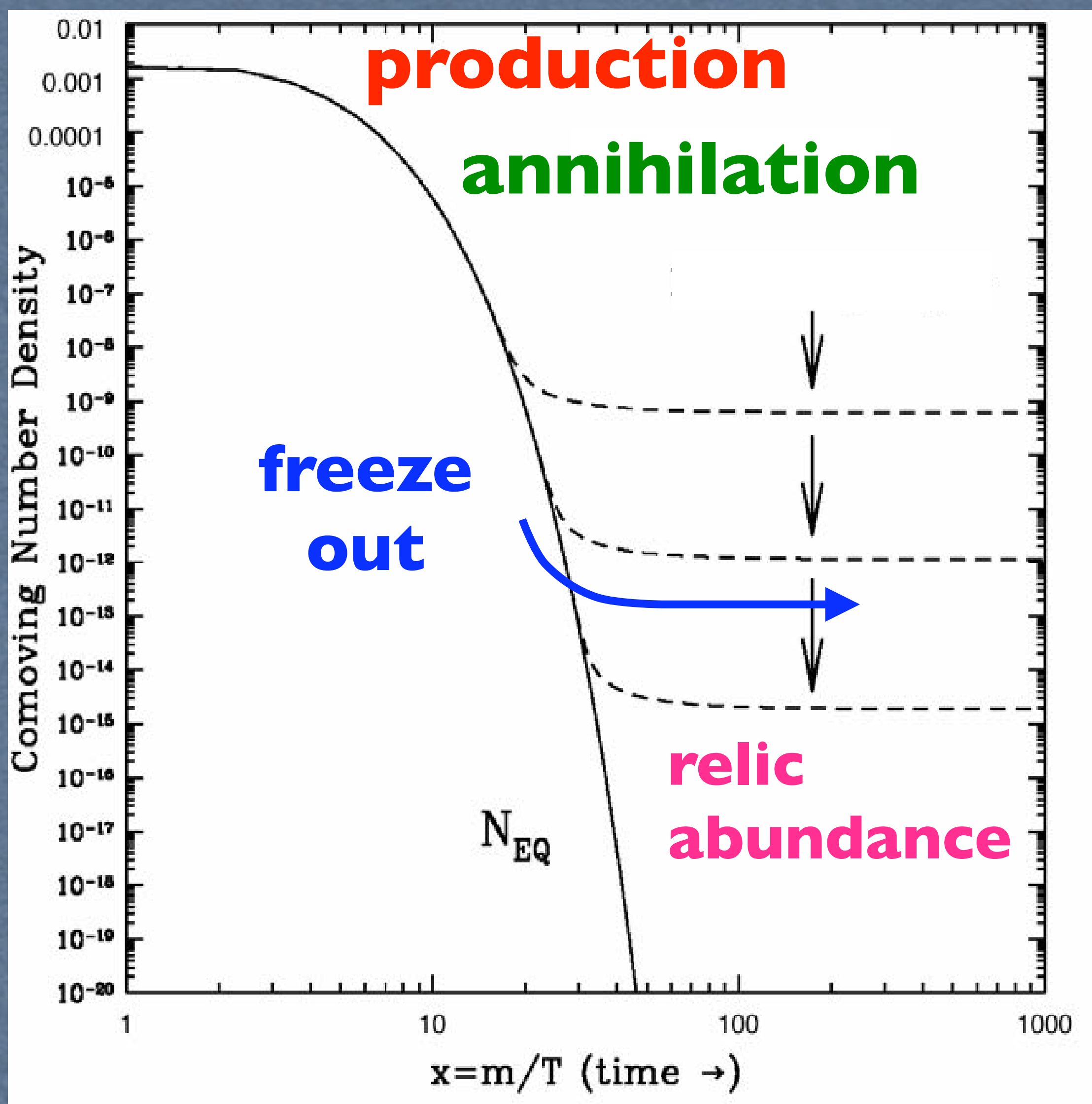
- Warm or **Cold**?
  - ordinary νs can not make up LSS of universe

What Could Dark Matter Be?



- Warm or **Cold**?
  - ordinary νs can not make up LSS of universe
- Baryonic or **Non-Baryonic**?
  - to avoid skewing formation of light elements in BBN

A Candidate is Born!



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27}}{< \sigma_\chi v >}$$

Weakly Interacting Massive Particles

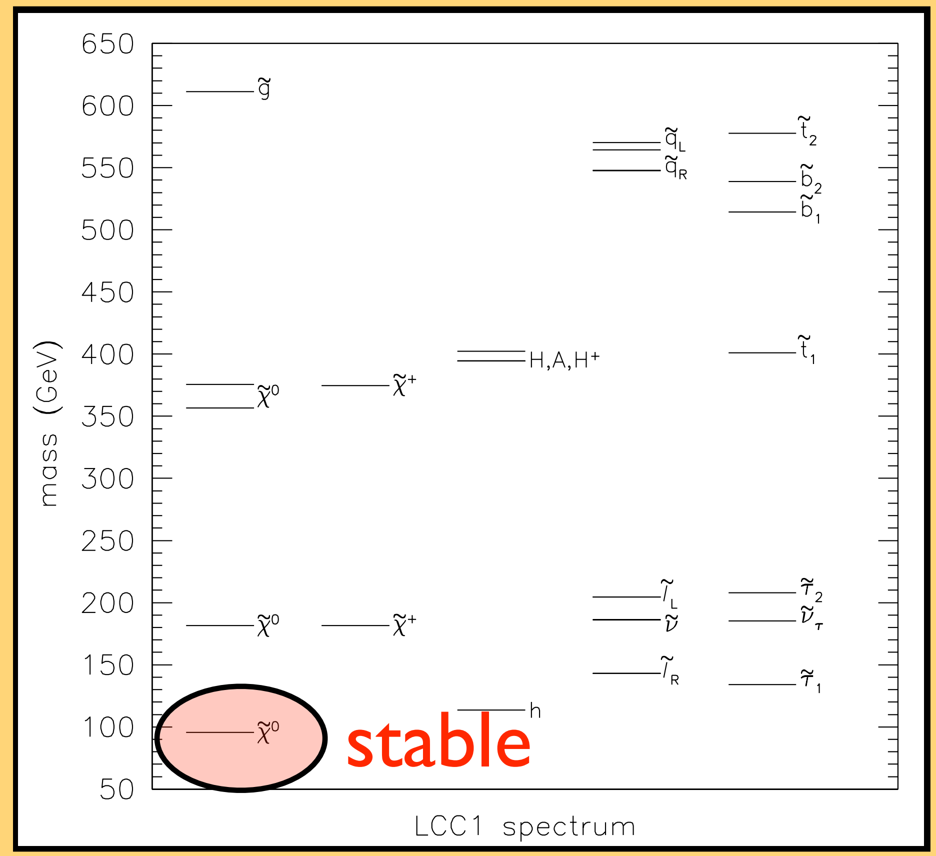
- New stable, massive particle produced thermally in early universe
- Weak-scale cross-section gives observed relic density

WMAP $0.095 < \Omega h^2 < 0.129$

$$\sigma_\chi \approx 10^{-37} cm^2$$

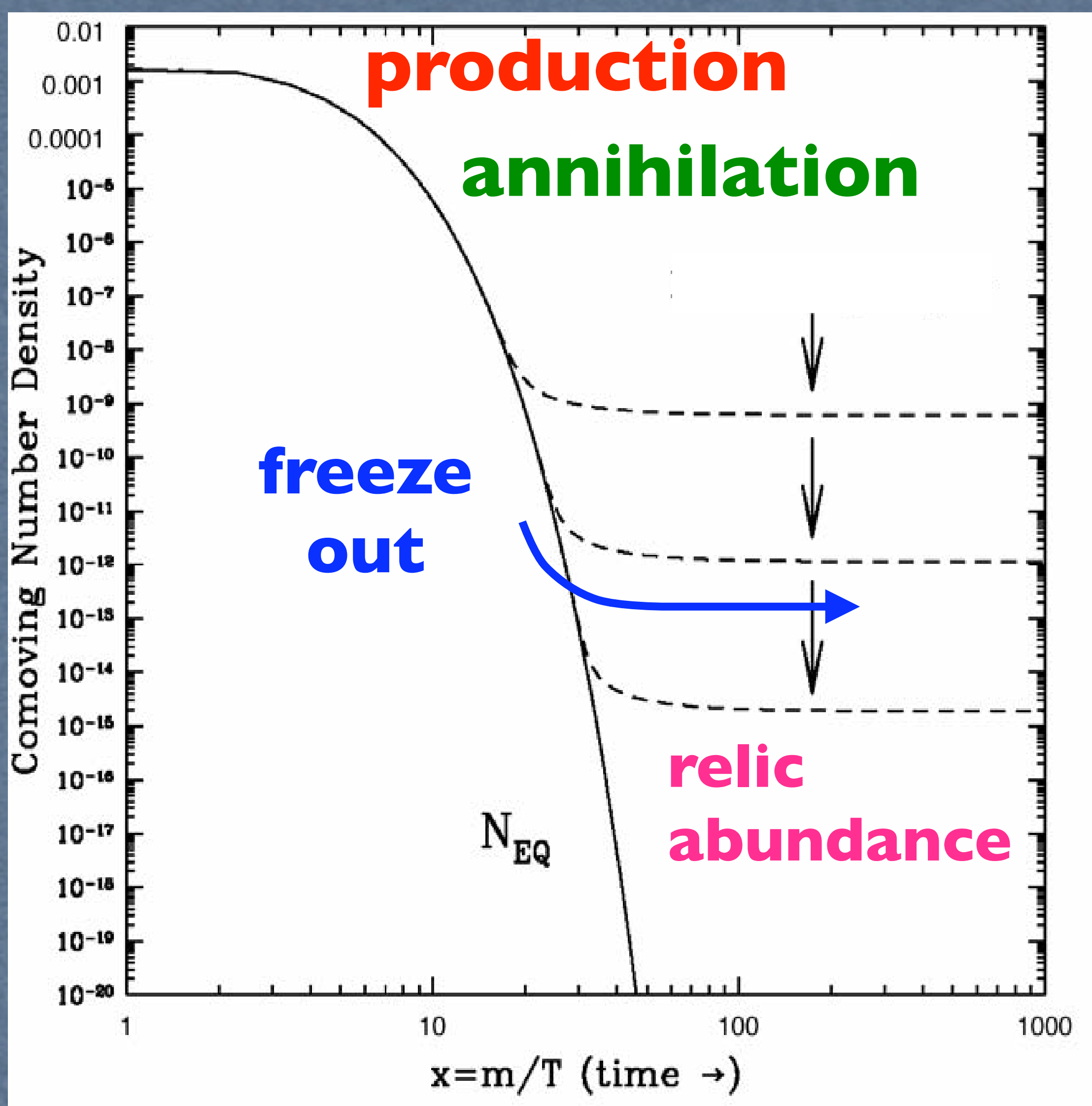
Motivated by Particle Physics Too!

- New TeV physics required to explain radiative stability of weak scale.
  - SuperSymmetry
  - Extra Dimensions
  - ...
- These theories give rise to convenient dark matter candidates.
  - LSP, LKP



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

Happy Coincidence!



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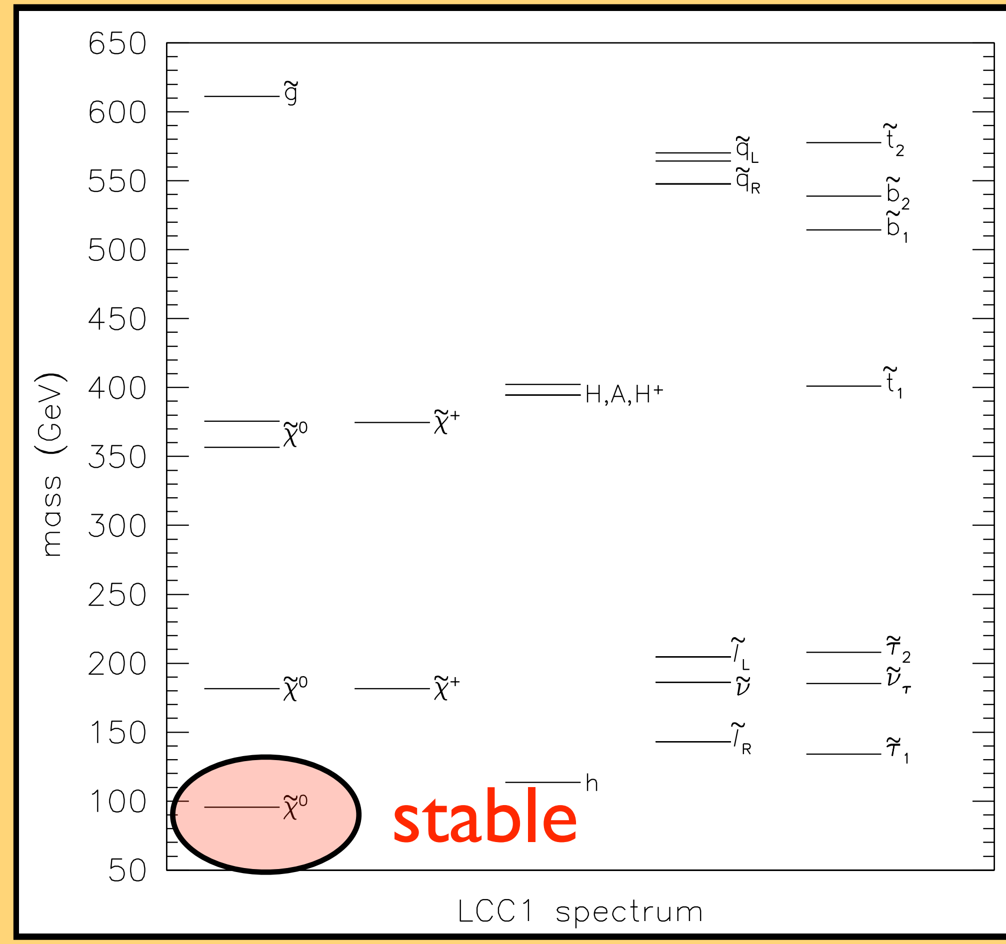

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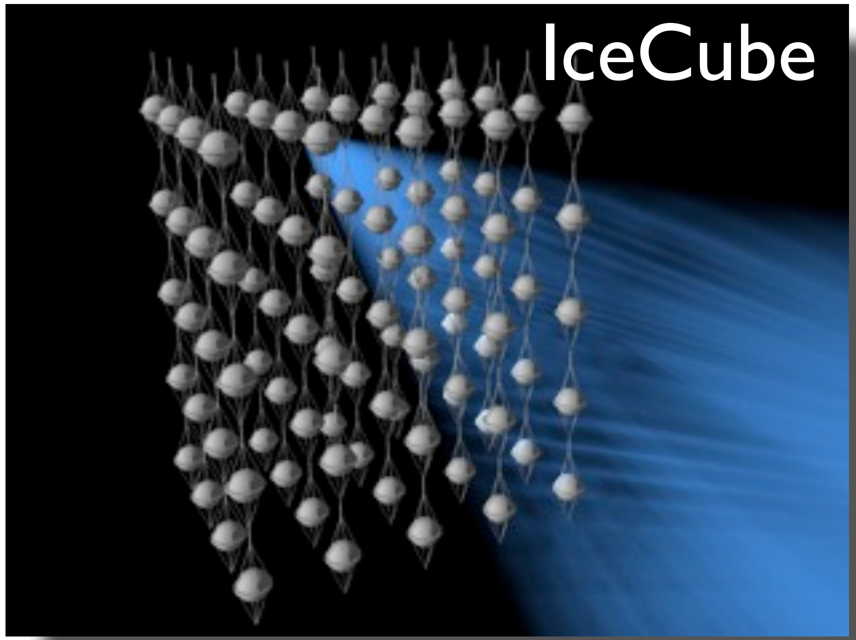
$$\sigma_\chi \approx 10^{-37} cm^2$$

How Do We Detect WIMPs?

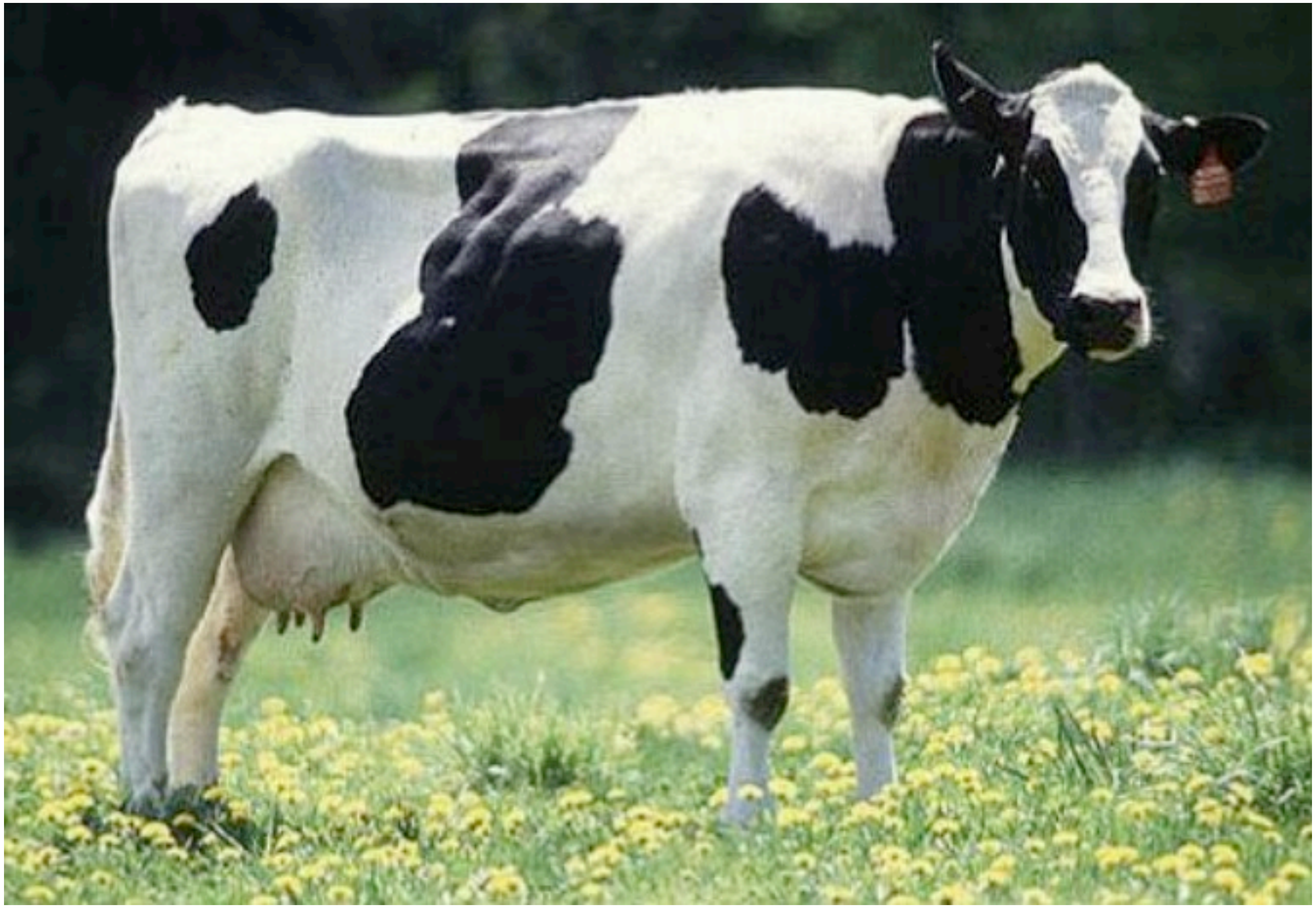
WIMP scattering on earth

WIMP production on earth



WIMP annihilation in the cosmos

The Spherical Cow

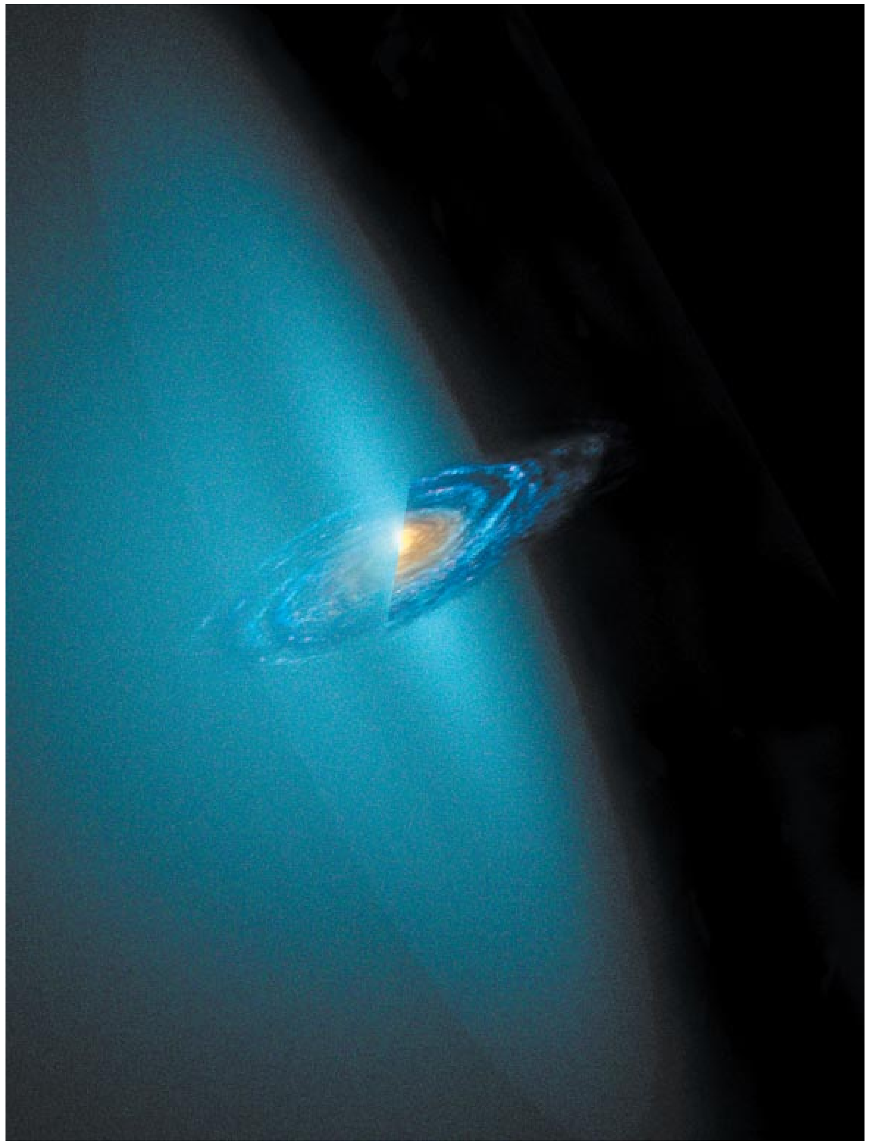


The Spherical Cow

Direct Detection Event Rates

"Spherical Cow" Halo Model

ρ_o = 0.3 GeV/cm^3,
Maxwellian distrubution,
v_o = 220 km/s,
v_{esc} = 650 km/s



Direct Detection Event Rates

"Spherical Cow" Halo Model

ρ_o = 0.3 GeV/cm^3,
Maxwellian distrubution,
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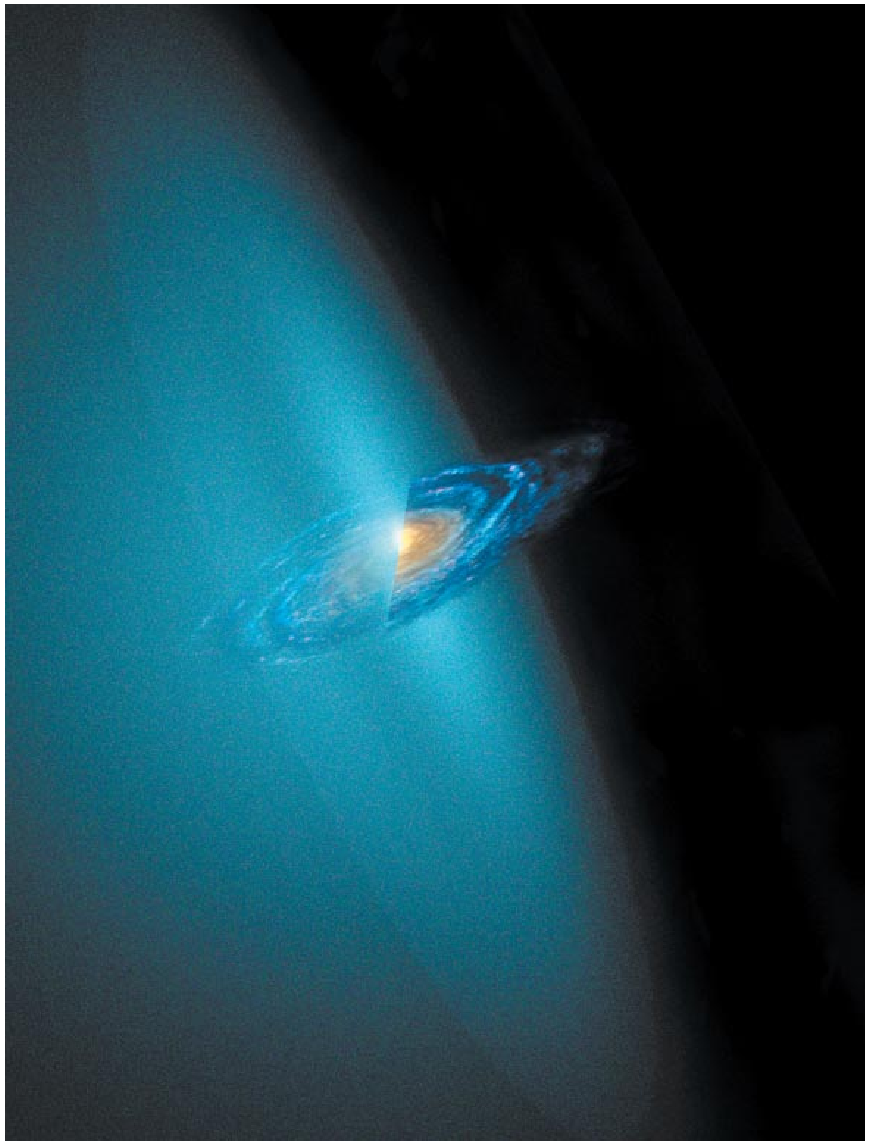
Interaction Details

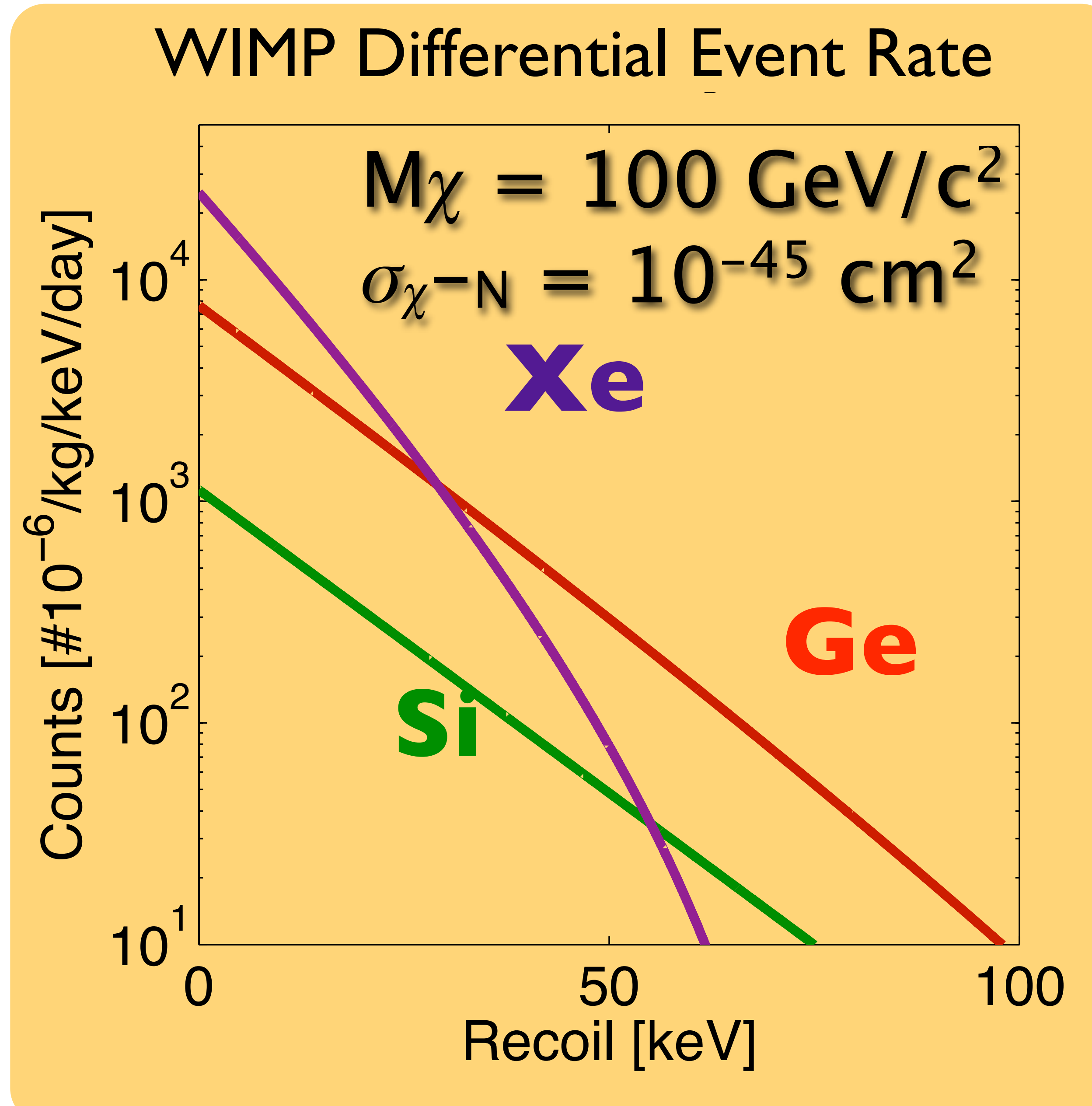
spin-independent,
coherent scattering

$\rightarrow \quad \sigma_\chi \propto A^2$



Direct Detection Event Rates

- Elastic scattering of a WIMP deposits small amounts of energy into recoiling nucleus (~ few 10s of keV)
- Featureless exponential spectrum
- **Expected rate: < 0.01/kg-d**
- Radioactive background of most materials higher than this rate.



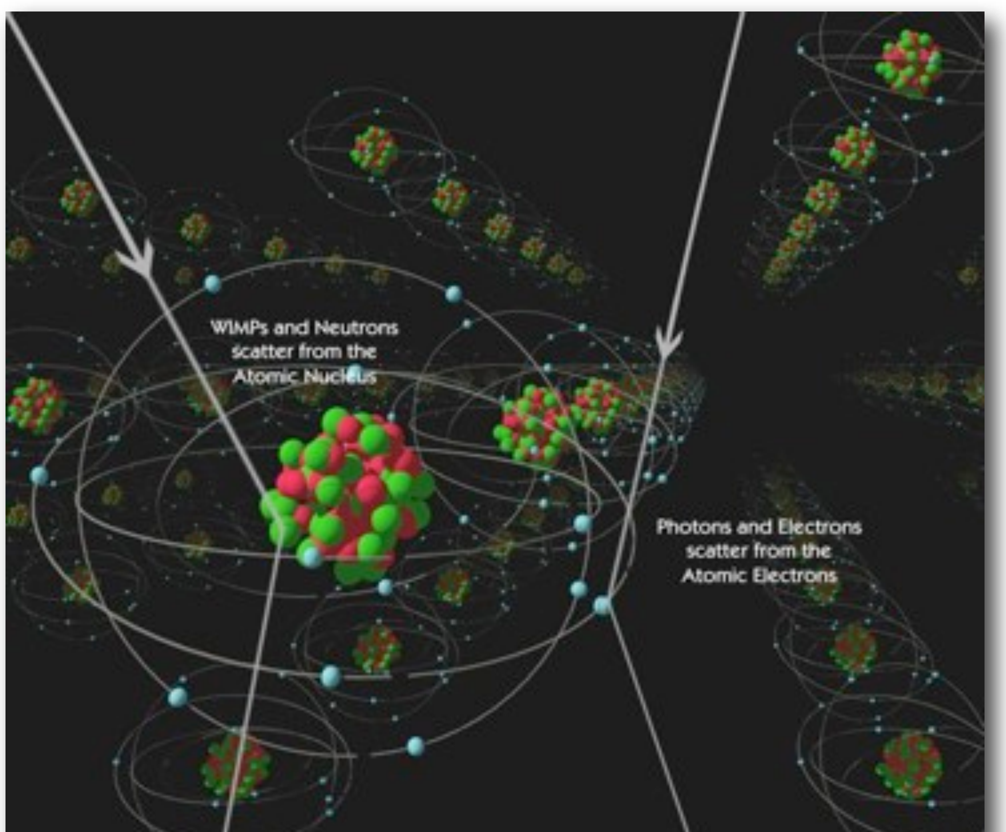
Detection Challenges

- ✓ **Low energy thresholds** (~10 keV)
- ✓ Ridged **background controls**
  - ➡ Clean materials
  - ➡ shielding
  - ➡ discrimination power
- ✓ Substantial **Depth**
  - ➡ neutrons look like WIMPS
- ✓ **Long exposures**
  - ➡ large masses, long term stablility

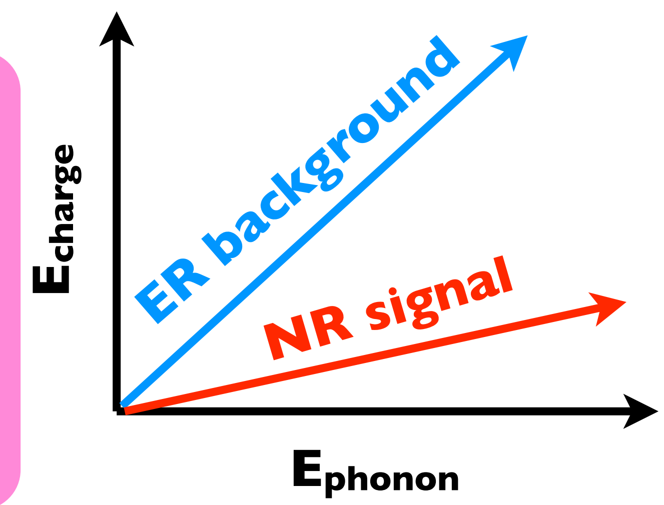
CDMS-II

CDMS-II: The Big Picture

Use a combination of **discrimination** and **shielding** to maintain a **"<1 event expected background"** experiment with **low temperature** semiconductor detectors



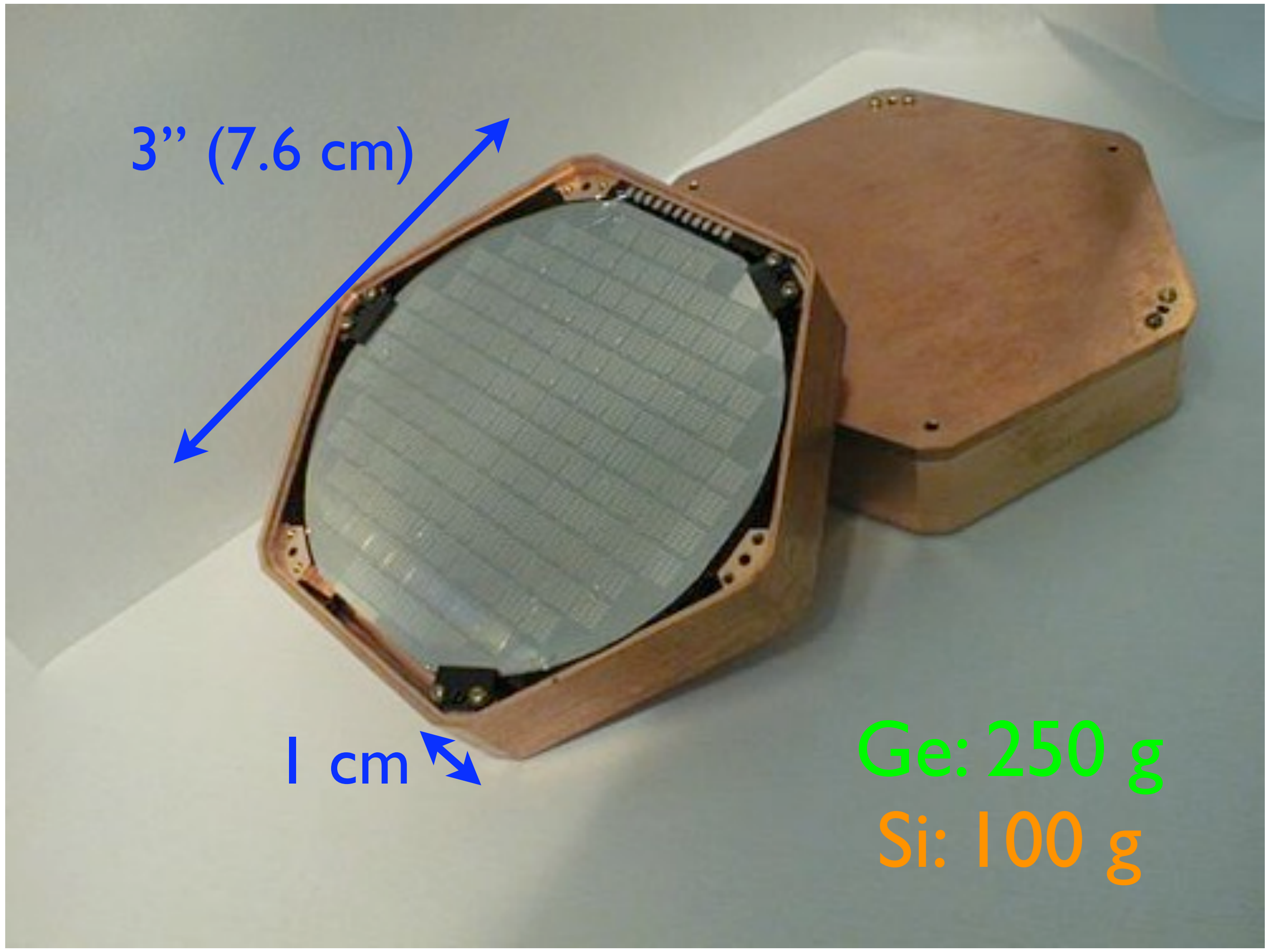
Discrimination from measurements of **ionization** and **phonon energy**.



Keep backgrounds low as possible through shielding.

CDMS-II ZIP Detectors

- **Z**-sensitive **I**onization and **P**honon mediated
- **250 g Ge** or **100 g Si** crystals (1 cm thick, 7.5 cm diameter)
- Photolithographically patterned to **collect athermal phonons** and **ionization signals**
  - xy-position imaging
  - Surface (z) event rejection from pulse shapes
- **30 detectors** stacked into **5 towers** of 6 detectors



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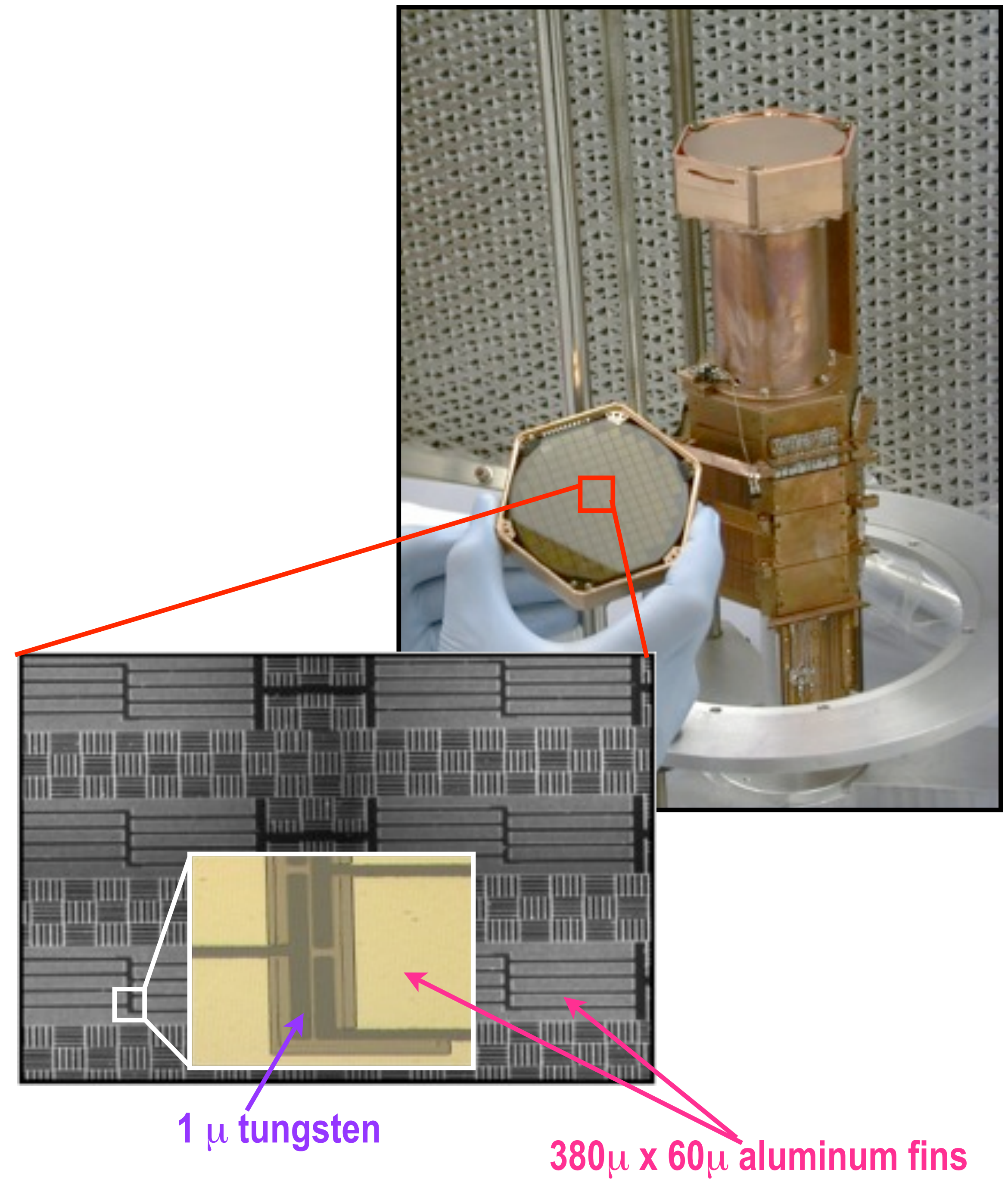
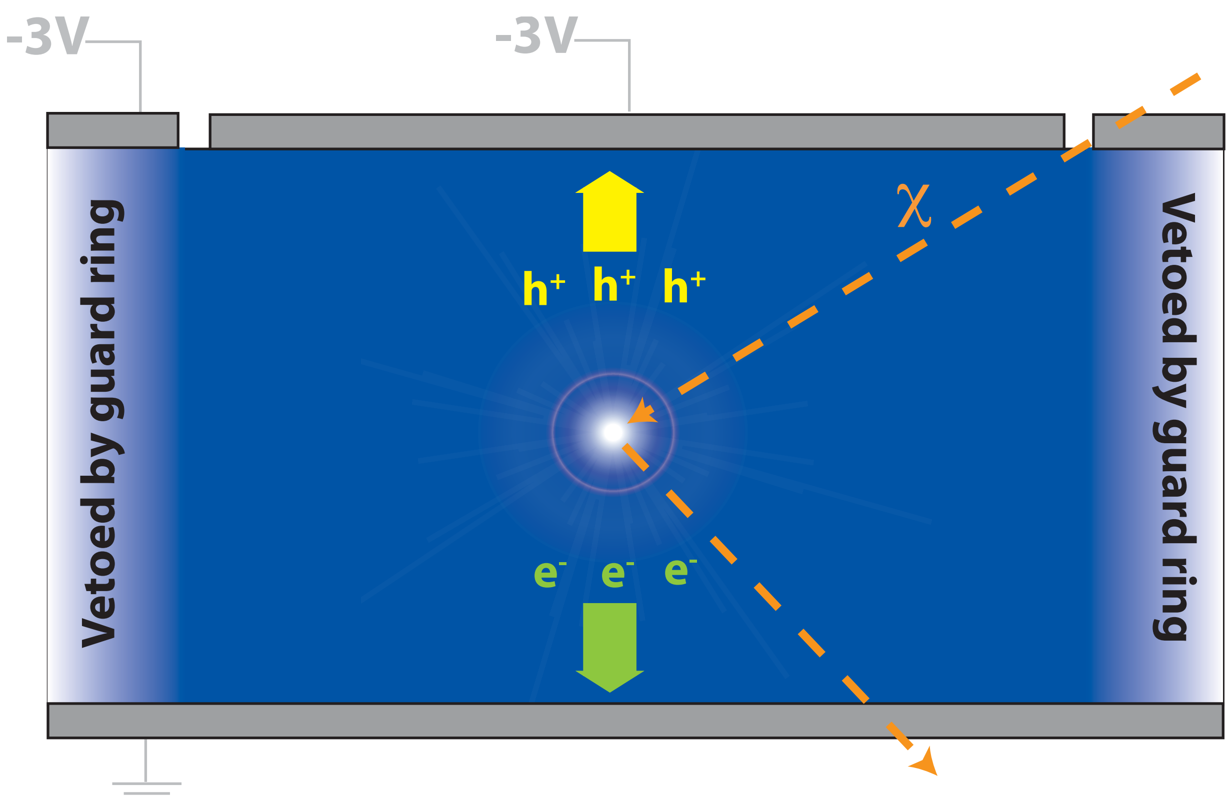
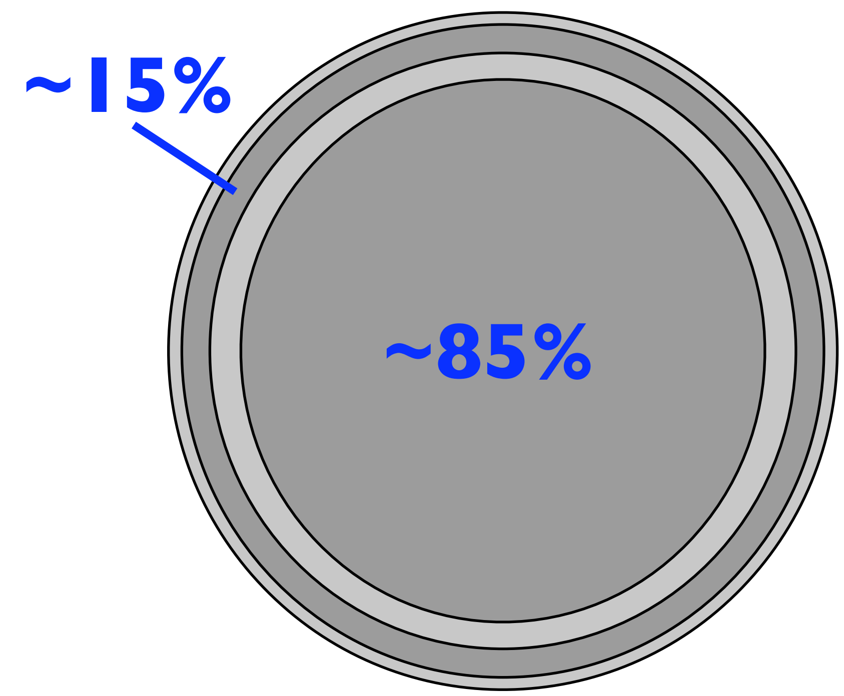


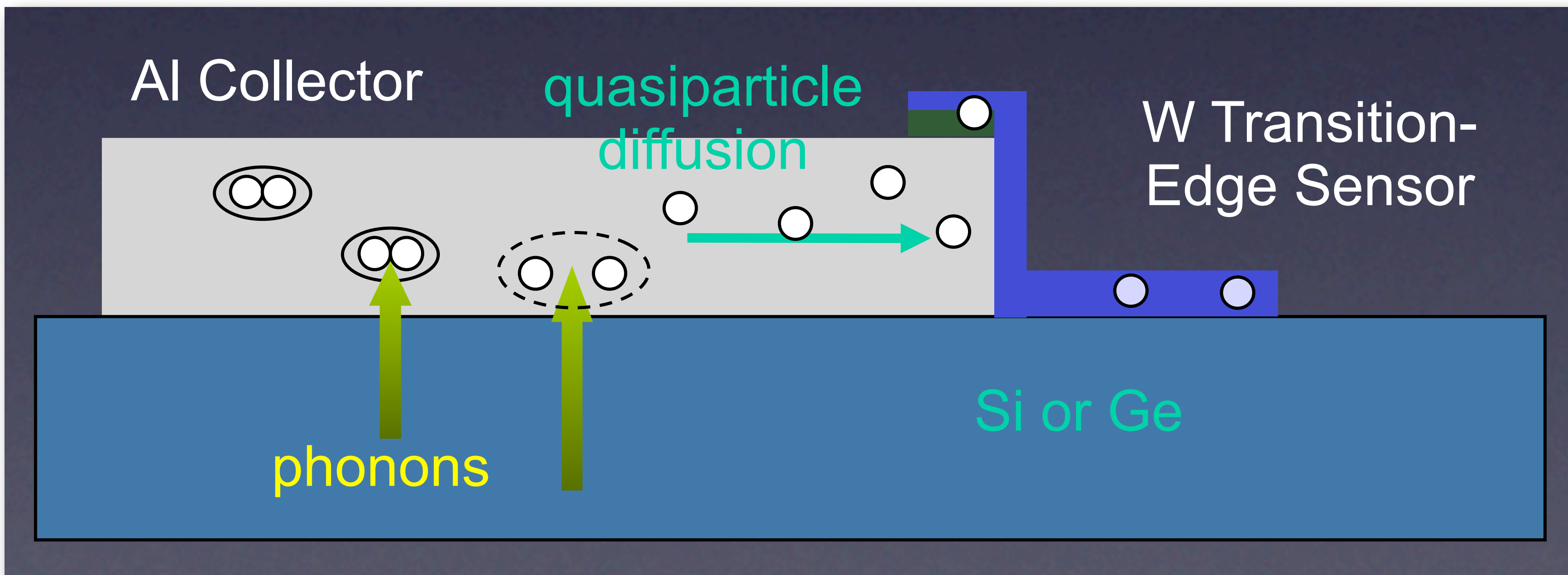
ZIP Detectors: Charge





Inner Channel: ionization measurement
Outer Channel: fiducial volume

ZIP Detectors: Phonons



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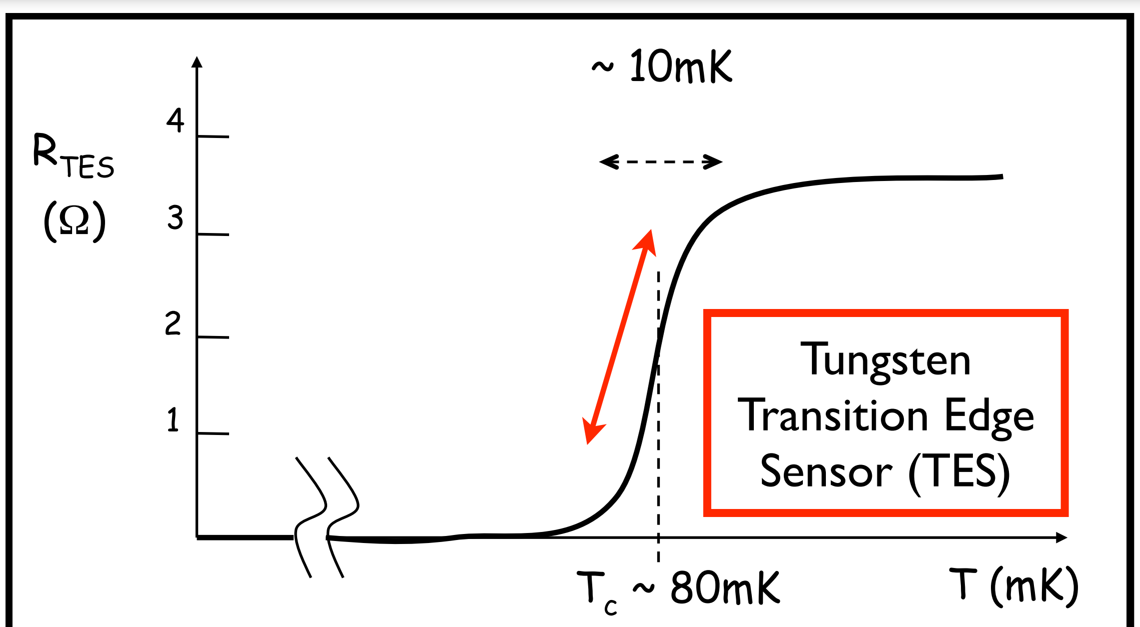
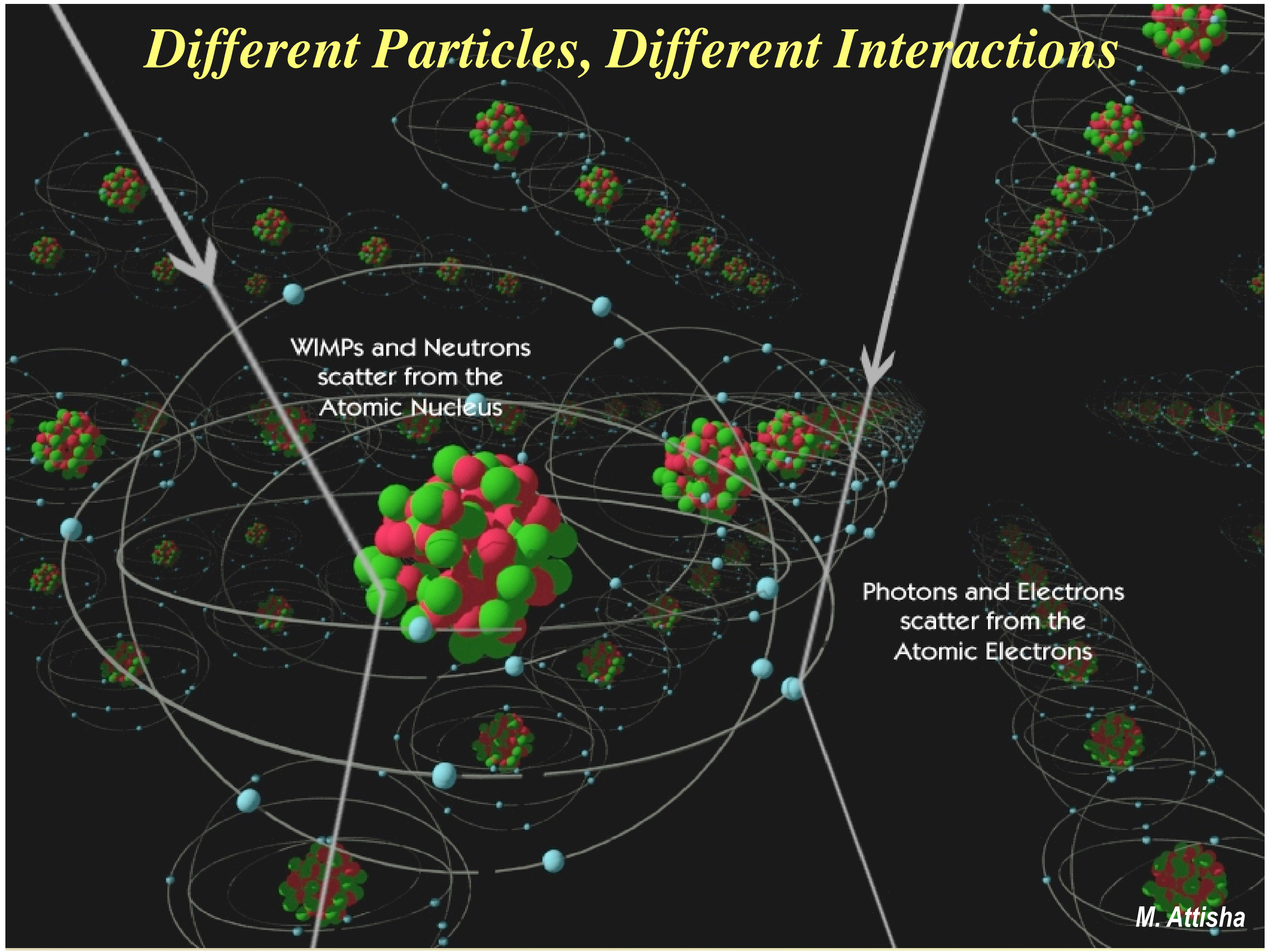


4 SQUID readout channels, each reads out 1036 TESs in parallel

Background Rejection

- Most backgrounds (e, γ) produce electron recoils
- WIMPS and neutrons produce nuclear recoils.



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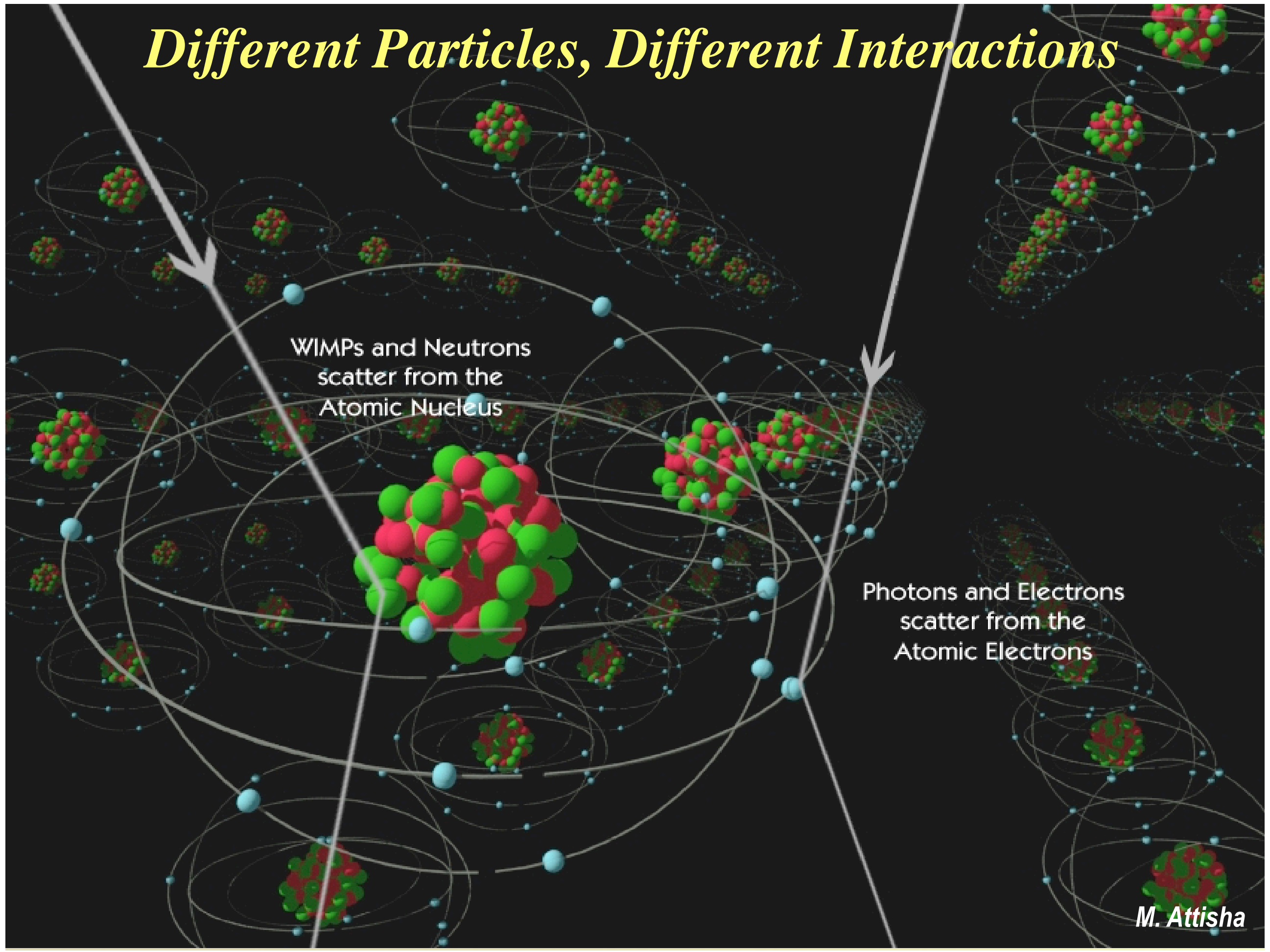

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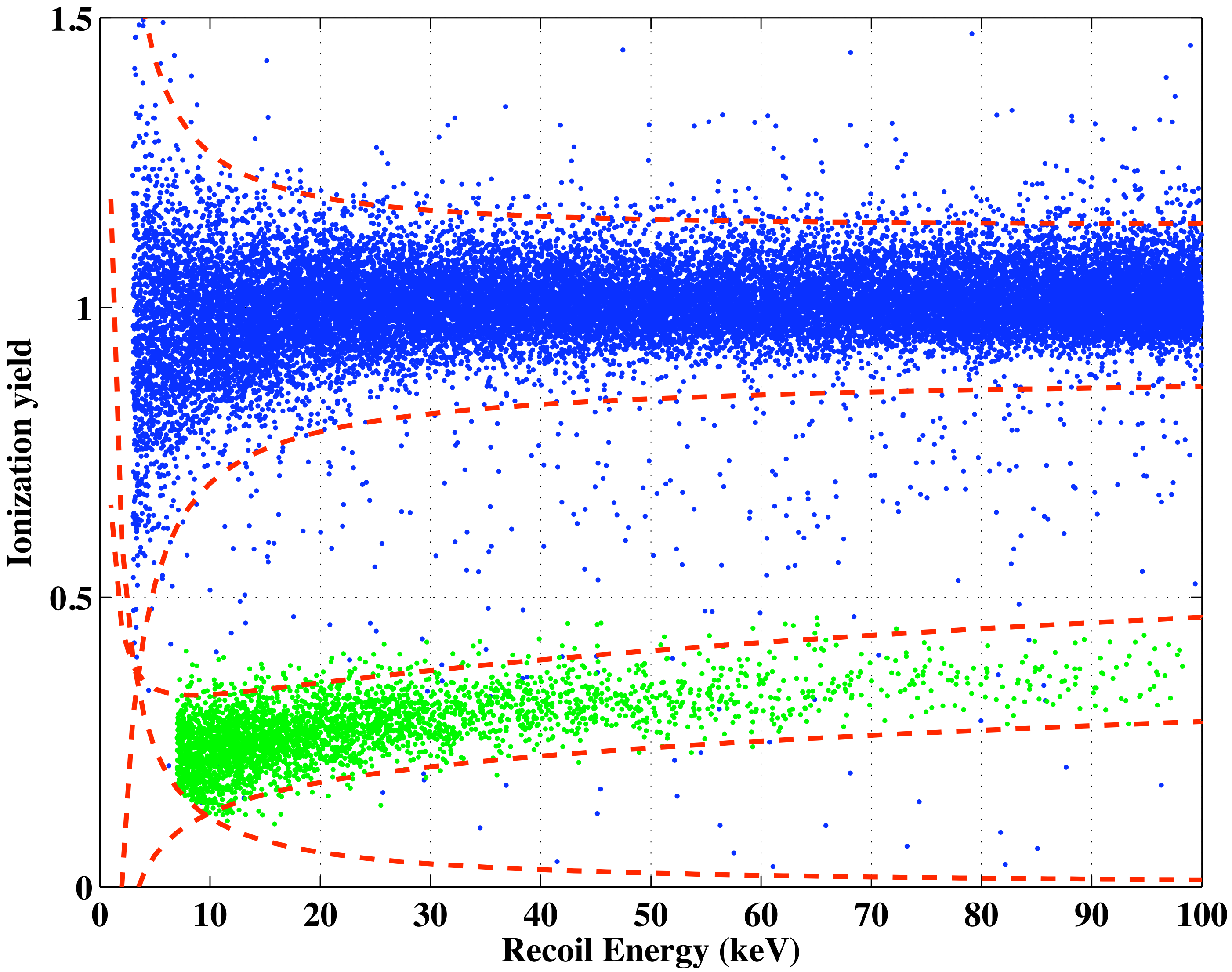

Background Rejection

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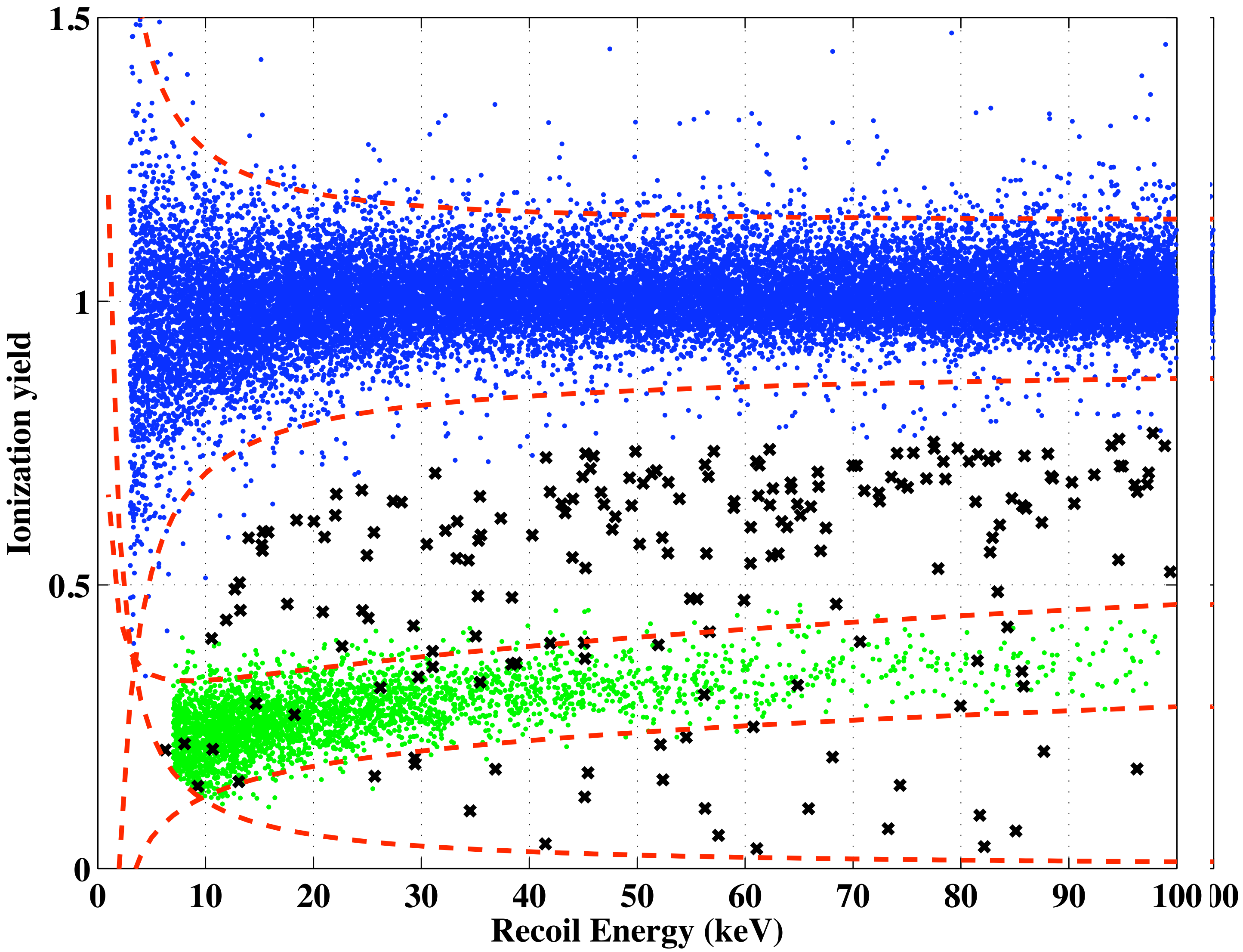
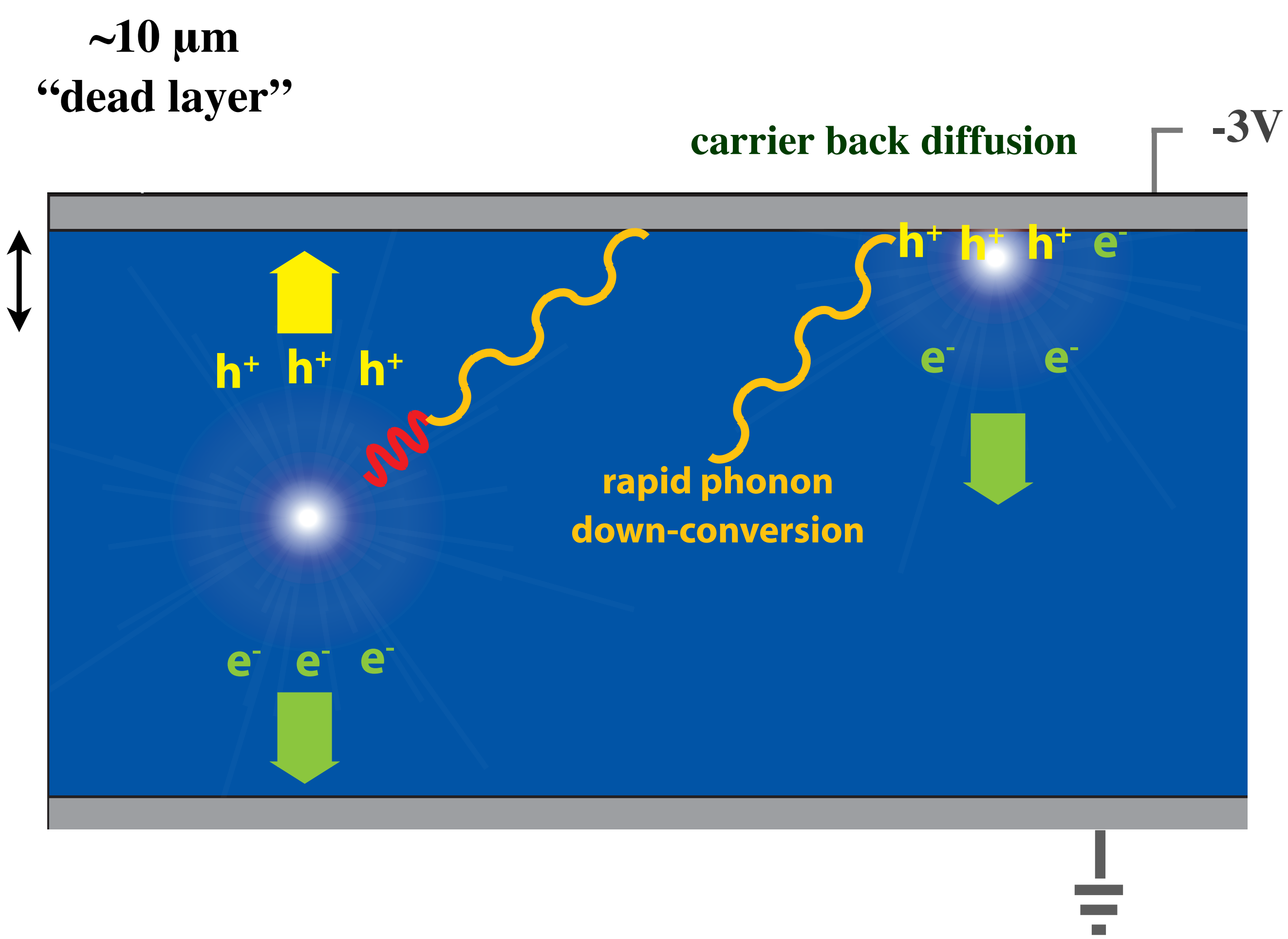
- WIMPS and neutrons produce nuclear recoils.
- Ionization yield (ionization energy per unit phonon energy) strongly depends on particle type.
- Particles that interact in the "surface dead layer" result in reduced ionization yield.

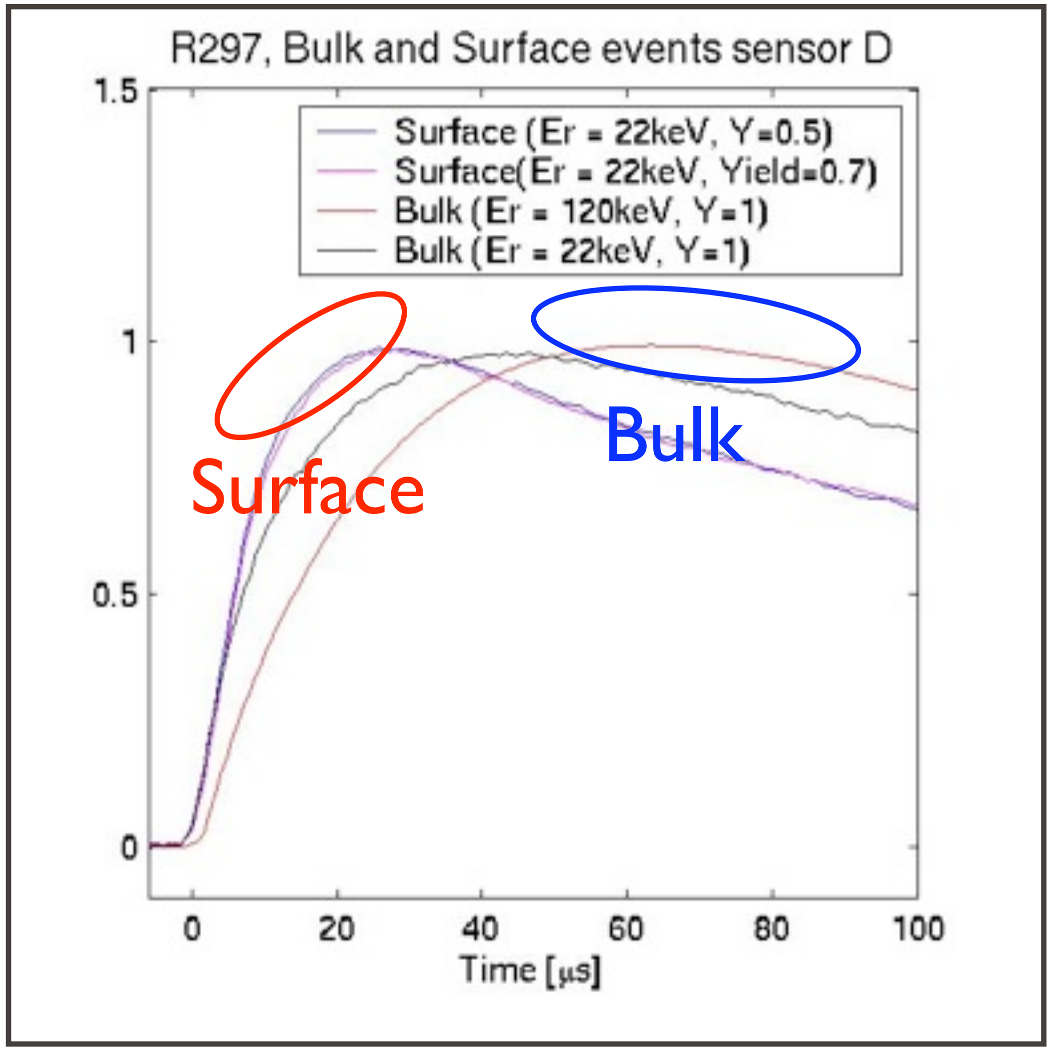


Reduced Ionization Yield

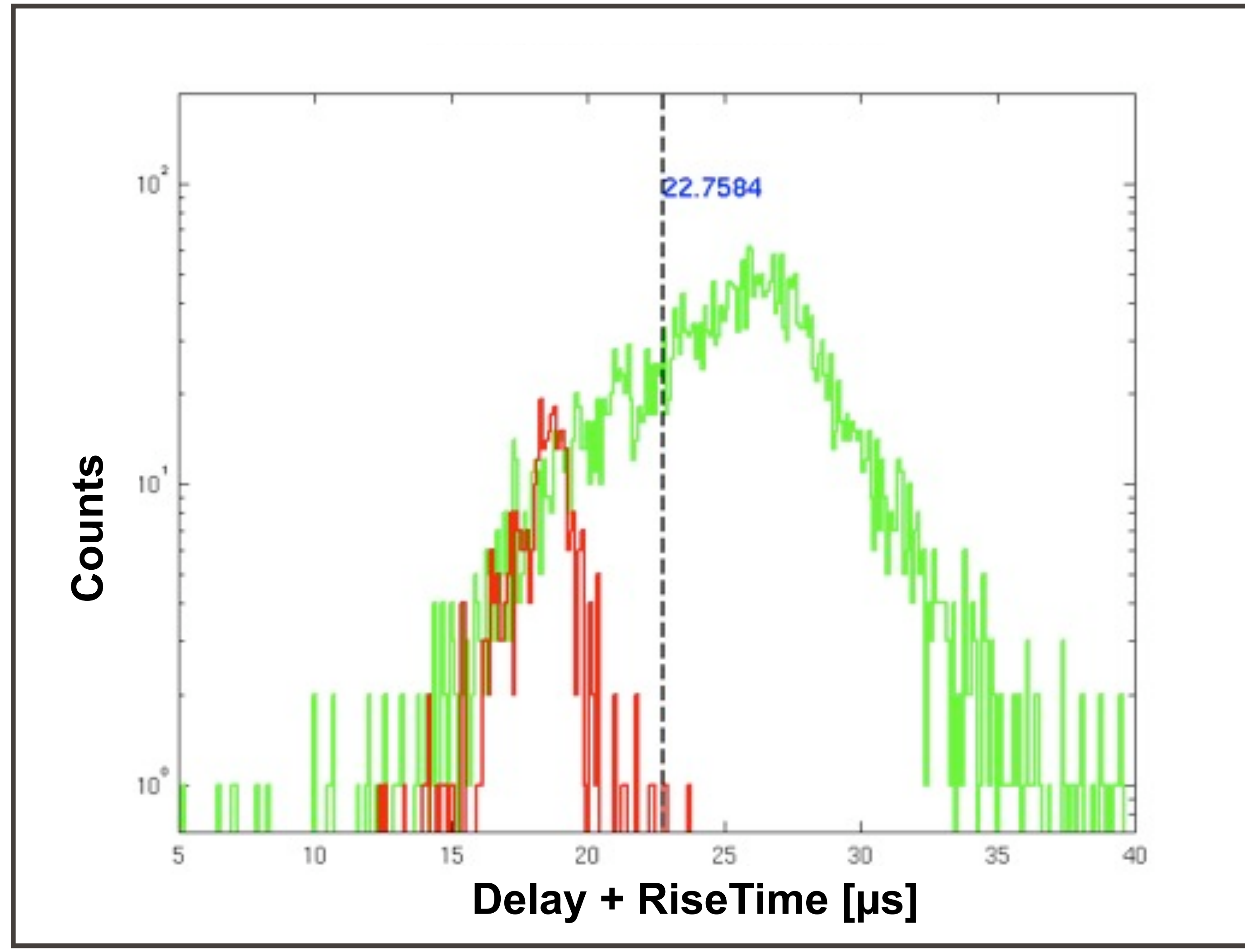


- Reduced charge yield is due to carrier back diffusion in surface events.
- "Dead layer" is within ~10µm of the surface.

Surface Event Rejection

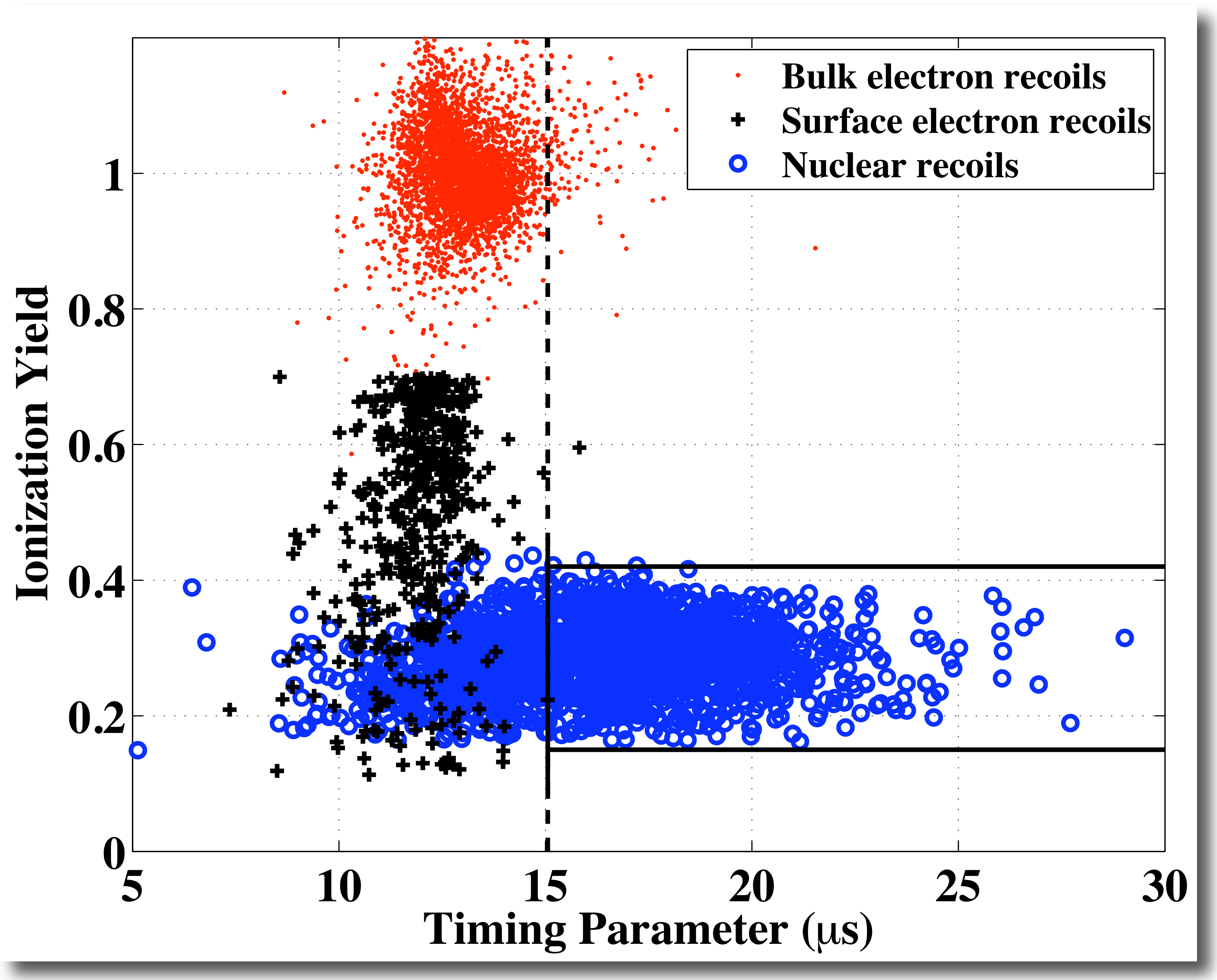


Phonons near surface travel faster, resulting in shorter risetimes of phonon pulse.



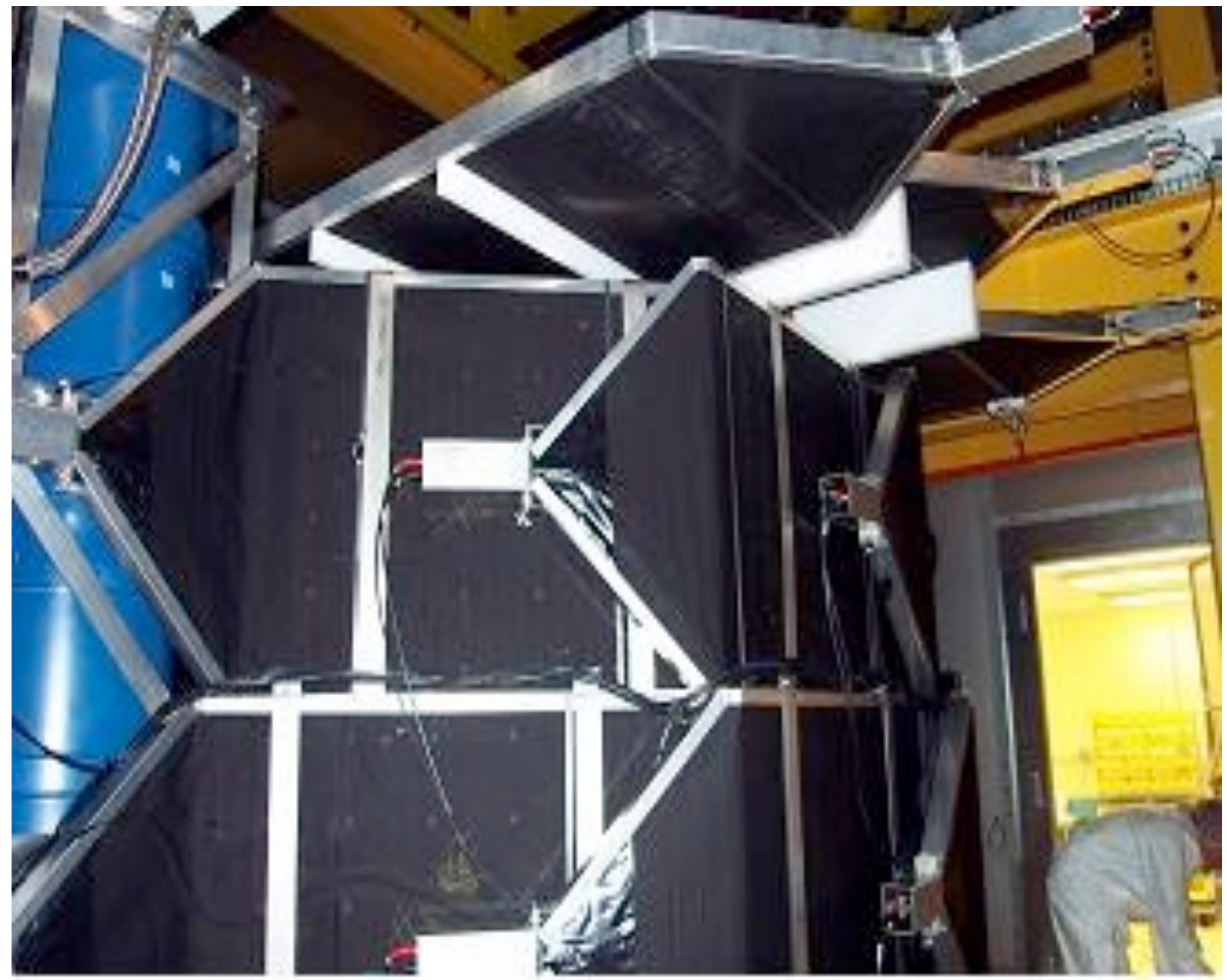
Selection criteria set to accept ~0.5 background events.

Another View of Discrimination



Peeling the Shielding Onion

Active Muon Veto:
rejects events from cosmic rays



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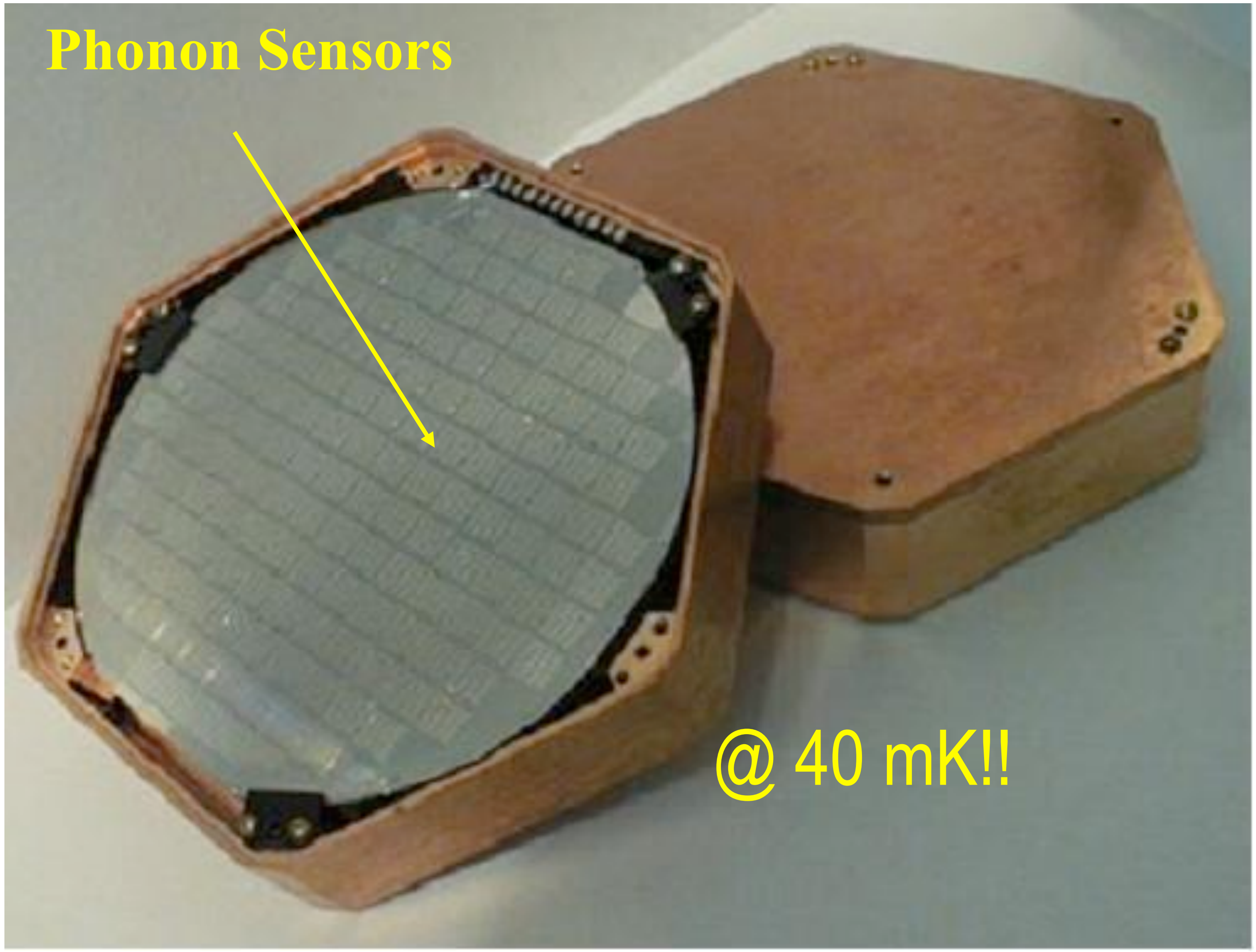
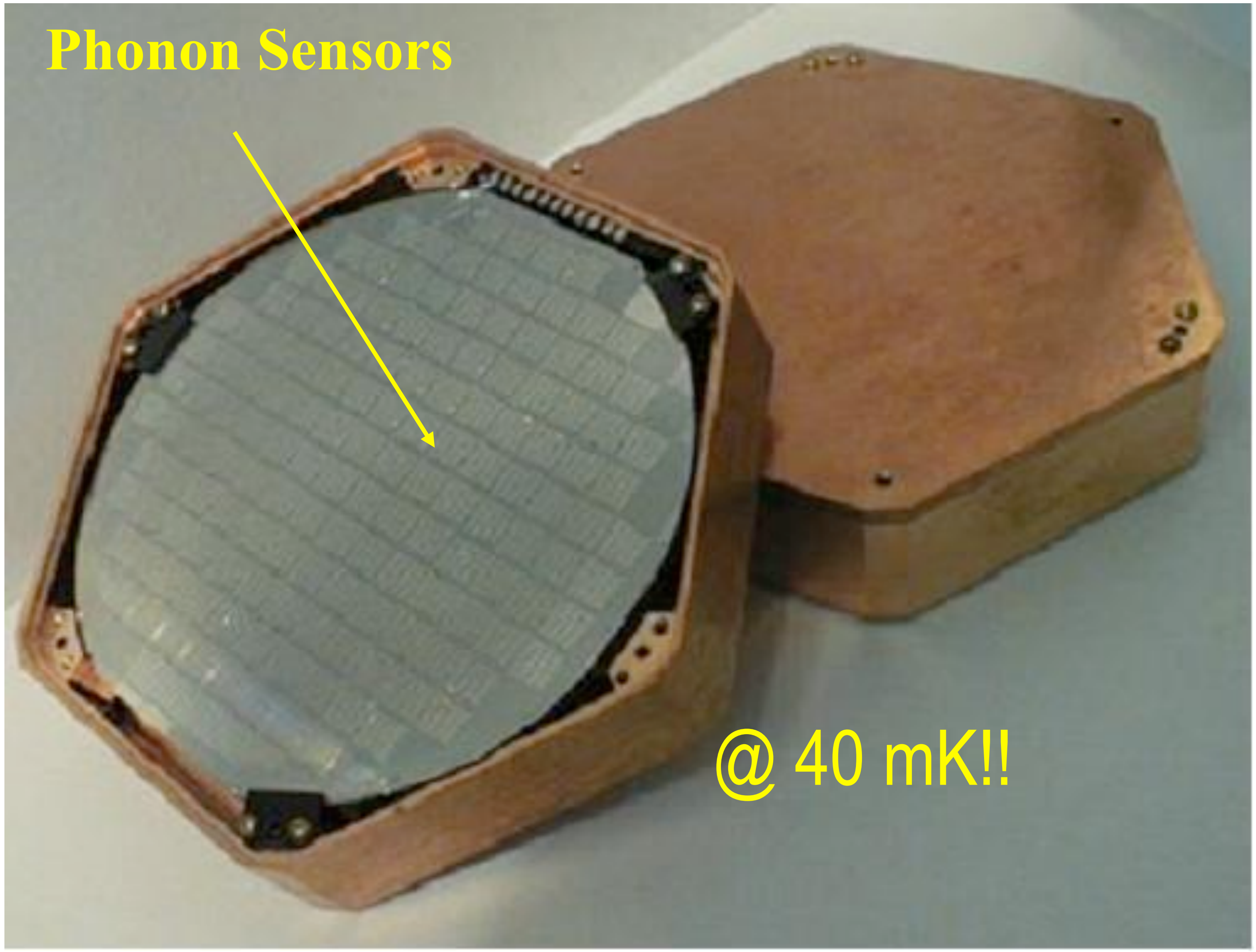


Peeling the Shielding Onion

Active Muon Veto: rejects events from cosmic rays

Pb: shielding from gammas resulting from radioactivity

Polyethyene: moderate neutrons produced from fission decays and from (α,n) interactions resulting from U/Th decays



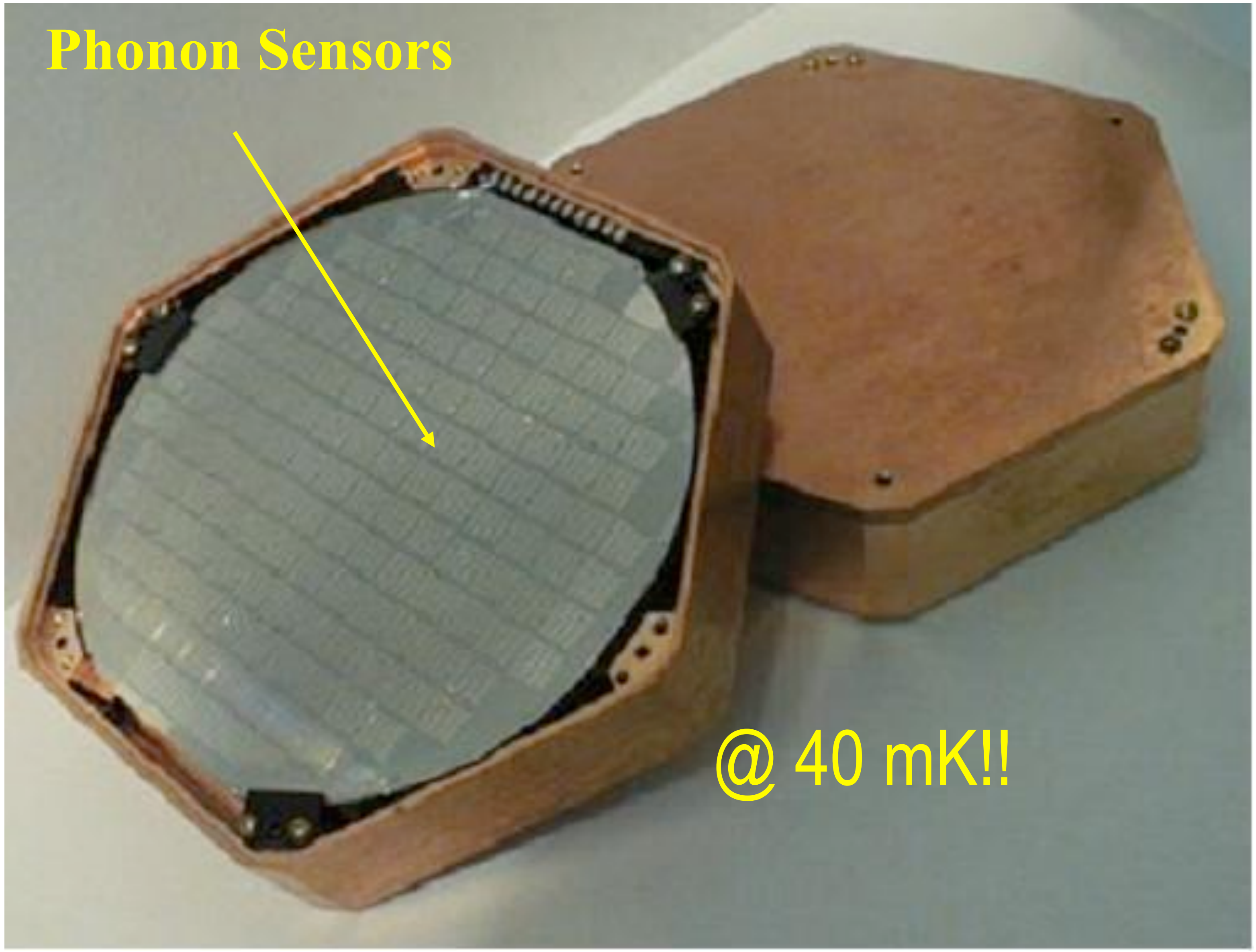
Peeling the Shielding Onion

Active Muon Veto: rejects events from cosmic rays

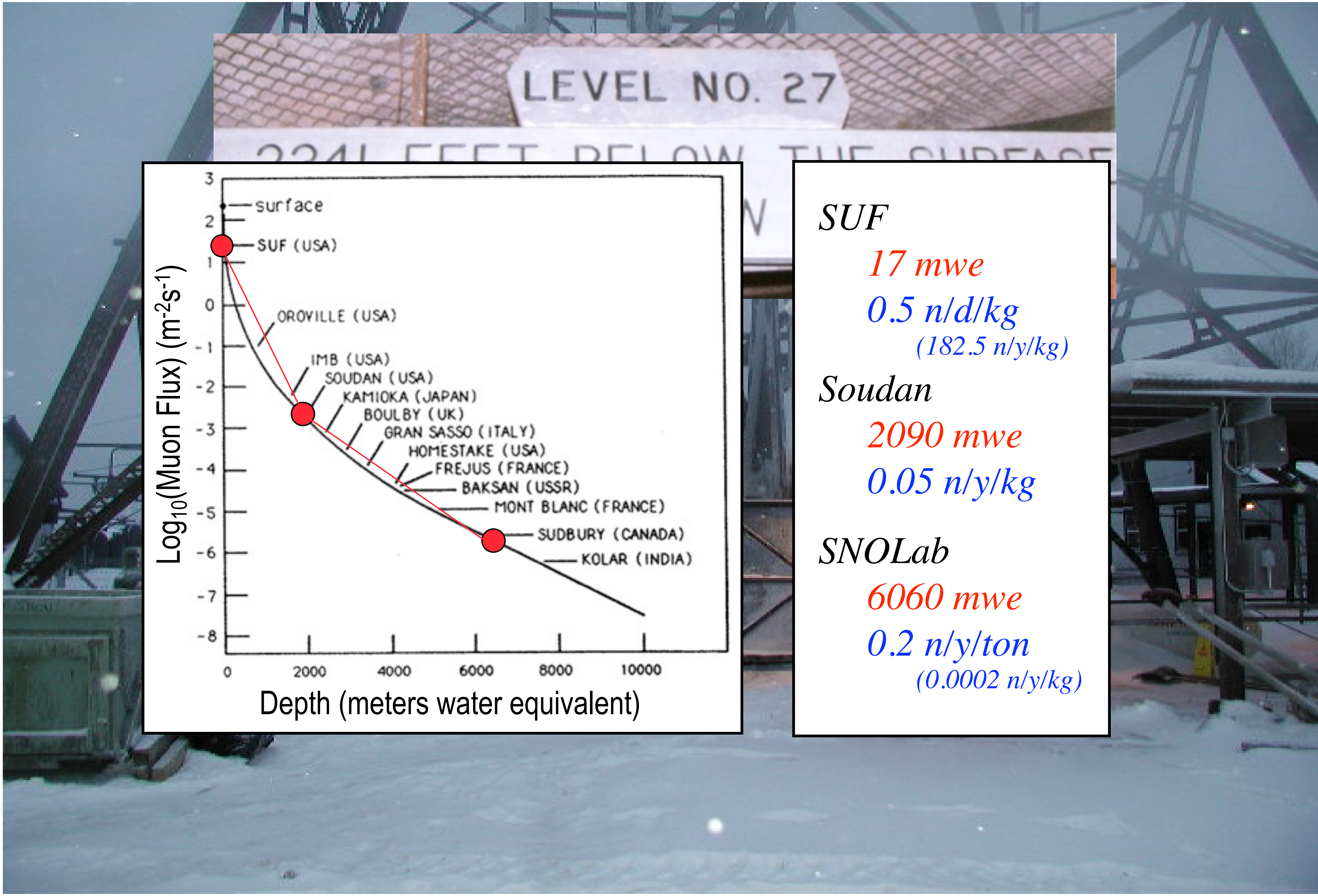
Pb: shielding from gammas resulting from radioactivity

Polyethyene: moderate neutrons produced from fission decays and from (α,n) interactions resulting from U/Th decays

Cu: shielding from gammas




LEVEL NO. 27
2341 FEET BELOW THE SURFACE
689 FEET BELOW SEA LEVEL



SUF

17 mwe

0.5 n/d/kg

(182.5 n/y/kg)

Soudan

2090 mwe

0.05 n/y/kg

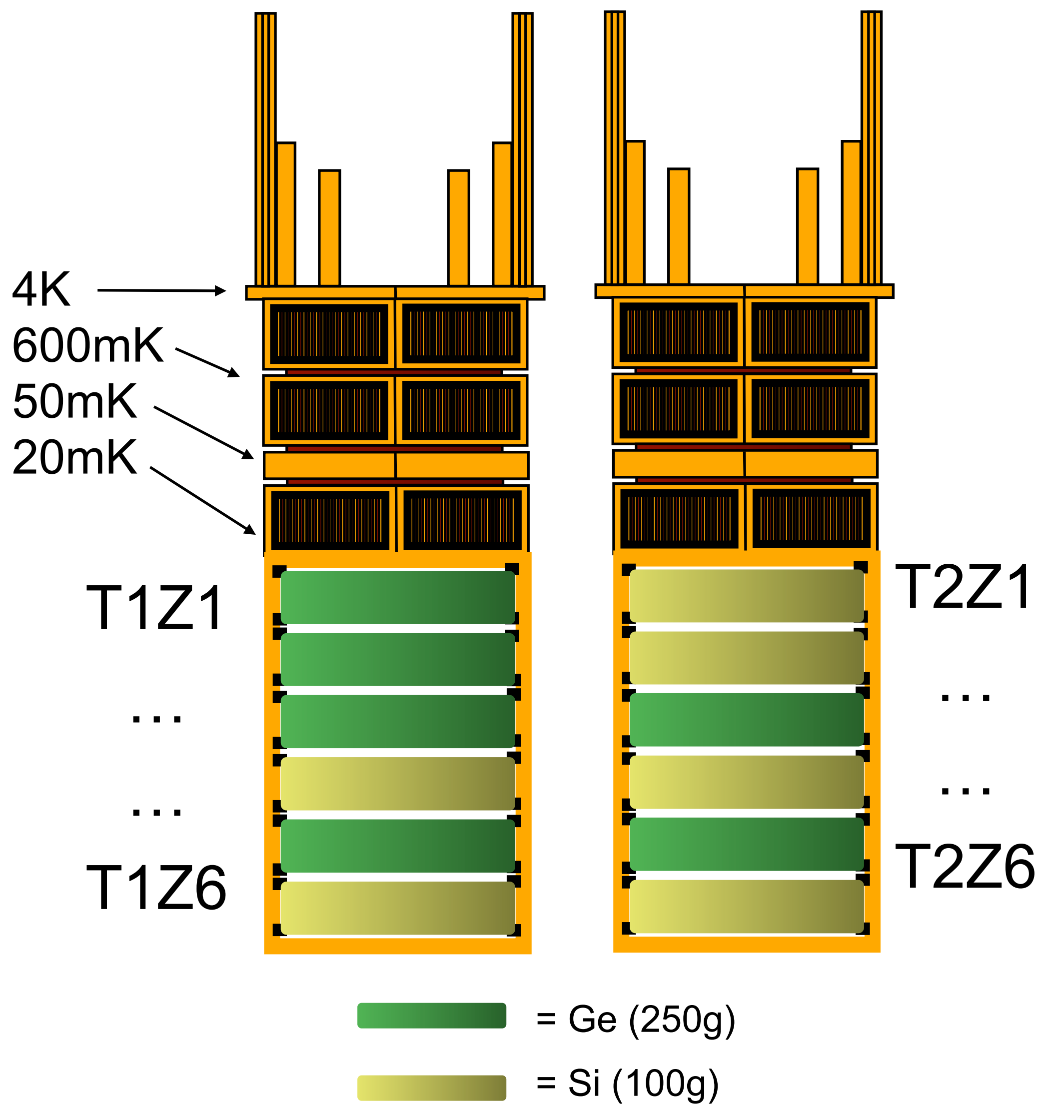
SNOLab

6060 mwe

0.2 n/y/ton

(0.0002 n/y/kg)

Initial Runs at Soudan



Run 118: 52.4 live days (2003-4)
1 kg Ge + 0.2 kg Si

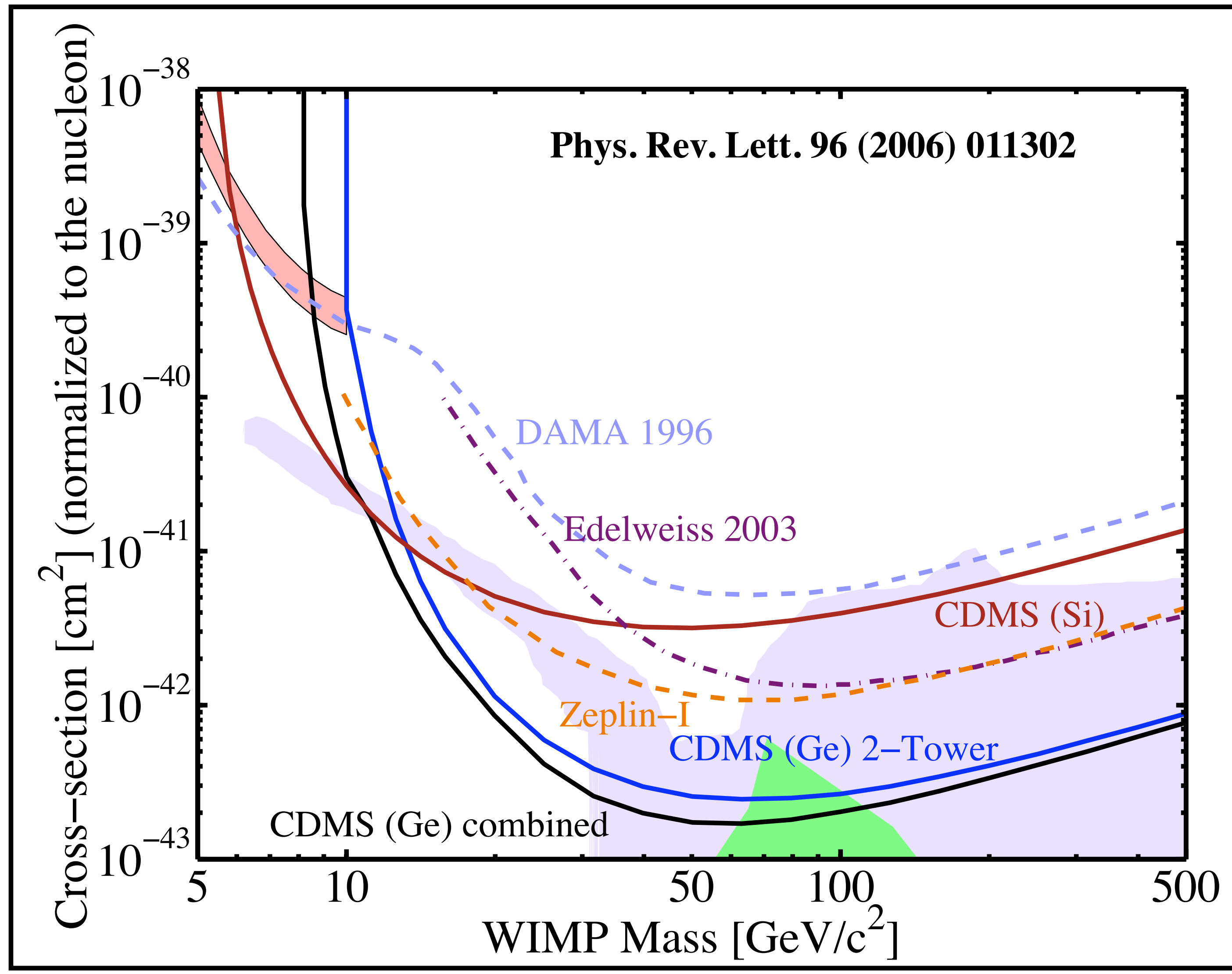
PRL **93**, 211301 (2004)
PRD **72,** 052009 (2005)

Run 119: 74.5 live days (2004)
1.5 kg Ge + 0.6 kg Si

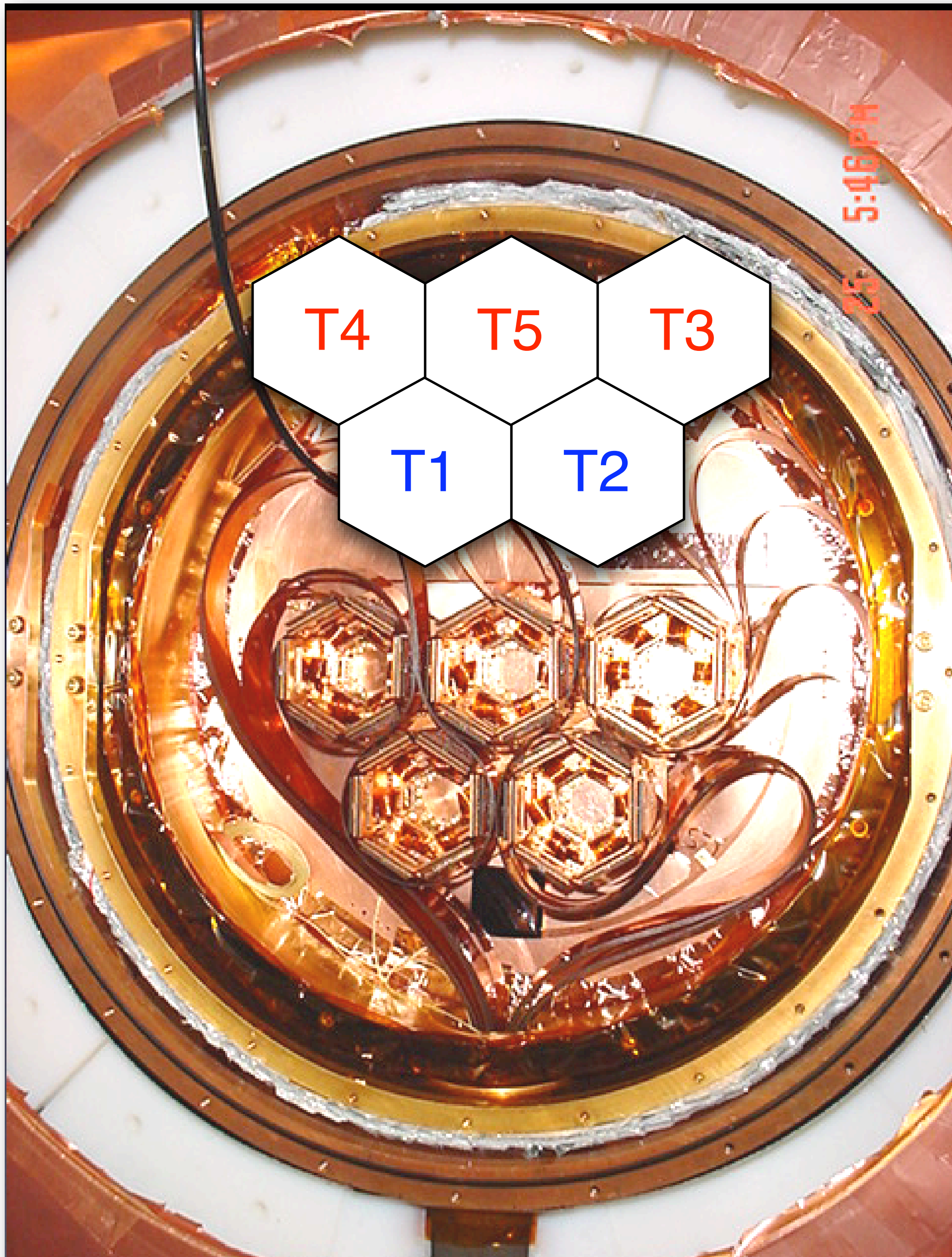
PRL **96**, 011302 (2006) *Combined reanalysis 2008 (in preparation)*

Two Tower Limits (2005)

- Upper limit on WIMP-nucleaon spin-independent σ is **1.6×10^{43} cm^2** for a WIMP of mass **60 GeV**.
- Excludes large regions of SUSY parameter space under some frameworks.
  - A. Bottino et al, Phys. Rev D 69, 037302 (2004) in purple.
  - J. Ellis et al., Phys. Rev. D 71, 095007 (2005) in green



CDMS II Experiment



- 30 detectors installed and operating in Soudan since June 06.
  - 4.75 kg of Ge, 1.1 kg of Si
- **Seven Total Data Runs:**
  - ✓ R123 - R124:
    - taken: (10/06 - 3/07) (4/07 - 7/07)
    - exposure: ~400 kg-d (Ge “raw”)
    - PRL 102, 011301 (2009)
  - ✓ R125 - R128
    - taken: (7/07 - 1/08) (1/08 - 4/08) (5/08 - 8/08) (8/08 - 9/08)
    - exposure: ~ 750 kg-d (Ge “raw”)
    - Under Analysis
  - ✓ R129:
    - taken: (11/08 - 3/09)

	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

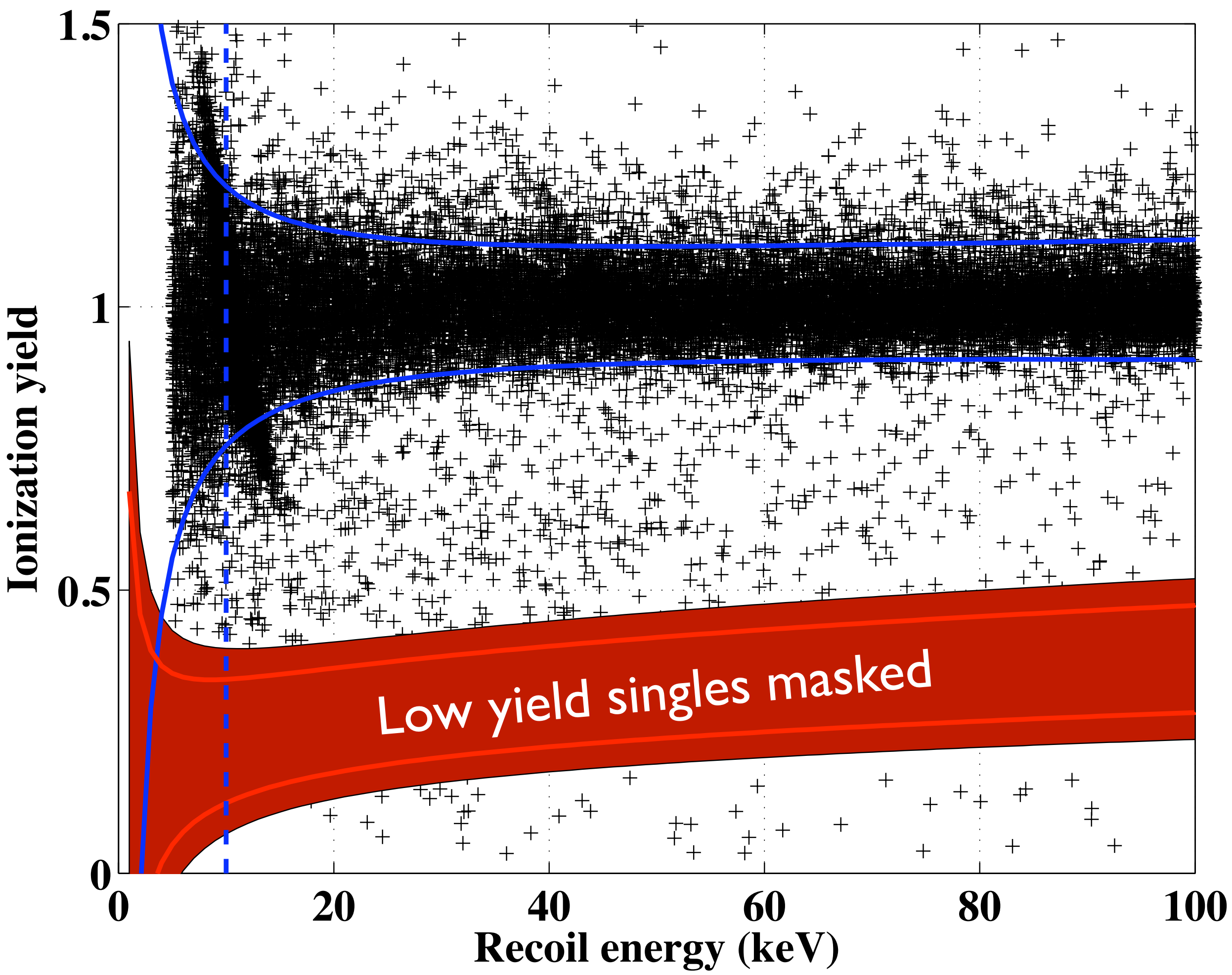
Side View

First Five Tower Results

PRL 102, 011301 (2009)

Blind Analysis:

Event selection and efficiencies were calculated without looking at the signal region of the WIMP-search data.



Event Selection:

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

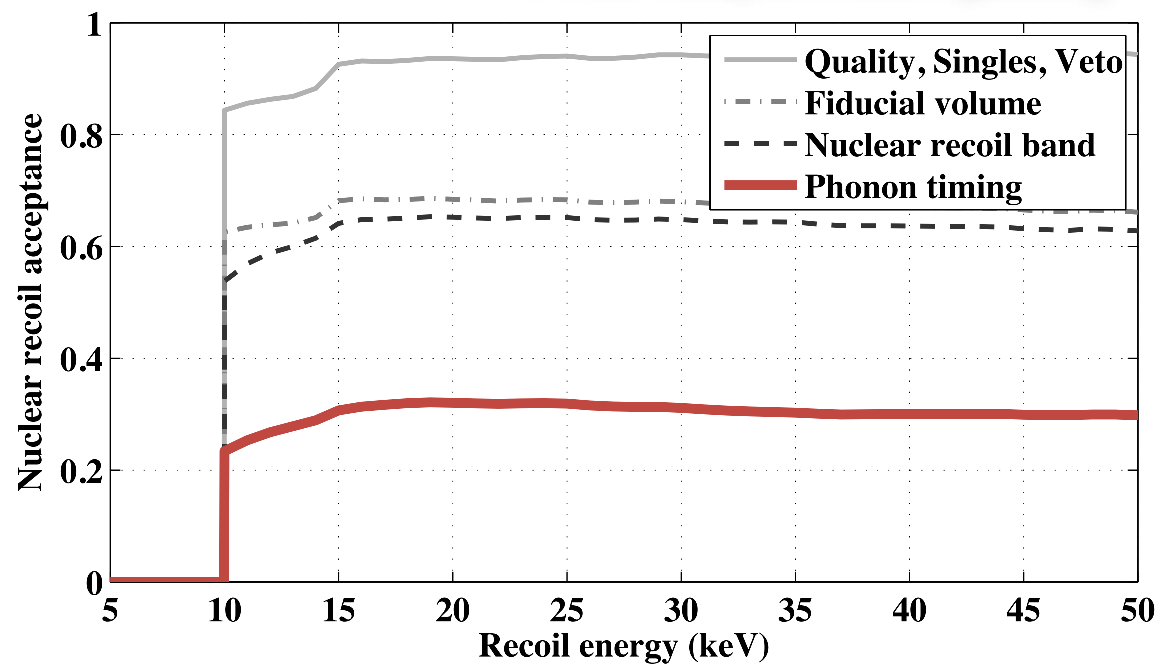
Analysis Summary

Surface Background

Estimated number of background events to pass surface cut in Ge

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

PRL 102, 011301 (2009)



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

398 raw kg-d
121 kg-d WIMP equiv. @ 60 GeV/c^2 (10 - 100 keV analysis energy range)

Opening the Box

Box opened Monday, February 4, 2008 for 15 Ge ZIPs.
Remaining 8 Si and 1 Ge undergoing further leakage studies.

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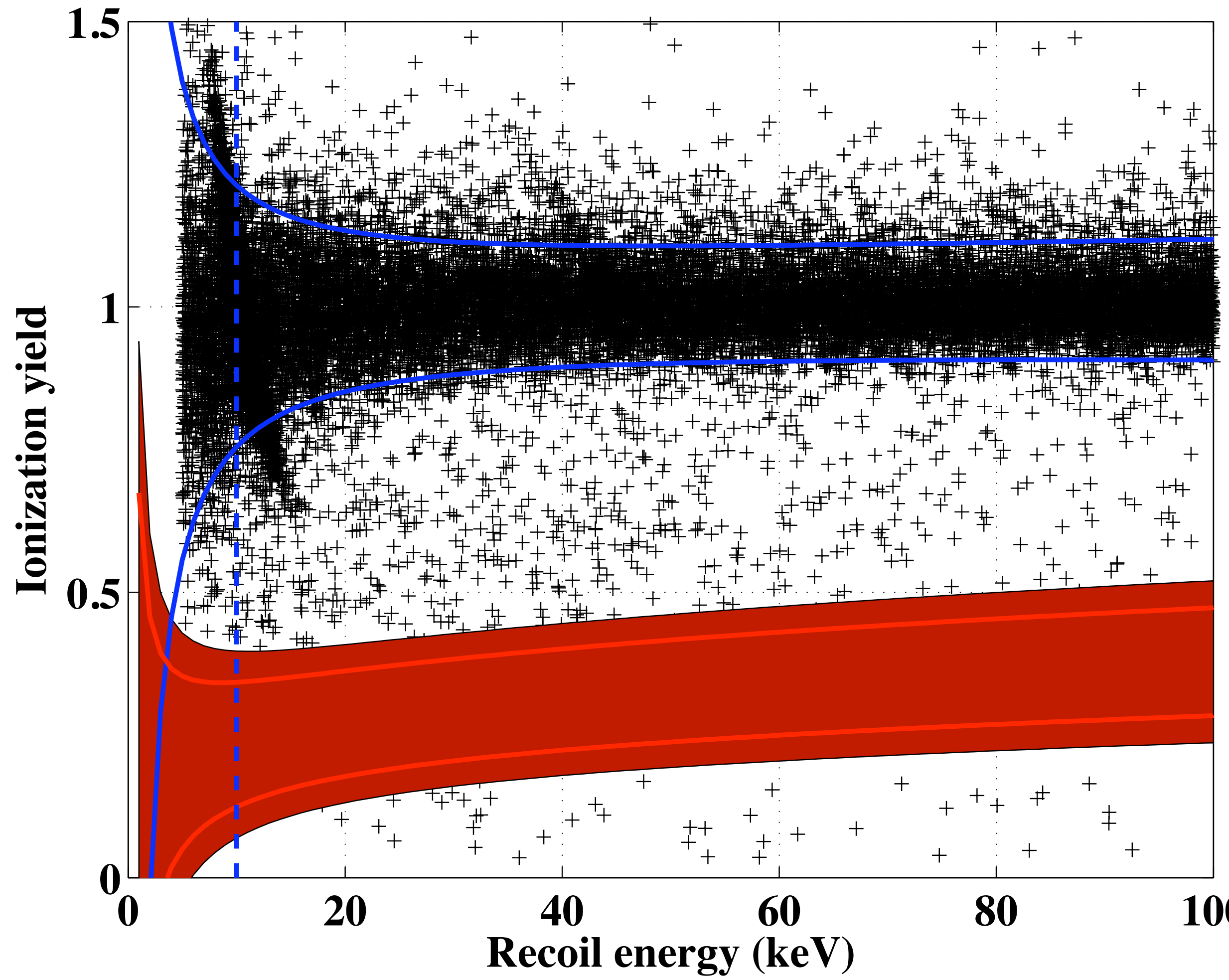
3σ region masked

☑ Hide unvetoed singles



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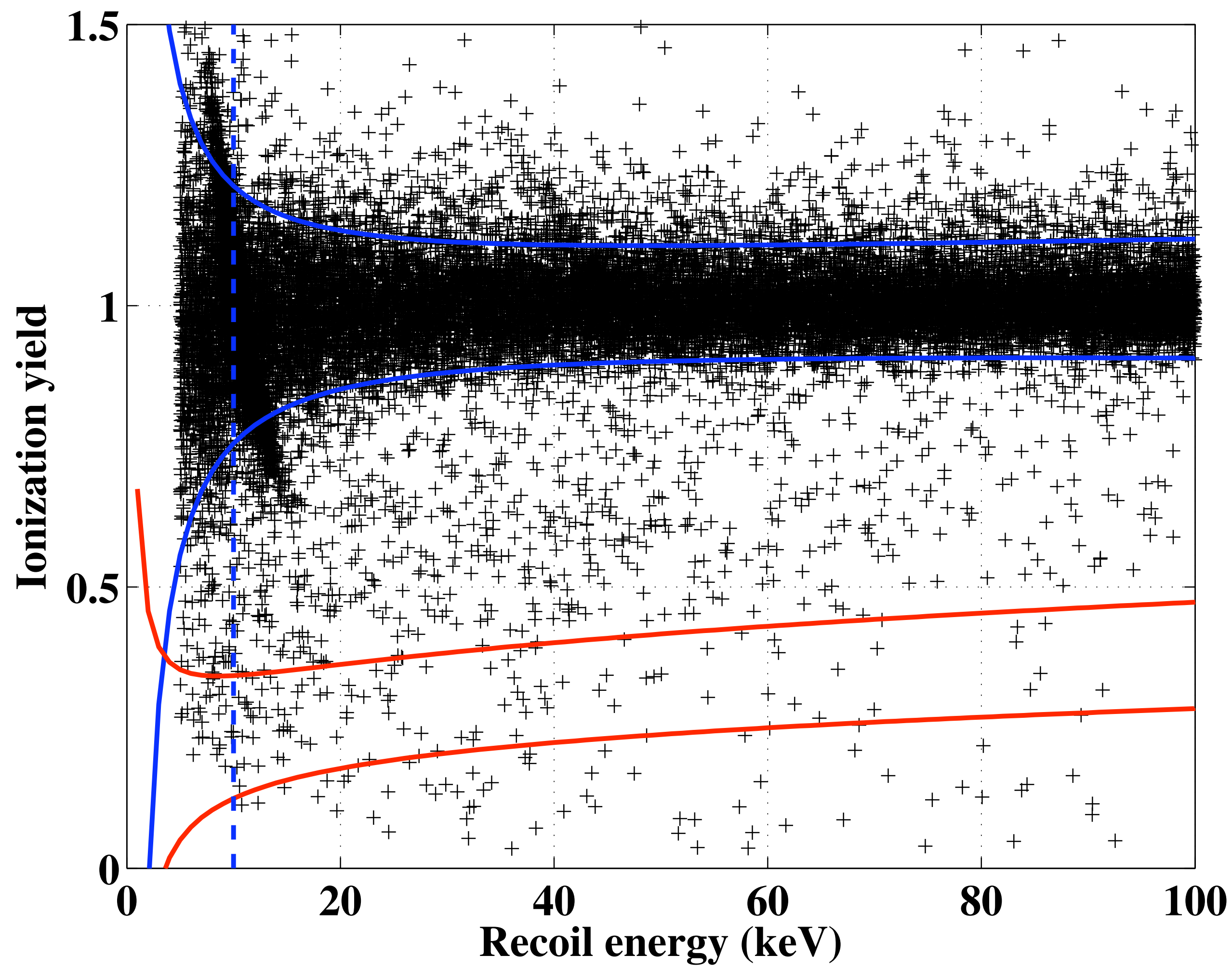
Lift mask, see 97 singles failing timing cut



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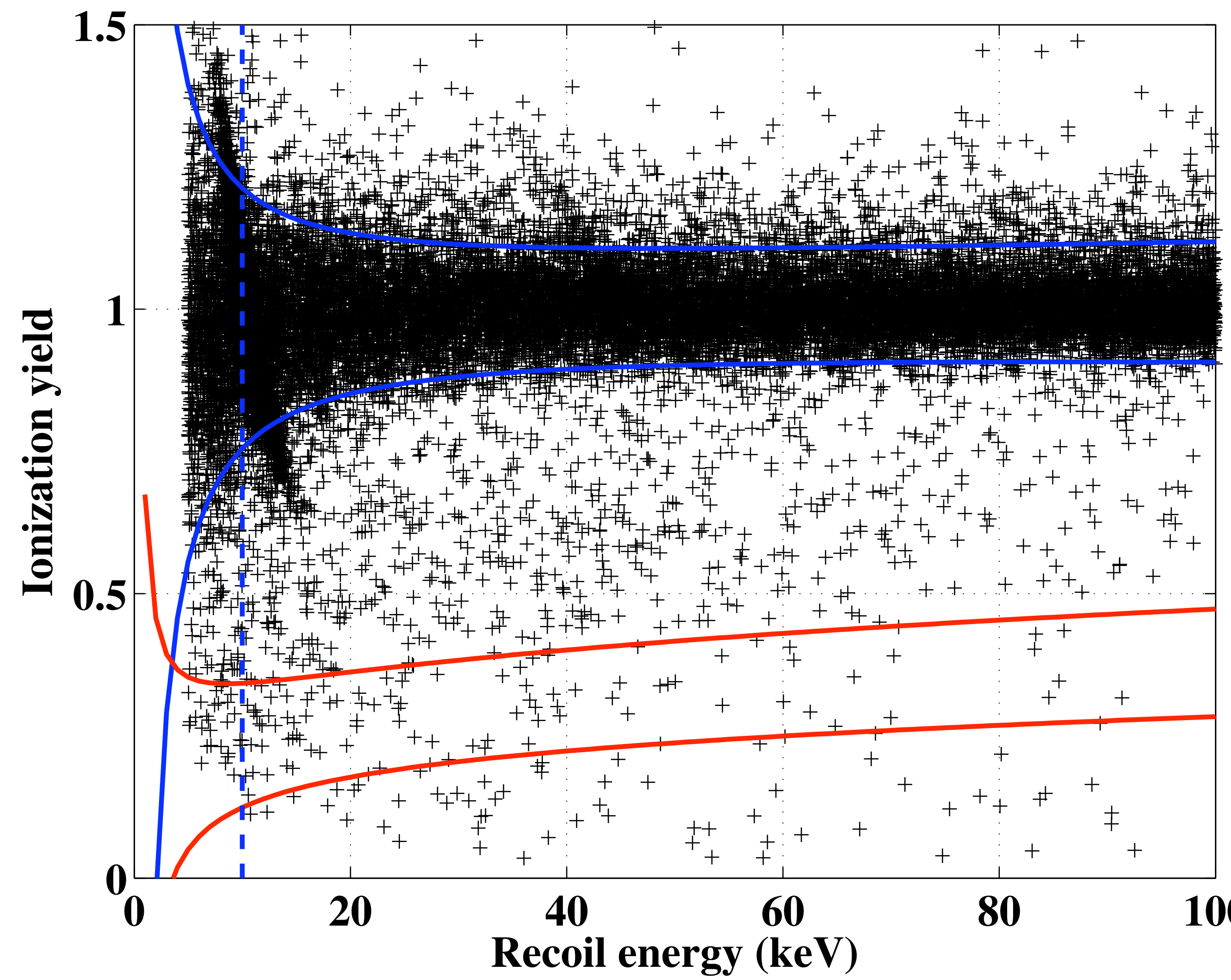
Apply the timing cut ...



Opening the Box

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Remaining 8 Si and 1 Ge undergoing further leakage studies.

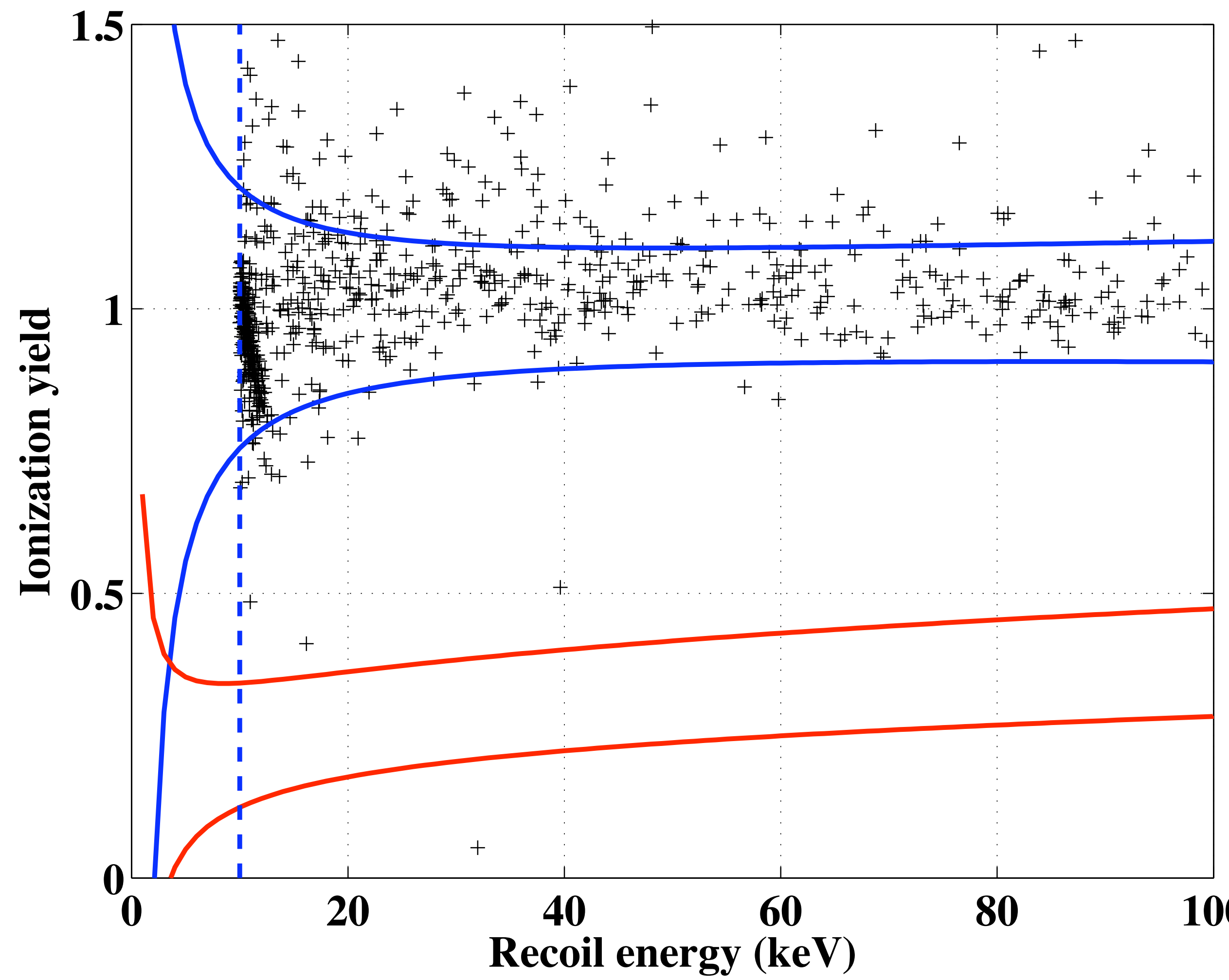
3σ region masked

☑ Hide unvetoed singles

Lift mask, see 97 singles failing timing cut

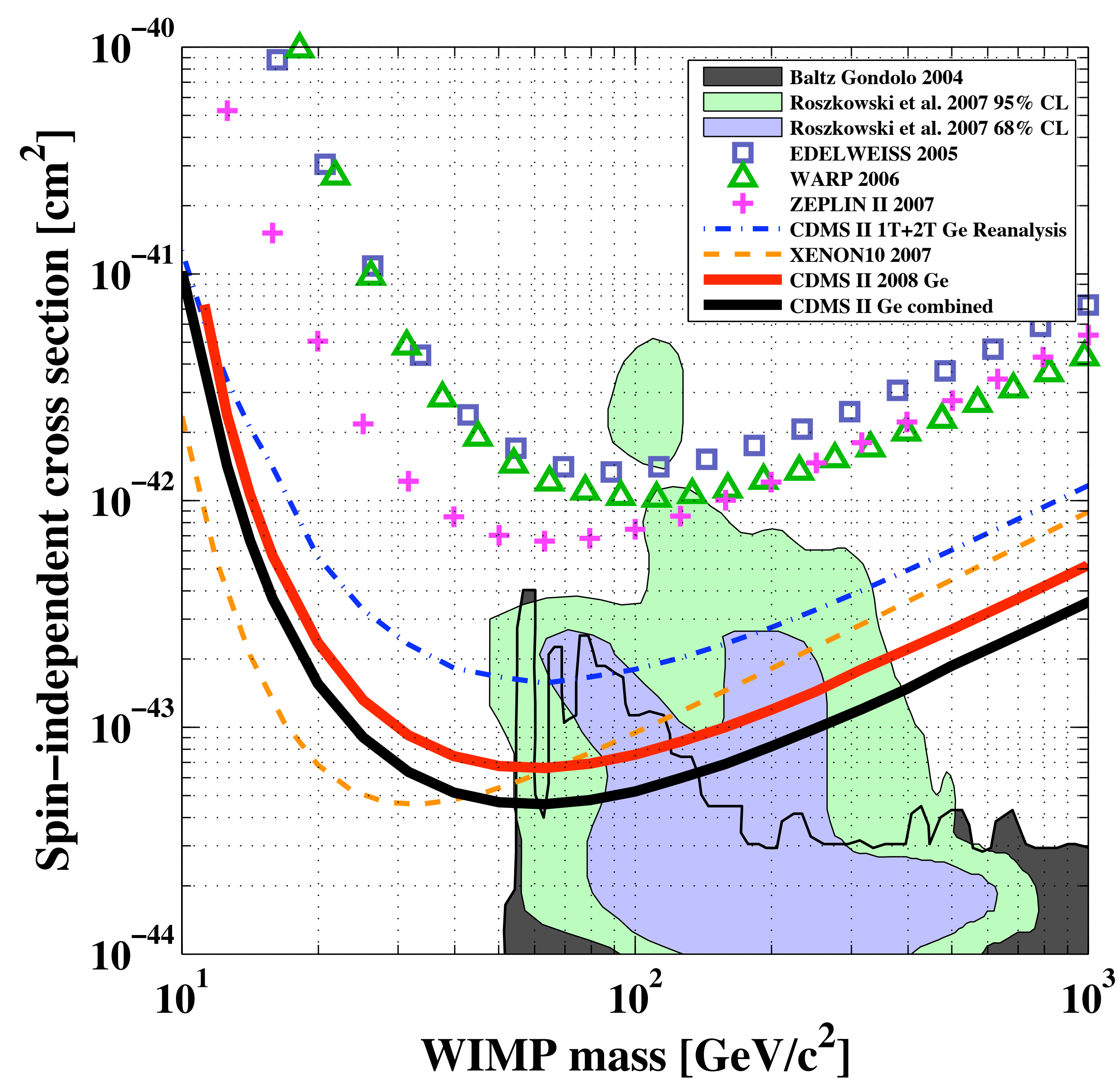
Apply the timing cut ...

NO EVENTS OBSERVED!



CDMS II Results

Upper limit at the 90% C.L. on the WIMP-nucleon cross-section is **4.6 x 10^{-44} cm^2** for a WIMP of mass **60 GeV/c^2**

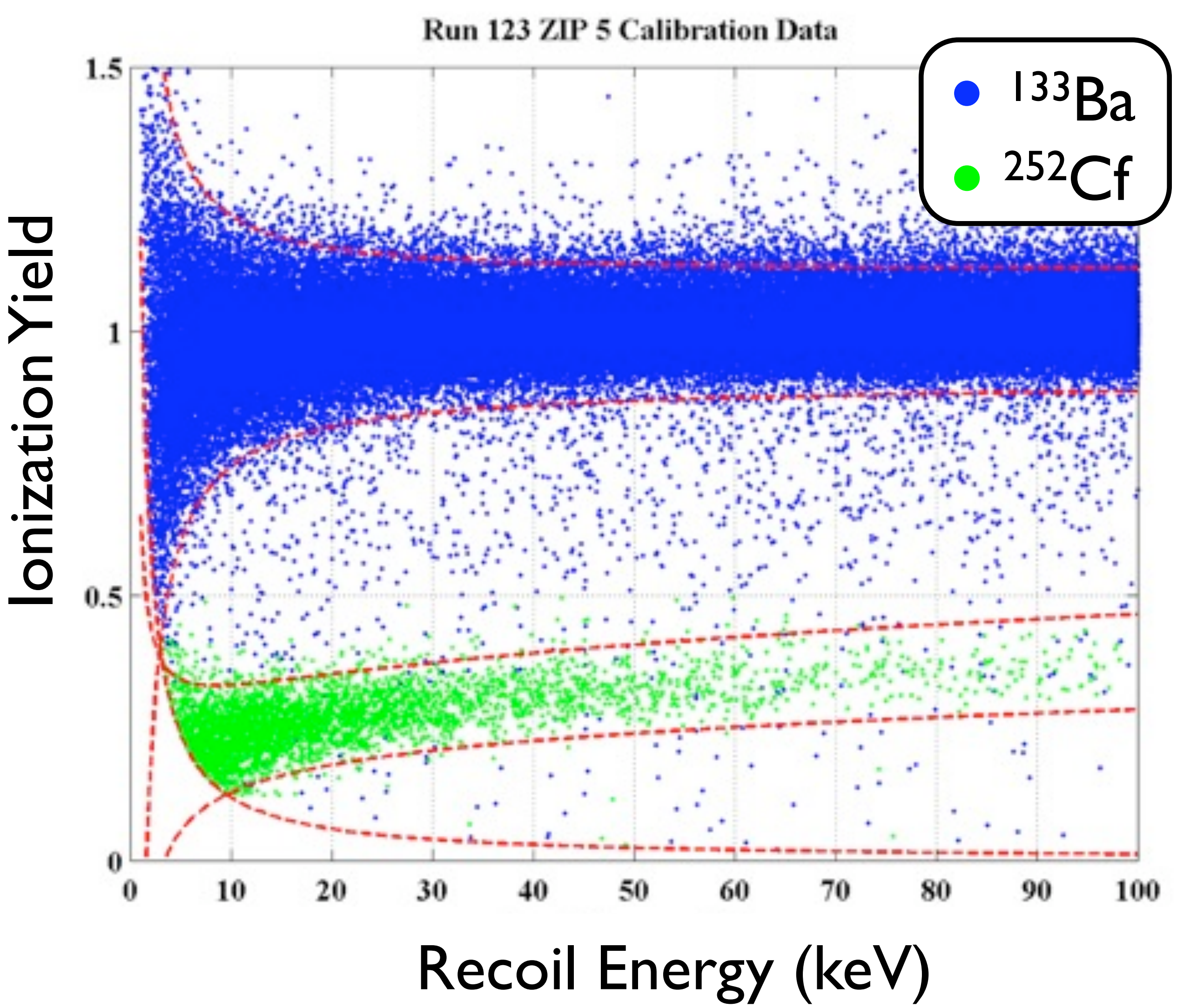


PRL 102, 011301 (2009)

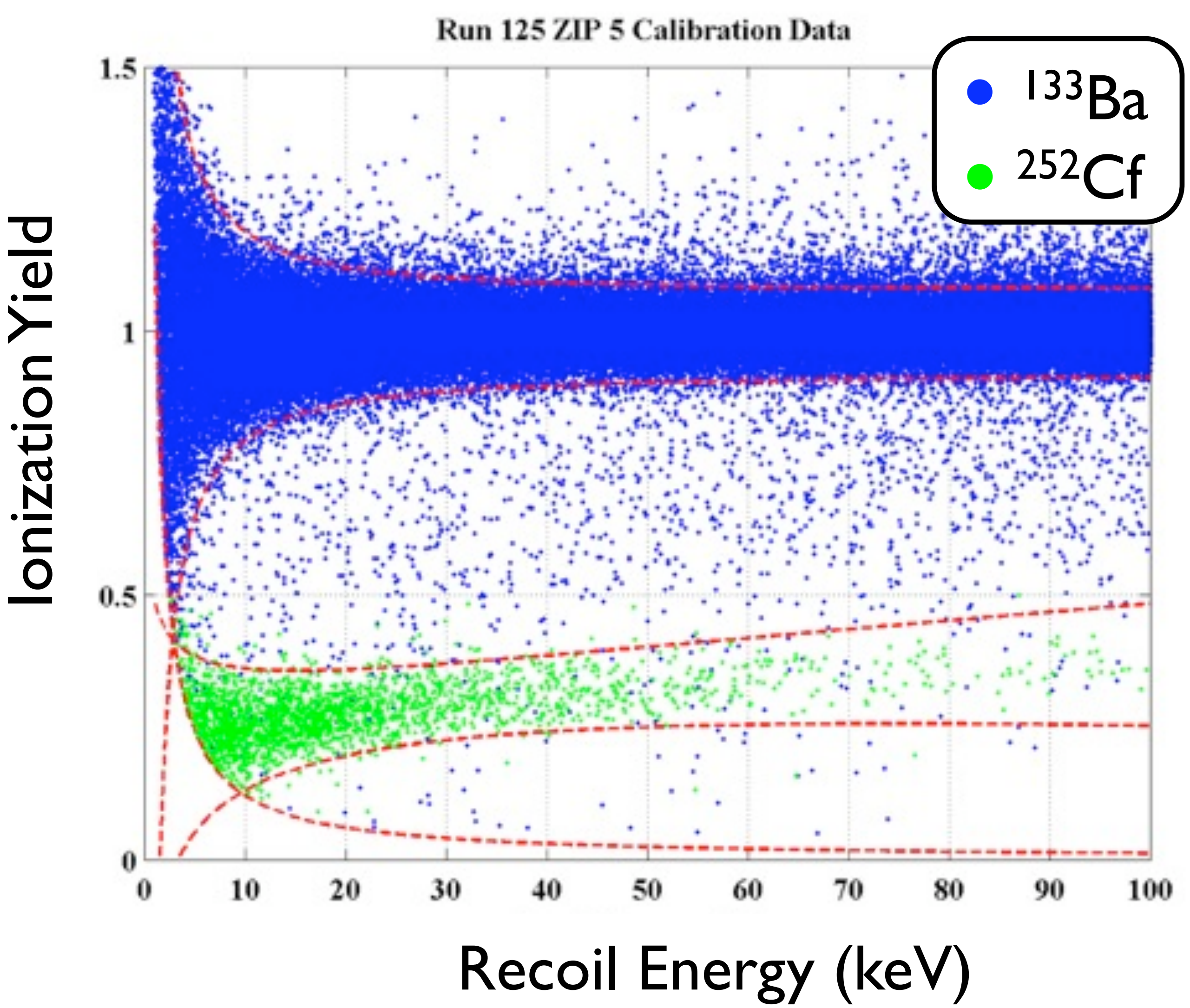
Yield Discrimination

Previous Analysis

PRL 102, 011301 (2009)



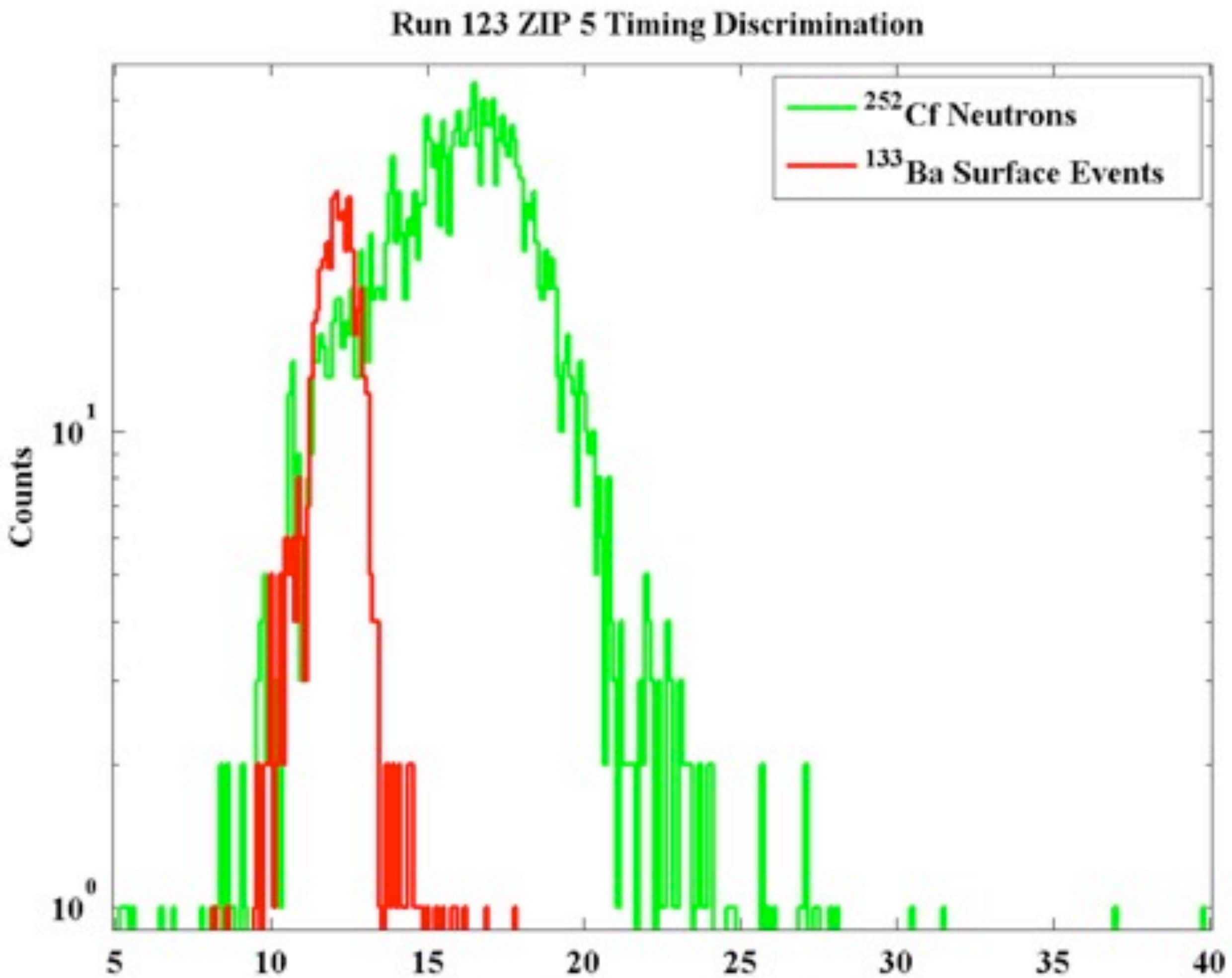
Current Analysis



Peak at Timing Quantities

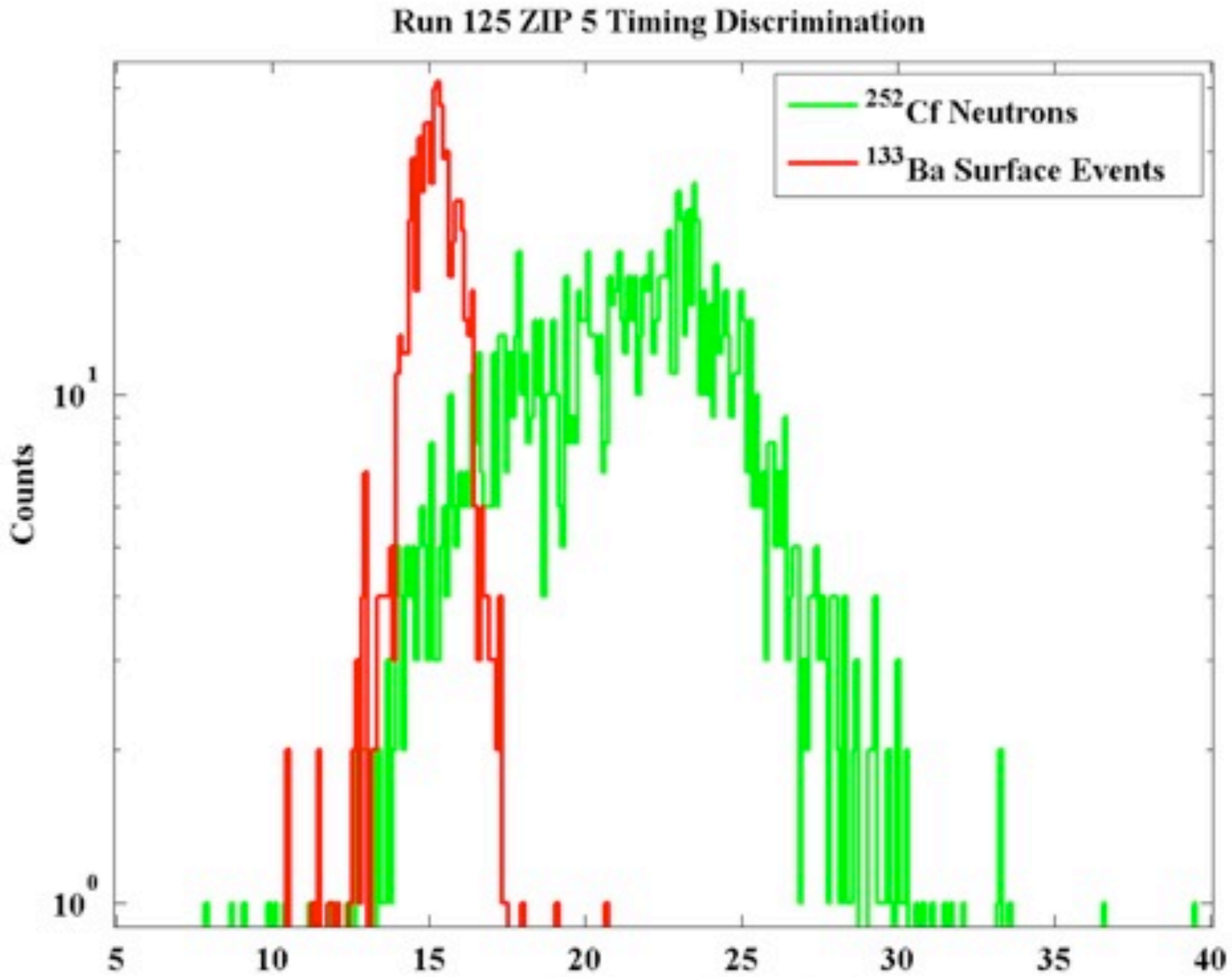
Previous Analysis

PRL 102, 011301 (2009)



Timing Parameter

Current Analysis

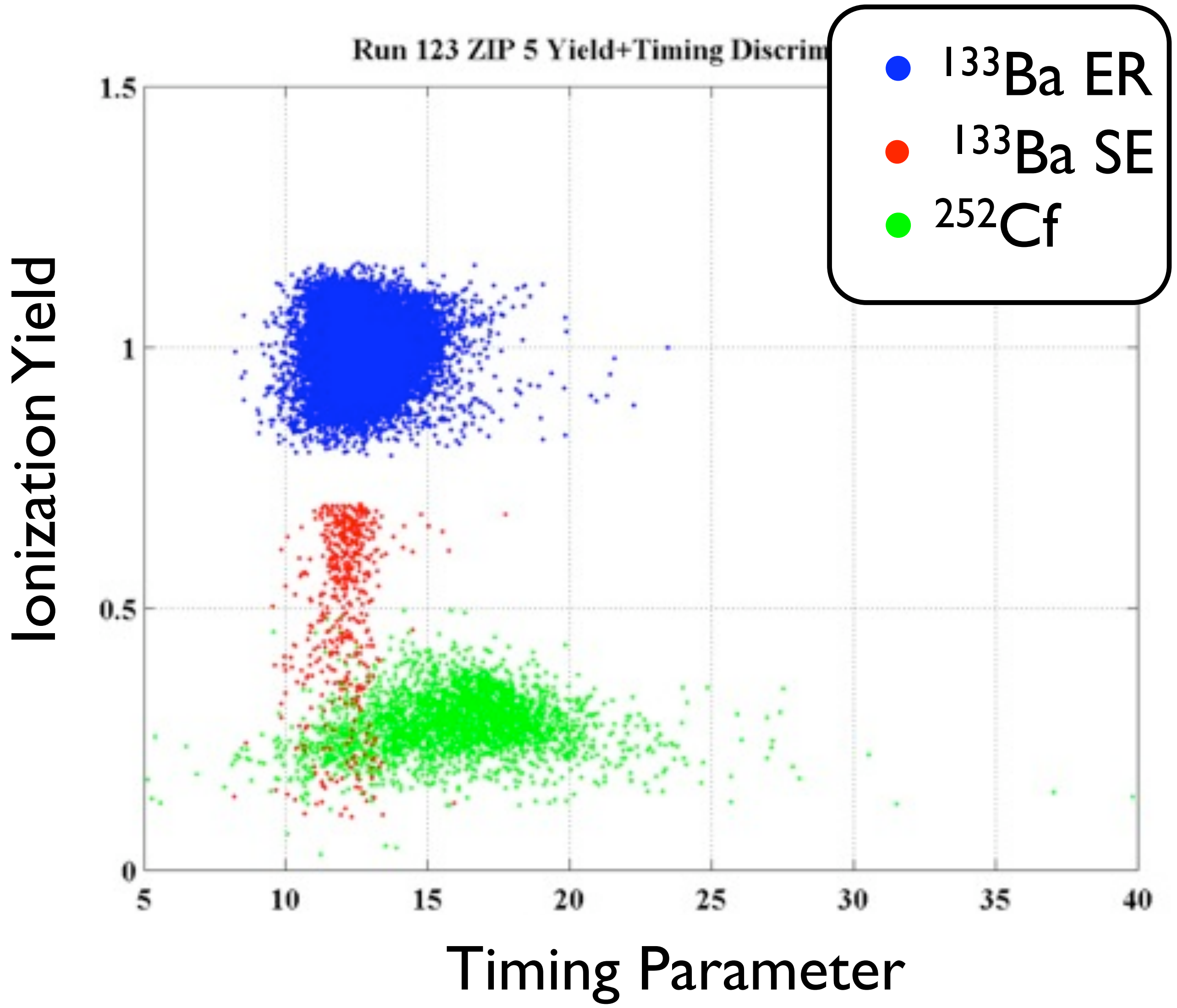


Timing Parameter

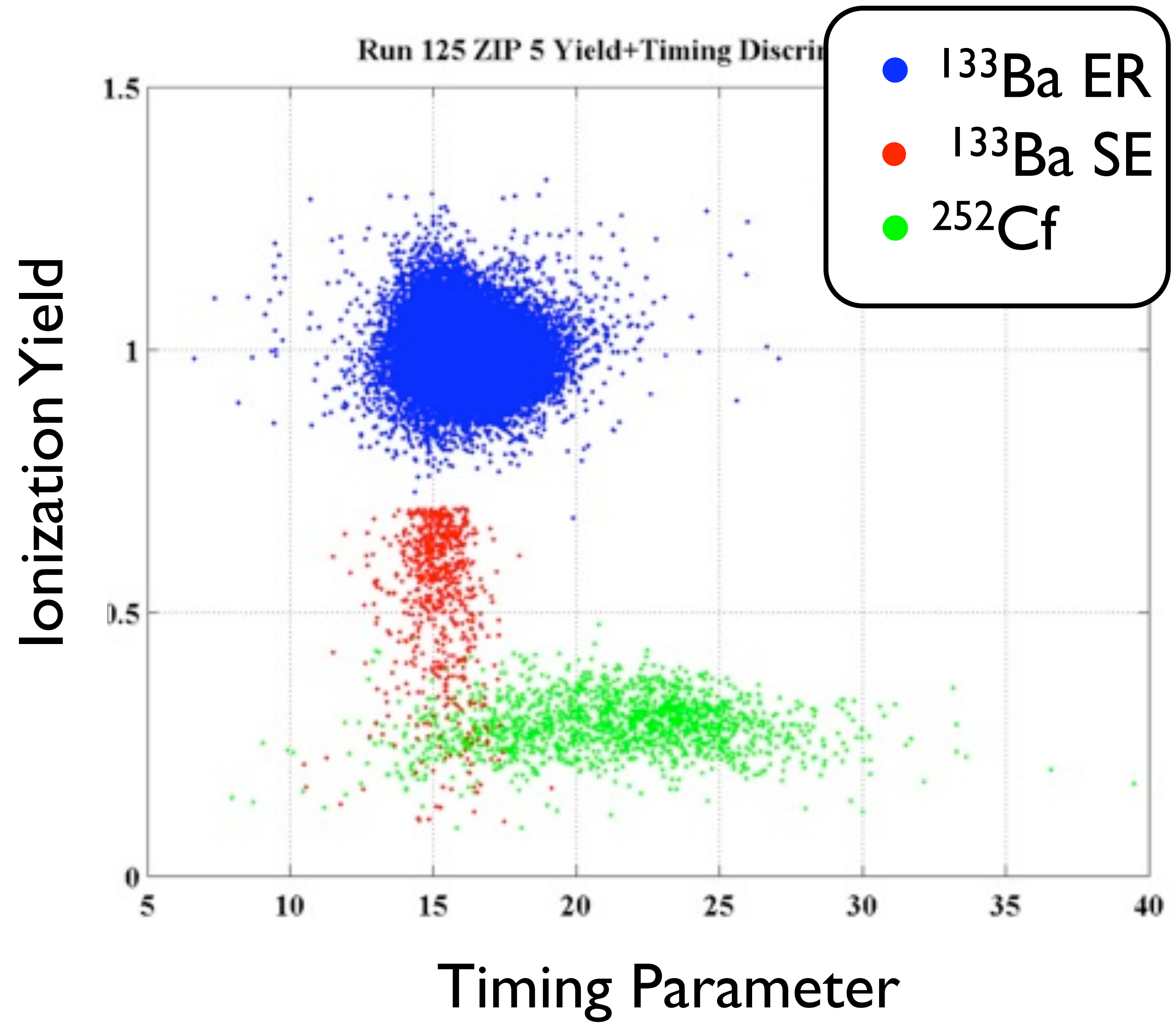
Another View of Discrimination

Previous Analysis

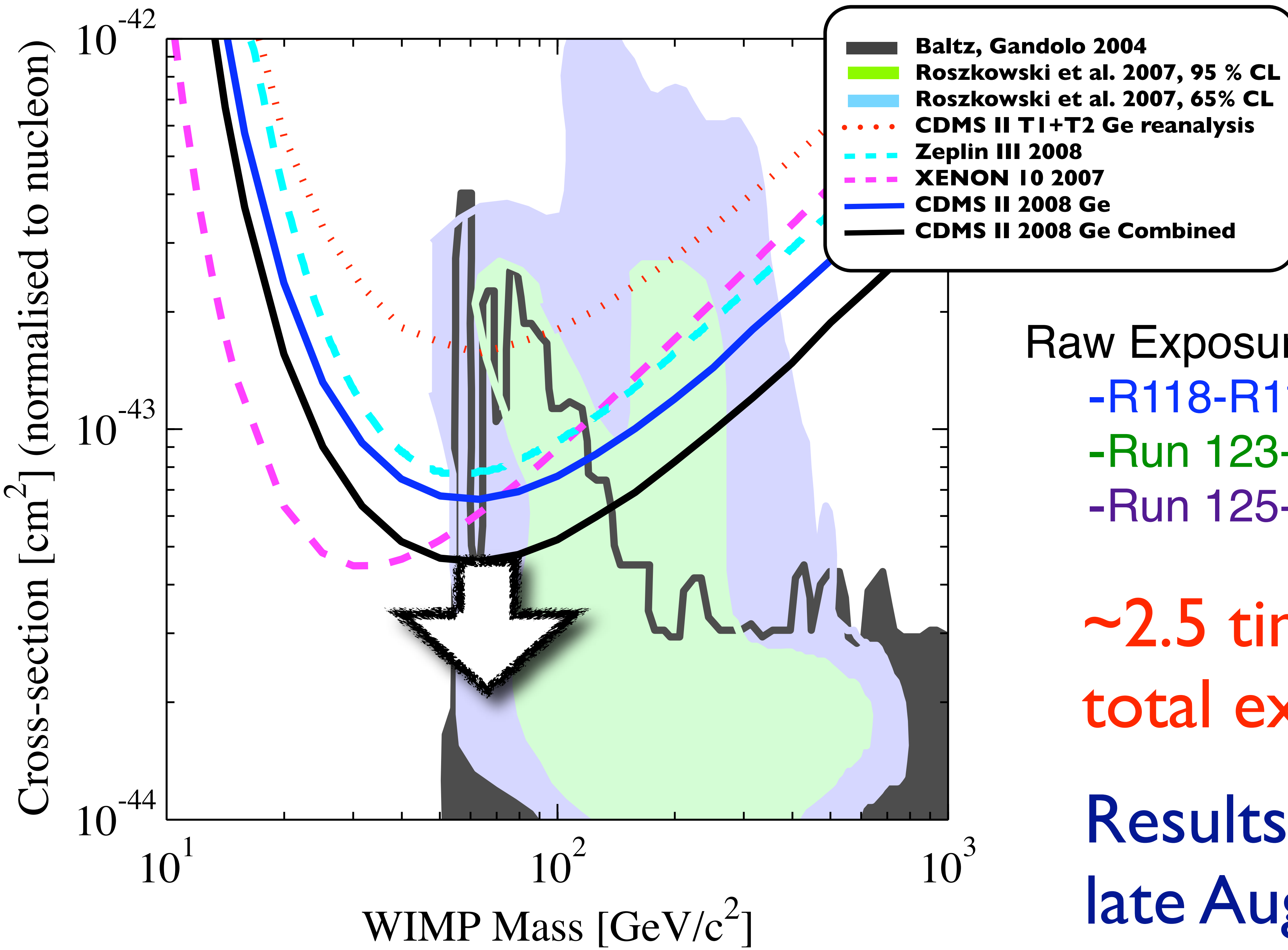
PRL 102, 011301 (2009)



Current Analysis



Projected Sensitivity (2009)



Raw Exposure

- -R118-R119 = ~120 kg-d
- -Run 123-124= ~400 kg-d
- -Run 125-128 = ~750 kg-d

~2.5 times more total exposure

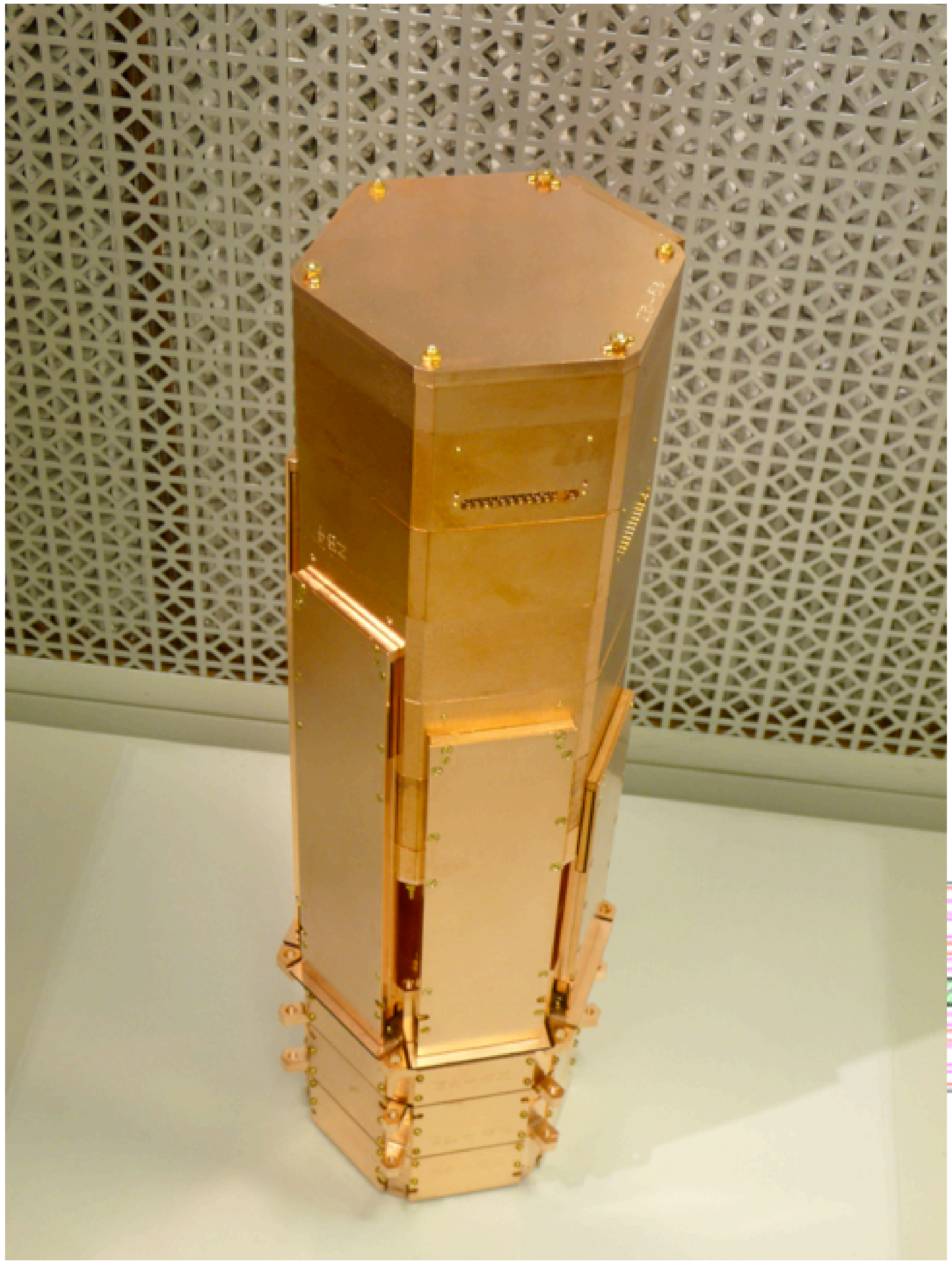
Results expected late Aug. 09

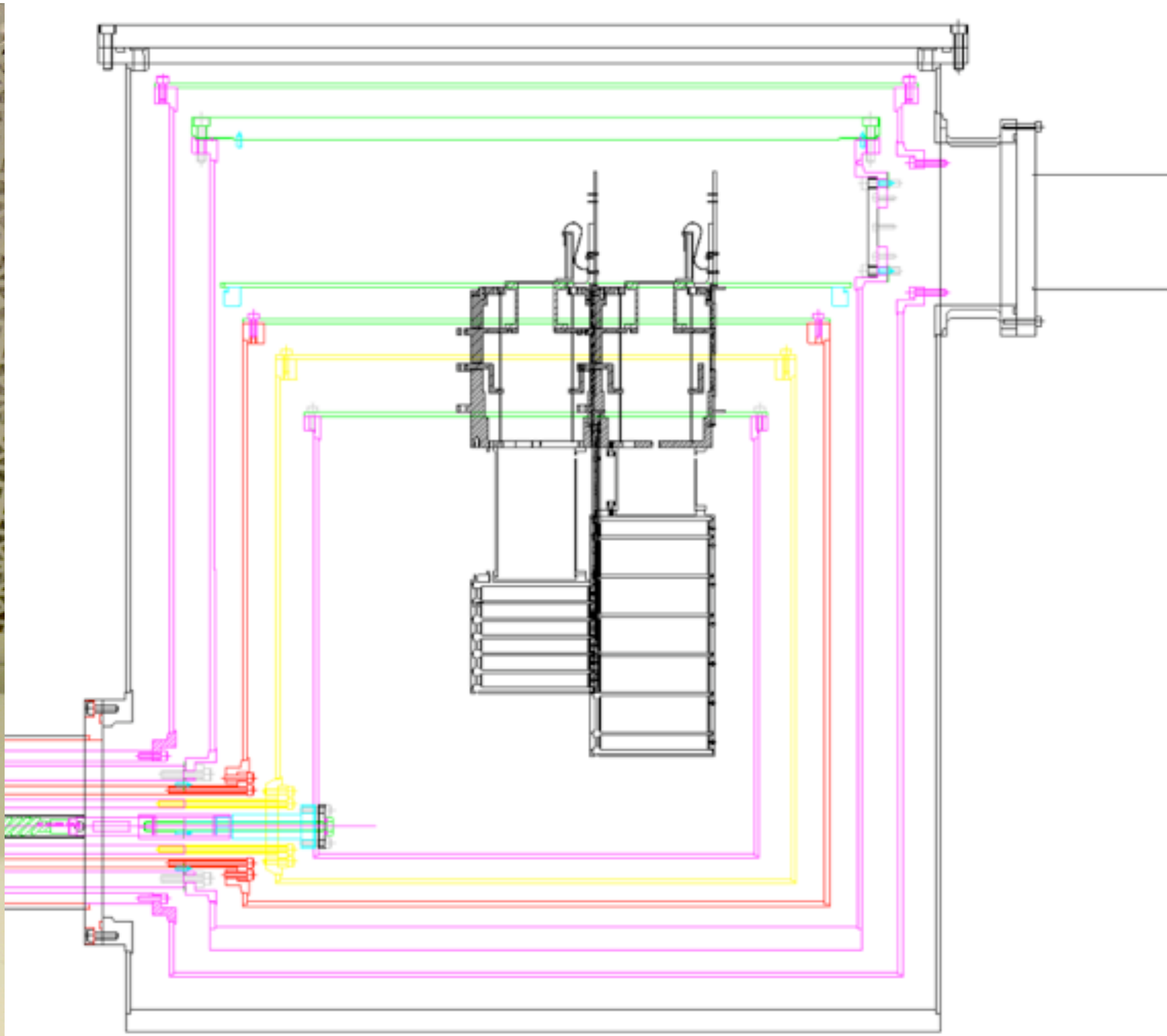
The Future

Next Step: SuperCDMS

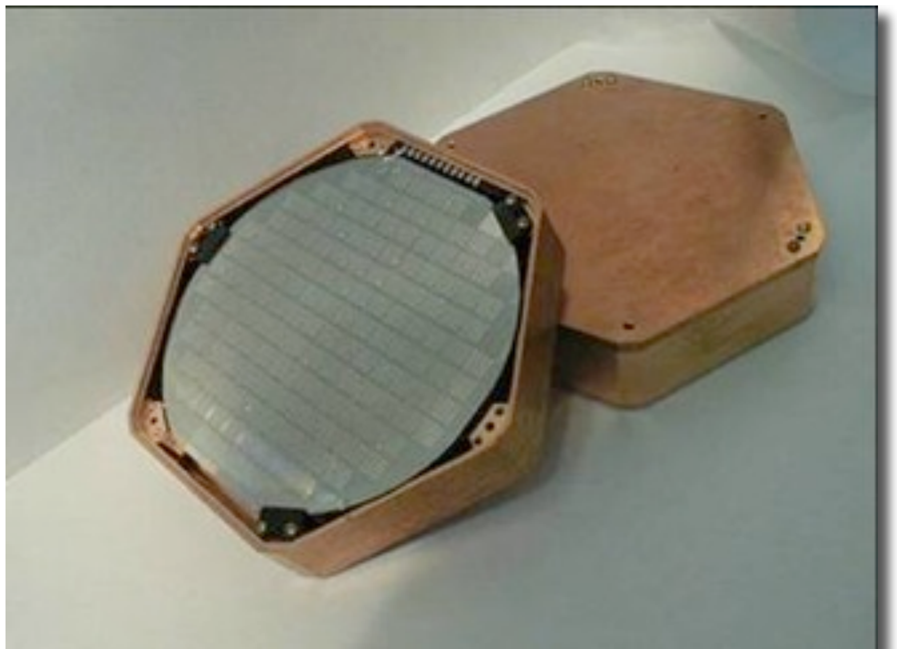
- Last CDMS II data run taken on March 18, 2009
- March 19, 2009: Warm up to begin the installation and commissioning of the first SuperCDMS detectors
- First step in realization of the proposed SuperCDMS Soudan project (15 kg Ge deployed in existing Soudan setup)
  - SuperTowers 1-2 funded
  - SuperTowers 3-5 under review
- Eventual goal: SuperCDMS SNOLAB (100 kg Ge deployed at SNOLAB)

What is a SuperTower?





Detector Improvements

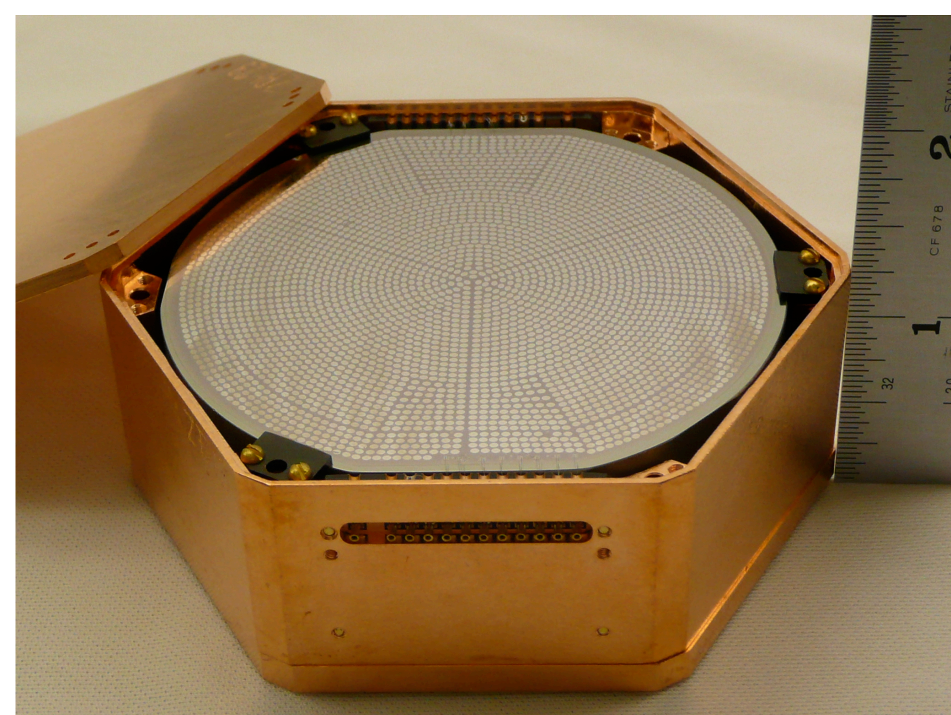


√ **SuperTower** = five 1-inch thick detectors + two 1-cm thick ionization only detectors

√ **Increase thickness** (2.5 x).

➡ better surface/volume

➡ increase manufacture



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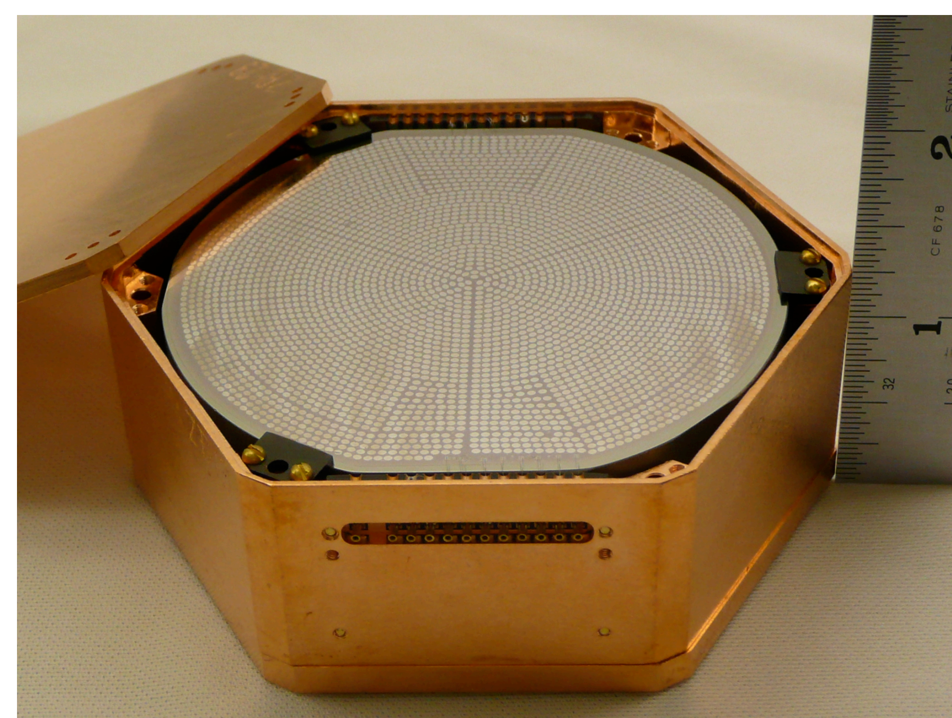

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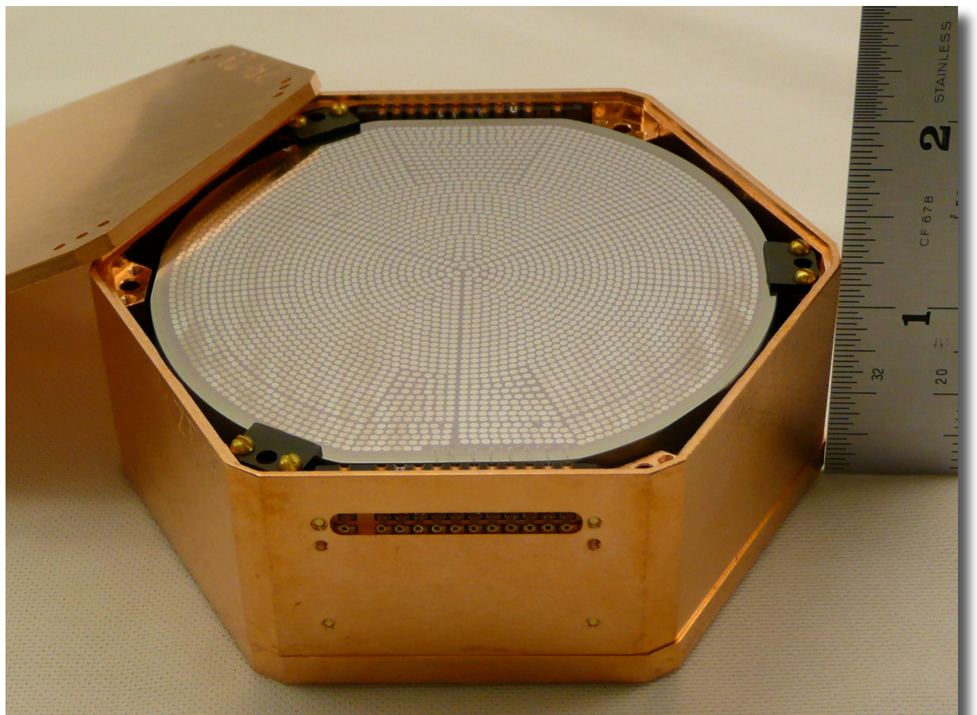

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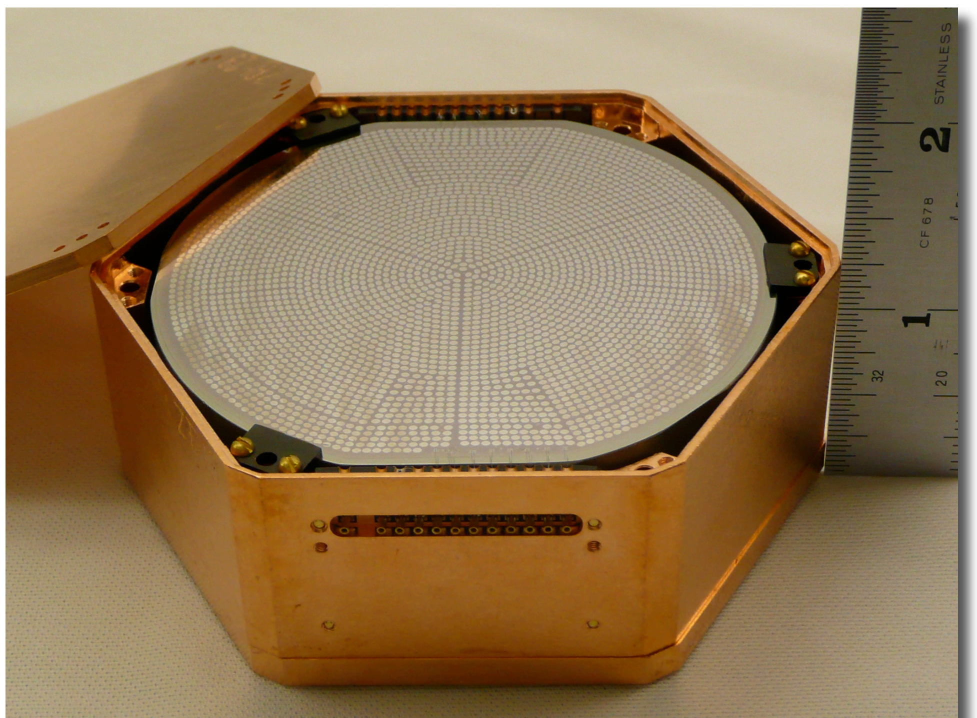

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√ enhance phonon signal to noise

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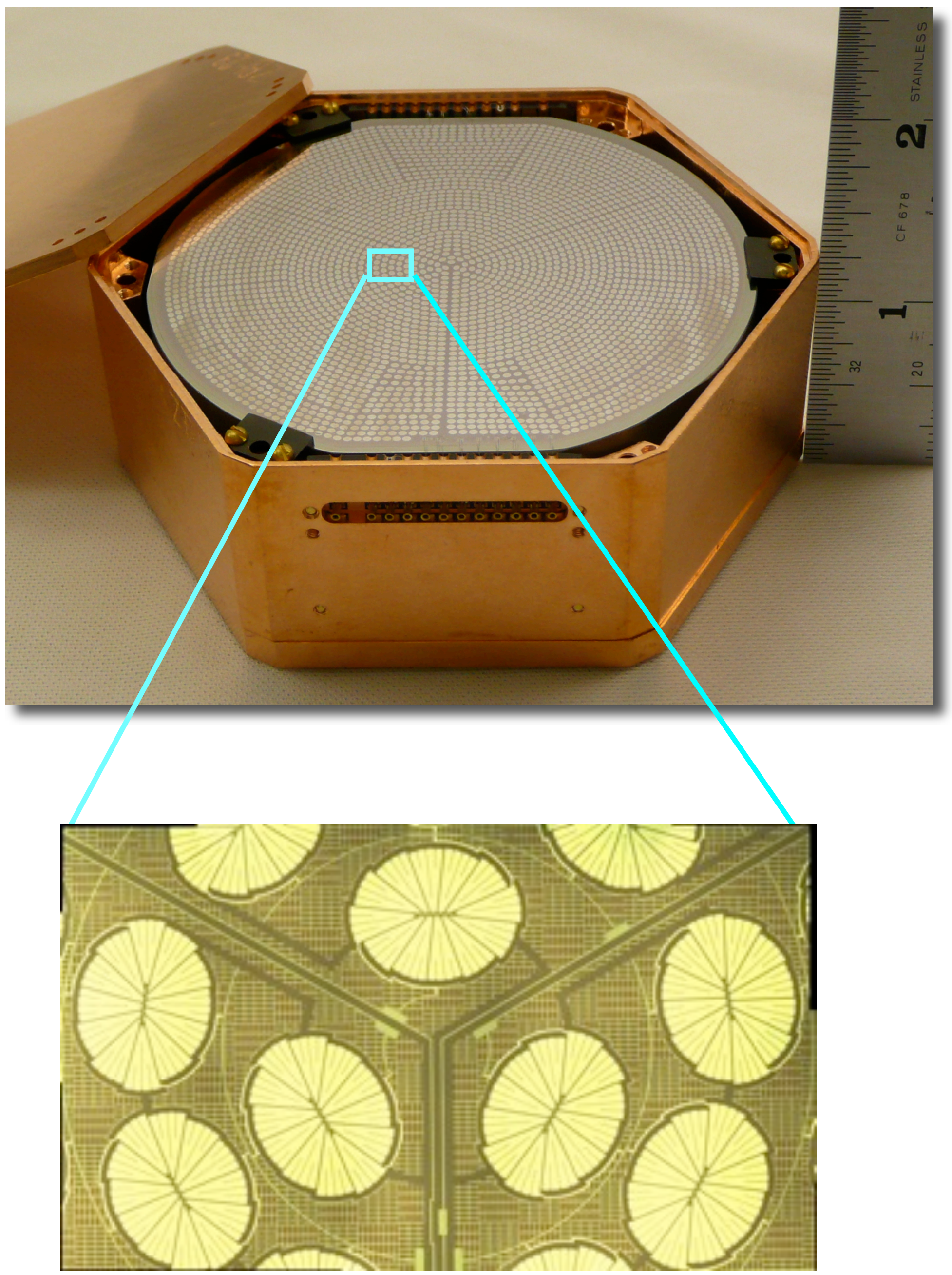

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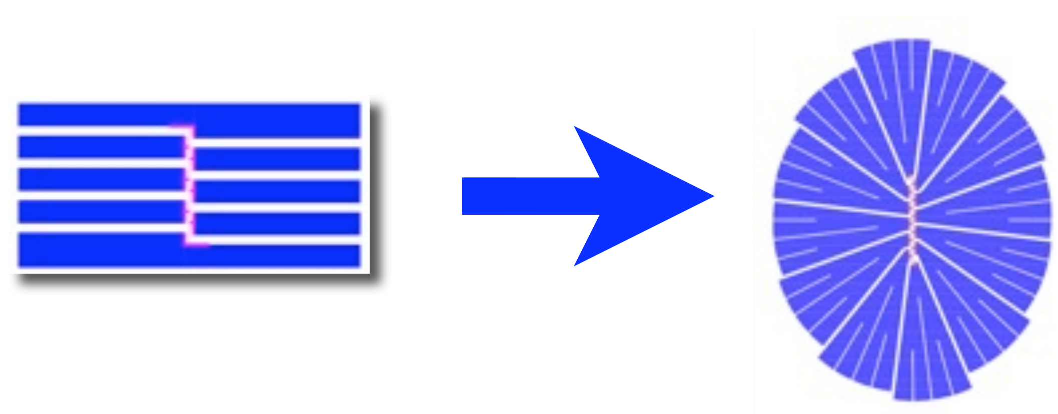

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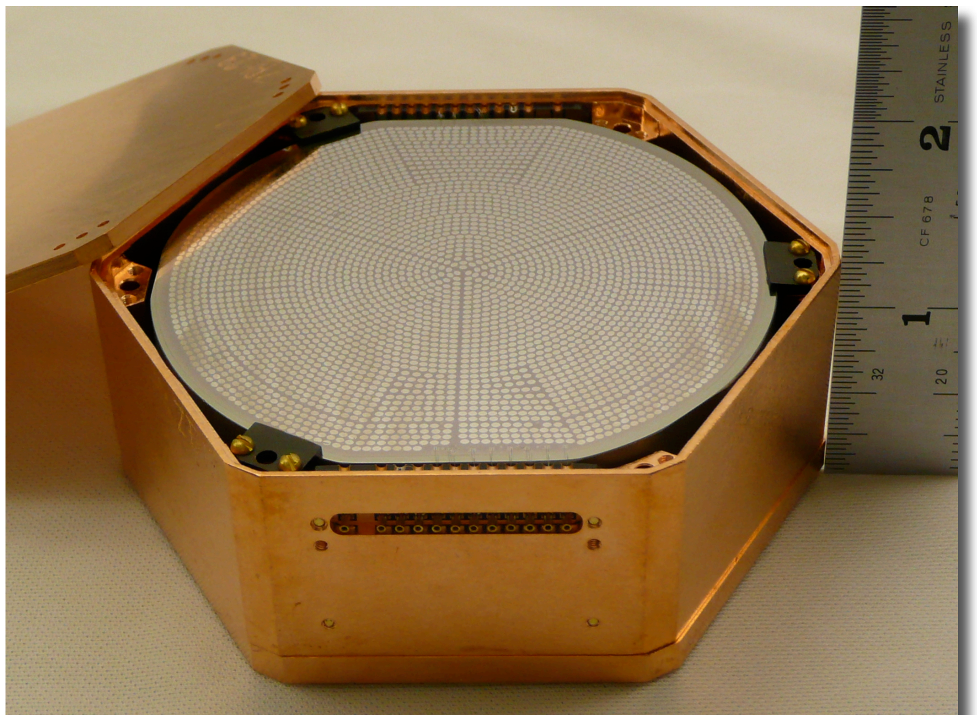

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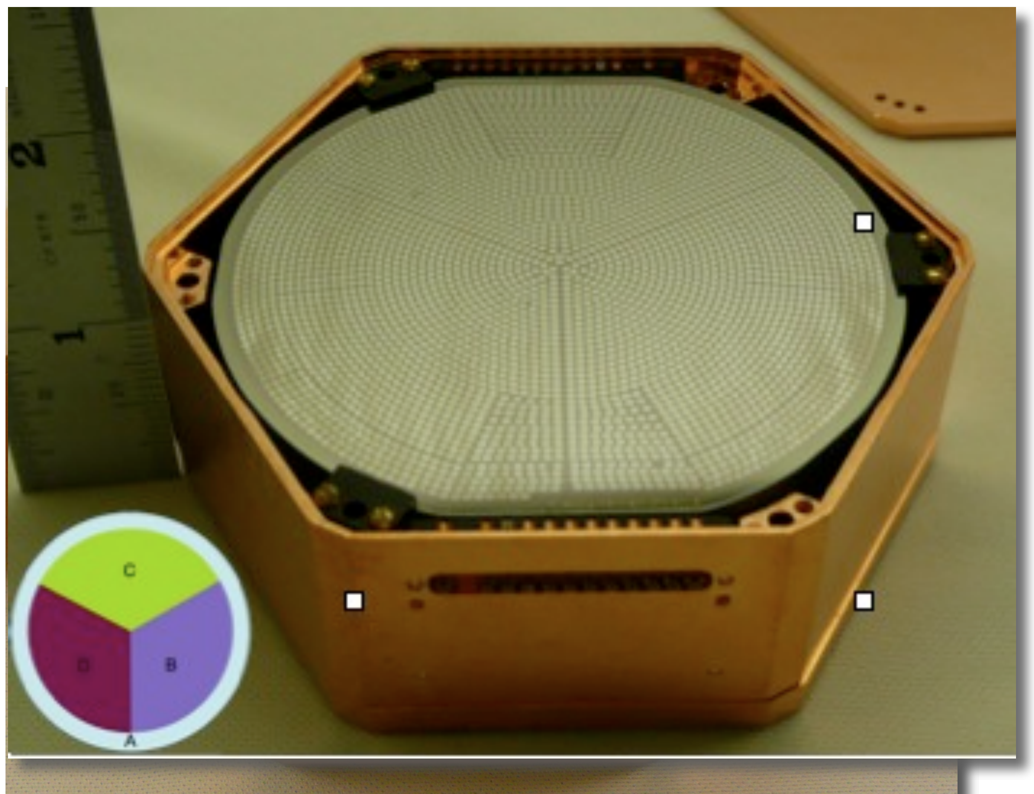

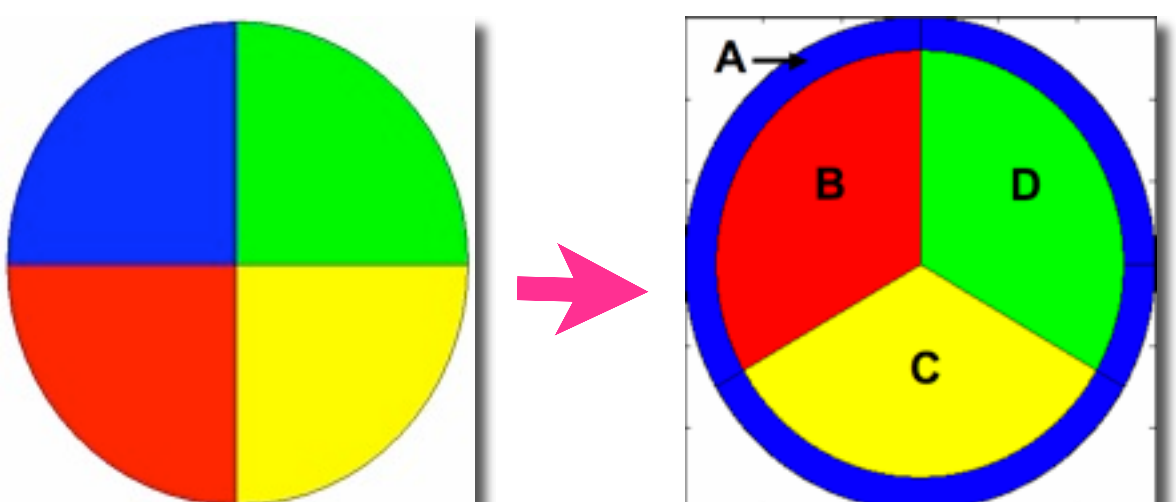

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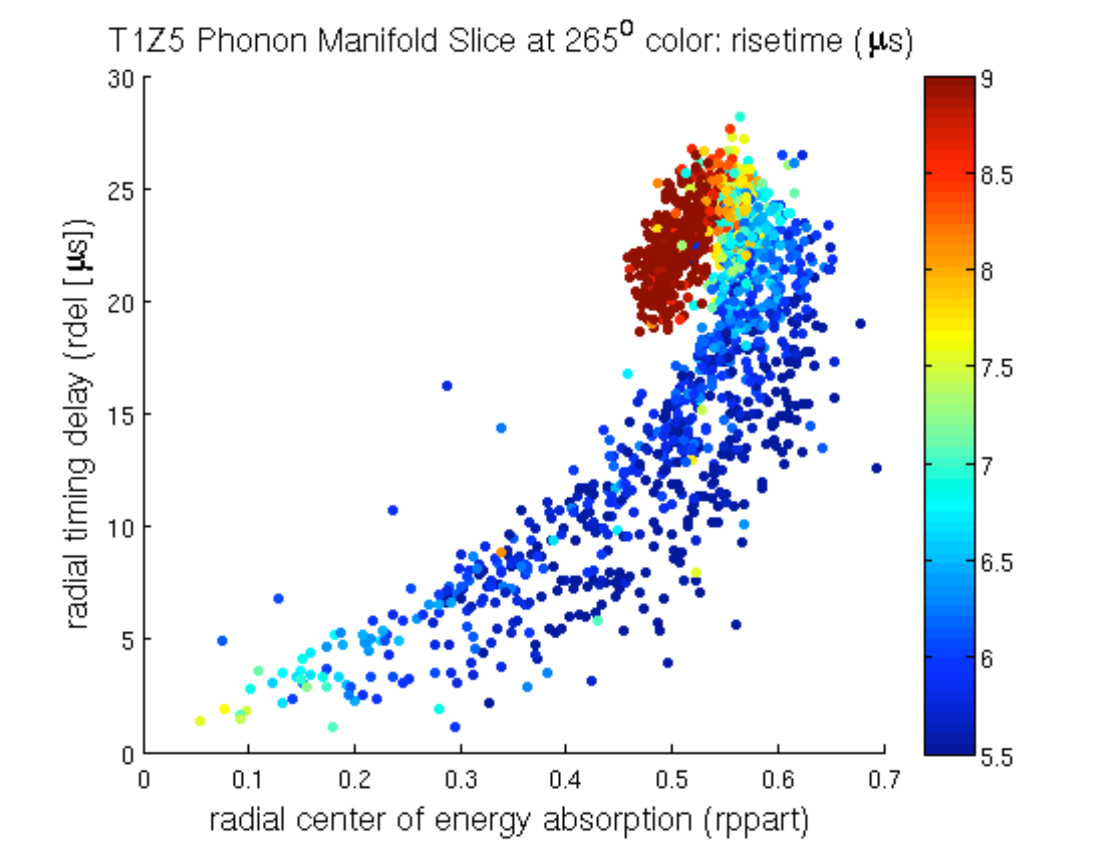
✓ **Optimize Al fin design** (increase Al coverage)
✓ enhance phonon signal to noise

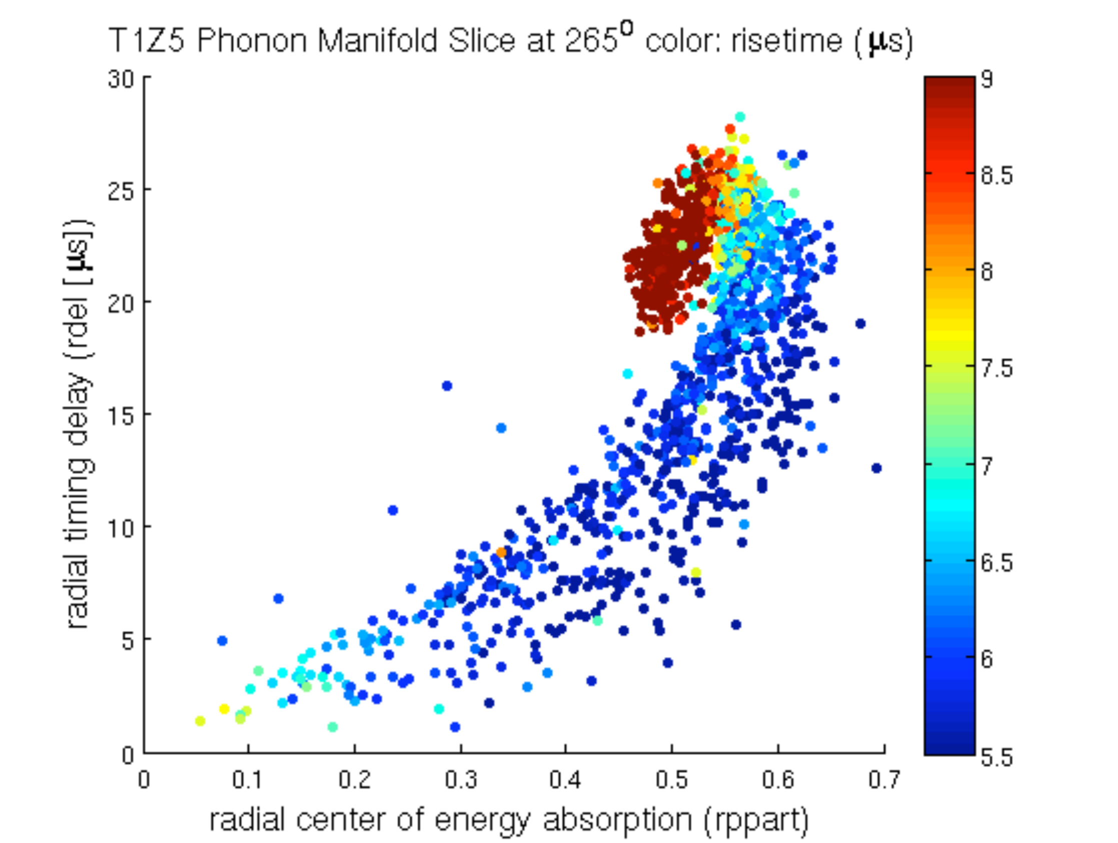
✓ **Optimize phonon sensor layout**
- ➡ better rejection of surface events

Phonon Sensor Layout



- Events at large radius have delay times similar to events at intermediate radius.
- Effect due to phonons reflecting off outer cylindrical walls back into central region of detector.

Phonon Sensor Layout



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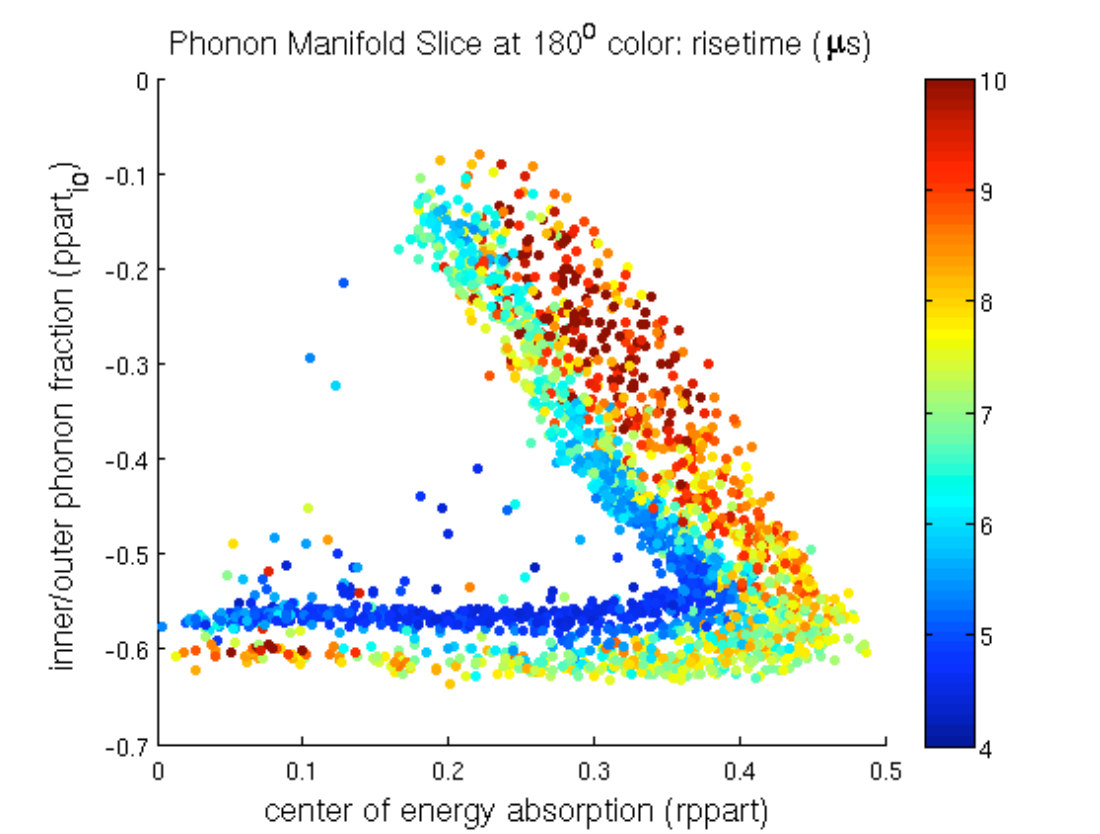
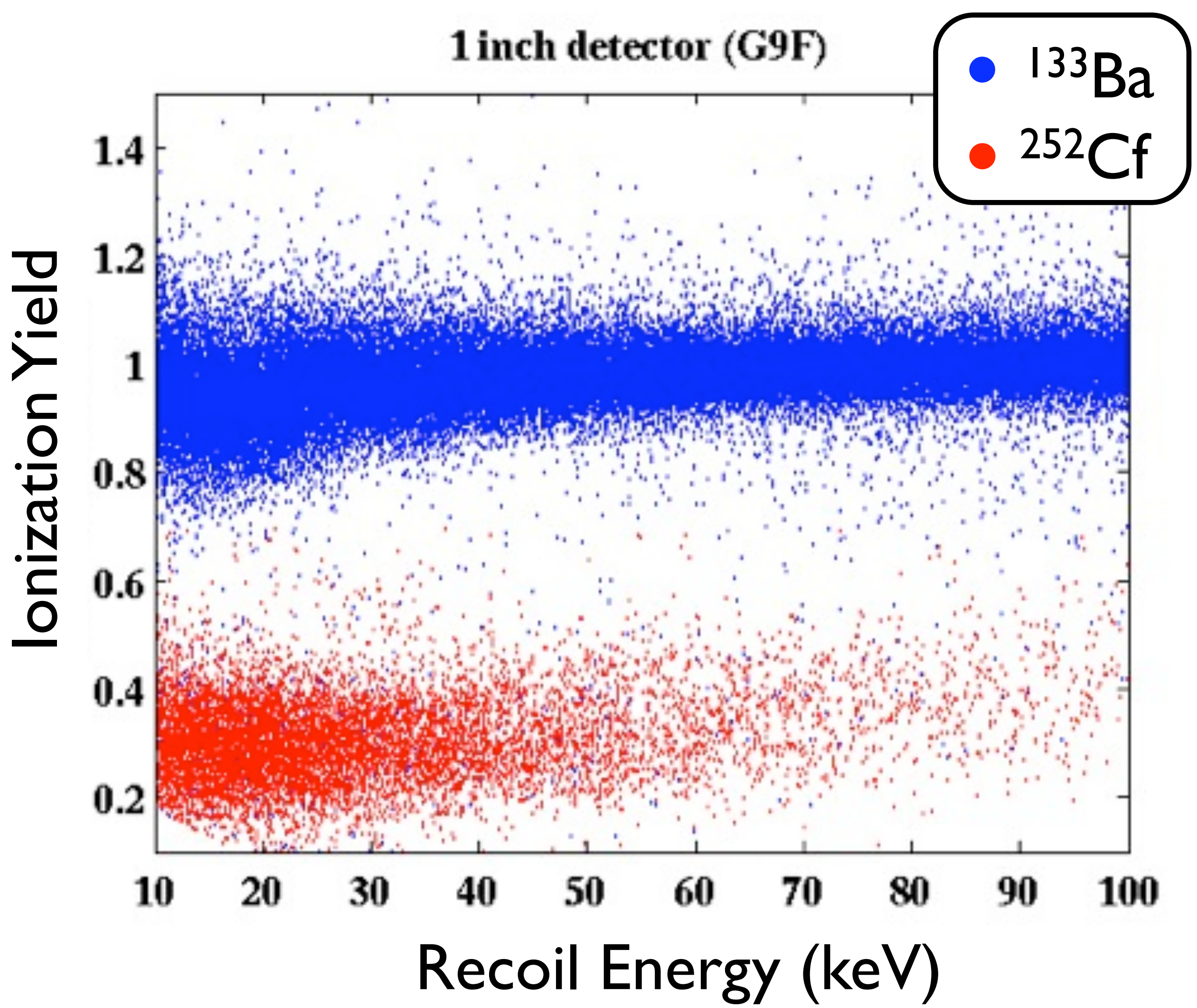


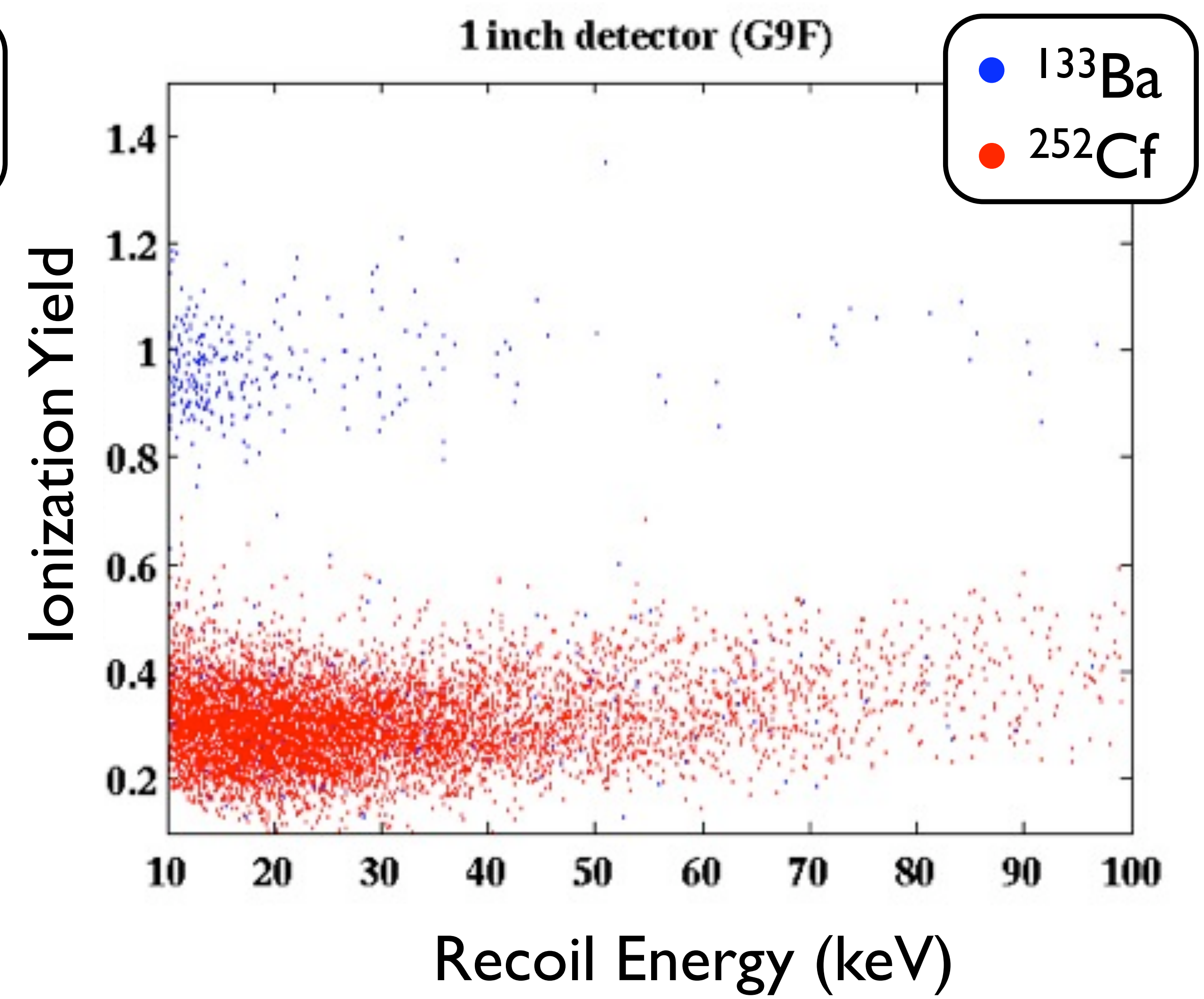
- New metric compares start times of inner 3 channels to the start time of outer channel, breaks degeneracy.

ST1 Surface Testing

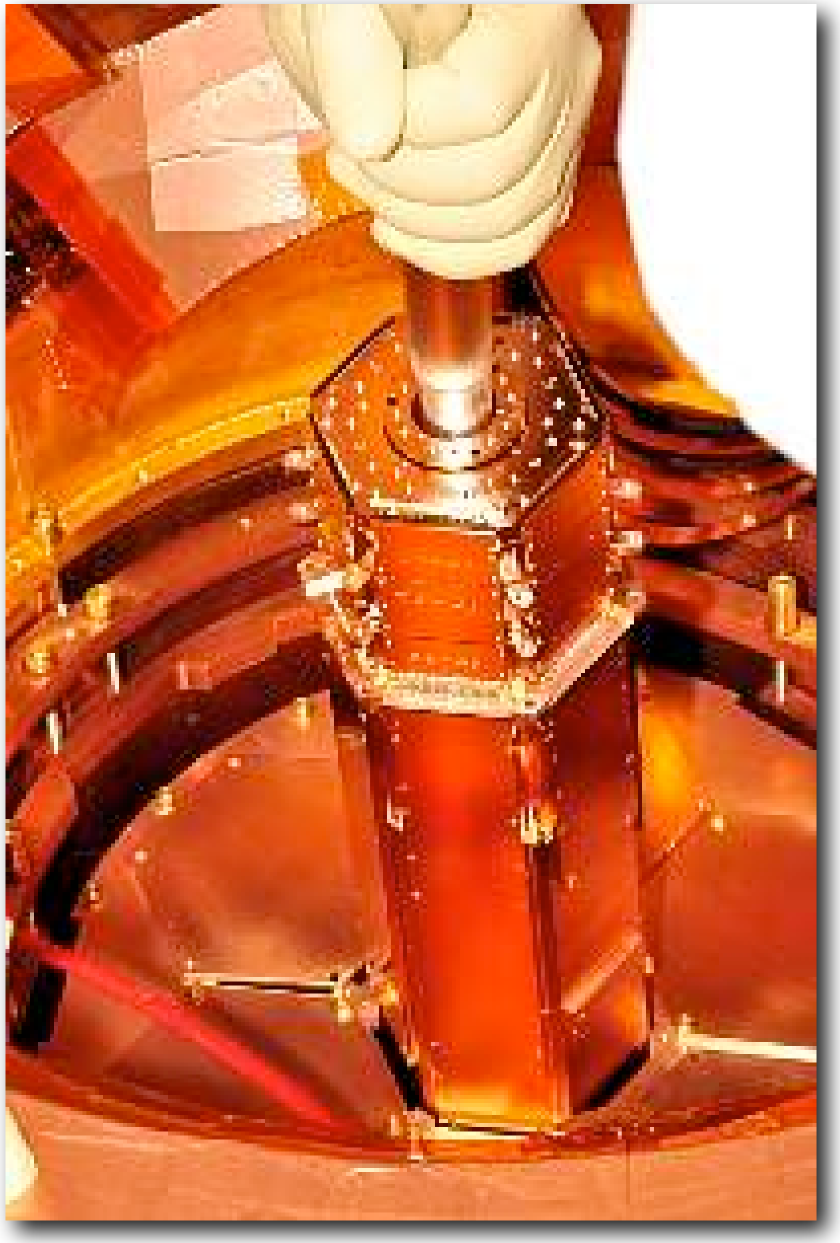
Before Timing Applied

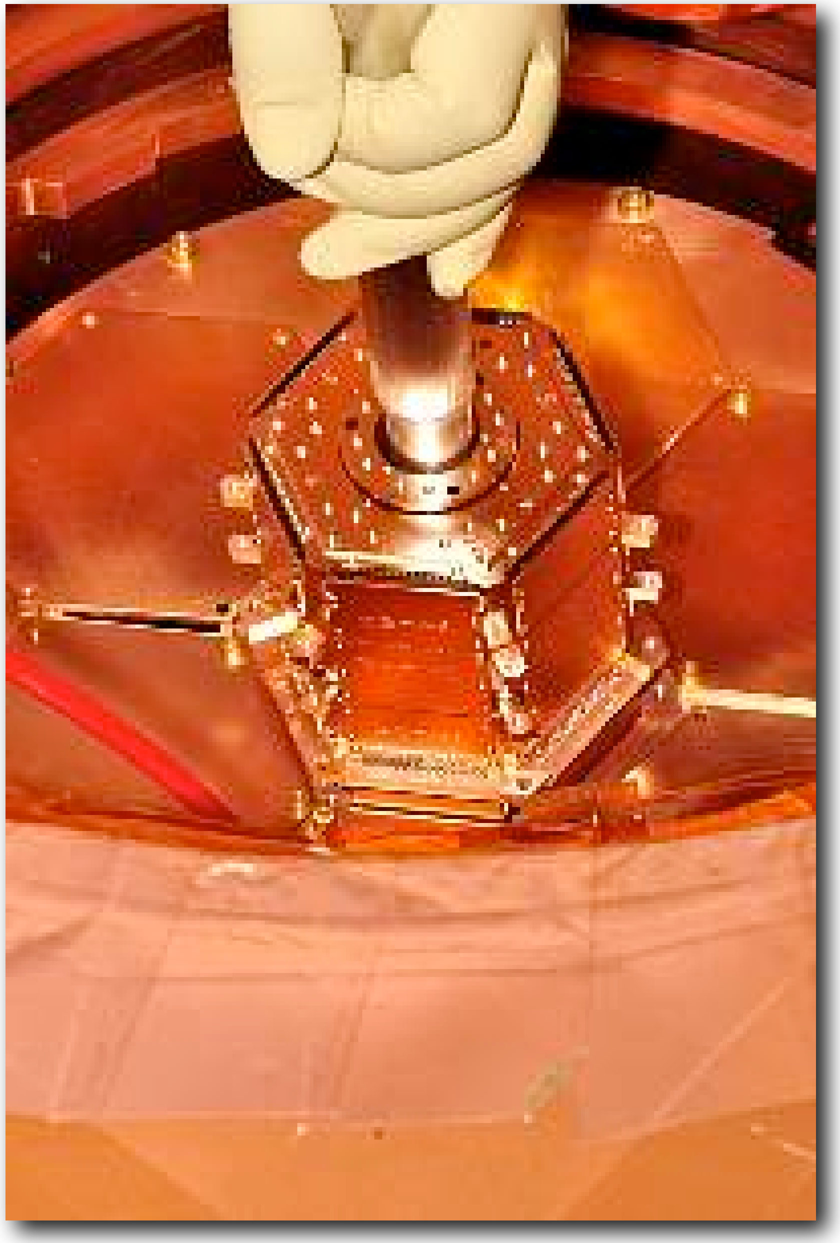


After Timing Applied



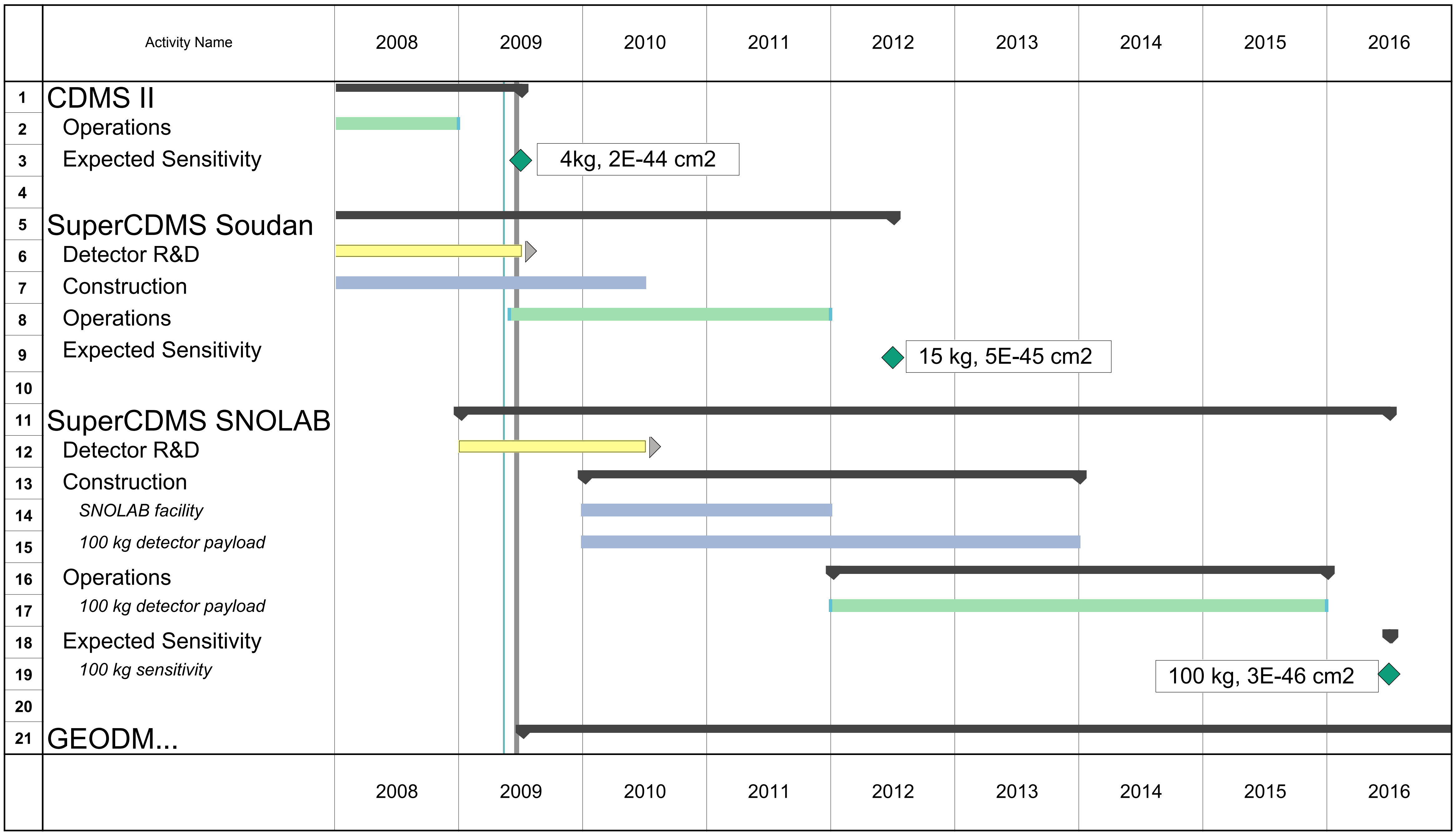
SuperTower 1 Installation





SuperTower 1 Installed

SuperCDMS Schedule



From CDMS to SuperCDMS to GEODM

CDMS II

7.5 cm x 1 cm ~ 0.25 kg / det
16 detectors = 4 kg
~ 2 yrs operation

SuperCDMS

7.5 cm x 1 in ~ 0.64 kg / det

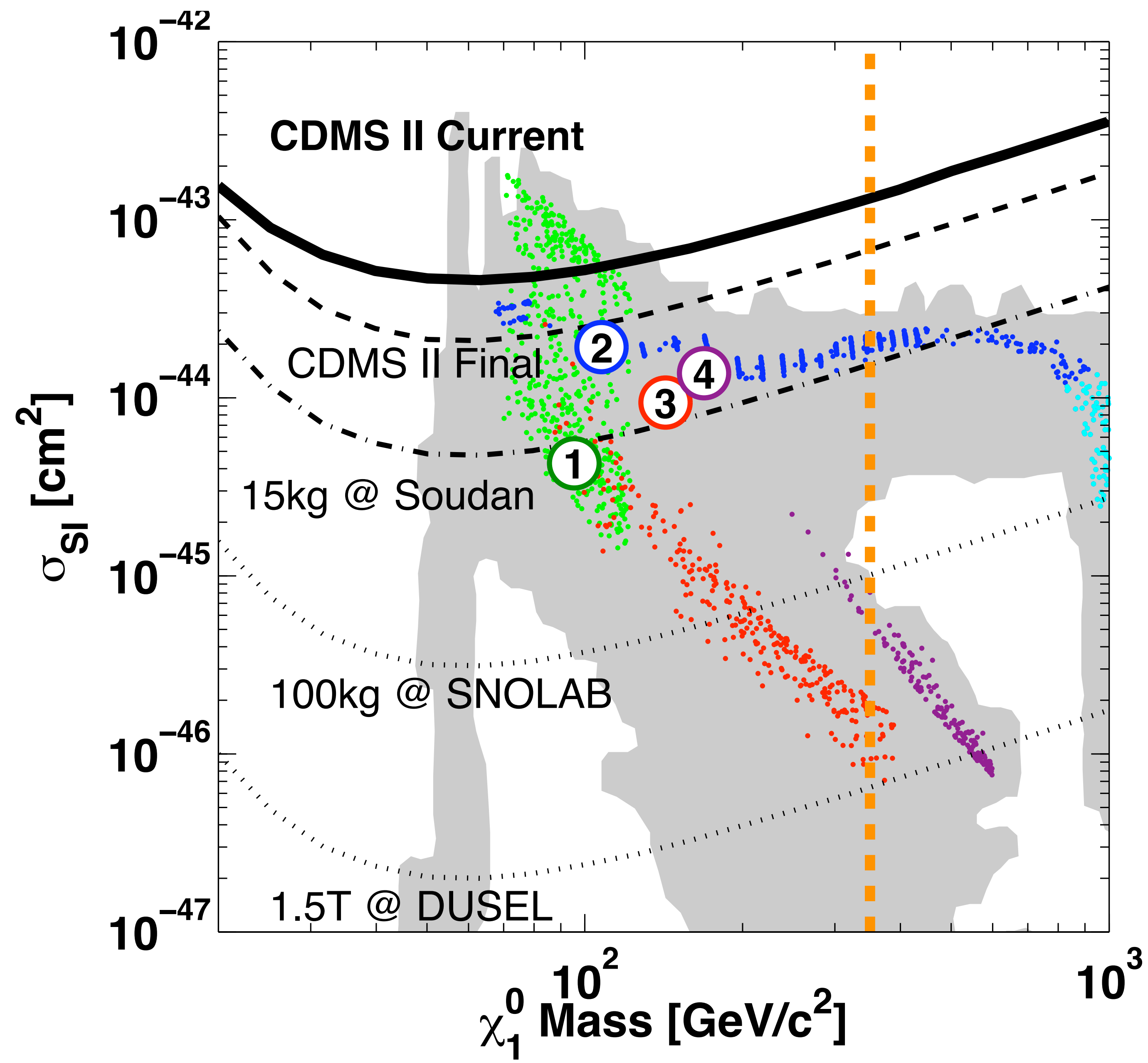
Soudan
25 detectors ~ 15 kg
2 yrs ~ 8000 kg-d

SNOLAB
150 detectors ~ 100 kg
3 yrs ~ 100,000 kg-d

SuperCDMS SNOLAB and Germanium Observatory for Dark Matter (GEODM)
15 cm x 2 in ~ 5.1 kg / det

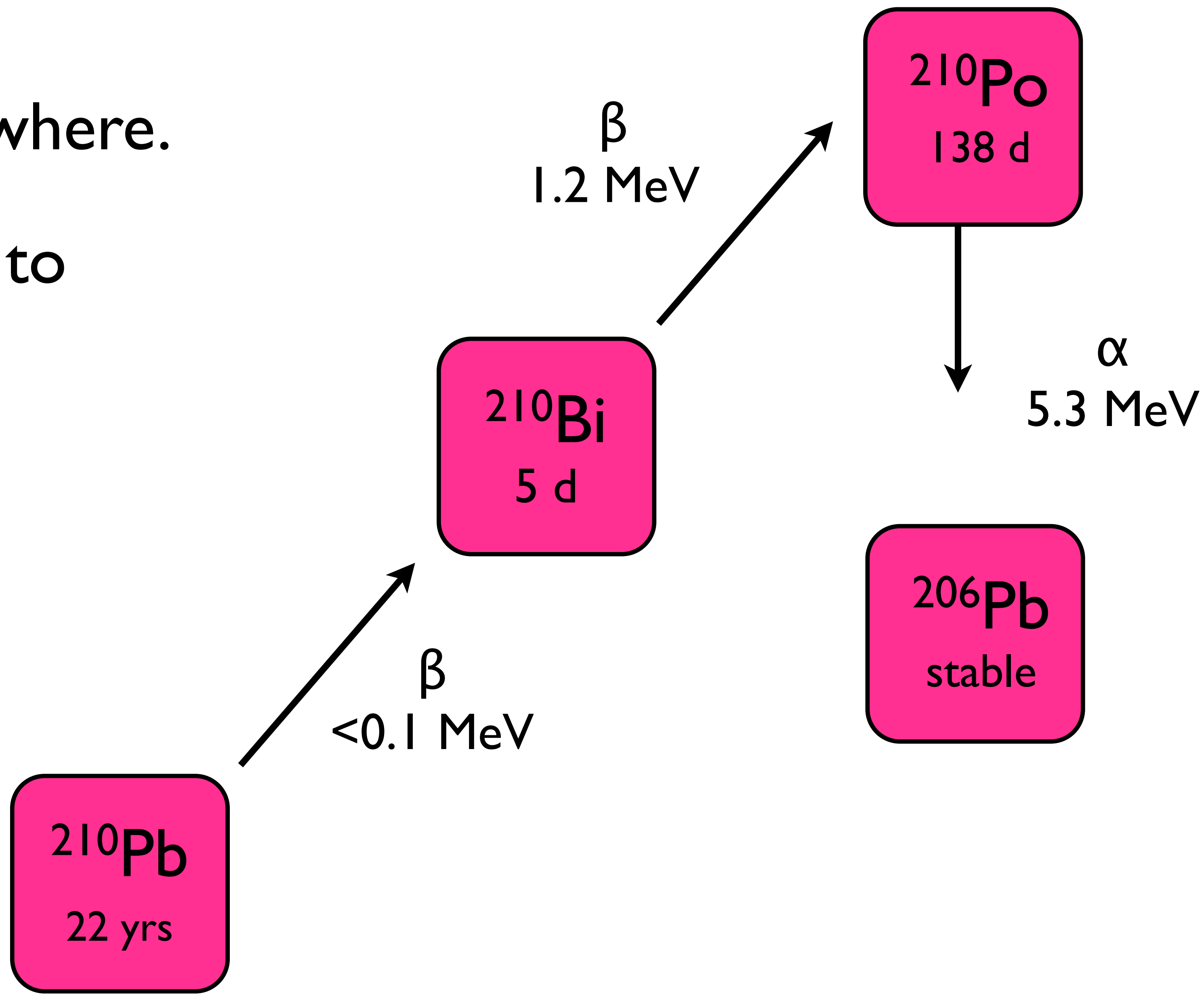
SNOLAB
20 detectors ~ 100 kg
3 yrs ~ 100,000 kg-d

DUSEL
300 detectors ~ 1.5 T
4 yrs ~ 1.5 Mkg-d



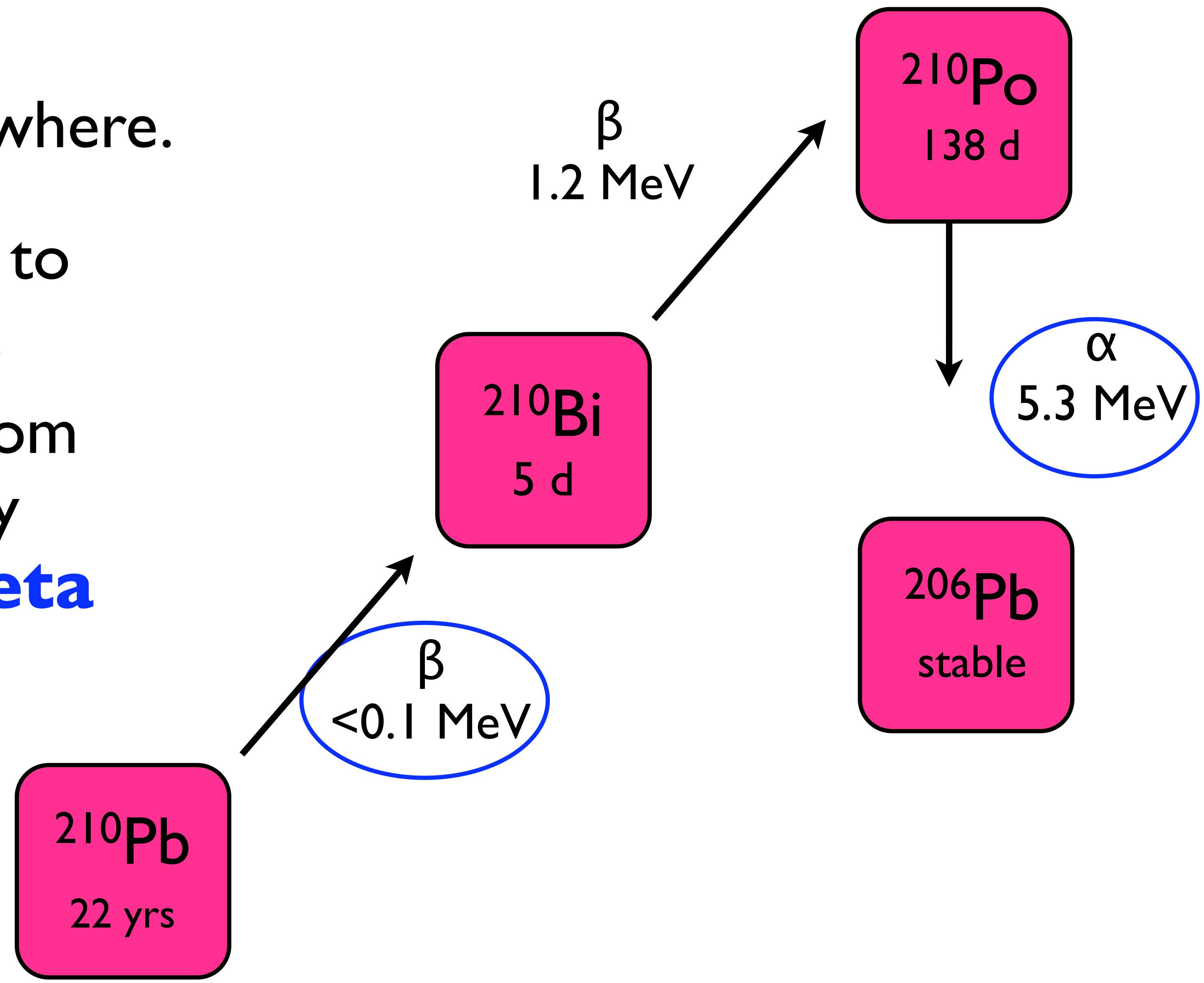
Surface Events: Radon Contamination

- Airborne **radon** is everywhere.
- It decays relatively quickly to **^{210}Pb (1/2 live 22yrs)**.



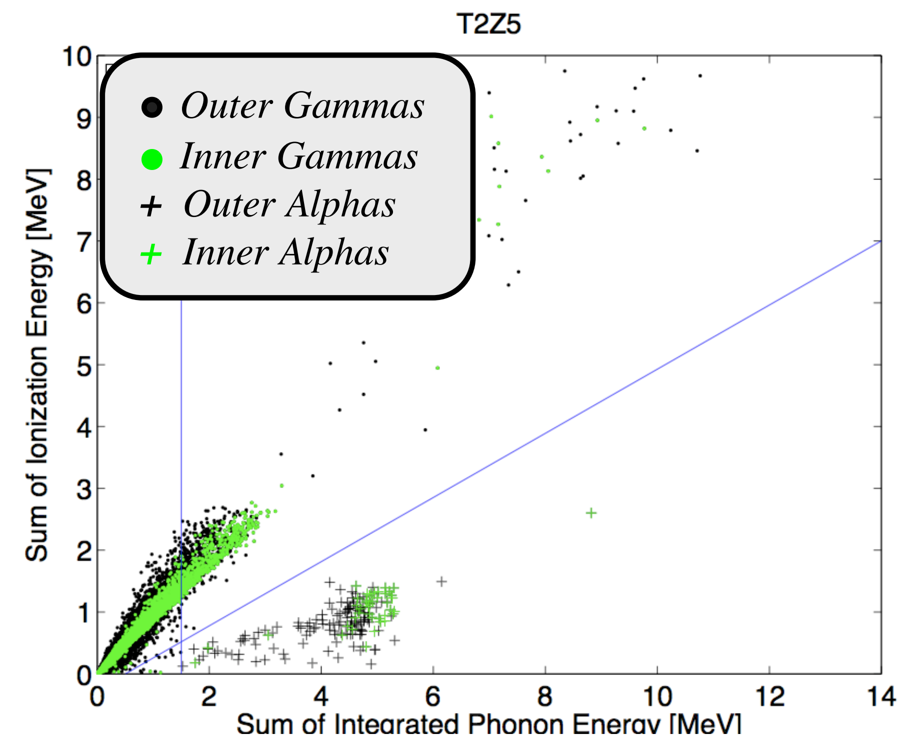
Surface Events: Radon Contamination

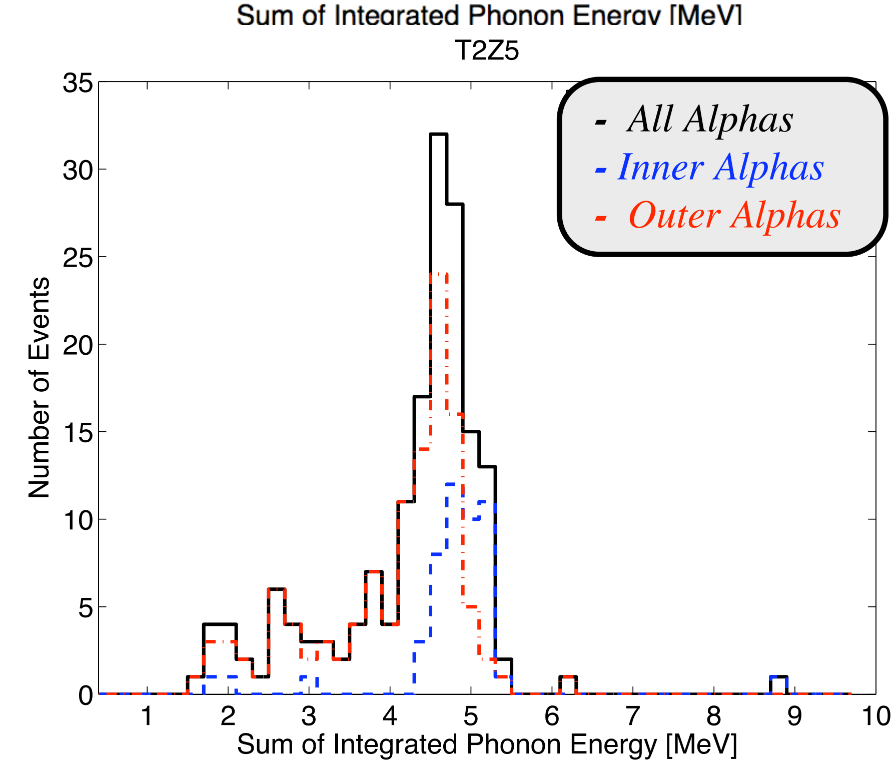
- Airborne **radon** is everywhere.
- It decays relatively quickly to **^{210}Pb (1/2 live 22yrs)**.
- Detector contamination from ^{222}Rn can be determined by **measuring alpha or beta particles** given of during these decays.



Surface Events: α Measurements

- We identify alphas by **reconstructing phonon and charge energies** for events in the MeV range.
- Events contained in the inner charge electrode have energy consistent with **^{210}Po alphas at 5.3 MeV**.
- **Alphas** are observed at a rate of **0.4/detector/day**.

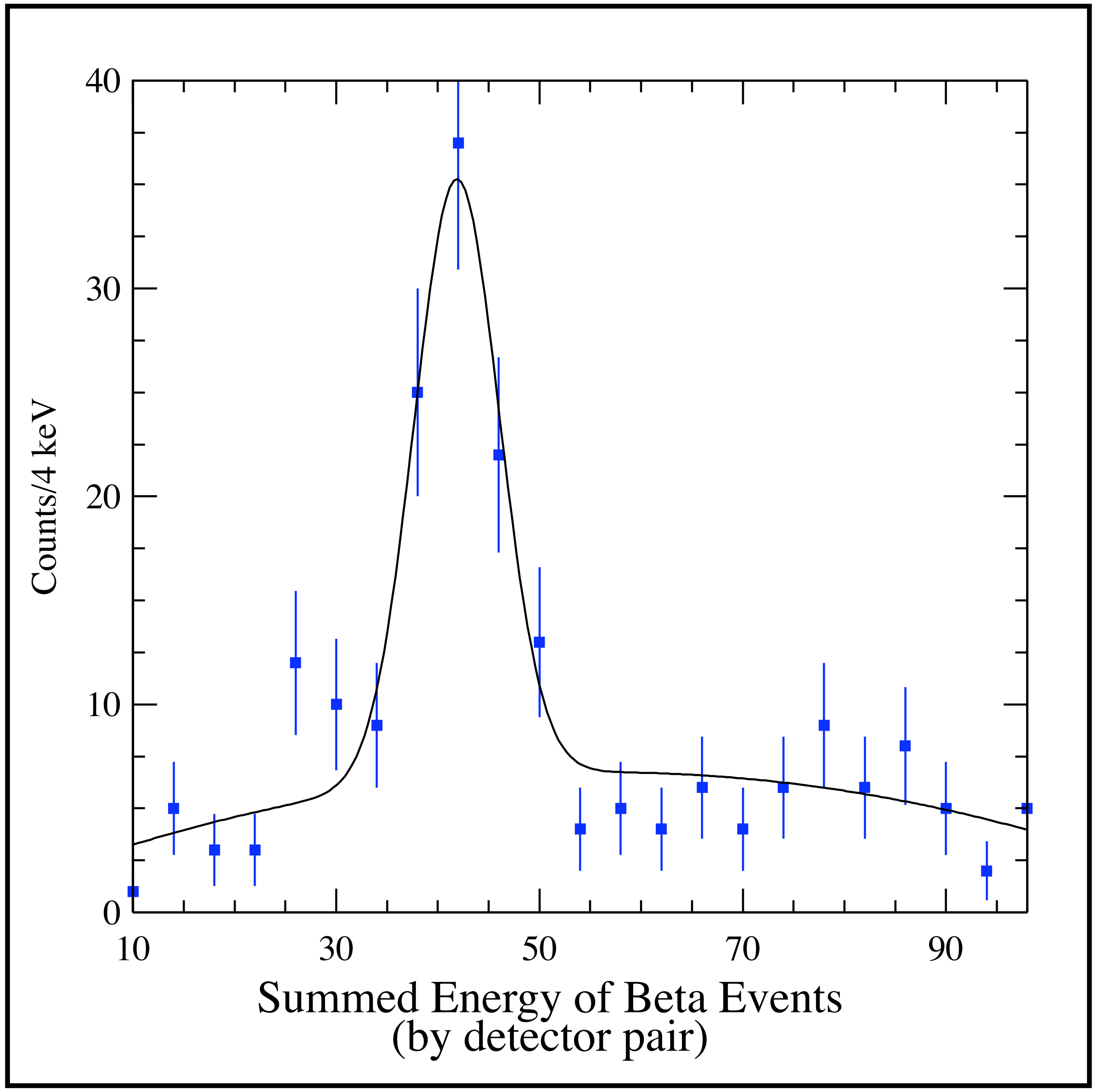




Surface Events: β Measurements

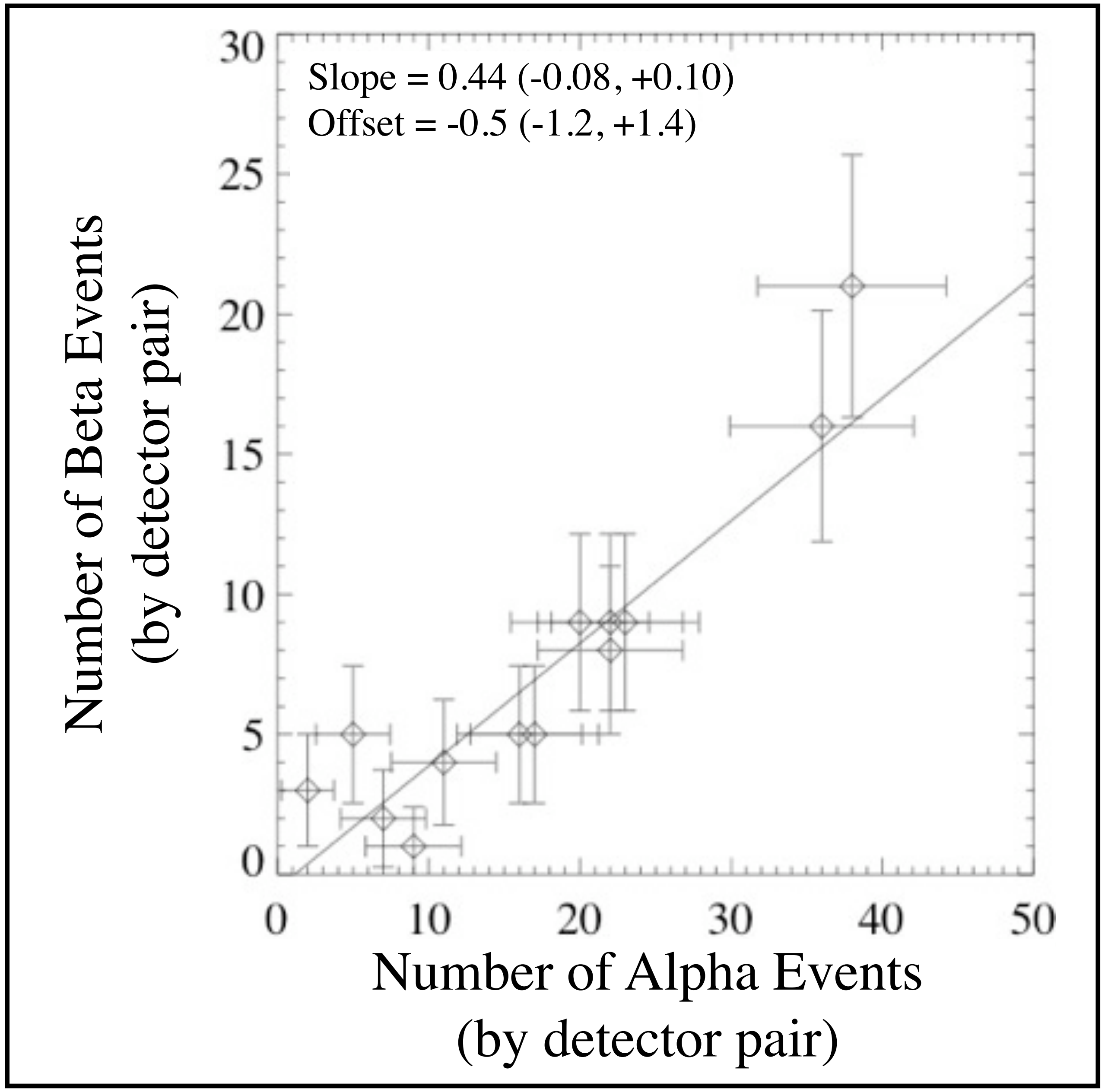
- **Betas** from ^{210}**Pb** decays are identified by looking for **coincident beta events** in neighboring detectors.

- This class of events produce a broad spectrum, **45 keV peak** of beta events consistent with predictions from ^{210}**Pb**.

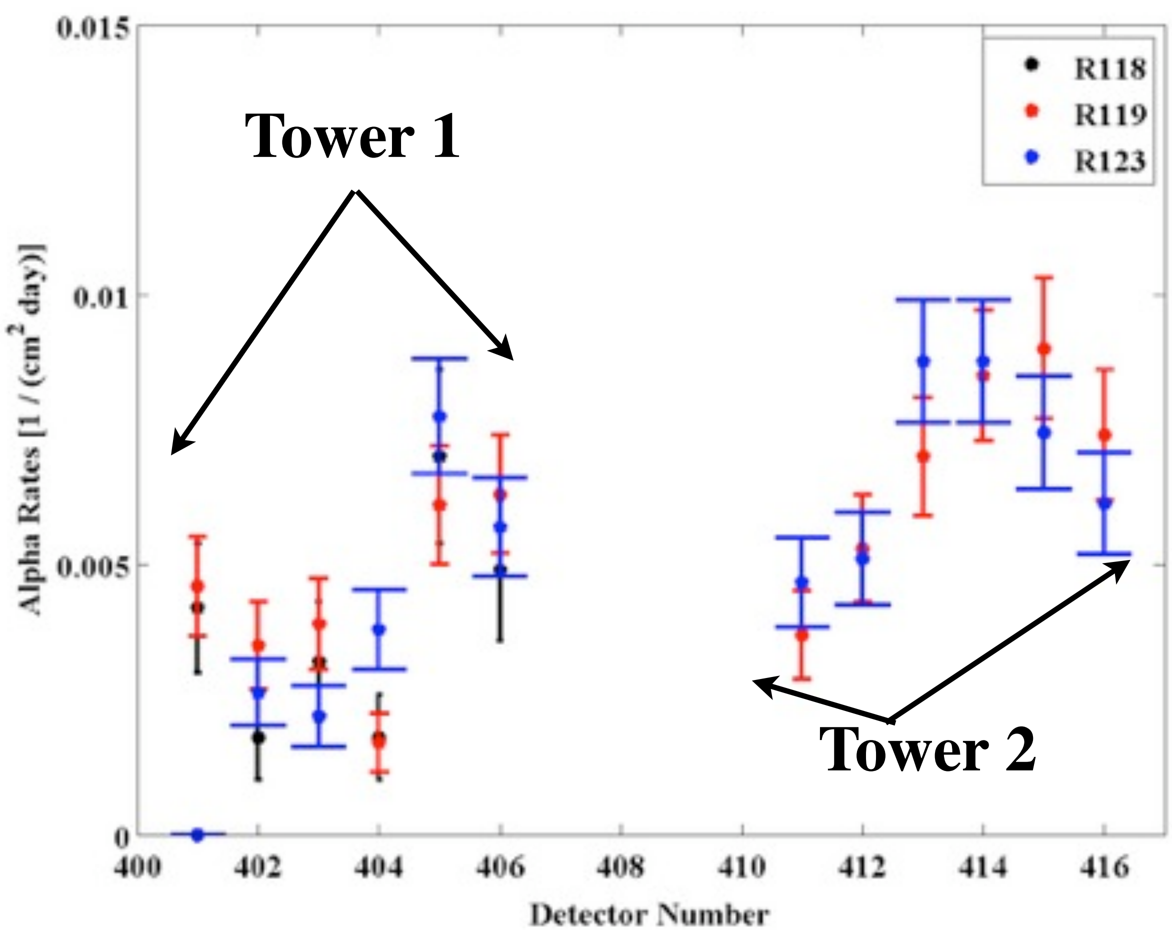


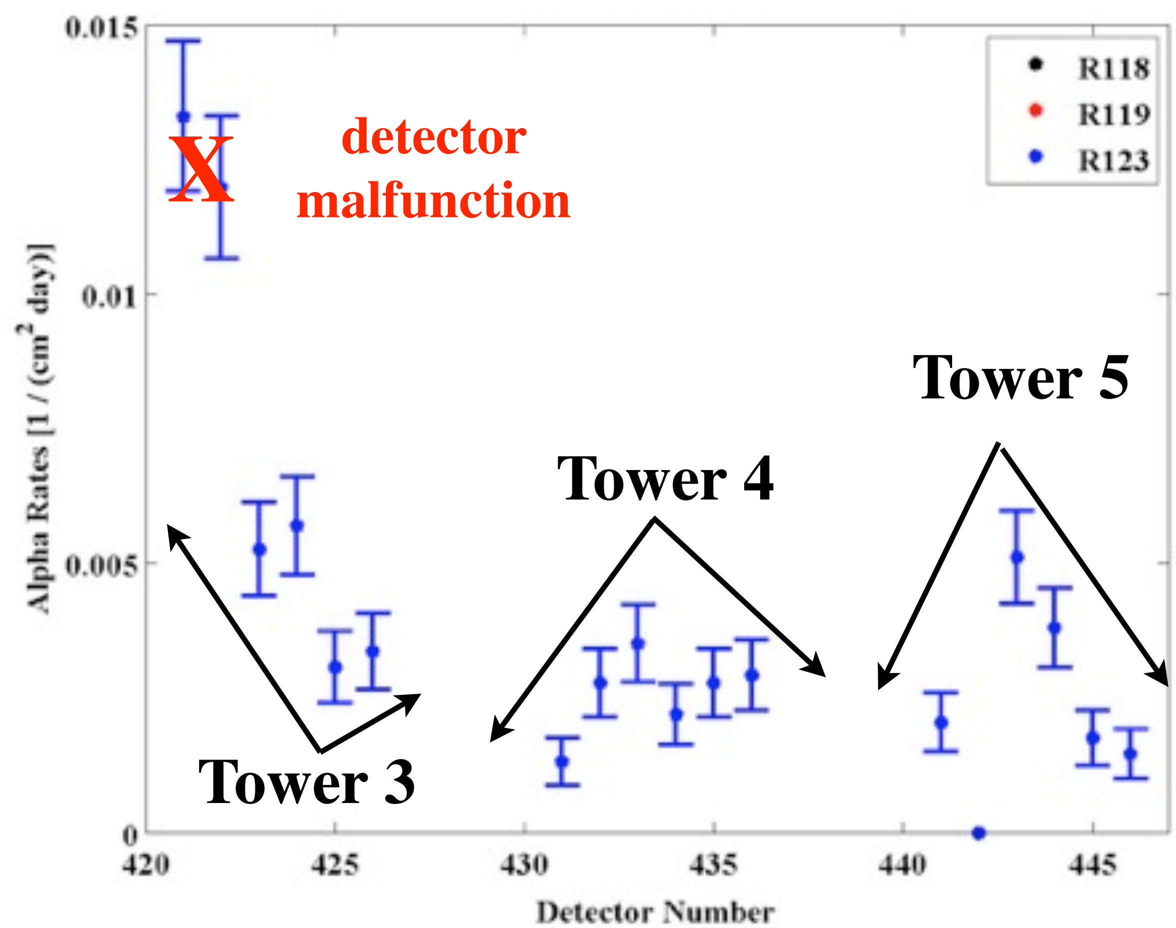
Alpha-Beta Correlation Analysis

Correlation between events identified in the 45 keV beta peak and alpha analyses for detector pairs is strong, corroborating the identification of the peak with ^{210}Pb.



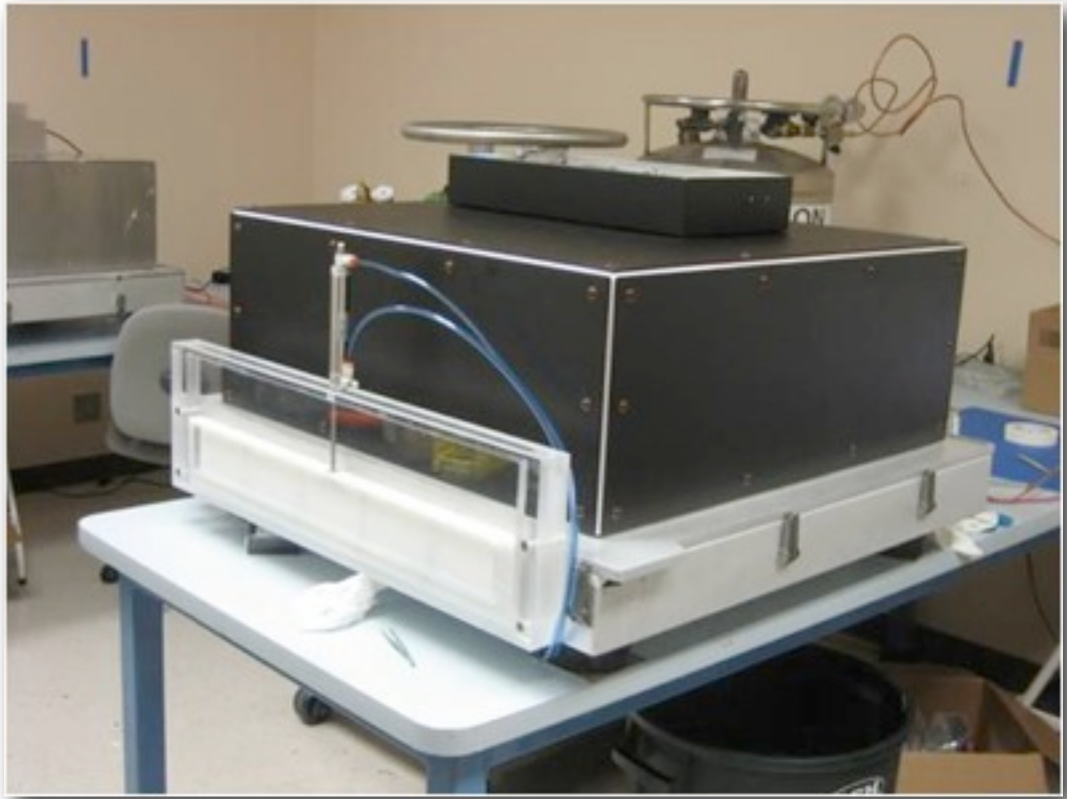
Improved Background Rates



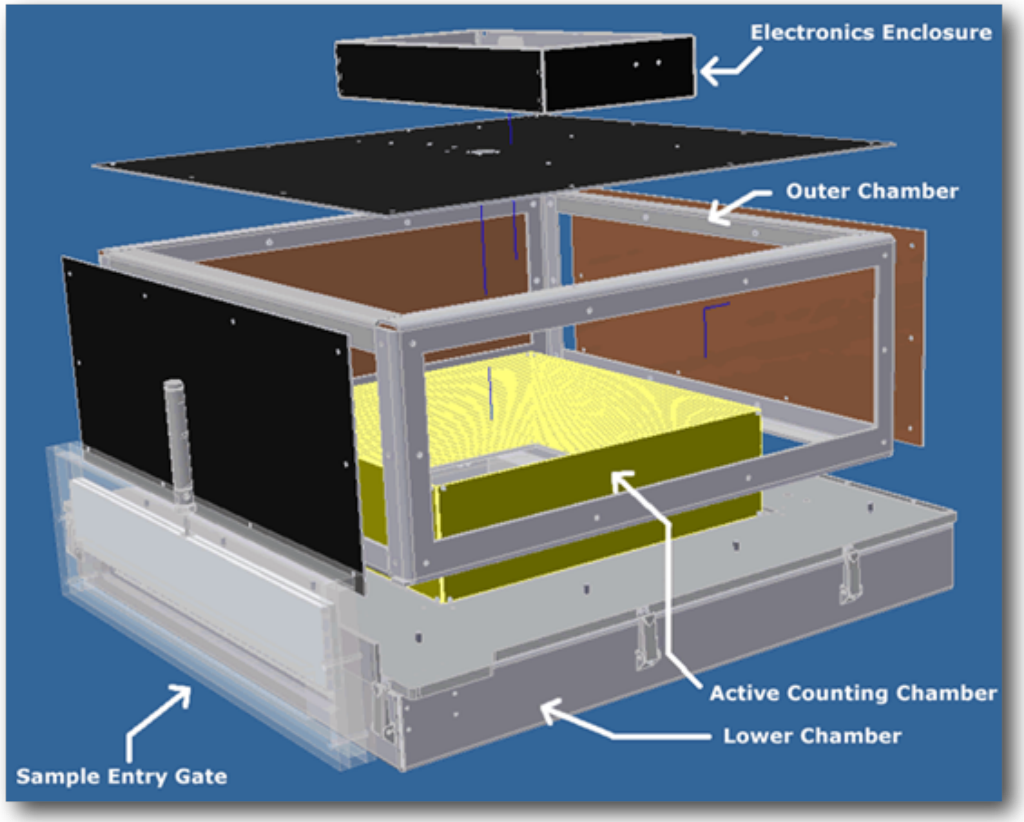


Alpha rates attributed to radon are a factor of ~ 2 times better in the new detectors.

XIA Alpha Counter

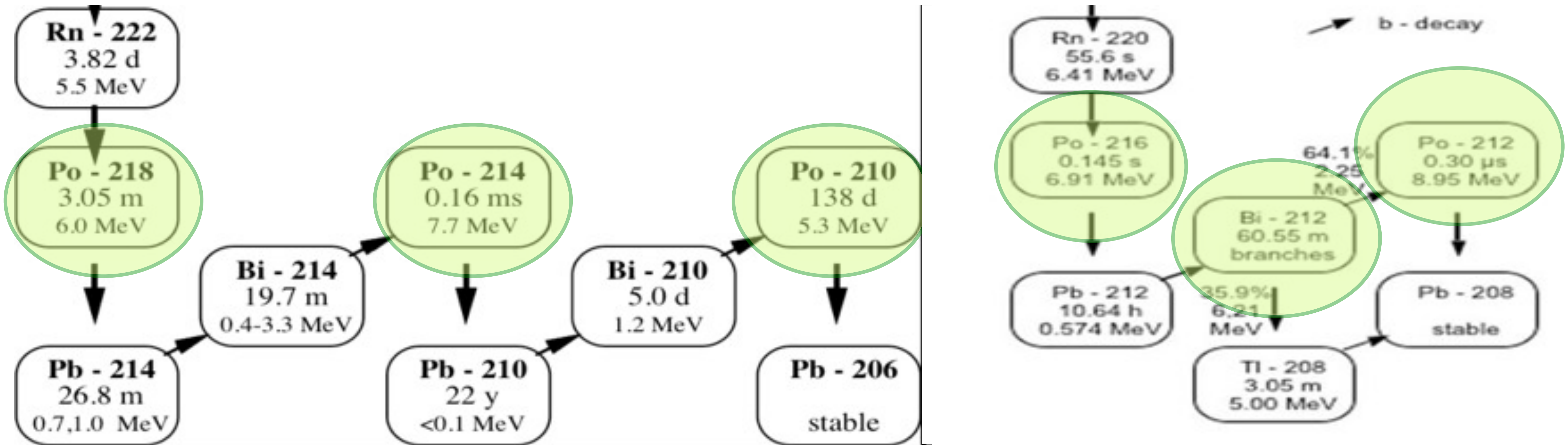


- Easiest way to **monitor ^{210}Pb** contamination is to measure **alpha-particle emission**.
- Goal: **0.32/detector/day**
  $4.6 \times 10^{-3}/cm^2/day$



- **XIA UltraLo 1800 prototype** evaluation and testing at Stanford
- Counting area: **1800 cm^2**
- Advertised sensitivity:
  $2.5 \times 10^{-3}/cm^2/day$

Initial Studies: ^{232}Th & ^{238}U



- Use Van der Graff generator to collect and then deposit Th & U daughters onto a Si wafer.
- Expect to see α-peaks at ~ 6 MeV, 7 MeV and 9 MeV.

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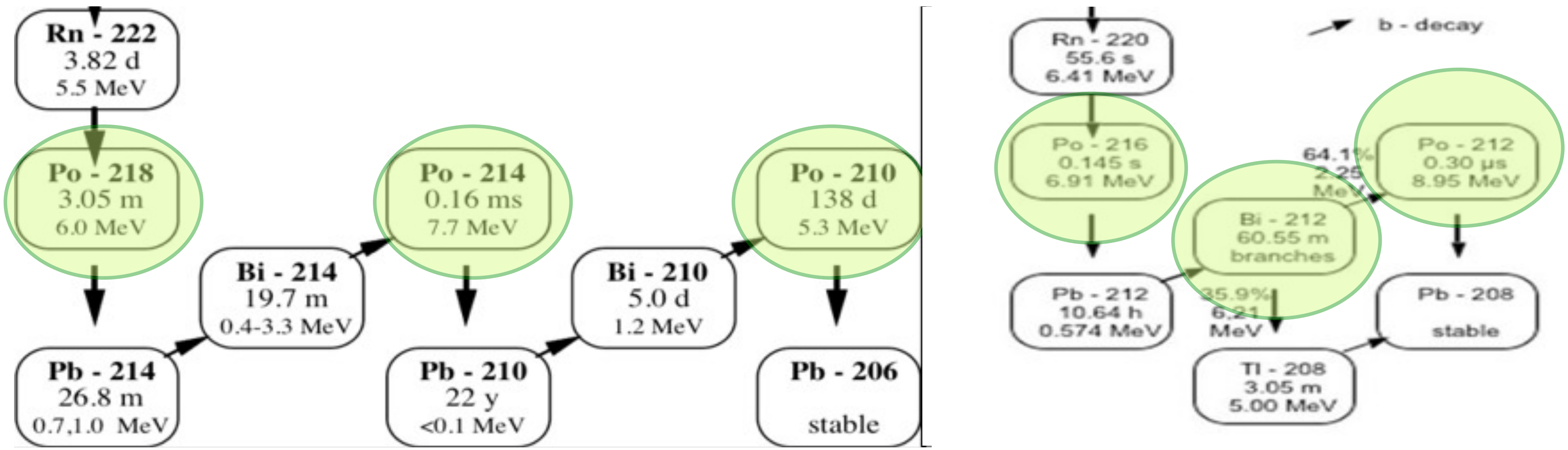

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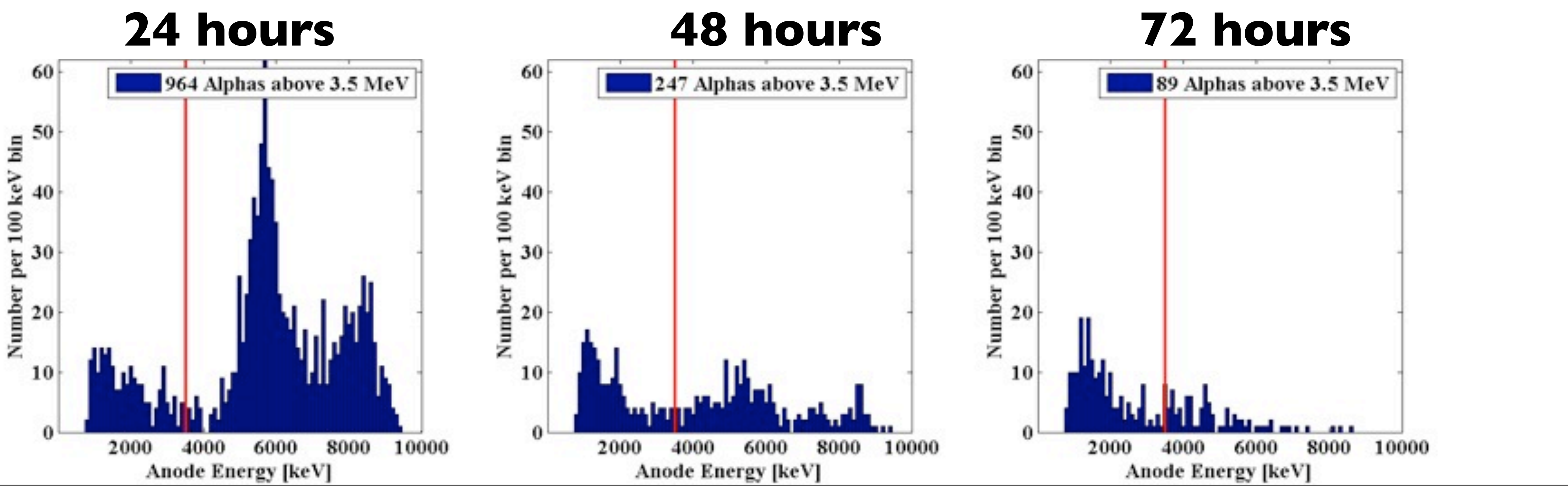

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Counter Progress and Plans

- ✓ We have made improvements to the counter and made gains in the alpha identification algorithms to meet advertised sensitivity.
- ✓ We continue to identify and screen cleaner materials.
- ✓ Currently, using counter to evaluate contamination by the different detector fabrication stages using witness samples.
- ✓ We are also conducting studies of cleanliness of various materials: Cu, gold-plated Cu, etc
- Eventually, detector will be moved to FermiLab where it will be used to screen detectors.

Conclusions

- Currently CDMS is operating and taking data at the design level of five towers of detectors.
- Data taken between Oct. 2006 and July 2007 has been analyzed and a cross section limit of < $4.6 \times 10^{-44} cm^2$ (90% CL) was placed for a WIMP of mass 60 GeV/c^2.
- SuperCDMS is an experiment under development by the CDMS collaboration which is planned for operation in Soudan. For this purpose we have enhanced the design of the CDMS detector.
- In an effort to operate our experiment in a 'background-free' mode, we are working to characterize and mitigate background events from the decay of omnipresent radon.

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- Data taken between Oct. 2006 and July 2007 has been analyzed and a cross section limit of < 4.6 x $10^{-44}cm^2$ (90% CL) was placed for a WIMP of mass 60 GeV/c^2.
- CDMS II finished taking data on March 18, 2009. We are currently analyzing the last data sets.
- SuperCDMS is an experiment under development by the CDMS collaboration which is planned for operation in Soudan. For this purpose we have enhanced the design of the CDMS detector.
- The first SuperTower has been installed at Soudan and is under commission. Initial tests on the surface are promising.
- In an effort to operate our detector in a "background free" mode, we are working to characterize and mitigate background events from the decay of omnipresent radon.

Back-up Slides