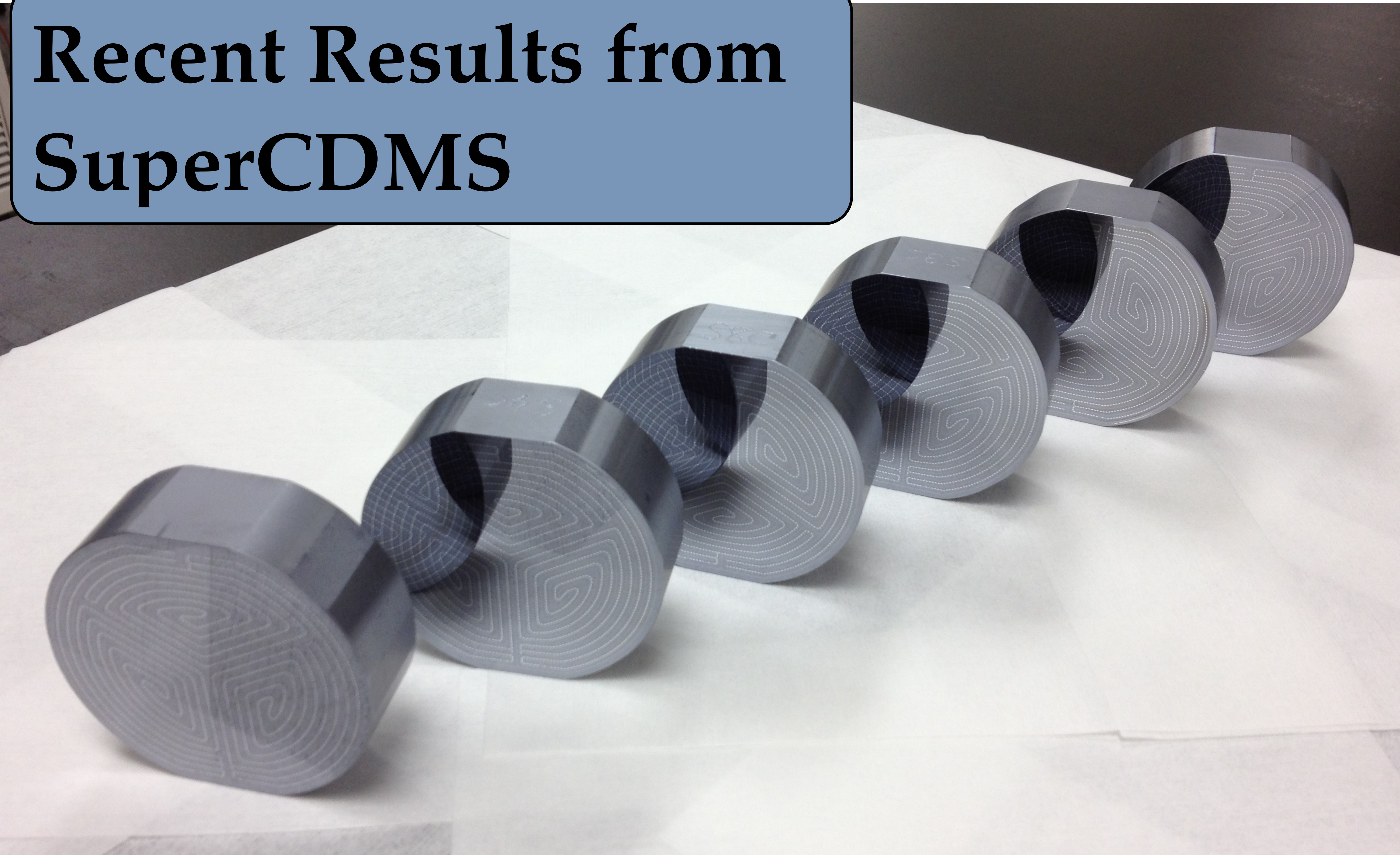
# Recent Results from SuperCDMS



SMU

Jodi Cooley
Southern Methodist University

# Outline

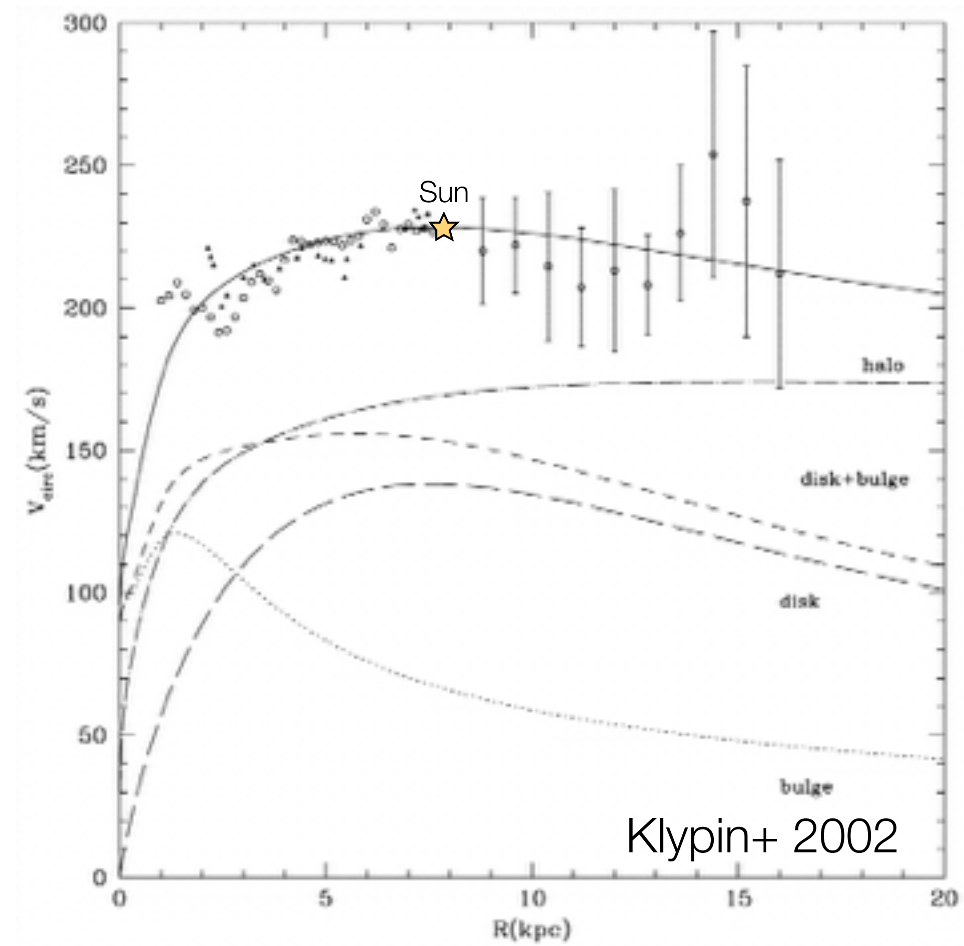
- Motivation and General Principles
- SuperCDMS at Soudan
  - Detection Principles
  - Results from CDMSlite
  - New Results from SuperCDMS LT

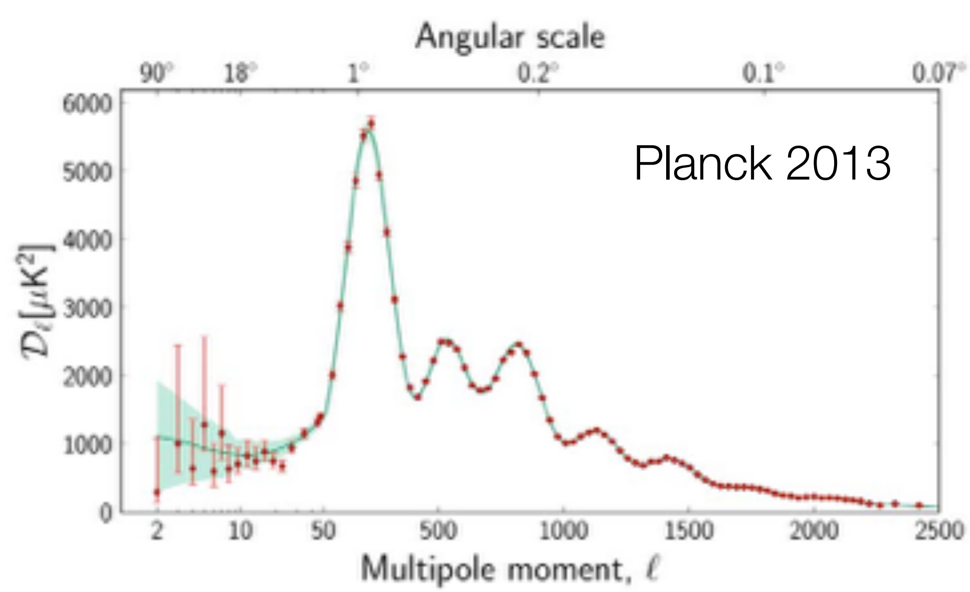
NEW!

- Plans for the SuperCDMS at SNOLAB experiment

# The Nature of Dark Matter

- **The Missing Mass Problem:**
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gravitational lensing
  - Large Scale Structure formation
- **Wealth of evidence for a particle solution**
  - Microlensing (MACHOs) mostly ruled out
  - MOND has problems with Bullet Cluster
- **Non-baryonic**
  - Height of acoustic peaks in the CMB ($\Omega_b$, $\Omega_m$)
  - Power spectrum of density fluctuations ($\Omega_m$)
  - Primordial Nucleosynthesis ($\Omega_b$)
- **And STILL HERE!**
  - Stable, neutral, non-relativistic
  - Interacts via gravity and (maybe) a weak force

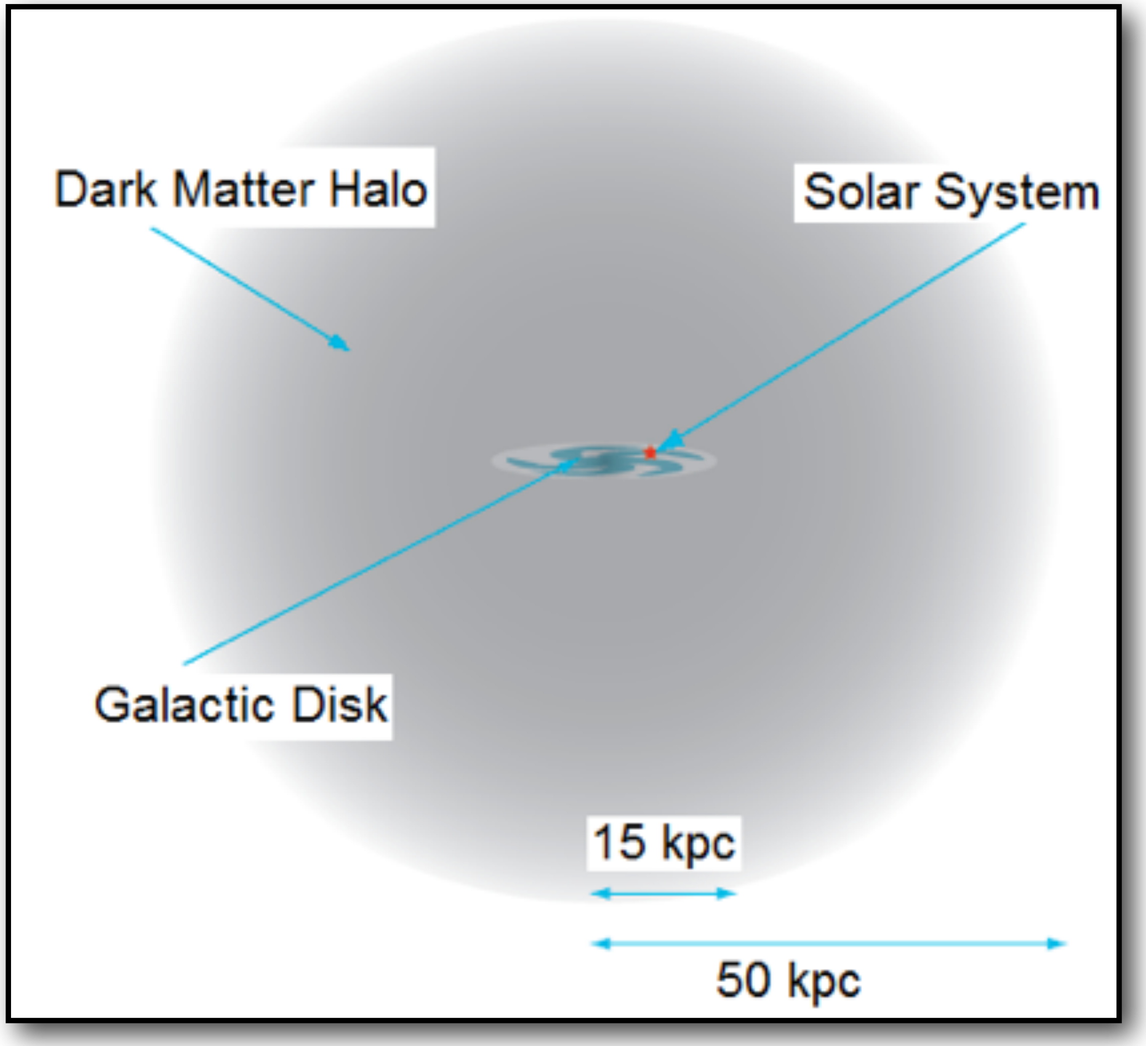


# Direct Detection Rates

**Standard Halo Model:**

- Energy spectrum and rate depend on details of WIMP distribution in the dark matter halo.
- Assume isothermal and spherical, Maxwell-Boltzman distrubution
    - $v_{rms}$ = 270 km/s , $v_o$ = 220 km/s, $v_{esc}$ = 544 km/s
    - $\rho o$ = 0.3 GeV/cm$^3$



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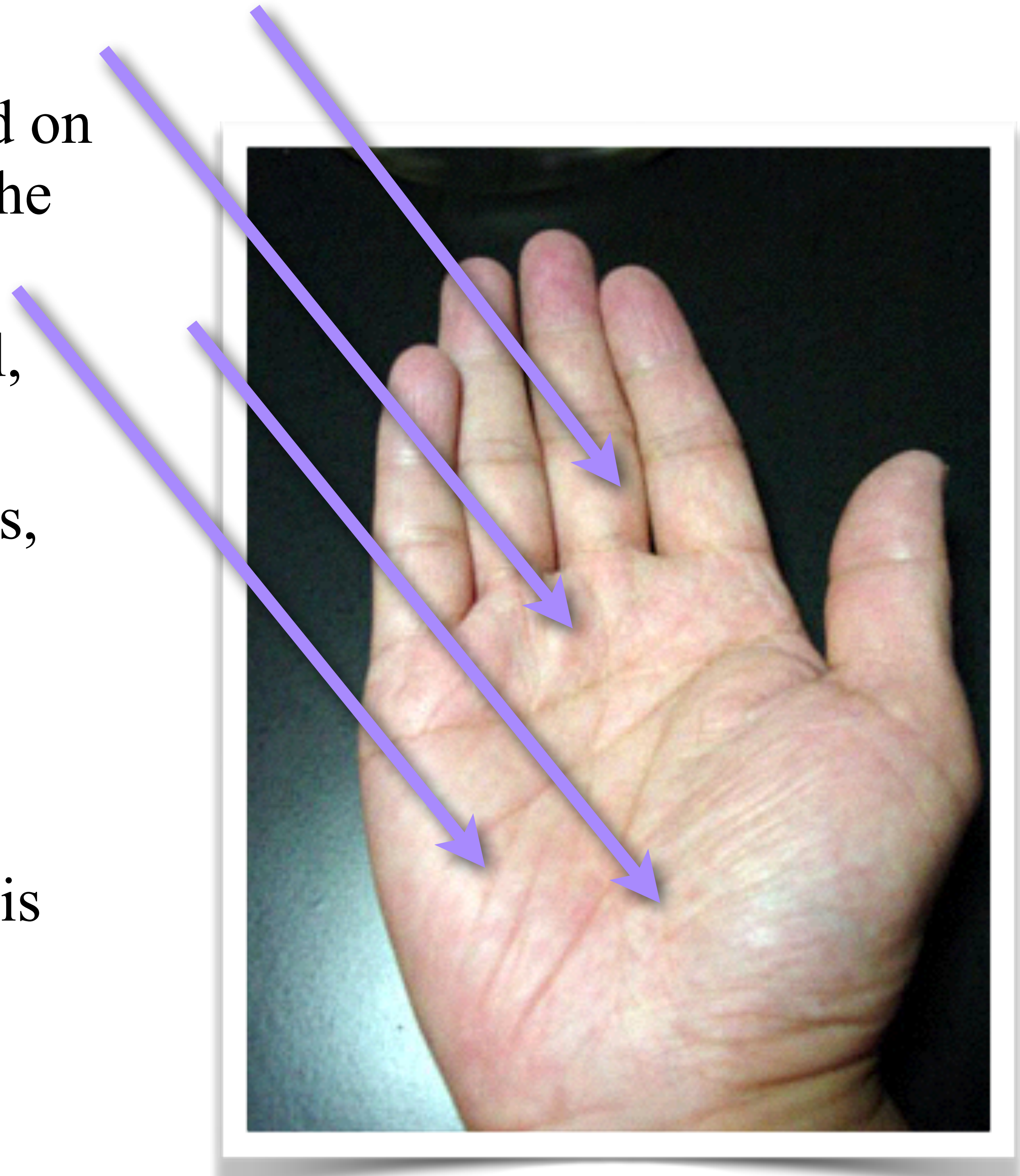
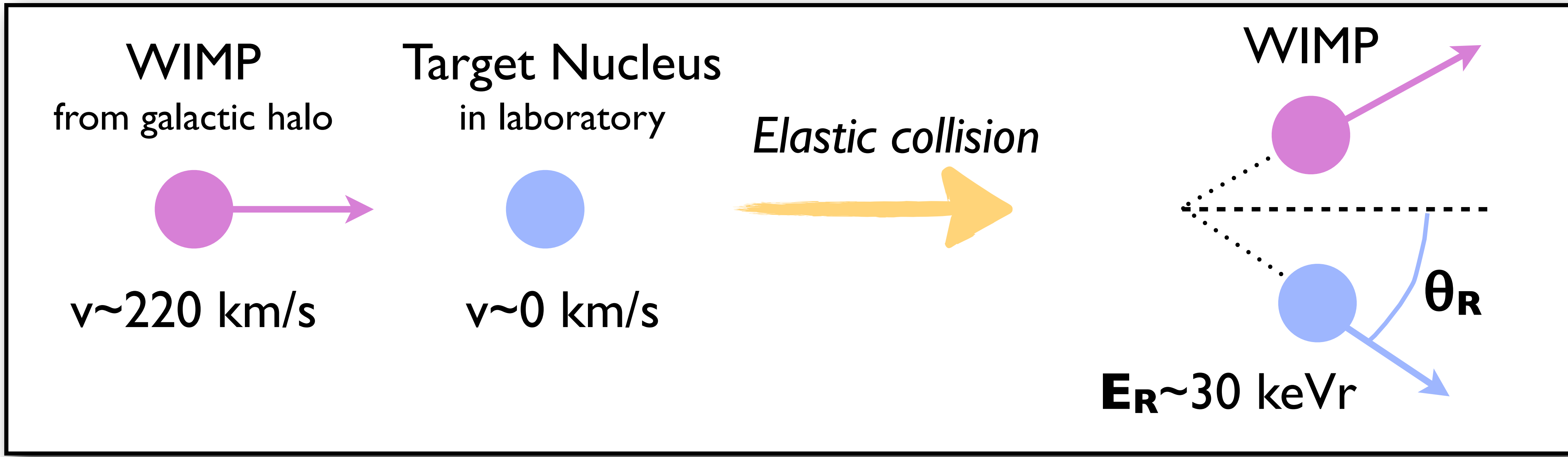


**Flux:**

- Assume the mass of the WIMP is 60 GeV/cm$^3$
- ~20 million/hand/sec

# WIMP - Nucleus Interaction

Assume that the dark matter is not only gravitationally interacting (WIMP).



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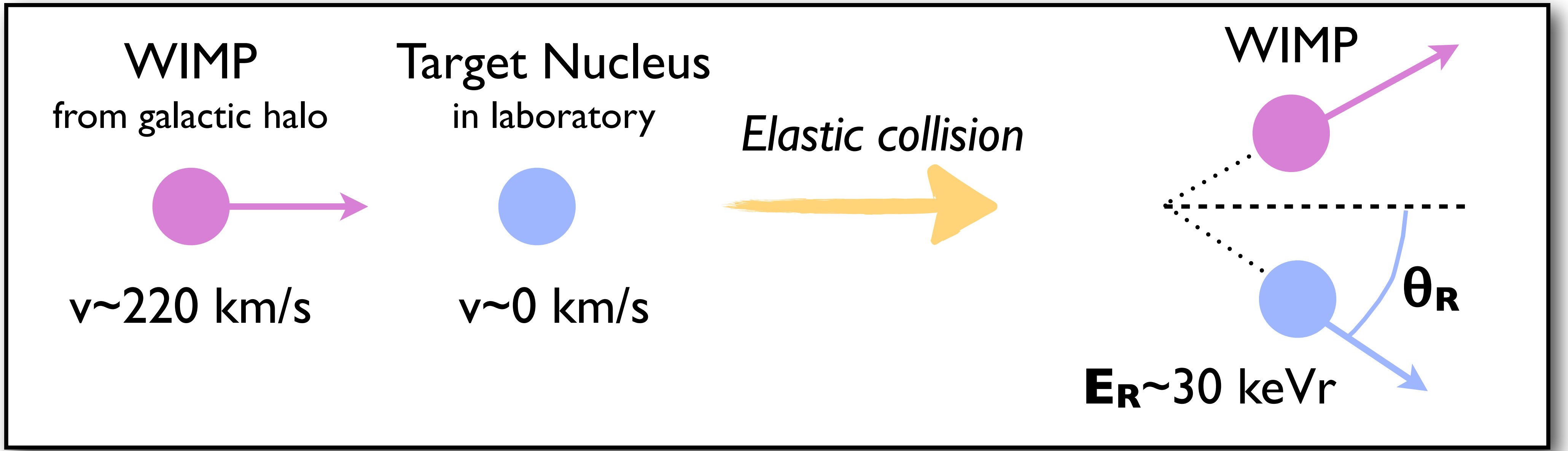



- Spin-Independent
  - The scattering amplitudes from individual nucleons interfere.
  - For zero momentum transfer collisions (extremely soft bumps) they add coherently:

$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2$$

Enormous enhancement for heavy nuclei target!

$f$: coupling constant; $A$: atomic mass

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$ = "reduced mass"

# Interaction Rate

Interaction Rate
[events/keV/kg/day]

particle theory — nuclear structure — local properties of DM halo

$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o\, T(E_R)}{v_o \sqrt{\pi}}$$

The Gory Details:

$F(E_R) \simeq \exp\left(-E_R\, m_N\, R_o^2/3\right)$ — "form factor" (quantum mechanics of interaction with nucleus)

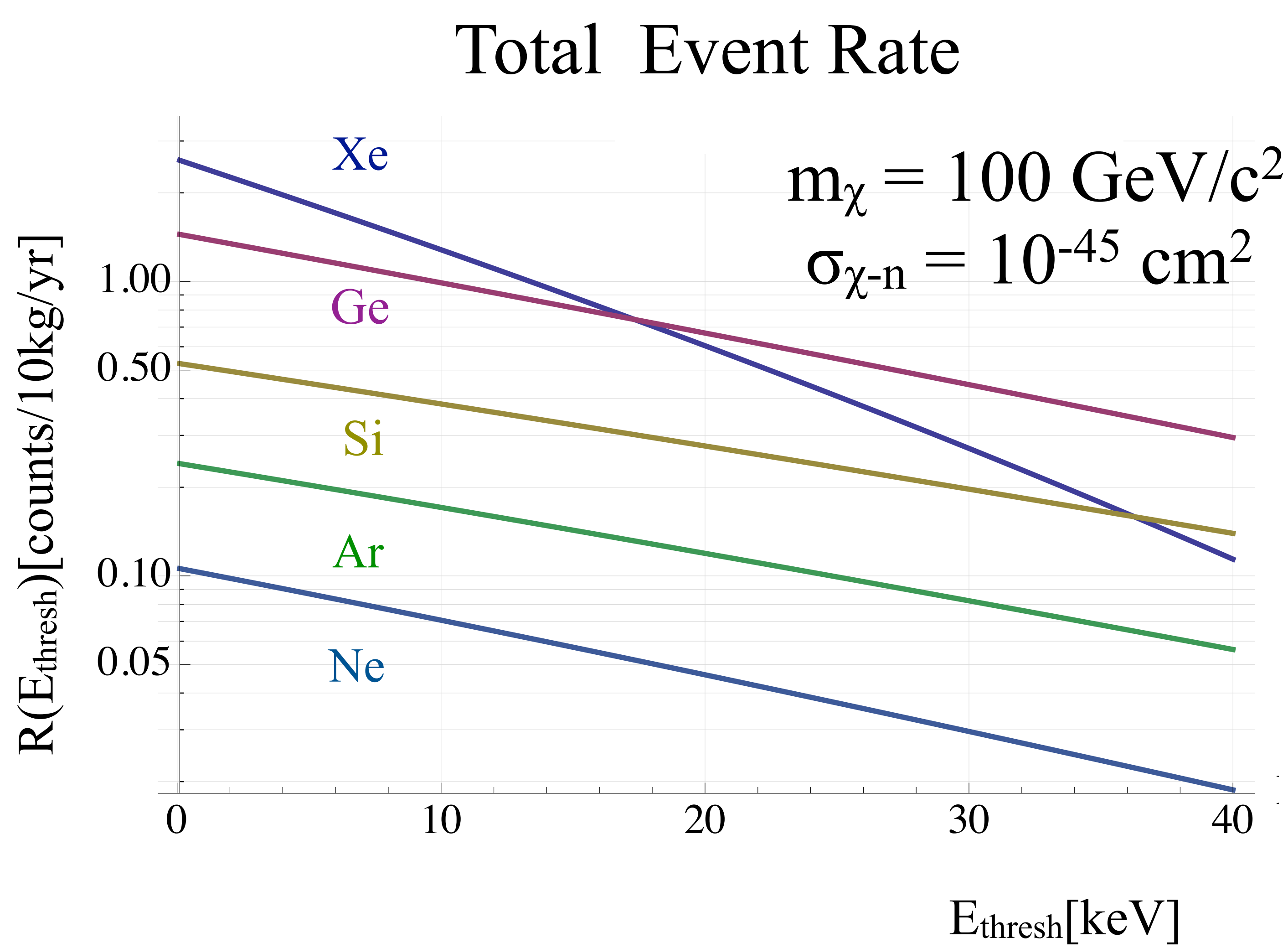
$m_r = \dfrac{m_\chi m_N}{m_\chi + m_N}$ — "reduced mass"

$T(E_R) \simeq \exp(-v_{\rm min}^2/v_o^2)$ — integral over local WIMP velocity distribution

$v_{\rm min} = \sqrt{E_R\, m_N/(2m_r^2)}$ — minimum WIMP velocity for given $E_R$

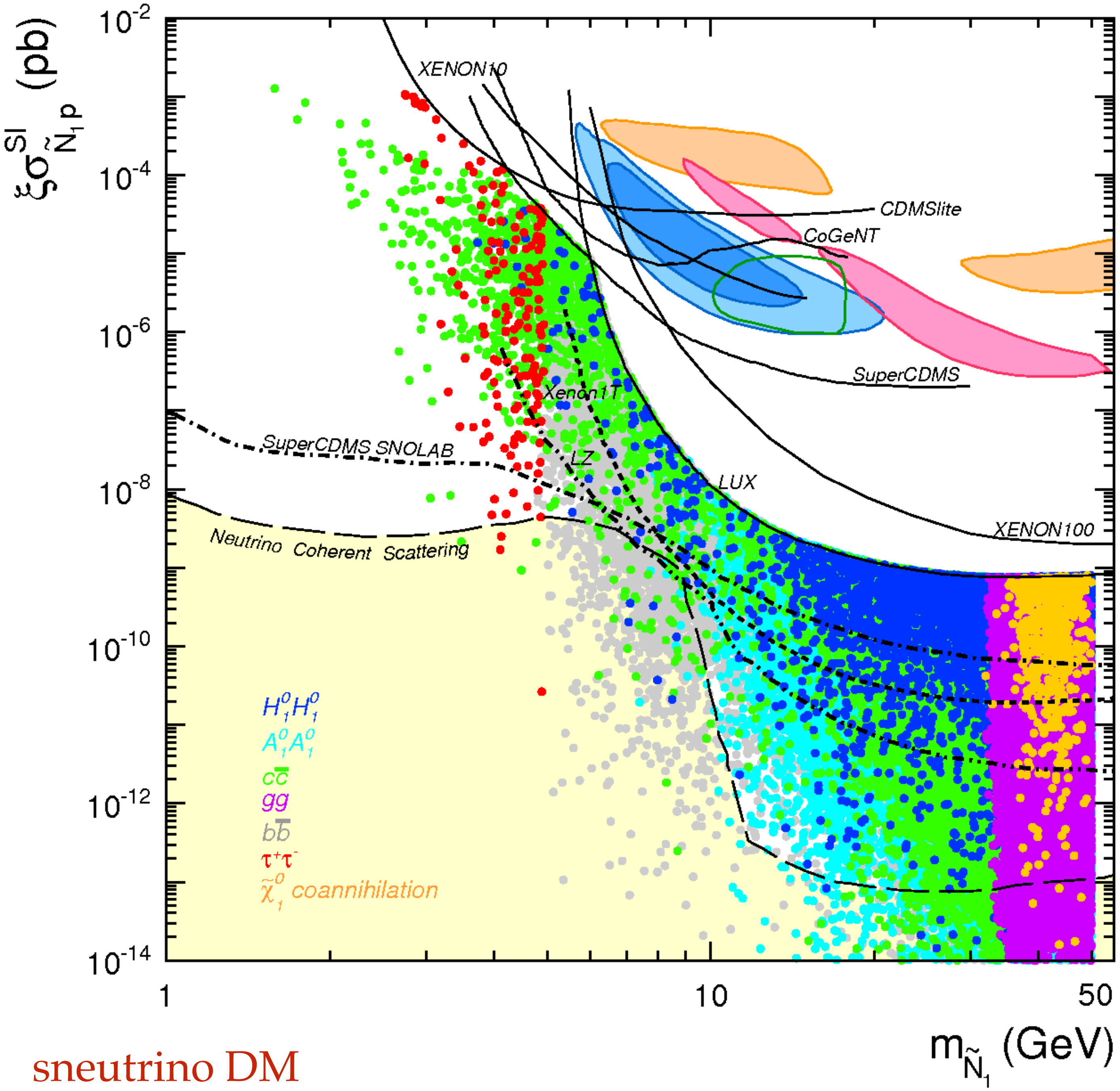
# Direct Detection Event Rates

- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.




- Radioactive background of most materials is higher than the event rate.

# Motivation for Low Mass WIMPS

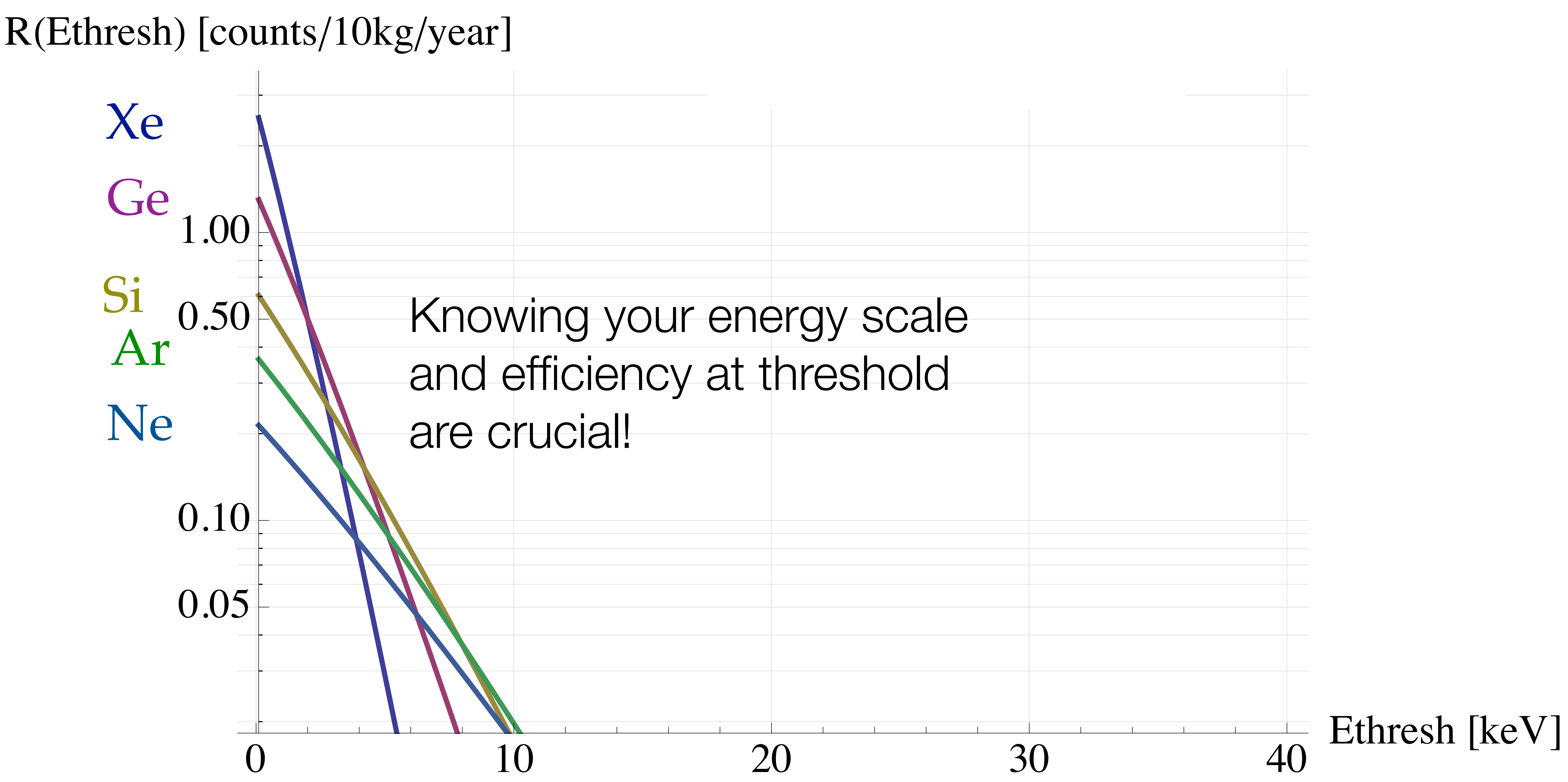



sneutrino DM
arXiv:1404.2572 (Cerdeno, Peiro, Robles)

- No signal has thus far been seen at higher mass by direct detection experiments or at the LHC.
- Particle Physics models provide candidates for light dark matter including (but not limited to):
  - Supersymmetry (neutralino in the MSSM or NMSSM, neutrino in extended models)
  - Asymmetric Dark Matter
  - others
- This parameter space is largely unexplored and must also be advanced!

# Direct Detection Event Rates

Total rate for different thresholds:
(assumed: $m_\chi = 10$ GeV/$c^2$, $\sigma_{\chi\text{-}n} = 10^{-45}$ cm$^2$)



# Challenges

- Low energy thresholds (>10 keV - 10s keV)
- Rigid background controls
  - Clean materials
  - shielding
  - discrimination power
- Substantial Depth
  - neutrons look like WIMPS
- Long exposures
  - large masses, long term stablility

# The SuperCDMS Collaboration

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**FNAL**
R. Basu Thakur , D.A. Bauer, D. Holmgren, L. Hsu, B. Loer

**Mass. Inst. of Tech.**
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**NIST Inst. of Tech.**
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**PNNL**
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**Syracuse University**
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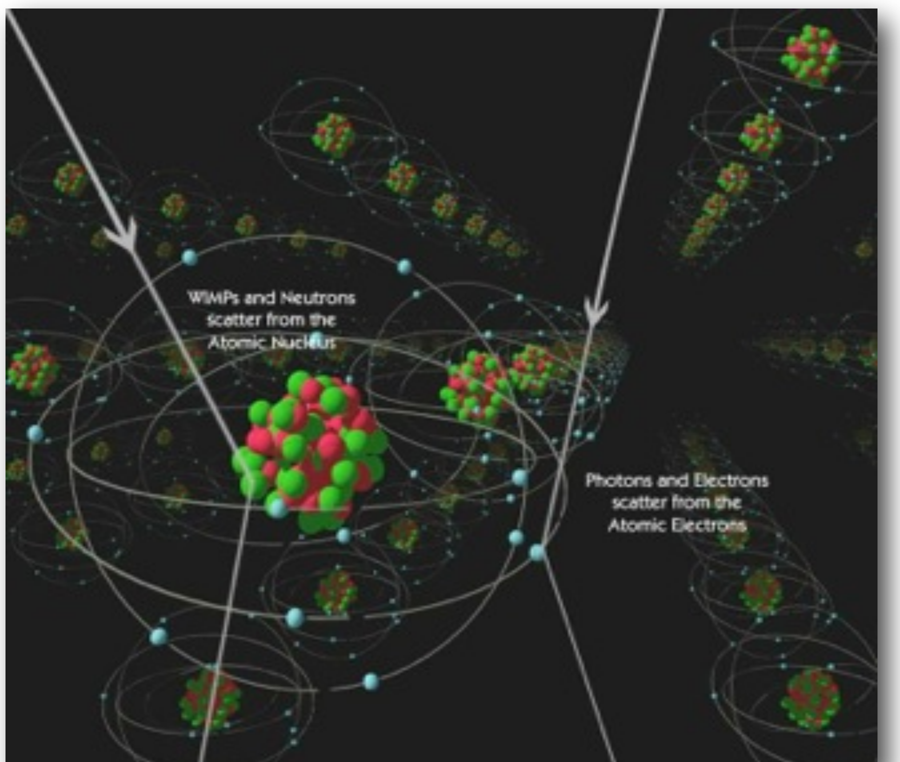
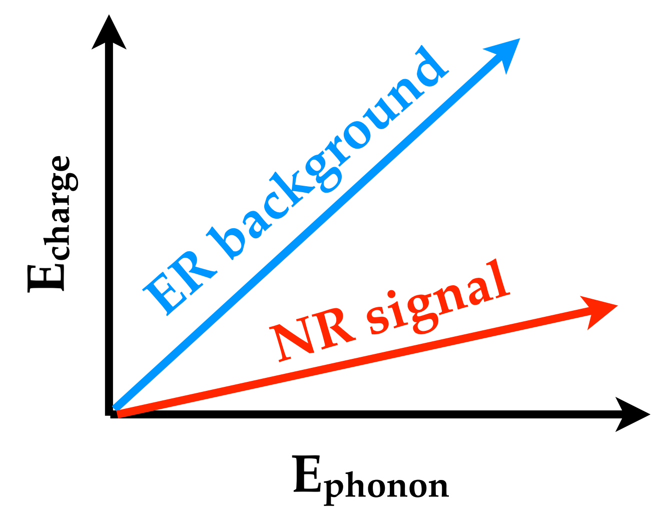
[+]The SMU SuperCDMS group is supported by the NSF under grant number 1151869.

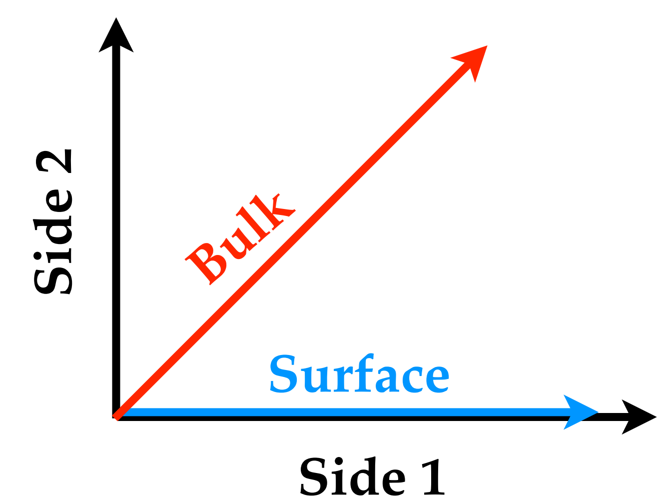
# SuperCDMS in a Nutshell

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



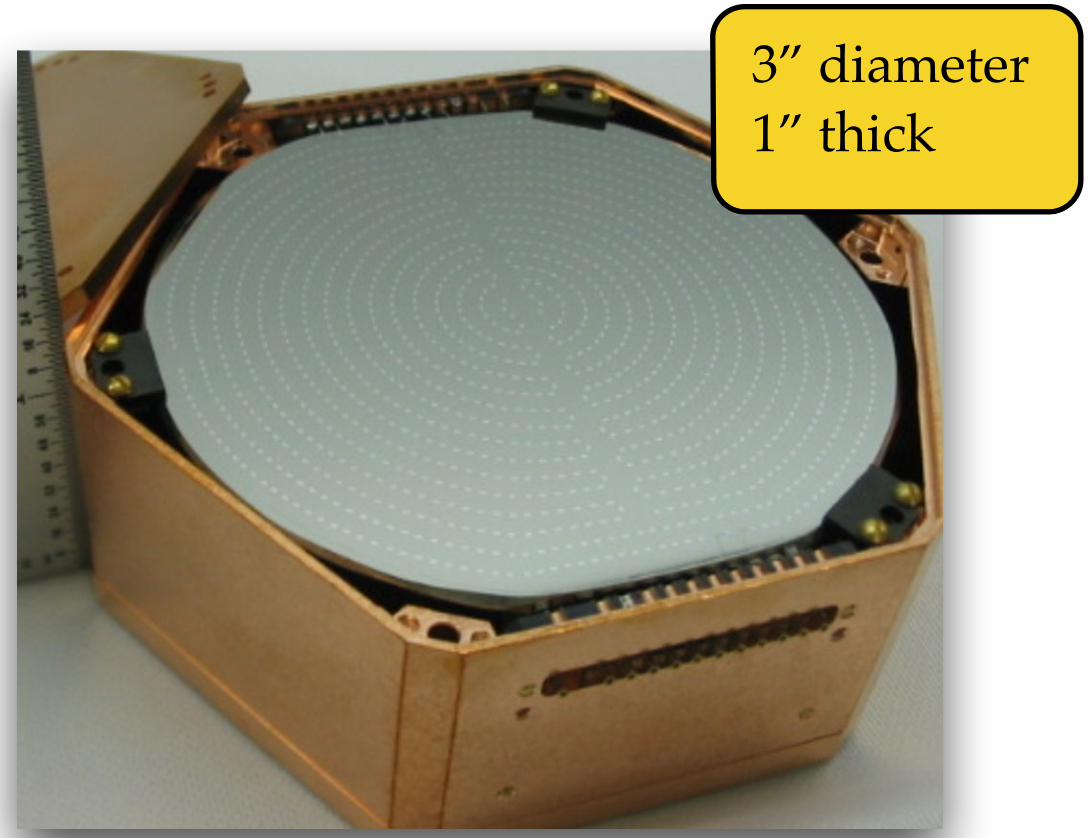

Discrimination from measurements of ionization and phonon energy **and** charge distributions



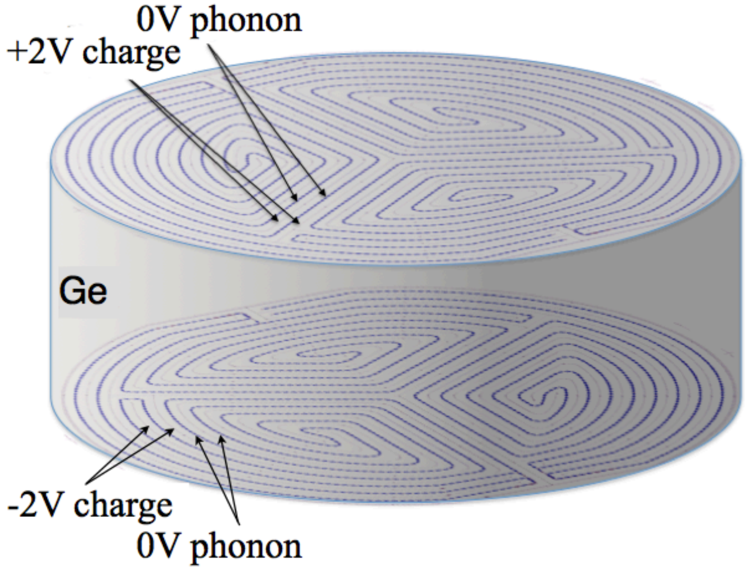




Keep backgrounds low as possible through shielding and material selection.

# SuperCDMS iZIP Detectors




- Ge crystal (600 g) **i**nterleaved **Z**-sensitive **I**onization and **P**honon detectors (**iZIP**)
- Ionization lines (±2 V) are interleaved with phonon sensors



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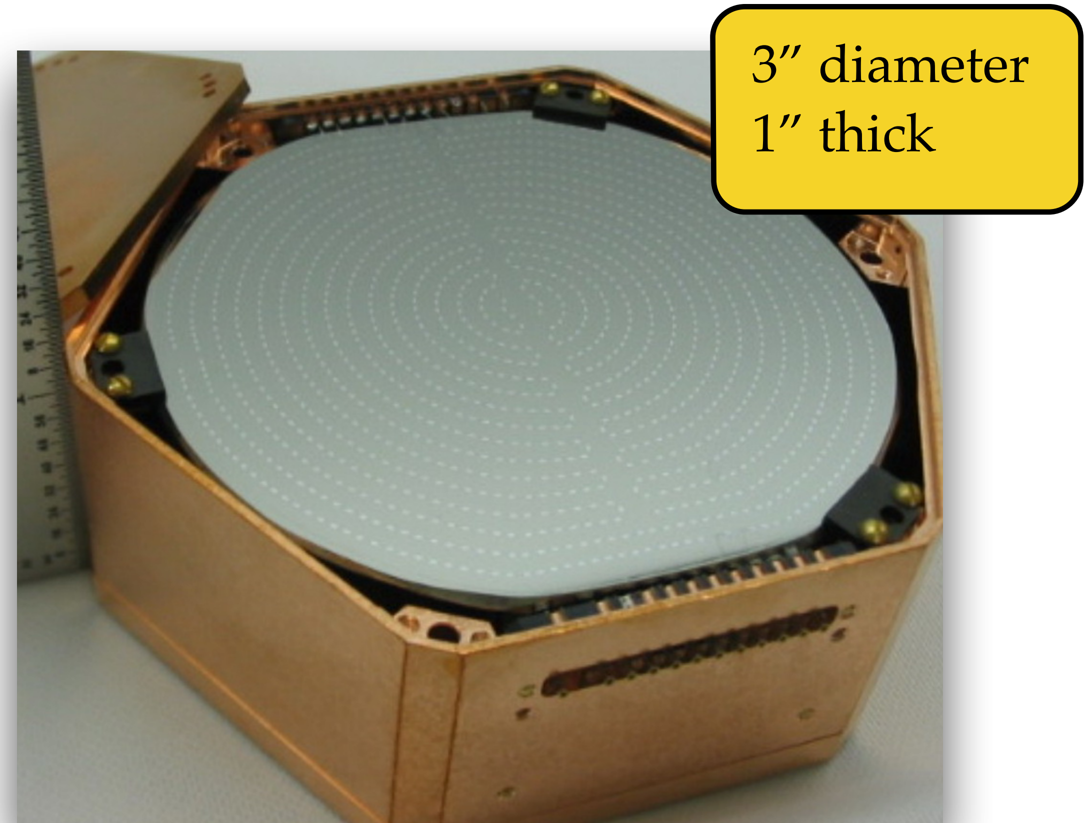


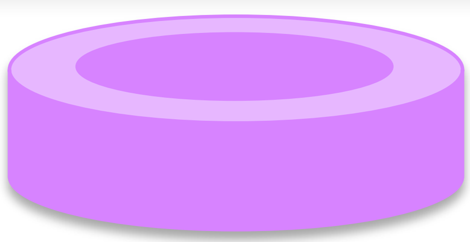

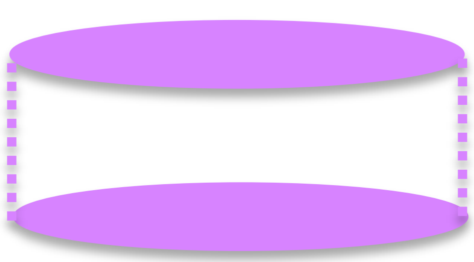

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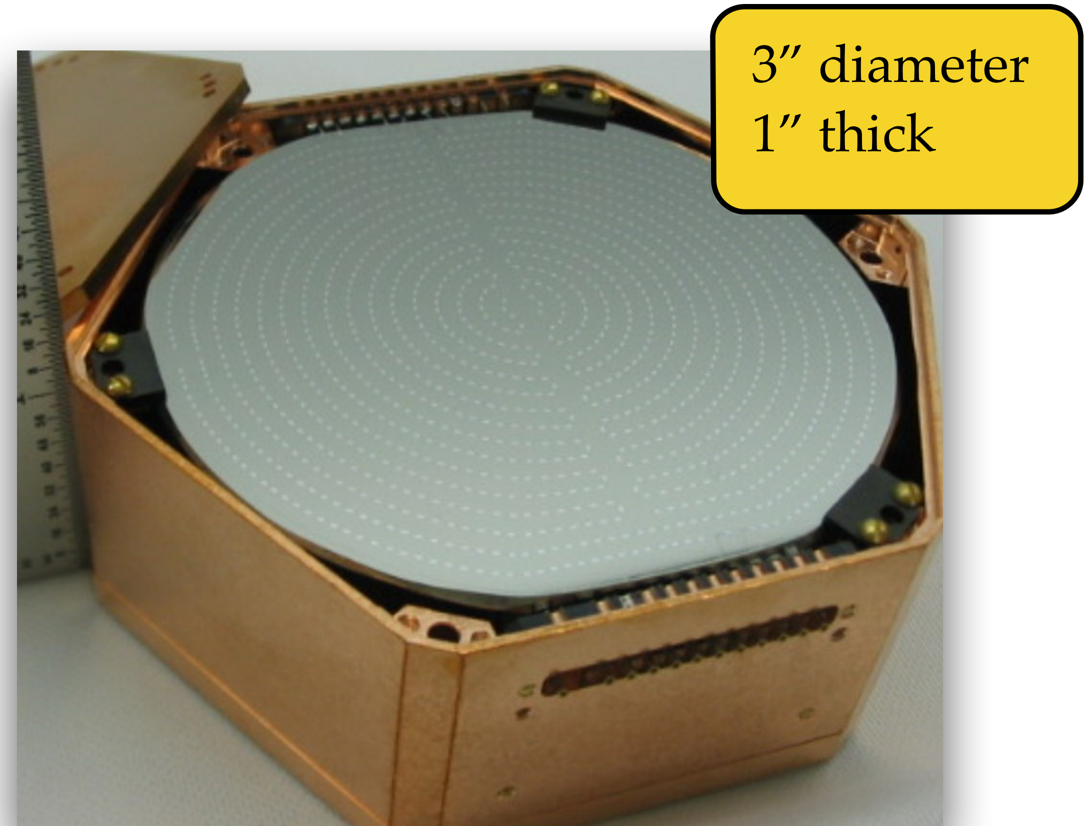
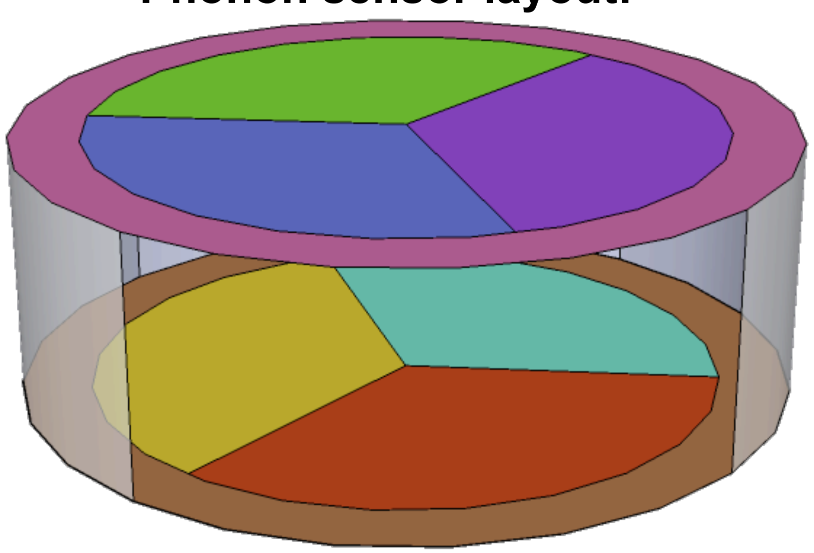



Phonon sensor layout:



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- Each side has one outer channel to reject zero charge events and 3 inner channels to reject surface and sidewall events.

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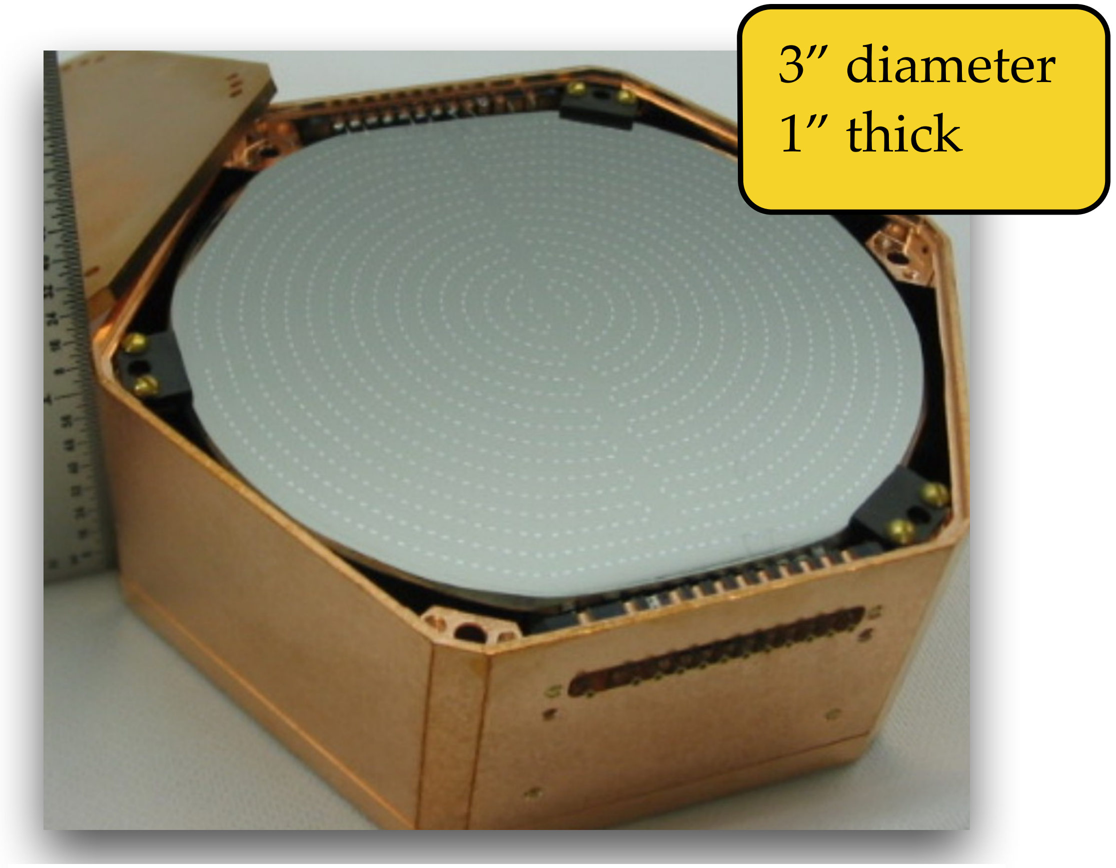


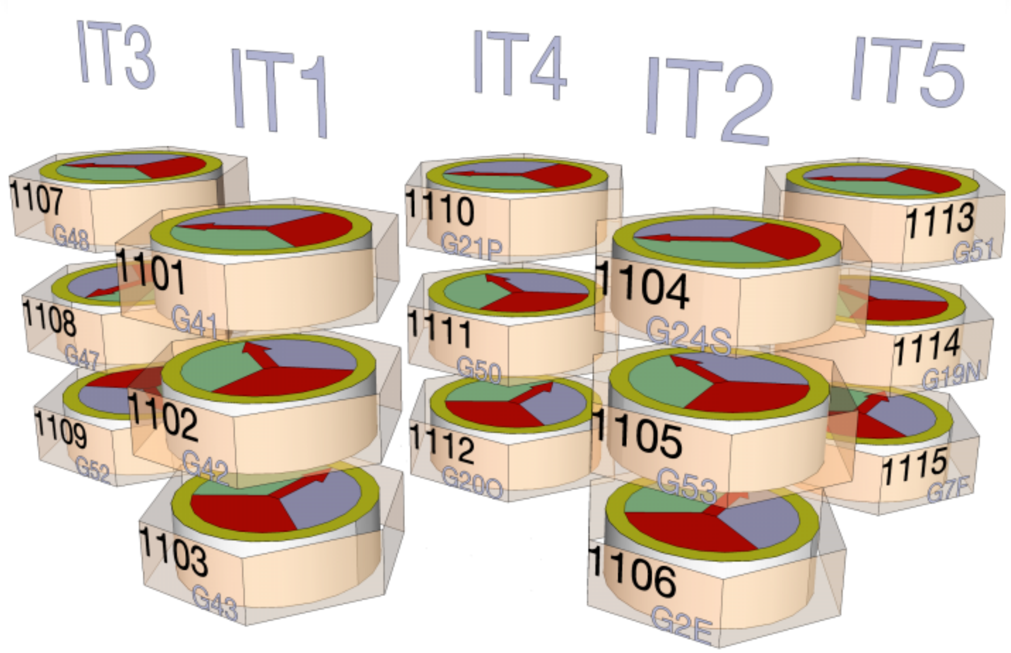


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- Each side has one outer channel to reject zero charge events and 3 inner channels to reject surface and sidewall events.
- 9 kg Ge (15 iZIP detectors, each with mass mass 600 g) stacked into 5 towers

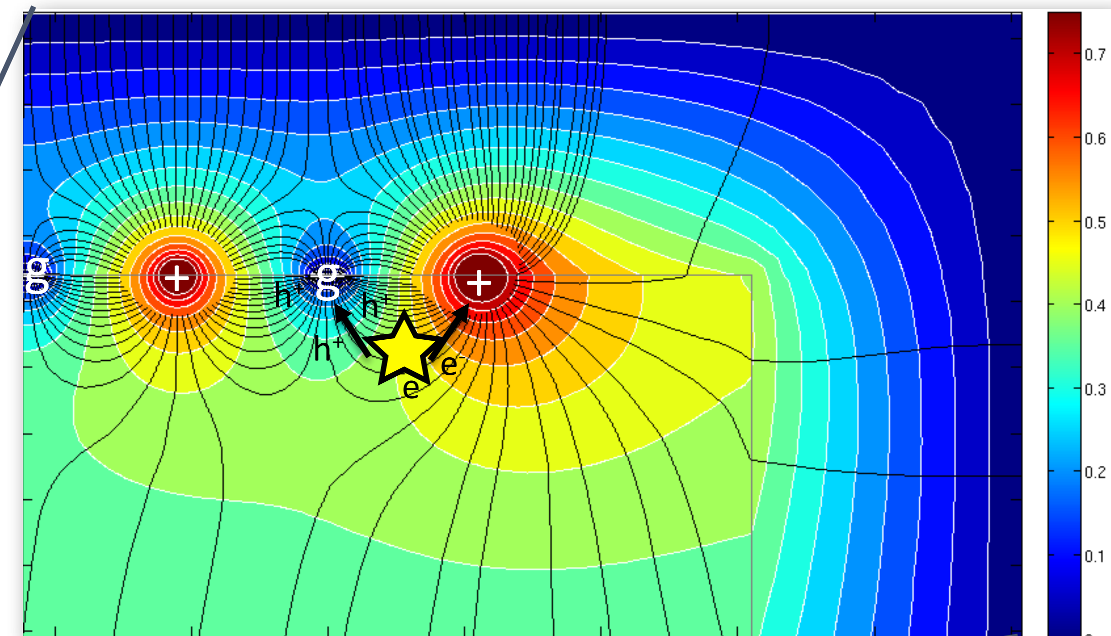
# SCDMS iZIPs: Charge Signal

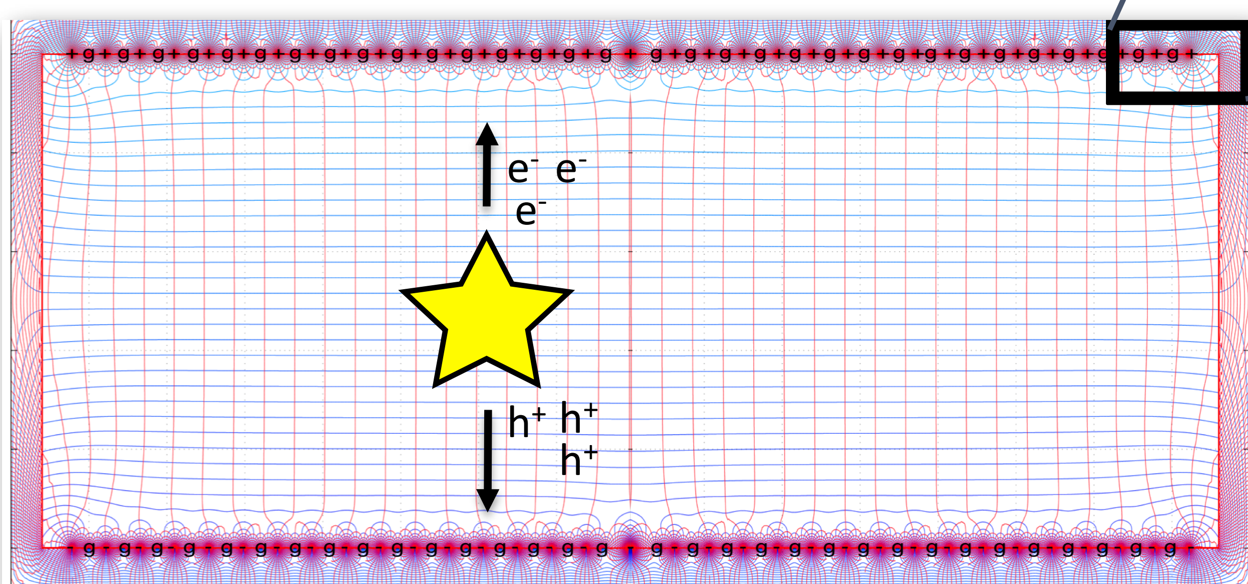
**Bulk Events:**

Equal but opposite ionization signal appears on both faces of detector (symmetric)

**Surface Events:**

Ionization signal appears on one detector face (asymmetric)



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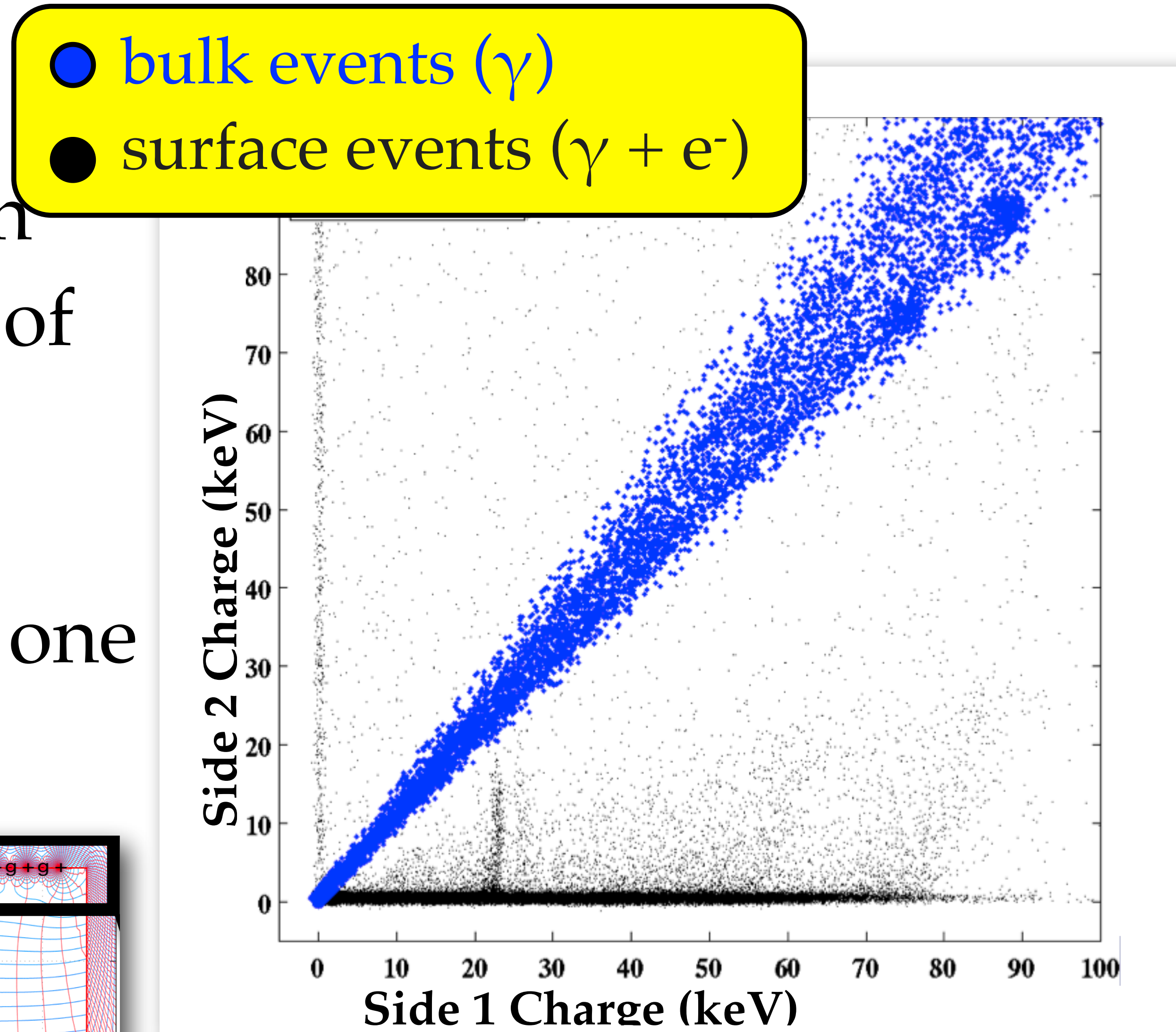
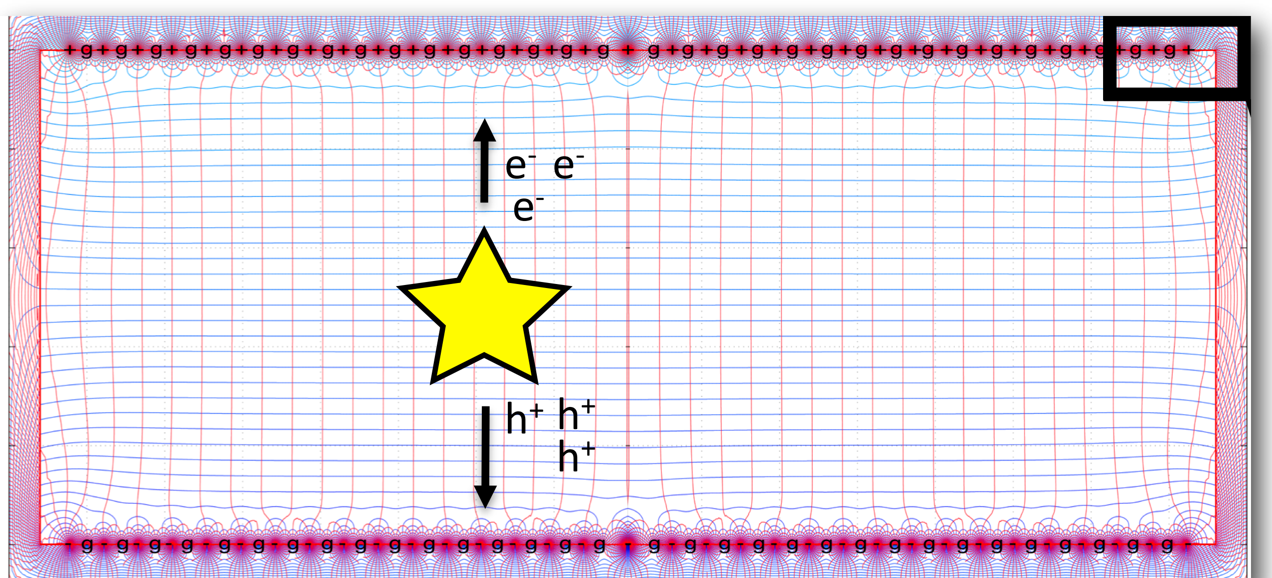
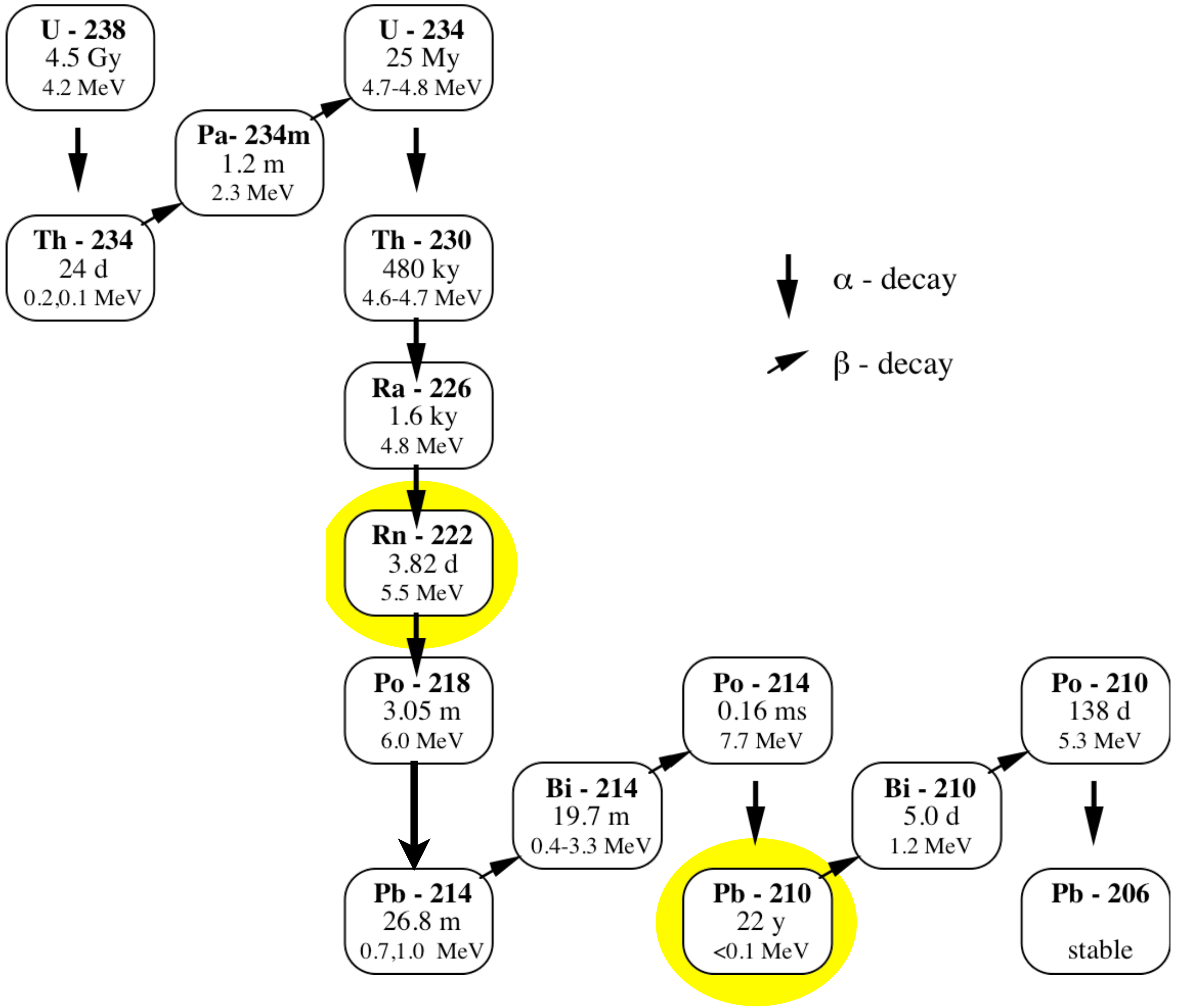



Ionization symmetry is a powerful way to discriminate surface events from bulk events.

# Backgrounds from $^{210}$Pb

- Airborne radon is everywhere. It can absorb onto detectors during fabrication and testing
- Quickly decays to $^{210}$Pb (22.5 year half-life)



# Backgrounds from $^{210}$Pb

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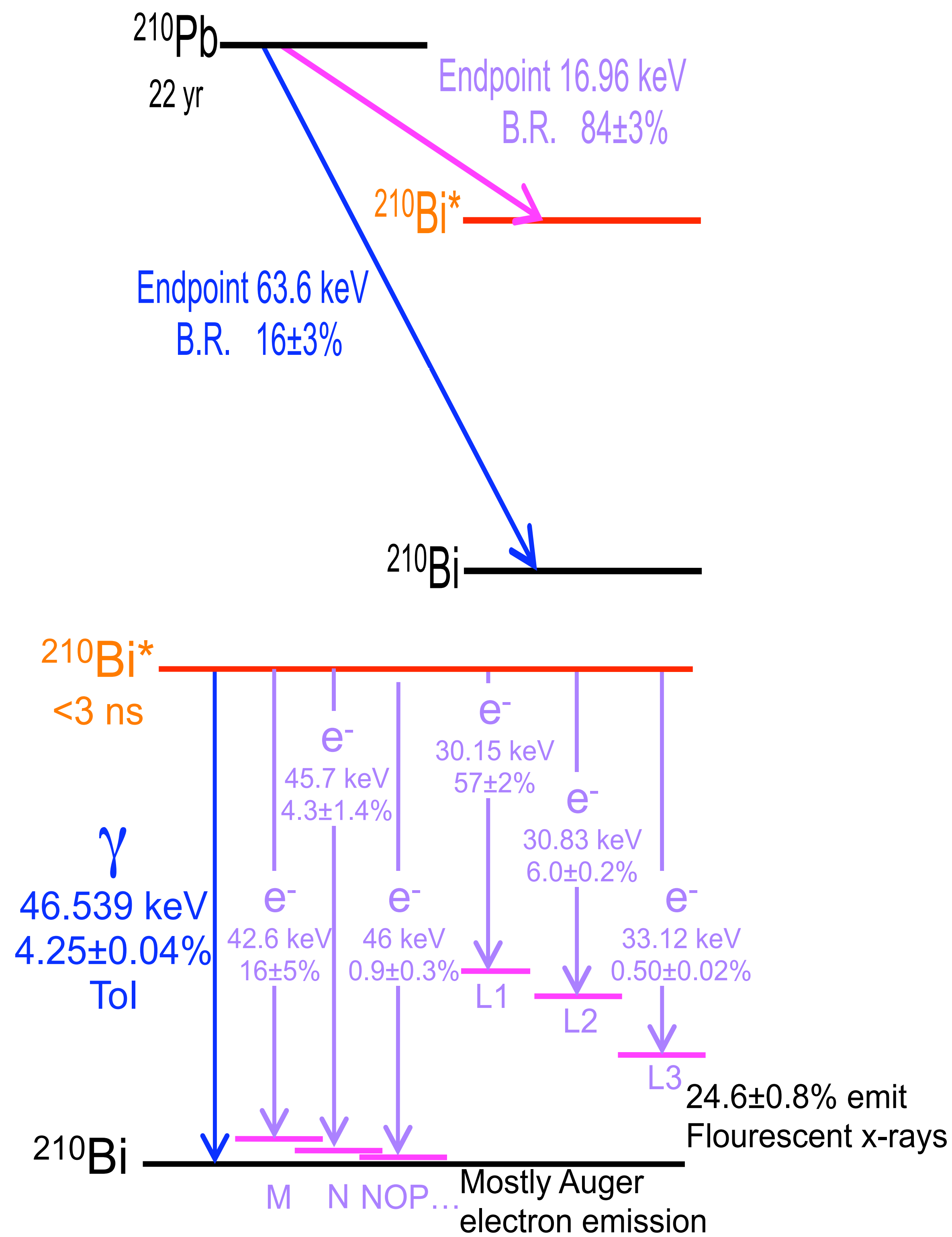
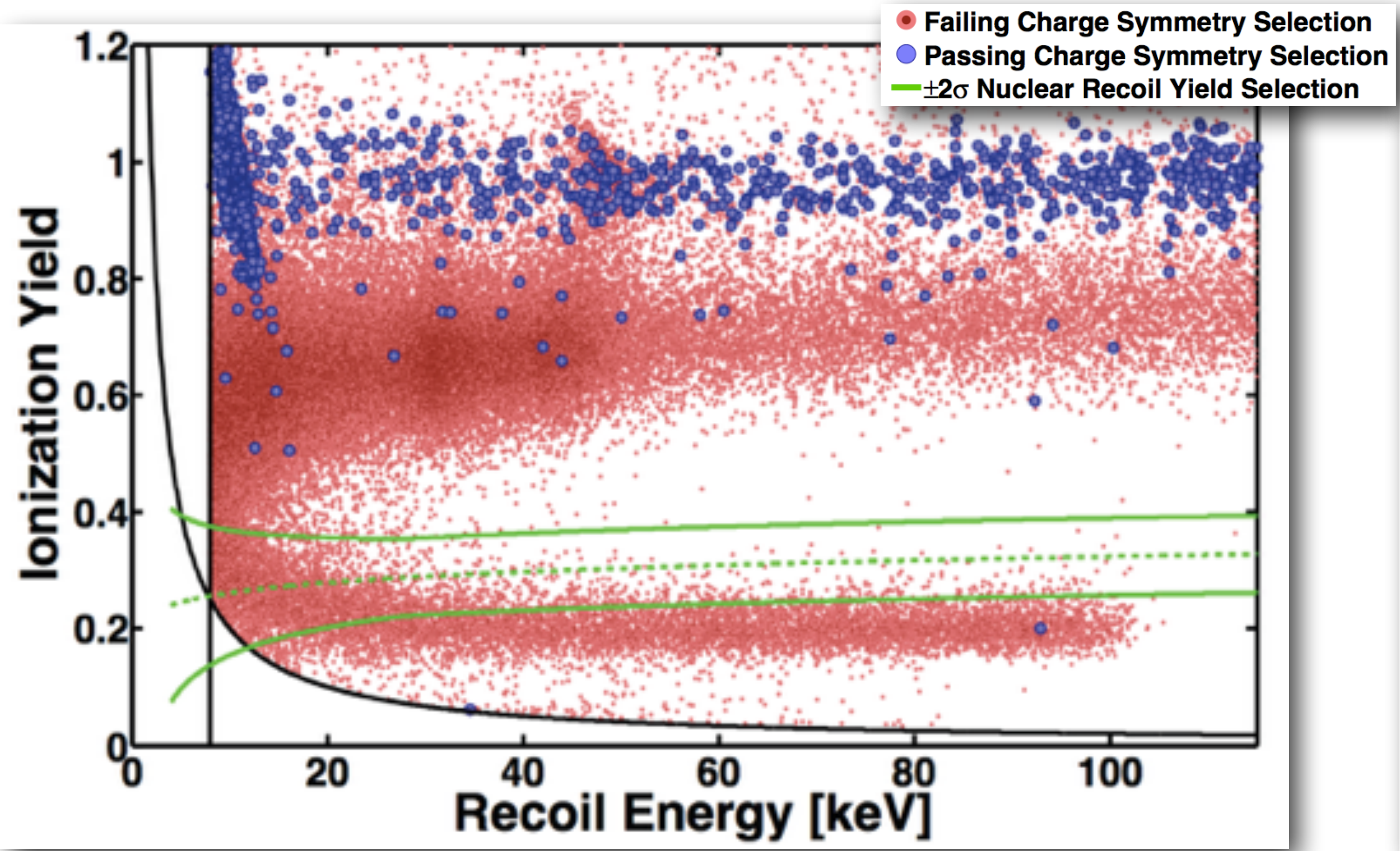
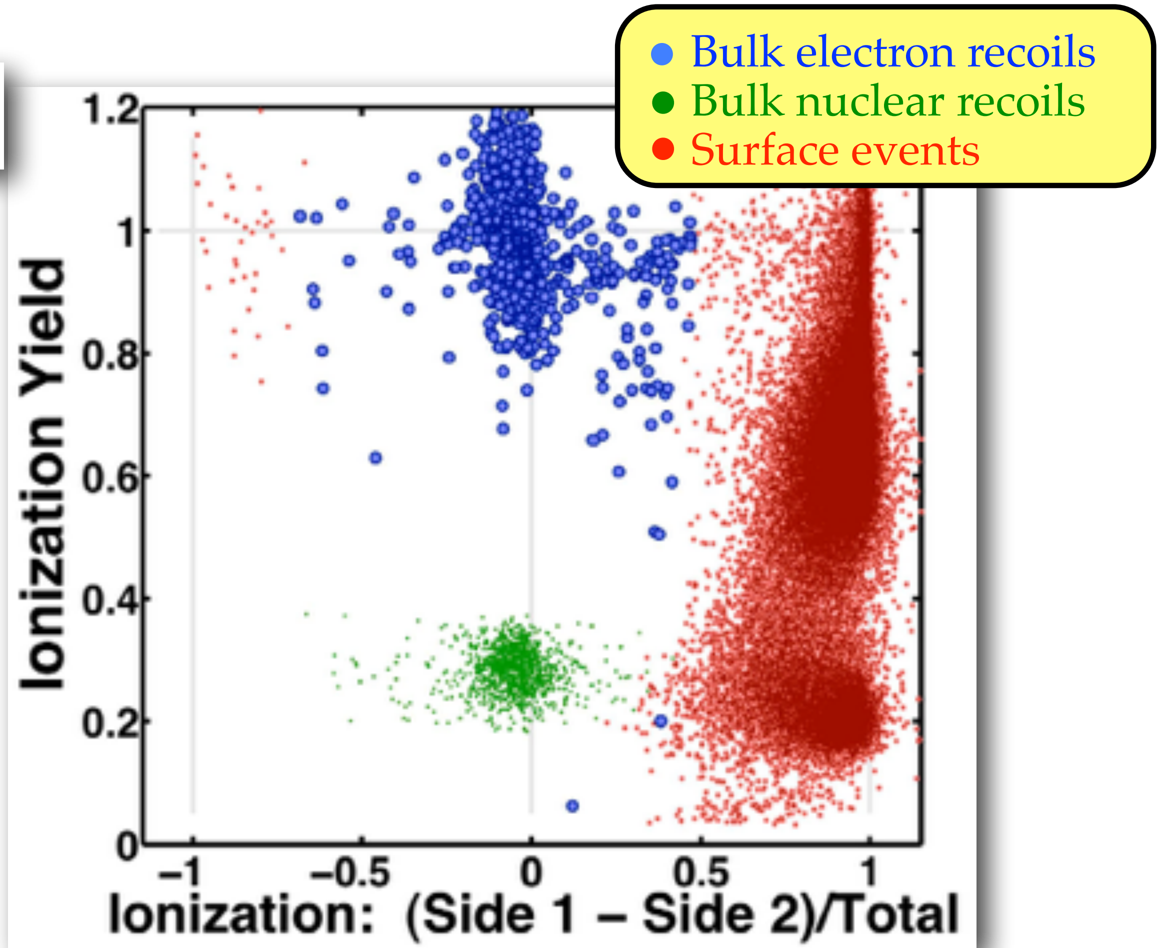
- Quickly decays to $^{210}$Pb (22.5 year half-life)
- $^{210}$Pb produces a class of surface events with energies in the WIMP search range (< 100 keV).
- To test the surface event rejection capabilities of the iZIP detectors, two $^{210}$Pb sources were deployed.



# SCDMS: $^{210}$Pb Test




- 71,525 (38,178) electrons and 16,258 (7,007) $^{206}$Pb recoil surface event collected from $^{210}$Pb source in 905.5 (683.8) live-hours
- In ~800 live hours 0 events leaking into the signal region (misID < $1.7 \times 10^{-5}$ @90% C.L.)
- ~50% fiducial volume (8-115 keVr)
- <0.6 events in 0.3 ton-years
- Allows an ~100 kg experiment run for 5 years at SNOLAB with less than 1 event background.

APL 103, 164105 (2013)

# Backgrounds

**Sources:**

Radioactive decays from naturally abundant radio-isotopes

Radioactive decays from "created" radio-isotopes (i.e. activated materials)

Interactions from cosmic rays and their daughter particles.

**Solutions:**

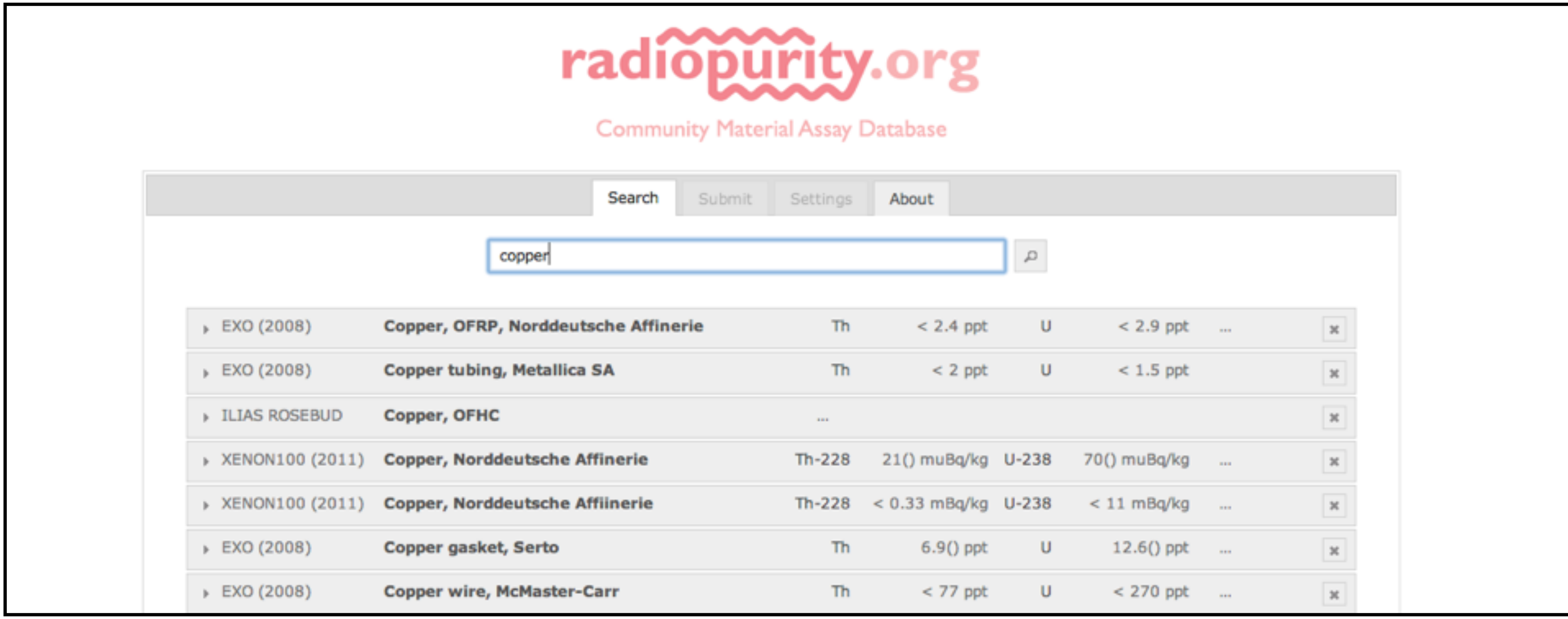
- Work with most radio-pure materials possible to minimize rates in detectors and components closest to the detectors.
- Install passive (active) shielding to suppress (detect) backgrounds from surrounding environment
- Carefully screen experimental components
- Powerful discrimination from analysis

- Minimize fabrication and handling time to suppress exposure to cosmic rays.

- Go underground.

# Community Assays Database

## Use Clean Materials


radiopurity.org

Community Material Assay Database

Search | Submit | Settings | About

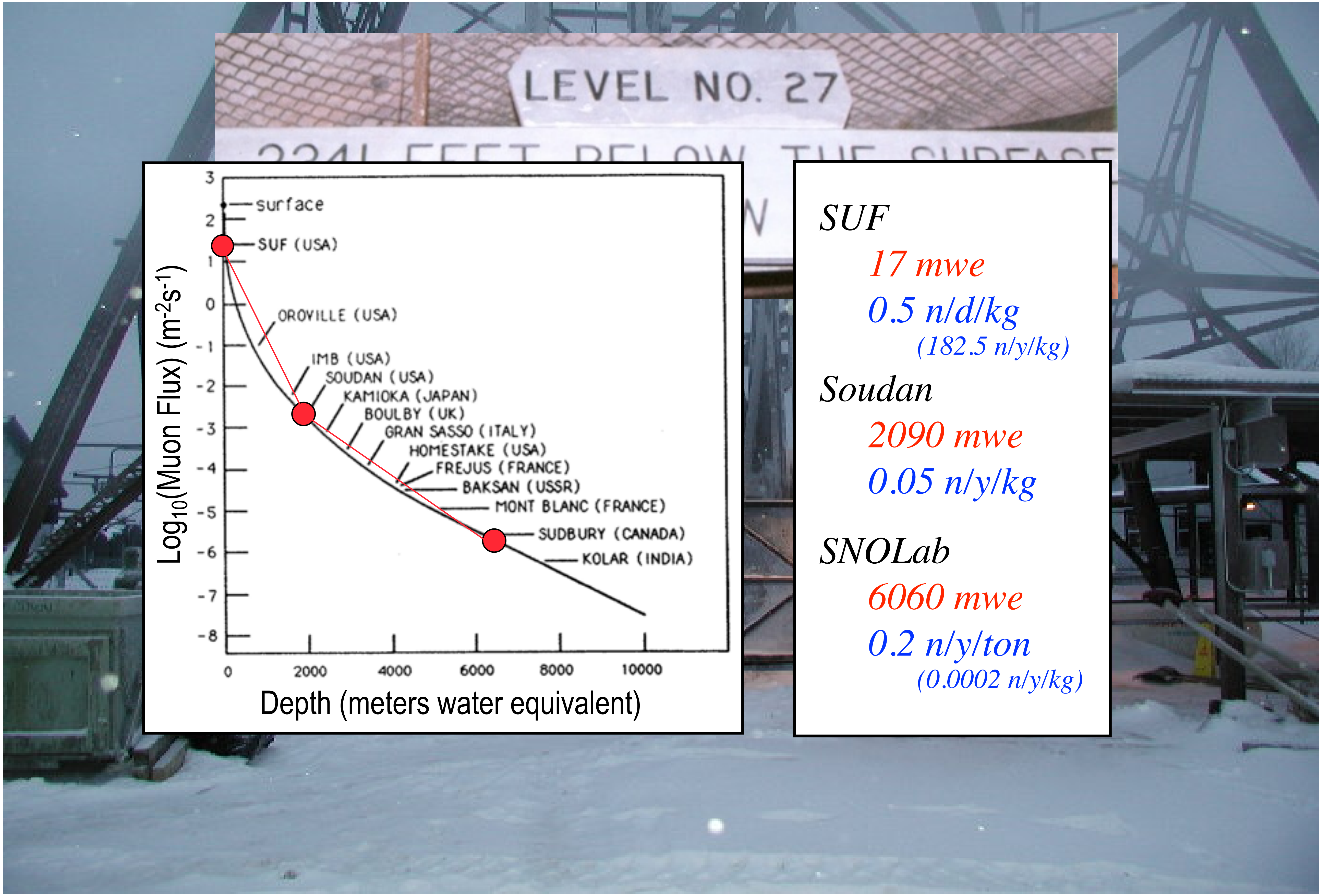
copper

| | | | | | | |
|---|---|---|---|---|---|---|
| EXO (2008) | Copper, OFRP, Norddeutsche Affinerie | Th | < 2.4 ppt | U | < 2.9 ppt | ... |
| EXO (2008) | Copper tubing, Metallica SA | Th | < 2 ppt | U | < 1.5 ppt | |
| ILIAS ROSEBUD | Copper, OFHC | ... | | | | |
| XENON100 (2011) | Copper, Norddeutsche Affinerie | Th-228 | 21() muBq/kg | U-238 | 70() muBq/kg | ... |
| XENON100 (2011) | Copper, Norddeutsche Affiinerie | Th-228 | < 0.33 mBq/kg | U-238 | < 11 mBq/kg | ... |
| EXO (2008) | Copper gasket, Serto | Th | 6.9() ppt | U | 12.6() ppt | ... |
| EXO (2008) | Copper wire, McMaster-Carr | Th | < 77 ppt | U | < 270 ppt | ... |

http://radiopurity.org

Supported by AARM, LBNL, MAJORANA, **SMU**, SJTU & others


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)*

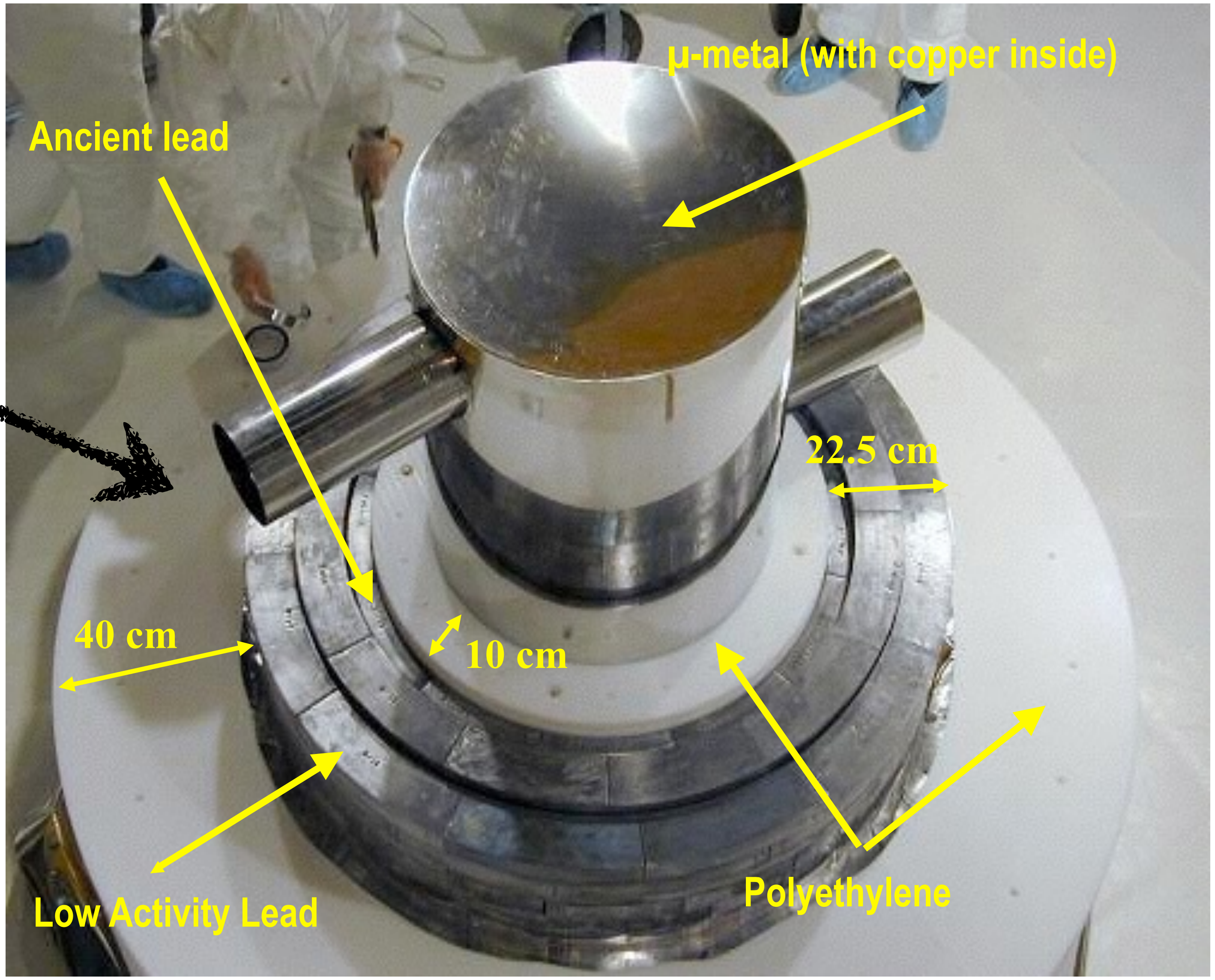
# Shielding: Peel the Onion

**Active Muon Veto:**
rejects events from cosmic rays

# Shielding: Peel the Onion

**Active Muon Veto:** rejects events from cosmic rays

**Polyethyene:** moderate neutrons from fission decays and ($\alpha$,n) interactions



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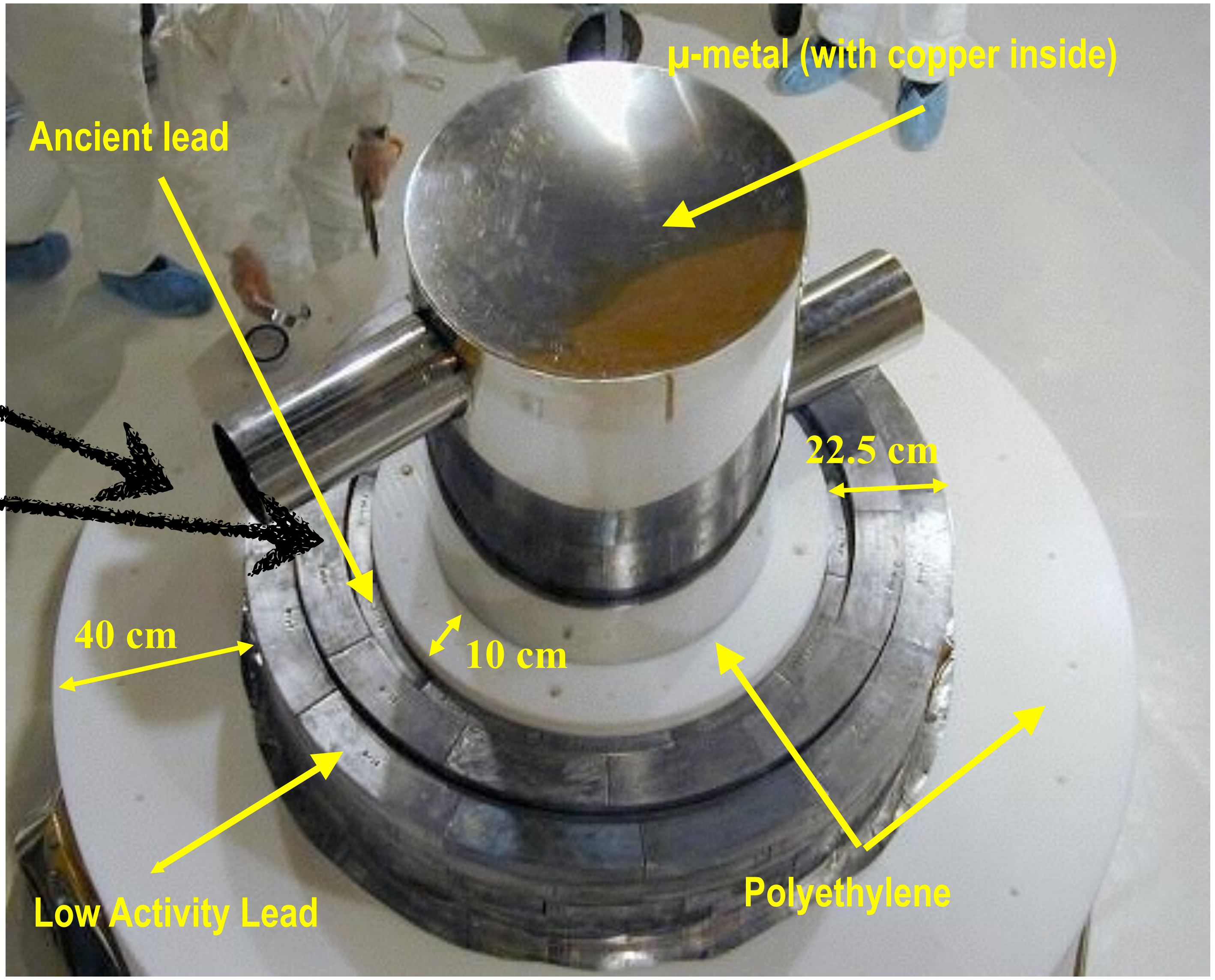

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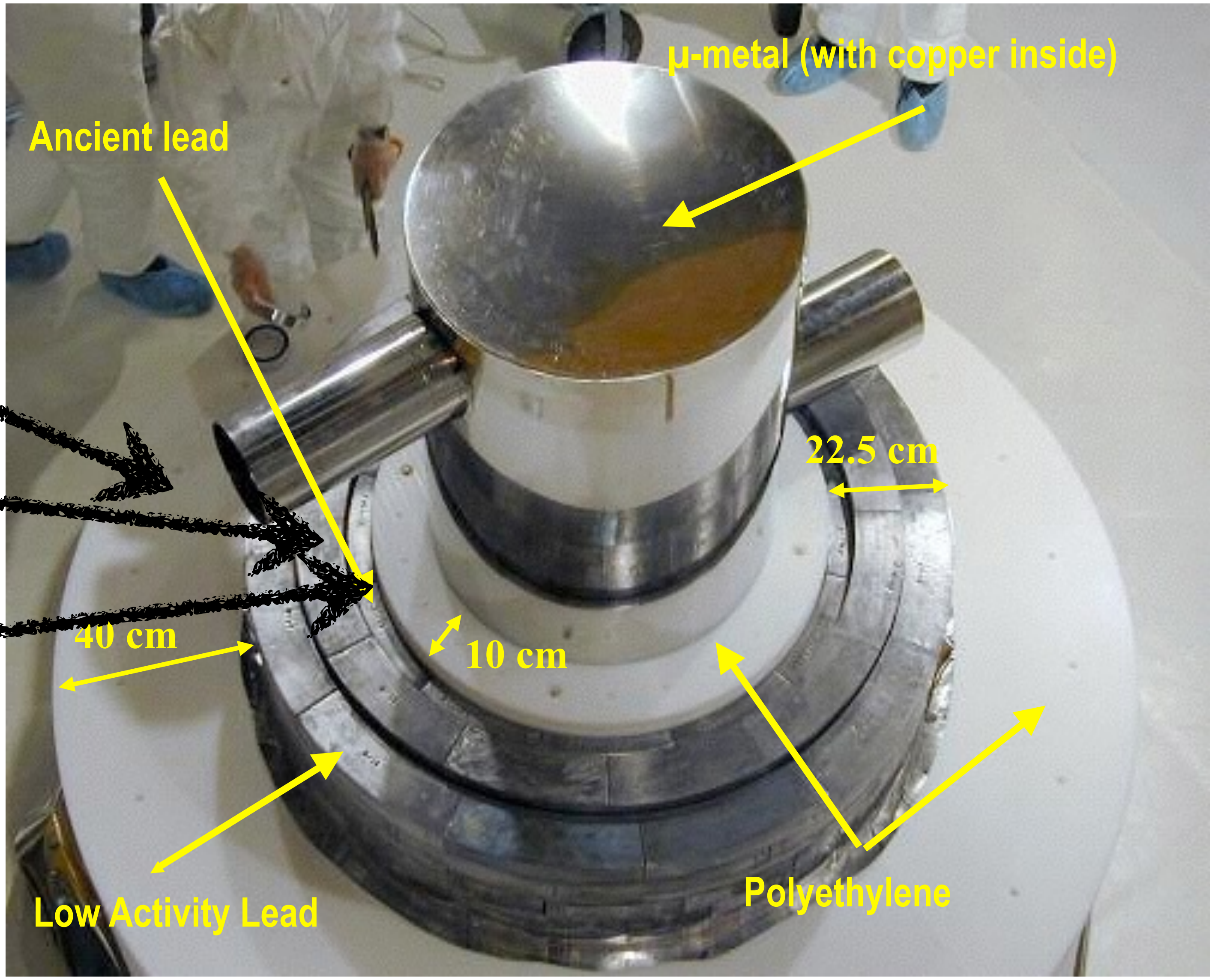
**Ancient Pb:** shields $^{210}$Pb betas



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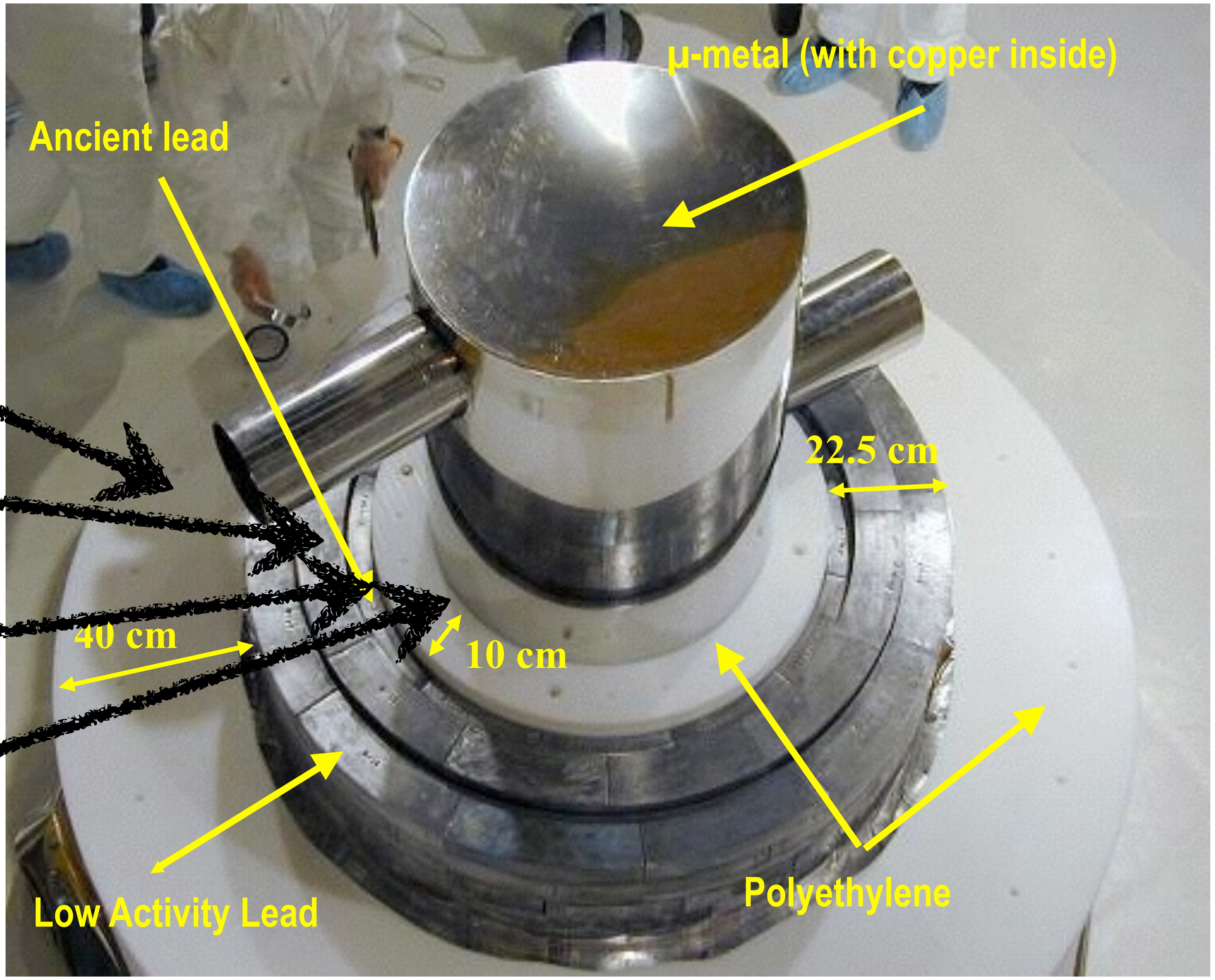

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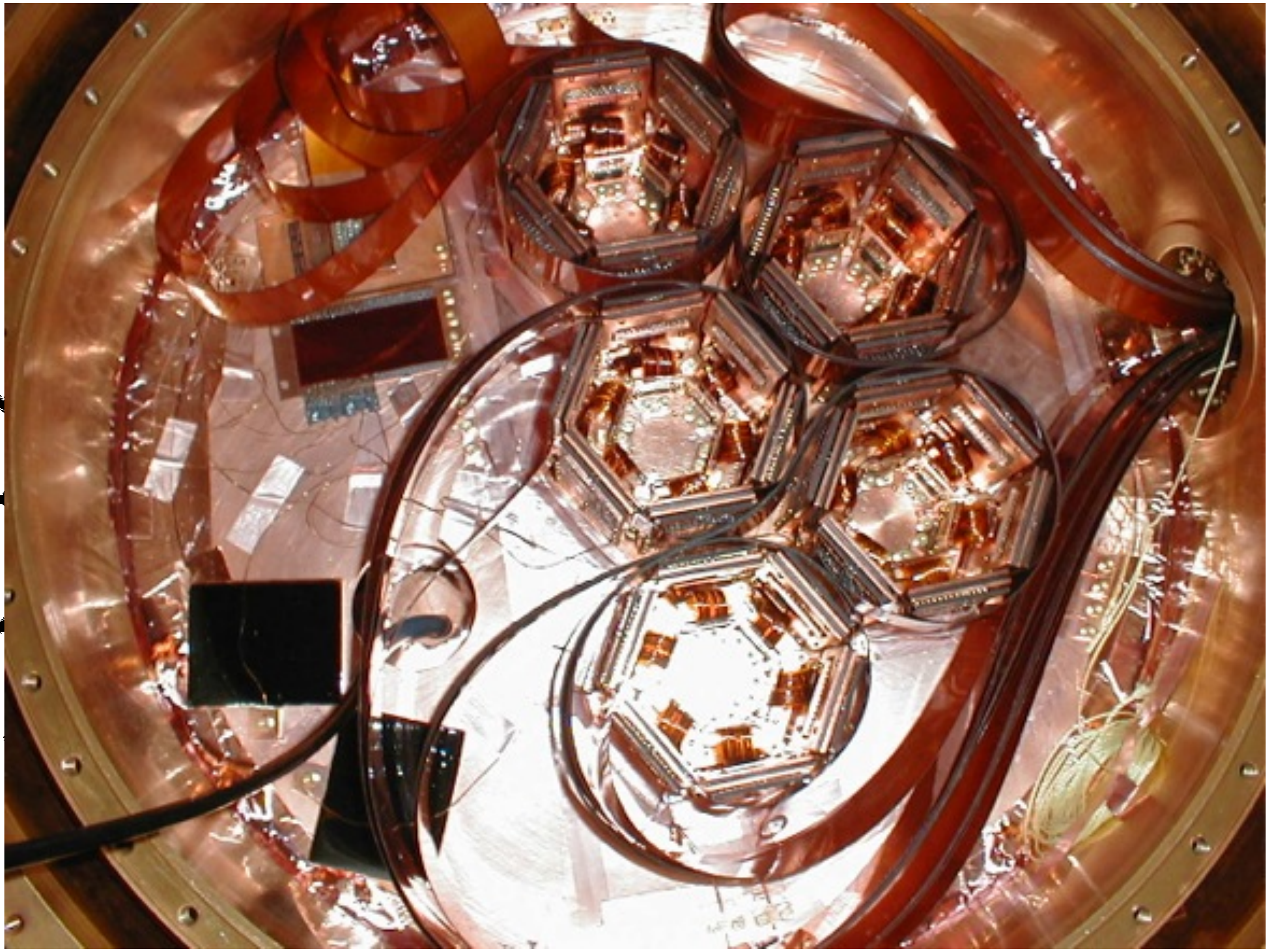
**Cu:** radio-pure inner copper can



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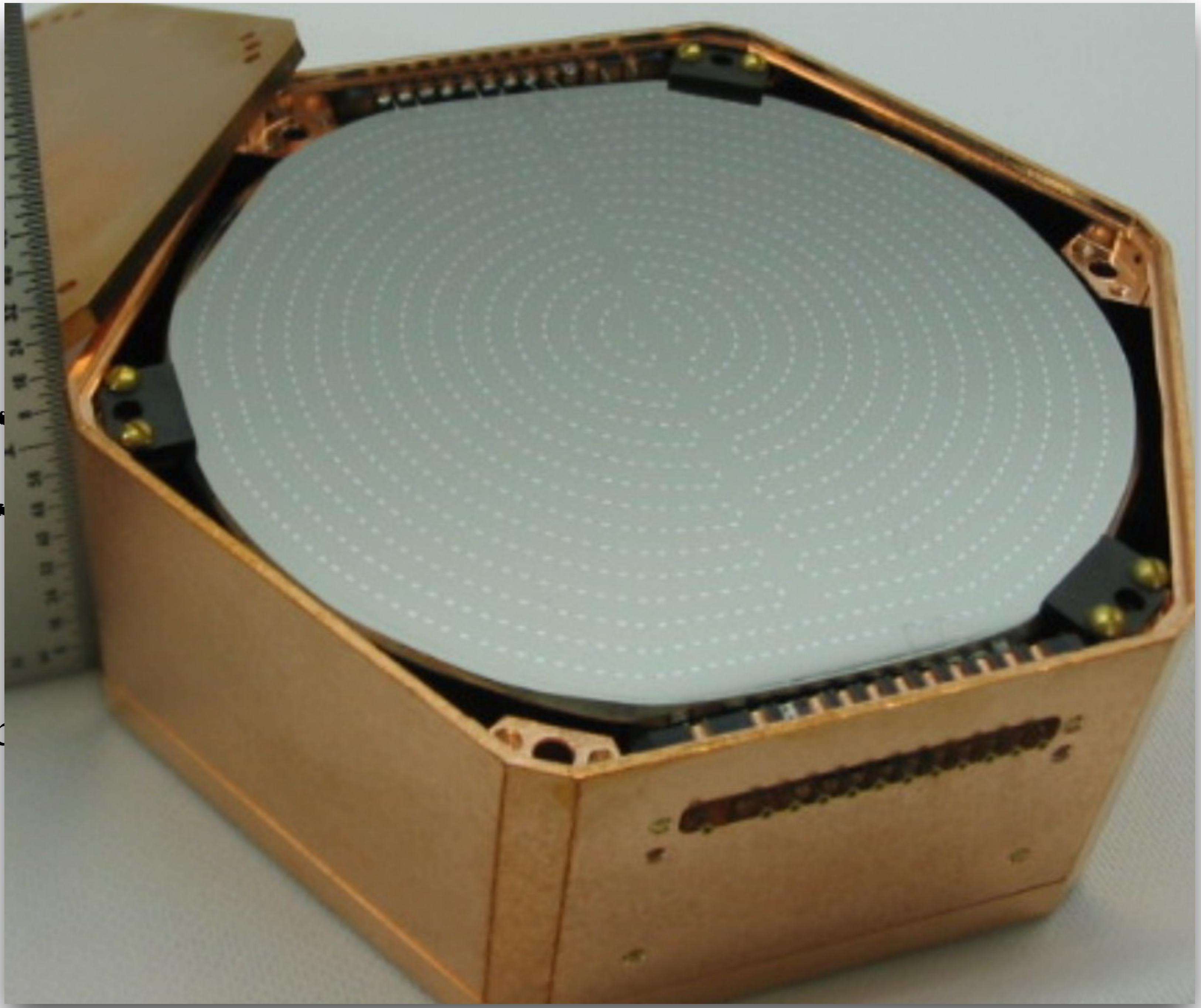
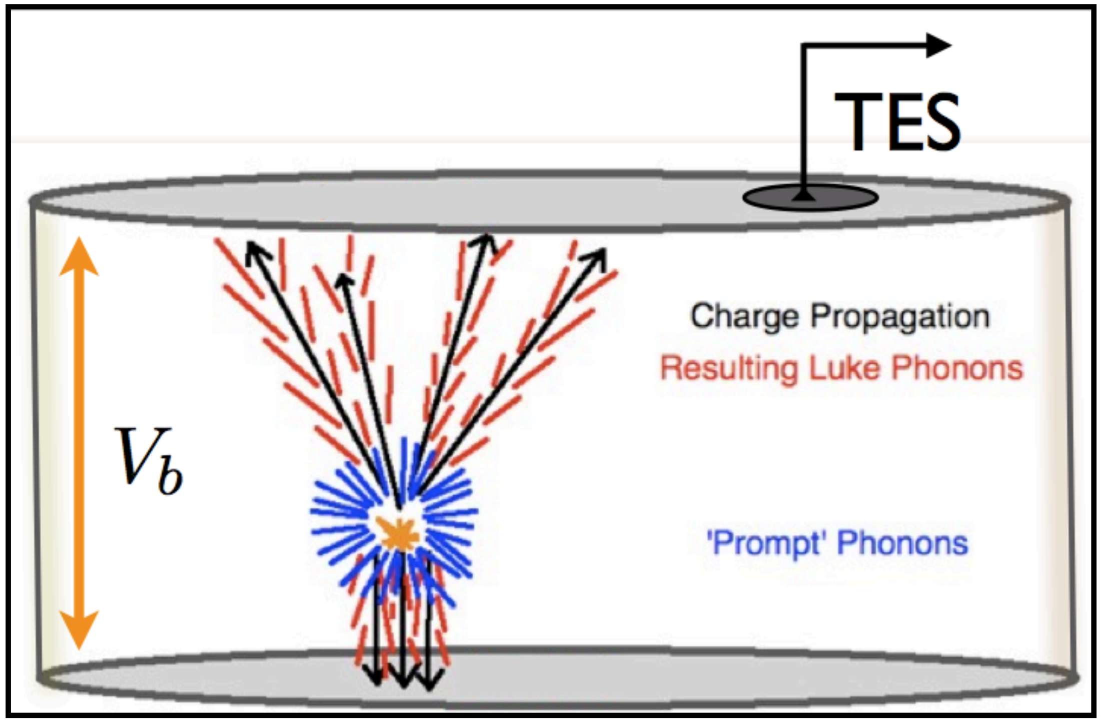
**Cu:** radio-pure inner copper can

**Ge:** target



# A Low Ionization Experiment




Luke energy scales as bias voltage and noise remains constant until breakdown

$E_{luke} = N_{e/h} \times eV_b$

- CDMSlite strategy leverages Neganov-Luke amplification to obtain low thresholds with high-resolution
  - Ionization only, uses phonon instrumentation to measure ionization
  - No event-by- event discrimination of nuclear recoils
- Drifting $N_e$ electrons across a potential (V) generates $qN_eV$ electron volts of heat

$$N_e = \frac{E_i}{\epsilon}$$

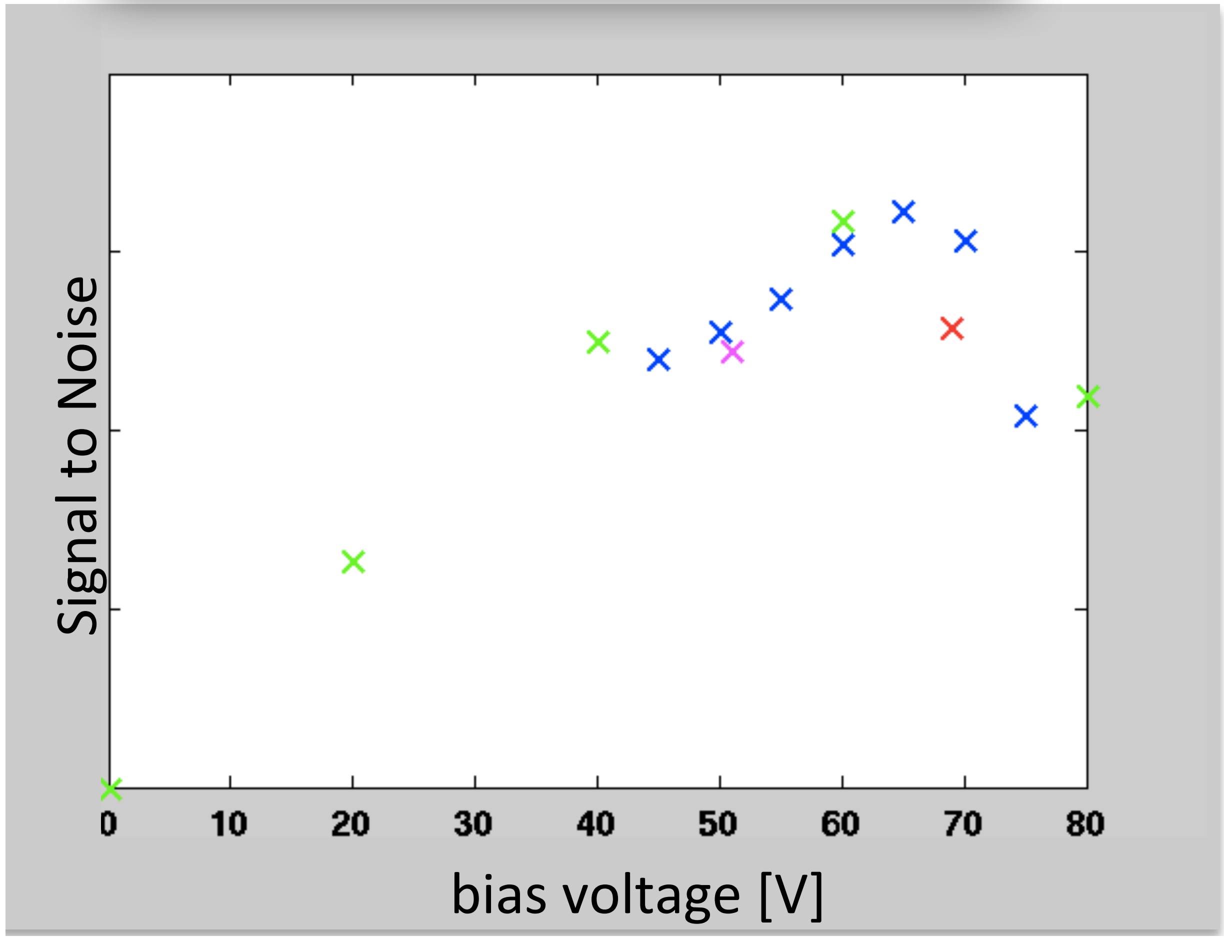
where $\epsilon = 3eV$ in Ge.

- The work done drifting the charges can be detected as heat.

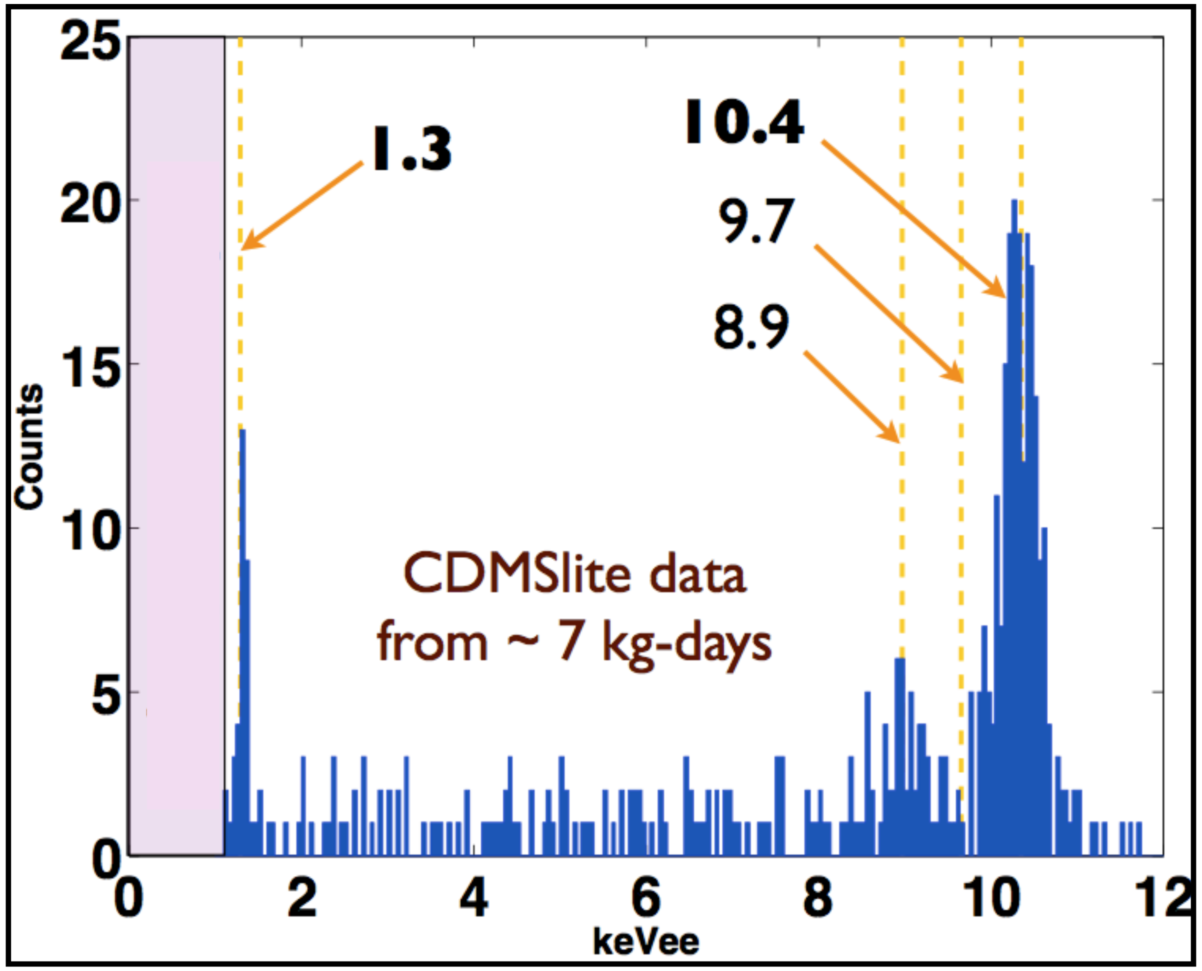
# CDMSlite - The Detector

- Custom electronics were installed to allow biases above 10V
  - Disable one side of iZIP and raising that entire side to the bias voltage.
- A voltage scan indicated 69 V was the optimal operating voltage.
  - At low voltage, the signal increases linearly with no charge noise.
  - At high voltage onset of leakage current increases the phonon noise.
- The signal gain at 69V is substantial.

$$G^* = \frac{E_t(V=69)}{E_t(V=0)} = \frac{1+qN_eV}{1} = 24$$

# CDMSlite




- Voltage assisted calorimetric ionization detection can improve energy resolution and threshold of bolometric devices.

- Resulting Luke amplification has excellent energy resolution down to 170 $eeV_{ee}$ in our detectors.

- Resolution of various Ge activation lines.

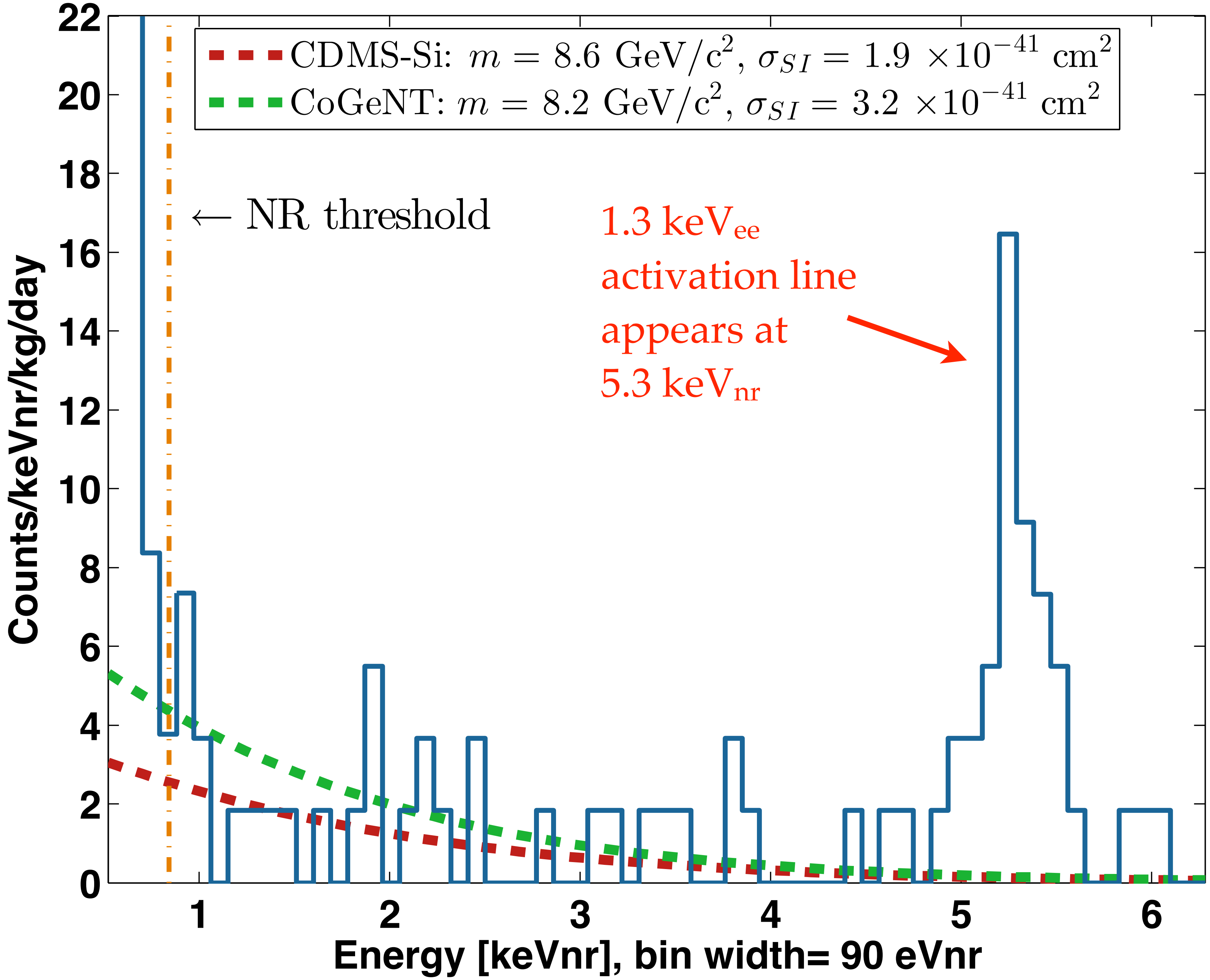
# CDMSlite: The Data

- Data were taken during three periods in 2012
- One iZIP was used, IT5Z2 – 0.6 kg
  - Selected for its low trigger threshold and low leakage current
- There were two neutron exposures ($^{232}$Cf)
  - Activation of Ge ($^{70}$Ge + n --> $^{71}$Ge) allowed determination of energy scale and monitoring of stability (10.36 $keV_{ee}$ and 1.29 $keV_{ee}$ lines).
- Raw exposure was 9.6 kg days (16 live days)

| Run Period | Starting Date | Ending Date | Raw Livetime [h] |
|---|---|---|---|
| 1 | August 18 | August 29 | 166.5 |
| 2 | September 7 | September 14 | 111.2 |
| 3 | September 18 | September 25 | 105.9 |

# CDMSlite: Results

PRL 112, 041302, 2014




Nuclear recoils create fewer charges than electron recoils.

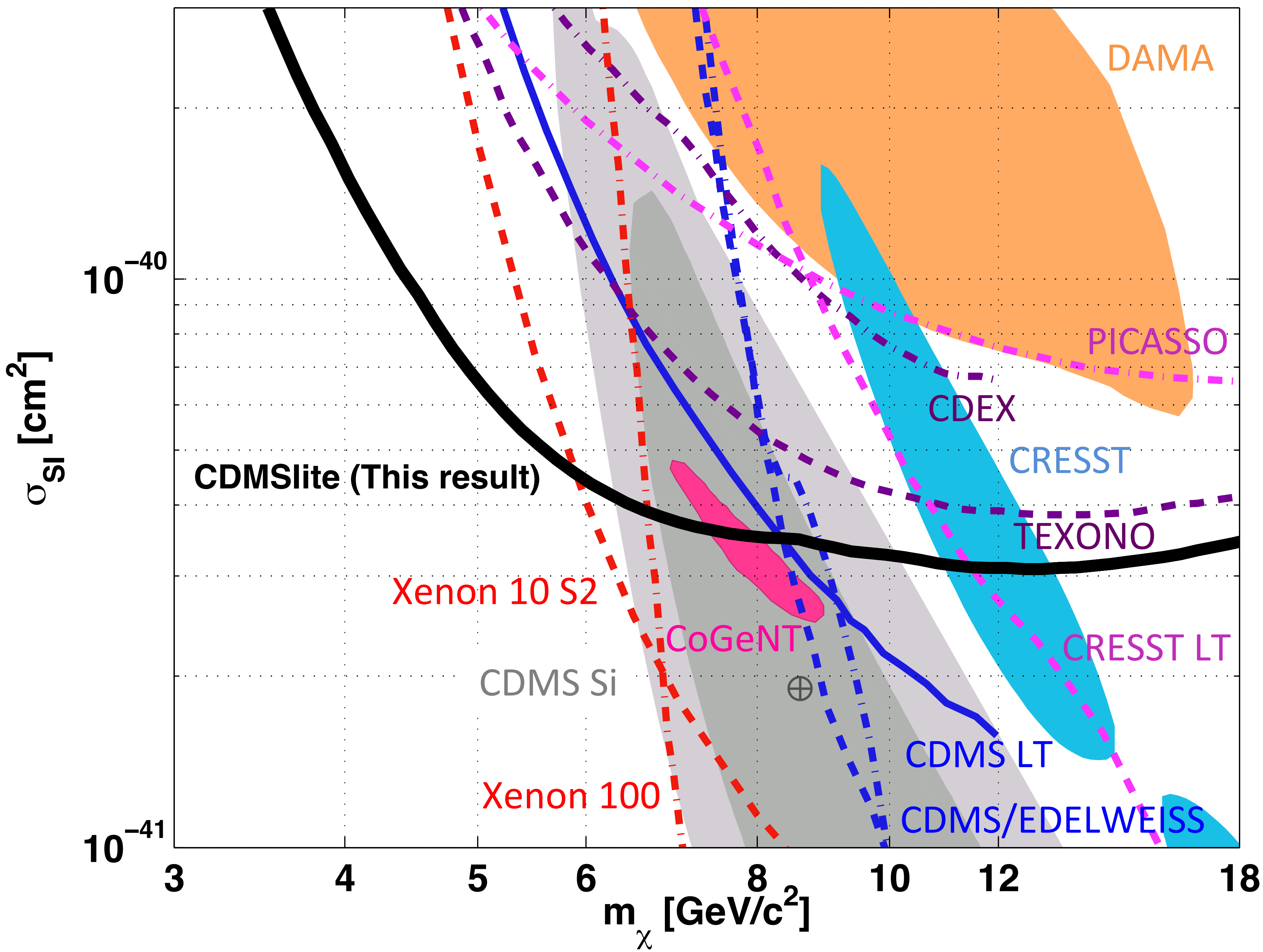
Conversion keVee to keVnr

$$E_{nr} = E_{ee}\frac{1+\frac{eV_b}{\epsilon}}{1+\frac{eV_b}{\epsilon}Y(E_{nr})}$$

where Y is the ionization yield, defined to be unity for electron recoils.

# CDMSite: Results

PRL 112, 041302, 2014



# SCDMS Low Threshold Strategy

**Challenge:**

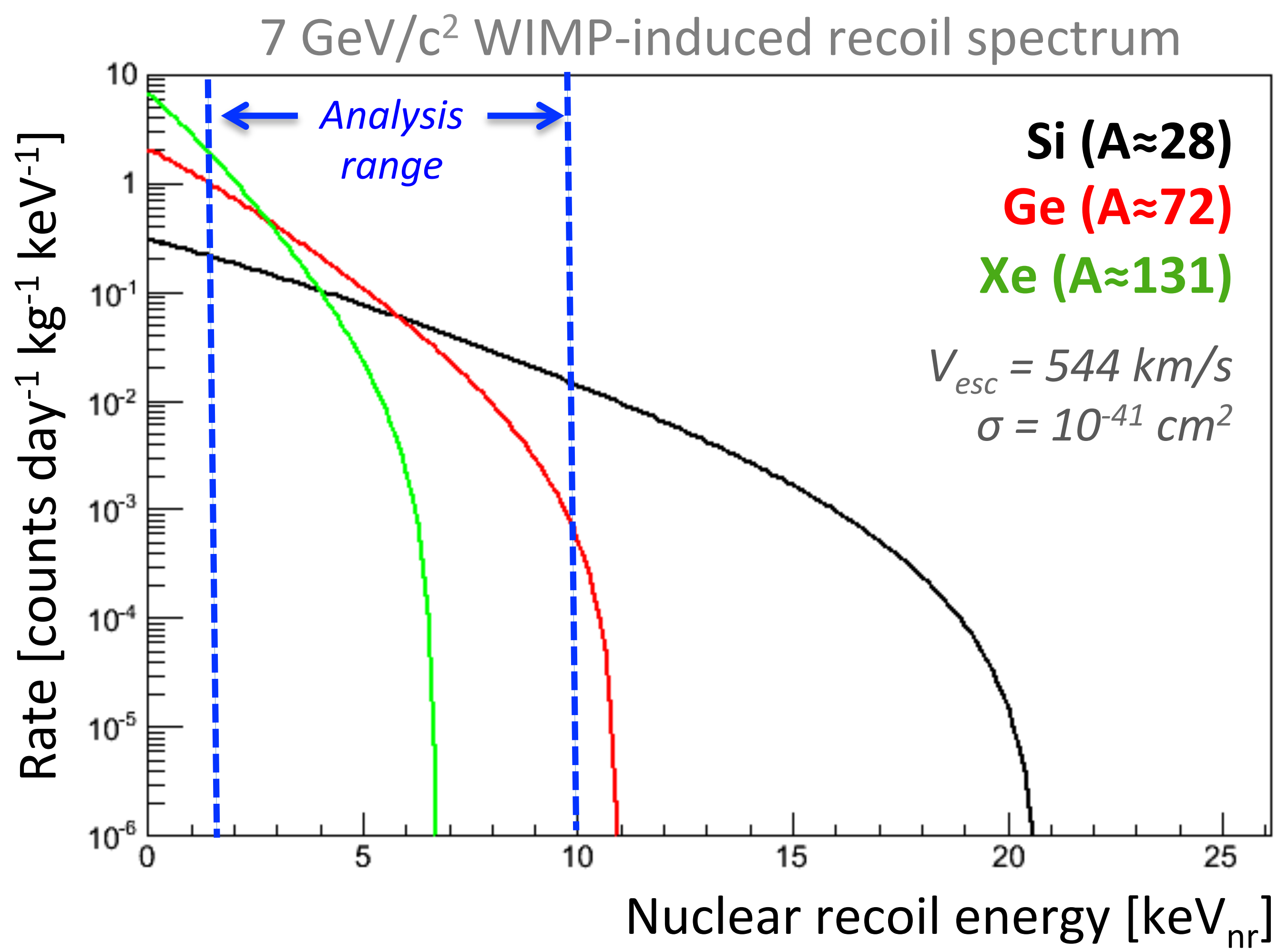
- Signal is at very low recoil energies where backgrounds are difficult to reject

**Strategy:**

- Use 7 detectors with lowest thresholds; lower the threshold as much as possible
  - 1.6 $keV_{nr}$ trigger threshold
- 557 kg-days exposure taken from Mar 2012 - Jul 2013.

**Trade-off:**

- Background is difficult to reject below 10 $keV_{nr}$. Try to reject as much background as possible.

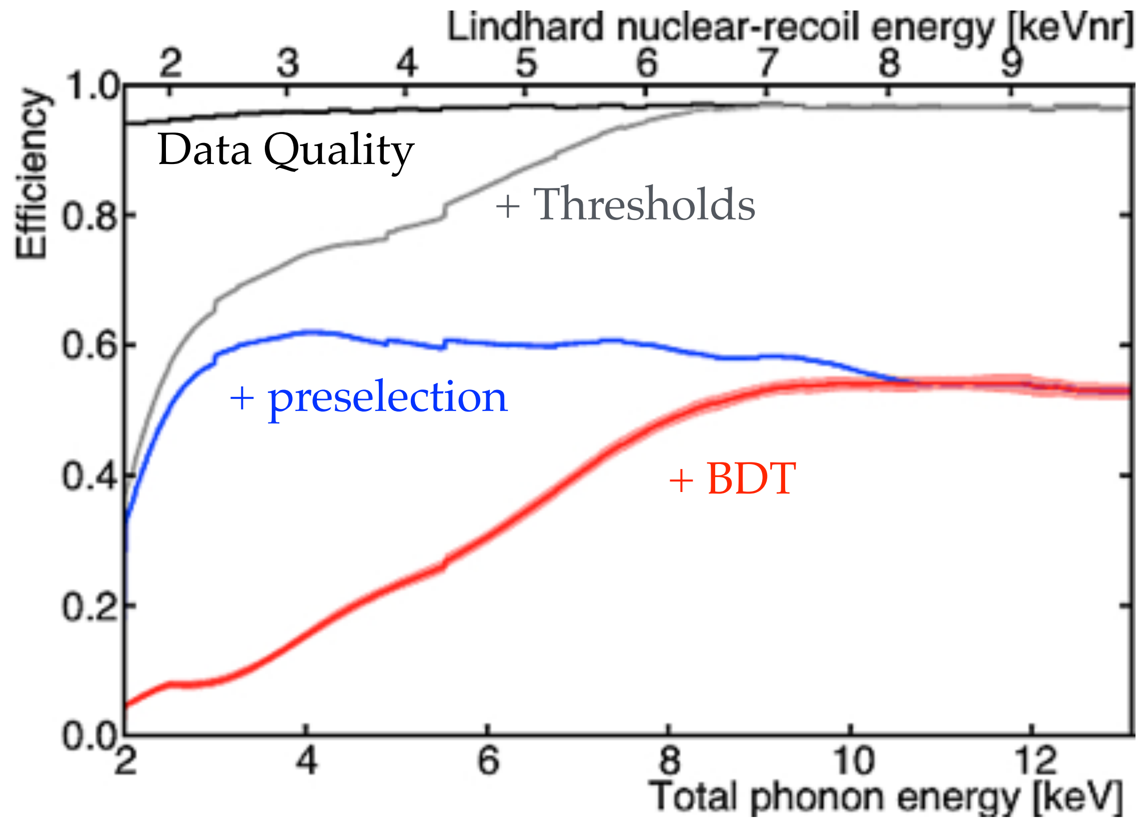



**We expect background events in the signal region!**

# Analysis Details

**Blind Analysis:**

All single-detector scatter events in energy range removed from study, except data following $^{232}Cf$ calibration due to activation.



# Analysis Details

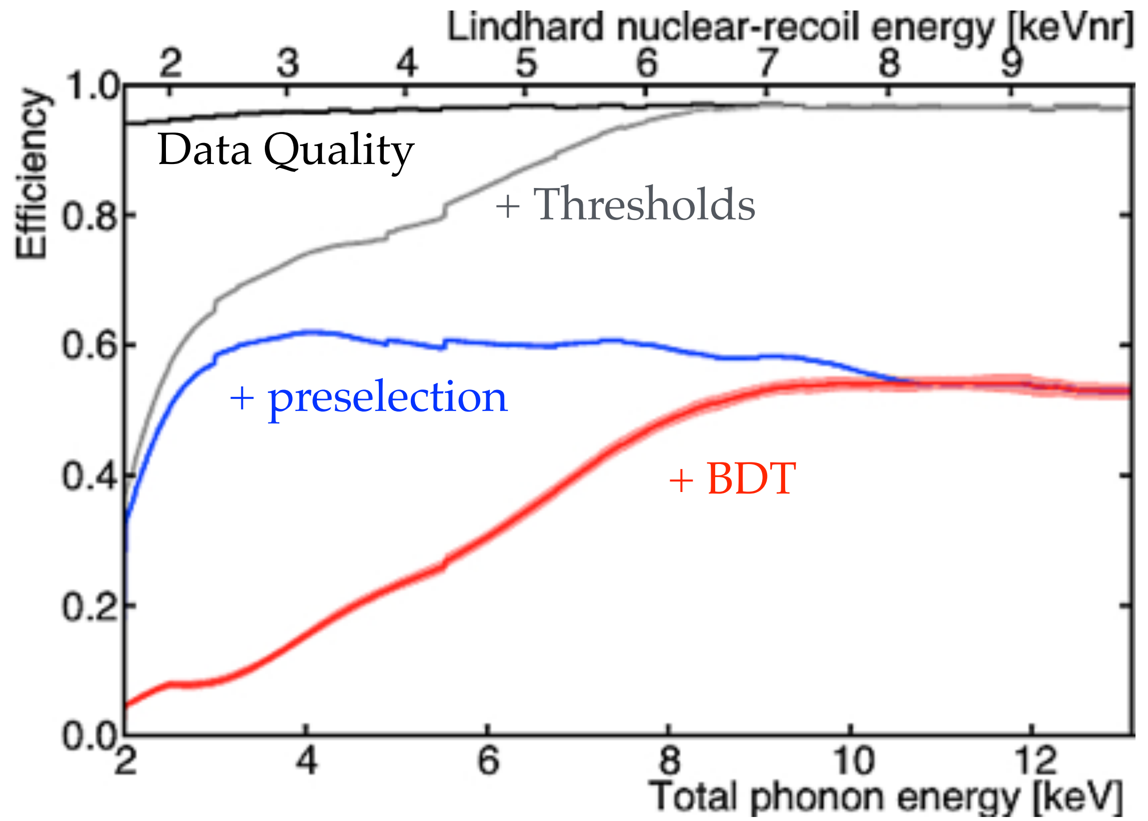
**Blind Analysis:**

All single-detector scatter events in energy range removed from study, except data following $^{232}$Cf calibration due to activation.

**Data Quality:**

Reject periods with poor detector performance.

Remove misreconstructed and noisy pulses

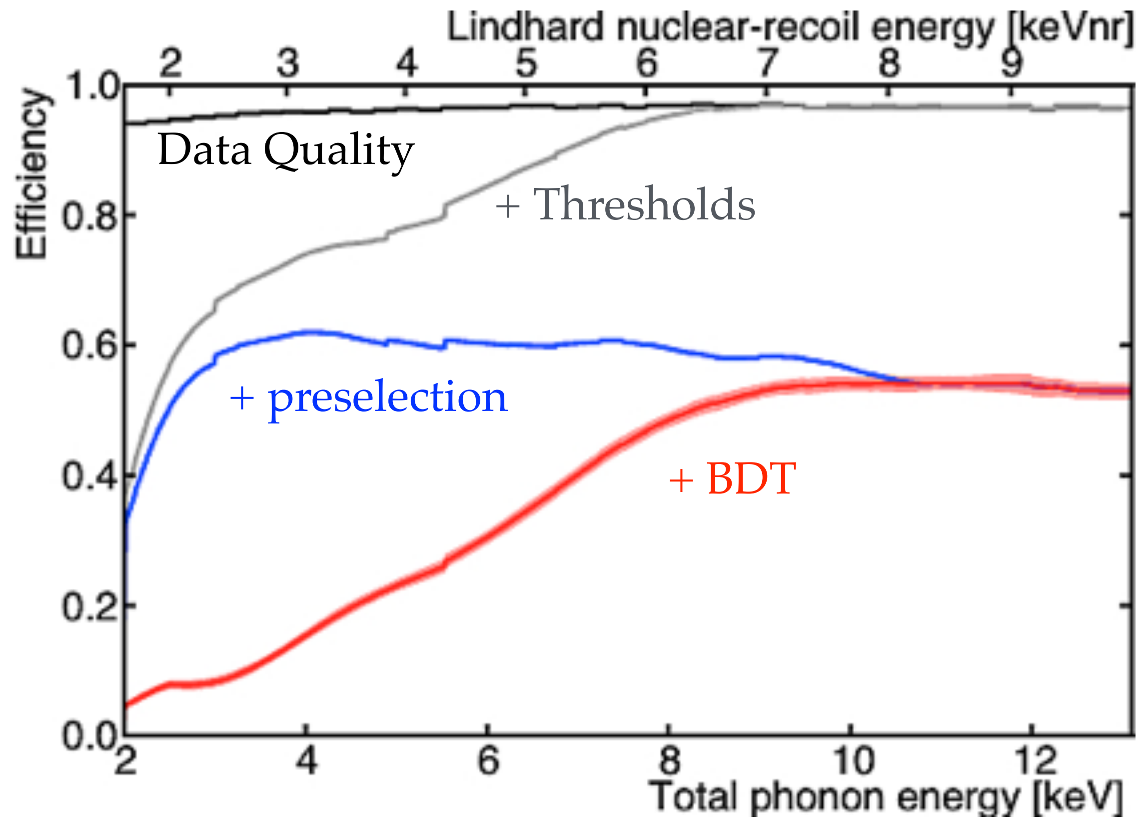


# Analysis Details

**Blind Analysis:**
All single-detector scatter events in energy range removed from study, except data following $^{232}Cf$ calibration due to activation.

**Data Quality:**
Reject periods with poor detector performance.
Remove misreconstructed and noisy pulses

**Trigger and Analysis Threshold:**
Select periods w/ stable well-defined trigger threshold



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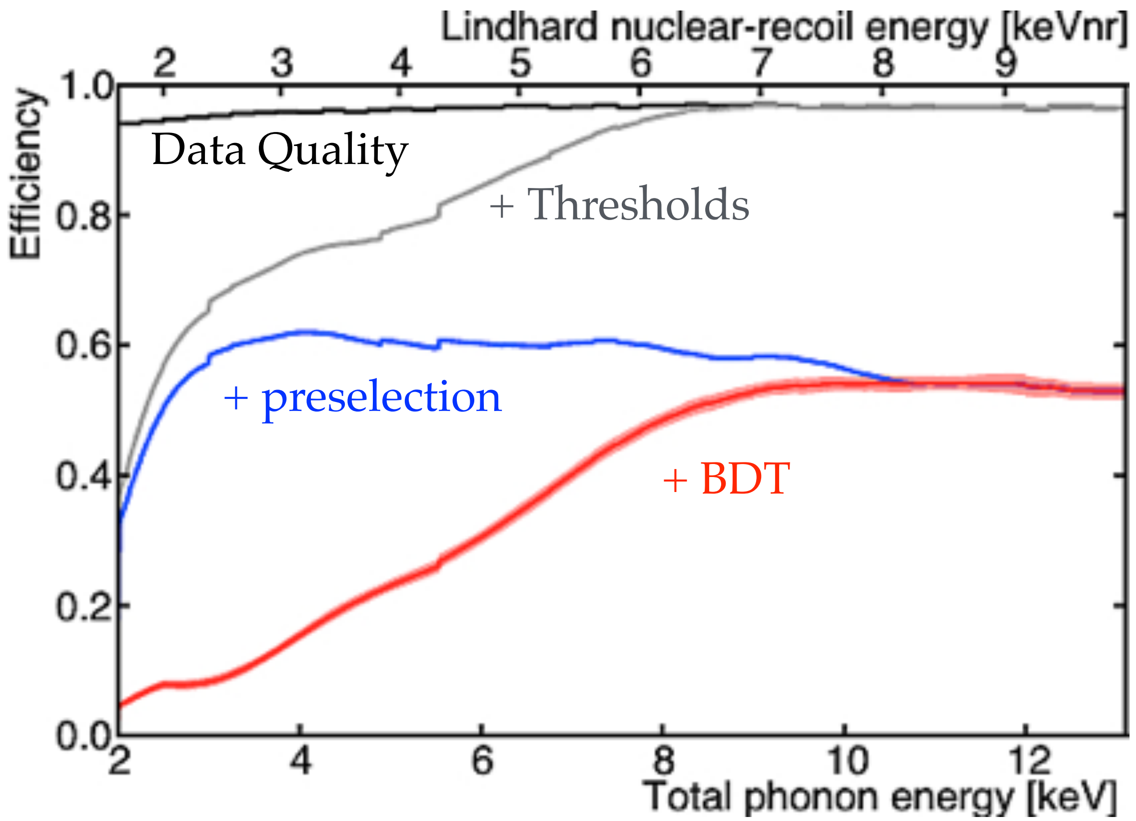
Remove misreconstructed and noisy pulses

**Trigger and Analysis Threshold:**
Select periods w/ stable well-defined trigger threshold

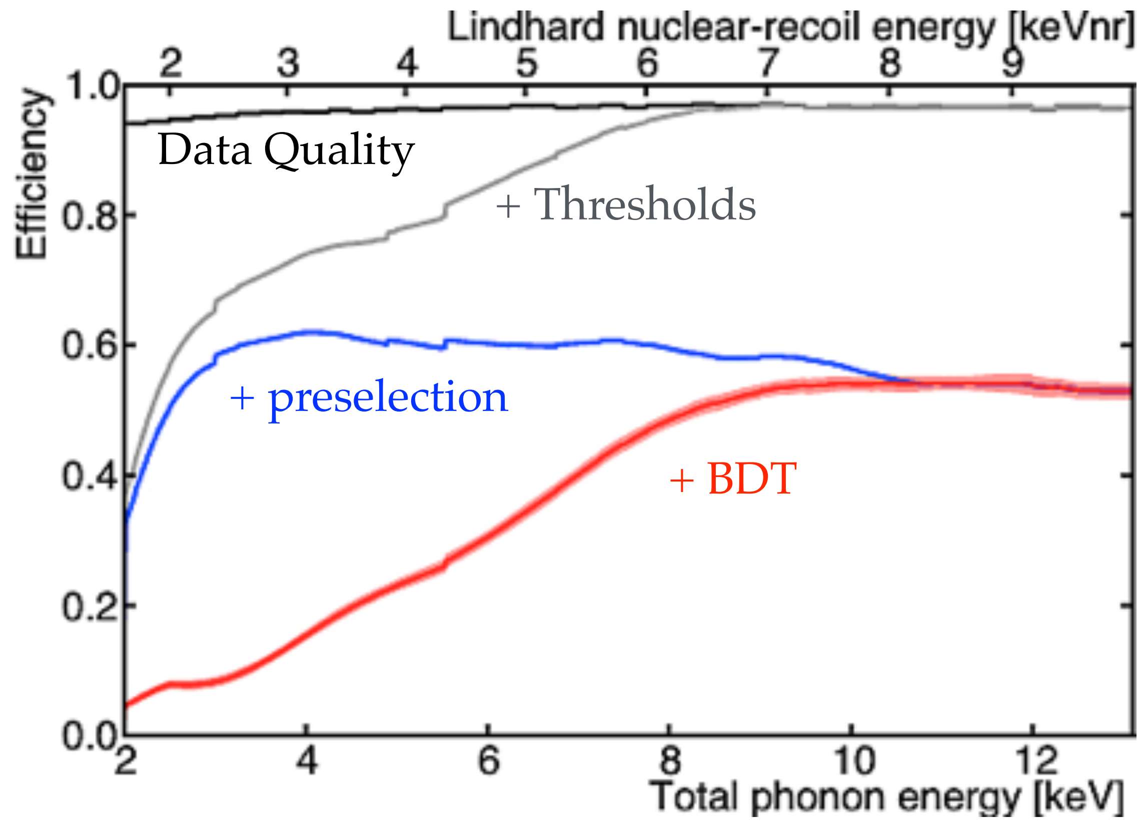
**Preselection:**
Single-detector scatter
Remove events coincident with muon veto
Ionization fiducial volume
Ionization and phonon partitions consistent with NR.



# Analysis Details

**Blind Analysis:**

All single-detector scatter events in energy range removed from study, except data following $^{232}Cf$ calibration due to activation.




**Data Quality:**

Reject periods with poor detector performance.

Remove misreconstructed and noisy pulses

**Trigger and Analysis Threshold:**

Select periods w/ stable well-defined trigger threshold

**Preselection:**

Single-detector scatter

Remove events coincident with muon veto

Ionization fiducial volume

Ionization and phonon partitions consistent with NR.

**Boosted Decision Tree:**

Optimized cut on the phonon fiducial volume and ionization yield at low energy.

# Analysis Details

**Blind Analysis:**

All single-detector scatter events in energy range removed from study, except data following $^{232}Cf$ calibration due to activation.

**Data Quality:**

Reject periods with poor detector performance.

Remove misreconstructed and noisy pulses

**Trigger and Analysis Threshold:**

Select periods w/ stable well-defined trigger threshold

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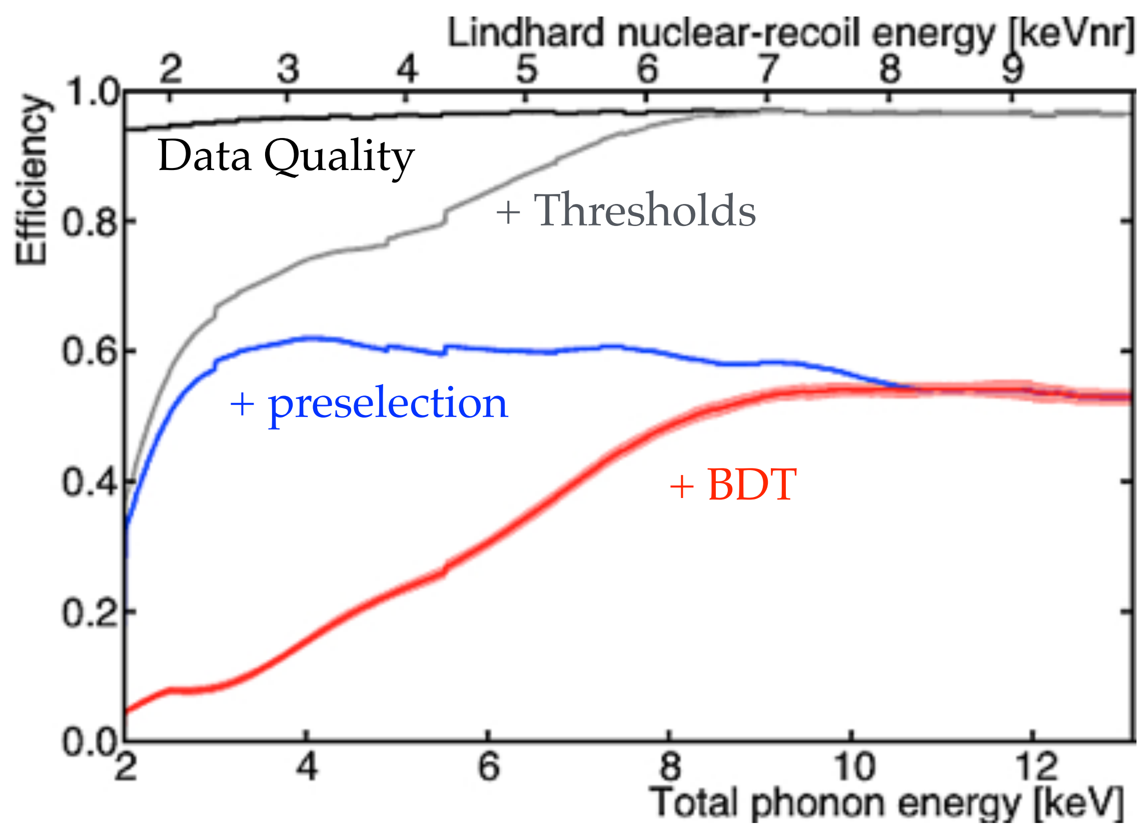
Single-detector scatter

Remove events coincident with muon veto

Ionization fiducial volume

Ionization and phonon partitions consistent with NR.




**Boosted Decision Tree:**

Optimized cut on the phonon fiducial volume and ionization yield at low energy.

**Efficiencies:**

Measured for neutrons from $^{252}Cf$.

Corrected for multiple scatter with Geant4.

# Background Estimates

- Prior to unblinding, background estimates were finalized, including known systematic effects.
- The background model was used to tune selection criteria. Unknown systematics preclude background subtraction for this blind analysis.

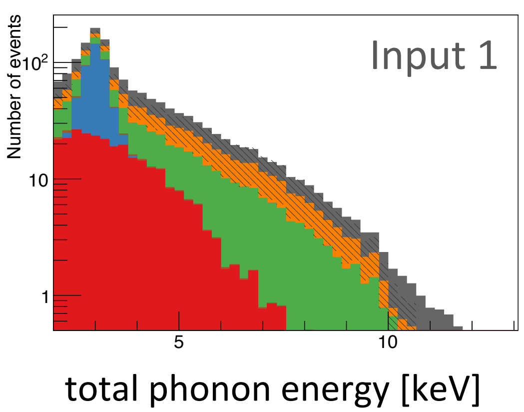
**We decided prior to unblinding to only set an upper limit.**

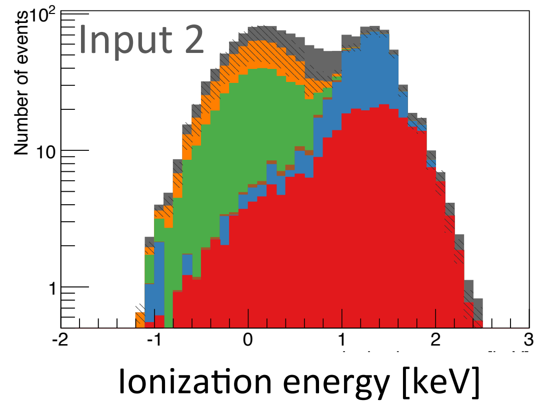
- 4 BDT cuts were optimized for 5, 7, 10 and 15 GeV/$c^2$ WIMPs. Accept events that pass any of the four cuts. Each cut was simultaneously tuned on all detectors, maximizing 90% C.L. poisson sensitivity for that mass.

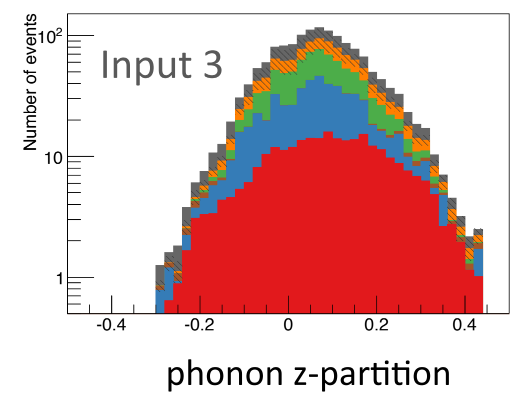
Background model expectation: $6.1^{+1.1}_{-0.8}$ events

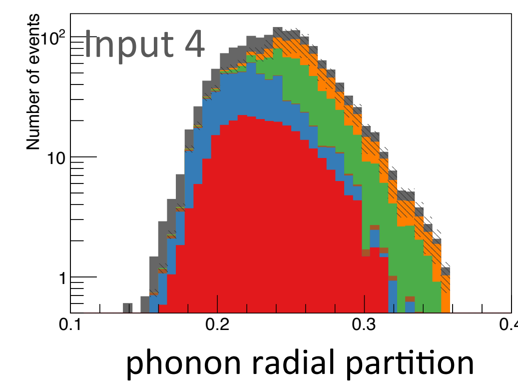
Neutron estimate: $0.1 \pm 0.02$ events

# Boosted Decision Tree (BDT)

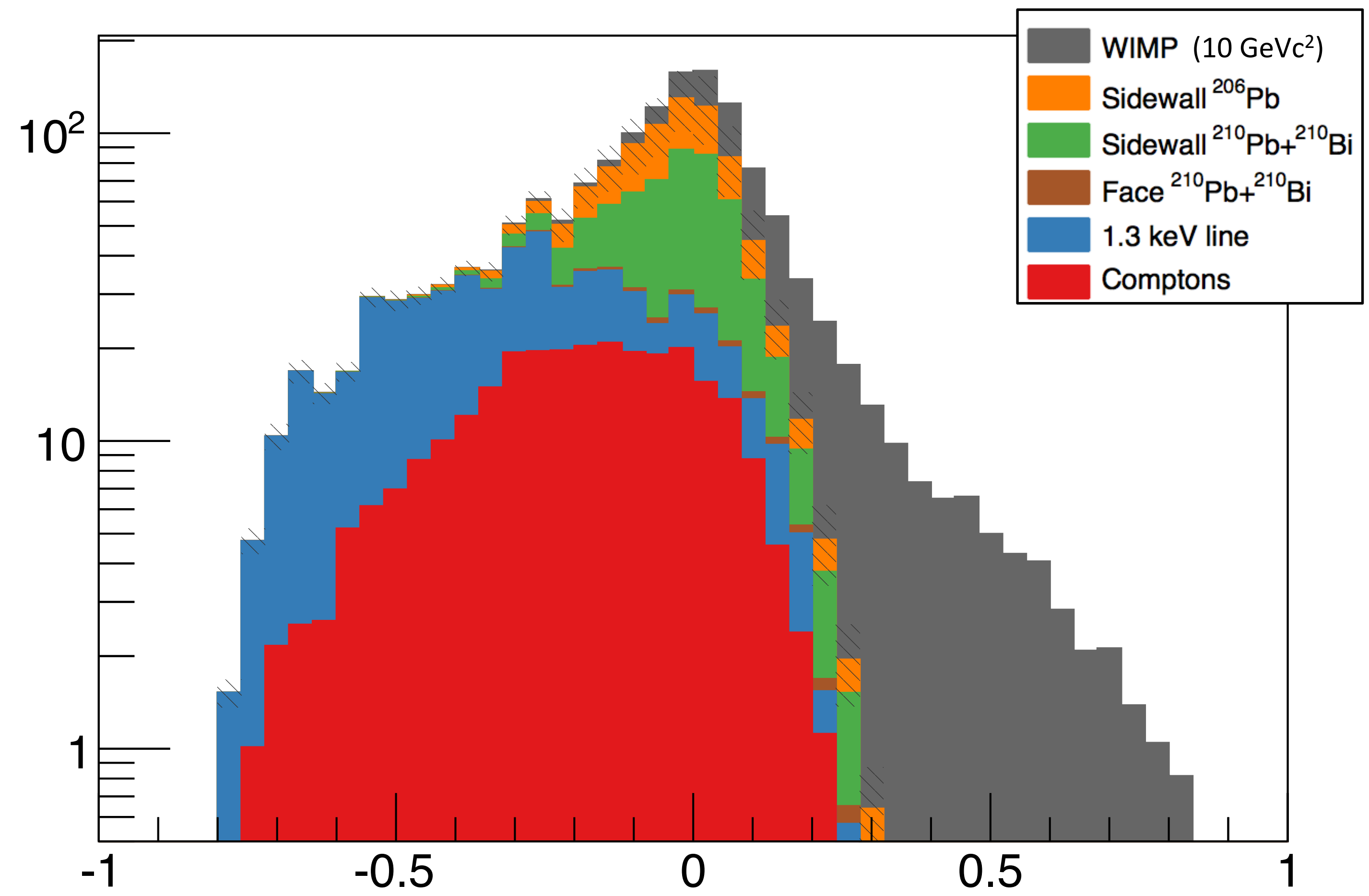


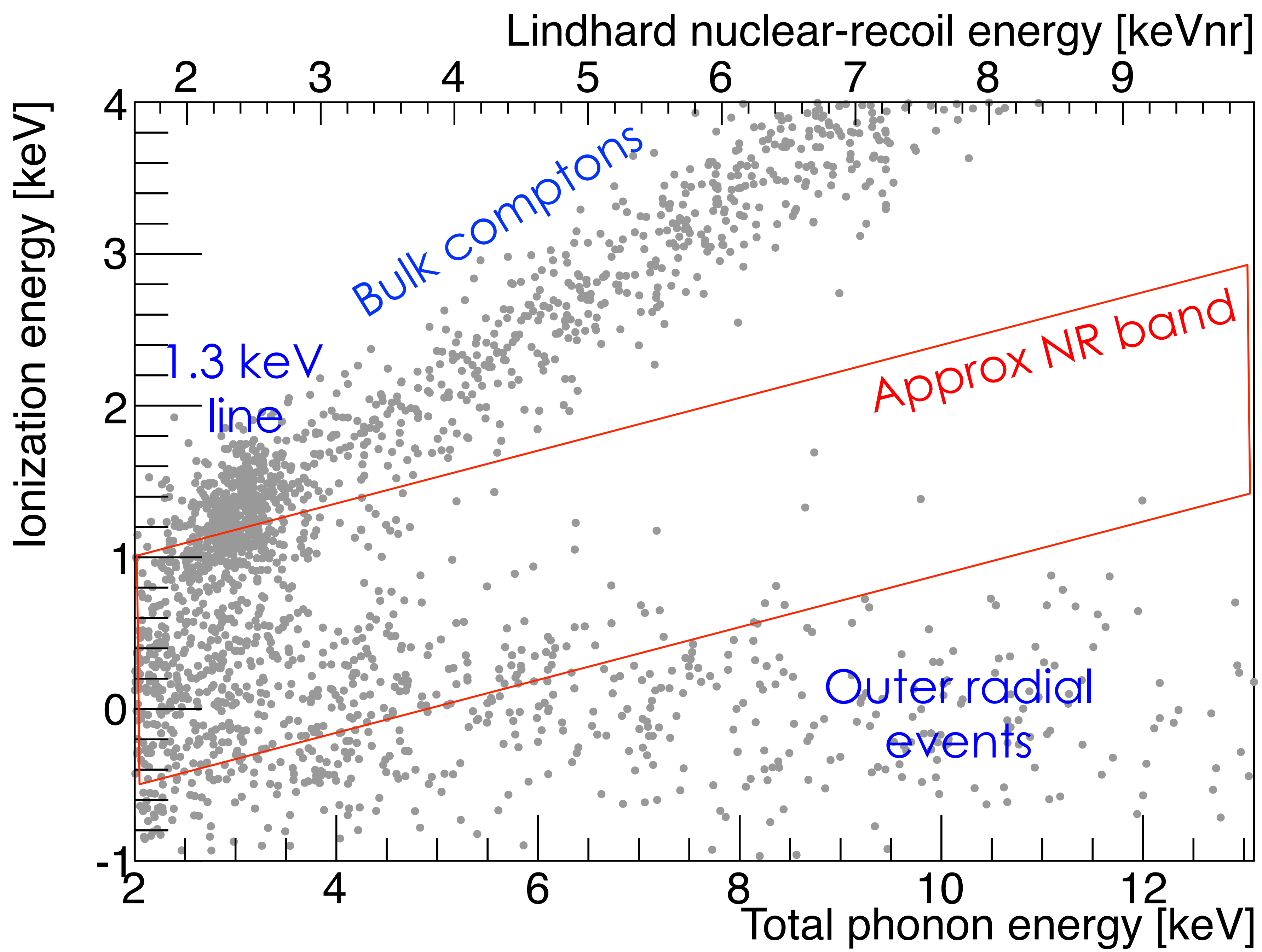




- **Backgrounds modeled with simulated data based on sidebands and calibration data.**
- **Signal modeled with nuclear recoils from $^{252}$Cf calibration data rescaled for 10 GeV/c$^2$ WIMP.**



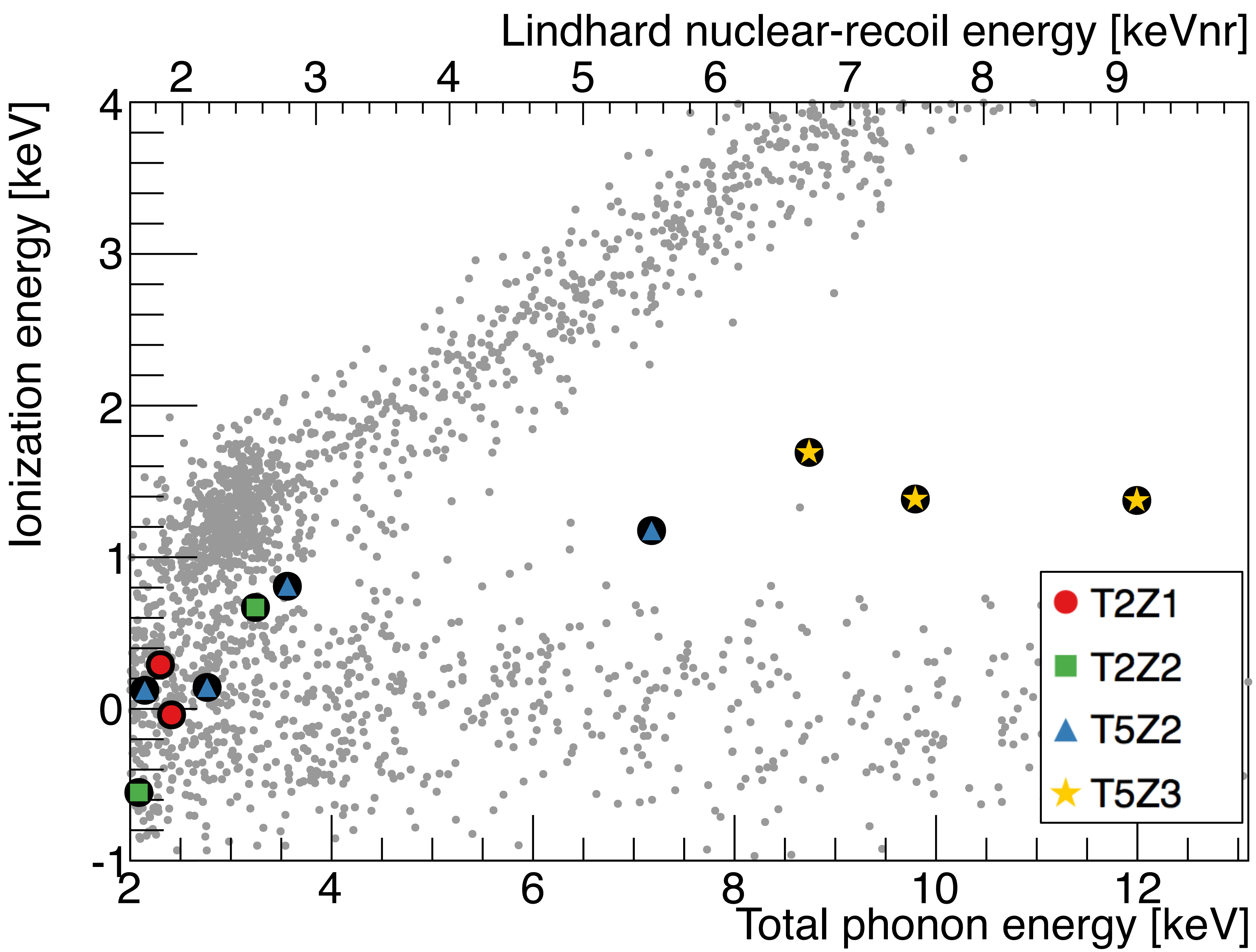
# Unblinding: Before BDT Cut

Events passing all cuts prior to applying BDT

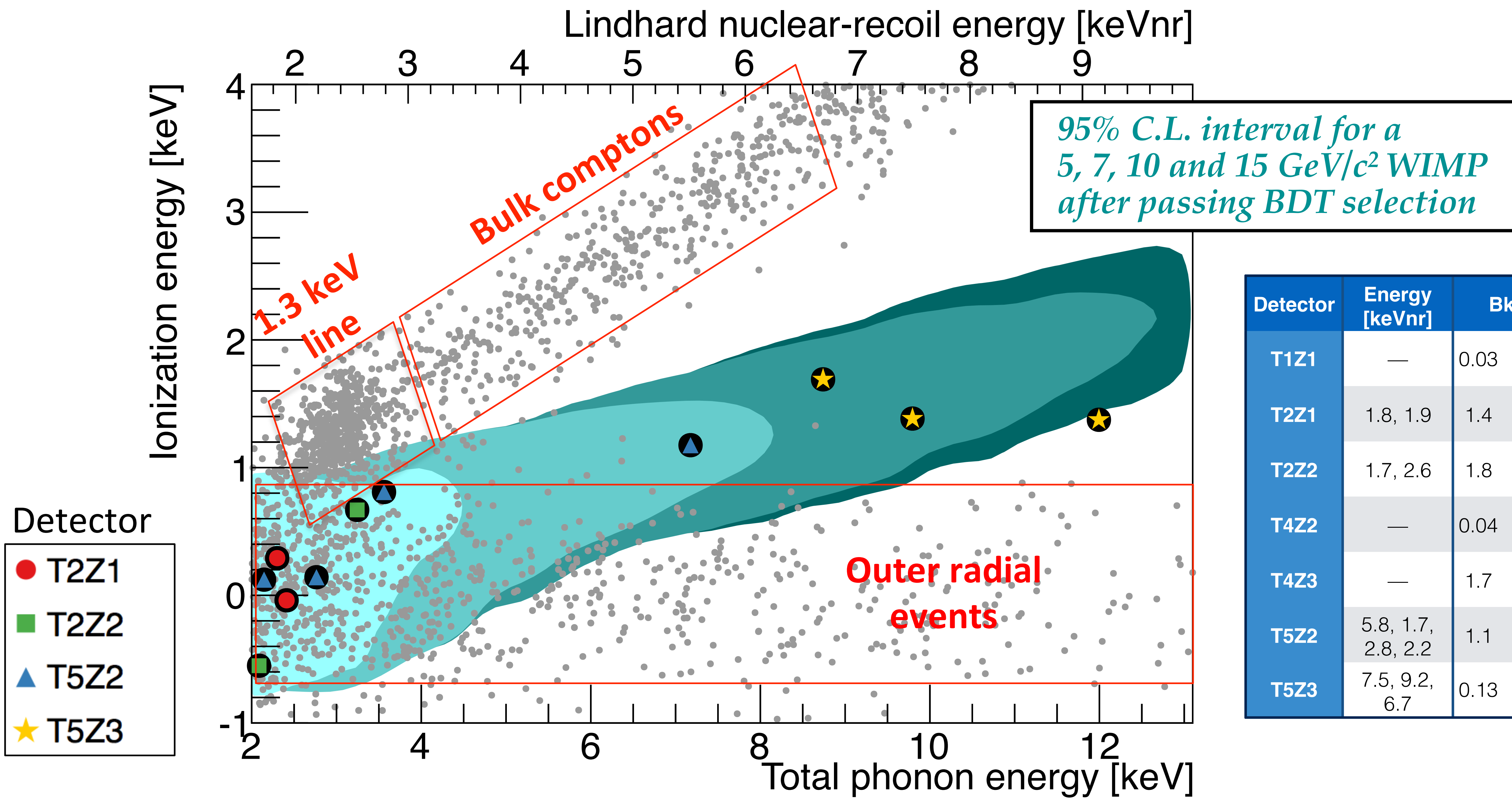


# Unblinding: After BDT cut

11 candidates observed, $6.2^{+1.1}_{-0.8}$ expected



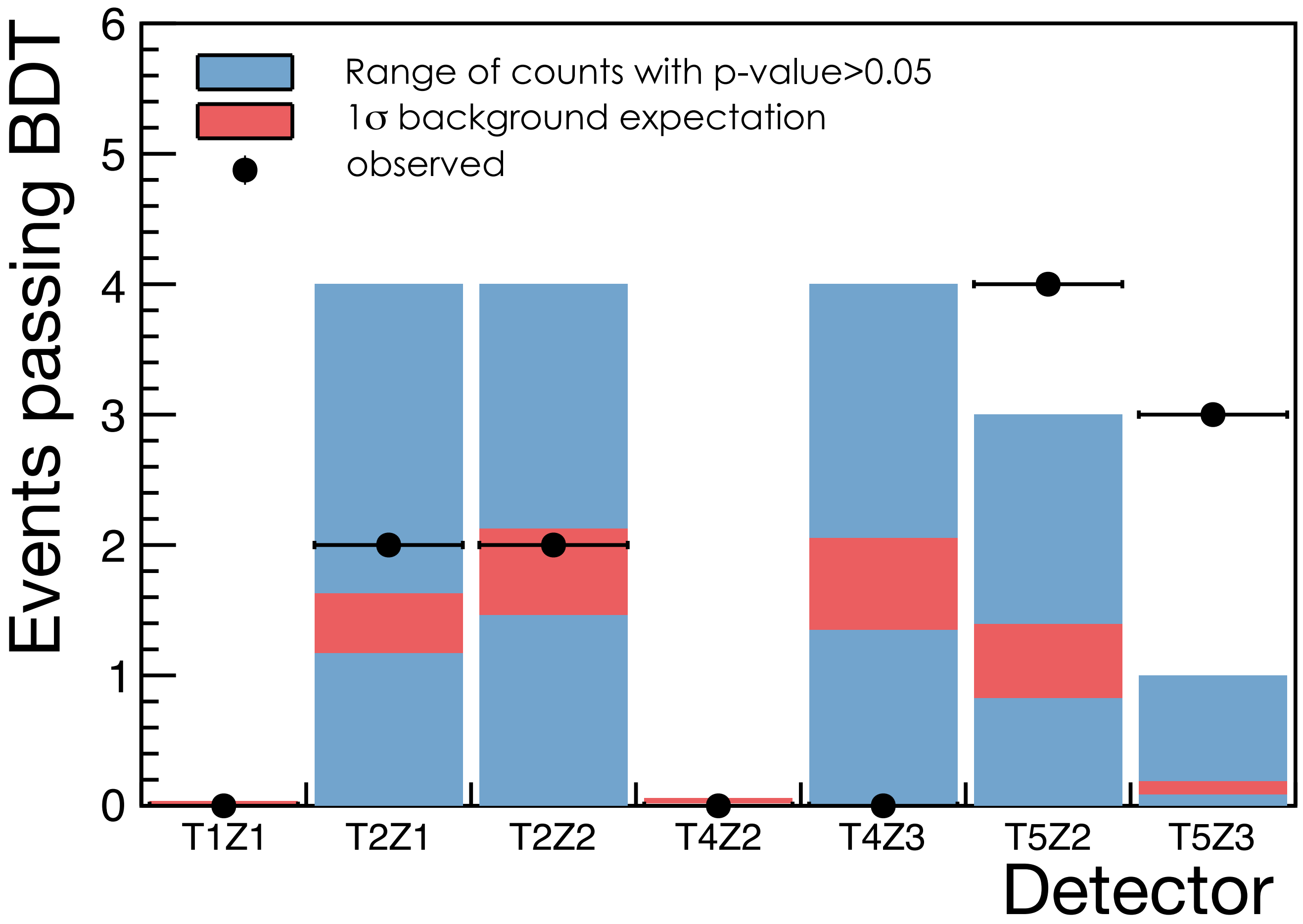
# 95% Confidence Intervals




| Detector | Energy [keVnr] | Bkgd |
|---|---|---|
| T1Z1 | — | 0.03 +0.01 −0.01 |
| T2Z1 | 1.8, 1.9 | 1.4 +0.2 −0.2 |
| T2Z2 | 1.7, 2.6 | 1.8 +0.4 −0.3 |
| T4Z2 | — | 0.04 +0.02 −0.02 |
| T4Z3 | — | 1.7 +0.4 −0.3 |
| T5Z2 | 5.8, 1.7, 2.8, 2.2 | 1.1 +0.3 −0.3 |
| T5Z3 | 7.5, 9.2, 6.7 | 0.13 +0.06 −0.04 |

# Post-unblinding Discussion

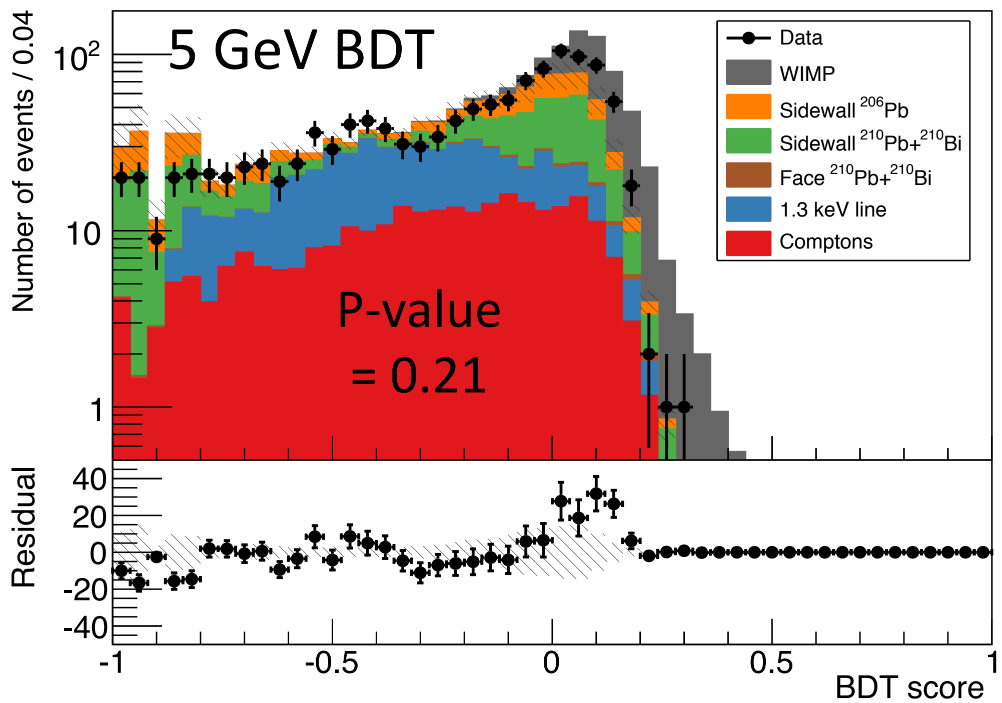
Events are high in quality. Only the lowest energy candidate looks like spurious noise.

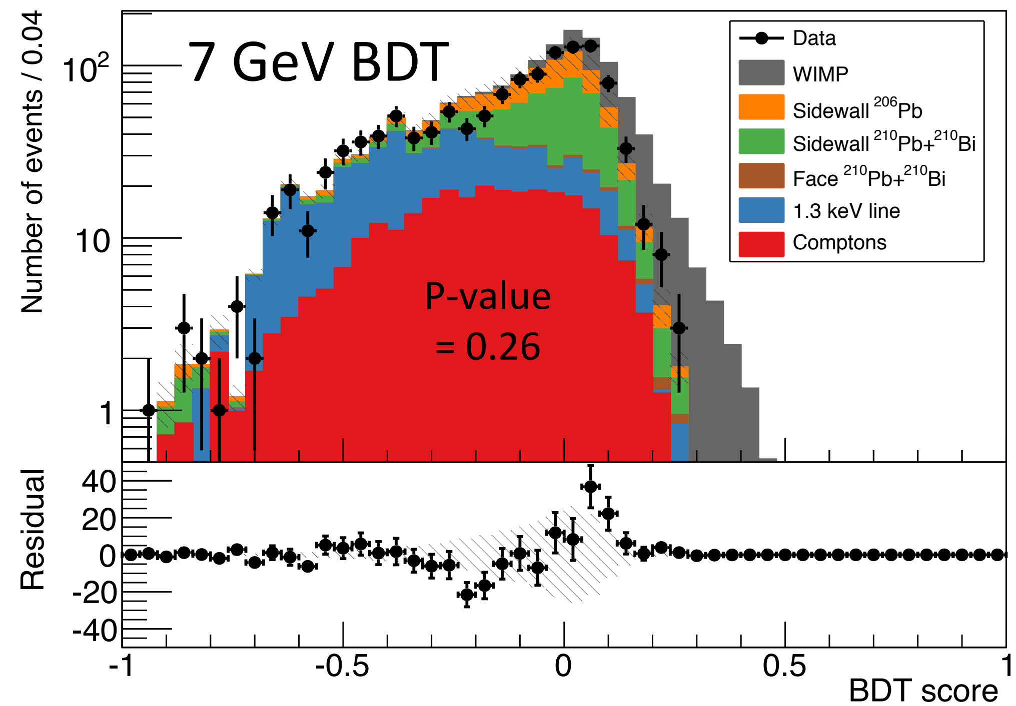


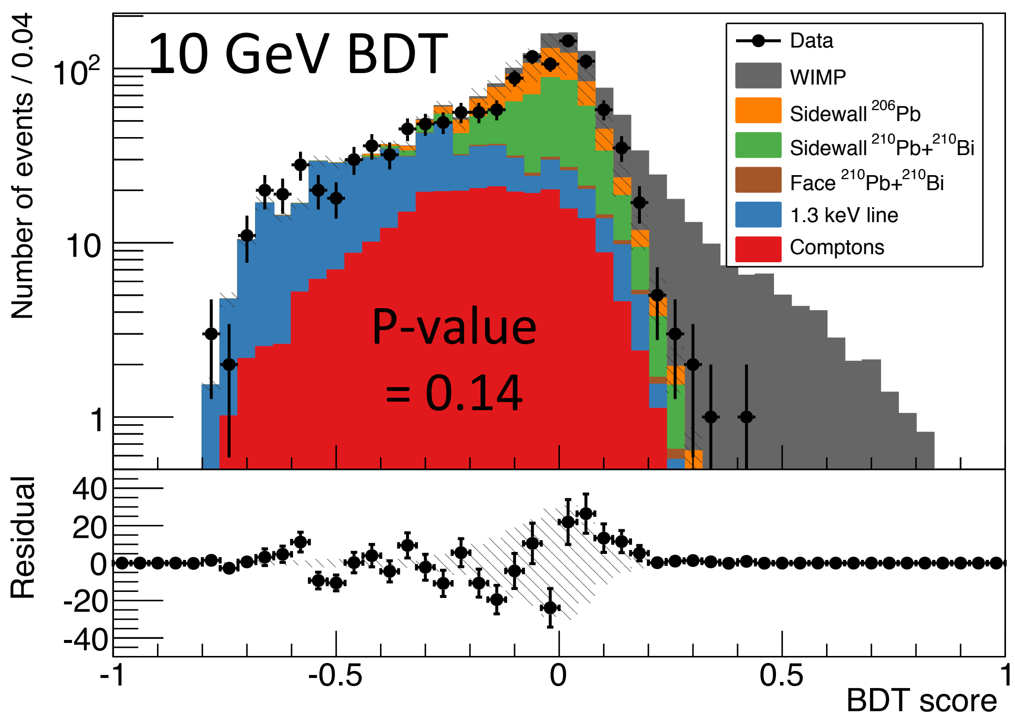

- Good agreement with predicted background on most detectors.
- T5Z3 observes the 3 highest-energy events. (Poisson p-value is 0.04%).

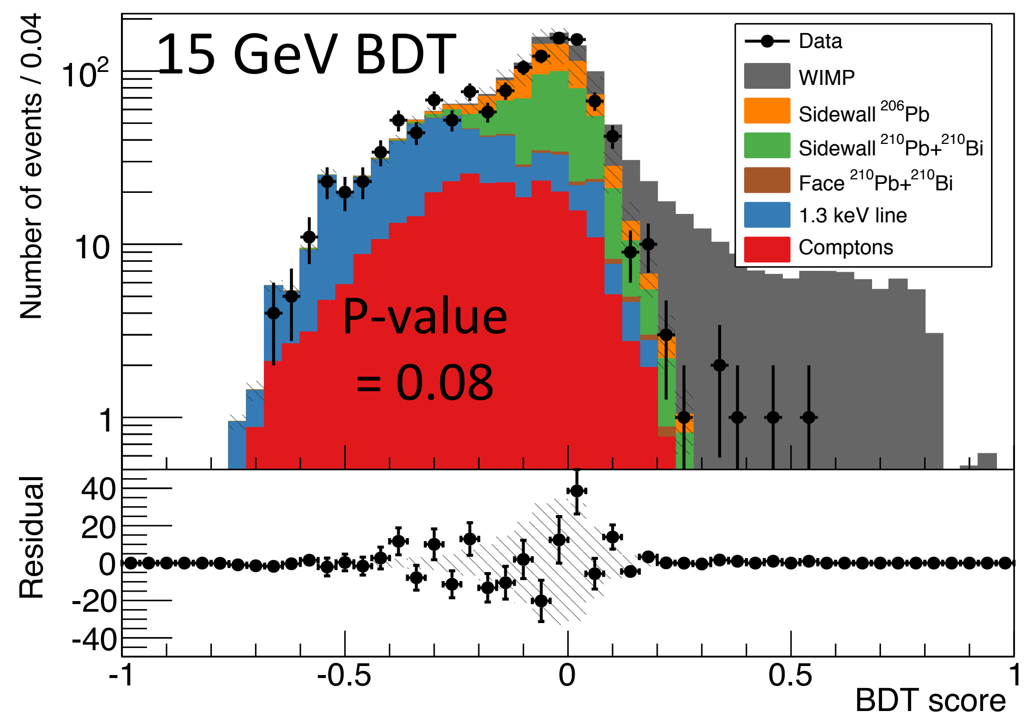
*T5Z3 detector has a shorted ionization guard which may have affected the background model performance. Additional studies underway.*

# Model to Data Comparison



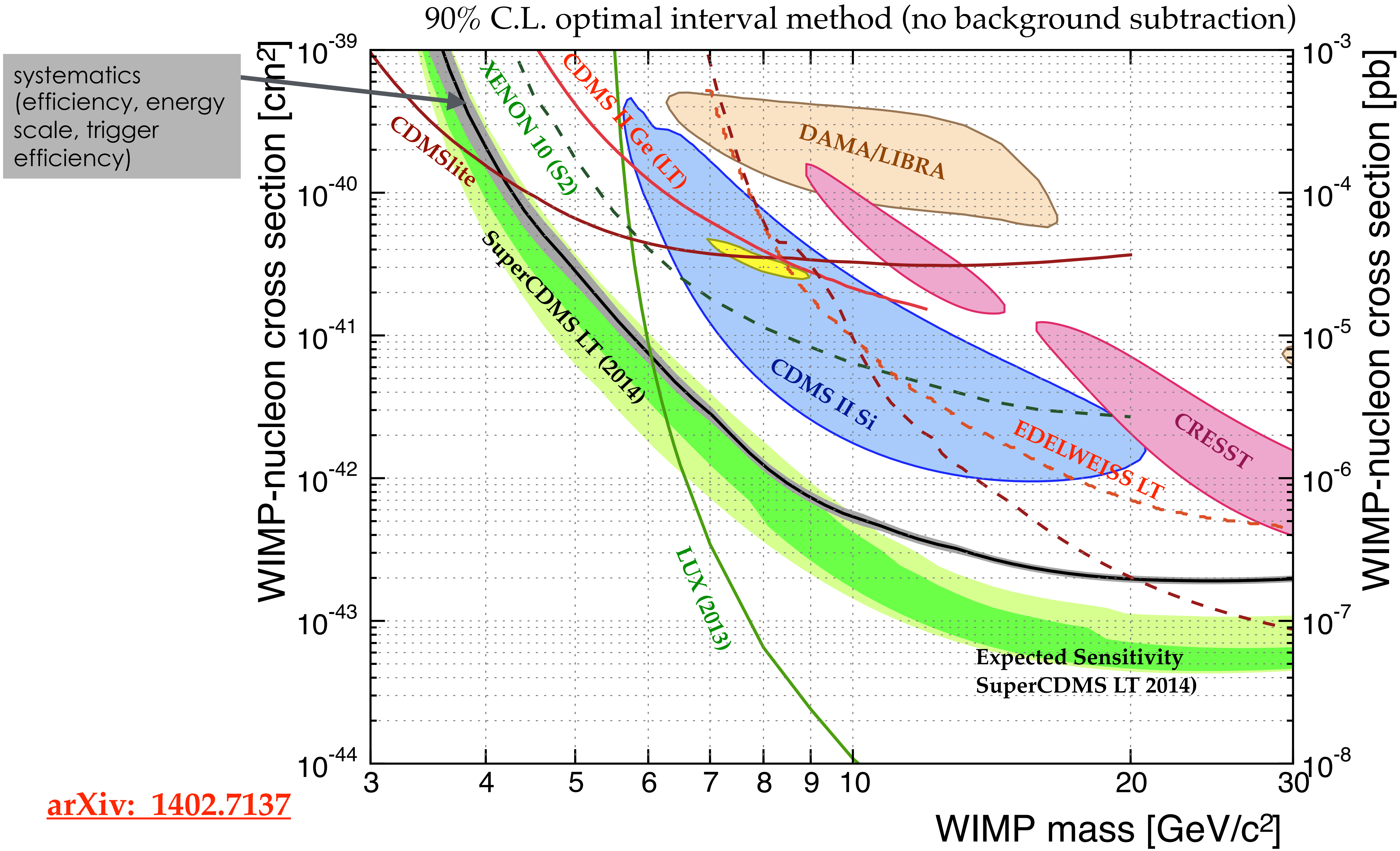




**For most detectors, there is good agreement with predicted background.**

# New Limit for Low Mass WIMPs

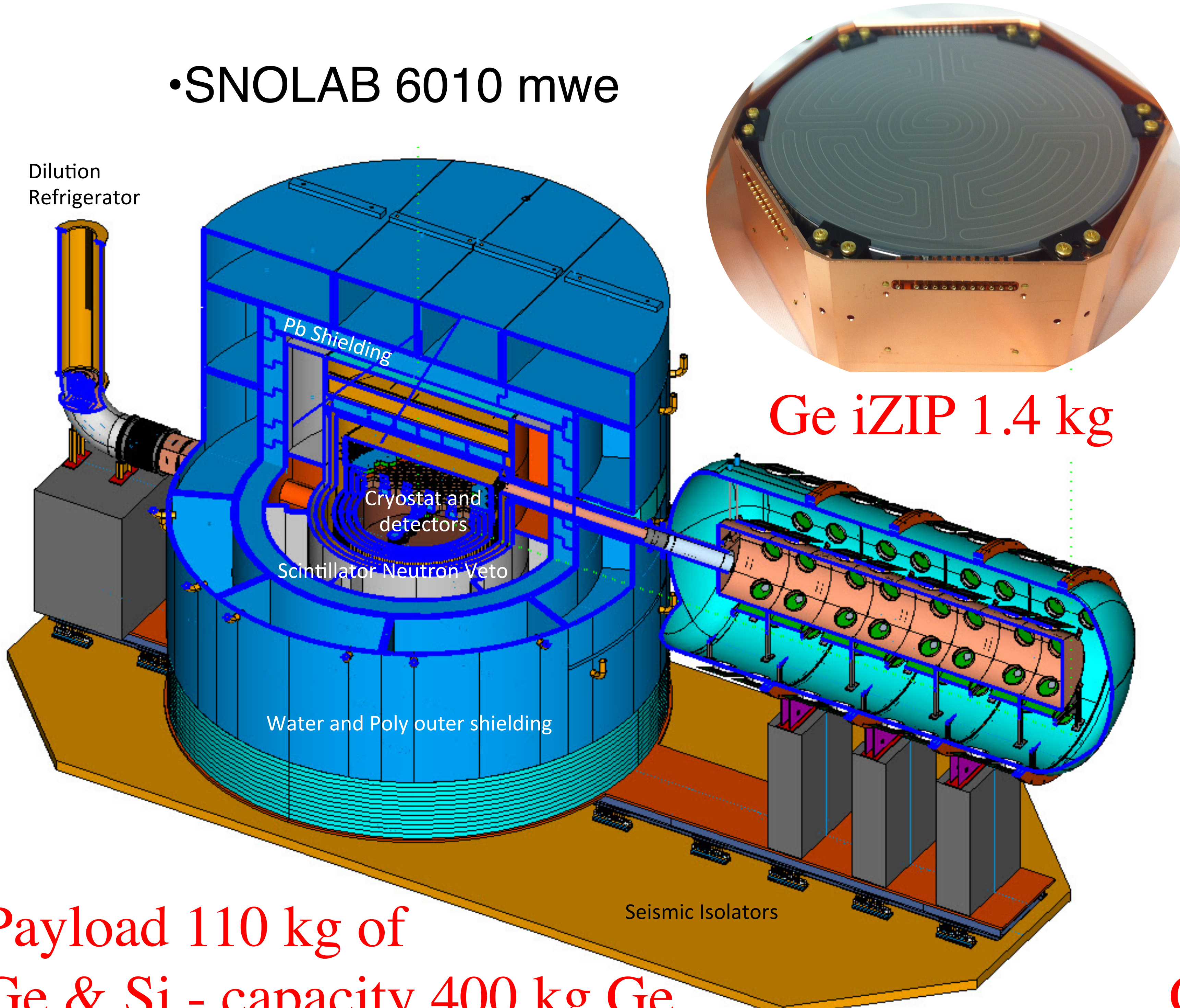
**Note: Assumes SHM, Spin-Independent Couplings: This plot changes if we change assumptions!**




arXiv: 1402.7137

# Future: SuperCDMS @ SNOLAB

- SNOLAB 6010 mwe

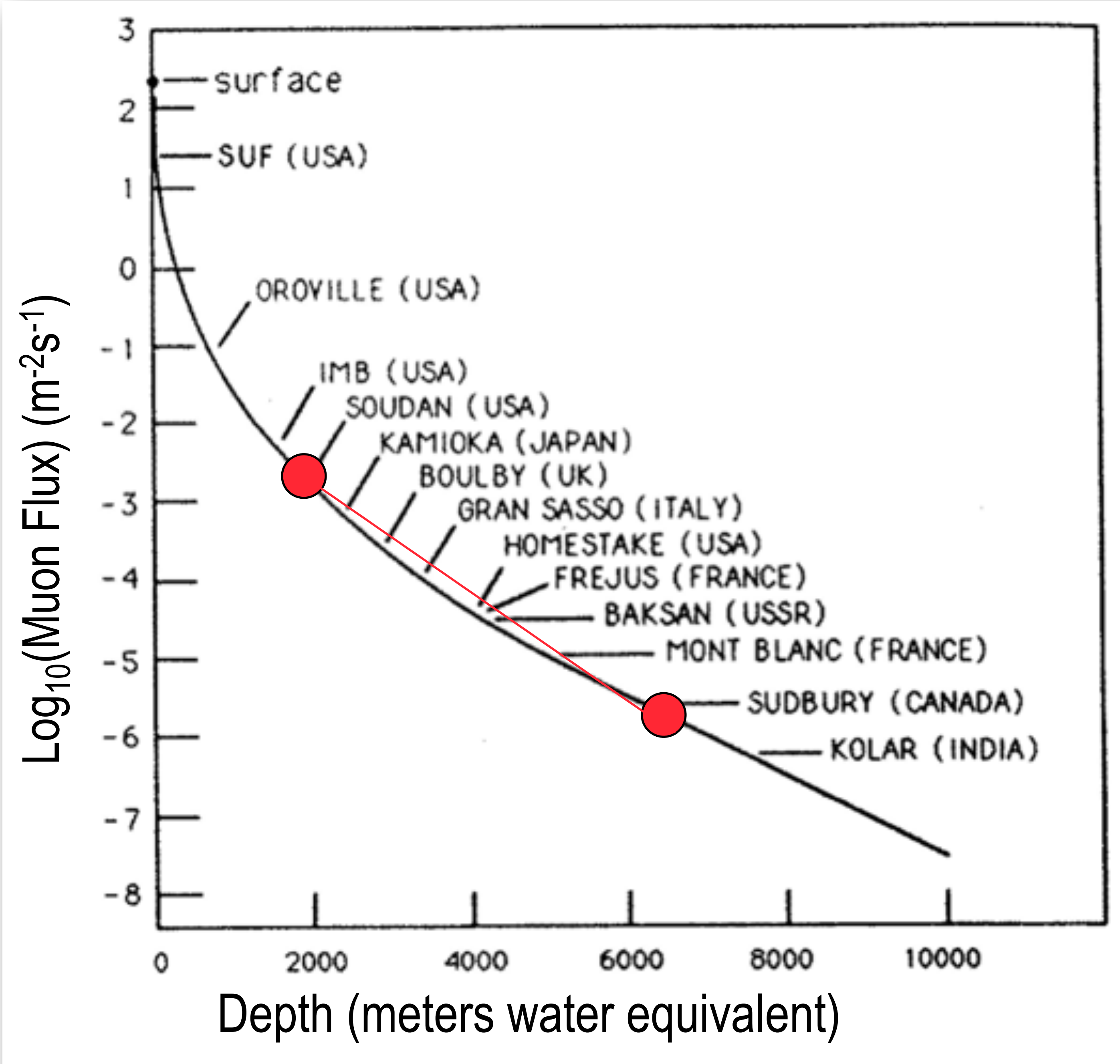



Ge iZIP 1.4 kg

Payload 110 kg of
Ge & Si - capacity 400 kg Ge

Ge Tower 8.4 kg

# Why SNOLAB?
# Depth is Important




*Soudan*
*2090 mwe*
*0.05 n/y/kg*

*SNOLab*
*6060 mwe*
*0.2 n/y/ton*
*(0.0002 n/y/kg)*

We only need to worry about radiogenic neutrons!

# Radiogenic Neutrons

**- External Radiogenic Neutrons**

- Resulting from fission and alpha-n interactions from U, Th in cavern rock
- Expected to be negligible with passive shielding

**- Internal Radiogenic Neutrons**

- Resulting from fission and alpha-n interactions from U, Th in copper cans, shielding and supports.
- Expected to be ~1 event, depending on material cleanliness

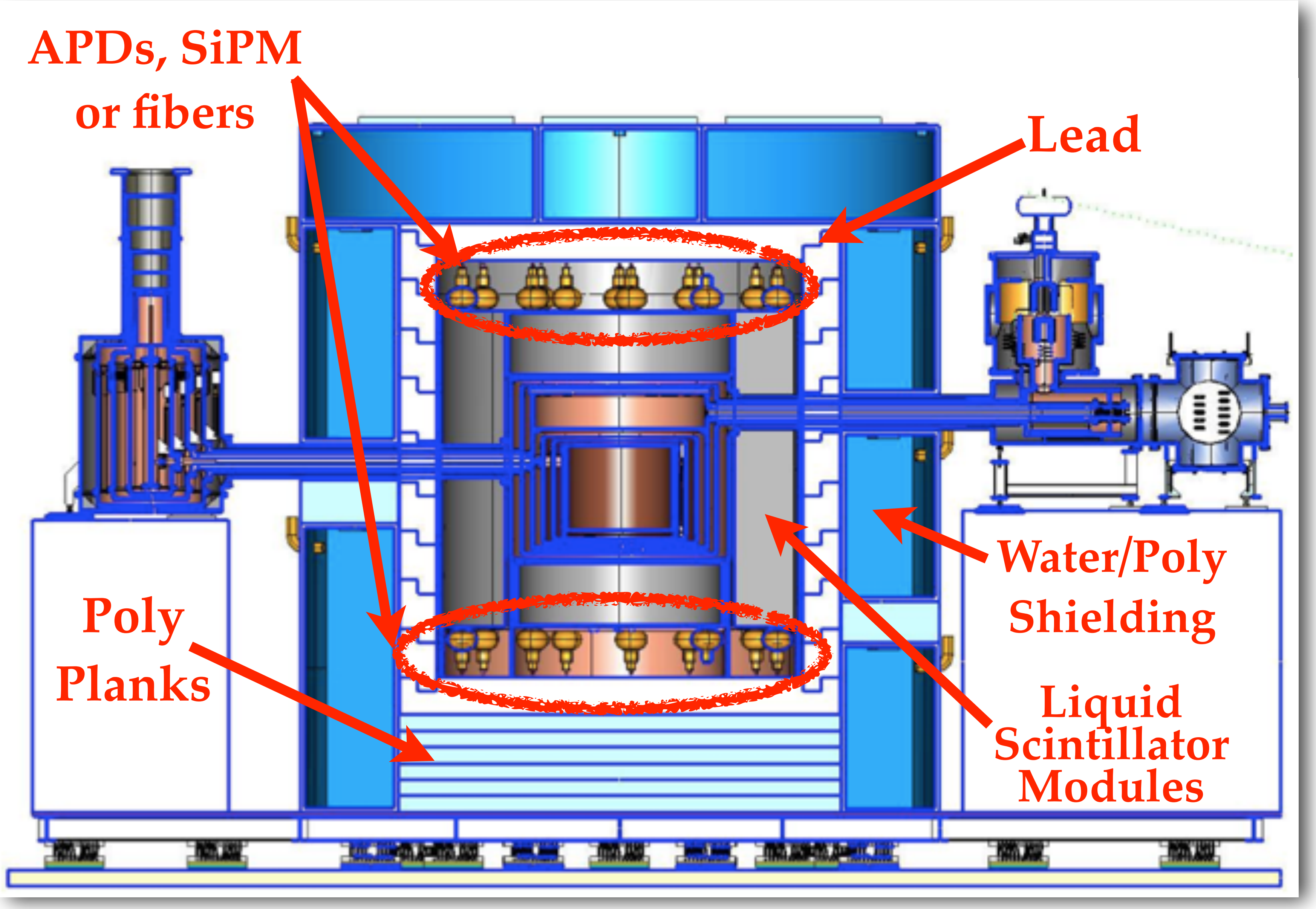
**For these reasons we are considering a neutron veto in the shield design.**

# Design Details

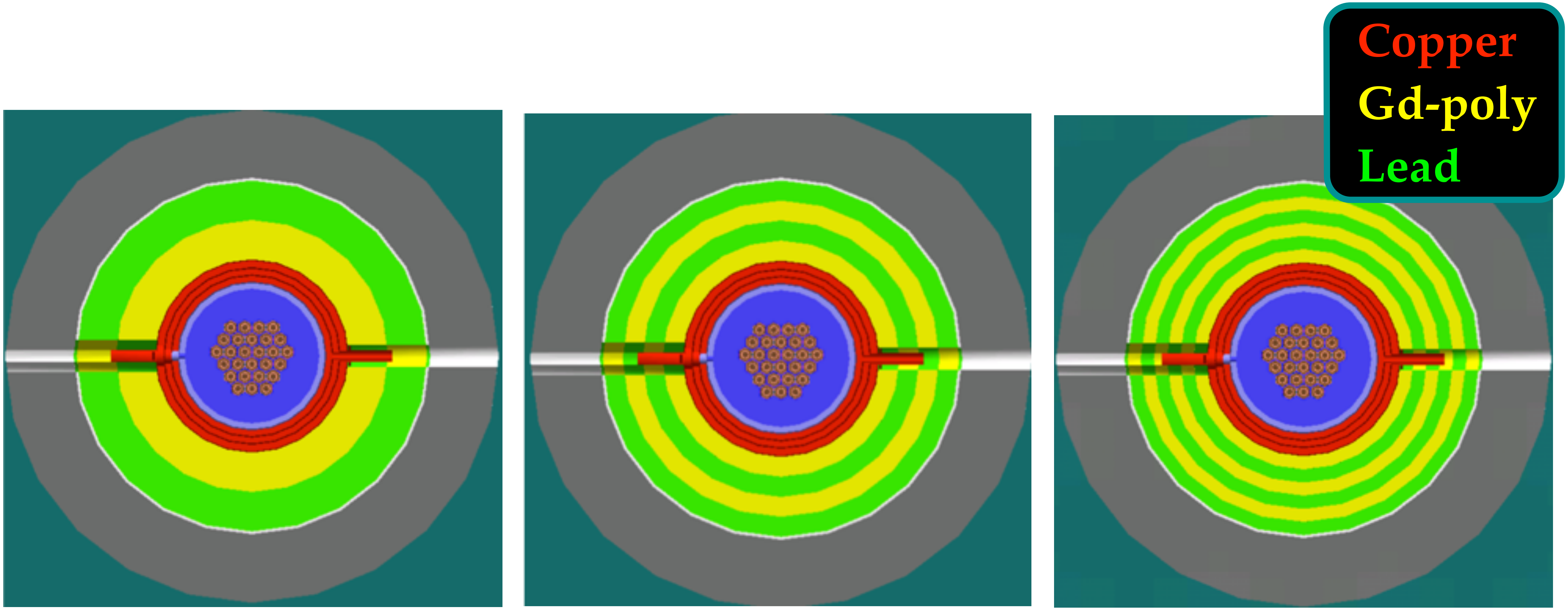
- Surround the cryostat with a high efficiency neutron detector to tag neutrons.

- Modular tanks of liquid scintillator, with radial thickness 0.4 m, viewed by phototubes.

- Details of scintillator to use (Gd- or B-loaded) under consideration.



# Alternate Design

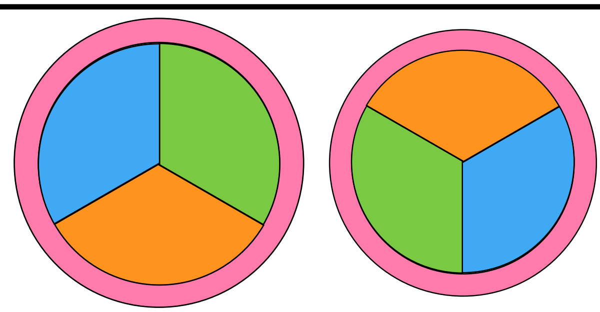



- Alternating layers of Gd-loaded poly/scintillator and lead.
- Preliminary studies underway.

# From Soudan to SNOLAB

<u>SuperCDMS Soudan</u>

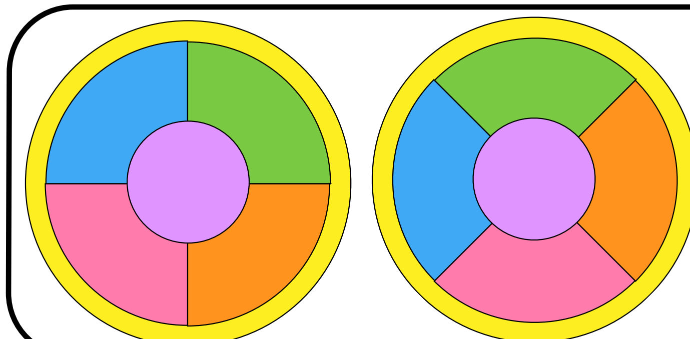
9.0 kg Ge (15 x 600g)
3” Diameter
2.5 cm Thick



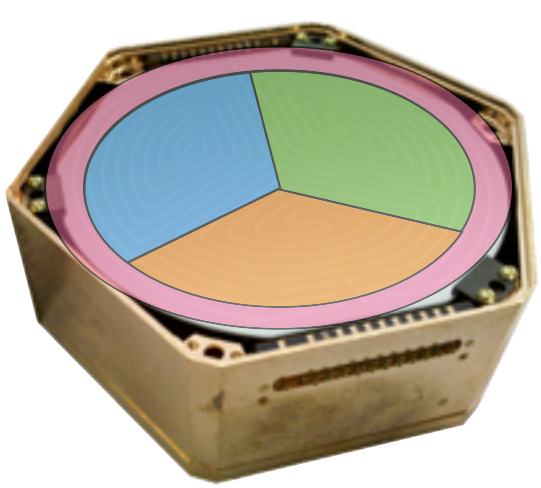
2 charge + 2 charge
4 phonon + 4 phonon

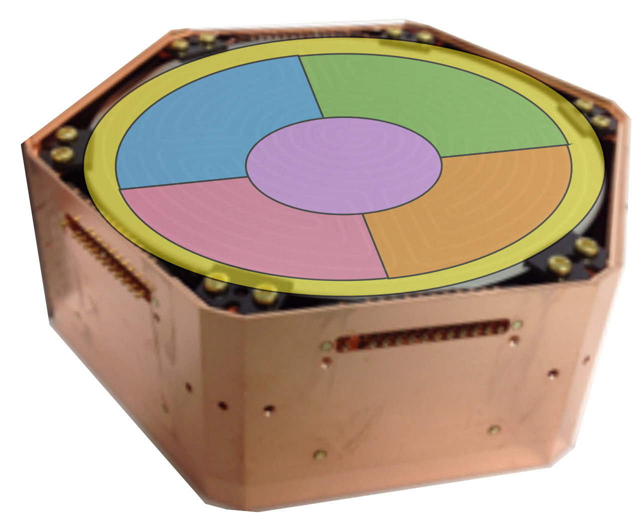
<u>SuperCDMS SNOLAB</u>

98 kg Ge (70 x 1.4 kg)
66 detectors @ nominal voltage + 4 @ HV
12 kg Si (20 x 0.6 kg)
18 detectors @ nominal voltage + 2 @ HV
4” Diameter
3.3 cm Thick



2 charge + 2 charge
6 phonon + 6 phonon

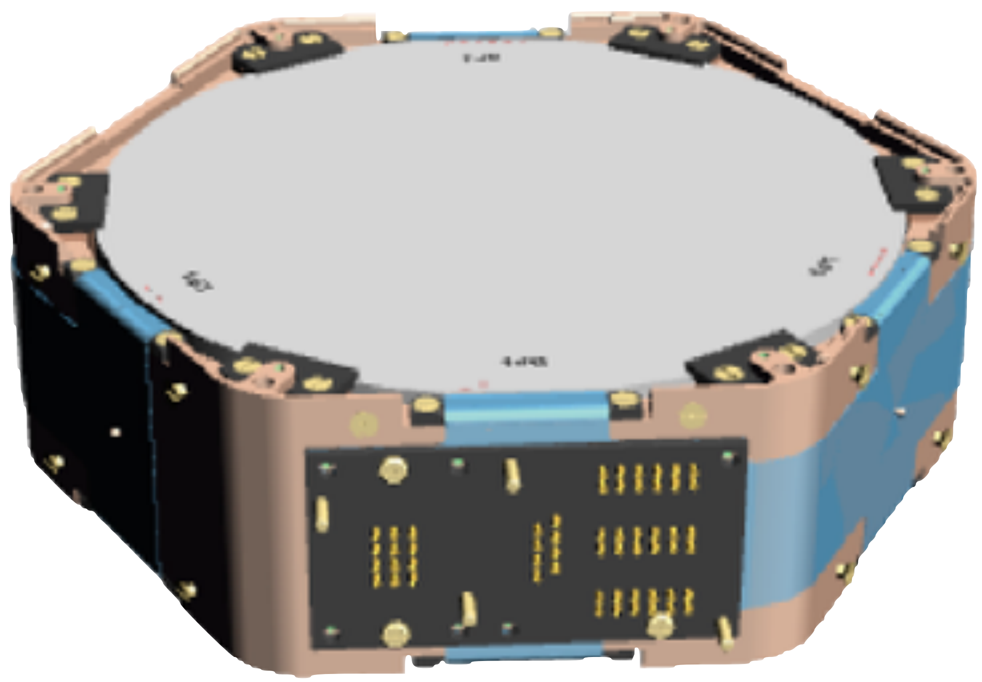


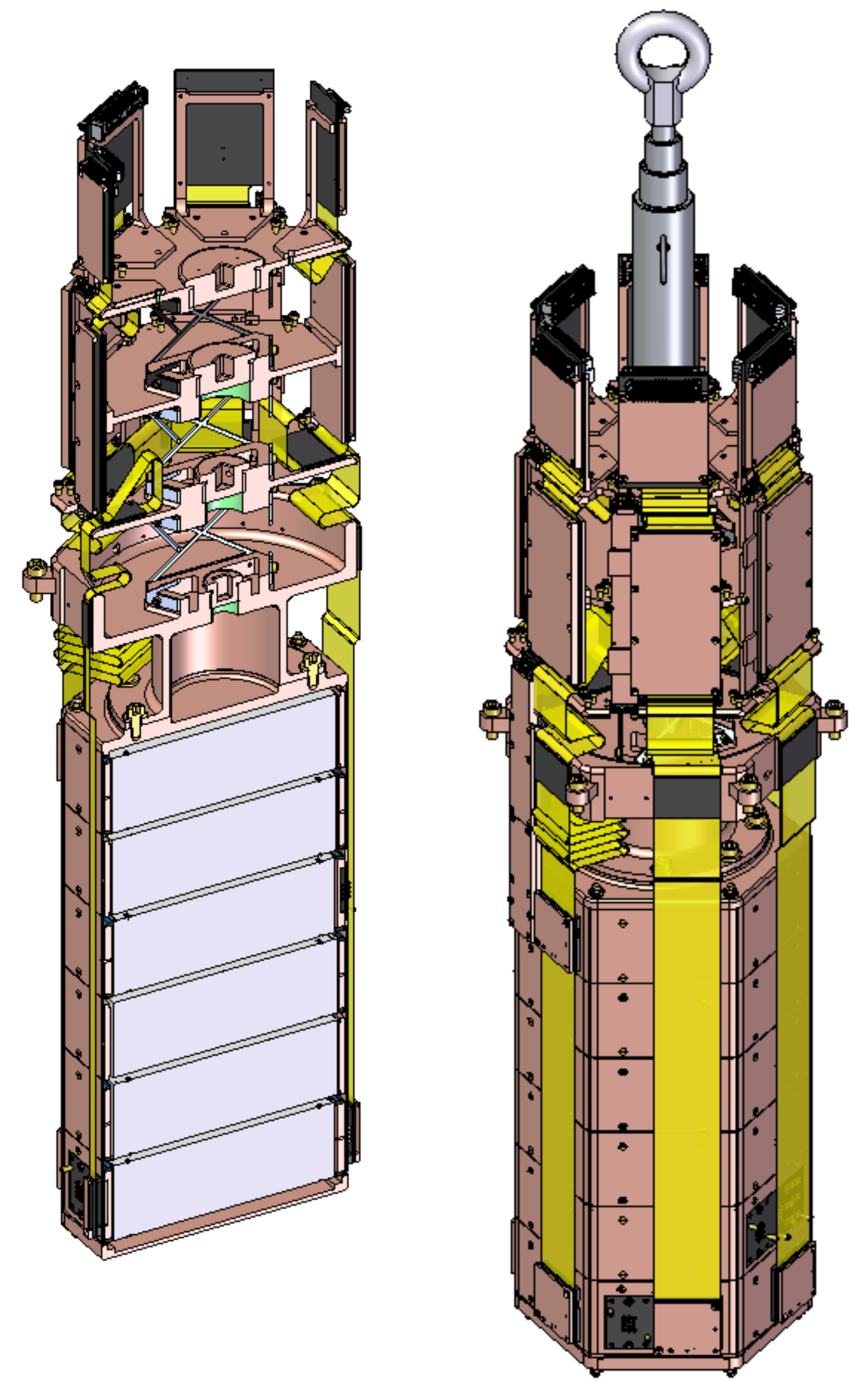


# SuperCDMS SNOLAB Towers

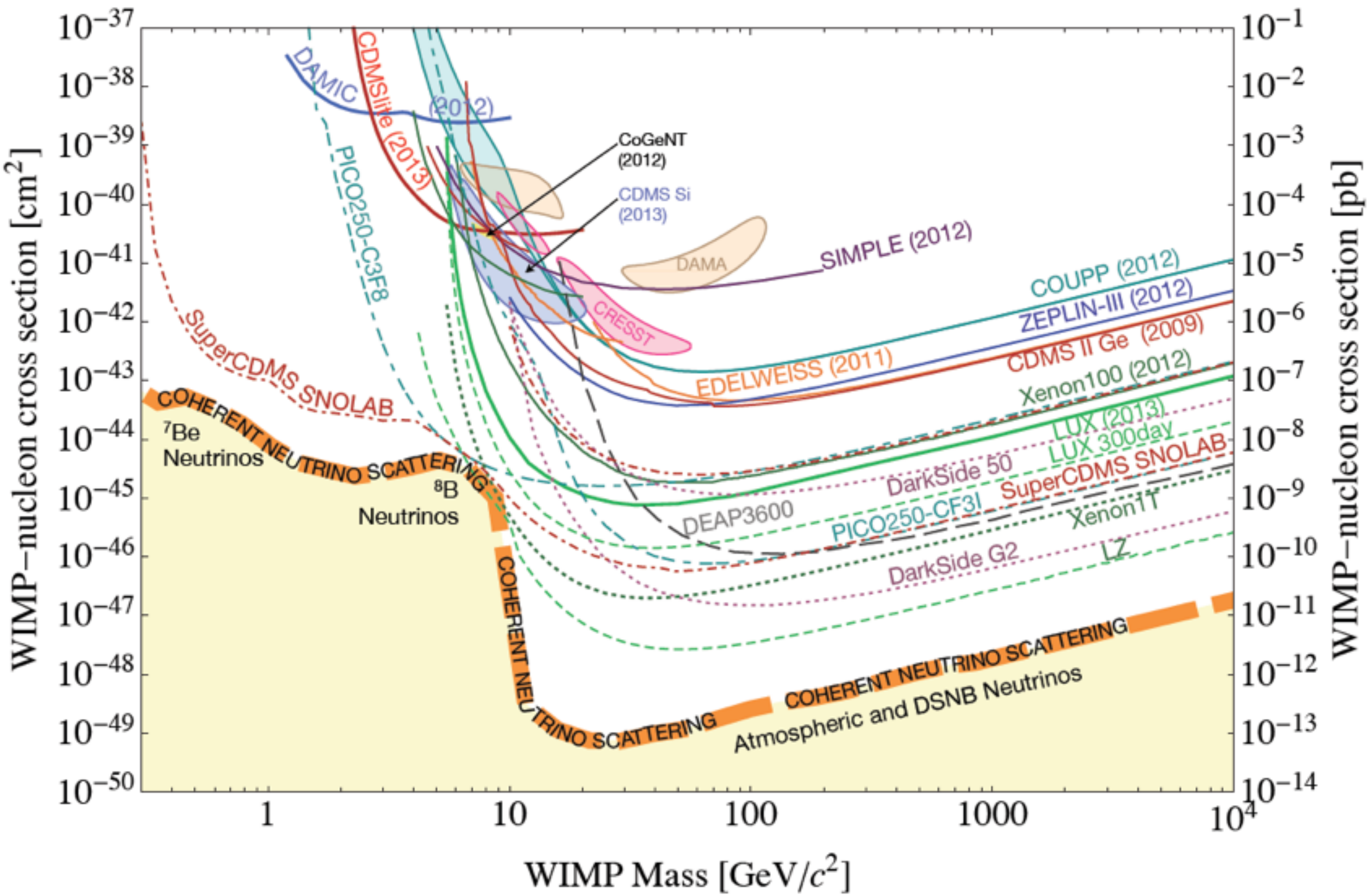
Improved Surface Event Rejection:

- Lower operating temperature gives us improved phonon resolution
- Improved charge resolution with HEMT readout
- Improved phonon resolution + more phonon channels + improved charge resolution
  - improved fiducialization
  - better surface event rejection





# Expected Sensitivities

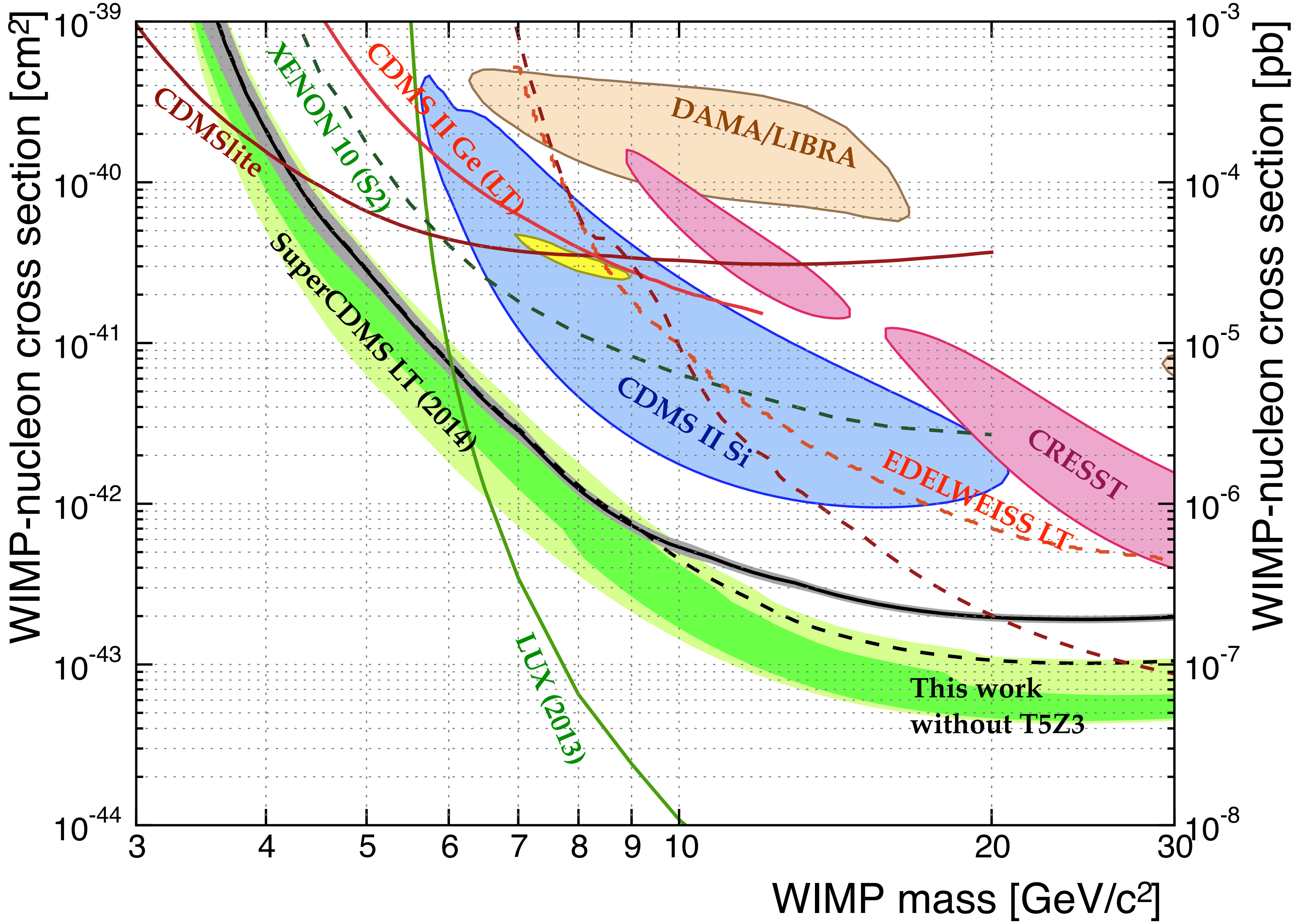


# Conclusions

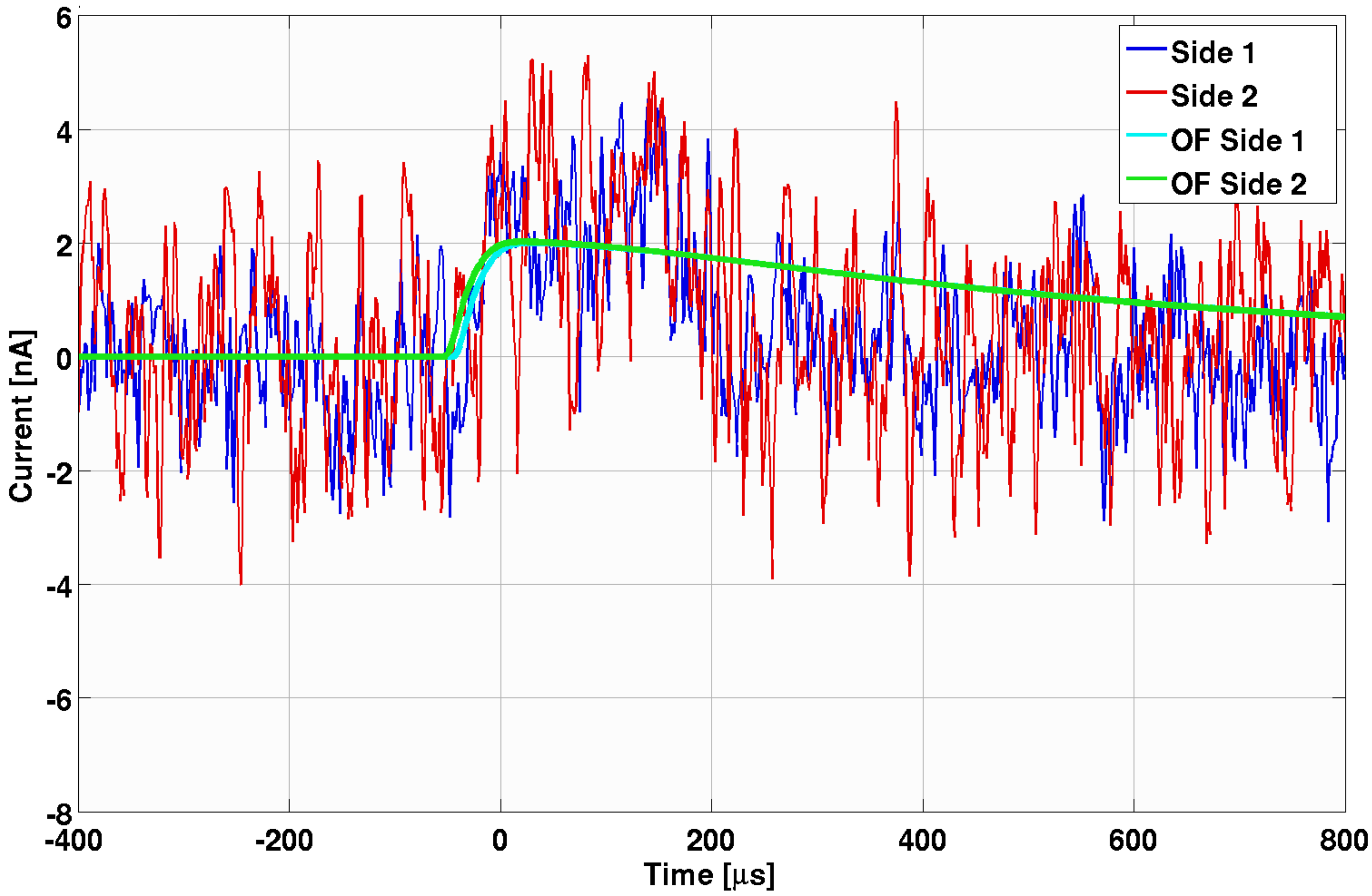
- First science results using the background rejection capability of the new SuperCDMS iZIP detectors.
- Seven iZIPs were analyzed resulting in a 557 kg-day exposure in the 1.6 $keV_{nr}$ - 10 $keV_{nr}$ energy range. This analysis yielded an upper limit on the spin-independent WIMP- nucleon cross section of less than $1.2 \times 10^{-42}$ $cm^2$ for WIMPs of mass 8 GeV/$c^2$.
- New phase space was explored for WIMPs in the mass range 4 - 6 GeV/$c^2$.
- The interpretation of the excess events seen by CoGeNT as a WIMP signal is disfavored. CDMS II (Si) disfavored assuming standard WIMP interactions and a standard halo model.
- The standard high threshold analysis of SuperCDMS is ongoing and aims for a background of less than 1 event.
- Plans for a 110 kg SuperCDMS SNOLAB experiment are well underway. If funded, the SuperCDMS SNOLAB experiment will have unprecedented sensitivity to low mass WIMPs.

# Backup Slides

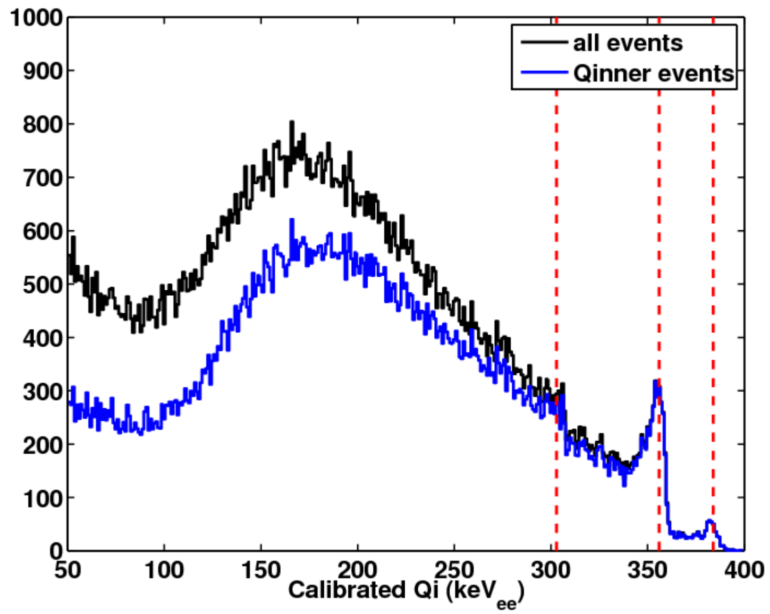
# SuperCDMS Limit w/o T5Z3



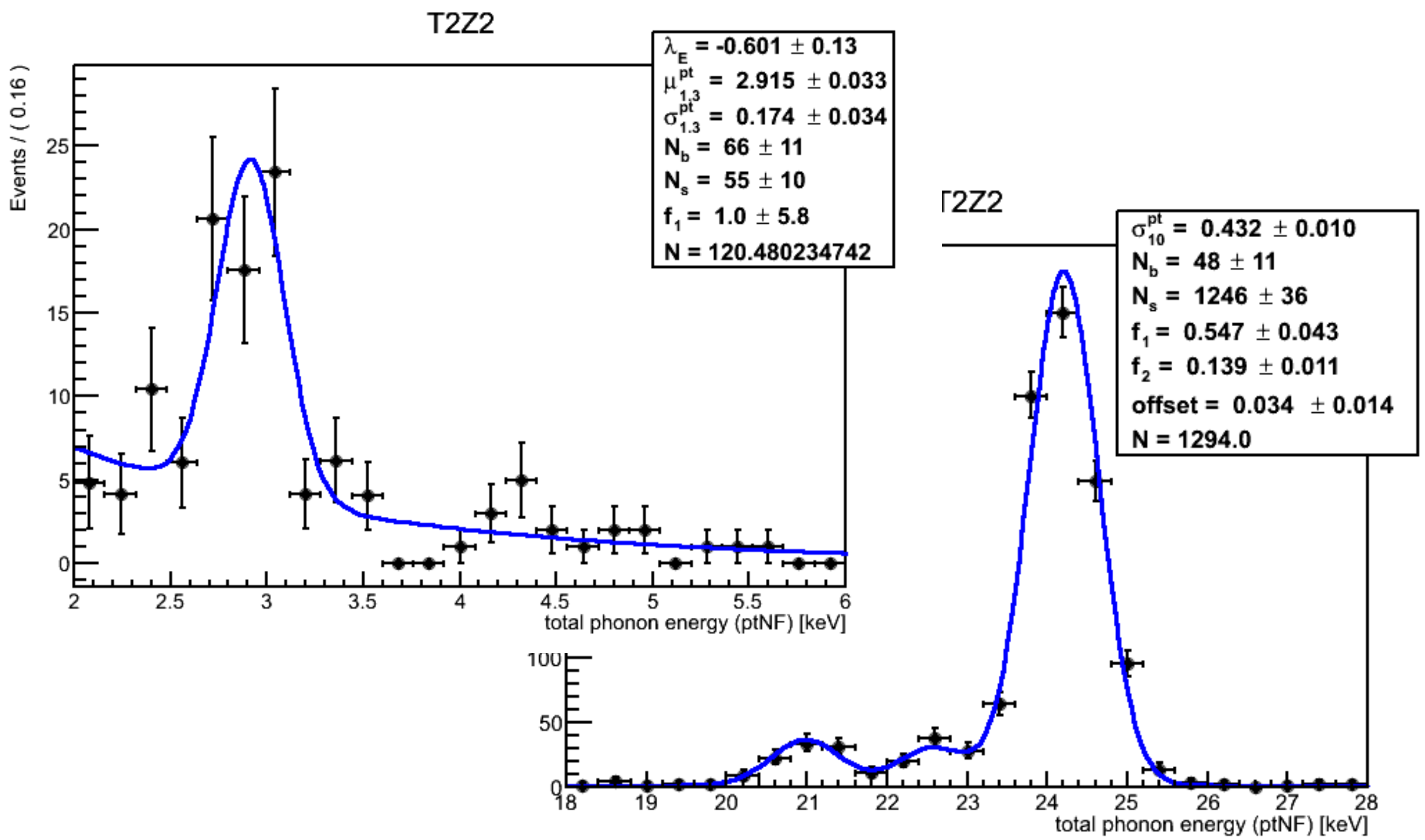
# T2Z2 Low Energy Candidate



# Electron Recoil Calibration

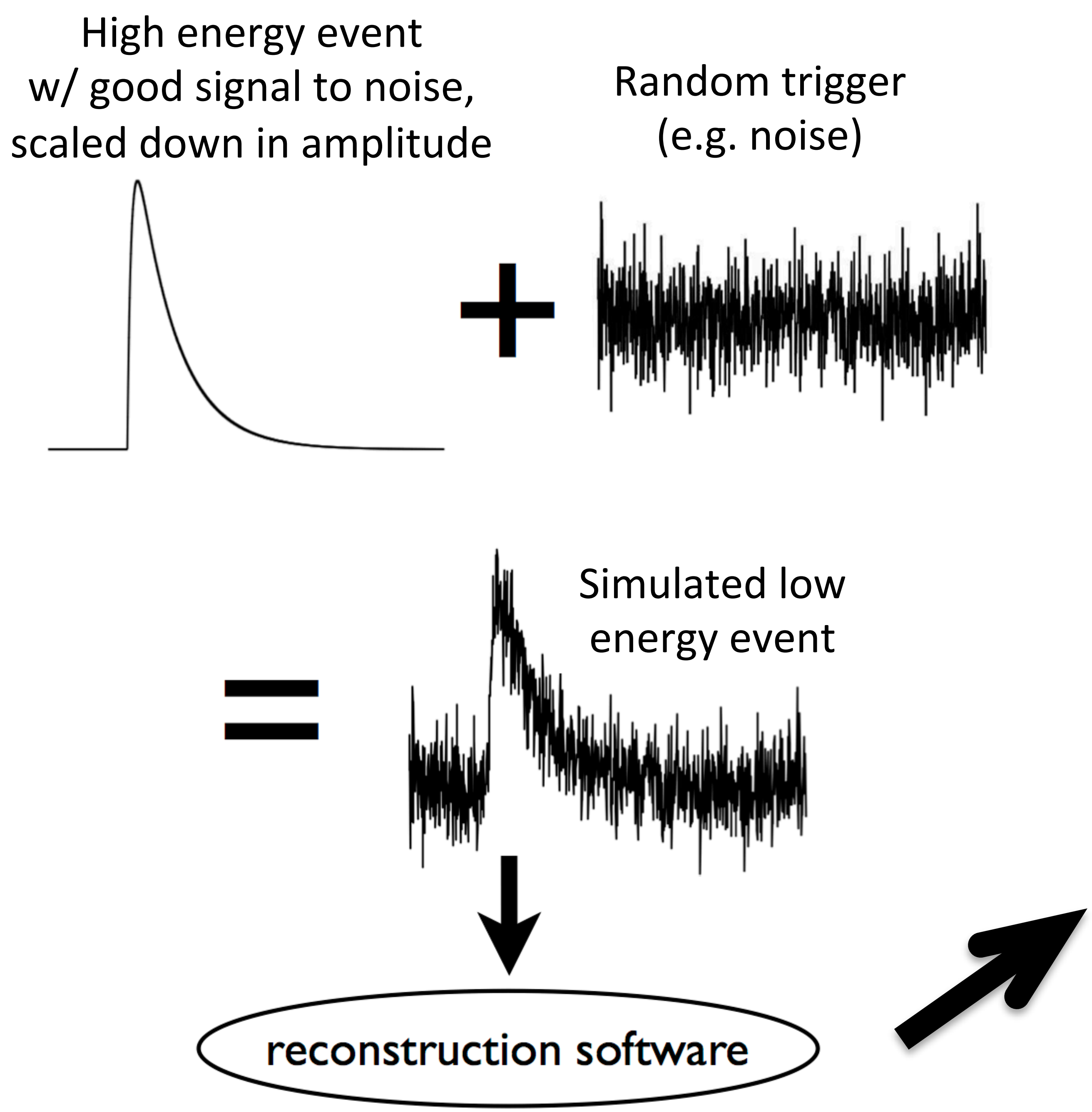



- Electron recoil ionization energy scale calibrated with $^{133}$Ba lines.
- Phonon energy calibrated to give ionization yield of 1.




- Linearity at low energies checked with 10.3 (k-shell) and 1.3 (l-shell) keV lines.

# Background Model w/ Pulse Simulations

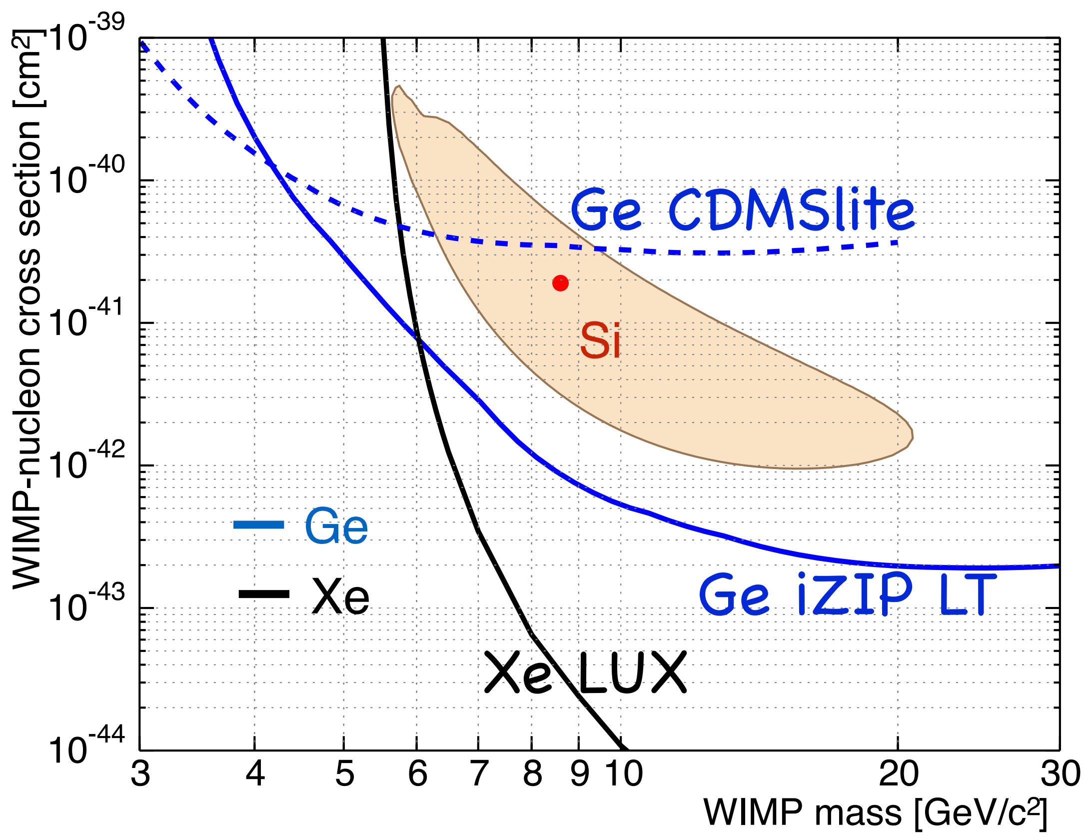


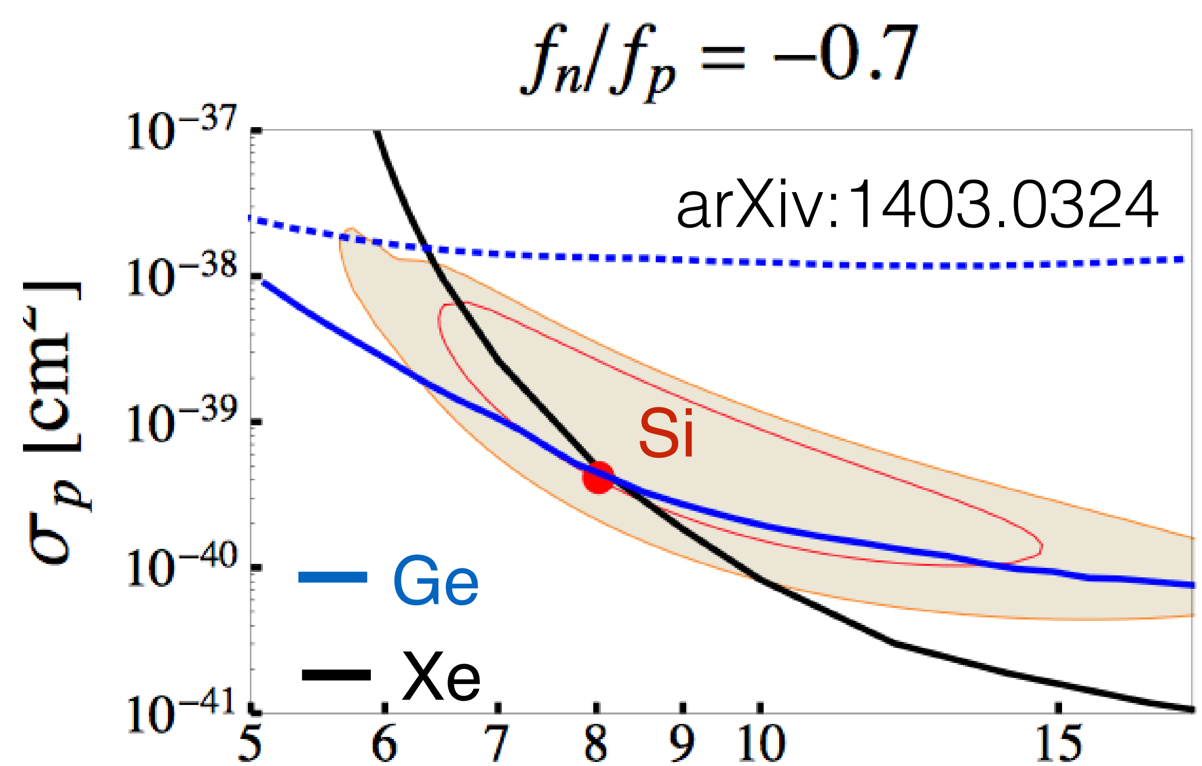

*Backgrounds at low energy are more difficult to separate from signal region due to poor signal to noise*

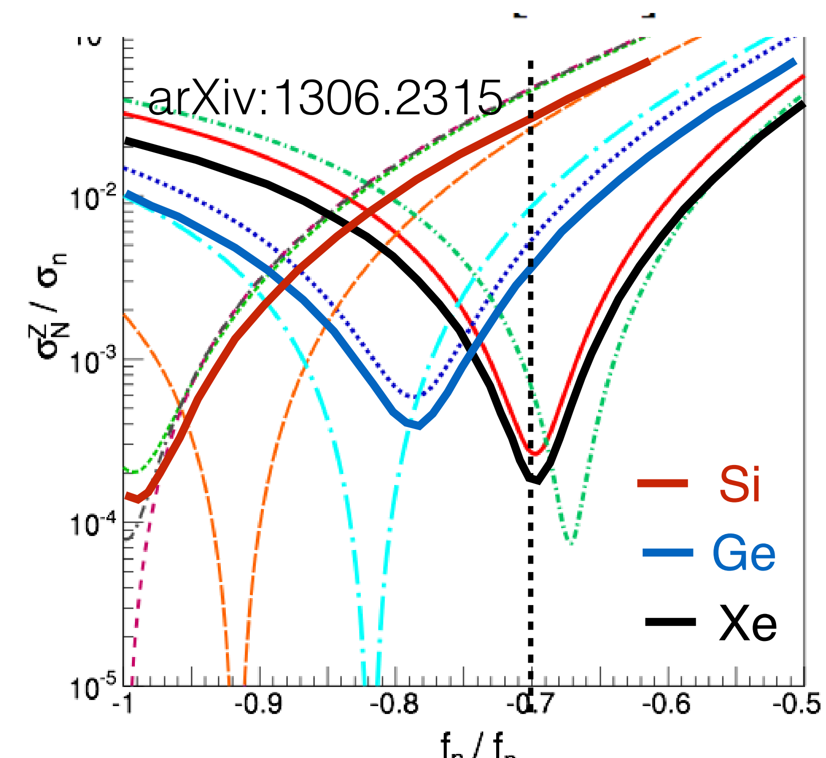
Study directly with a pulse simulation; using high energy events in sidebands and calibration data

weight events as a function of energy to match low energy spectrum

# Isospin Violating Dark Matter



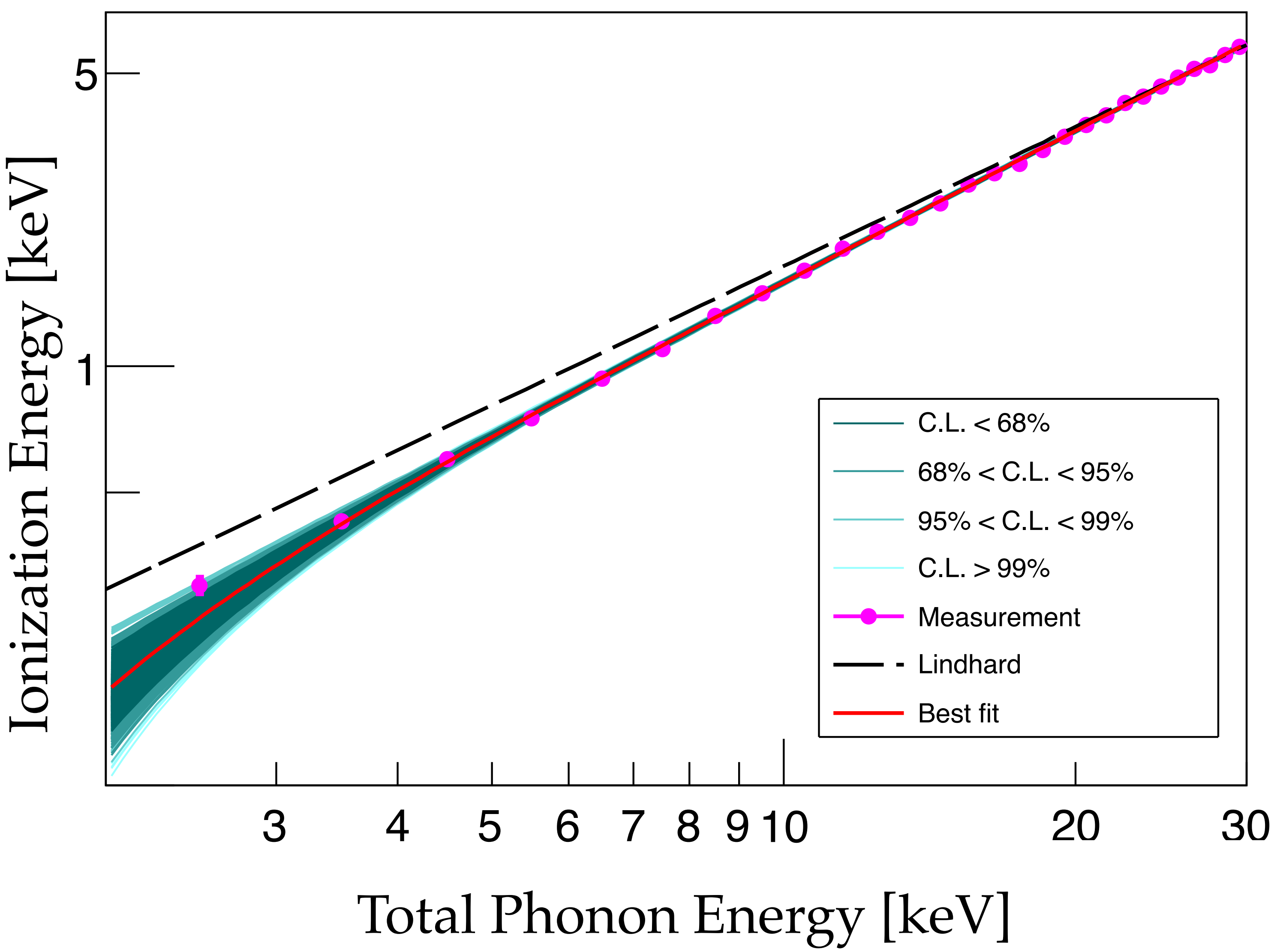




As an example, changing the ratio of $f_n/f_p$ changes the interpretation of the results.

# Nuclear Recoil Energy

Ionization for nuclear recoils measured from $^{252}$Cf data




Total phonon energy =

$$E_{total} = E_{luke} + E_{recoil}$$

$E_{total}$ is measured with phonons

$E_{luke}$ is the energy from propagating the charges

NR equivalent energy =

$$E_{total} - E_{luke\ NR}$$

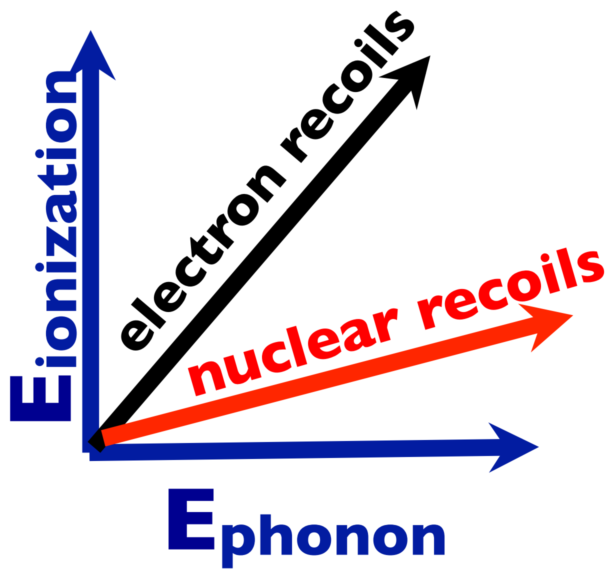
$E_{luke\ NR}$ is estimated from the mean NR ionization. It varies with $E_{total}$

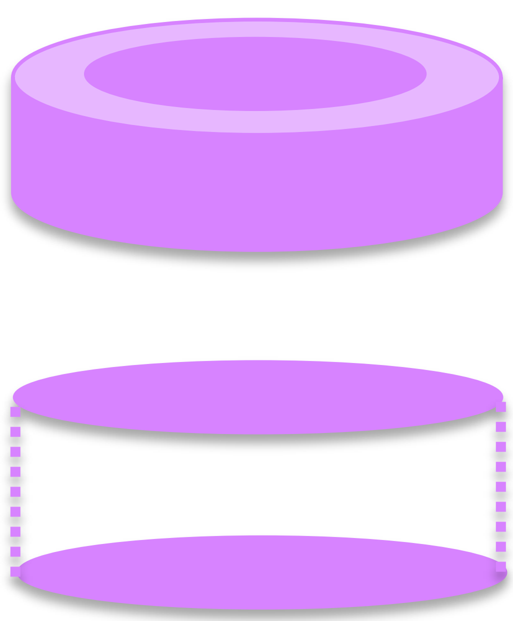
# Analysis Background Discrimination

**Bulk Electron Recoils:**

Primary sources: Compton background and 1.3 keV activation line

- *Use ionization and phonon energy to discriminate NR from bulk ER*



**Sidewall and Surface Events:**

Primary sources: betas and x-rays from $^{210}$Pb, $^{210}$Bi, $^{206}$Pb recoils; outer radial Compton background; and ejected electrons from Compton scattering

- *Use division of energy between inner and outer electrodes*
- *Use division of energy between sides 1 and 2.*