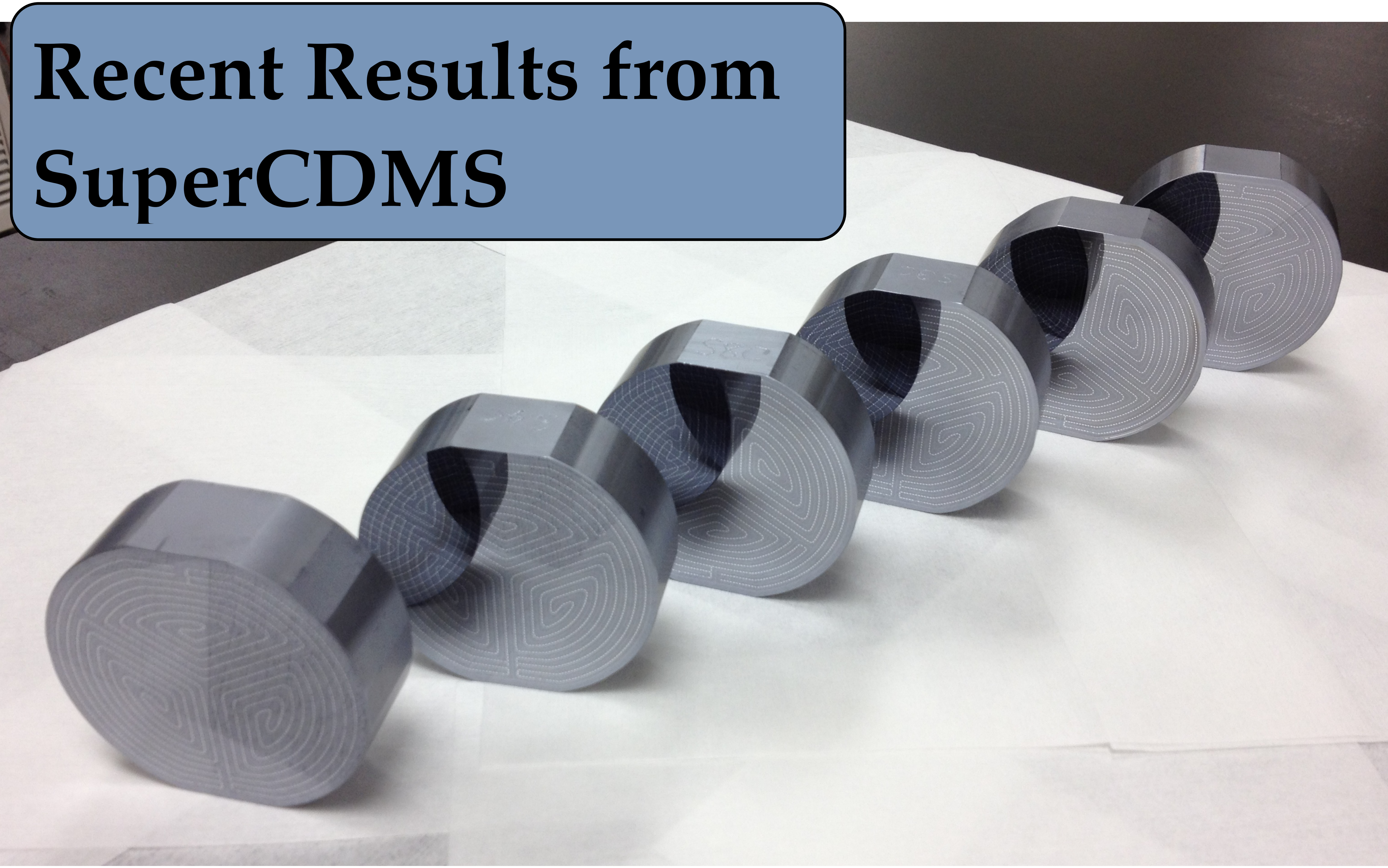
# Recent Results from SuperCDMS



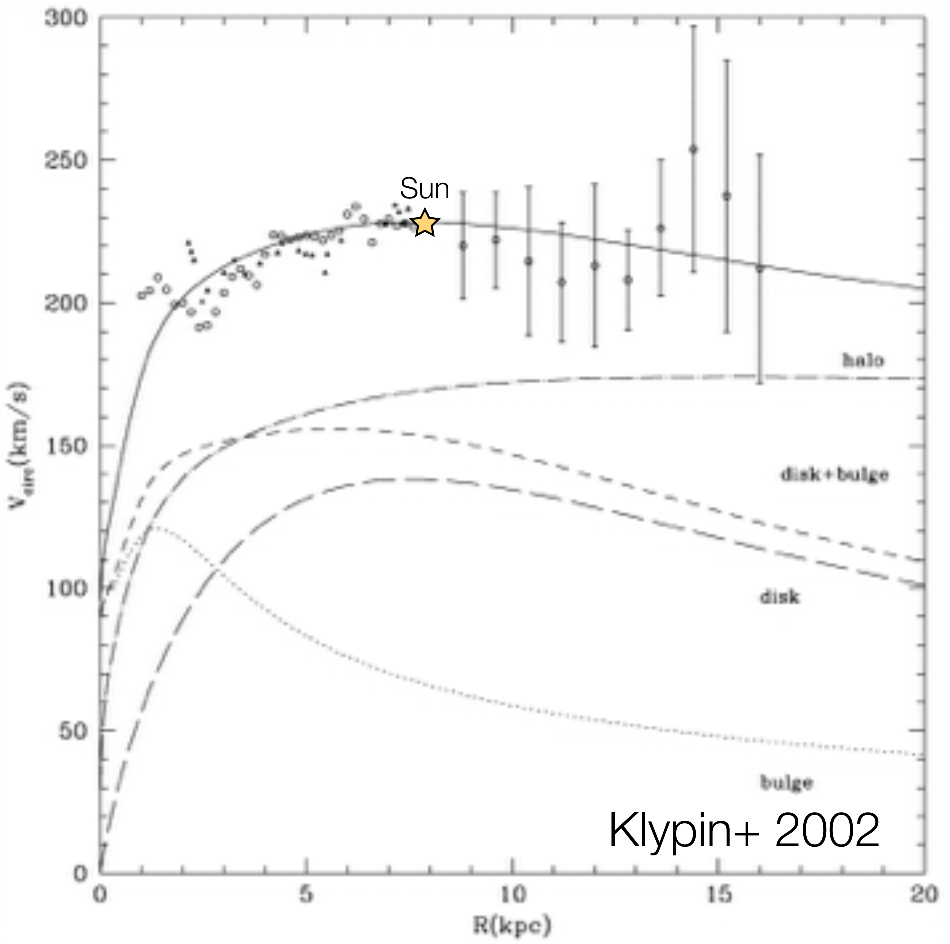
Jodi Cooley
Southern Methodist University

# Outline

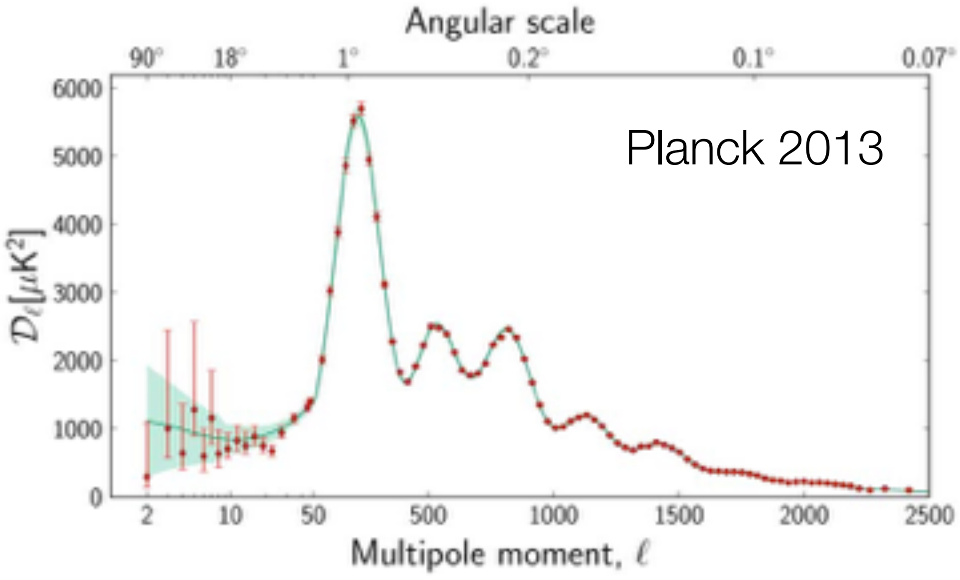
- Motivation and General Principles
- SuperCDMS at Soudan
  - Detection Principles
  - New Results from SuperCDMS - CDMSlite Run 2
- Plans for the SuperCDMS at SNOLAB experiment

# 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



Klypin+ 2002

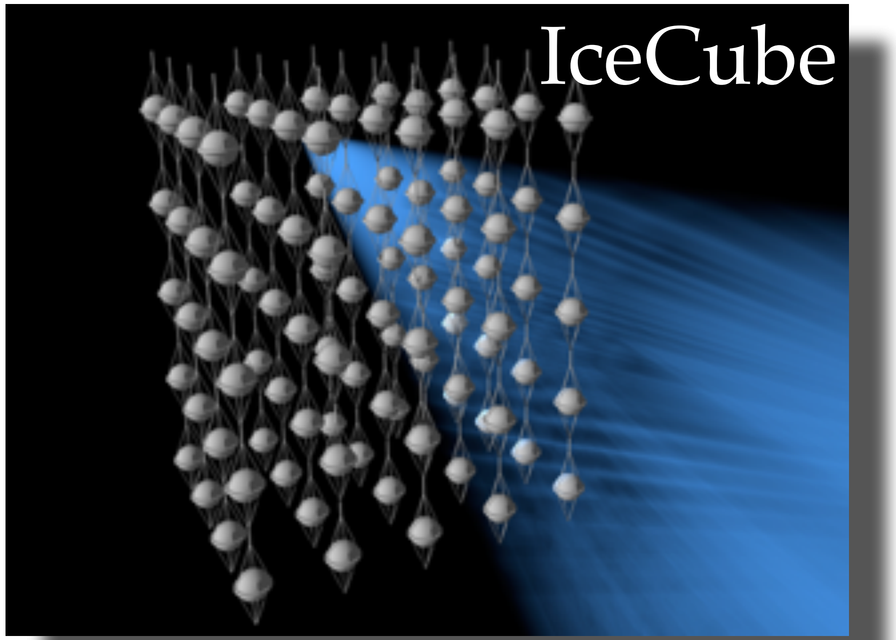


Planck 2013

# How to Detect Dark Matter

← WIMP scattering on Earth

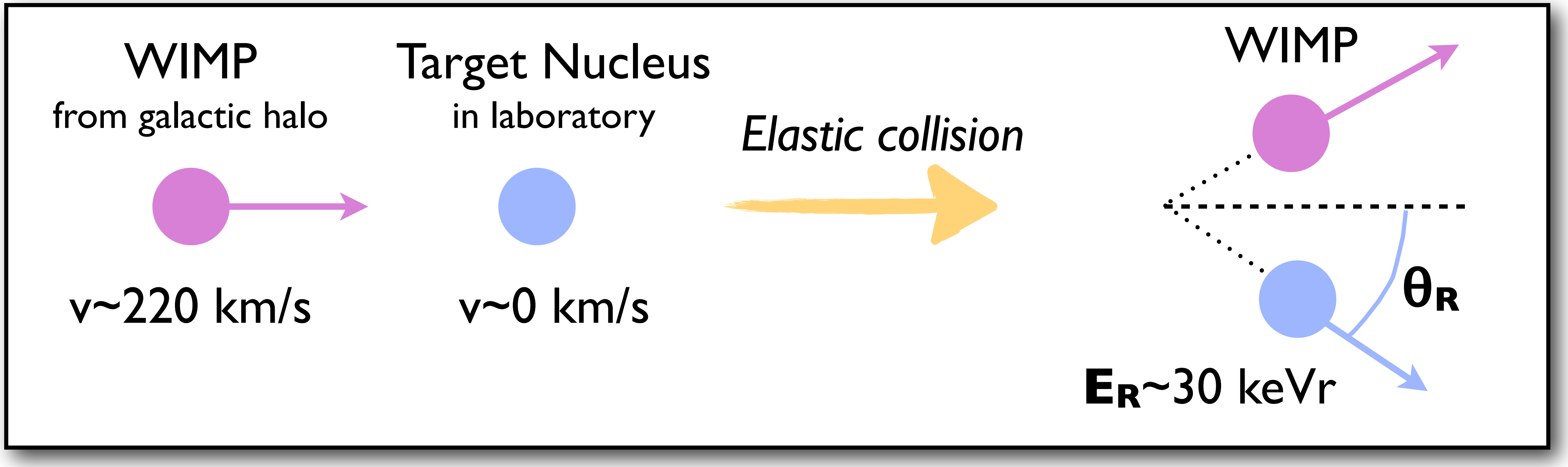
WIMP production on Earth →



← WIMP annihilation in the cosmos

# WIMP - Nucleus Interaction

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



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

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

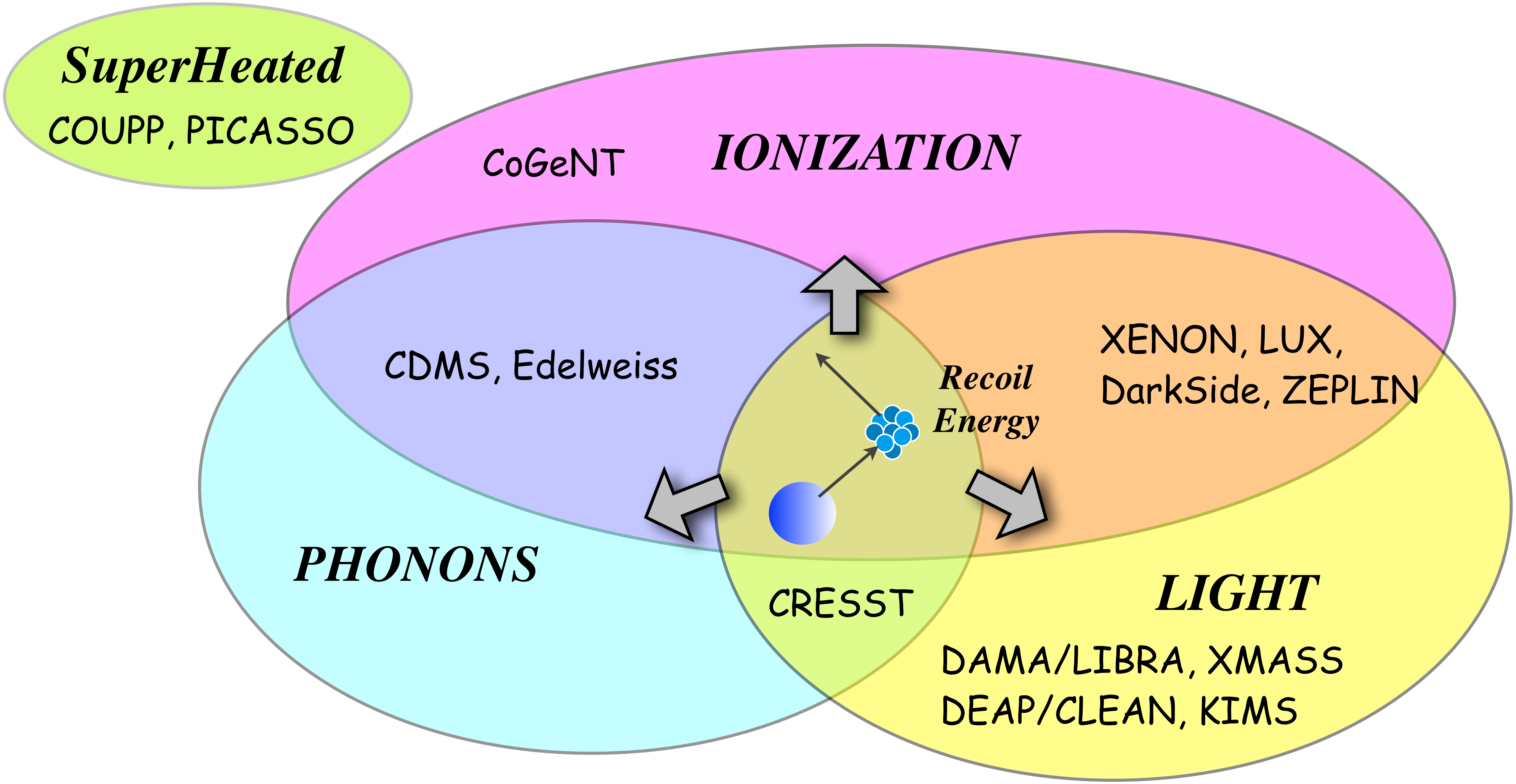
Enormous enhancement for heavy nuclei target!

$A$ ← atomic mass

$f$ ← coupling constant

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

# Direct Detection Principles



# Interaction Rate

Interaction Rate
[events/keV/kg/day]

particle theory | nuclear structure | local properties of DM halo

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

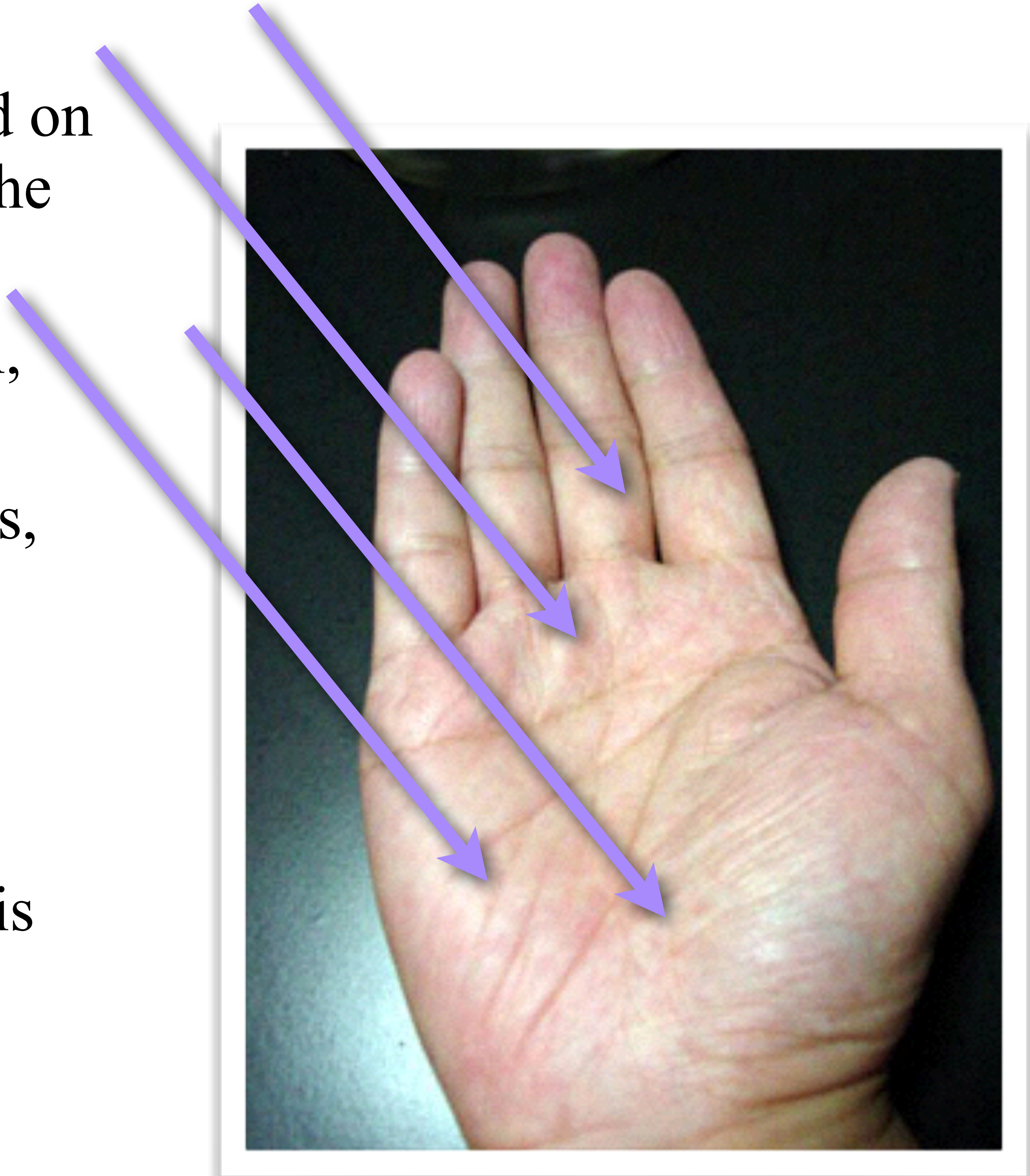
The Gory Details:

| | |
|---|---|
| $F(E_R) \simeq \exp\left(-E_R \, m_N \, R_o^2/3\right)$ | “form factor” (quantum mechanics of interaction with nucleus) |
| $m_r = \dfrac{m_\chi m_N}{m_\chi + m_N}$ | “reduced mass” |
| $T(E_R) \simeq \exp(-v_{\text{min}}^2/v_o^2)$ | integral over local WIMP velocity distribution |
| $v_{\text{min}} = \sqrt{E_R \, m_N/(2m_r^2)}$ | minimum WIMP velocity for given $E_R$ |

# 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$^3$



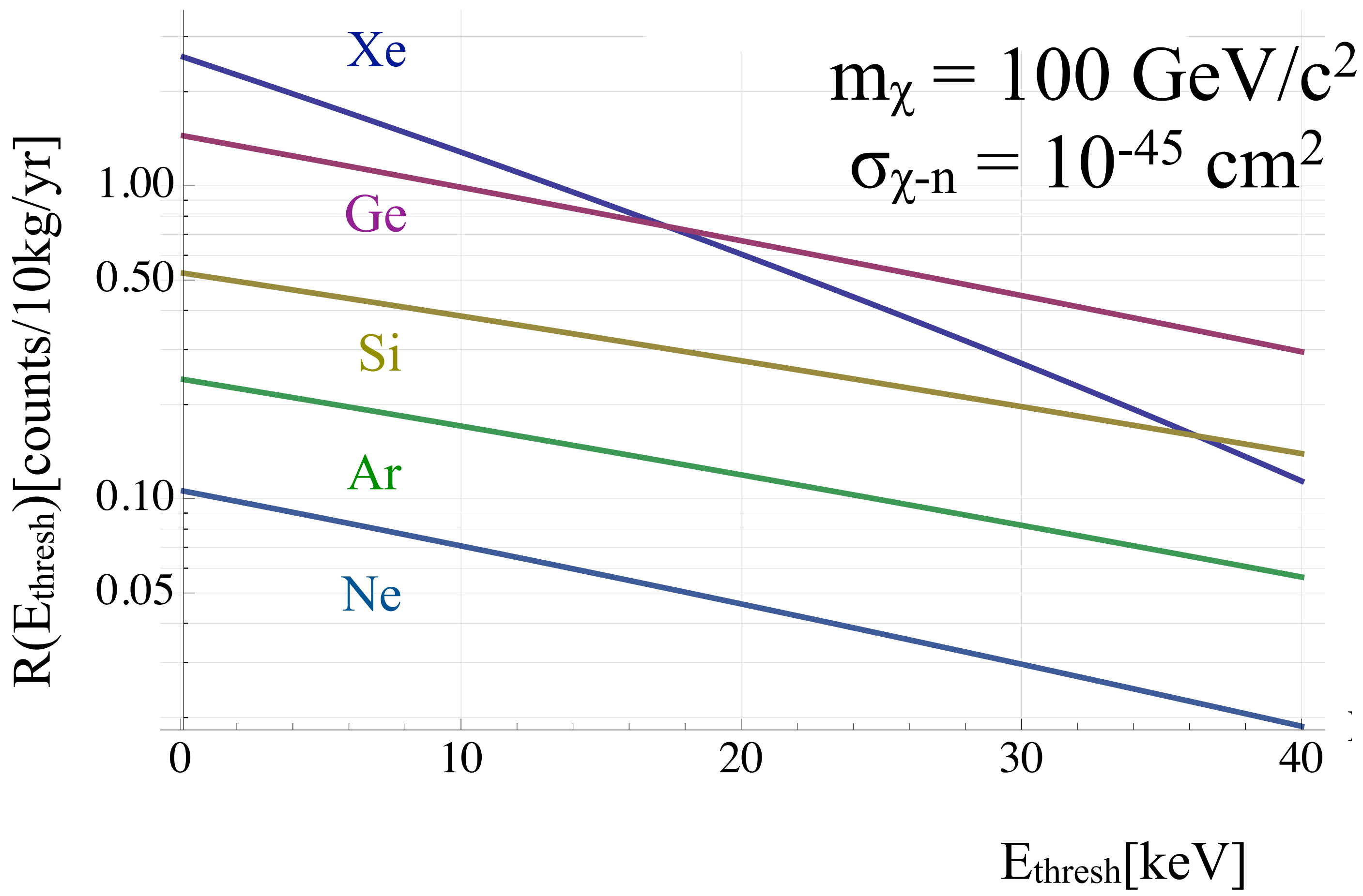
**Flux:**

- Assume the mass of the WIMP is 100 GeV/c$^2$
- ~10 million/hand/sec

# Direct Detection Event Rates

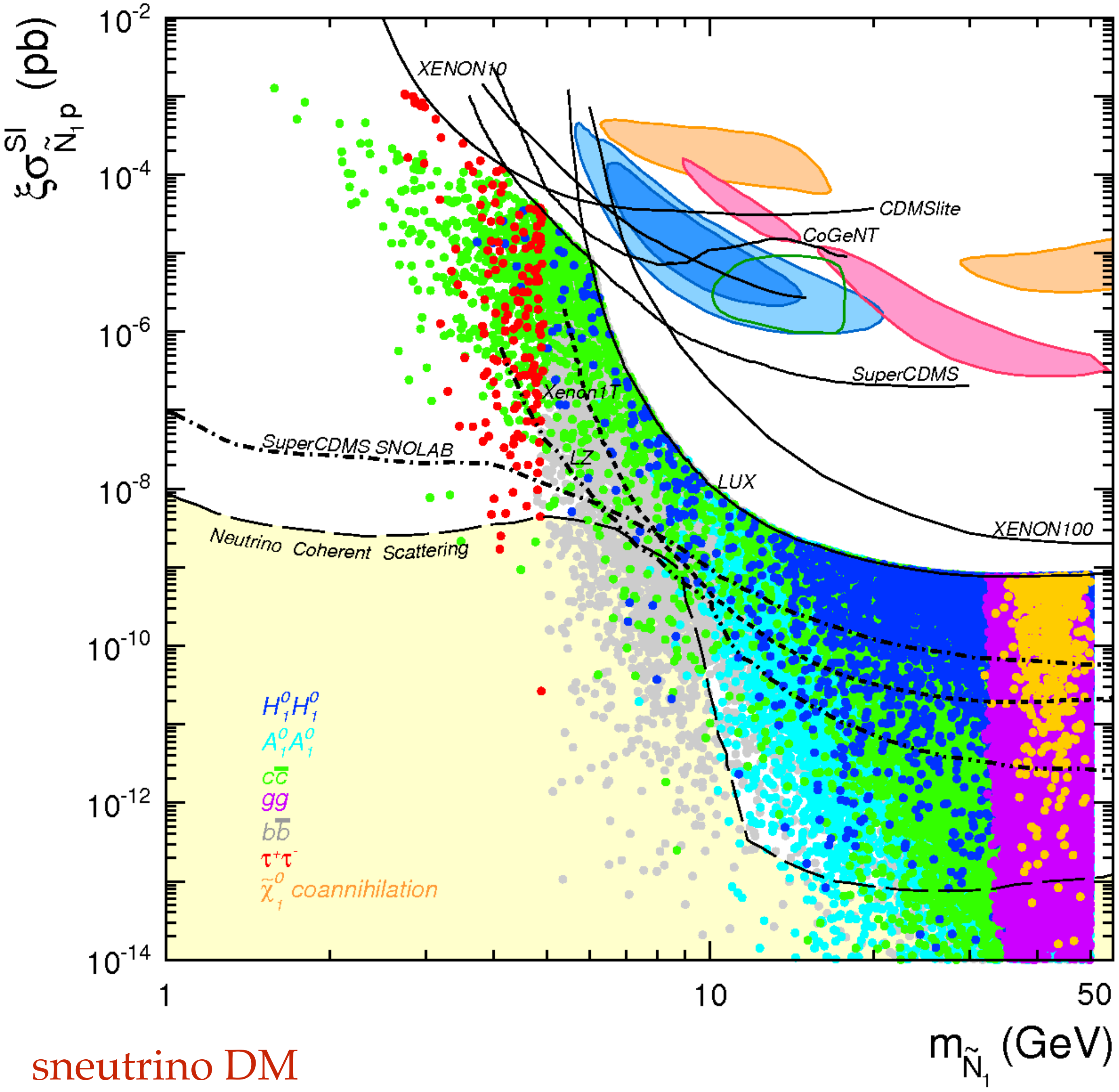
- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.

Total Event Rate



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

# Motivation for Low Mass WIMPS

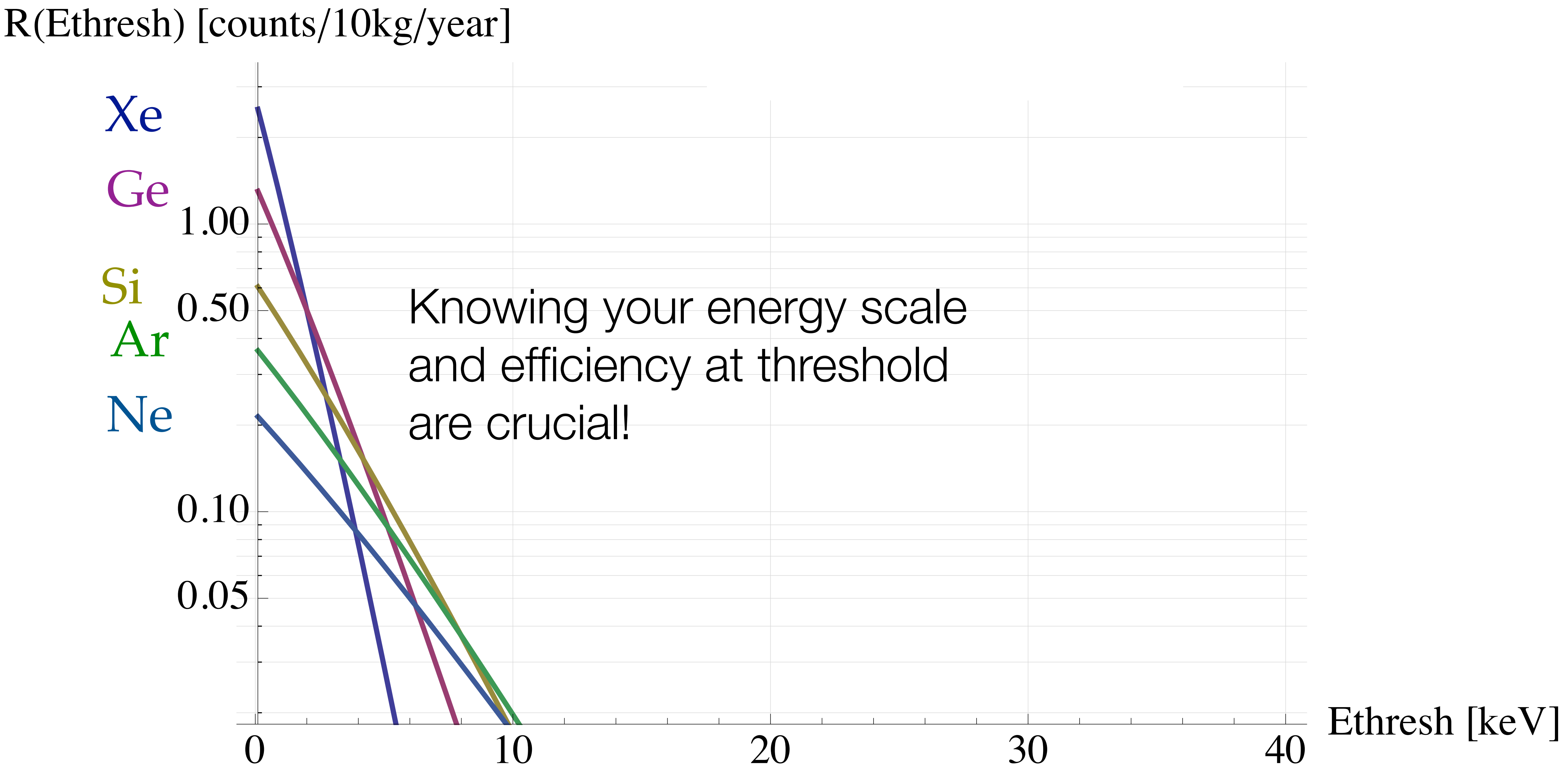


sneutrino DM
arXiv:1404.2572 (Cerdeno, Peiro, Robles)

- 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$^2$)



Knowing your energy scale and efficiency at threshold are crucial!

# 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

California Inst. of Tech.

CNRS-LPN*

Durham University

FNAL

NISER

NIST*

Northwestern

PNNL

Queen's University

Santa Clara University

SLAC

Southern Methodist U.+

South Dakota SM&T

Stanford University

Texas A&M University

U. British Columbia

U. California, Berkeley

U. Colorado Denver

U. Evansville

U. Florida

U. Minnesota

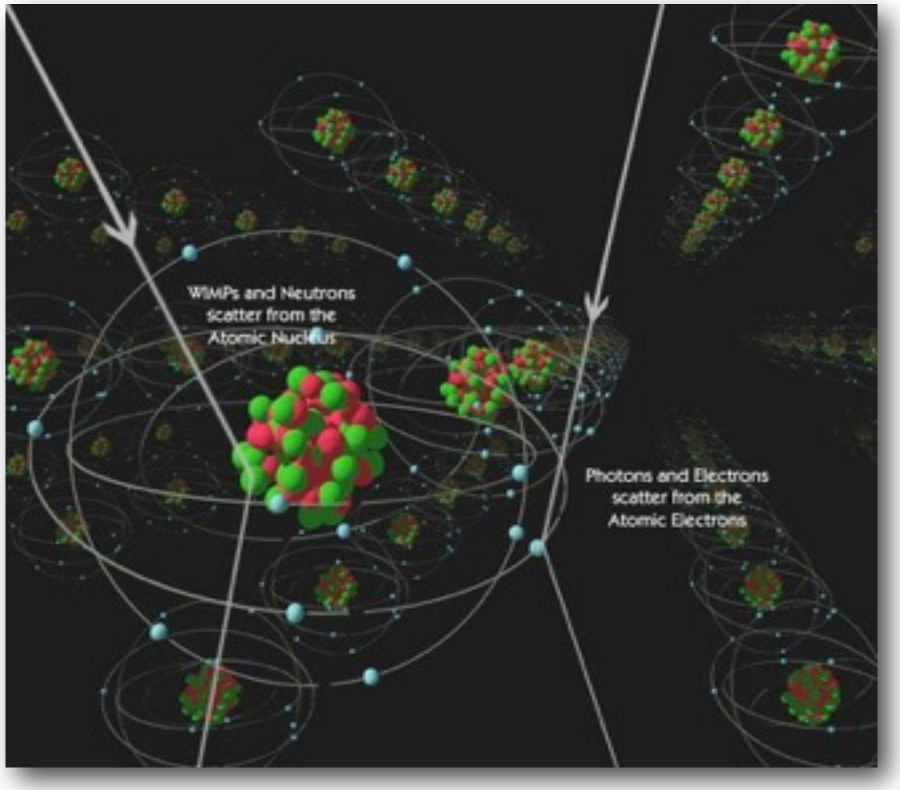
U. South Dakota

* Associate members

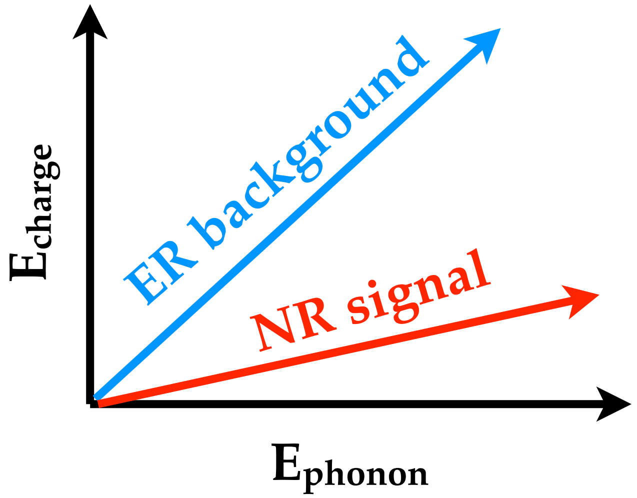
+The SMU SuperCDMS group is supported by the NSF under grant number 1151869.

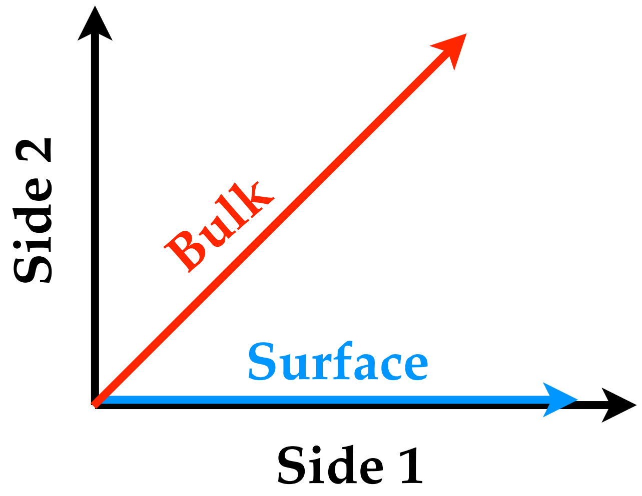
# SuperCDMS in a Nutshell

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



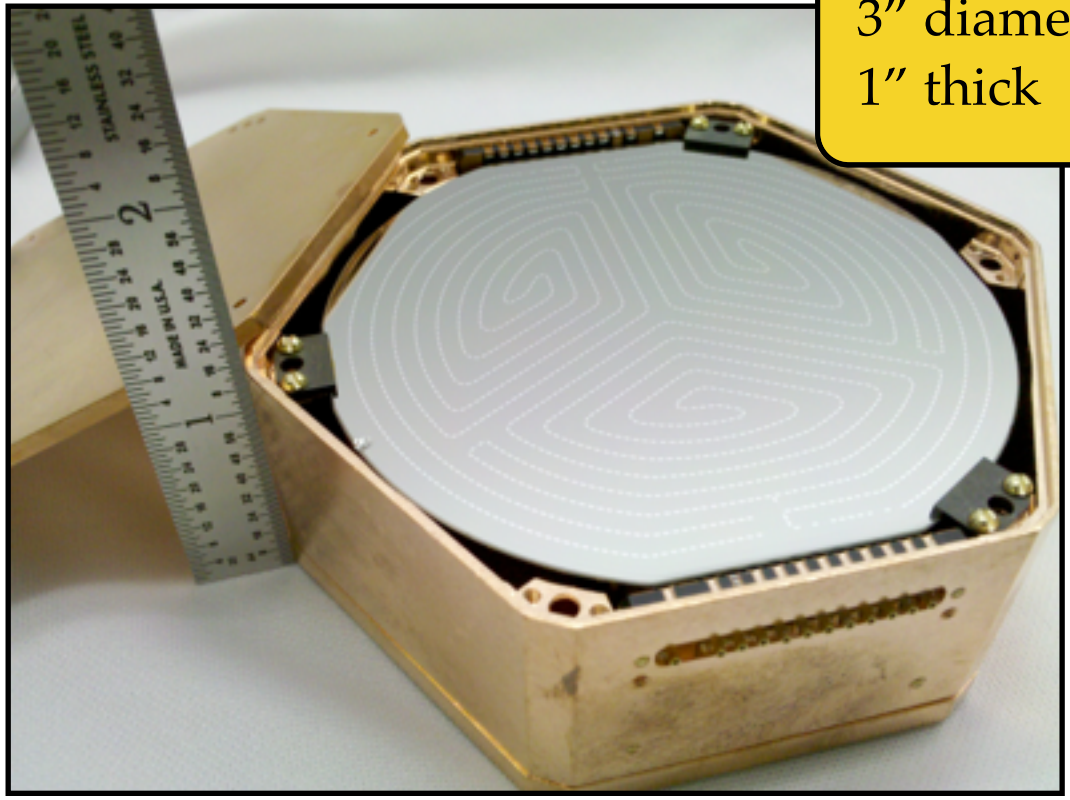
Discrimination from measurements of **ionization** and **phonon energy** **and charge distributions**



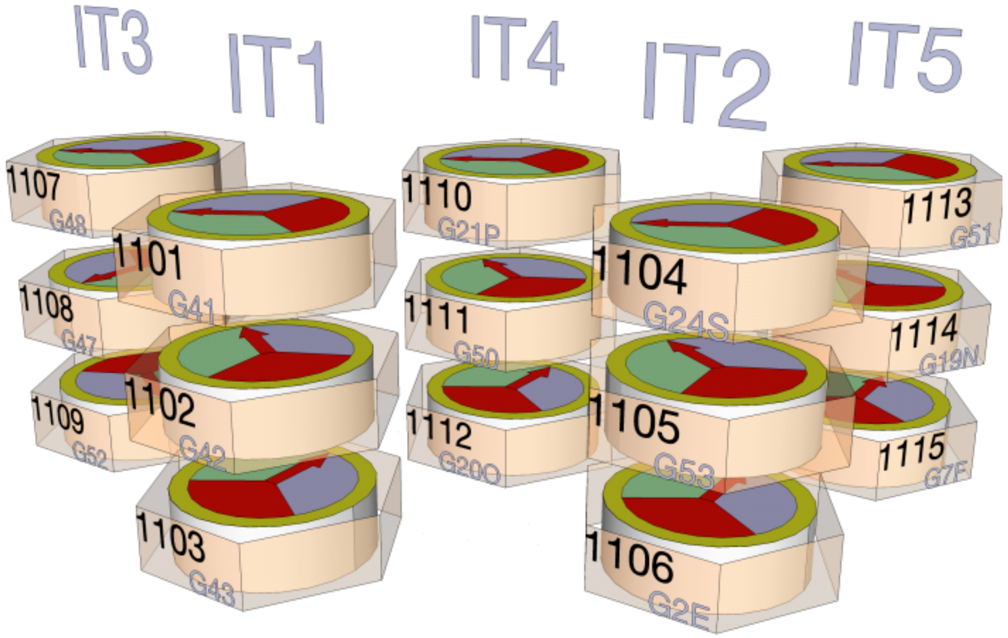


Keep backgrounds low as possible through shielding and material selection.

# SuperCDMS iZIP Detectors

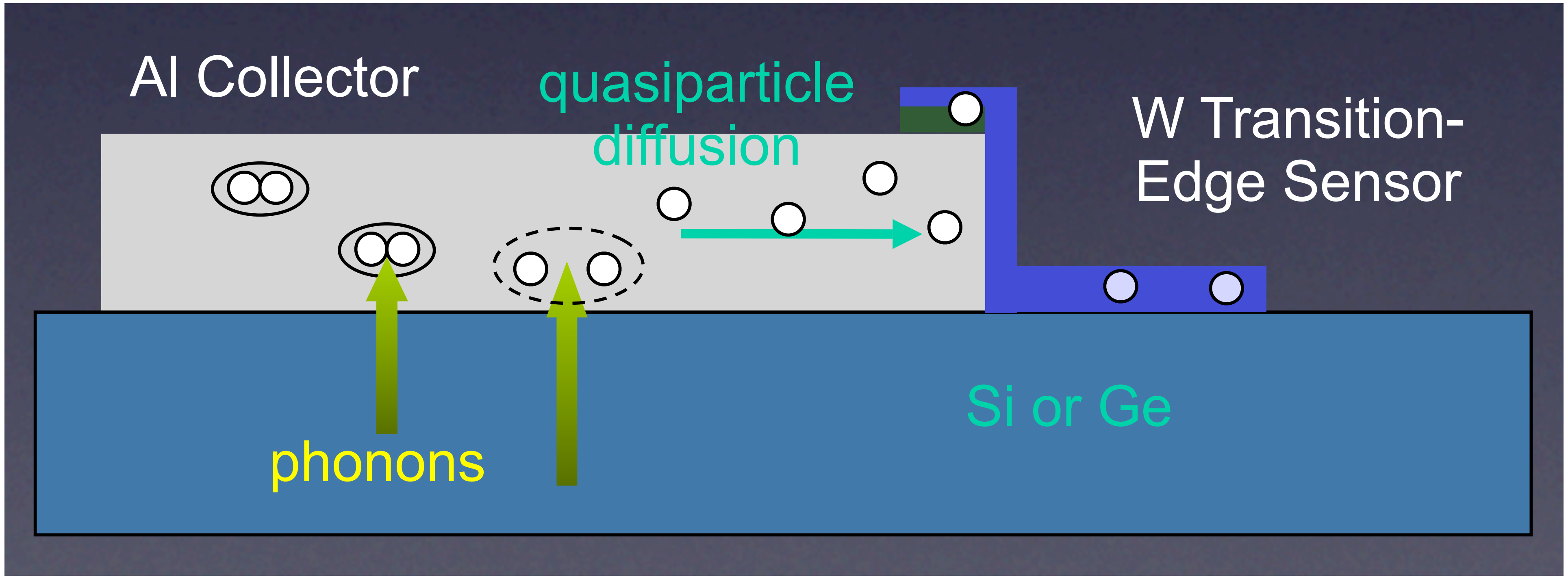


3” diameter
1” thick



- Ge crystal (600 g) **i**nterleaved **Z**-sensitive **I**onization and **P**honon detectors (**iZIP**)
- Ionization lines (±2 V) are interleaved with phonon sensors
- Two charge channels on each face can be used to reject surface and sidewall events
- Phonon sensors and their layout are optimized to enhance phonon signal to noise ratio
- 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

# Phonon Detection



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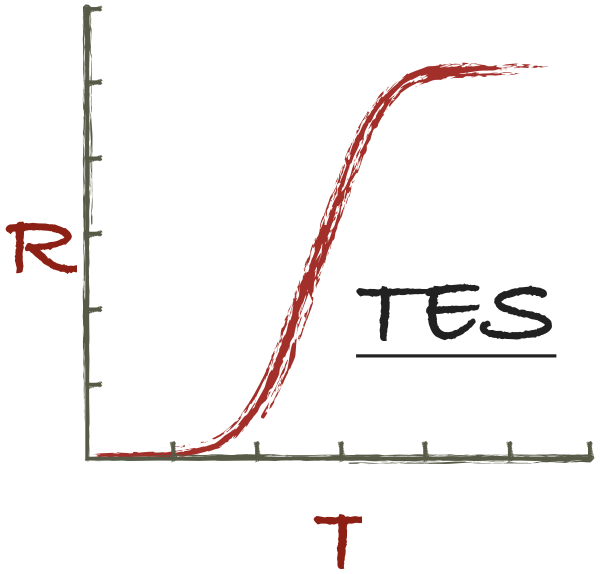


4 SQUID readout channels, each reads out 1036 TES in parallel

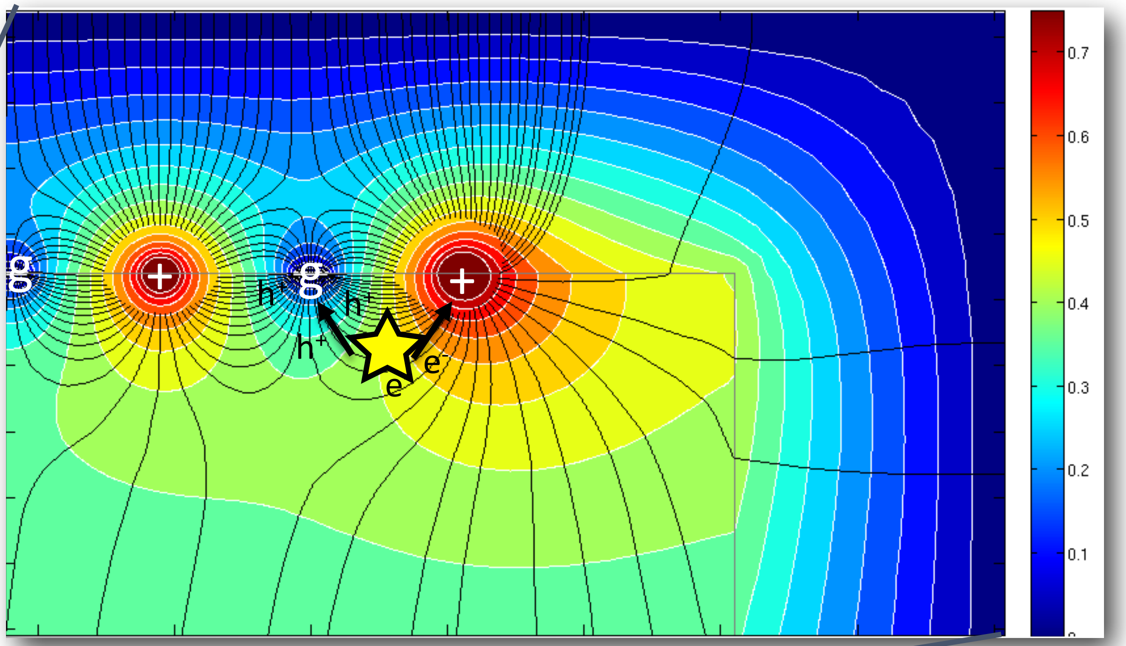
# SCDMS iZIPs:  Charge Signal

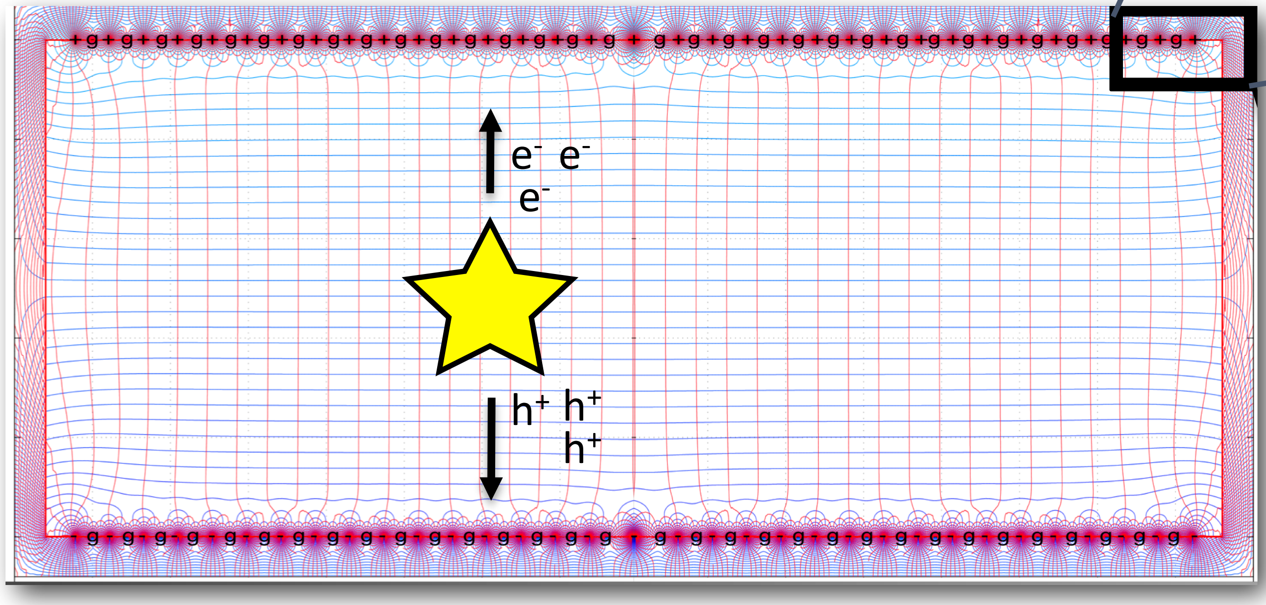
**Bulk Events:**

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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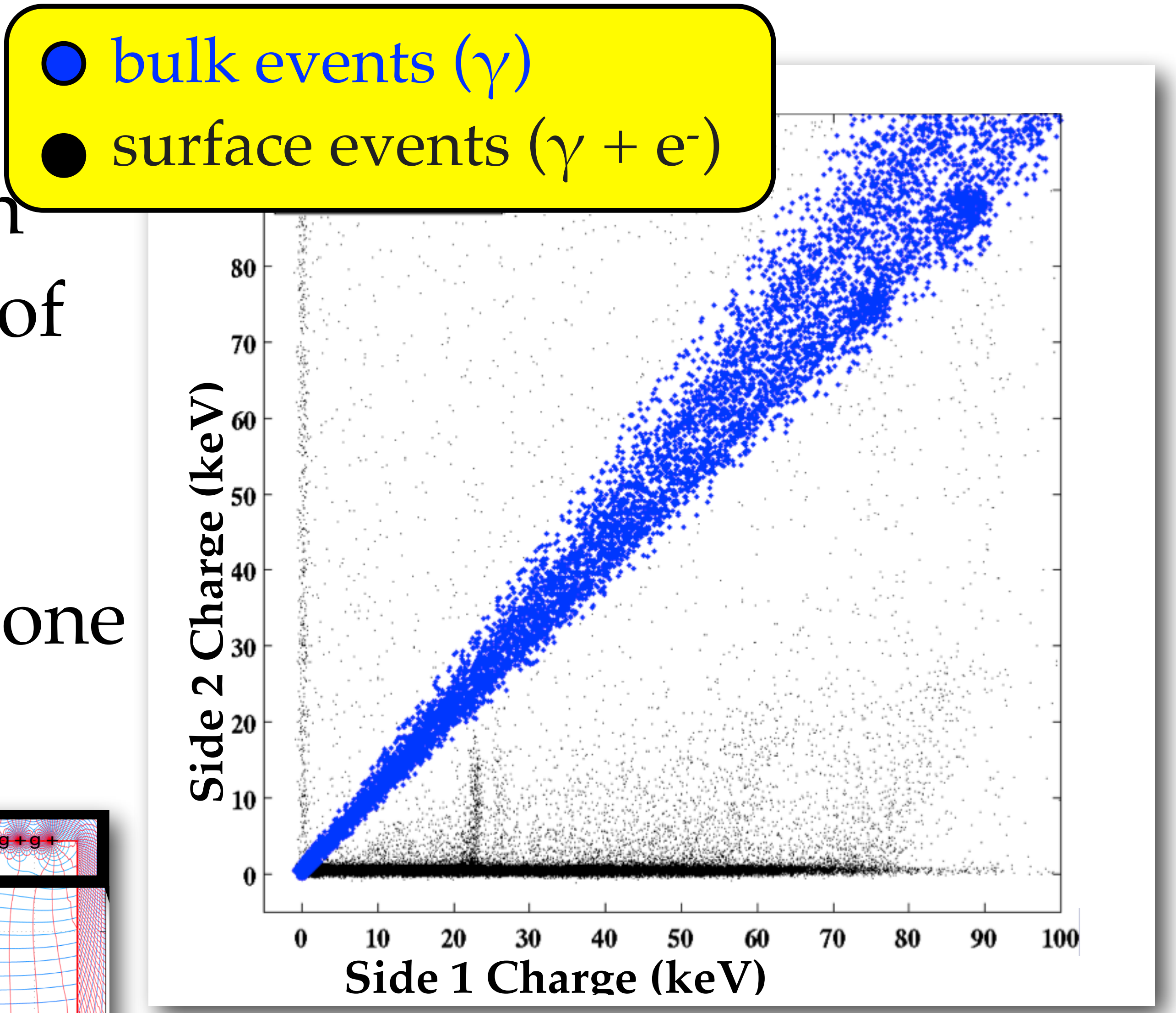
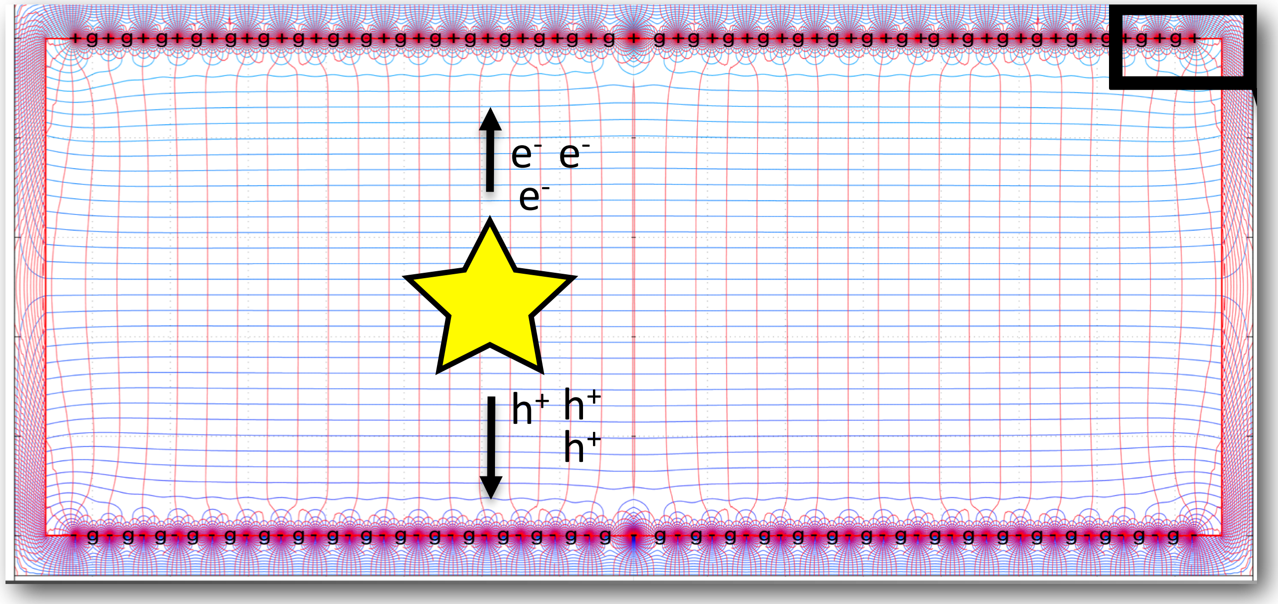
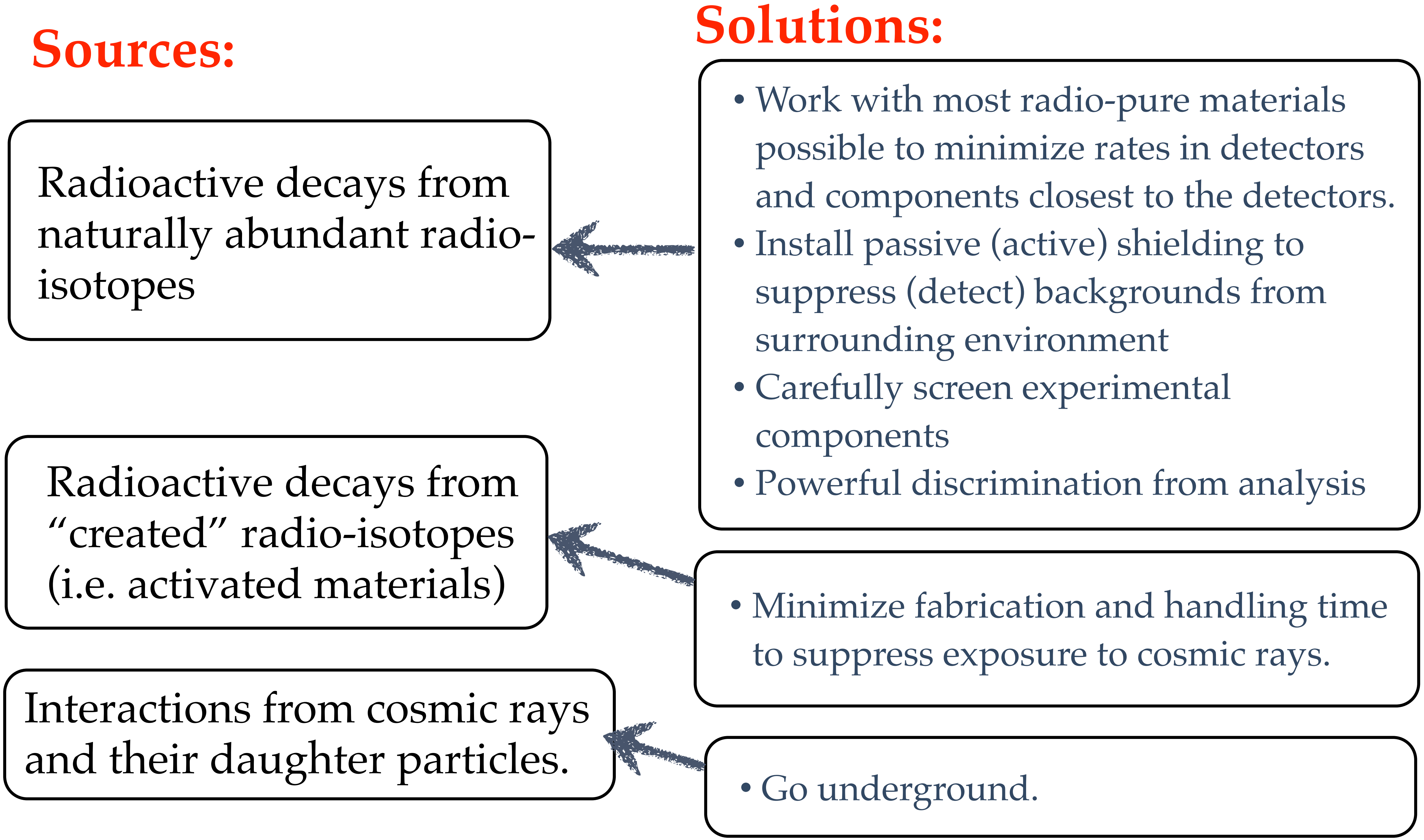




Ionization symmetry is a powerful way to discriminate surface events from bulk events.

# Backgrounds



**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:**

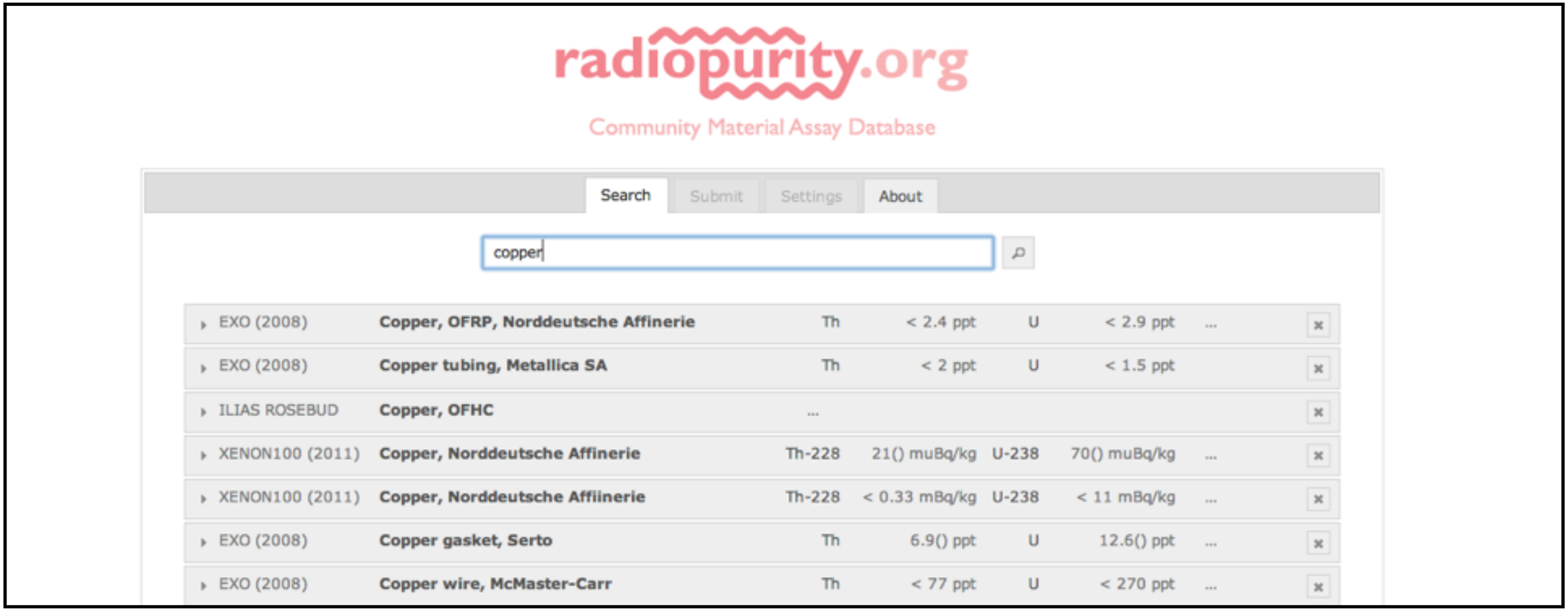
- Work with most radio-pure materials possible to minimize rates in detectors and components closest to the detectors.
- Install passive (active) shielding to suppress (detect) backgrounds from surrounding environment
- Carefully screen experimental components
- Powerful discrimination from analysis

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

- Go underground.

# Community Assays Database

## Use Clean Materials

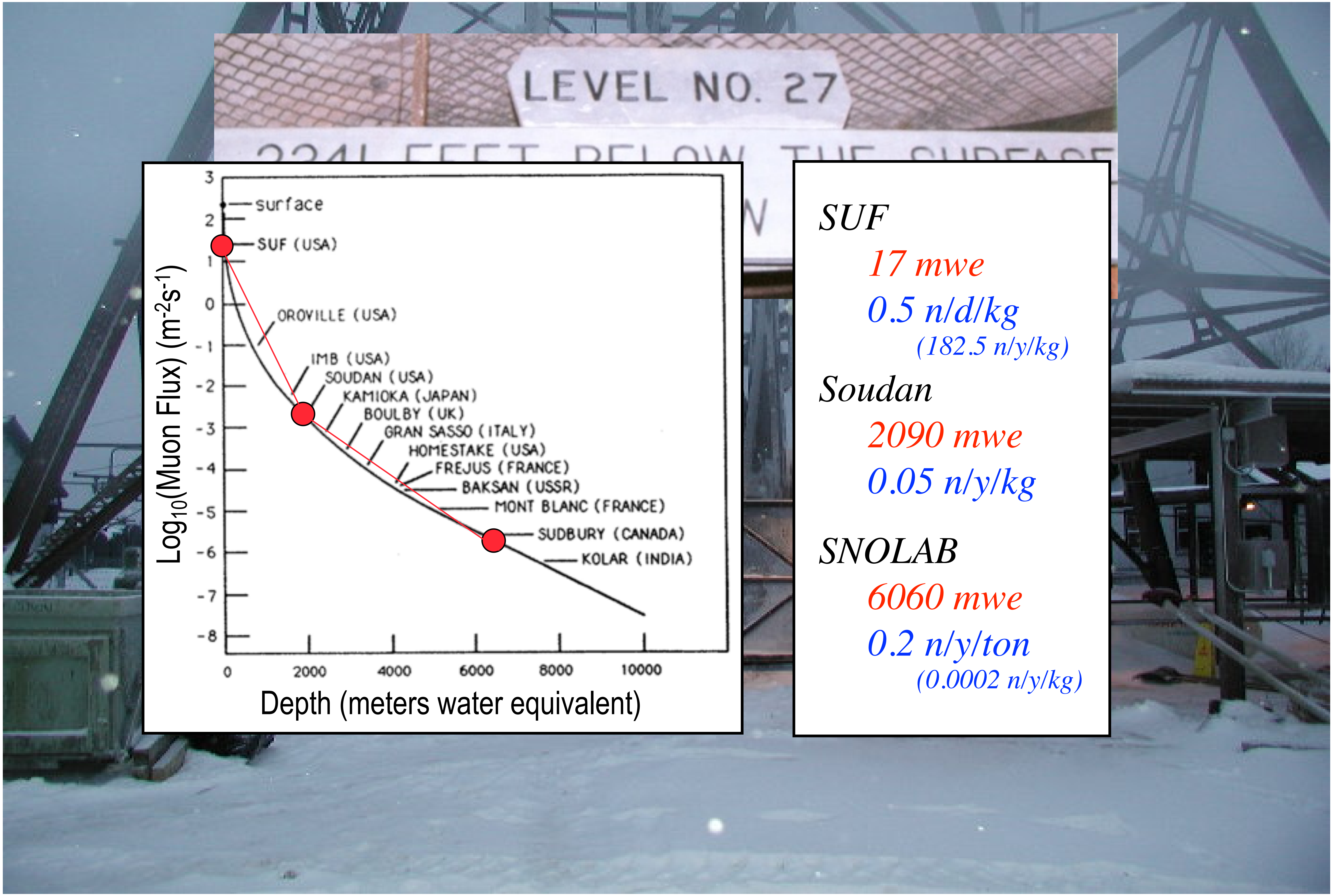


copper

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| 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](http://radiopurity.org)

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



*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

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

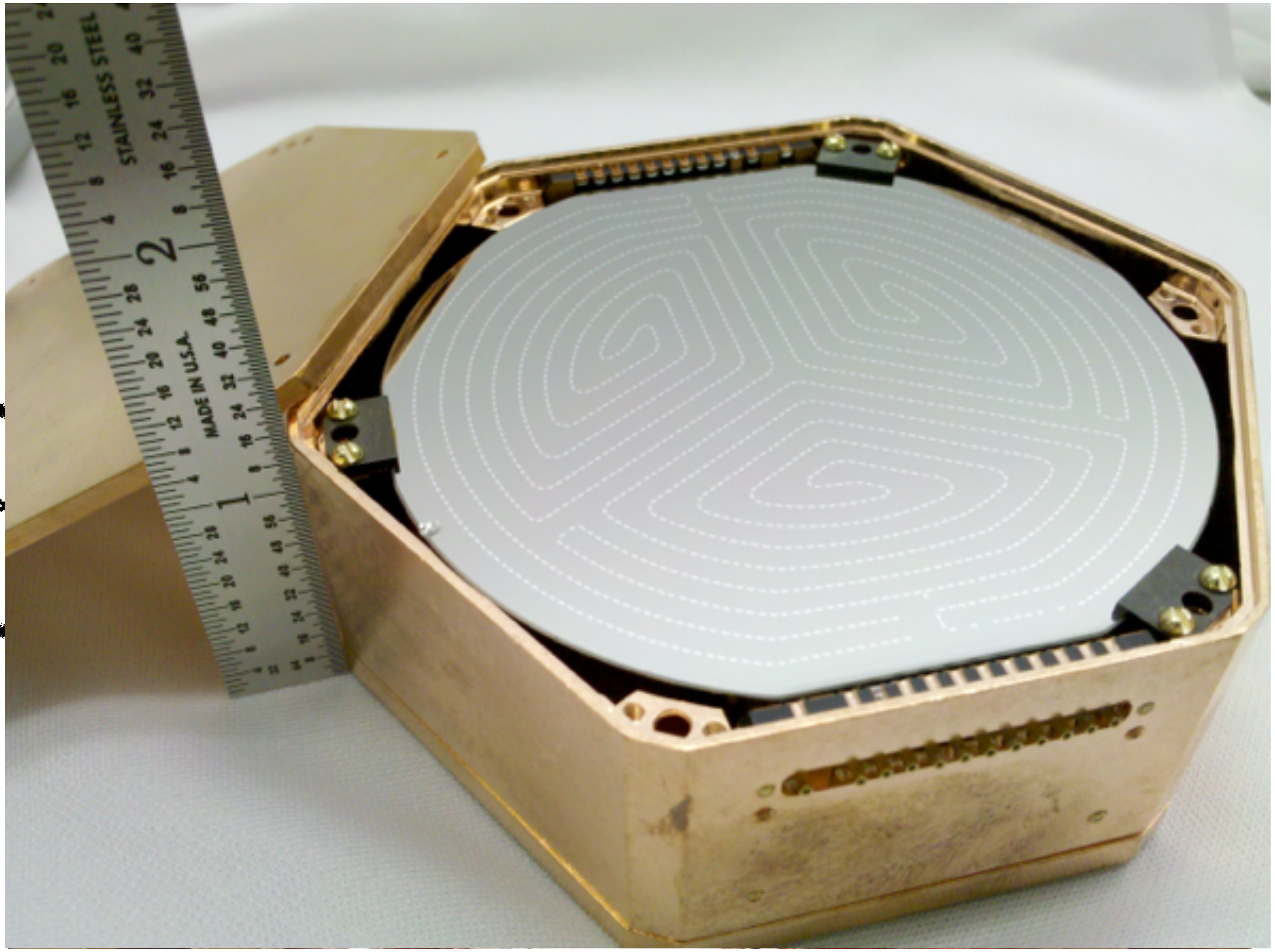
**Pb:** shielding from gammas resulting from radioactivity

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

**Polyethyene:** shields ancient Pb

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

**Ge:** target



# CDMSlite

# A Low Ionization Experiment

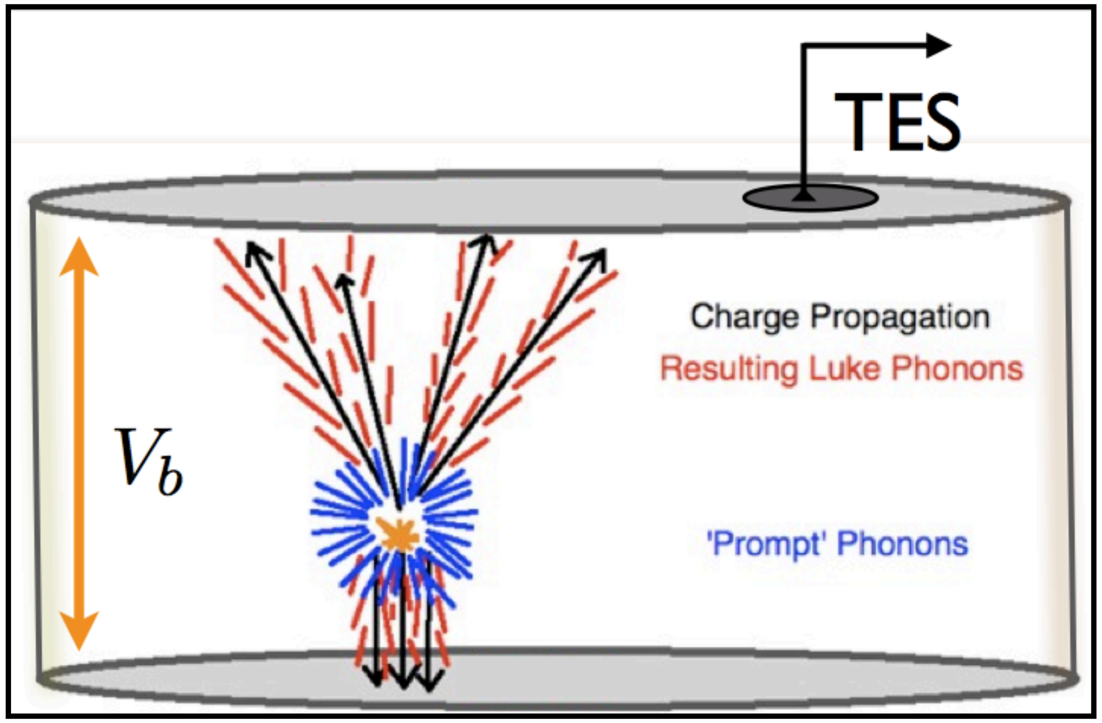
- CDMSlite uses Neganov-Luke amplification to obtain low thresholds with high-resolution
  - Ionization only, uses phonon instrumentation to measure ionization
  - No event-by- event discrimination of nuclear recoils
- Drifting electrons across a potential (V) generates a large number of phonons (Luke phonons).

$$E_t = E_r + N_{eh} e V_b$$

*total phonon energy*

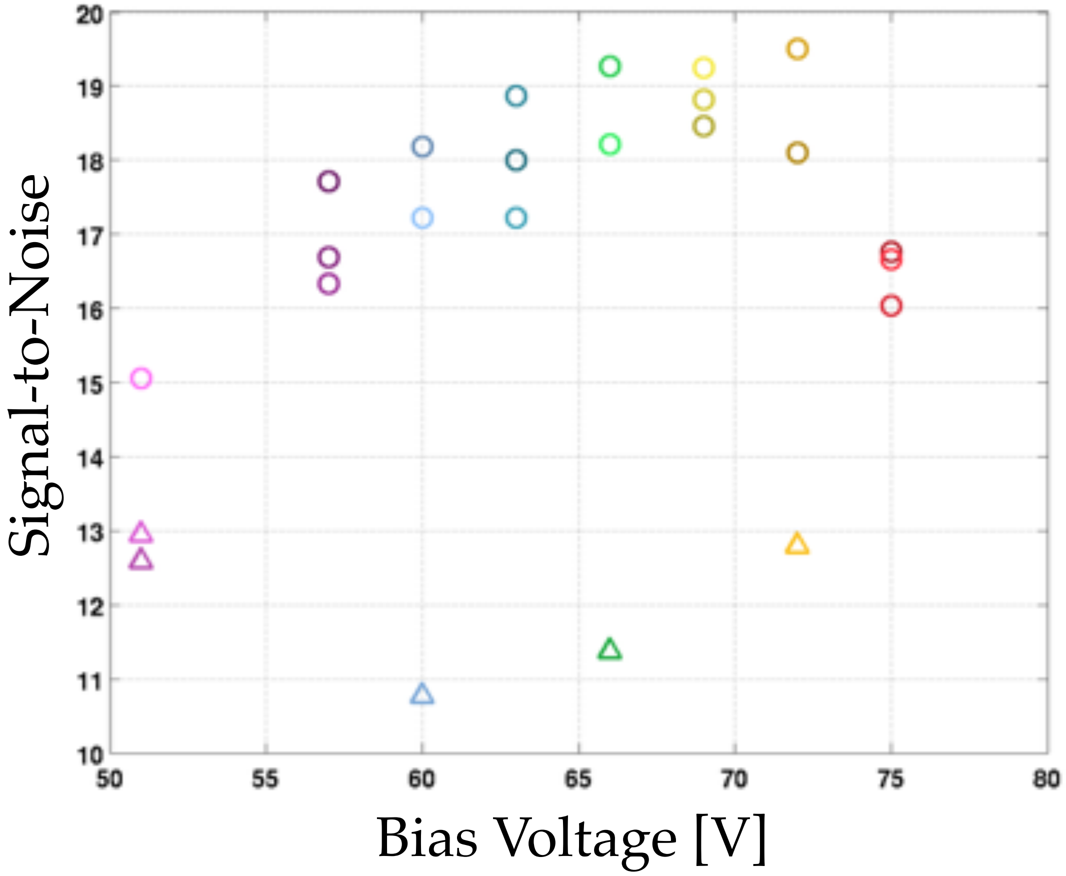
*primary recoil energy*

*Luke phonon energy*

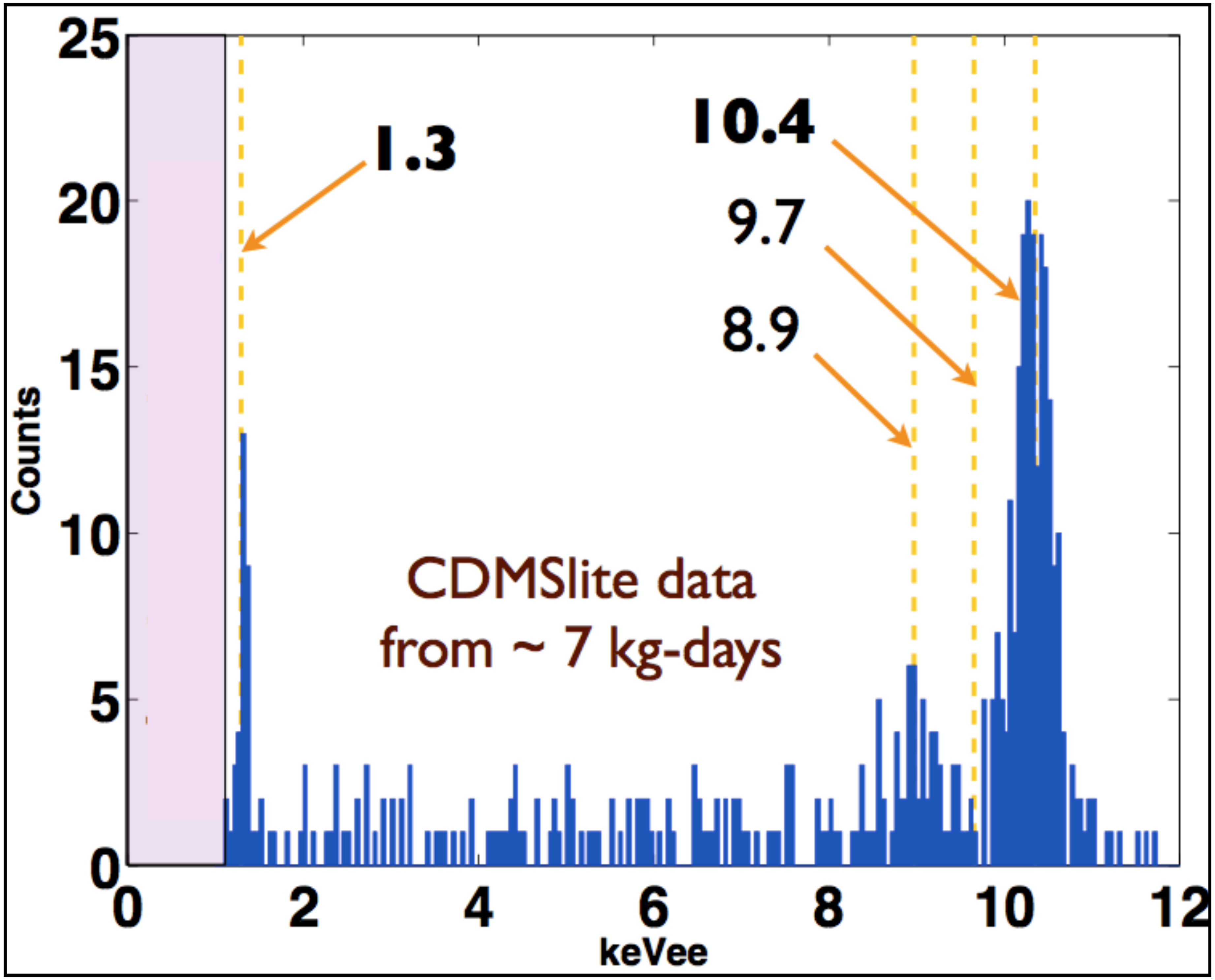


# CDMSlite - The Detector

- Custom electronics were installed to allow biases above 10 V
  - Disable one side of iZIP and raising that entire side to the bias voltage.
- A voltage scan indicated 70 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.



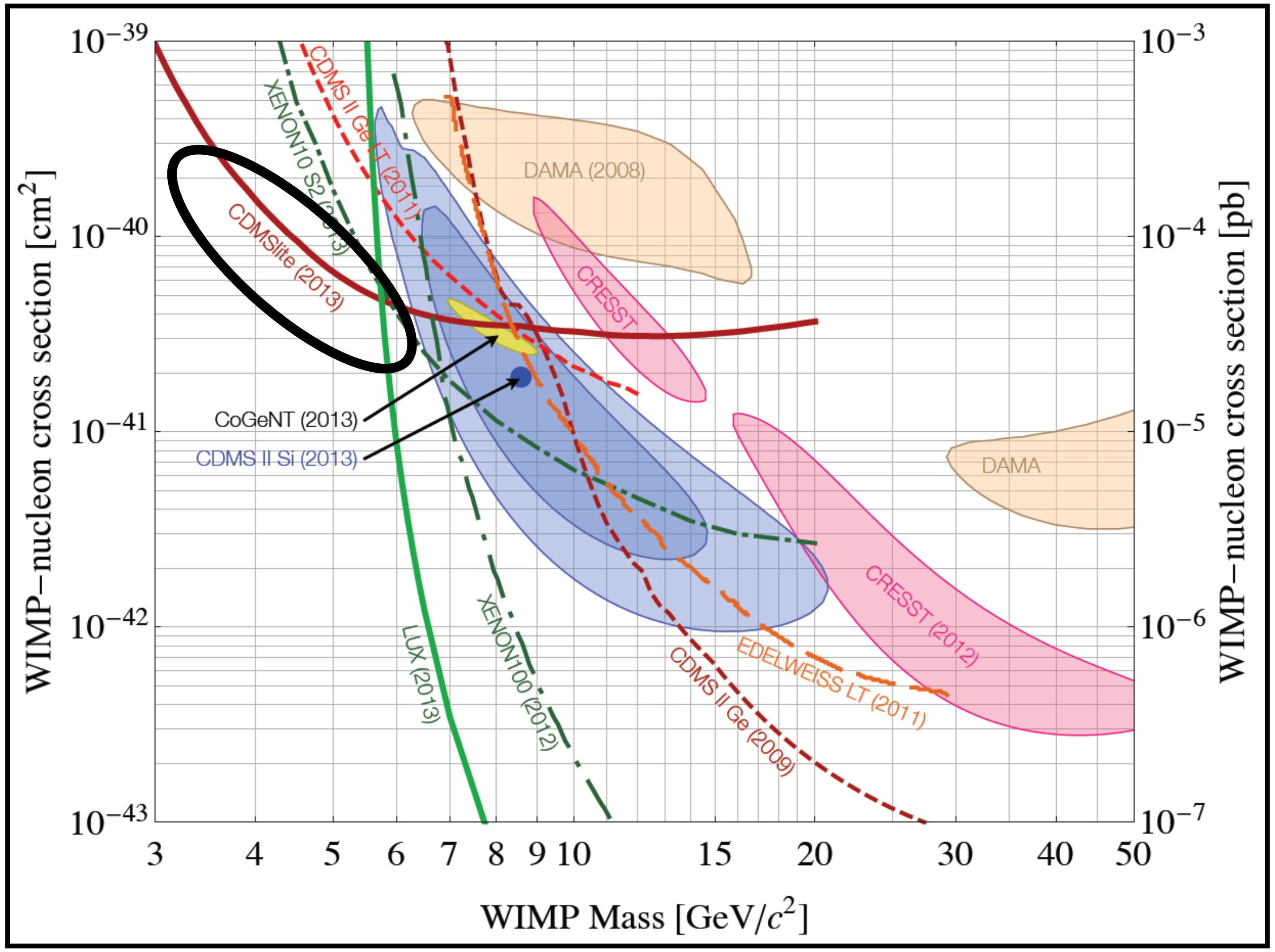
# CDMSlite - Run 1



# CDMSlite: Run 1 Data

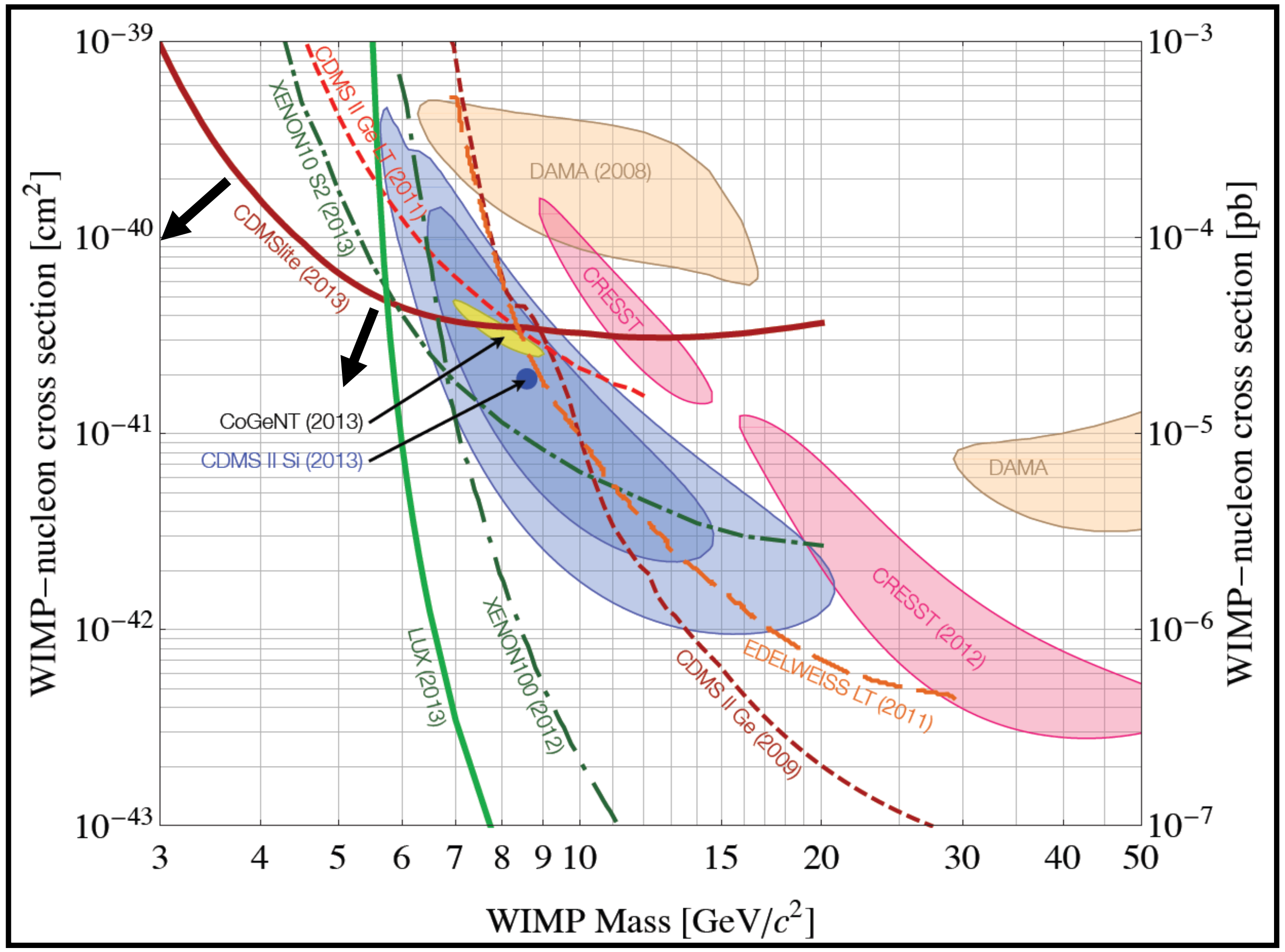
**PRL 112, 041302, 2014**

- Data were taken during three periods in 2012
    - 6.5 kg-days exposure
- One iZIP was used, IT5Z2 – 0.6 kg
    - Selected for its low trigger threshold and low leakage current
    - 160 eV ionization threshold



# CDMSlite: Run 2 Data

- Same iZIP was used, IT5Z2 – 0.6 kg
- 70 kg-days of data taken between Feb - Nov 2014.
  - Two data periods 59.32 kg-days and 10.78 kg-days



- Improvements over Run 1
  - Mitigate transient detector leakage current
  - Improved electronics board reduced variation in bias potential
  - Vibration sensors installed to monitor cryocooler low frequency noise.

- Analysis improvements lead to better energy calibration, low frequency noise rejection and improved fiducial volume.

Reached energy threshold for electron recoils of 56 eV!

# CDMSlite:  Analysis Details

**Singles and Muon Veto:**

Single detector scatter

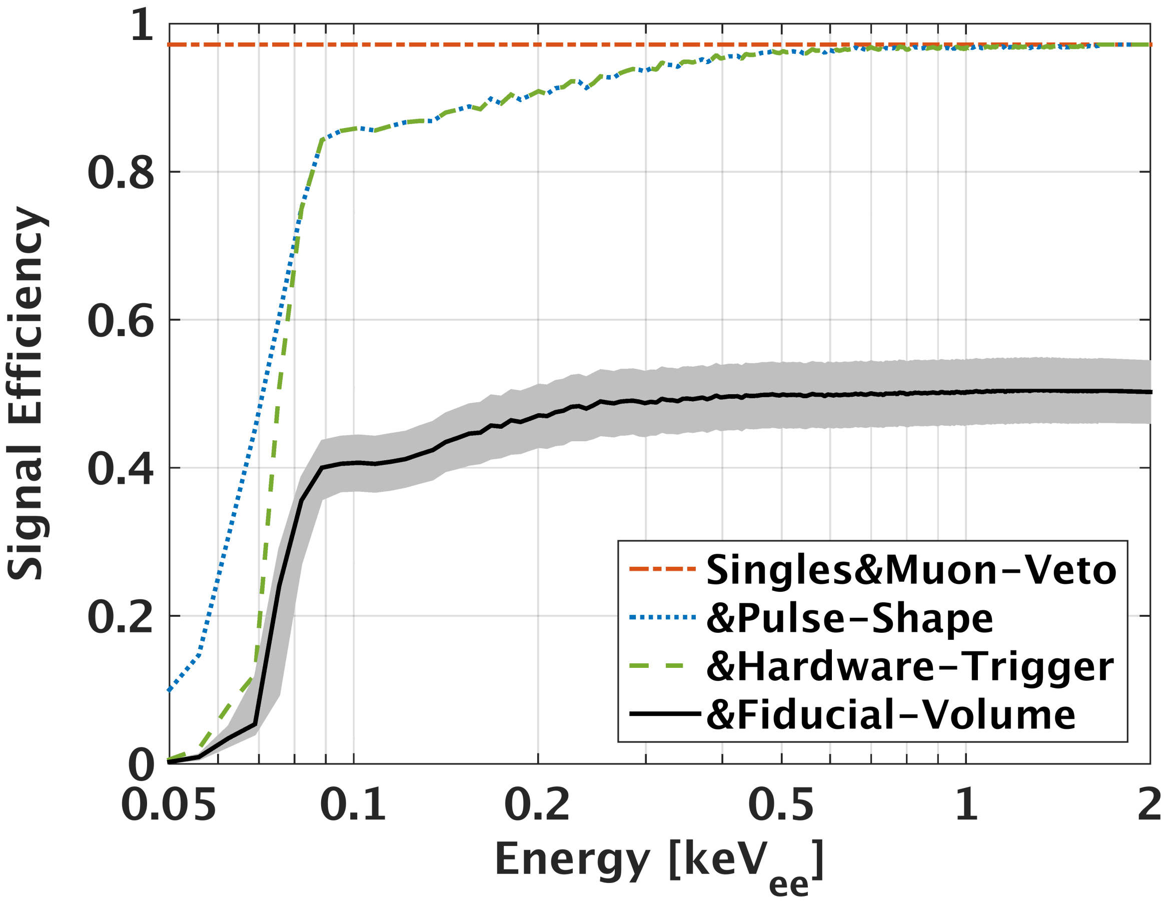
Remove events in coincidence with muon veto

**Pulse shape:**

Reject events with sharp rise- or fall-times, poor reconstruction, and events compatible with LF noise.

**Fiducial Volume:**

Reject events near detector surfaces.

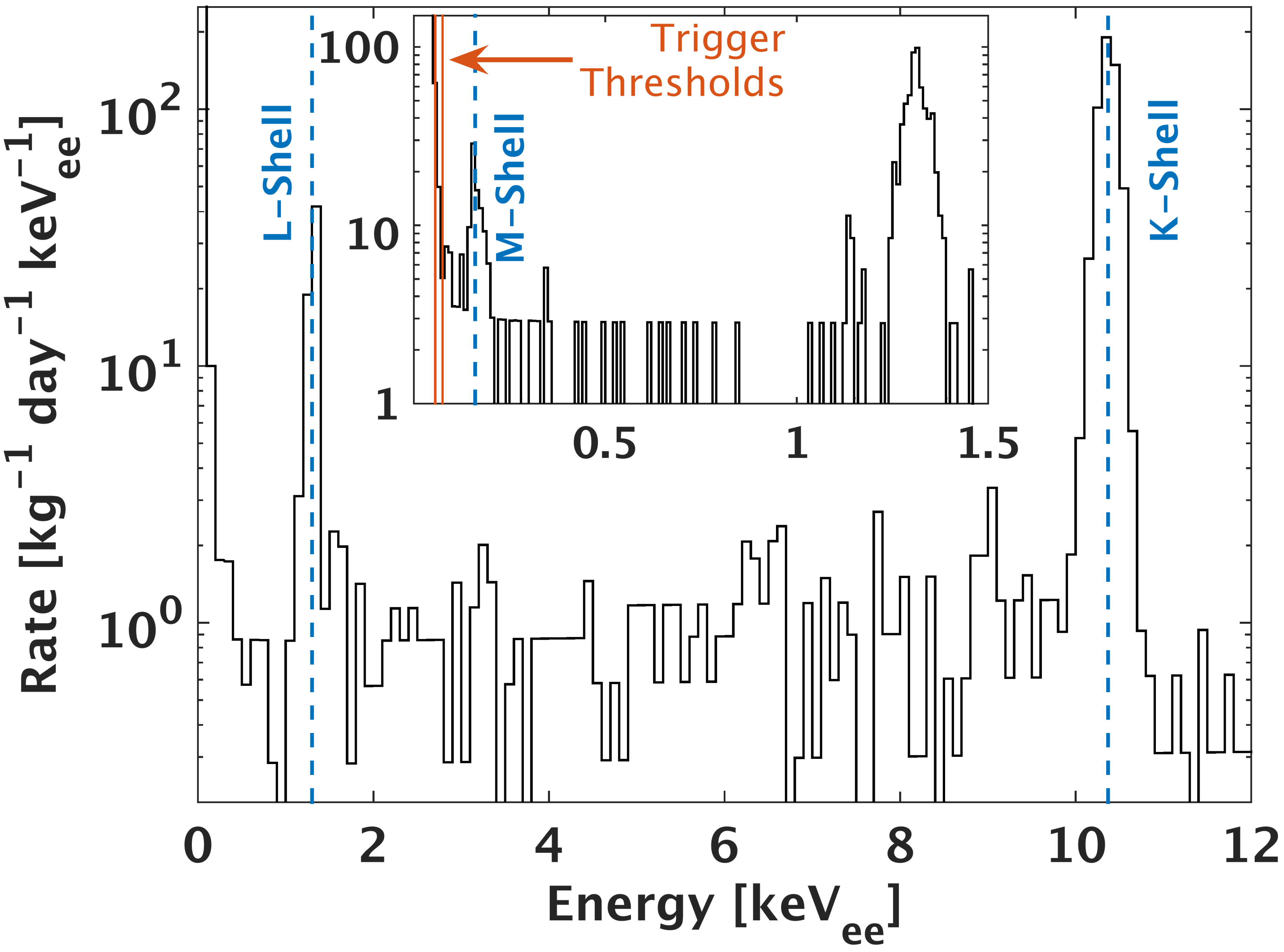


**Efficiencies:**

Calculated using calibration data and simulation

# CDMSlite: Run 2 Results

arXiv: 1509.02448



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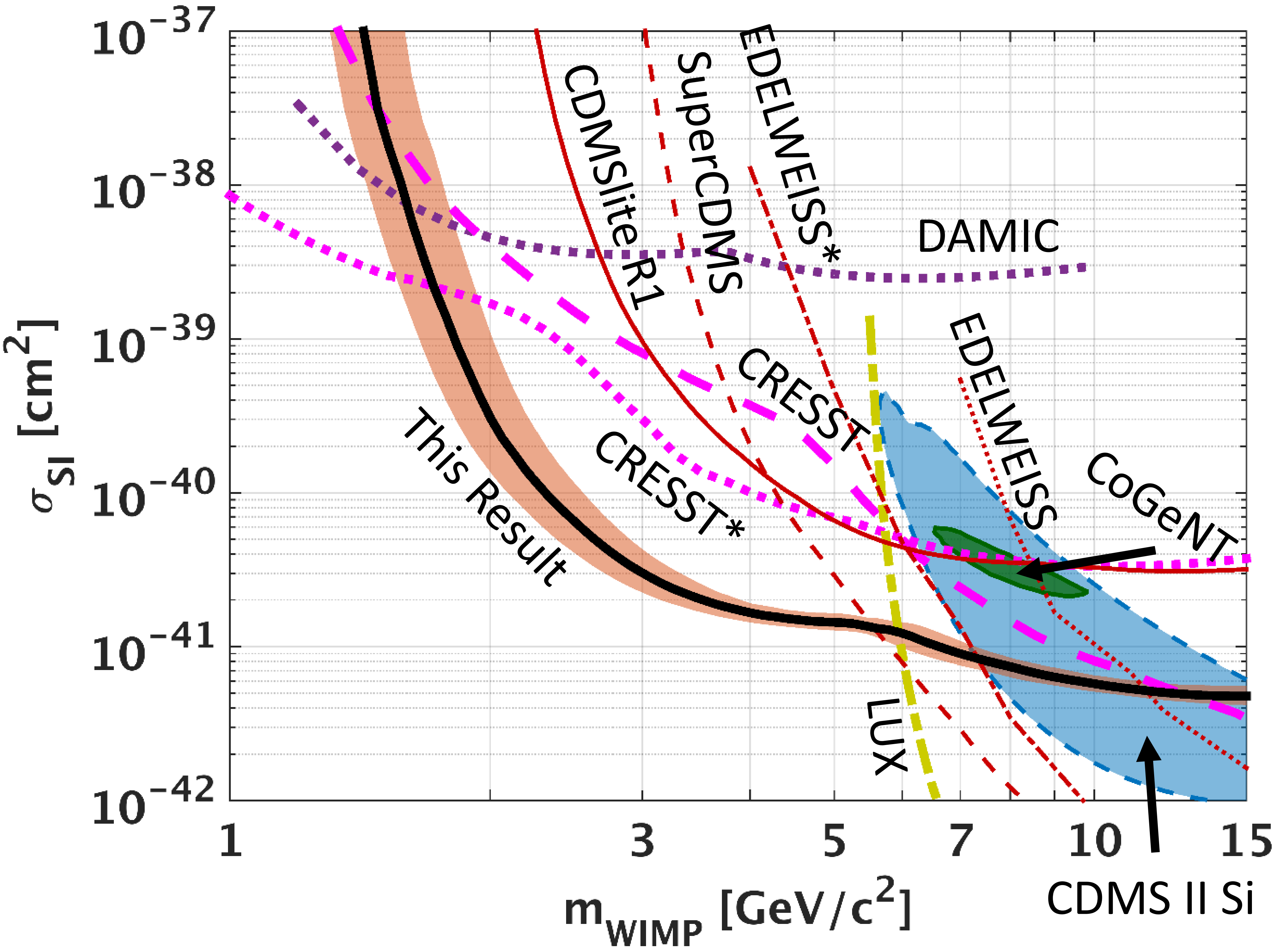
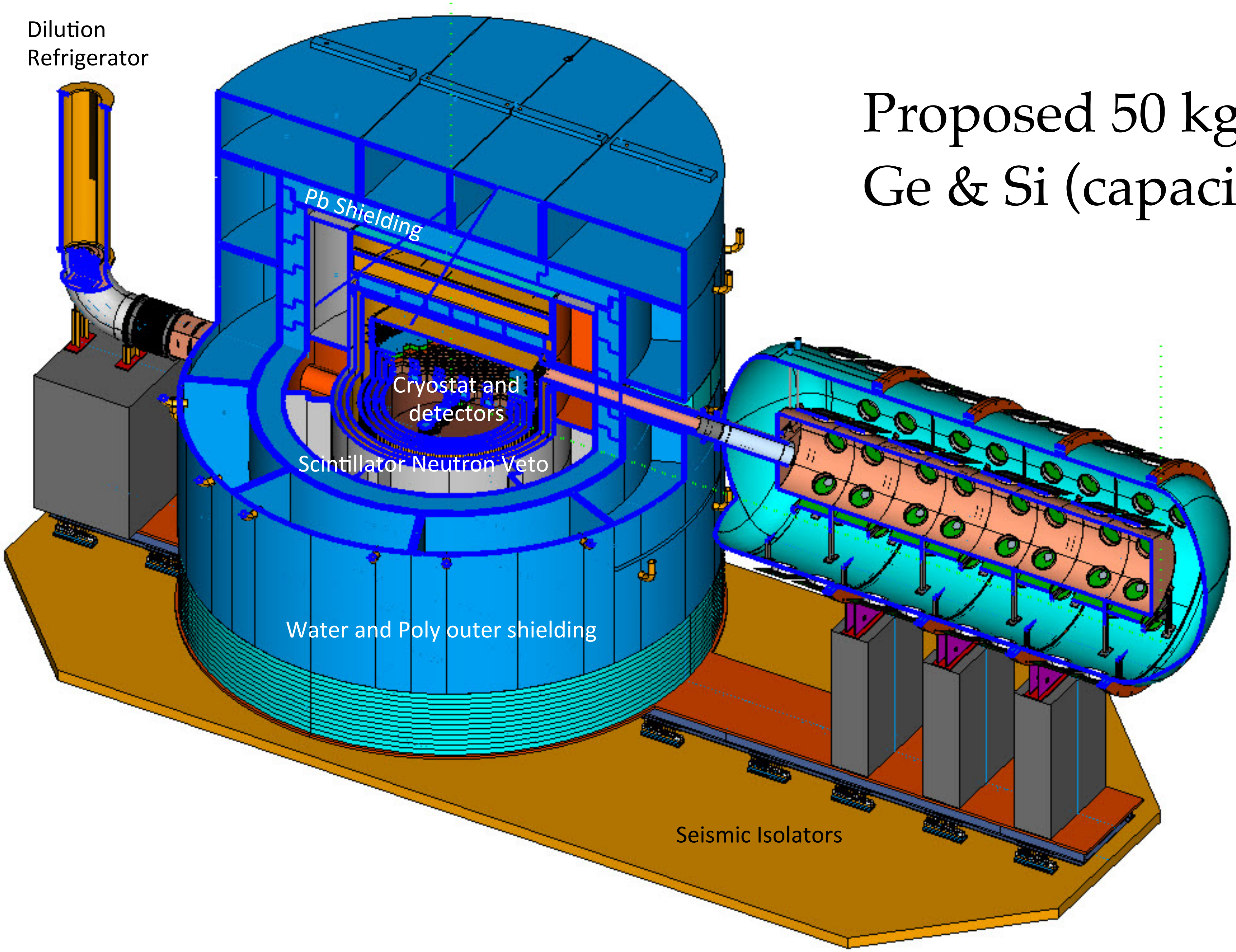


arXiv: 1509.02448

# SuperCDMS @ SNOLAB

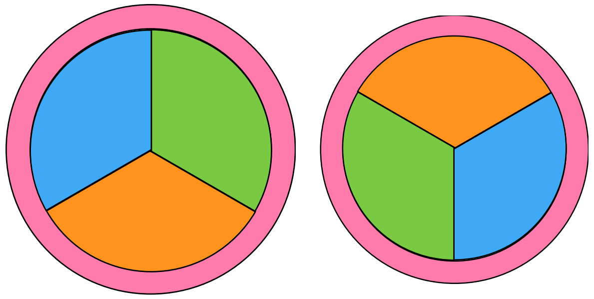


Proposed 50 kg payload of Ge & Si (capacity 400 kg Ge)

# From Soudan to SNOLAB

**SuperCDMS Soudan**

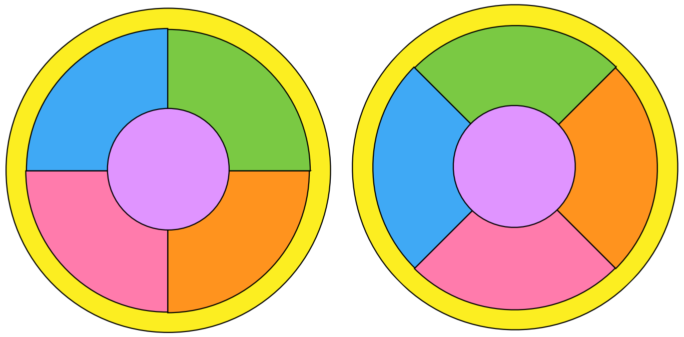
3” Diameter
2.5 cm Thick
600 g Ge crystals



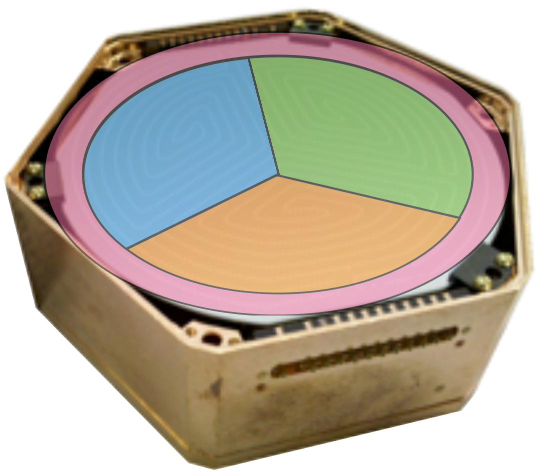
2 charge + 2 charge
4 phonon + 4 phonon

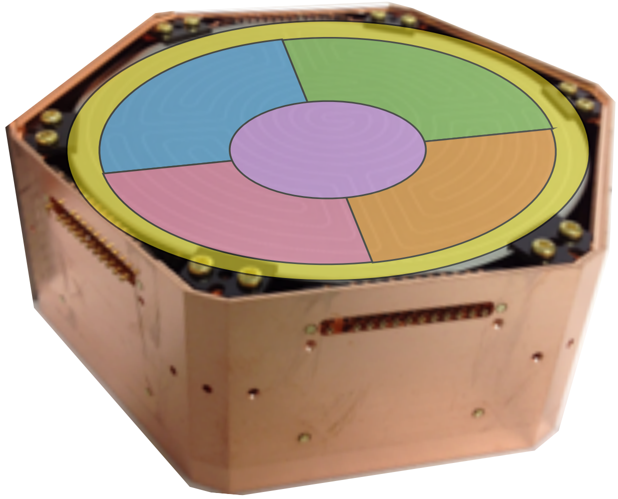
**SuperCDMS SNOLAB**

4” Diameter
3.3 cm Thick
1.4 kg Ge crystals / 615 g Si crystals



2 charge + 2 charge
6 phonon + 6 phonon

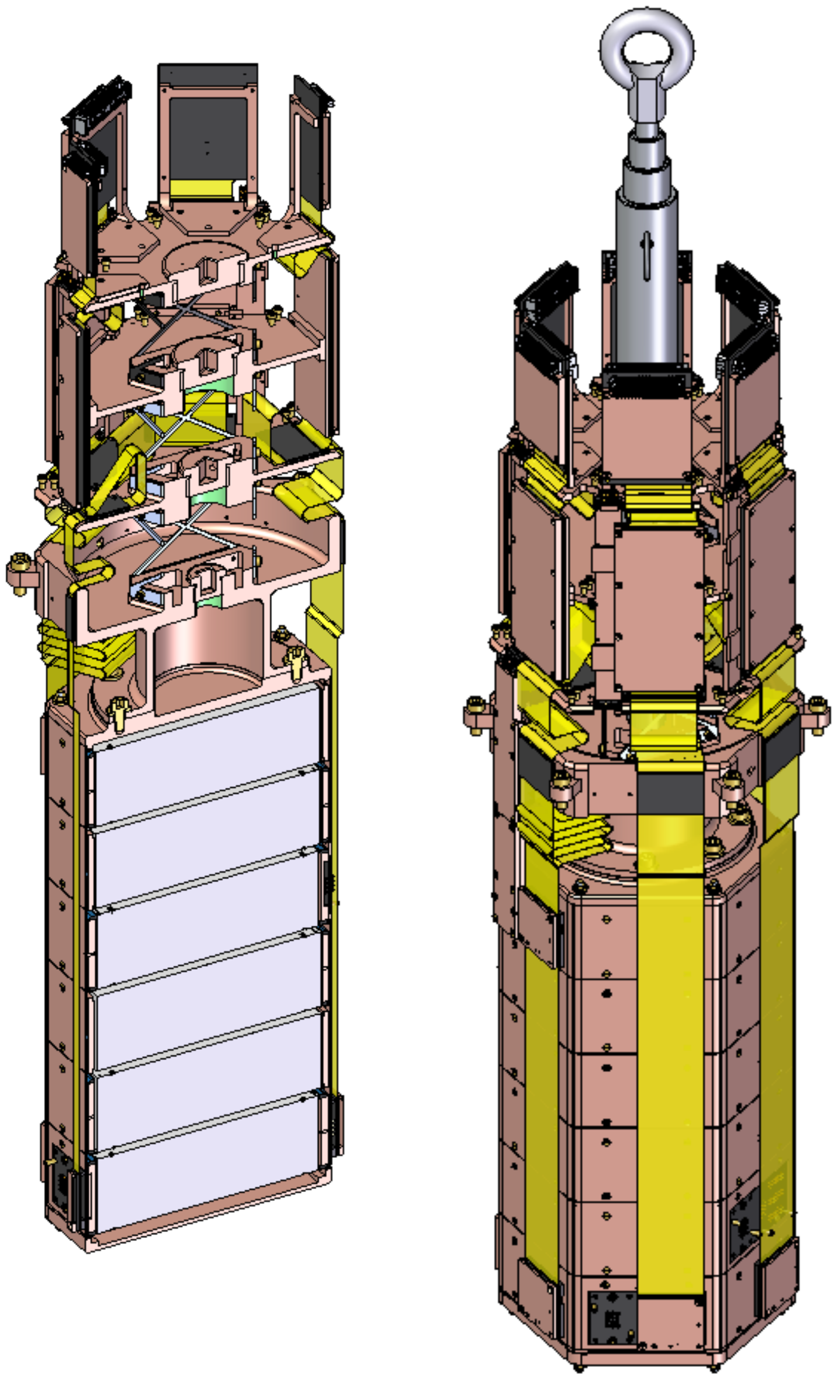


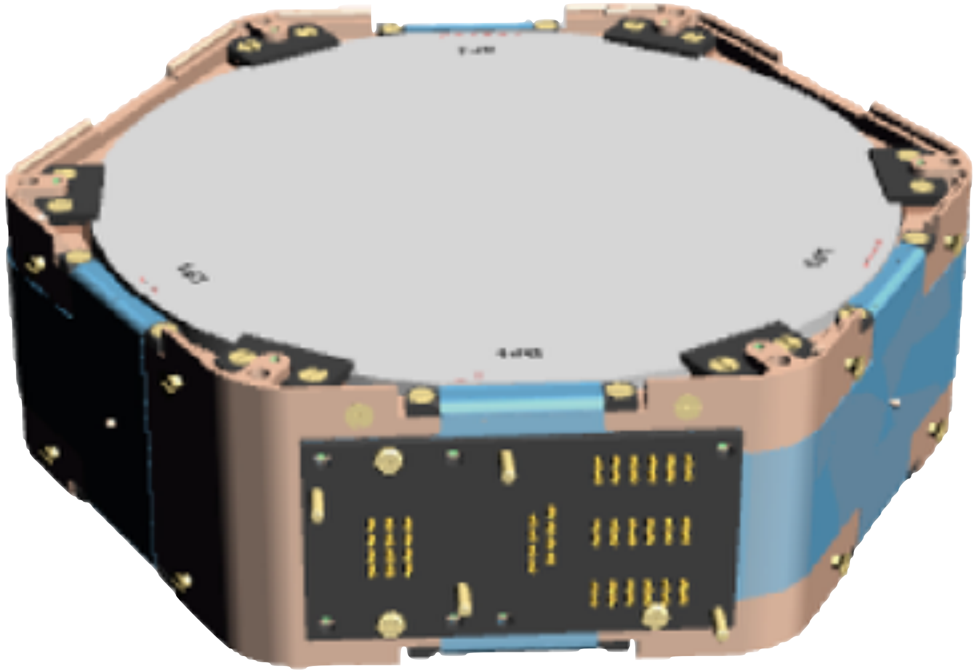


# SuperCDMS SNOLAB Towers

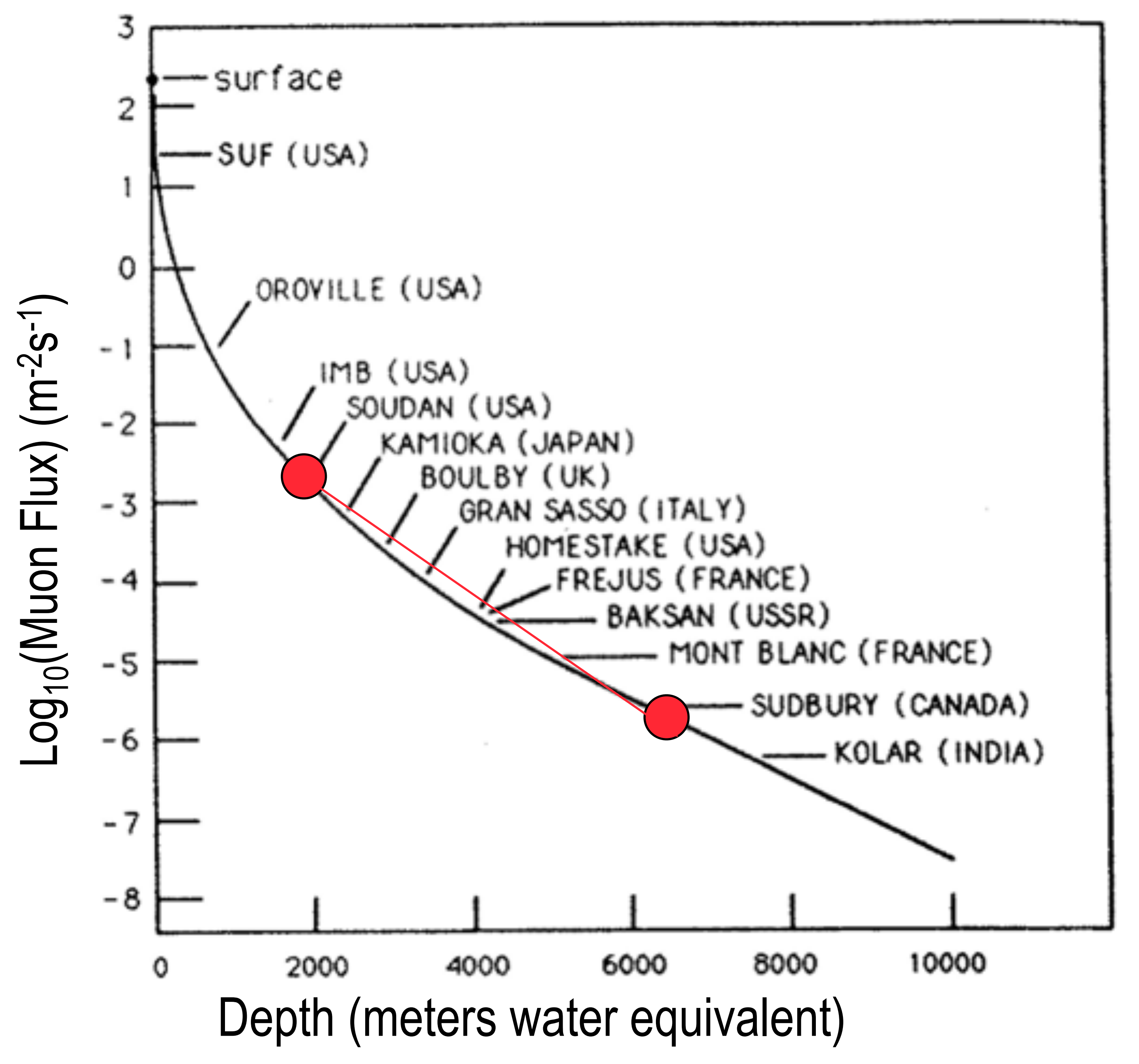
## Improved Surface Event Rejection:

- 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





# Why SNOLAB?
# Depth is Important



*Soudan*

*2090 mwe*

*0.05 n/y/kg*

*SNOLAB*

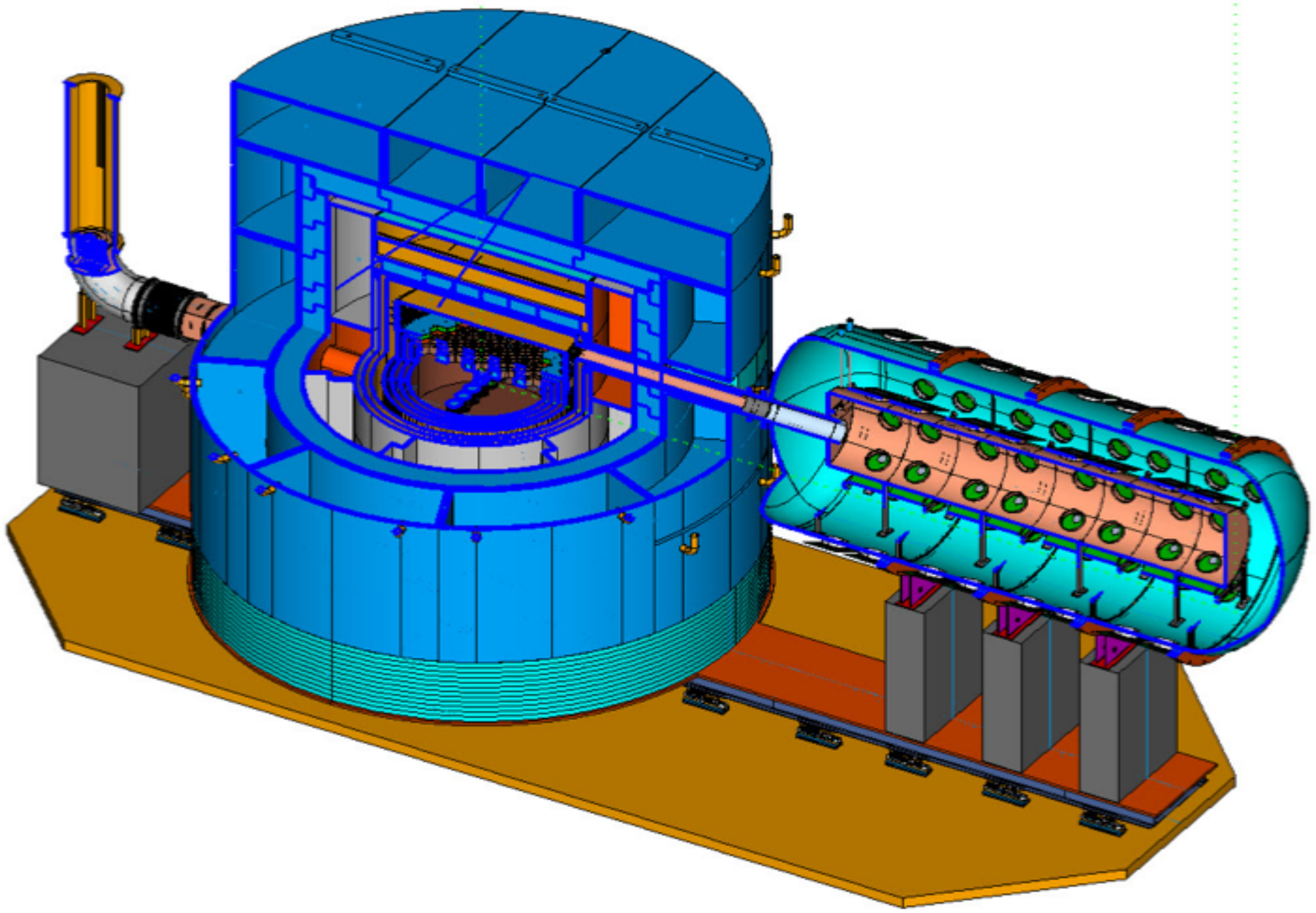
*6060 mwe*

*0.2 n/y/ton*

*(0.0002 n/y/kg)*

We only need to worry about radiogenic neutrons!

# Compton Background



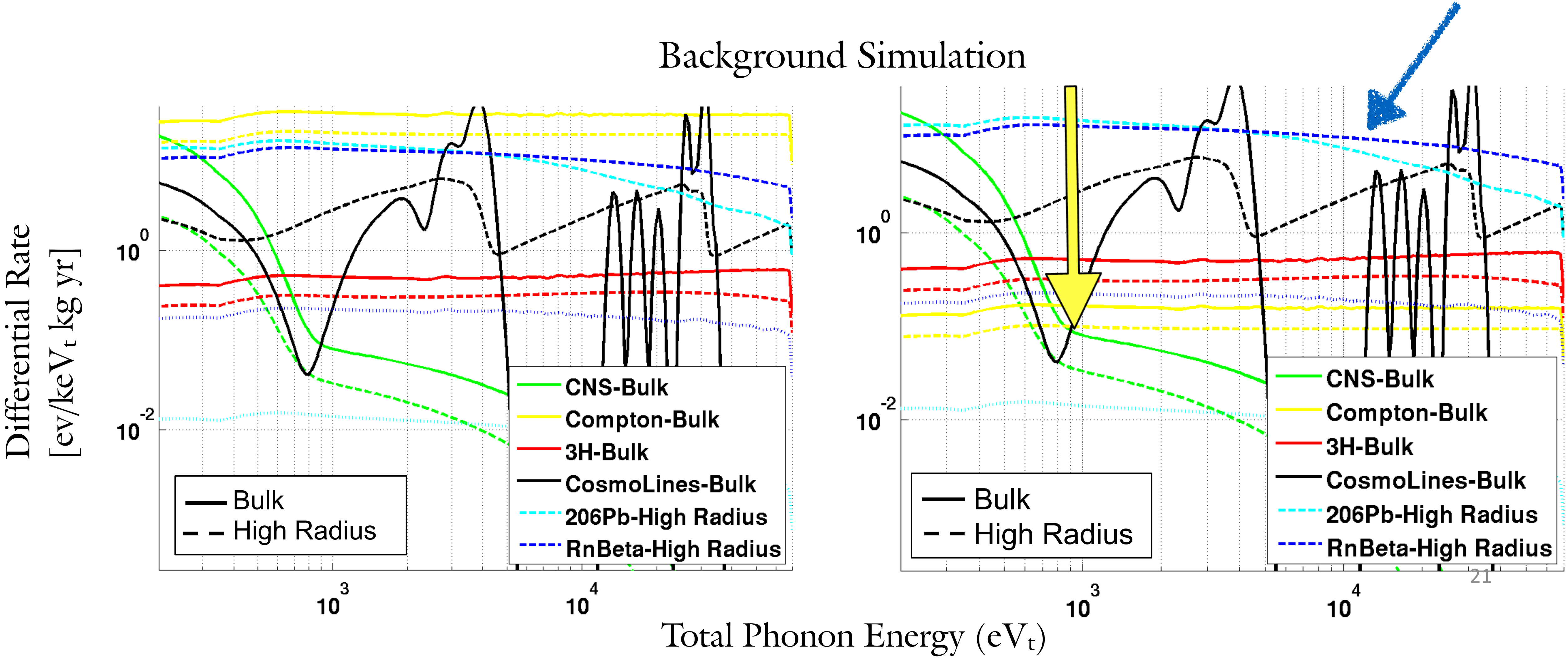
- Photon Rate at Soudan: 1100 ev/keV$_r$ kg yr
- Not an issue for the Soudan experiments because we had NR/ER discrimination at high energies.

- Dominant source of these photons is the cryostat.
- Target for SNOLAB cryostat: 5 ev/keV$_r$ kg yr (~220x < Soudan)

# Compton Background: Cleaner Cryostat

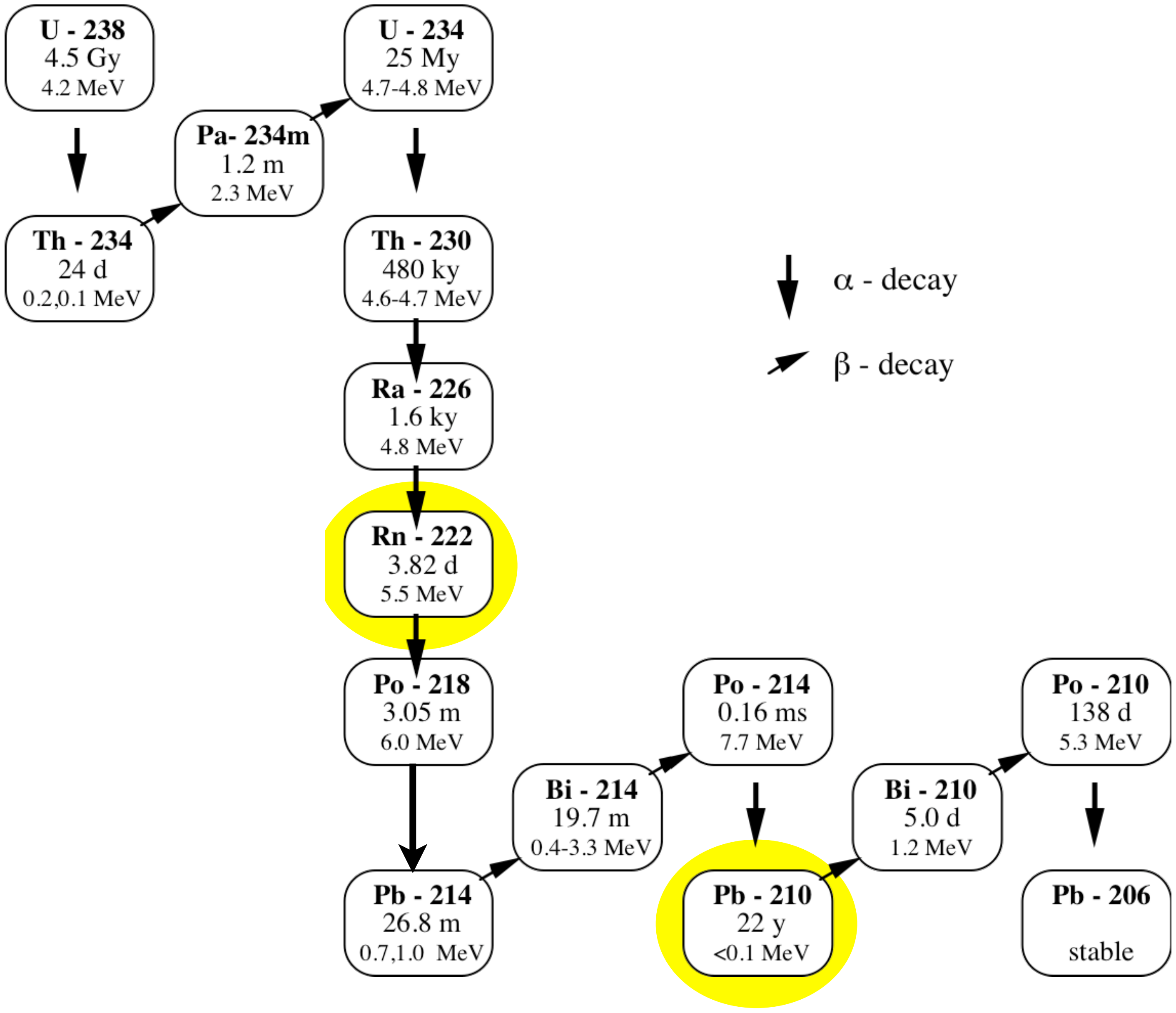
| Material | $^{238}$U | $^{232}$Th | $^{40}$K | Reference |
|---|---|---|---|---|
| Polyethylene | 0.03 mBq/kg | 0.02 mBq/kg | 0.1 mBq/kg | DEAP [121] |
| Copper | 0.07 mBq/kg | 0.02 mBq/kg | 0.04 mBq/kg | XENON100 [122] |
| Lead | 0.66 mBq/kg | 0.5 mBq/kg | 7.0 mBq/kg | XENON100 [122] |

Dominant background now results from Rn.


Background Simulation

# Radon Contamination

- Airborne radon is everywhere. It can absorb onto detectors during fabrication and testing
- Quickly decays to 210Pb (22.5 year half-life)
- $^{210}$Pb emits two βs and an α while decaying to $^{206}$Pb
- Detector (or detector housing) contamination by $^{222}$Rn can be determined by measuring alpha or beta particles given off during these decays.



**U - 238**
4.5 Gy
4.2 MeV

**Th - 234**
24 d
0.2,0.1 MeV

**Pa- 234m**
1.2 m
2.3 MeV

**U - 234**
25 My
4.7-4.8 MeV

**Th - 230**
480 ky
4.6-4.7 MeV

**Ra - 226**
1.6 ky
4.8 MeV

**Rn - 222**
3.82 d
5.5 MeV

**Po - 218**
3.05 m
6.0 MeV

**Pb - 214**
26.8 m
0.7,1.0 MeV

**Bi - 214**
19.7 m
0.4-3.3 MeV

**Po - 214**
0.16 ms
7.7 MeV

**Pb - 210**
22 y
<0.1 MeV

**Bi - 210**
5.0 d
1.2 MeV

**Po - 210**
138 d
5.3 MeV

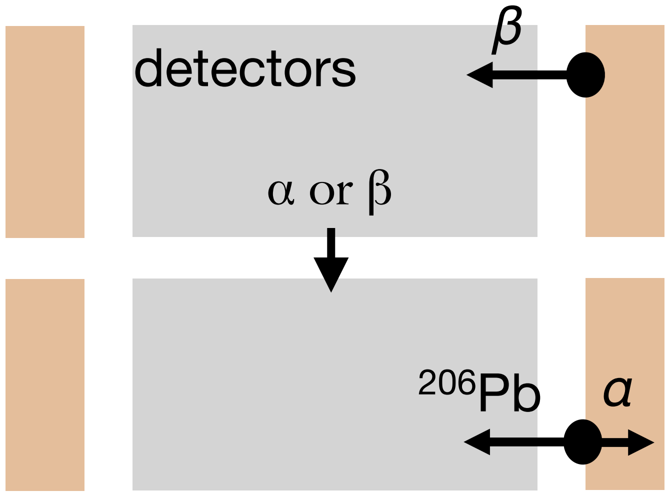
**Pb - 206**
stable

α - decay

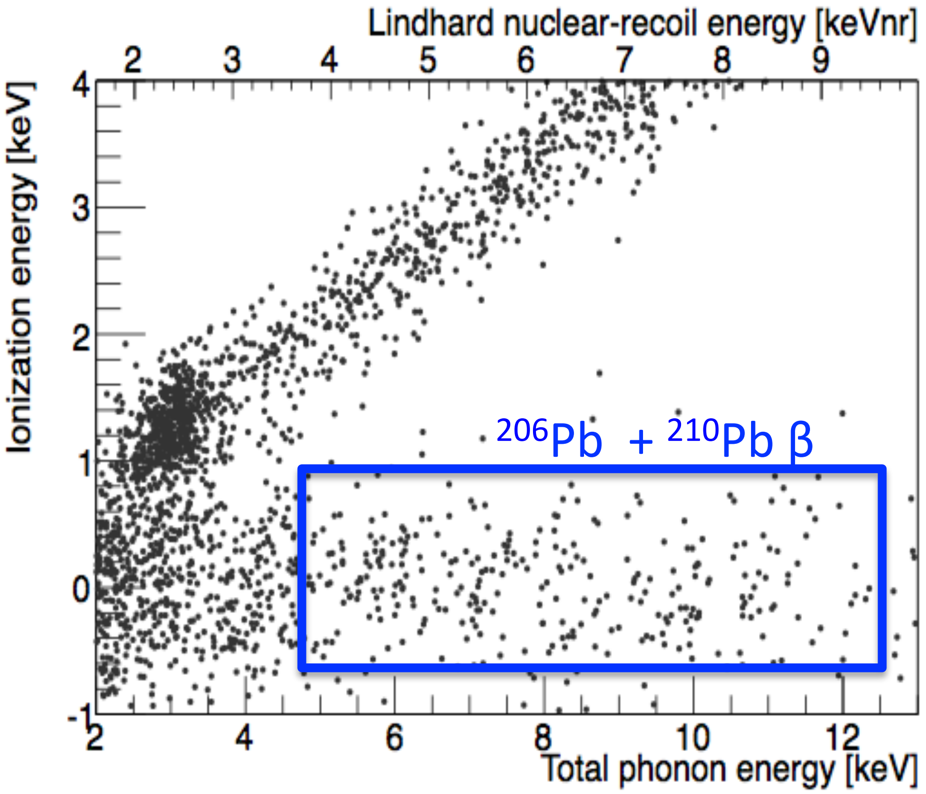
β - decay

# Radon Contamination

- Surface contamination from Cu housing dominated in the SuperCDMS Soudan experiment.
- For SNOLAB we will require the same surface event rate for copper housing as the detectors.



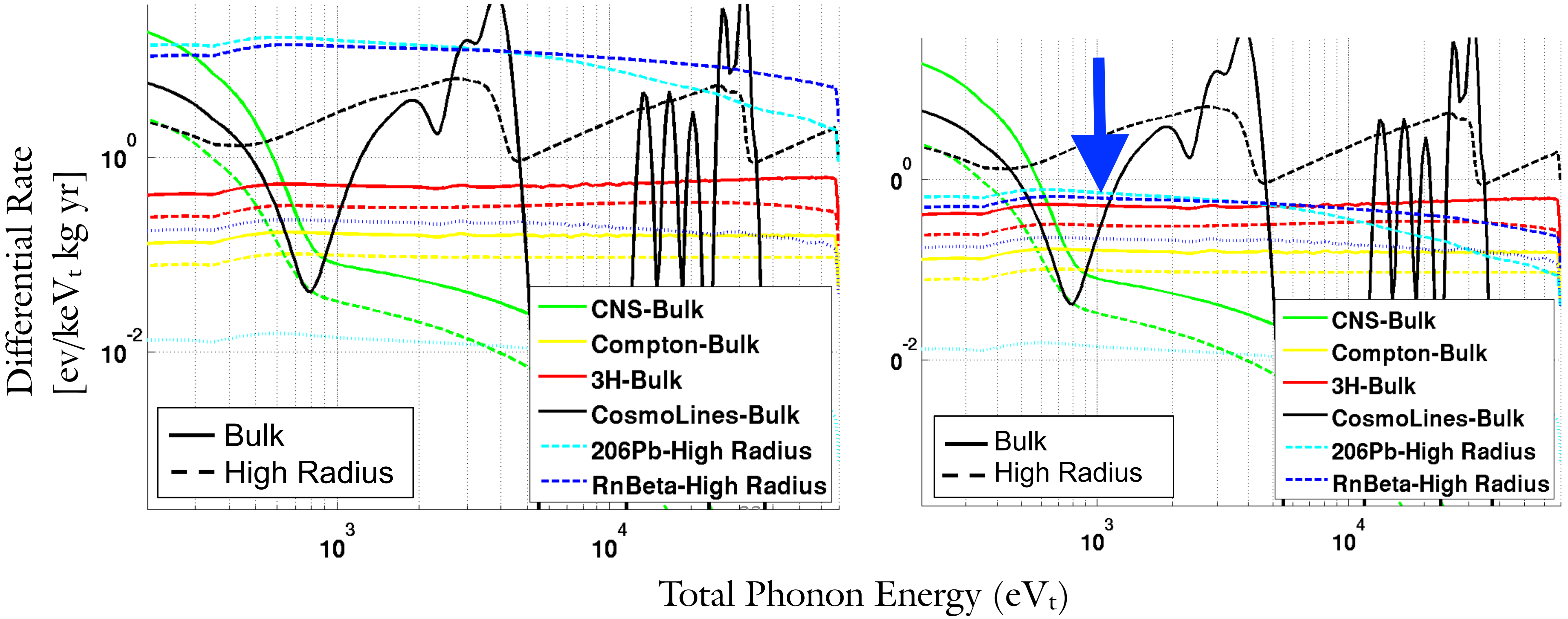
| Soudan 210Pb Surface Contamination | α Rate uBq/m$^2$ | $^{206}$Pb Singles Rate (evt/kgyr) |
|---|---|---|
| Ge/Si | 260 | 7 |
| Cu Housing | 5600 | 900 |



# Radon Background: Radon Mitigation

Radon exposure can be mitigated by
- surface cleaning procedures
- radon reduced environments for material/detector storage
- monitoring and tracking of materials and components

Background Simulation



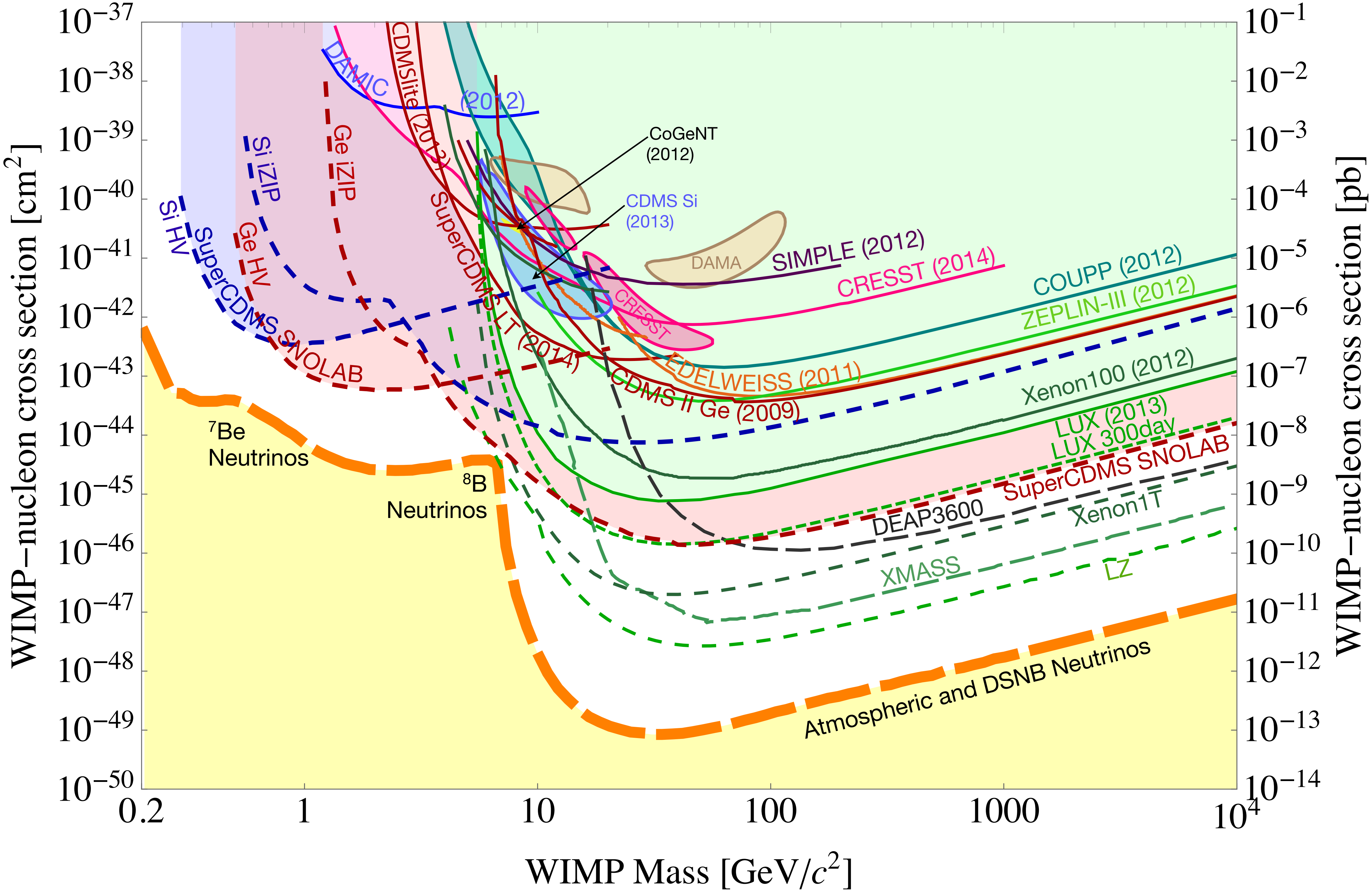
# Cosmogenic Backgrounds

Backgrounds resulting from activation of materials exposed to cosmic rays are currently being assessed.

| Material | Cosmogenic Isotope |
|---|---|
| Cu | $^{22}$Na, $^{49}$V, $^{54}$Mn, $^{55}$Fe, $^{57,58,60}$Co, $^{63}$Ni, $^{65}$Zn |
| Ge | $^{3}$H, $^{7}$Be, $^{22}$Na, $^{49}$V, $^{51}$Cr, $^{54}$Mn, $^{55}$Fe, $^{57,58,60}$Co, $^{56}$Ni, $^{68}$Ga, $^{68}$Ge, $^{73,74}$As |
| Si | $^{3}$H, $^{7}$Be, $^{22}$Na, $^{32}$Si |

- Transportation of Ge from US vendors will be done via ground.
- Need to complete a study of trade-offs between air transport vs ship for European vendors.
- Appropriate packaging will be used for both crystal boules and crystal that have been cut, shaped and polished.
- Underground storage when possible.

# Expected Sensitivities



# Conclusions

- CDMSlite Run 2 has produced world leading limits in the search for low mass WIMPs. It excludes parameter space for WIMPs with masses between 1.6 and 5.5 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 50 kg SuperCDMS SNOLAB experiment are well underway. If funded, the SuperCDMS SNOLAB experiment will have unprecedented sensitivity to low mass WIMPs.