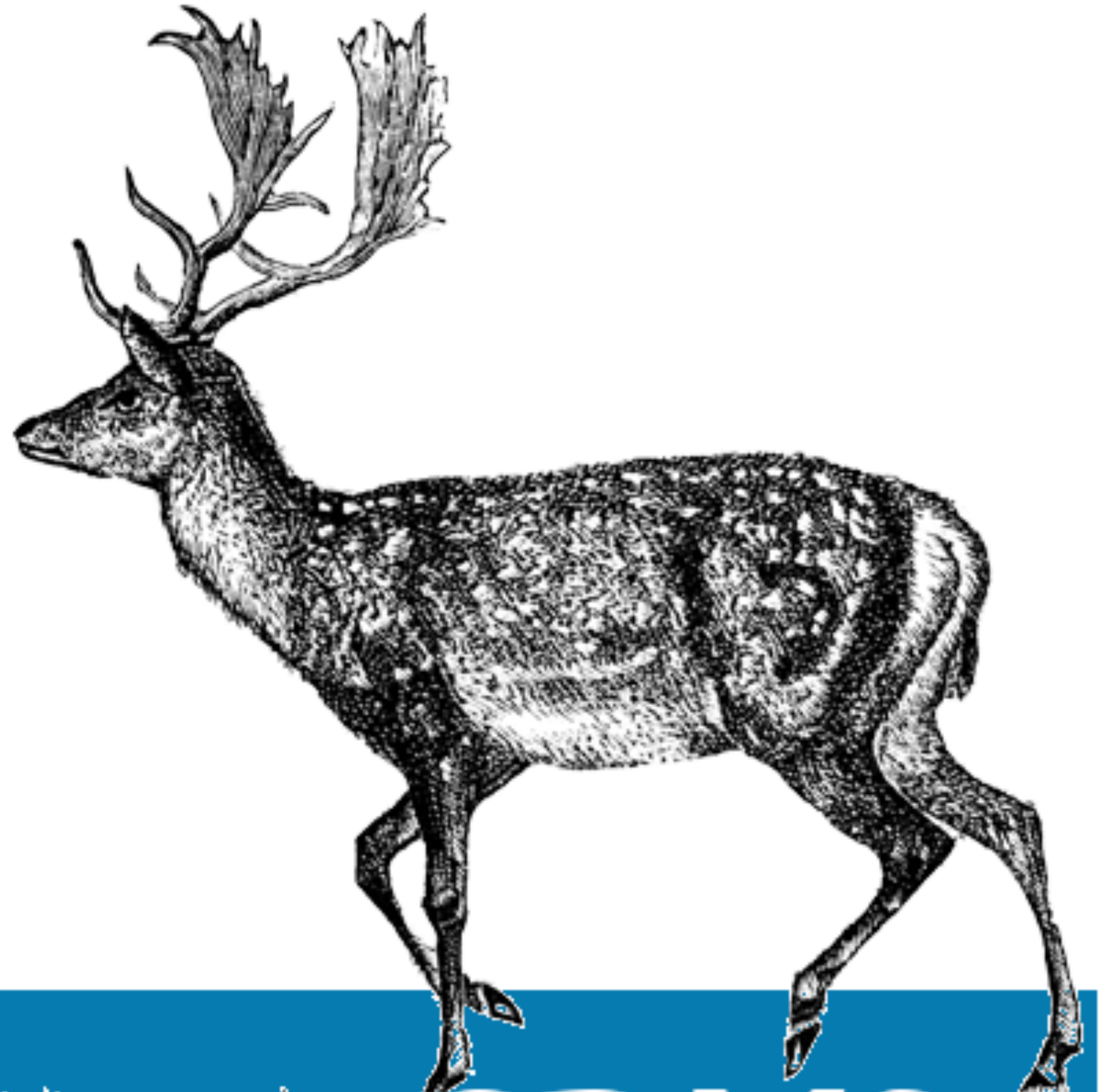
When they go high, we go low.



SuperCDMS in a Nutshell

The Definitive Guide

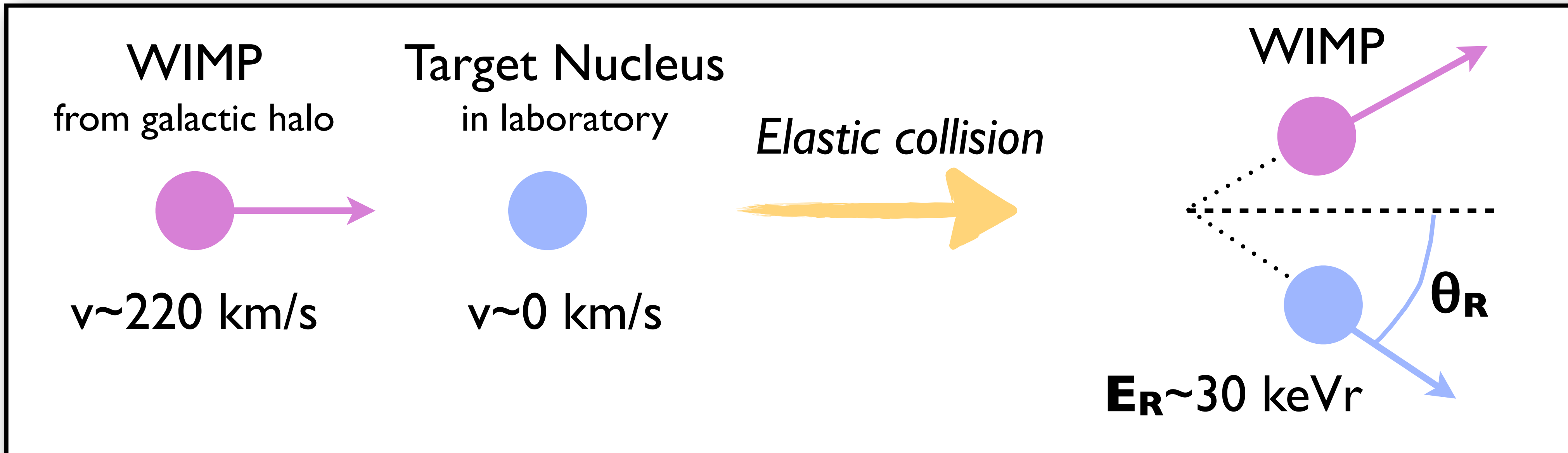
O RLY?

Jodi Cooley

Jodi Cooley
SMU / SuperCDMS

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"

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)

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

"reduced mass"

$$T(E_R) \simeq \exp(-v_{\rm min}^2/v_o^2)$$

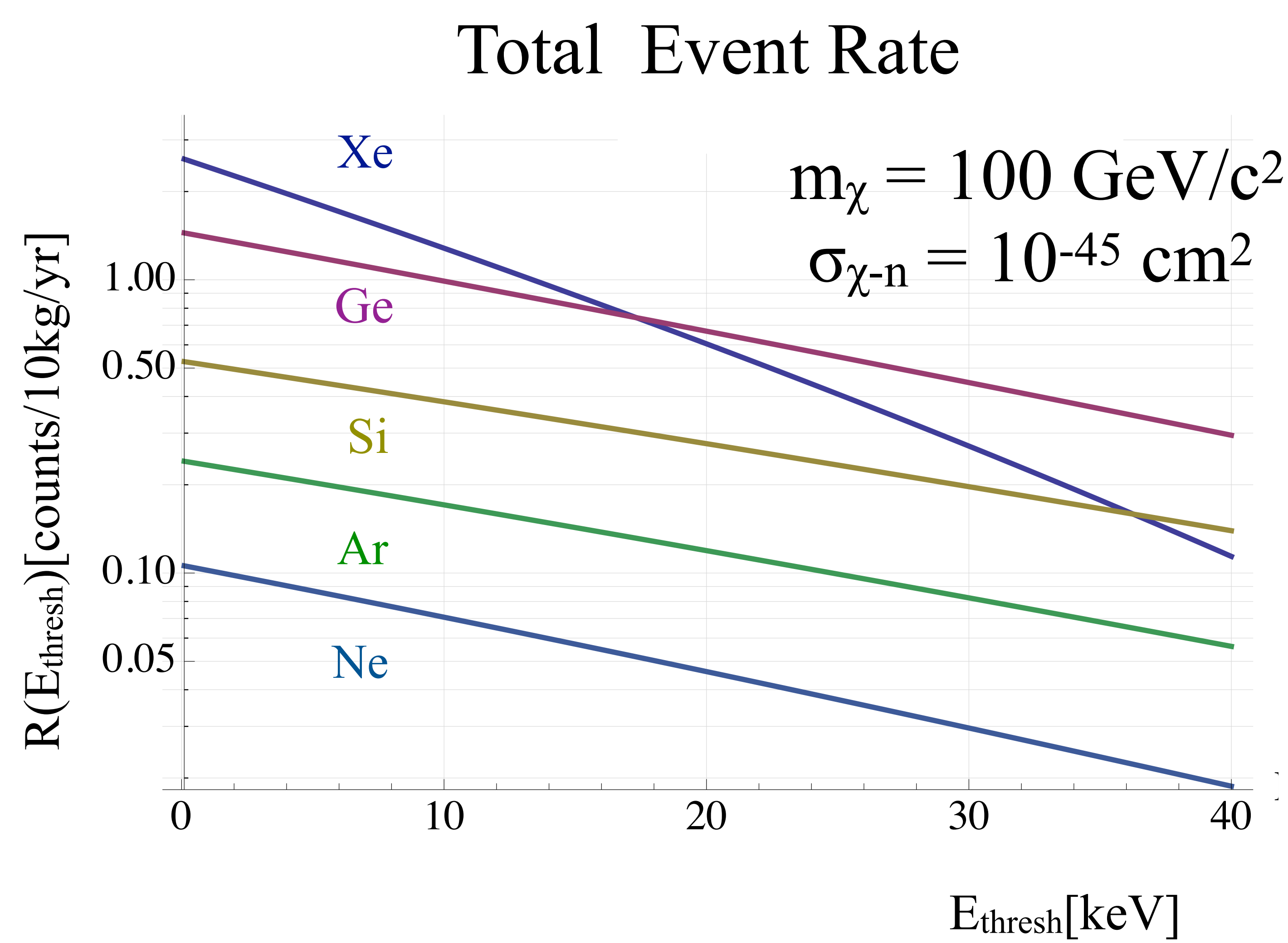
integral over local WIMP velocity distribution

$$v_{\rm min} = \sqrt{E_R\, m_N/(2m_r^2)}$$

minimum WIMP velocity for given E_R

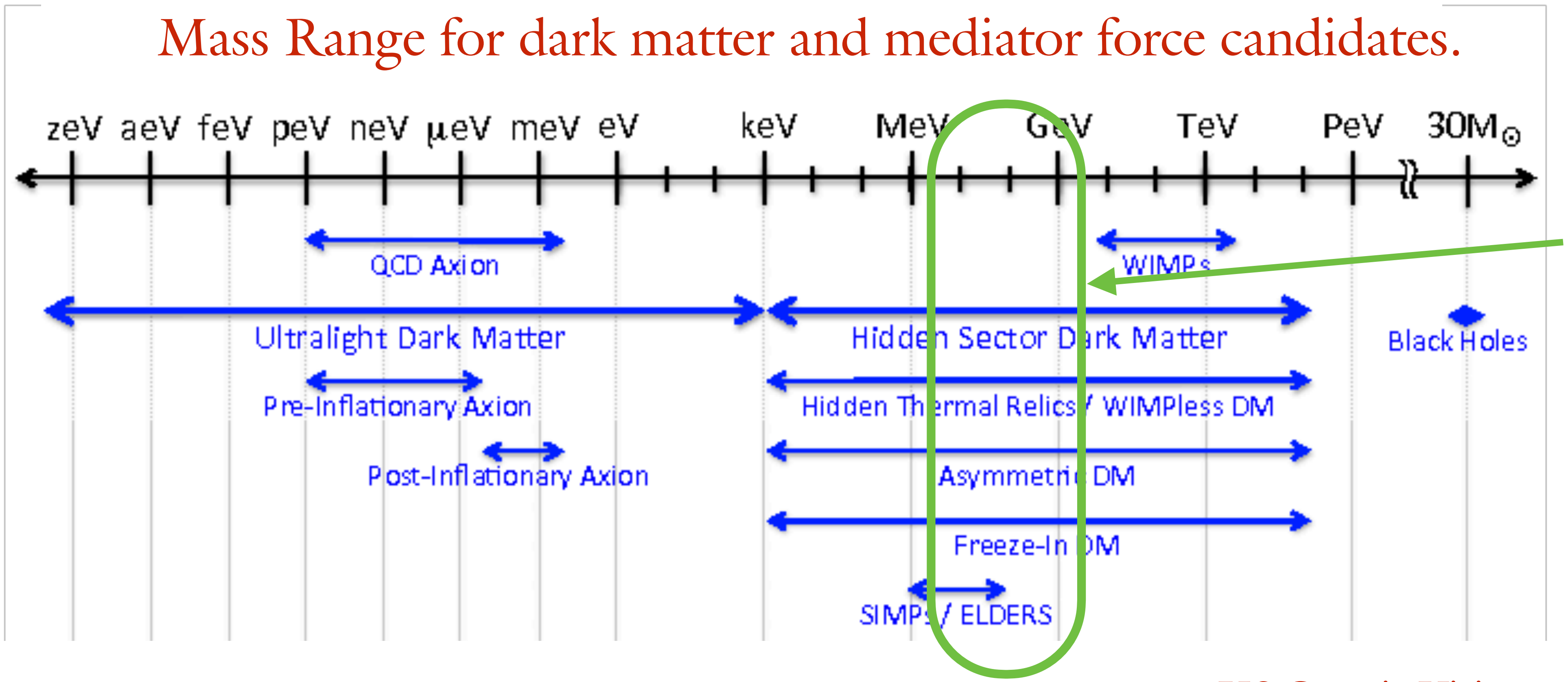
Direct Detection Event Rates

- 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.

The Case for Low Mass Dark Matter

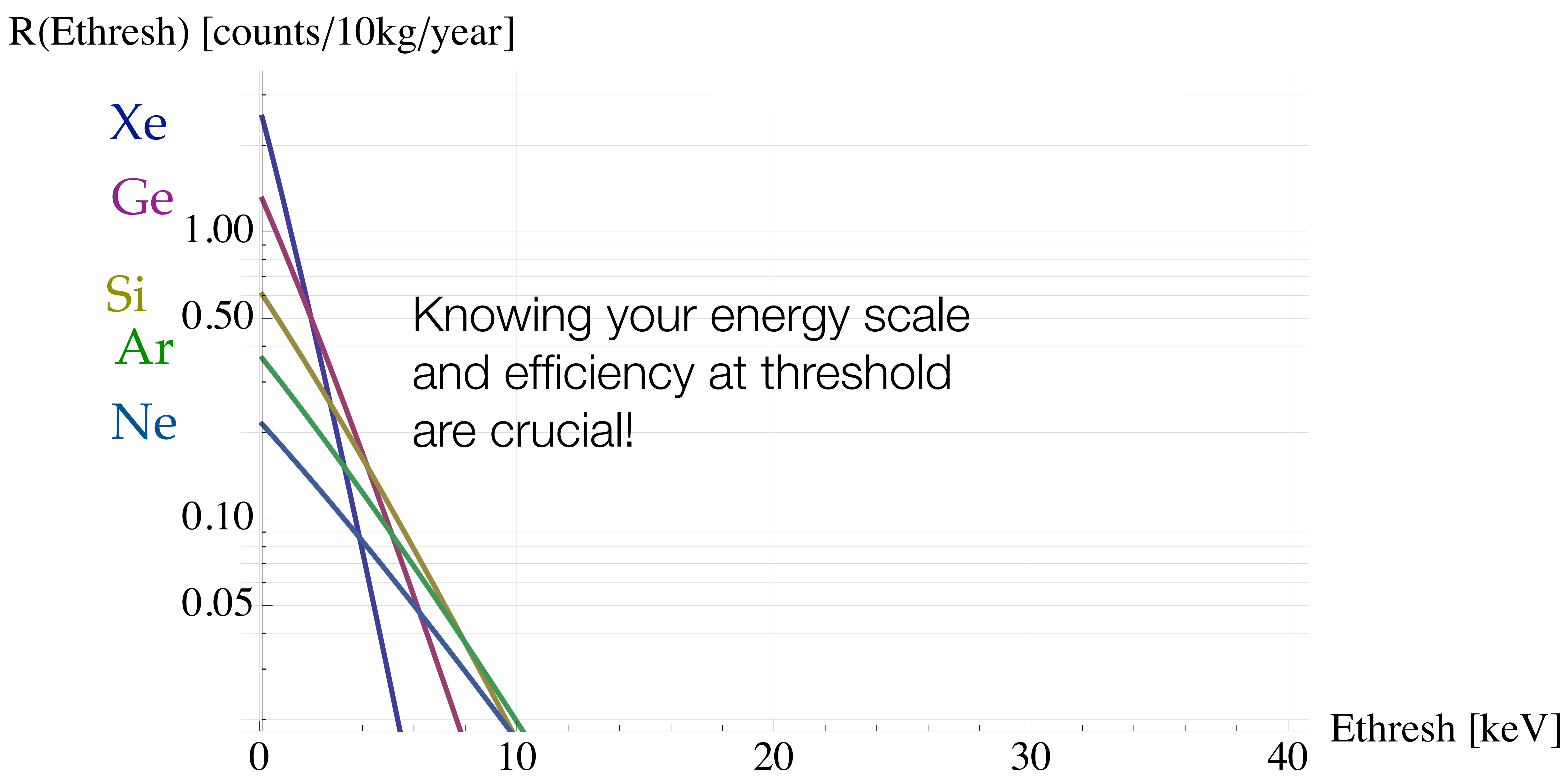


US Cosmic Visions: arXiv:1707.04591

- Much work has gone into looking for the canonical WIMP
    - No evidence from direct searches and no evidence of SUSY from LHC
- If we broaden our thoughts and loosen our cosmology or theory priors, we still have reasonable dark matter candidates — many with lower masses!

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 control
  - Clean materials
  - shielding
  - discrimination power
- Substantial depth
  - neutrons look like WIMPs!
- Long exposures
  - Large masses, long term stability

The CDMS II Collaboration- Circa 2002

Recognize Anyone?

The SuperCDMS Collaboration

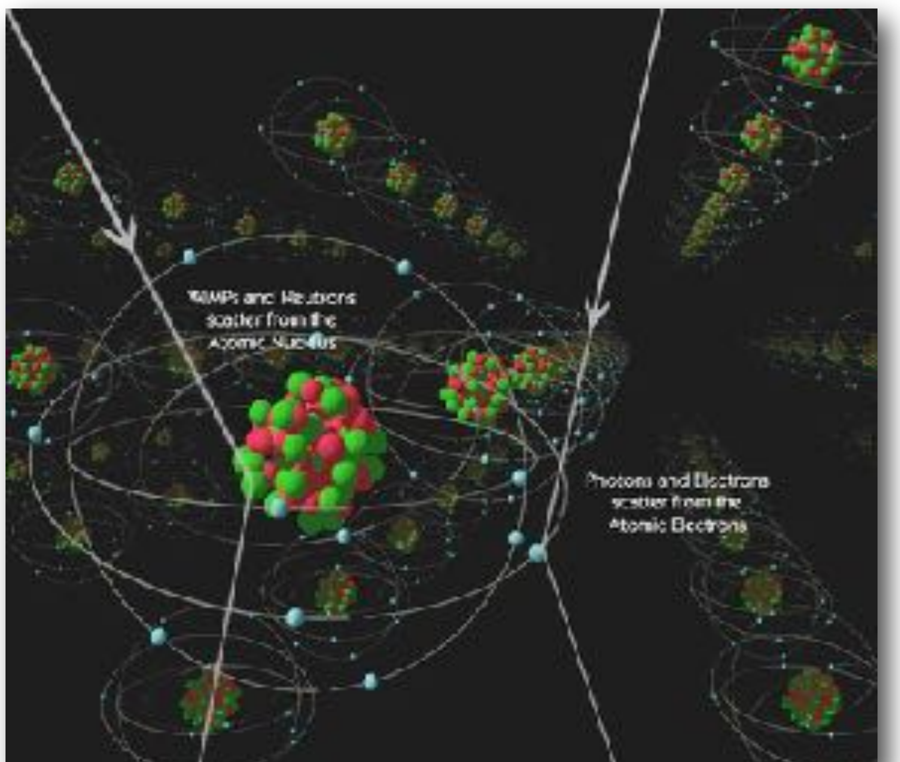
California Inst. of Tech.
CNRS-LPN*
Durham University
FNAL
NISER
NIST*
Northwestern
PNNL
Queen's University
Santa Clara University
SLAC
+ South Dakota SM&T
SMU
SNOLAB
Stanford University
Texas A&M University
TRIUMF
U. British Columbia
U. California, Berkeley
U. Colorado Denver
U. Evansville
U. Florida
U. Montréal
U. Minnesota
U. South Dakota
U. Toronto

* Associate members

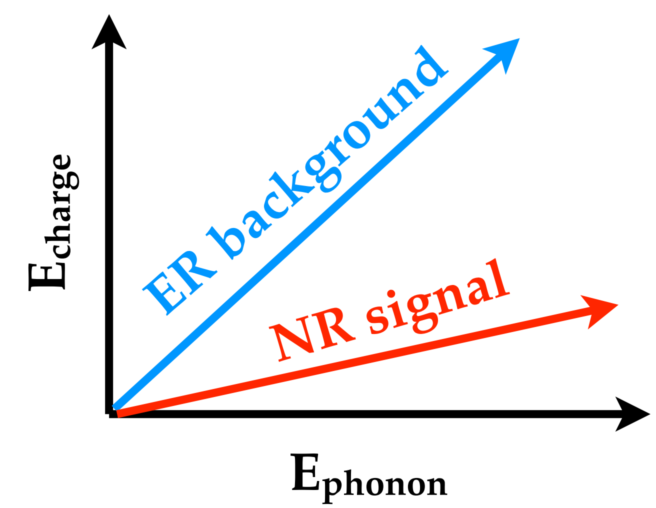
+The SMU SuperCDMS group is supported by the NSF under grant number 1151869.

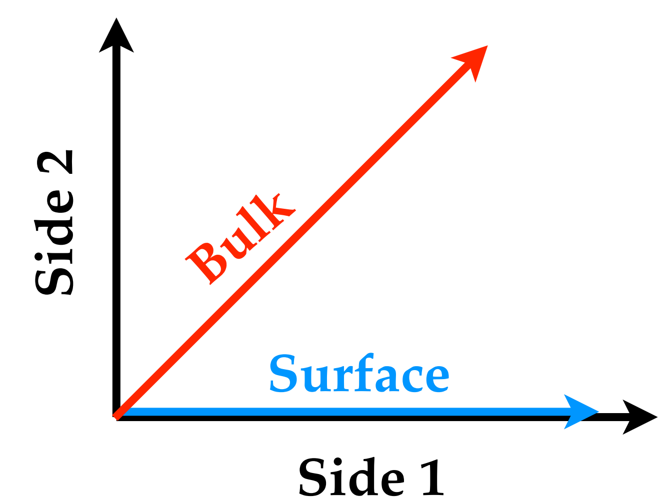
Historically: SuperCDMS in a Nutshell*

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



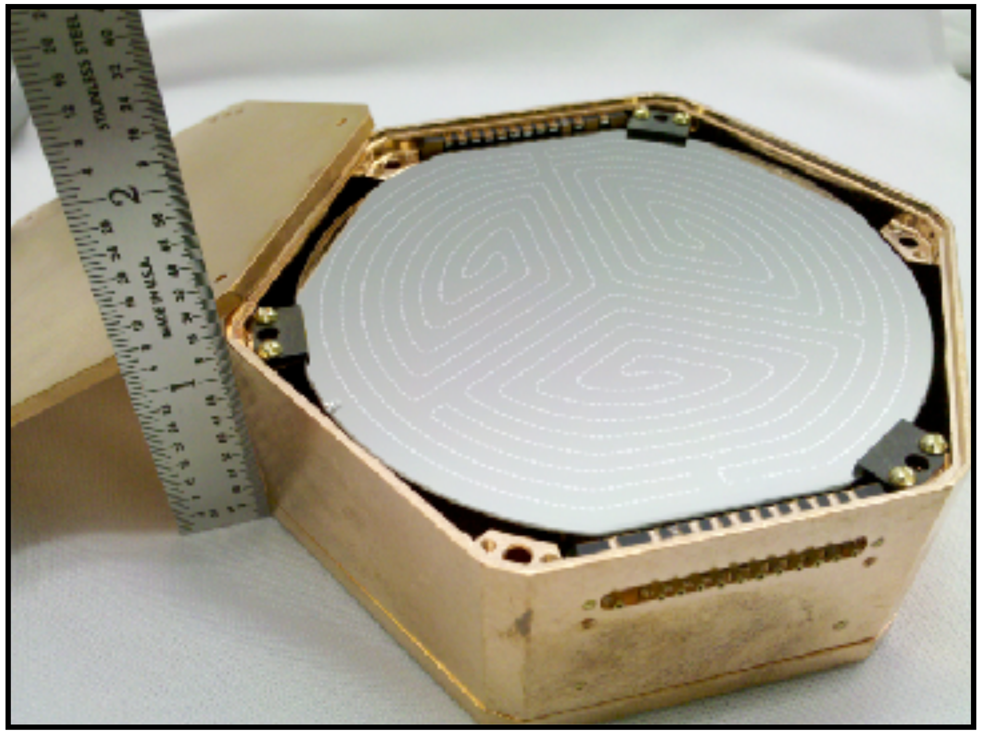
Discrimination from measurements of ionization and phonon energy **and** charge distributions





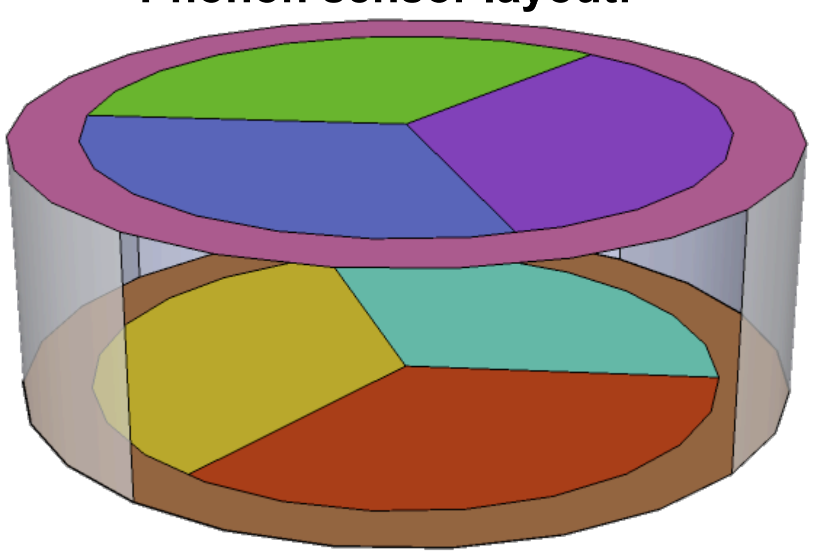
Keep backgrounds low as possible through shielding and material selection.

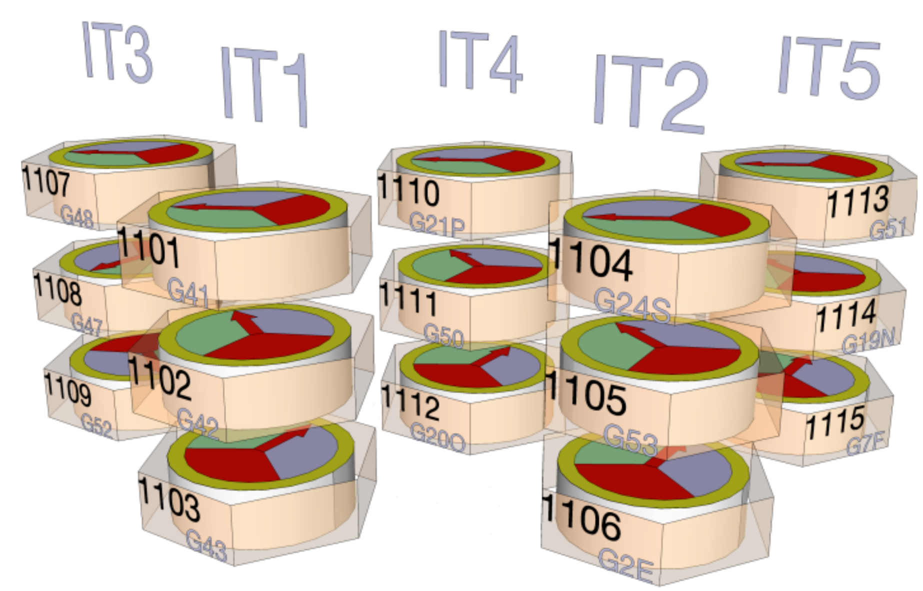
Overview: SuperCDMS Soudan



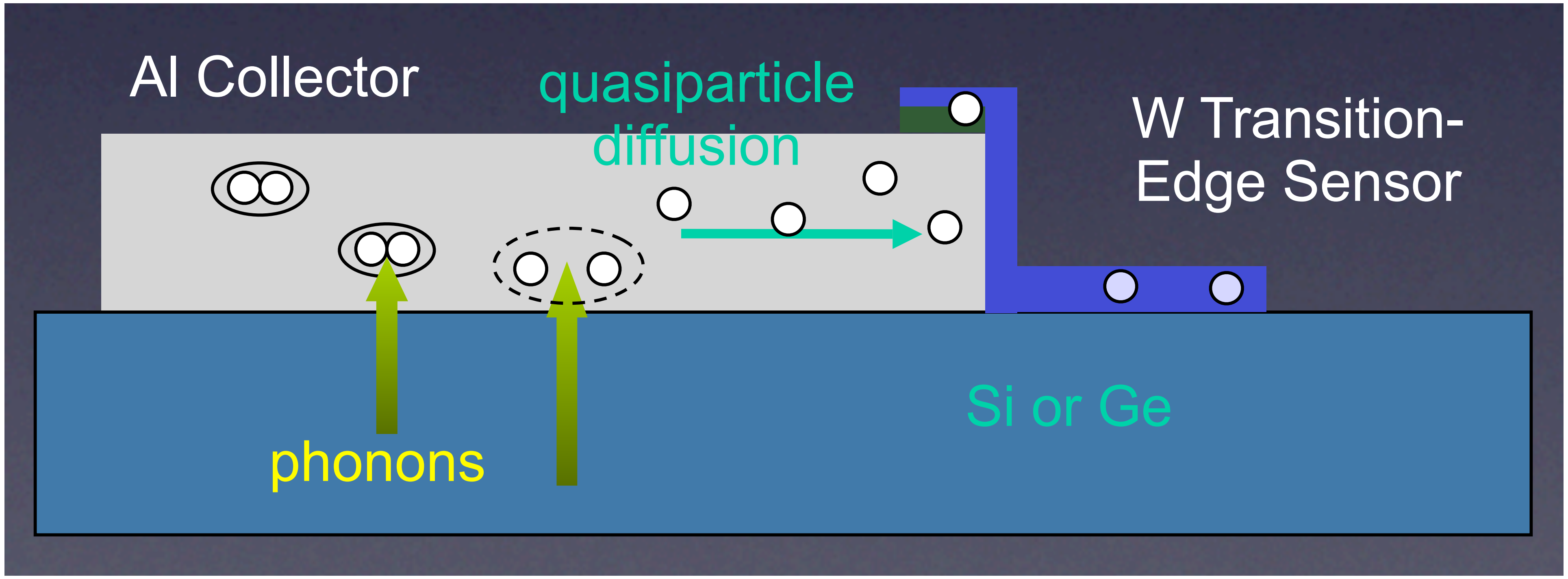
- Location: Soudan Underground Laboratory, Minnesota, USA @ ~2090 mwe
- Science operations from Mar. 2012 - late 2015.
- Experiment contains 15 iZIP detectors, stacked into 5 towers
  - **i**nterleaved **Z**-sensitive **I**onization and **P**honon detectors (**iZIP**)
- Each side instrumented with 2 charge (inner + outer) & 4 phonon (1 inner + 3 outer) sensors

Phonon sensor layout:





Phonon Detection



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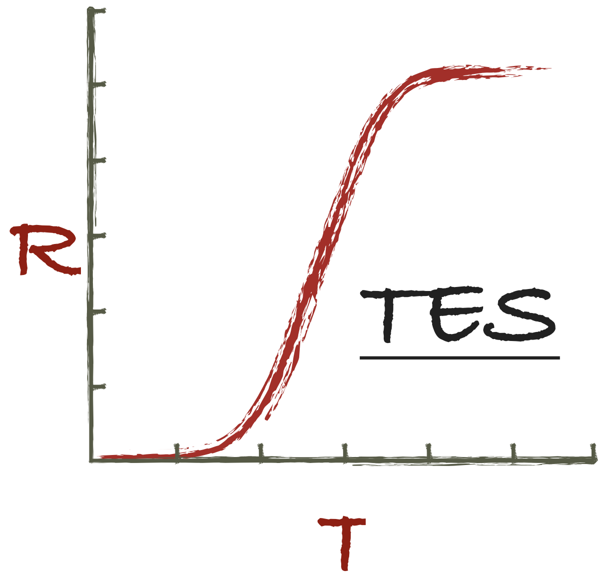


4 SQUID readout channels, each reads out 1036 TES in parallel

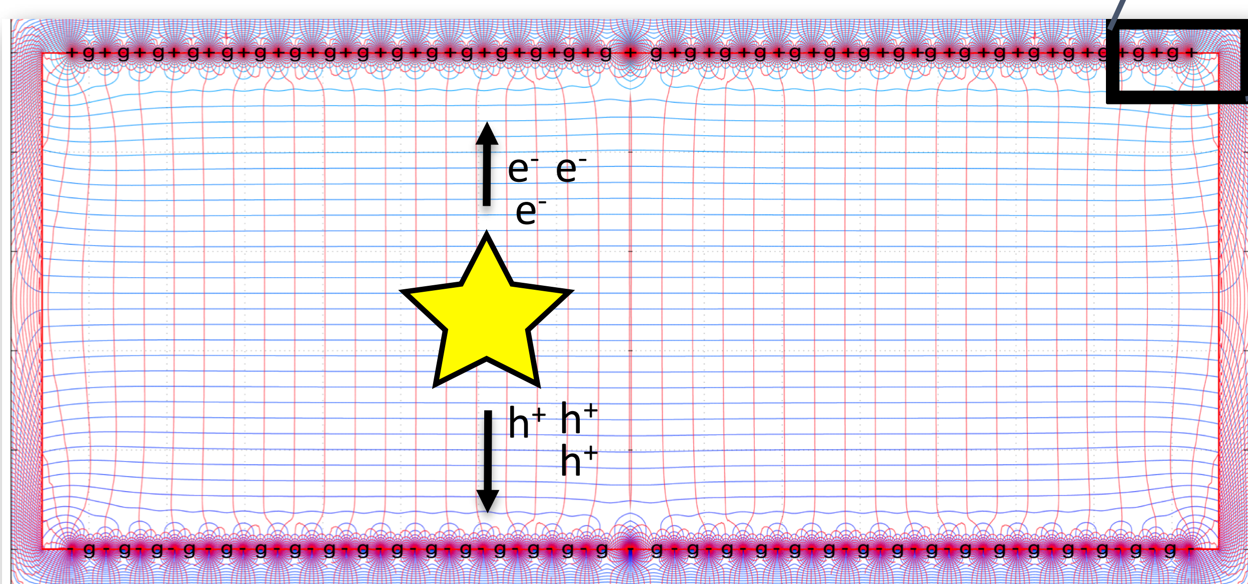
SCDMS iZIPs: Charge Signal

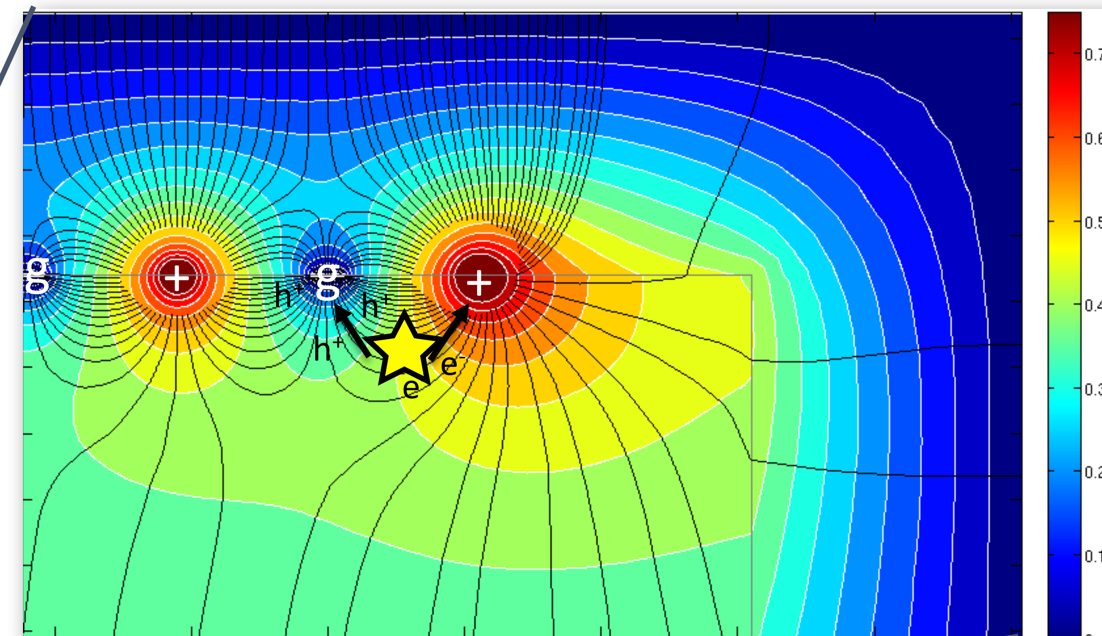
Bulk Events:

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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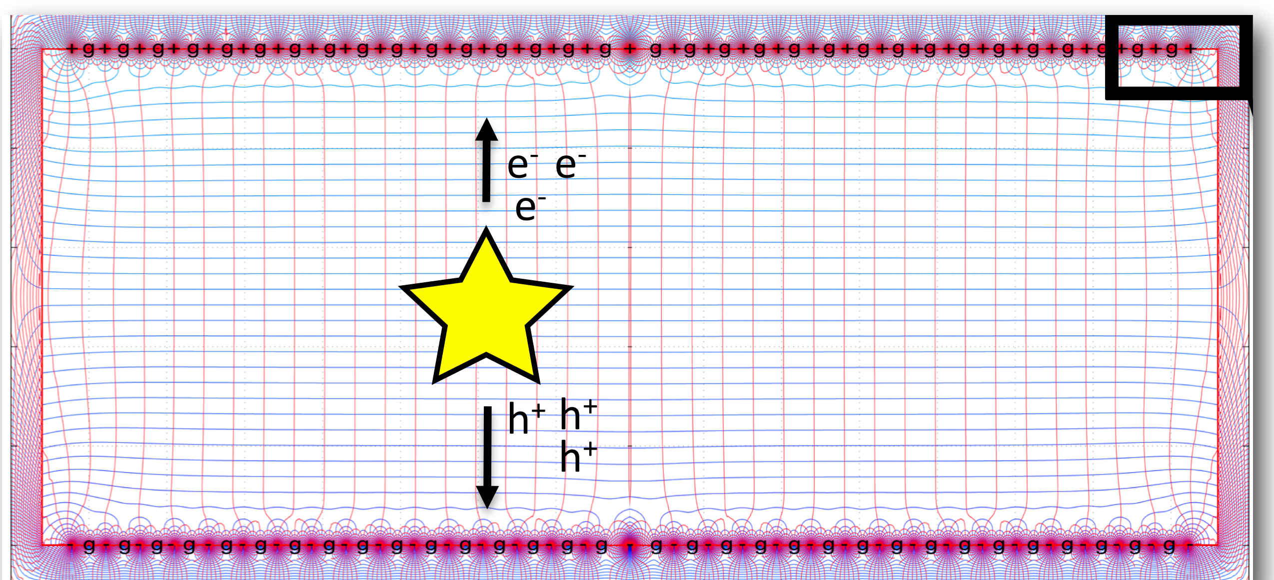
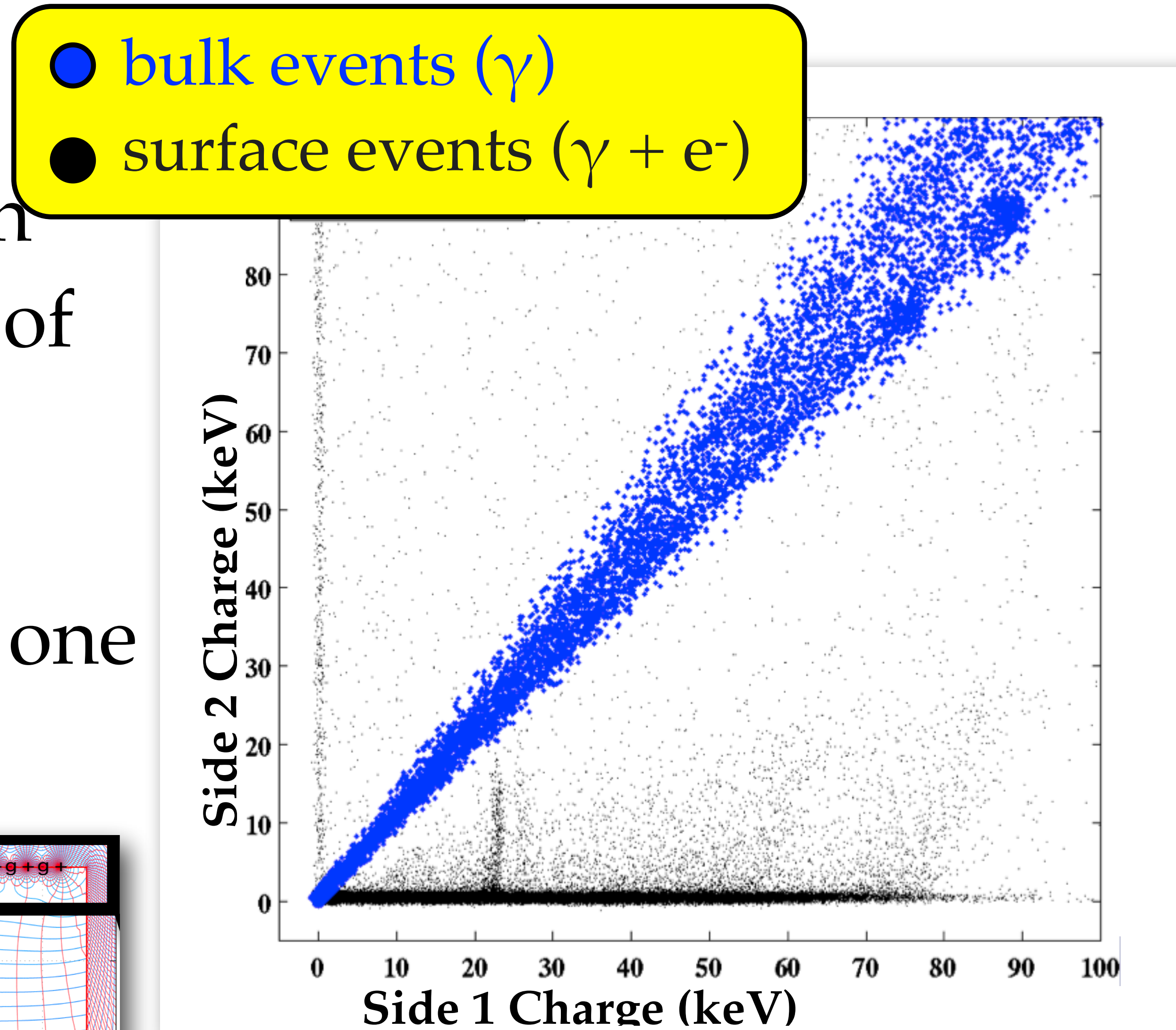
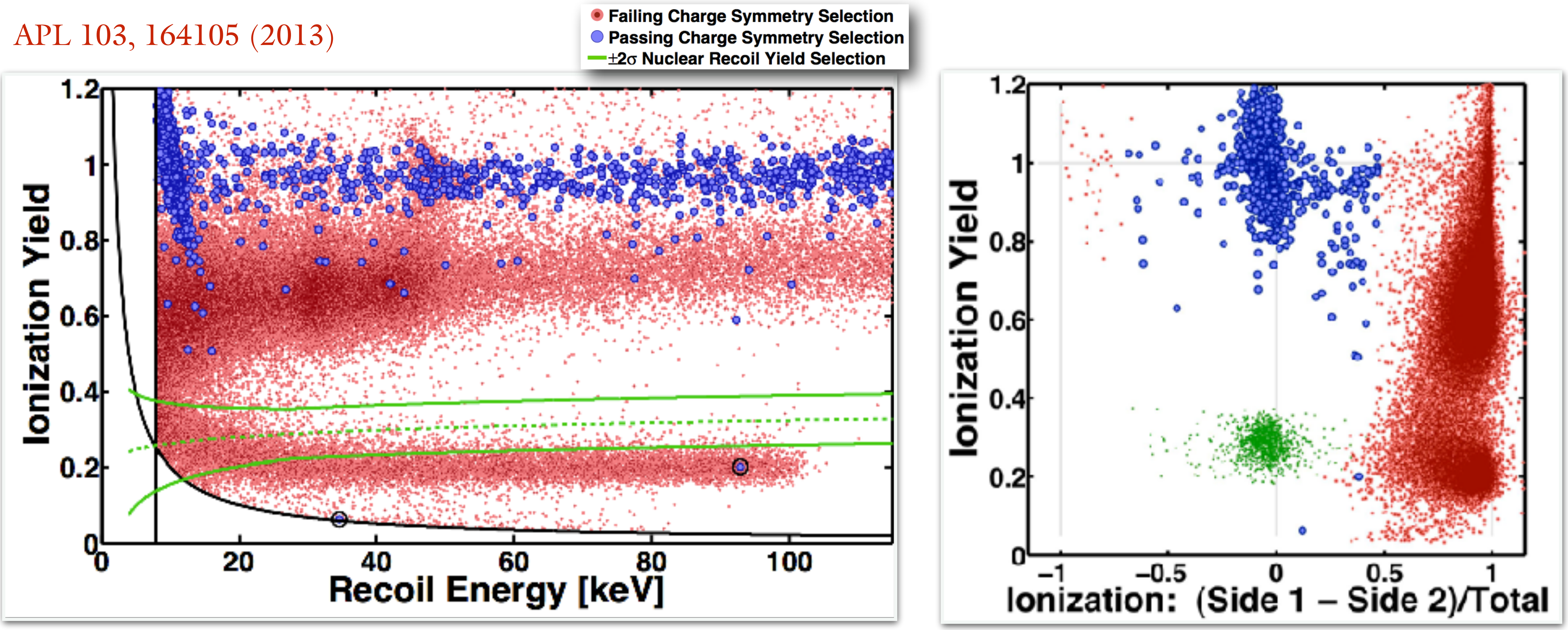




Ionization symmetry is a powerful way to discriminate surface events from bulk events.

iZIP Discrimination

APL 103, 164105 (2013)



- misID < 1.7 x 10^{-5} @90% C.L.
- Allows an ~100 kg experiment run for 5 years at SNOLAB with less than 1 event background.

Backgrounds

Sources:

Radioactive decays from naturally abundant radio-isotopes

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

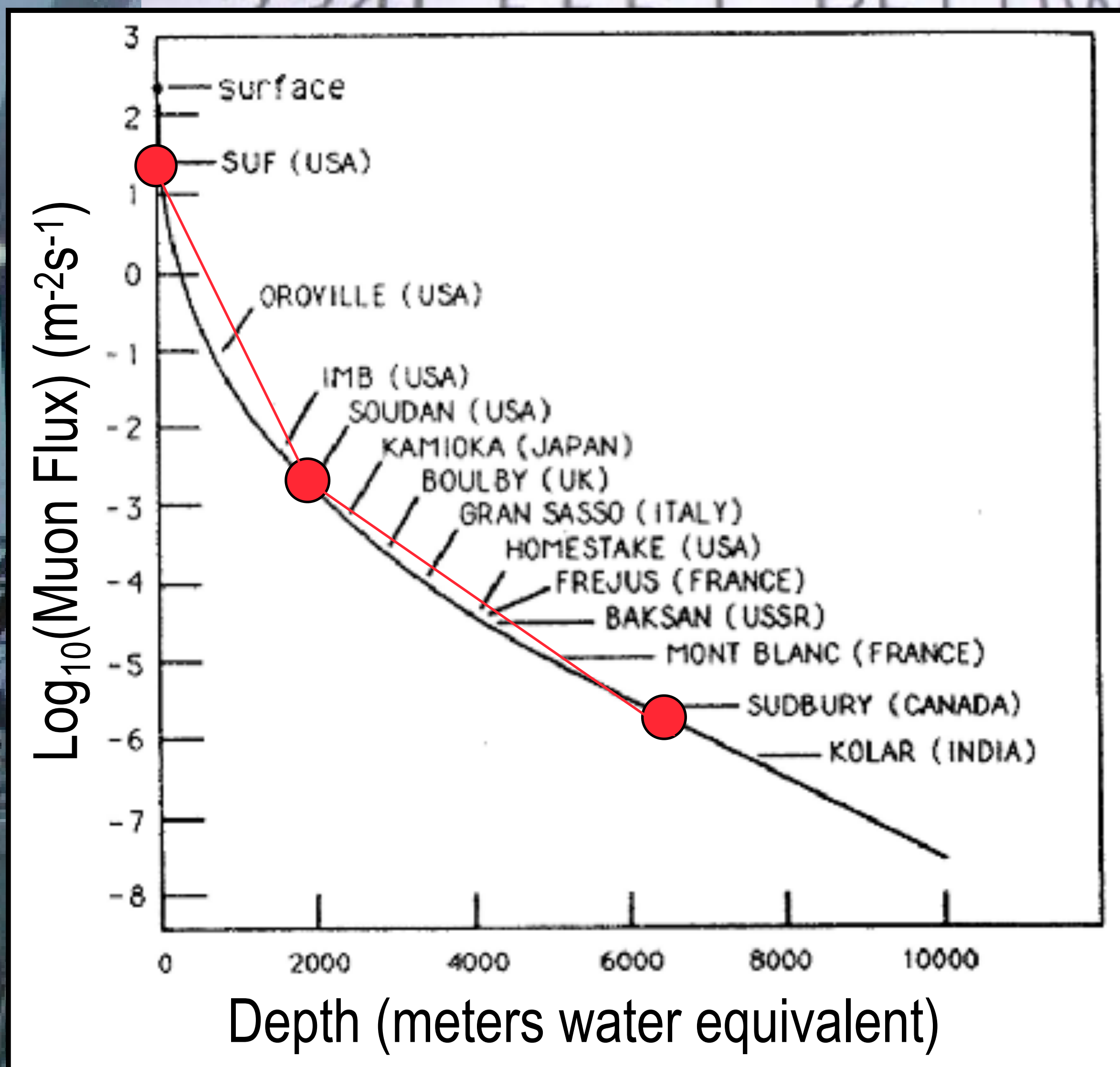
Interactions from cosmic rays and their daughter particles.

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.



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 (α,n) interactions

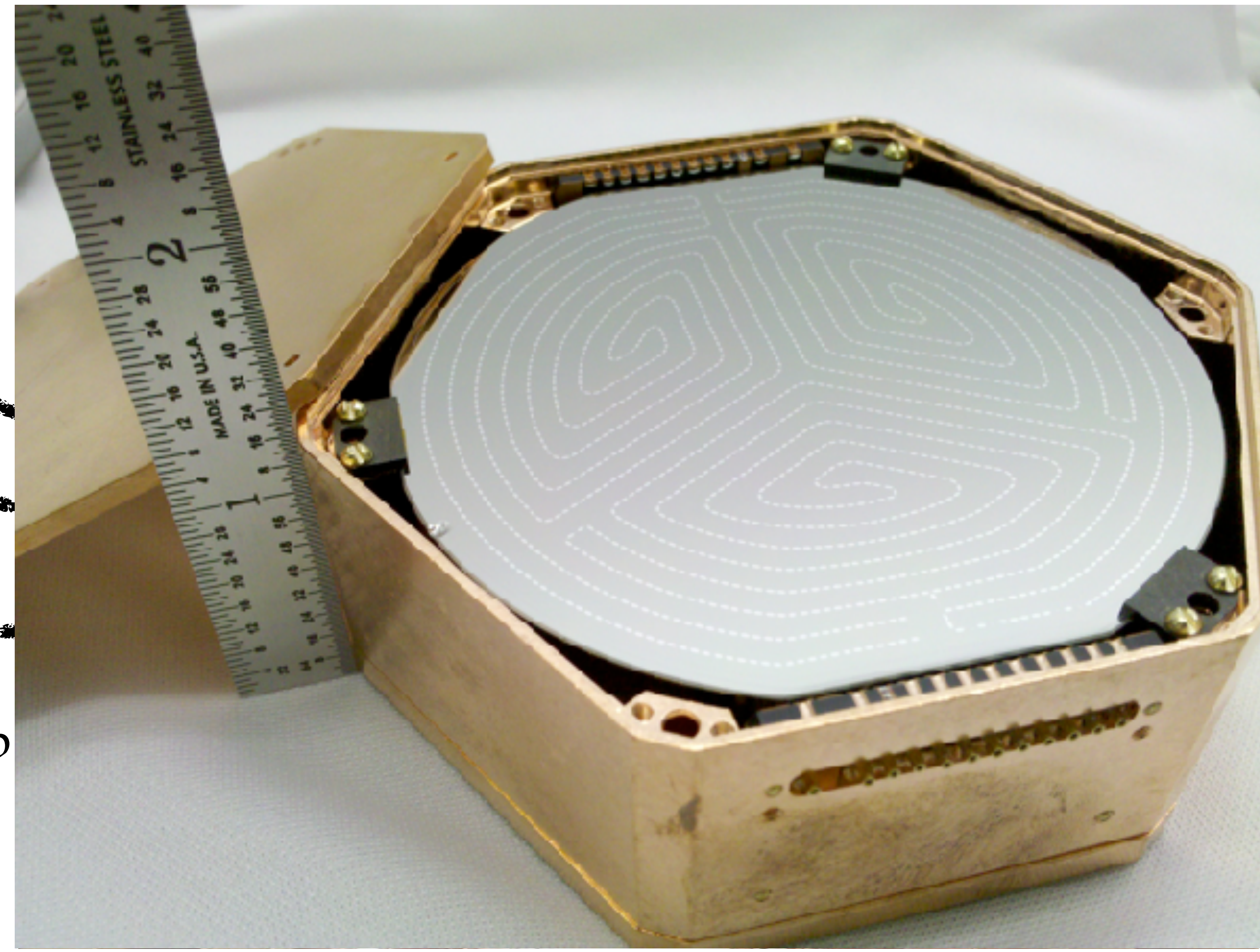
Pb: shielding from gammas resulting from radioactivity

Ancient Pb: shields ^{210}Pb betas

Polyethyene: shields ancient Pb

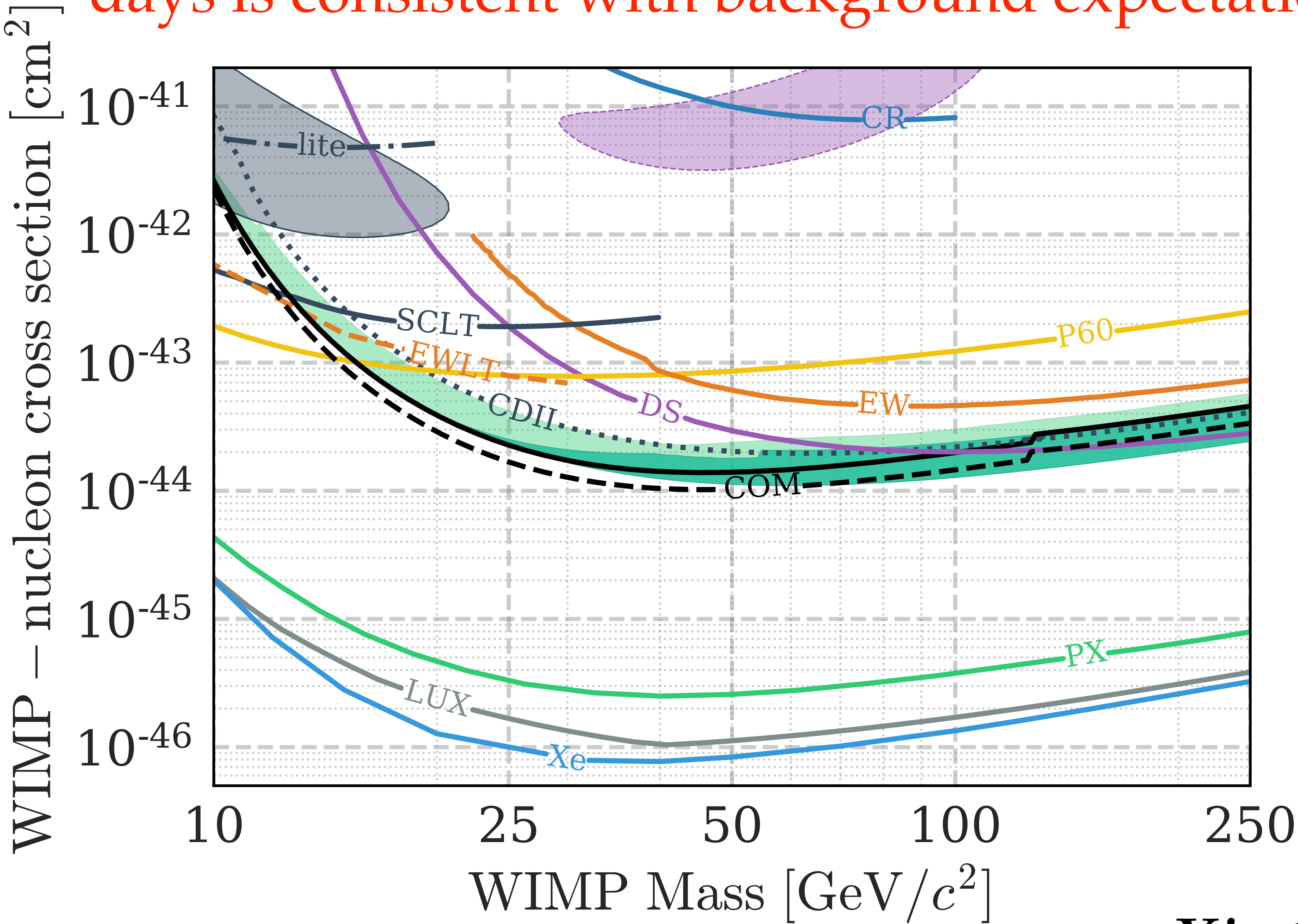
Cu: radio-pure inner copper can

Ge: target



Soudan High Threshold Analysis Limit

This result based on 1 event seen in 1690 kg - days is consistent with background expectations.



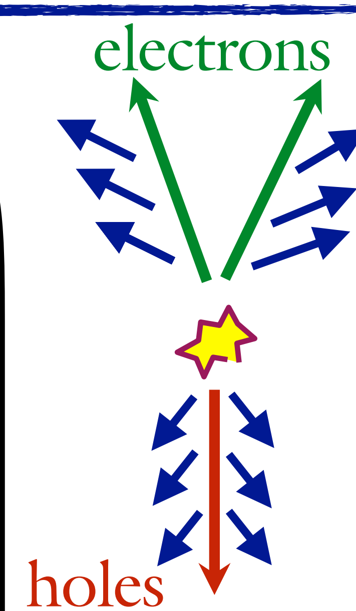
arXiv:1708.08869

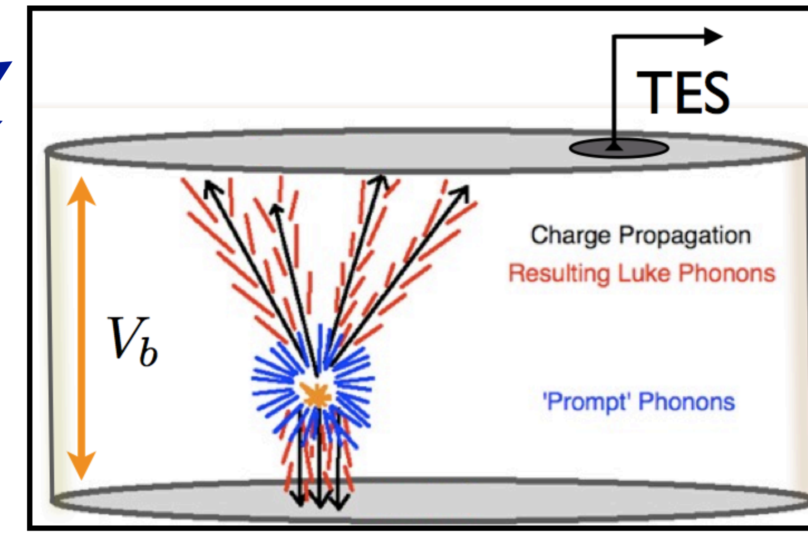
*CDMSlite: A Low Ionization Experiment

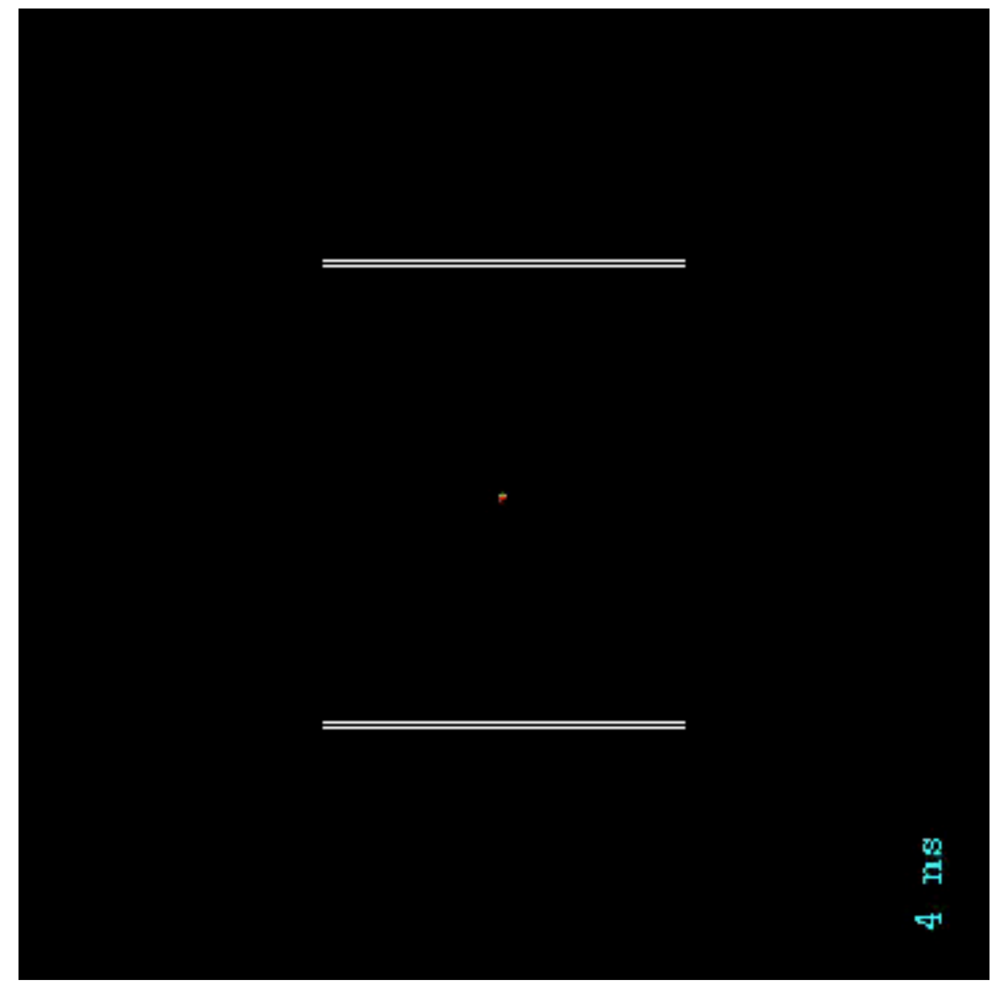
- CDMSlite uses Neganov-Luke amplification to obtain low thresholds with high-resolution
    - Ionization only, uses phonon instrumentation to measure ionization
    - No event-by- event discrimination of nuclear recoils
- Drifting electrons across a potential (V) generates a large number of phonons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

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

total phonon energy — *primary recoil energy* — *Luke phonon energy*

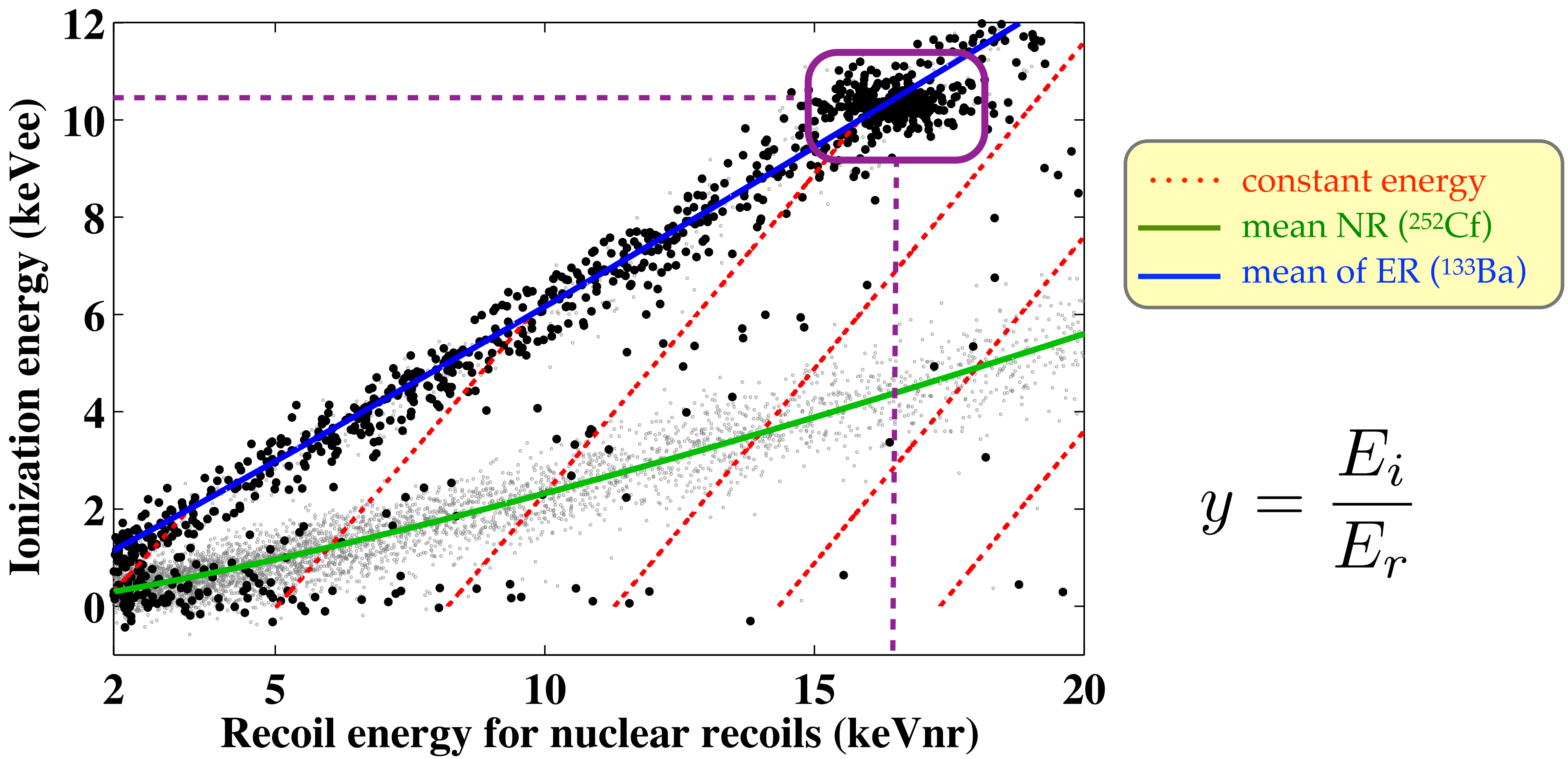






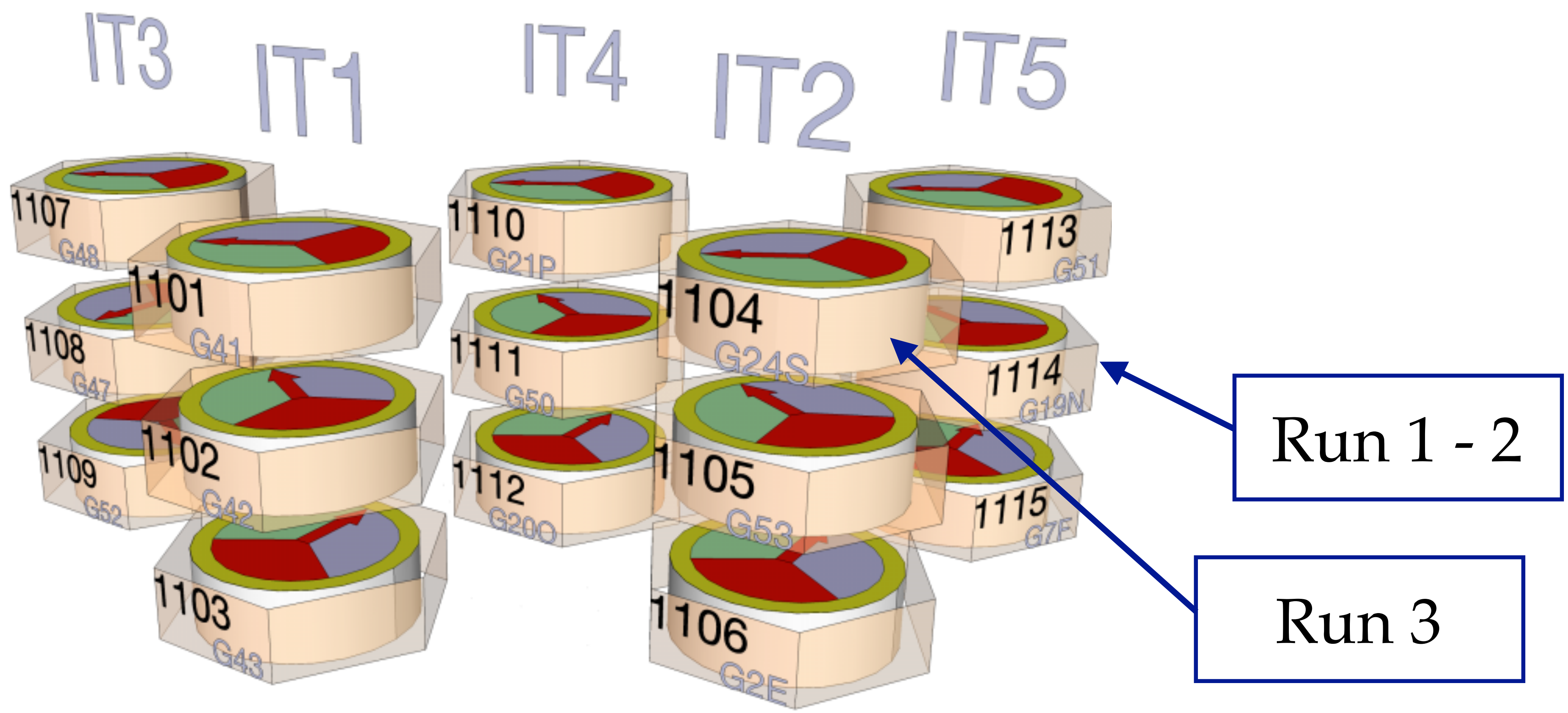
Aside: keVee vs keVnr

Ionization energy vs recoil energy assuming NR scale consistent with Luke phonon contributions for NR.



$$y = \frac{E_i}{E_r}$$

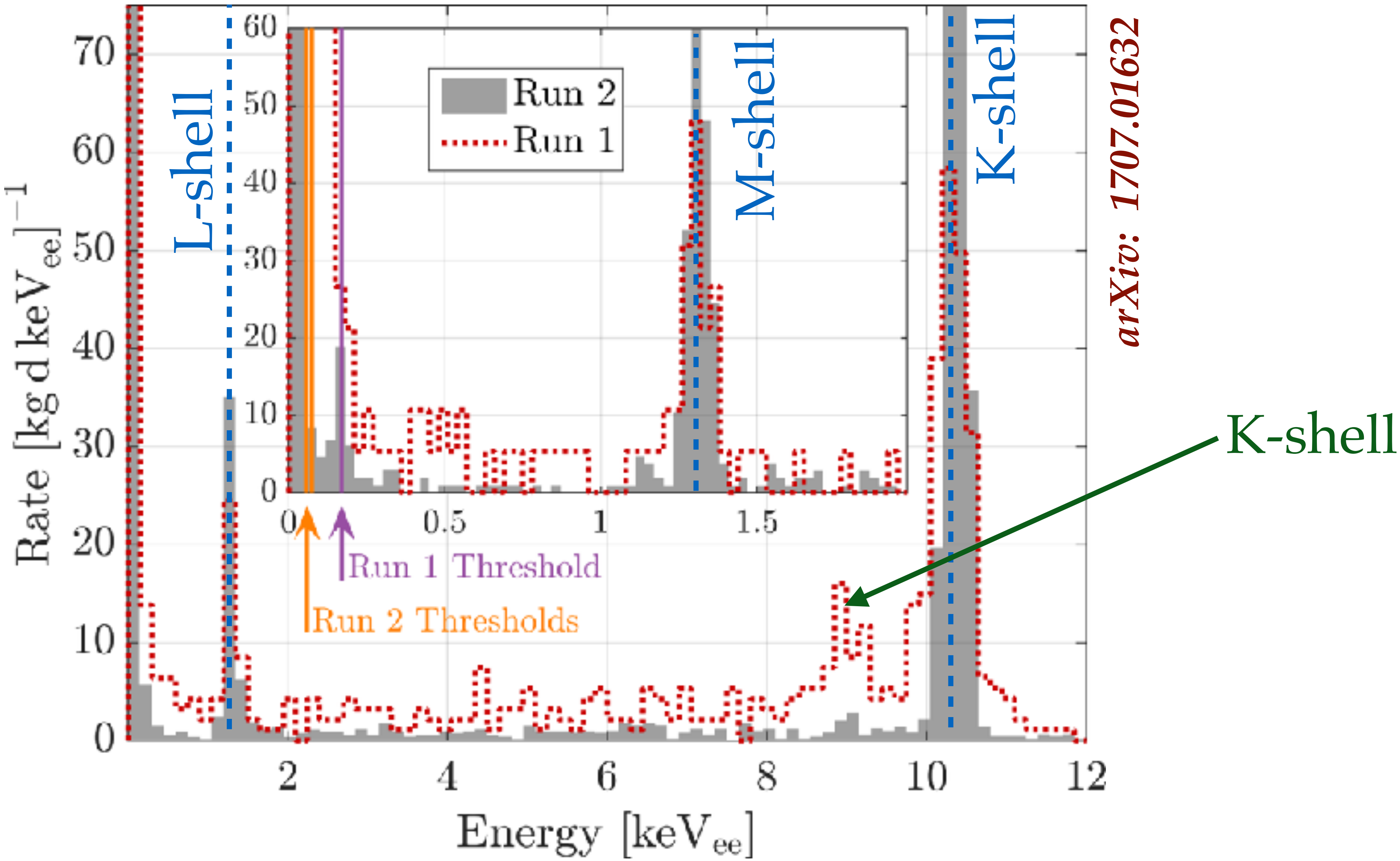
CDMSlite Data



- Run 1: Aug. - Sept. 2012 *[PRL 112, 041302, 2014]*
- Run 2 (period 1): Feb. - July 2014
- Run 2 (period 2): Sept. - Nov. 2014

[PRL 116, 071301 ,2016]

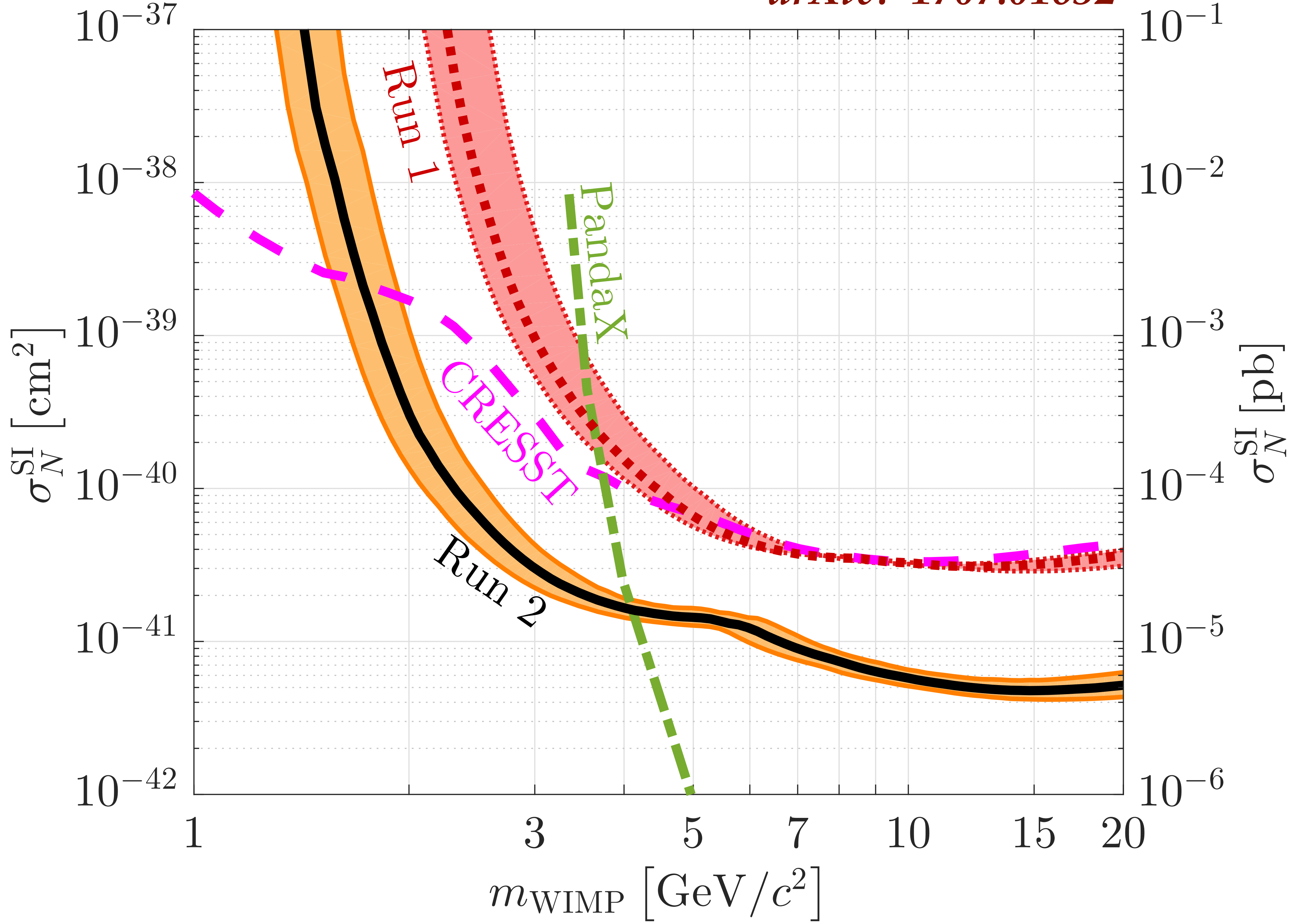
- Run 3: Feb. - May 2015 (analysis ongoing)



- ^{71}Ge activation peaks are visible in both Runs 1 & 2.
- ^{65}Zn K-shell electron capture peak visible in Run 1.
- Run 1 threshold 170 eV$_{ee}$
- Run 2 (period 1) threshold 75, (period 2) 56 eV$_{ee}$

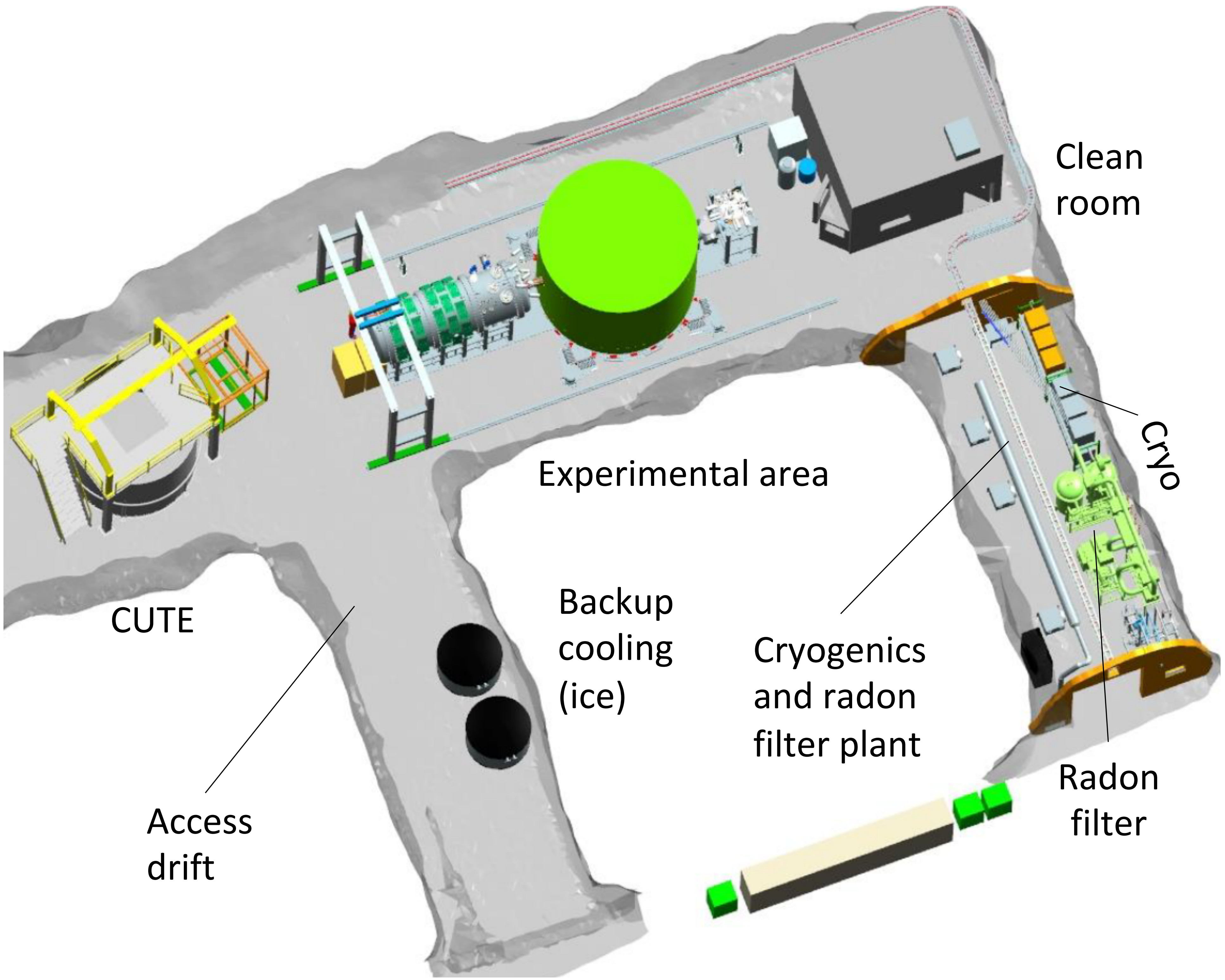
CDMSlite Results

arXiv: 1707.01632



SuperCDMS SNOLAB

SuperCDMS Layout in SNOLAB



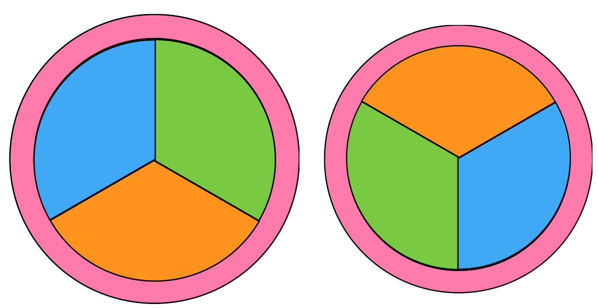
From Soudan to SNOLAB

SuperCDMS Soudan

3” Diameter
2.5 cm Thick
600 g Ge crystals
15 Ge iZIP

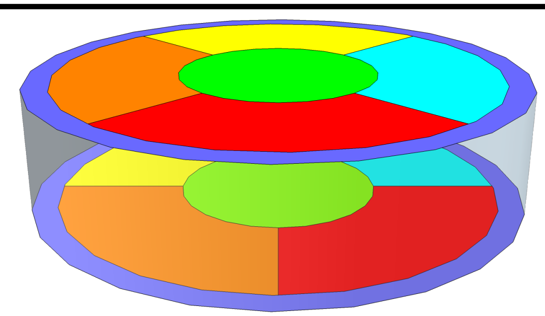
SuperCDMS SNOLAB

100 mm Diameter
33.3 mm Thick
1.39 kg Ge crystals / 0.61 kg Si crystals
10 Ge iZIP, 2 Si iZIP, 8 Ge HV, 4 Si HV

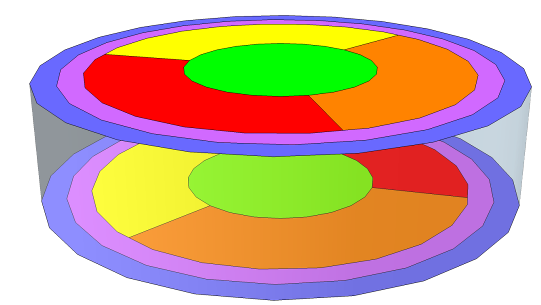


2 charge + 2 charge
4 phonon + 4 phonon

iZIP:

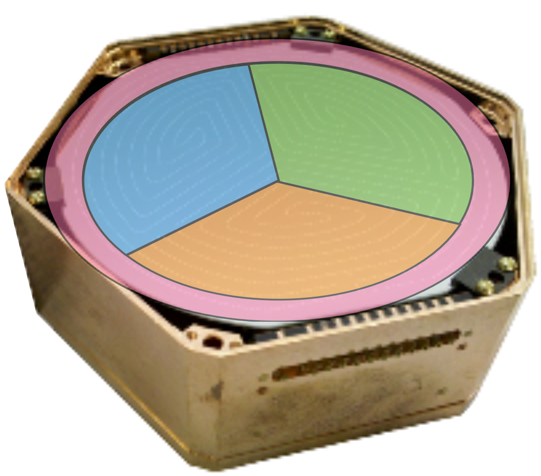


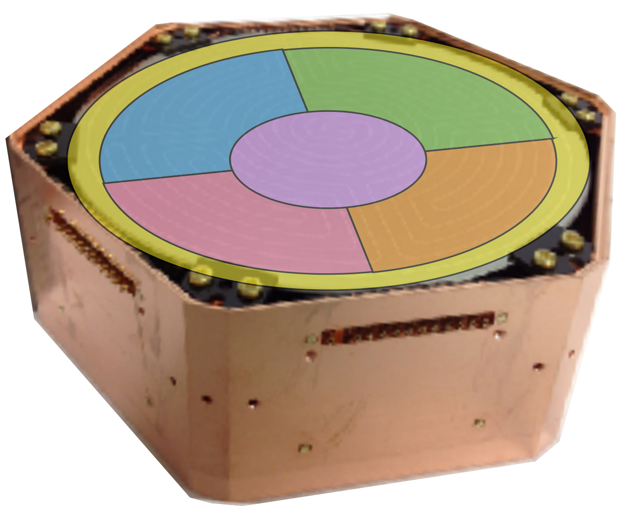
HV:

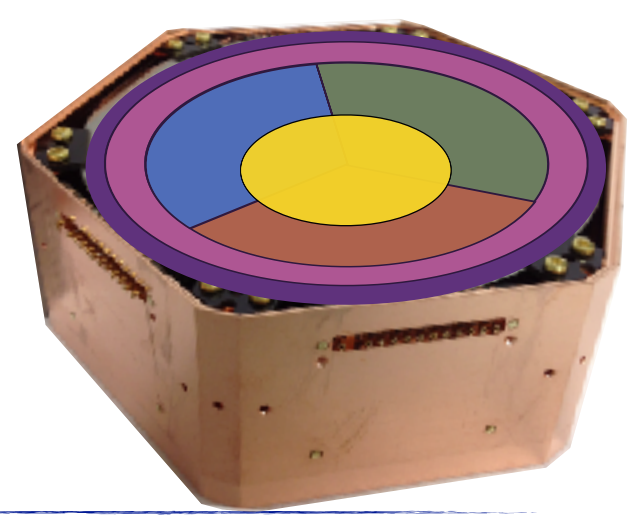


2 charge + 2 charge
6 phonon + 6 phonon

6 phonon + 6 phonon



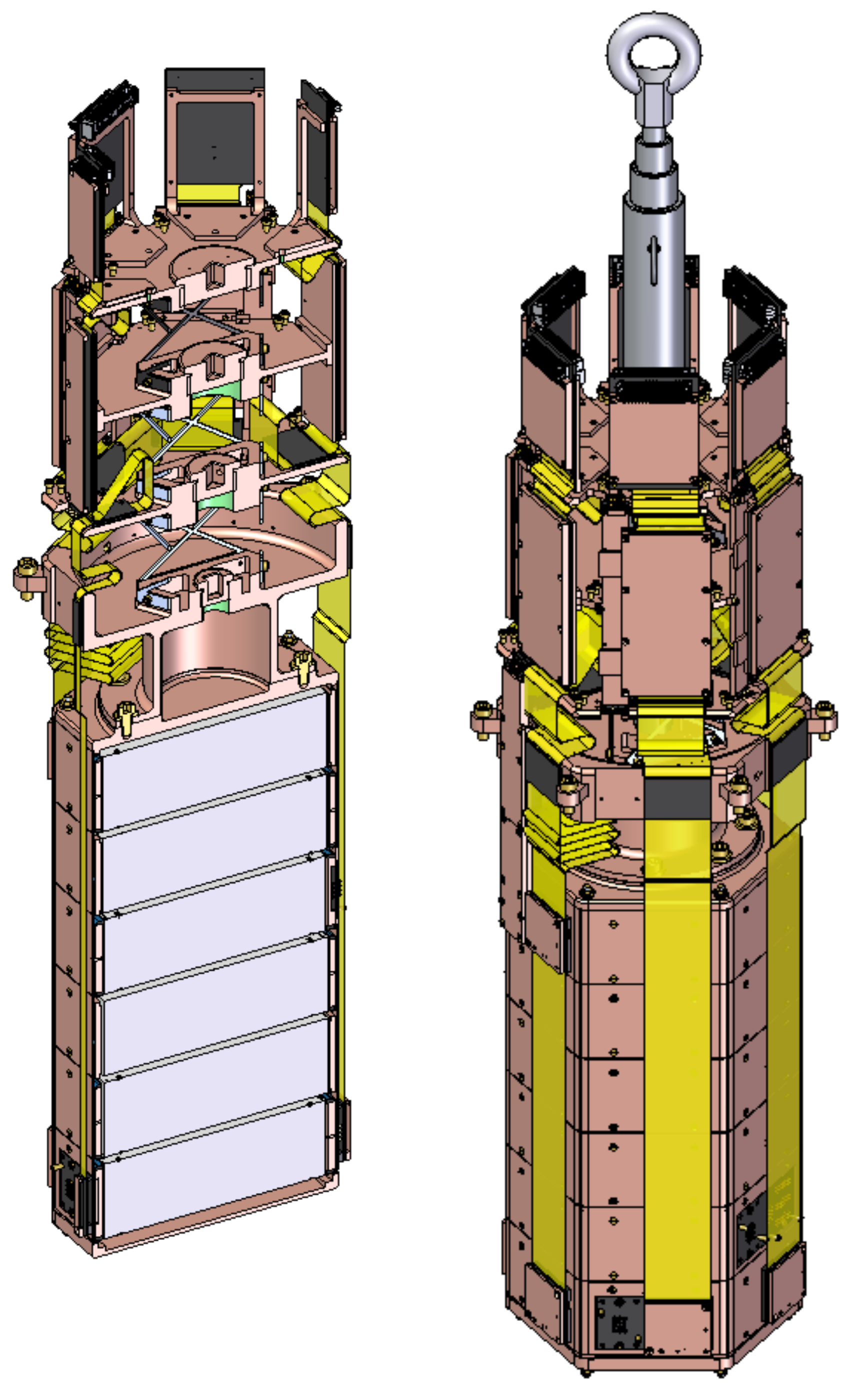




SuperCDMS SNOLAB Towers

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

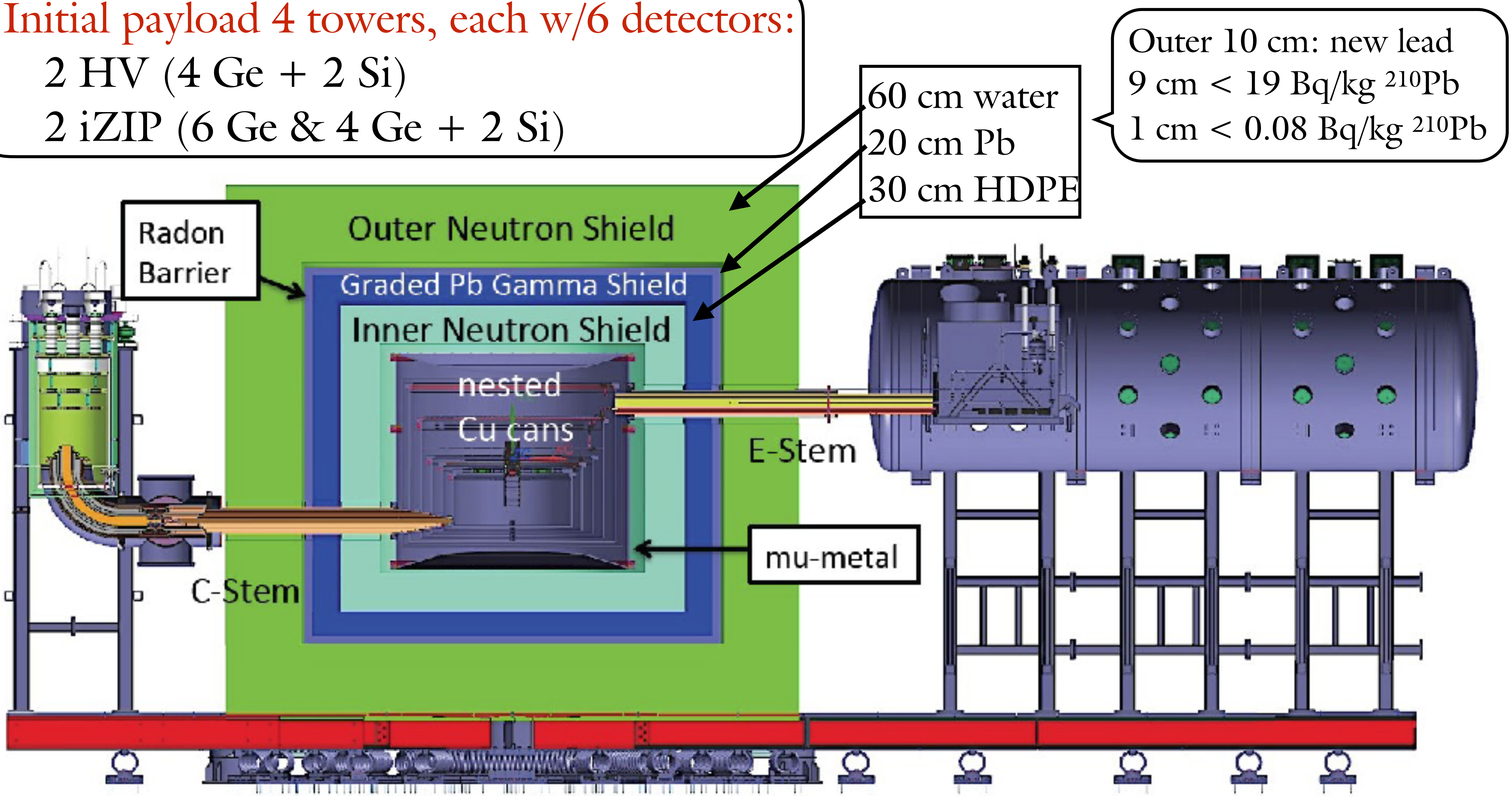


SuperCDMS SNOLAB

Initial payload 4 towers, each w/6 detectors:

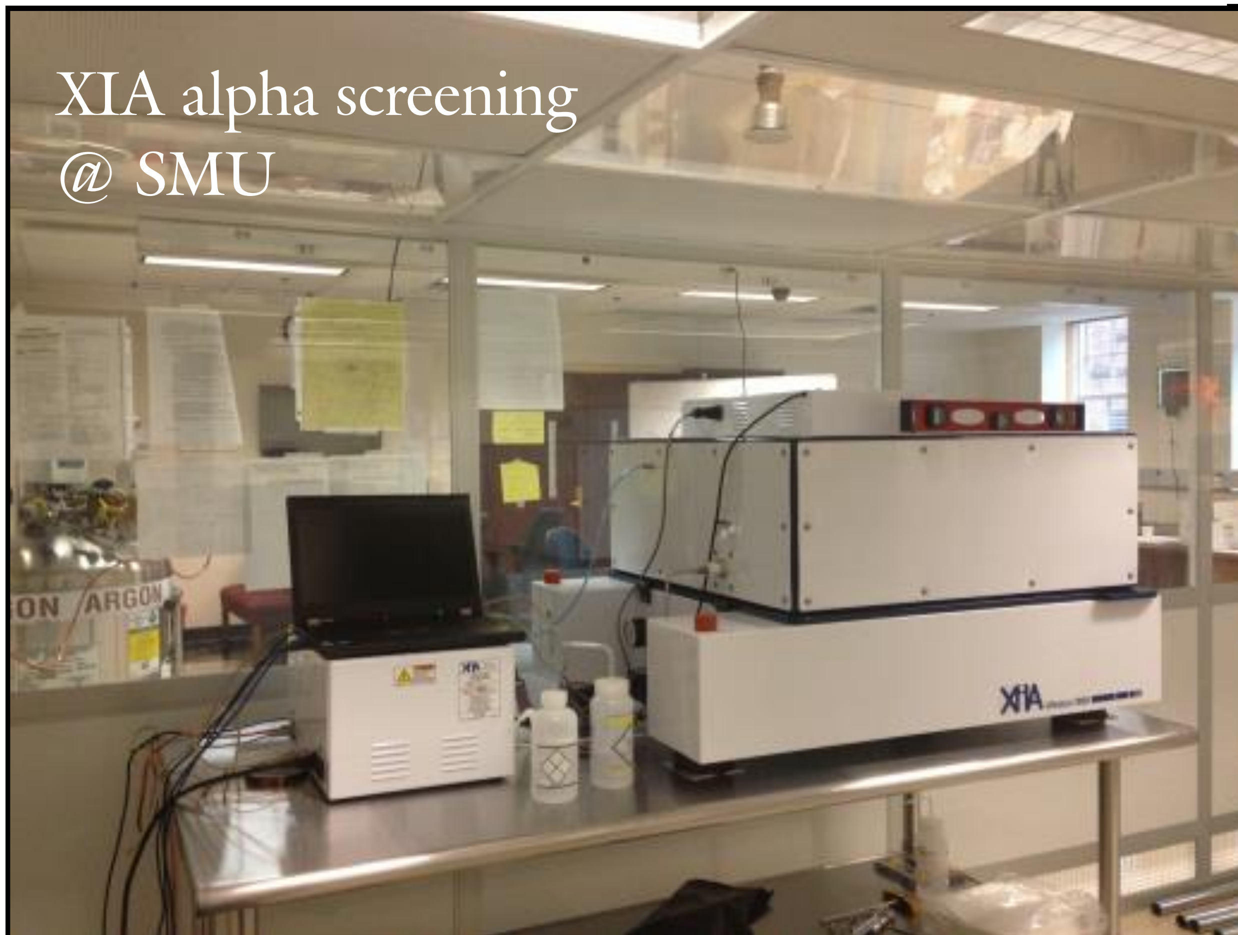
2 HV (4 Ge + 2 Si)

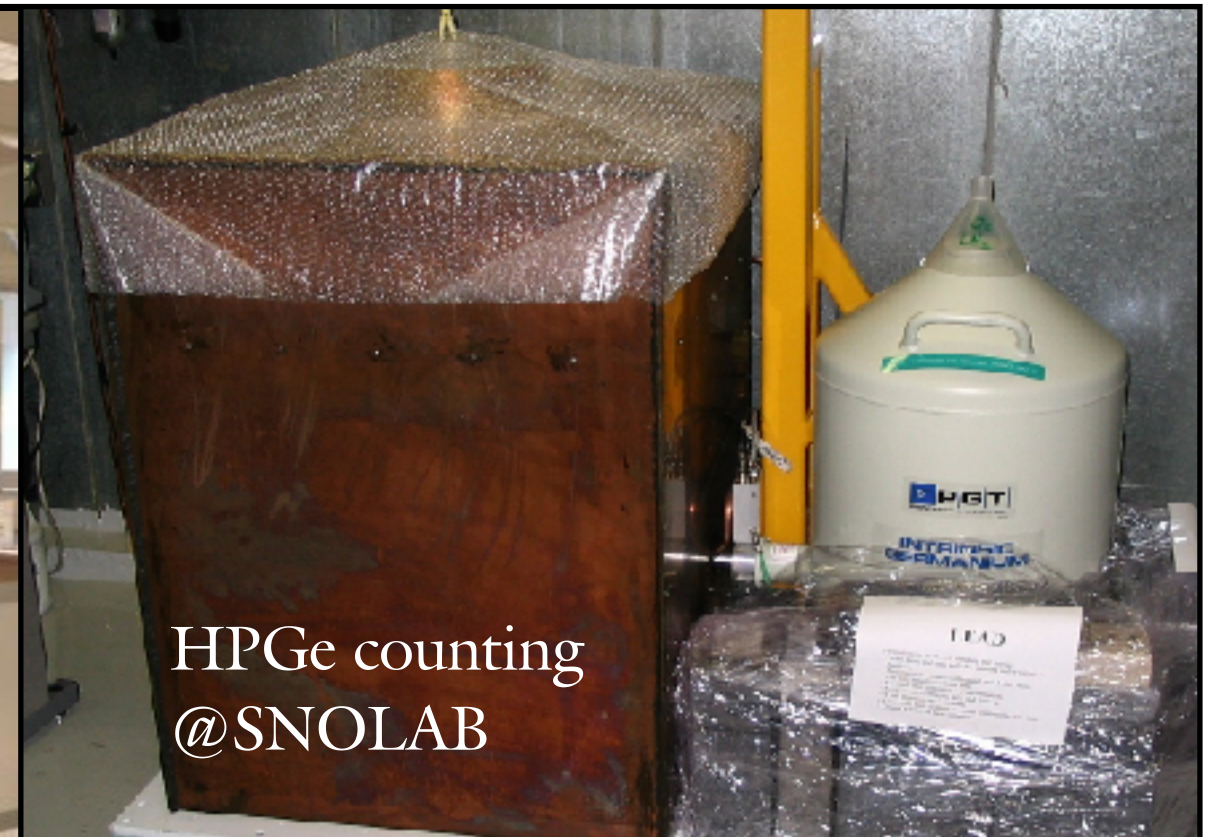
2 iZIP (6 Ge & 4 Ge + 2 Si)

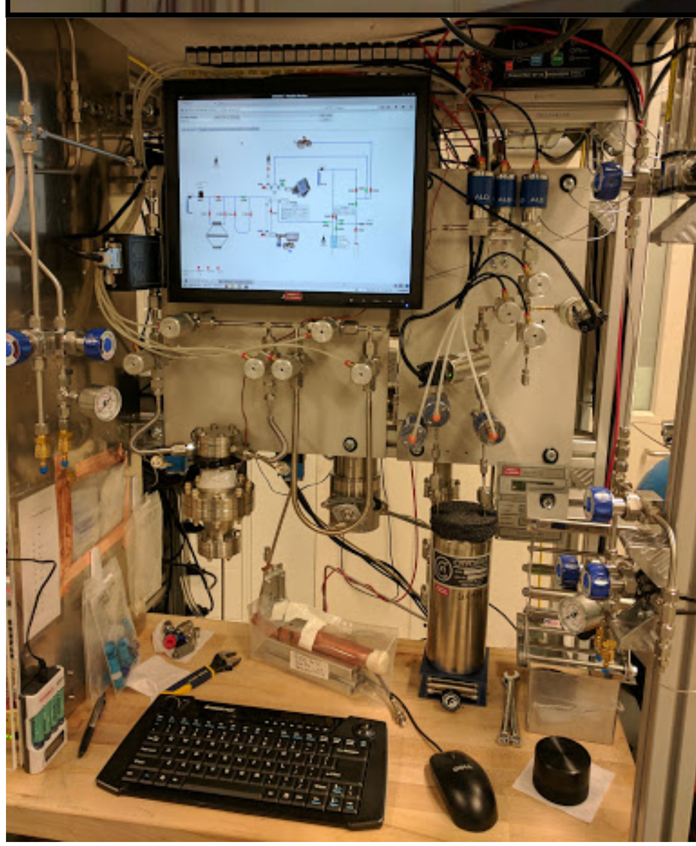


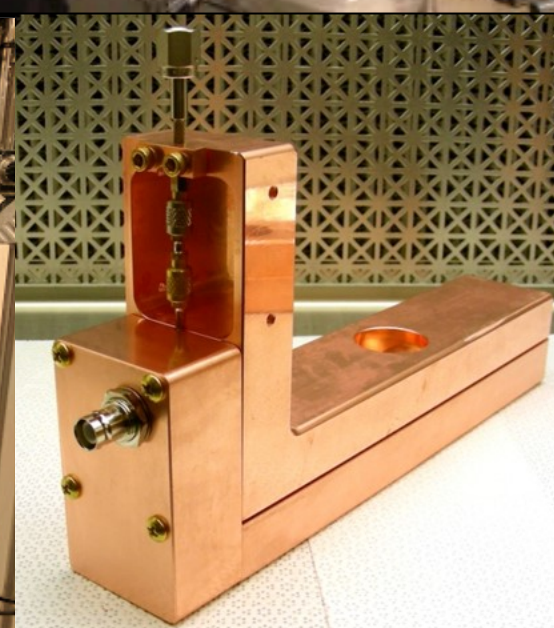
Fridge, cryostat capable of 31 towers, nominal 15 mK

Materials Assay & Screening


XIA alpha screening @ SMU


HPGe counting @SNOLAB



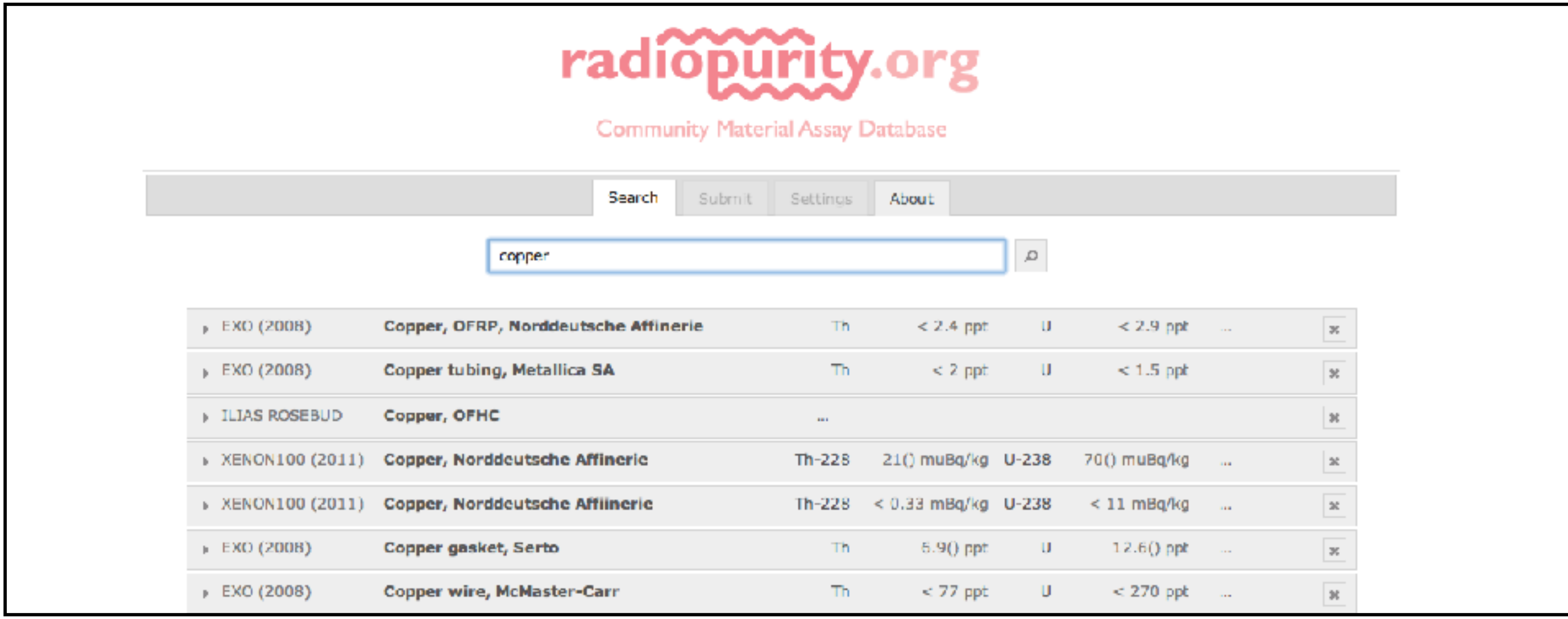

Radon Emanation @ PNNL


ICPMS @LNGS

In most cases, looking for materials at levels of < 1 ppb.

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 Affinerie	Th-228	< 0.33 mBq/kg	U-238	< 11 mBq/kg	...	
EXO (2008)	Copper gasket, Serto	Th	5.9() 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

Background Inventory

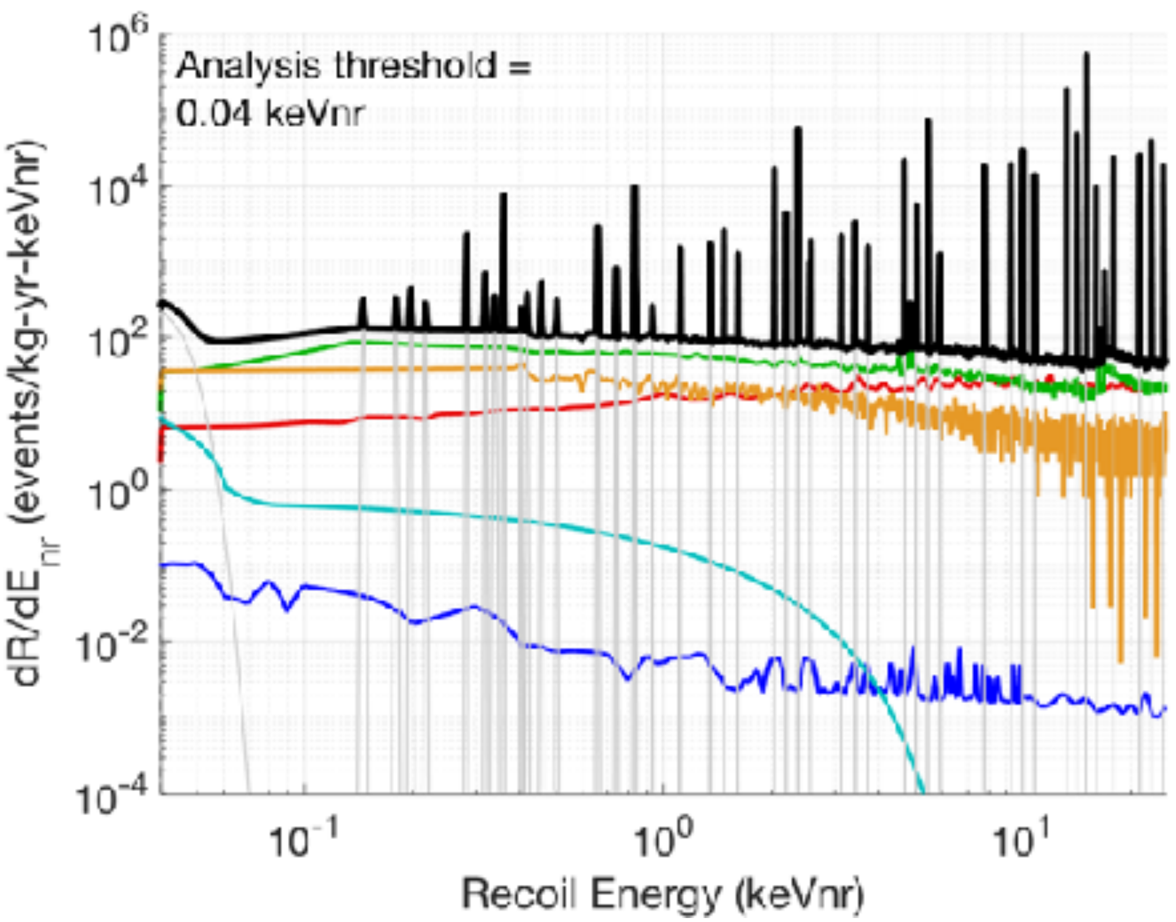
Predicted rates in counts / kg*keVr*year

Category	Ge HV ERsingles	Si HV ERsingles	Ge iZIP ERsingles	Si iZIP ERsingles	Ge iZIP NRsingles ($x10^{-6}$)	Si iZIP NRsingles ($x10^{-6}$)
-Total	48.	360.	50.	400.	3200.	2300.
Coherent Neutrinos					2300.	1600.
Detector Internal Contamination	24.	280.	4.7	250.	0	0
Tritium	24.	33.	4.7	6.6	0	0
Silicon-32	0	250.	0	250.	0	0
Other						
Material Internal Contamination	17.	66.	36.	120.	370.	460.
+Housing and Towers	6.5	34.	19.	65.	51.	66.
Readout Cables	0.31	0.46	0.39	0.80	11.	15.
+SNOBOX Cans	4.0	13.	6.5	22.	68.	75.
Kevlar Ropes	2.1	5.1	2.7	8.3	3.6	4.0
Calibration	0.92	3.0	1.2	3.6	0.05	0.05
Shield Materials	3.5	10.	5.3	17.	240.	300.
Bulk Pb-210 in Lead	0.07	0	0.22	0.75		
-Material Internal Activation	2.3	8.4	3.9	13.		
Housing and Towers	0.64	2.5	1.0	4.1		
+SNOBOX	1.5	5.6	2.8	8.9		
Shield	0.07	0.28	0.14	0.41		
Other						
Non-line-of-sight Surfaces	1.6	5.0	2.9	9.3	35.	41.
Prompt Interstitial Radon	0.61	1.8	0.87	2.7		
+Cavern Environment	2.3	3.5	2.0	9.6	330.	160.
Cosmic Ray Flux	0.00	0.00	0.00	0.00	85.	99.

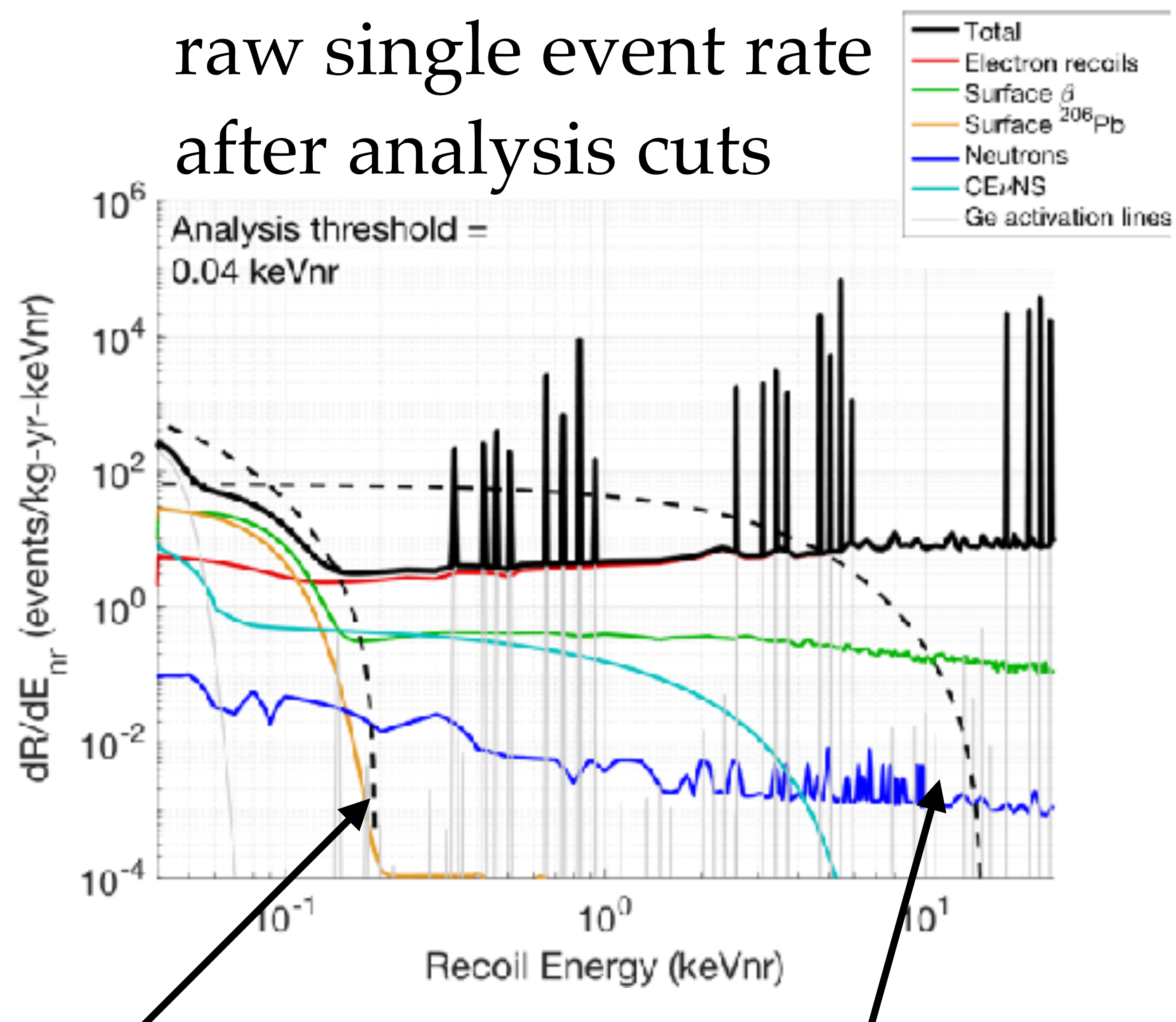
Simulated Raw Background Spectra

HV - Ge Detectors

raw single event rate



raw single event rate
after analysis cuts



1 GeV/c² WIMP

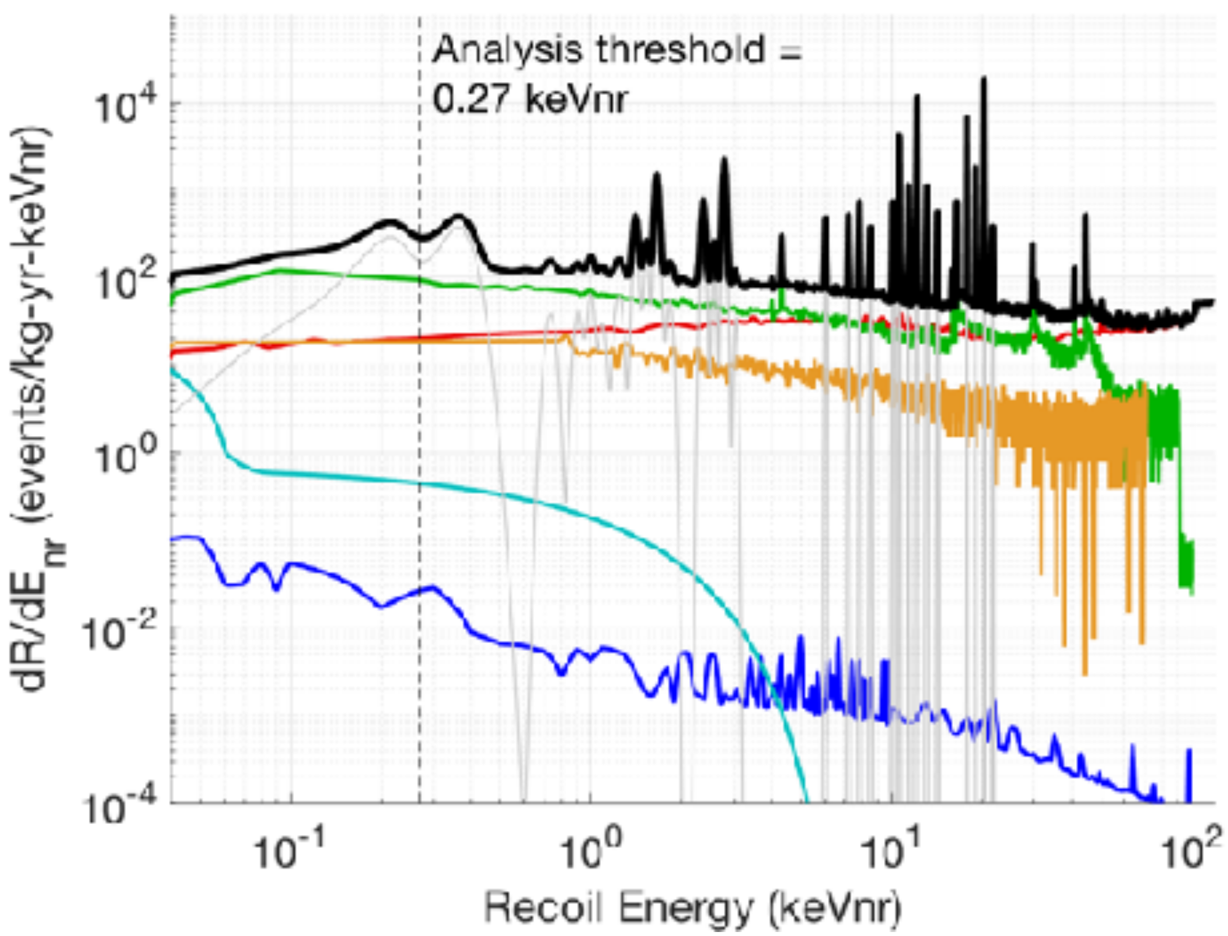
10 GeV/c² WIMP

- - - - 10^{-42} cm² WIMP-nucleon σ

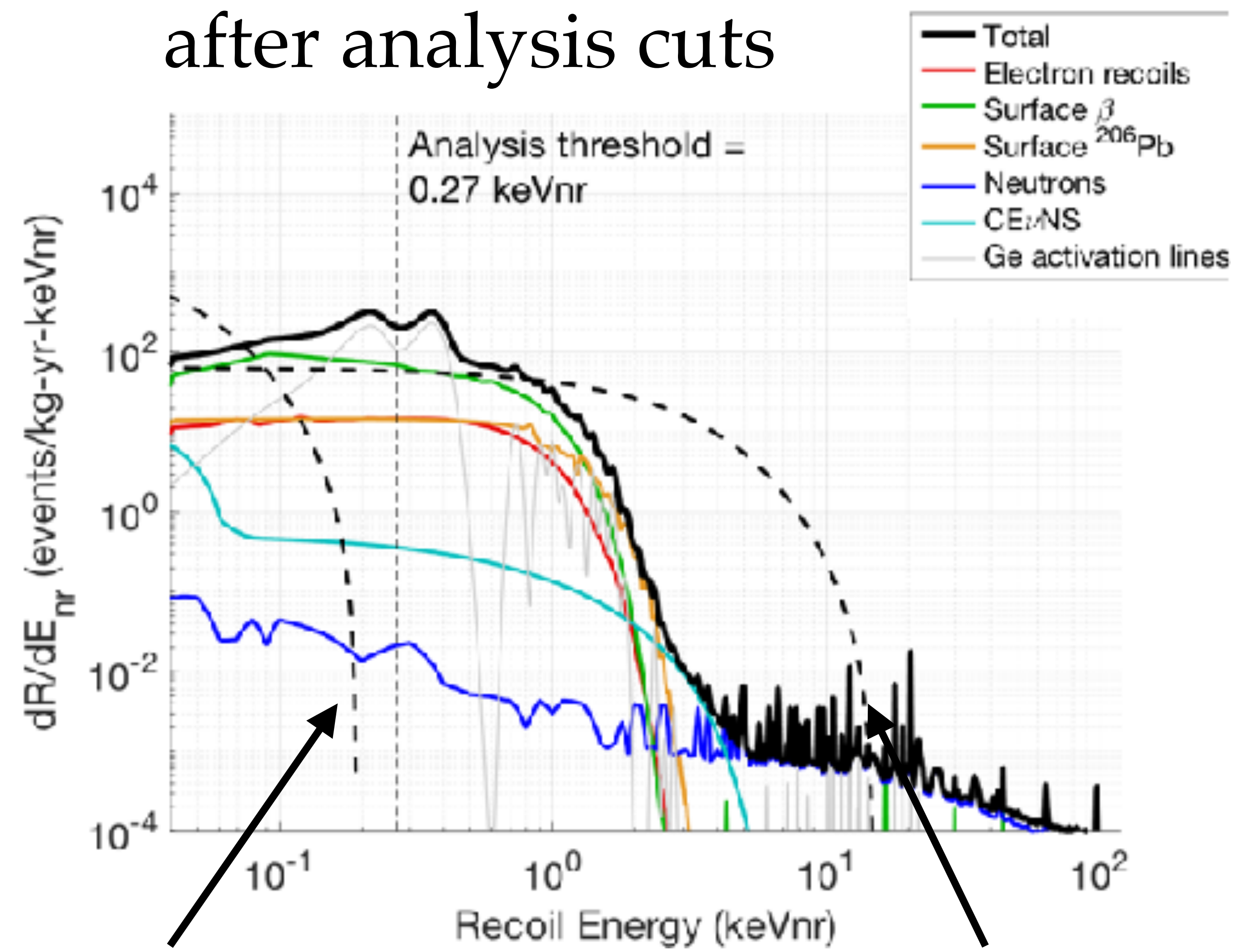
Simulated Raw Background Spectra

iZIP - Ge Detectors

raw single event rate



raw single event rate
after analysis cuts

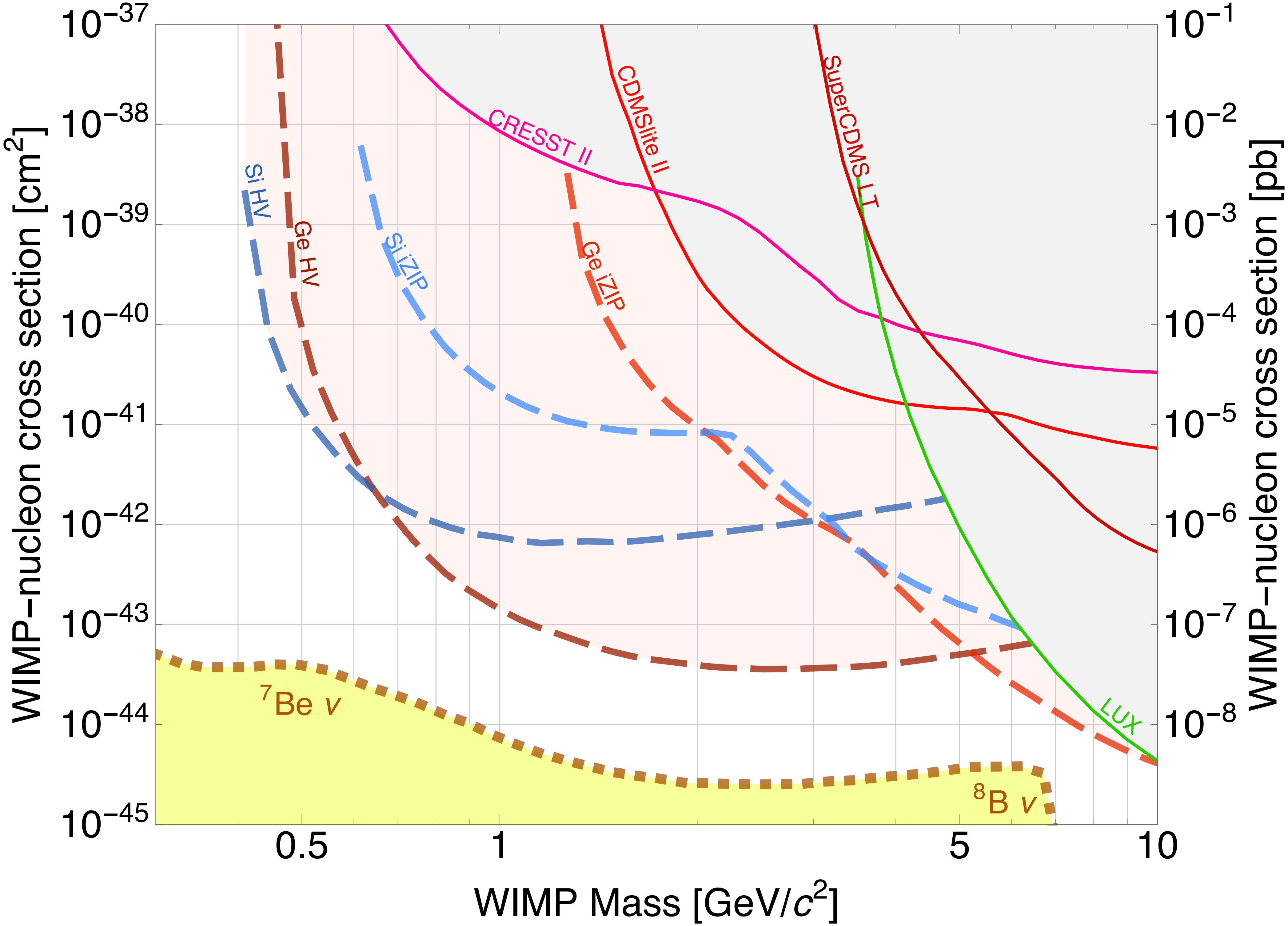


1 GeV / c^2 WIMP

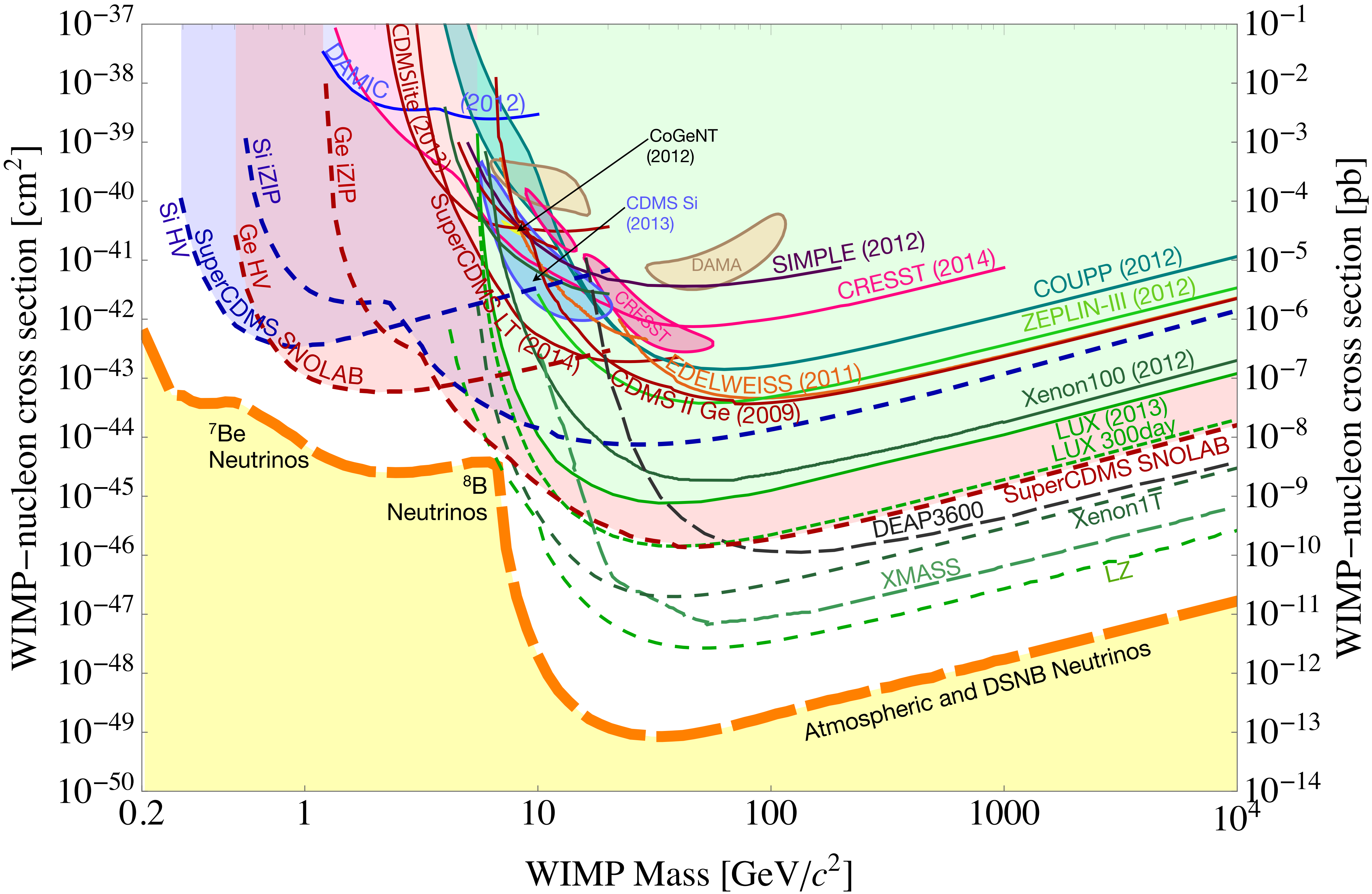
10 GeV / c^2 WIMP

- - - - 10^{-42} cm^2 WIMP-nucleon σ

Expected Sensitivities



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.
- With an exposure of 1690 kg days, a single candidate event is observed, consistent with expected backgrounds. The SuperCDMS collaboration sets a combined upper limit on the spin-independent WIMP–nucleon cross section of 1.4×10^{-44} (1.0×10^{-44}) cm^2 at 46 GeV/c^2 which are the strongest limits for WIMP– germanium-nucleus interactions for masses >12 GeV/c^2 .
- Plans for a SuperCDMS SNOLAB experiment are well underway. Background estimations and mitigation plans are in place. When built the SuperCDMS SNOLAB experiment will have unprecedented sensitivity to low mass WIMPs.