The Cryogenic Dark Matter Search: Results and Prospects

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CDMS-II (2001)

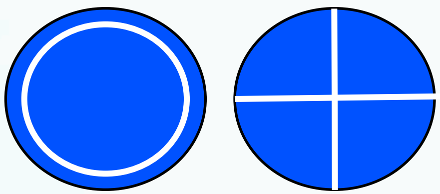
SuperCDMS (2011)

An Evolving Detector

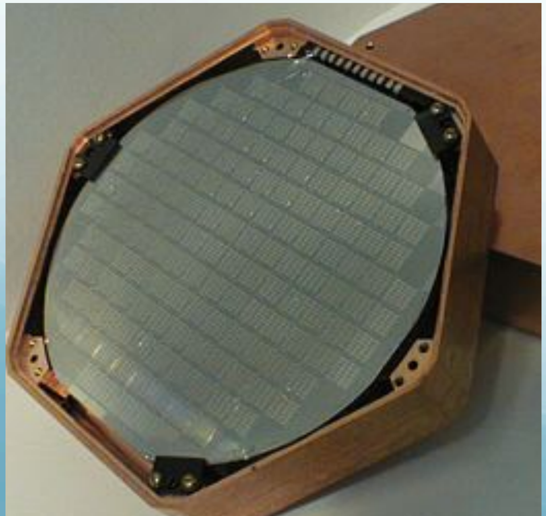
CDMS II

Single-sided
1 cm thick
3”diameter
230 g Ge

2 charge + 4 phonon



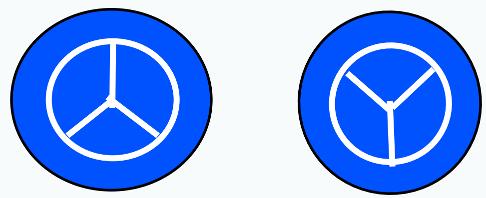
5 towers of 6 det each



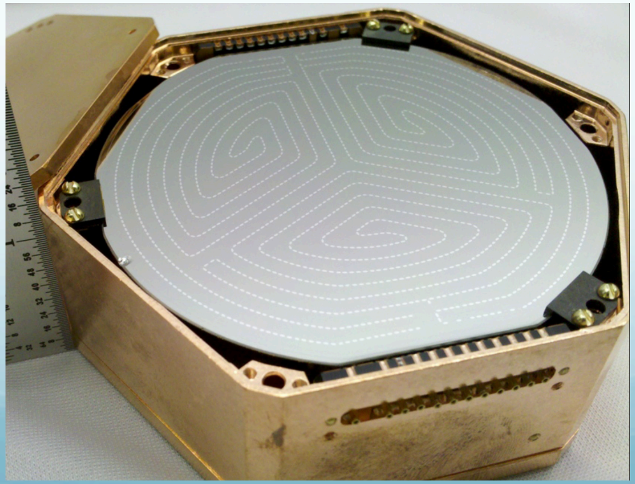
SuperCDMS Soudan

Double-sided
2.5 cm thick
3”diameter
620 g Ge

2 charge + 2 charge
4 phonon + 4 phonon



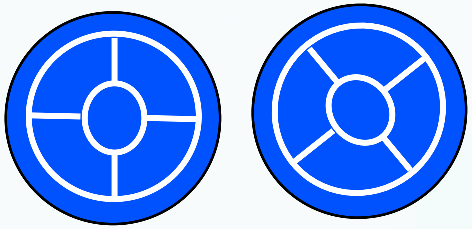
5 towers of 3 det each



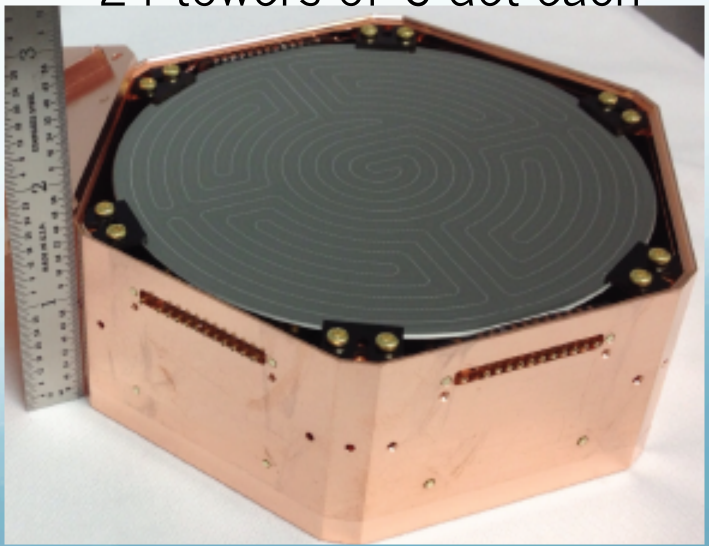
SuperCDMS SNOLAB

Double-sided
3.3 cm thick
4”diameter
1.38 kg Ge

2 charge + 2 charge
6 phonon + 6 phonon

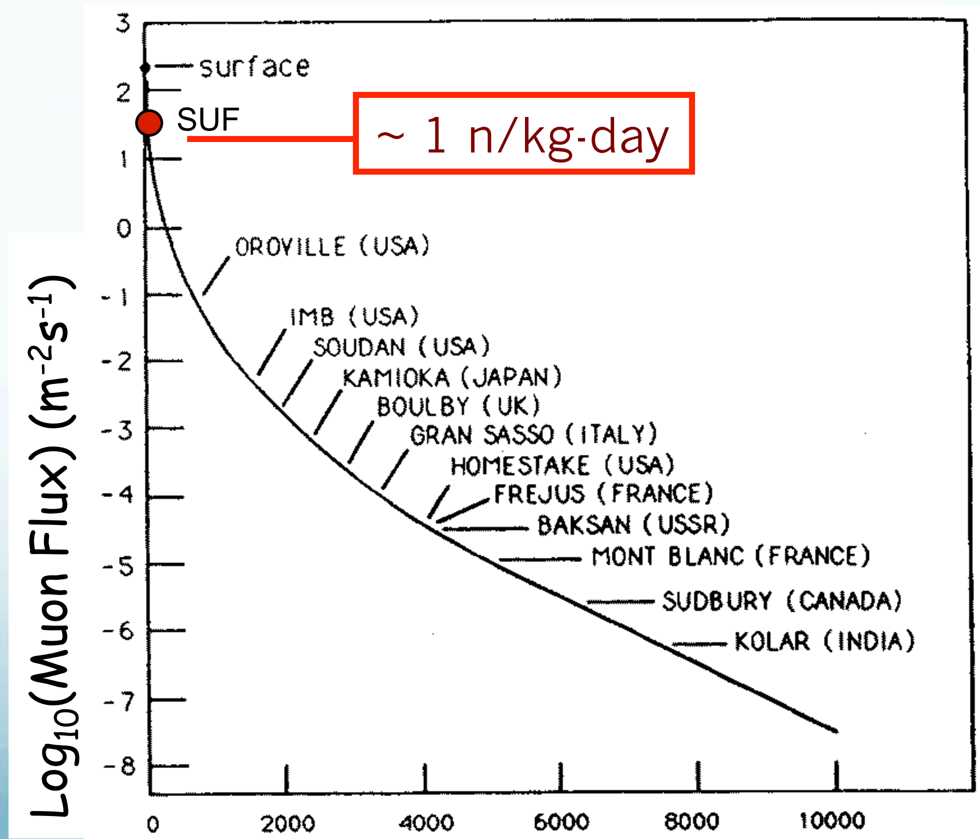


24 towers of 6 det each



CDMS Background Rejection keeps pace with Exposure

Experiment	Net Exposure	Cosmo neutrons	Shield neutrons	Surface events	Fiducial Volume
CDMS-I SUF	28 kg-d	18	---	2	---
CDMS-II Soudan	1 kg-y	.01	.07	1.2	37%
SuperCDMS Soudan	6 kg-y	.07	.24	.005	68%
SuperCDMS SNOLAB	385 kg-y	.03	.1	<.24	73%



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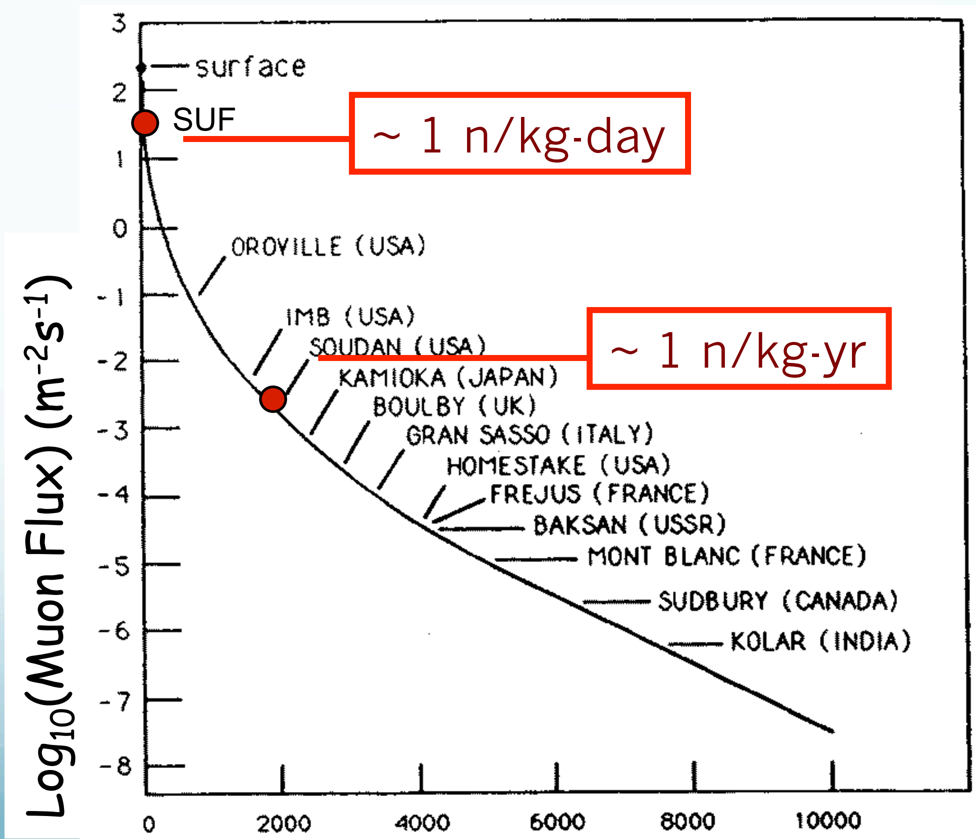

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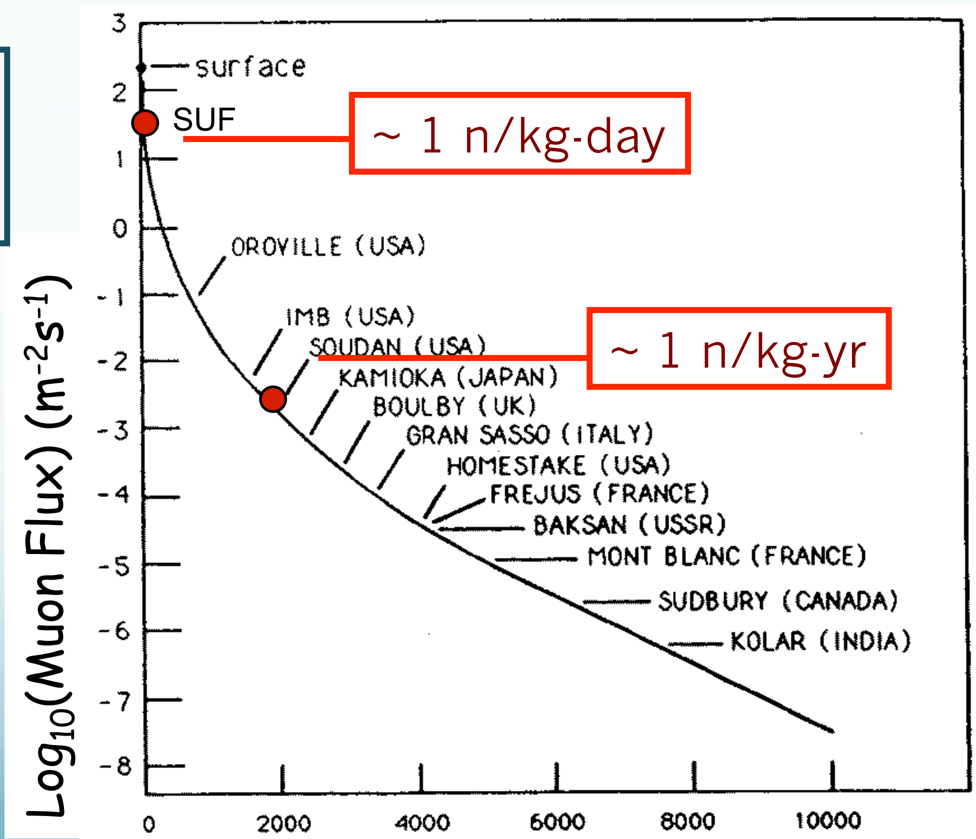
The beauty of SuperCDMS technology
Bulk photon rejection 10^{-7}
Surface "beta" rejection 10^{-5}



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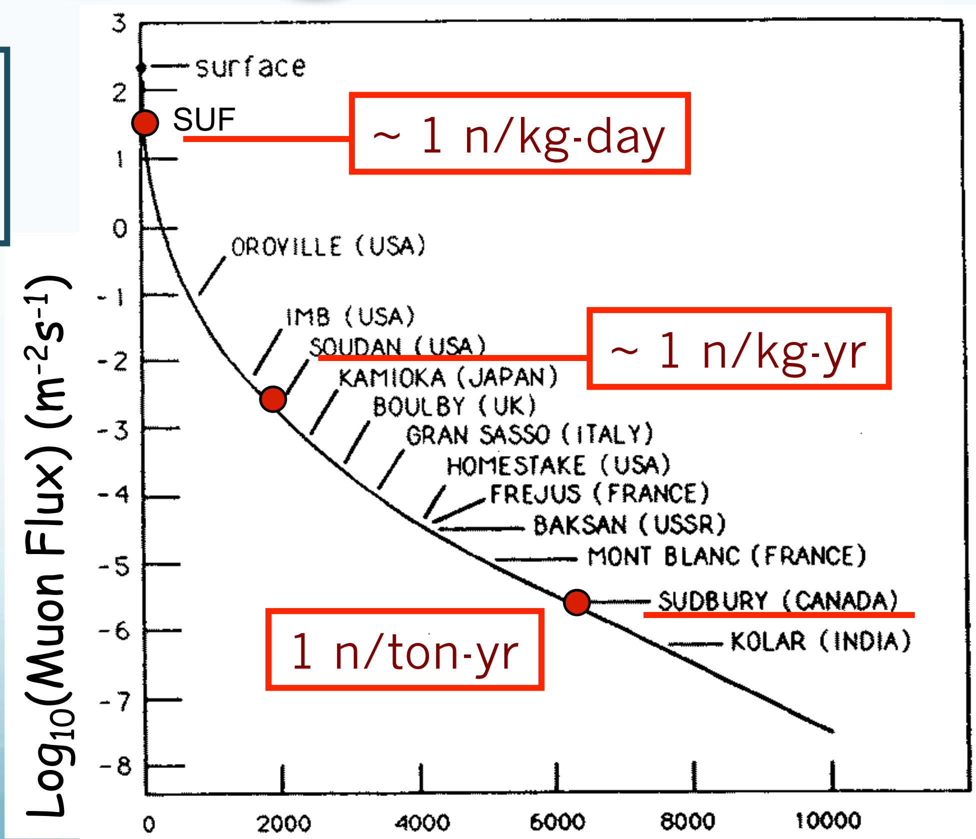
The beauty of SuperCDMS technology
Bulk photon rejection 10^{-7}
Surface "beta" rejection 10^{-5}

No muon veto at SNOLAB
Neutron veto/monitor could reduce dependence on shielding radiopurity



Status and Prospects

Continue to mine the "ReAnalyzed" CDMS II data

Germanium data: better limits, study analysis techniques
Silicon data: new results for runs 125-8, see some candidates
Finished up Si analysis for runs 123-124
Push Si and Ge to lower thresholds
Push annual modulation to lower energies

Running iZIPs at Soudan

Establish the surface event rejection of iZIPs
Finish a blind analysis of the low threshold data
Continue data taking for sensitivity across all masses
Run with high "Luke Gain" to lower thresholds even further

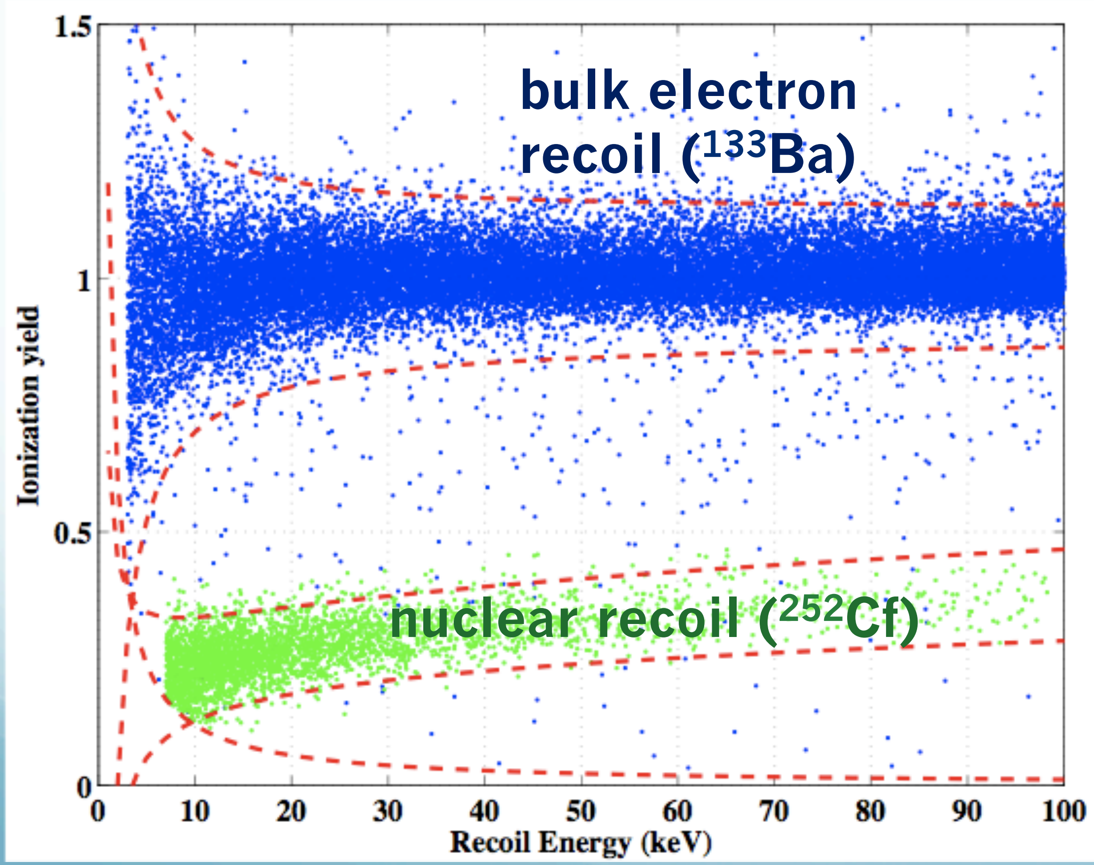
Develop advanced detectors at SNOLAB

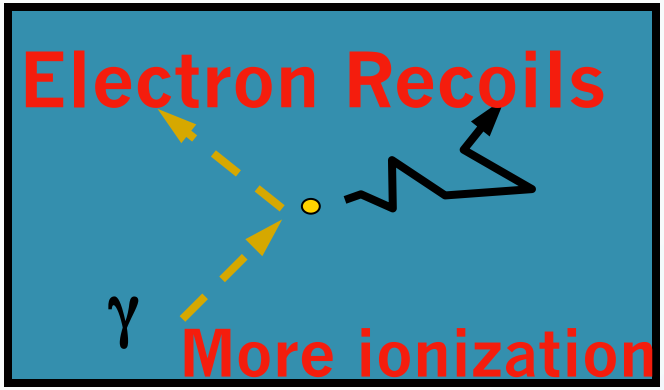
R&D on large detectors and Tower design
Neutron Veto and Shield Radiopurity
Explore reach to neutrino floor in low mass regime

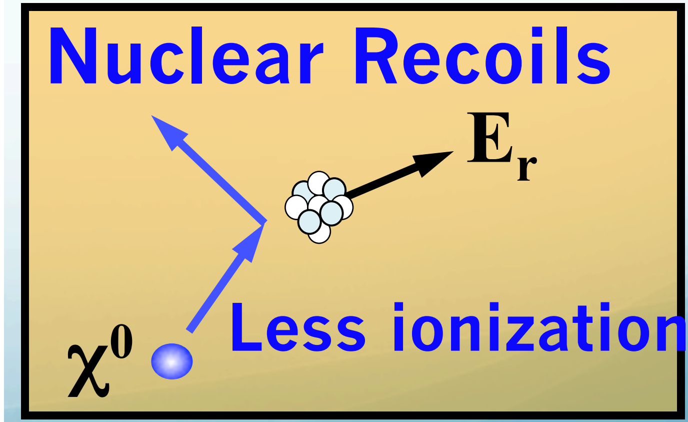
Yield = Bulk Gamma Rejection

$$= \frac{\text{ionization energy}}{\text{phonon energy}}$$

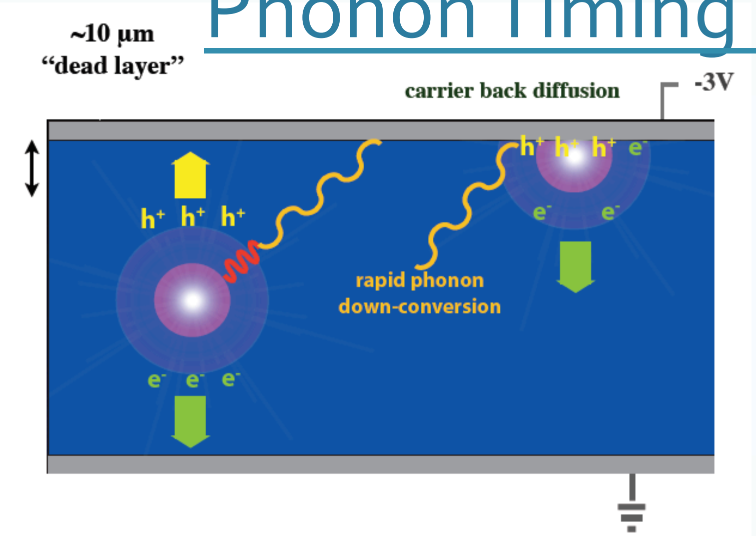
Primary electron recoil rejection >10,000:1



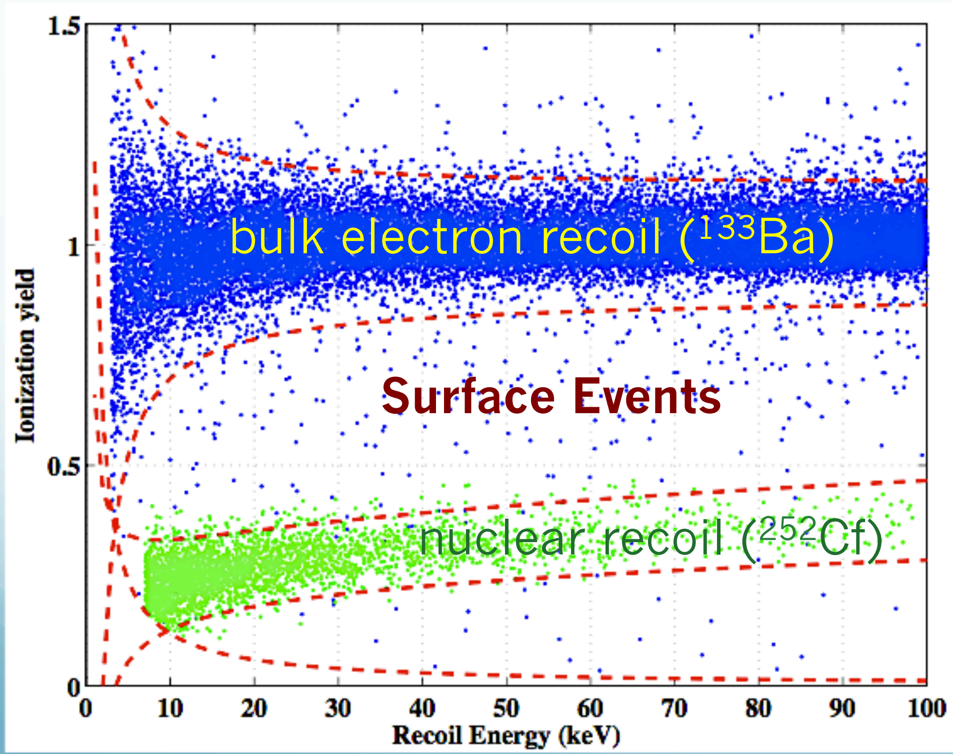




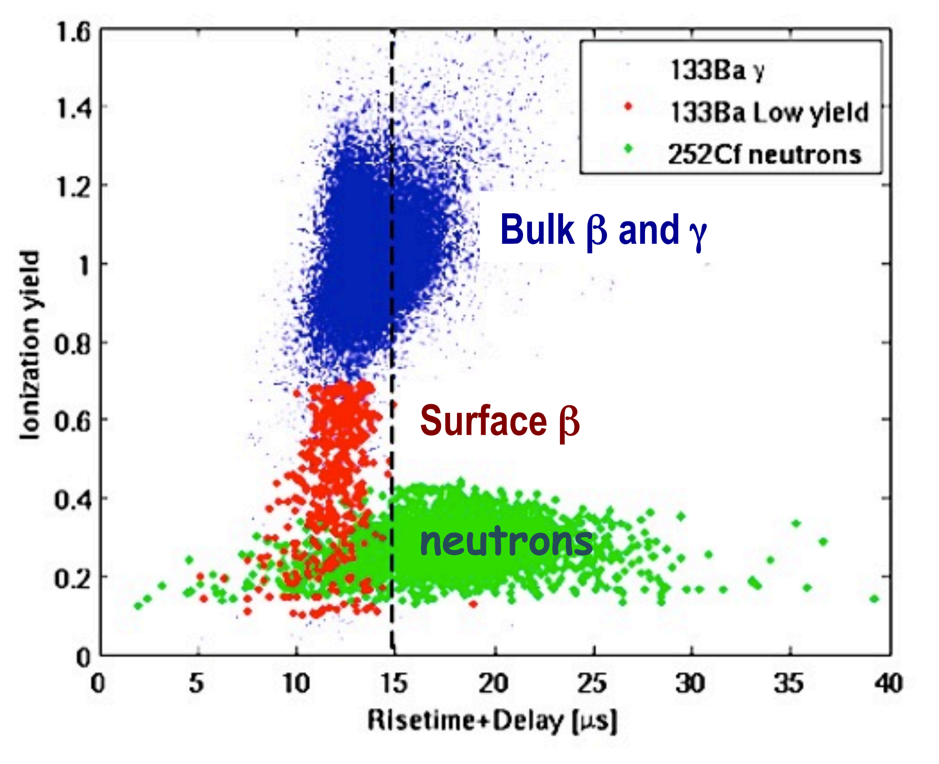
Phonon Timing = Surface Event Rejection



Phonons created near surface travel faster through crystal (ballistic)



Calibration Data



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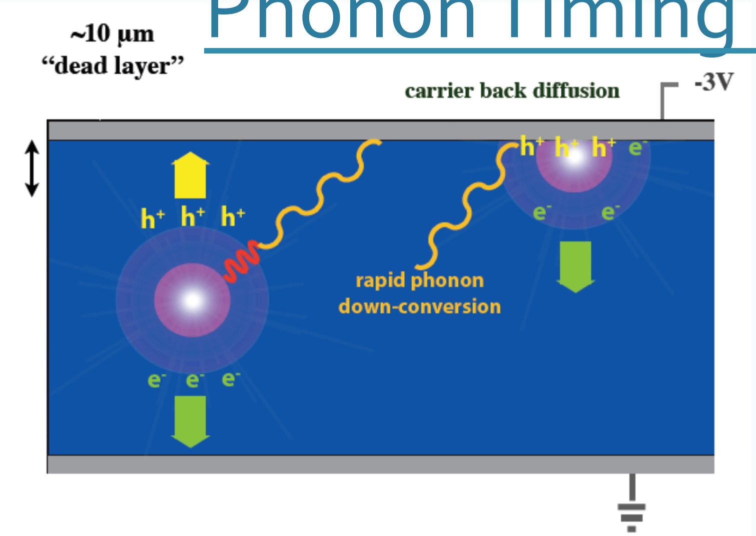

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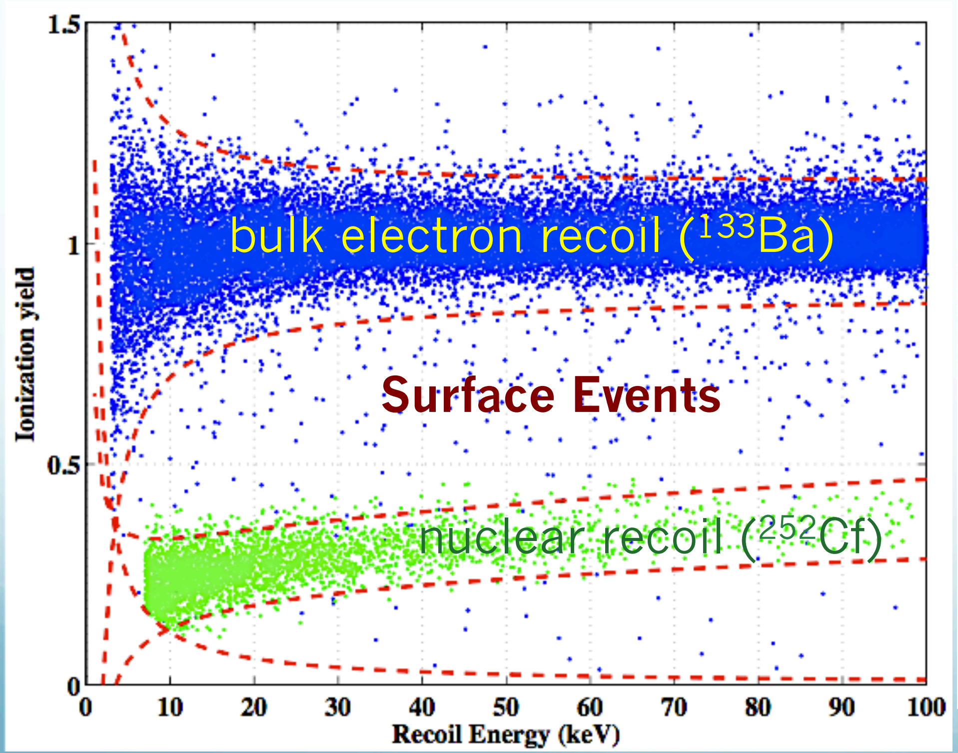
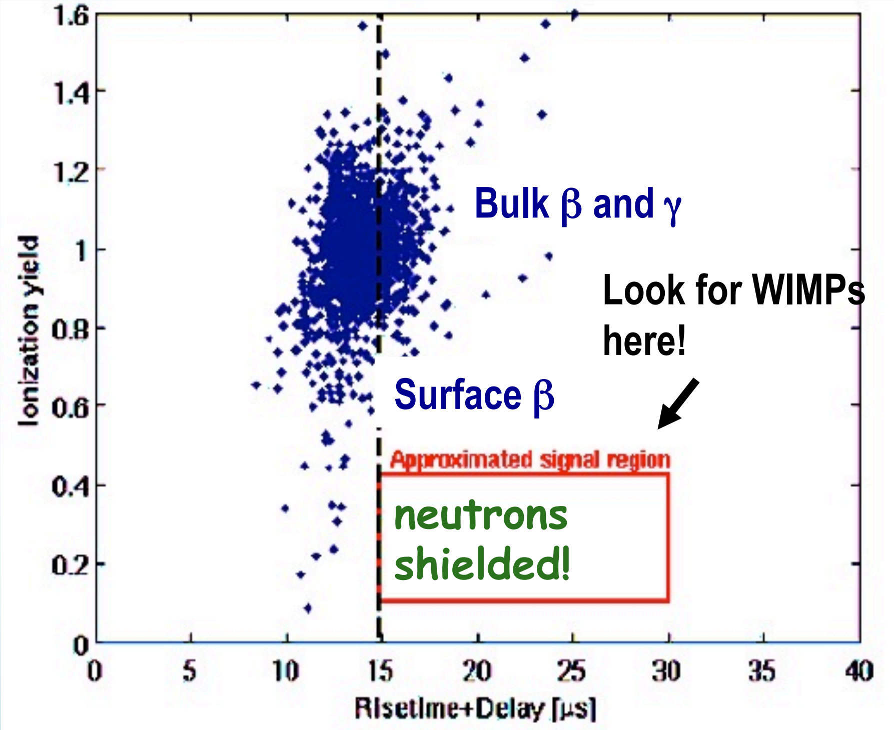
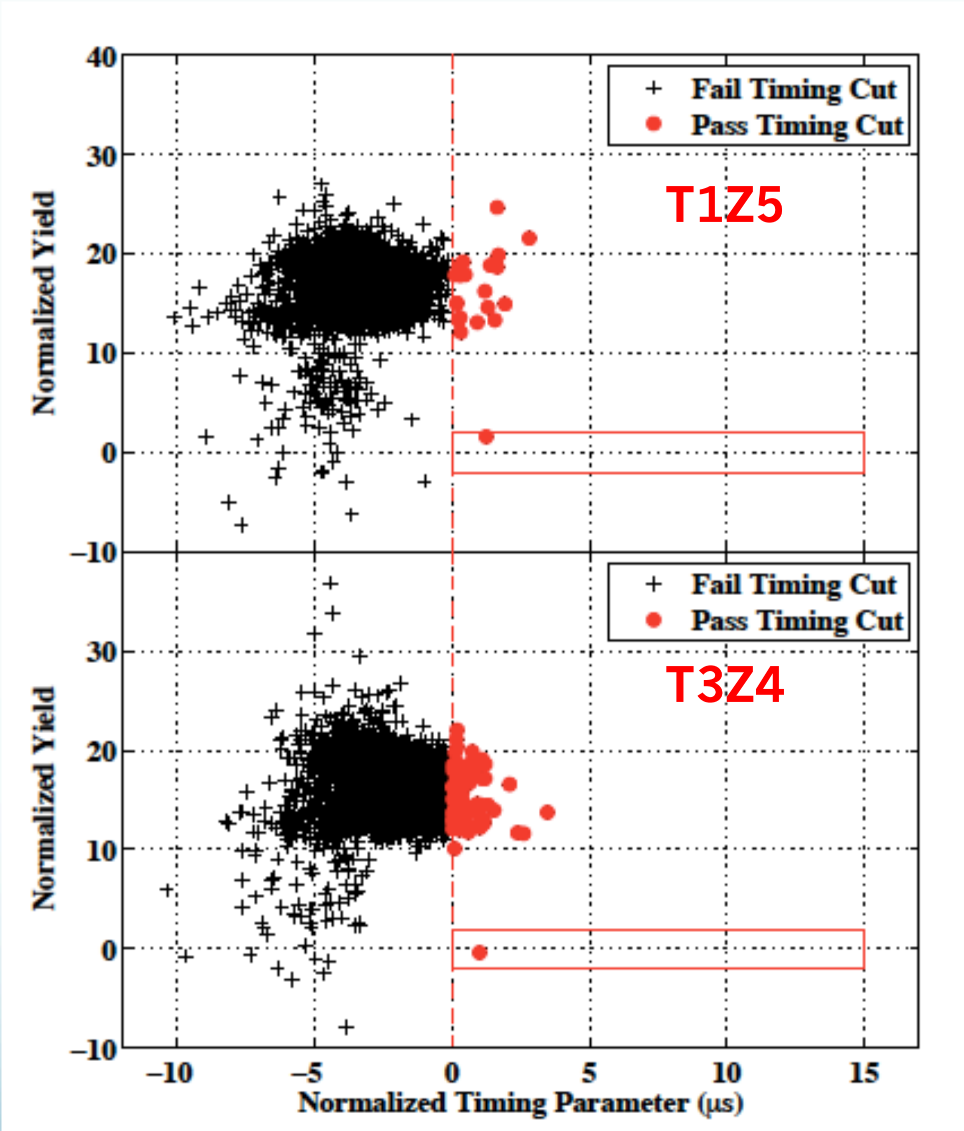


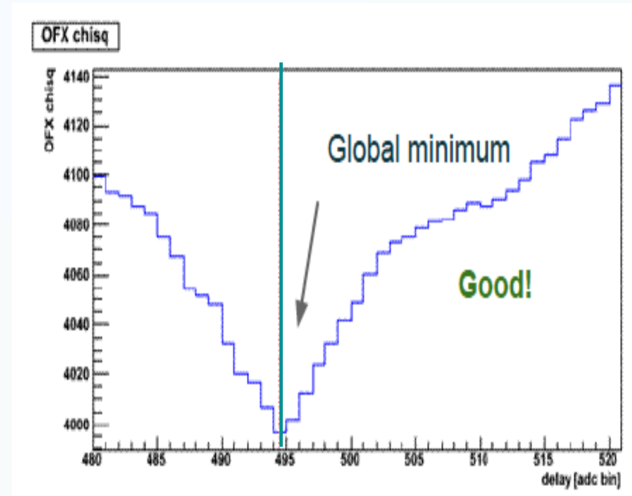
WIMP Search Data

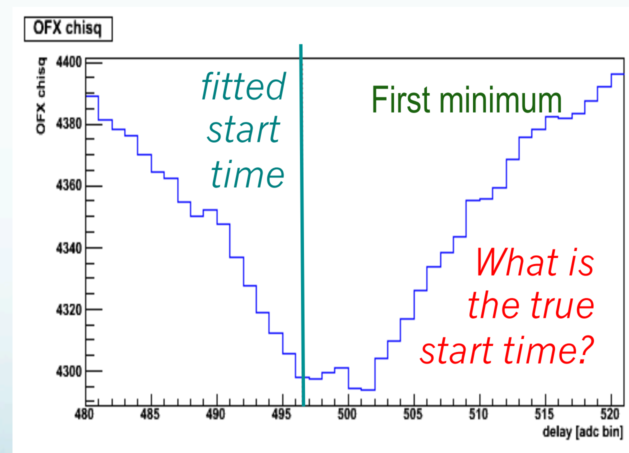


2010 CDMS-II paper had 2 candidate evts in Ge



Reanalysis chooses global rather than local min chisq





Only affects 1% events with Q < 6 keV.

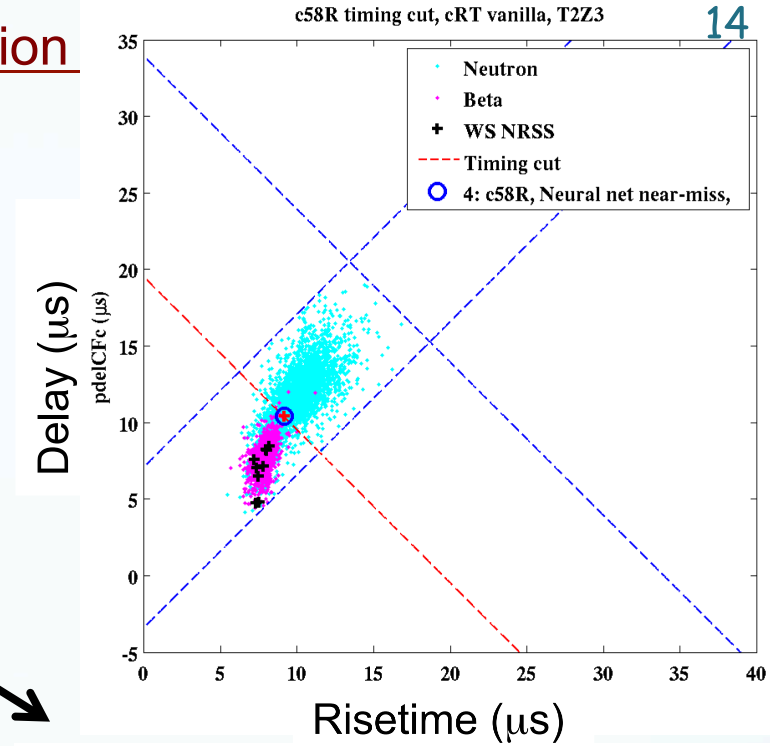
Pre-unblinding leakage estimate accounted for this!

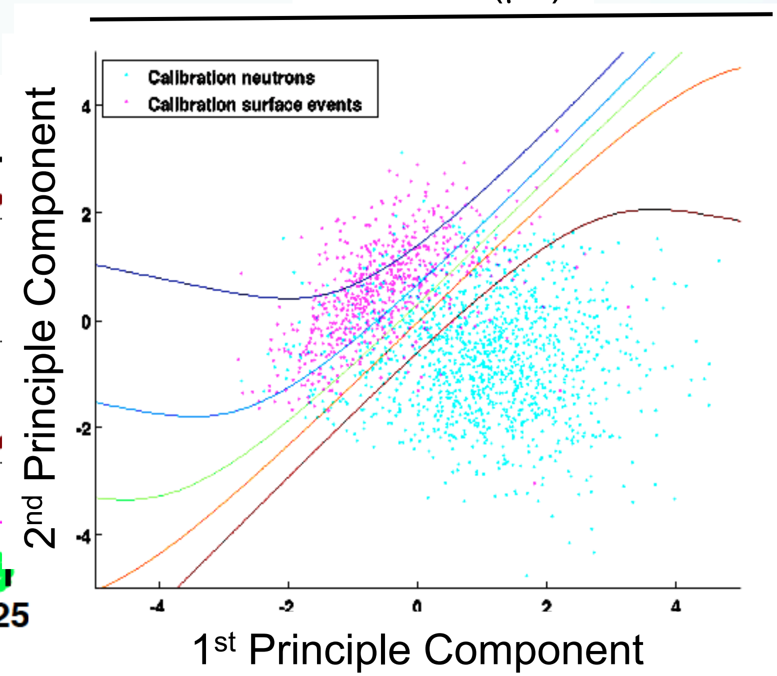
Timing cut tuned to 0.6 surface evts, but leakage est. = 0.8 ± 0.1(stat) ± 0.2(sys)

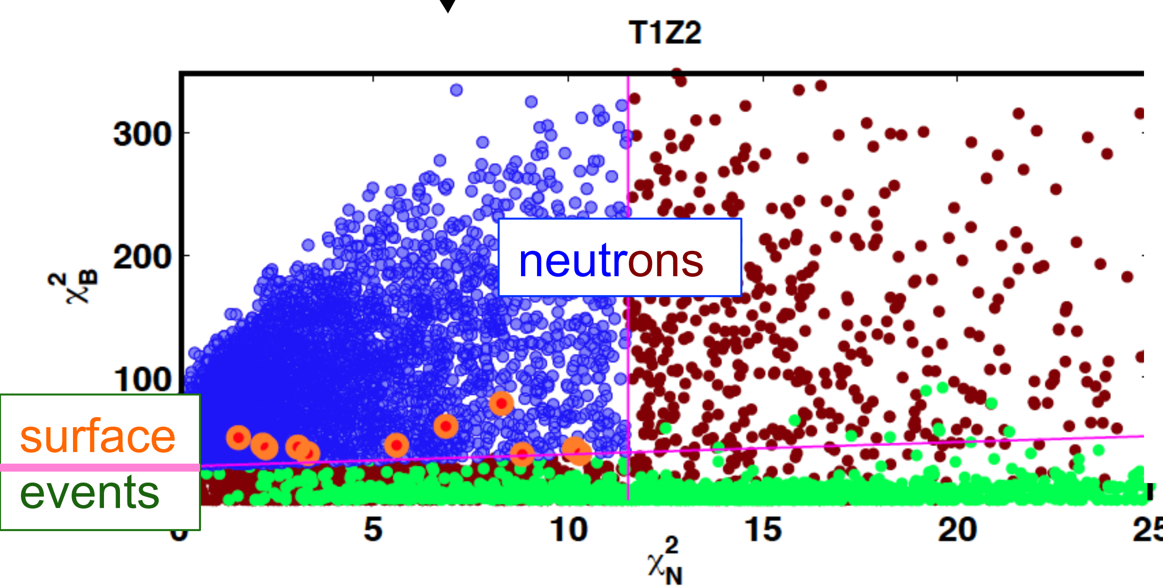
Reanalysis used 3 techniques for surface rejection

tuned to maximize sensitivity for a 60 GeV WIMP with 0.5 leakage evts.

* Classic timing cut (219.1 kg-d)
• Contour cuts based on neural networks (216.4 kg-d)
* 5D χ^2 optimization (262.3 kg-d)



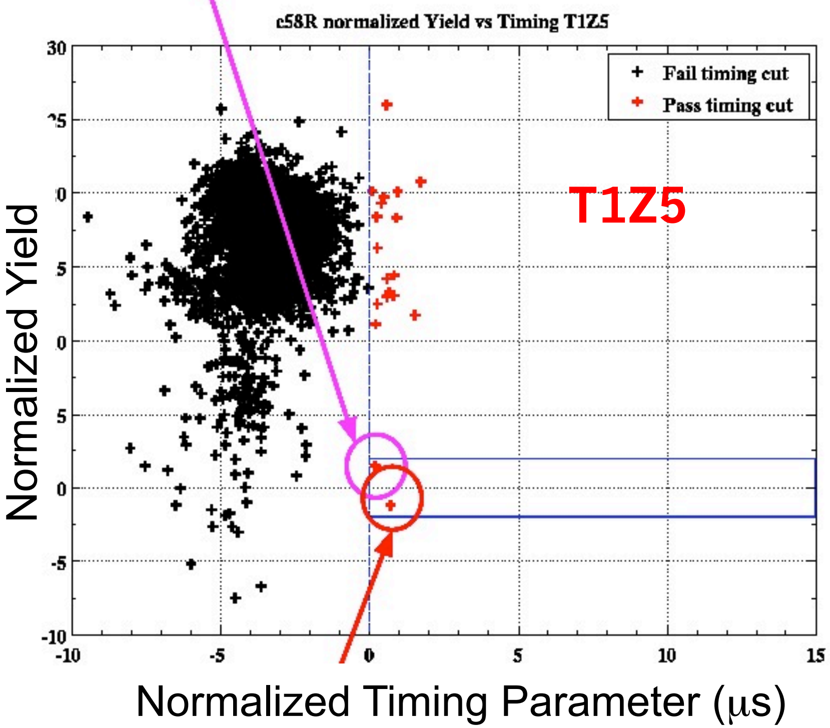


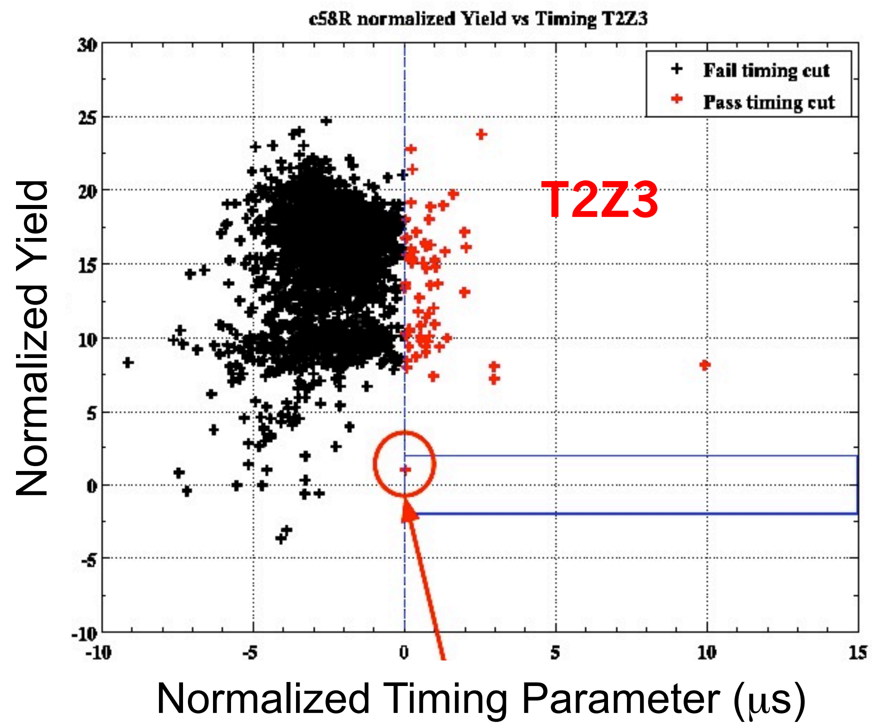


Germanium Reanalysis Results

The candidate from T3Z4 moved below all new, optimized timing cuts, but the other one remained in 2 out of 3 of the timing cut choices. New ones show up.

27 Oct 2007
12.30 keV
NN + Classic + **2010**



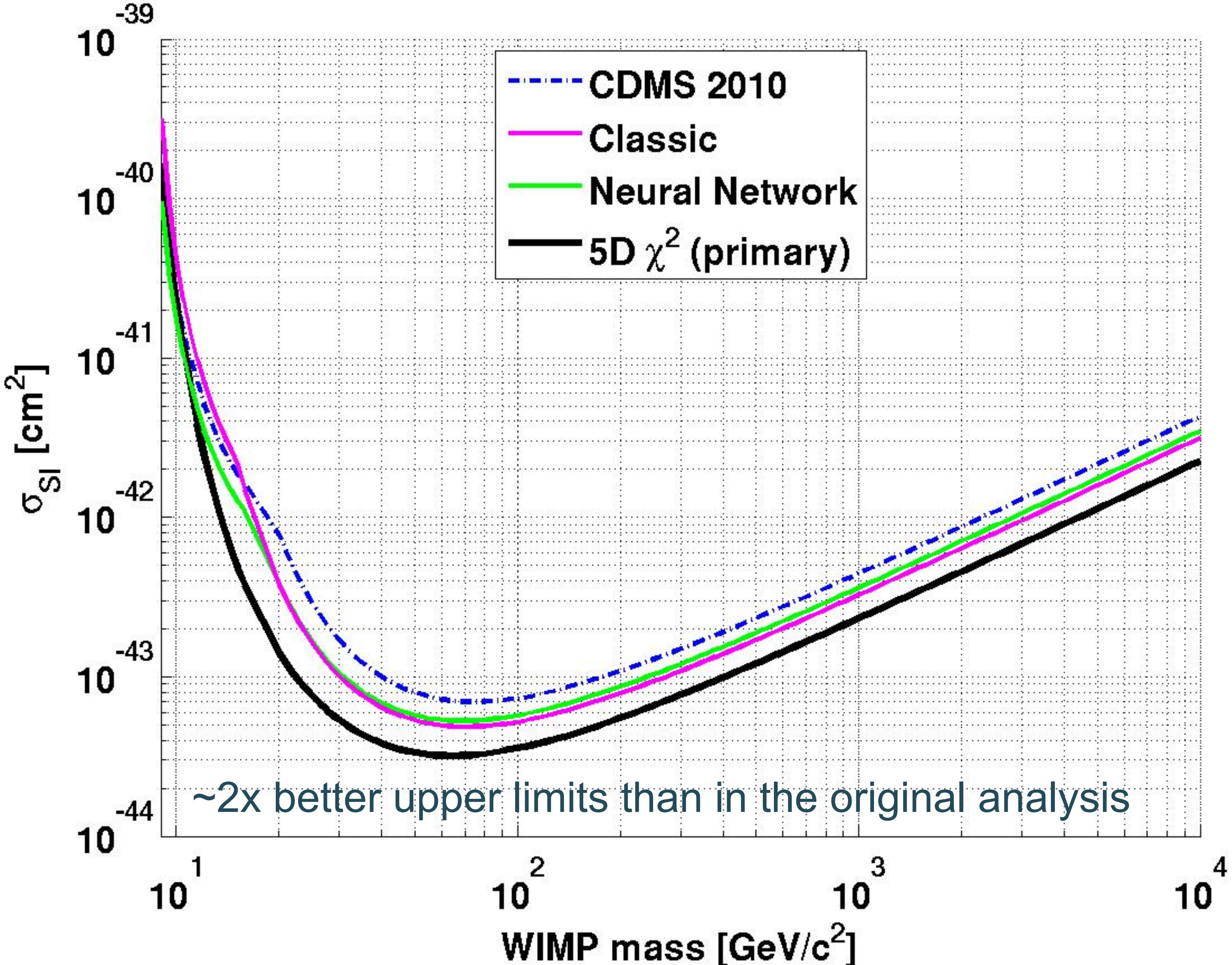


1 Feb 2008
13.44 keV
NN + Classic

30 May 2008
10.81 keV
Classic

90% Confidence Upper Limits

Total exposure Ge limits now include reanalyzed 125-8



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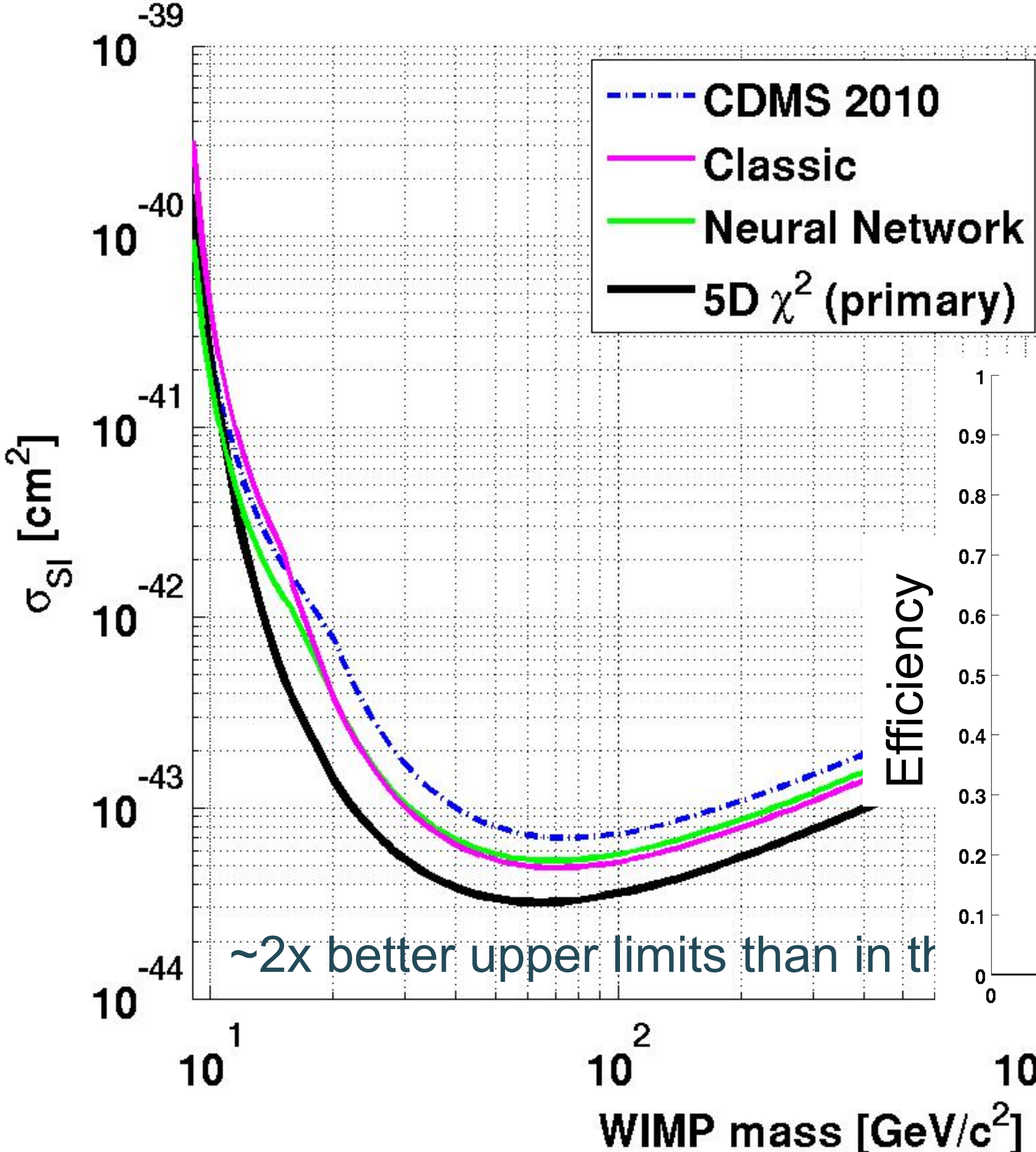
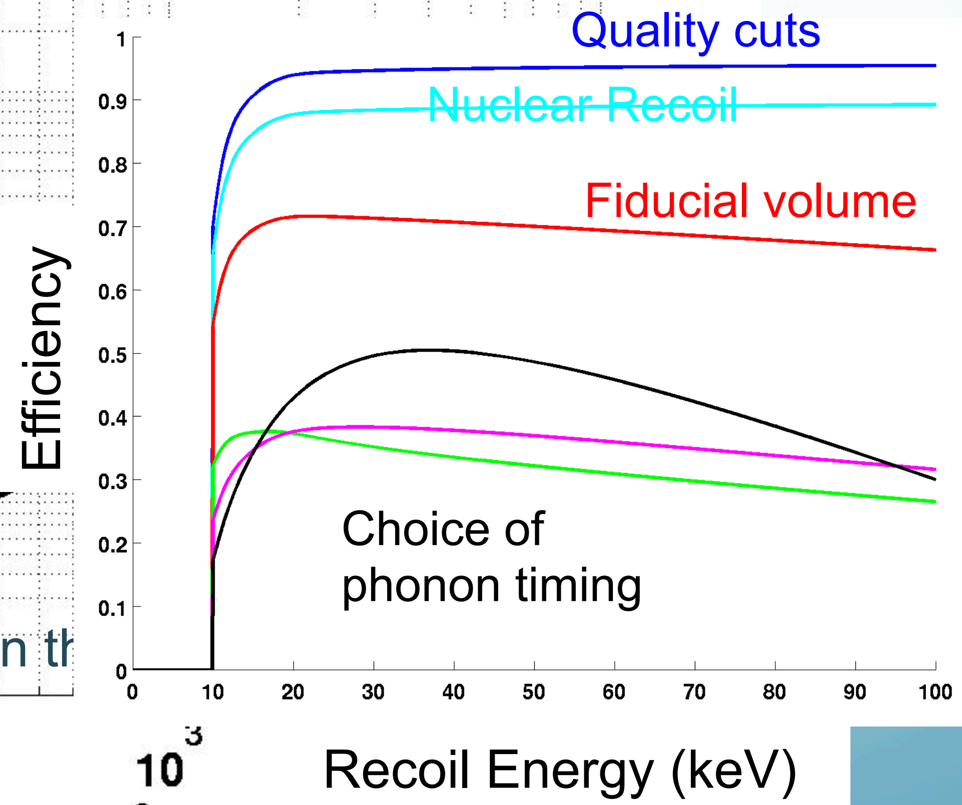
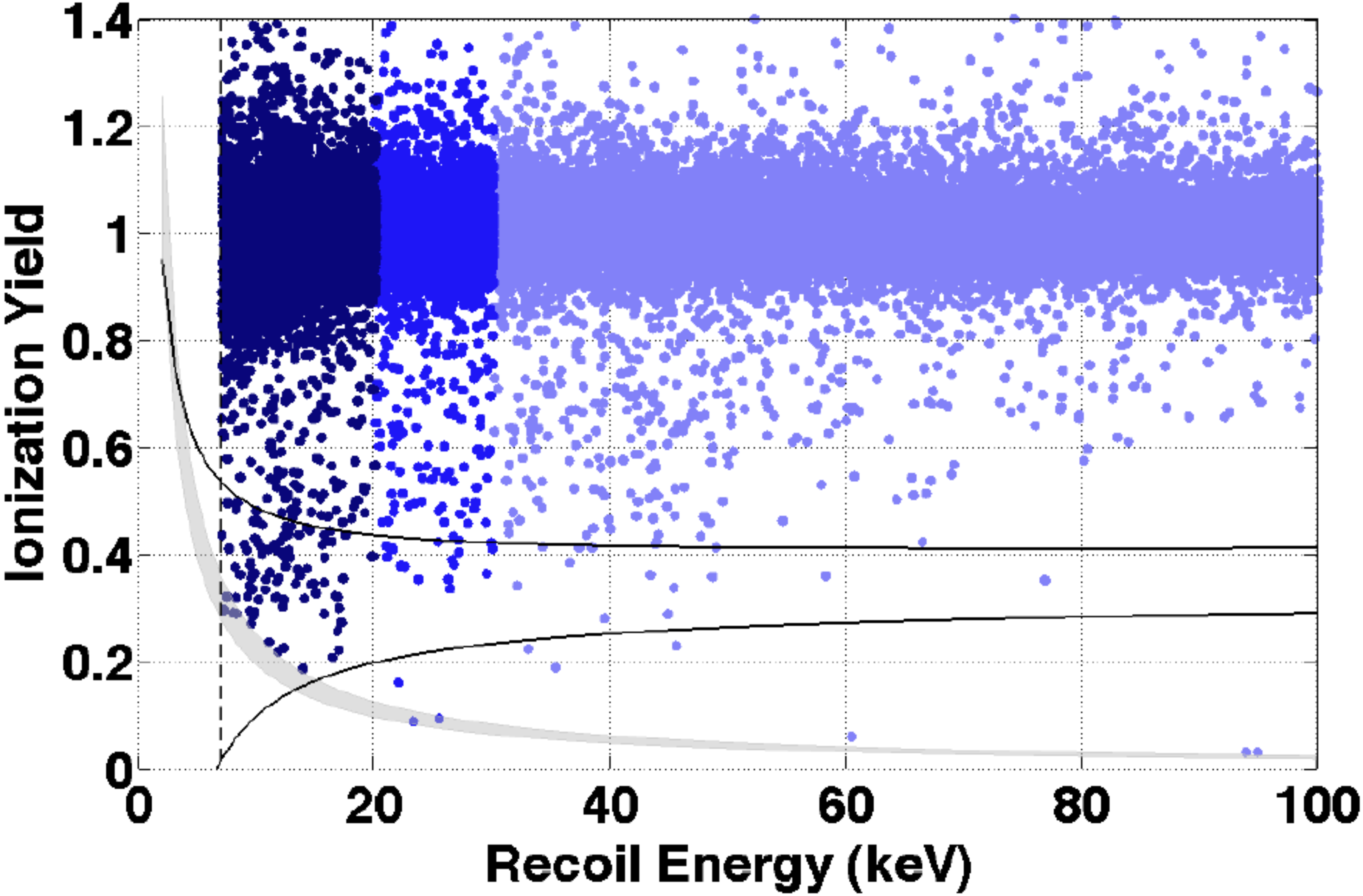


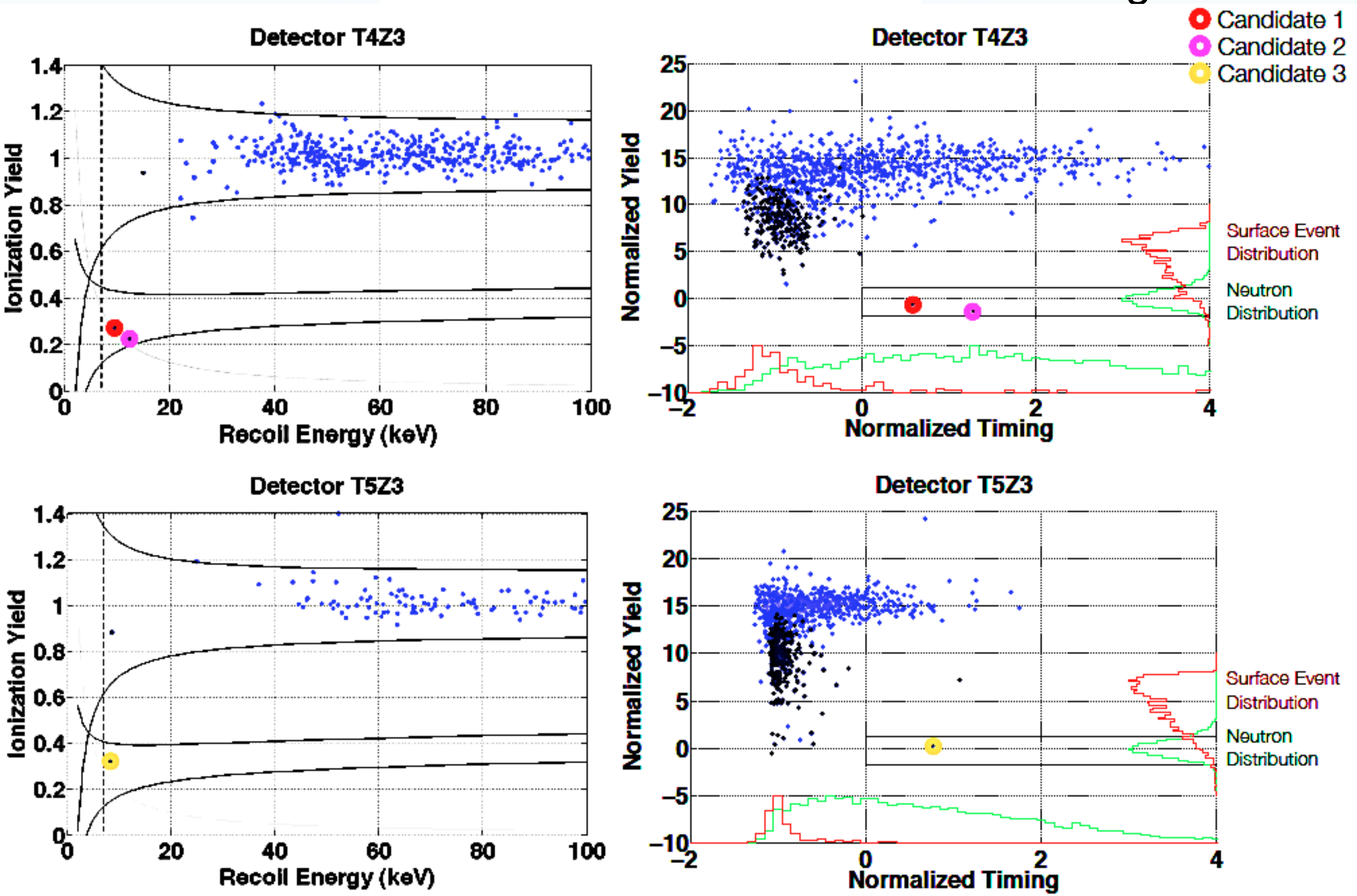


Also analyze the Silicon data from runs 125-128

Before applying timing cut (all detectors superposed)

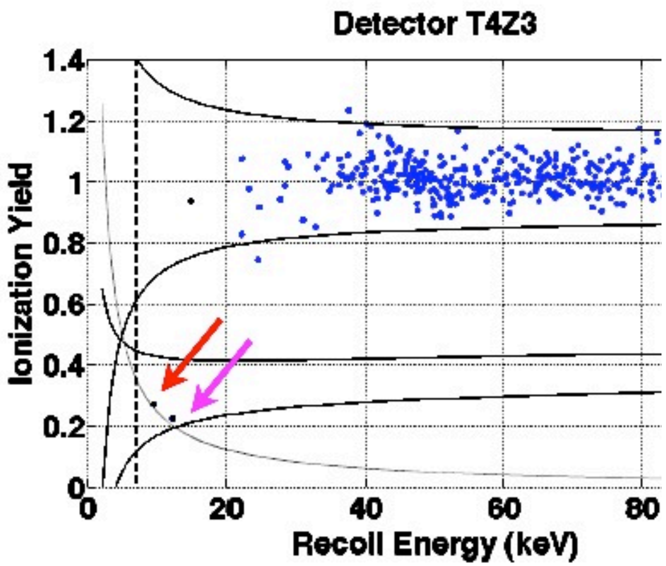


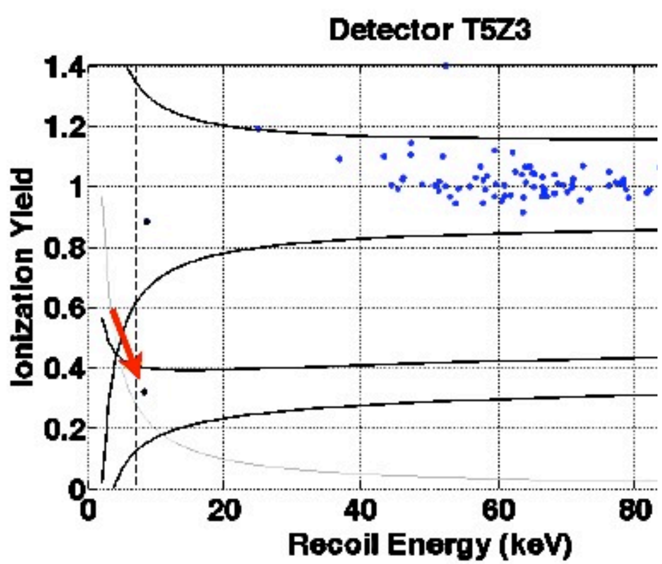
Using a modified version of the 5D χ^2 phonon timing cut, Silicon reveals 3 events with expected surface leakage of

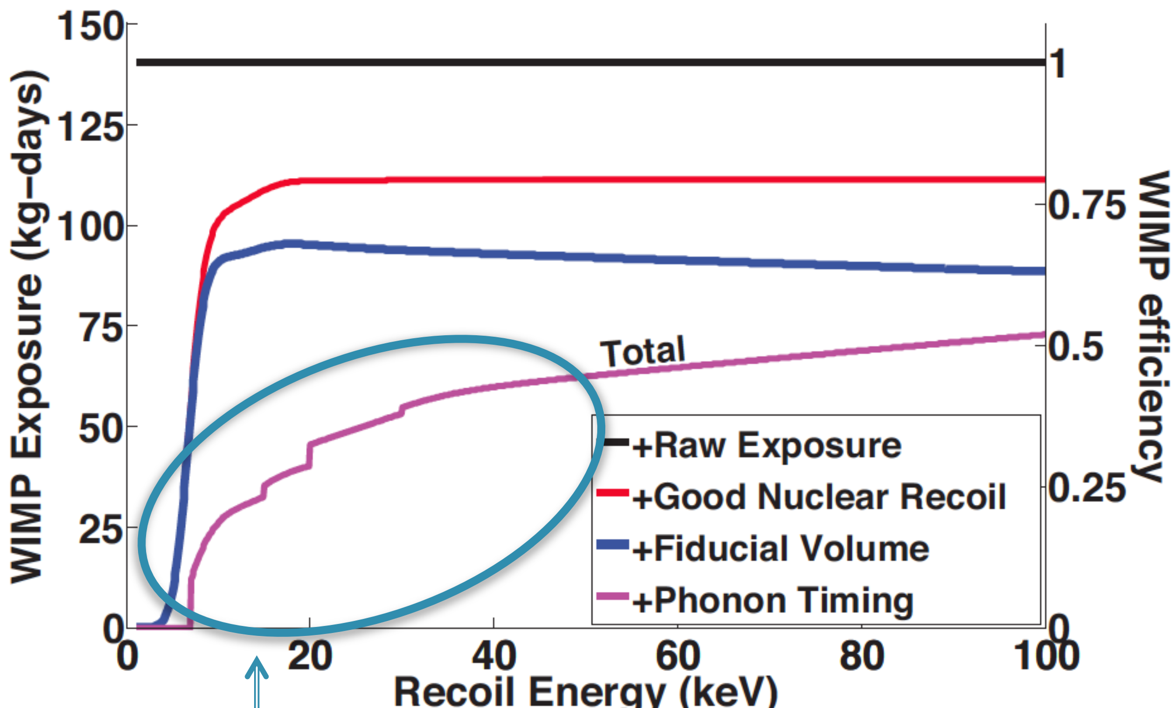


Using a modified version of the 5D χ^2 phonon timing cut, Silicon reveals 3 events with expected surface leakage of

$$0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$$



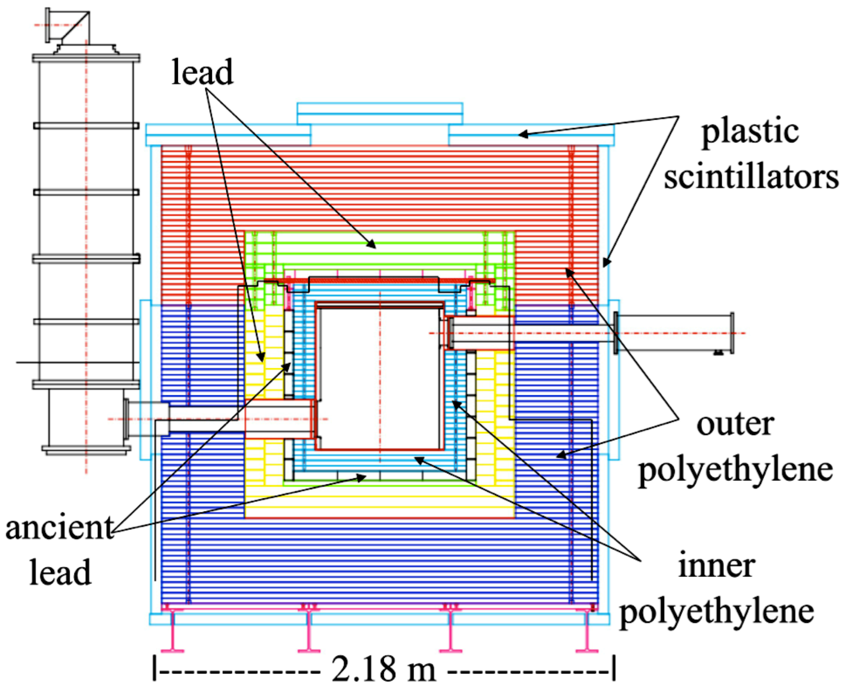




Room for Threshold Reduction.
Work ongoing.

Neutron background also needs to be estimated

CDMS II Si detectors in runs 125-8
140 kg-d raw exposure



Cosmogenic

Full Geant4 Simulation starting from muon files using Soudan2/MINOS slant path data.

Normalize to veto-coincident data

Using 1 single : **0.032 NR (-0.028 + 0.069)**
+ also 3 multiples: **0.021 NR (-0.008 + 0.011)**

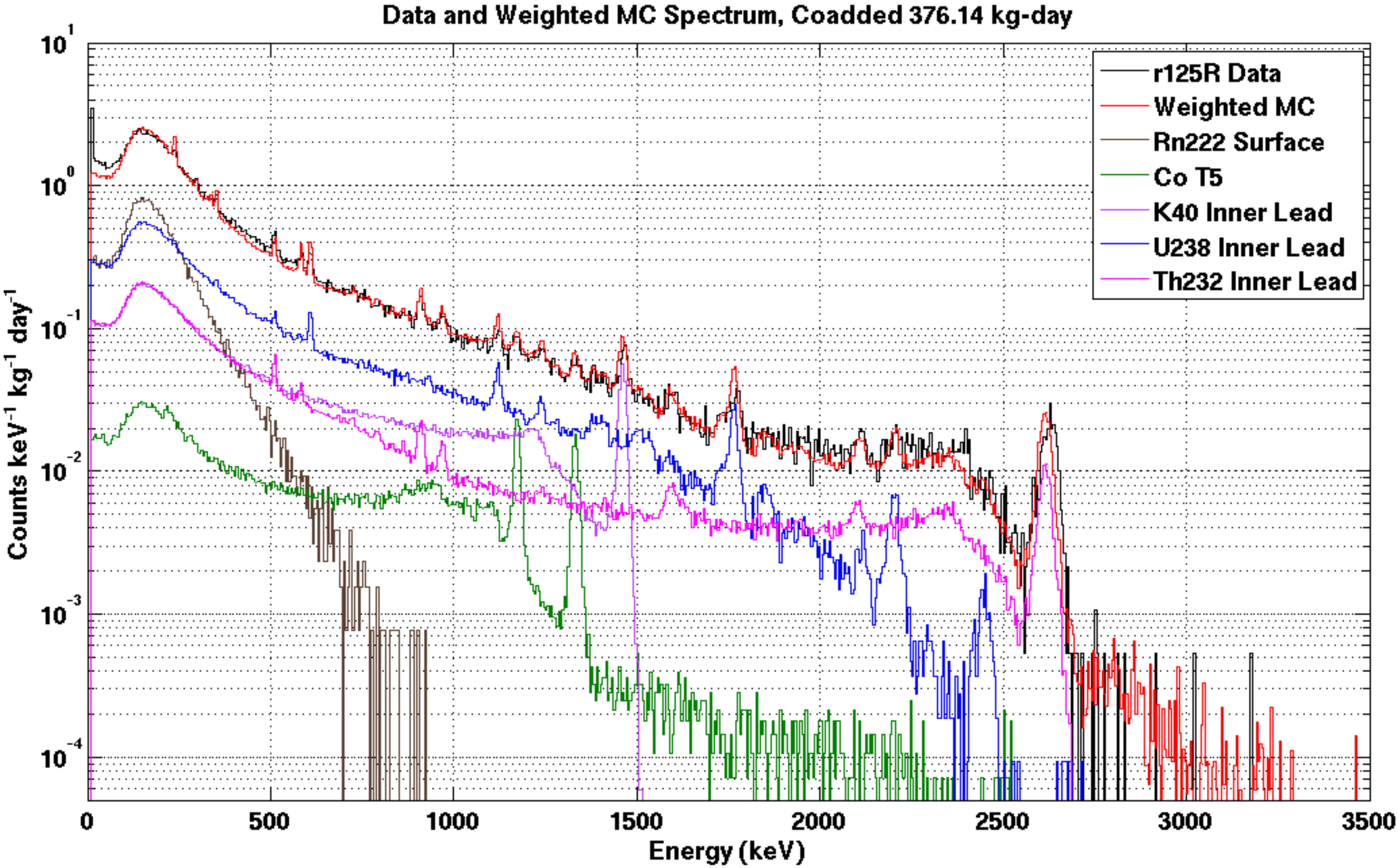
Radiogenic

Create simulated gamma spectra individually from U/Th/K/Co in each shield element
Global fit to data (electron recoil spectrum) determines contaminant levels
Materials screening results (HPGe) limit ambiguities in global fit
Once levels are determined, run Geant4 to find the flux of α-n and fission neutrons from shielding and towers with these contaminants.

0.017 NR (-0.002 + 0.002)

Si Paper quotes
.032+.069 + .017+.002 ➔ < 0.13 neutrons

Example of global gamma fit to electron recoil data
(input to radiogenic neutron simulation)



Combining the neutron simulations gives not only the background rate, but also the spectrum of neutron-induced nuclear recoils.

What is the significance of 3 Si candidate events?

Monte Carlo simulations of a background-only model (H_0) gives a probability of **5.4%** for a statistical fluctuation producing $\geq$3 evts anywhere in the signal region.

$$q_0 = -2\log\left\{\frac{\mathscr{L}(m_\chi, \sigma_{\chi-n}=0, \hat{\hat{\vec{\nu}}})}{\mathscr{L}(\hat{m}_\chi, \hat{\sigma}_{\chi-n}, \hat{\vec{\nu}})}\right\} \equiv 2\log\left\{\frac{\mathscr{L}(H_1)}{\mathscr{L}(H_0)}\right\}$$

A likelihood ratio test favors a WIMP + Background hypothesis at 99.81% CL
e.g. the p-value of a Background-only hypothesis is **0.19% or ~ 3σ**

The maximum likelihood occurs at a

M_W = 8.6 GeV/c^2

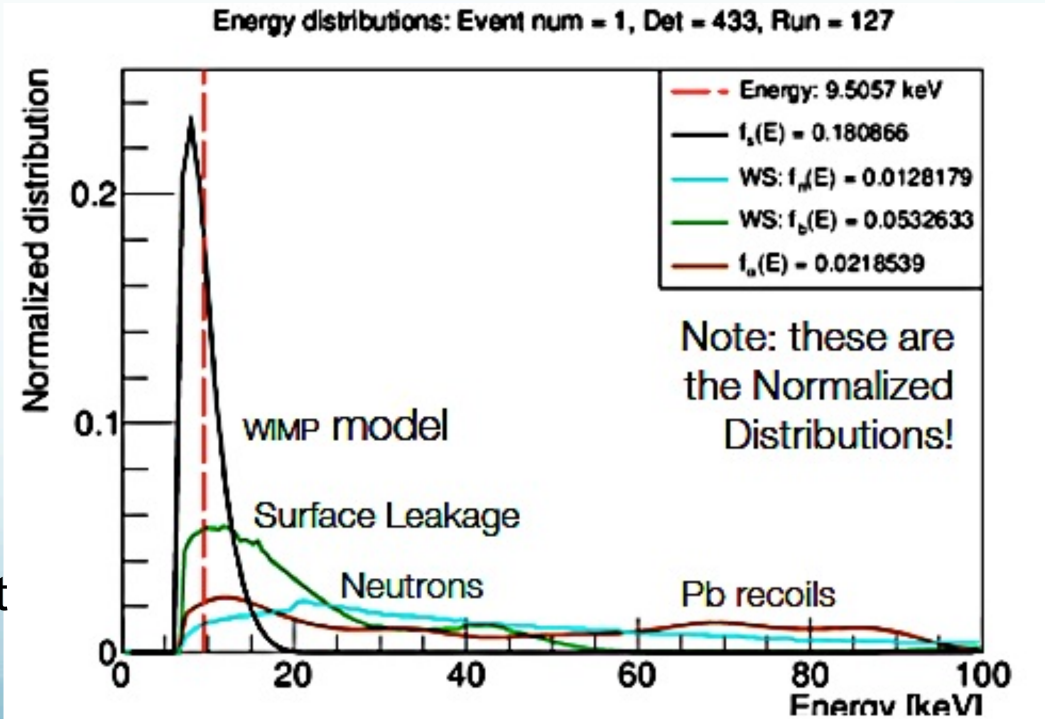
σ_{SI} = 1.9 x 10^{-41} cm^2

<u>Goodness of fit</u>

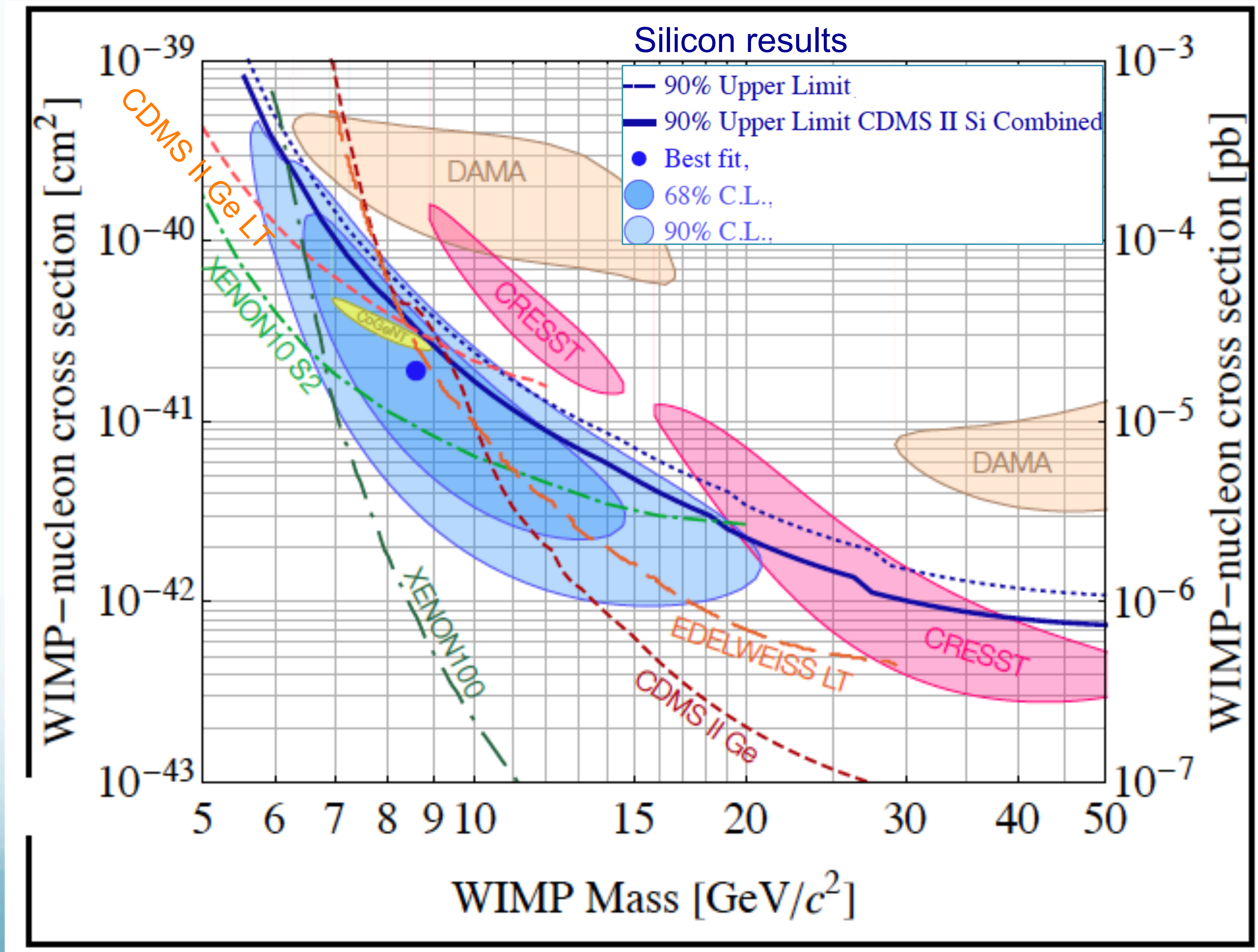
WIMP + Background = 68.6%

Background only = 4.2%

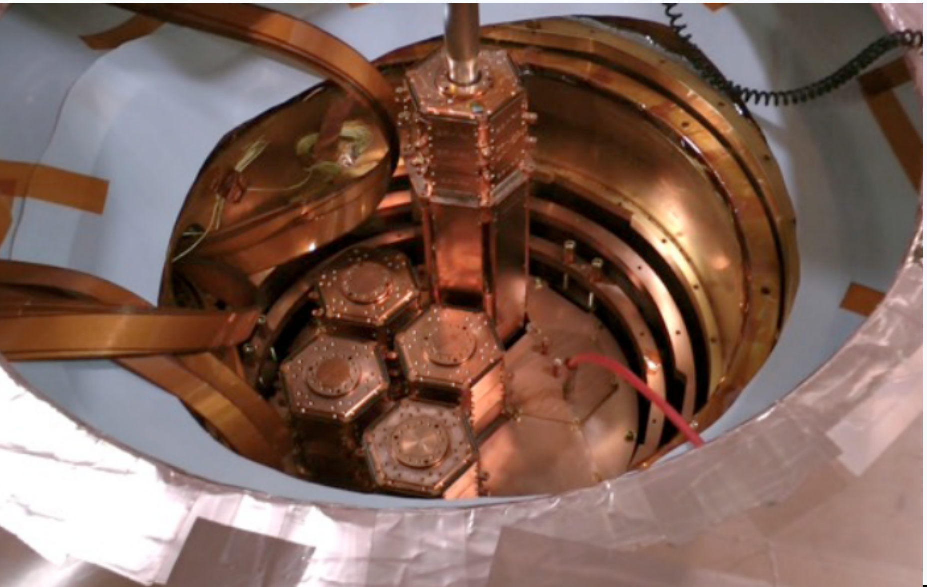
We could have done an optimal gap limit
➔ 2.4 x 10^{-41} cm^2 for a 10 GeV WIMP

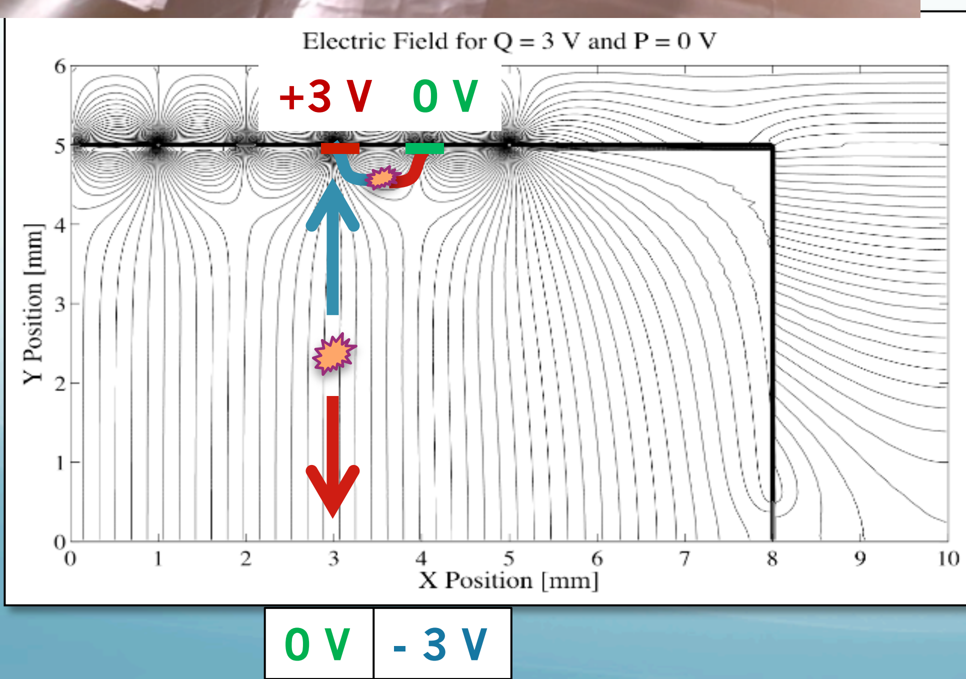


PDFs of the expected background contaminations


Silicon results
90% Upper Limit
90% Upper Limit CDMS II Si Combined
Best fit,
68% C.L.,
90% C.L.,
DAMA
CRESST
CoGeNT
CDMS II Ge LT
XENON10 S2
XENON100
EDELWEISS LT
CDMS II Ge
WIMP−nucleon cross section [cm^2]
WIMP−nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
5 6 7 8 9 10 15 20 30 40 50

SuperCDMS-Soudan





5 towers of 3 Germanium **iZIP**s each

interleaved
Z-sensitive **I**onization and **P**honon

9 kg total target mass.

Operating since October 2011

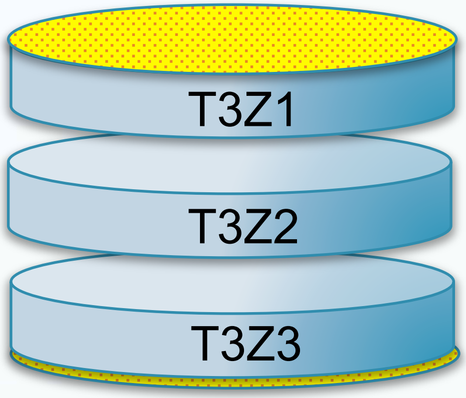
Plan to run through March 2014

Silicon will be considered if our low threshold run results warrant it

New E-field Configuration
Surface events will fail
a charge symmetry cut

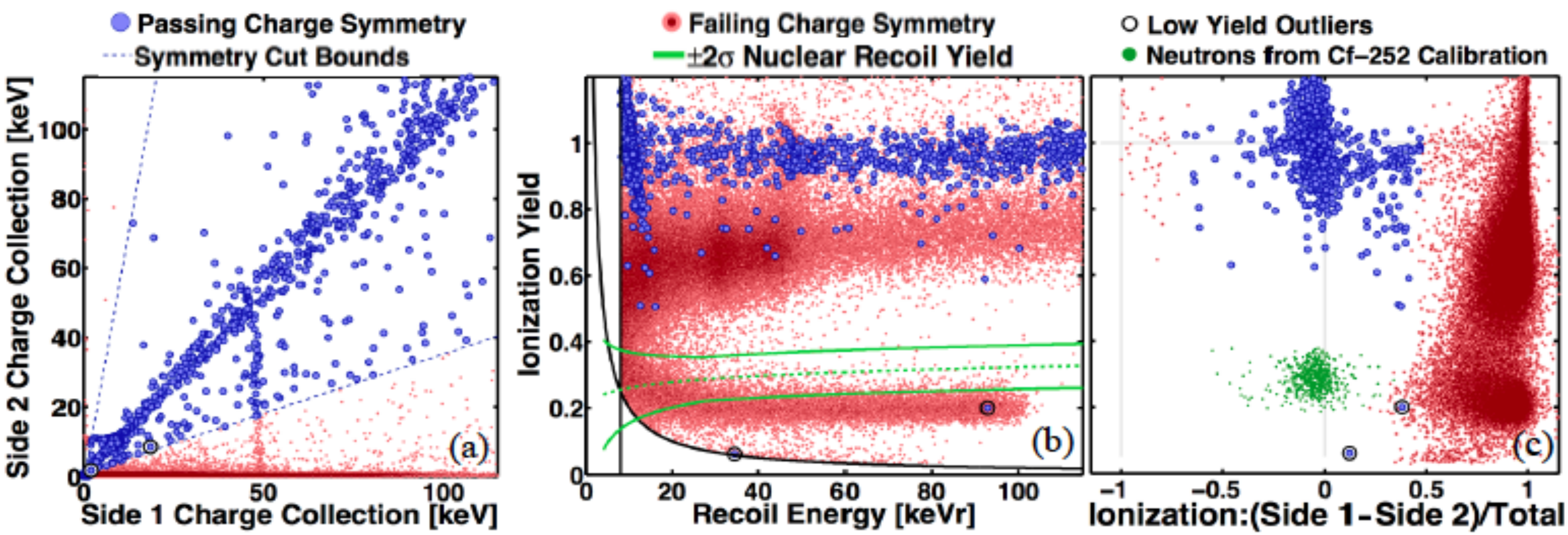
Surface Event Calibration

Two Si wafers implanted with ^{210}Pb via radon exposure.
37.6 live days of data on these detectors.
130 beta decays/hr



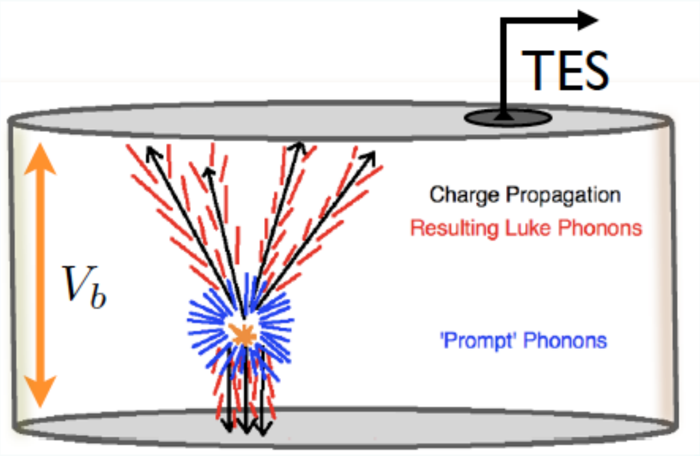
Surface evt leakage via charge asymmetry:
1.7×10^{-5} at 90% CL
For a 50% fiducial cut on 60 GeV/c^2 WIMP

Even better if we add in phonon timing & asymmetry.
Good enough for ton scale



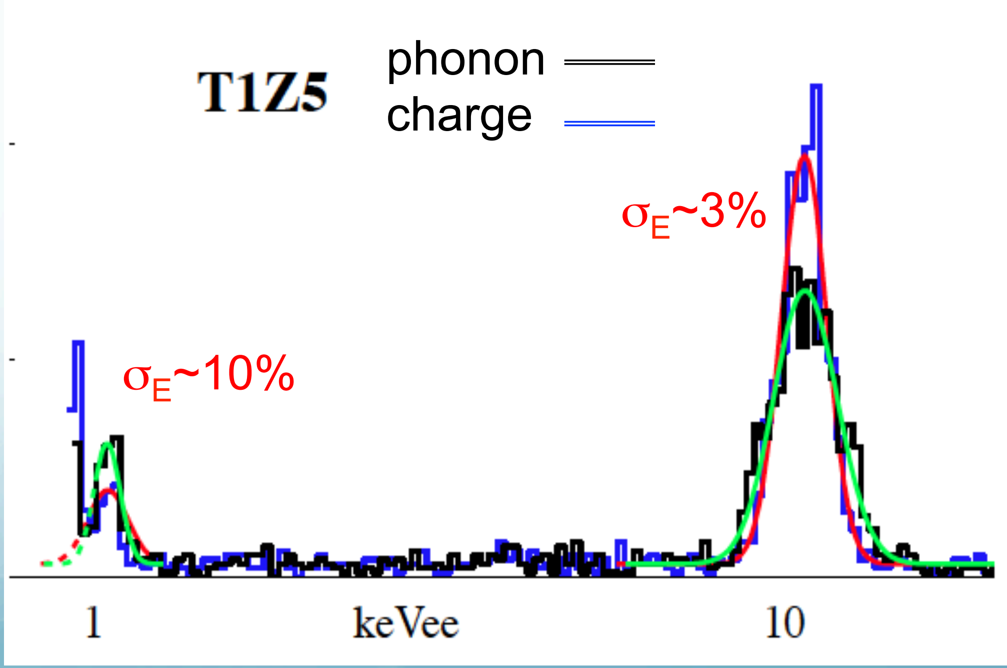
CDMSLite: Low Ionization Threshold Experiment

$$E(\text{phonon}) = E(\text{recoil}) + \frac{eV_b}{\varepsilon} E(\text{charge})$$



Luke Phonons interfere with timing cut and complicate yield discrimination
So CDMS runs with V_b <10 (Luke Gain ~ 2) to minimize effect

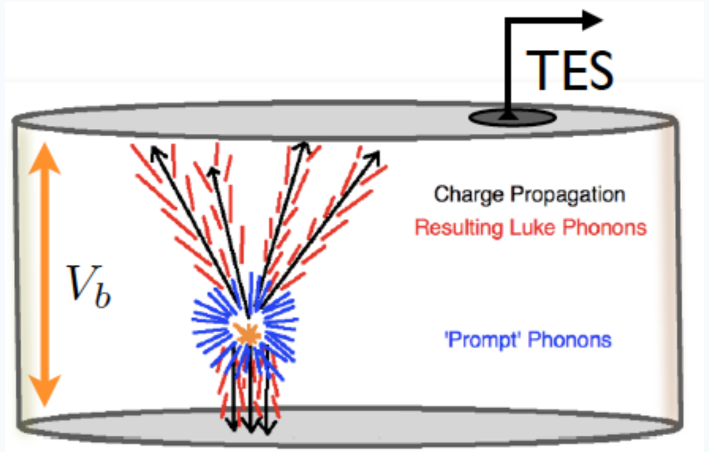
Neutron activation lines at 1.3 keV, 10.4 keV



To lower threshold, crank up the gain
Use ionization readout to measure Phonons. Improves resolution

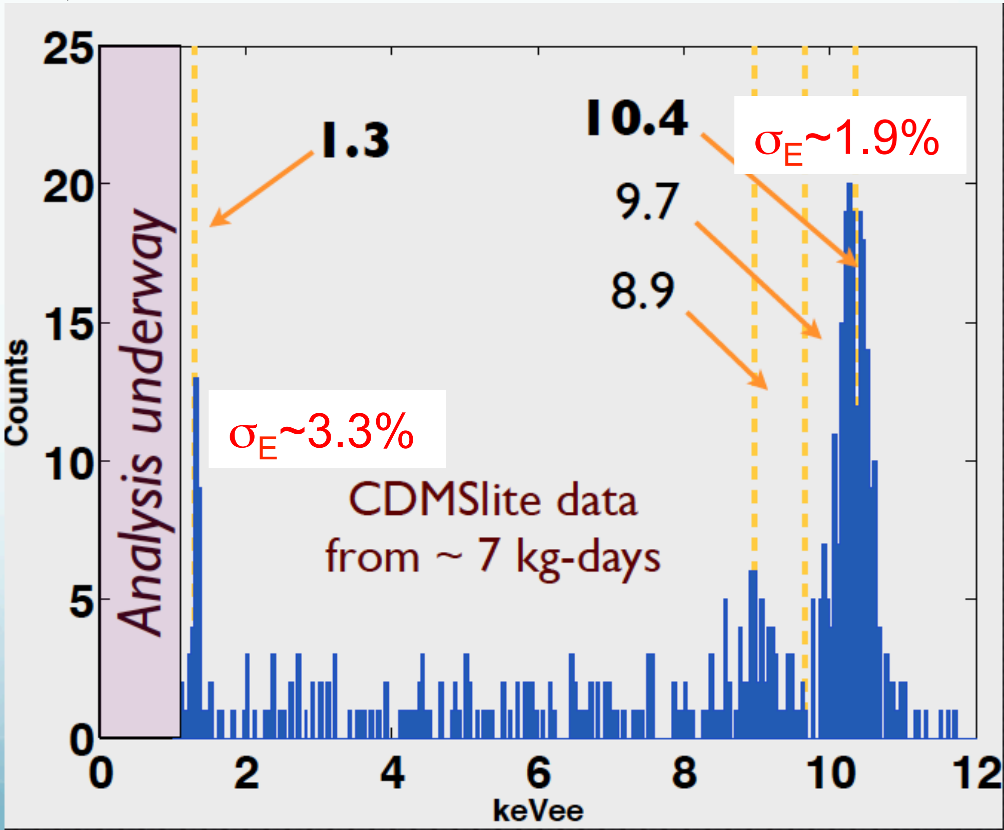
For V_b ~ 70 v (Ge iZIP stable running)
Gain ~ 24

CDMSLite: **L**ow **I**onization **T**hreshold **E**xperiment



$$E(\text{phonon}) = E(\text{recoil}) + \frac{eV_b}{\varepsilon} E(\text{charge})$$

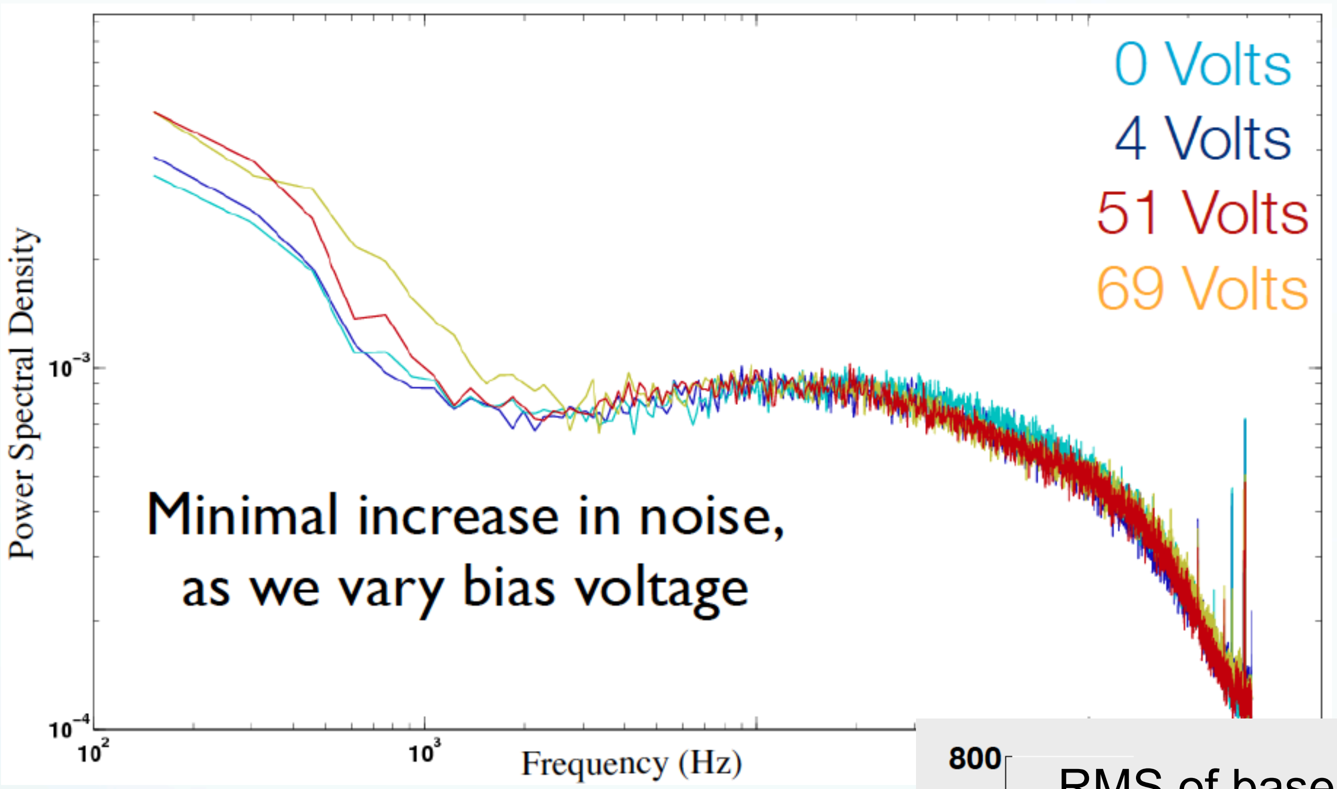
Luke Phonons interfere with timing cut and complicate yield discrimination
So CDMS runs with V_b <10 (Luke Gain ~ 2) to minimize effect



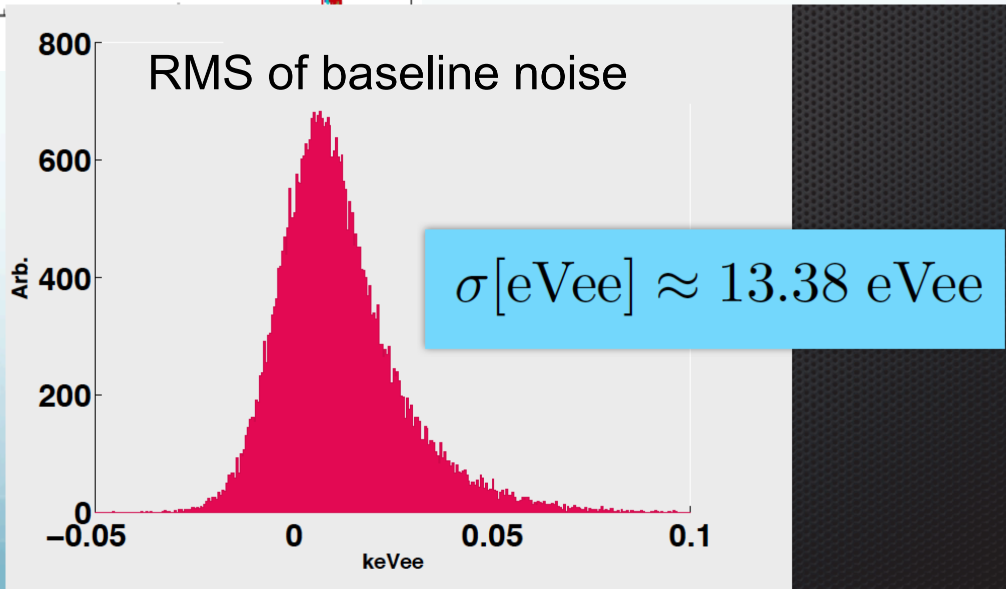
To lower threshold, crank up the gain
Use ionization readout to measure Phonons. Improves resolution from

For V_b ~ 70 v (Ge iZIP stable running)
Gain ~ 24

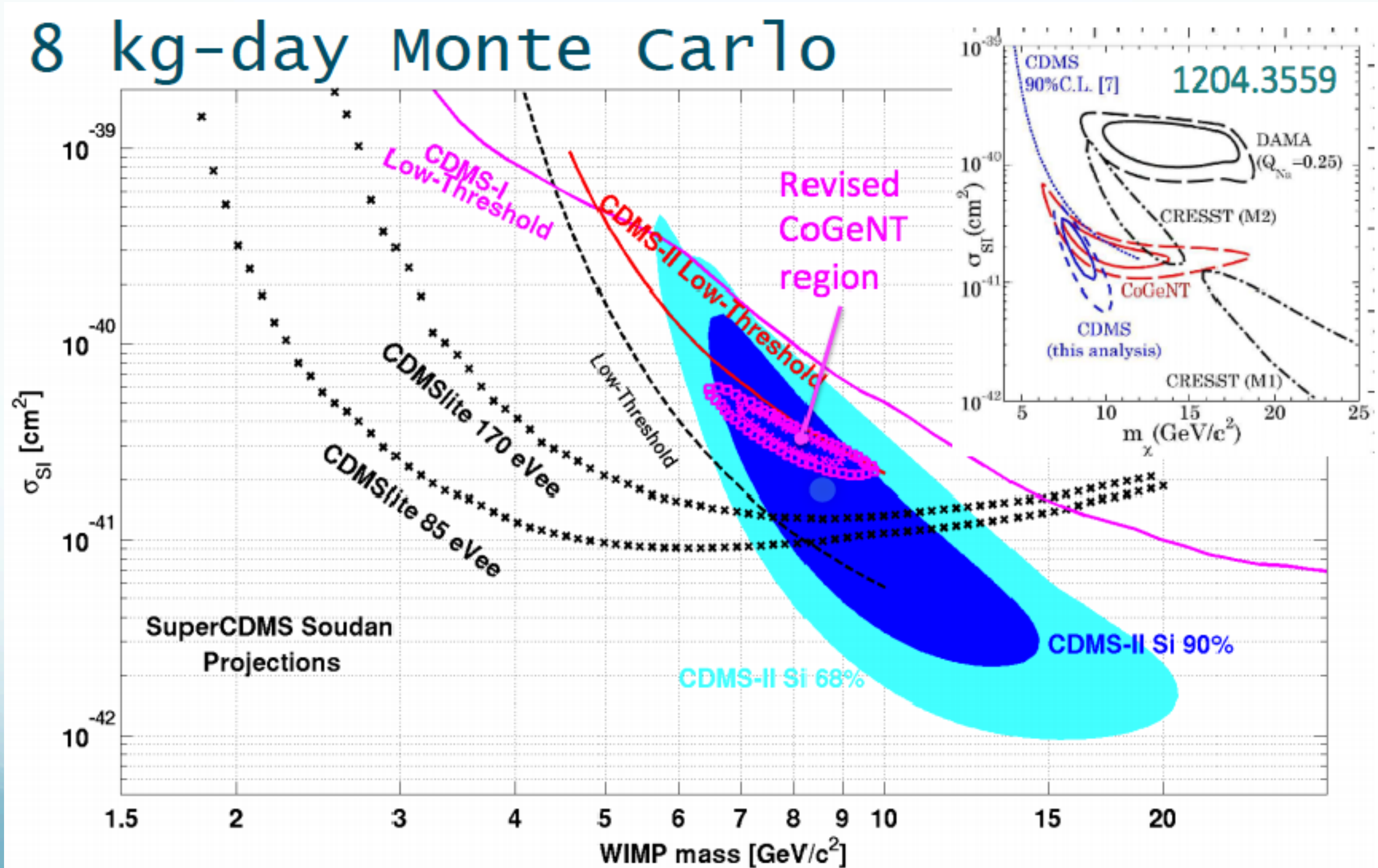
CDMSLite: Low Ionization Threshold Experiment



The threshold we can attain depends on the baseline noise at Soudan and how high we can push the gain, yet remain stable.



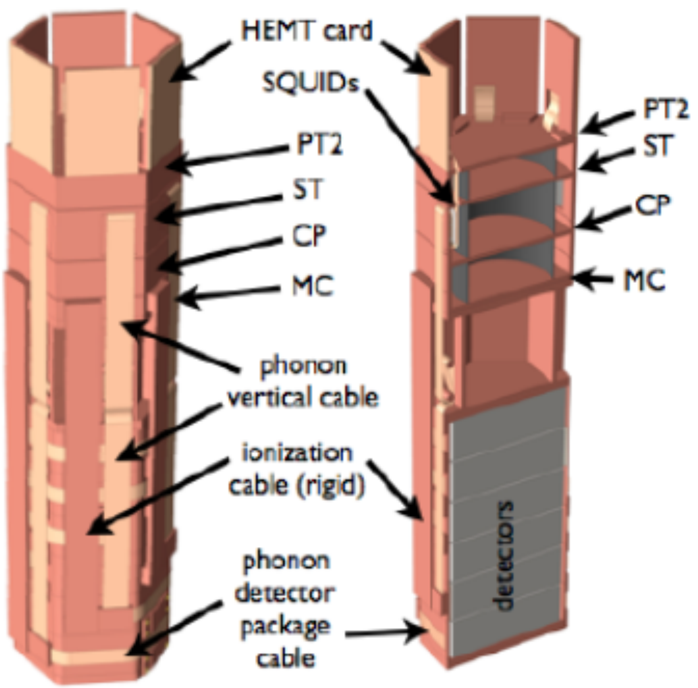
CDMSLite: Low Ionization Threshold Experiment

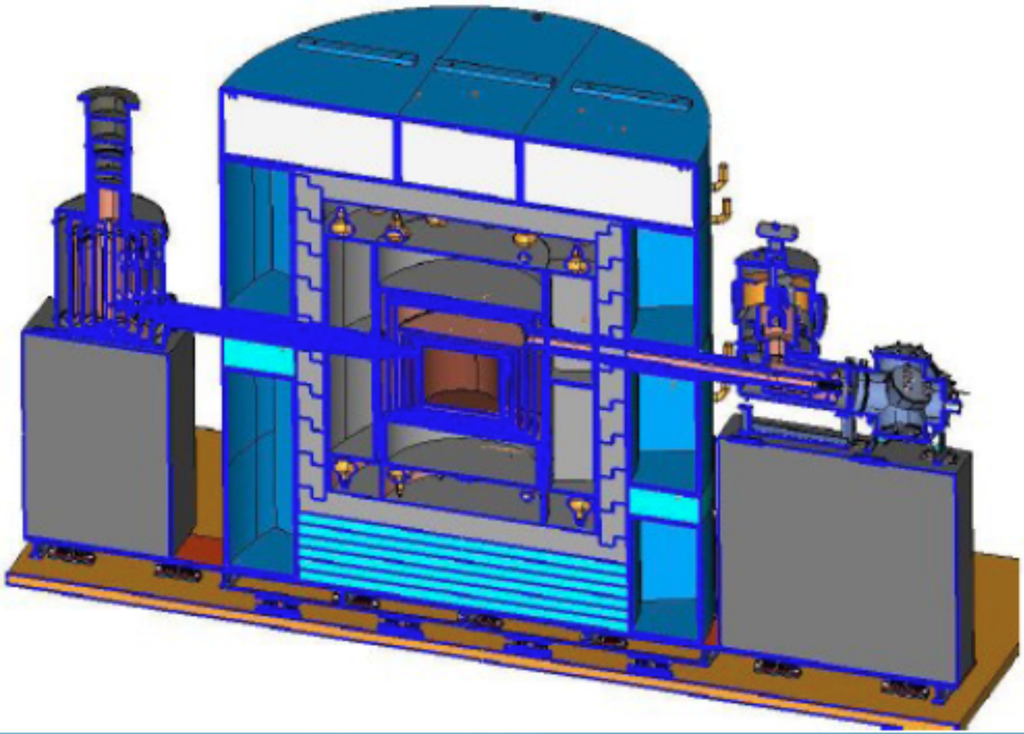


Moving to SNOLAB

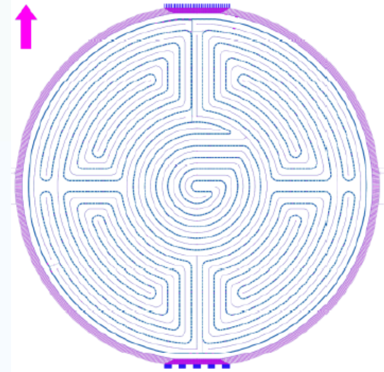
Experiment & cryostat

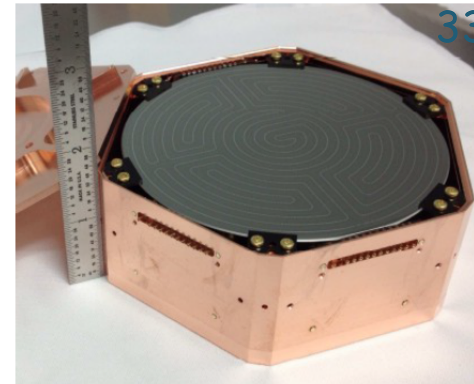
- Detector towers will be accomodated inside
- Need to cool hundreds of kg to tens of mK
- Requires improvements compared to SuperCDMS Soudan
  - » Use HEMT instead of JFET for charge read-out to control heat load



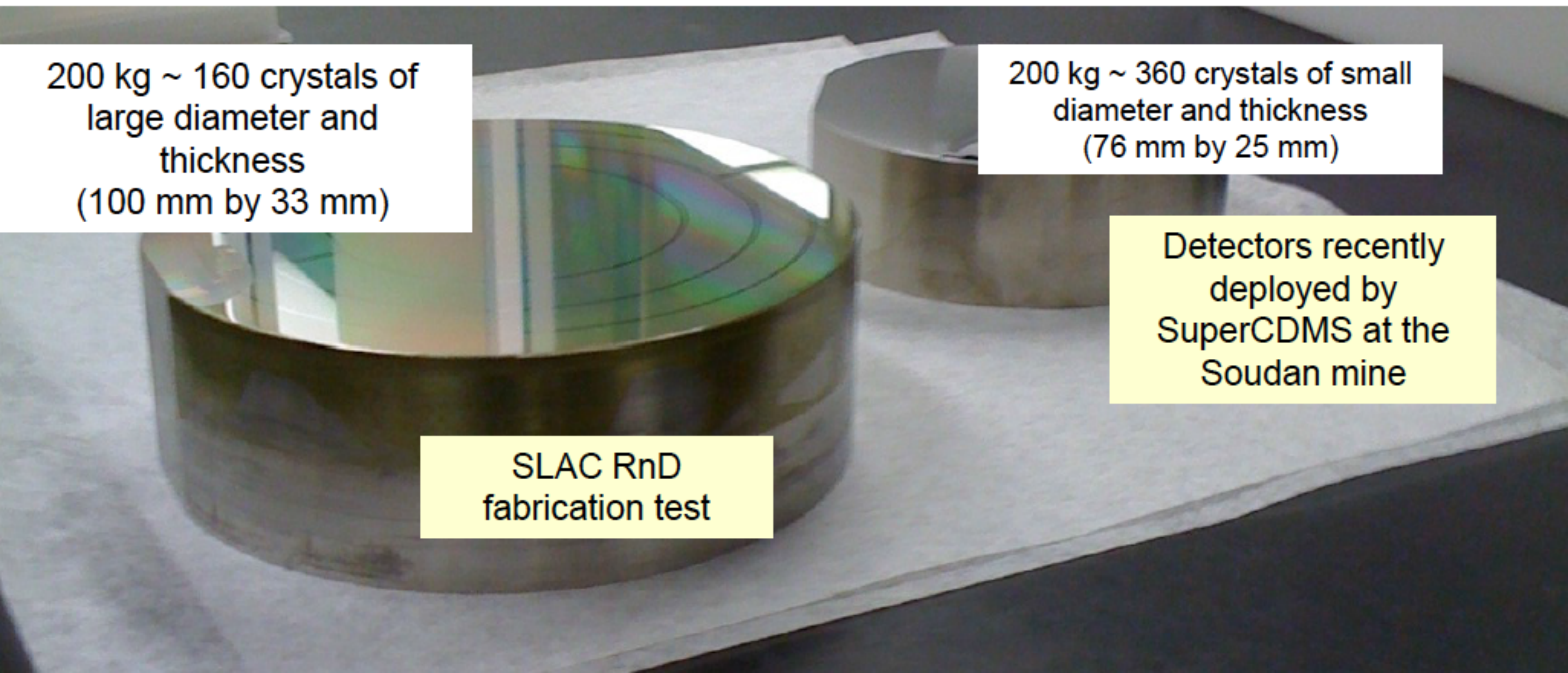


BIGGER DETECTORS For better scalability & volume to surface ratio



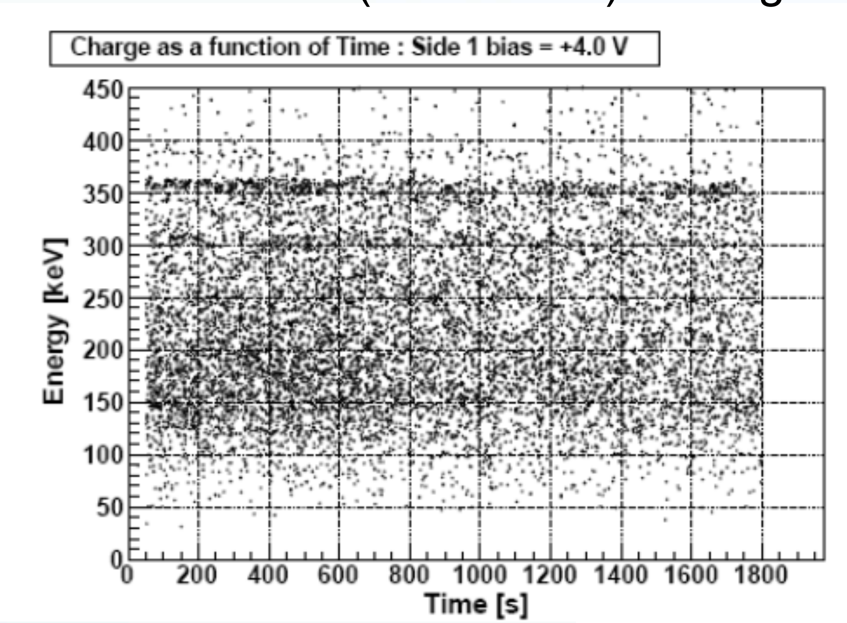


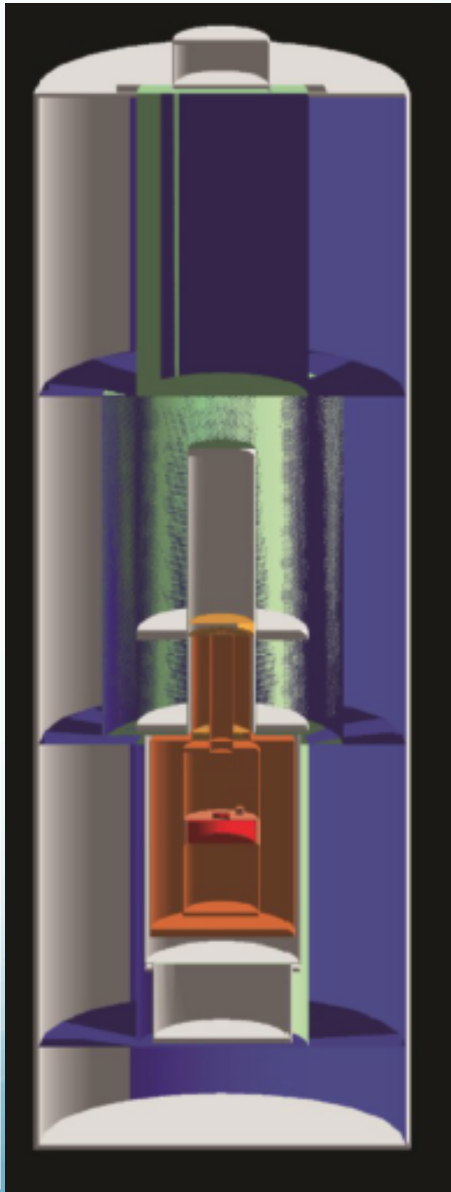
- Production time scales with number of detectors, not mass
- Qualify larger crystals and demonstrate production rate



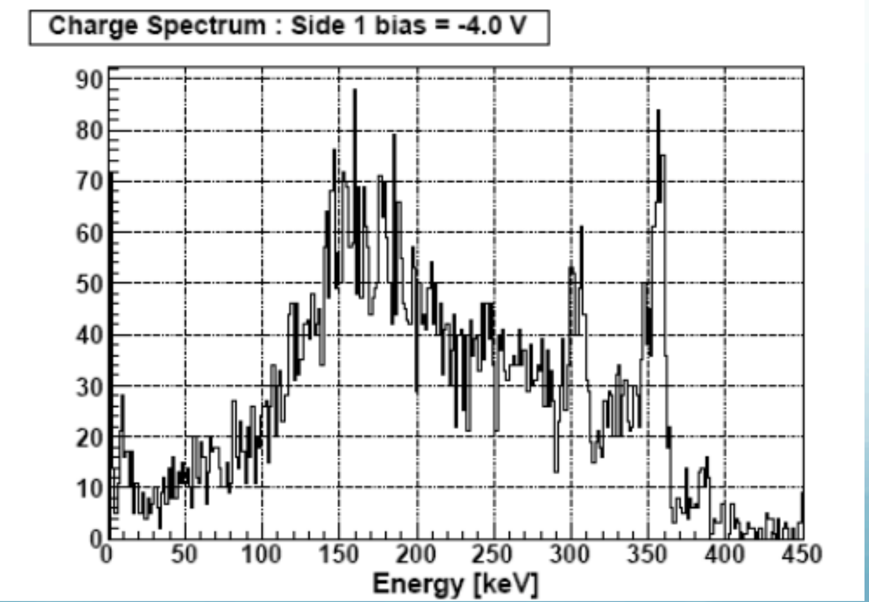
Dilution Fridge at Minnesota can accommodate 100 mm iZIPs

Tests of 100 mm (since 2012) show good charge collection stability over time

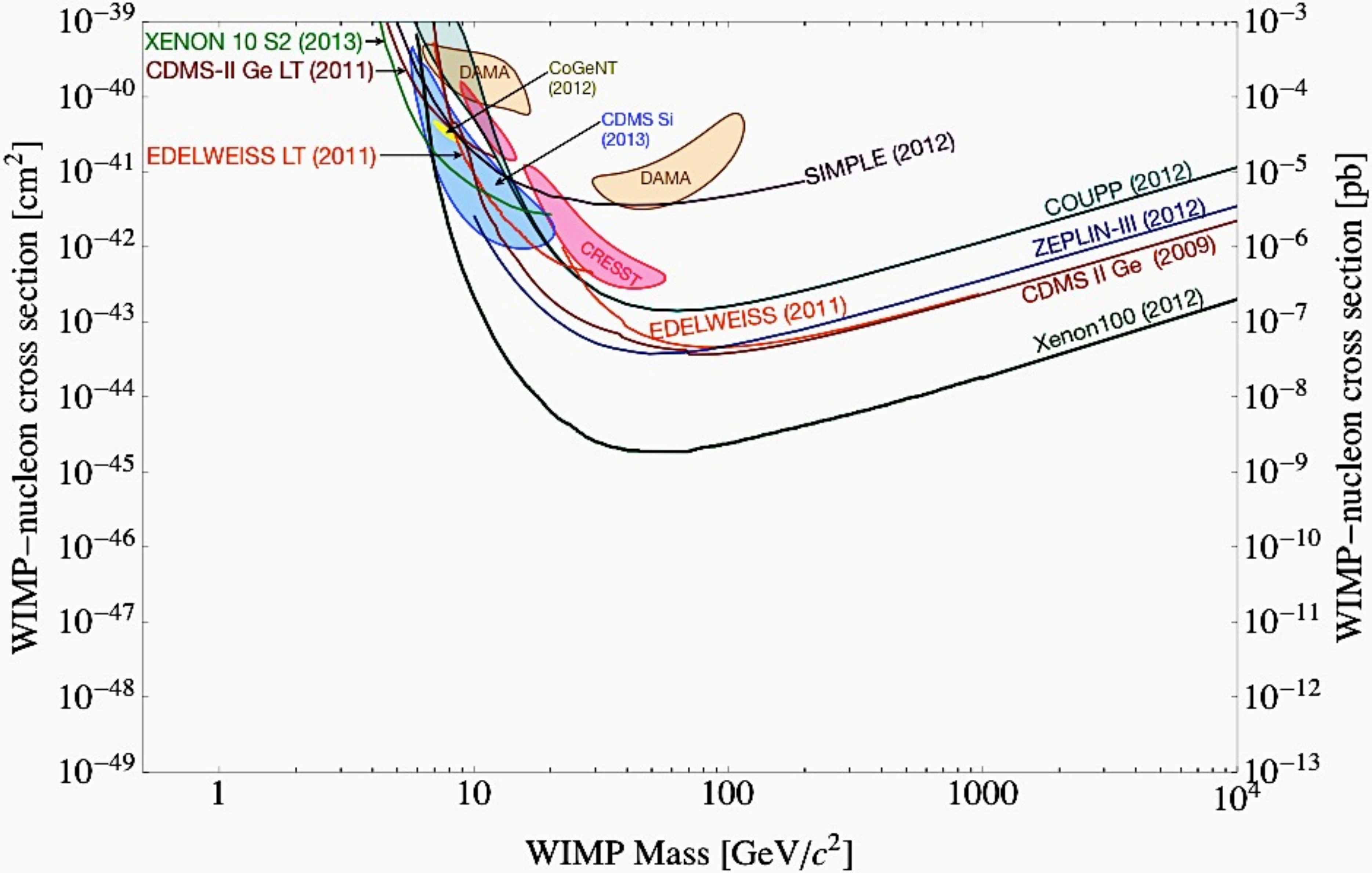




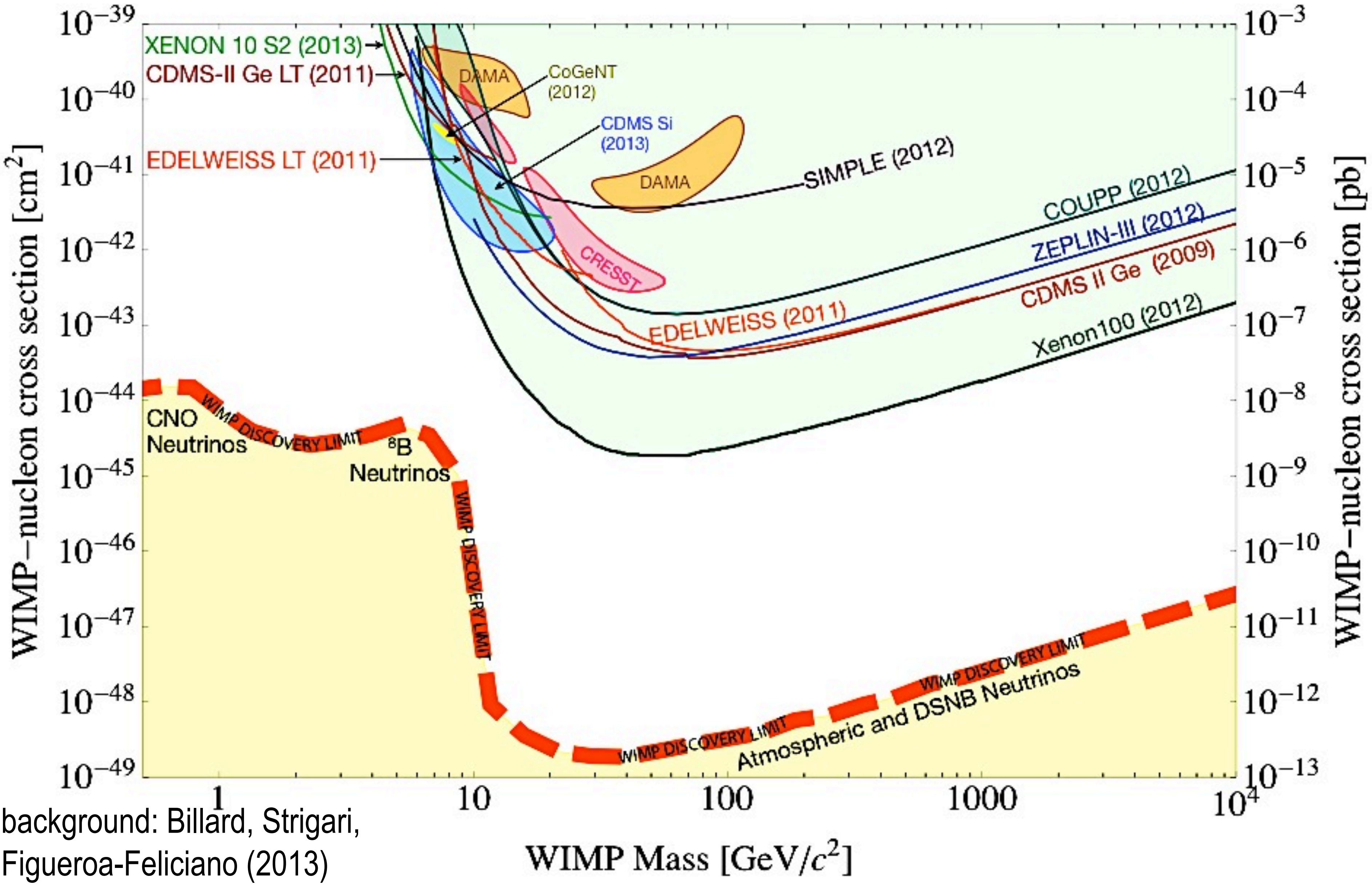
And the ^{133}Ba lines can be easily seen



Current limits

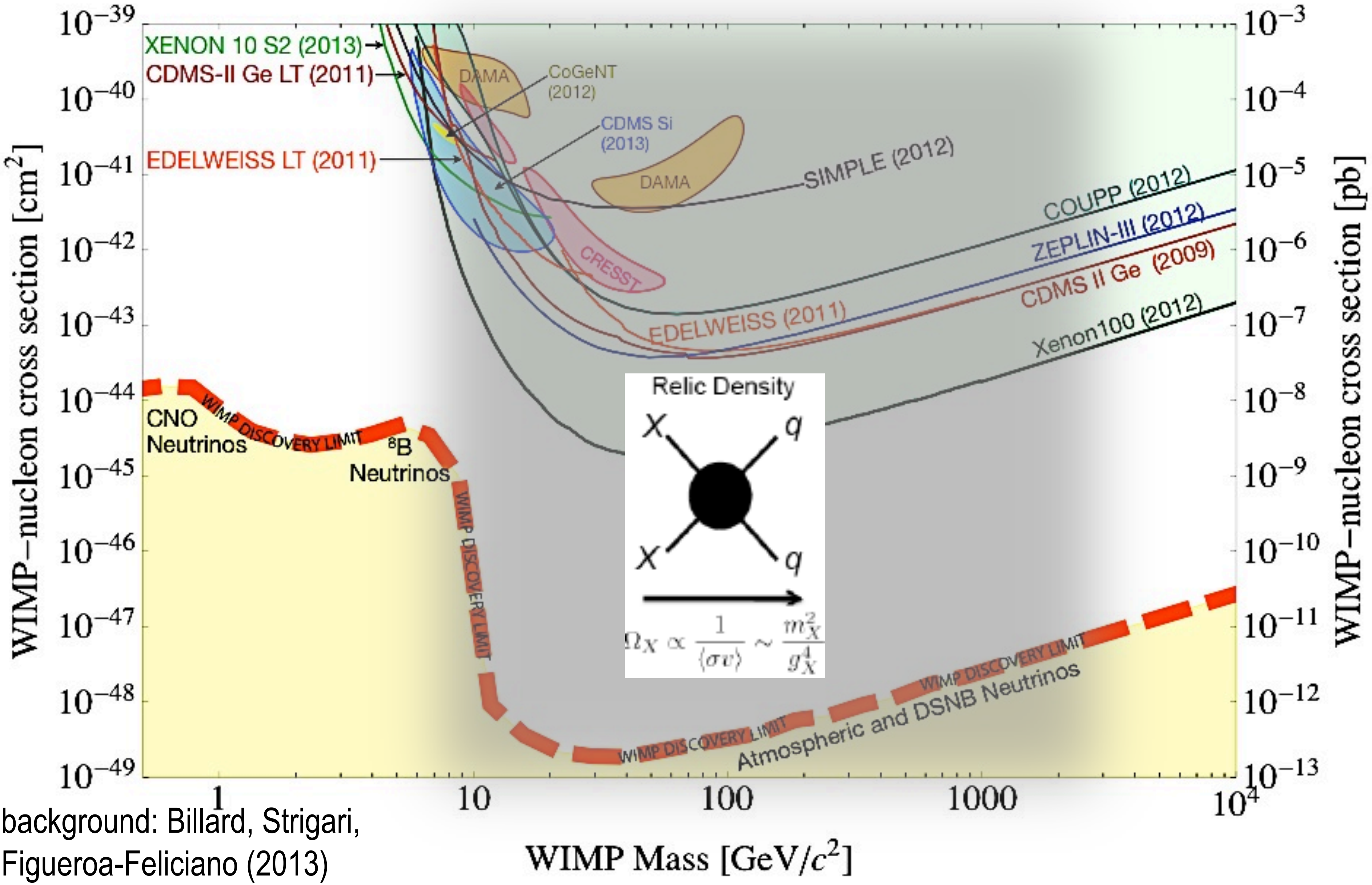


The Neutrino Floor



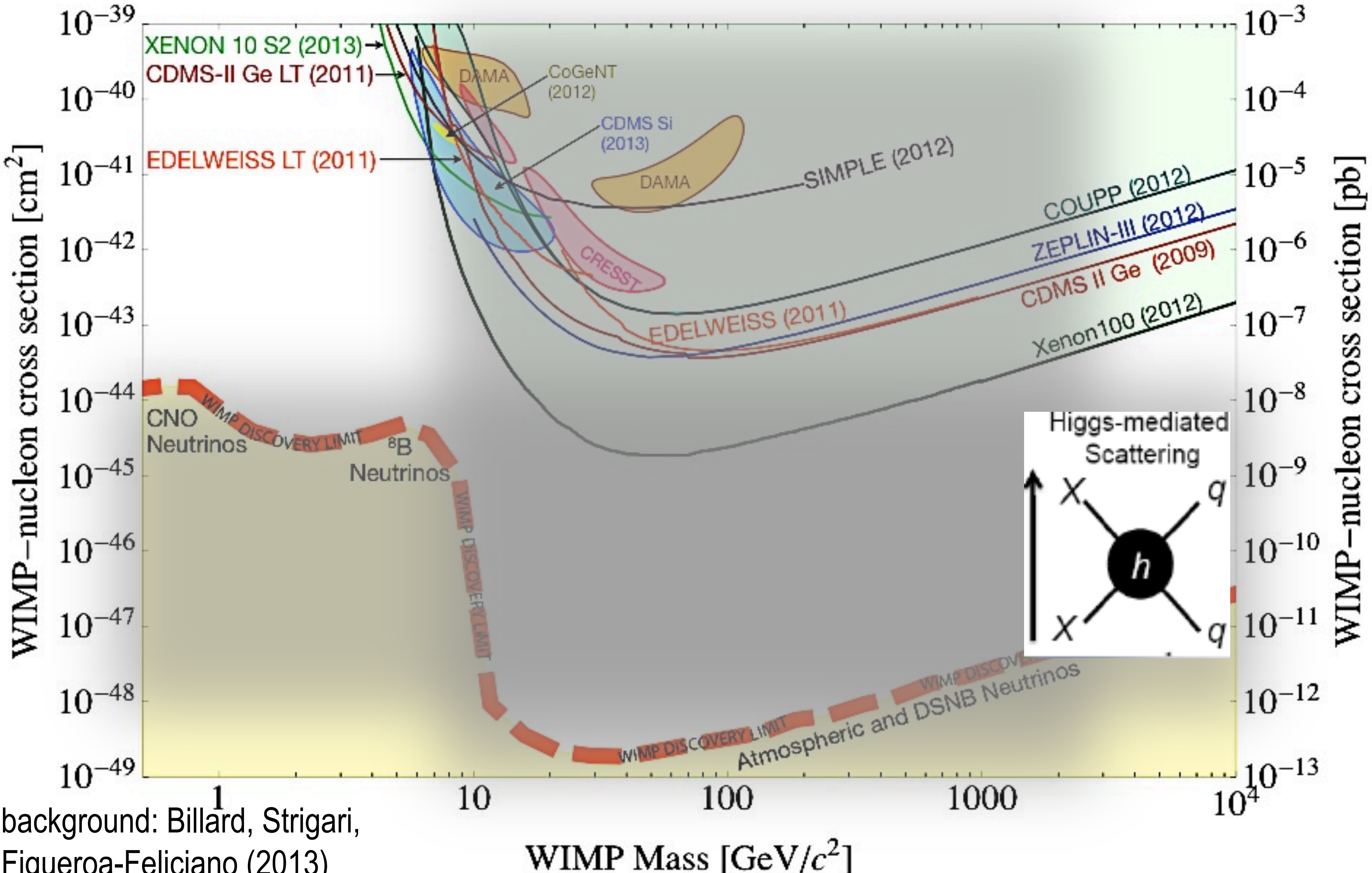
background: Billard, Strigari, Figueroa-Feliciano (2013)

Where are the WIMPs?



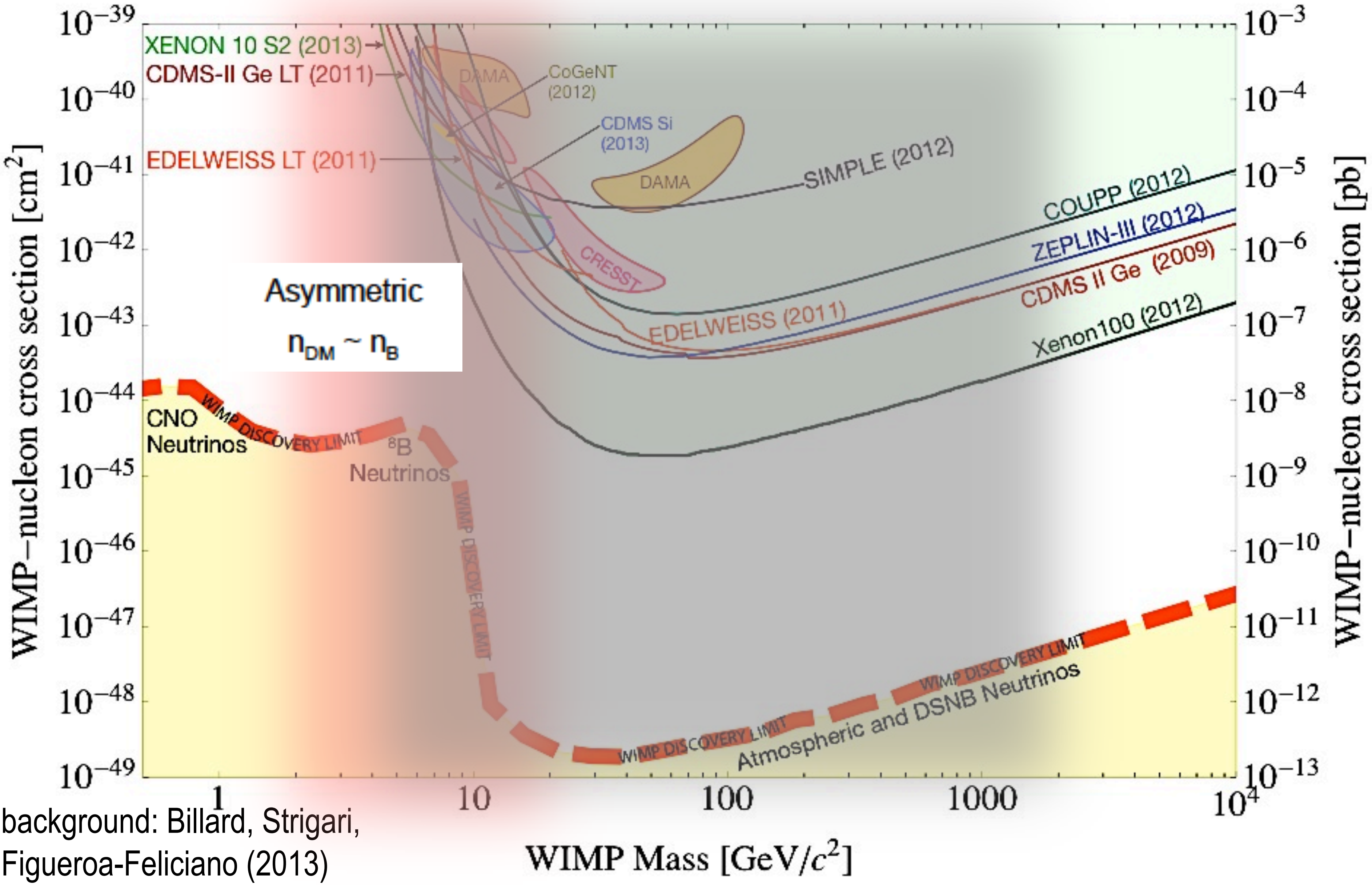
background: Billard, Strigari, Figueroa-Feliciano (2013)

Where are the WIMPs?



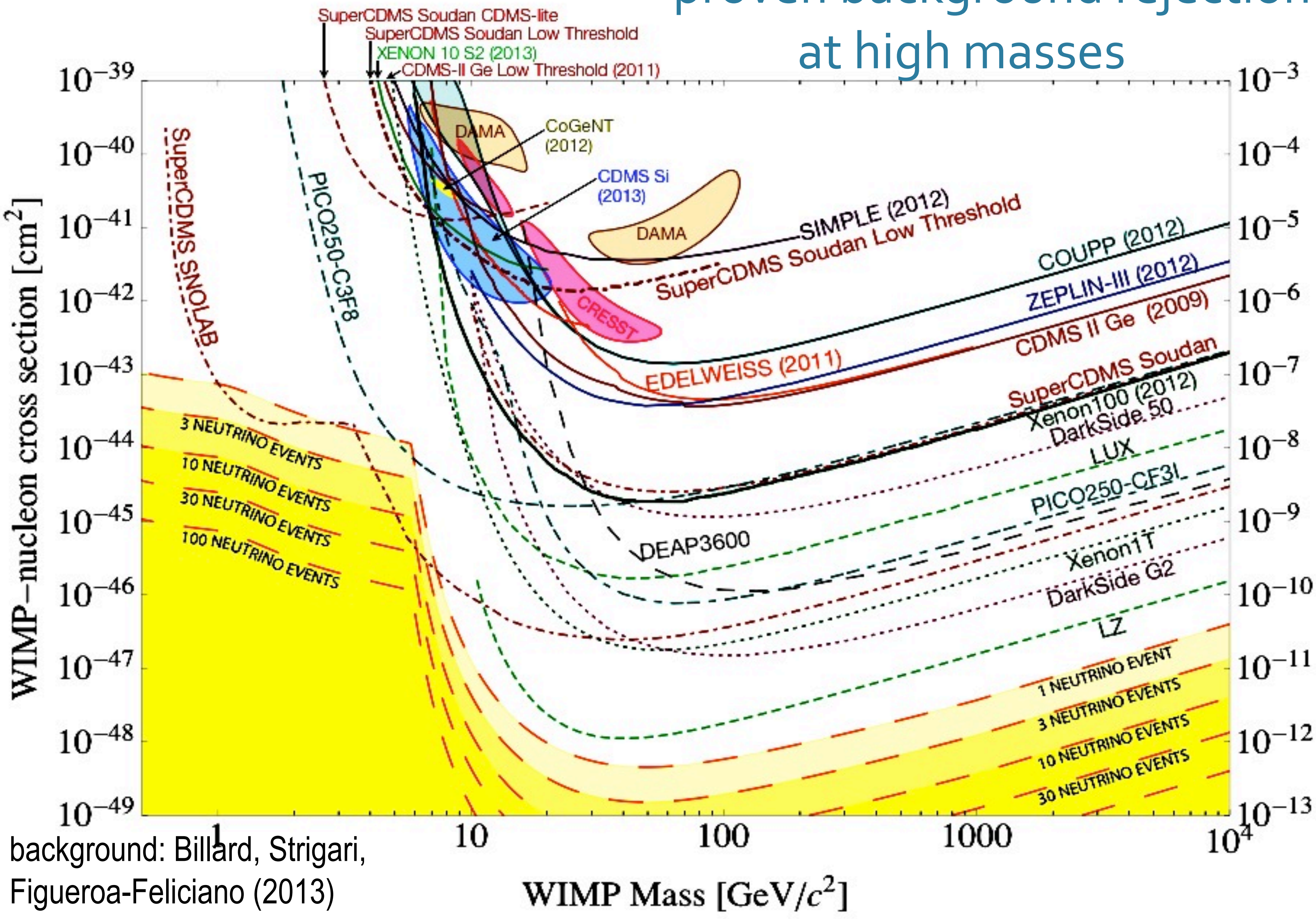
background: Billard, Strigari, Figueroa-Feliciano (2013)

Where are the WIMPs?



background: Billard, Strigari, Figueroa-Feliciano (2013)

SuperCDMS has both frontier low mass sensitivity and proven background rejection at high masses



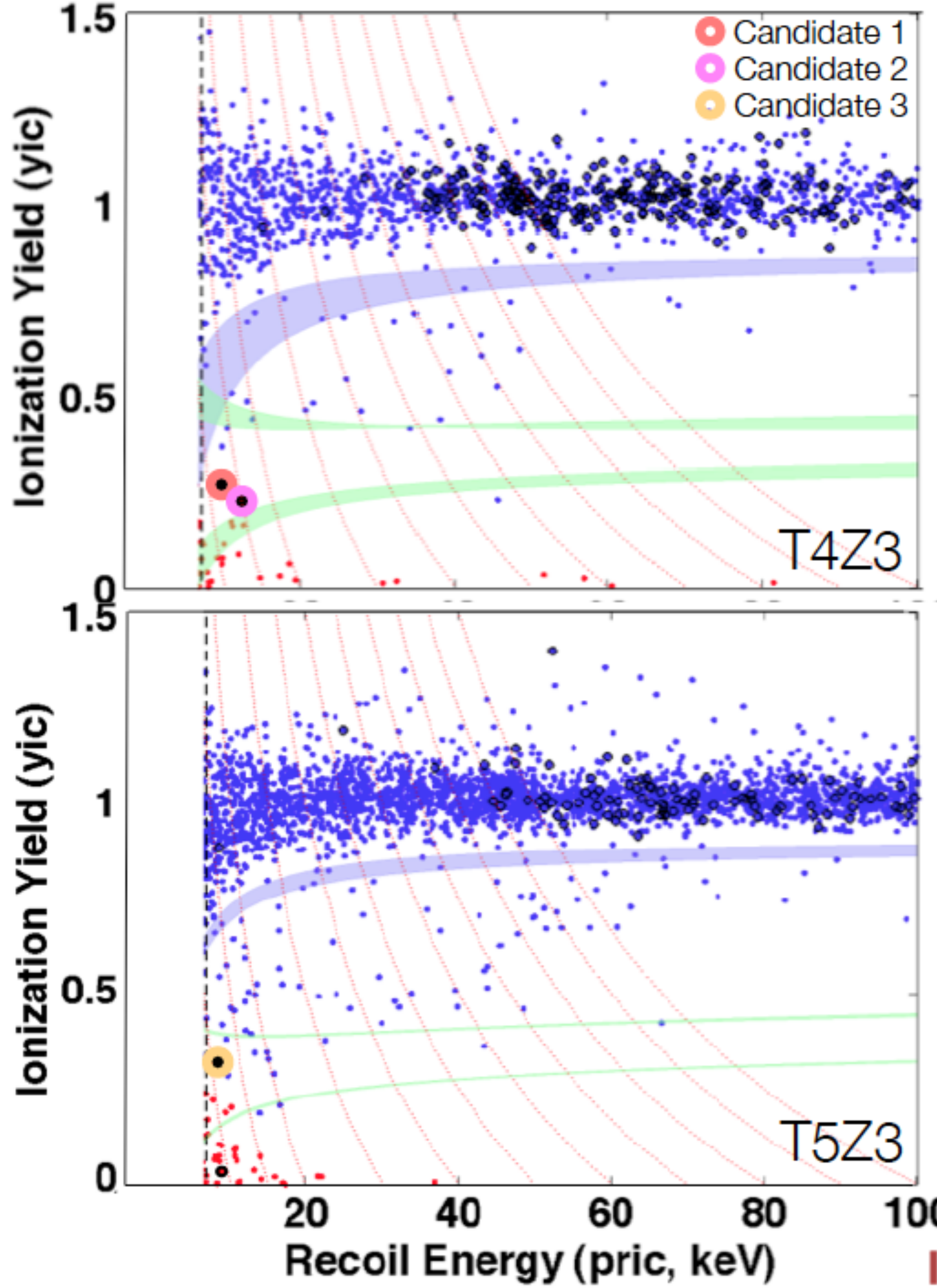
background: Billard, Strigari, Figueroa-Feliciano (2013)

Backup Slides

Next Steps: A look Below the Charge Threshold...

- Looking below the charge threshold, no large population of events passing the timing cut is seen.

PRELIMINARY

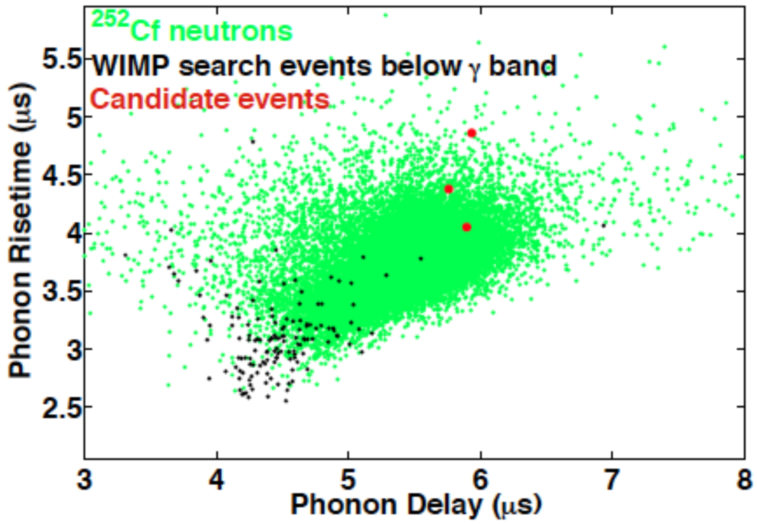


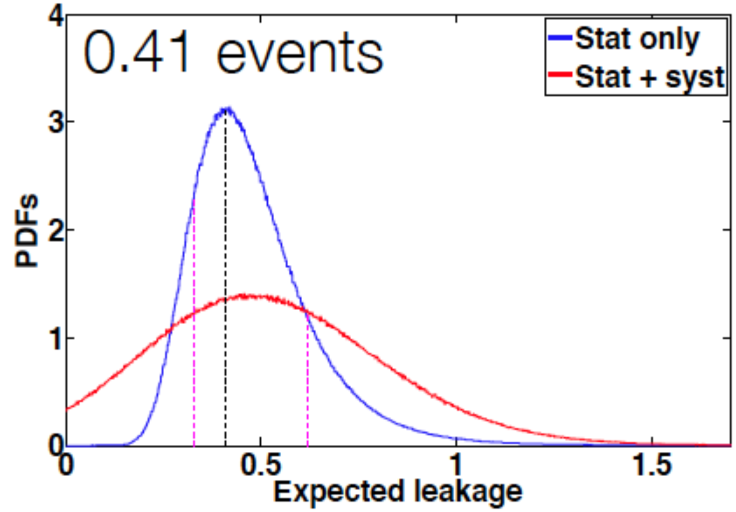
Post unblinding checks on the Silicon Data

- After unblinding, the data quality was re-checked.
  - Events occurred during high-quality data series
  - Events were well-reconstructed
  - Checked energy in other detectors to verify events were single scatters
- Surface event background estimated from the tails of three different NR sideband distributions to be:

$$0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$$

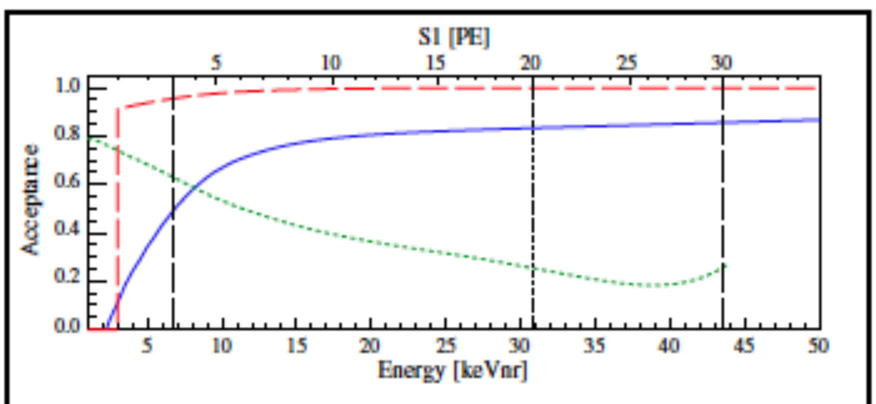
- Checked for the possibility of 206Pb recoils from 210Po decay, and limited this to be <0.08 events.

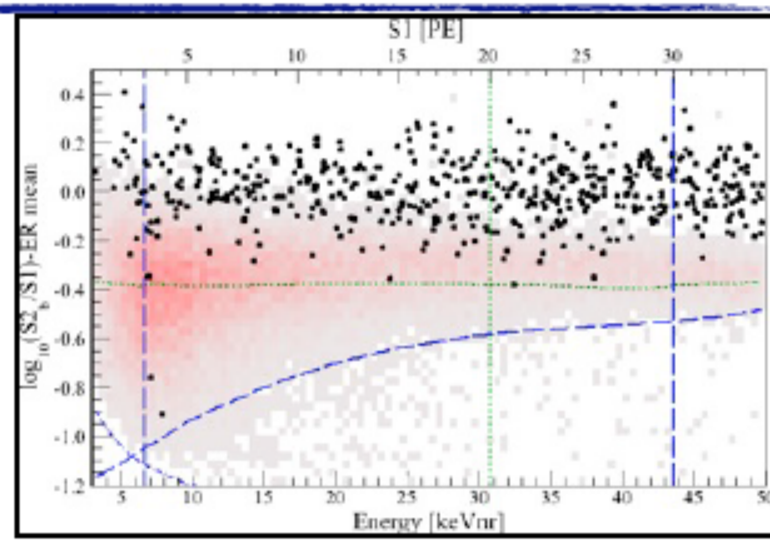


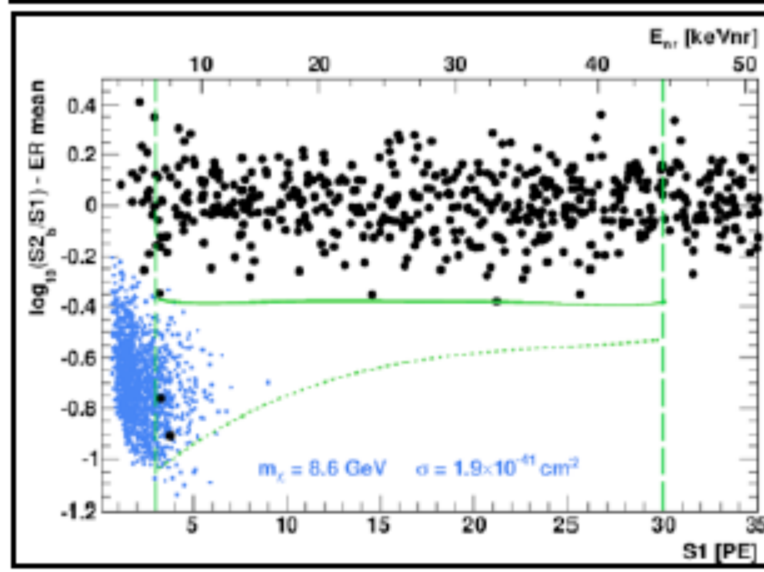


Has XENON Ruled this Region Out?

- Two events observed by XENON100 in 224 days of exposure
- At face value this is NOT compatible with CDMS
- Depends strongly on the nuclear energy scale, the efficiency, and threshold...



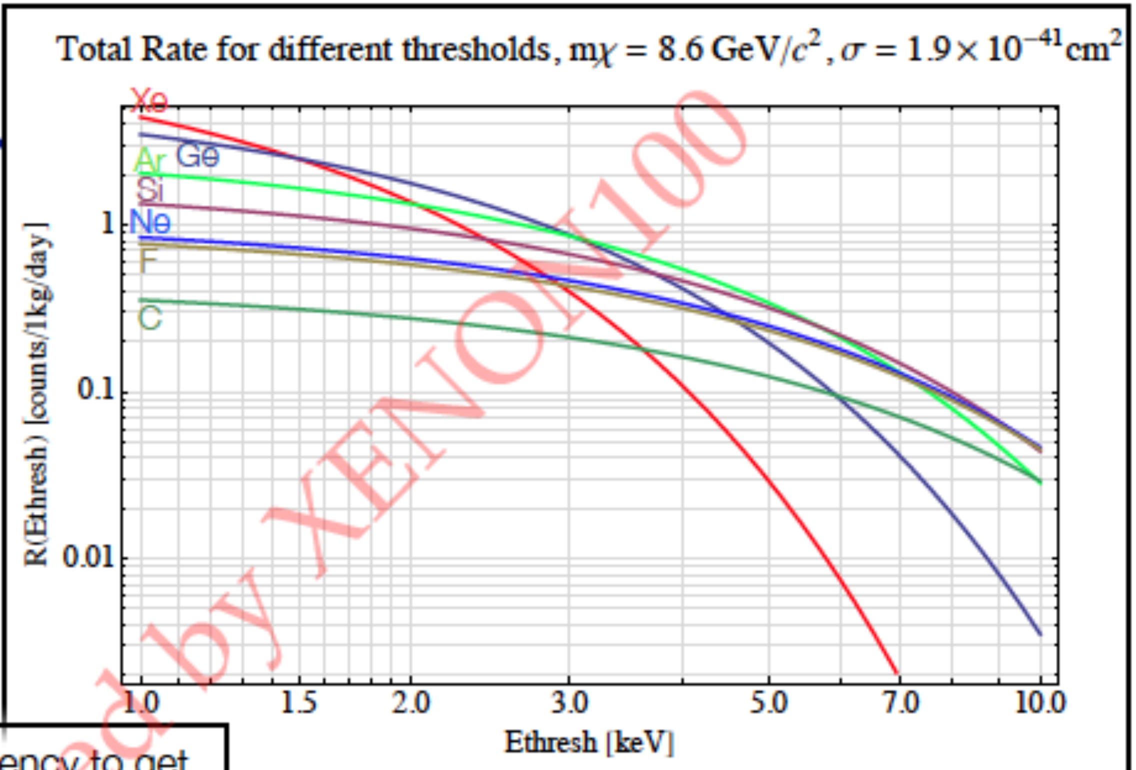




Figures from A. Melgarejo's talk at the Light Dark Matter Workshop: http://www.umich.edu/~mctp/SciPrgPgs/events/2013/dm2013/index.html

Compatible?

- Two events observed by XENON100 in 224 days of exposure
- Depends strongly on the nuclear energy scale, the efficiency, and threshold…

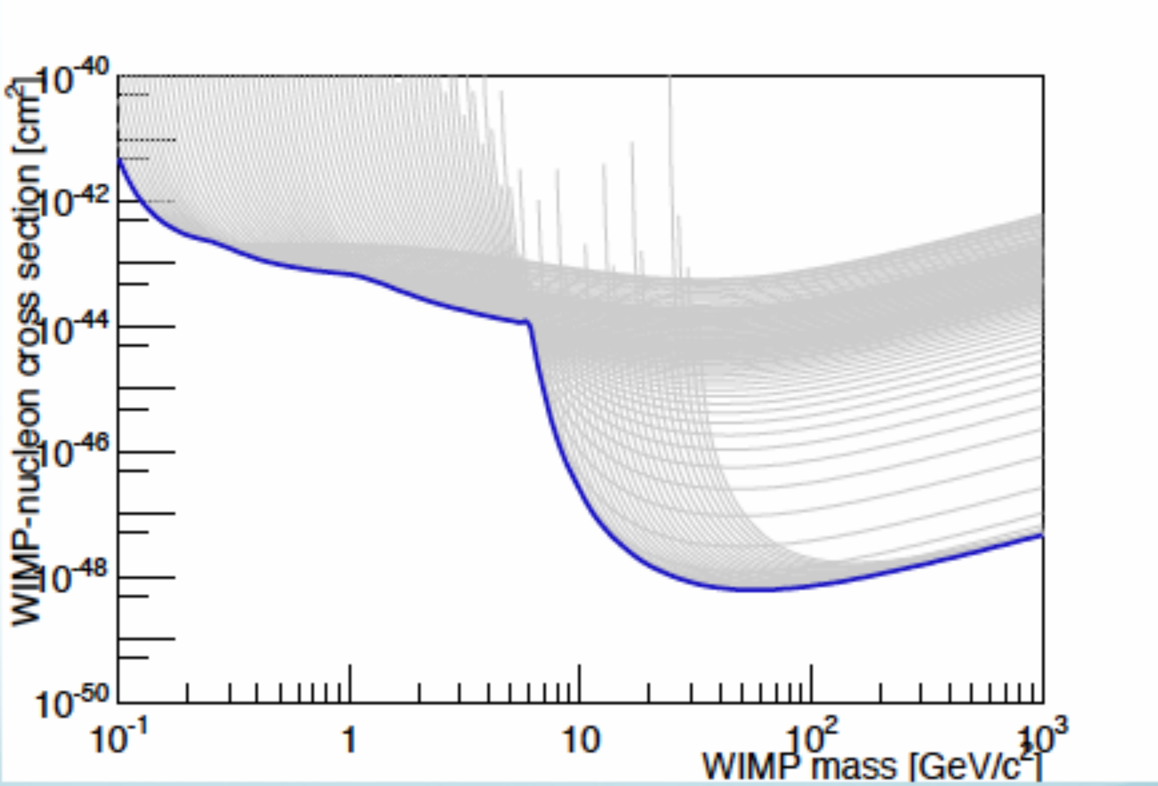


Threshold	Spectrum-Averaged Efficiency to get 2.1 events in XENON100 from a WIMP with $m\chi$=8.6 GeV/c^2, σ=1.9x10^{-41} cm^2
7 keV	14%
6 keV	3.7%
5 keV	0.95%
4 keV	0.25%
3 keV	0.07%

- Could be indicating to non-standard DM-nucleon interactions…
- …or SCDMS events are not due to dark matter

Calculate for many different thresholds, what exposure gives you 1 neutrino event, and then show the sensitivity of that exposure (i.e., what cross section gives you 2.3 WIMP events) for every threshold. Take the minimum cross-section for each mass, and that gives us a curve that represents the optimum threshold/ exposure pair that gives you the best sensitivity at a particular mass in the face of the neutrino background.

From this curve, make the neutrino floor curve, which tell you how close to seeing neutrino events a particular experiment is, given a background-free 100% efficient exposure curve for a 90% limit.



Annual Modulation Study

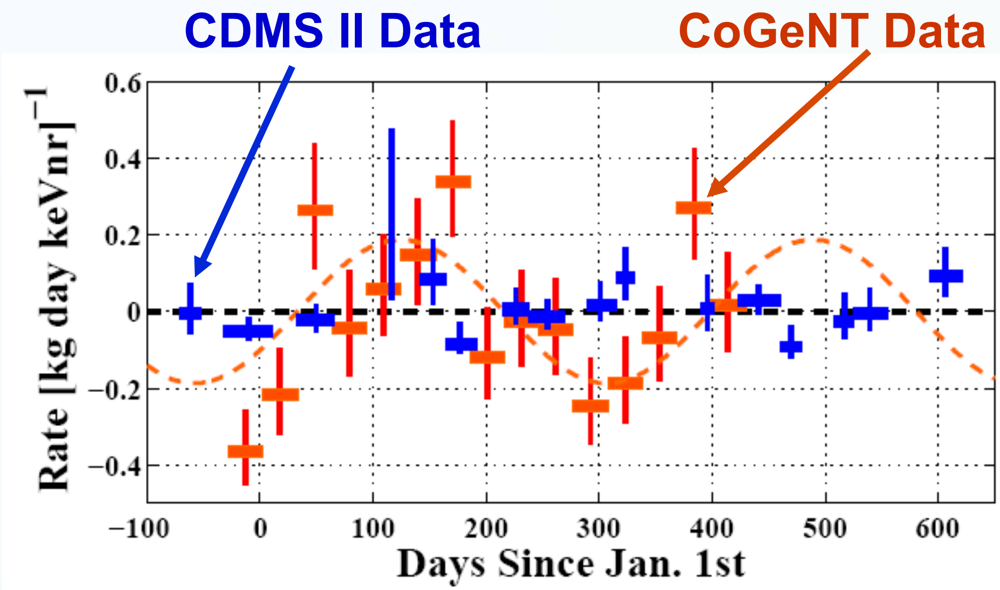
- If only a small fraction of the CoGeNT excess is due to WIMPs, the CDMS II constraints can be avoided.
- But, this implies large fractional modulation (~100% instead of ~15%).
- Can search for annual modulation in CDMS II data, at low energies.
- Use the same data as for the Ge low-energy study.
  - Except, consider the 2-sigma nuclear recoil band.
- Nearly two annual cycles: October 2006 – September 2008.
- Lower the recoil energy threshold to 5 keV_{nr}.
  - Trigger efficiency ~100% at 5 keV, cannot influence modulation analysis.
  - CoGeNT considers [1.2,3.2] keV_{ee}, which corresponds to [5,11.9] keV_{nr}.
  - Look at three energy bins: [5,7.3], [7.3,9.6], [9.6,11.9] keV_{nr}.

Rate vs Time

- Single-scatter nuclear-recoil events:
  - Grouped the data into 16 time intervals (~25 days each).
- No apparent modulation.
- Define (Poissonian) likelihood function for each energy bin:

$$\ell_\alpha = \prod_{\beta,d} e^{-m_{\alpha\beta d}} \left(m_{\alpha\beta d}\right)^{n_{\alpha\beta d}}$$

$$m_{\alpha\beta d} = \left\{\Gamma_\alpha + M_\alpha \cos\left[\omega\left(t_\beta - t_{o\alpha}\right)\right]\right\} \varepsilon_{\alpha\beta d} \frac{dL_{\beta d}}{dt} \Delta t_\beta$$



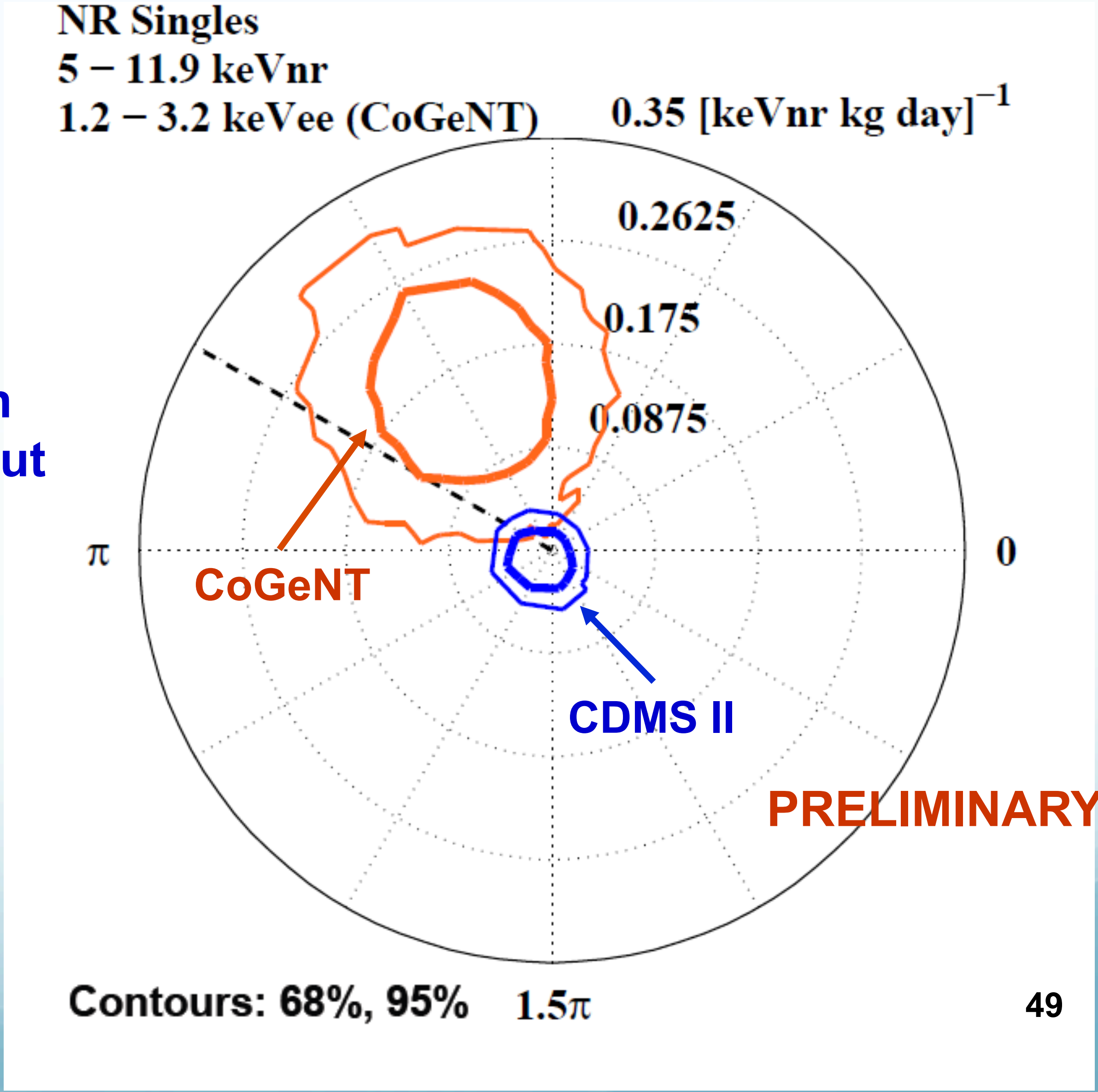
DC-subtracted CDMS II NR-band rate for [5,11.9] keV_{nr} bin.

No Annual Modulation Observed

For the [5,11.9] keV_{nr} bin:

- **Modulation larger than 0.1/keV/kg/day ruled out with 99% confidence.**

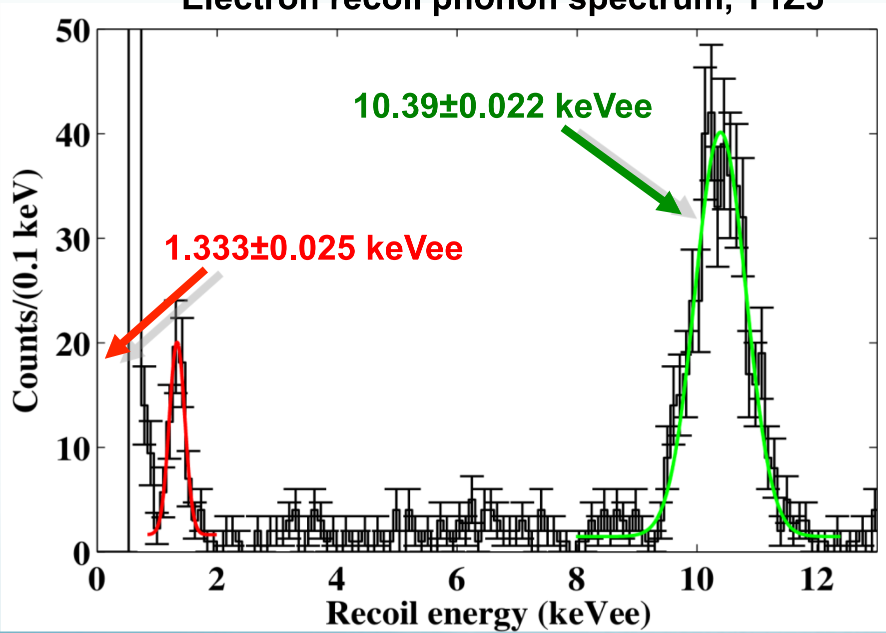
- **Inconsistent with CoGeNT at >95% confidence.**



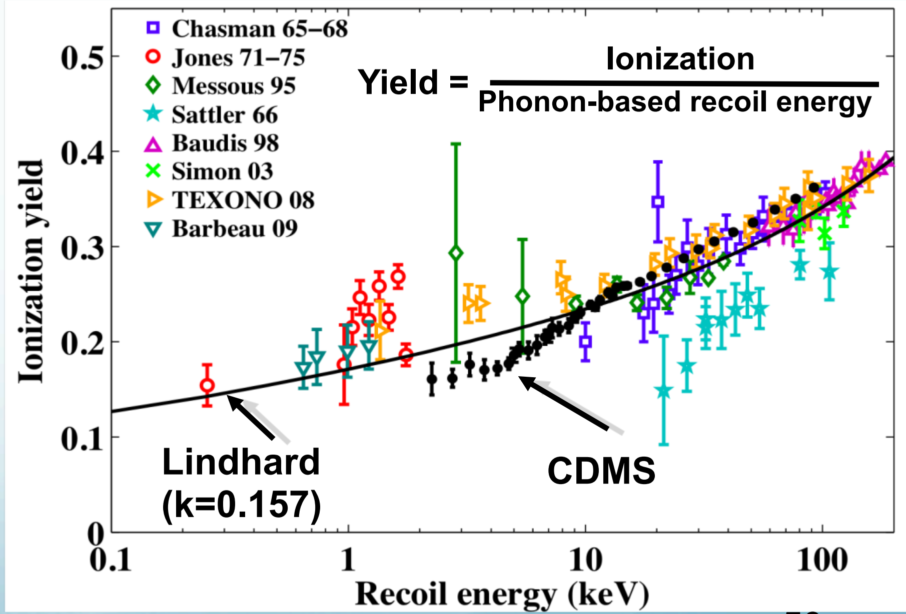
Nuclear Recoil Energy Calibration: Ge

- **Critical for low-energy analysis, targeting low-mass WIMPs.**
- **Phonon energy scale set by electron recoil lines at 1.3 keV and 10.37 keV.**
  - **Activation from ^{252}Cf neutron source calibration.**
- **Nuclear recoil ionization yield compared with literature, found to be conservative (Fallows).**

Electron recoil phonon spectrum, T1Z5

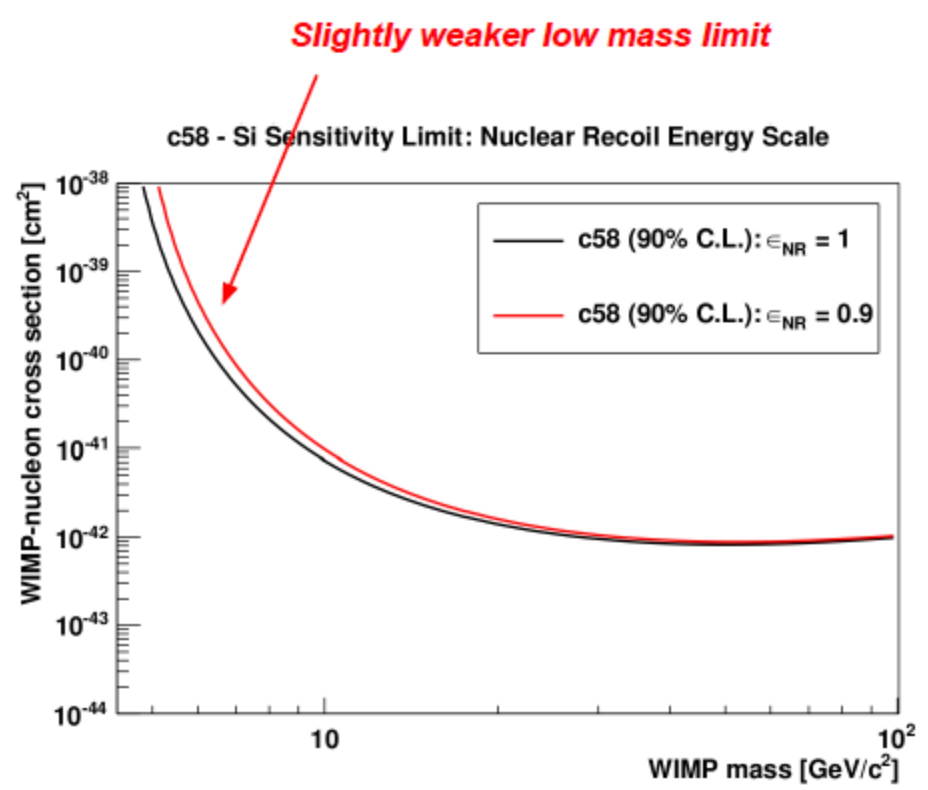


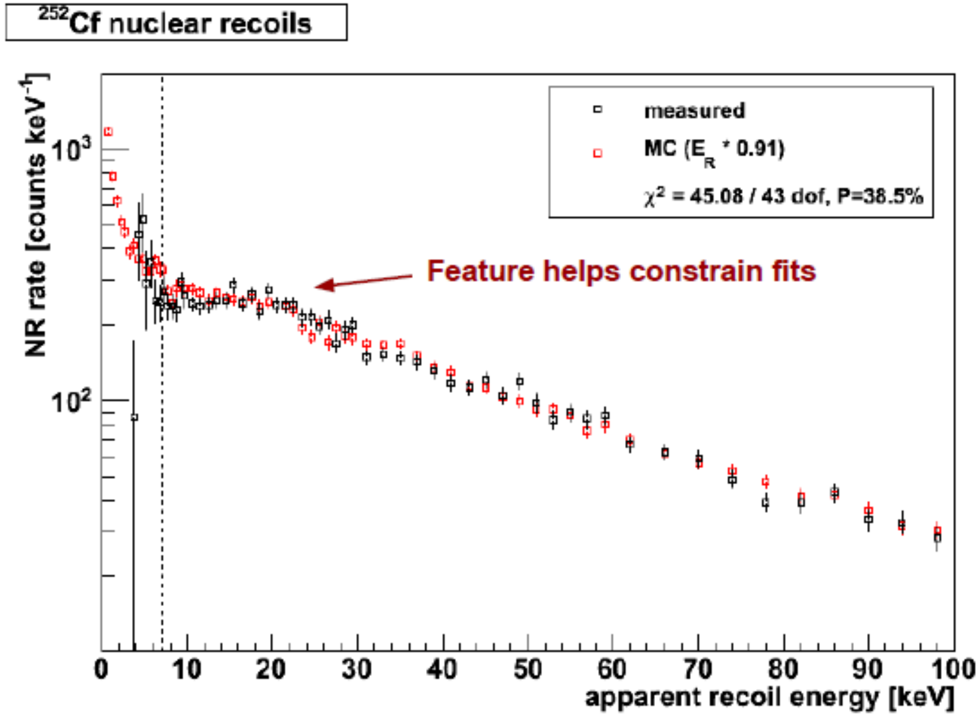
Nuclear recoil ionization yield:



Nuclear Recoil Energy Calibration: Si

- **Resonant feature in scattering of neutrons from ^{252}Cf.**
- **Direct energy calibration of nuclear recoils.**



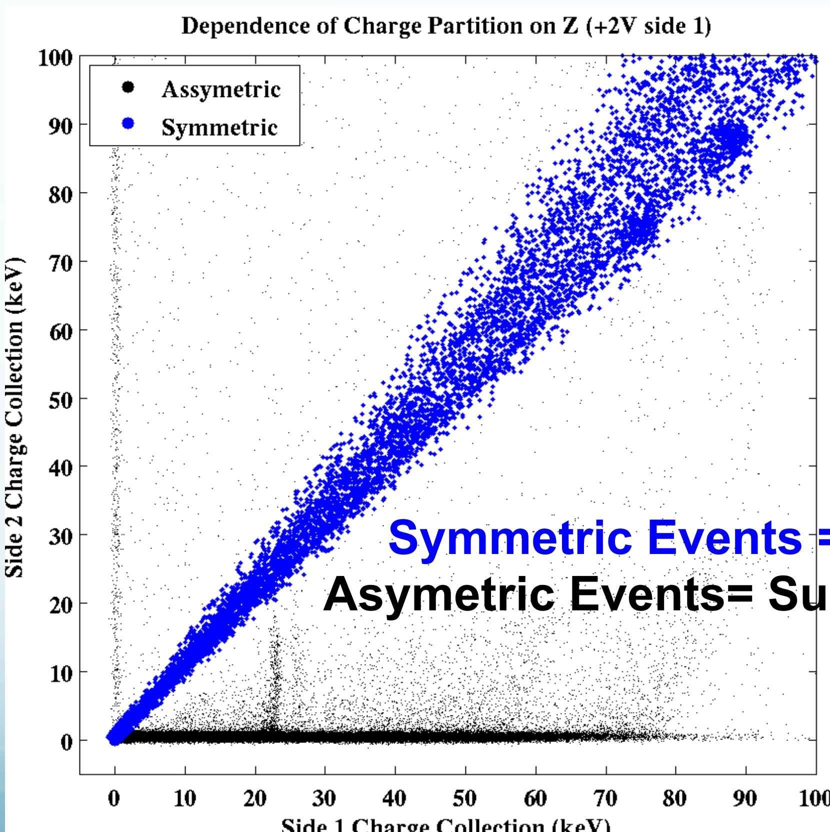


S. Fallows

New Discriminating Techniques

SuperCDMS-Soudan, 75 mm iZIPs

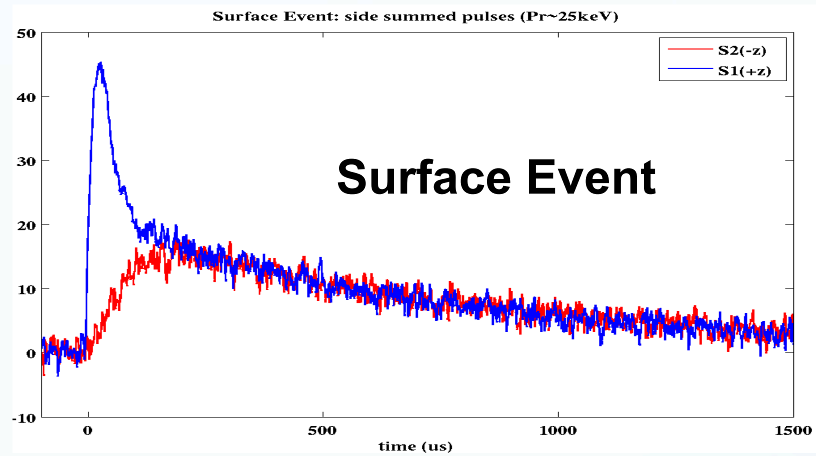
Charge Side-Asymmetry

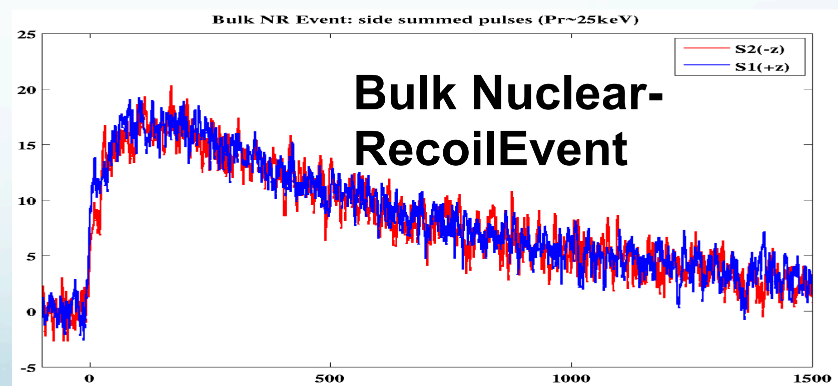


Symmetric Events = Bulk

Asymetric Events= Surface

Phonon Side-Asymmetry

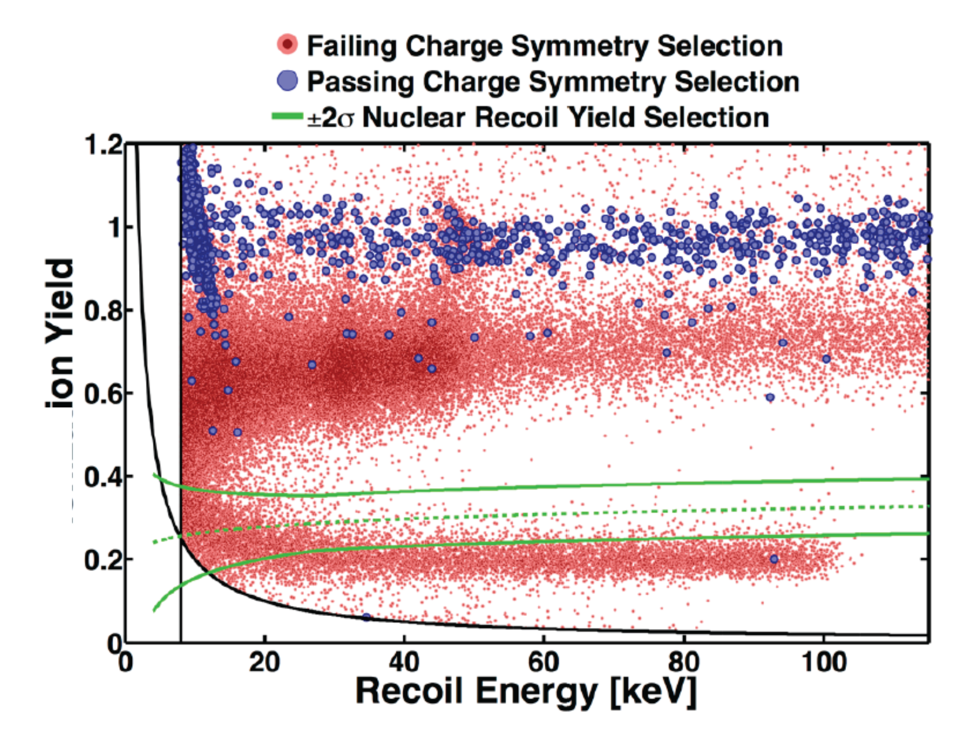


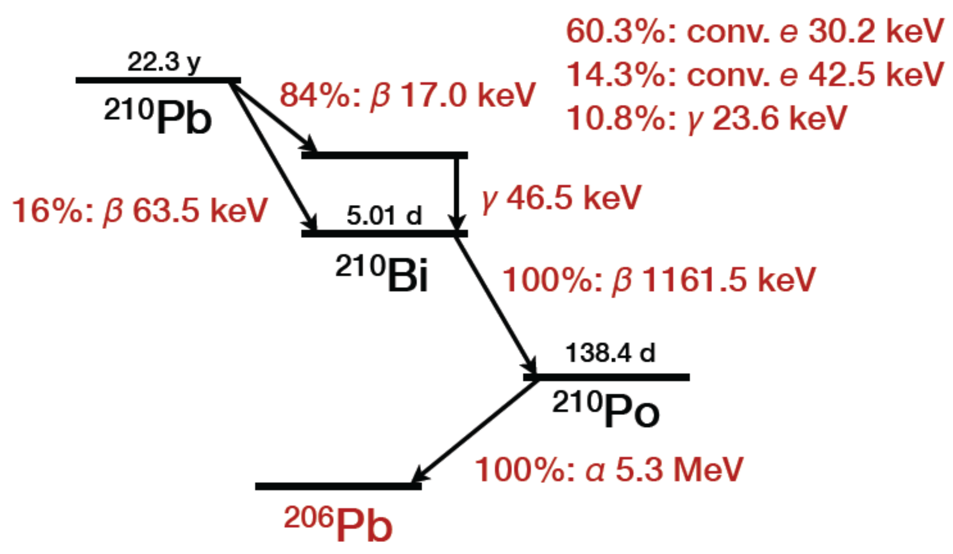


Calibration data from the UCB surface test facility.

Surface Event Calibration

- 2 Si wafers implanted with ^{210}Pb via radon exposure.
- Placed above two end detectors at Soudan.
- 37.6 live days of data on these detectors.





Surface Event Rejection

Charge asymmetry:
Leakage fraction < 1.7 x 10^{-5}

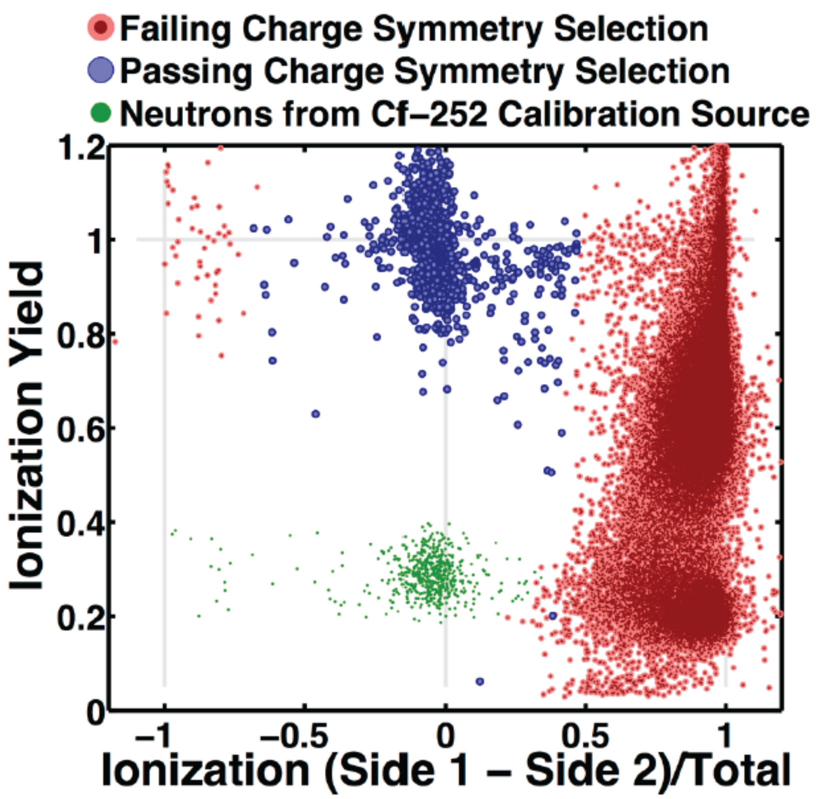
NR acceptance = 50%

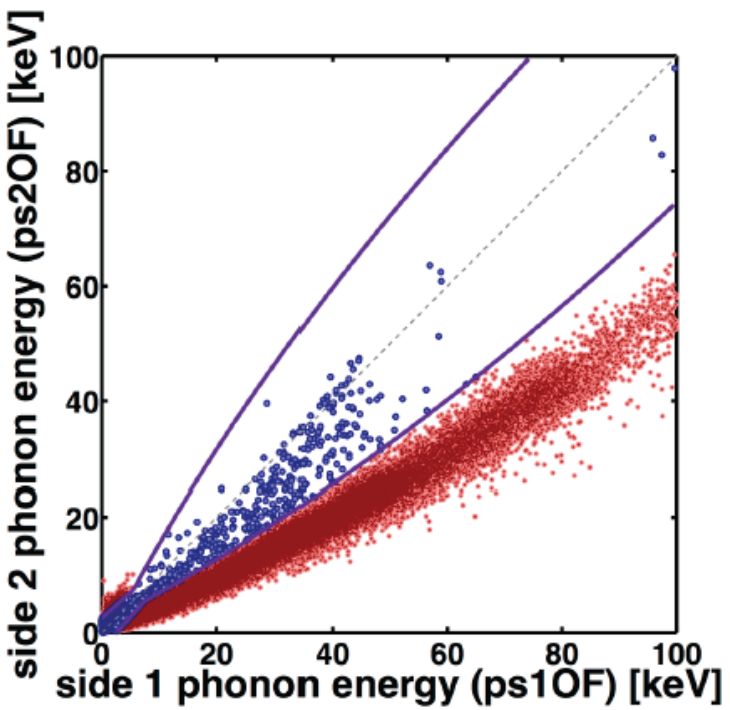
Energy range: 8-115 keVnr

Phonon asymmetry:
Leakage fraction = 3.5 x 10^{-4}

NR acceptance = 46%

Energy range: 8-115 keVnr





Cryo-Lab at UMN

- New cryogenic facility on campus.
- Kelvinox-100 (K100) cryostat:
  - Refurbished to host up to 6” diameter crystals, standard CDMS detector readout.
  - Major role in testing and characterization of SuperCDMS-Soudan detectors.
- Janis-25 (Little Blue)
  - Quick turn-around, basic functionality checks.
- Clean-room:
  - Class 10,000, with class-1000 bench space.
  - LN boiloff purge for radon-free storage.

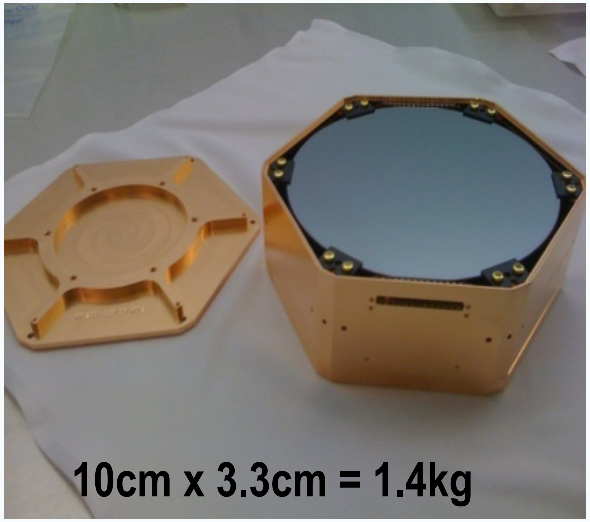
Team: Chagani, Radpour, Kennedy, Monin, Zhang, Codoreanu, Phenicie.

100mm Ge Detectors

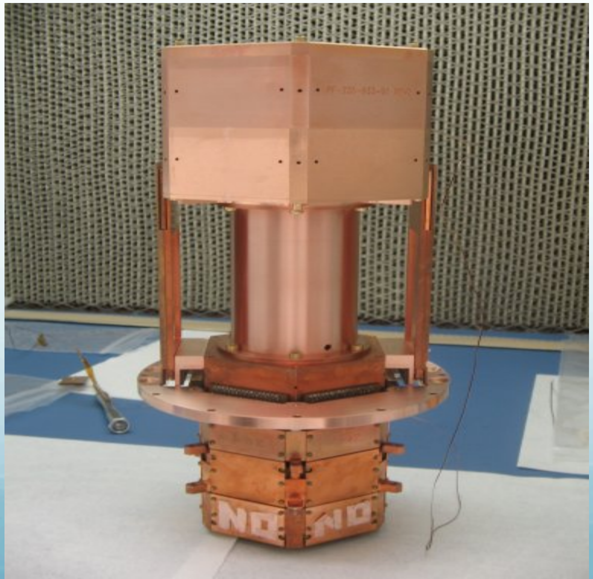
SuperCDMS-SNOLab: plan to use detector-grade 100 mm x 33 mm Ge crystals (1.5 kg).

Sensor depositions done at SLAC.

Tested at UMN: currently the only facility capable of such tests.



10cm x 3.3cm = 1.4kg



Mounted on the standard CDMS Tower (3")

Sophisticated transportation packaging!

100mm: Ionization Tests

- Four concentric ring electrodes on one surface, ground plane on the other.
- One ^{241}Am γ-source mounted above each electrode (~20 Hz rate).
- Charge collection efficiency consistent with the old measurements (on 1-cm thick crystals).