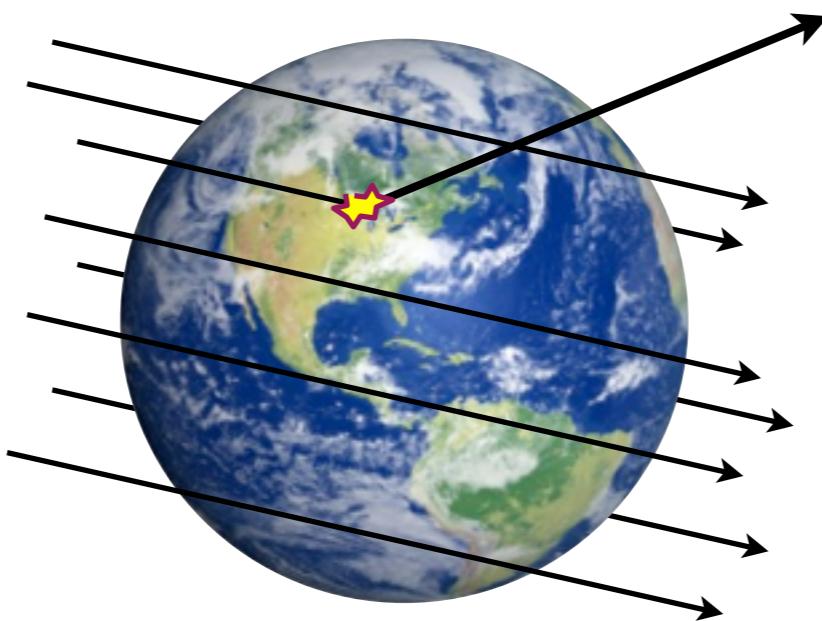


# Direct Detection of Dark Matter: Hints, Exclusions, and Future



Enectali Figueroa-Feliciano

# The Hunt for Dark Matter



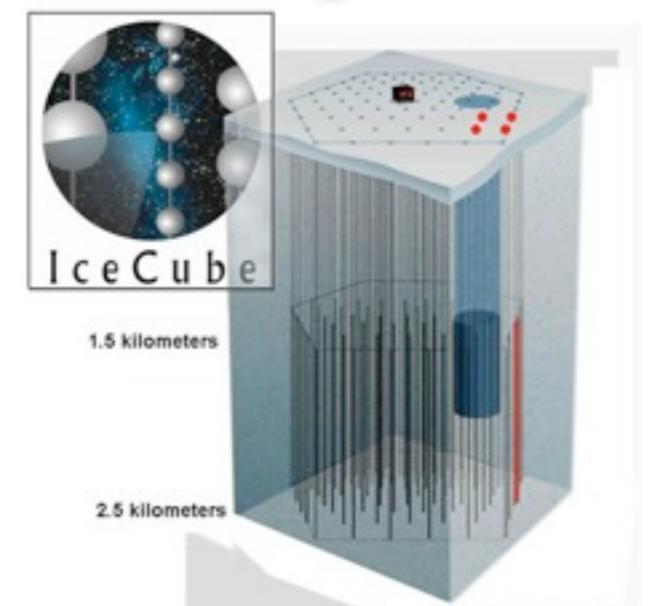
AMS-02



FERMI,  
Pamela,  
ATTIC



HESS, VERITAS,  
Magic



1.5 kilometers

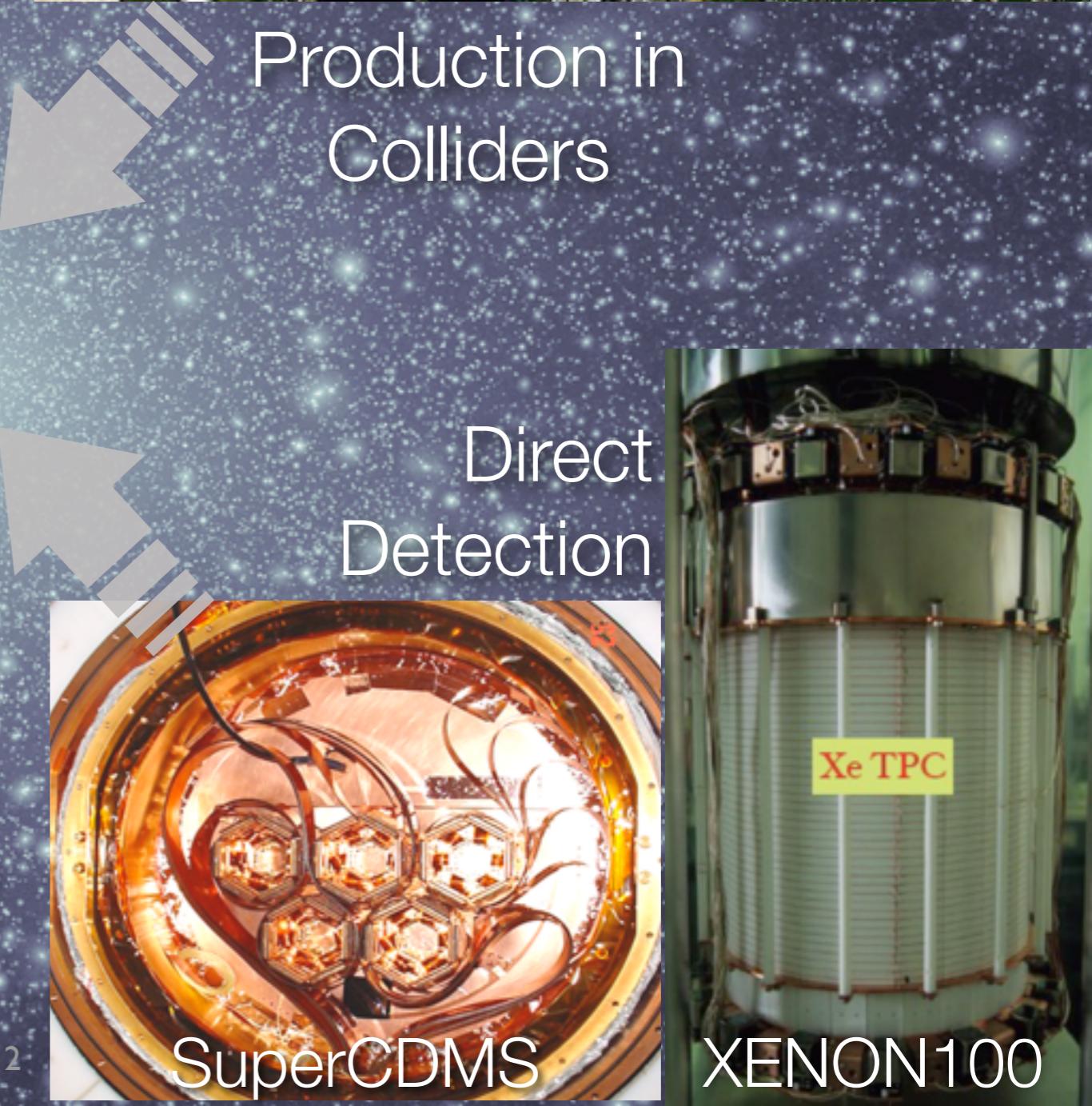
2.5 kilometers

Annihilation  
in the  
Cosmos

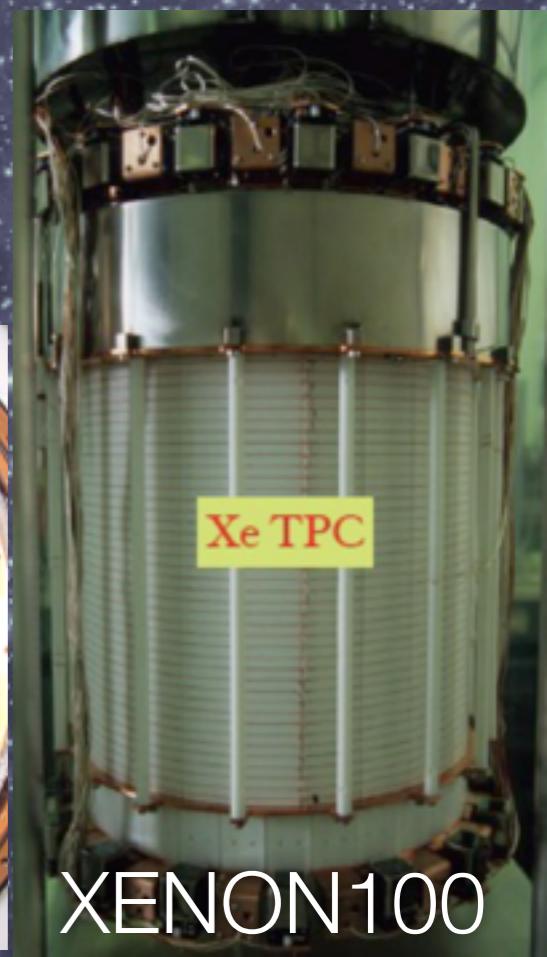
Astro-physics  
Measurements



LHC



SuperCDMS



Xe TPC

XENON100

# Direct Detection Fundamentals

Interaction Rate [events/keV/kg/day]	$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}$	particle theory	nuclear structure	local properties of DM halo
--	---	--------------------	----------------------	--------------------------------

$$F(E_R) \simeq \exp(-E_R m_N R_o^2/3)$$

“form factor” (quantum mechanics of interaction with nucleus)

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

“reduced mass”

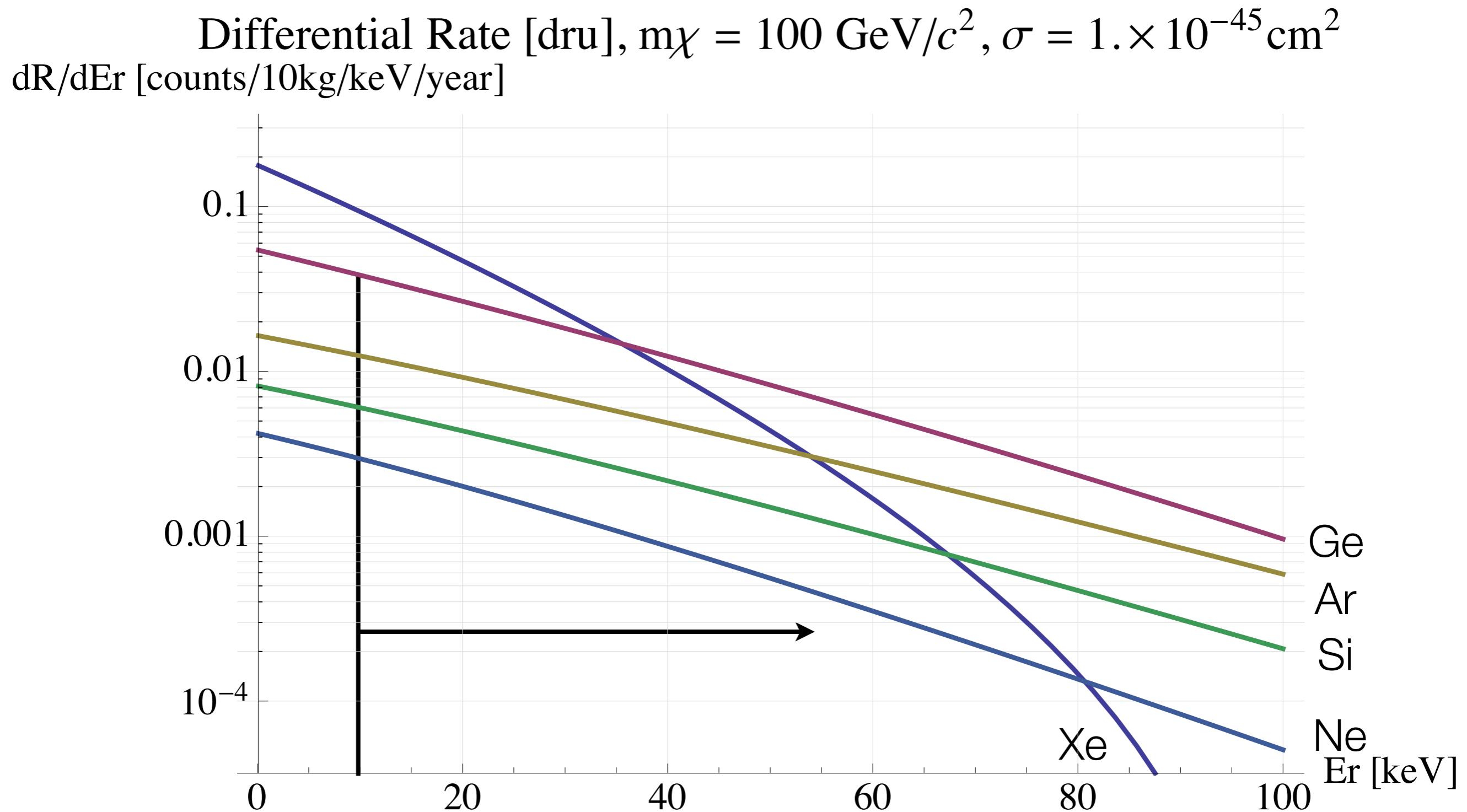
$$T(E_R) \simeq \exp(-v_{\min}^2/v_o^2)$$

integral over local WIMP velocity distribution

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

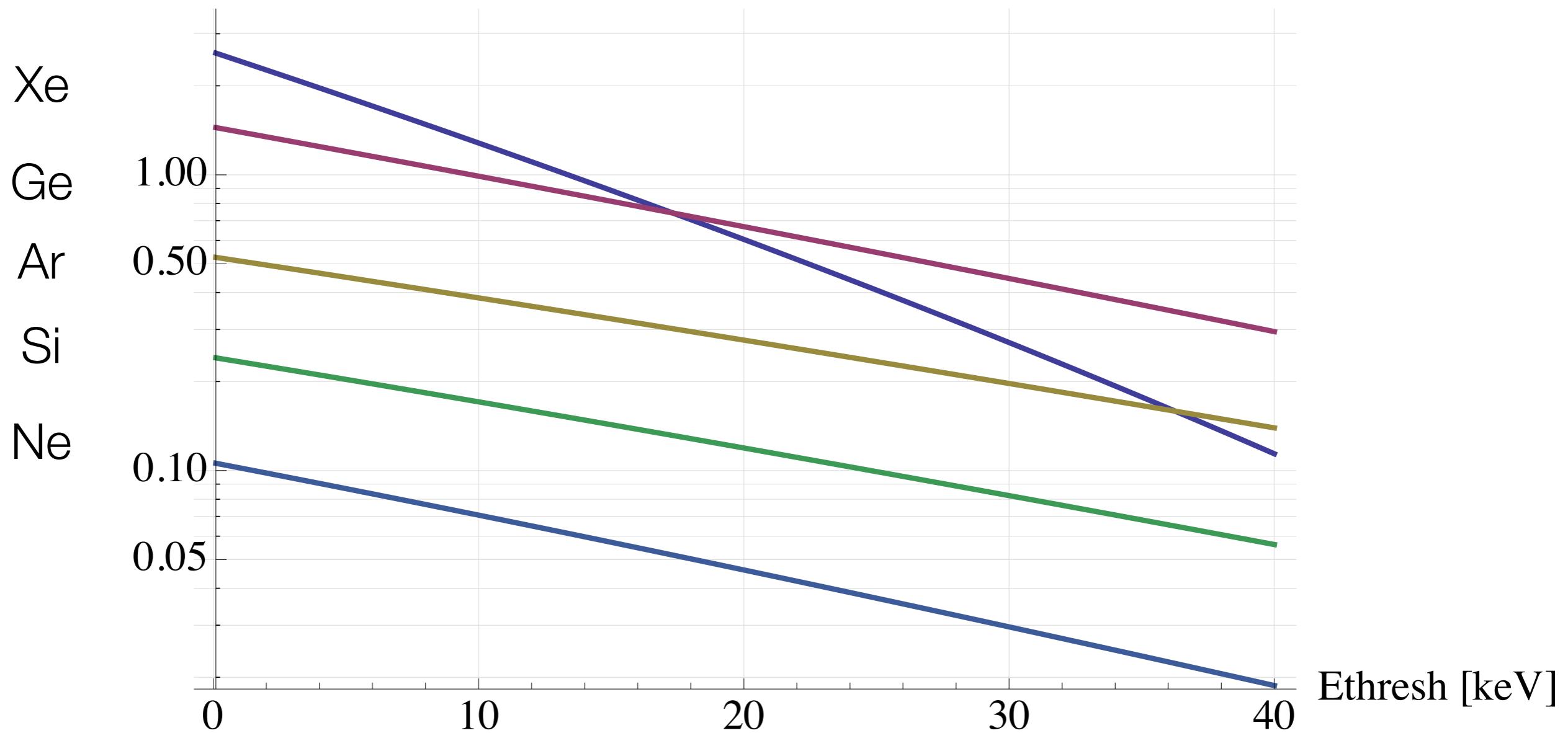
minimum WIMP velocity for given  $E_R$

# The expected direct detection rates are LOW!



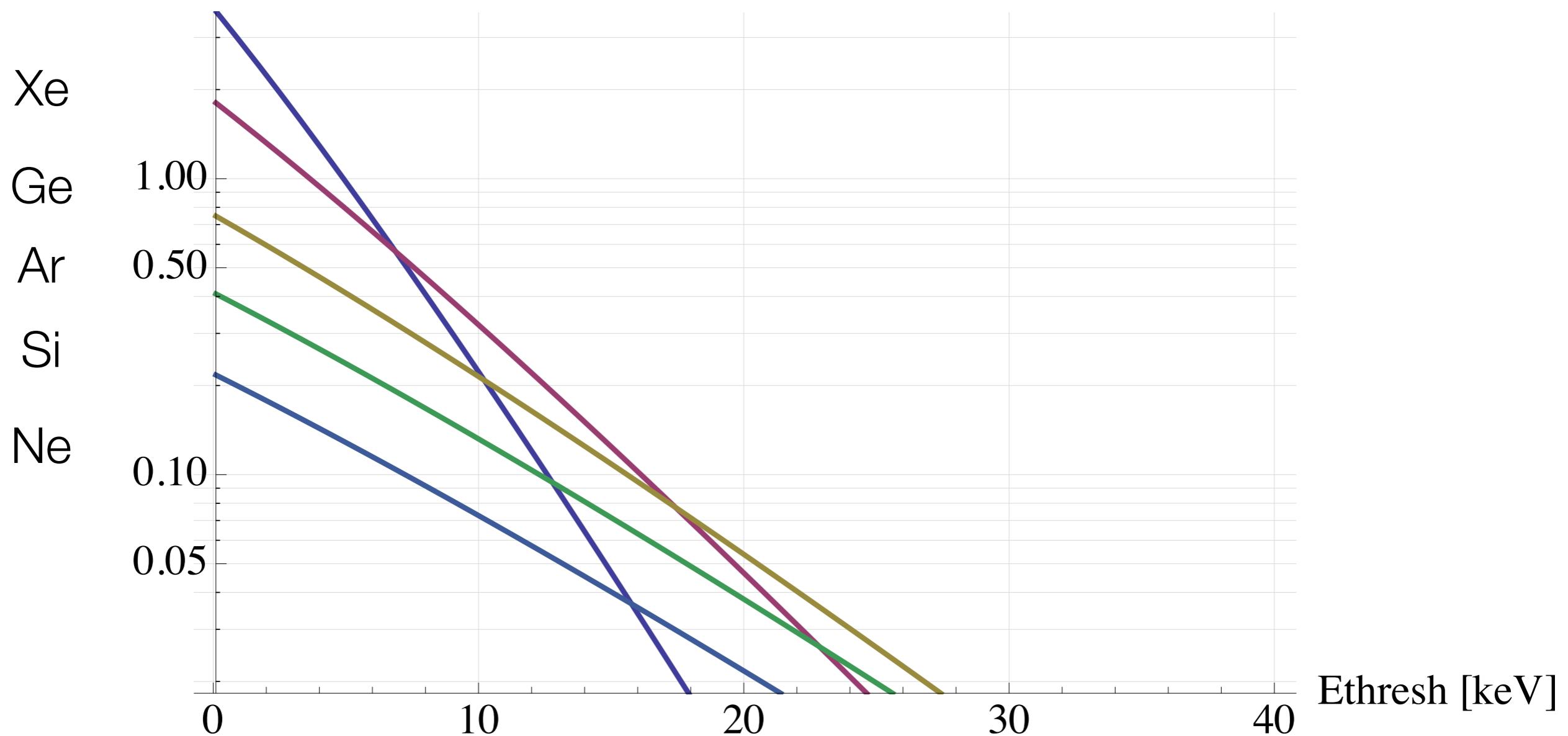
# Integrated Rate as a function of low-energy threshold of experiment

Total Rate for different thresholds,  $m\chi = 100 \text{ GeV}/c^2$ ,  $\sigma = 1. \times 10^{-45} \text{ cm}^2$   
 $R(\text{Ethresh})$  [counts/10kg/year]



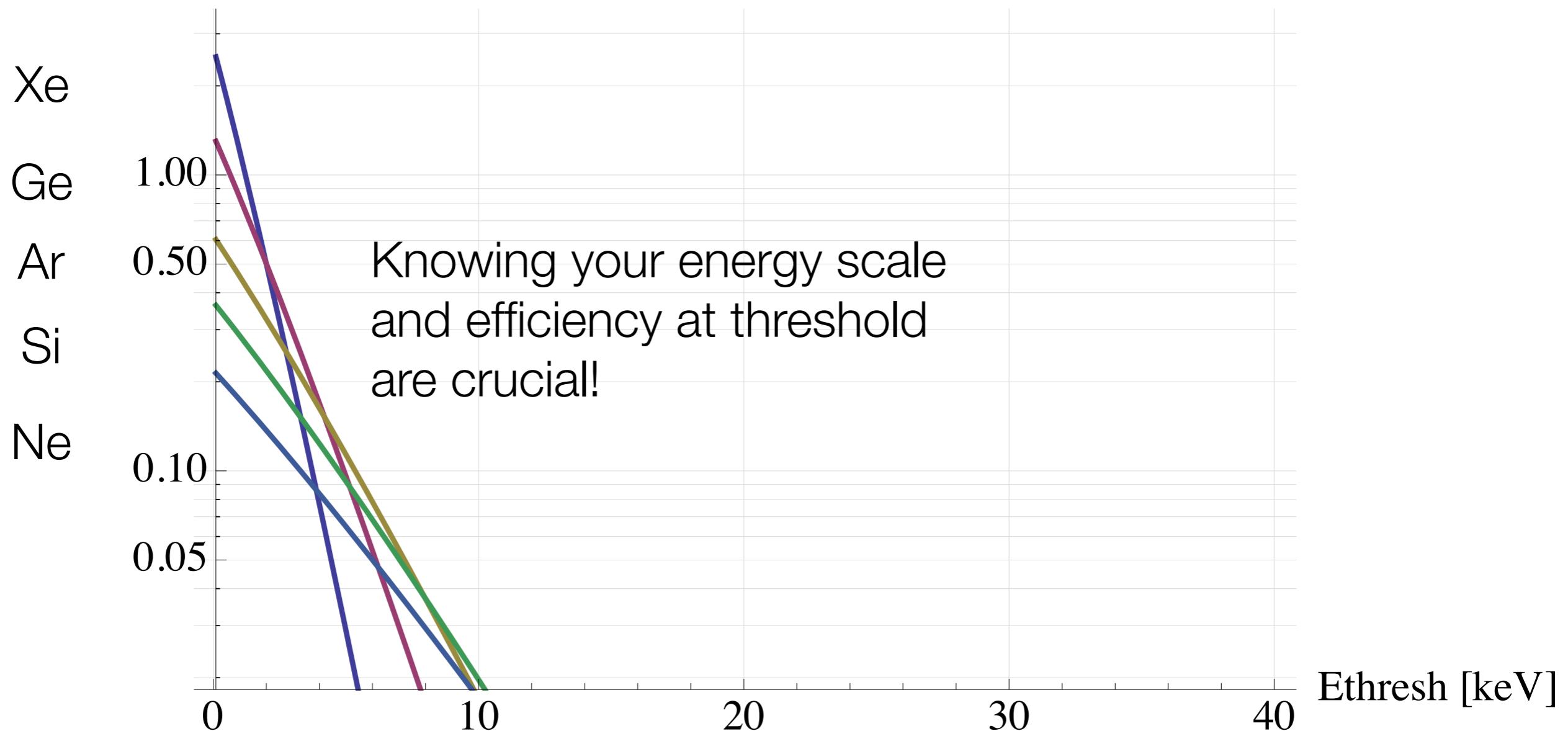
# Integrated Rate as a function of low-energy threshold of experiment

Total Rate for different thresholds,  $m\chi = 20 \text{ GeV}/c^2$ ,  $\sigma = 1. \times 10^{-45} \text{ cm}^2$   
 $R(\text{Ethresh})$  [counts/10kg/year]



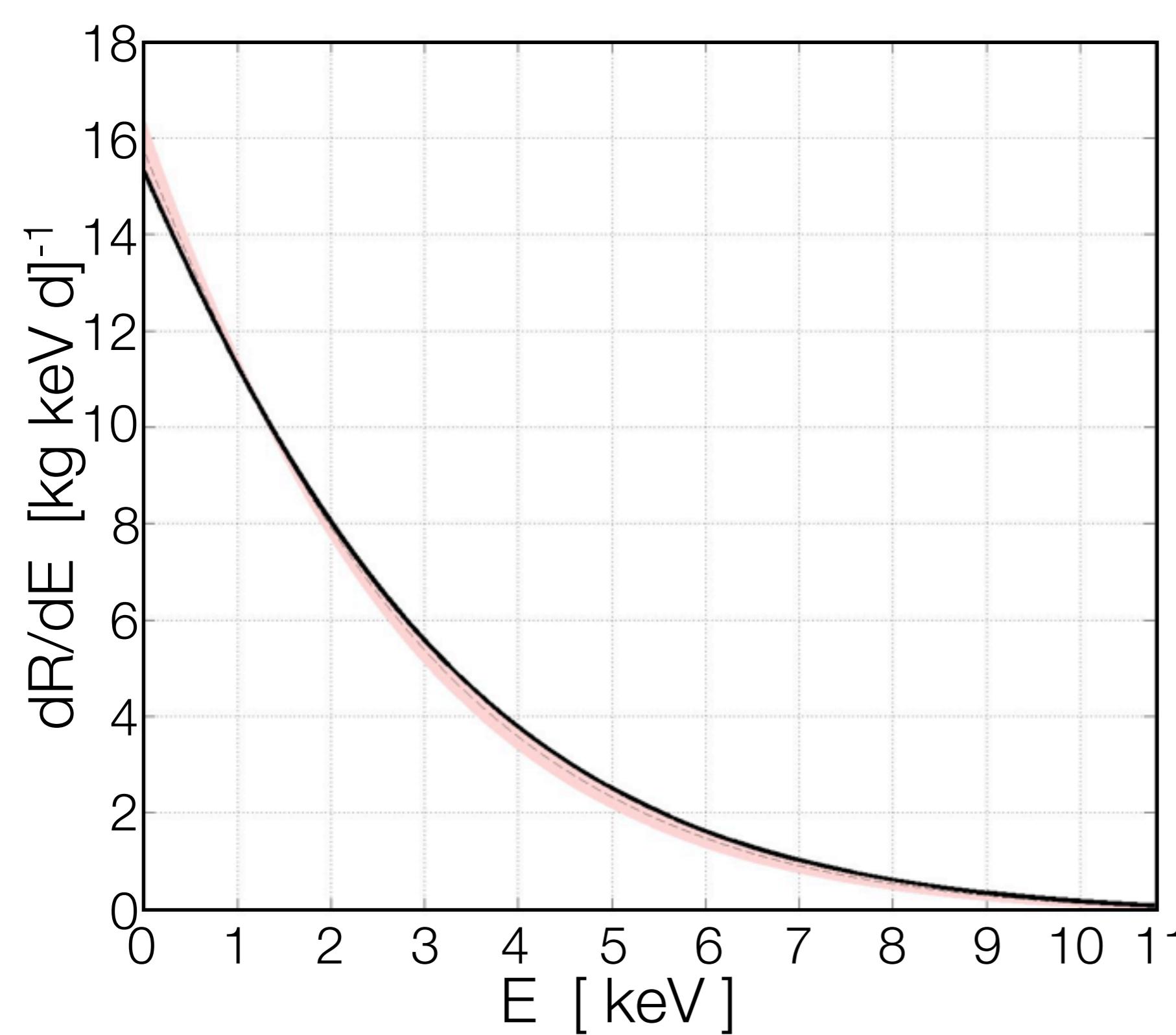
# Integrated Rate as a function of low-energy threshold of experiment

Total Rate for different thresholds,  $m\chi = 10 \text{ GeV}/c^2$ ,  $\sigma = 1. \times 10^{-45} \text{ cm}^2$   
 $R(\text{Ethresh})$  [counts/10kg/year]

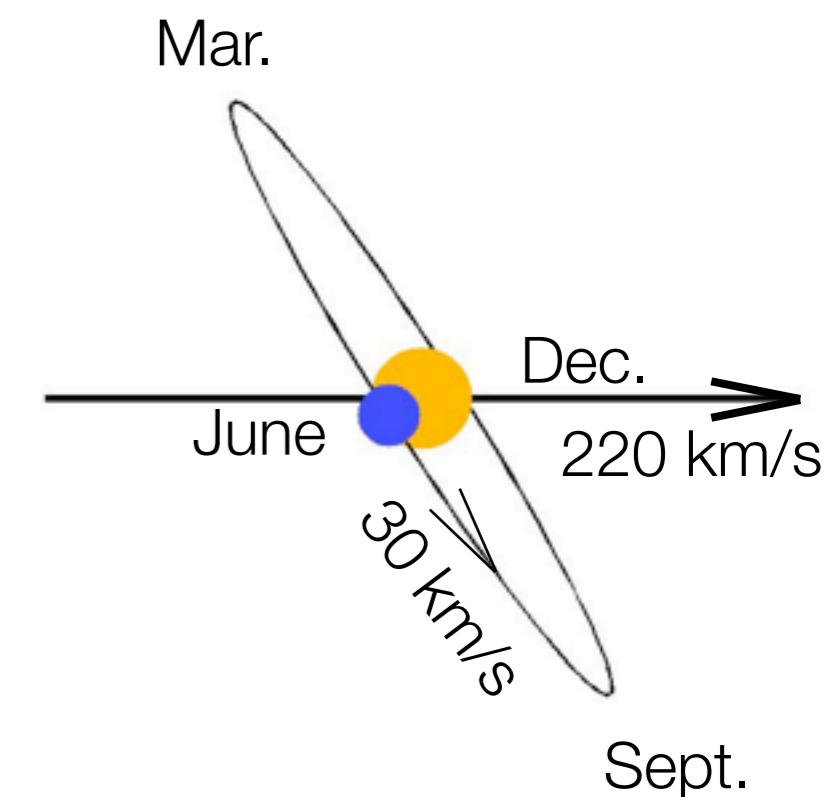


# Are we seeing Dark Matter signals?

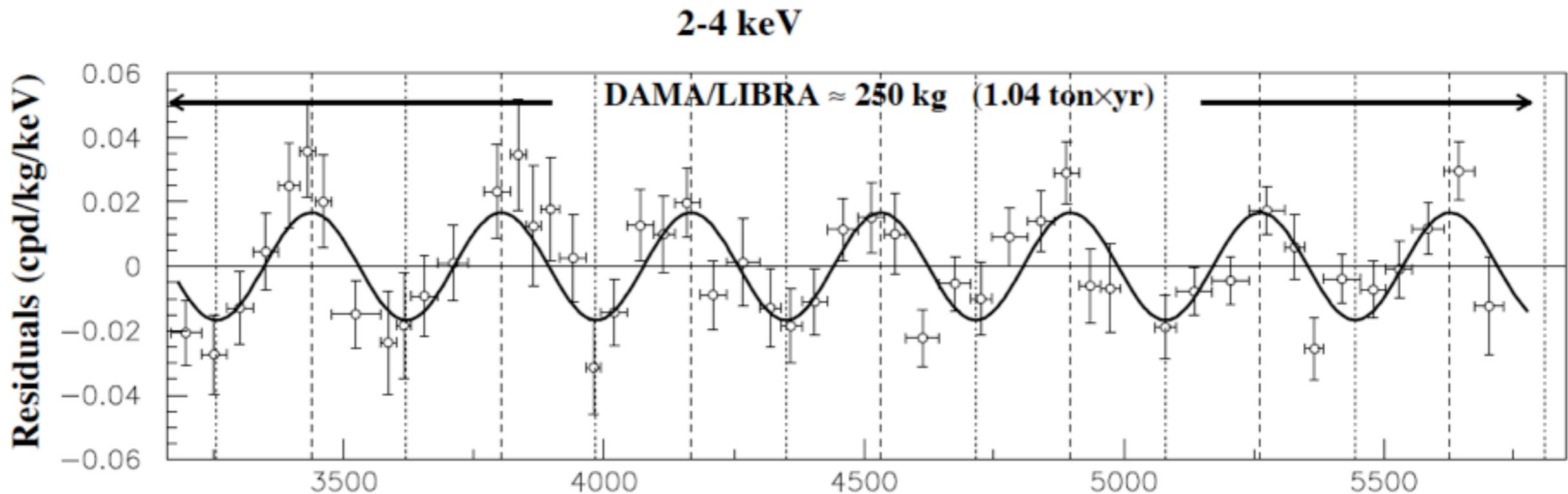
# Annual Modulation



Target: Ge  
 $\sigma_{\text{SI}} = 1 \times 10^{-4} \text{ pb}$   
 $M_x = 10 \text{ GeV/cm}^2$



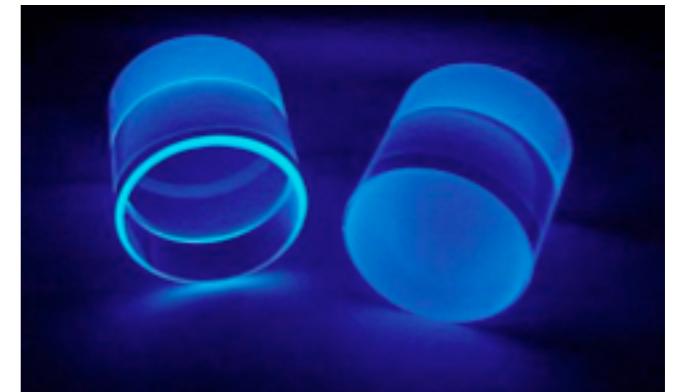
# DAMA/LIBRA - New Results!



- Using an array of radiopure NaI crystals, DAMA/NaI reported an annual modulation in event rate consistent with dark matter, observed over 7 annual cycles.
- In 2008, follow-up experiment, DAMA/LIBRA, confirms the annual modulation. Together the DAMA experiments now report an effect with a statistical significance of  $9.3\sigma$  with a 1.33 ton-yr exposure over 14 annual cycles.
- To date no other experiments have confirmed this signal, yet efforts are ongoing to directly test this.

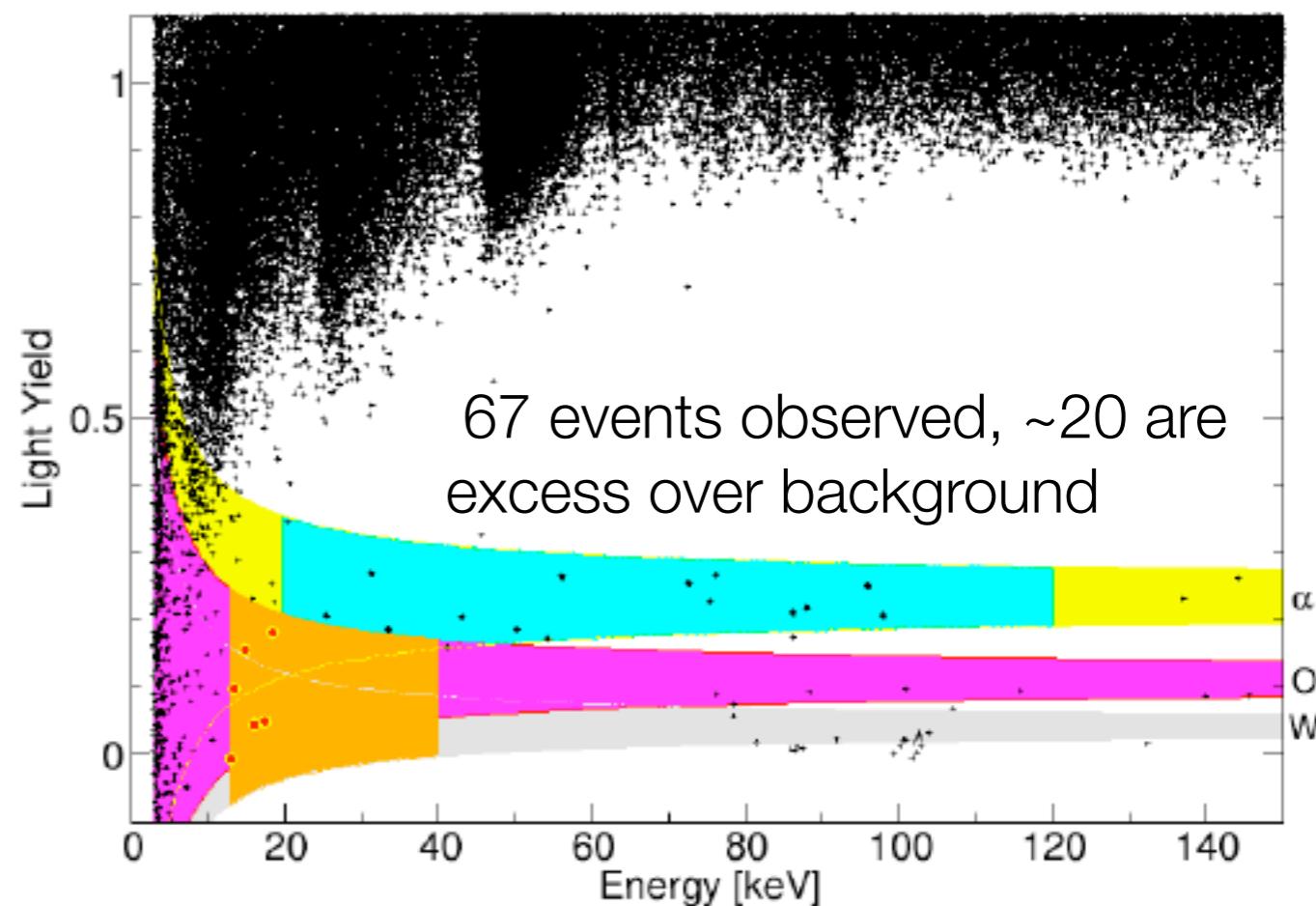
Time (day)  
Eur. Phys. J. C  
(2010) 67: 39–49  
arXiv: 1308.5109

- Looks for WIMP scatters off of Ca, W and O nuclei
- CaWO<sub>4</sub> crystals detect scintillation light and phonons, providing capability to identify scatters off specific nuclei
- Analysis of data taken in 2011 reveals excess nuclear recoils at  $>4\sigma$  significance, which are consistent with WIMPs



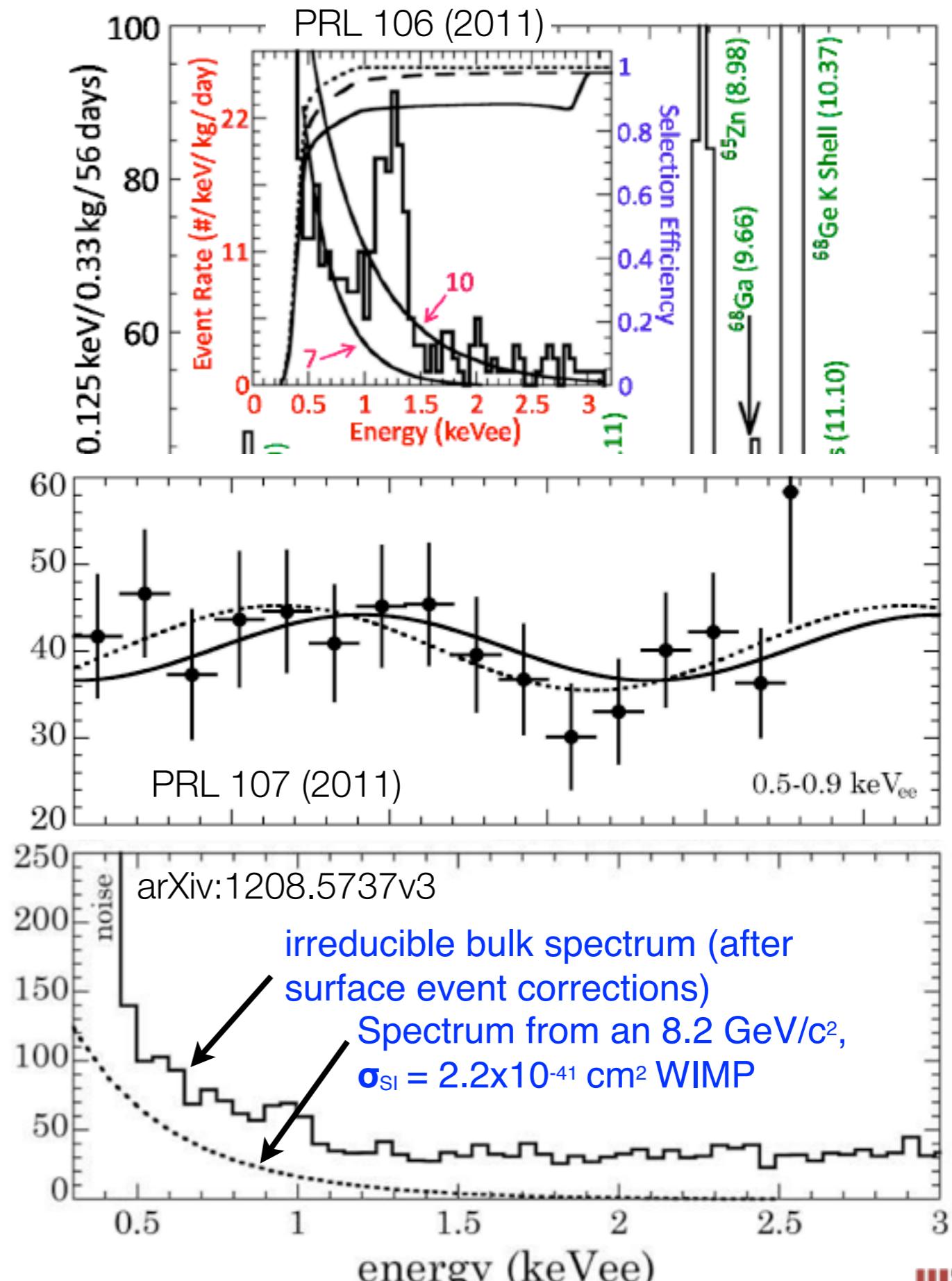
Eur. Phys. J. C (2012) 72:1971

- Favored masses and cross sections are in tension with other experiments; now trying to reduce Rn-daughter contaminants in detector housing components (clamps)



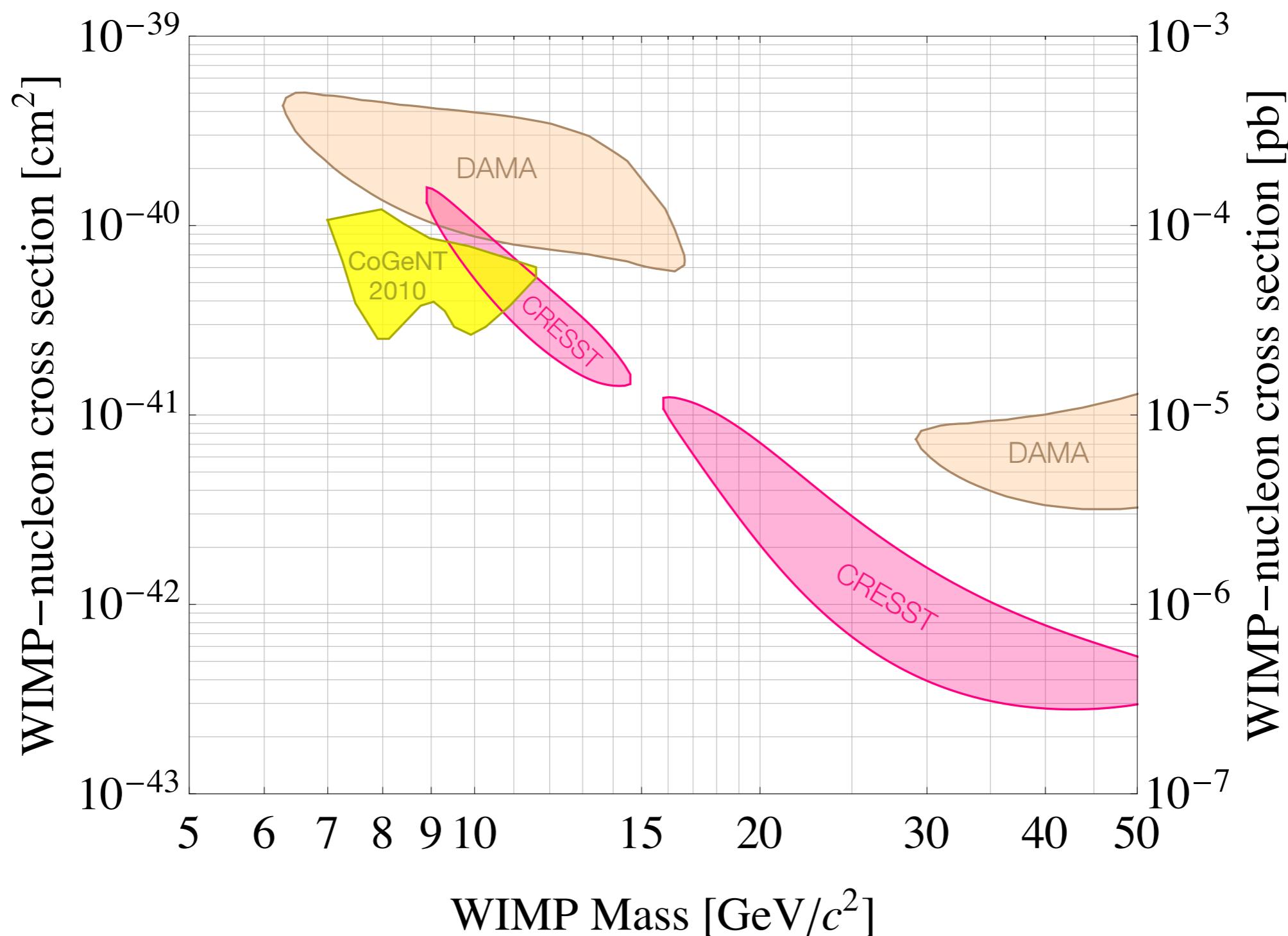
# CoGeNT

- In 2010, CoGeNT using PPC Ge to push ionization thresholds down to <0.5 keV; reported an excess of low-energy events with spectrum consistent with a  $\sim 10$  GeV/c<sup>2</sup> WIMP
- In 2011, reports a modulation of events in the 0.5-3.0 keVee region with  $\sim 2.8\sigma$  significance, corresponding to a large fractional modulation
- 2012/2013: CoGeNT revises background estimates and reports smaller, but still statistically significant, excess of low energy events



# Overlapping ROIs from Different Experiments!

Very suggestive results from potential WIMP interpretations of three different experiments...

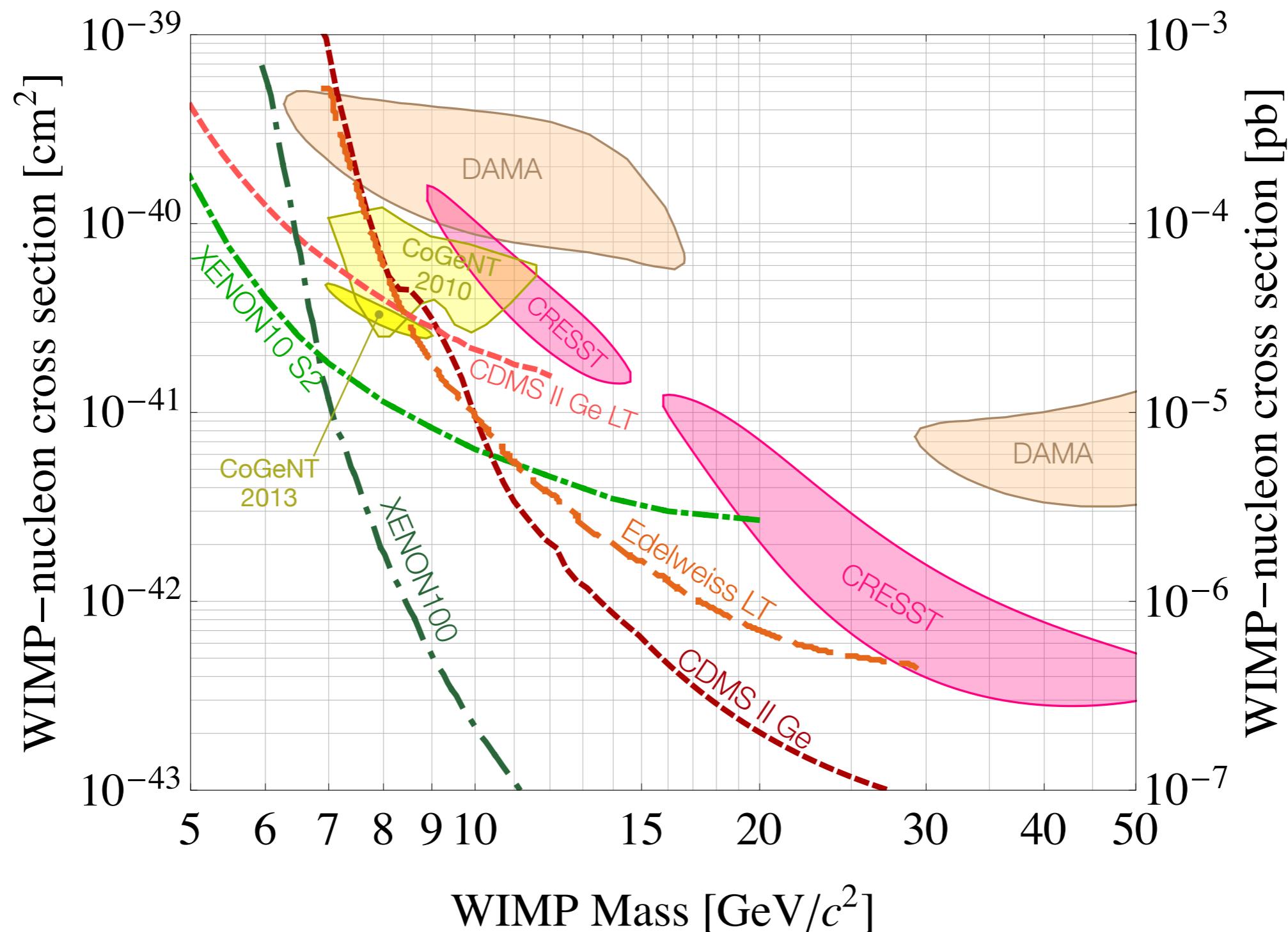


Are we seeing Dark Matter  
signals?

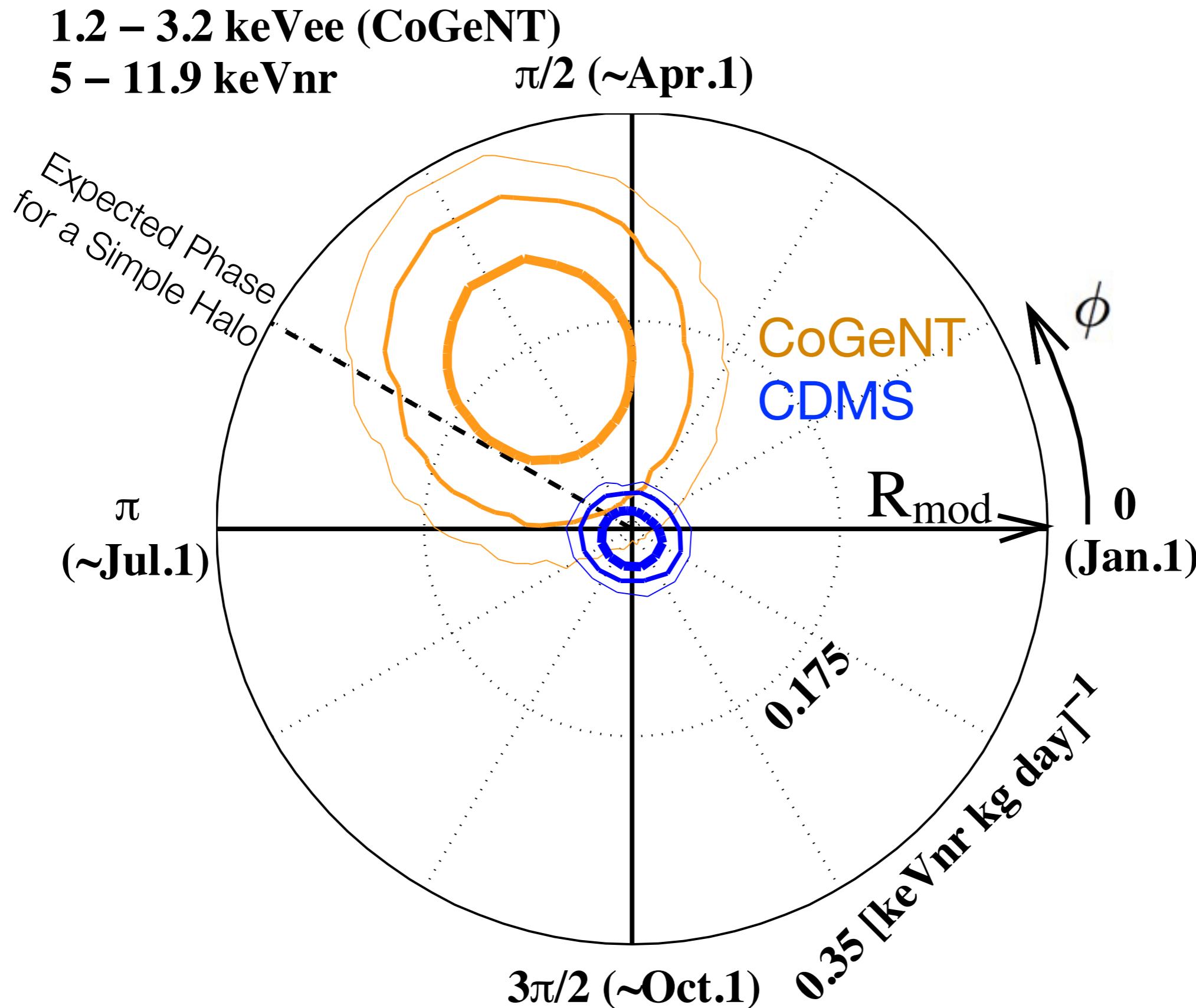
...or NOT?

# Null Results from Ge Low Threshold and XENON10/100

CDMS II, XENON 100, XENON 10 and EDELWEISS all set upper limits based on rate of events seen in signal regions.

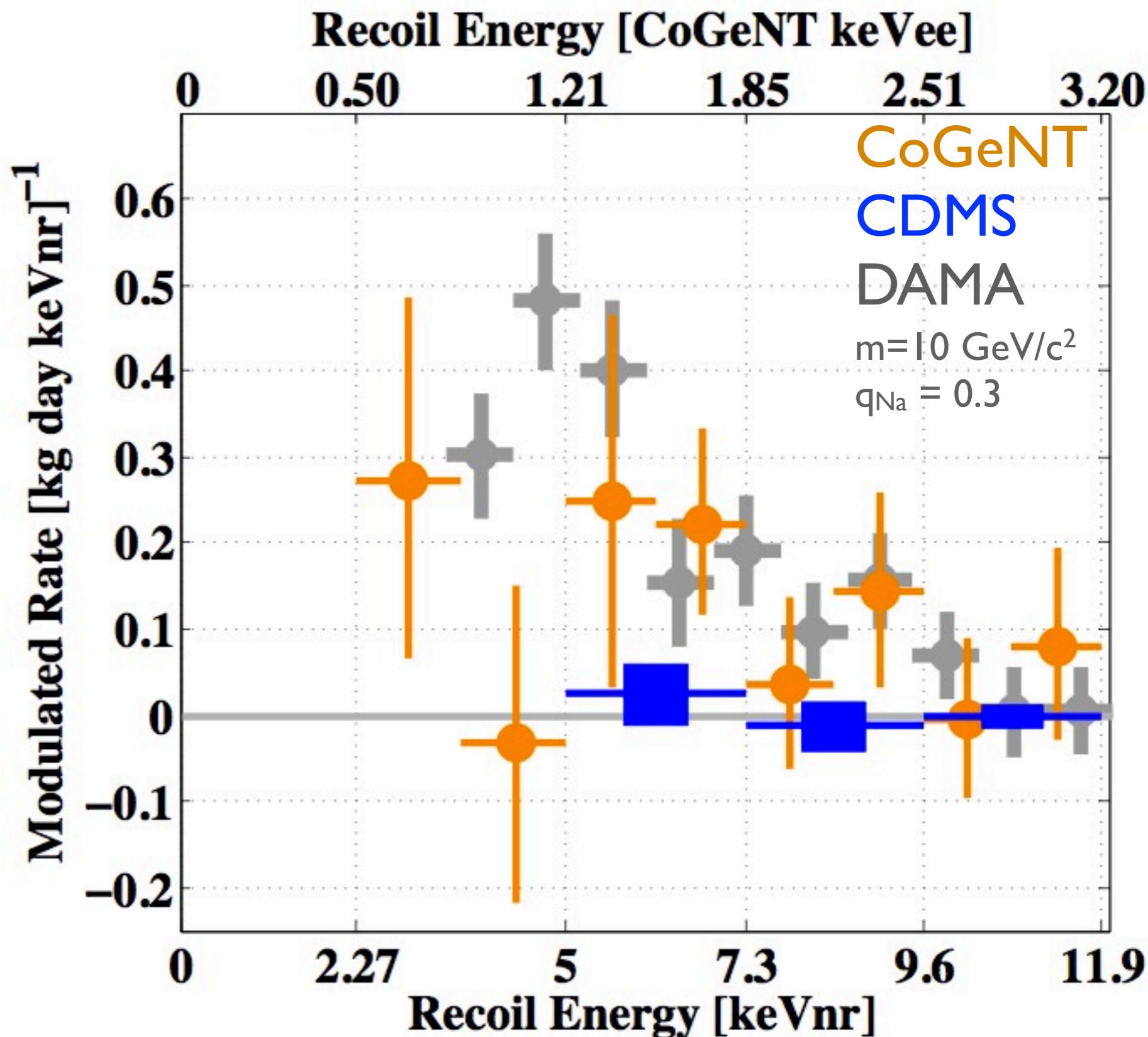


# Null Results from CDMS II Annual Modulation



# Null Results from CDMS II Annual Modulation

152.5-day phase  
(Simple Halo Model)



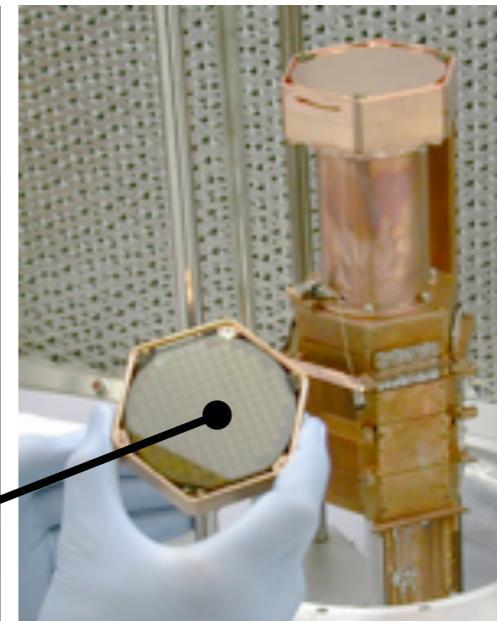
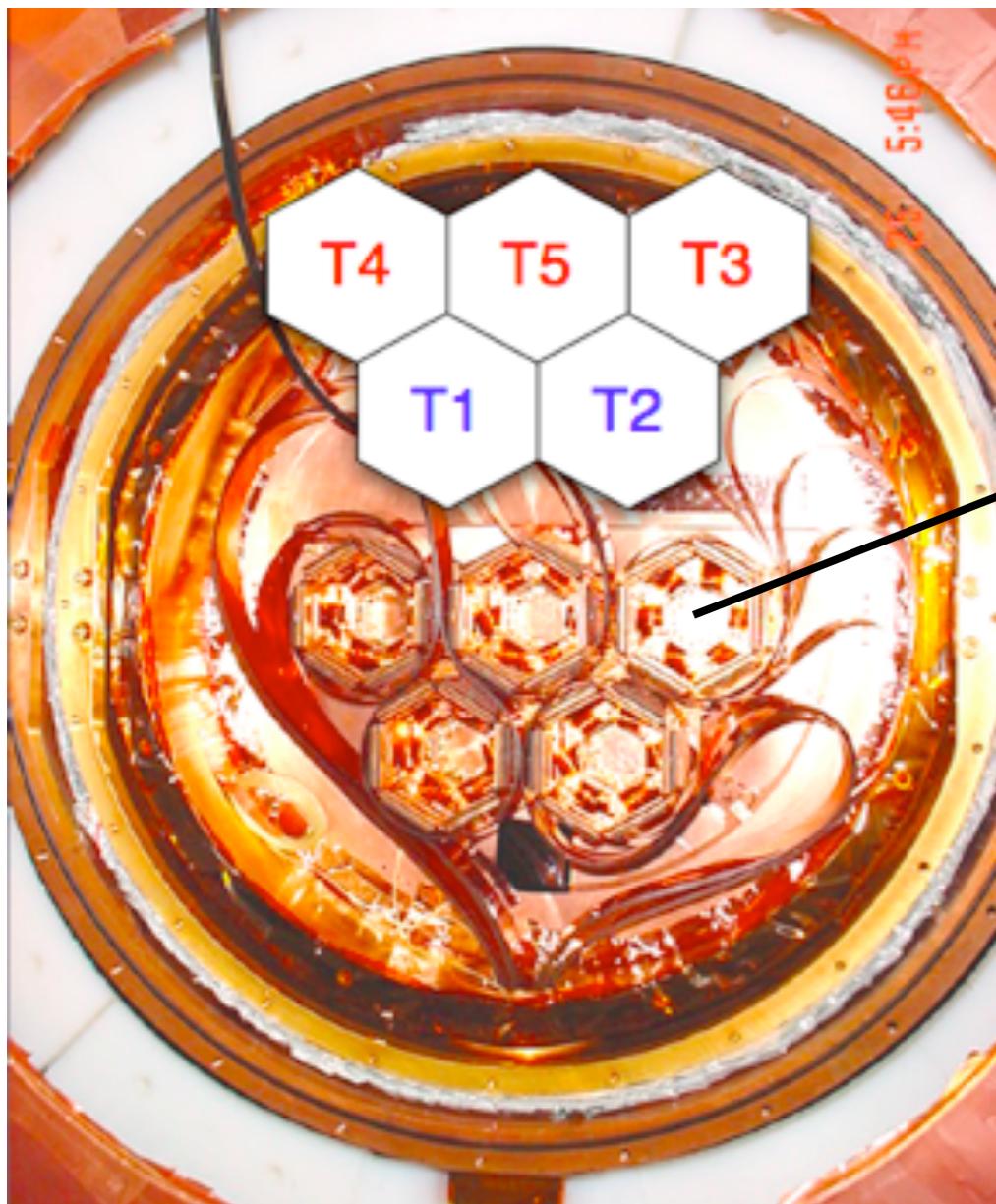
Are we seeing Dark Matter  
signals?

...or NOT?

...or actually maybe YES?

# CDMS II Search with Silicon

- Reporting results from blind analysis of 140 kg-days of Si data (8 detectors), gathered from July 2007- September 2008
- Lighter Si target nucleus is advantageous for low mass WIMP searches !

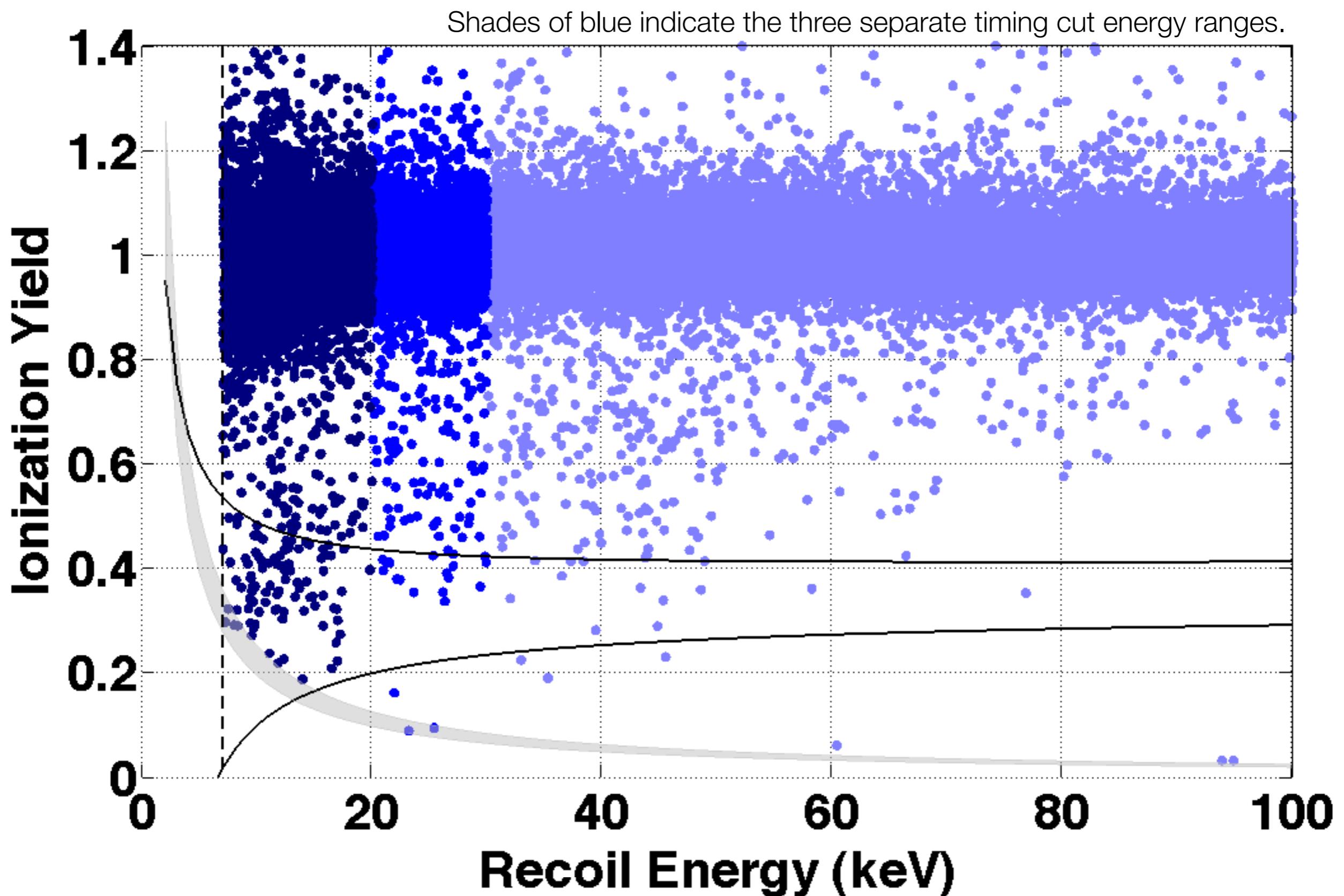


Five Towers (30 ZIPS)  
Operated 2006-2009  
4.6 kg Ge ( $A=73$ )  
1.2 kg Si ( $A=28$ )

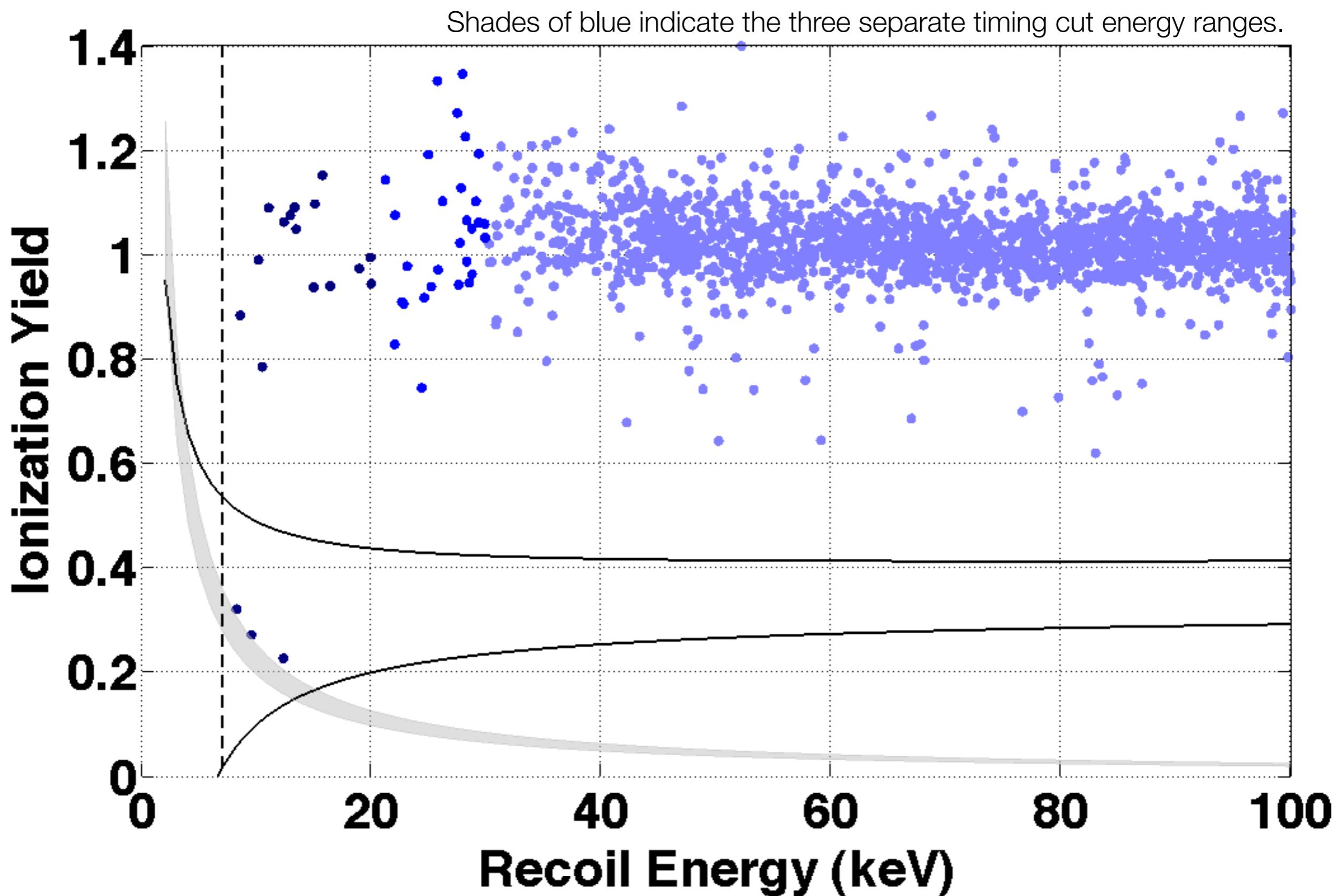
	$T1$	$T2$	$T3$	$T4$	$T5$
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24

Side View

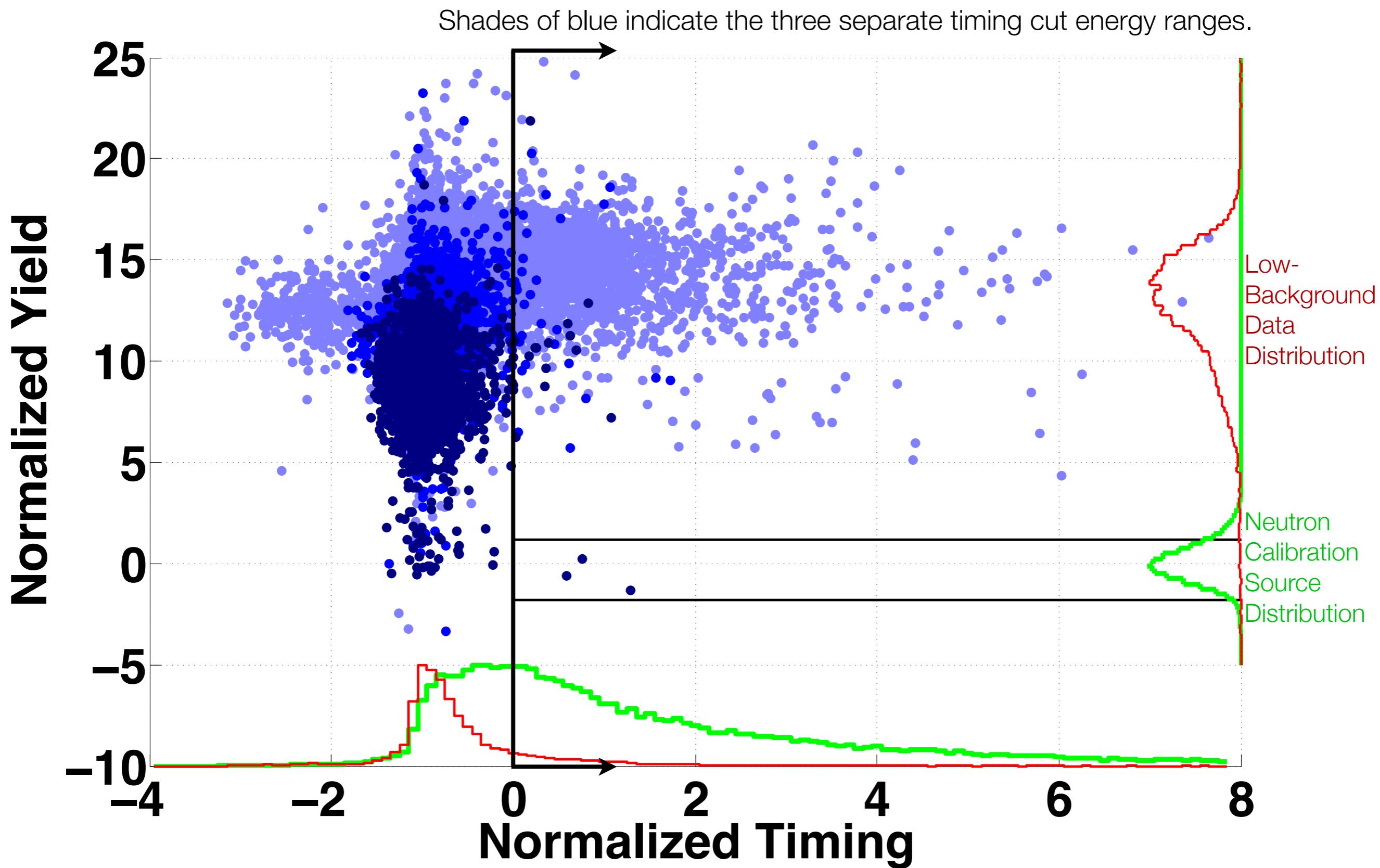
# Unblinding Results - before timing cut



# Unblinding Results - after timing cut



# Unblinding Results - Yield vs Timing

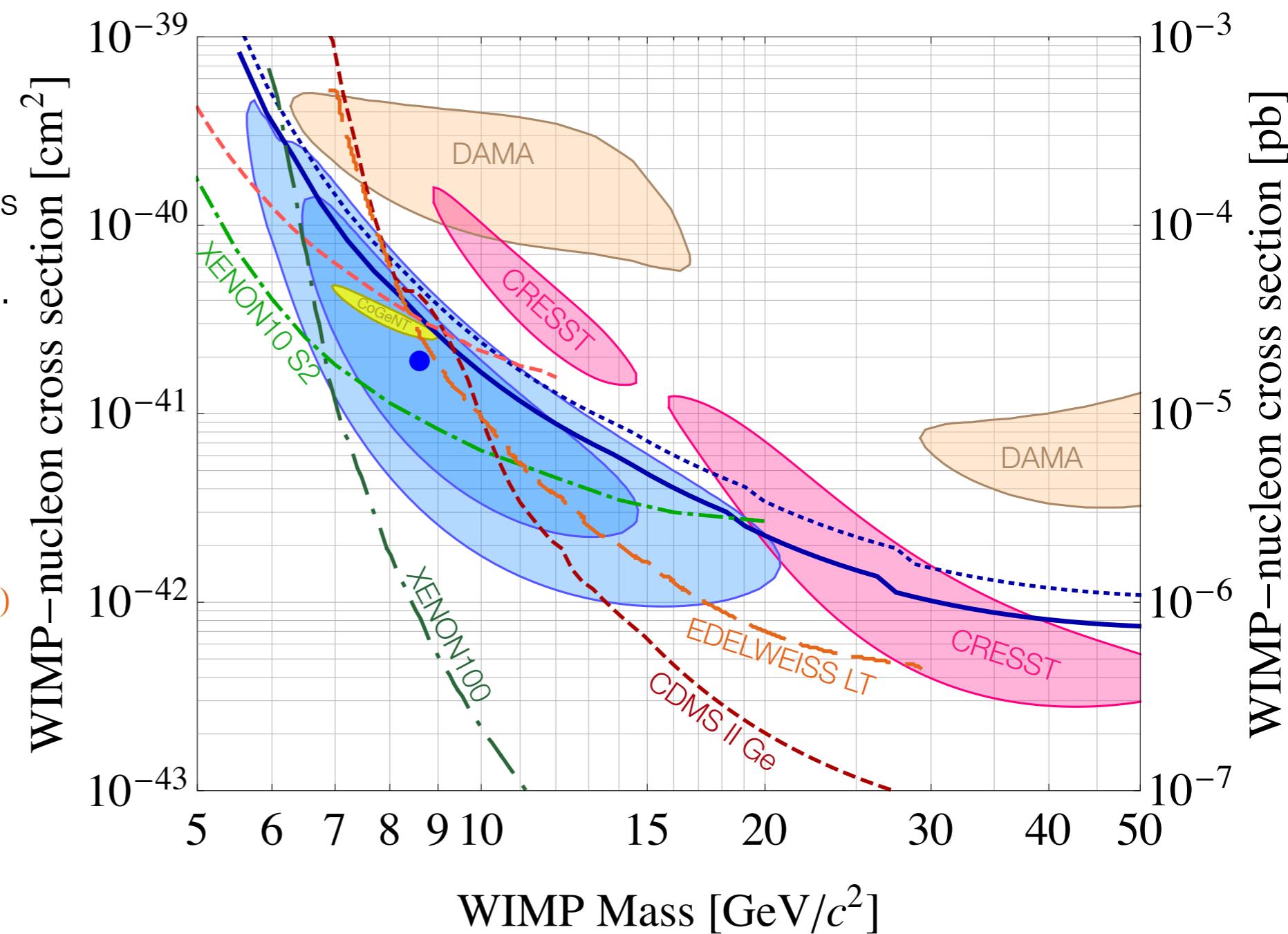


# Profile Likelihood Analysis

- A profile likelihood analysis favors a WIMP +background hypothesis over the known background estimate as the source of our signal at the 99.81% confidence level ( $\sim 3\sigma$ , p-value: 0.19%).
- Probability of a statistical fluctuation producing  $\geq 3$  events anywhere in signal region 5.4%
- We do not believe this result rises to the level of a discovery, but does call for further investigation.

- CoGeNT (2013)
- CRESST-II (2012)
- DAMA/LIBRA (2008)
- XENON100 (2012)
- XENON10 S2 (2013)
- EDELWEISS Low-threshold (2012)
- CDMS II Ge (2010)
- CDMS II Ge Low-threshold (2011)
- 90% U.L. CDMS II Si (2013 PRL)
- 90% U.L. CDMS II Si Combined
- Best fit, CDMS II Si (2013 PRL)
- 68% C.L., CDMS II Si (2013 PRL)
- 90% C.L., CDMS II Si (2013 PRL)

- The maximum likelihood occurs at a WIMP mass of 8.6  $\text{GeV}/c^2$  and WIMP-nucleon cross section of  $1.9 \times 10^{-41} \text{cm}^2$ .



Are we seeing Dark Matter  
signals?

...or NOT?

...or actually maybe YES?

So where are we Now?

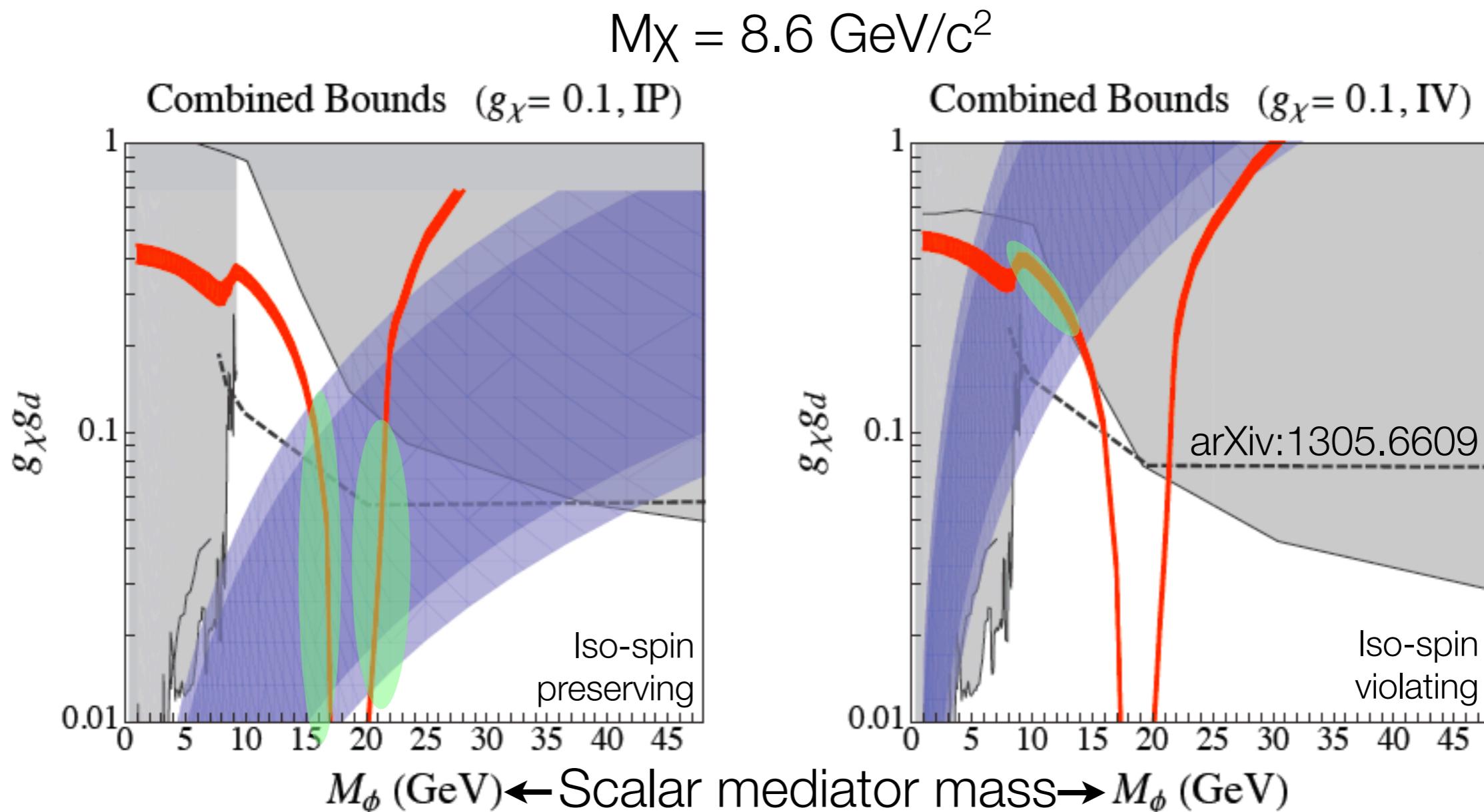
# Where are we? Unclear!

---

- The field continues to be in a state with “hints” of signals from some experiments and null results from others. Hints aren’t in strong agreement with each other either.
- The CDMS II Silicon results are interesting in that they are the first data set with a near-zero expected background that reports an excess of events potentially consistent with a dark matter signal.
- Are we seeing the beginnings of new particle physics phenomena, or are all the reported excesses due to not-understood backgrounds?
- Aside from DAMA, no other experiment’s results are high in statistical significance and no one else has claimed to be seeing WIMPs.

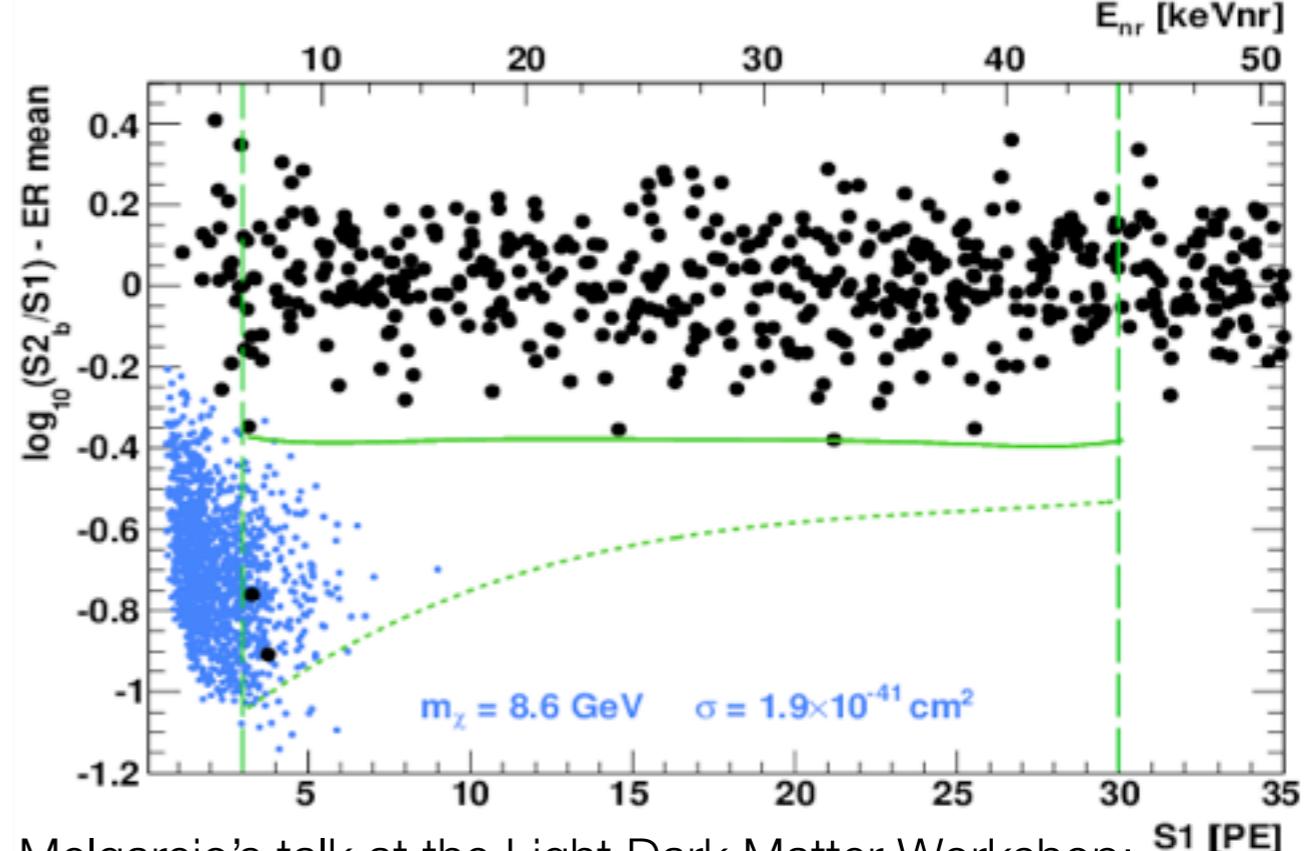
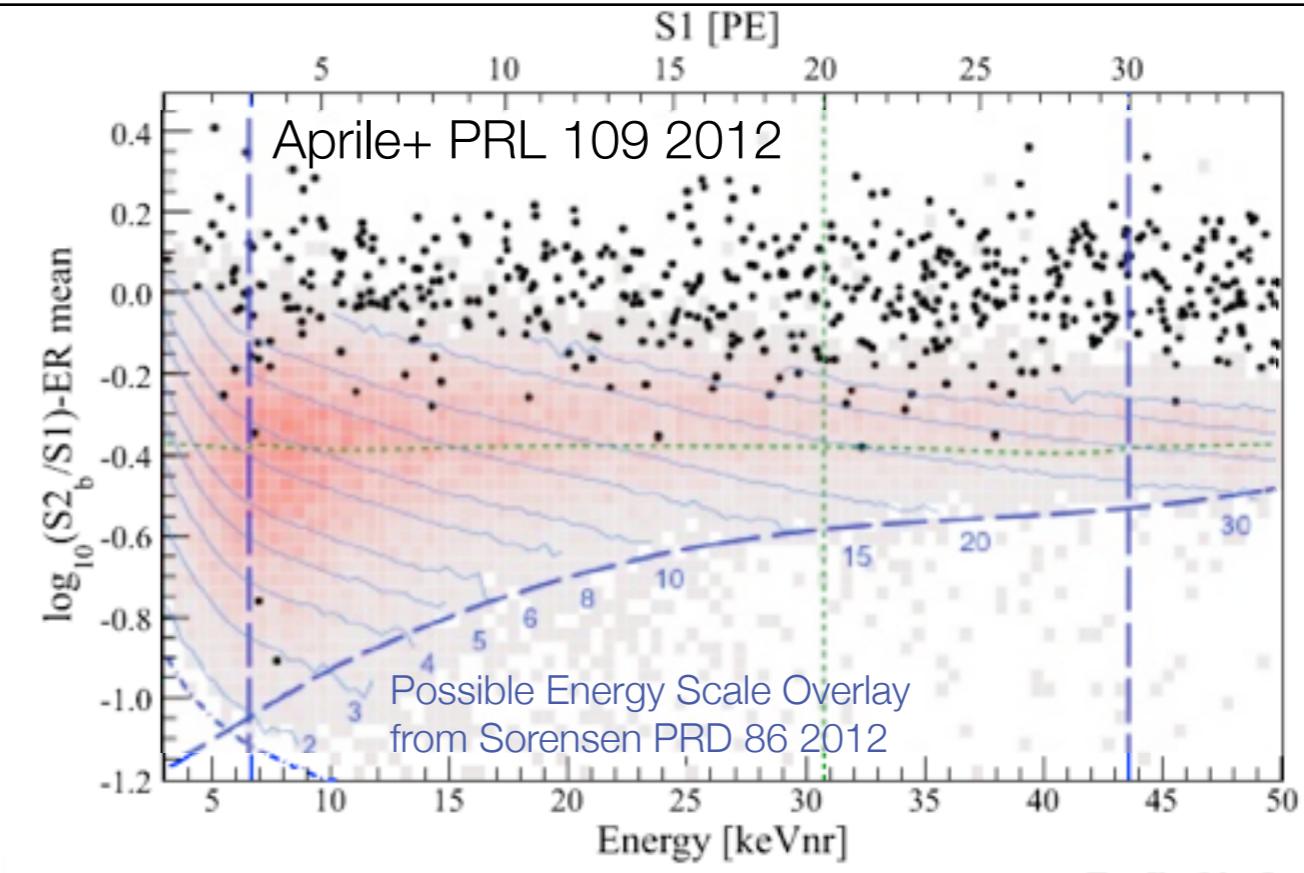
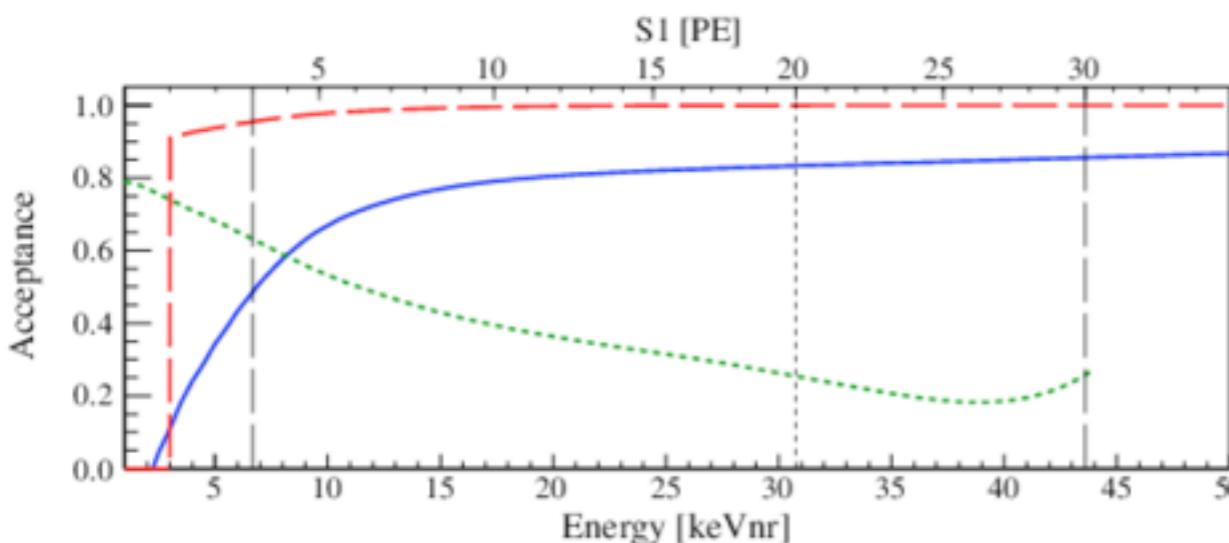
# Has the LHC Ruled this region out?

- LHC rules out contact interactions between  $\chi$  and SM particles with heavy mediators.
- For light mediators, solutions exist that evade all bounds (see for example arXiv:1305.6609).



# What about XENON100?

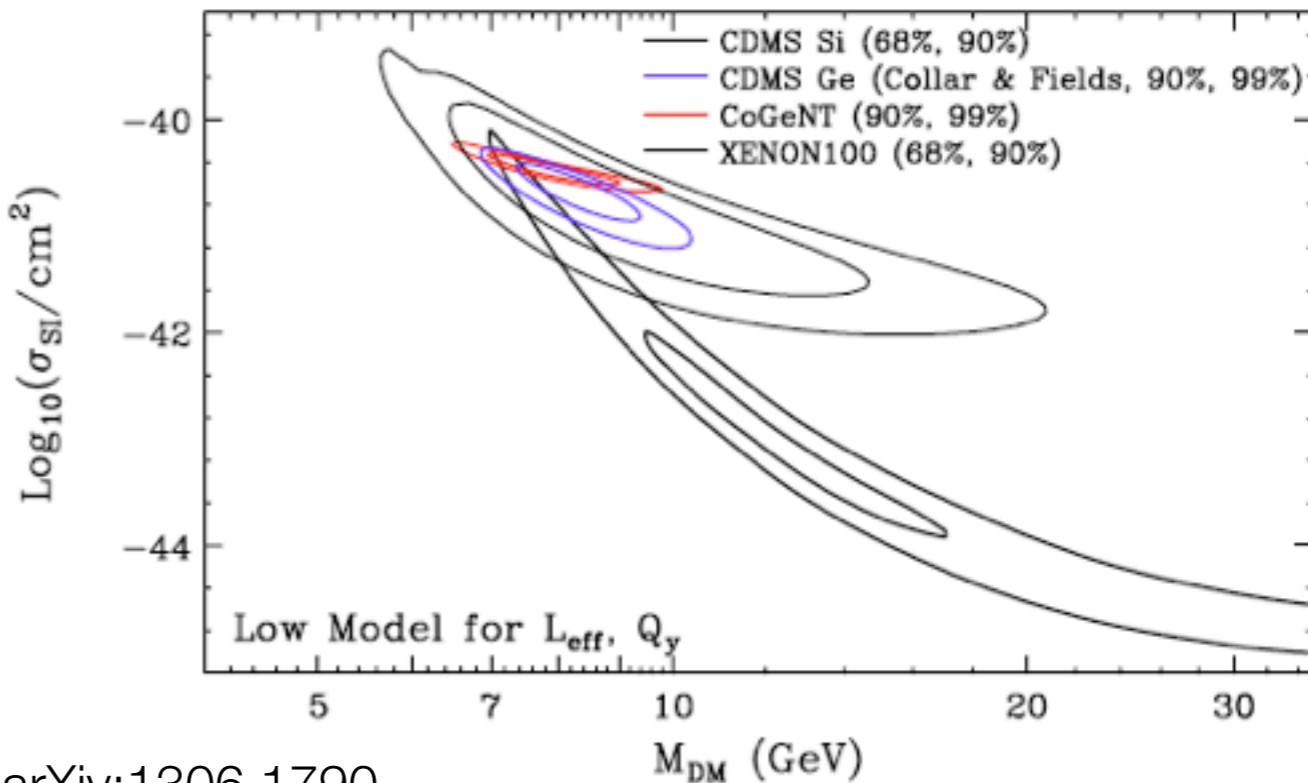
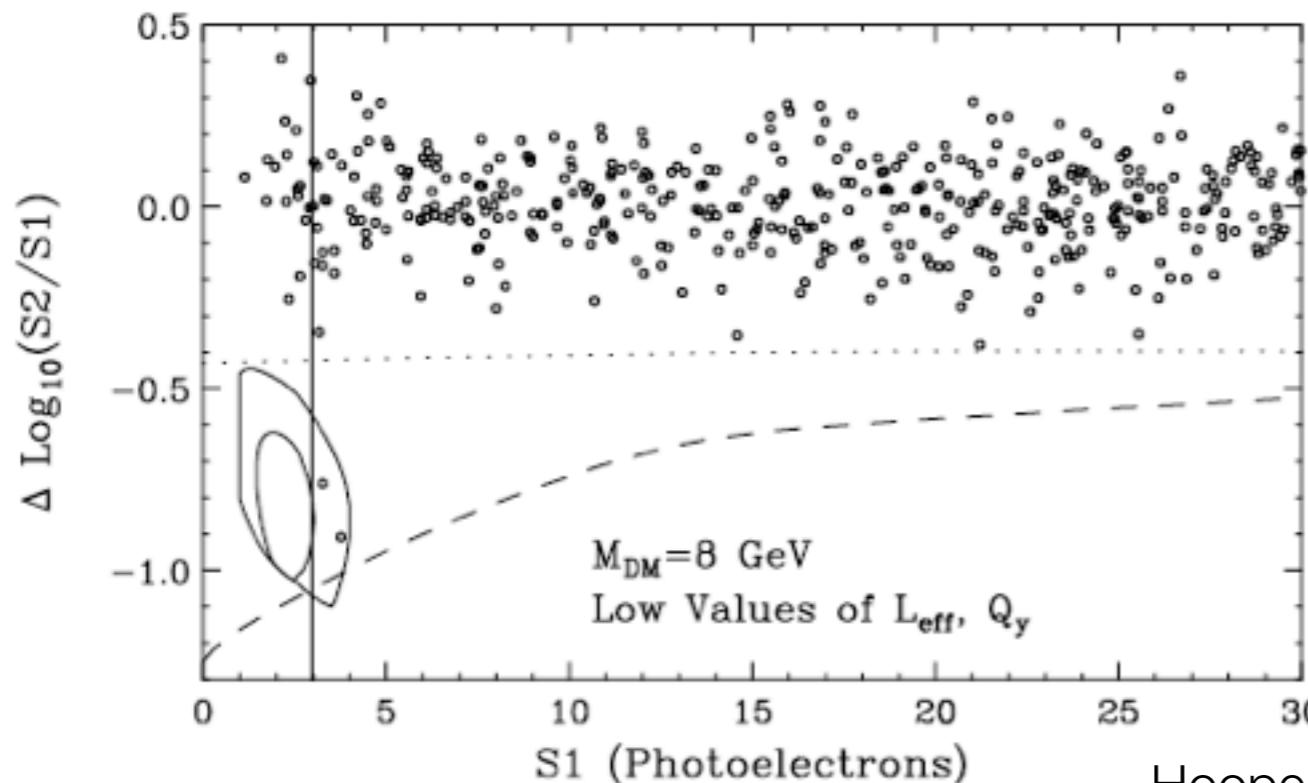
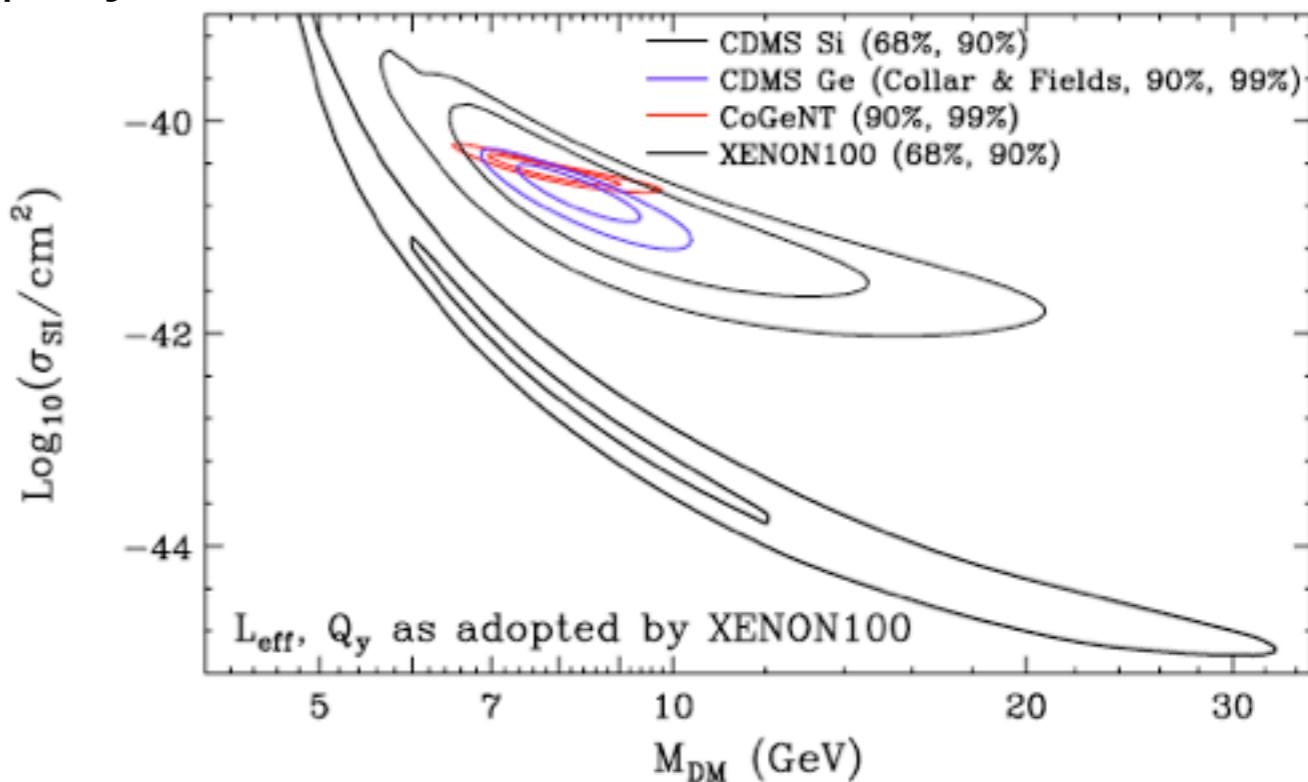
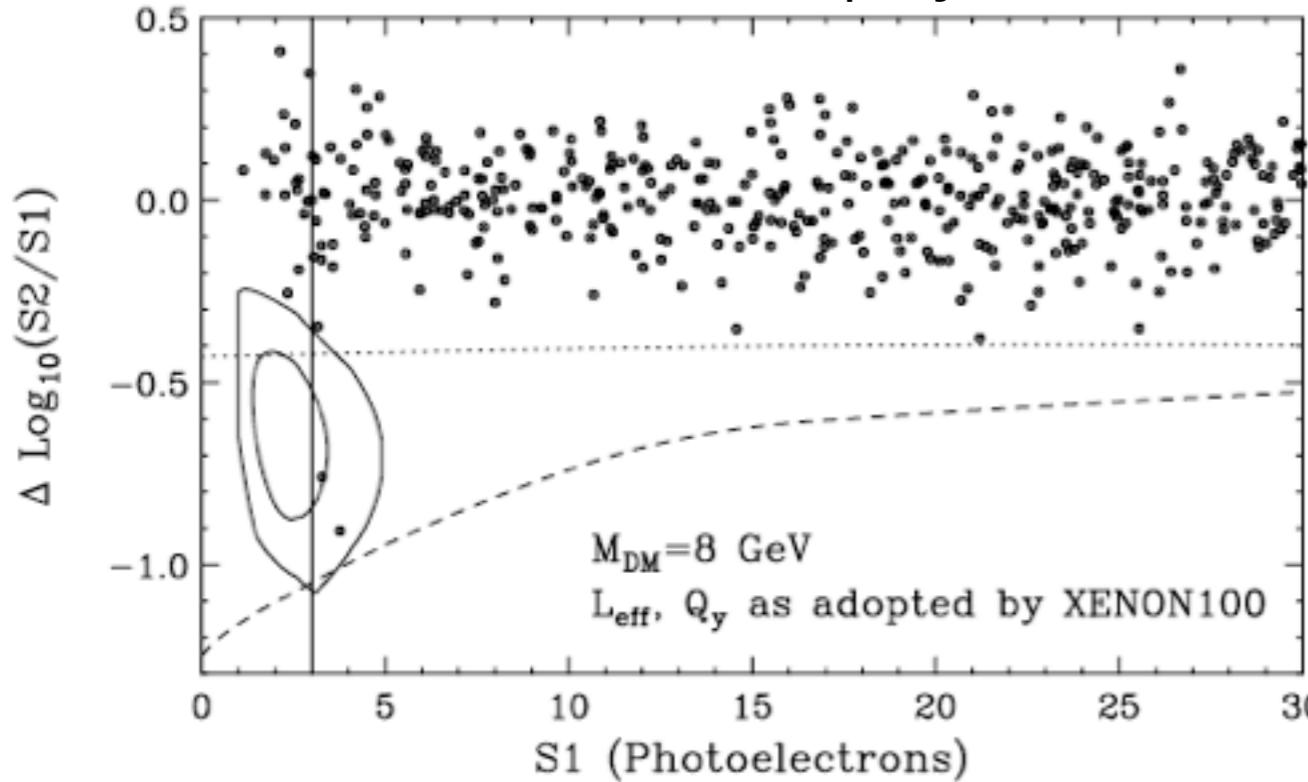
- XENON100's exposure =  $34 \text{ kg}^* 224 \text{ days} = 7636 \text{ kg-day!}$
- They see two events... could this be compatible? At face value, NO!
- Depends strongly on the nuclear energy scale, the efficiency, and threshold...



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

# What about XENON100?

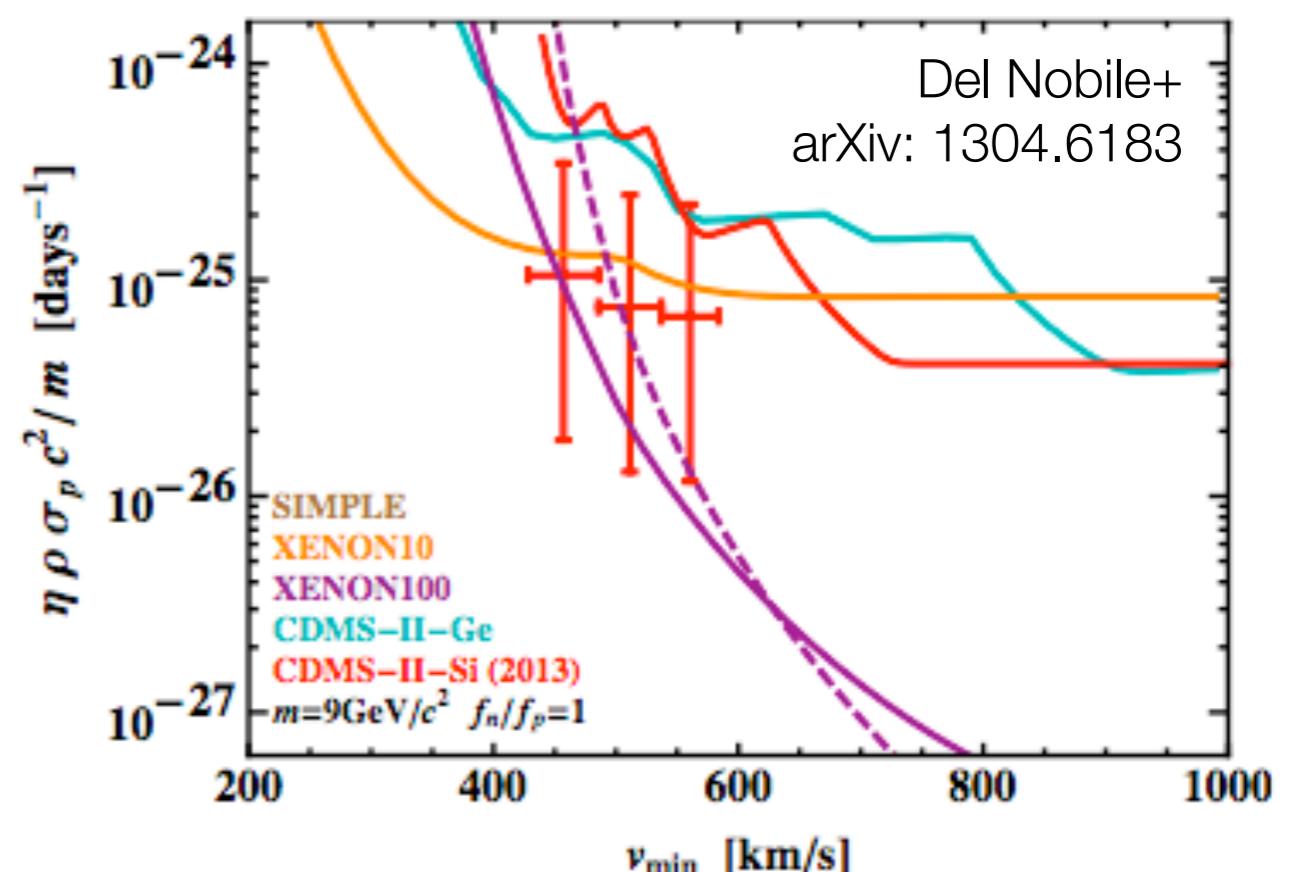
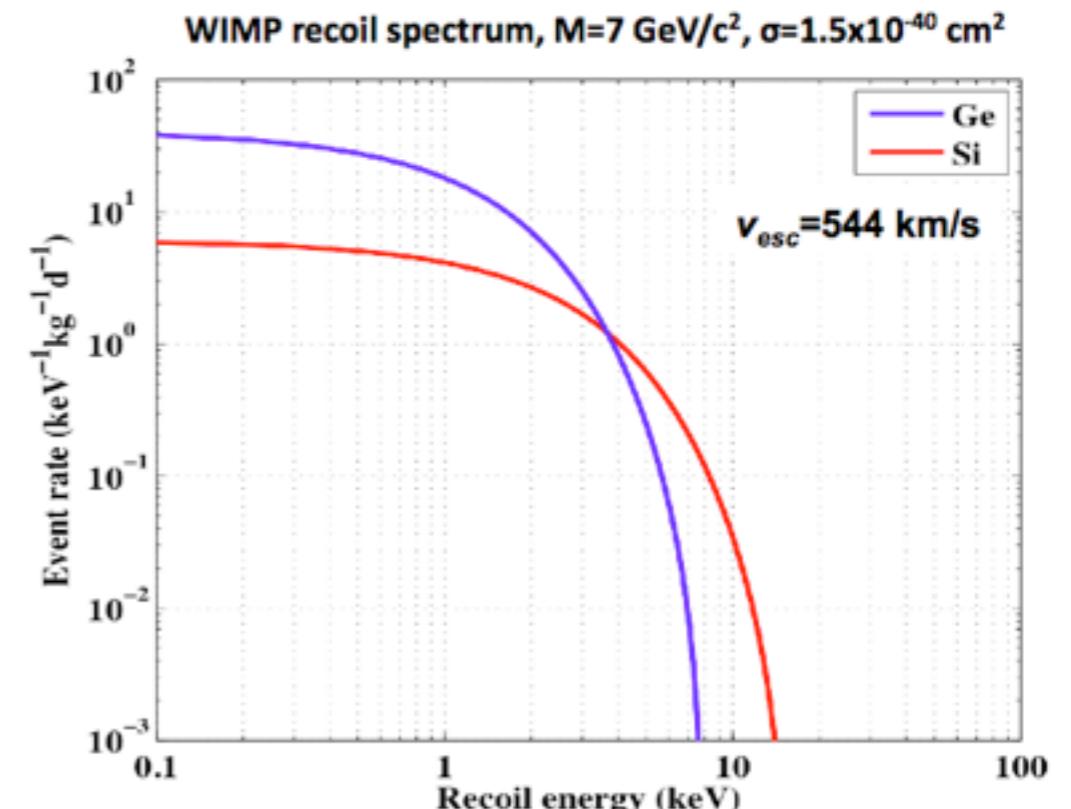
Calibration issues with  $L_{\text{eff}}$  or  $S_{\text{nr}}$  could reconcile the experiments, although astrophysics could play a role too...



Hooper arXiv:1306.1790

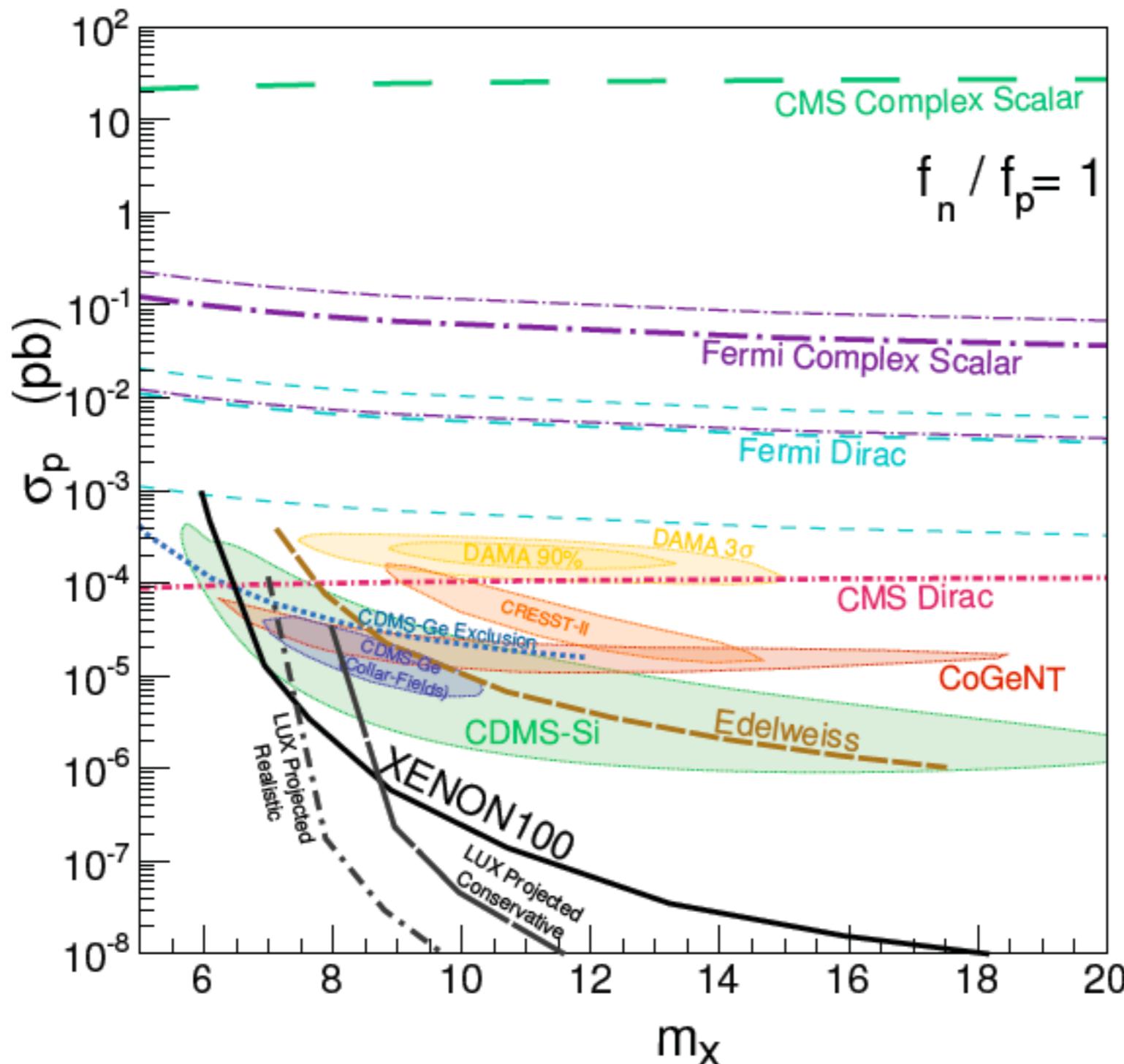
# What about Astrophysical Uncertainties?

- Searches for low mass WIMPs can be sensitive to uncertainties in astrophysical parameters in ways that depend on the target nucleus mass
- Could that resolve the tension between experiments?
- Can remap from default “cross-section vs mass” into a halo-independent parameter space. In this example, tensions between Xe and Si data remain so it seems astrophysical uncertainties are not enough(!)



# What about Non-Standard Interactions?

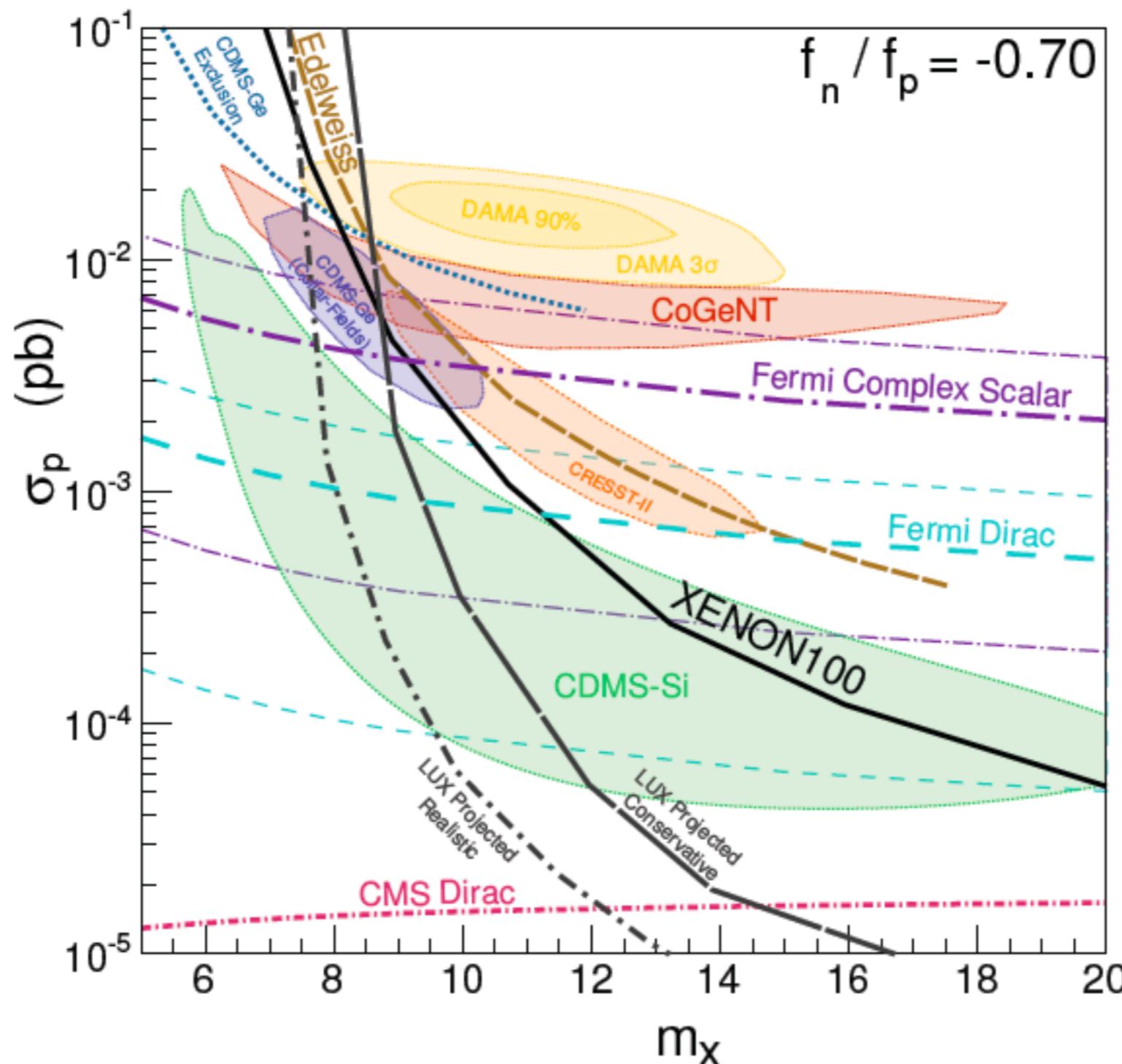
- As another example, tensions between Si and all Xe data can be removed by applying isospin violation (coupling of WIMPs differs between protons and neutrons).



Feng, Kumar, Sanford  
arXiv: 1306.2315

# What about Non-Standard Interactions?

- As another example, tensions between Si and all Xe data can be removed by applying isospin violation (coupling of WIMPs differs between protons and neutrons).



Feng, Kumar, Sanford  
arXiv: 1306.2315

Are we seeing Dark Matter  
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...or NOT?

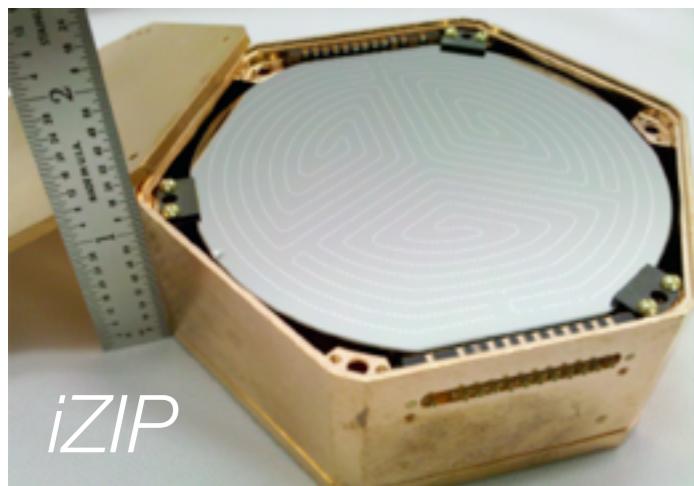
...or actually maybe YES?

So where are we Now?

Path towards resolution

Avoid systematics near the energy threshold by  
designing experiments where recoils of interest  
are well above the threshold

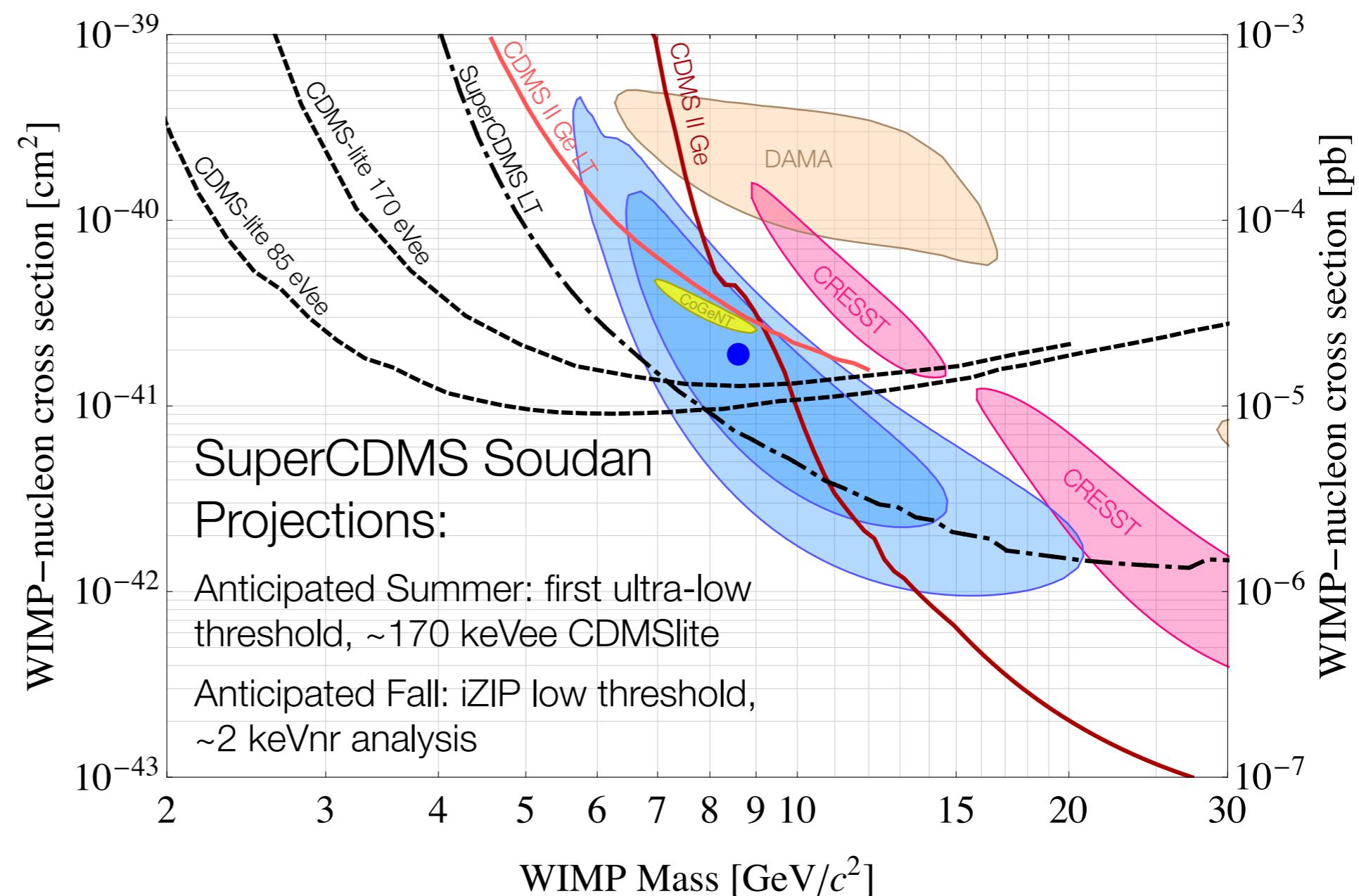
# Next Steps: SuperCDMS Soudan!



iZIP

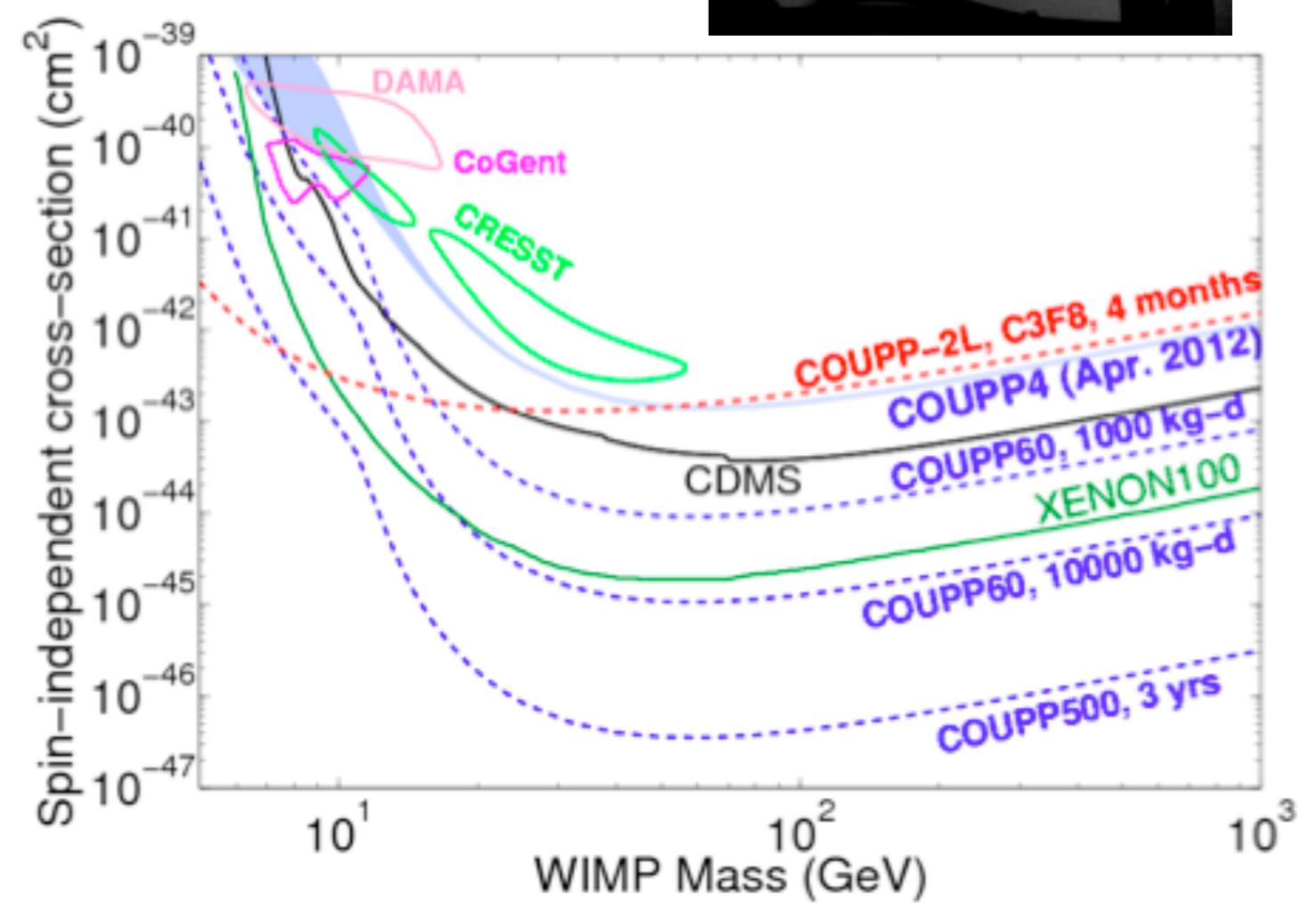
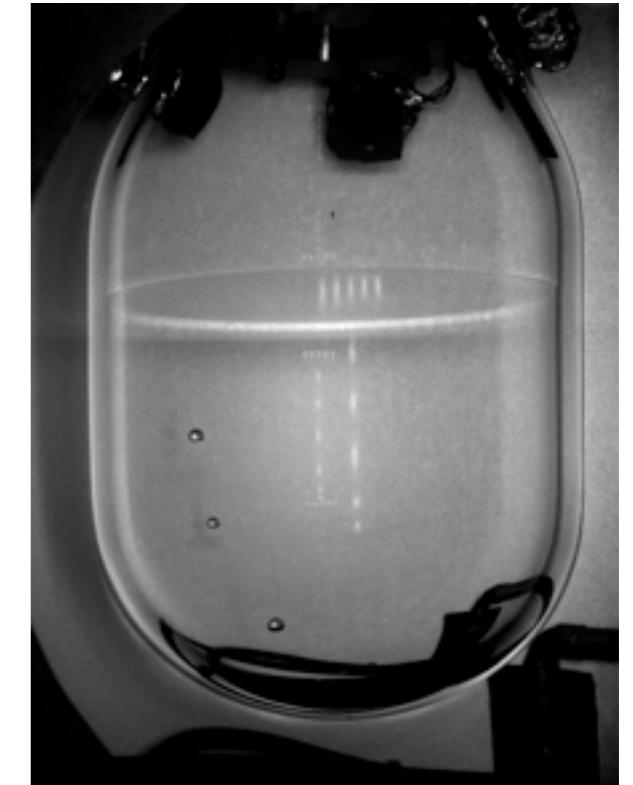
iZIP's solve the problem of surface events for a next-generation dark matter search.

9 kg of Ge iZIP detectors gathering physics data since March 2012



# COUPP/PICASSO

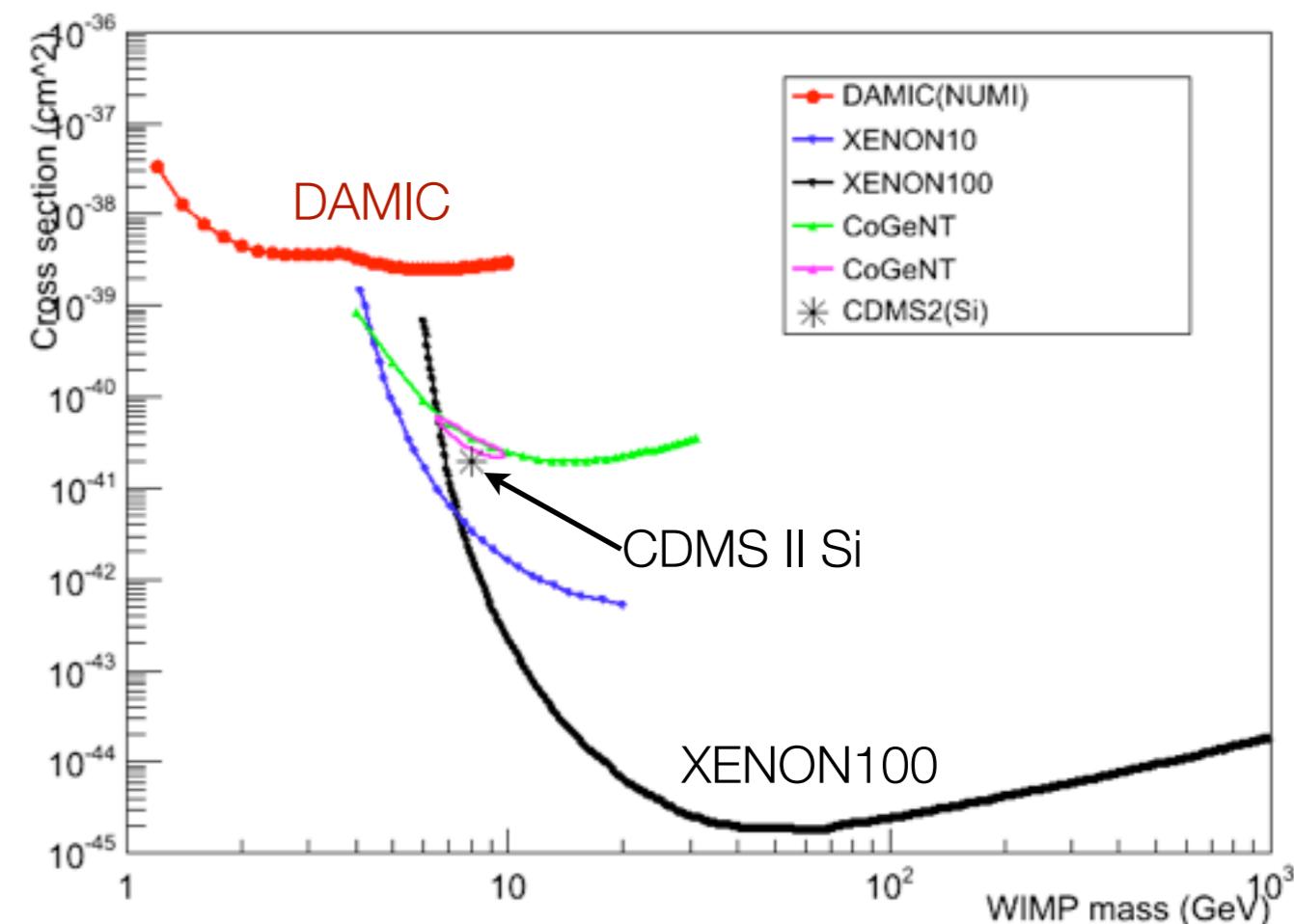
- Will replace target  $\text{CF}_3\text{I}$  fluid with  $\text{C}_3\text{F}_8$  to yield impressive sensitivity at low masses (and significant gains in SD sensitivities)
- Improved efficiencies at low recoil energies compared to  $\text{CF}_3\text{I}$
- PICASSO has long-time experience with this fluid
- Will be a joint project between COUPP and PICASSO
- First bubbles expected this summer



# DAMIC: CCD's as Dark Matter Detectors

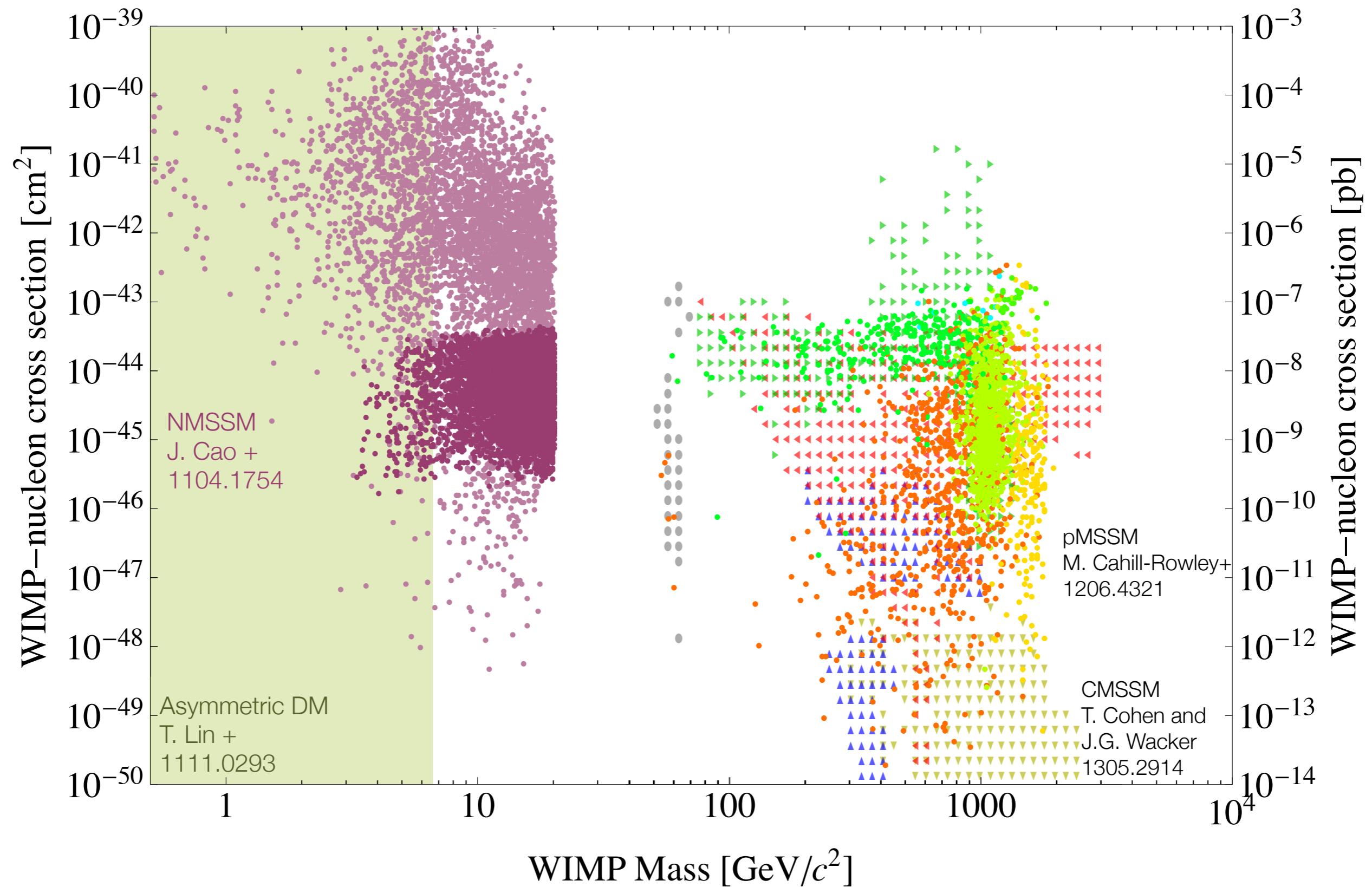


- Aside from CDMS, the only other direct detection experiment with a Si target, but with significantly different technology!
- DAMIC100 will have 100g of target and could see  $O(100)$  events per year for  $8.6 \text{ GeV}/c^2$  WIMP and  $\sigma = 2 \times 10^{-41} \text{ cm}^2$



If the low-mass ROI turns out  
not to be from WIMPs,  
how far down in cross  
section can we go?

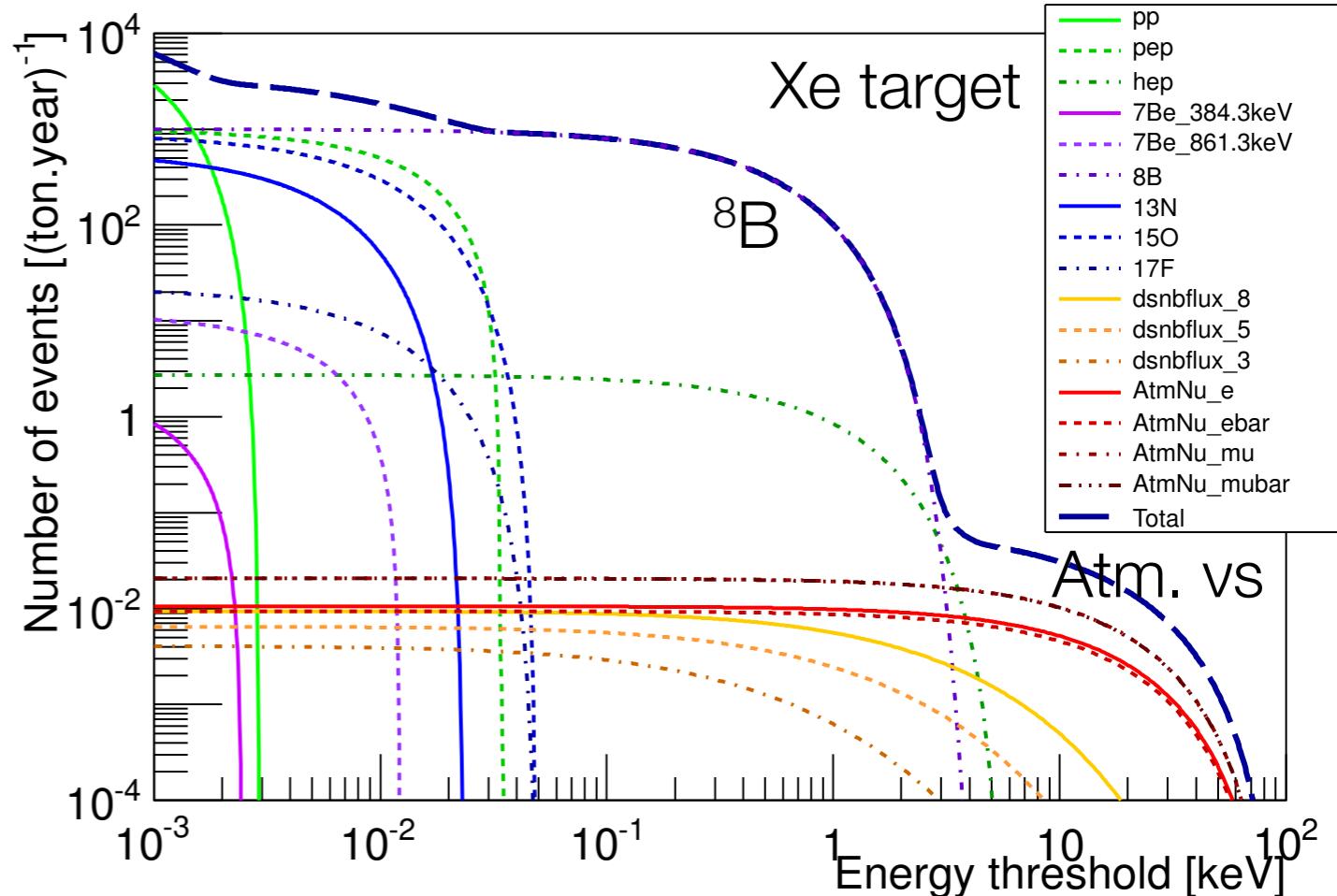
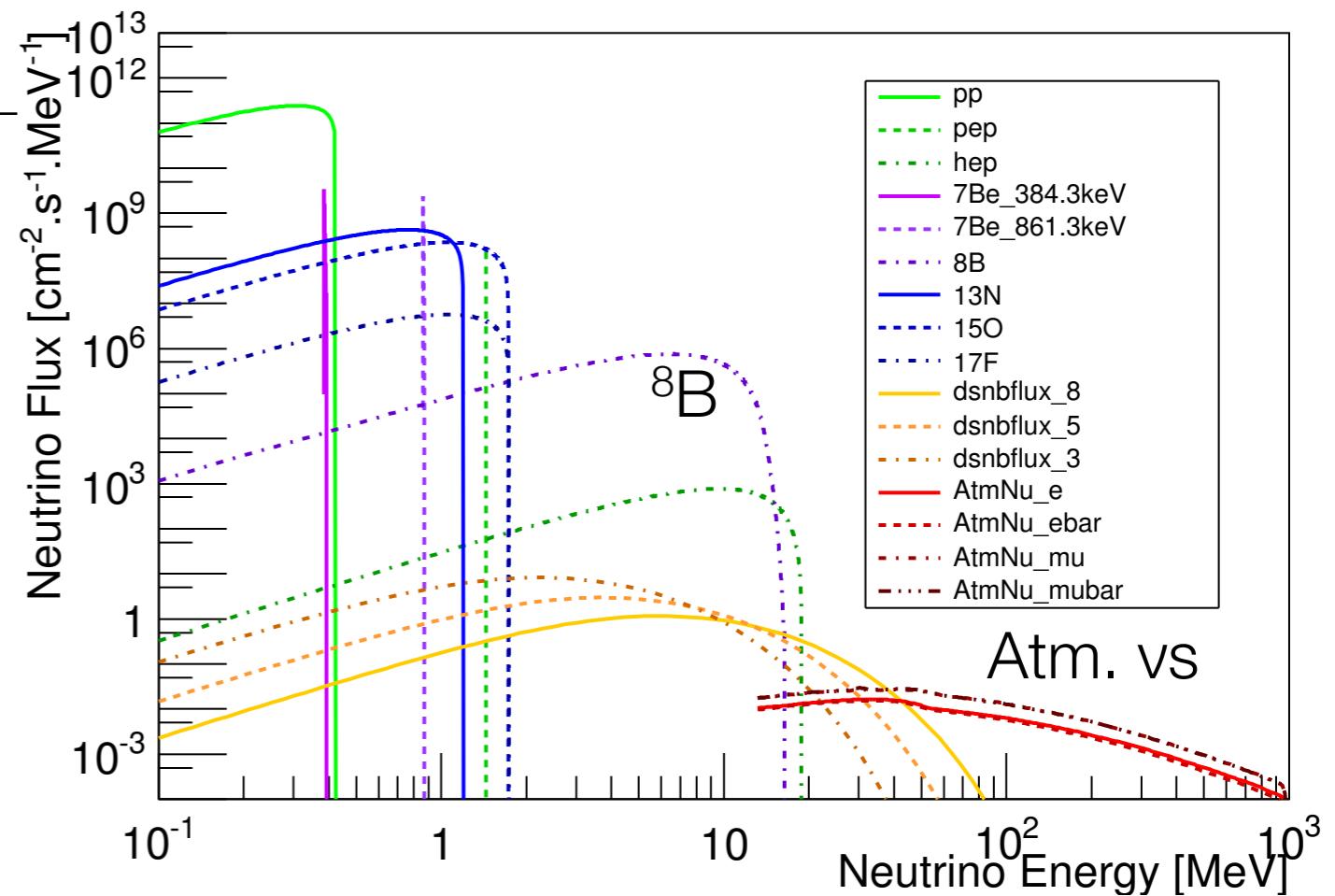
# Theoretical Landscape: Lots of Options!



# Neutrinos vs. WIMPS

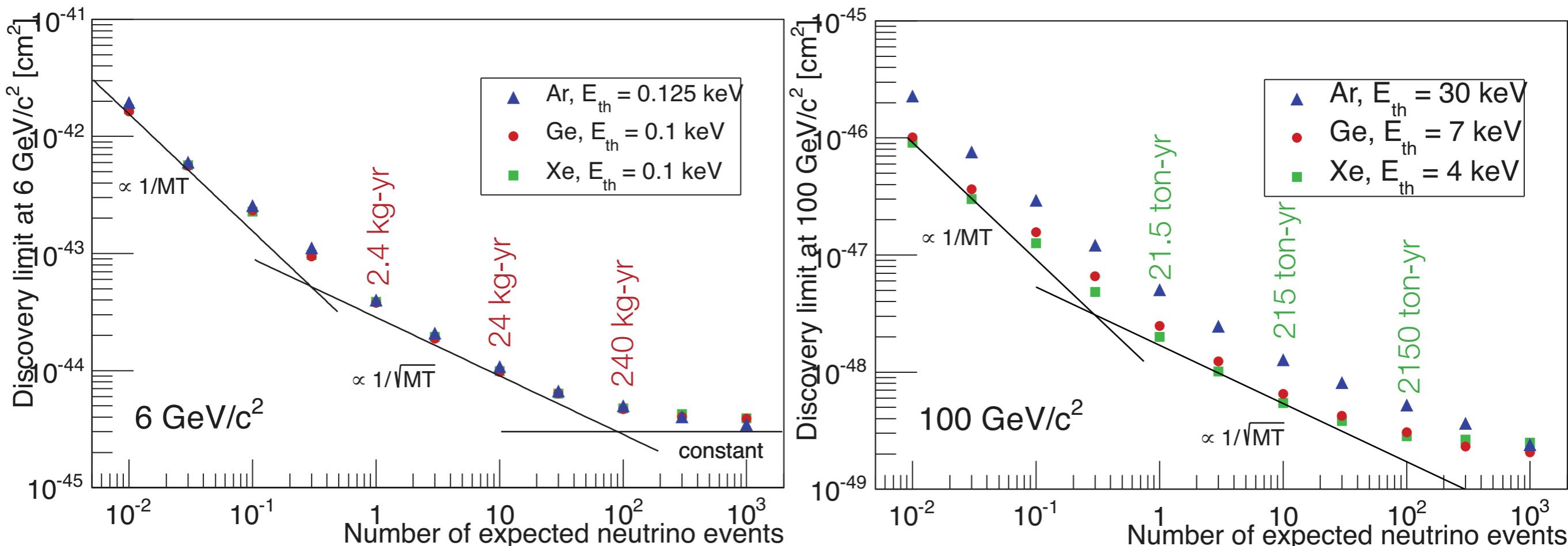
*“Your signal is my background”*

- Cosmogenic neutrinos interact through coherent neutrino-nucleus scattering with dark matter detectors.
- These neutrinos form an irreducible background and limit the WIMP-nucleon cross sections that are accessible to direct detection searches.

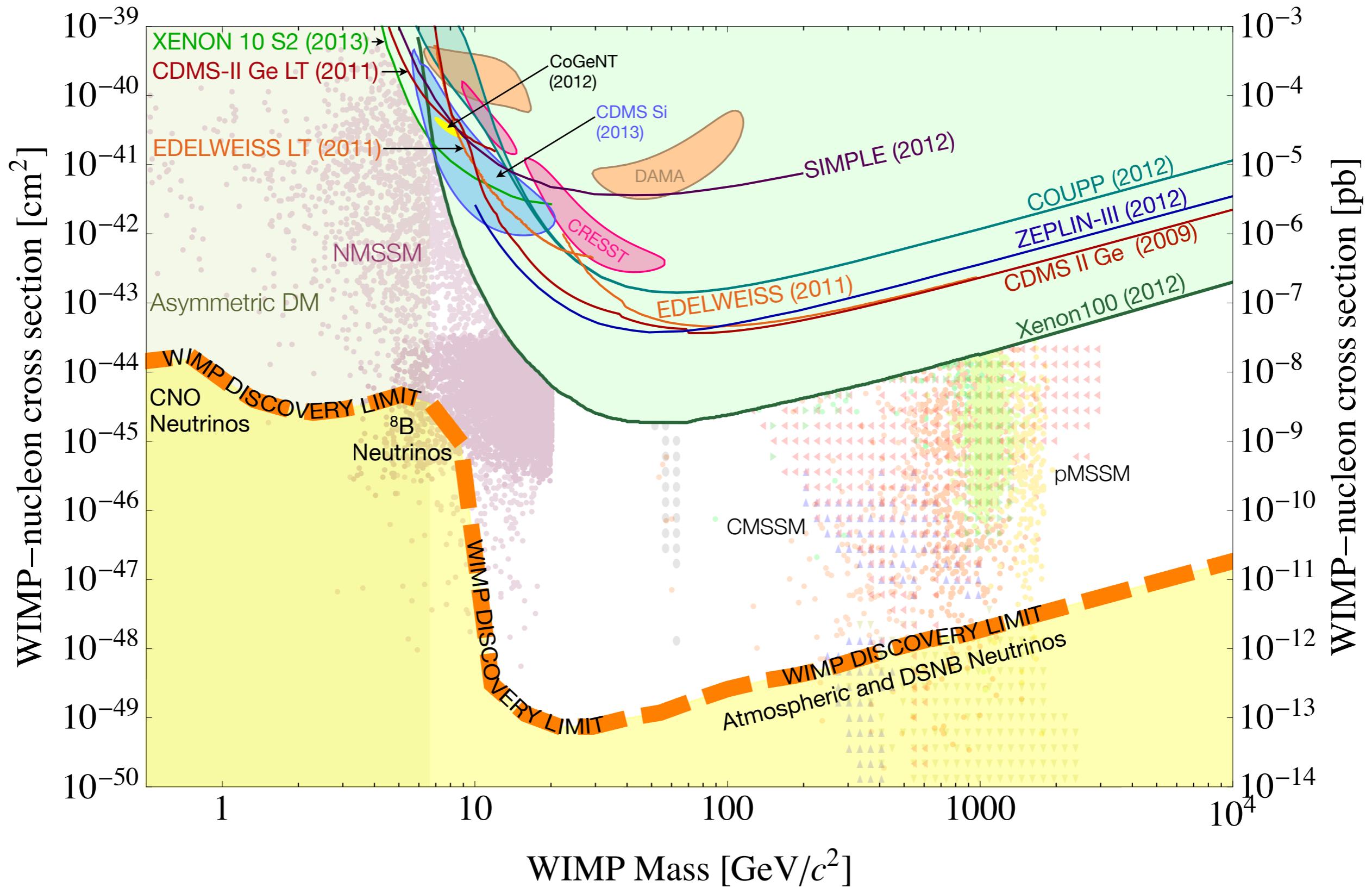


# WIMP Discovery Limit

- For a given WIMP mass, we find the WIMP-nucleon cross section for which a profile likelihood analysis favors a WIMP +neutrino hypothesis over a neutrino-only hypothesis at a  $3\sigma$  confidence level in 90% of our mock experiments.
- As experiment exposures increase and neutrino events are seen, the discovery potential flattens out, reaching a neutrino-induced “floor.”



# Current Status



# Lots of Data Coming... Stay Tuned!

