Results of a Dark Matter Search with the Silicon Detectors of the CDMS II Experiment

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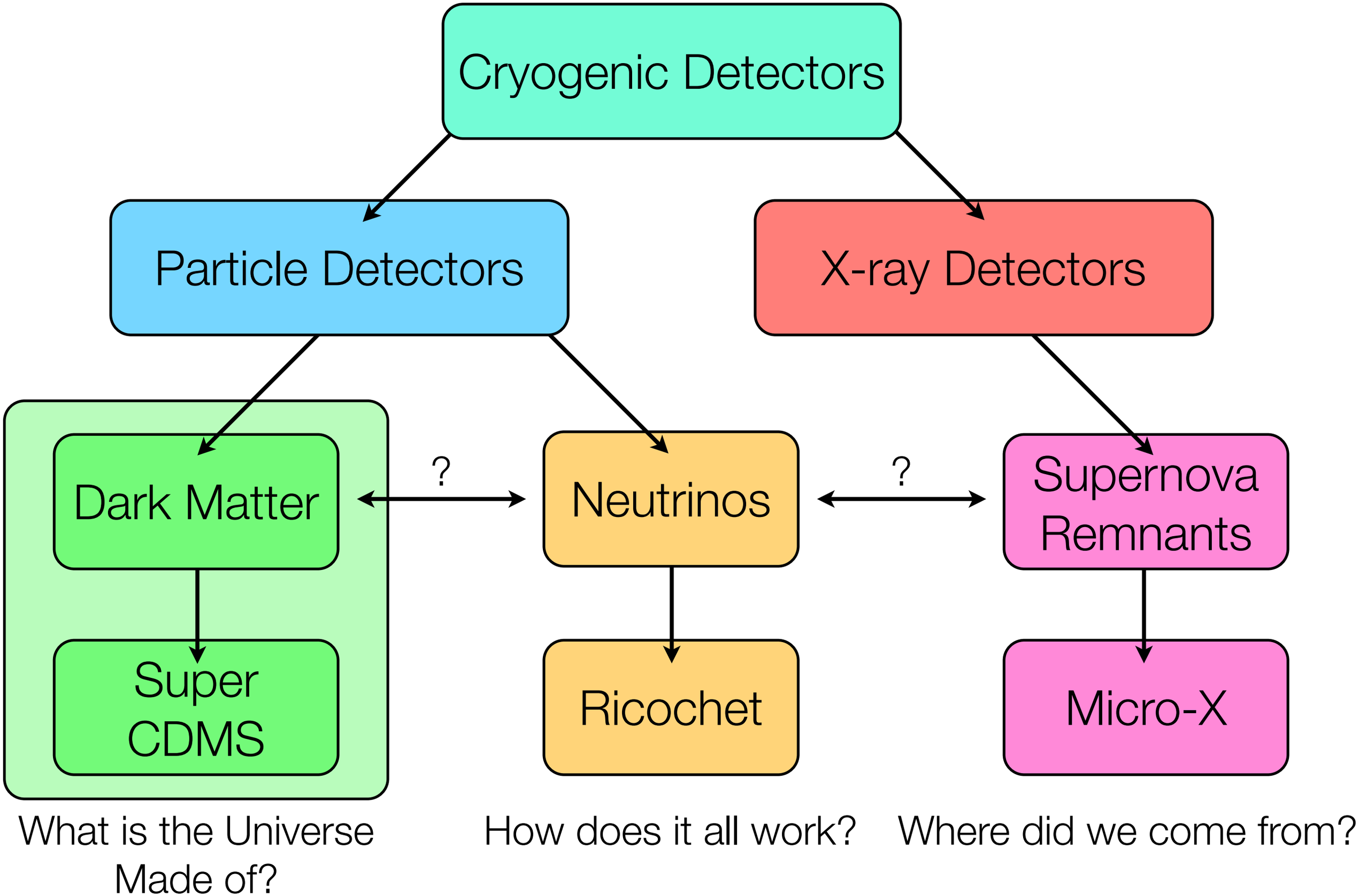
http://cdms.berkeley.edu

What is the Universe Made of?

Where did we come from?

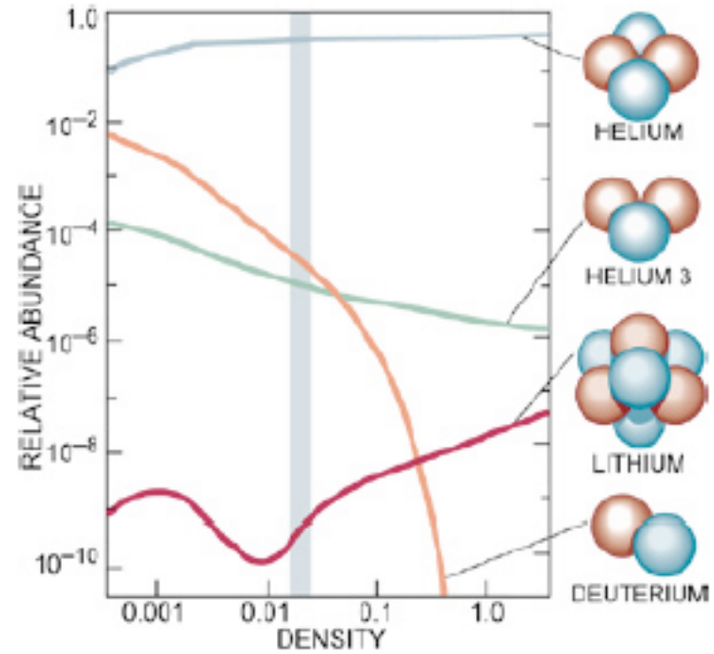
How does it all work?

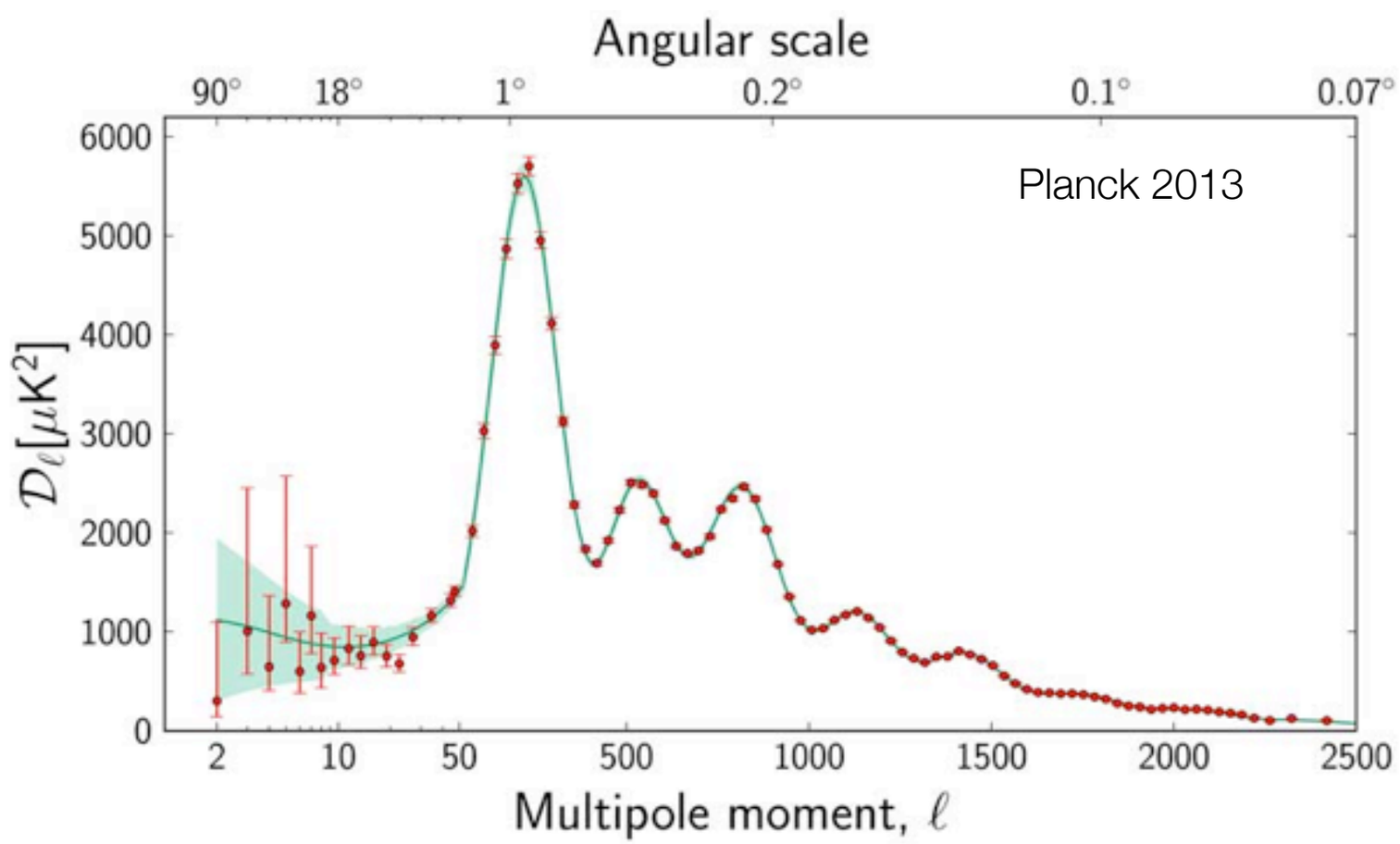
My contribution to these questions

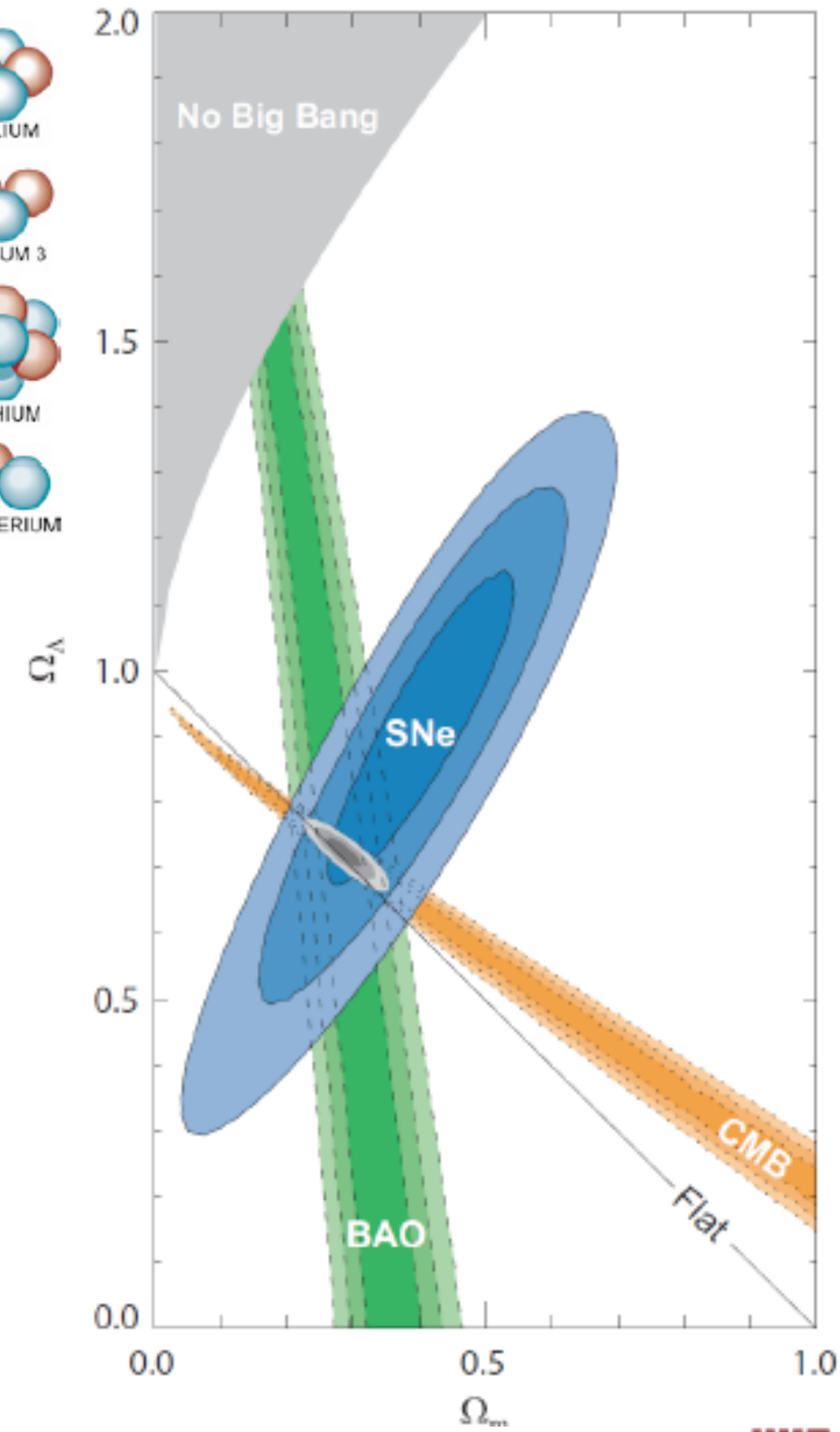


The ΛCDM Model of Cosmology

One model has emerged that fits all the observations with only 6 parameters.

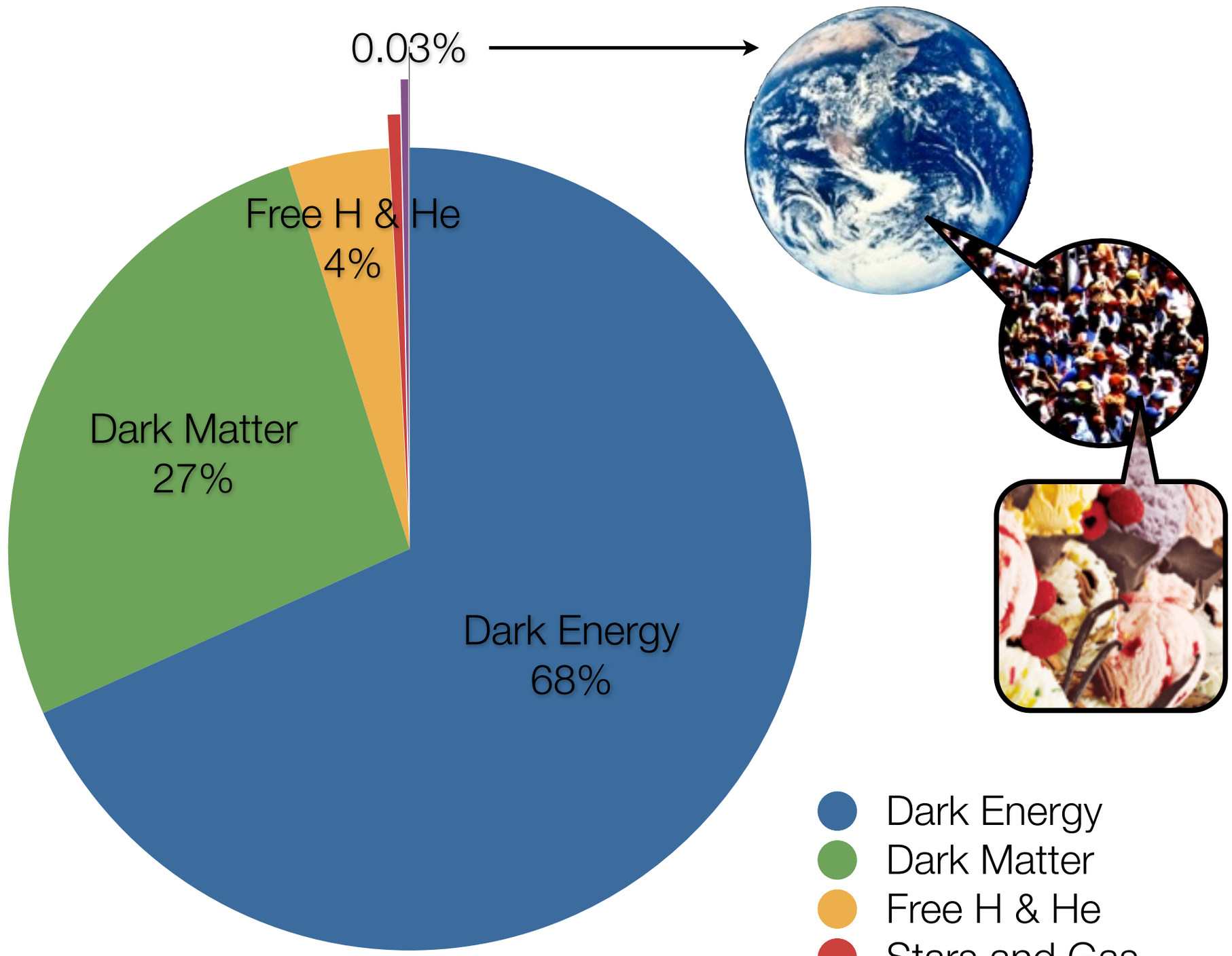






What is the Universe Made of?

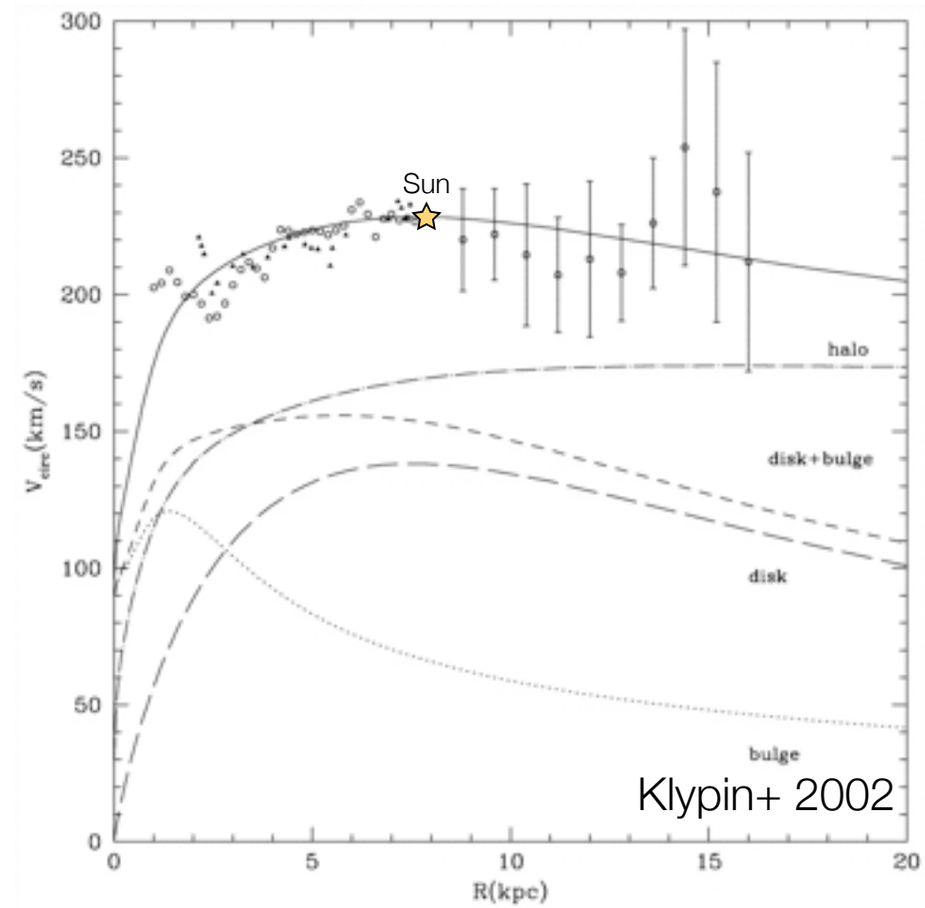
- This model raises some truly fundamental questions about where we live.

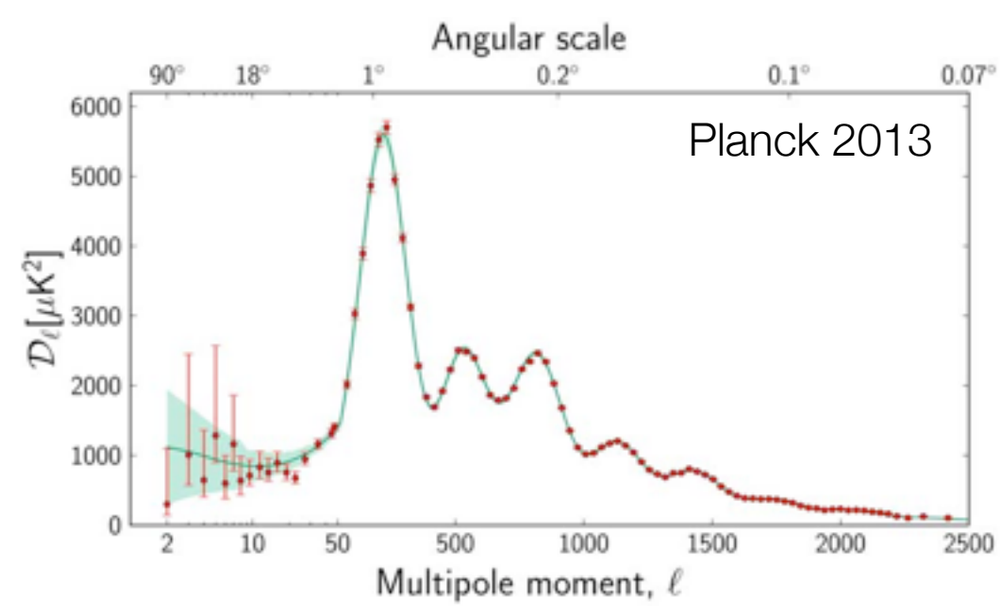


We don't know what 95% of the Universe if made of!

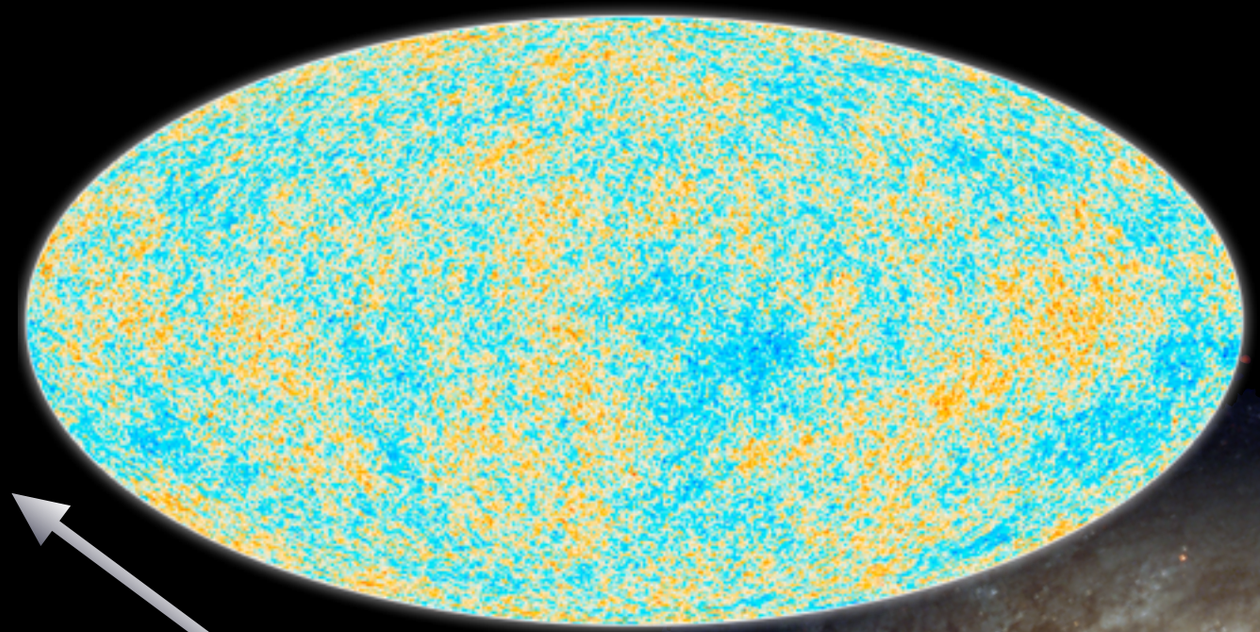
The Nature of Dark Matter

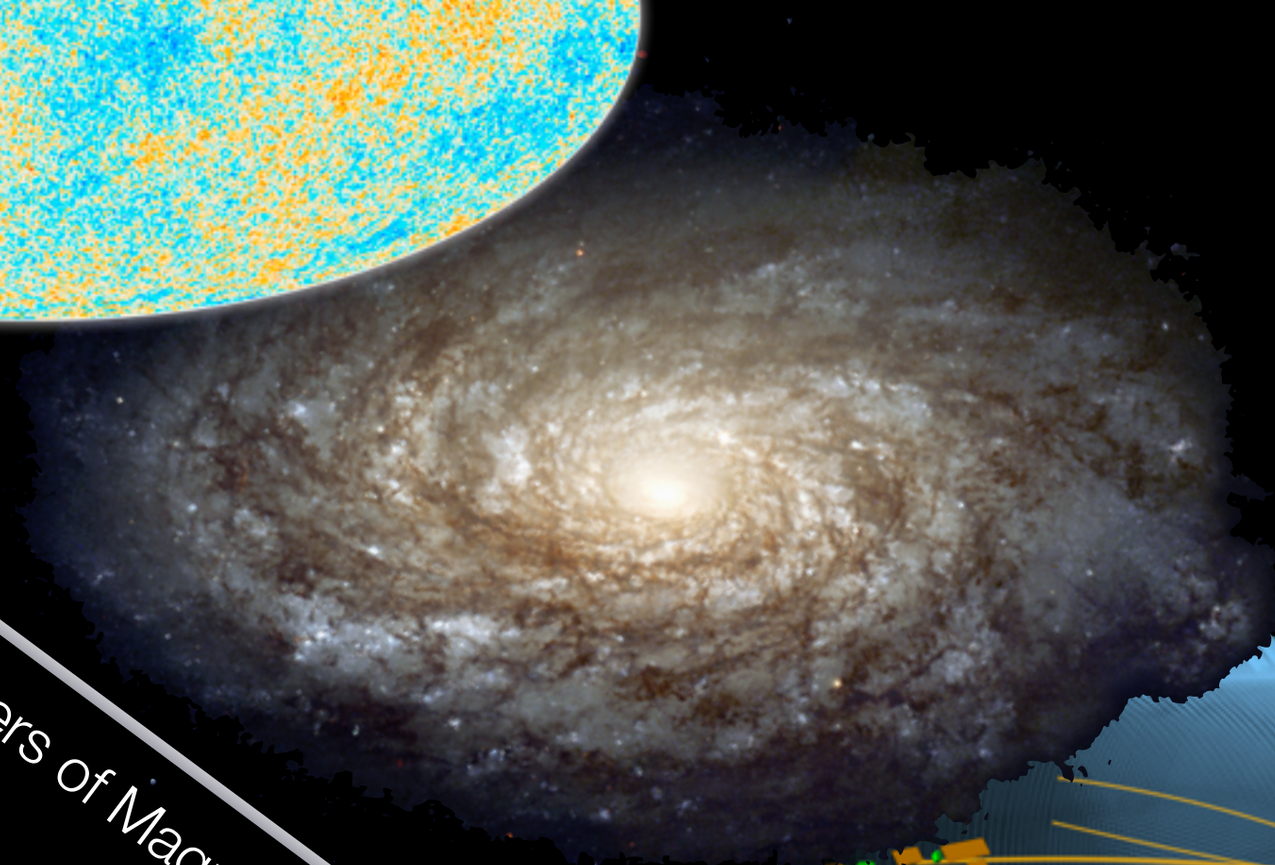
- The Missing Mass Problem:
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gas density, gravitational lensing
  - Large Scale Structure formation
- Wealth of evidence for a particle solution
  - MOND has problems with Bullet Cluster
  - Microlensing (MACHOs) mostly ruled out
- Non-baryonic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

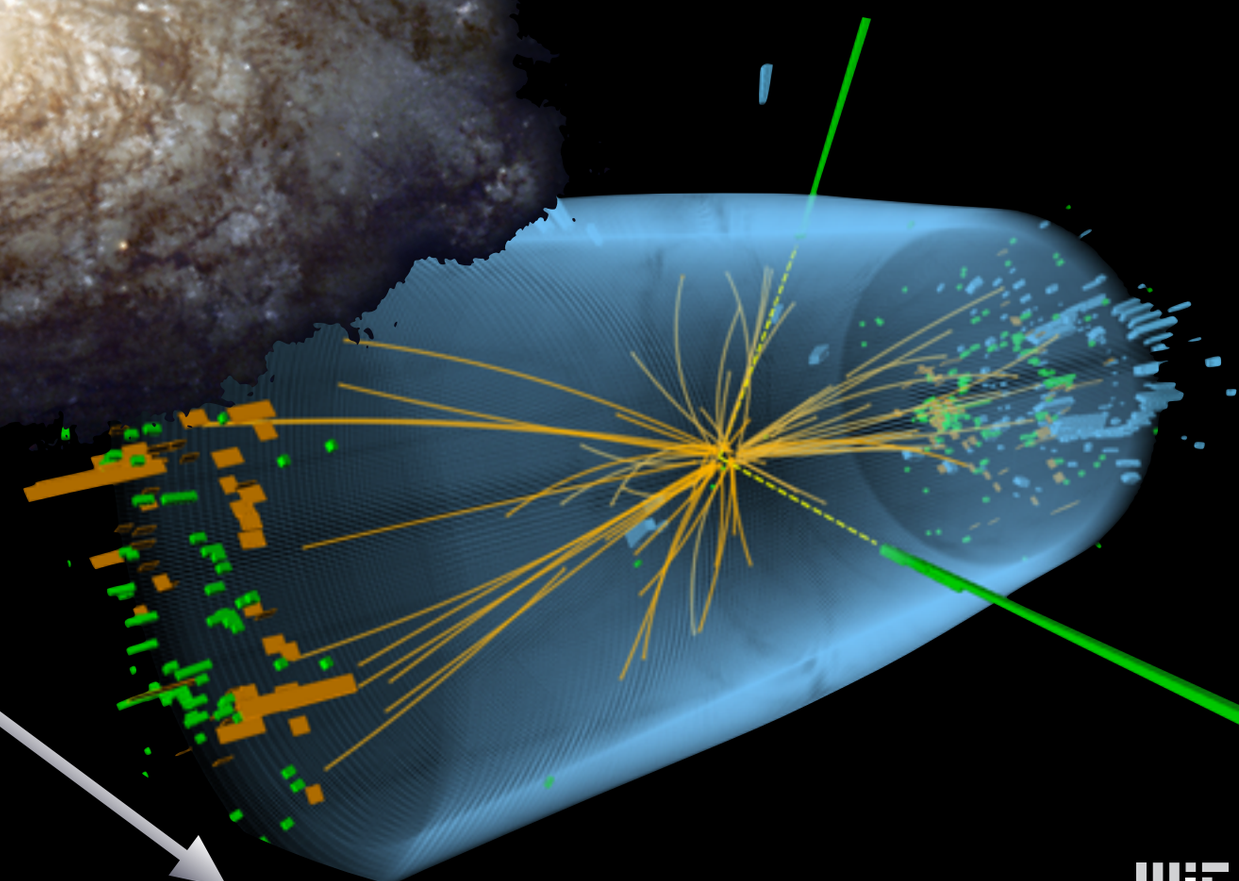




A Beautiful Problem in Physics

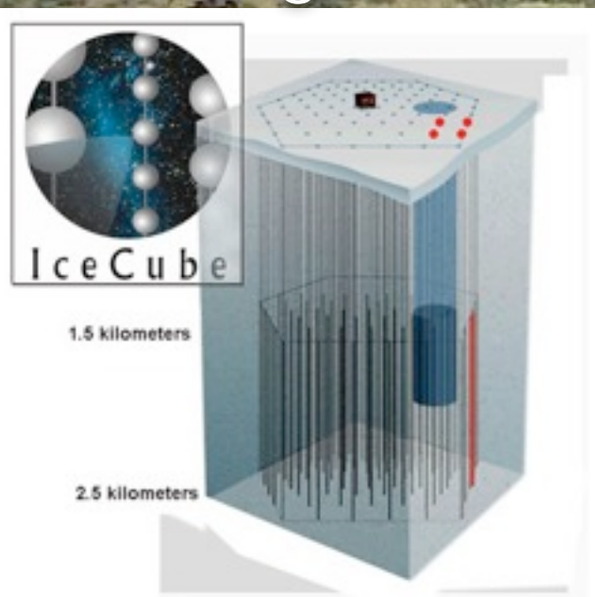






40 Orders of Magnitude!

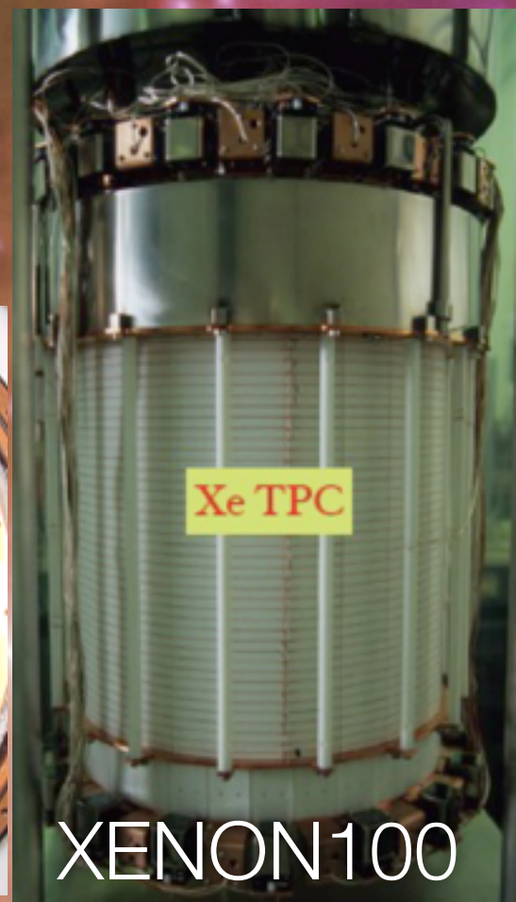
The Hunt for Dark Matter



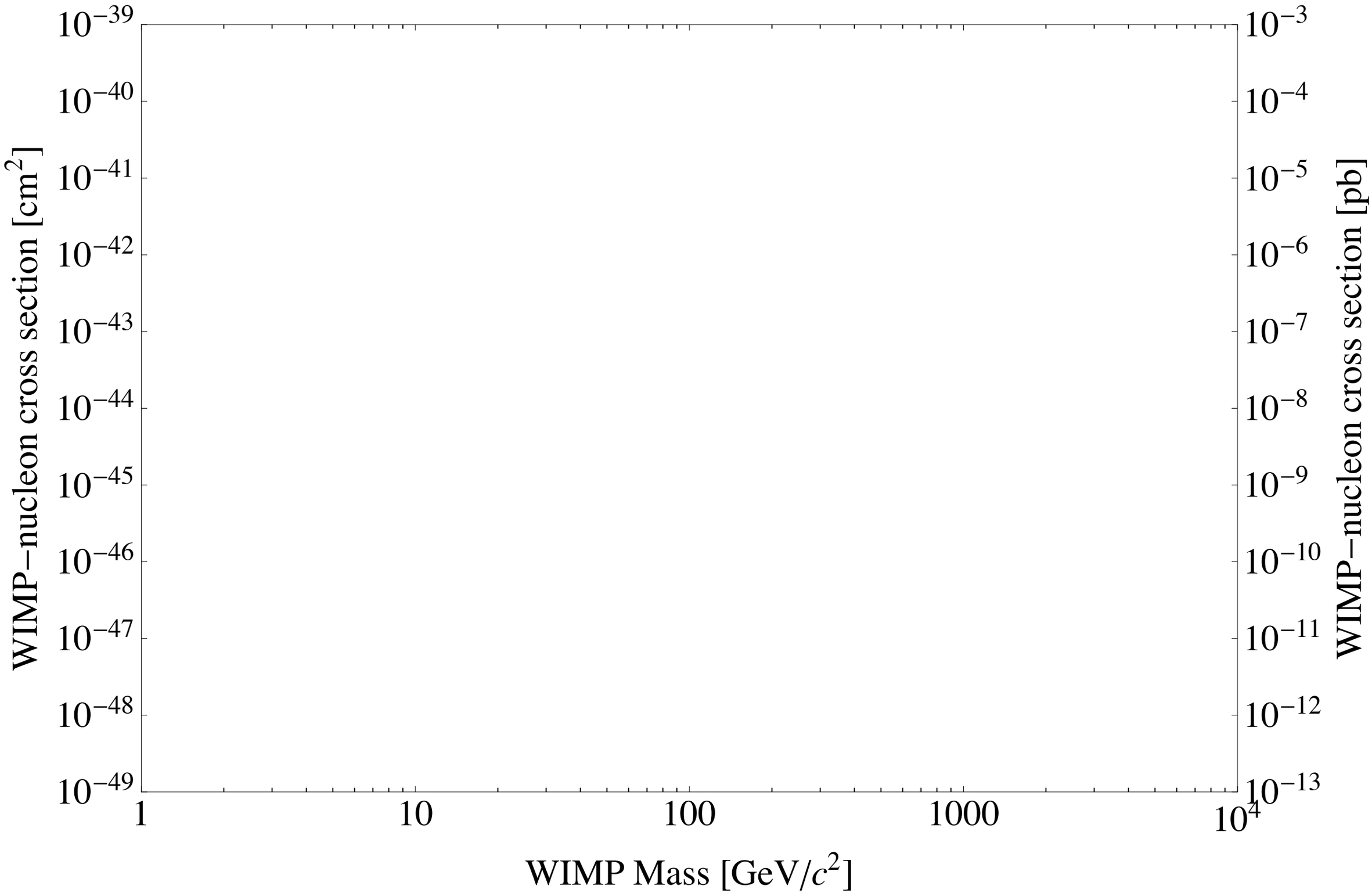
Production in Colliders

Annihilation in the Cosmos

Direct Detection



The Big Picture



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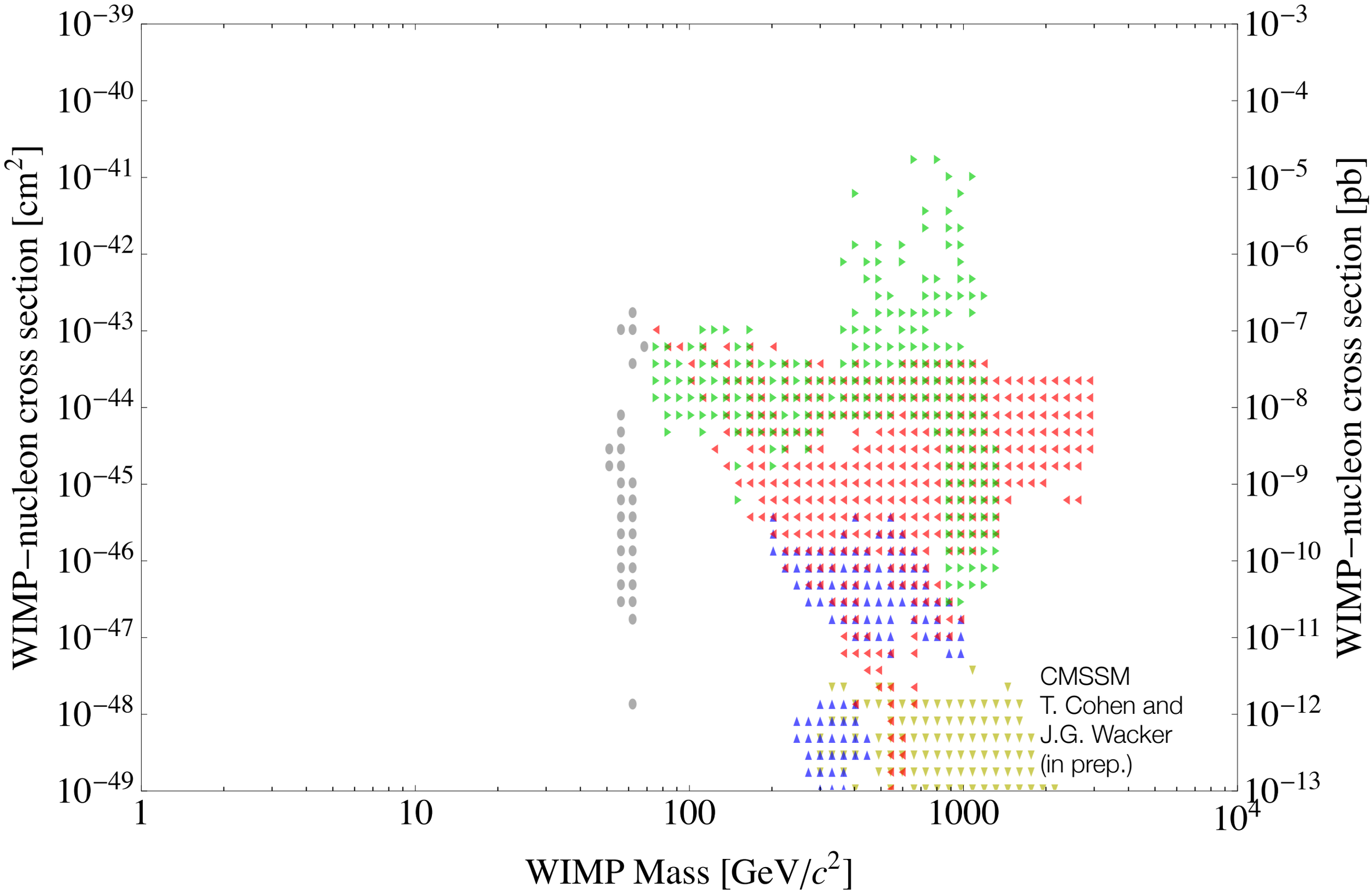

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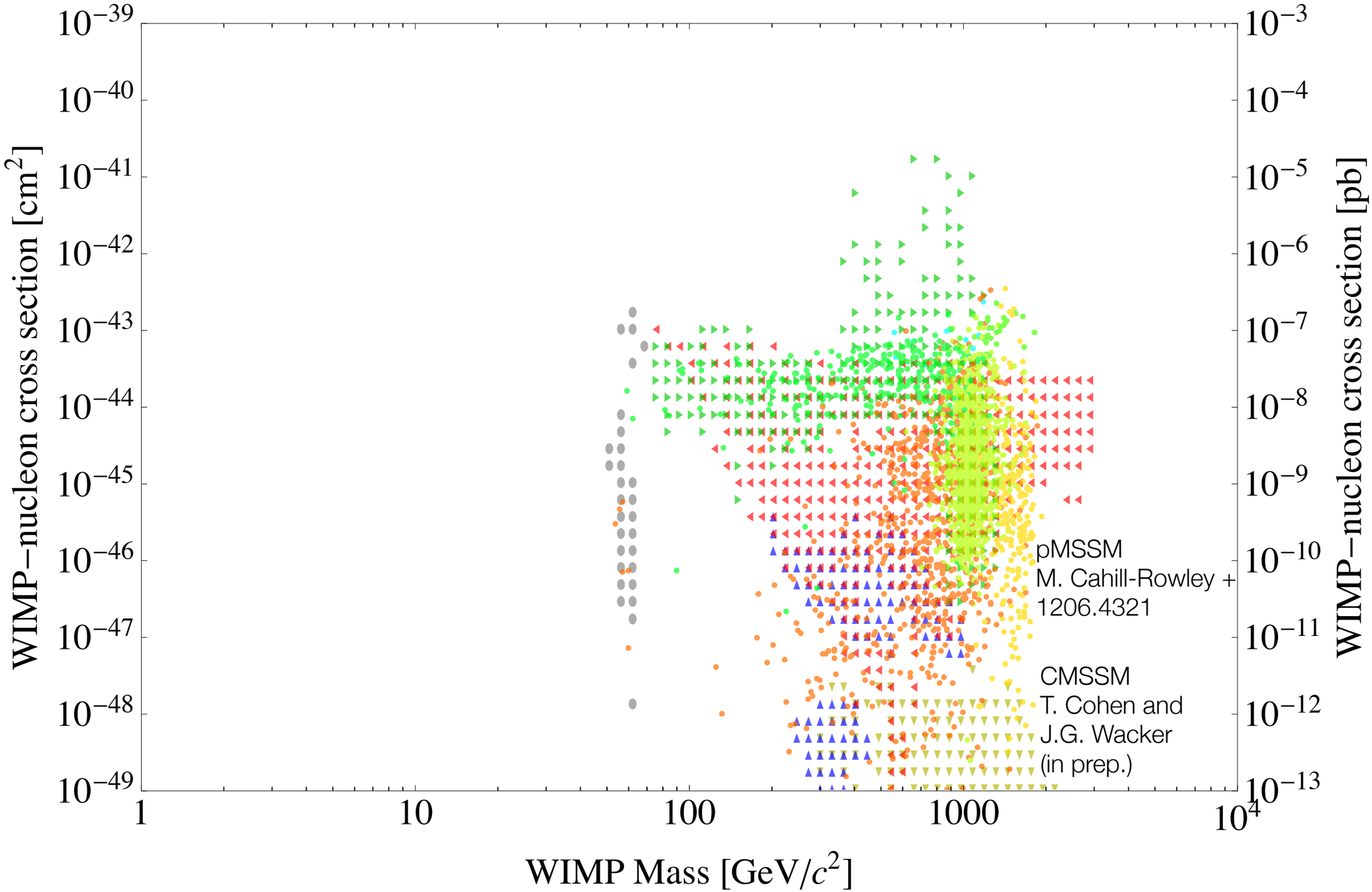

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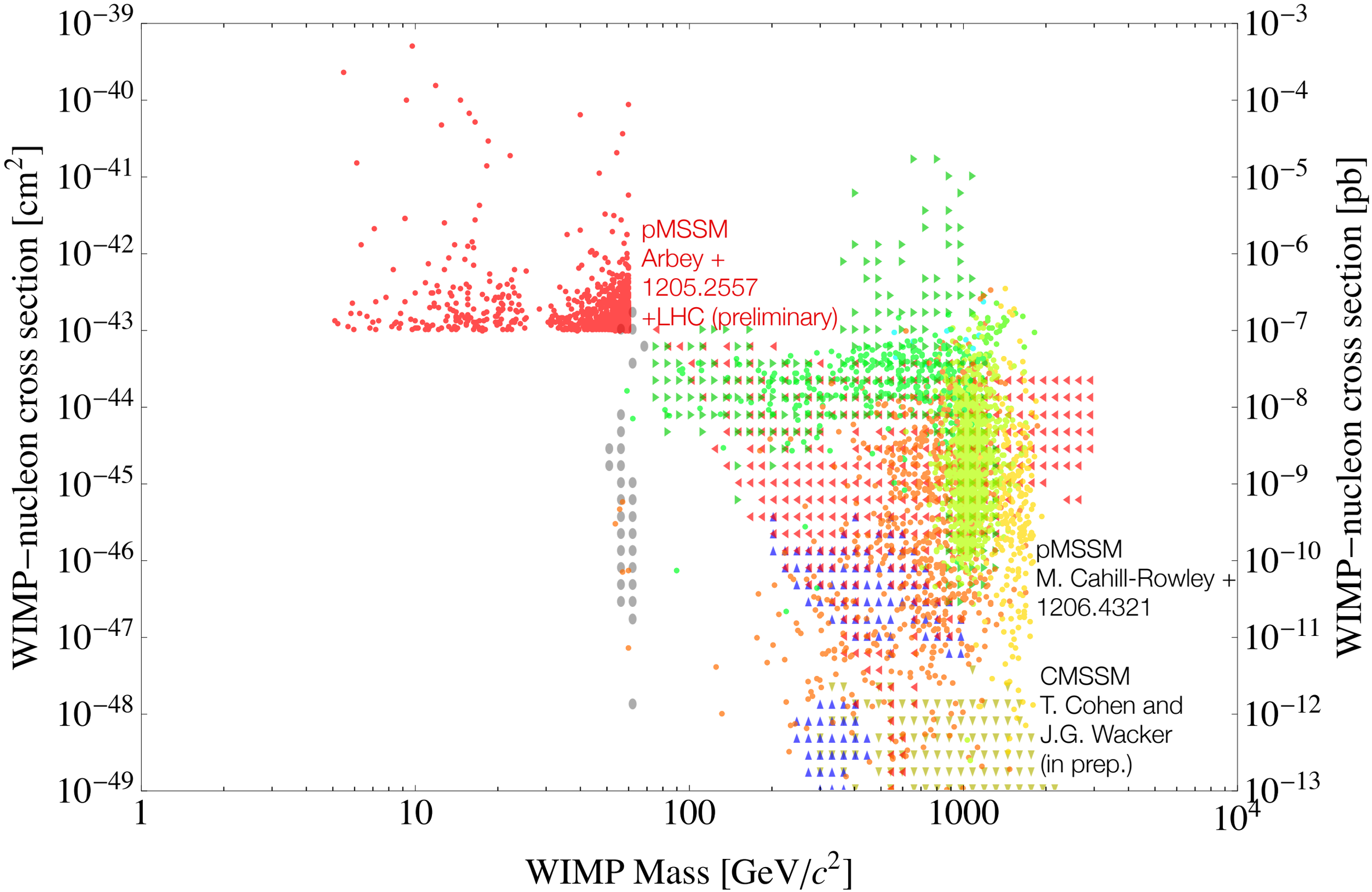

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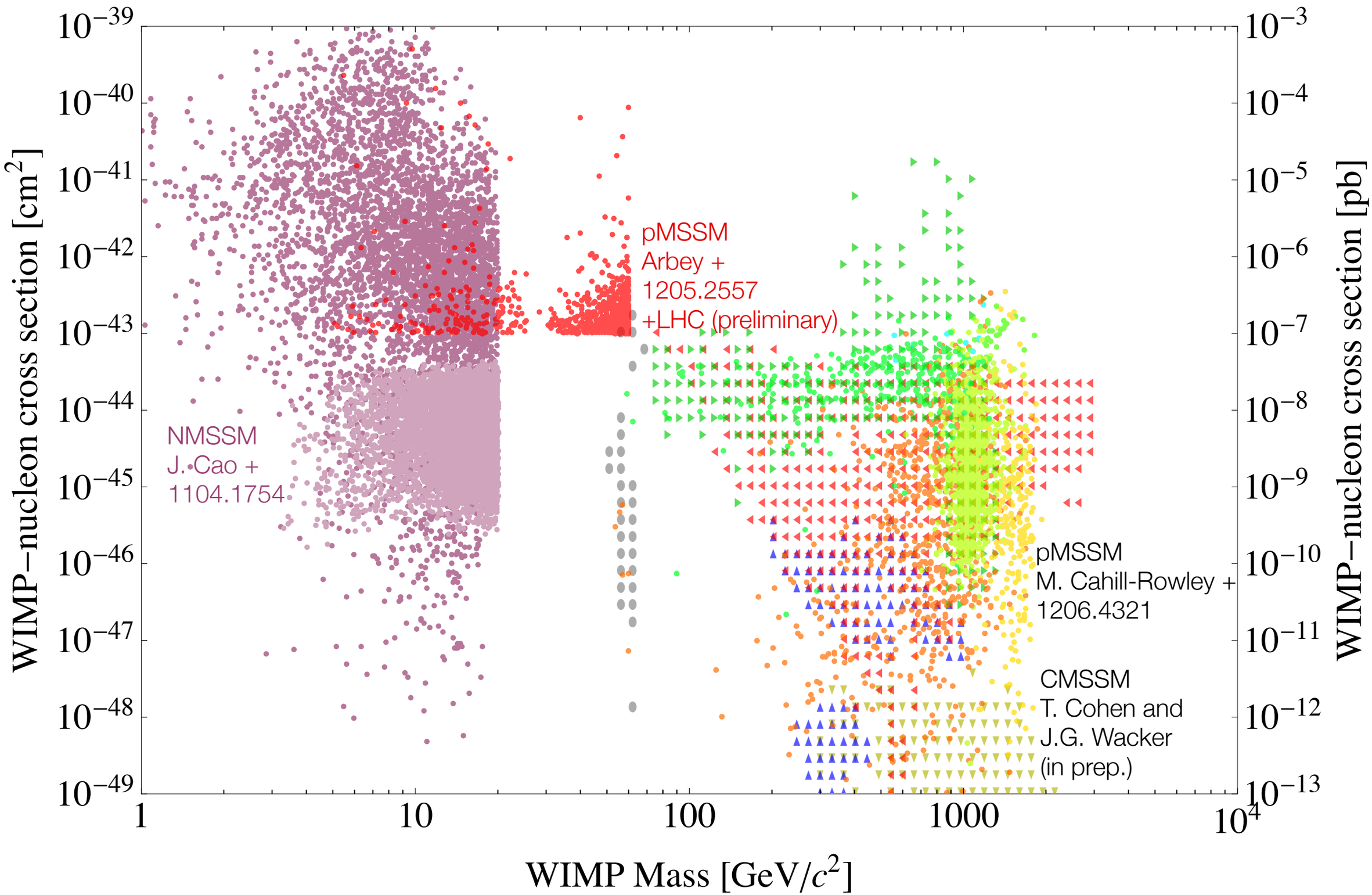

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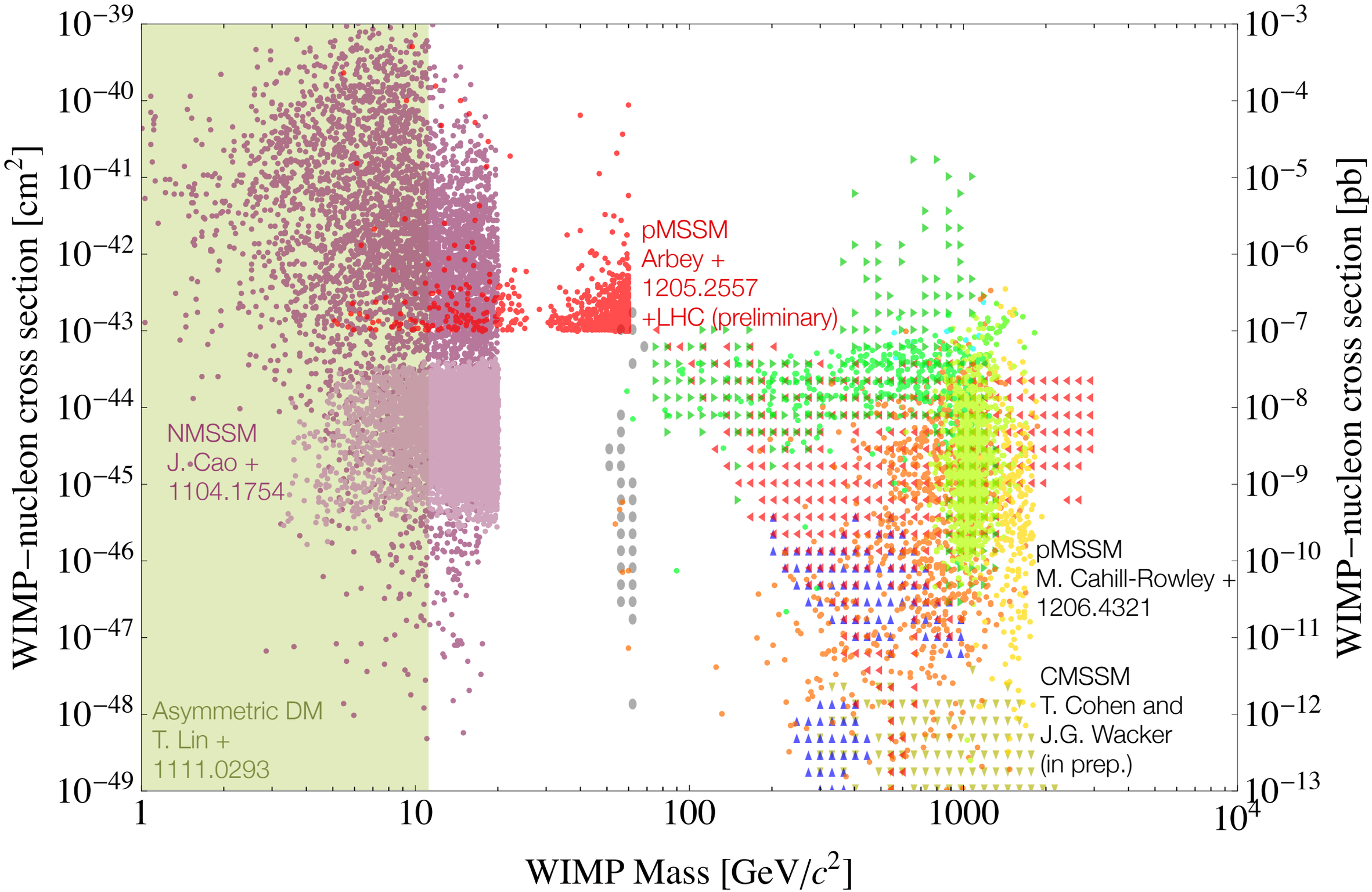

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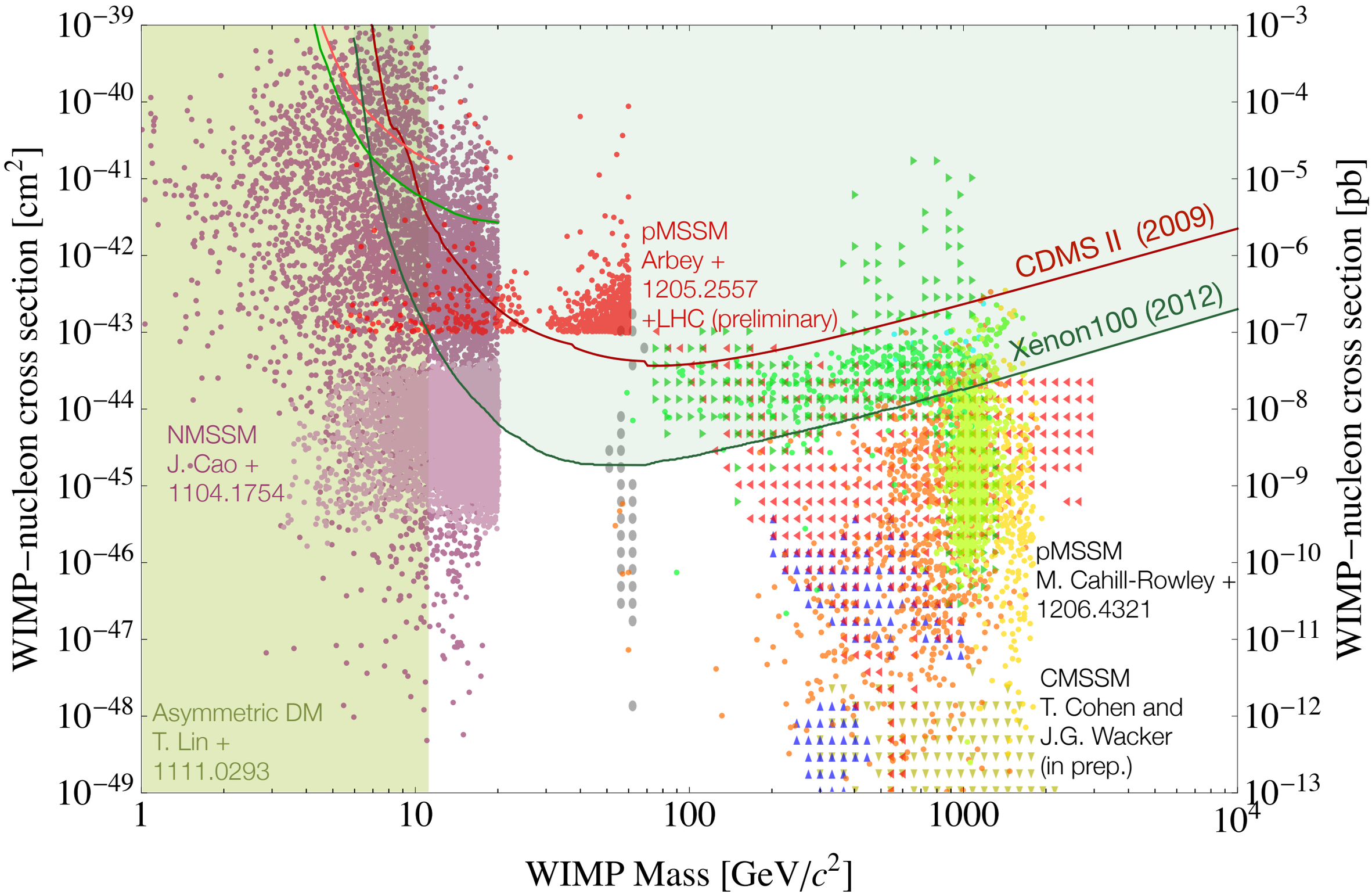

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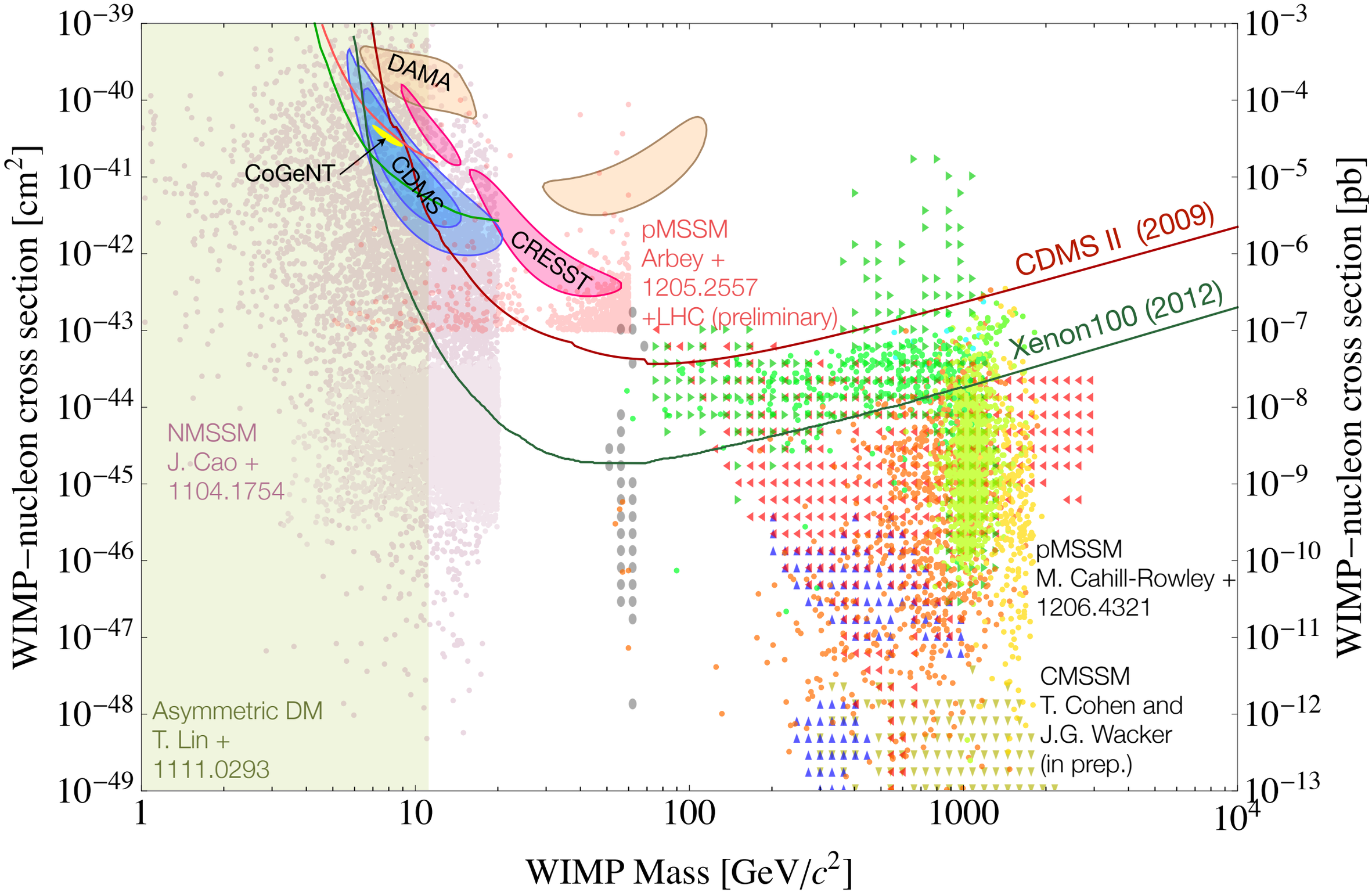


Dark Matter - Lots of Options!

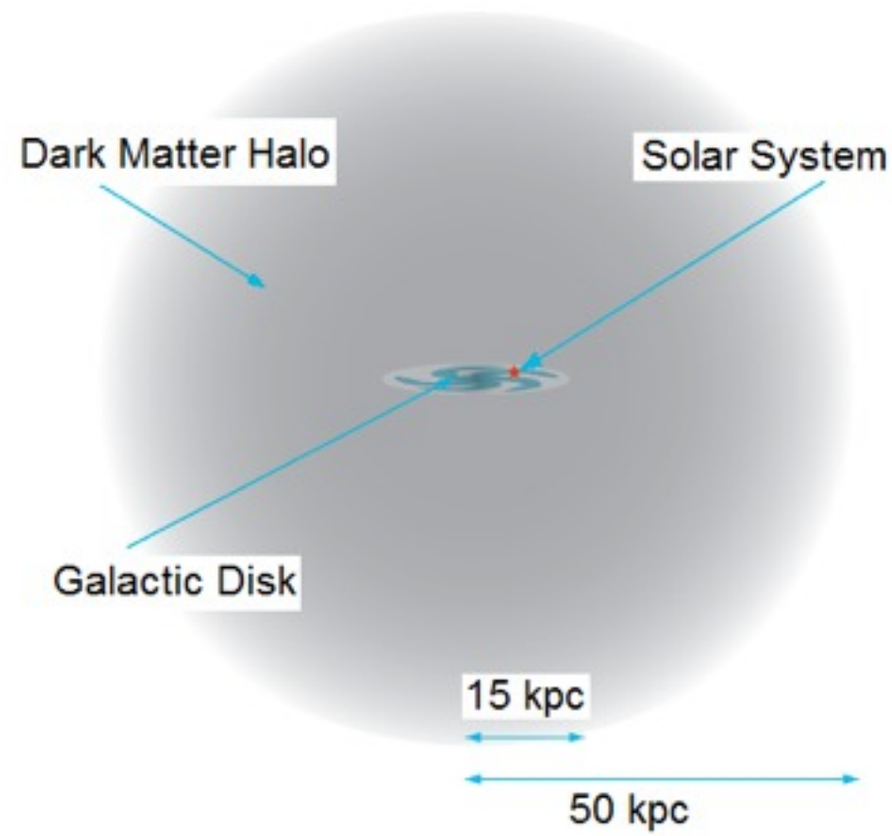
- Expanding your options beyond CMSSM opens up a lot of parameter space
  - pMSSM, NMSSM, UED, Asymmetric, Hidden Sector, (insert your favorite model here), ...
- Many models predict dark matter outside of the “WIMP miracle” window, so fine tuning of parameters is often necessary
- While that may not very satisfying, it could be how nature works!
- Models like asymmetric dark matter or hidden sectors can work with dark matter down to very light masses (~ MeV), while still satisfying structure formation bounds (its still “lukewarm”).

Direct Detection Fundamentals

Dark Matter Astrophysics

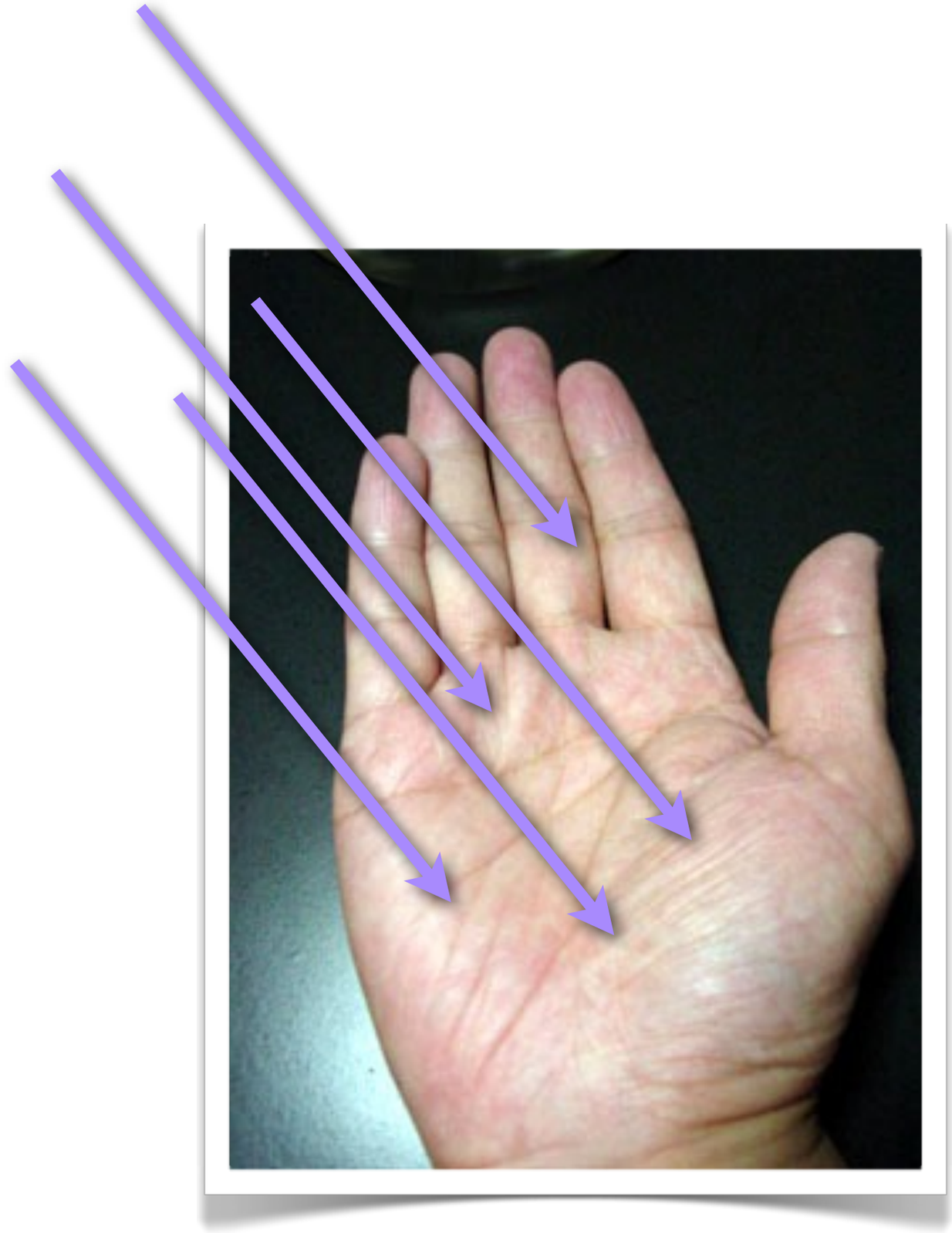
- Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo
- “Spherical-cow” assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution
- v_o = 220 km/s, v_{rms} = 270 km/s, v_{esc}= 544 km/s
- ρ = 0.3 GeV / cm3
- Assume mass = 60 GeV/c2
- Density = 5000 part/m3

10 WIMPs
on average, inside a 2 liter bottle
(if mass=60 x proton)



Flux

- Density: 0.3 GeV/cm^3
- Mass: assume 60 GeV/c^2
- ~220 km/s
- ~100,000 particles/cm^2/sec
- About 20 million/hand/sec



WIMP-Nucleus Interaction

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

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

atomic mass

coupling constant

Enormous enhancement for heavy nuclei target!

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

Principles of Particle Detection

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

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

"form factor" (quantum mechanics of interaction with nucleus)

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

"reduced mass"

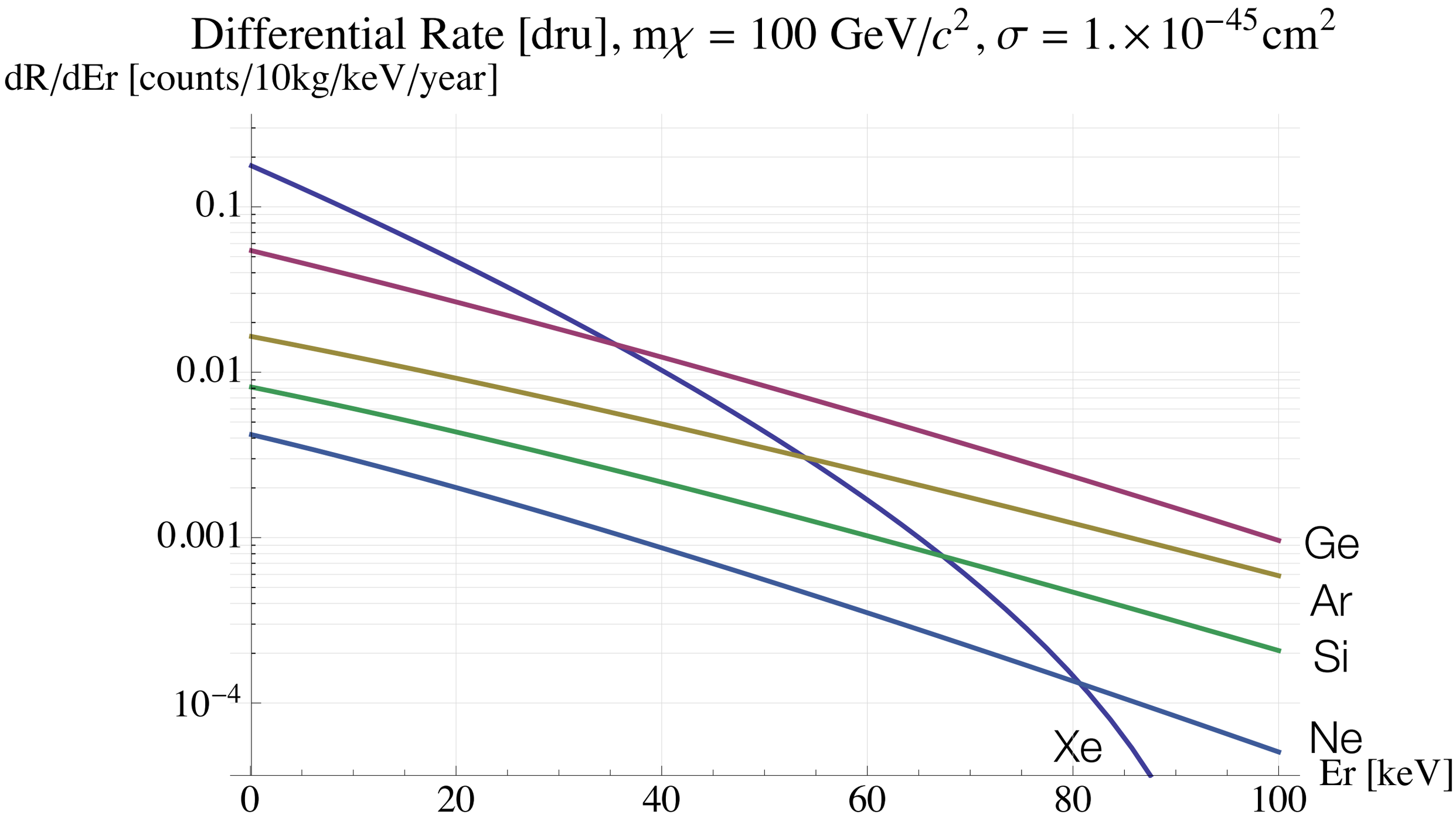
$$T(E_R) \simeq \exp(-v_{\rm min}^2/v_o^2)$$

integral over local WIMP velocity distribution

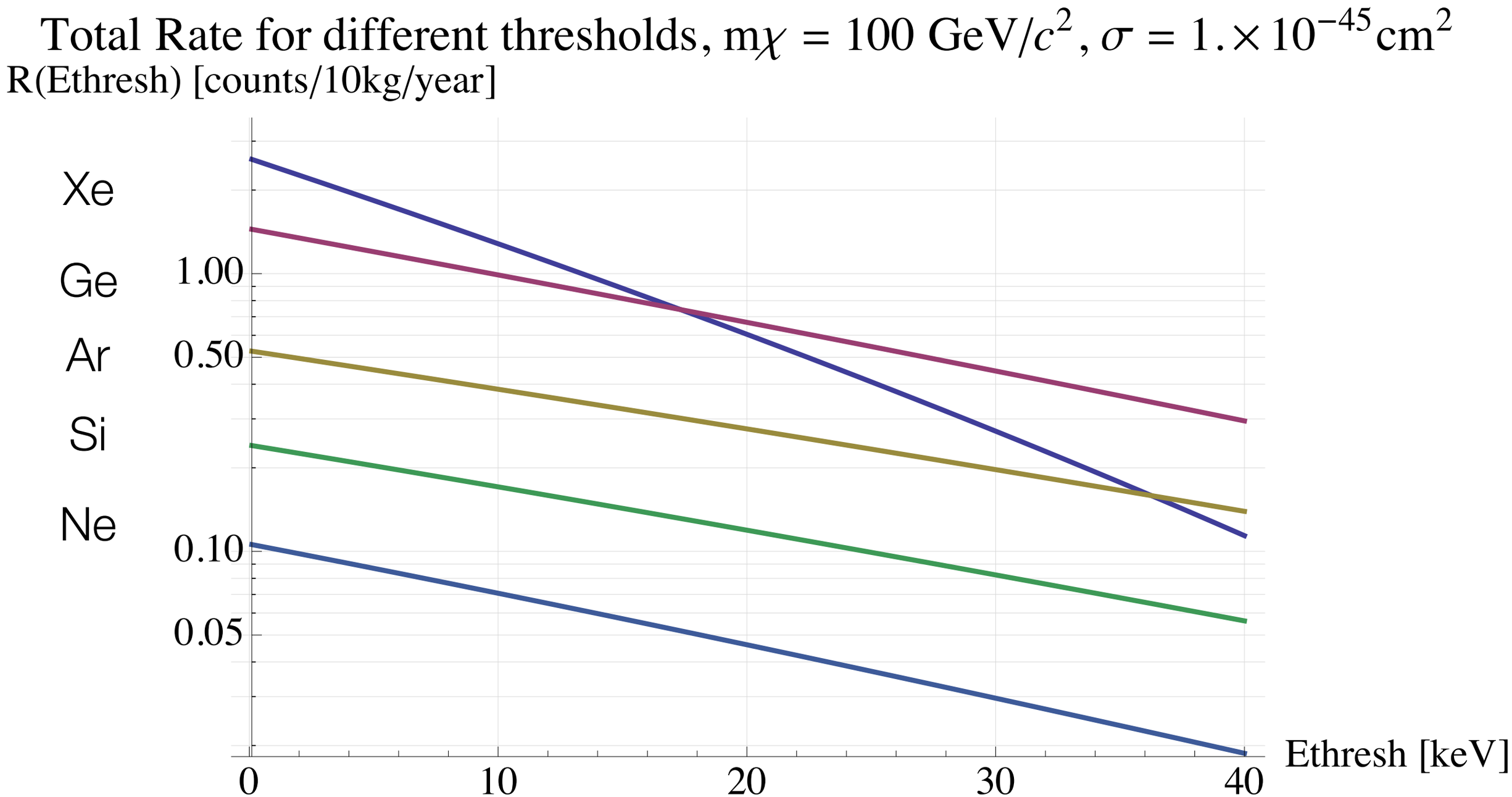
$$v_{\rm min} = \sqrt{E_R\, m_N/(2m_r^2)}$$

minimum WIMP velocity for given E_R

The expected direct detection rates are LOW!



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



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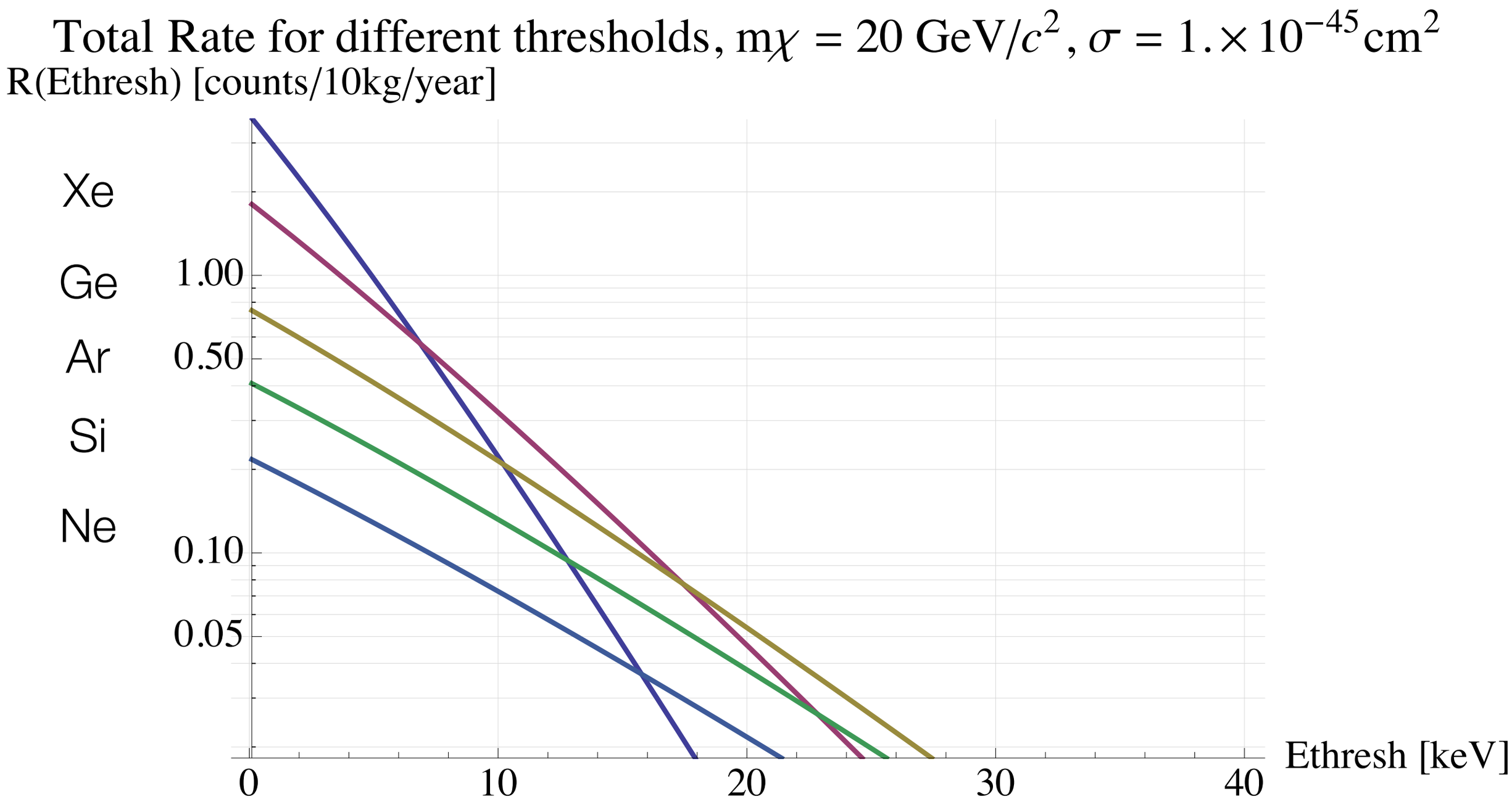

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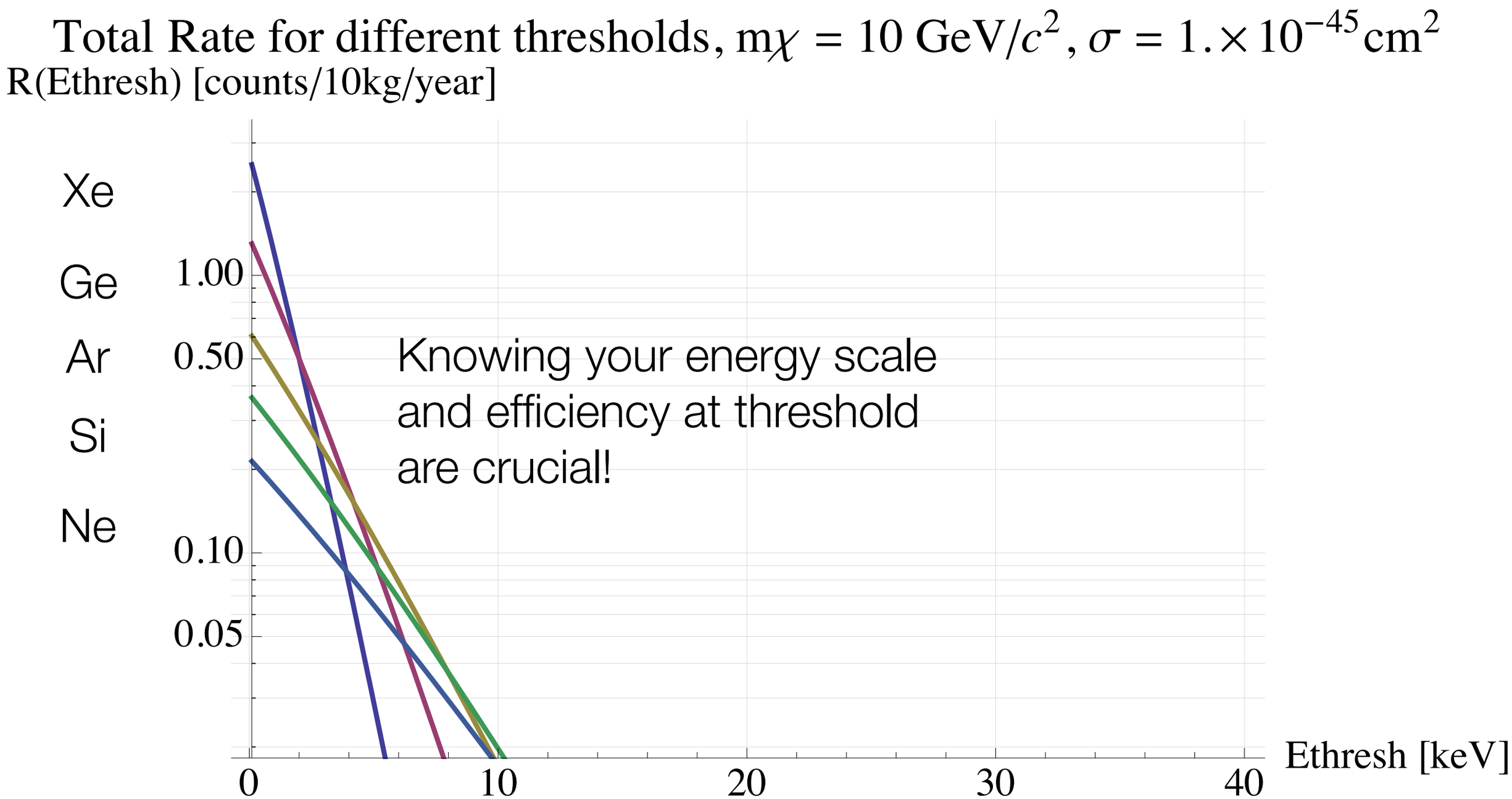


Requirements

1: Large Exposure (Mass x Time)

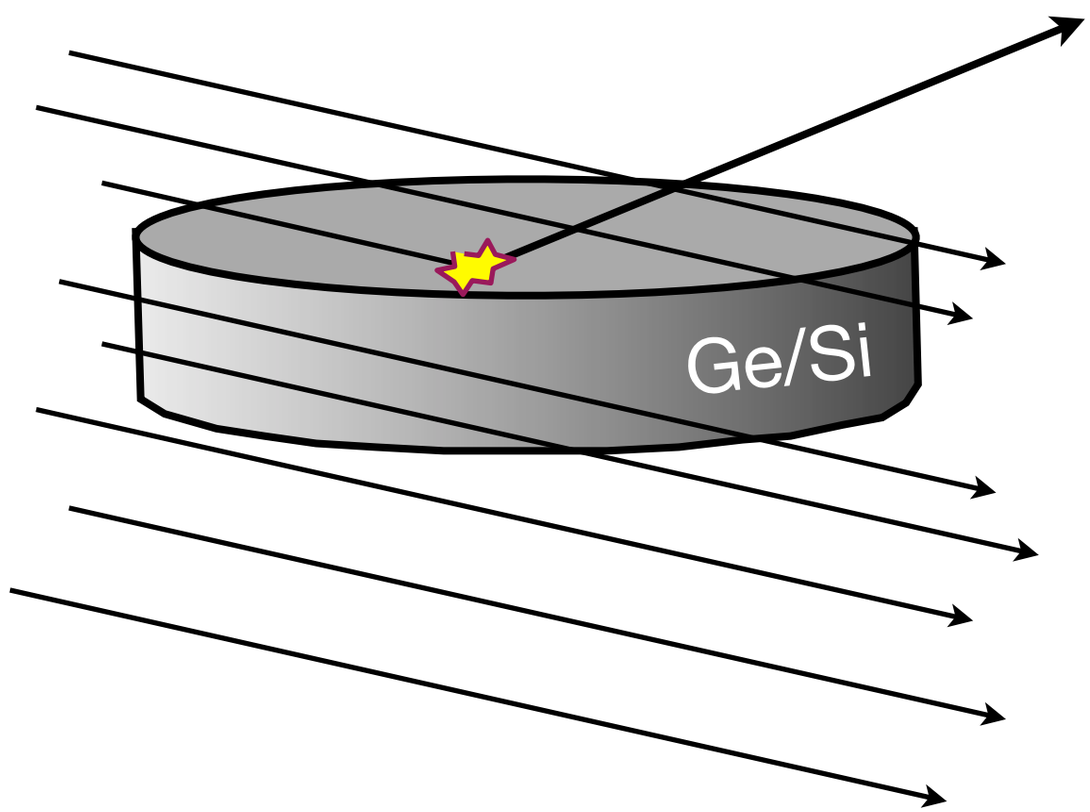
2: Low Energy Threshold ~2-10 keV

3: Low Background Rate ~100 events per kg-day

4: Separation of Nuclear Recoils and Electron Recoils

<1 leakage per
10^6 background
(in the fiducial volume)

CDMS II Detectors



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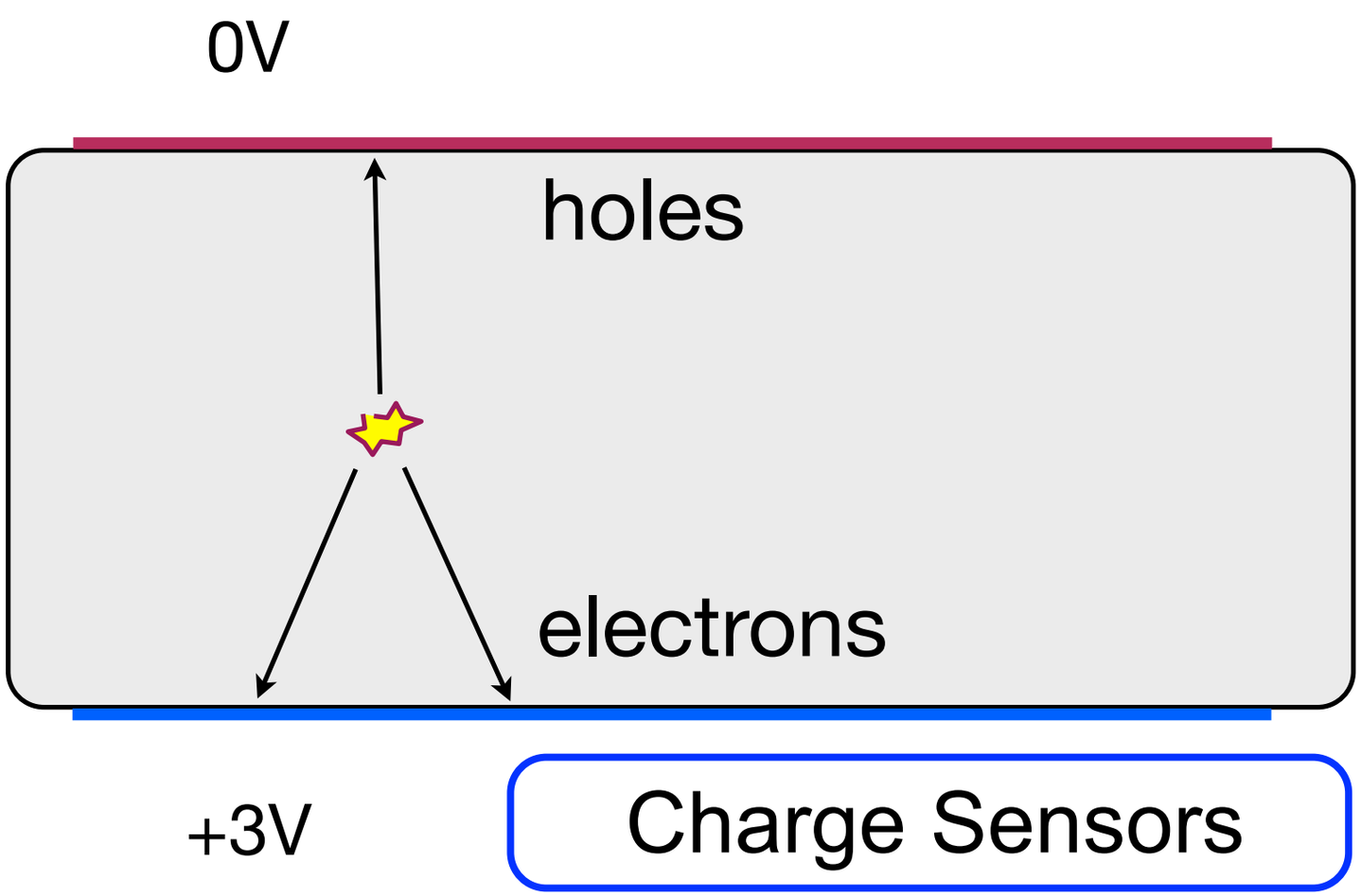

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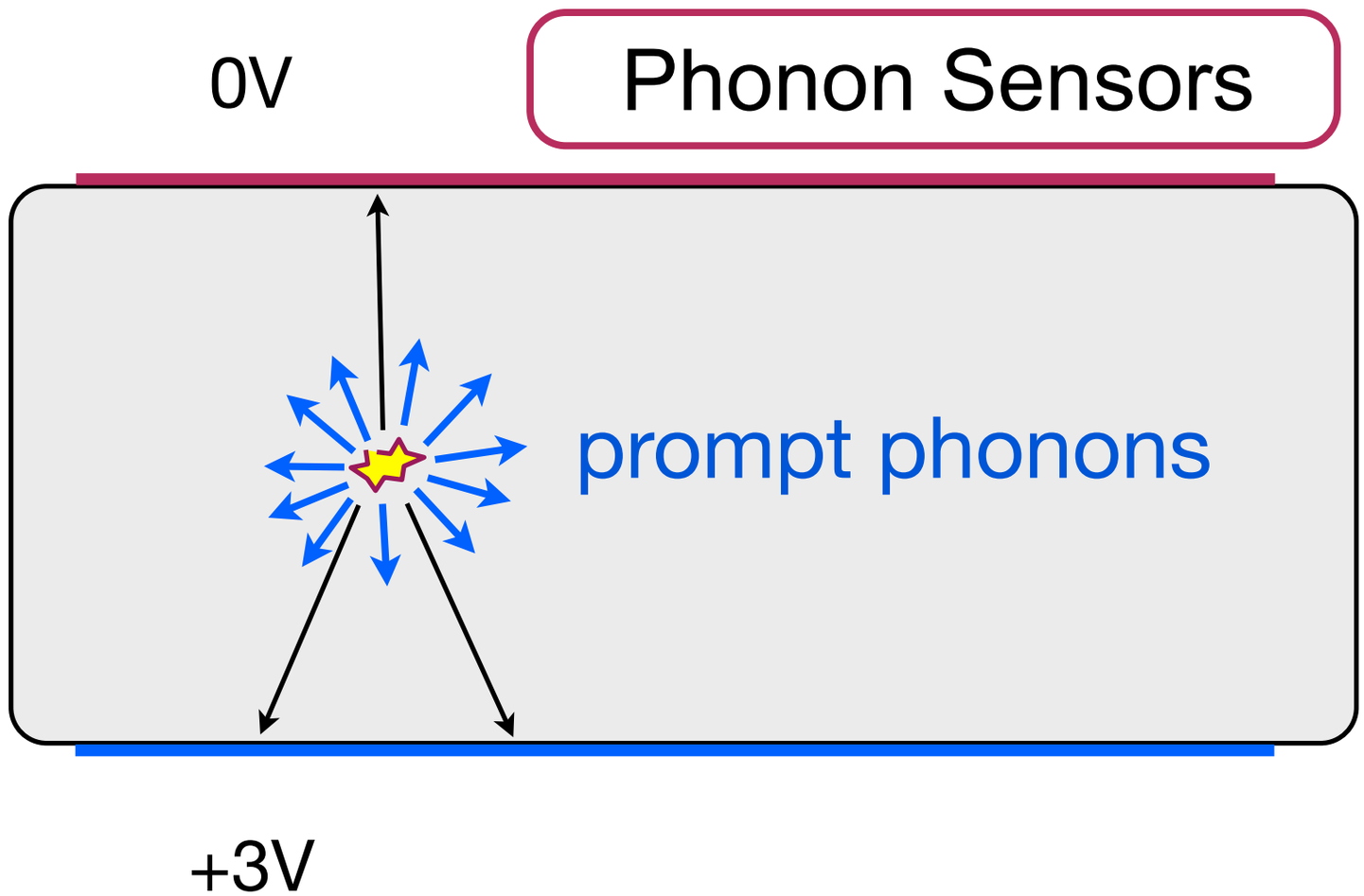

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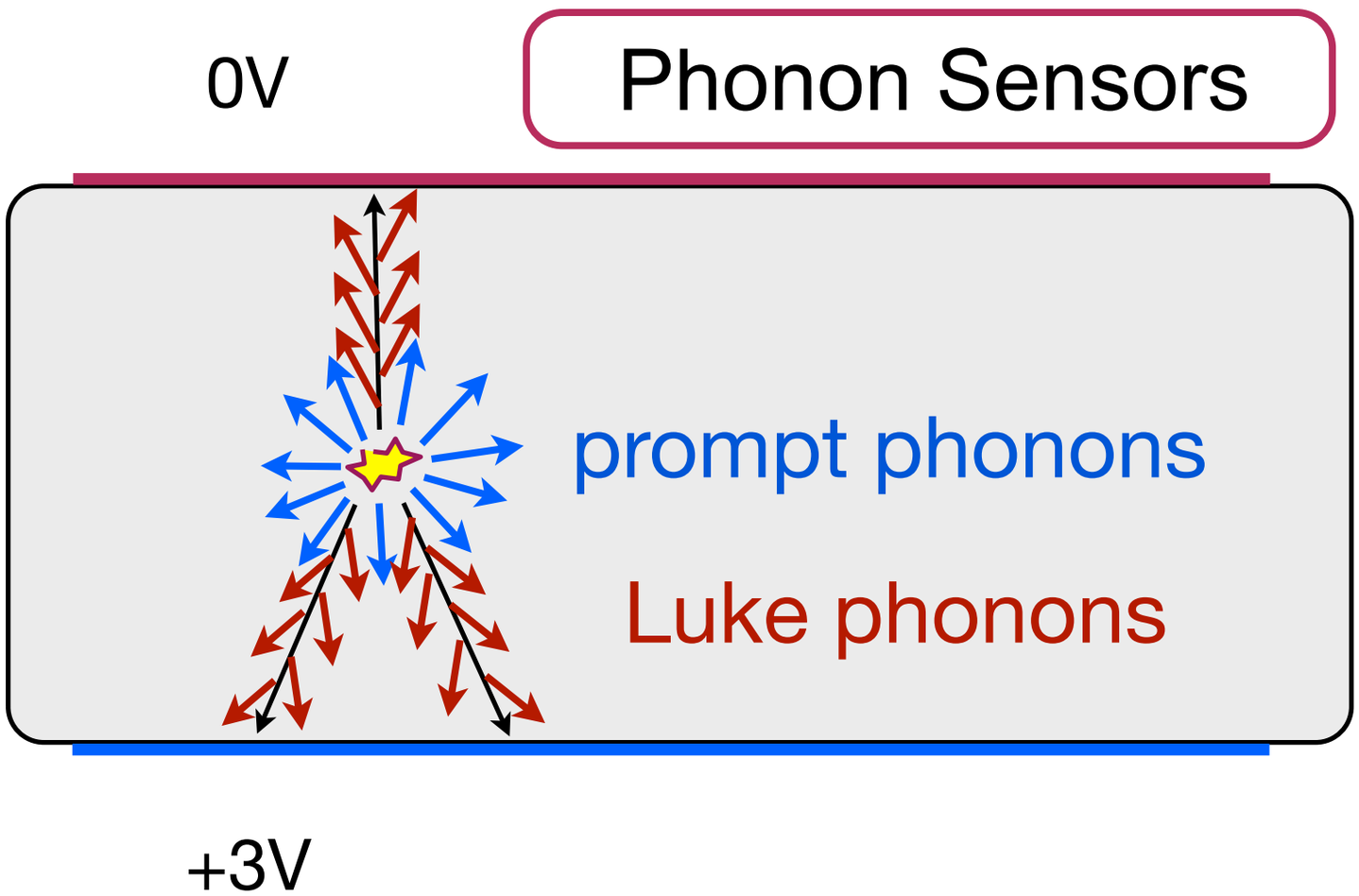
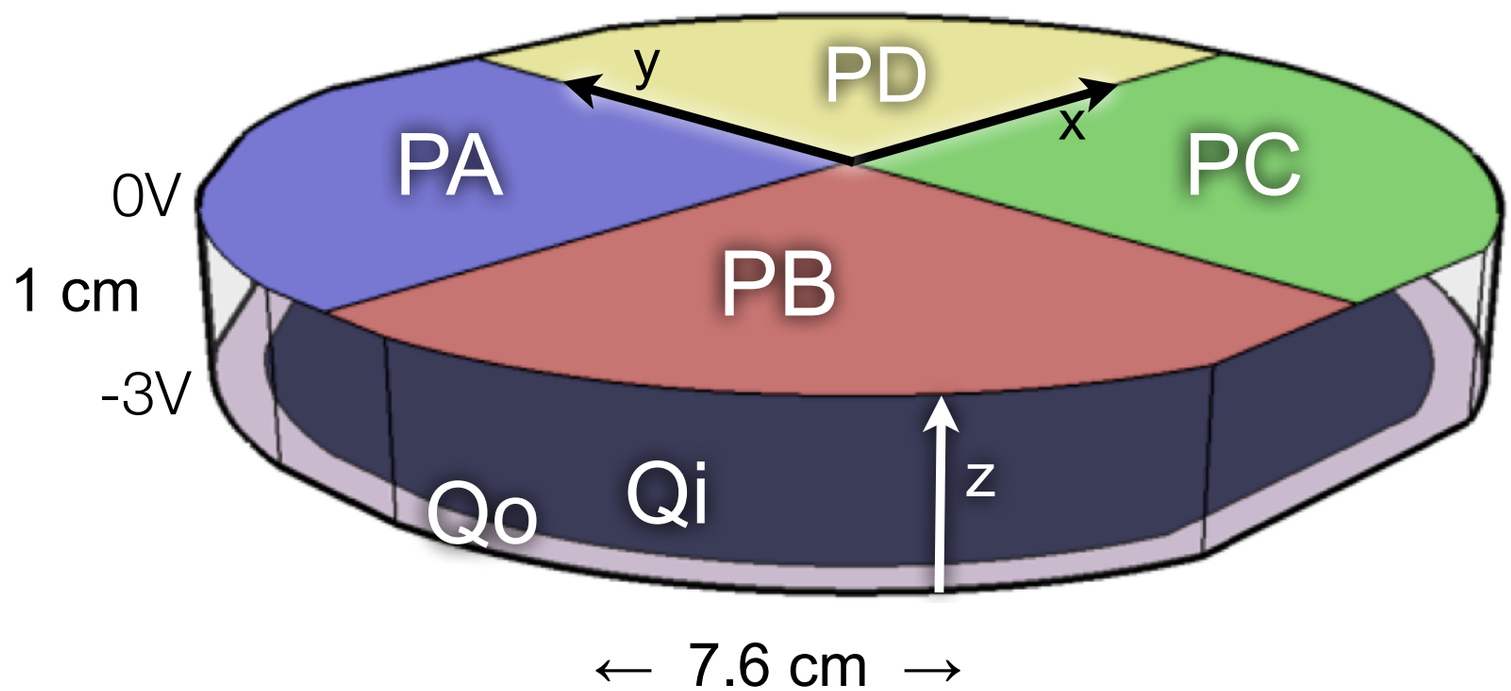


Luke Energy
$= \Delta V\ [e\ N_{eh}]$

$P_{tot} = E_{recoil} + E_{Luke}$

CDMS II

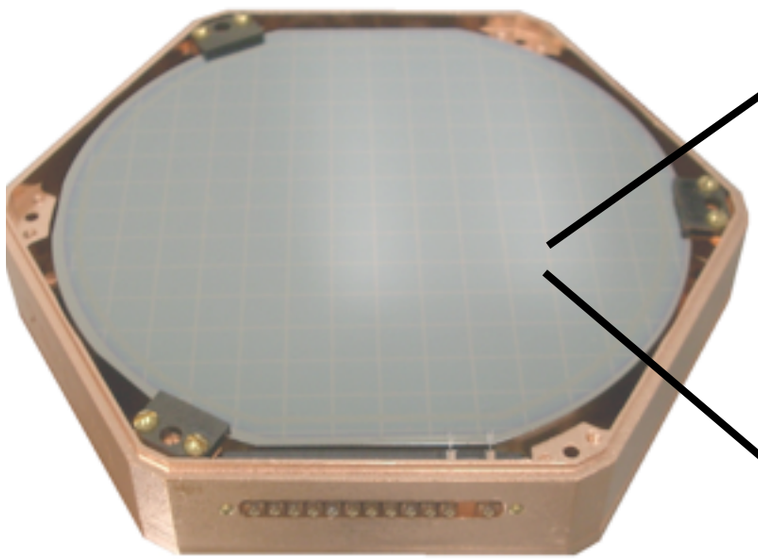


4 Phonon Channels

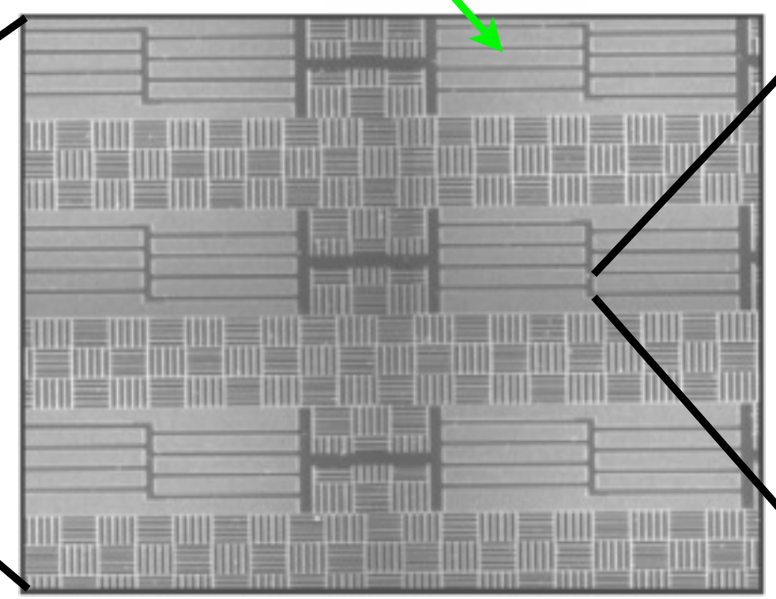
2 Charge Channels

CDMS II

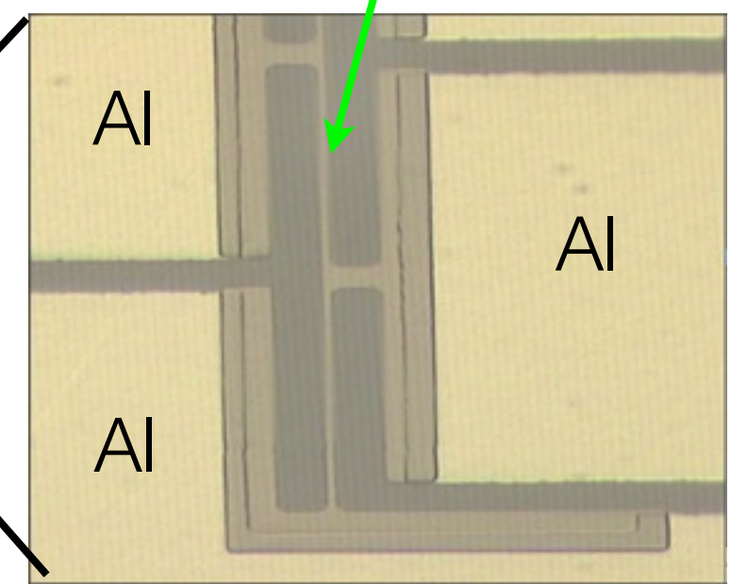
Ge/Si Crystal

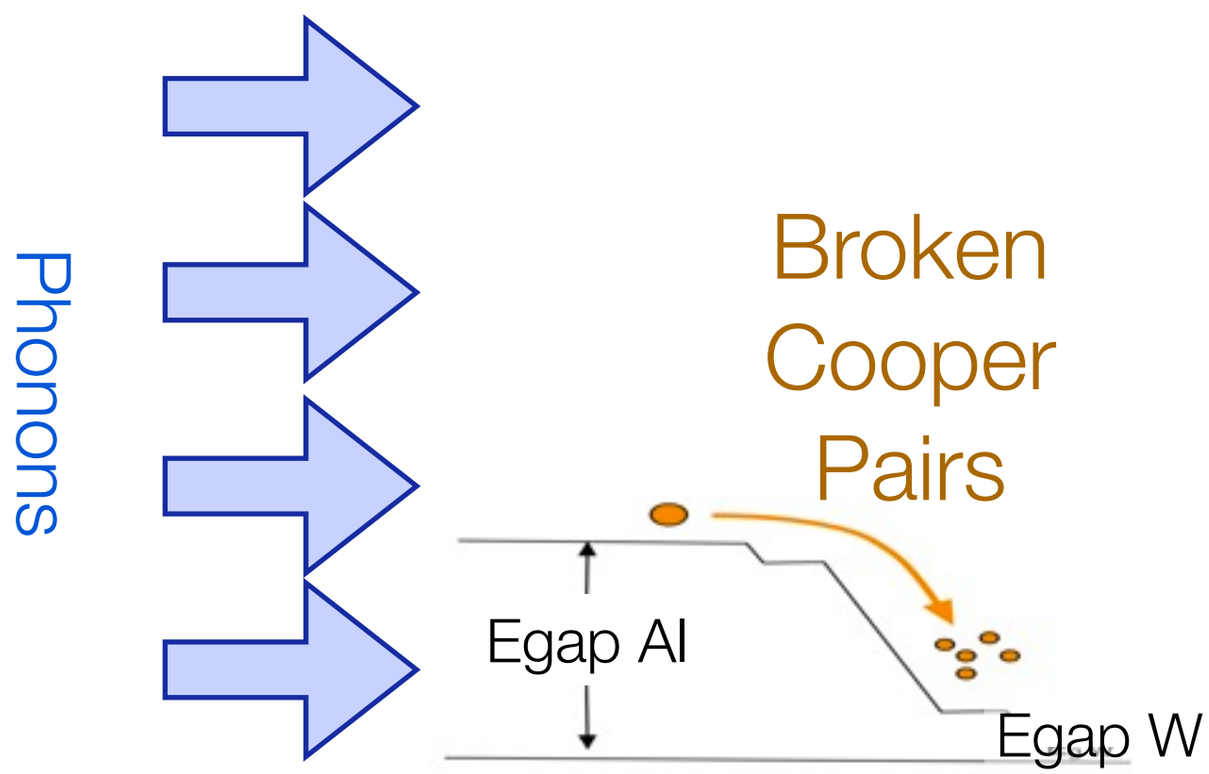


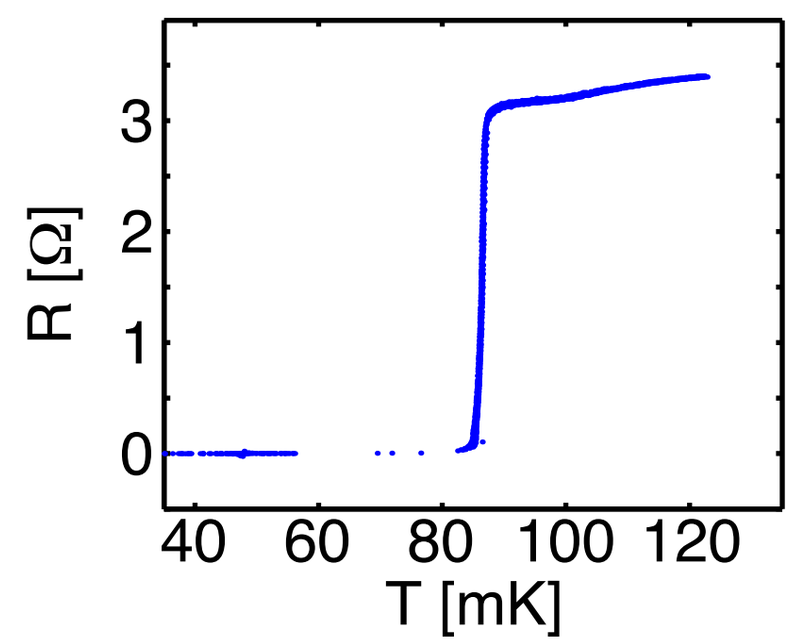
Al Fins



W TES



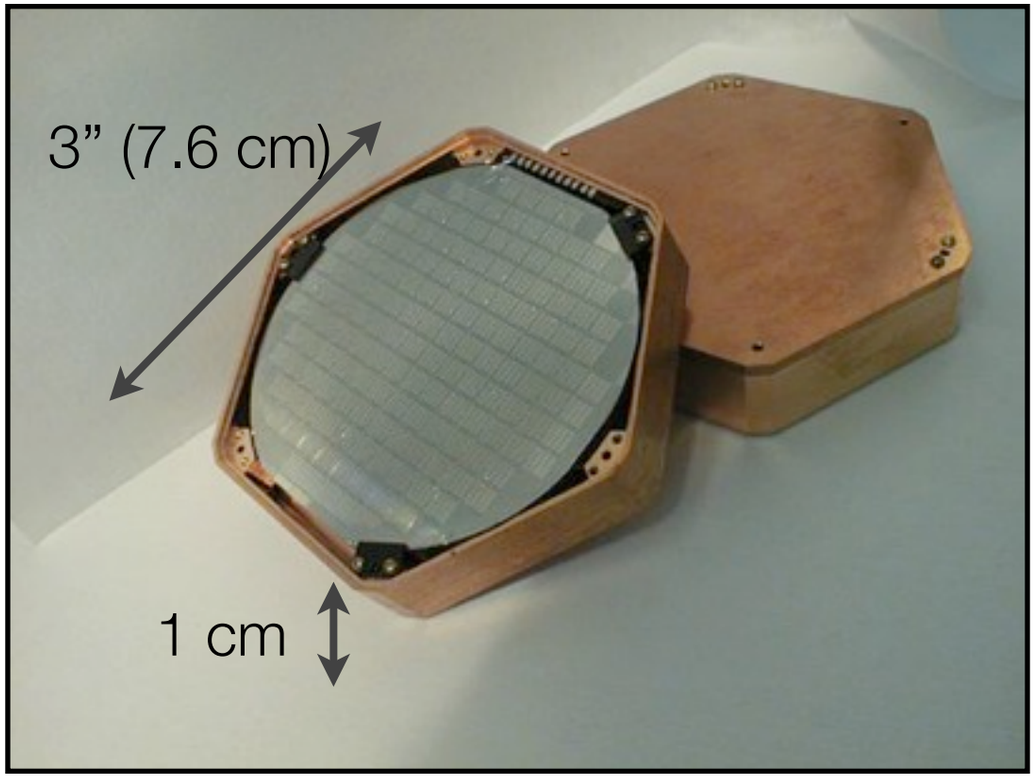




The CDMS-II Experiment

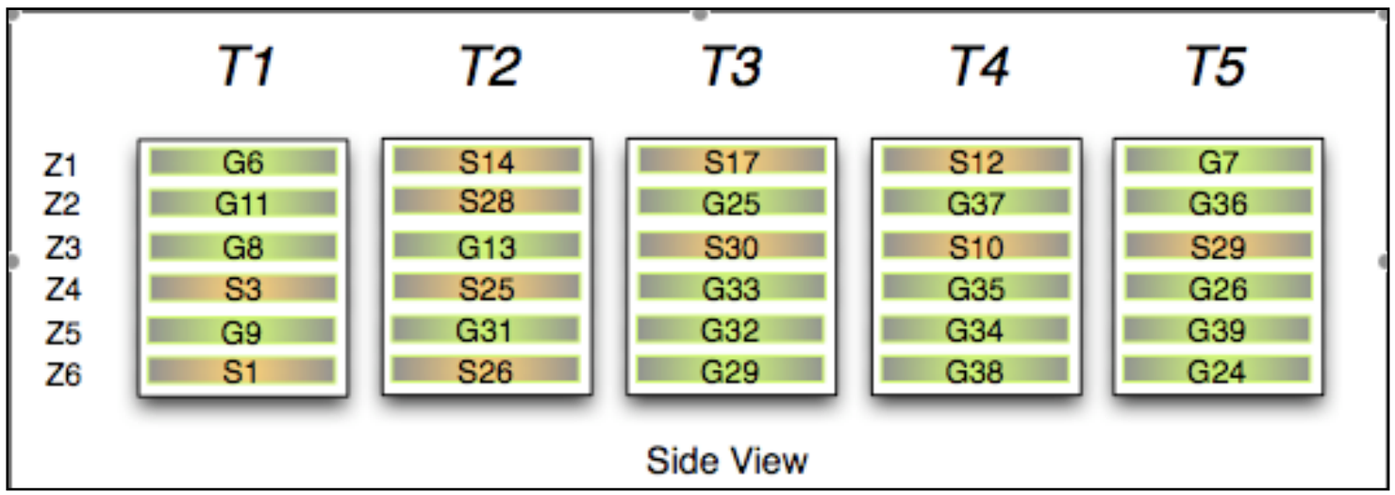
ZIP Detectors

- **Z**-sensitive **I**onization and **P**honon mediated
- 230 g Ge or 106 g Si crystals
  (1 cm thick, 7.5 cm diameter)
- Photolithographically patterned to collect athermal phonons and ionization signals
- Direct xy-position imaging
- Surface (z) event rejection from pulse shapes and timing
- 30 detectors stacked into
  5 towers of 6 detectors



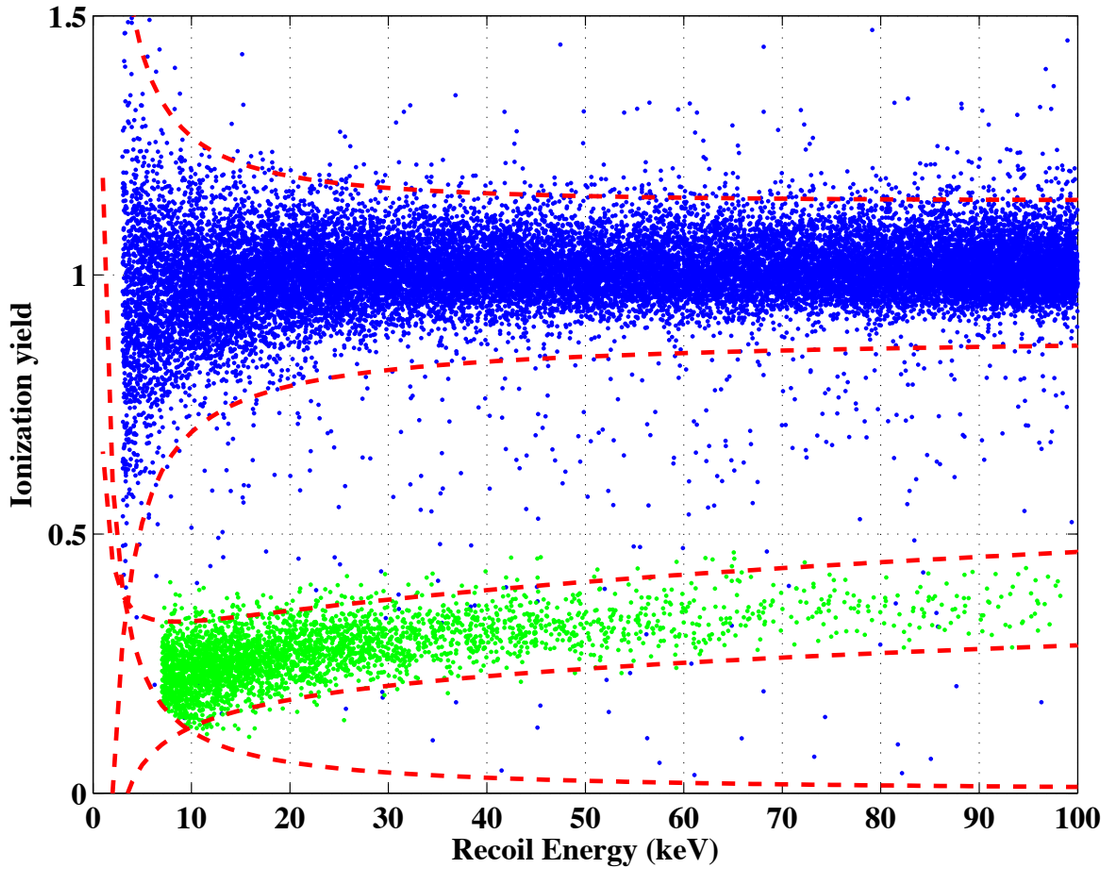
CDMS-II Exposure

- Oct. 2003 - Aug. 2004
  - 42.7 kg-days in 4 Si detectors
- Oct. 2006 - July 2007
  - 55.9 kg-days in 6 Si detectors
- July 2007 - Sep. 2008
  - 140.23 kg-days in 8 Si detectors



CDMS II Surface Background Rejection

- Most backgrounds (e, γ) produce electron recoils
- WIMPs and neutrons produce nuclear recoils.
- Ionization yield (ionization energy per unit recoil energy) strongly depends on recoil type.



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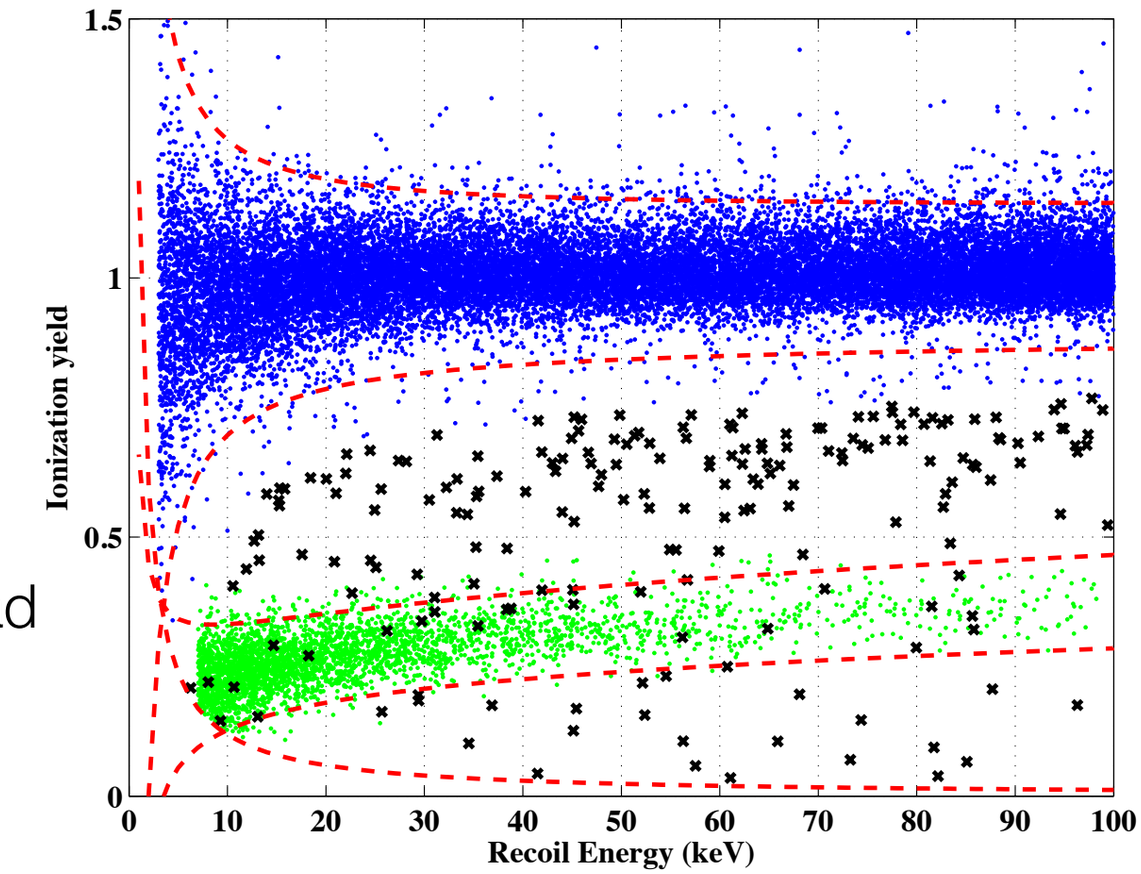
- Particles that interact in the "surface dead layer" result in reduced ionization yield.



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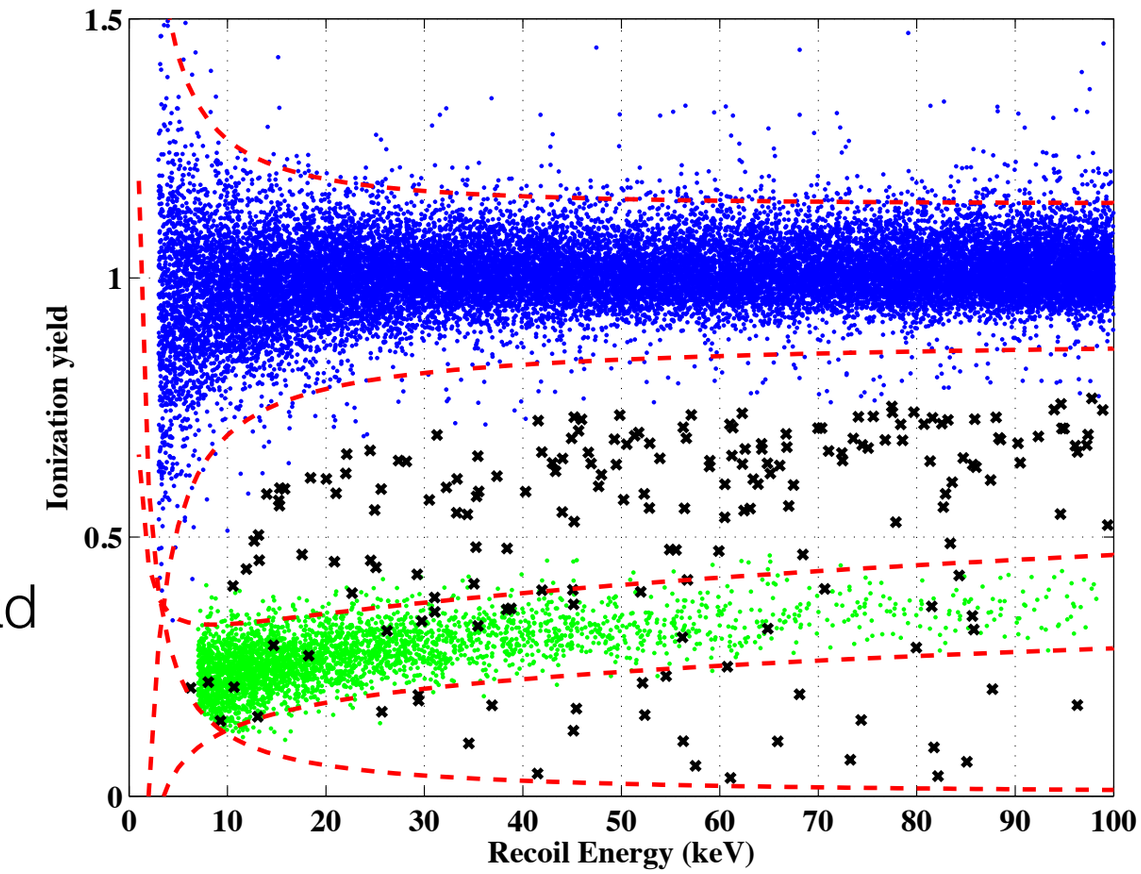
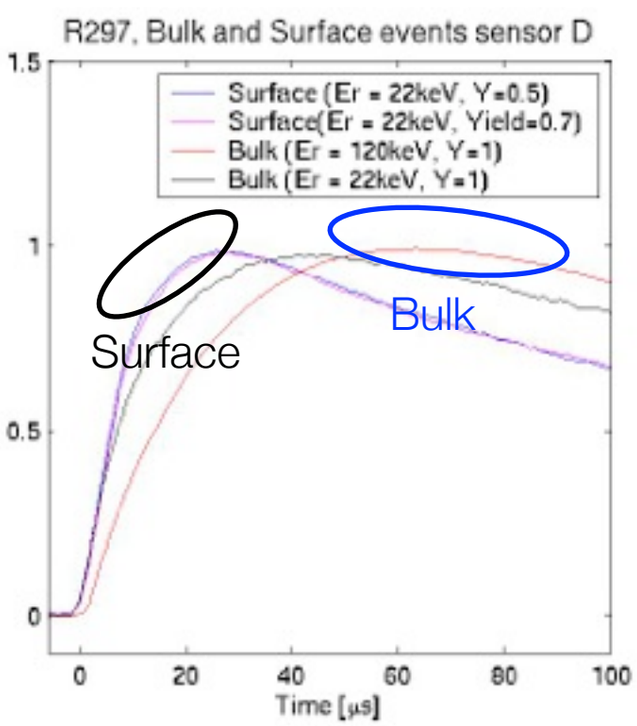
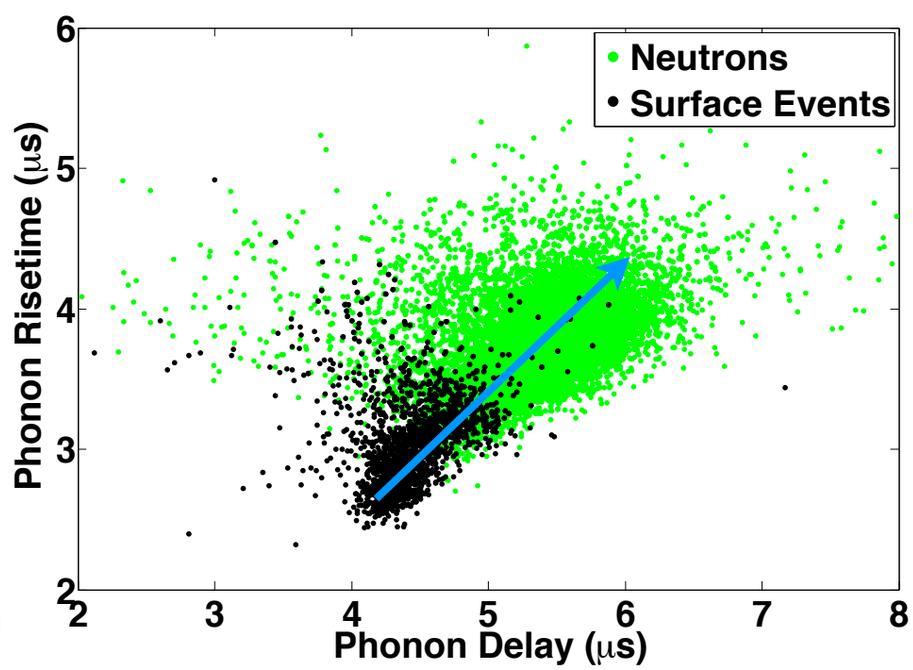
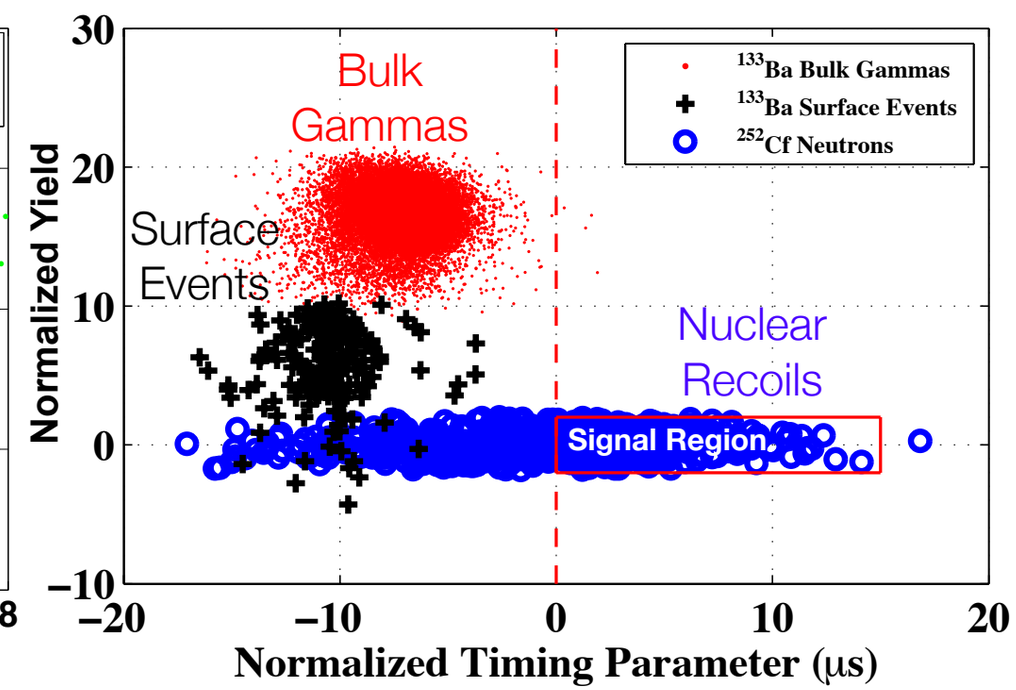
- Ionization yield (ionization energy per unit recoil energy) strongly depends on recoil type.
- Particles that interact in the "surface dead layer" result in reduced ionization yield.
- These surface events can be rejected through a pulse shape rise time cut.



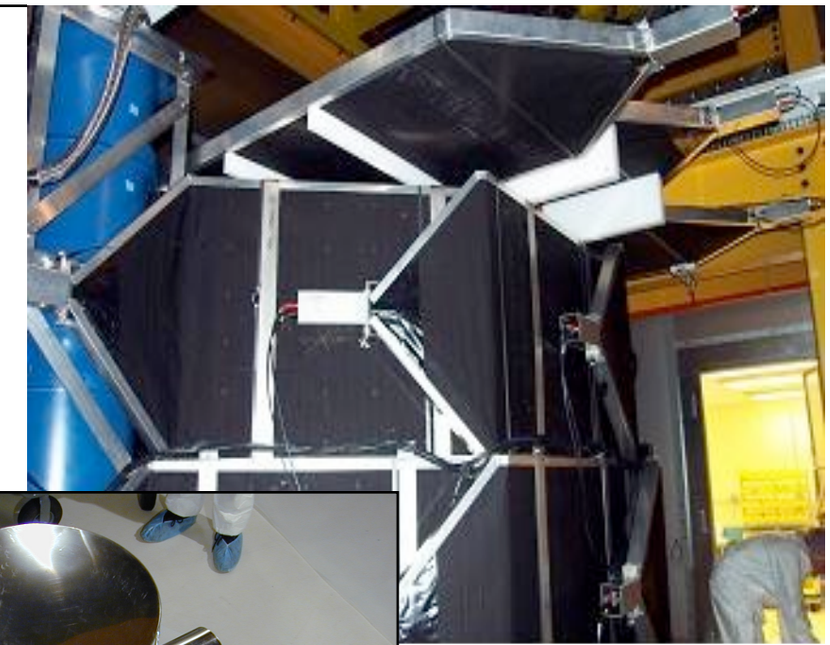


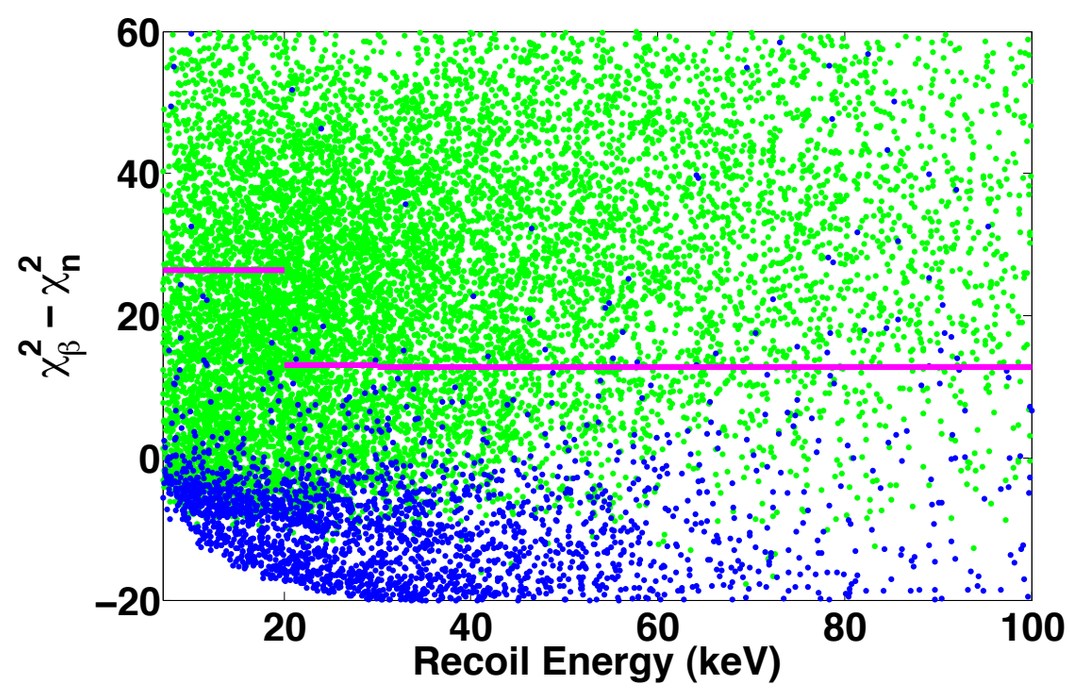




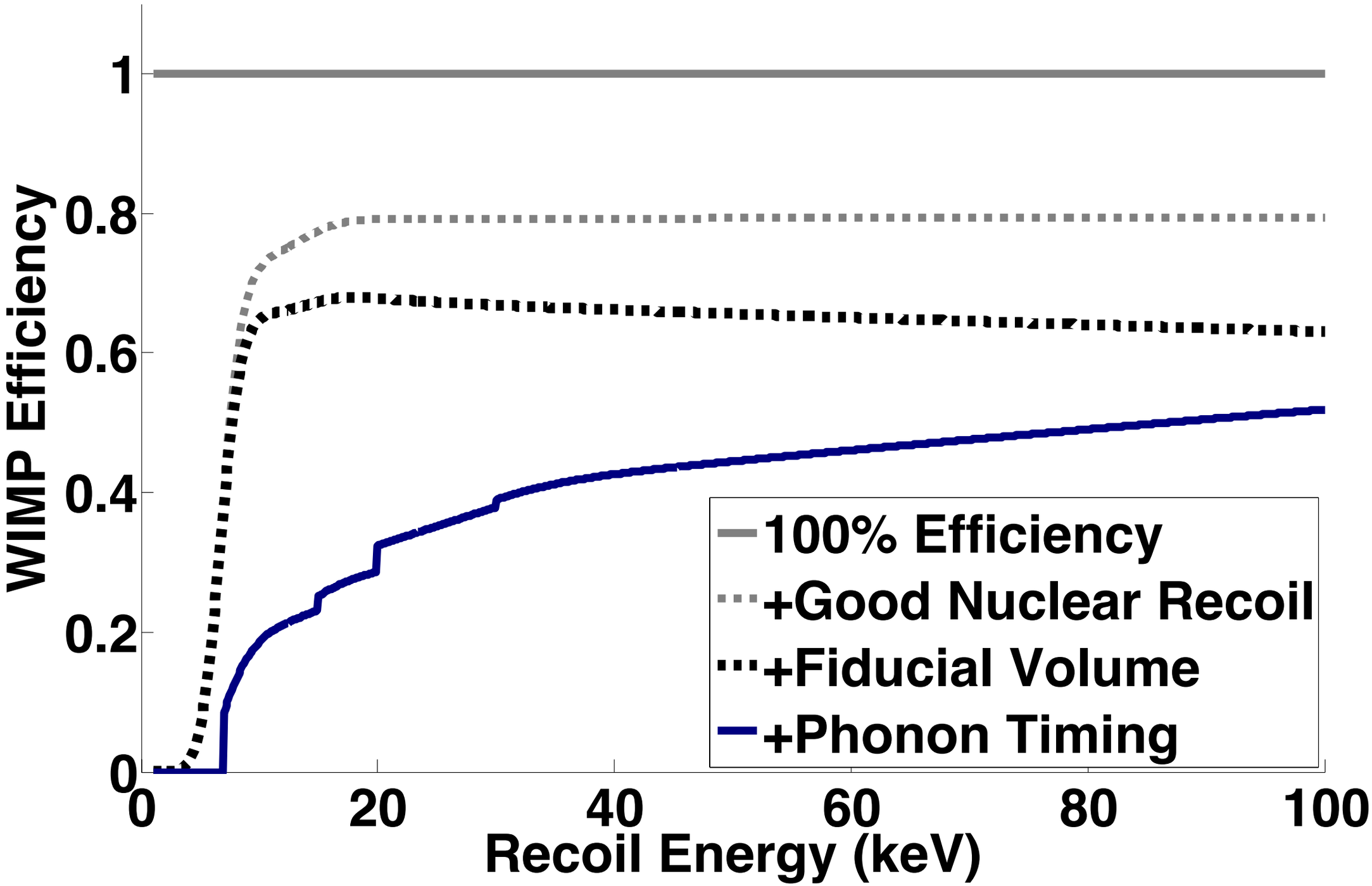
Background Estimate

- **Neutrons**
  - Indistinguishable from WIMPs!
  - Cosmogenic: active veto
  - Radiogenic: passive shielding & materials screening
  - < 0.13 expected events
- **Surface events**
  - Discriminate using phonon timing
  - Optimize in 3 energy bins
    - 7-20, 20-30, 30-100 keV
  - 0.47 expected events estimated before unblinding.



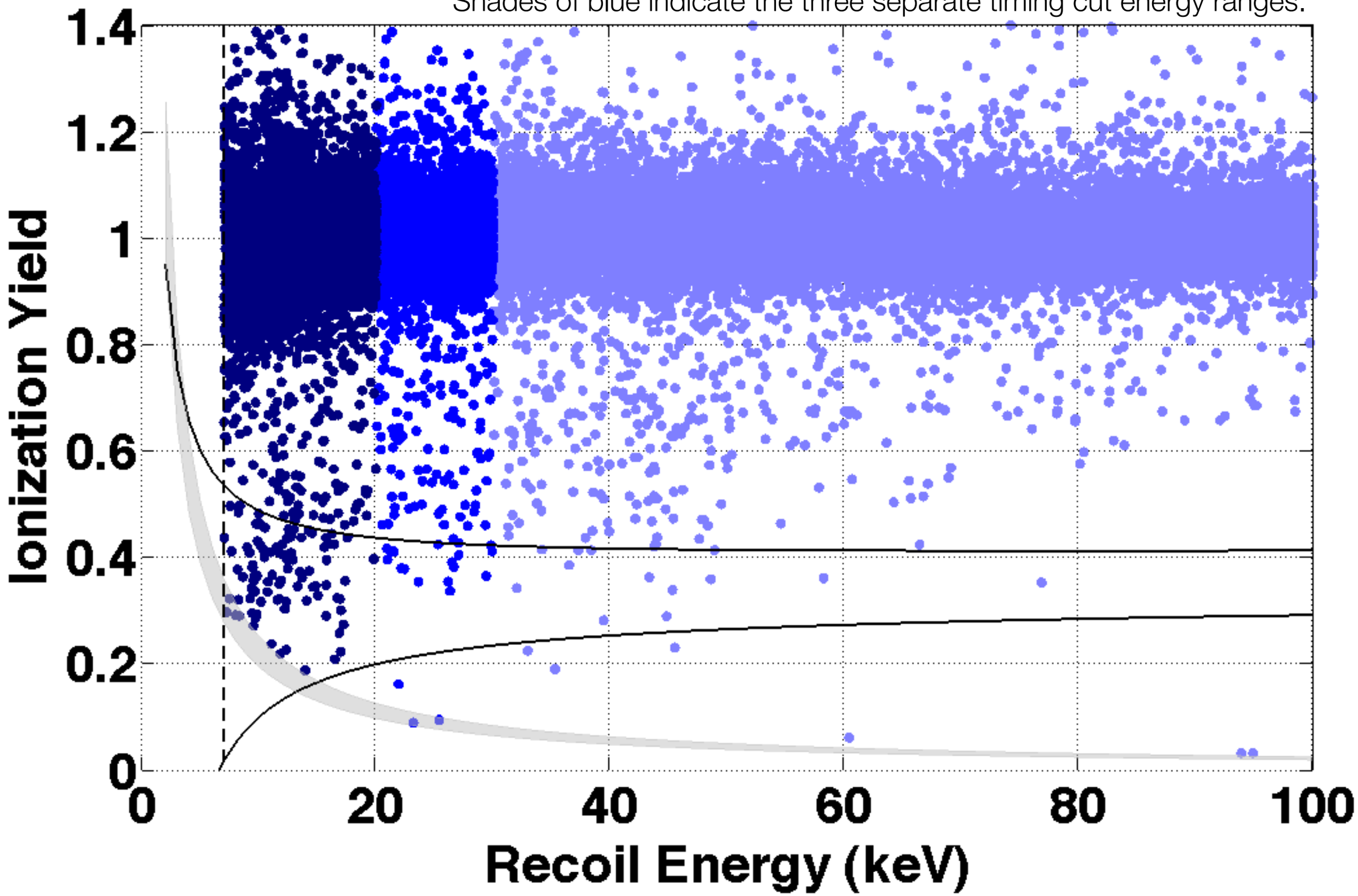


Exposure vs. Recoil Energy

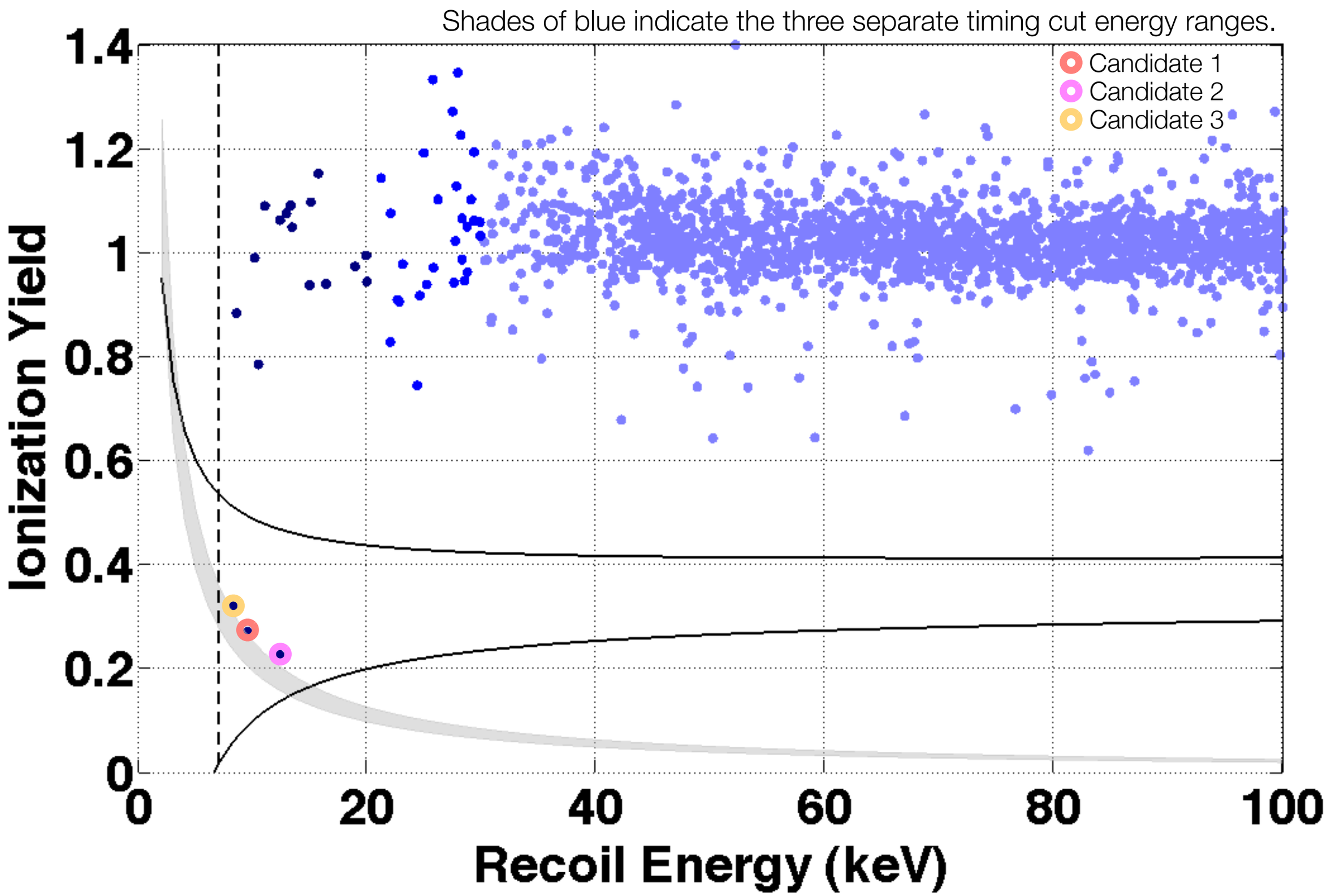


Unblinding Results - before timing cut

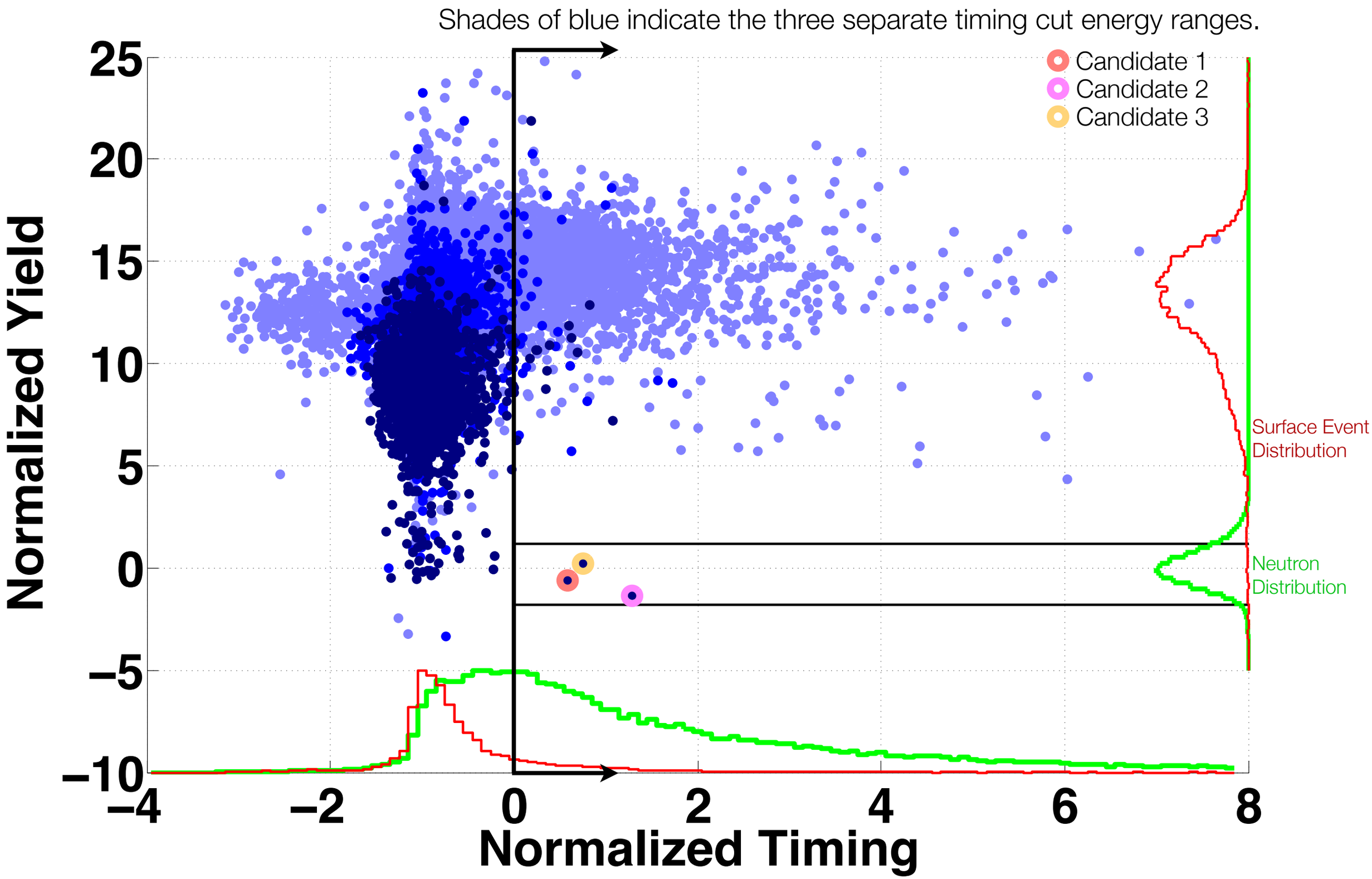
Shades of blue indicate the three separate timing cut energy ranges.



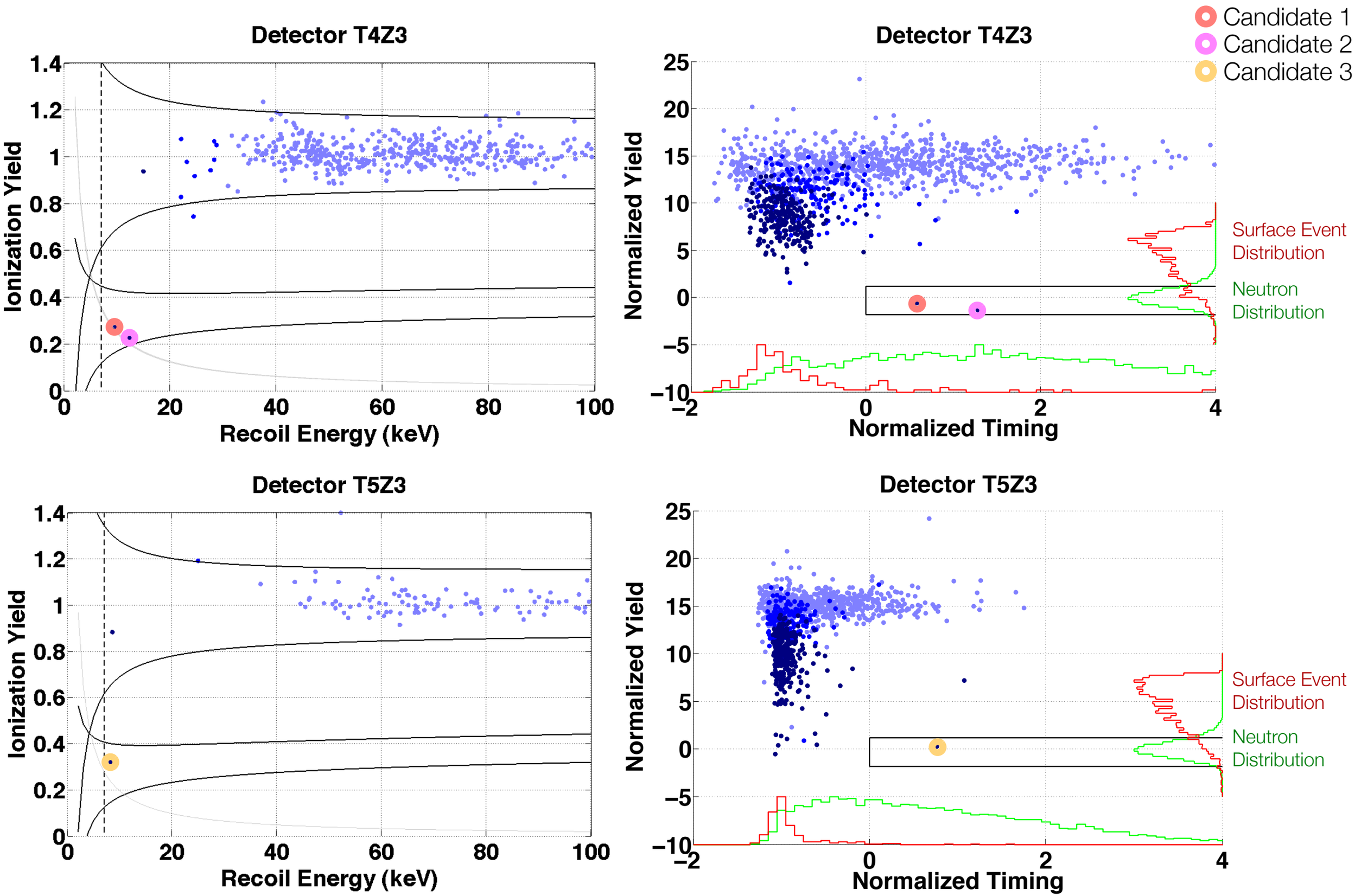
Unblinding Results - after timing cut



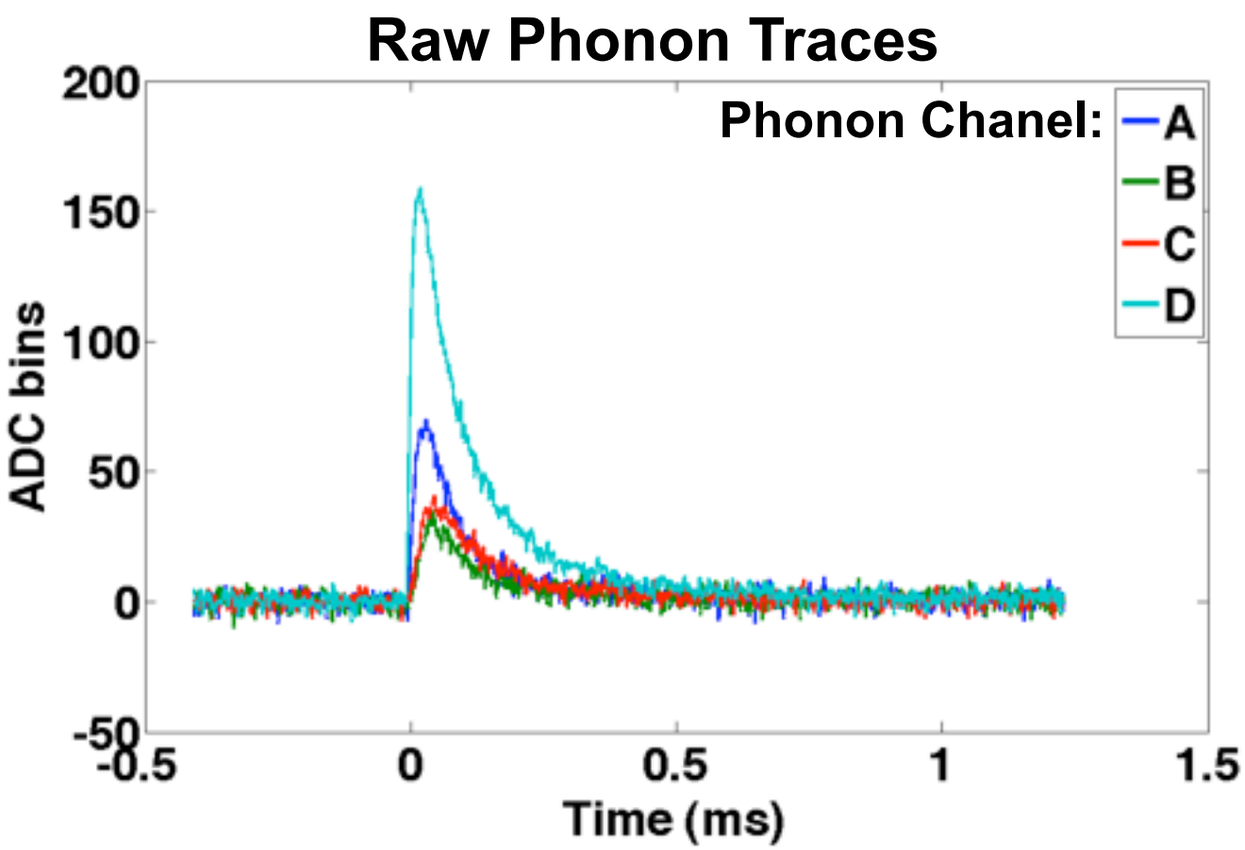
Unblinding Results - Yield vs Timing

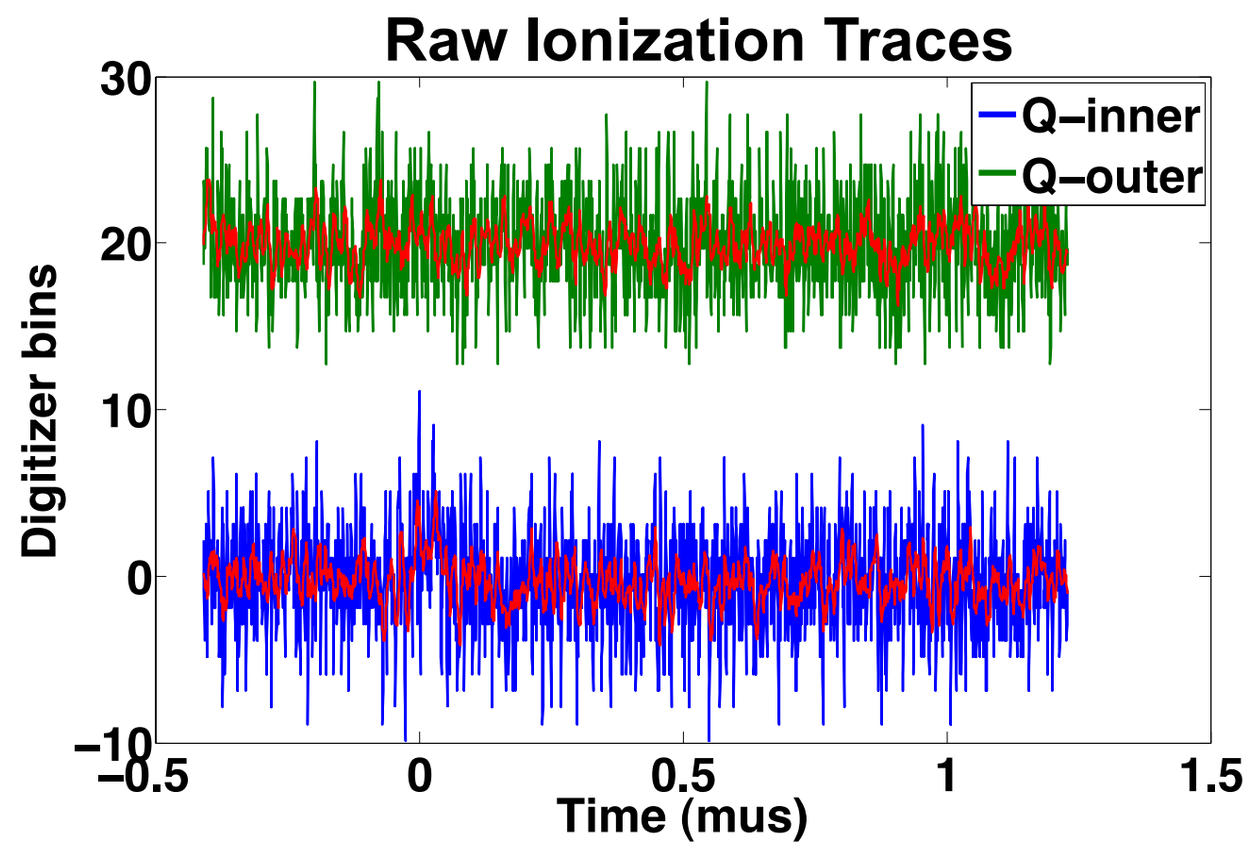


Three Events!



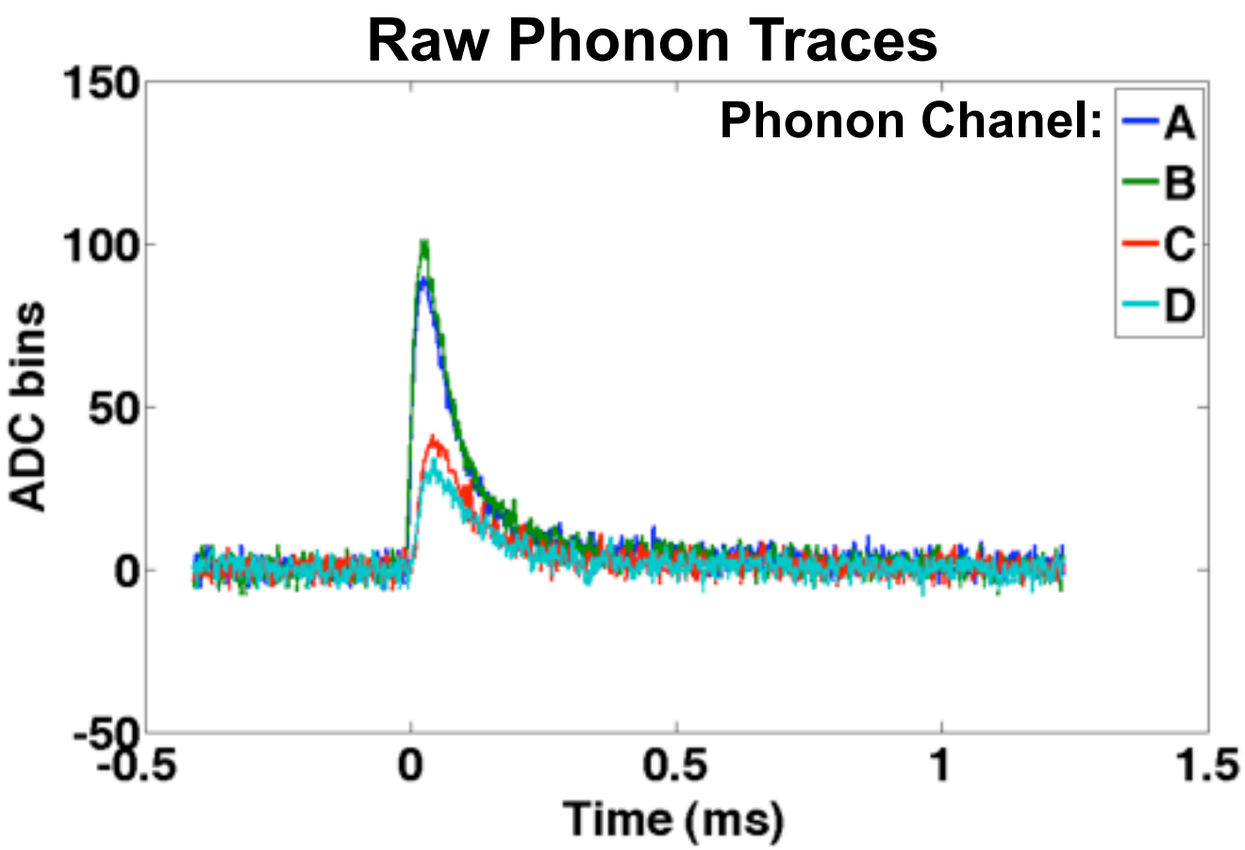
Candidate 1

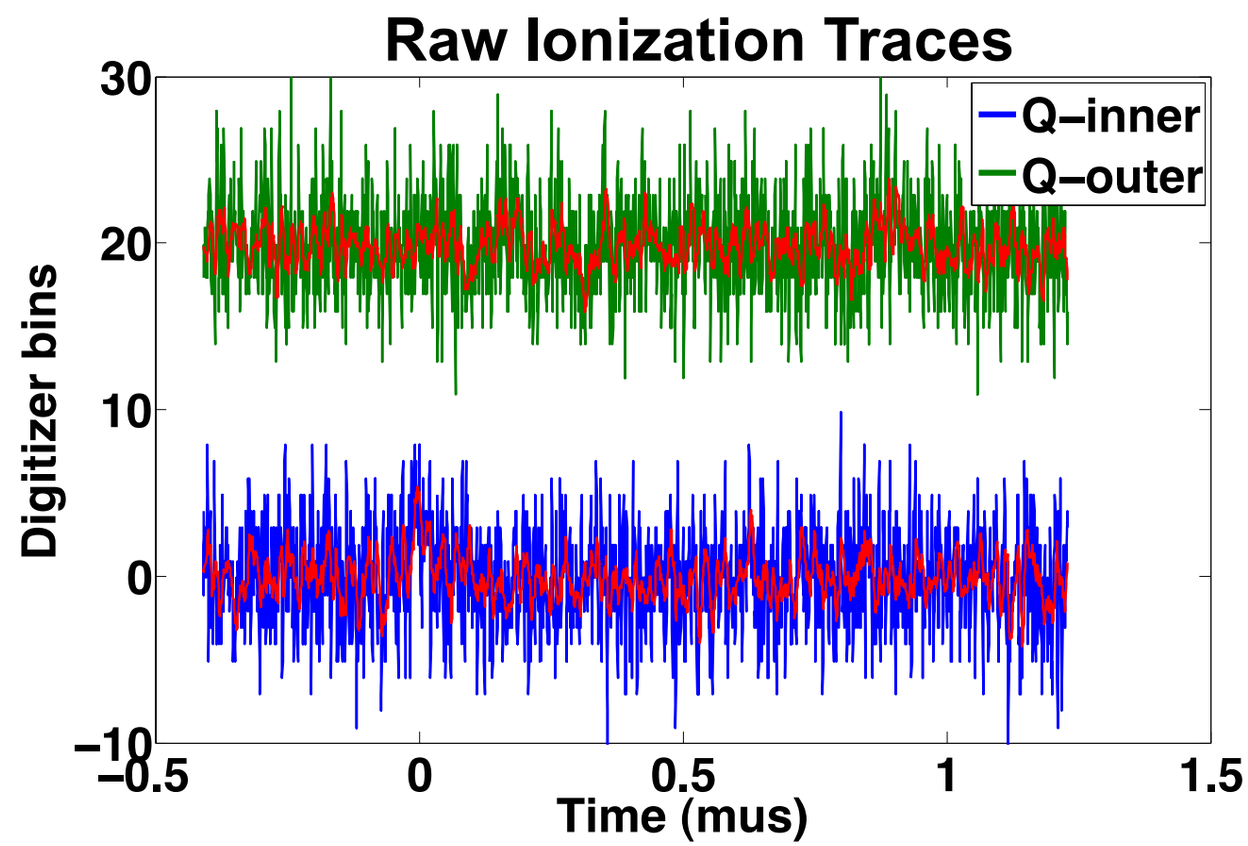




Detector	Recoil Energy	Yield	Charge Signal to Noise	Single Scatter Probability	Date
T4Z3	9.51 keV	0.27	4.87 σ	96.1%	July 1, 2008

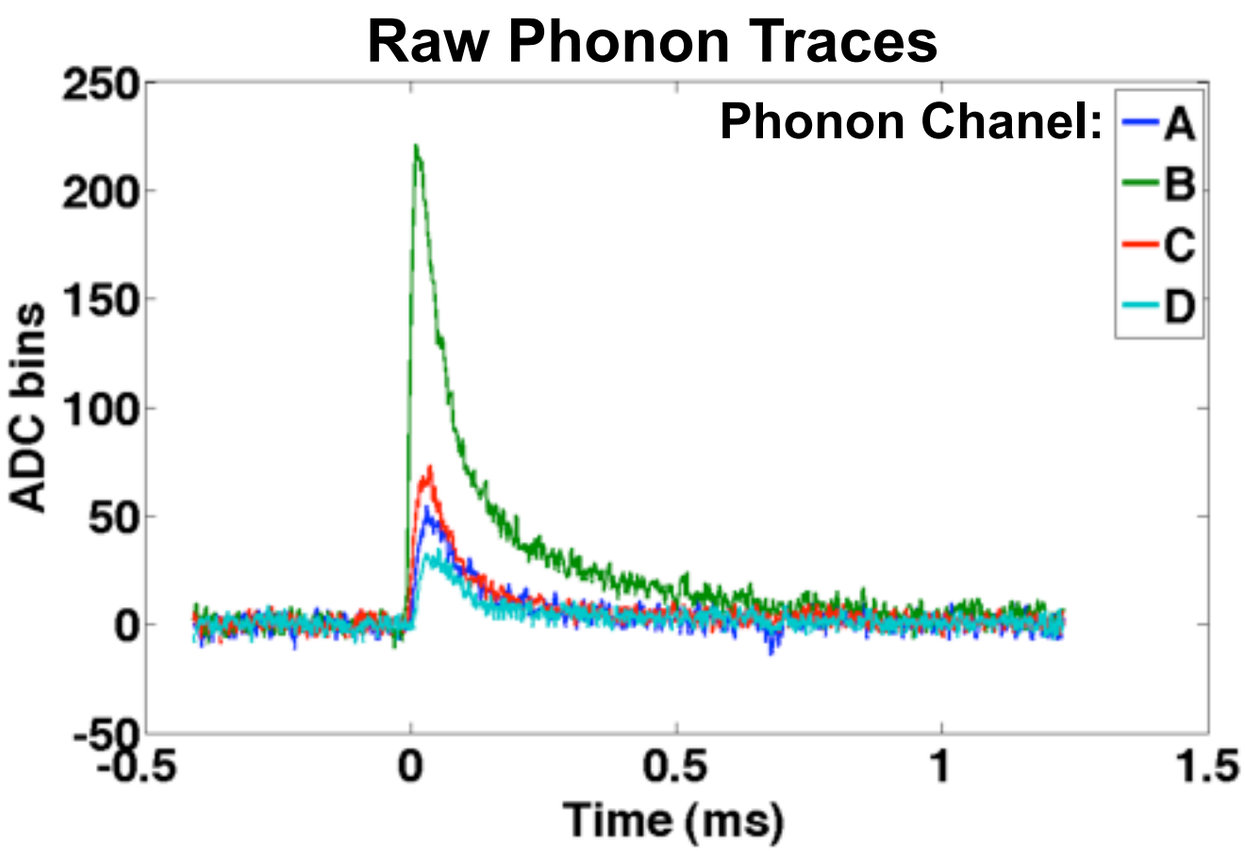
Candidate 2

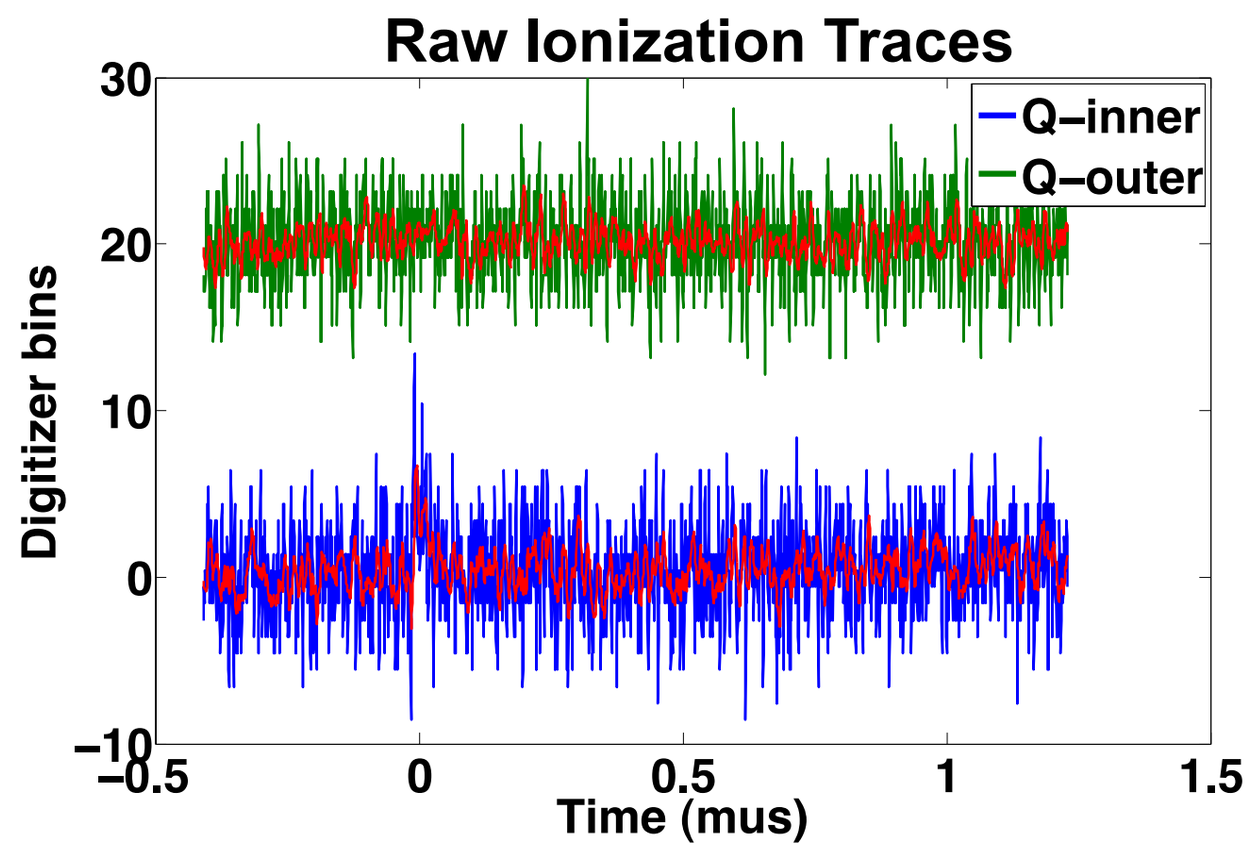




Detector	Recoil Energy	Yield	Charge Signal to Noise	Single Scatter Probability	Date
T4Z3	12.29 keV	0.23	5.11 σ	99.7%	Sep 6, 2008

Candidate 3





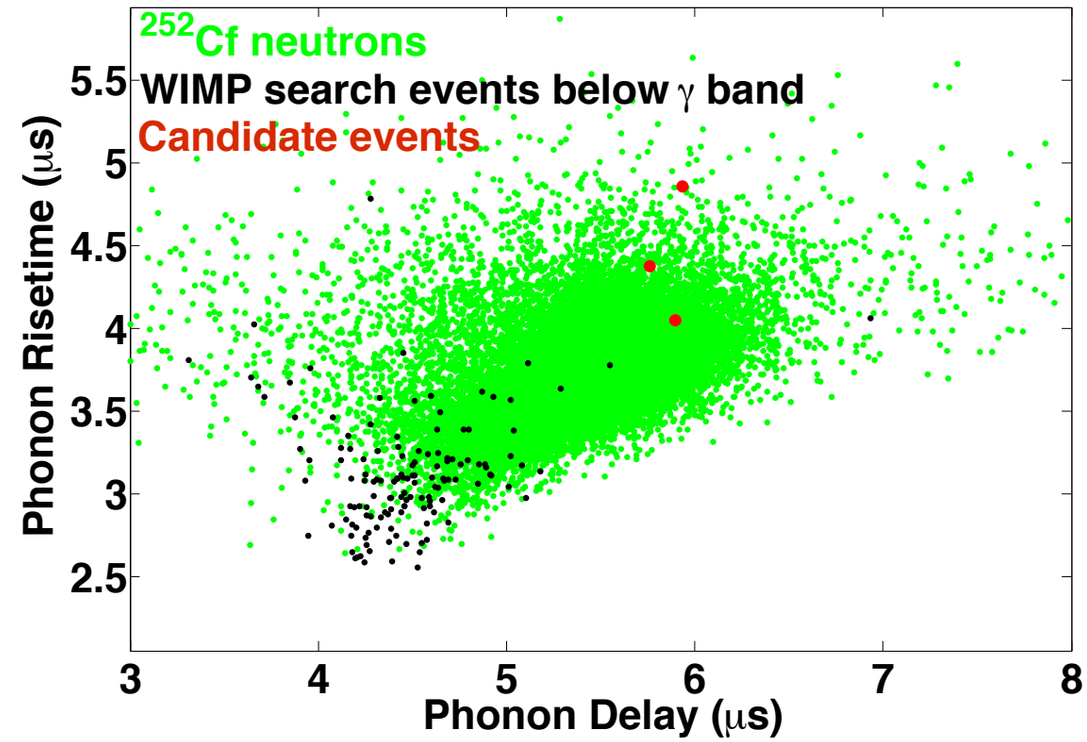
Detector	Recoil Energy	Yield	Charge Signal to Noise	Single Scatter Probability	Date
T5Z3	8.20 keV	0.32	6.66 σ	99.7%	March 14, 2008

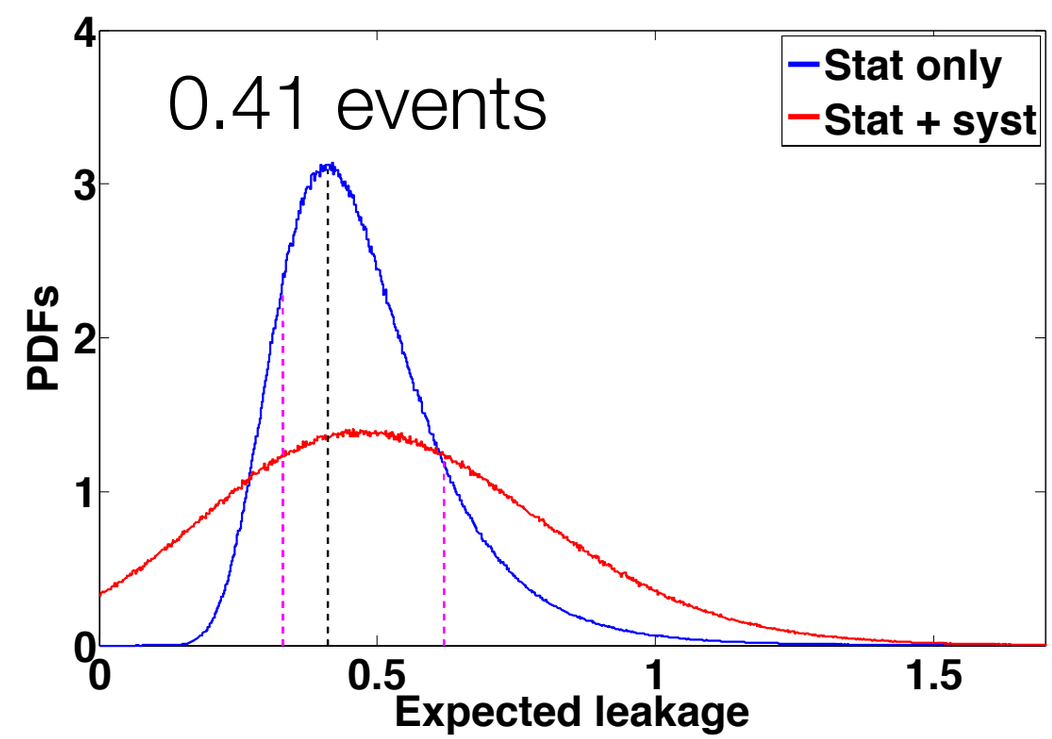
Post-Unblinding Checks

- 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 (next slide)
- 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 ^{206}Pb recoils from ^{210}Po decay, and limited this to be <0.08 events.





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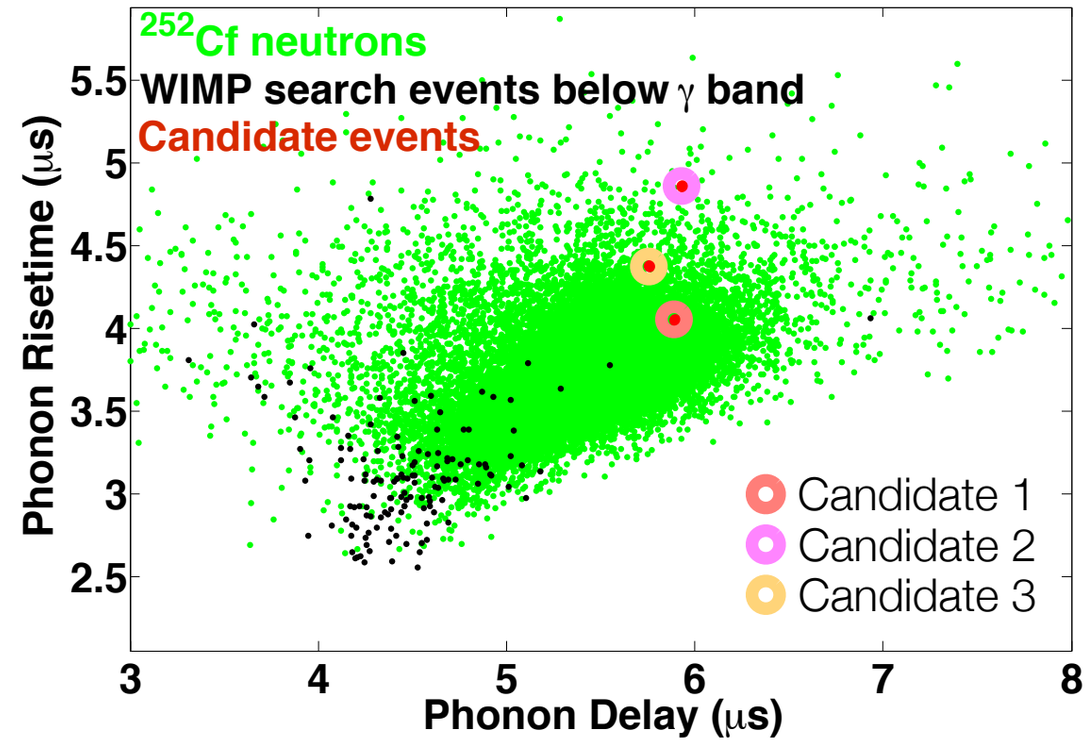
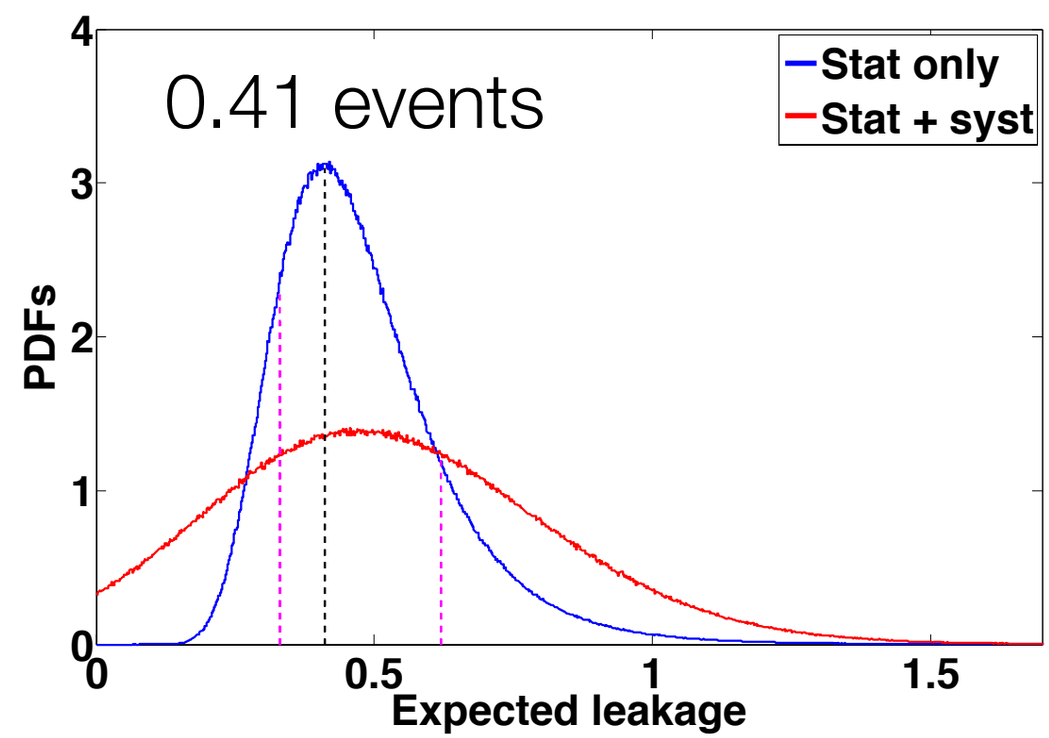
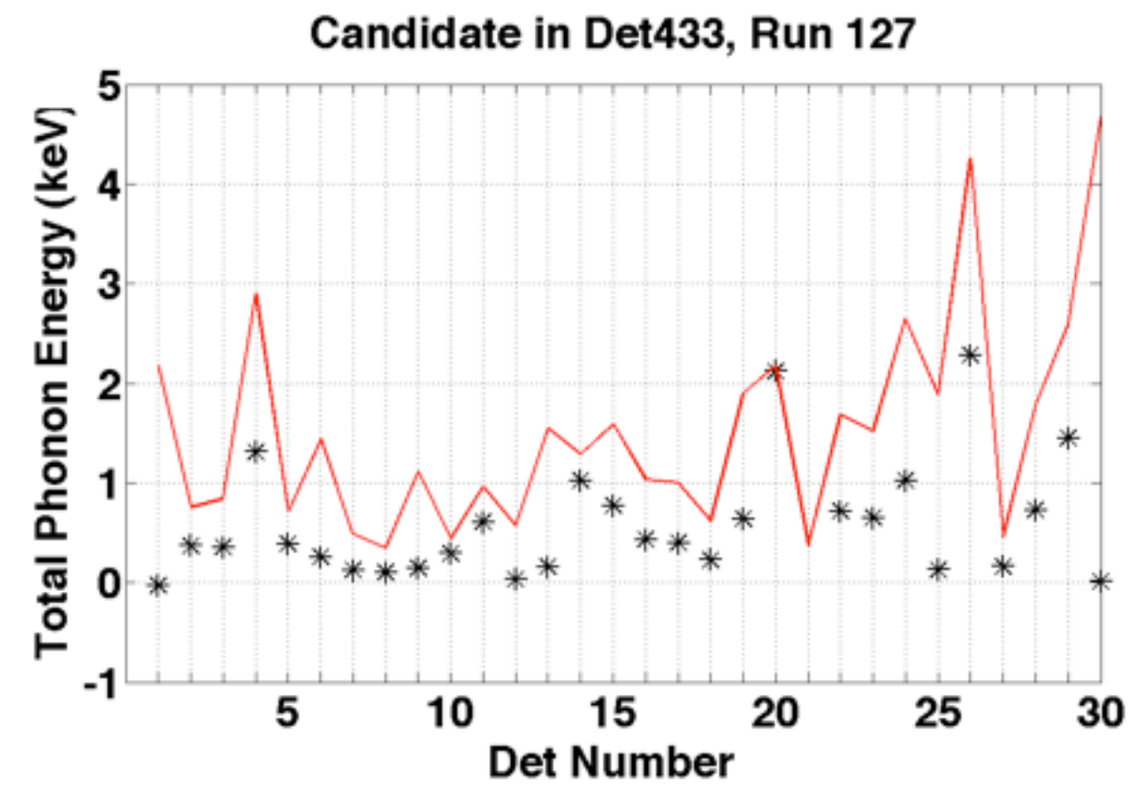


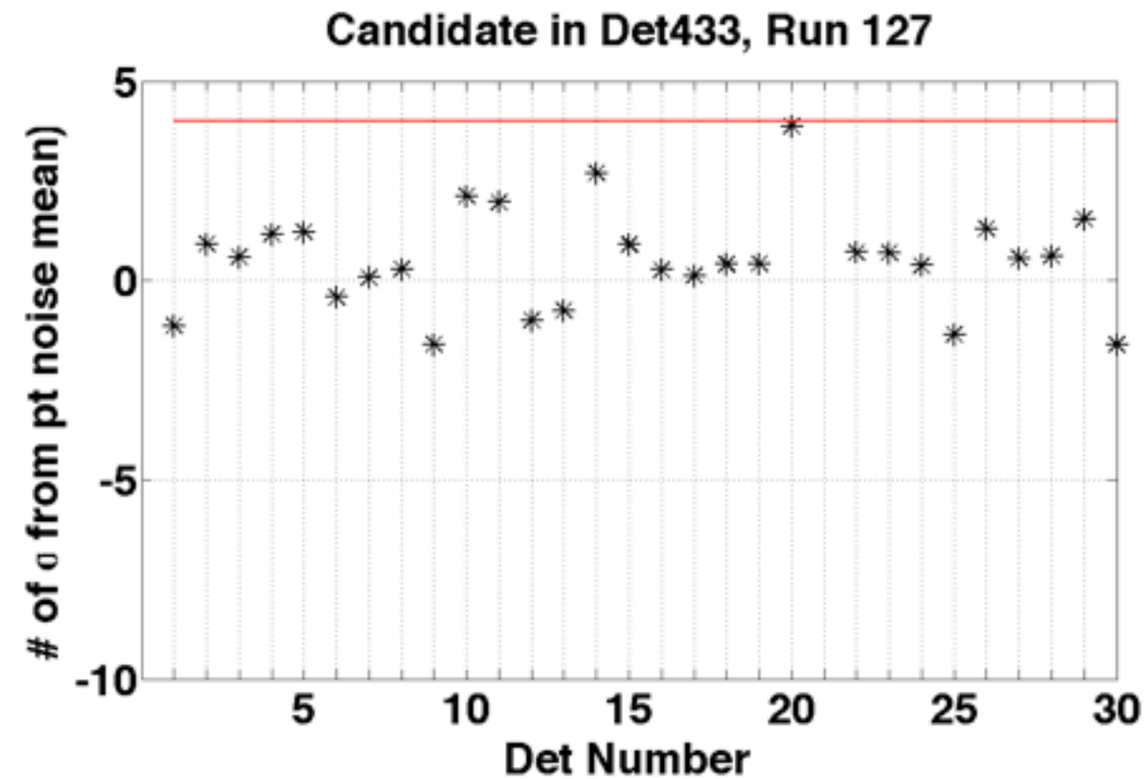


Is Candidate 1 a Multiple?

- Candidate 1 on T4Z3 had a 3.9σ signal in its neighboring detector (T4Z2)
- Events are declared "multiples" if any other detector as a phonon signal > 4σ from that detector's phonon noise distribution.
- Although by our pre-set criteria the event is a single, we calculated what probability such an event had of being a multiple.

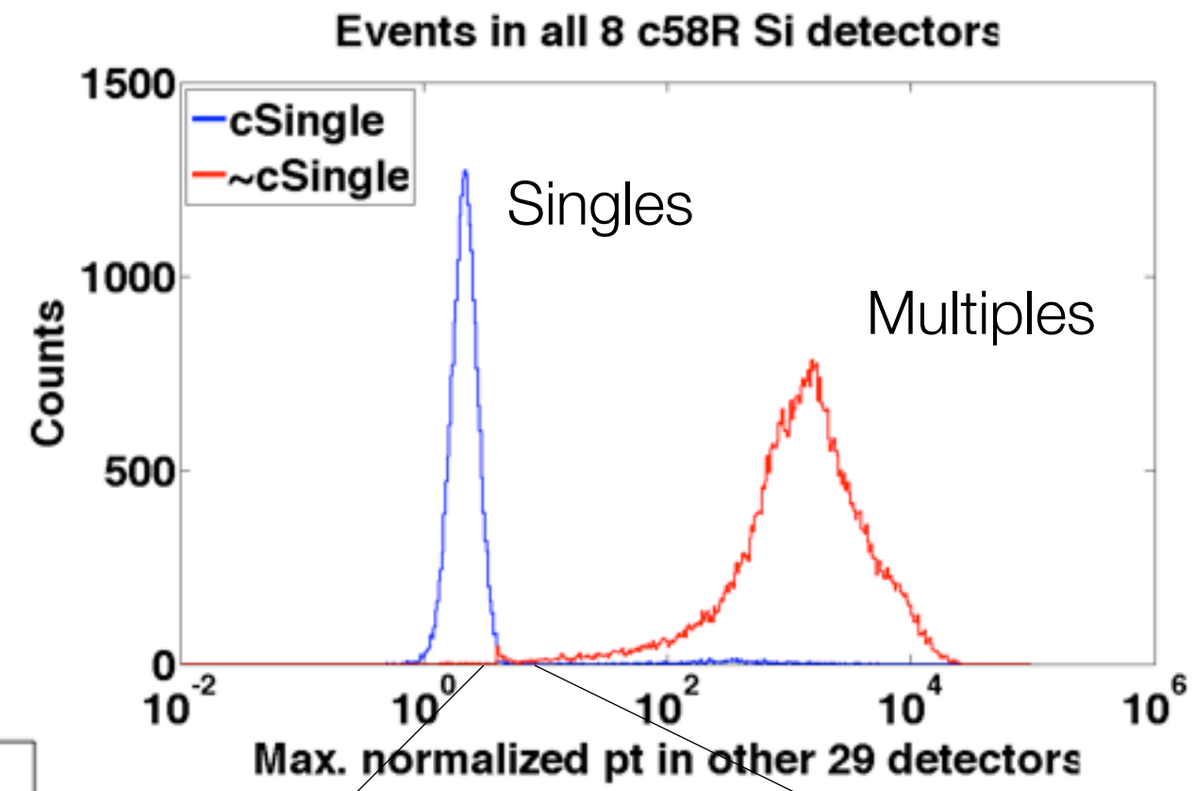
Event nearest to being a multiple

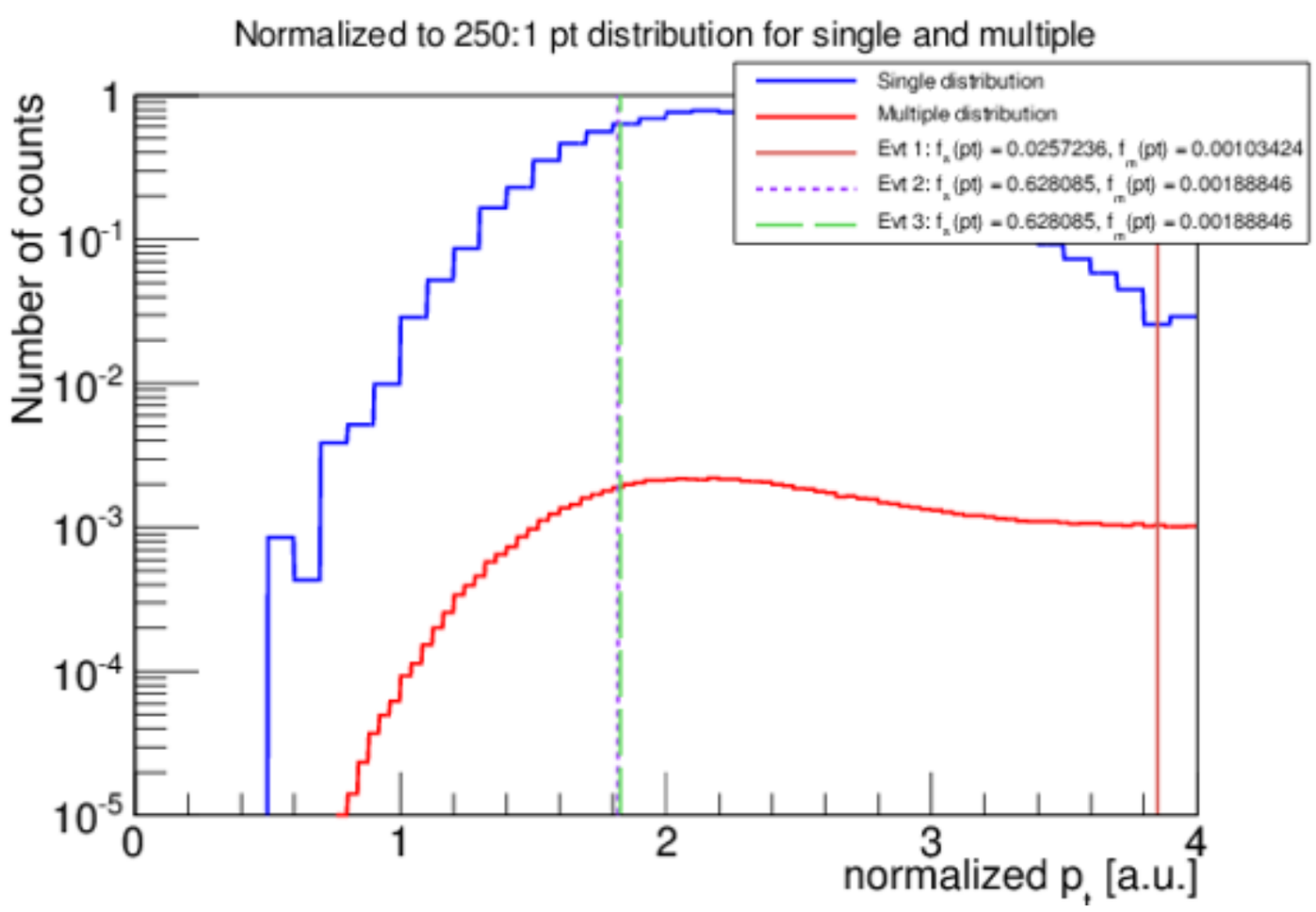


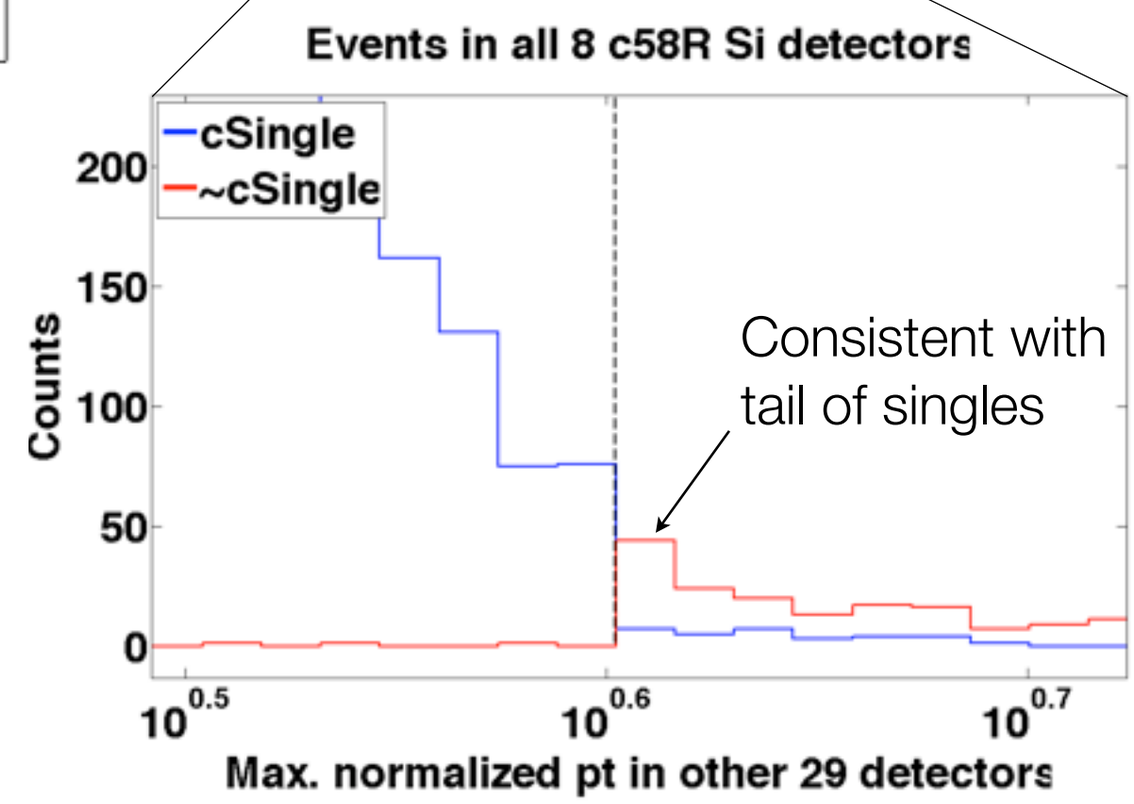


Is Candidate 1 a Multiple?

- We modeled the distribution of “next to largest phonon signals” below the 4σ multiples threshold from the 30-detector CDMS-II array using the measured multiples distribution

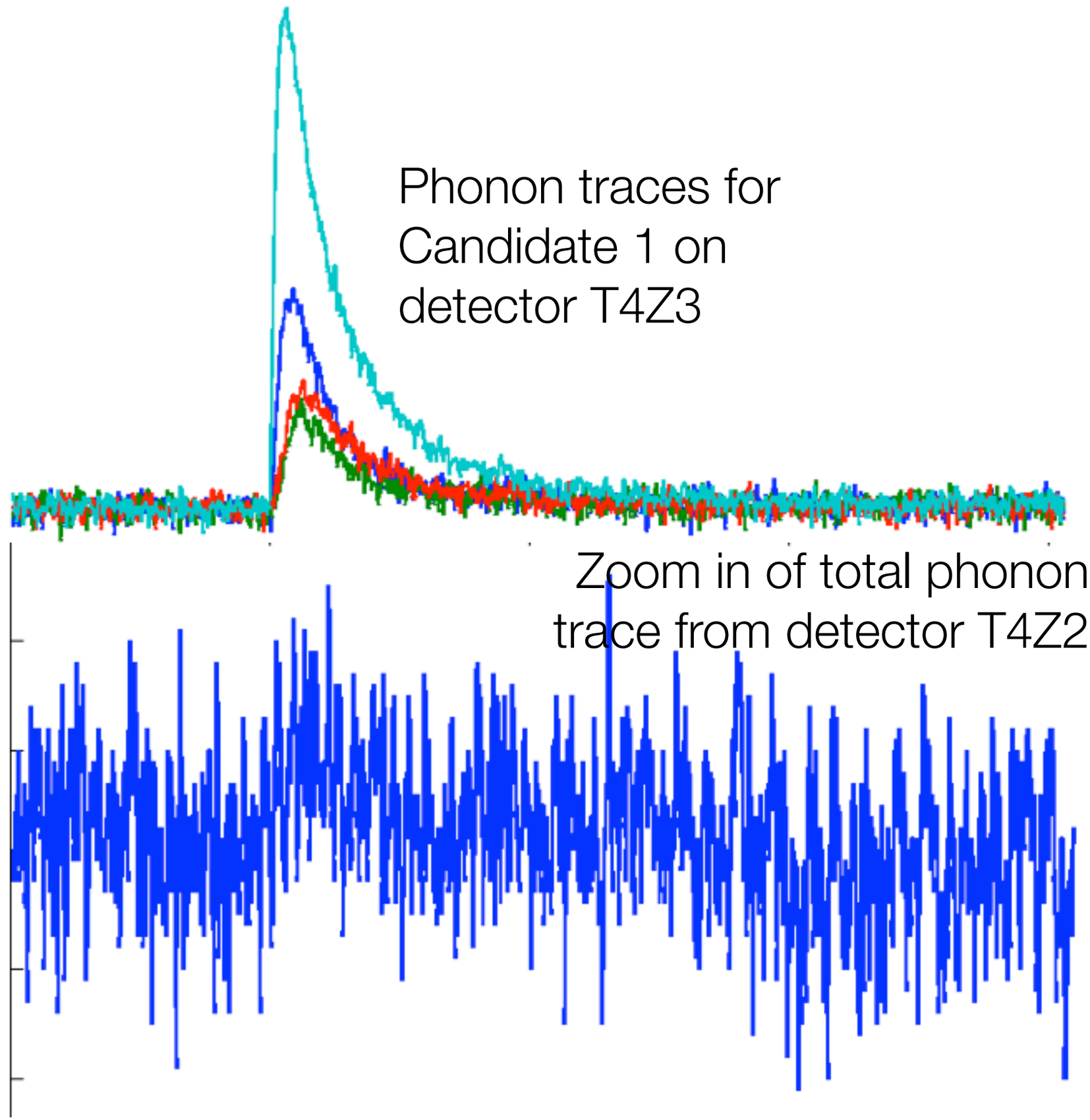




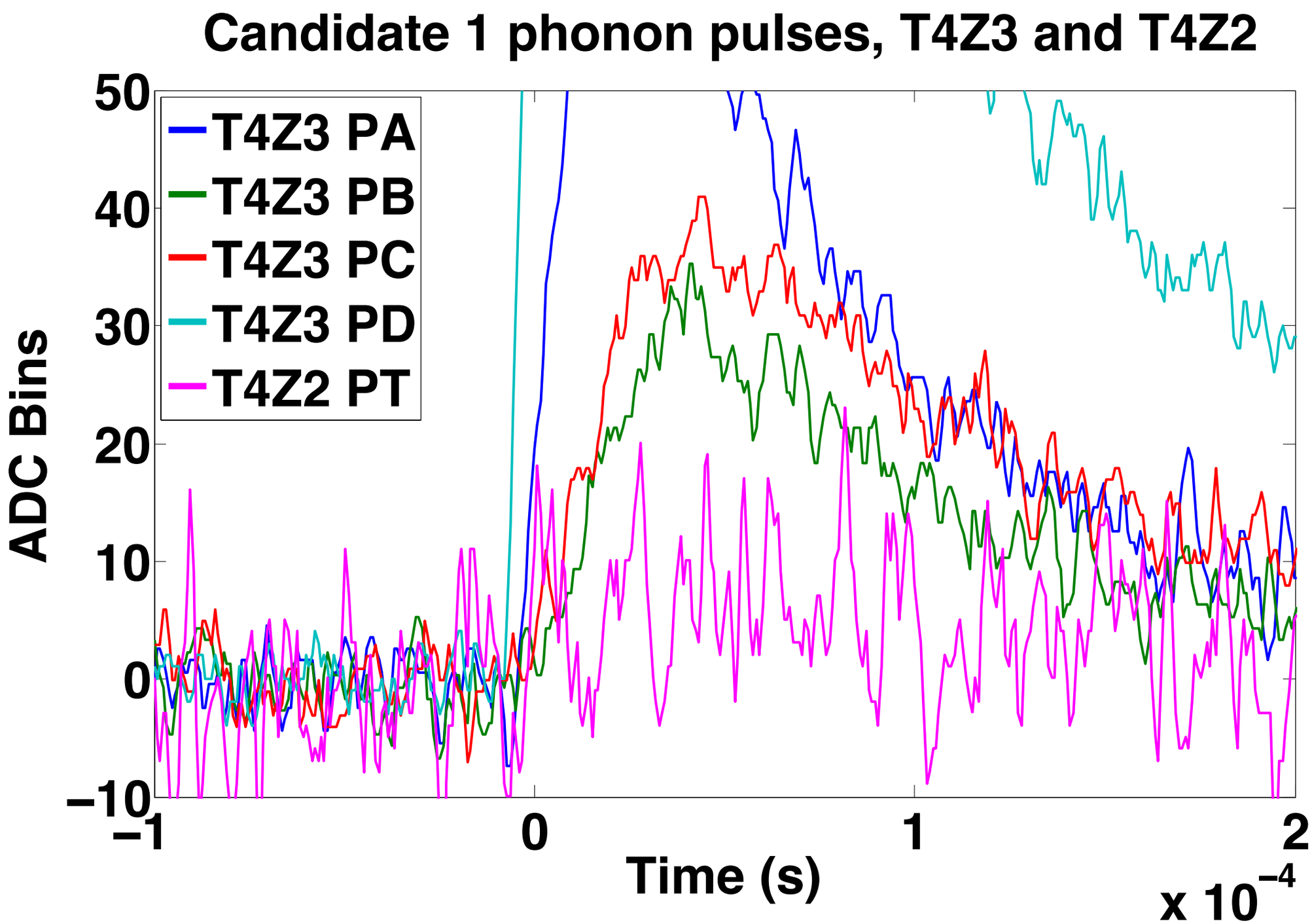


Is Candidate 1 a Multiple?

- The calculated probability of a signal with a 3.9σ “next-to-largest-phonon signal” being a multiple is 3.9%.
- Phonon trace seems consistent with low-frequency noise.

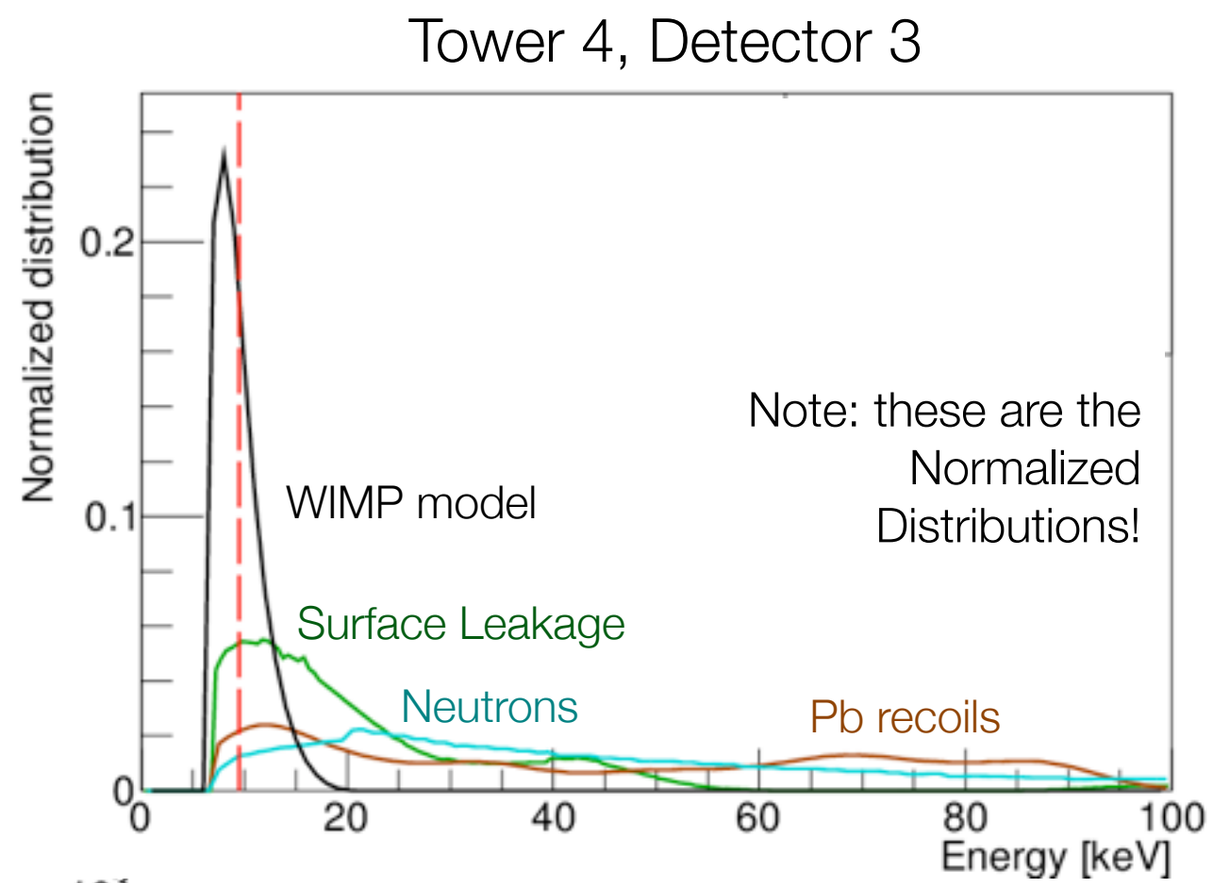


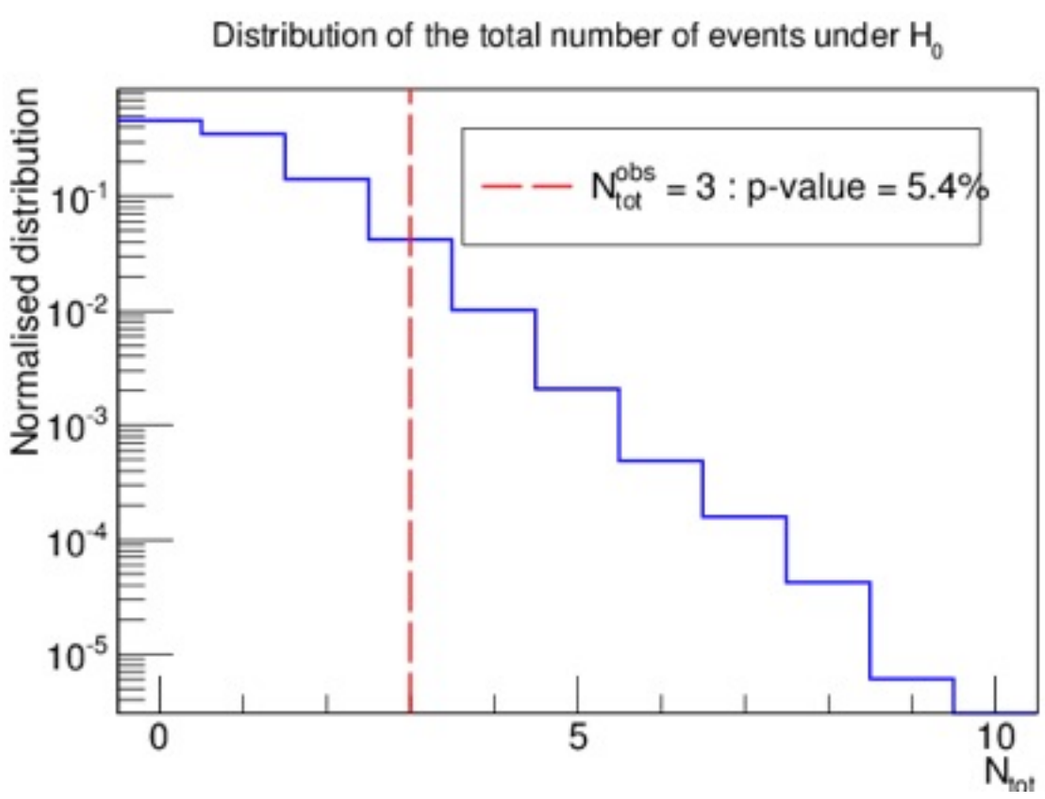
Is Candidate 1 a Multiple? Probably not.

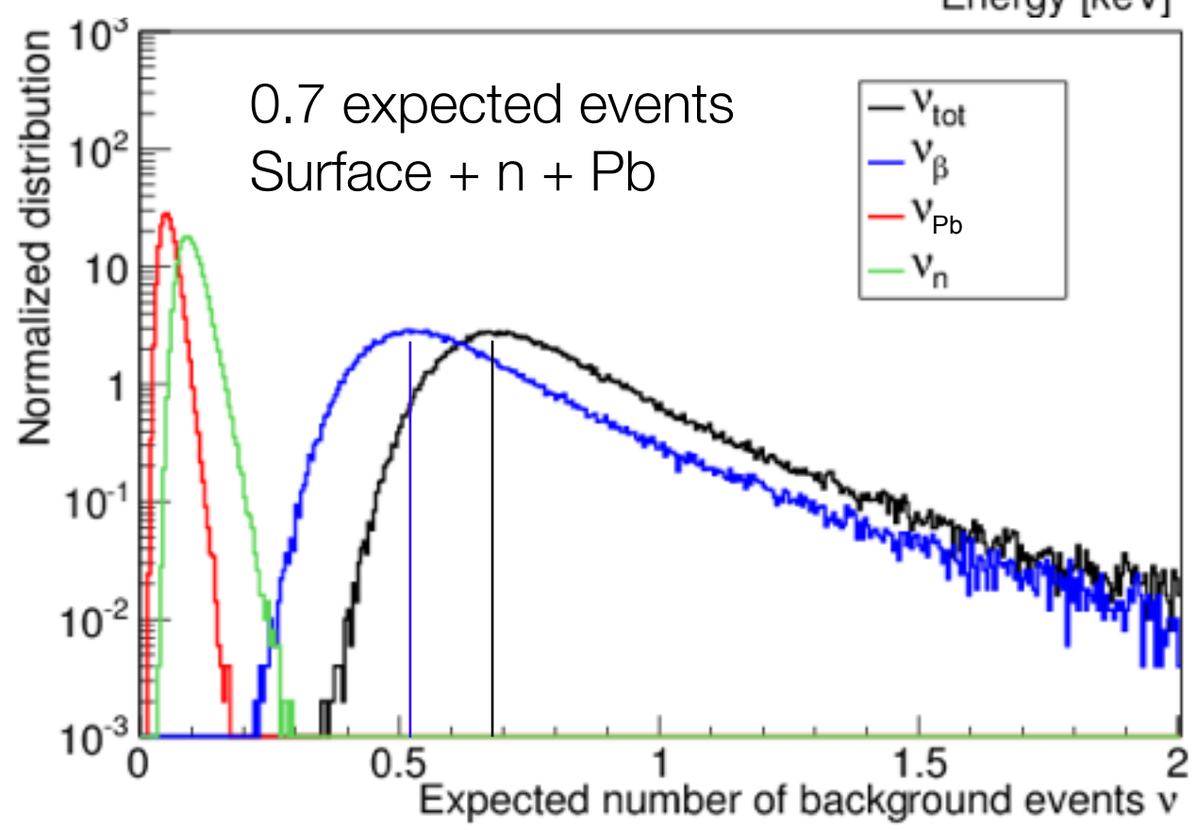


Profile Likelihood Analysis

- Incorporated data-driven background models into a WIMP+background likelihood analysis.
- Monte Carlo simulations of the background-only model indicate the probability of a statistical fluctuation producing three or more events anywhere in our signal region is 5.4%.





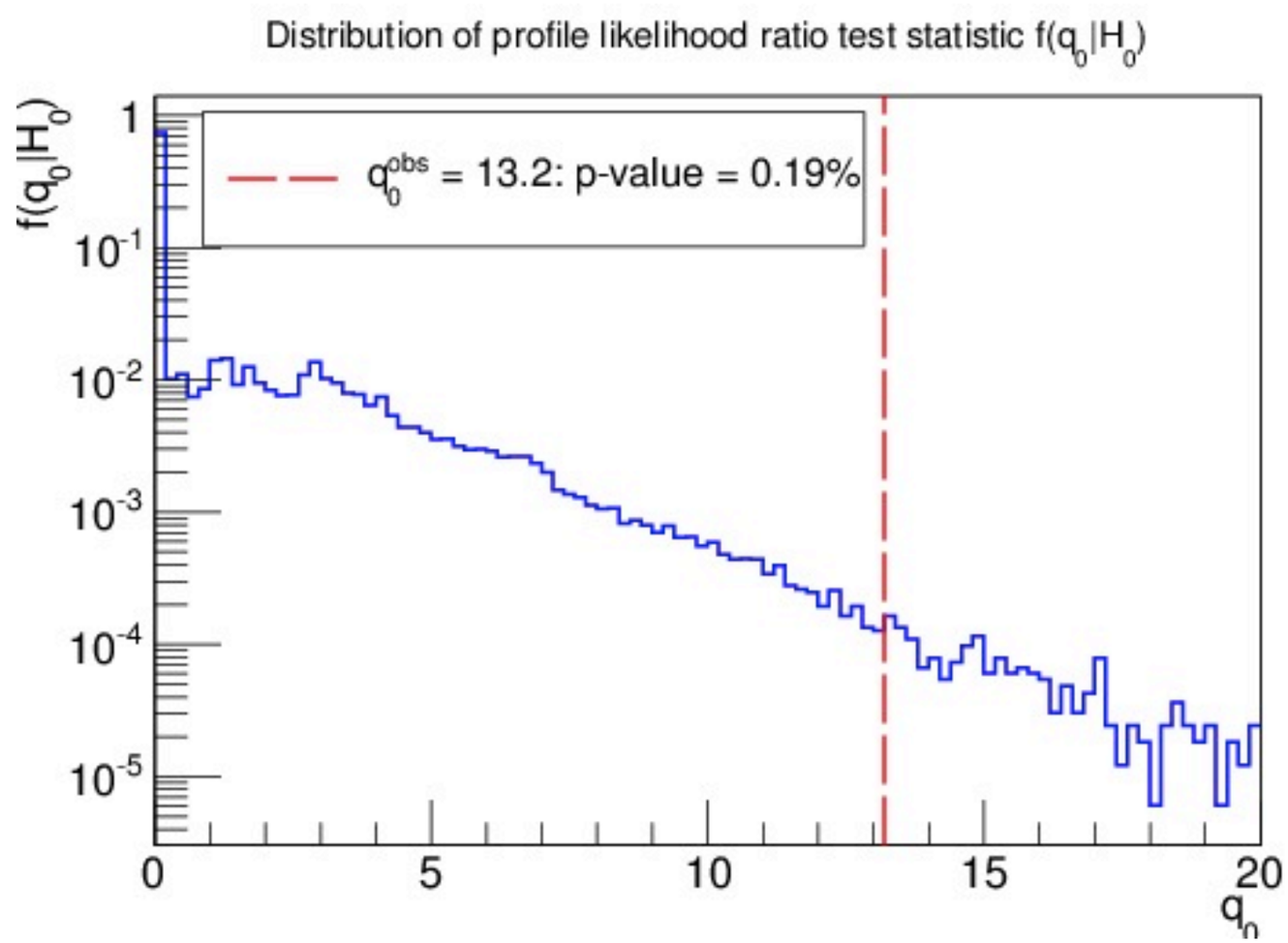


Profile Likelihood Analysis - cont.

Testing our known background estimate against a WIMP+background hypothesis

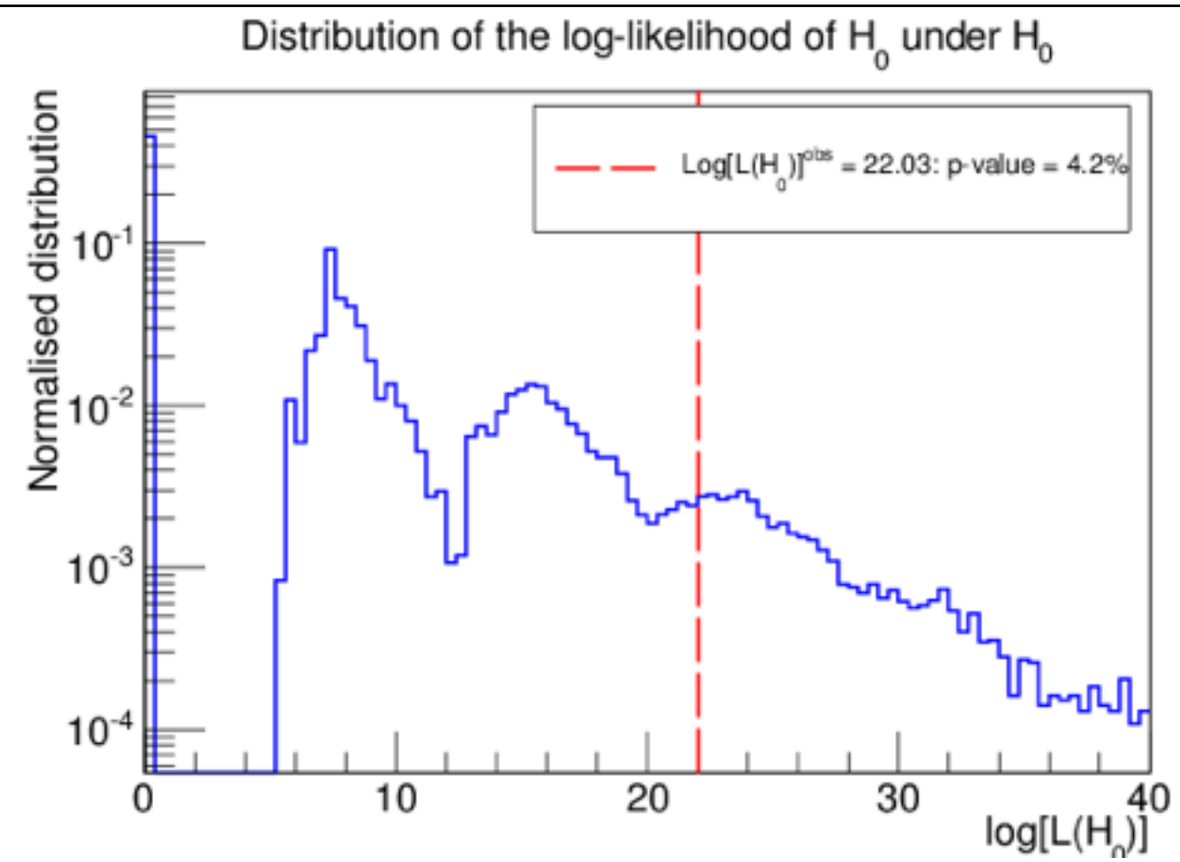
$$q_0 = -2\log\left\{\frac{\mathscr{L}(m_\chi, \sigma_{\chi-n}=0, \hat{\hat{\vec{\nu}}})}{\mathscr{L}(\hat{m}_\chi, \hat{\sigma}_{\chi-n}, \hat{\vec{\nu}})}\right\} \equiv 2\log\left\{\frac{\mathscr{L}(H_1)}{\mathscr{L}(H_0)}\right\}$$

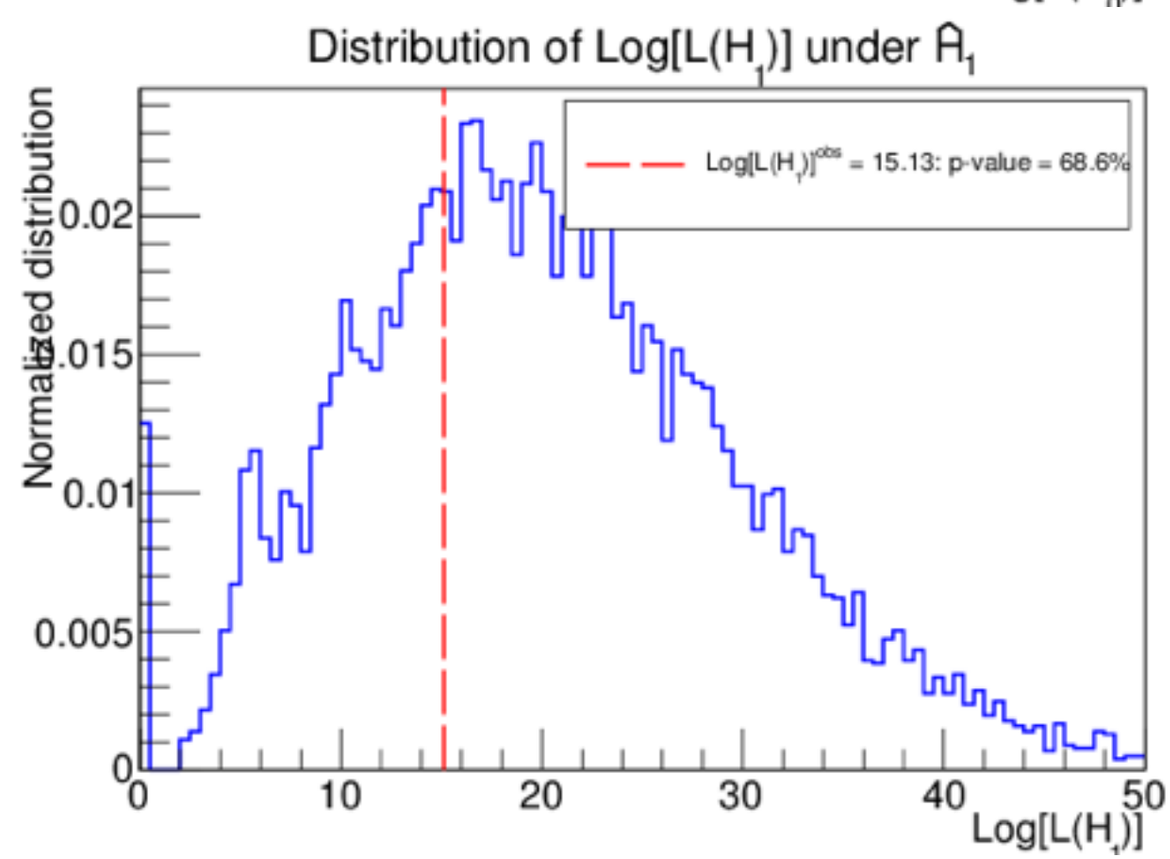
- A likelihood ratio test favors a WIMP+background hypothesis over the known background estimate as the source of our signal at the 99.81% confidence level (p-value:0.19%, ~3σ).
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9×10^{-41} cm^2.



Profile Likelihood Goodness of Fit

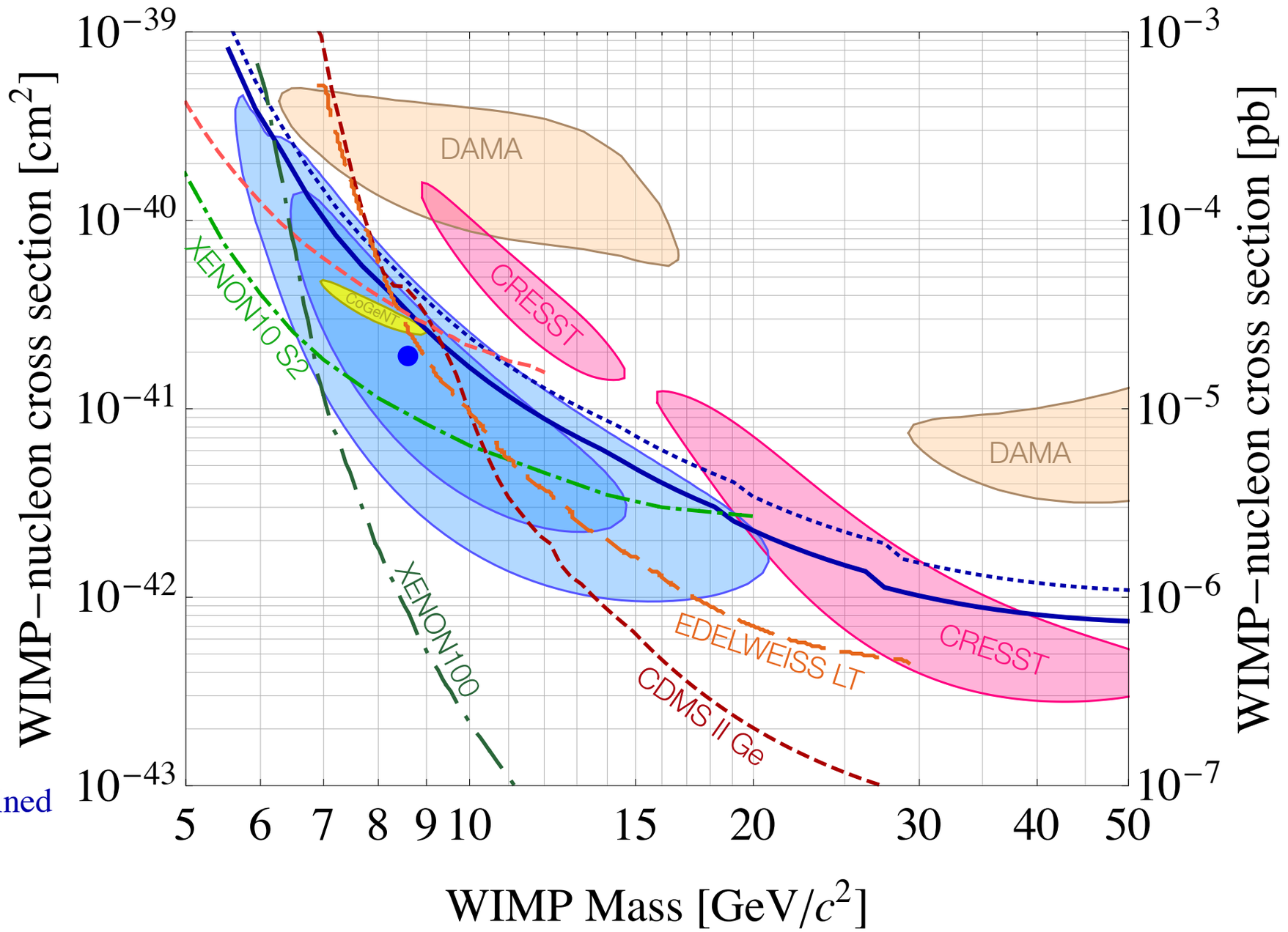
- Its very important to check if the WIMP+background actually fits the data well.
- The goodness of fit of the known-background-only hypothesis is 4.2%
- The goodness of fit of the WIMP+background hypothesis is 68.6%





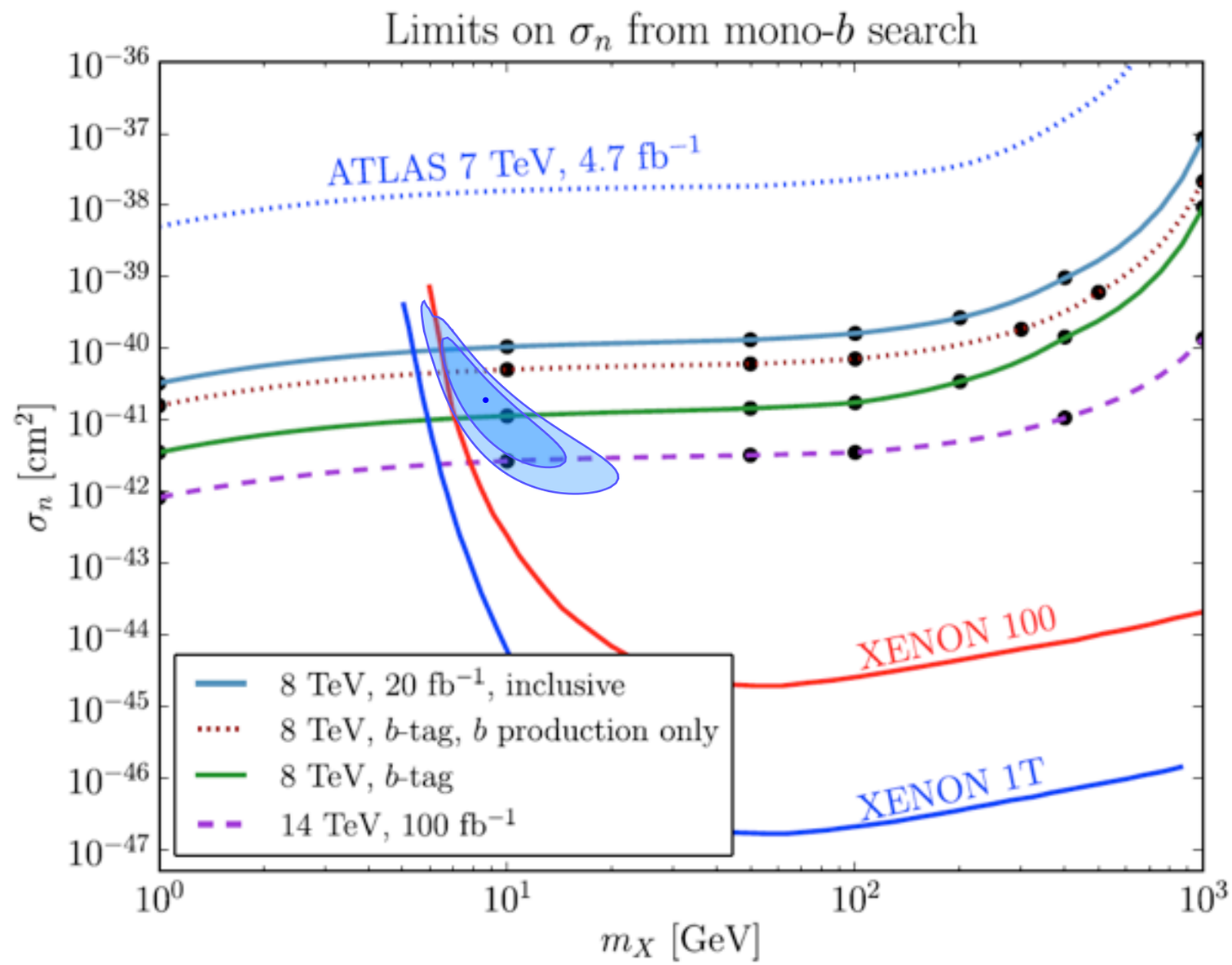
Profile Likelihood Confidence Intervals

- 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 (~3σ, p-value: 0.19%).
- We do not believe this result rises to the level of a discovery, but does call for further investigation.
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9×10^{-41} cm^2.



Has the LHC Ruled this region out?

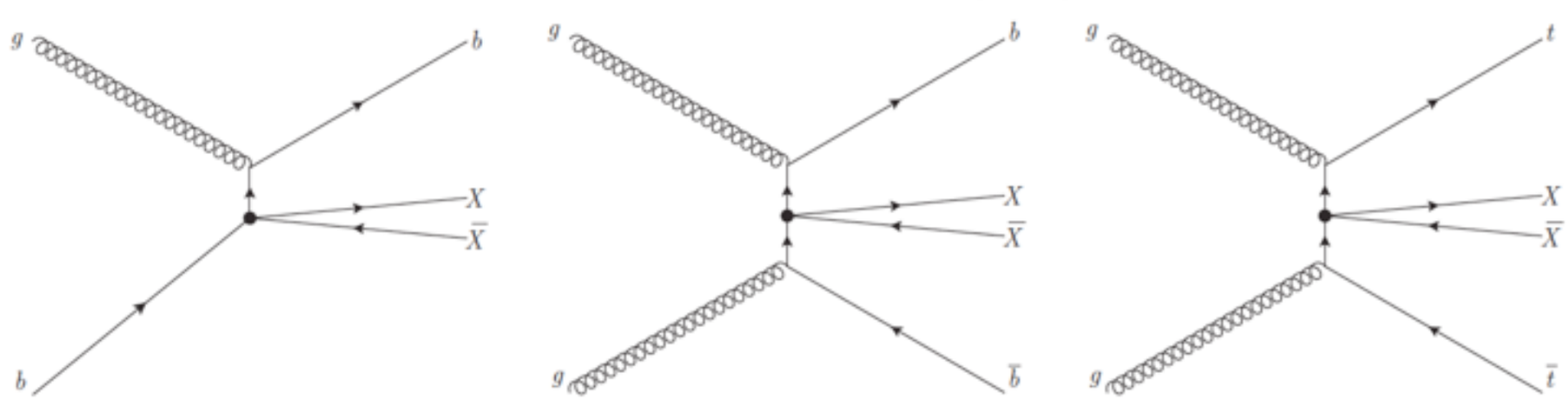
- LHC rules out contact interactions between χ and SM particles with heavy mediators.
- If this is DM, then the mediator is probably light (or there is a nearly degenerate NLSP).



Lin, Kolb, Wang
arXiv:1303.6638

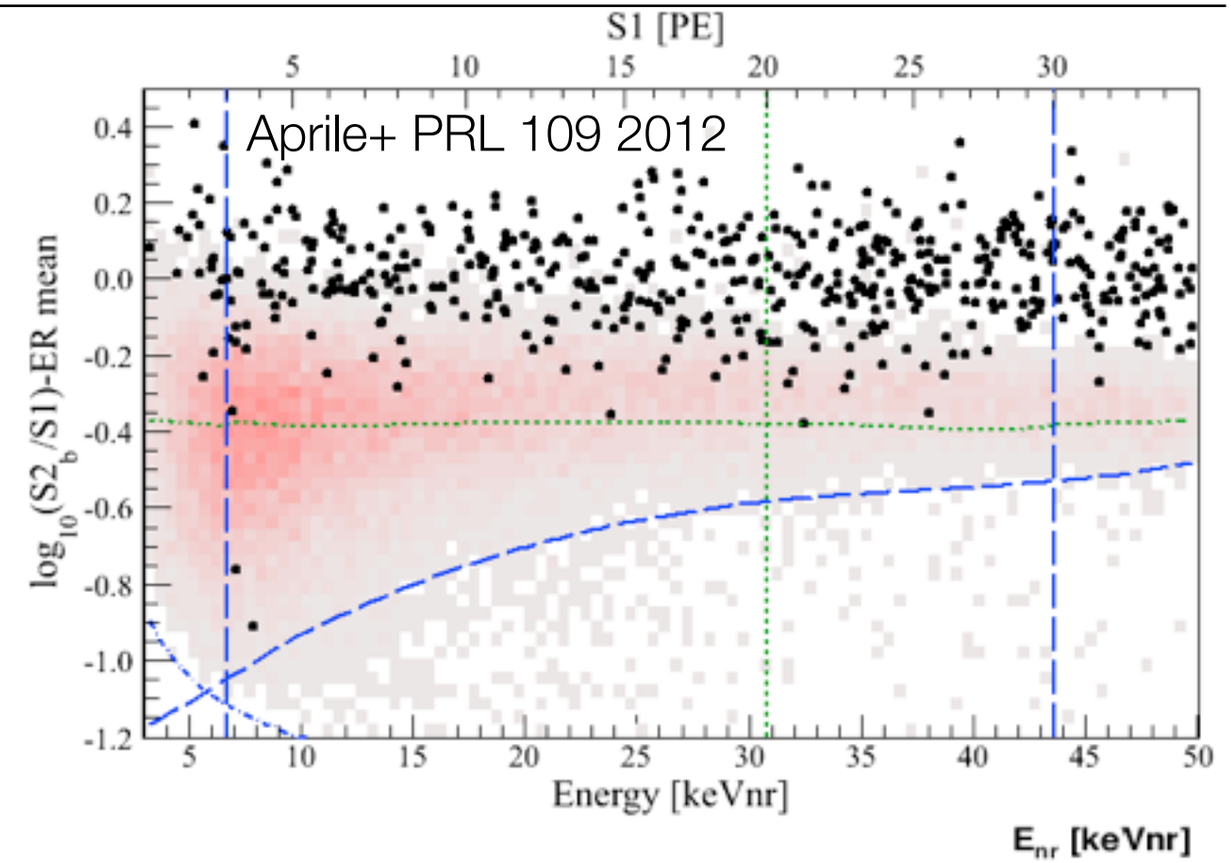
$$\not{E}_T > 350\,\mathrm{GeV}$$

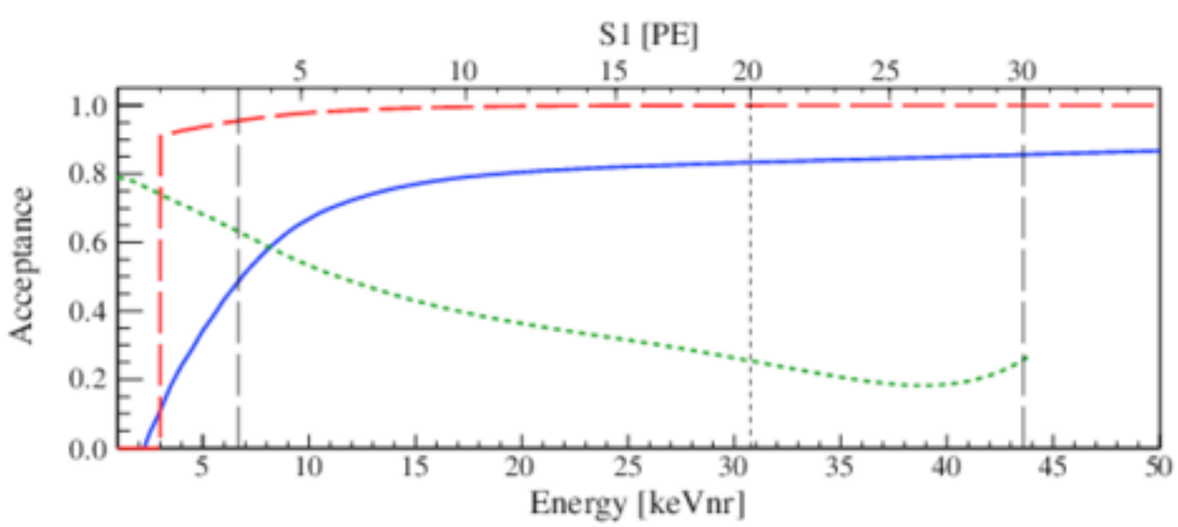
$$p_T > 100\,\mathrm{GeV}$$

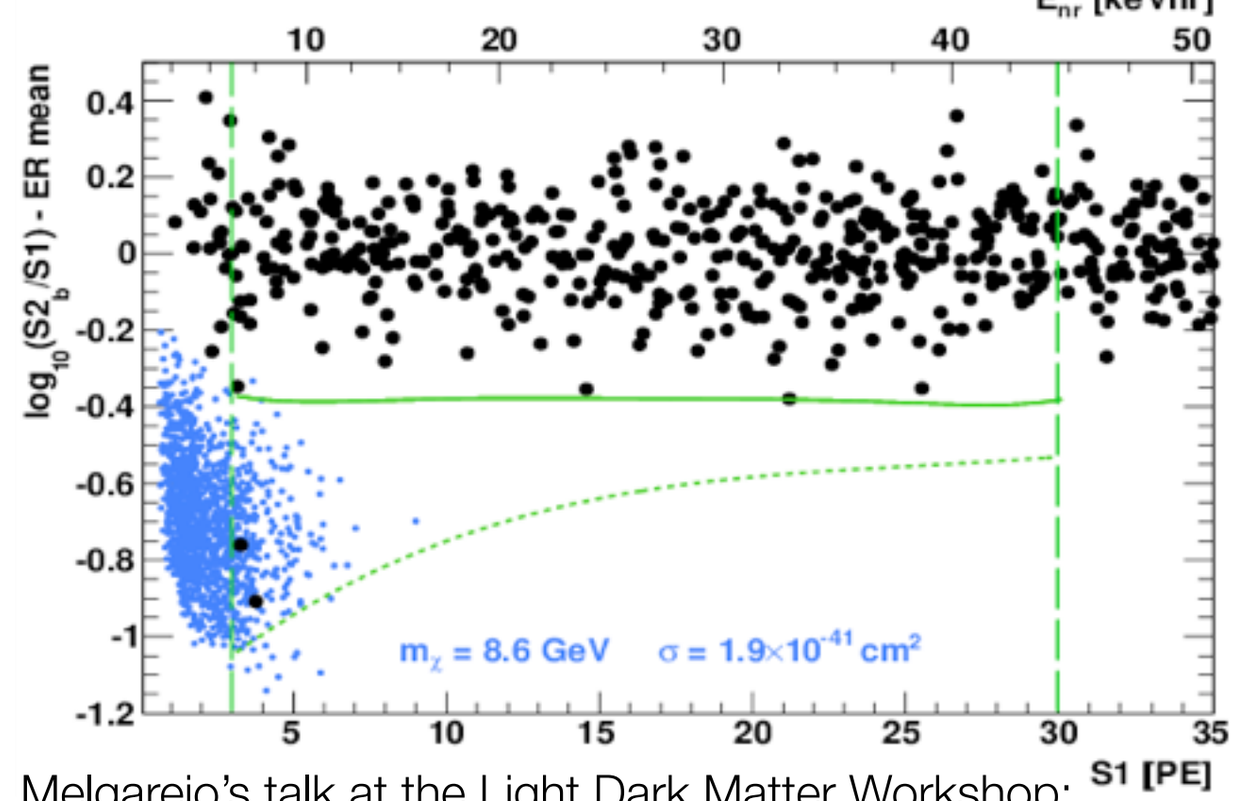


What about XENON100?

- XENON100's exposure = 34 kg * 224 days = 7636 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

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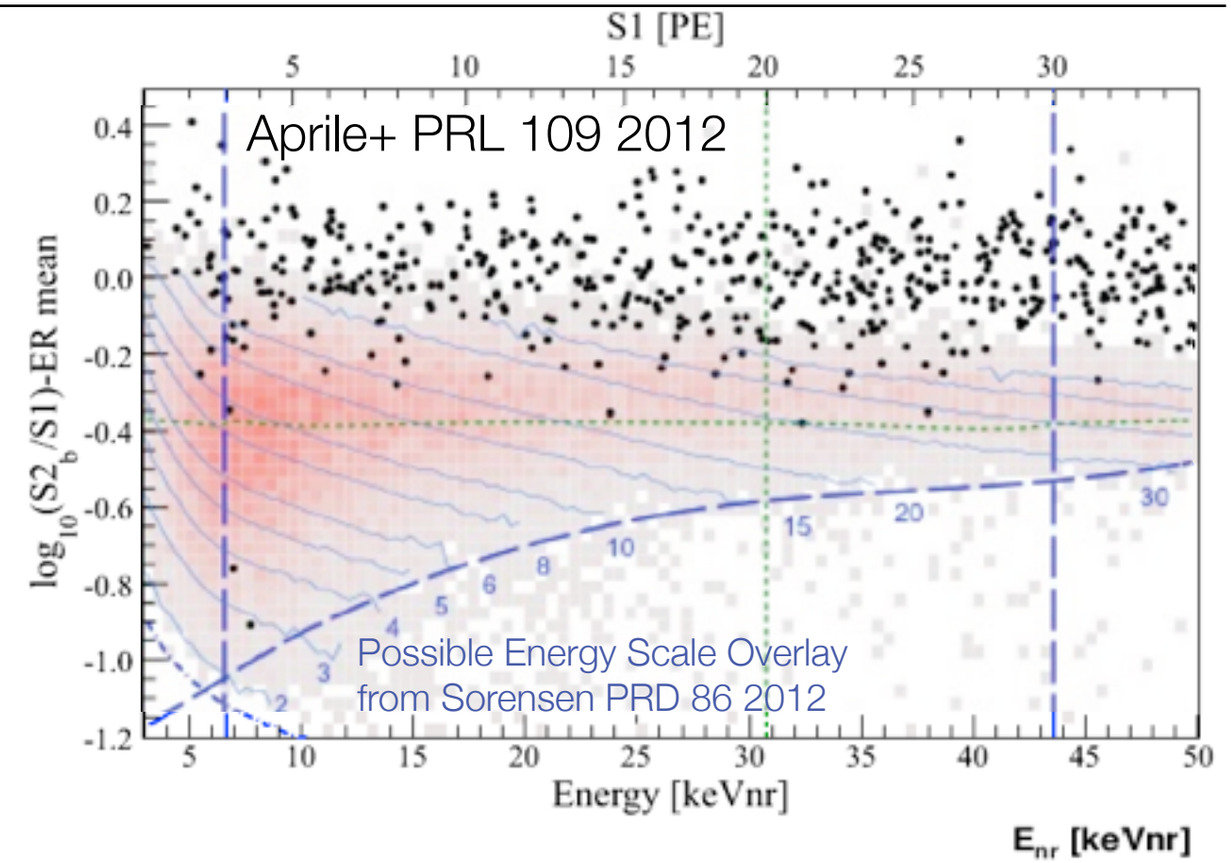
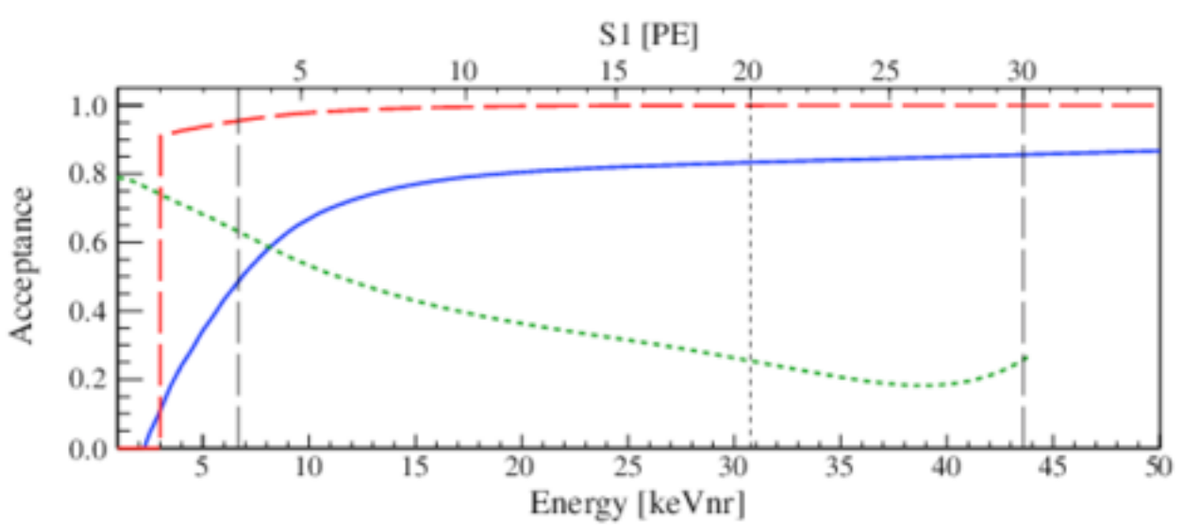
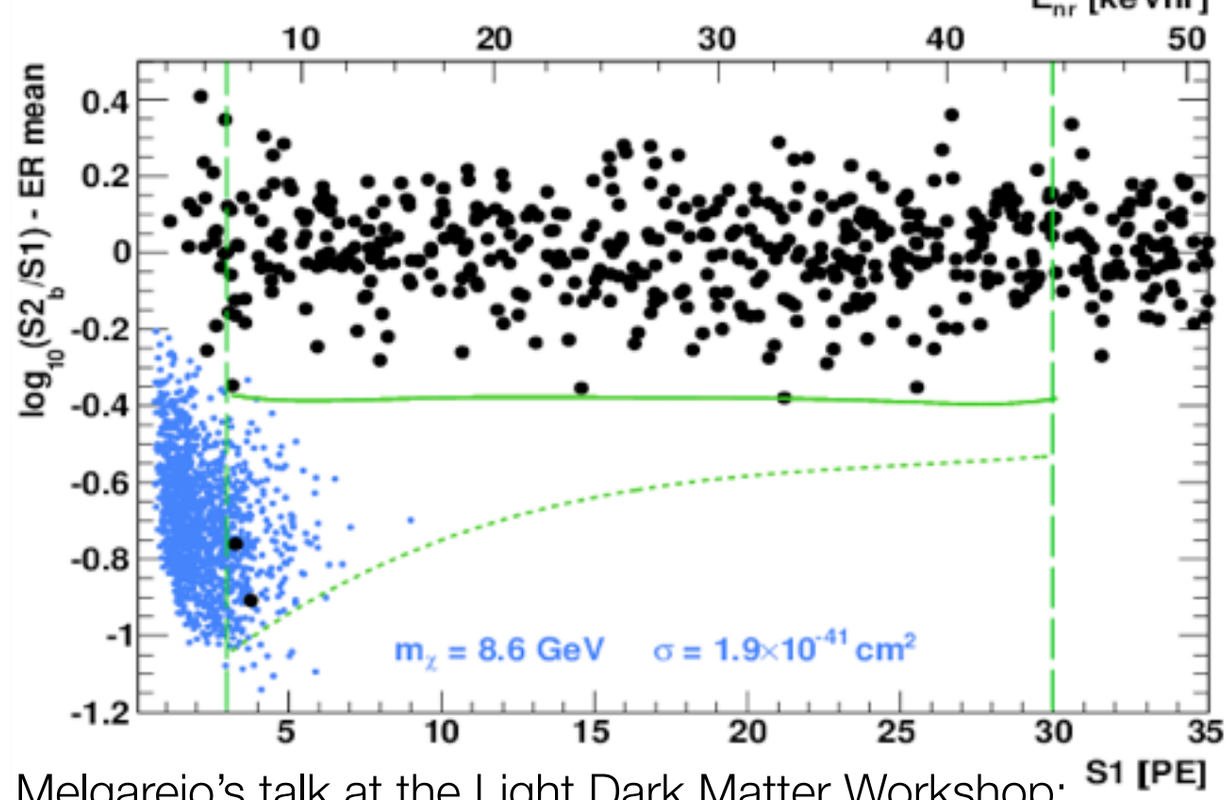


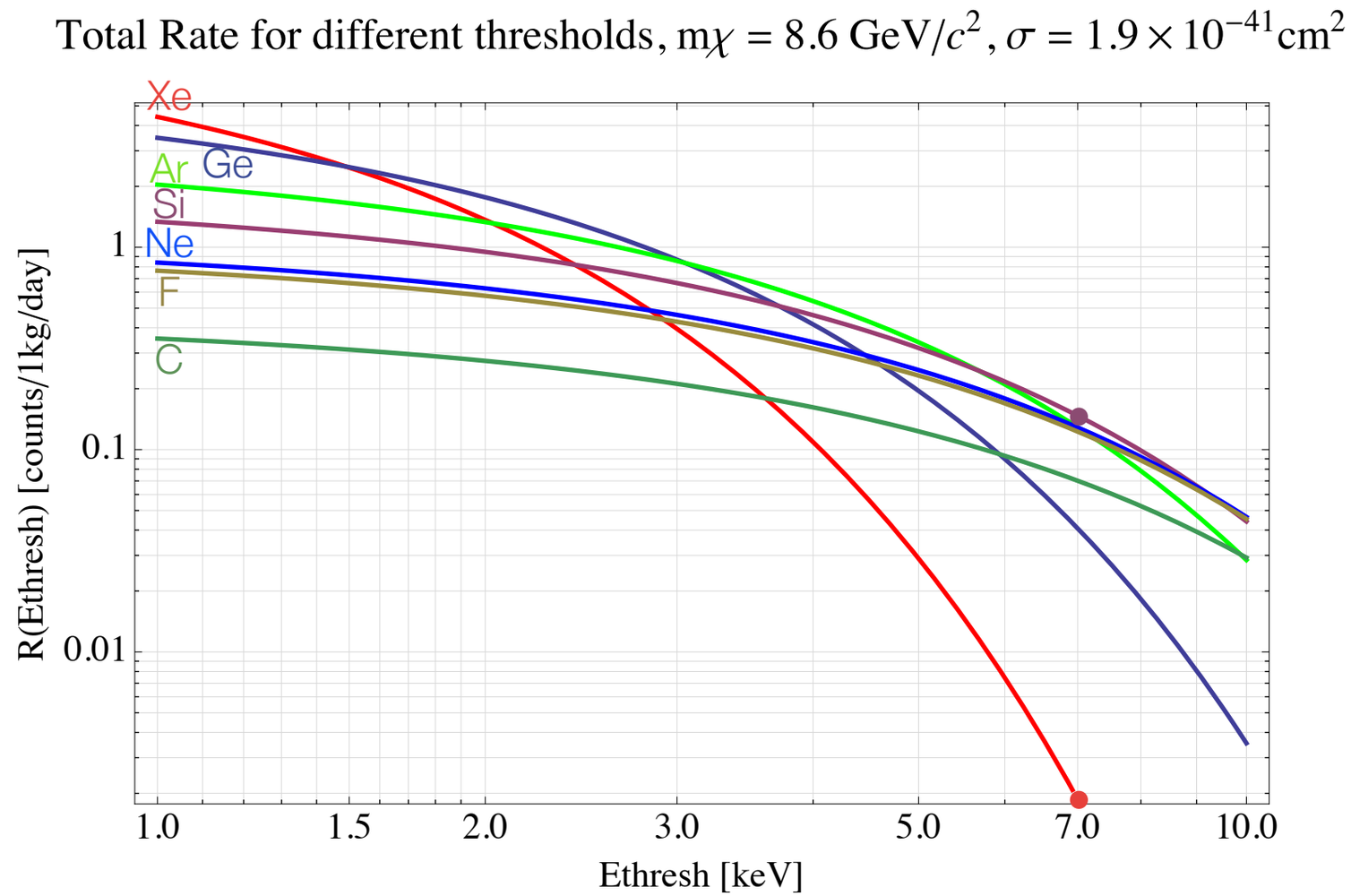




Figures from A. Melgarejo's talk at the Light Dark Matter Workshop: http://www.umich.edu/~mctp/SciPrgPgs/events/2013/dm2013/index.html

What about XENON100?

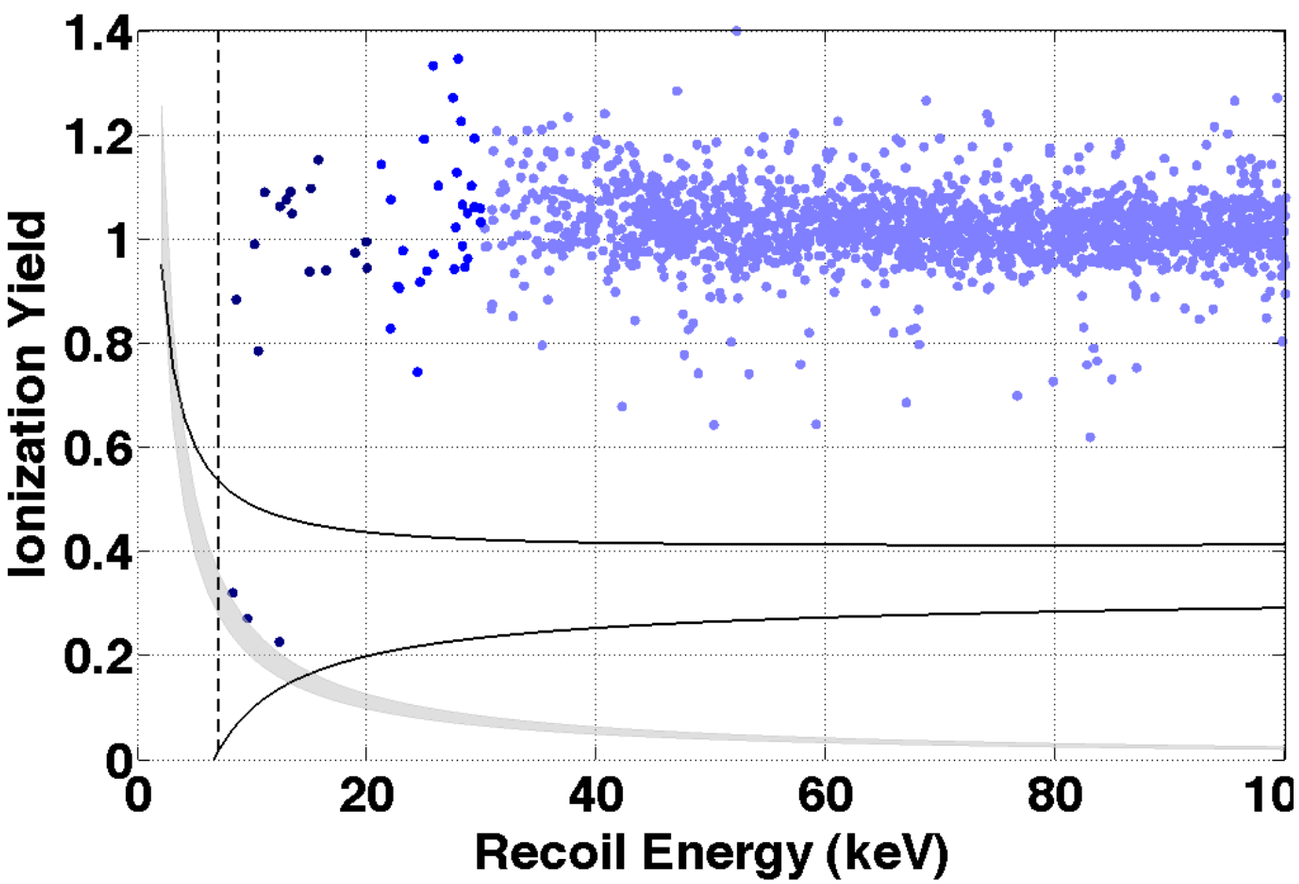
- Compatibility...
- ...depends strongly on the nuclear energy scale, the efficiency, and threshold
- ...or halo velocity structure
- ...or non-standard DM-nucleon interactions
- ...or some combination of the above
- ...or our events are not due to DM.

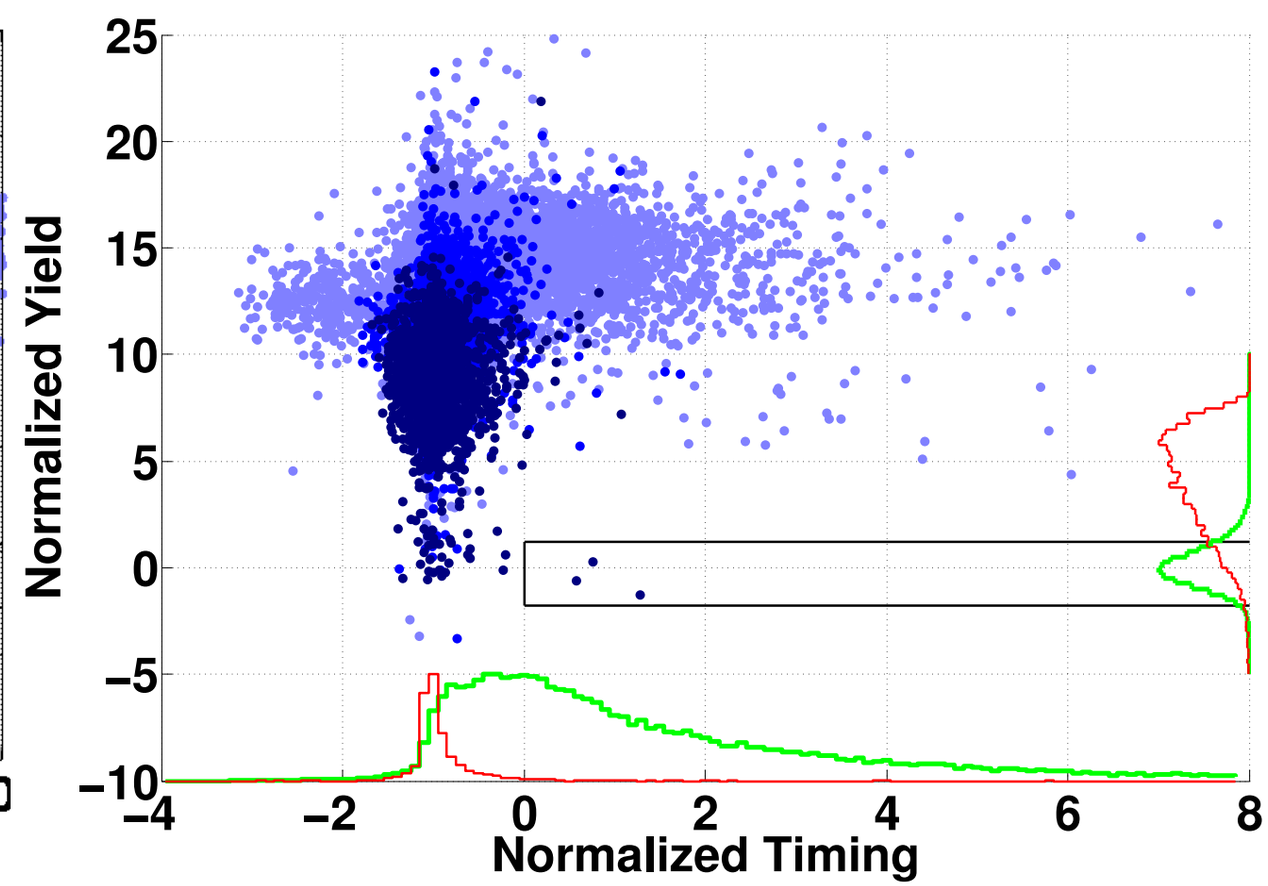


Threshold	Spectrum-Averaged Efficiency to get 2.1 events in XENON100 from a WIMP with m_χ=8.6 GeV/c^2, σ=1.9x10^{-41} cm^2
7 keV	14%
6 keV	3.7%
5 keV	0.95%
4 keV	0.25%
3 keV	0.07%

Next Steps: Move the WIMP Box Boundaries!

- Analysis ongoing to look for consistency of the best-fit WIMP+background hypothesis as timing, phonon, and charge thresholds are relaxed.
- As we relax these boundaries, both the expected leakage and the expected signal would increase.

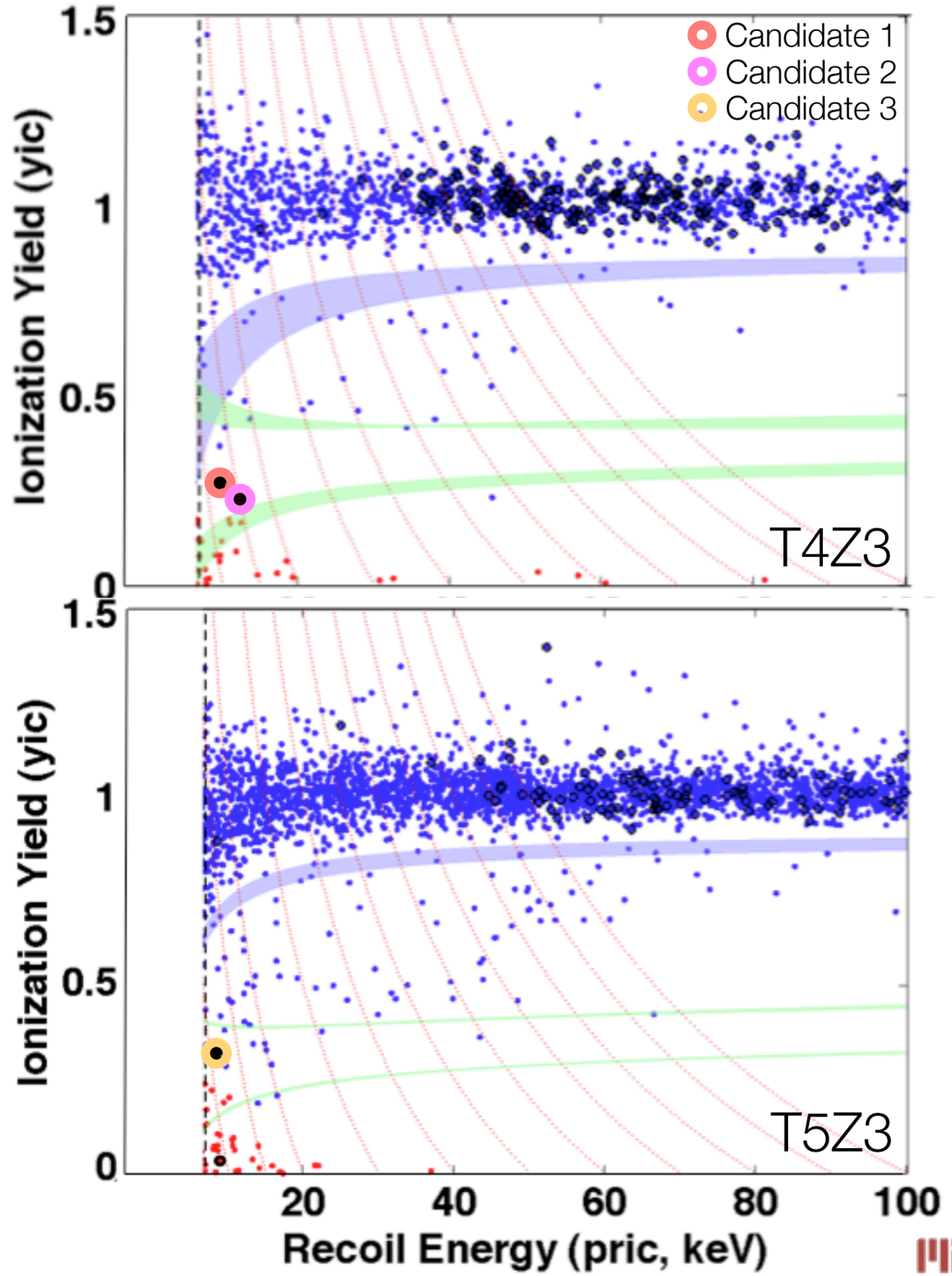




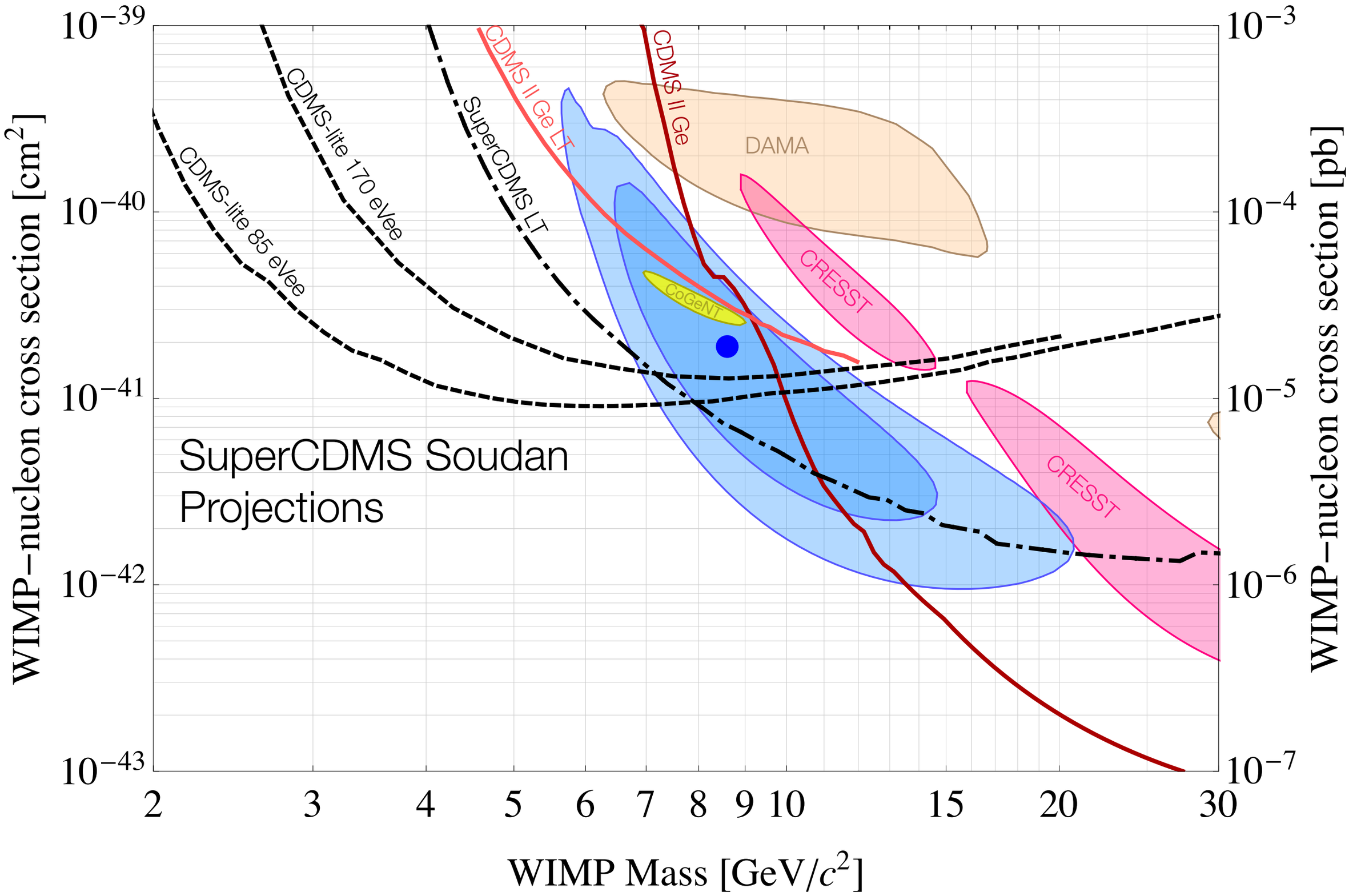
Next Steps: A look Below the Charge Threshold...

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

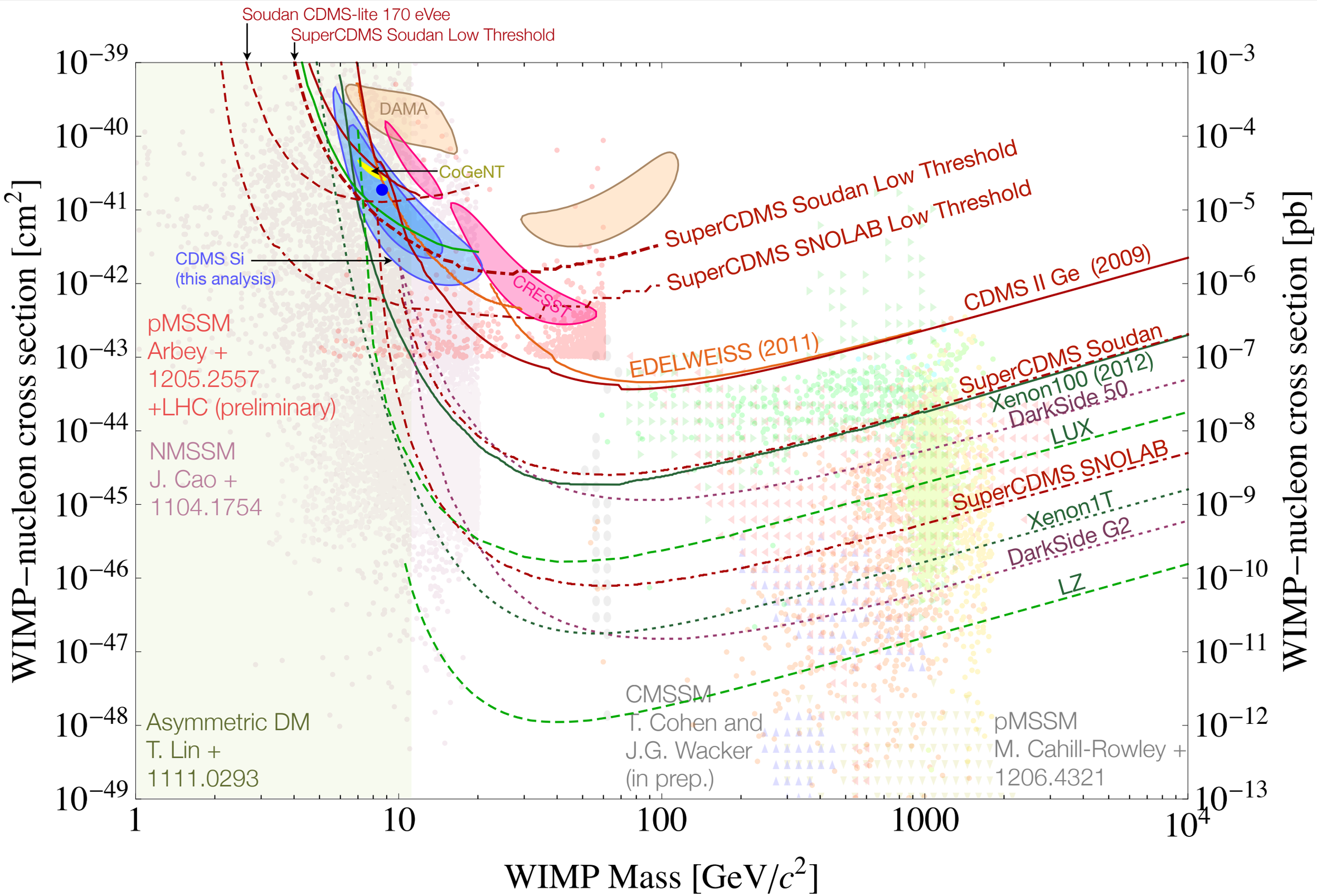
PRELIMINARY

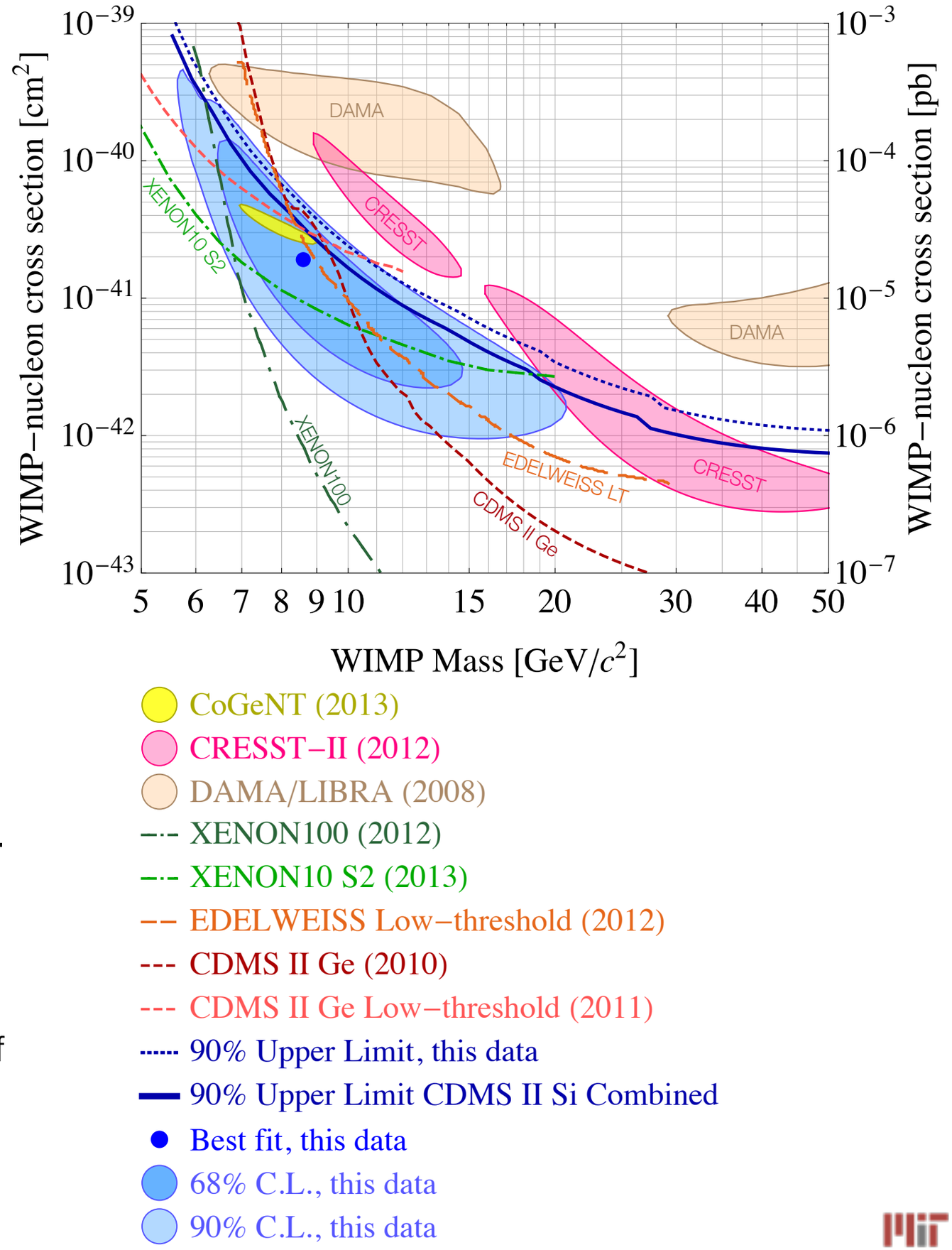


Next Steps: SuperCDMS Soudan!



Next Steps: SuperCDMS SNOLAB and beyond



Conclusions

- Analysis of a 140.23 kg-day exposure of the CDMS-II Si detectors has been performed.
- Three events were seen in the signal region with a total expected background of <0.7 events.
- An optimal gap analysis sets a limit for the spin-independent WIMP-nucleon cross section of $2.4 \times 10^{-41} cm^2$ for a WIMP mass of 10 GeV/c^2.
- Monte Carlo simulations of the background-only model indicate that the probability of a statistical fluctuation producing three or more events anywhere in our signal region is 5.4%.
- 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 (~3σ, p-value: 0.19%).
- We do not believe this result rises to the level of a discovery, but does call for further investigation.
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of $1.9 \times 10^{-41} cm^2$.