XENON

First Indication of Solar ^{8}B Neutrinos with XENONnT

arXiv: 2408.02877, DOI: 10.1103/PhysRevLett.133.191002

Juehang Qin

On behalf of the XENON Collaboration

Dec 2024

RICE UNIVERSITY

The XENON Collaboration

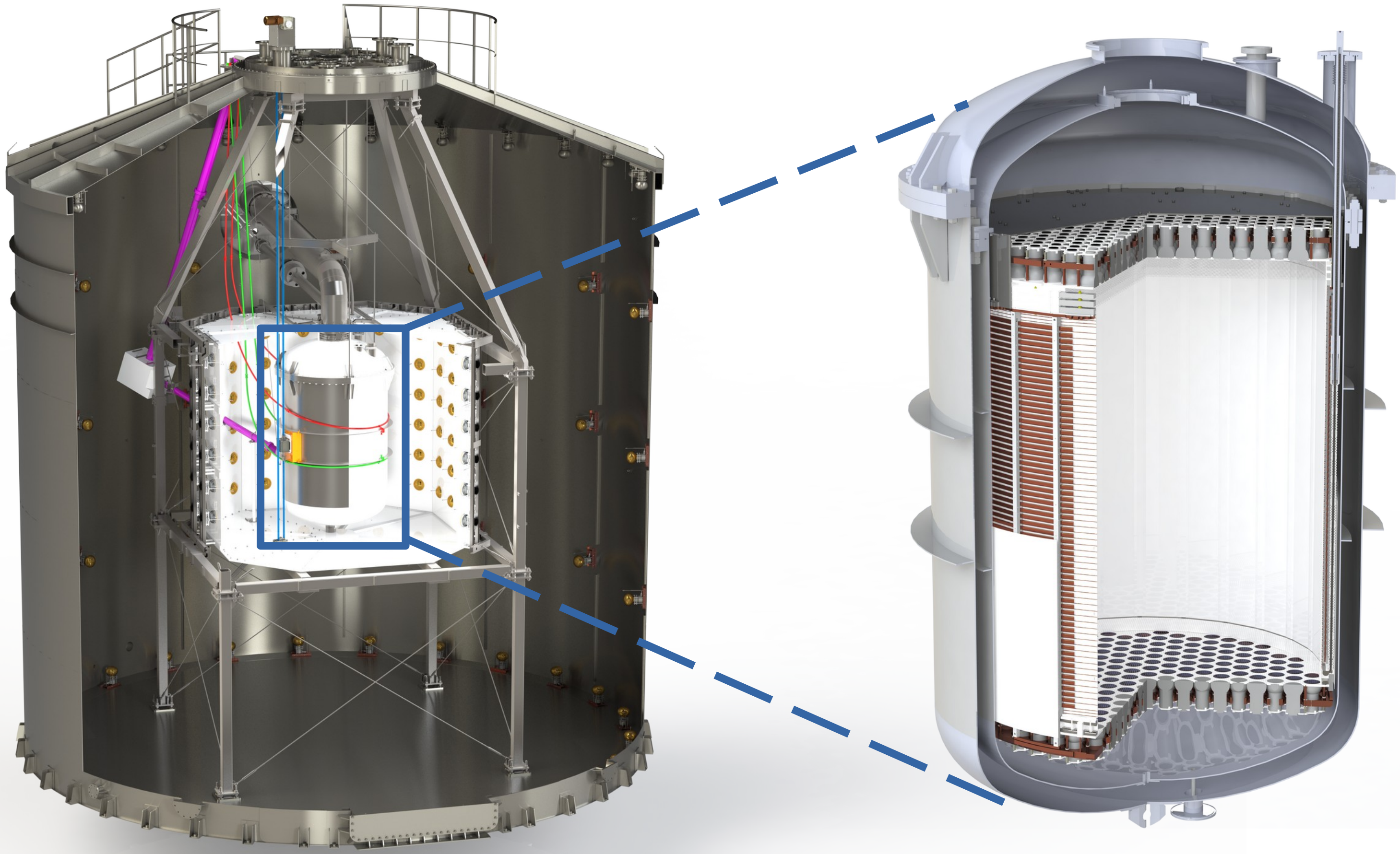
12 countries,
29 institutions,
~200 scientists

Overview

1. Introduction: The XENONnT Experiment and ^{8}B Neutrinos
2. Signals: Calibration and Signal Model
3. Backgrounds: Background Models and Mitigation
4. Results: Inference, Unblinded Results, and Conclusion

Introduction

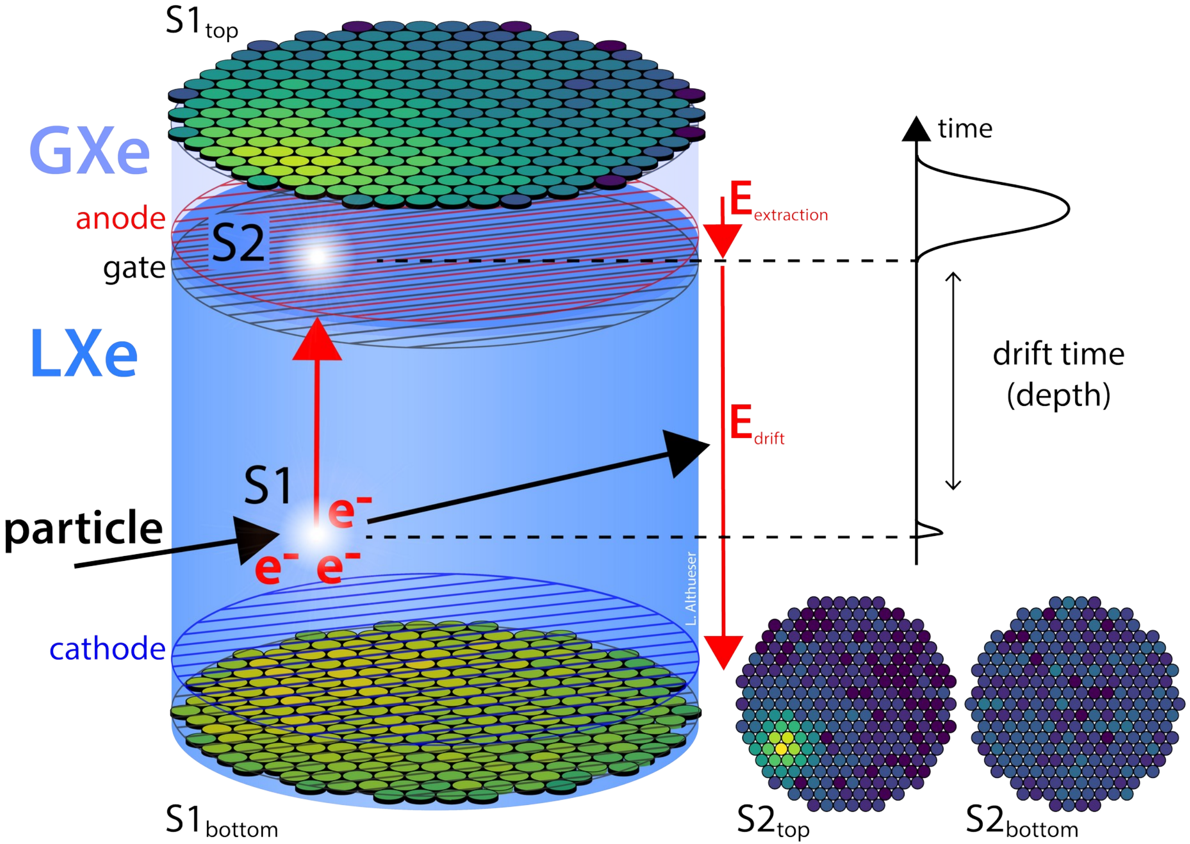
The XENONnT Experiment



- Located under the Gran Sasso mountain range
- Water Cherenkov outer detectors act as active vetos
- Dual-phase xenon time projection chamber contains 5.9t of xenon in active volume

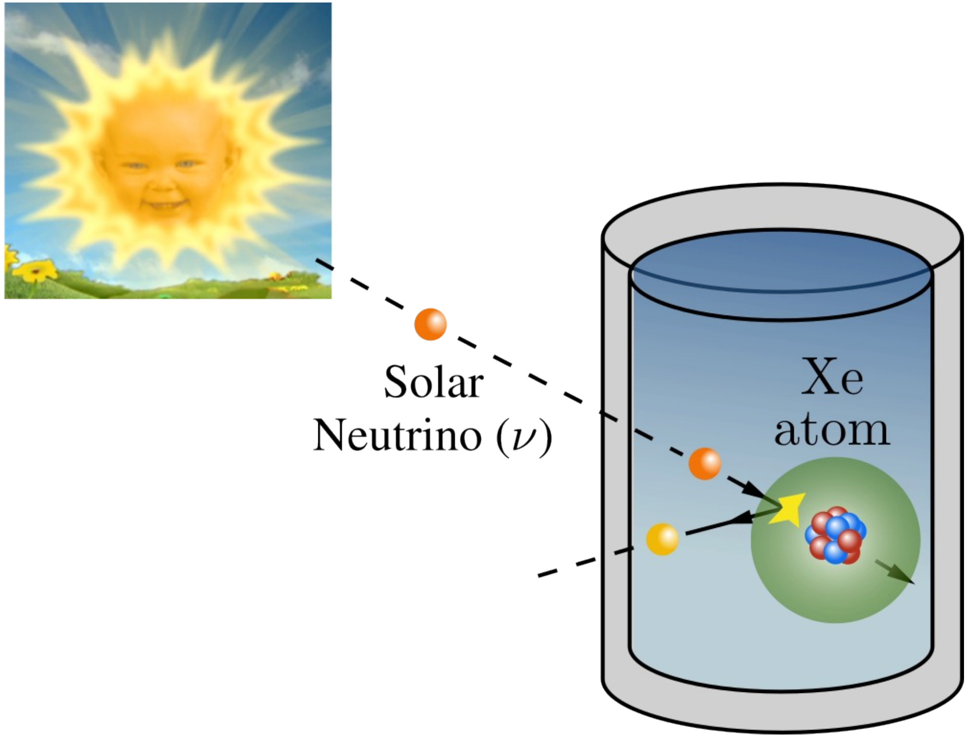
arXiv:2402.10446

The Dual-phase Time Projection Chamber

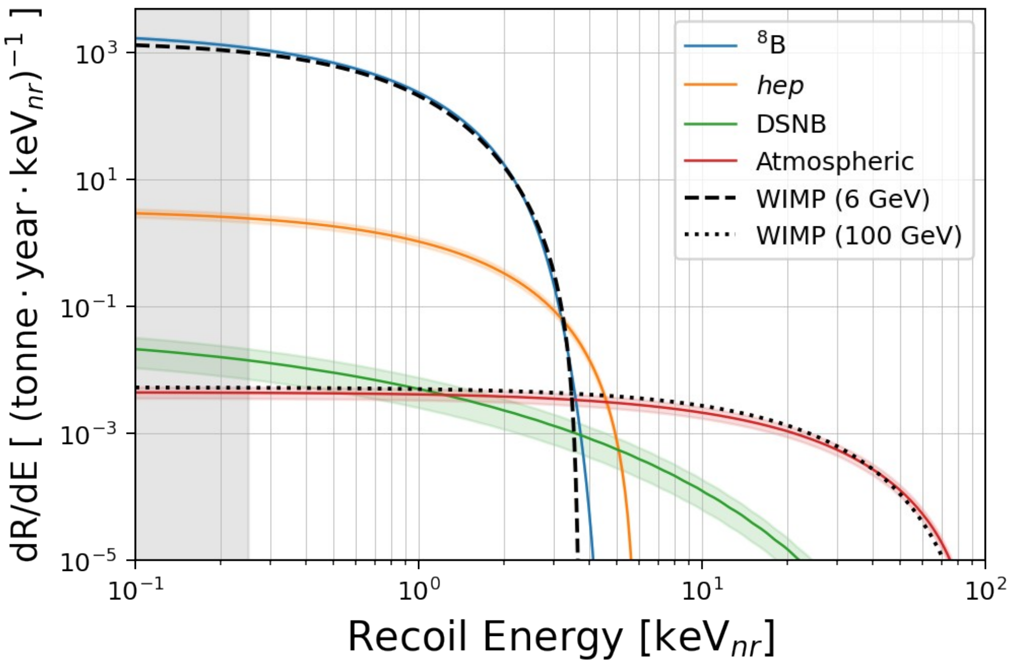


- Interactions produce an initial light signal (S1), followed by a delayed charge signal (S2).
- S1/S2 ratio allows us to identify interaction type.
- 3D position reconstruction helps with rejection of surface backgrounds.

^{8}B Solar Neutrinos in XENONnT



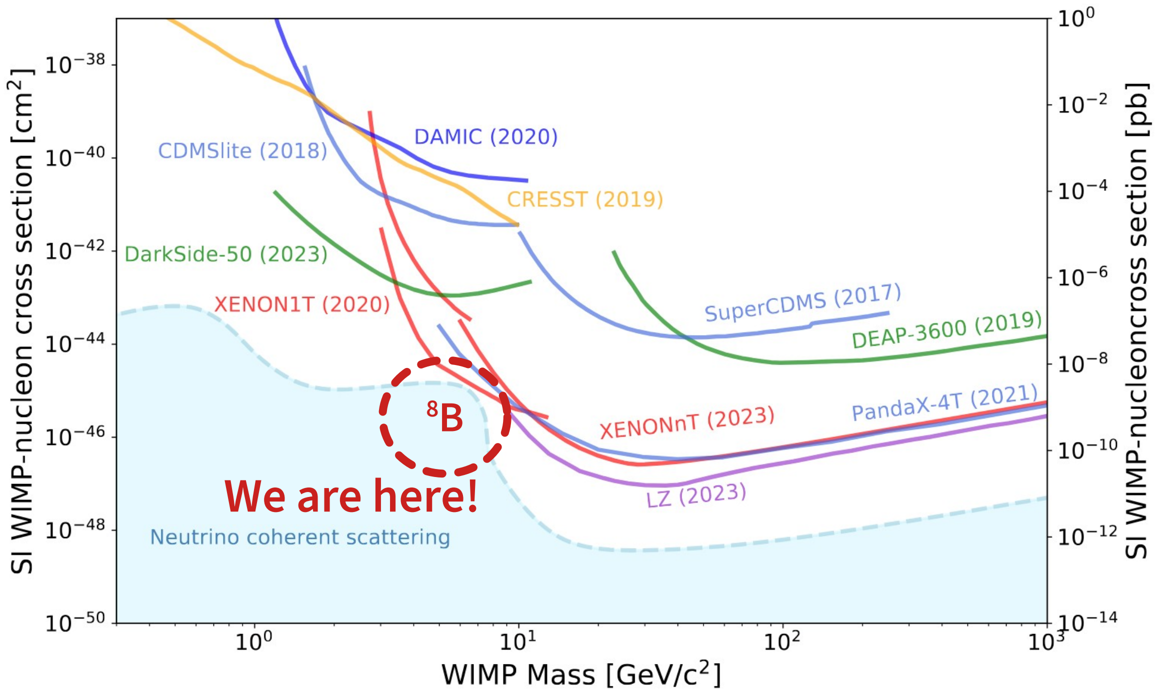
The ^{8}B spectrum is identical to 6GeV WIMPs!



D. Amaral, S. Liang, J. Qin, arXiv:2405.14932

X. Xiang et al., arXiv:2304.06142

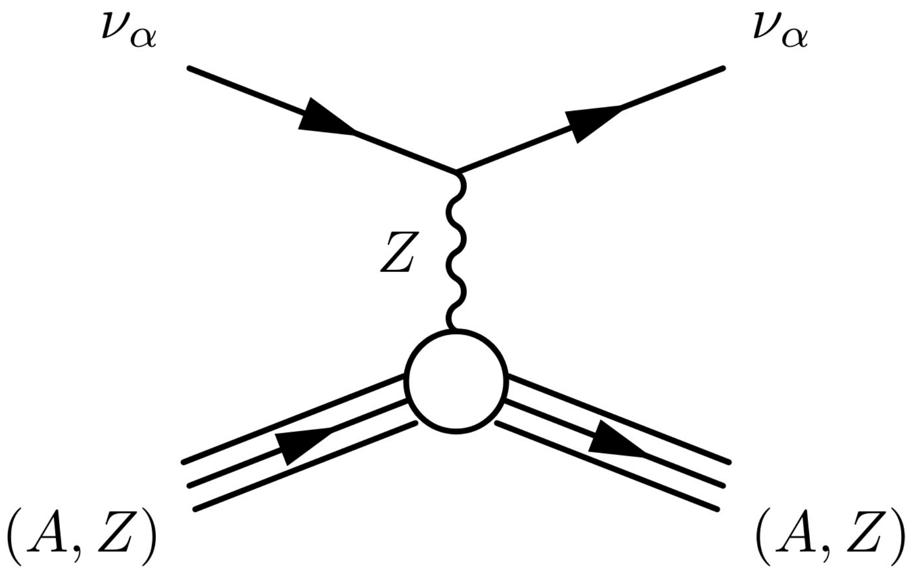
The Neutrino Fog



The Review of Particle Physics (2024)

- The primary mission of XENON is to search for dark matter
- Neutrino nuclear recoil (NR) signals are similar to 6 GeV/c^2 WIMPs
- Detecting WIMPs below this “neutrino fog” becomes increasingly difficult
- On the other hand, neutrinos!

Coherent Elastic Neutrino-Nucleus Scattering



- Flavour-independent neutral current interaction
- Coherence: higher cross-section for heavy nuclei:

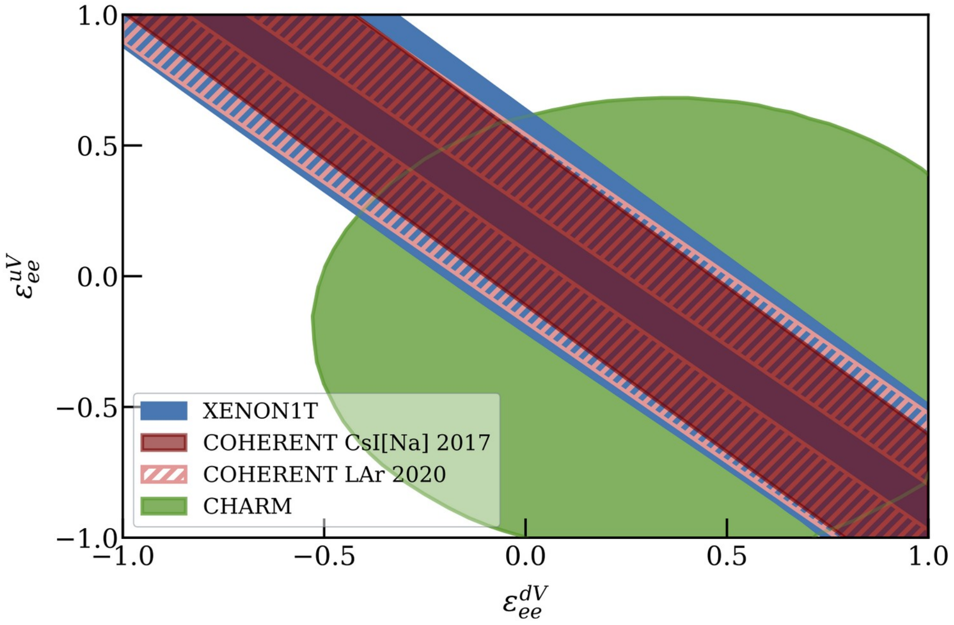
$$\frac{\mathrm{d}\sigma(E_\nu, T_R)}{\mathrm{d}T_R} = \frac{G_f^2}{\pi} m_N \boxed{(Z g_v^p + N g_v^n)^2} \times \left(1 - \frac{m_N T_R}{2E_\nu^2}\right) F^2(T_R),$$

D.K. Papoulias, T.S. Kosmas, Y. Kuno, arXiv:1911.00916

J. Aalbers et al., arXiv:2203.02309

Why Do We Care?

Example of NSI limits from XENON1T and COHERENT:

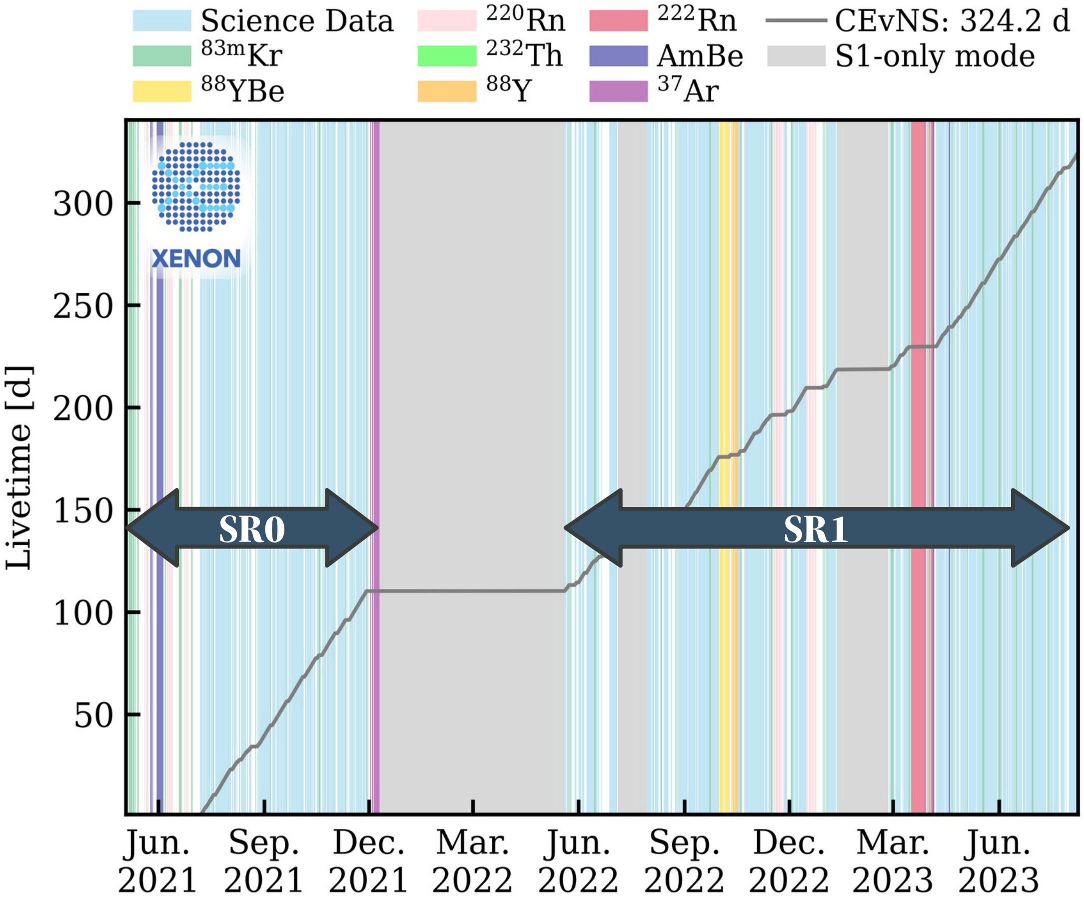


XENON Collaboration: arXiv:2012.02846

- Complementary with measurements from other experiments that use flavour-dependent interactions
- ER (neutrino-electron scattering) and NR (CEvNS) from LXe experiments are also complementary! (see: D. Amaral, S. Liang, **J. Qin**, arXiv:2405.14932)

Signals

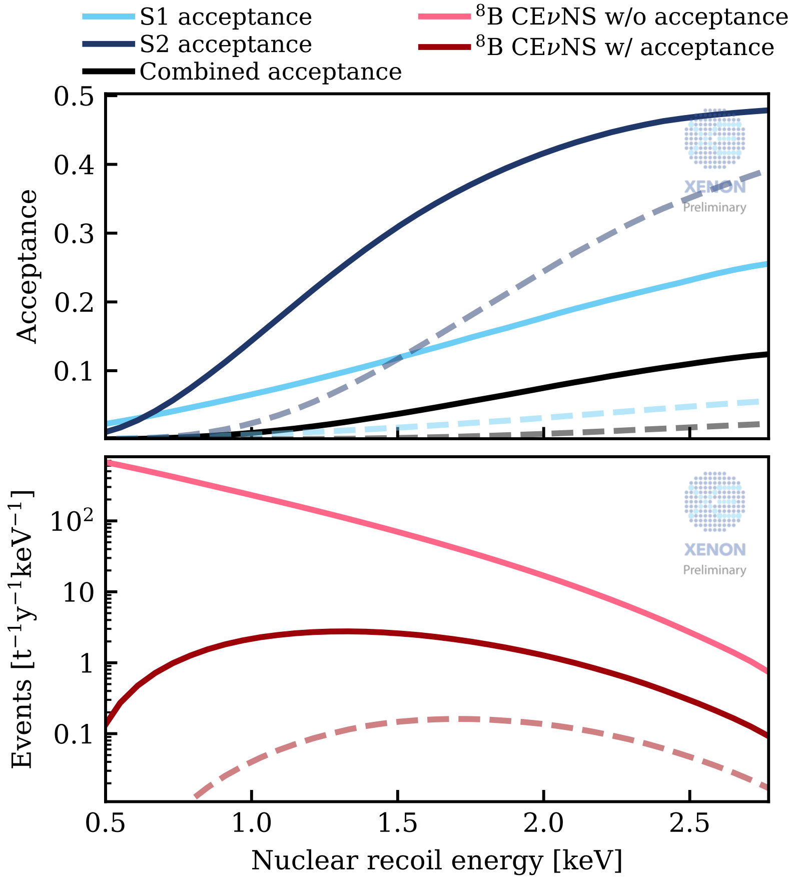
Science Data



- Data from two science runs used for this analysis
  - 108.0 d (SR0) + 208.5 d (SR1)
  - 3.5 tonne × years of exposure
- **Blind** analysis performed
- Good stability over time period

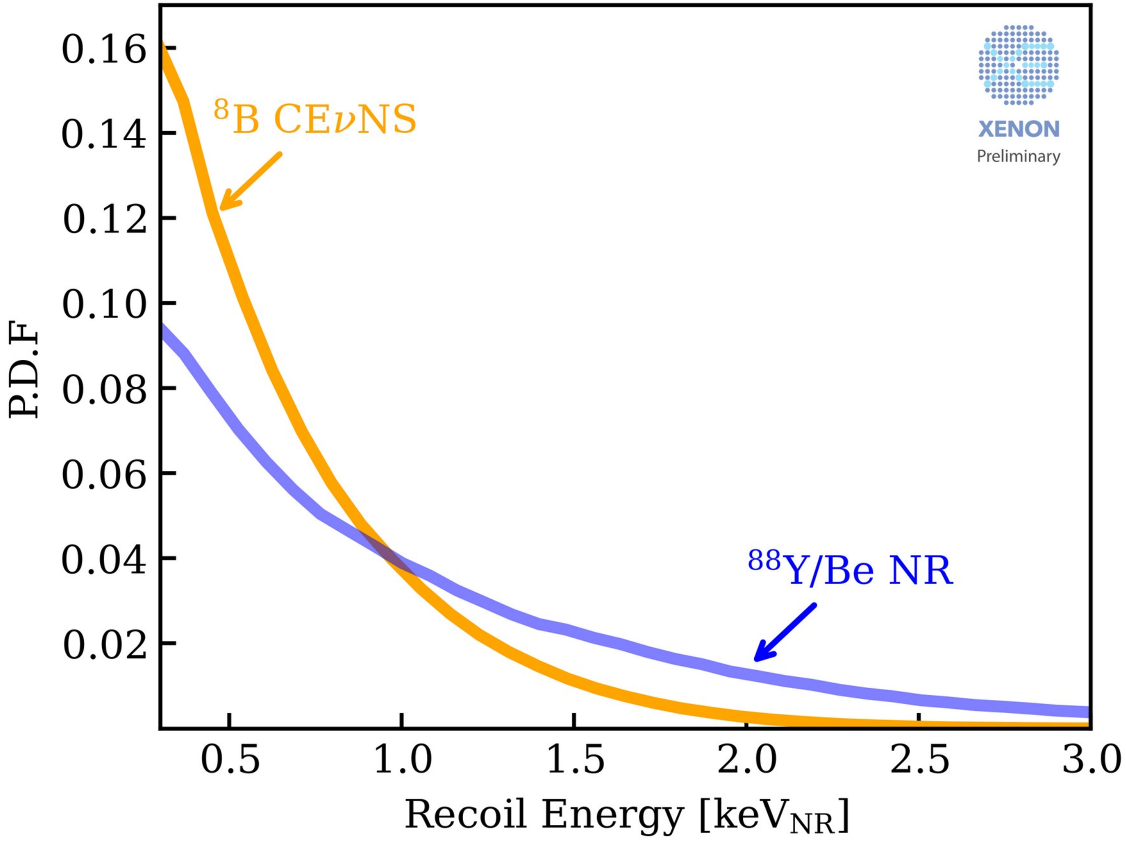
Note: plot is not deadtime corrected

Detecting Signals Near Threshold



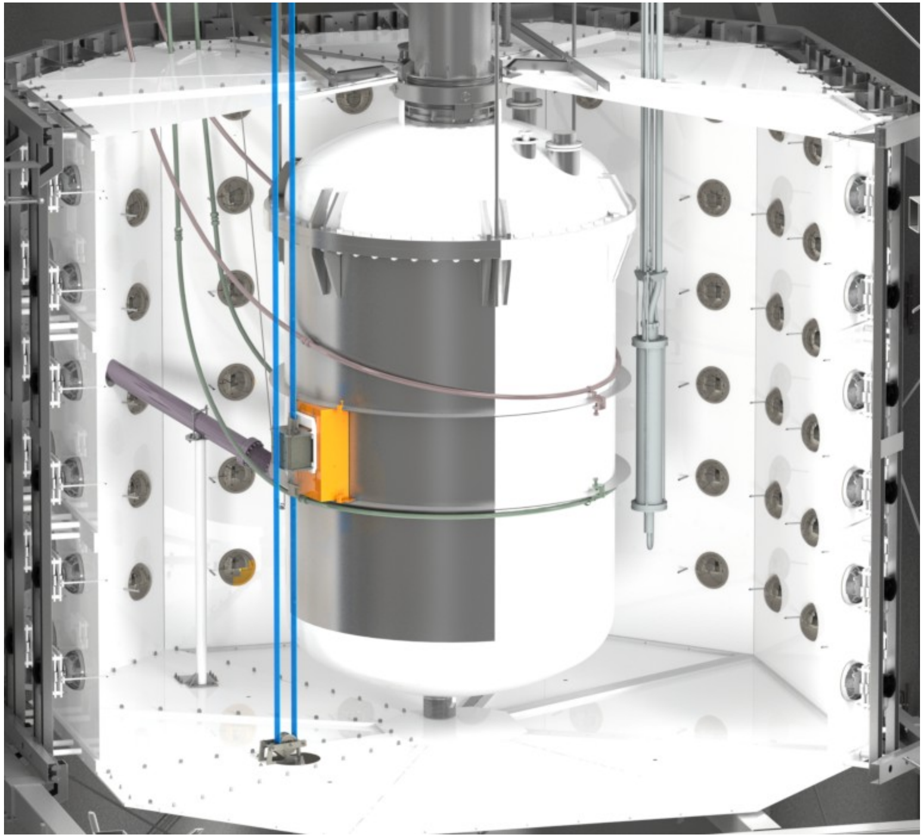
- Pushing the threshold down using 2-fold coincidence is necessary!
- We are working in a regime where both energy resolution and acceptances are low.
- Good understanding of yields and acceptances is very important.

Calibration is Key



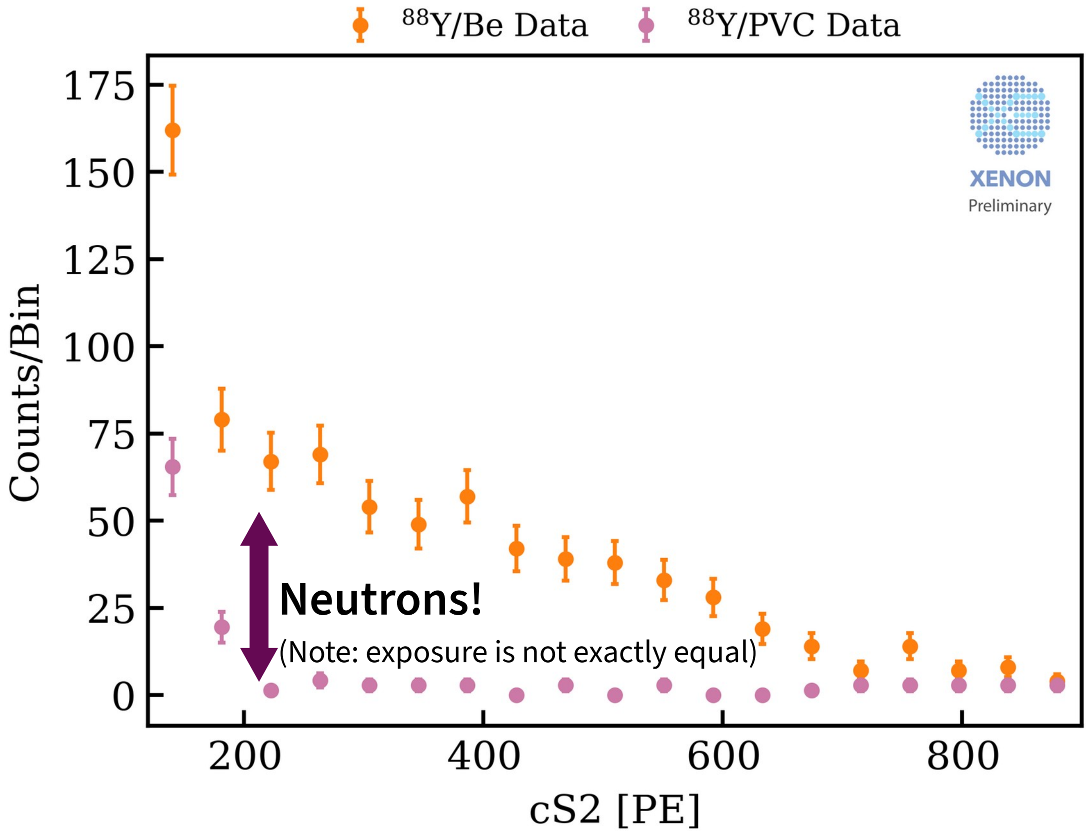
- One way to be sure of our analysis is to have a calibration source that closely resembles the signal.
- We conducted a calibration using a photoneutron source with ^{88}Y and Be.
- This is my primary contribution to the ^{8}B effort!

^{88}YBe Calibration Design



- The (γ,n) reaction has a low cross-section, 0.65 mb
- This corresponds to a mean trajectory length between photodisintegration of ~100m in beryllium!
- Tungsten shield used to reduce the gamma rate in the TPC
- Air box used to displace water between the neutron source and the cryostat to reduce the moderating effect of water

On-off Calibration



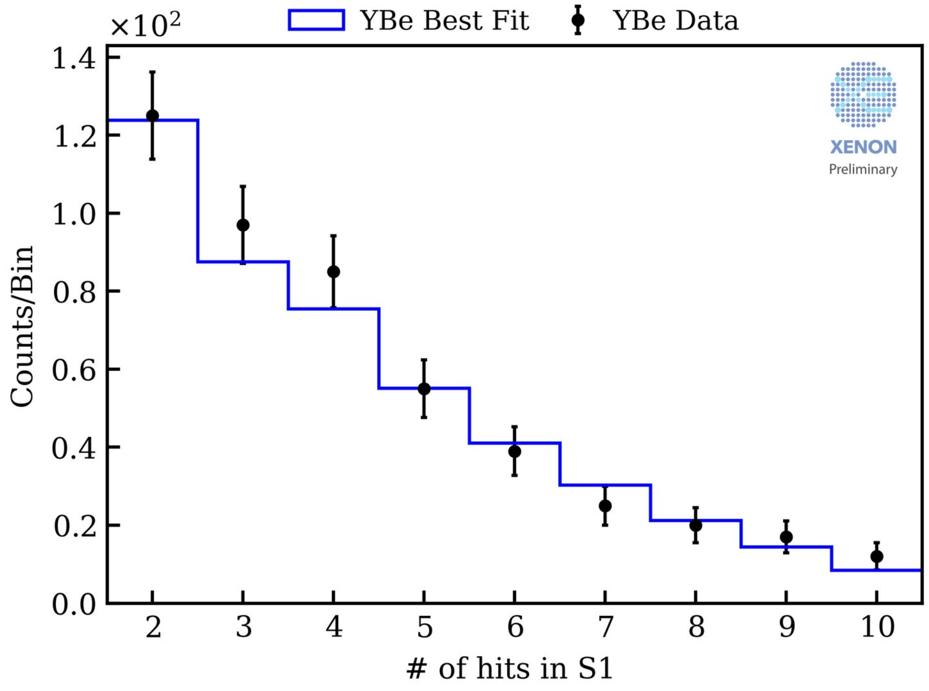
- How do we gain confidence in a calibration with significant backgrounds near the threshold?
- Simple: we turn it off!
- In this case, we replace the beryllium targets with inert PVC.

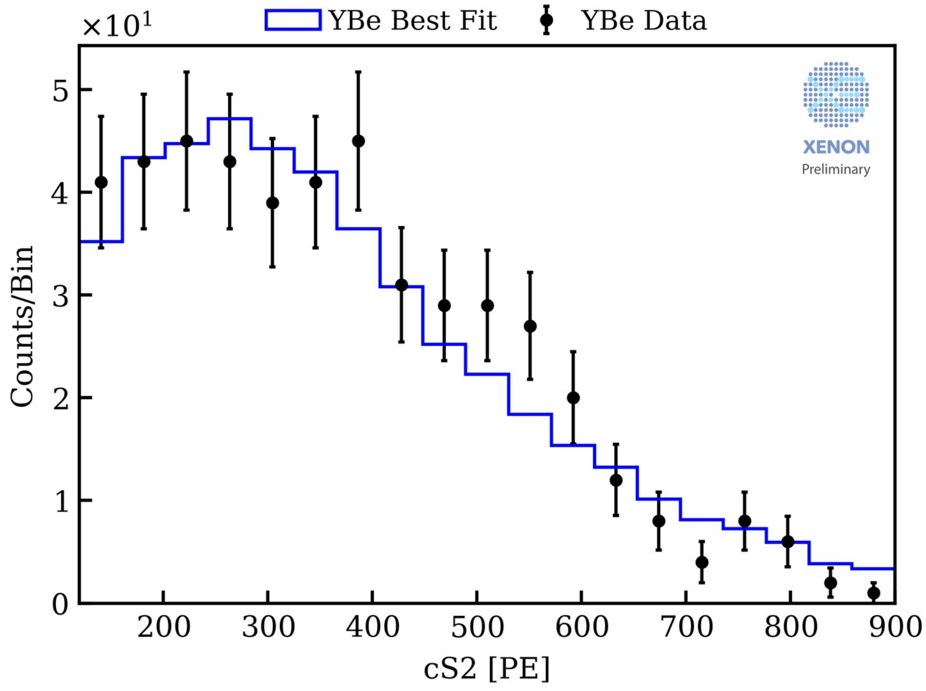
Excellent Fit with Data

appletree 0.5.1

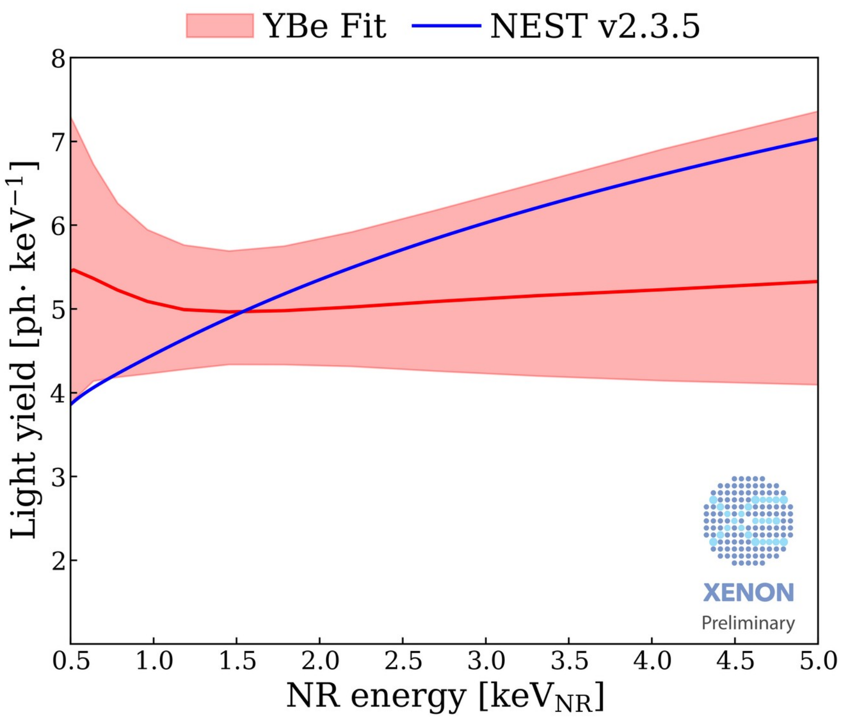
```
pip install appletree
```

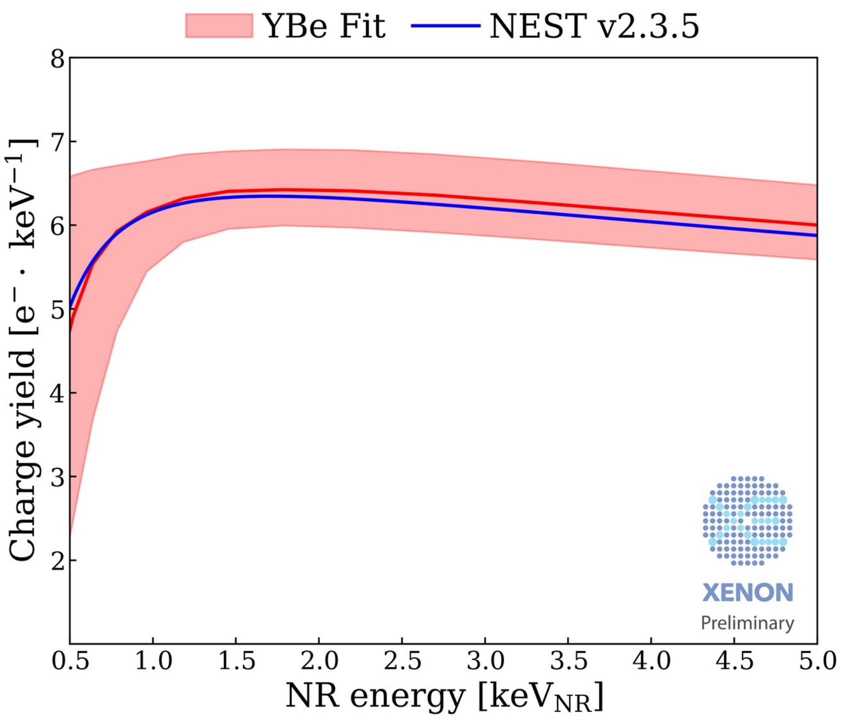
Also used to simulate the signal model!





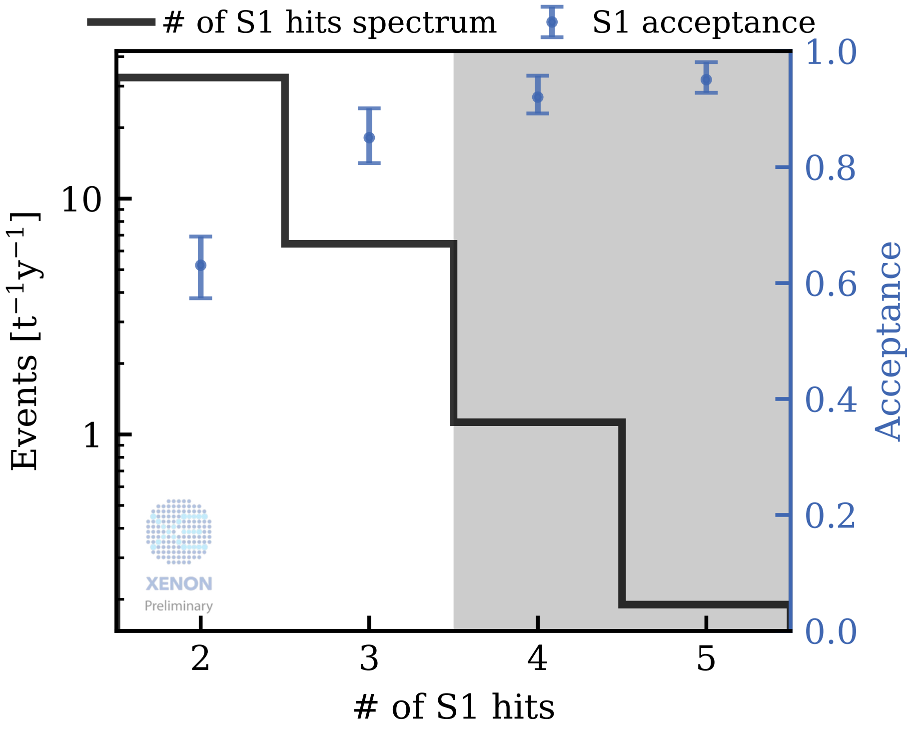
Calibrated Yields

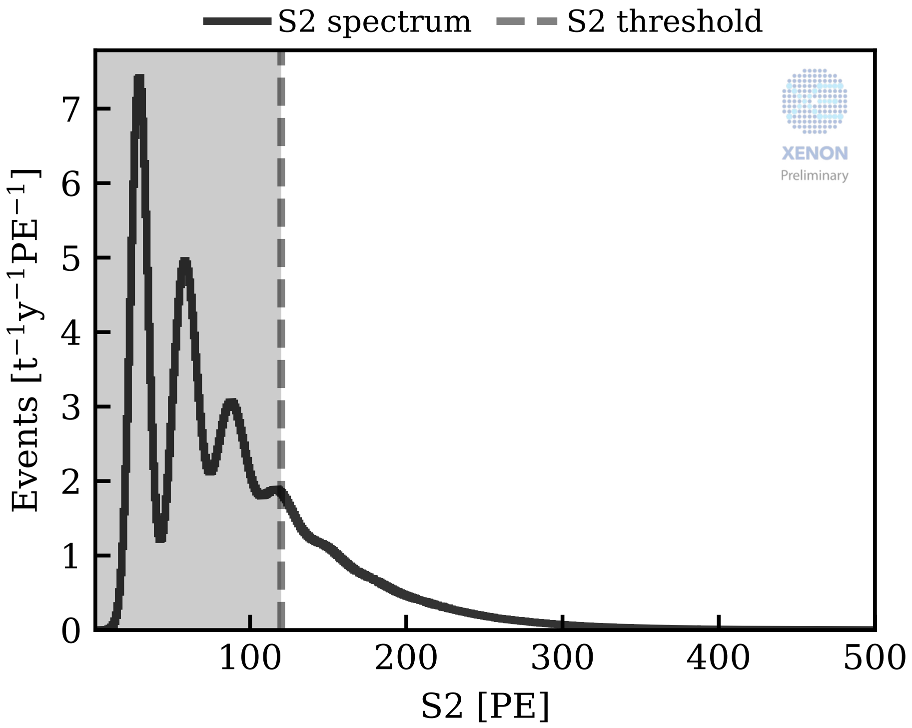




- Robust calibration allows us to be confident in our signal model and analysis strategy
- Yields are poorly constrained with low E-fields

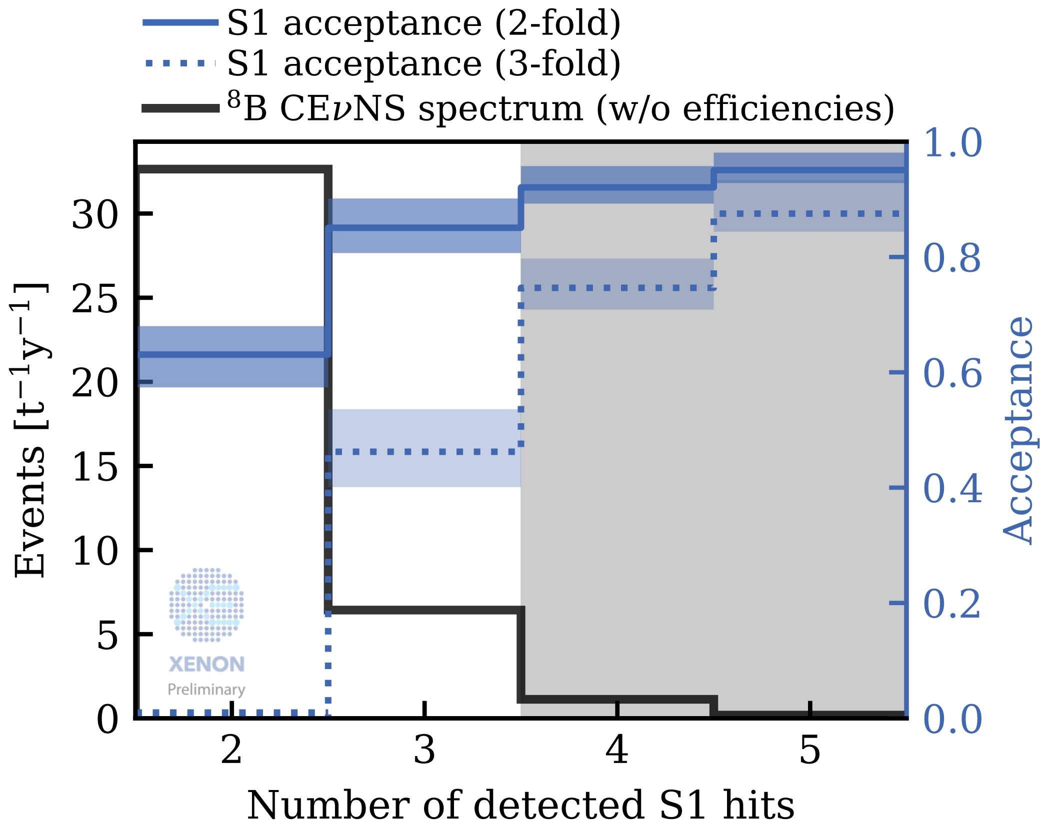
^{8}B Region of Interest





- "hits" refer to single PMT signals that typically corresponds to a single photon.
- S2 threshold is chosen to reject the background of single- and few-electron emission in Lxe TPCs.

Pushing the Threshold Down



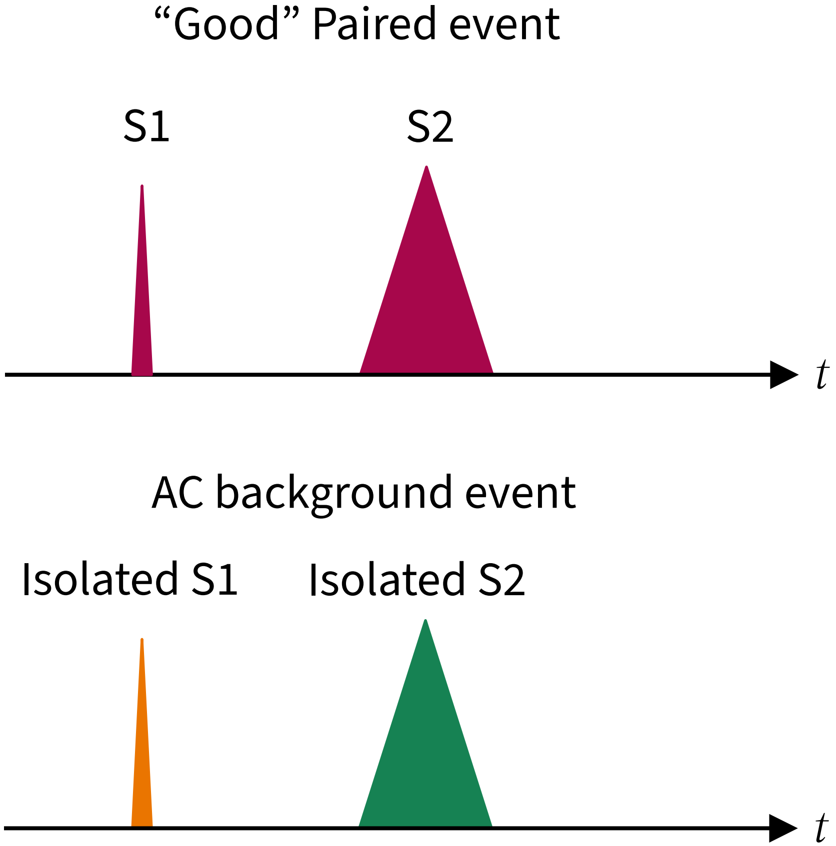
- Signal rate increases massively with 2-fold analysis!
- This is also true for 6 GeV WIMPs...why do we usually require 3-fold coincidence?

Backgrounds

Backgrounds

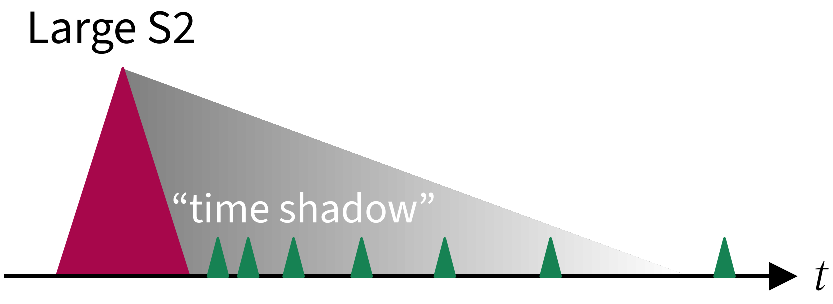
1) **Accidental Coincidence** ← **The dominant background by far!**
2) Surface
3) Neutron
4) Electronic Recoils

Accidental Coincidences



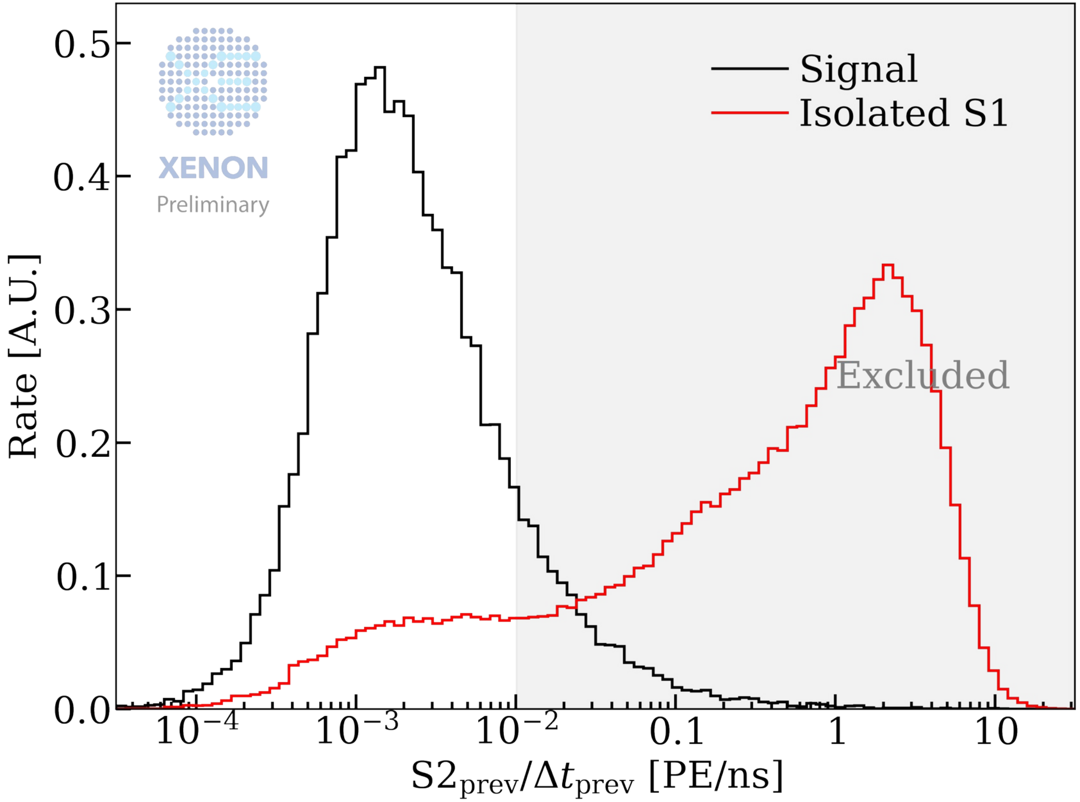
- Matching of light signals (S1) and ionisation signals (S2) is done by coincidence time
  - S1s and S2s with time-separation smaller than the maximum drift time represent possible interactions
- This does not reject "accidental" pairings of peaks!
- This is a key low energy background because of the spectrum of isolated S1 and S2 signals.

Reducing the Isolated Peak Rate

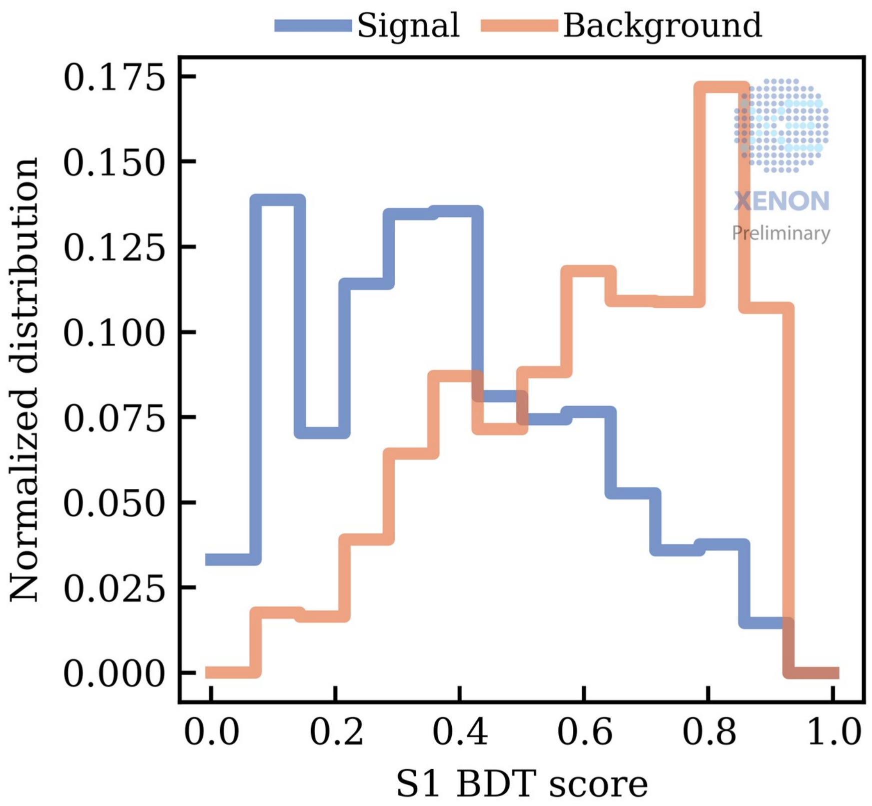


Small S1 and S2s are observed after large signals in the TPC

In SR1, we also include position information in the cut, as events in the “shadow” are also correlated to the originating signal in x-y position

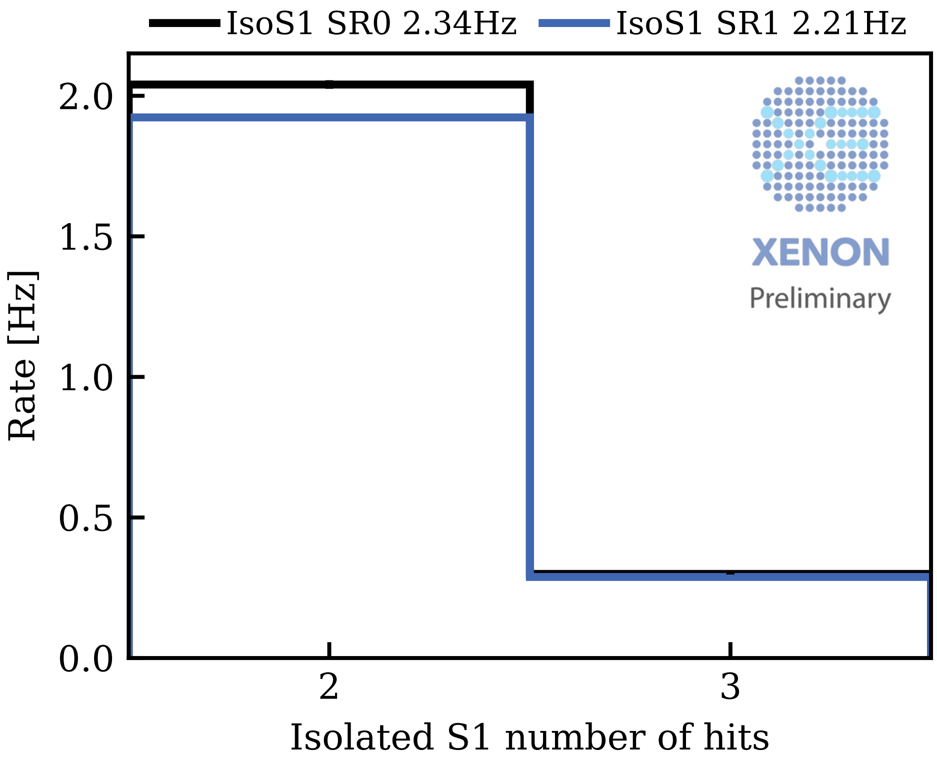


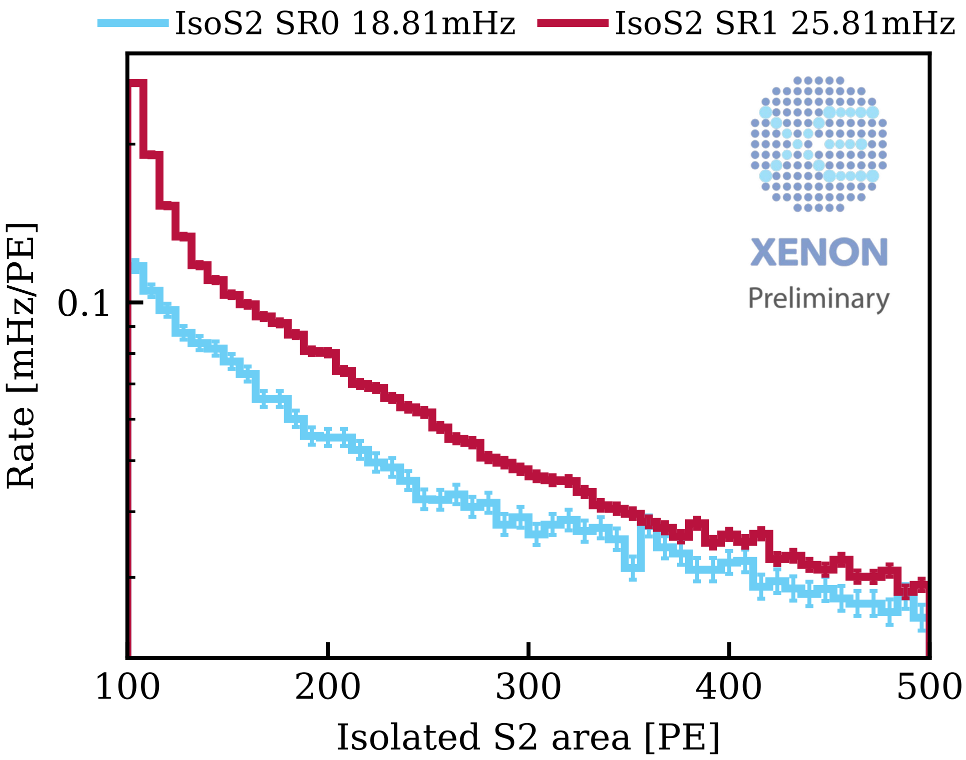
Reducing AC backgrounds using ML



- Gradient-boosted decision trees trained on AC background versus simulated signals
- BDT scores also used as a dimension for inference!

Spectrum of Isolated Peaks

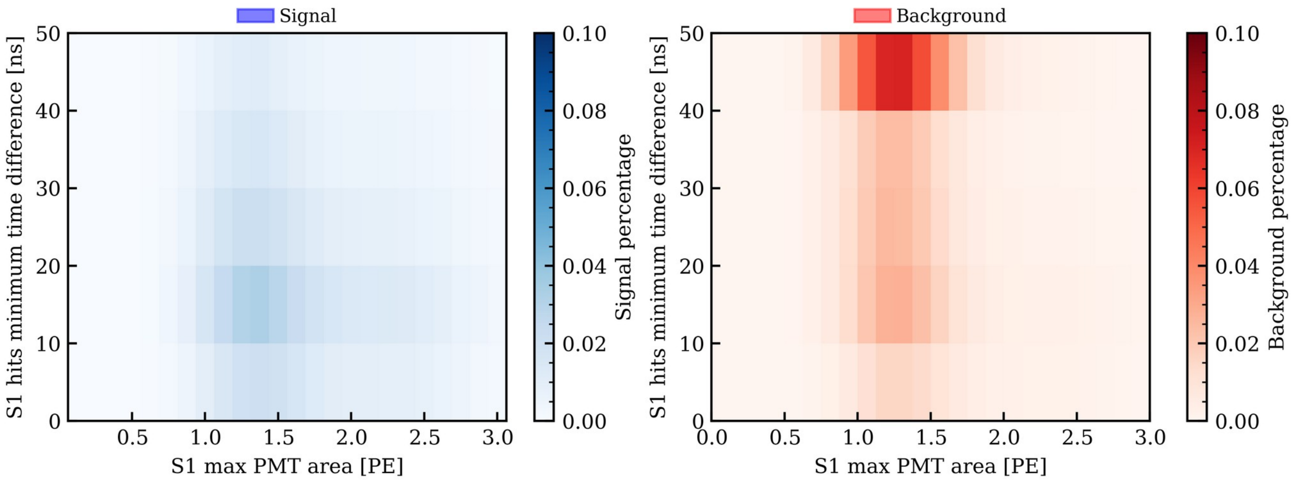




Reducing AC backgrounds using ML

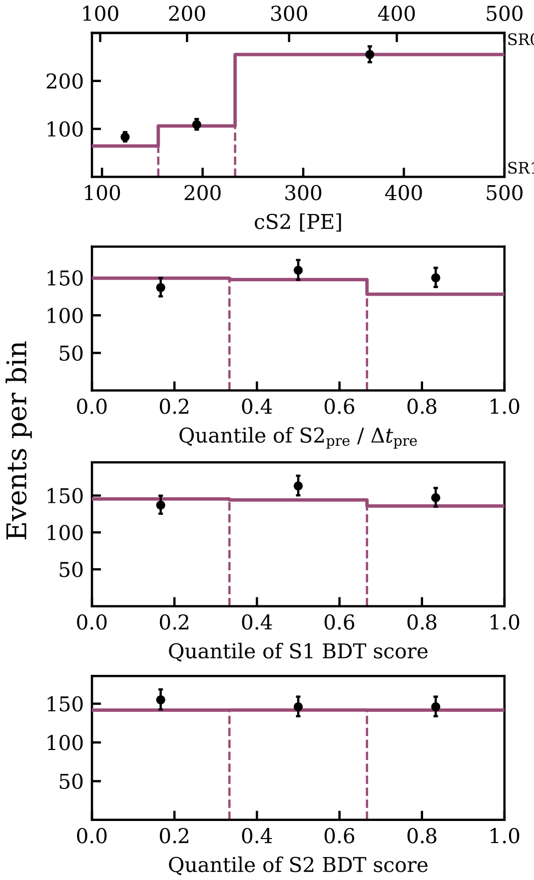
- S1 classifier used the distribution of hits (typically single photon signals) in time and between the top and bottom array

- S2 classifier used S2 waveform shape and the time difference between the S1 and S2 signals



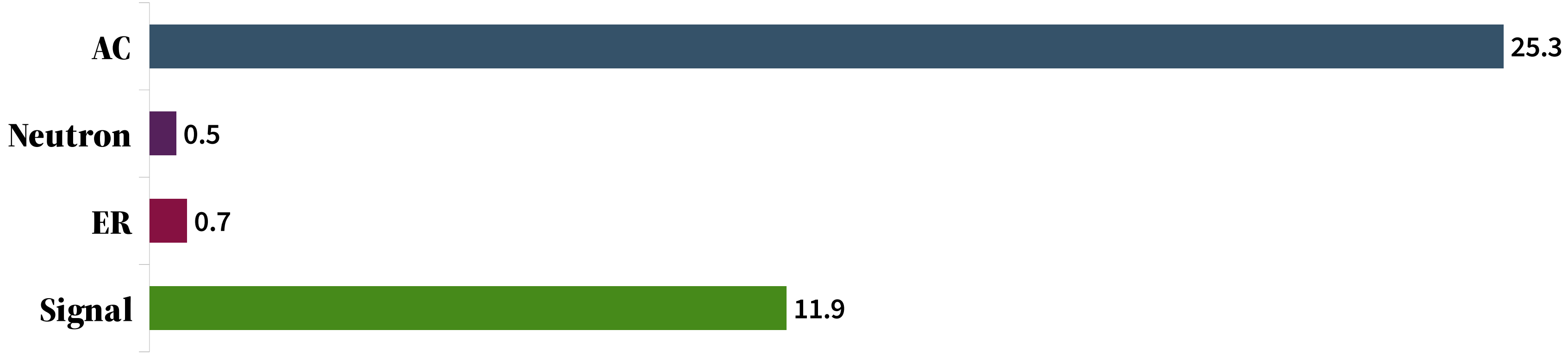
- Signals and backgrounds are distributed differently in various features due to different physical origin

Verifying AC Model with Sideband Data



- Sidebands are unblinded before unblinding of physics data to verify background model
- Sideband events primarily fail the S2 BDT cut designed to reduce the AC background rate
- Statistical uncertainty of the sideband is used as the systematic uncertainty for the final model

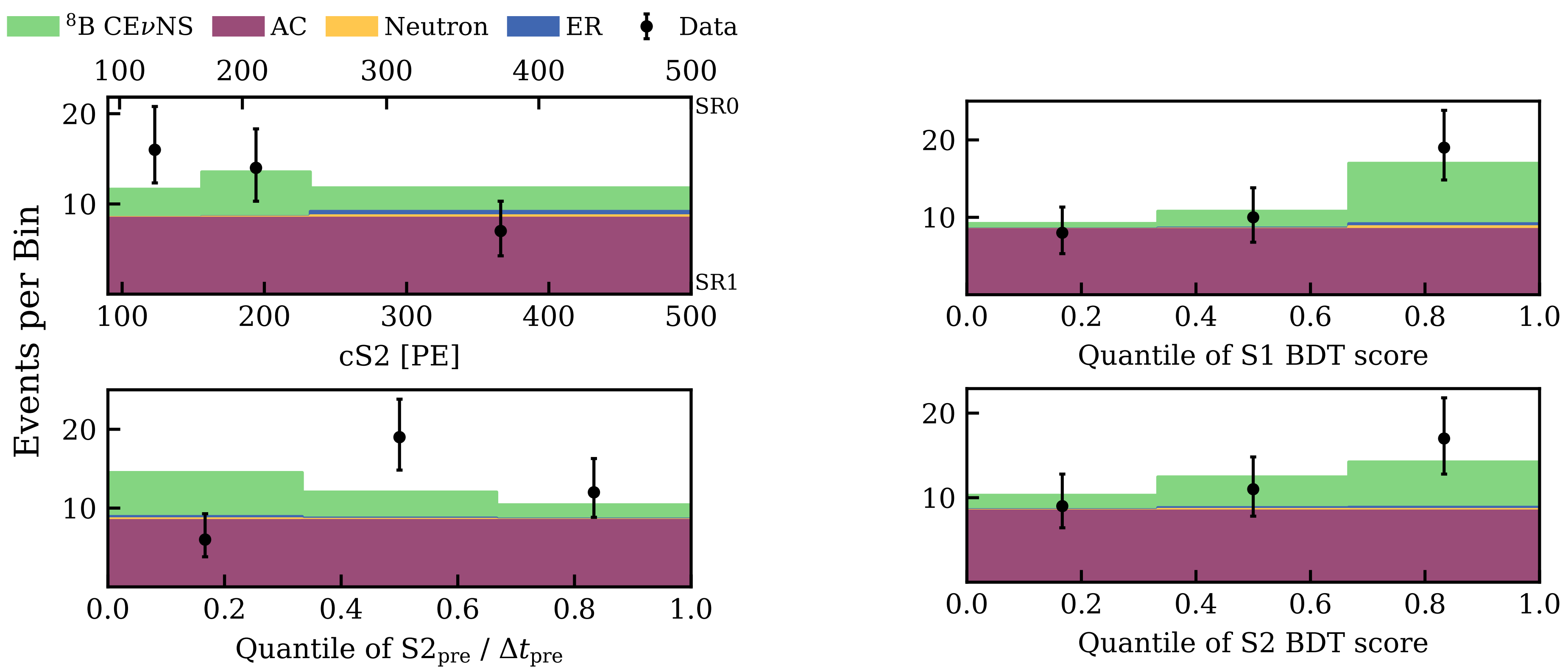
Background and Signal Expectation



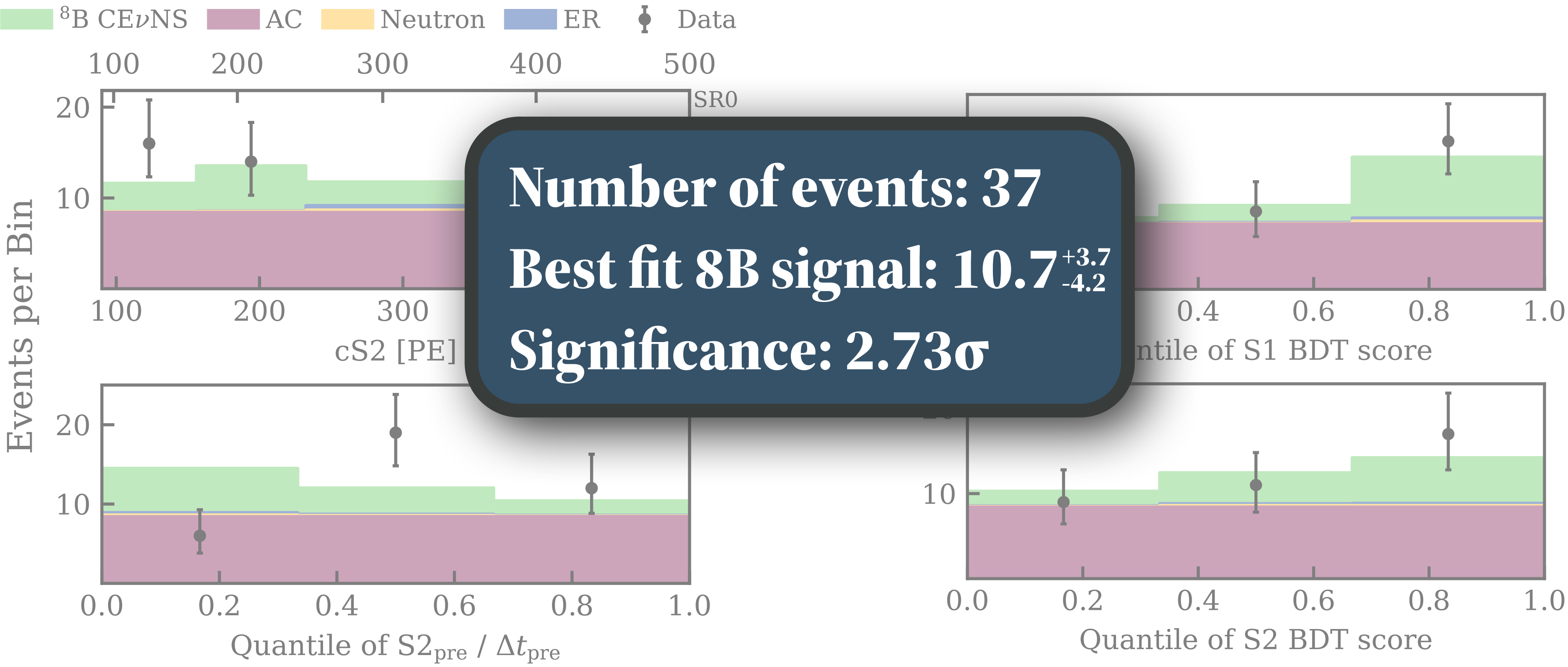
- Almost all of the background is caused by ACs, also validated using ^{37}Ar calibration
- ER background is derived from fitting the ER band > 20 keV
- Radiogenic neutron background derived from simulation, and verified using events tagged by the neutron and muon vetos

Results

Unblinded Data



Unblinded Data



Number of events: 37

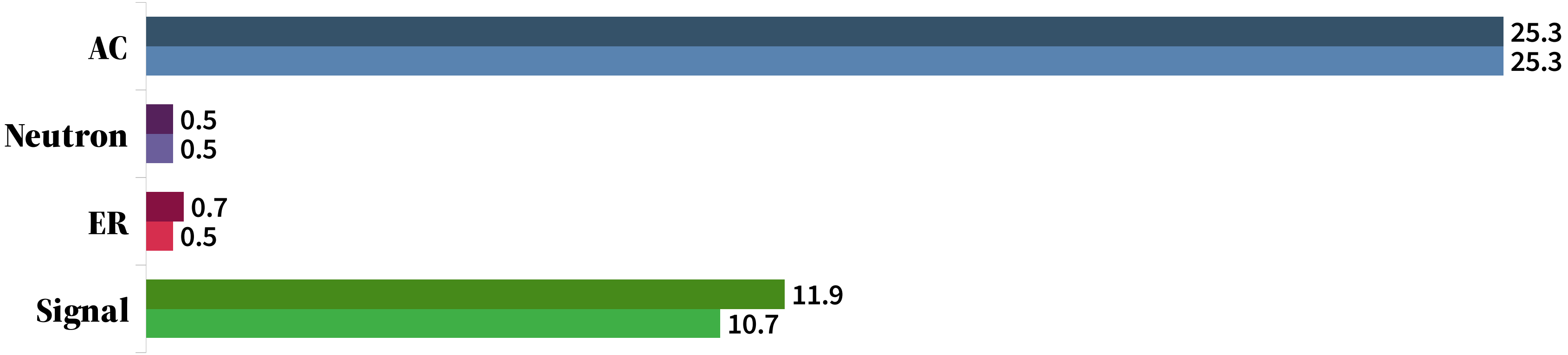
Best fit 8B signal: $10.7^{+3.7}_{-4.2}$

Significance: 2.73σ

In Hindsight...

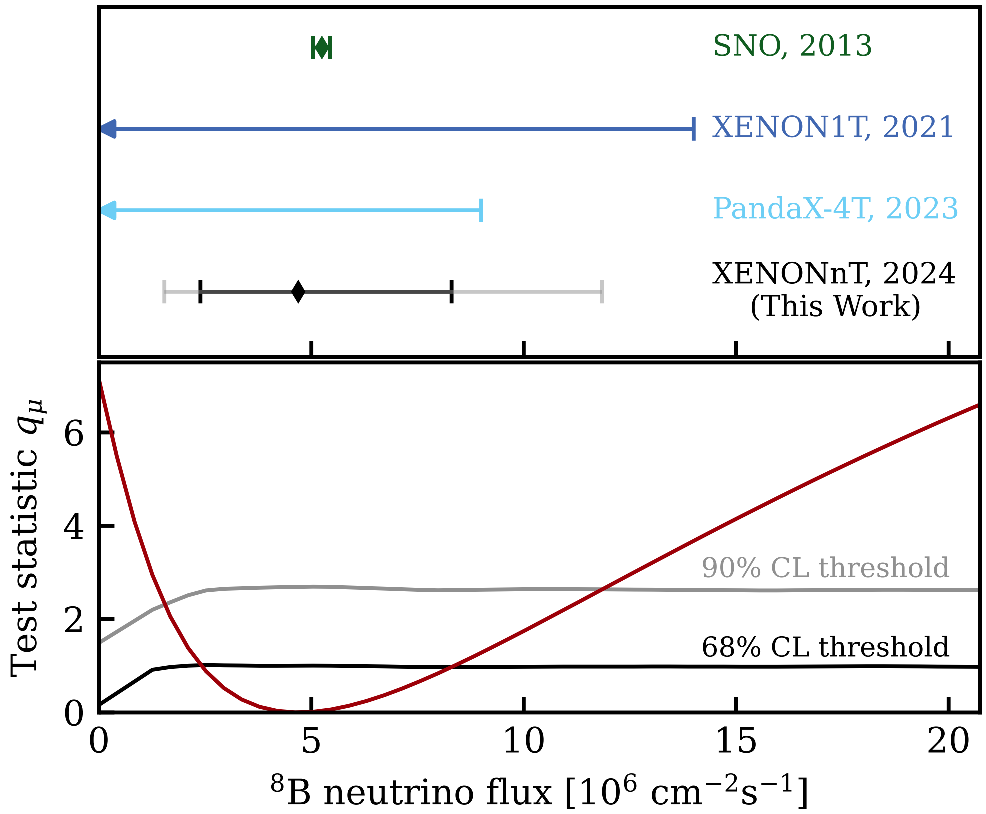
- Significance improves to 3.22σ if $S2_{pre}/\Delta t_{pre}$ is excluded from inference
- Of course, as we are doing a blind analysis, we cannot have our cake and eat it too, but alas!

Expectations vs. Best-fit



Expectations on top, best-fit below.

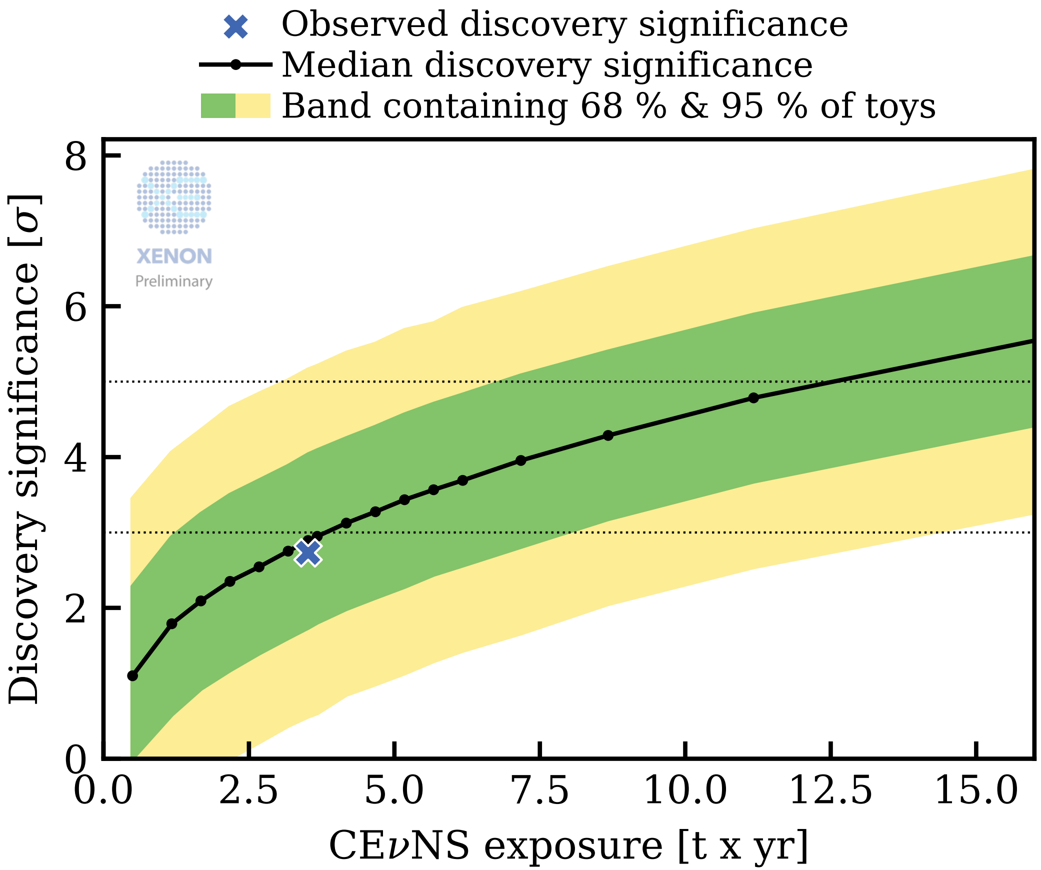
^{8}B Neutrino Flux



- First measurement of CEvNS cross section in xenon! (Together with PandaX, though with differences)
  - Detector response is calibrated with ^{88}YBe
  - ^{37}Ar sideband unblinding to verify signal and background models
  - 2-fold science data was blinded throughout with no “reblinding”
- 2.73σ → p=0.003

Future Outlook

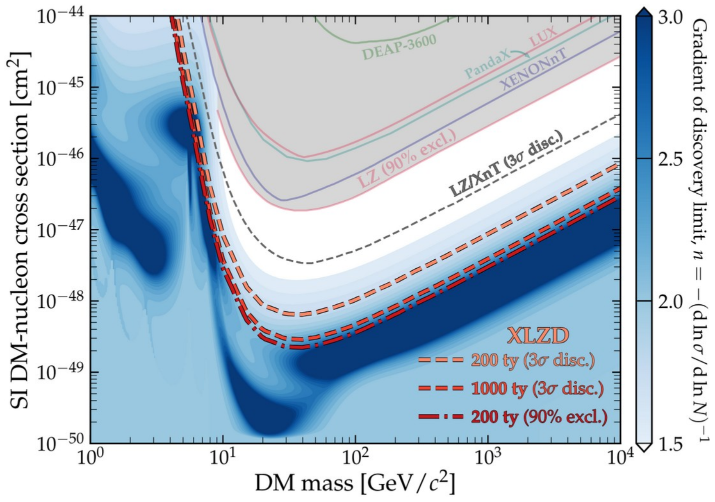
- Indications of ^{8}B solar neutrinos observed in XENONnT!
- Significant measurements within reach of future data
- CEvNS measurements carry the potential for complementary neutrino physics limits
- Light WIMP results from the same channel: **First Search for Light Dark Matter in the Neutrino Fog with XENONnT (arXiv:2409.17868)**

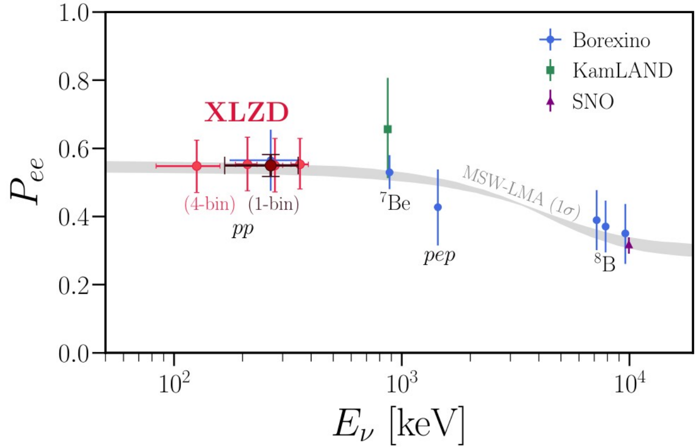


Future Outlook

- We are now making our first steps into neutrino measurements using LXe
- XLZD will be a bona fide neutrino experiment in both ER and NR channels!
- Strong implications for future neutrino NSI measurements and limits (see: D. Amaral et. Al, arXiv:2302.12846; also, talk to me about this!)

Laura Baudis, arXiv:2404.19524, figure by Ciaran O'Hare





XLZD Collaboration, arXiv:2410.17137

Other Things I Work On

- Searching for dark matter with mechanical impulse/force sensors (Windchime, Polonaise)
- Exploring the neutrino NSI space using advanced inference techniques and probabilistic programming (arXiv: 2405.14932)
- ML techniques for XENON analysis, eg. using normalising flows
- **Do talk to me if interested!**