Latest Results from the XENONnT Experiment

Ananthakrishnan Ravindran
On behalf of the XENON collaboration.

IRN Terascale | IP2I Lyon | Nov 13-15

The XENON Collaboration

200+ Scientists	29 Institutions	12 Countries

Main Motivation

Discover **Weakly Interacting Massive Particles (WIMPs)**.

Other studies

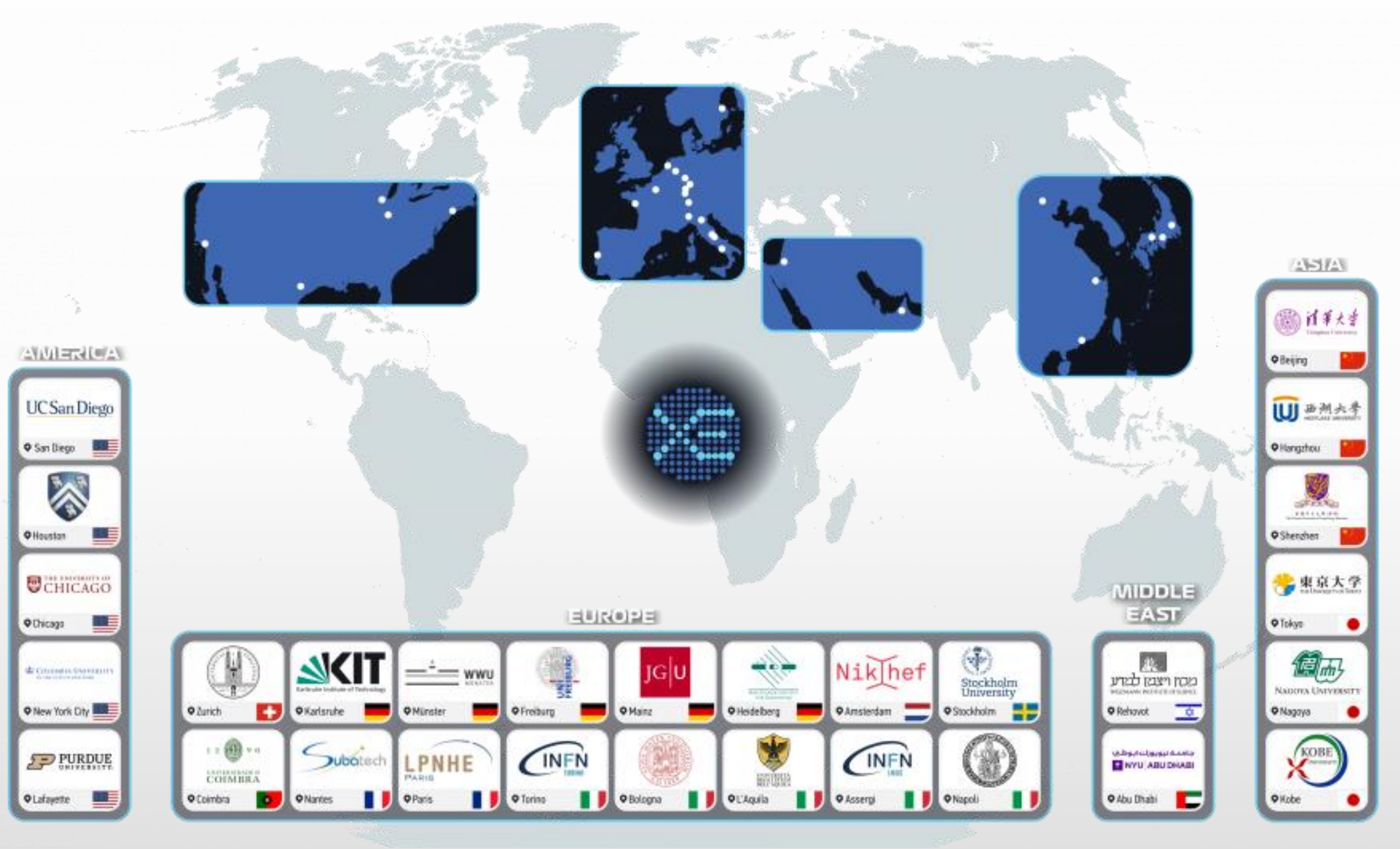
New Results!!

Coherent Elastic Neutrino-Nucleus Scattering **(CEvNS)**, $0\nu\beta\beta$, Solar Axions and ALPs, Supernovae, etc.

How we do it:

- **Very low backgrounds:** active and passive shielding, fiducialization, etc.
- Robust tools to correct detector effects and look for very small signals.
- Perform a “blind analysis”.

The XENON Collaboration



200+ Scientists

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XENON program timeline

XENON10
25kg LXe

2006
58.6 livedays
BG: 600 /(t.d.keV)

XENON100
160kg LXe

2008
477 livedays
BG: 5.3 /(t.d.keV)

XENON1T
3200kg LXe

2015
279 livedays
BG: 0.2 /(t.d.keV)

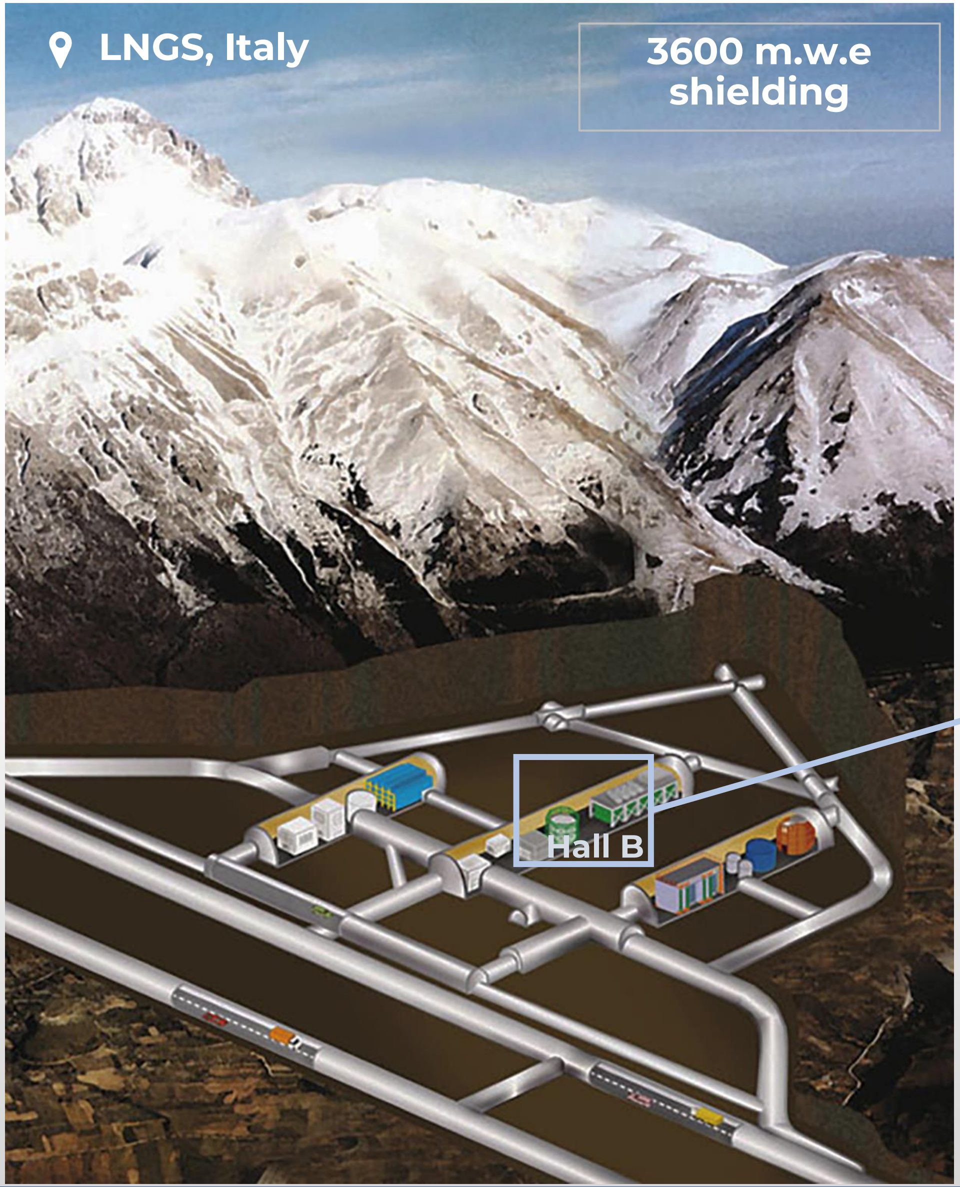
XENONnT
8600kg LXe

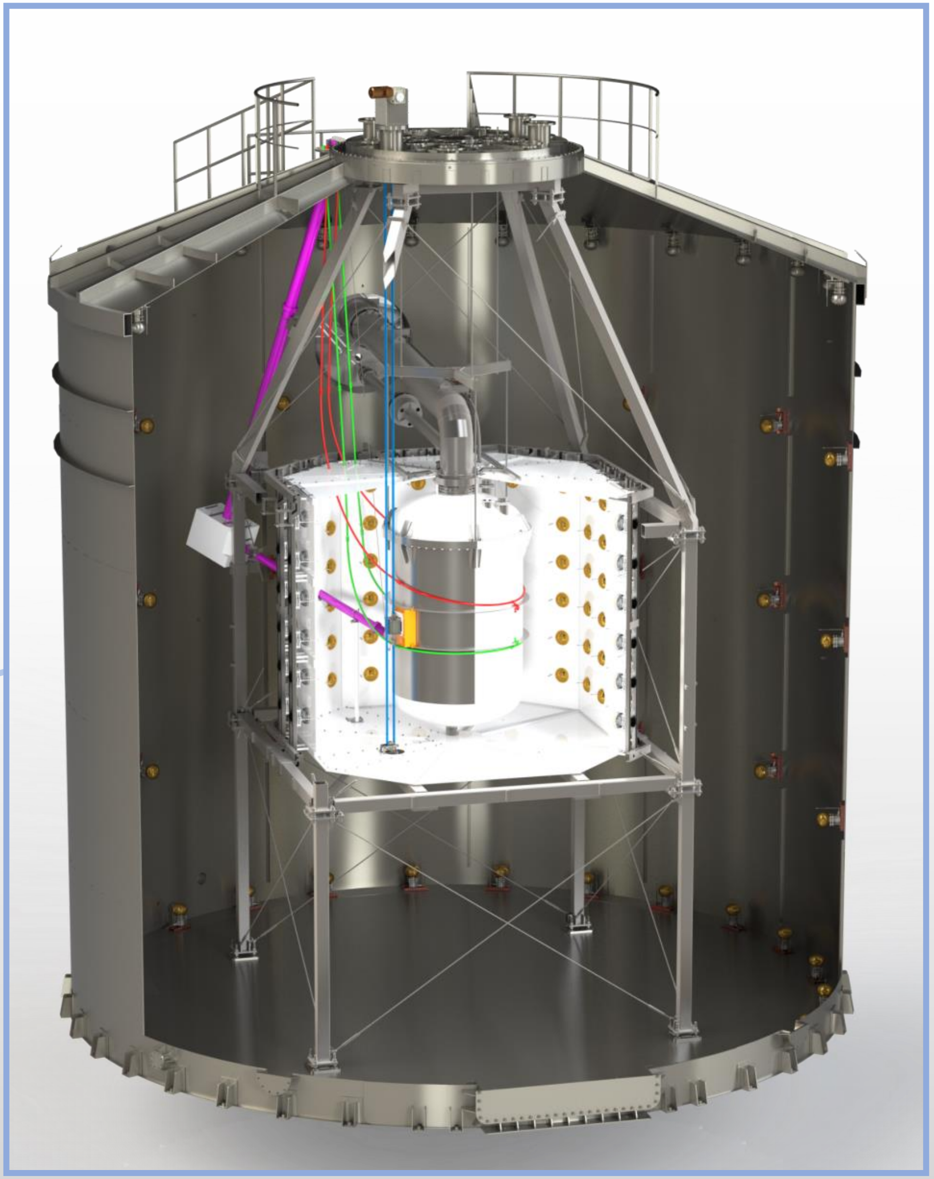
2020
300+ livedays
(ongoing)

BG: 0.04 /(t.d.keV)

Lowest ER background level ever achieved in a LXe based experiment!!

XENONnT Experiment



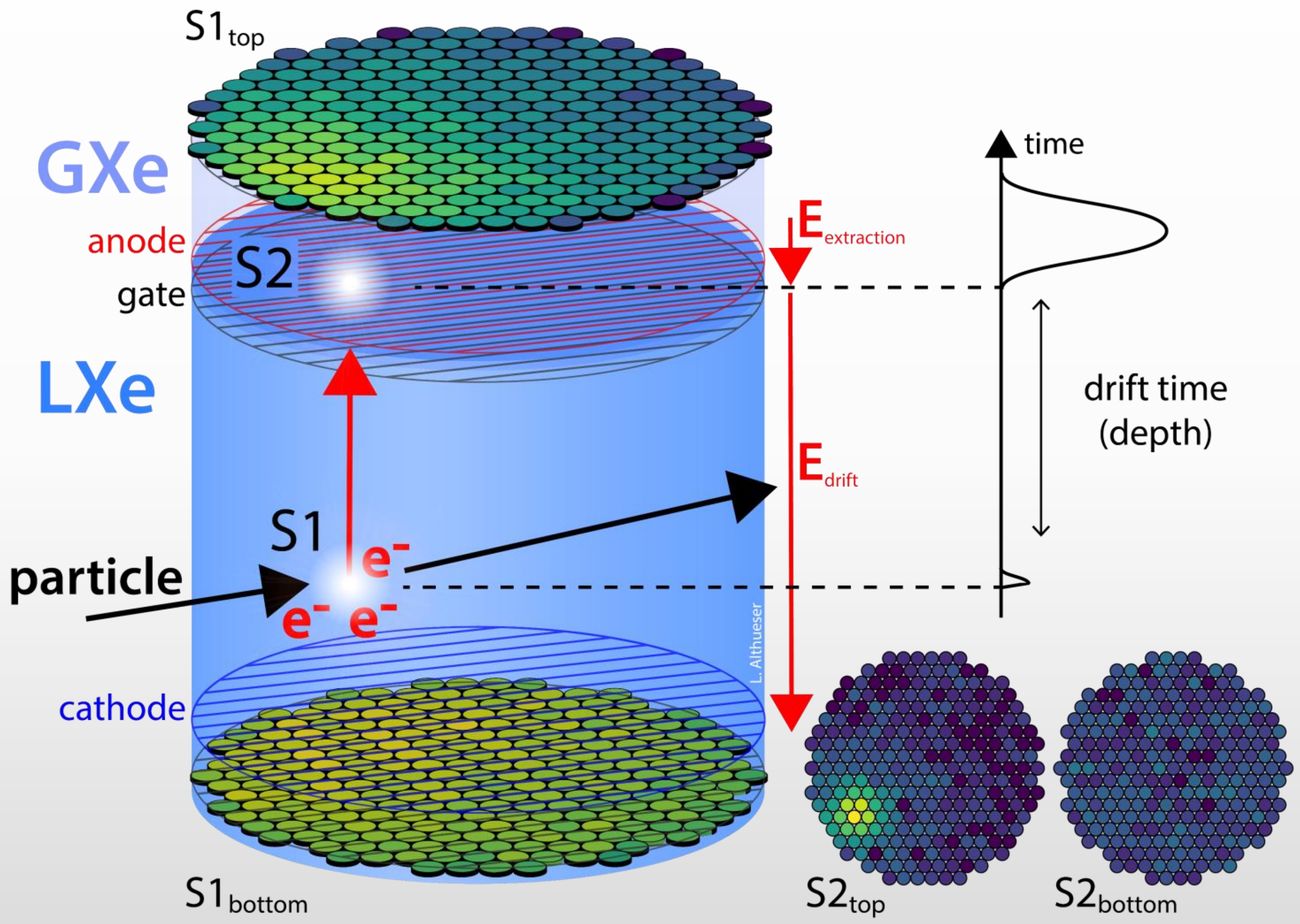


3 Nested Detectors

Sharing the same DAQ

- LXe Dual Phase **Time Projection Chamber (TPC)** with 5.9t active volume. (Eur. Phys. J. C 84, 784 (2024), JCAP11(2020)031)
- Gd-doped Water Cherenkov **Neutron Veto (NV)**.
- Gd-doped Water Cherenkov **Muon Veto (MV)** (2014 JINST 9 P11006)

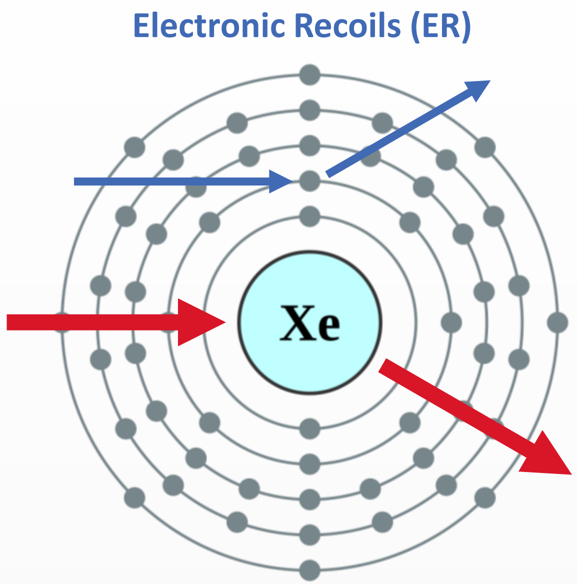
Dual Phase Time Projection Chamber



- Particle interaction in LXe create both **prompt scintillation(S1)** and **delayed ionization** signals.
- Ionization electrons drifted upwards by **drift field** ($E_{drift\_XnT} = 23V/cm$) and extracted into gas phase by **extraction field** ($E_{extraction\_XnT} = 2.9kV/cm$); leads to **electroluminescent light(S2)**.
- Signals collected a total of 493 PMTs in the top and bottom arrays.

3D Position Reconstruction	**Energy Reconstruction**
x, y : S2 hit pattern z: Drift time of e-	Combined S1 and S2 area; calibrated with known sources.

Recoil Type Discrimination: ER or NR?



Nuclear Recoils (NR)

NR

- ✗ | Neutrons
- ✓/✗ | Neutrinos (CEvNS)
- ✓ | WIMPs

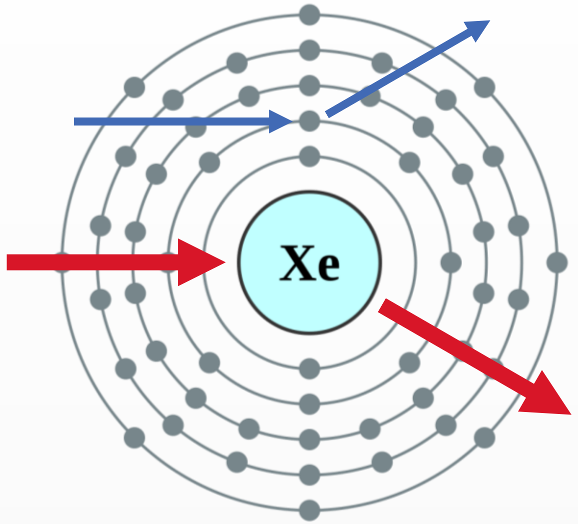
ER

- ✗ | Gamma & Beta
- ✓/✗ | ^{136}Xe $0\nu\beta\beta$, $2\nu\beta\beta$.
- ✓/✗ | Neutrino elastic scattering.
- ✓ | Solar axions, ALPs.

✓ Signal ✗ Background

Recoil Type Discrimination: ER or NR?

Electronic Recoils (ER)



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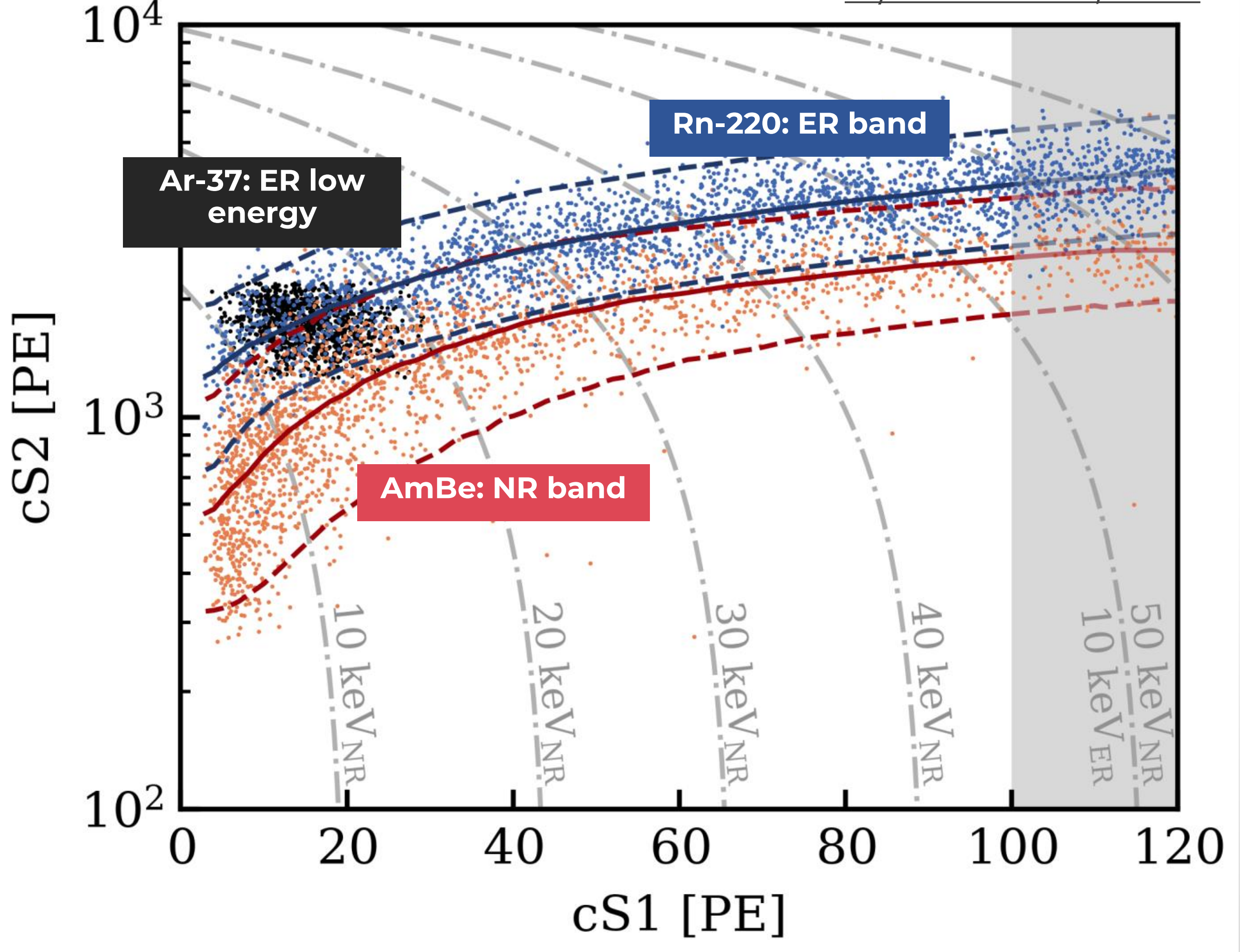
Phys. Rev. Lett. **131**, 041003



Discriminated via different S2/S1 ratio.

Other Calibrations

Kr83m

TPC characterization and signal correction.

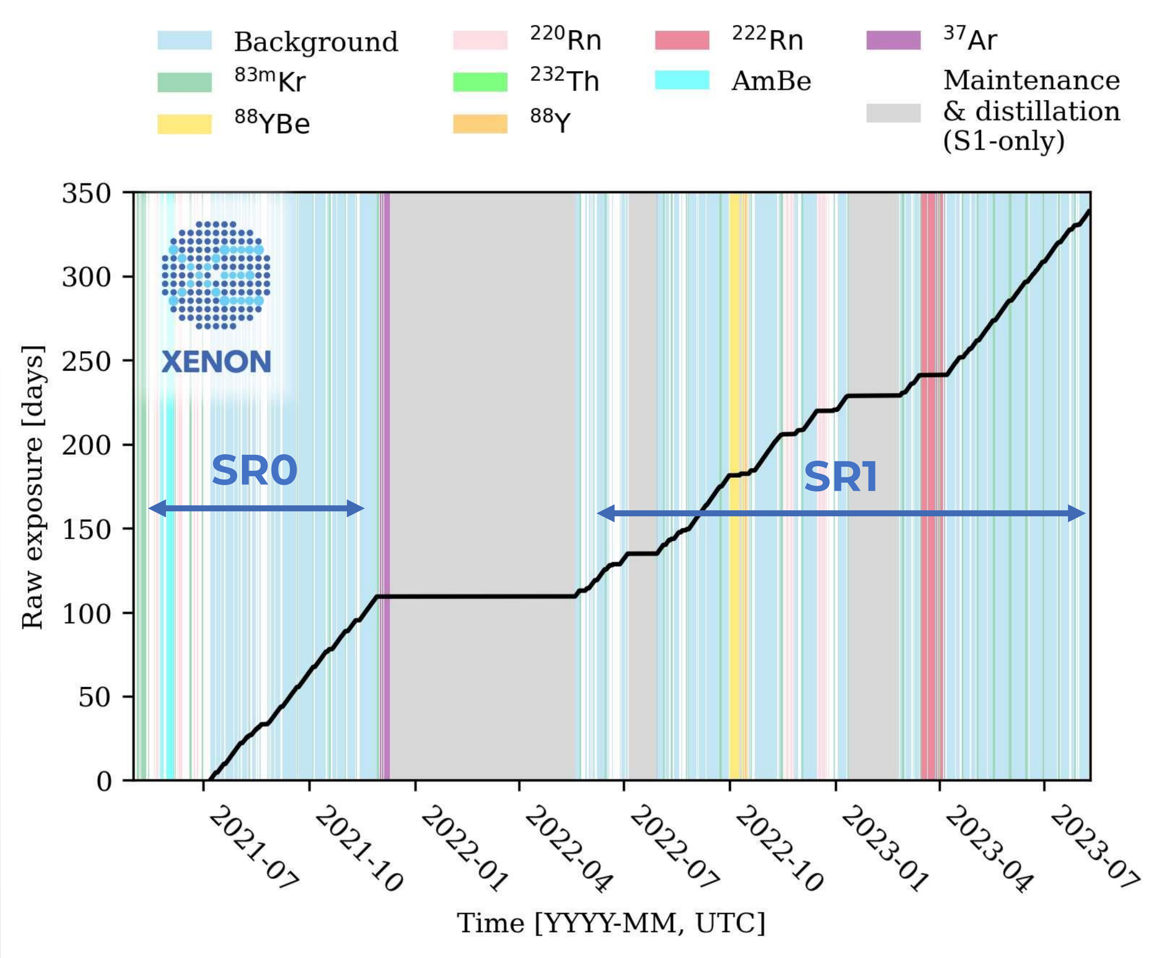
Th232

High energy response.

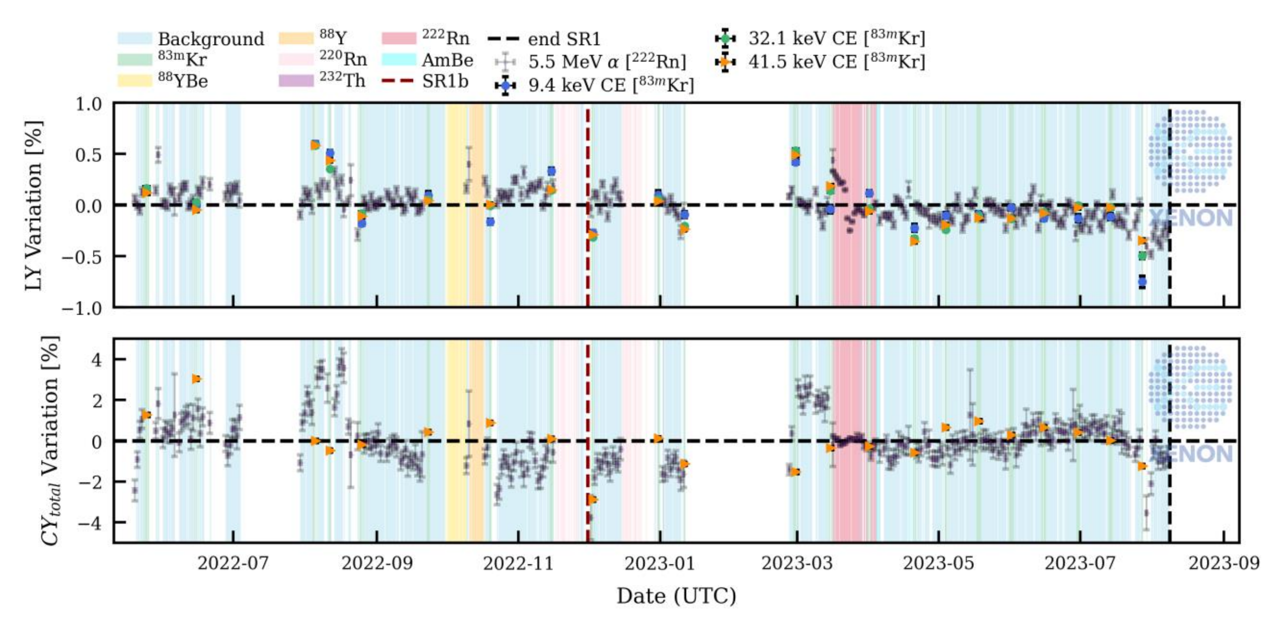
YBe

Low energy NR response specially tuned for the CEvNS search.

XENONnT Science Data

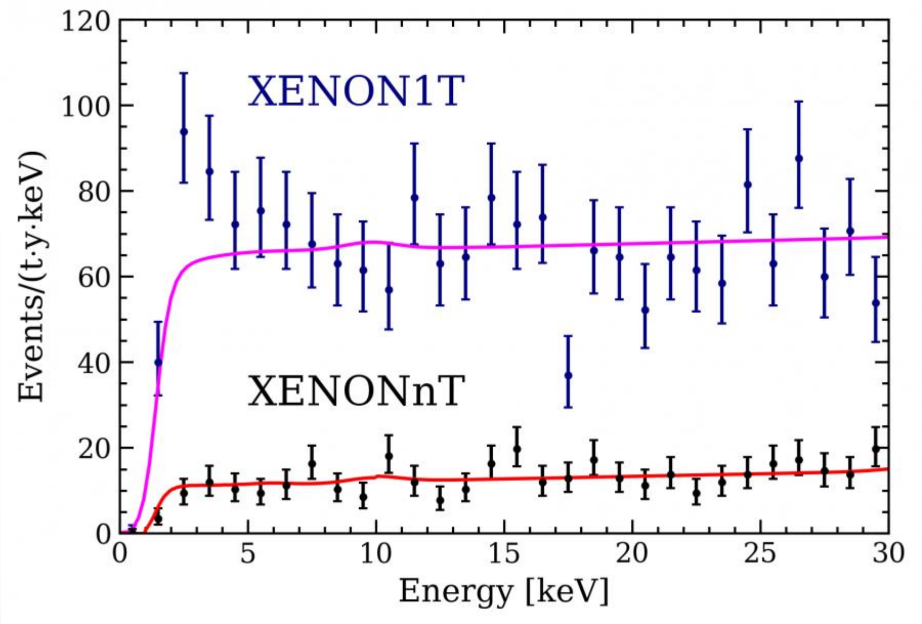


- Science data divided into various **Science Runs (SR)**. Total exposure ~340 days.
- Very stable detector conditions. <1%(<3%) variation in Light (Charge) Yield.



- **High liquid xenon purity**: electron lifetime ~20ms

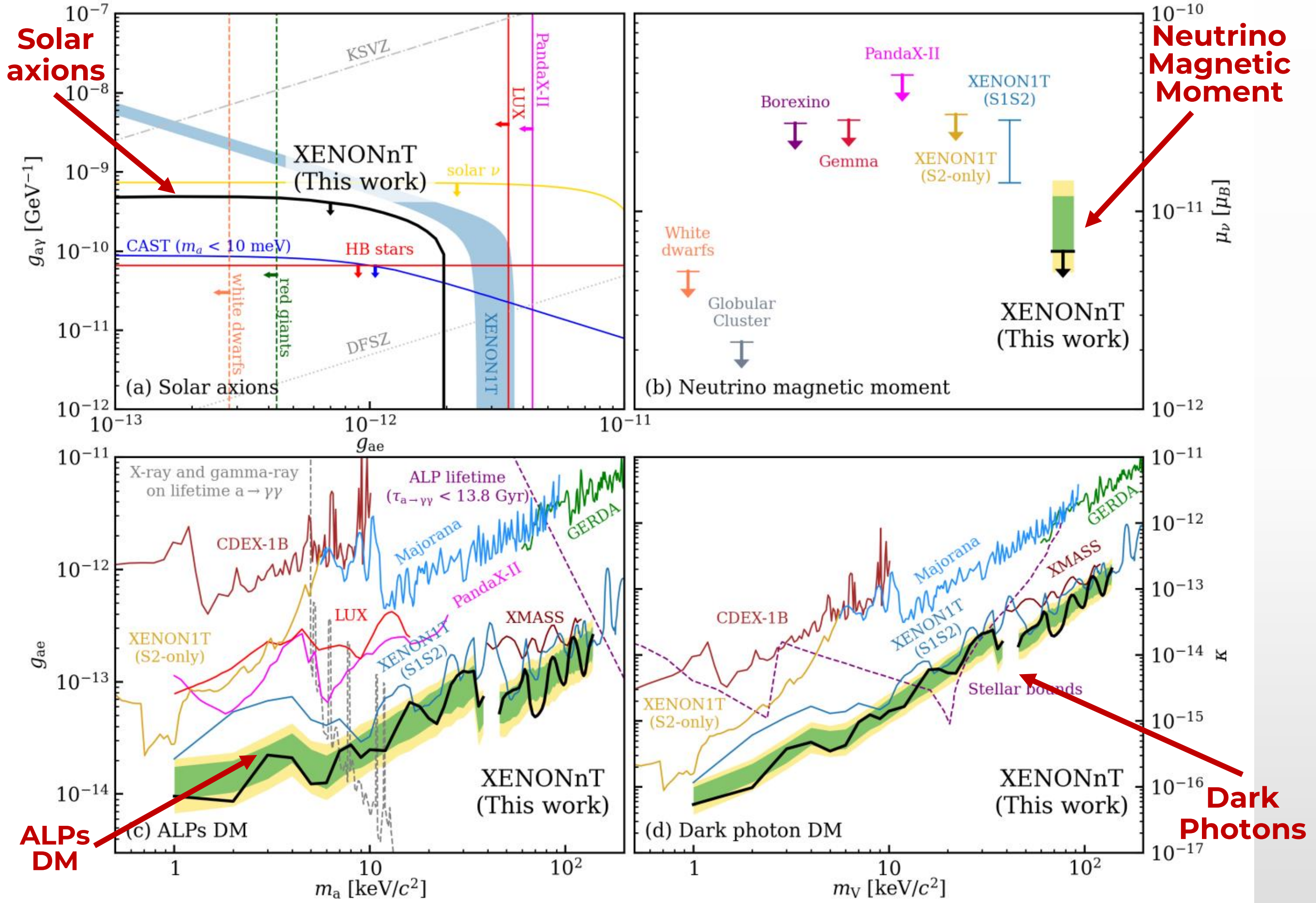
SR0 Results: LowER



Excluded LowER Excess observed in XENON1T at 4σ

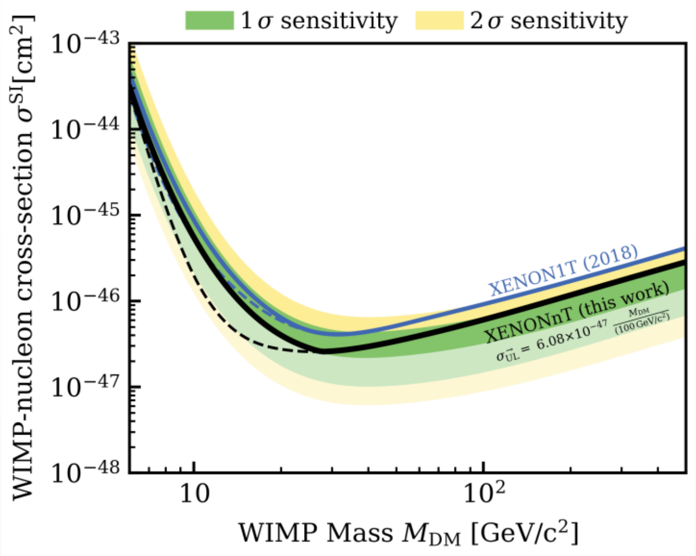
Lowest level of ER background in any Lxe experiment:
$15.8\ events/(t.y.keV)$

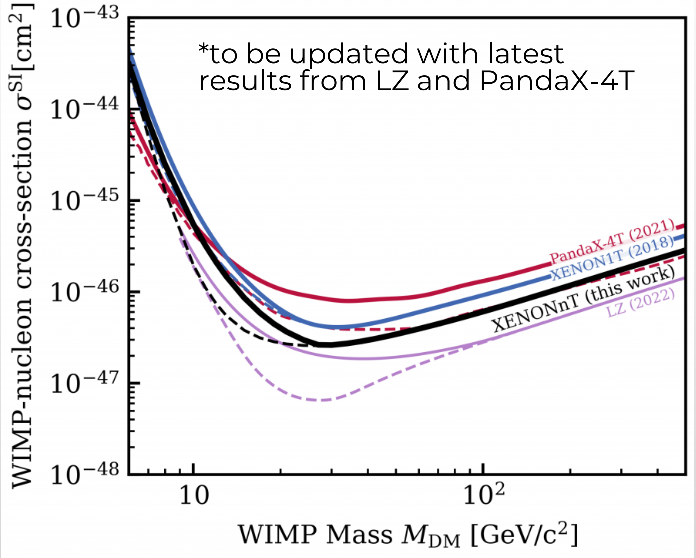
Phys. Rev. Lett. 129, 161805



World leading laboratory results for 'Beyond Standard Model' Signals.

SR0 Results: WIMPs



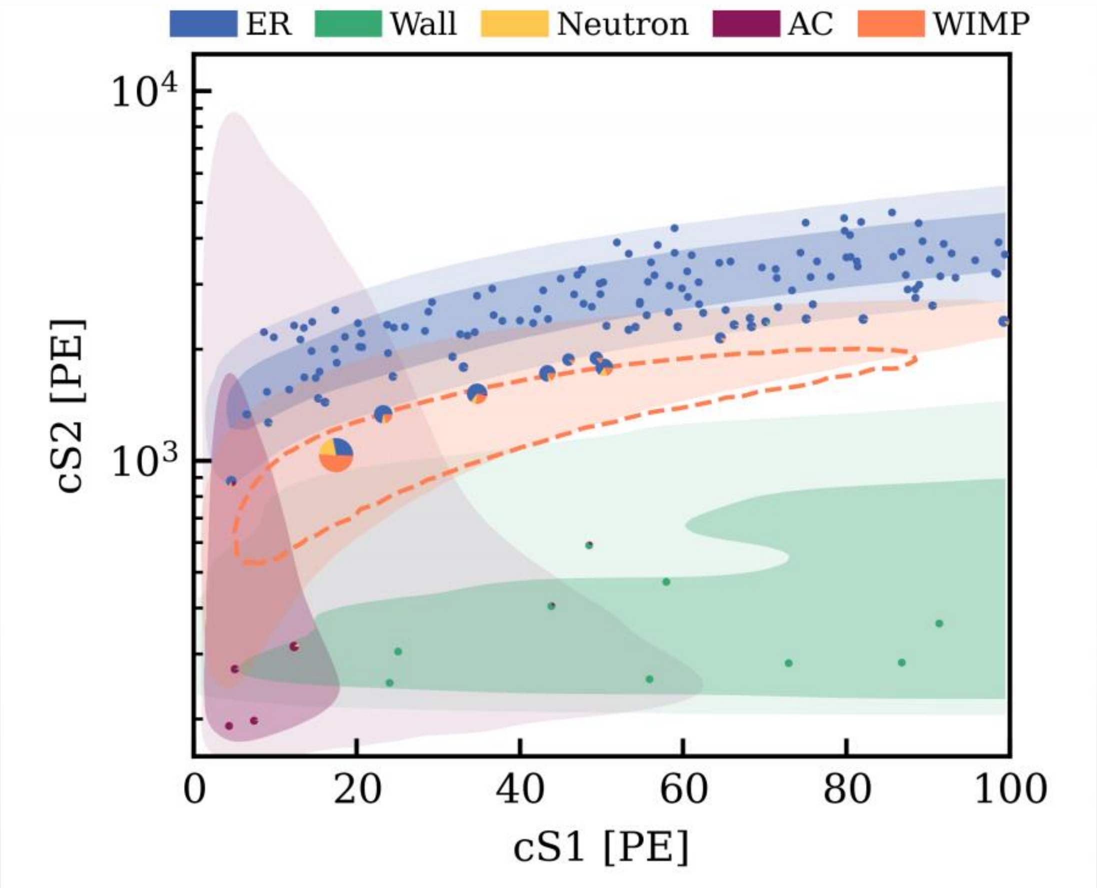


Blind analysis performed with **1.09ty** exposure.

No significant excess observed.

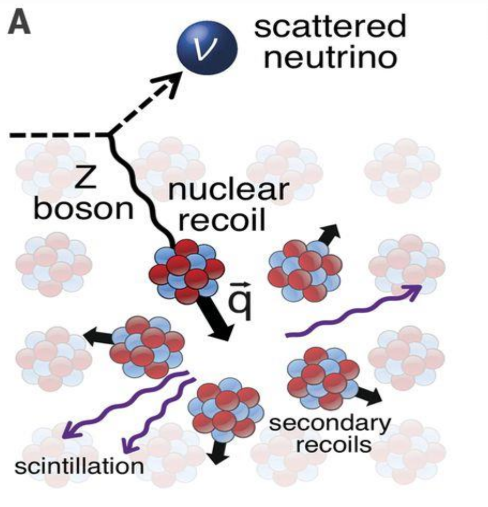
Best exclusion limit of $\mathbf{2.6 \times 10^{-47} cm^2}$ at $28 GeV/c^2$.

Phys. Rev. Lett. **131**, 041003



Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- Neutrino interacting coherently with the nucleus due to the weak current, allowed by SM. First predicted in **1974** (Phys. Rev. D 9, 1389). First observed by COHERENT in **2017** (D. Akimov et al, Science 357 (2017)).
- **Previously, never measured** with a Xenon target or with neutrinos from astrophysical sources.
- Solar neutrinos from ^8B is expected to have the highest number of detectable signals in XnT.



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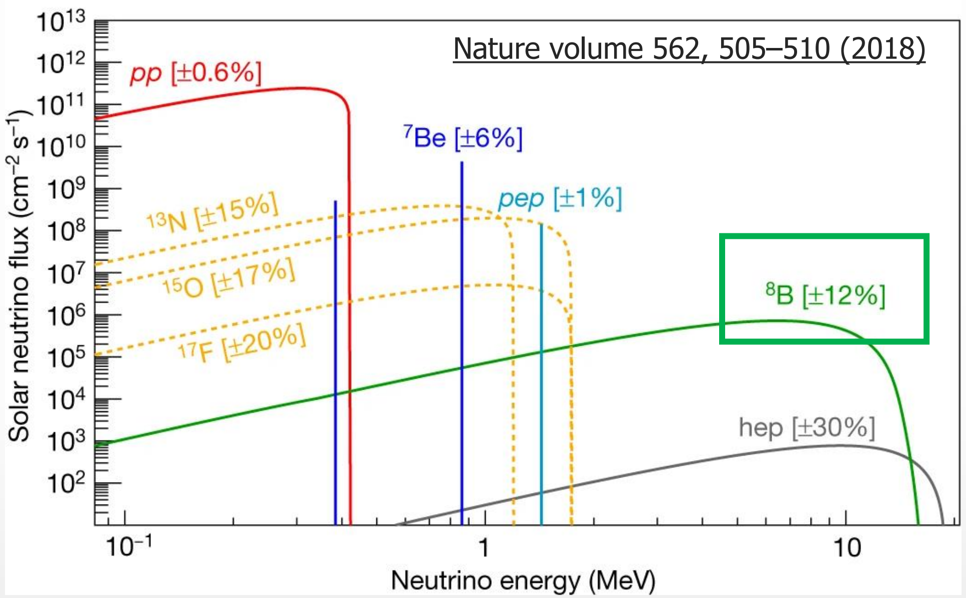


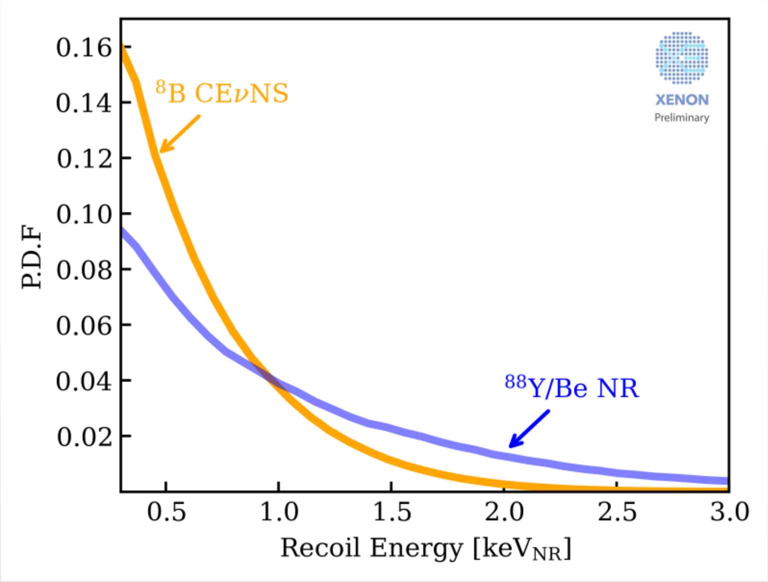
Why measure ^8B CEvNS?

- Important validation of solar neutrino spectrum and SM.
- Signal is almost **indistinguishable** from a 5.5GeV WIMP; important information about background to future WIMP searches.

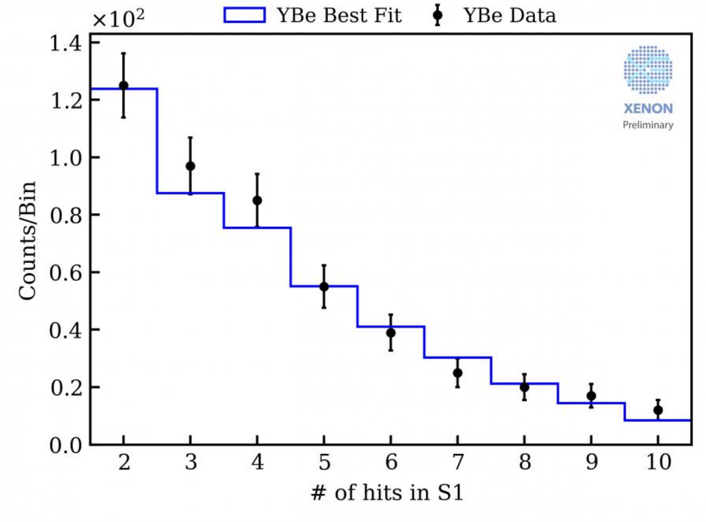
^{88}YBe Calibration: Low Energy NR response

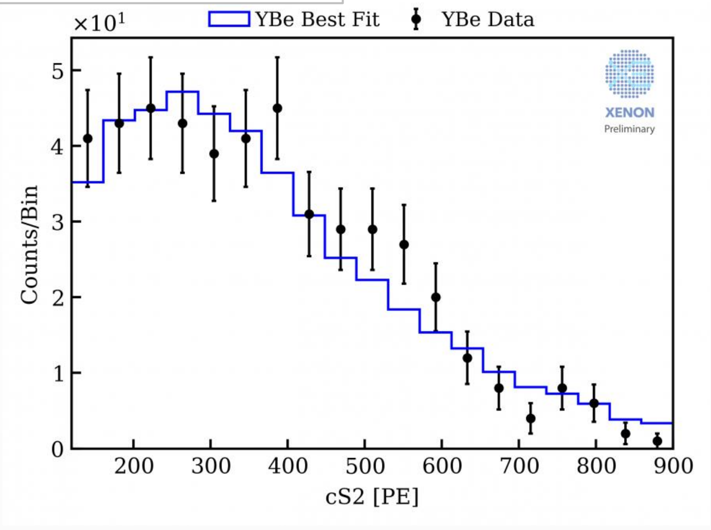
Dedicated publication in preparation.

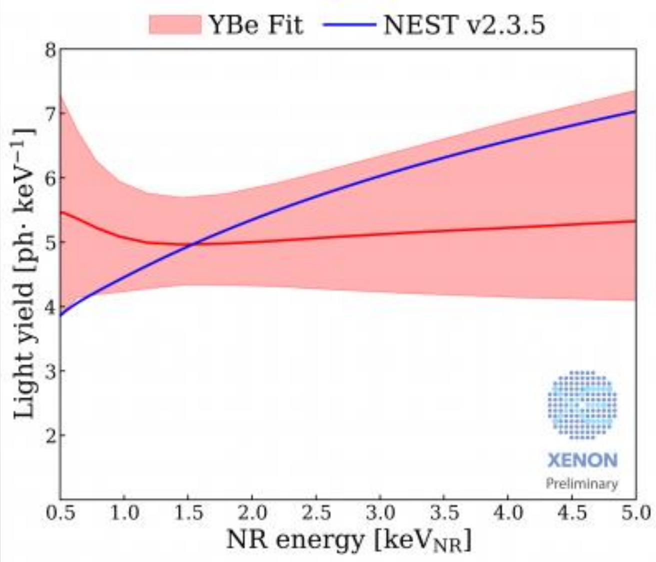
- **152keV neutrons** produced by **photodisintegration of ^{9}Be due to γ from ^{88}Y** show similar recoil energy spectrum in TPC as ^{8}B CEvNS.

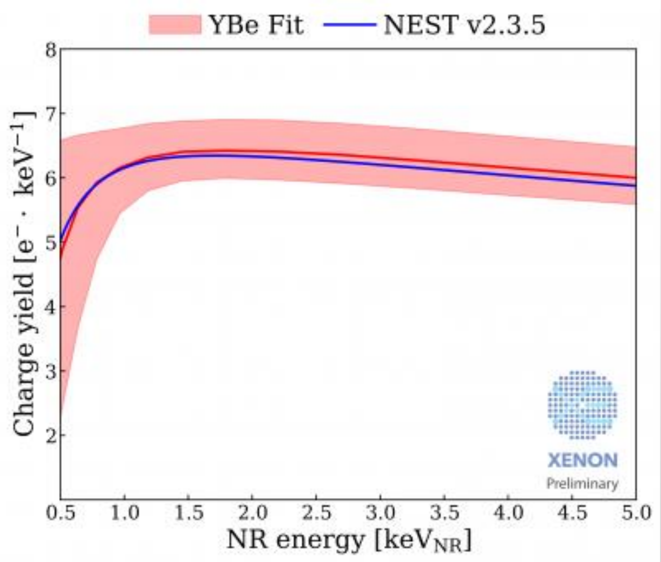


- **Excellent matching with model**. Light and charge yield are constrained by fit of ^{88}YBe data on NEST model at 23V/cm.



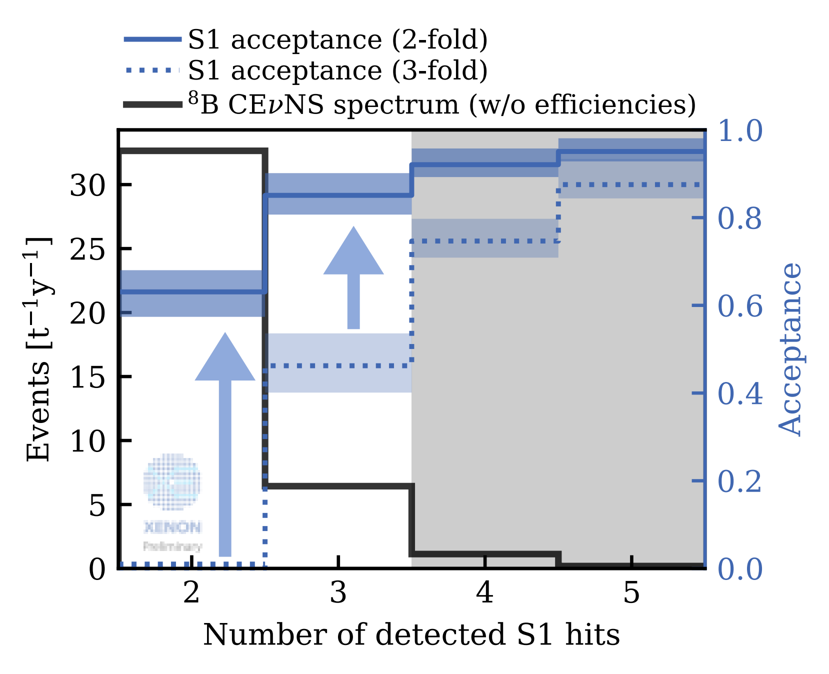






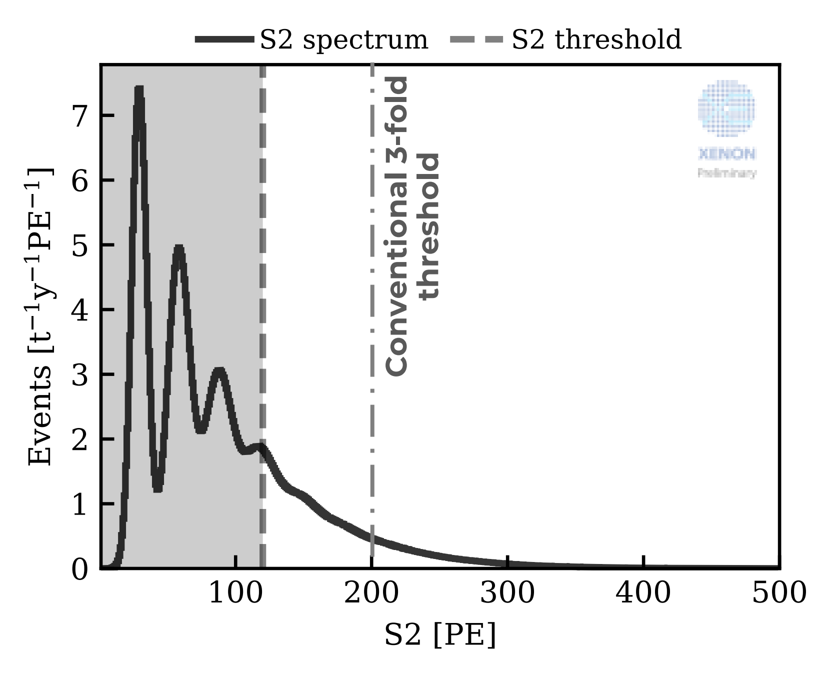
Region of Interest for ^{8}B CEvNS Signal

^{8}B CEvNS rate is too small for detection with classical 3-fold analysis (requiring 3 PMT coincidence; 3 hits).



S1 ROI: 2 or 3 PMT coincidence.

S2 threshold also has to be reduced, but should be high enough to reject high isolated S2rate.



S2 ROI: 120 – 500 PE.

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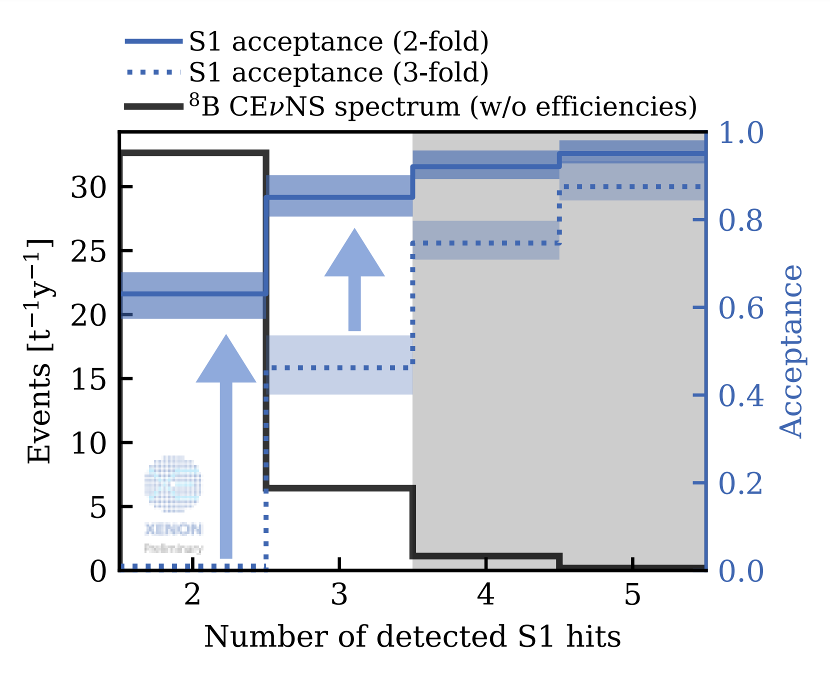

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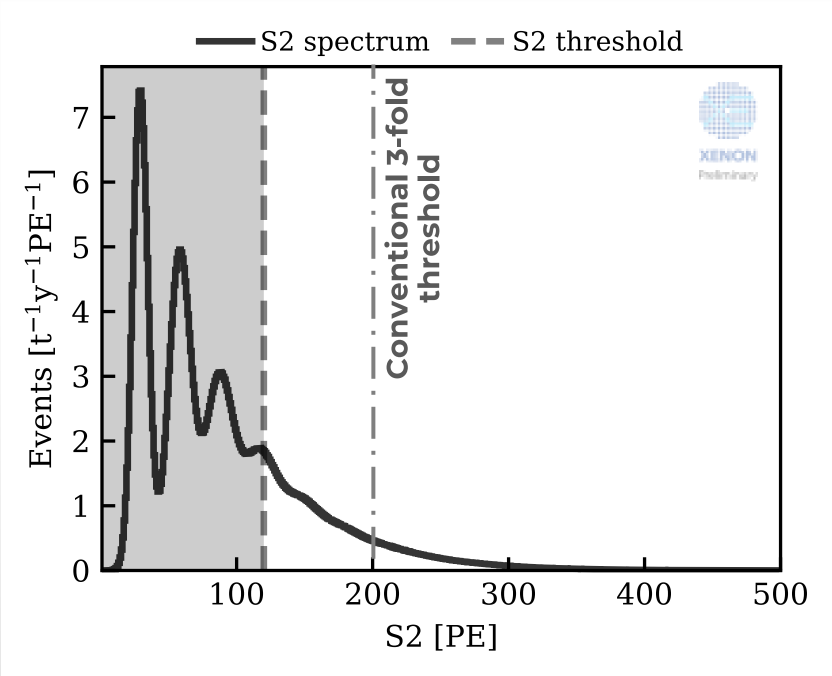
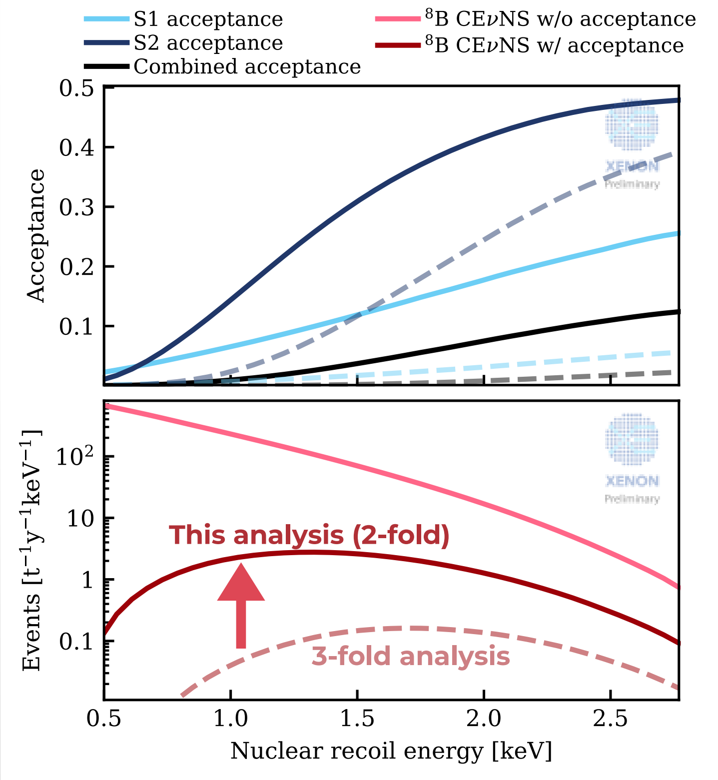


S2 ROI: 120 – 500 PE.

^{8}B CEvNS Signal Acceptance for the search.



arXiv:2408.02877 [nucl-ex]

Backgrounds: Accidental Coincidences(AC)

- ACs are accidental pairings of **Isolated S1** and **Isolated S2** signals.
- AC rate before mitigation:
  - Isolated S1 rate: ~15 Hz
  - Isolated S2 rate: ~150mHz
  - Raw AC rate: **~400 events/day**

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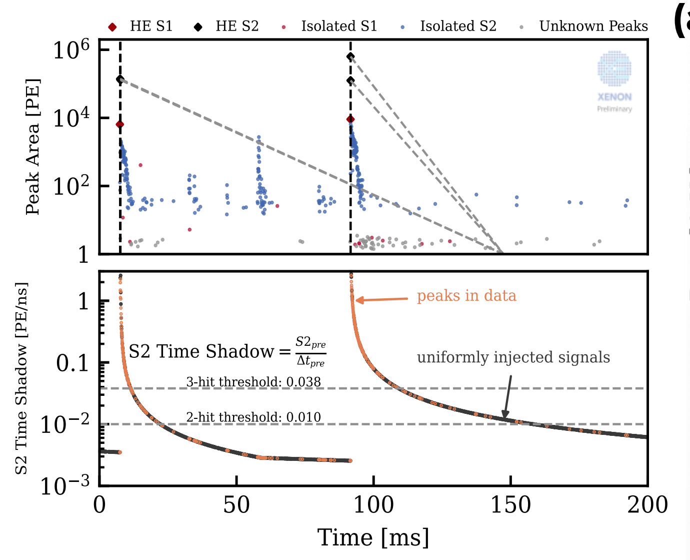
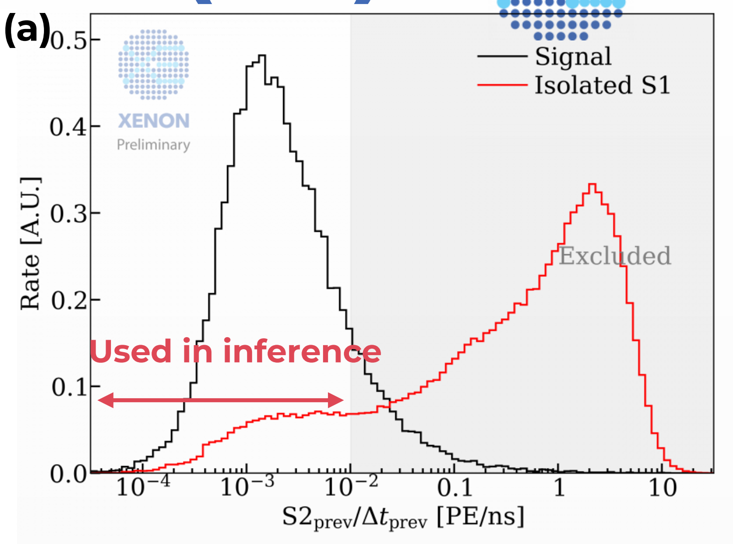
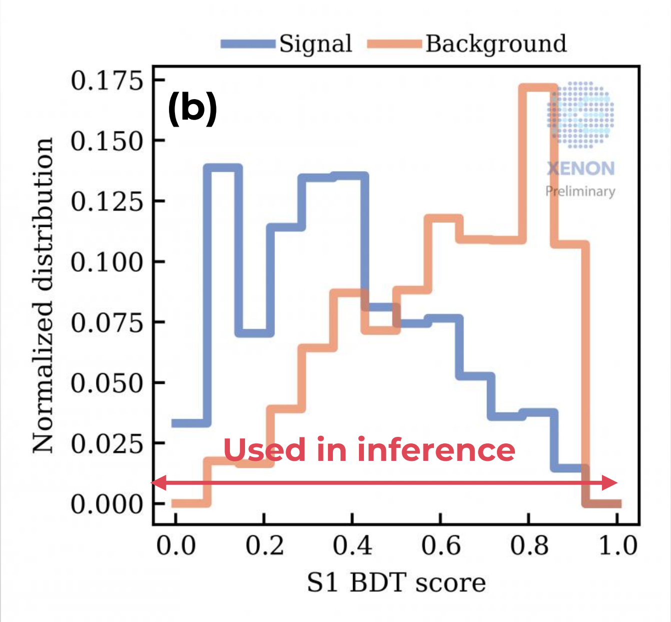
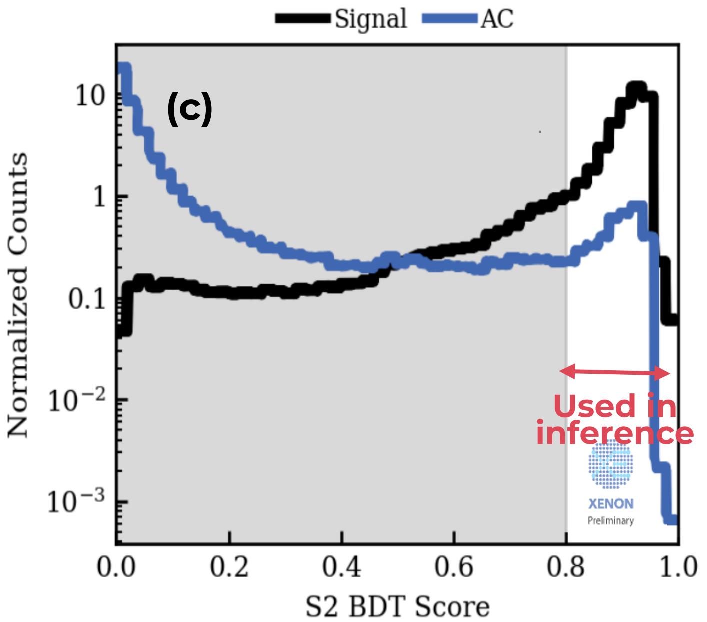




- **ACs mitigation:**
  - **a) Time Shadow Cut:** Uses the time correlation of the previous large S2 peak from HE event.
  - **b) S1 Boosted Decision Tree:** Uses information from the S1 pulse and spatial distribution; discriminate signals from random PMT pileups.
  - **c) S2 Boosted Decision Tree:** Uses S2 width correlation with diffusion of electron cloud during drift. No correlation expected for Isolated S2s.





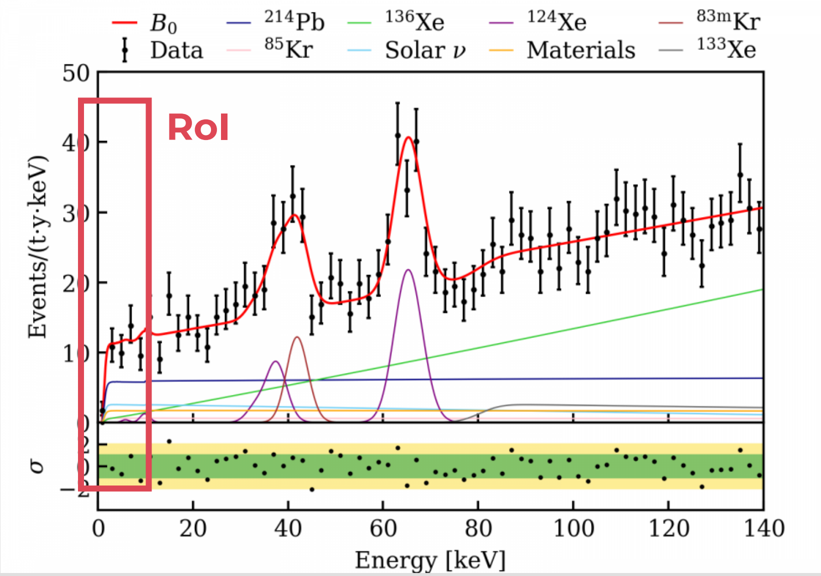
Expected AC Events:

SR0: 7.5 $\pm$ 0.7 | SR1: 17.8 $\pm$ 1.0

Backgrounds: NR, ER and Surface

Electronic Recoil Background

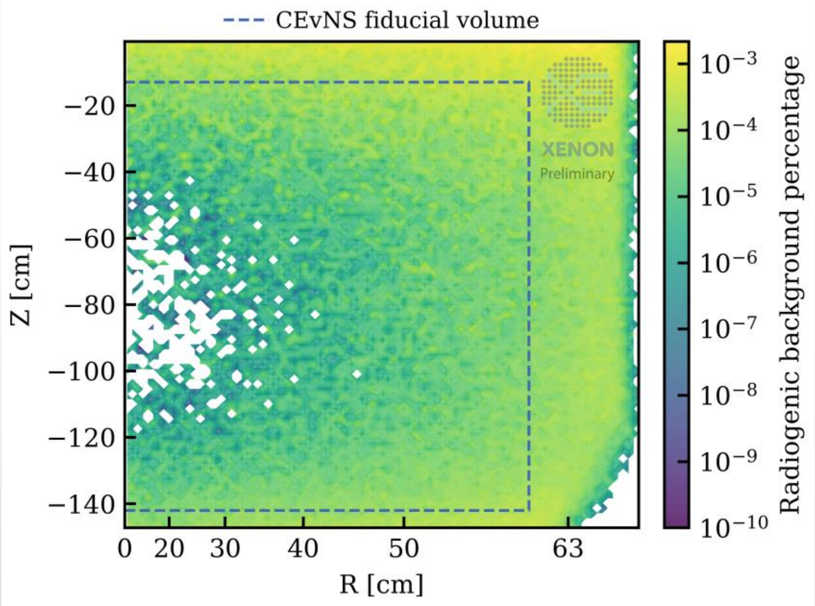
- Dominated by ^{214}Pb decays.
- Assumed flat spectrum with a conservative 100% uncertainty on yields.



- SR0: $\mathbf{0.13 \pm 0.13}$ | SR1: $\mathbf{0.56 \pm 0.56}$ events.

Nuclear Recoil Background

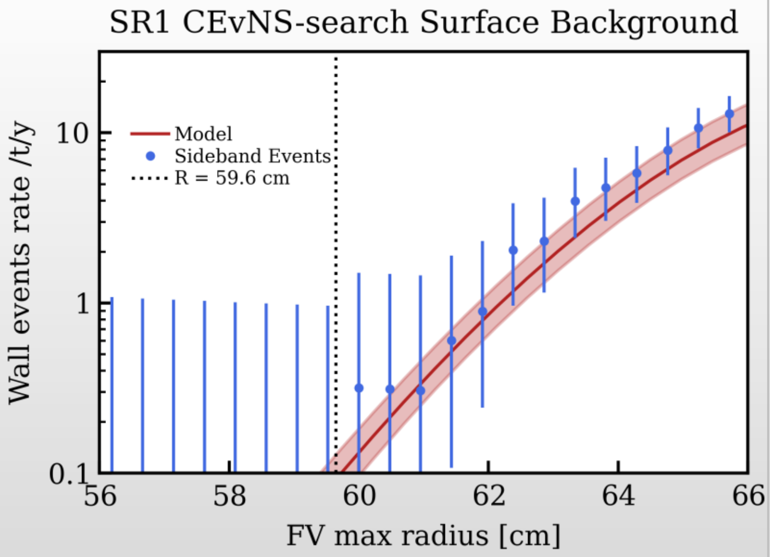
- Fission reactions and (α, n) reactions.
- Modelled by data and MC.



- SR0: $\mathbf{0.13 \pm 0.07}$ | SR1: $\mathbf{0.33 \pm 0.19}$ events.

Surface Background

- Electronic recoils from ^{210}Pb from the walls.
- Impact in RoI negligible due to choice of boundaries to Fiducial Volume.



Prediction before Unblinding

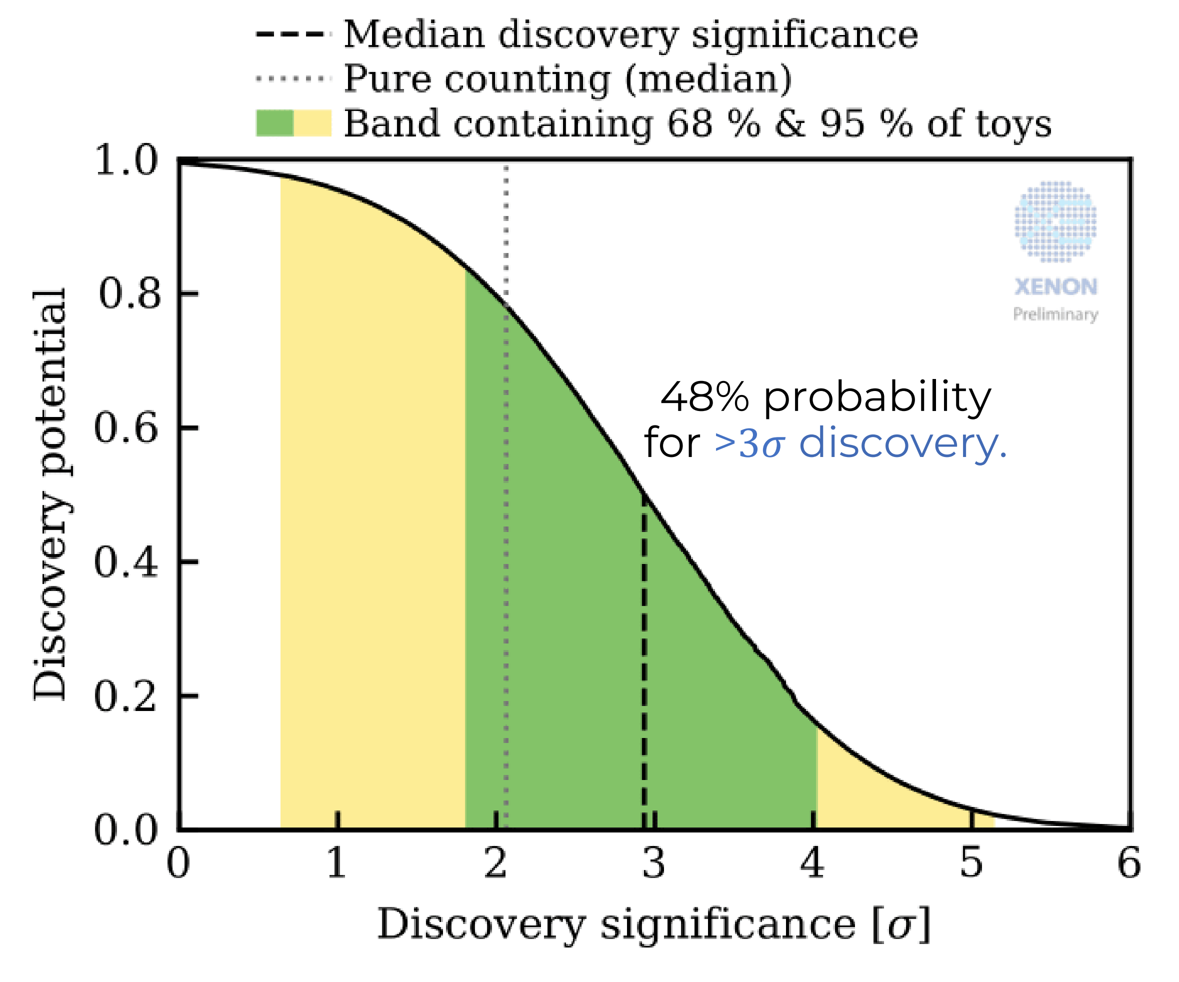
Inference Likelihood

- Binned likelihood in **4-D space** (3^4 bins).
- Likelihood dimensions: (cs2, S1 BDT, S2 BDT, Time Shadow)
- Separate terms for SR0 and SR1.

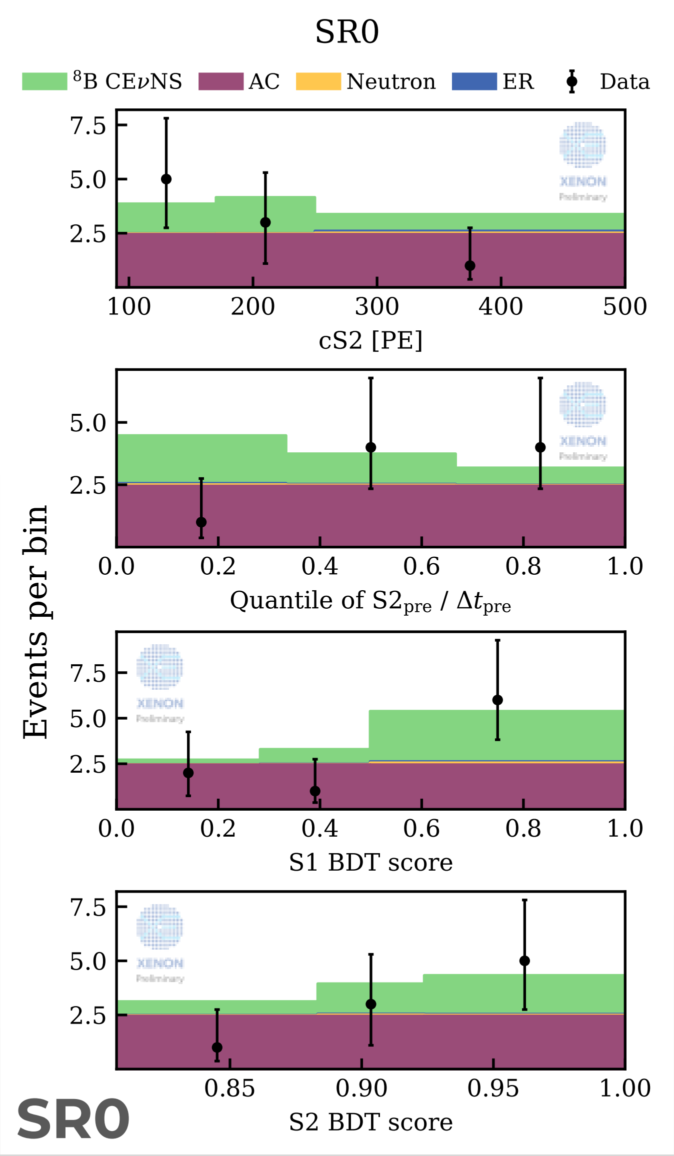
Total Exposure: **3.51** ton years.

Expected Background: **26.4** $\pm$ **1.5** events

Expected Signal: **12** $\pm$ **3** events



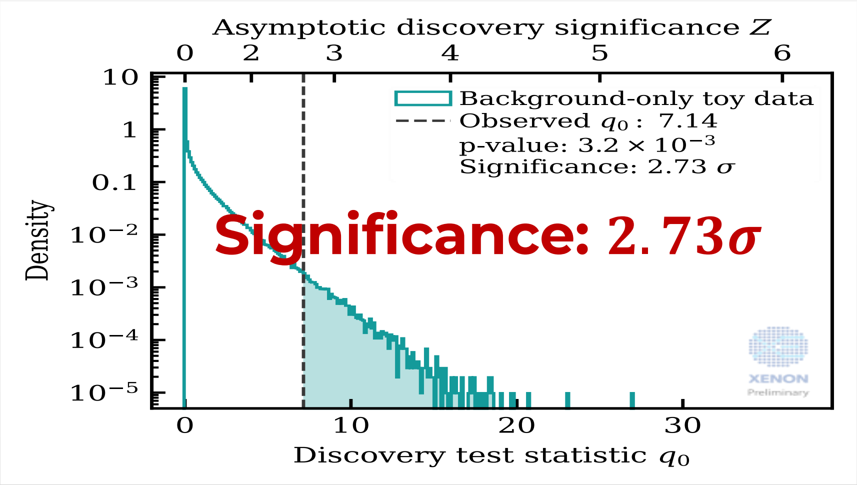
Unblinded Results

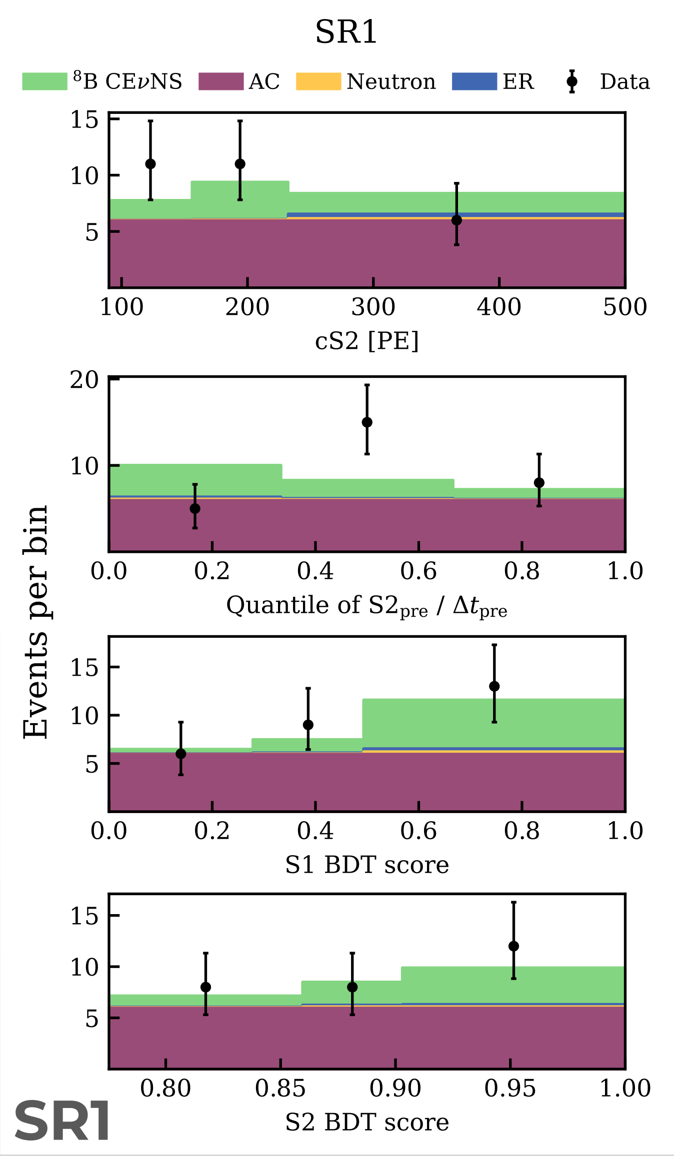


Expected Background: $\mathbf{26.4 \pm 1.5}$
Expected Signal: $\mathbf{12 \pm 3}$

Observed Events: **37**

Best-fit no. of ^{8}B events:
$\mathbf{10.7^{+3.7}_{-4.2}}$





arXiv:2408.02877 [nucl-ex]

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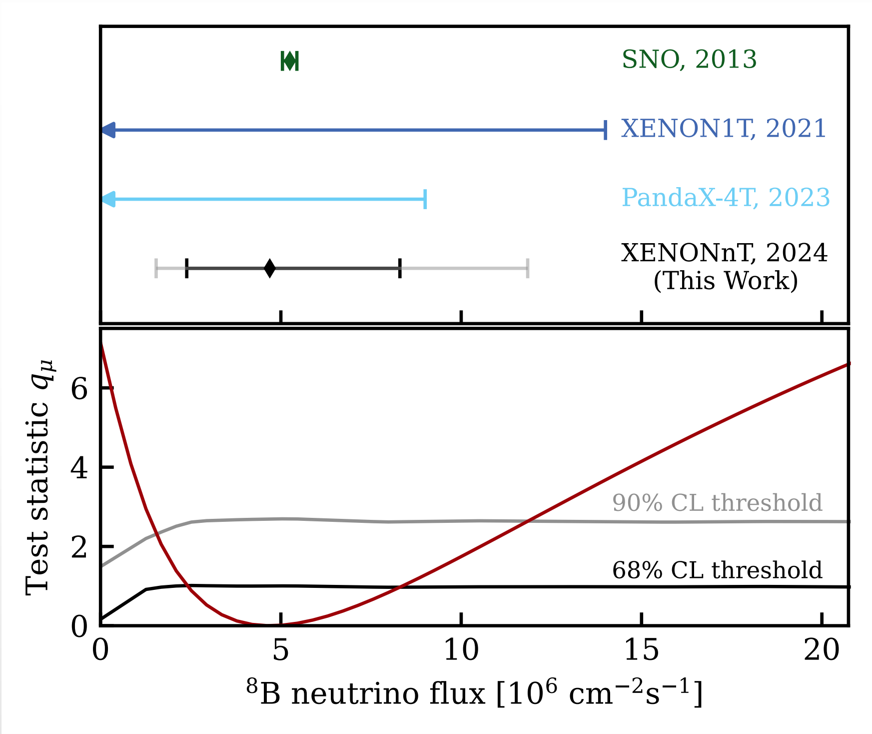
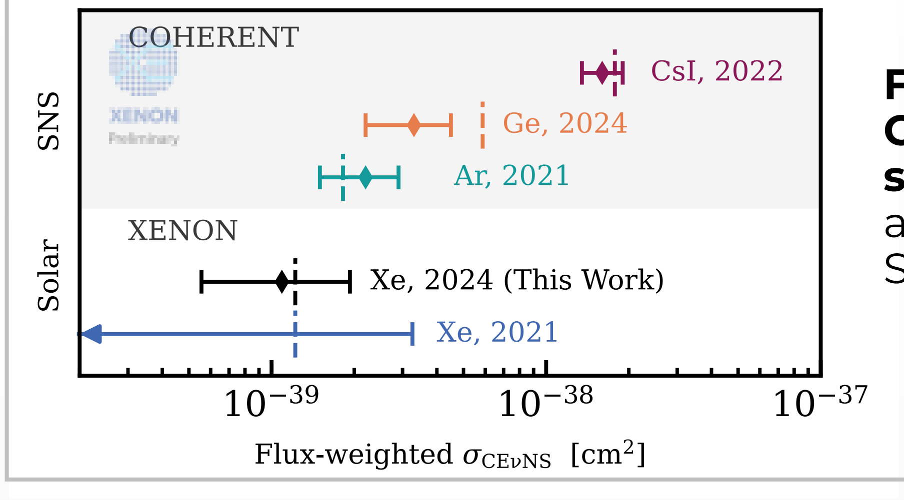
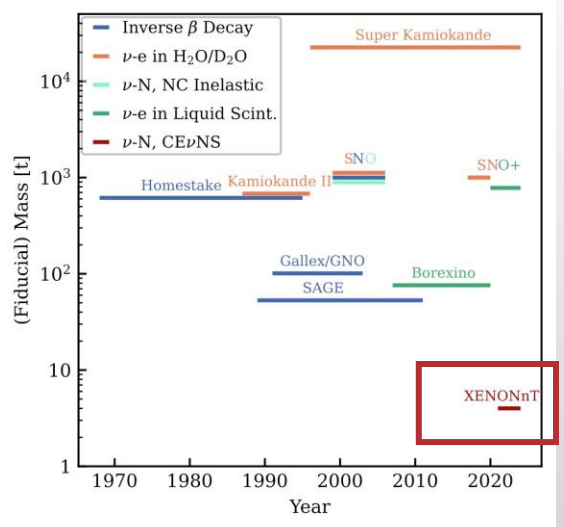


Measured ^{8}B flux: $(4.7^{+3.6}_{-2.7}) \times 10^6 cm^{-2}s^{-1}$.
In agreement with other measurements.



Flux weighted CEvNS cross-section in agreement with Standard Model.



First measurement of CEvNS cross section **in Xe.**

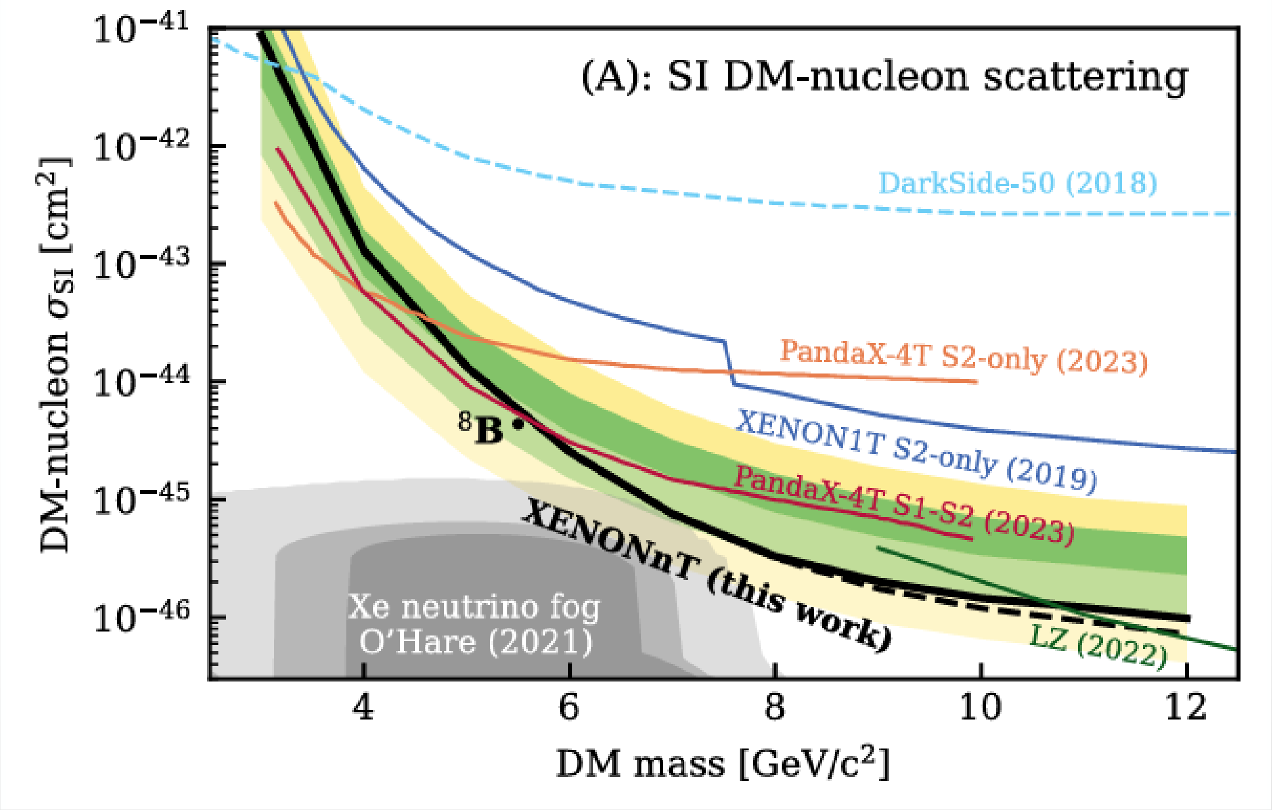
First DM experiment to enter the **neutrino fog.**

Smallest solar neutrino detector.

arXiv:2408.02877 [nucl-ex]

Low-mass WIMP Search

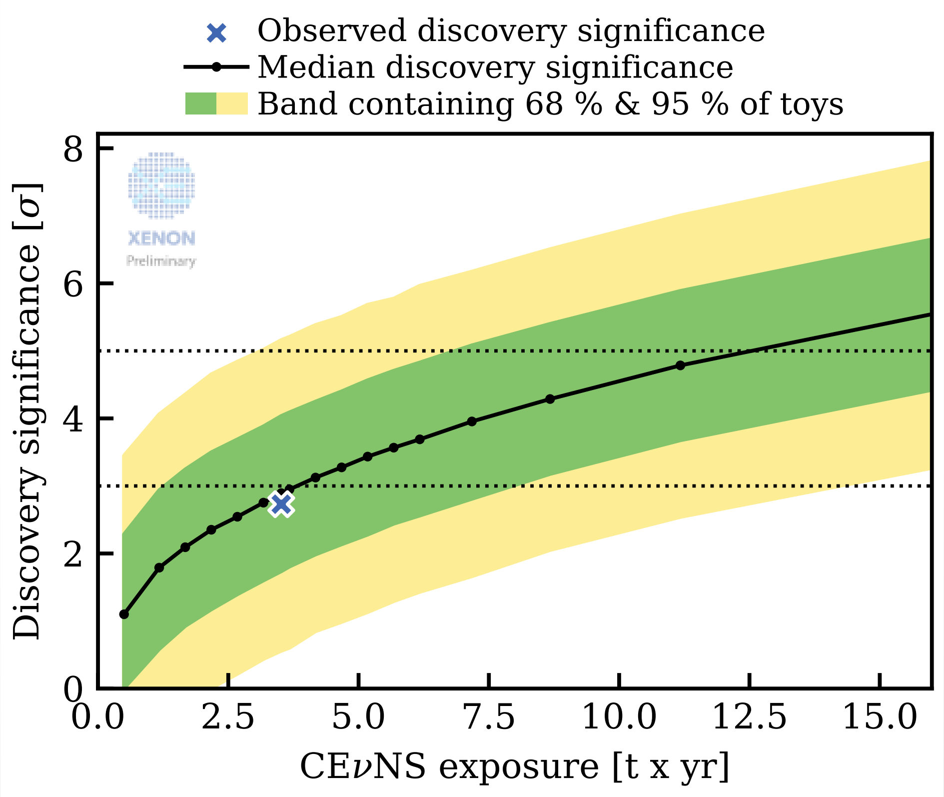
- Same dataset and analysis framework for CEvNS search is used.
- Here, **^{8}B CEvNS becomes a background**.
- **No excess** over background observed.
  - ➢ New parameter space excluded.
  - ➢ First search into the neutrino fog.



arXiv:2409.17868 [hep-ex]

Summary and Outlook

- **First measurement** of solar neutrinos with a DM detector and **first measurement** of CEvNS cross section in Xe. Observes **^{8}B CEvNS at 2.73σ** significance.
- XENONnT becomes the **first experiment to step into the neutrino fog.**
- XENONnT continues to collect blinded data: Precision measurements for CEvNS possible.
- Classical **3-fold WIMP** analysis with more exposure ongoing. **More exciting results very soon!**



Thank you for your attention!

XENON

XENON Website: https://xenonexperiment.org/

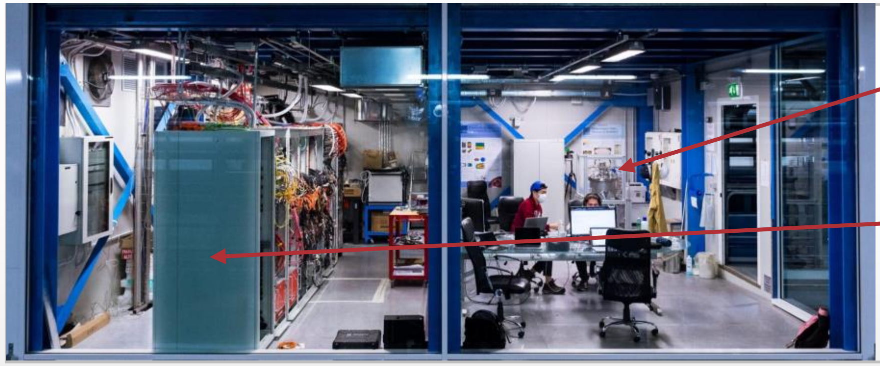
Backup Slides

XENONnT Infrastructure

Rn Column

- Continuous online distillation.
- 222 Rn conc (SR0): $\mathbf{1.8\mu Bq/kg}$
- 222 Rn conc (SR1): $\mathbf{0.8\mu Bq/kg}$

Eur. Phys. J. C (2022) 82: 1104



Kr Column

- ^{nat}Kr/Xe concentration **< 50 ppt**

Eur. Phys. J. C 77, 275 (2017)

nT DAQ

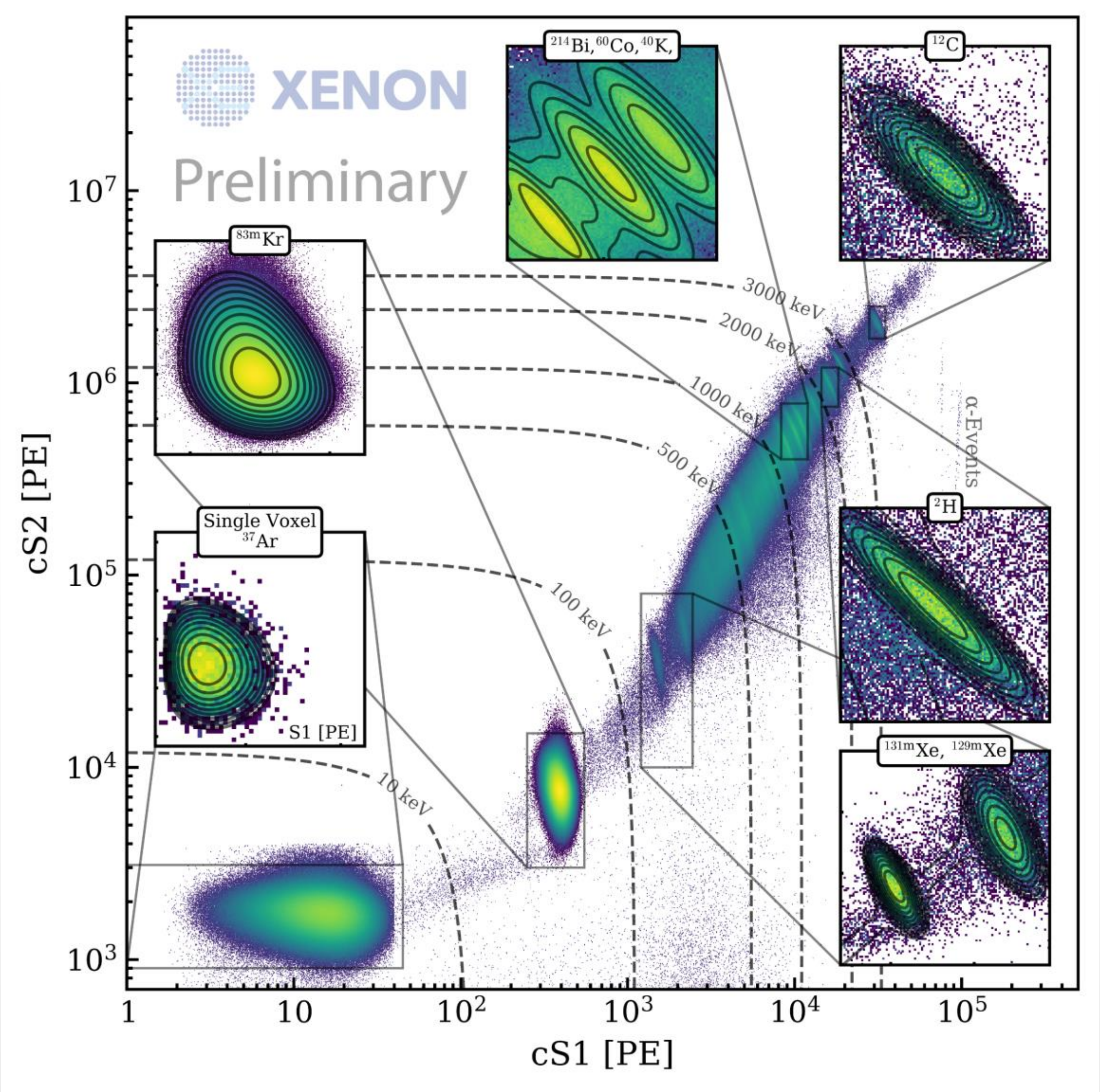
- **Triggerless** DAQ. Shared between three detectors. 2023 JINST 18 P07054

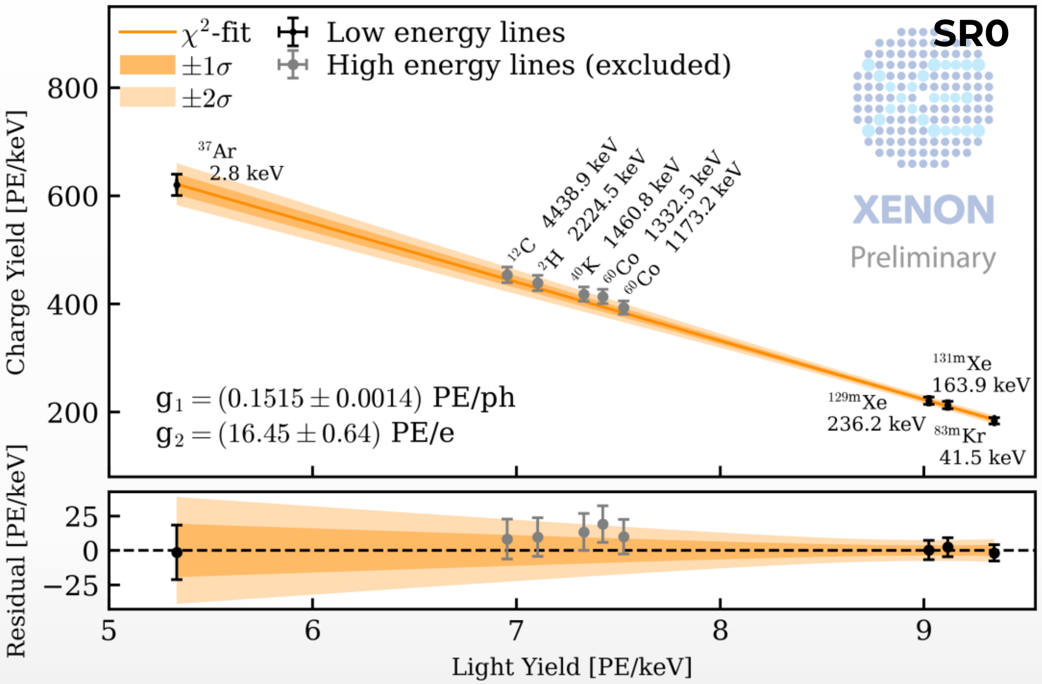
Lxe Purification

- Removes **electronegative** impurities.
- Electron lifetime **~ 15ms.**
- Turn-around time **~0.9 days** for 8.6t.

Eur. Phys. J. C (2022) 82: 860

Energy Calibration: g1,g2

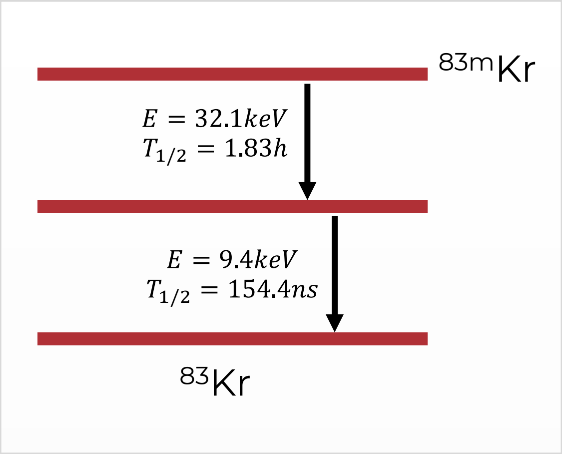




- g1,g2 calculated using monoenergetic peaks in cs1-cs2 space and the 'doke' plot.
- Combined energy scale: $E_{ces} = 13.7eV \times (cs1/g1 + cs2/g2)$

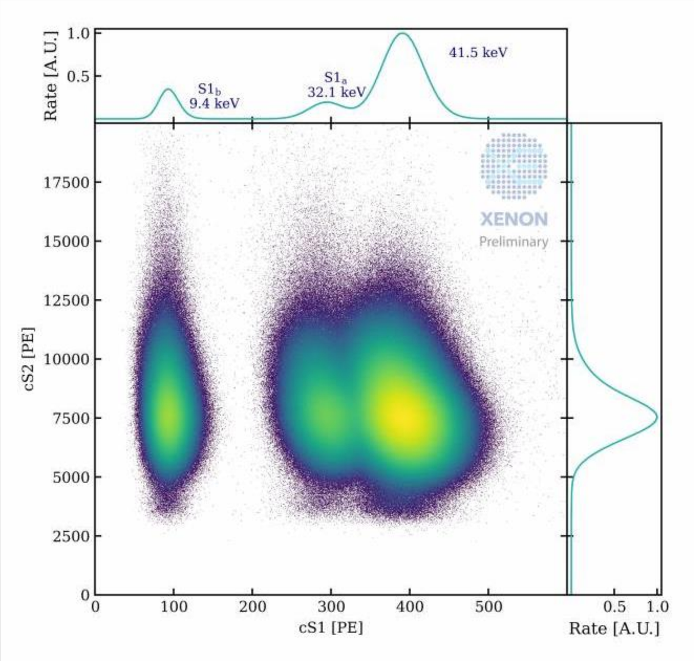
SR0	SR1
g1: $(0.151 \pm 0.001) PE/ph$	g1: $(0.136 \pm 0.001) PE/ph$
g2: $(16.45 \pm 0.64) PE/e$	g2: $(16.85 \pm 0.46) PE/e$

Corrections to Detector Effects

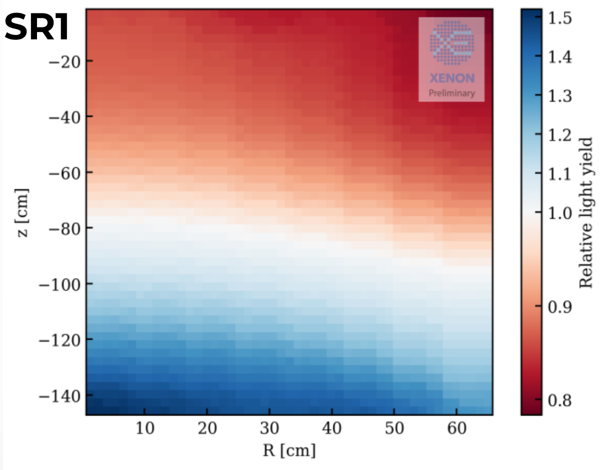


Calibrations using ^{83m}**Kr**

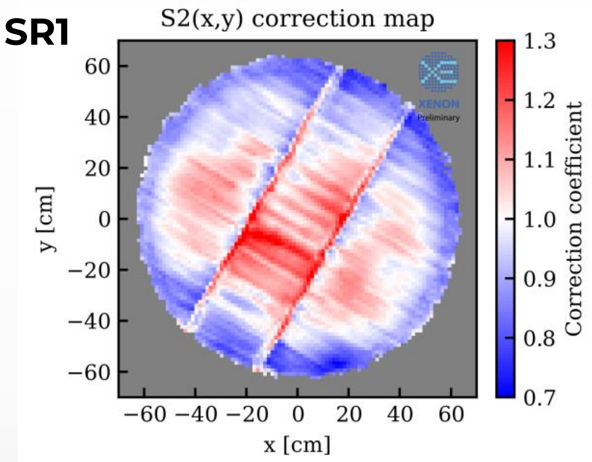
- Perform regular (~biweekly) calibration using internal calibration source.
- ^{83m}Kr **uniformly distributed** in the TPC

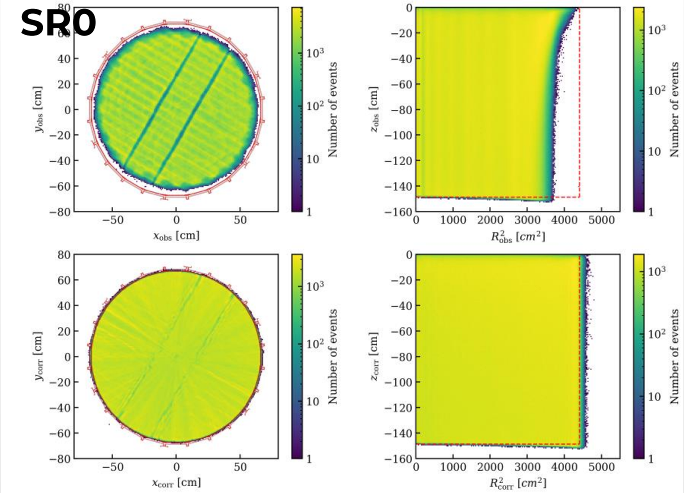


S1 Light collection efficiency



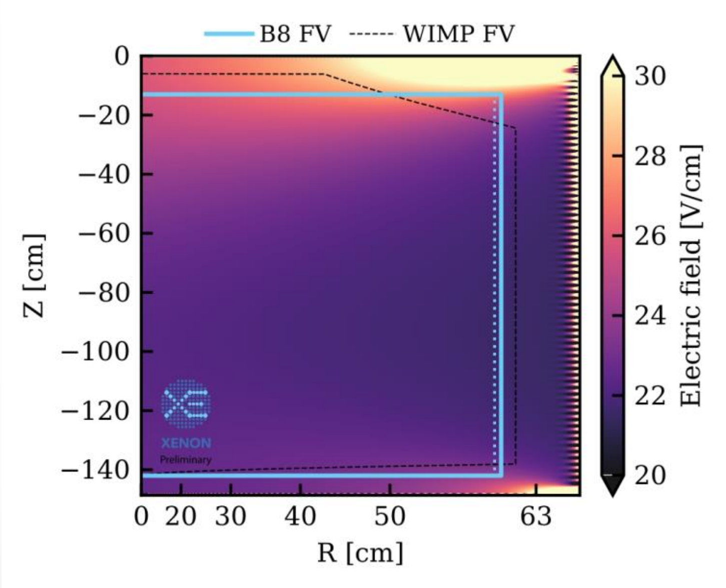
S2 Light collection efficiency

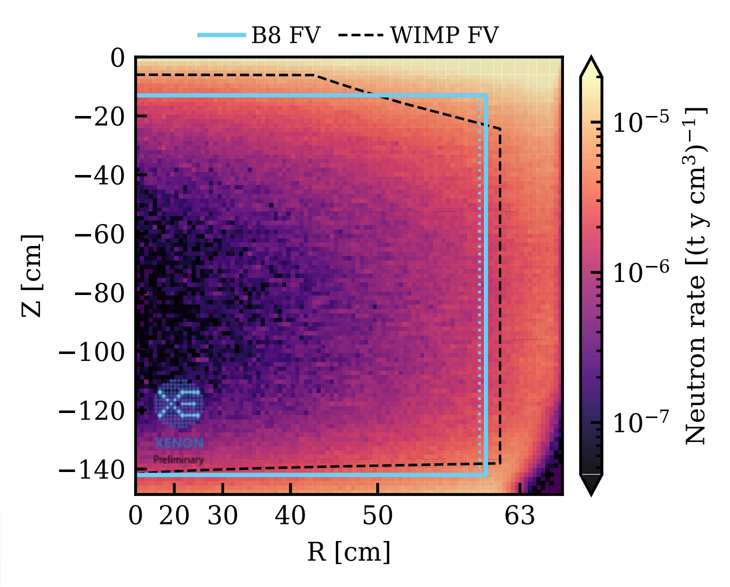




Field Distortion Correction

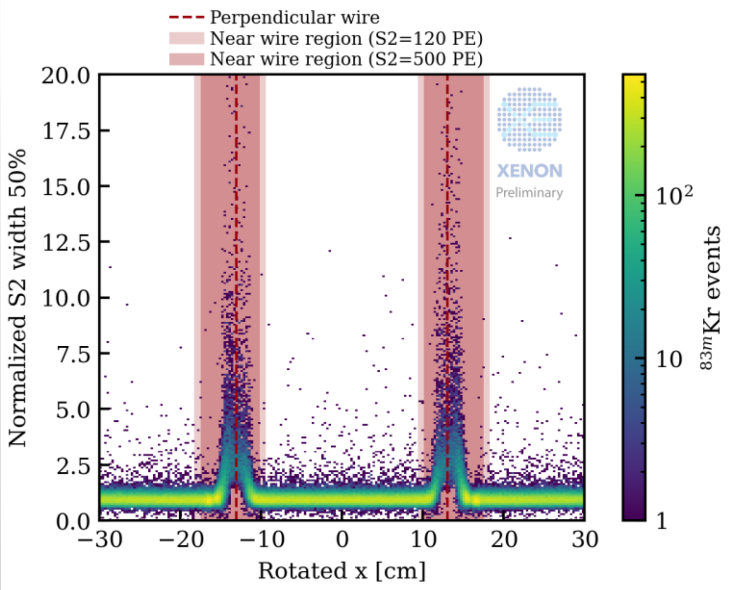
Choice of **Fiducial Volume**





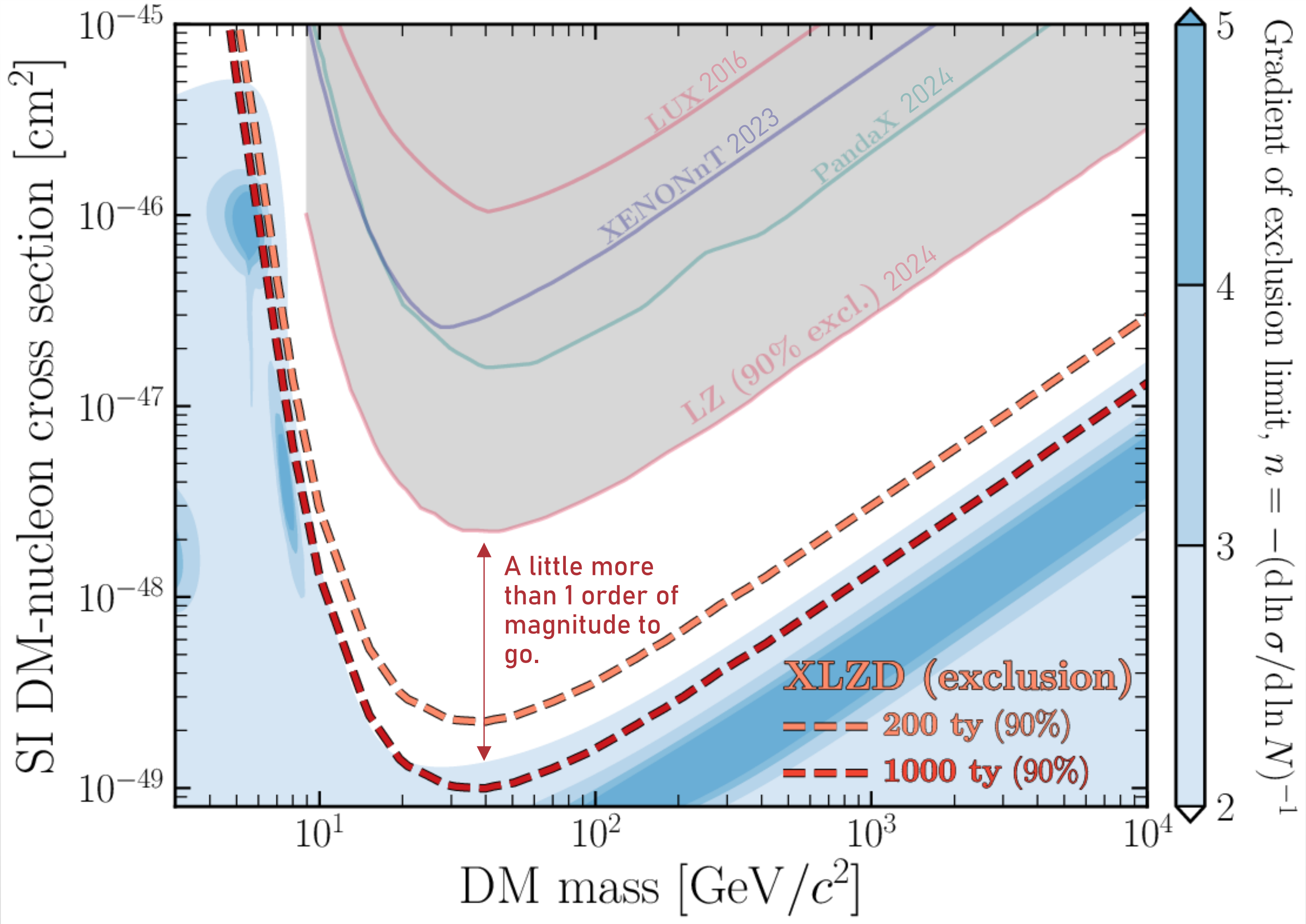
2023 WIMP analysis; FV chosen to give the best signal-background discrimination ratio.

2024 CEvNS analysis; FV chosen to exclude regions with limited detector modelling and higher background rates.



Regions **near the perpendicular wire are also excluded** from analysis as effects from the wire are not sufficiently well simulated, and thus may bias the S2 BDT score (trained on simulations).

Status of WIMP searches with LXe



- The current best exclusion limits for SI DM-nucleon cross section is at $2.1 \times 10^{-48} cm^2$ at $36\ GeV/c^2$ (arXiv:2410.17036 [hep-ex]).
- Design sensitivities for XENONnT at 20ty and LZ at 15ty are ~$10^{-48} cm^2$.
- About 1 order of magnitude remains to the "**neutrino fog**": where neutrinos from the atmosphere become an irreducible background.

XLZD is a collaboration between researchers in XENON, LZ and DARWIN to build the ultimate LXe based TPC with active target mass up to **80t**.

Design sensitivity all the way to the neutrino fog in the WIMP RoI.

arXiv:2410.17137 [hep-ex]

Impact on Signal from uncertainties on Yield

Two morphers t_{ly} and t_{qy} used to **parameterize the uncertainty** on the yield model from fit of NEST model on YBe calibration data.

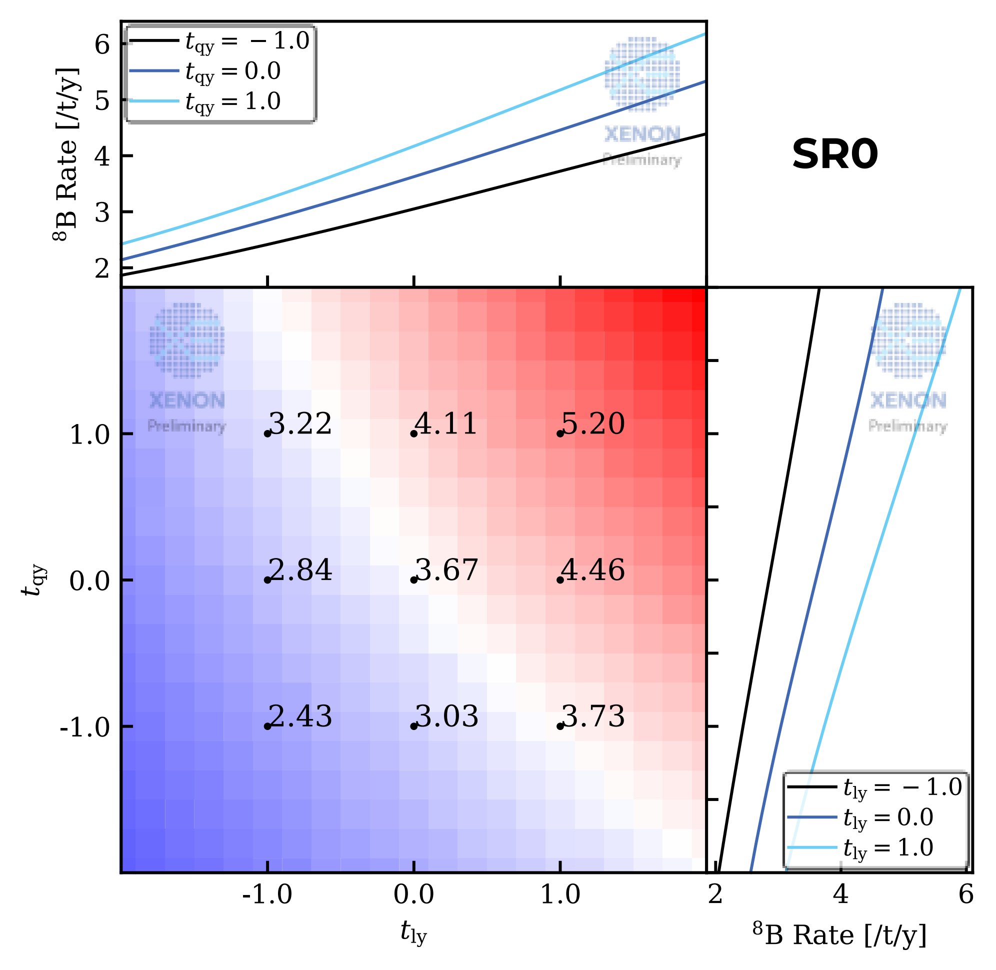
Median from fit (23V/cm)

Uncertainty band in fit

$$L_y(t_{ly}) = \langle L_y \rangle + t_{ly} \times \sigma_{ly}\left(sign(t_{ly})\right)$$
$$Q_y(t_{qy}) = \langle Q_y \rangle + t_{qy} \times \sigma_{qy}\left(sign(t_{qy})\right)$$

$t_{l(q)y} \sim N(0, 1)$

Morphers (t_{ly} and t_{qy}) are used as nuisance parameters in the final inference.

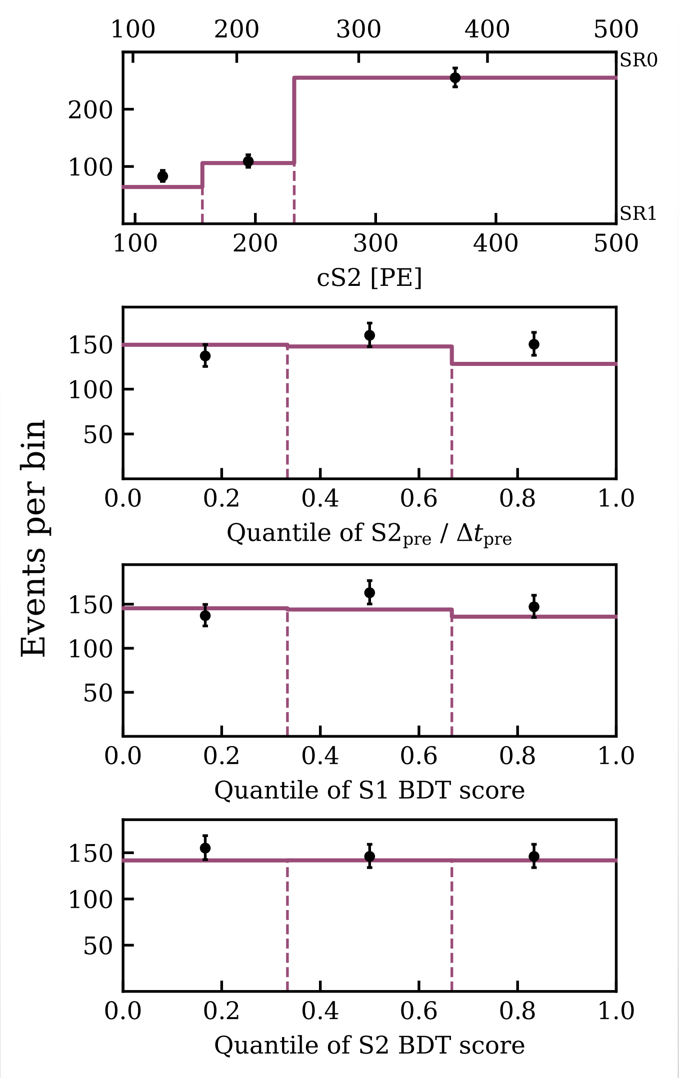


Expected ^{8}B rate at different light and charge yields.

Dedicated publication in preparation.

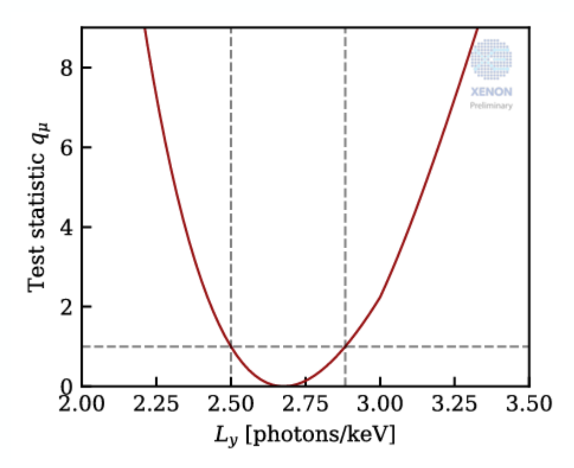
AC Model: Validation

AC Sideband

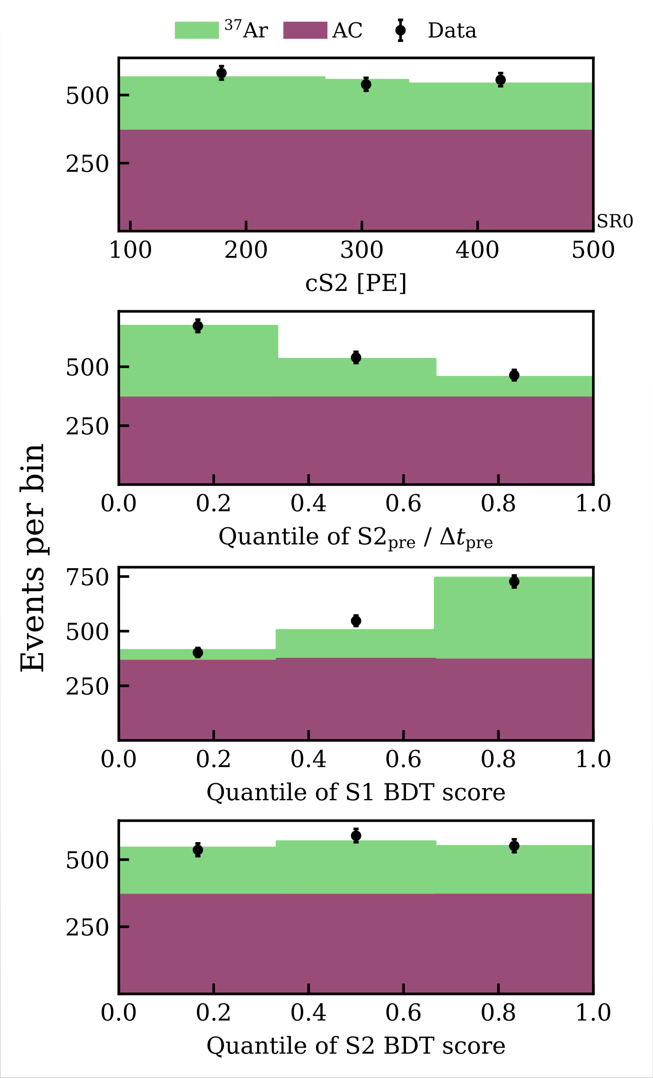


- The AC Model was validated on the AC sideband (events that fail the S2 width and S2 BDT cut) and the 0.27keV ^{37}Ar L-shell EC calibration data.
- Shows good match. The <10% difference is considered while estimating the systematic uncertainties.

^{37}Ar looks like the CEvNS signal; also allows for validation of signal model and constraining the light yield at low energies.

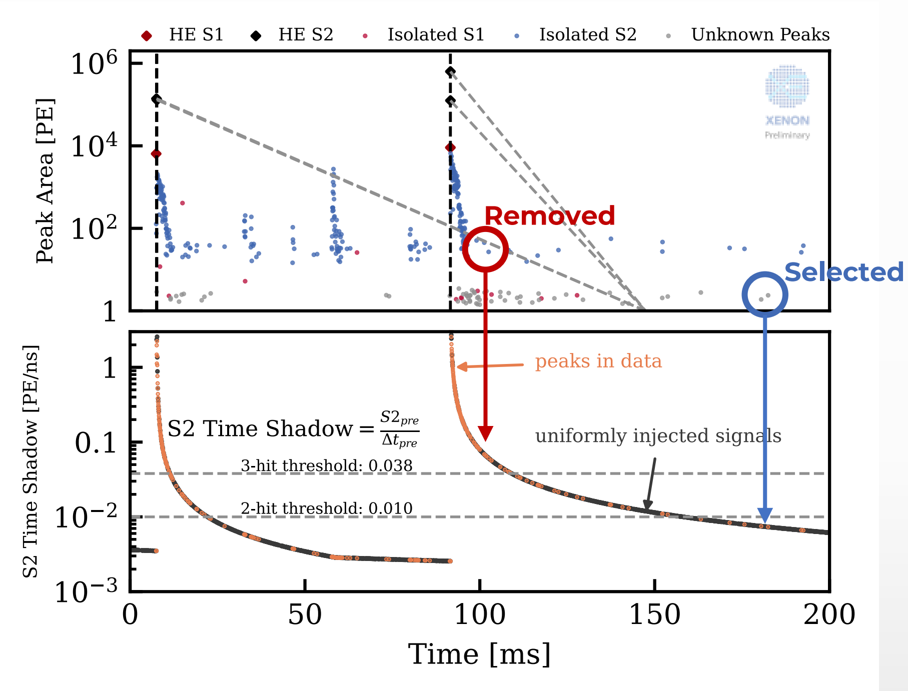


^{37}Ar L-Shell



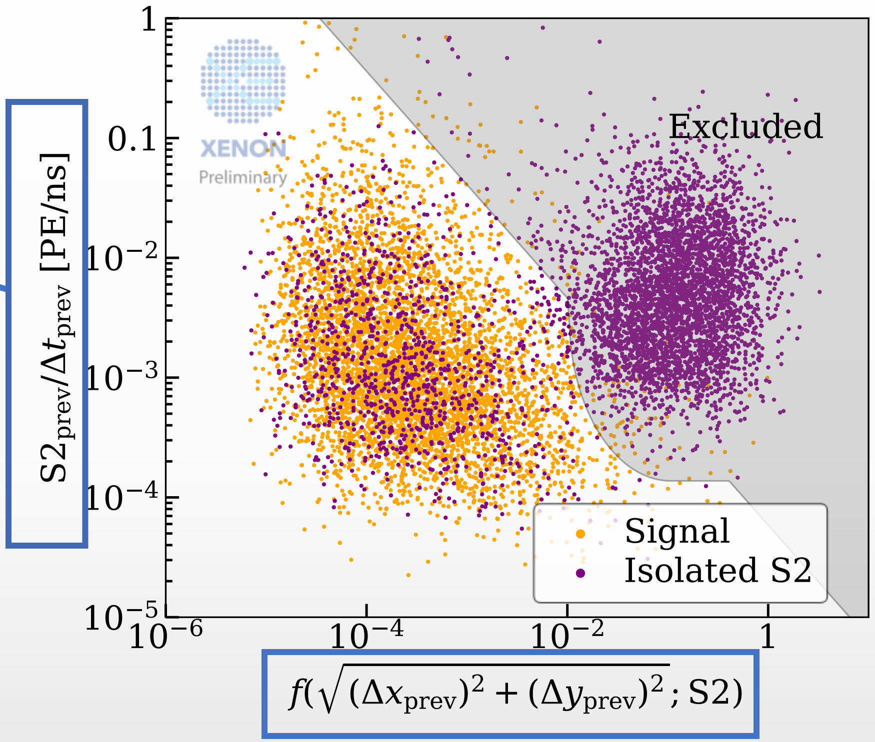
Time and Position Shadows

Time Shadow



- High chance of a train of delayed electrons and lone hits after of **large S2** (or S1) from a HE event: HE S2 causes a "shadow effect".
- "Signal" uniformly distributed in time.
- Time shadow ($S2_{pre}/\Delta t$) of **Iso-S1s** typically larger than of signal.

Position Shadow



Function providing the position correlation of a large S2 and Iso-S2s, accounting for resolution.

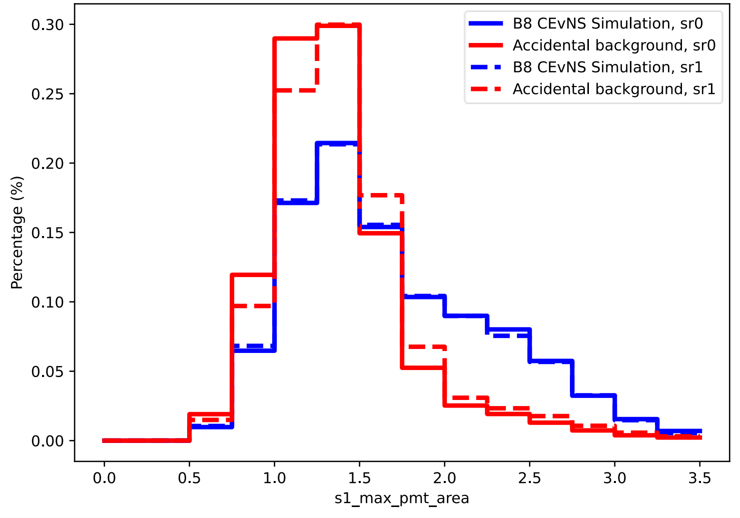
- Using the position information, **Iso-S2s** can be removed by combination of time and position shadow.

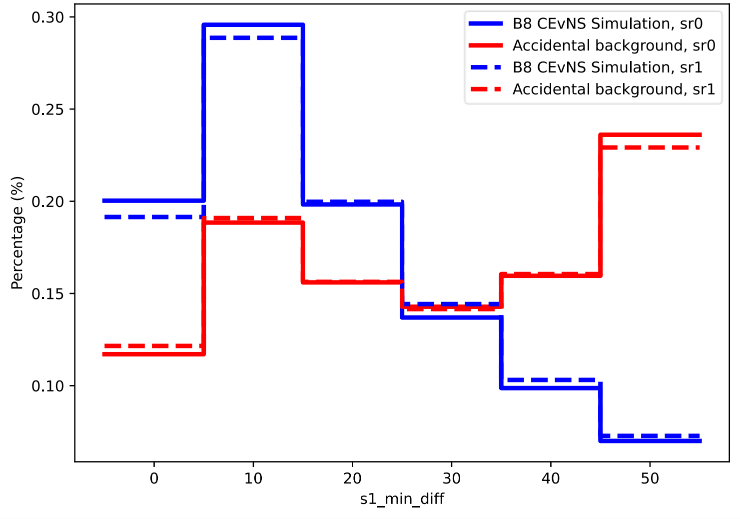
Dedicated publication in preparation.

S1 BDT Features

First: Max S1 hit area

ACs are mostly lone hits; S1 > 2PE on one PMT is unlikely to be AC.



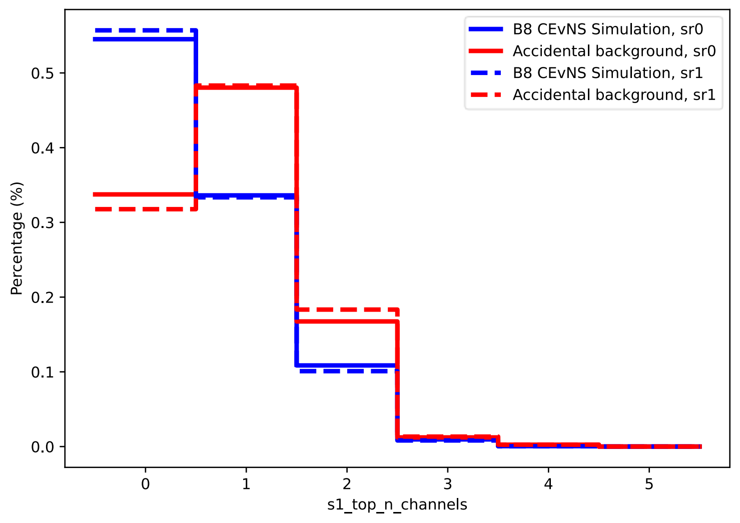


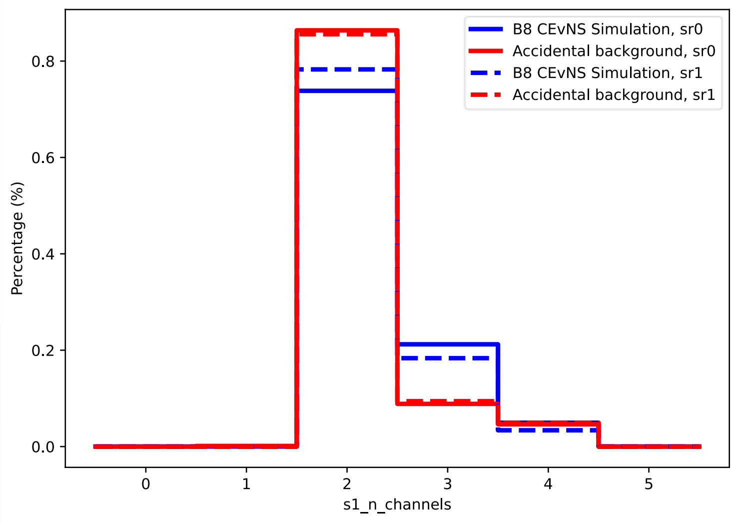
Second: Min time between S1 hits

Signal S1 pulse timing impacted by physical processes and DAQ response, AC is random

Third: No. of hits in top PMT array

Due to LXe-GXe interface, most signal S1s are collected at bottom array. ACs are random.



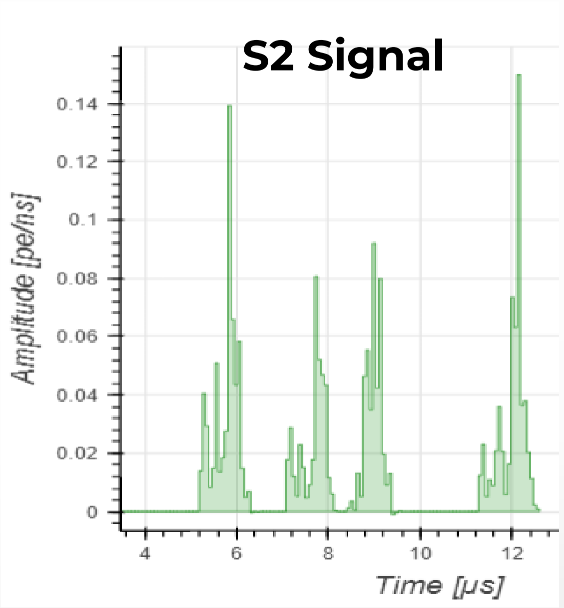


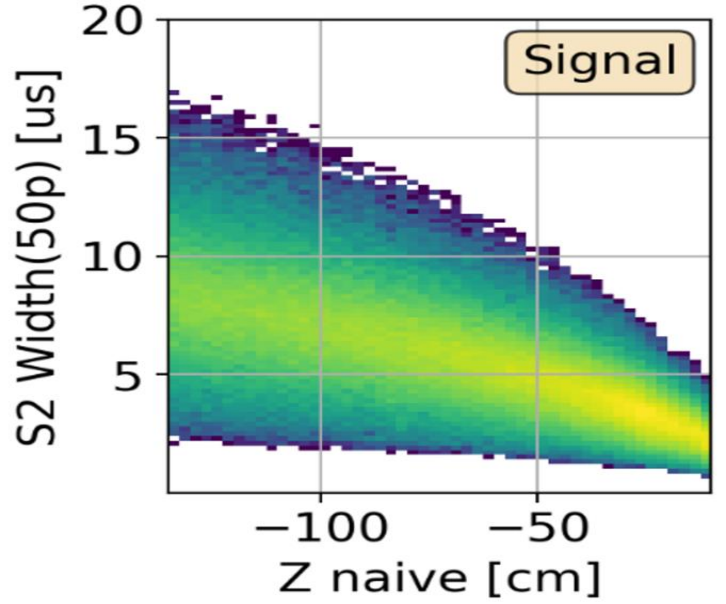
Fourth: Total no. of hits

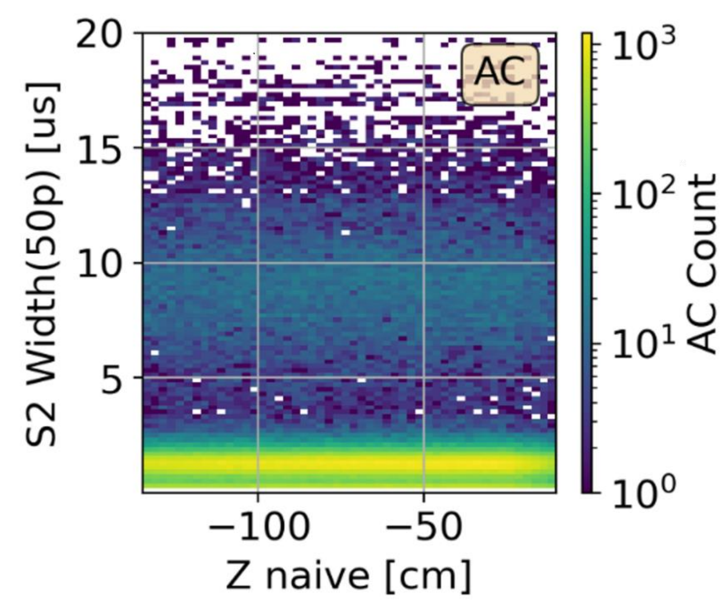
Reproduces the full recoil spectrum.

Dedicated publication in preparation.

S2 BDT Features







Relies on information about the drift and diffusion of the electron cloud.

First: 50% area width **Second: Risetime** **Third: 90% area width** **Fourth: Drift time**

Signal events will respect the diffusion model for the drift of the electron cloud; very identifiable distributions in some parameter spaces. ACs are random pairings; would not show the same patterns.