First Indication of Coherent Elastic ν-Nucleus Scattering of Solar ^{8}B Neutrinos in XENONnT

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- ✧ Introduction
- ✧ XENONnT
- ✧ Analysis
- ✧ Summary

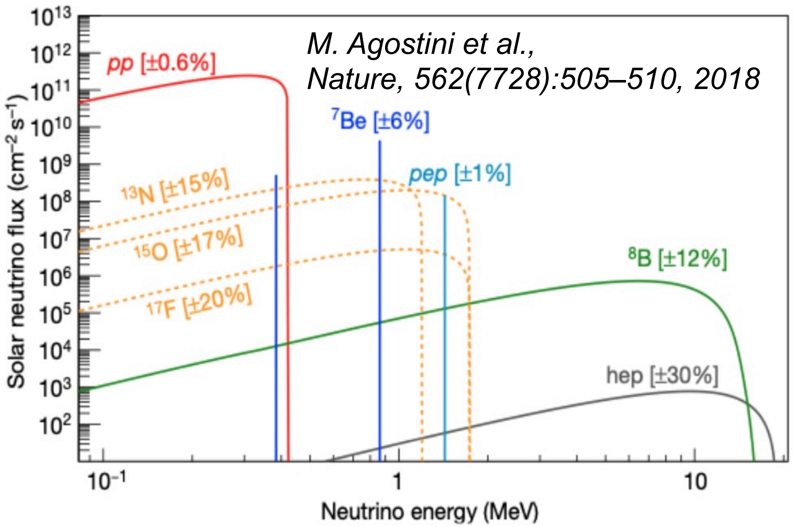
Solar ^{8}B Neutrinos CEνNS in XENONnT?

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

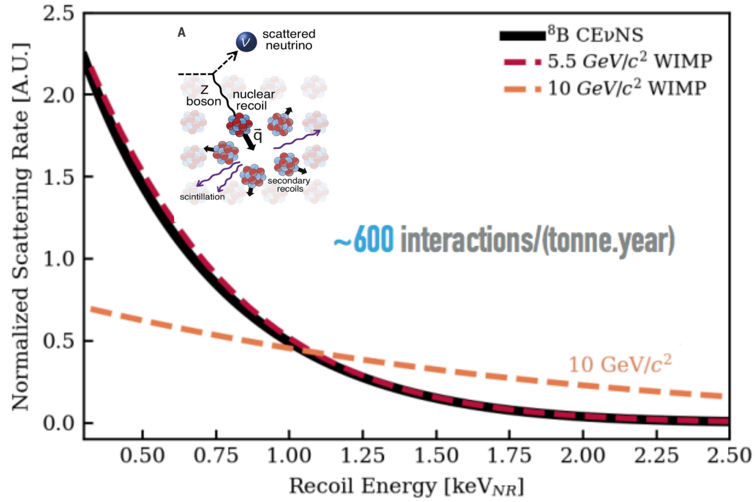
- First measured by COHERENT (2017) from a spallation neutron facility
- Never measured in a xenon target

^{8}B CEνNS: Expected to have the largest detectable number of CEνNS events in xenon

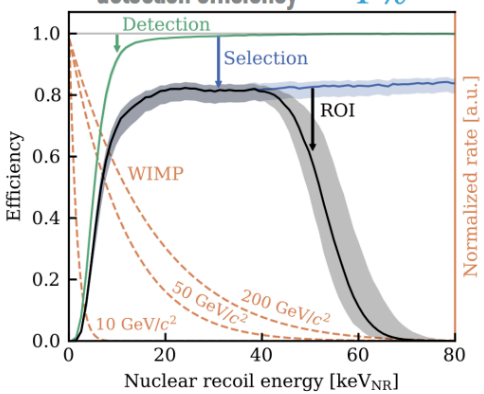
- Signature nearly indistinguishable from 5.5 GeV/c^2 WIMP with spin-independent $\sigma_{SI} = 4.4 \times 10^{-45}$ cm^2 nuclear recoil



^{8}B CEνNS Typical recoil energy: ≤ 1.5 keV$_{NR}$



Conventional "3-fold analysis": detection efficiency $\sim 1\ \%$

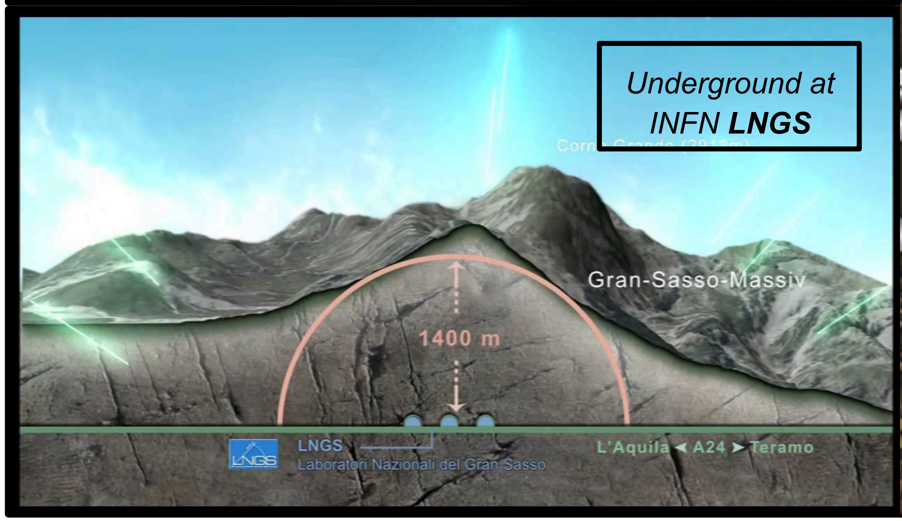


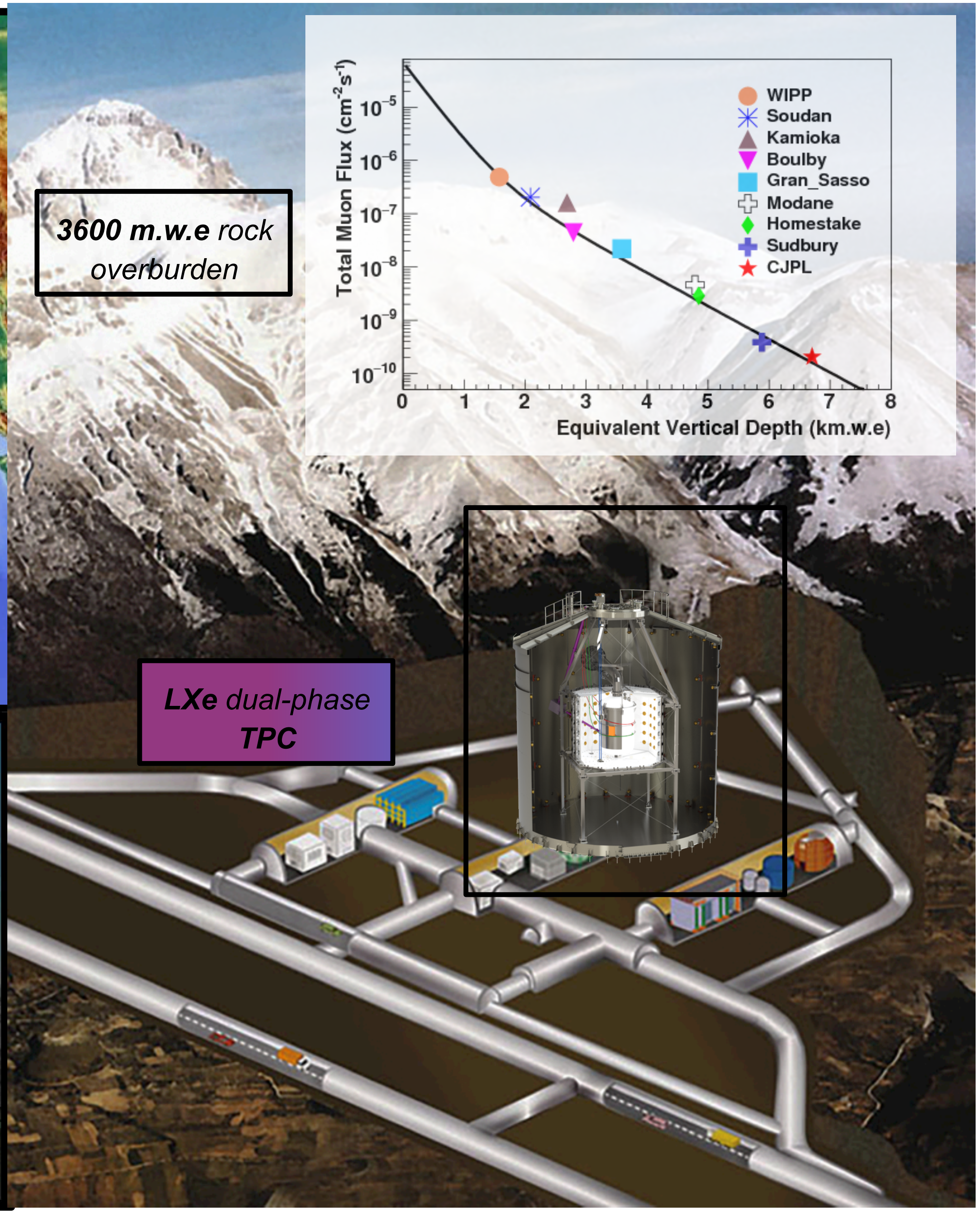
- Nearly invisible in conventional 3-fold analysis that requires ≥ 3 detected photons
  - Can try to measure by **lowering energy threshold** in analysis
  - Need to be sensitive to nuclear recoil with energy ~1 keV$_{NR}$
- Goal: A **BLIND** search for ^{8}B CEνNS

XENONnT : Who?

- 200+ scientists
- 29 institutions
- 12 countries

XENONnT : Where?





XENONnT : What?

3 Nested Detectors sharing the same DAQ

LXe - GXe time projection chamber

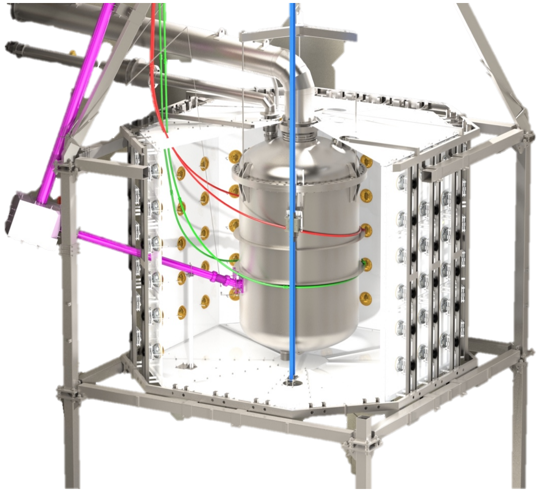
TPC

EPJ C 84 (2024) 138

5.9 t active LXe mass
1.3 x 1.5 m diameter x height
494 PMTs (3” Hamamatsu R11410-21)
23 V/cm operating drift electric field
2.9 kV/cm extraction field (e^- LXe → GXe)

Gd-doped water Cherenkov detector (NV)

NEUTRON VETO

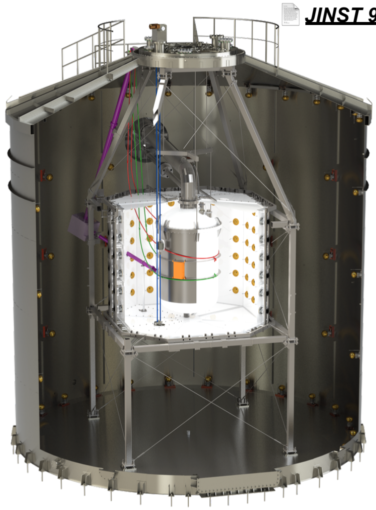


33 t water contained
~2 x 3 m diameter x height
120 PMTs (8” Hamamatsu R5912)
0.05% GdSO concentration (since 2023)
0.5% GdSO concentration (final goal)

Gd-doped water Cherenkov detector (MV)

MUON VETO

JINST 9 P11006

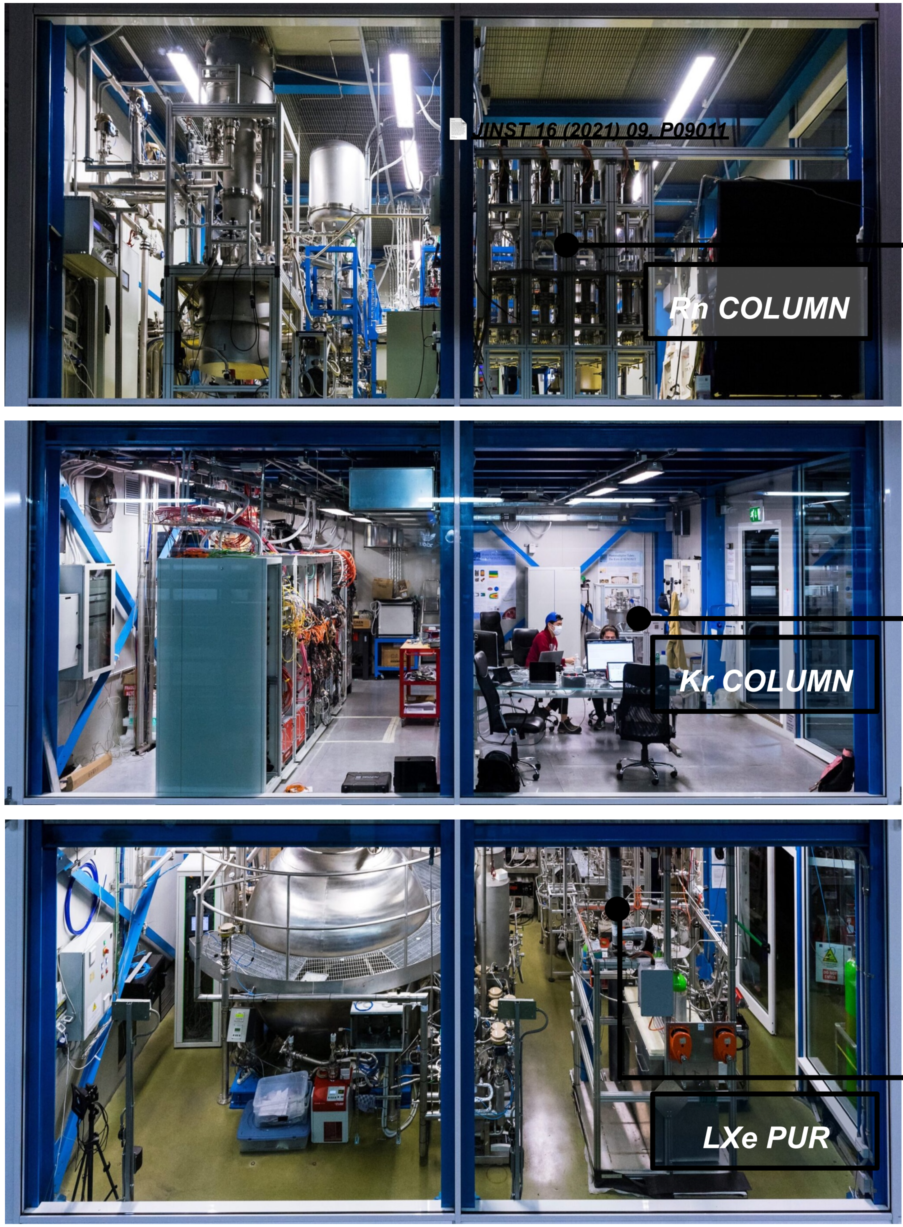


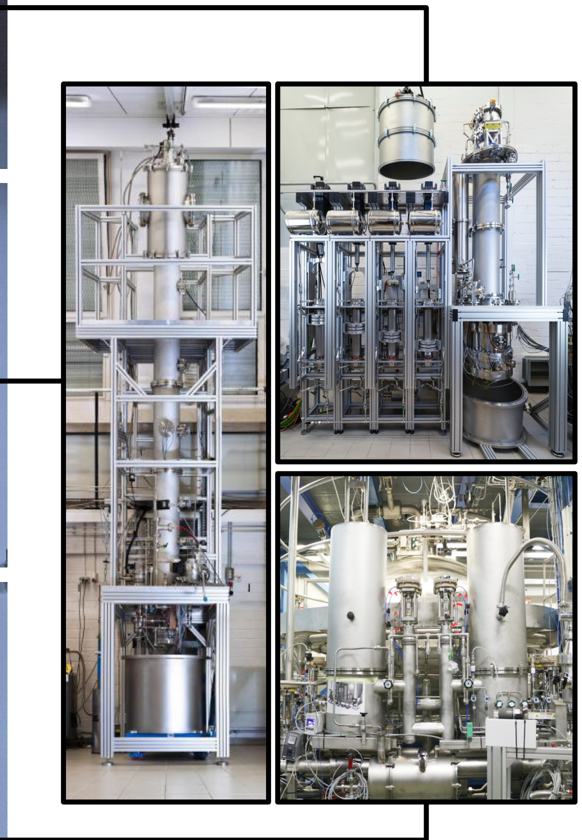
700 t water contained
~10 x 10 m diameter x height
84 PMTs (8” Hamamatsu R5912-ASSY)
Shares same water with NV but optically separated detectors

All detectors’ materials very carefully selected for excellent radiopurity

XENONnT : What?

Purification System





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

Liquid purification and cryogenic distillation

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

^{222}Rn CRYO-DISTILLATION

Continuous online distillation

^{222}Rn conc. (SR0): ***1.8 µBq/kg***

^{222}Rn conc. (SR1): ***0.8 µBq/kg !***

Was the dominant bkg in XENON1T

EPJ C77, 275

^{85}Kr CRYO-DISTILLATION

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

Made subdominant since XENON1T

ELECTRON LIFETIME

Removal of electronegative impurities

GXe and LXe purification systems

Electron lifetime achieved: ***>30 ms !***

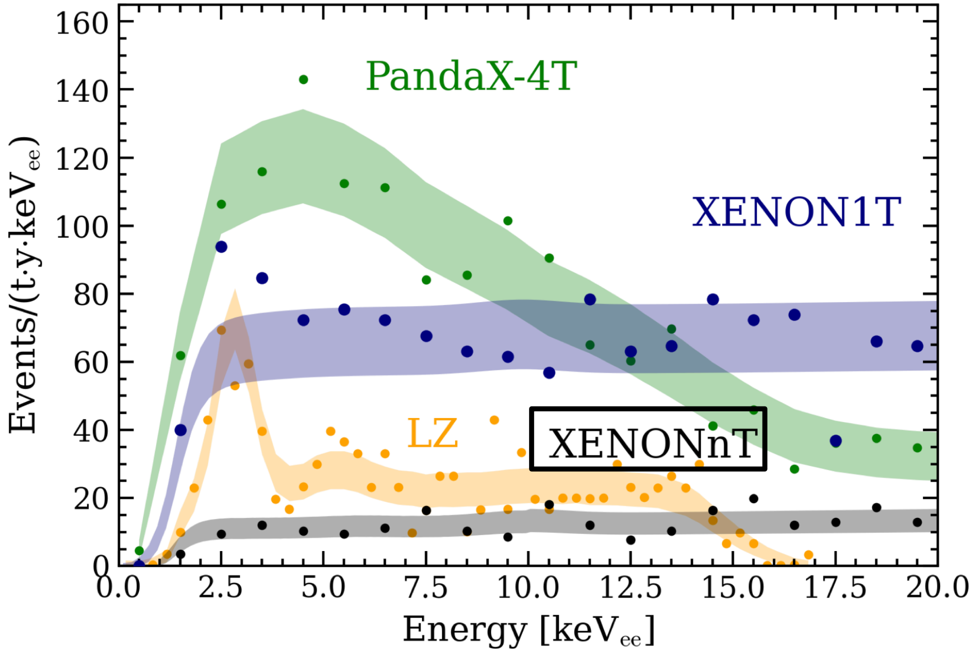
Full TPC drift time: 2.2 ms

XENONnT : What?

LOW-ENERGY
ER BACKGROUND RATE

Relative improvement of XENON detectors

XENON10 ••••••••••••	*1*
XENON100 •••••••••	*$5 \cdot 10^{-3}$*
XENON1T ••••••••••••	*$2 \cdot 10^{-4}$*
XENONnT •••••••••	***$3 \cdot 10^{-5}$***

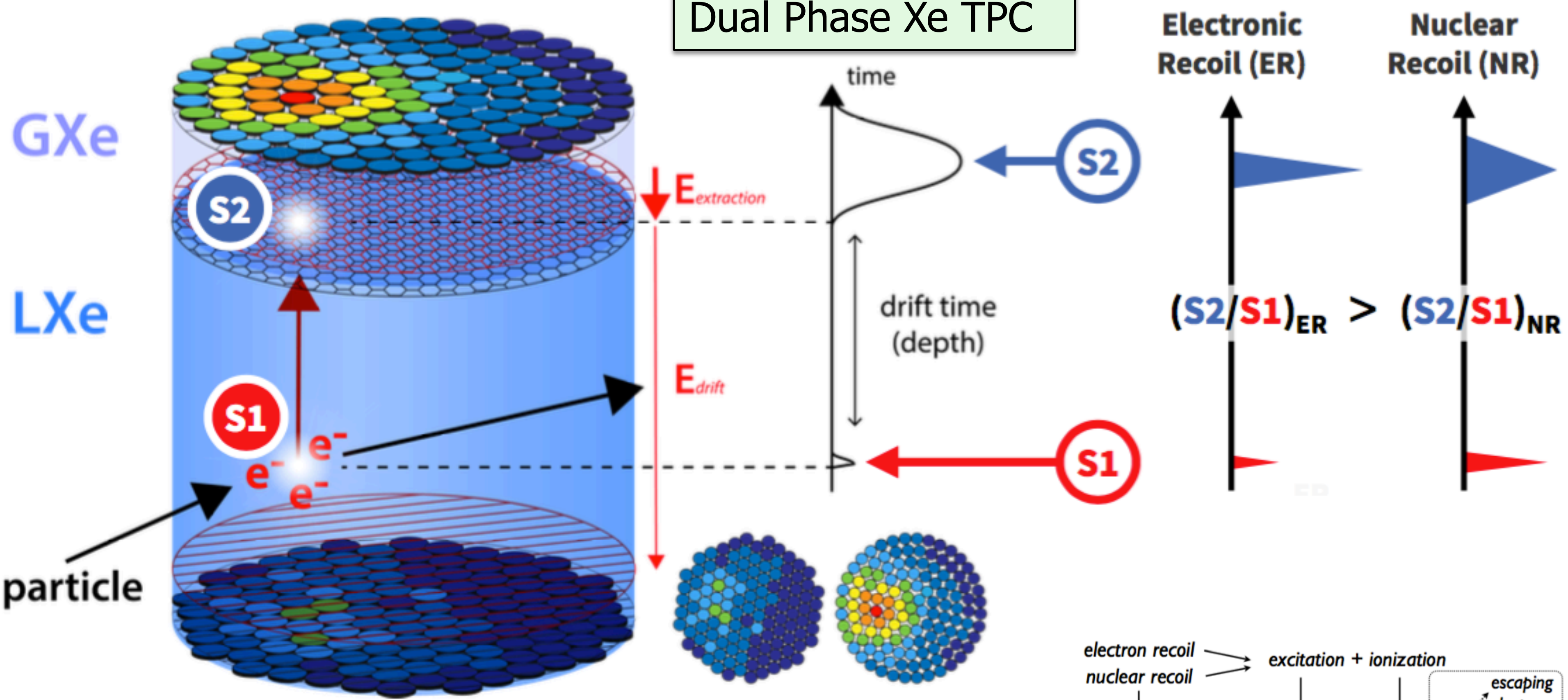


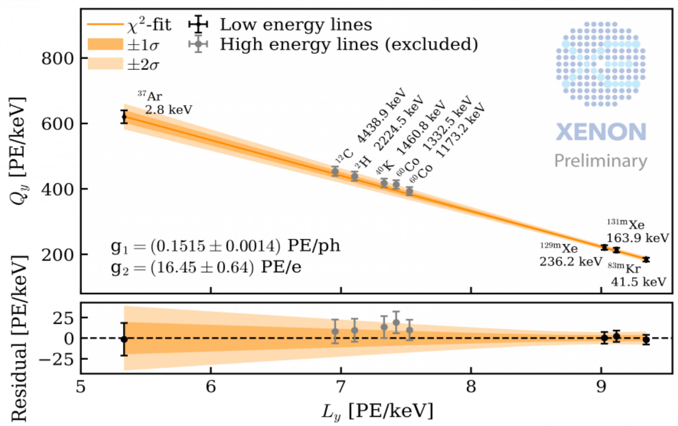
Lowest background rate ever achieved in LXe-based dark matter detectors

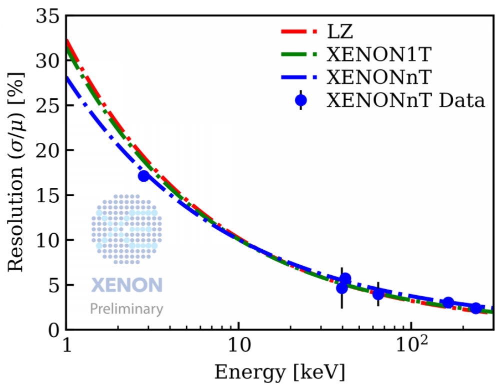
ER BKG RATE
16 ± 1
events / (t•y•keV)

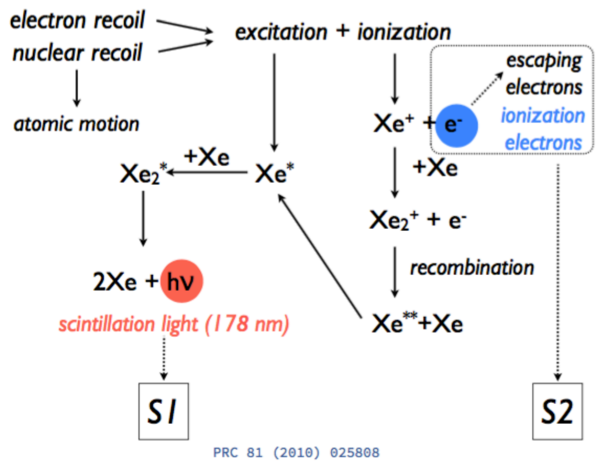
XENONnT : How?

Dual Phase Xe TPC



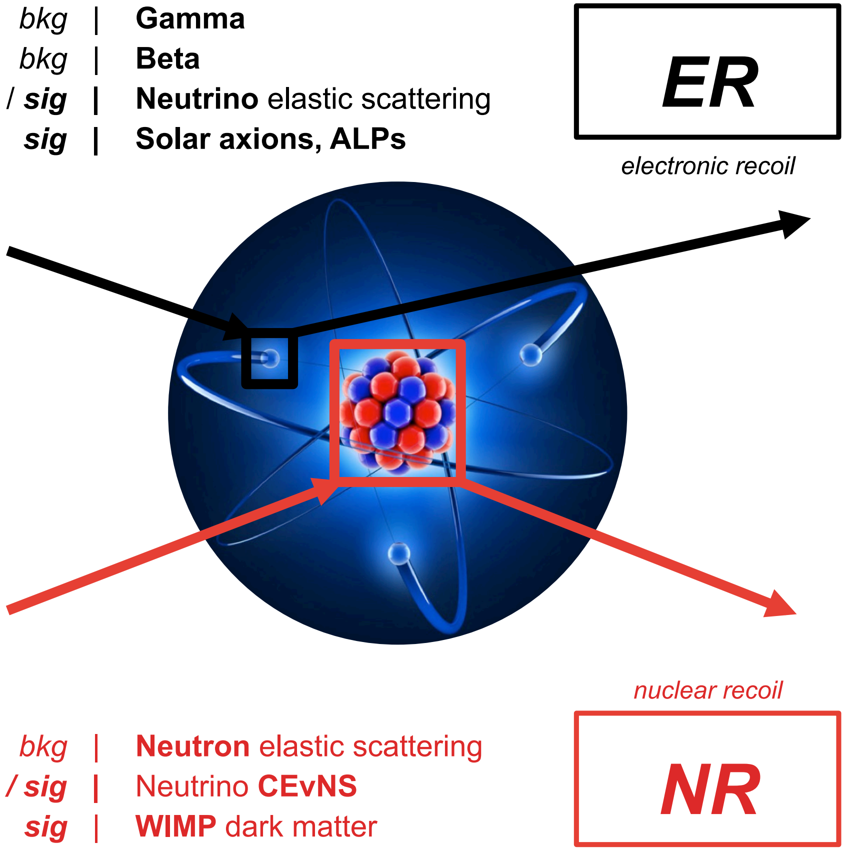






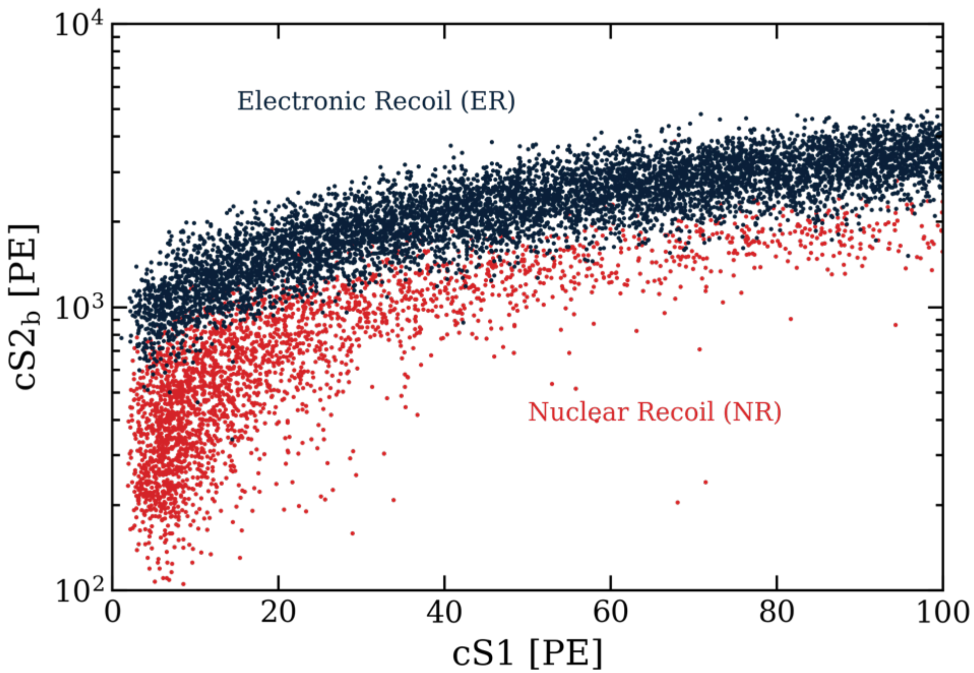
Nuclear vs Electronic Recoil Discrimination

bkg | **Gamma**
bkg | **Beta**
bkg / ***sig*** | **Neutrino** elastic scattering
sig | **Solar axions, ALPs**



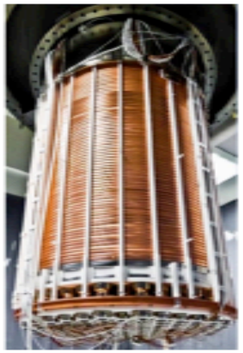
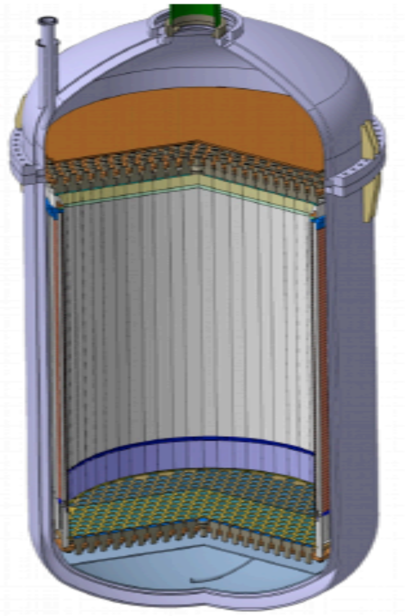
bkg | **Neutron** elastic scattering
bkg / ***sig*** | Neutrino **CEvNS**
sig | **WIMP** dark matter

For ultra-low-background searches for ultra-rare events



XENONnT : When?

More than 15 years of growing size detectors, always with world-leading sensitivities

PAST Up to 2007	PAST 2008-2014	PAST 2015-2020	PRESENT 2021-2026	FUTURE From 2027
				

	XENON10	XENON100	XENON1T	XENONnT	DARWIN
Height	15 cm	30 cm	96 cm	148 cm	2.6 m
Diameter	20 cm	30 cm	97 cm	133 cm	2.6 m
Total mass	25 kg	161 kg	3.2 tons	8.3 tons	50 tons
Active mass	14 kg	62 kg	2.0 tons	5.9 tons	40 tons

XENONnT : When?

CONSTRUCTION

Mar 2020 | TPC installation

Jun - Dec 2020 | NV installation

Cryostat filling (LXe)

MV/NV filling (water)

Jan – Jun 2021 | Commissioning

SCIENCE RUN 0

Jul 2021 | Start of SR0

Nov 2021 | End of SR0

SCIENCE RUN 1

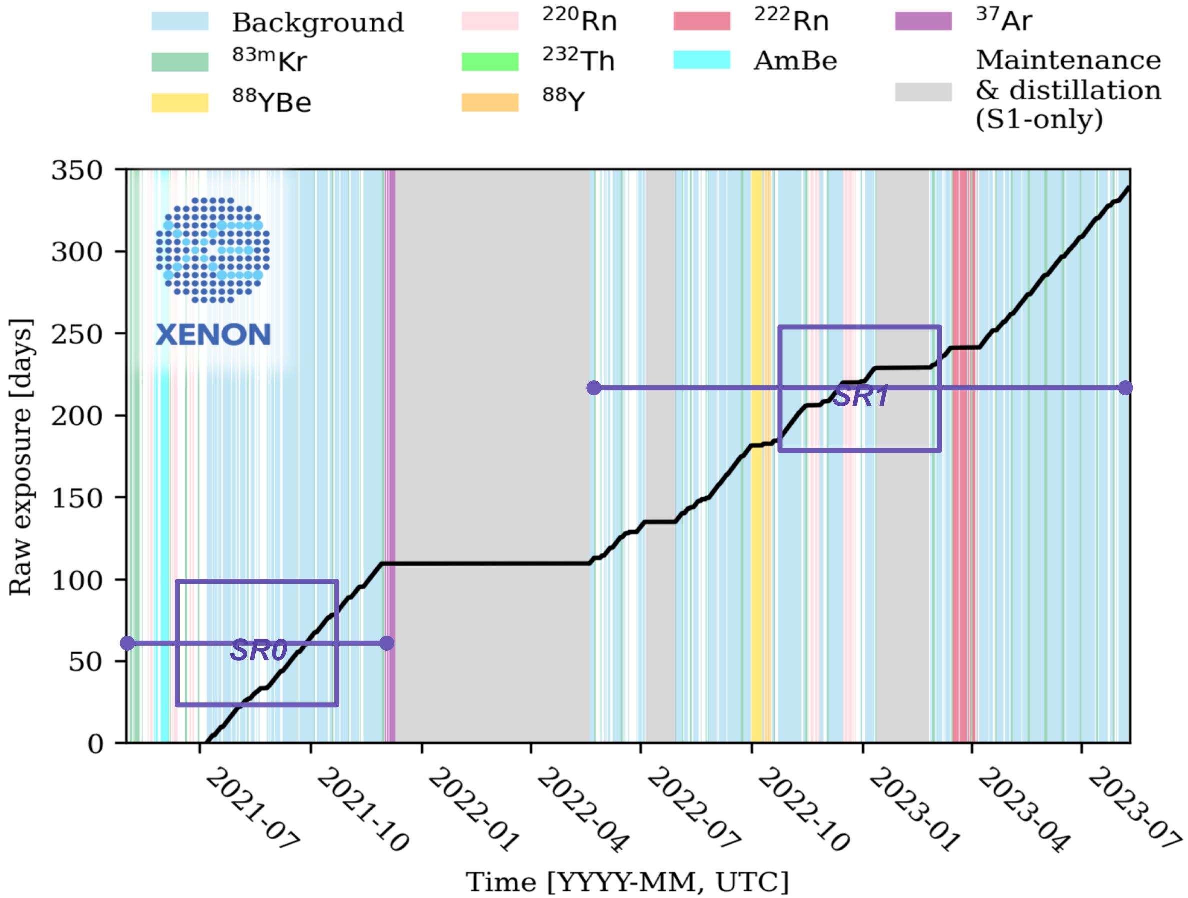
May 2022 | Start of SR1

Aug 2023 | End of SR1

POST-SR1

2023 | GdSO insertion in water

2023 | Start of SR2



SCIENCE RUN 2
ongoing

EXCELLENT STABILITY

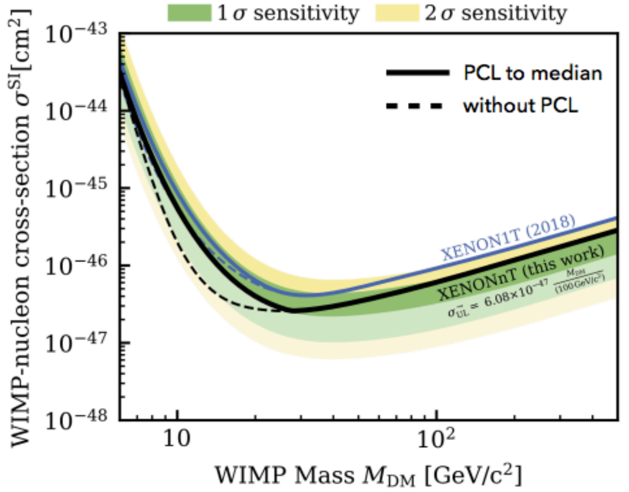
PHOTOSENSORS
after 4 years of operation
478 of 494 PMTs still active (97%)
with stable gain

SIGNAL RESPONSE
stability of both light and charge
yields within 1%

SR0 & SR1 SCIENCE DATA *Blind Analysis*

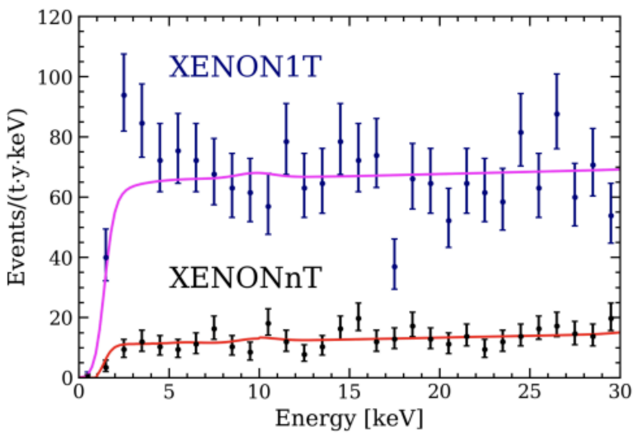
- Data taken between 2021-07 and 2023-08: ~340 days of **raw exposure**
- **Stable detector response**: <1% (<3%) light (charge) yield variation
- **High liquid xenon purity**: Electron lifetime ~20ms
- Regular calibrations:
  - **g1**: 0.1515 ± 0.0014 PE/ph (SR0) & 0.1367 ± 0.0010 PE/ph (SR1)
  - **g2**: 16.45 ± 0.64 PE/e (SR0) & 16.85 ± 0.46 PE/e (SR1)

Blind search for WIMP



Phys. Rev. Lett. 131, 041003 (2023)

Unprecedented low ER background



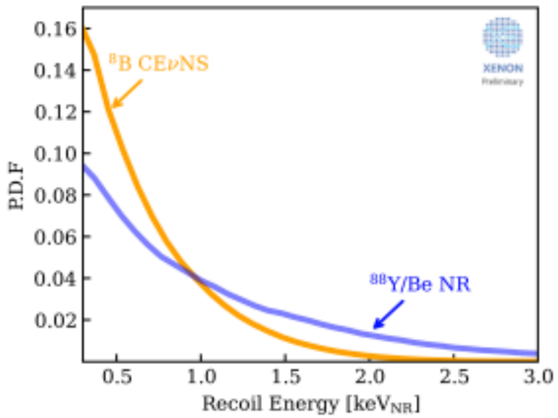
Phys. Rev. Lett. 129, 161805 (2022)

WIMP SR0 result

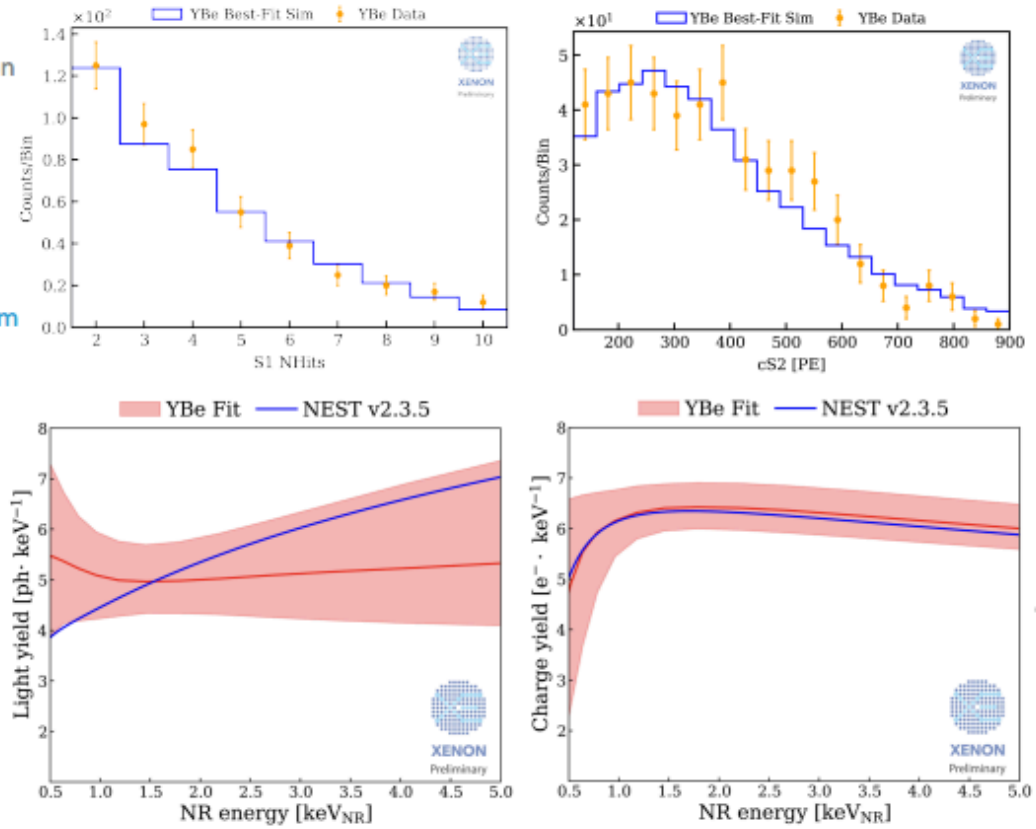
^{8}B CEνNS Analysis : Calibration

^{88}YBe LOW ENERGY NR CALIBRATION

- Low energy NR yield model significantly affects ^{8}B CEνNS detection efficiency
- 152 keV neutrons from photo-disintegration of ^{9}Be by γ-ray of ^{88}Y
  - **Recoil energy spectrum similar to ^{8}B CEνNS**
- Good match between simulation and data
- **Light/charge yield model** are constrained by ^{88}YBe data at 23V/cm
  - Yield model uncertainty leads to ~34% signal rate uncertainty

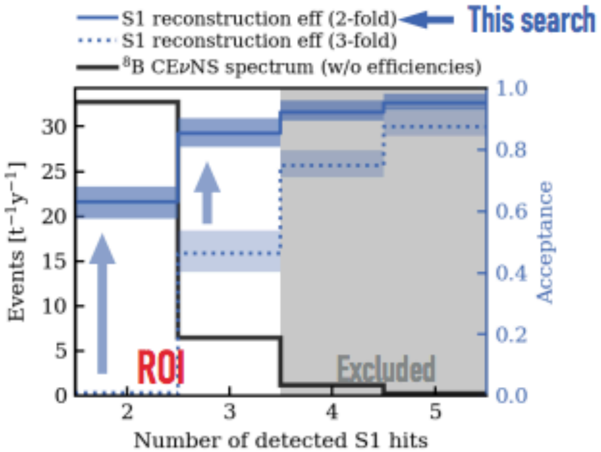


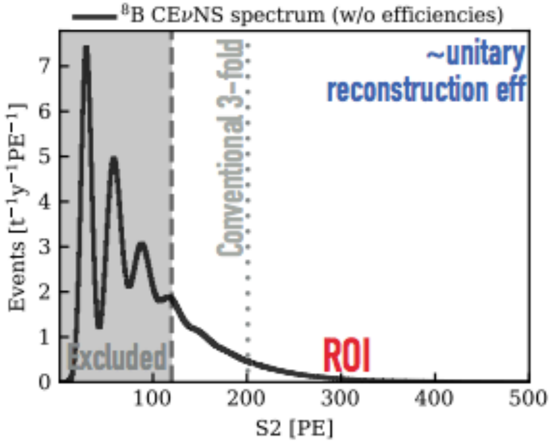
Publication in preparation

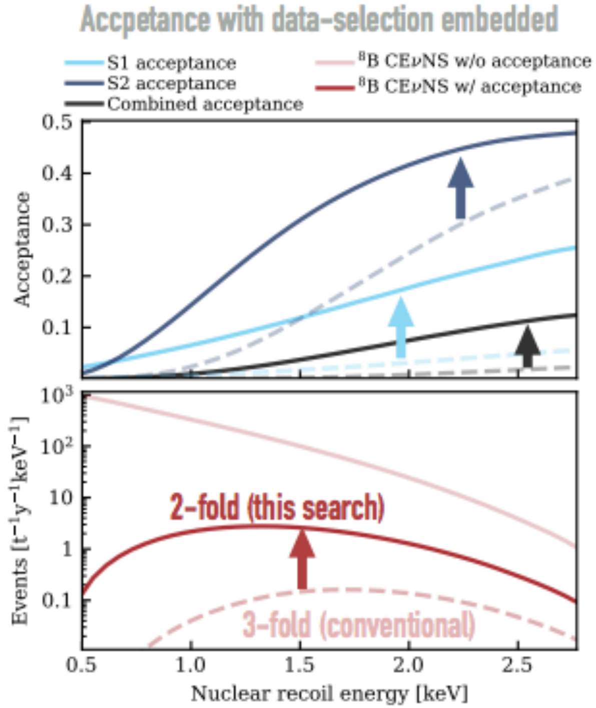


^{8}B CEνNS Analysis : Selection

ENERGY THRESHOLD AND REGIONS OF INTEREST







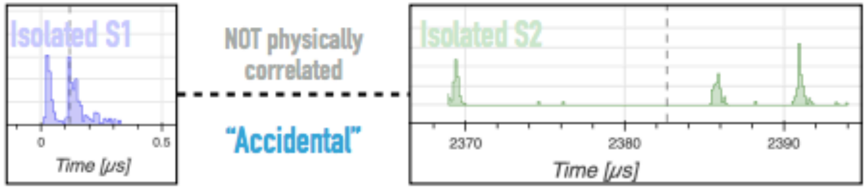
- **S1 ROI:** 2 or 3 hits
  - An S1 hit corresponds to a detected photon
    - Relaxed S1 waveform shape requirement from conventional 3-fold analysis
- **S2 ROI:** 120 - 500 PE
  - ~Equivalent to 4 - 16 extracted electrons
  - Lowered S2 threshold from conventional analysis (200 PE)

~17 TIMES MORE EVENTS

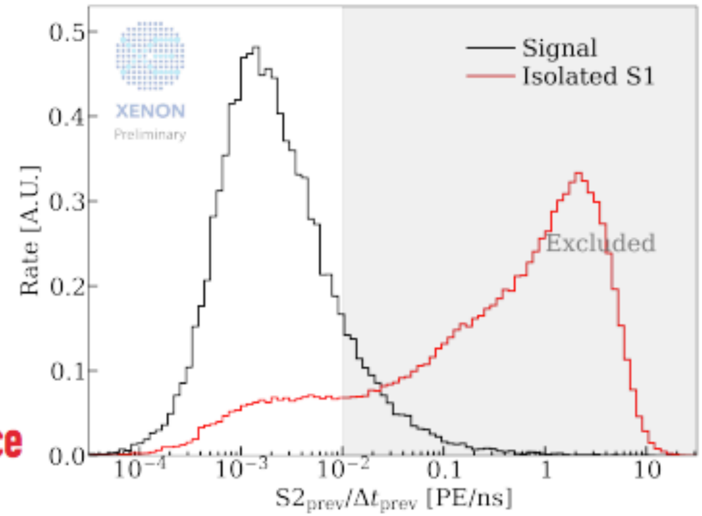
arXiv:2408.02877

DOMINANT BACKGROUND: ACCIDENTAL COINCIDENCE

- **Accidental Coincidence (AC)**: Random unphysical pairing of isolated S1 and isolated S2
  - Isolated peaks are believed to be side products of high energy (HE) interactions
  - Exact physical mechanisms of isolated peaks are under investigation
  - Isolated-S1 Rate before mitigation: 15 Hz
  - Isolated-S2 Rate before mitigation: 150 mHz
- **Mitigated** by utilizing selections based on space&time correlation to previous HE interactions
  - Isolated-S1 rate after mitigation: 2.3 Hz
  - Isolated-S2 rate after mitigation: 25 mHz



TimeShadow $\equiv \mathrm{Max}(S2_{pre}/\Delta t_{pre})$ used in inference

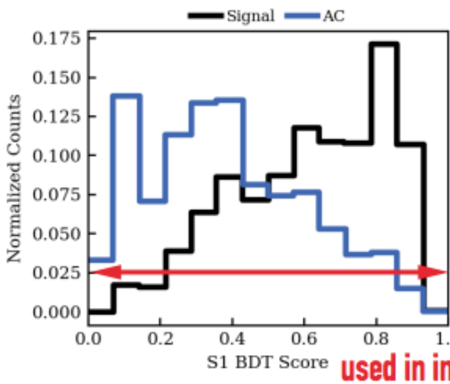


eg. TimeShadow selection on Isolated S1s

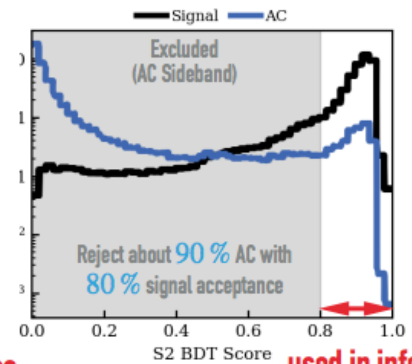
- **Further suppressed** AC by 2 Boosted Decision Tree (BDT) selections:
  - **S1 BDT**: VUV photon spectrum + S1 pulse shape & spectrum
  - **S2 BDT**: S2 pulse shape compatible with diffusion law
- 3^4-bins **4D search space** for better discrimination power against AC:
  - (cS2, S1 BDT, S2 BDT, TimeShadow)

Expected # of AC events:

7.5 ± 0.7 for SR0 & 17.8 ± 1.0 for SR1

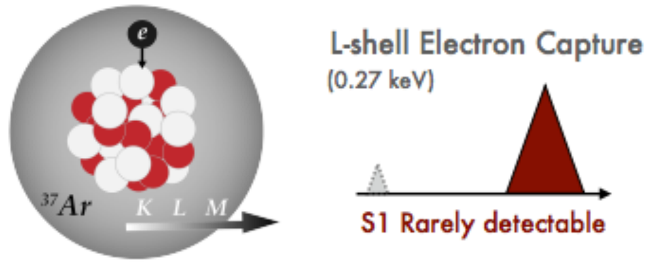


used in inference



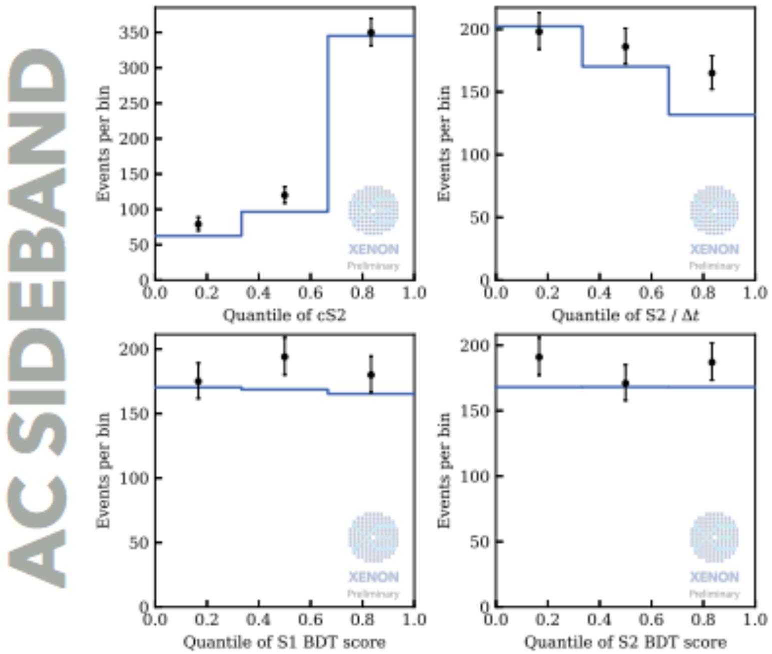
used in inference

^{8}B CEνNS Analysis : Background

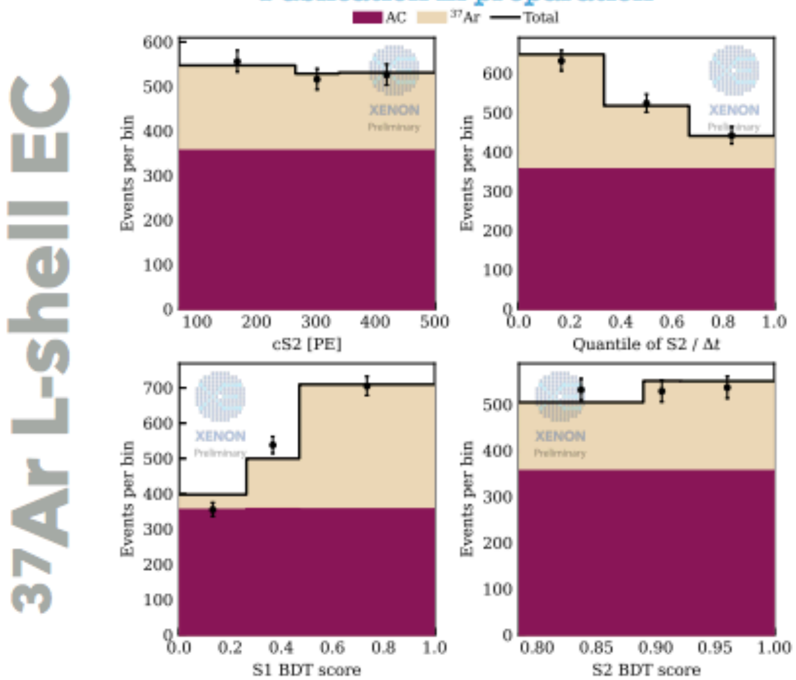


VALIDATION OF AC MODEL

arXiv:2408.02877



Publication in preparation



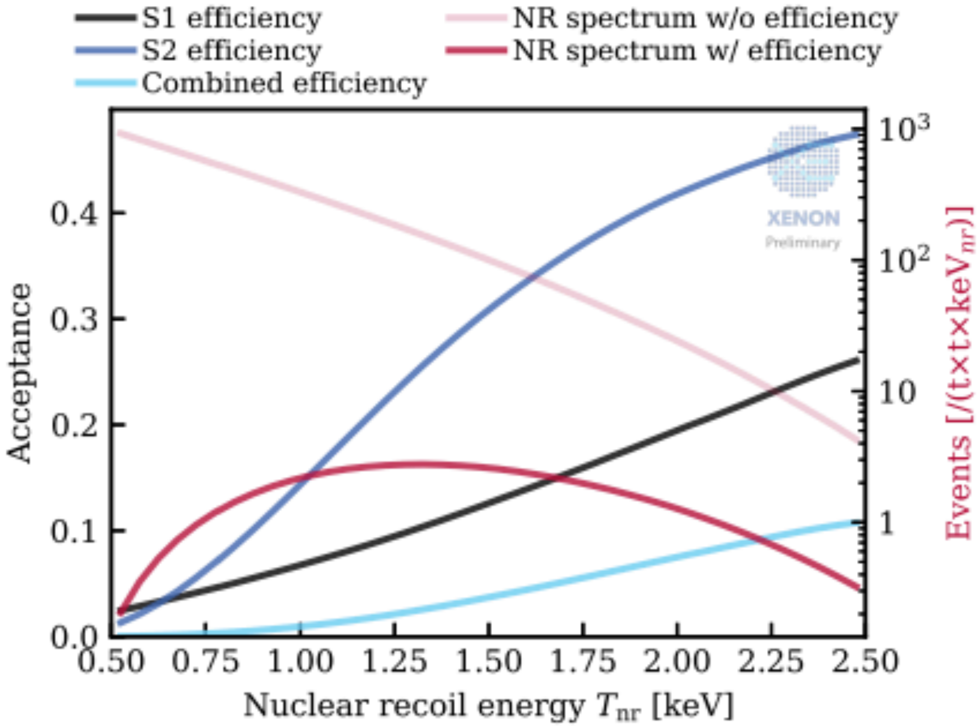
- **Validated** by AC sideband unblinding (events that failed S2 BDT cuts)
- The difference (<10%) is considered when determine systematic uncertainty

- **Validated** by ^{37}Ar L-shell 0.27 keV ER calibration data
- Constrained ER light yield with 1598 observed events

Other subdominant backgrounds (ER, Radiogenic Neutrons,Surface,...) negligible (O(1) evt)

Final Prediction of ^{8}B Signal and Background

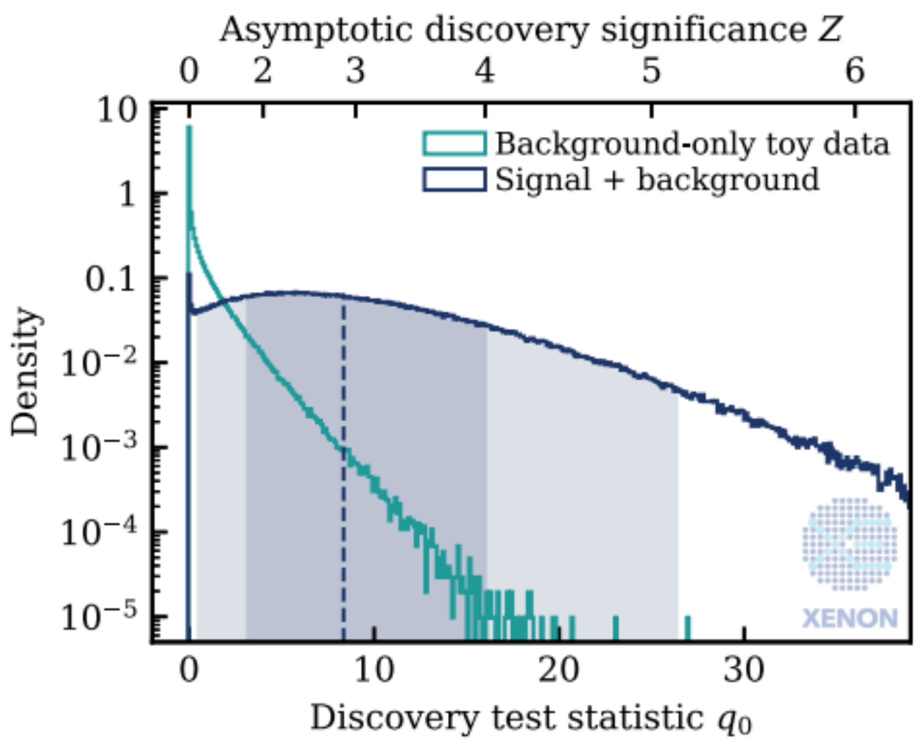
Component	Rate [Events]
AC - SR0	7.48 ± 0.52
AC - SR1	17.77 ± 1.23
ER	0.68 ± 0.68
NR	0.47 ± 0.32
Total Background	26.4 ± 1.5
^{8}B	11.93 ± 3.1

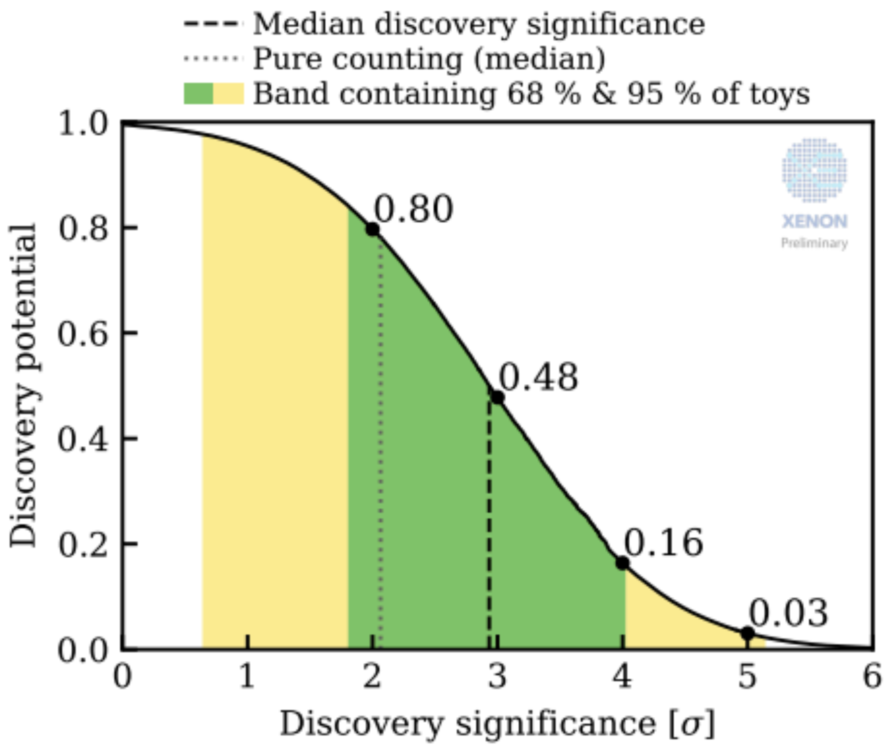


We expect solar ^{8}B neutrinos at a median significance of ~2σ, with a counting-only analysis

^{8}B CEνNS Analysis : Discovery Potential

Projected Discovery Potential of ^{8}B Signals

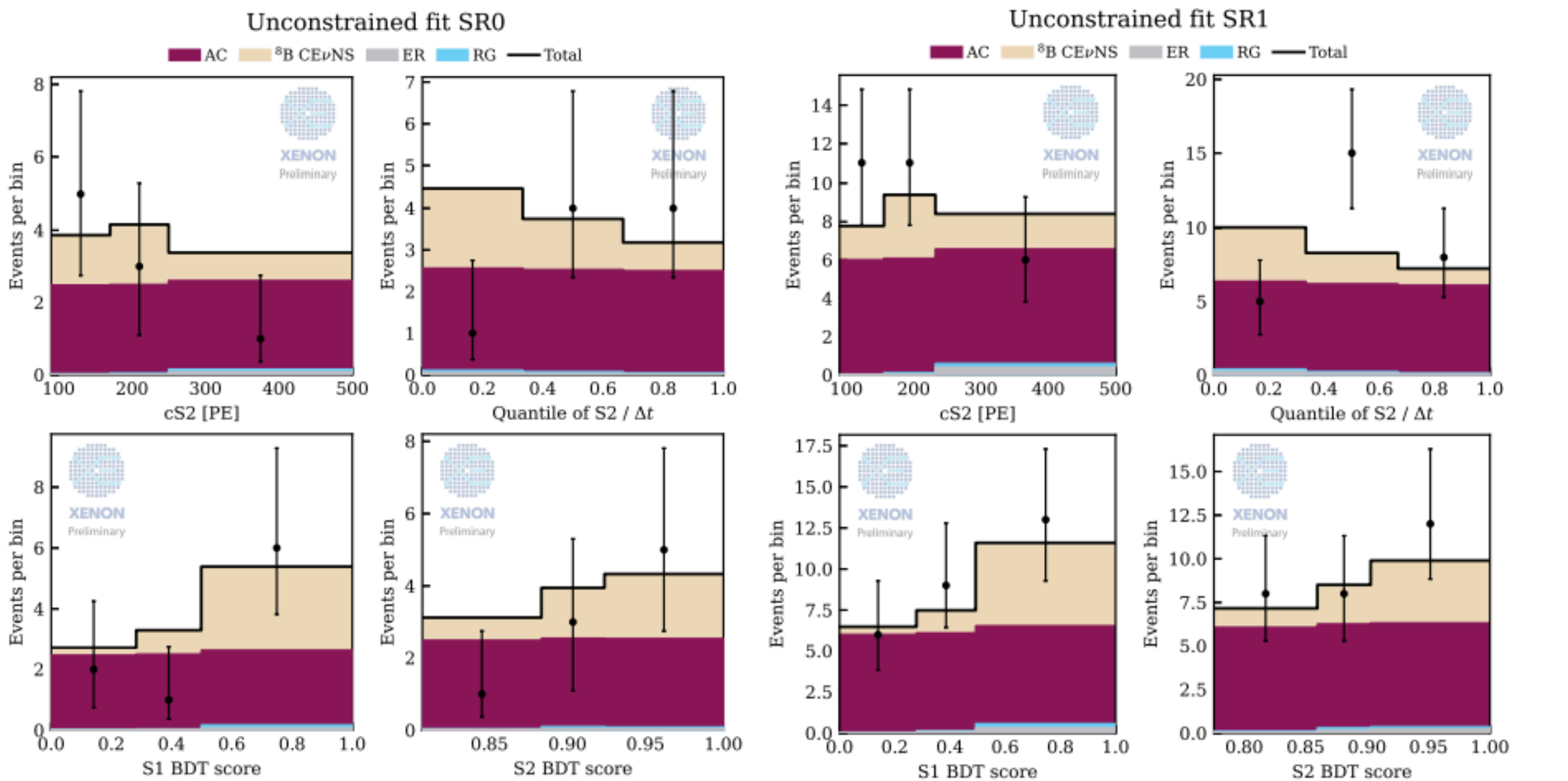




We expect to see solar ^{8}B neutrinos at >3(2) sigma significance with a probability of 0.48 (0.80), with a full 4-D analysis

^{8}B CEνNS Analysis : Unblinding

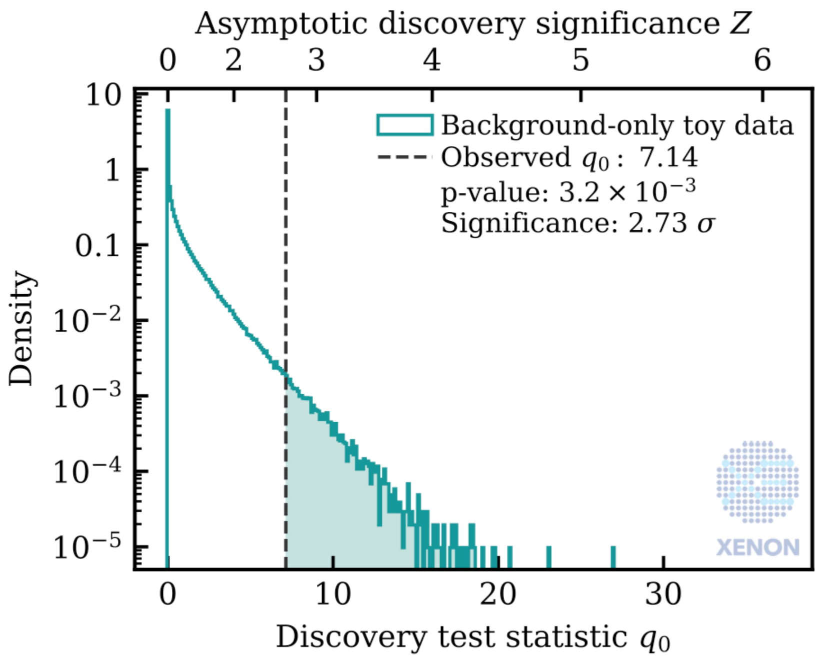
Results from Unblinding, 07/03/2024



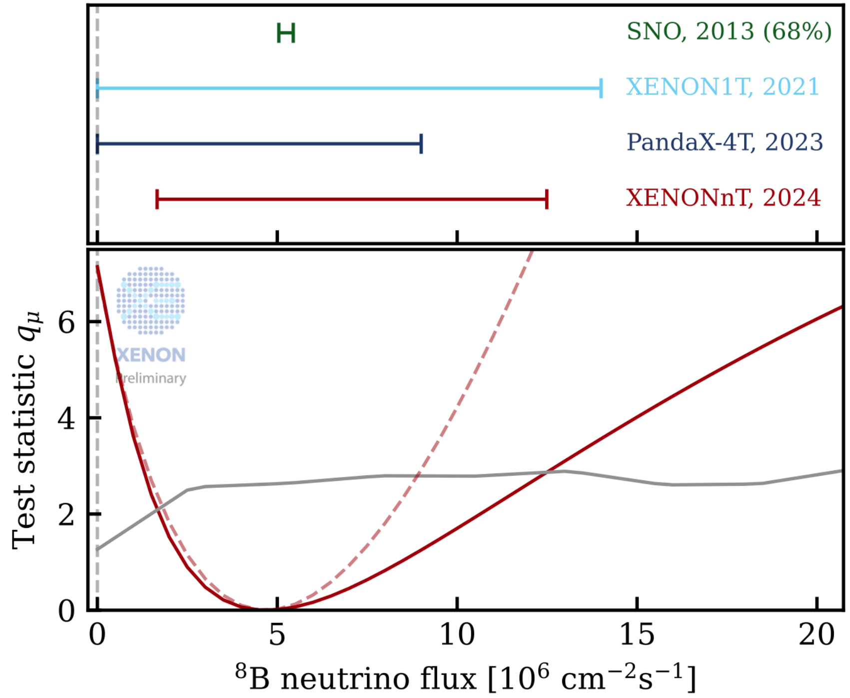
Data agrees with the signal + background expectation!

^{8}B CEνNS Analysis : Results

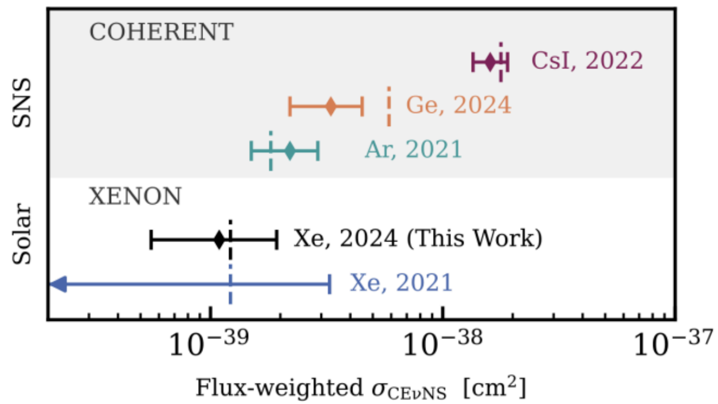
Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	



The background-only hypothesis is disfavored at 2.73σ



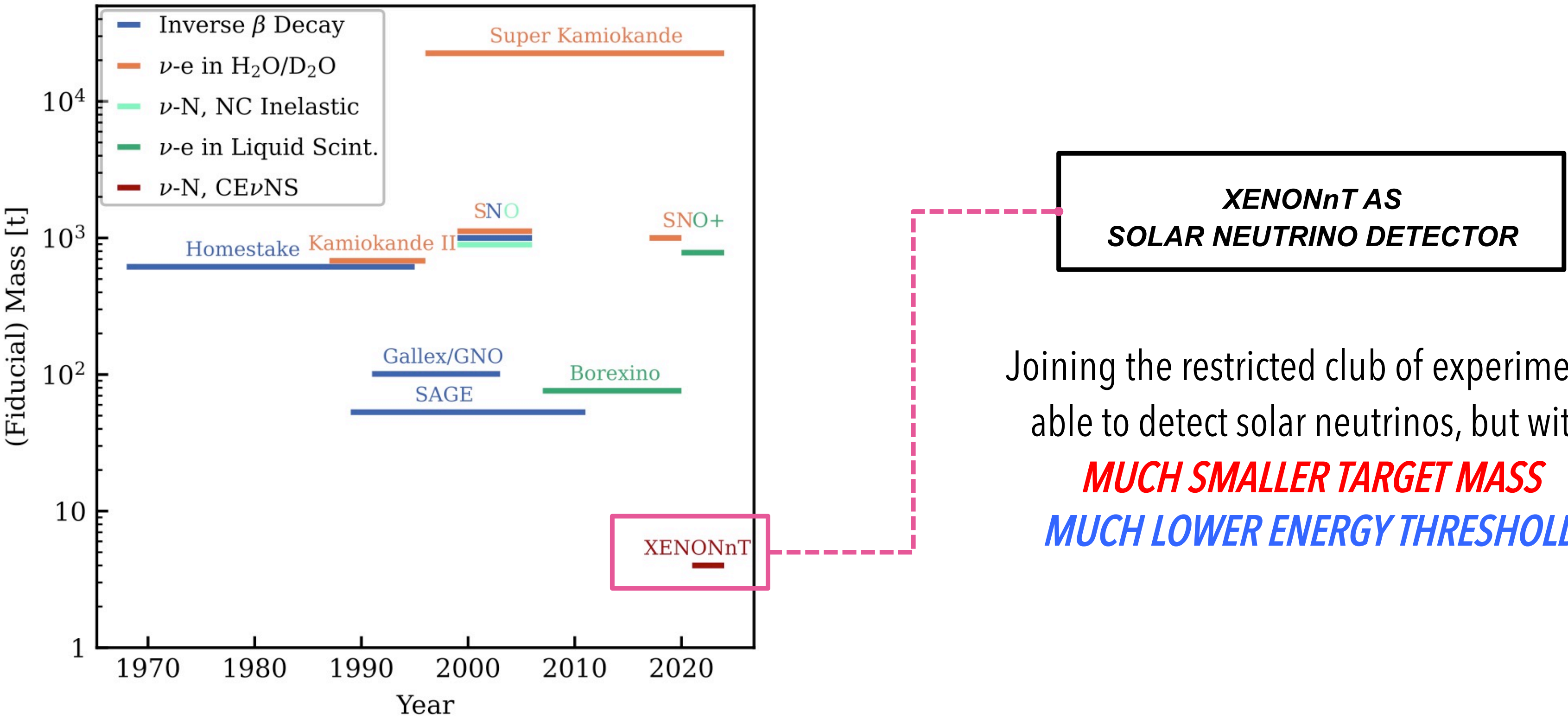
solar ^{8}B flux measurement via CEvNS as [1.72, 10.6] x 10^6 cm^{-2} s^{-1} at 90% C.L.



Summary

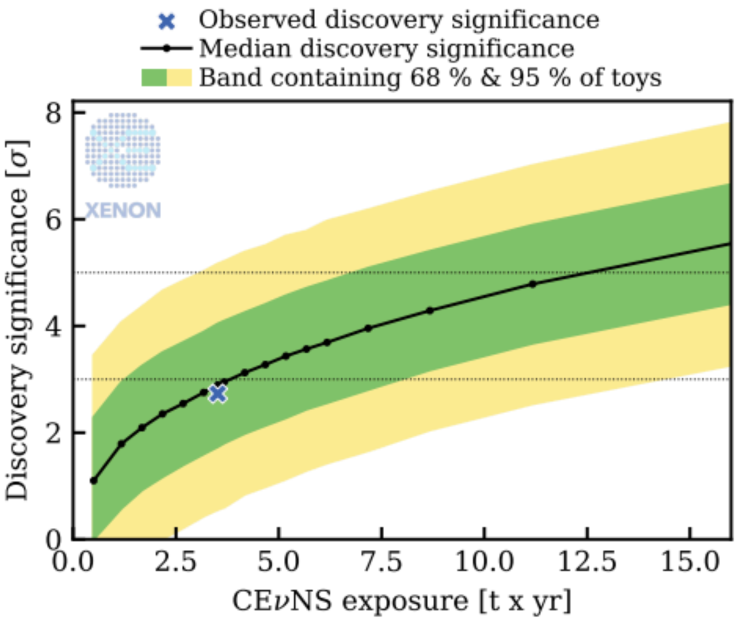
Solar ^{8}B Neutrinos CEνNS in XENONnT!

FIRST detected astrophysical ν in a **dark matter detector**
FIRST measured CEνNS from **astrophysical** ν source
FIRST measured CEνNS with a **Xe** target



Joining the restricted club of experiments able to detect solar neutrinos, but with
MUCH SMALLER TARGET MASS
MUCH LOWER ENERGY THRESHOLD

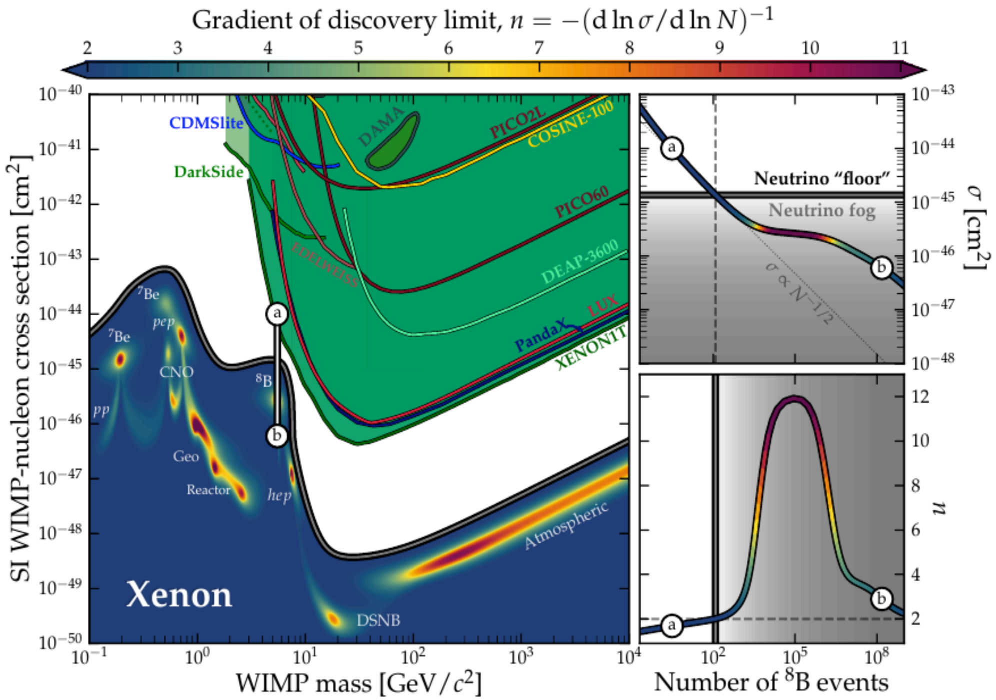
Outlook



With more exposure, XENONnT will measure Solar ^{8}B Neutrinos CEνNS with higher significance and better constrain Solar ^{8}B Neutrino flux

XENONnT is entering
ν "fog"region
for WIMP search!

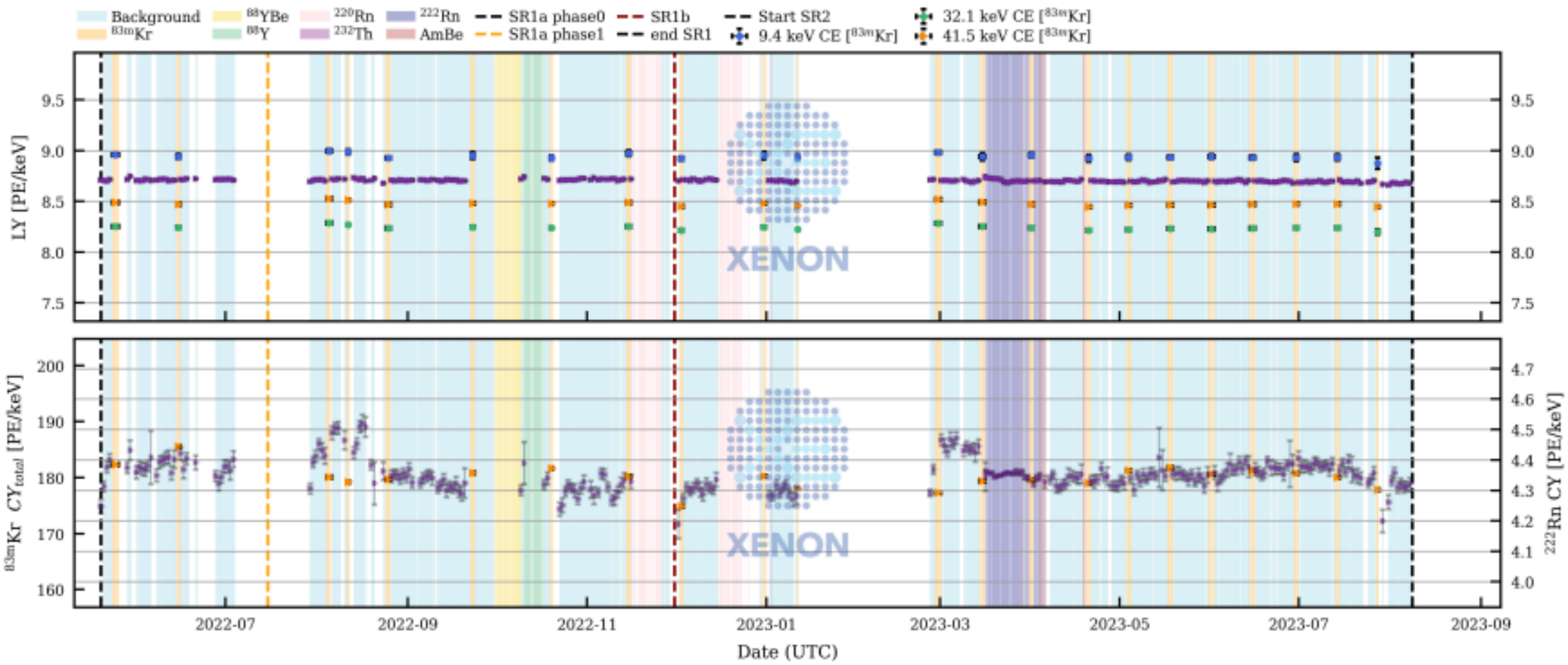
C.A.J. O'Hare, Phys. Rev. Lett. 127, 251802 (2021)



Backup

Stability

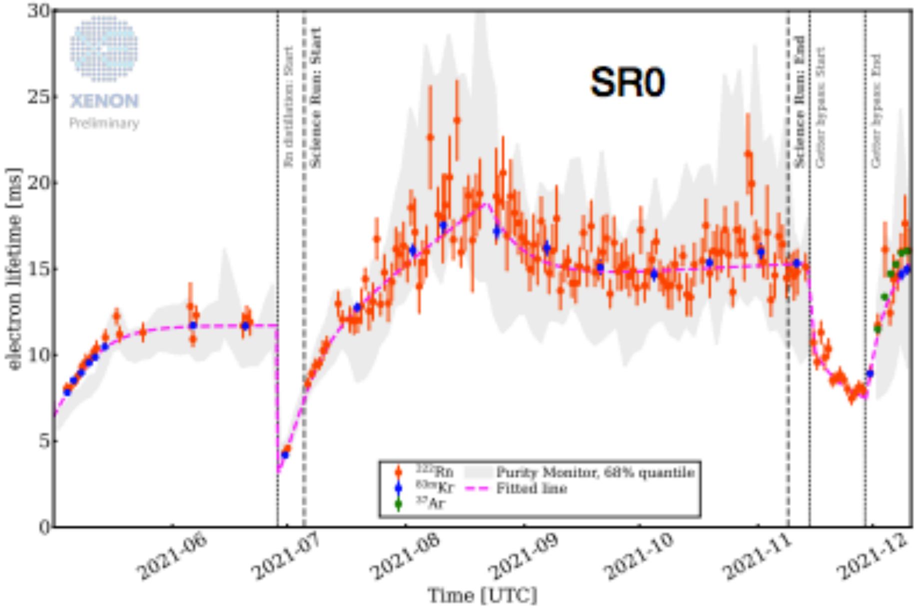
Stability of XENONnT During Science Runs

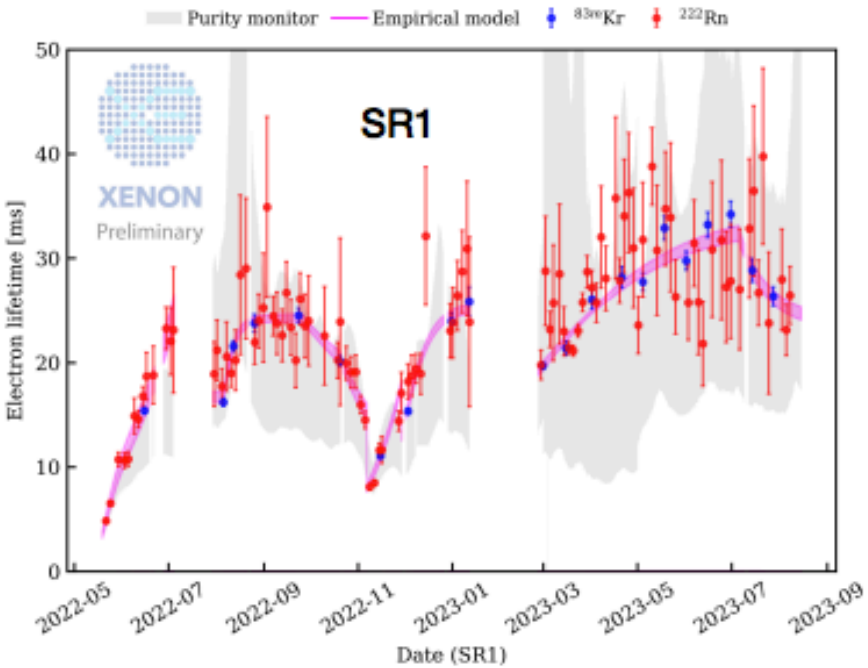


The stability of XENONnT is well established in both SR0 and SR1

Purity

Liquid Xenon Purity During Science Runs

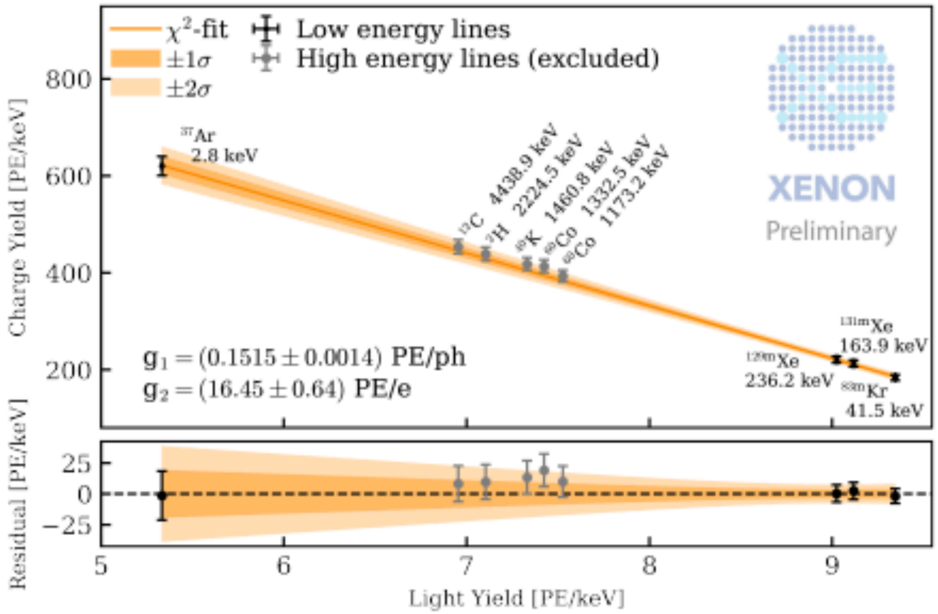




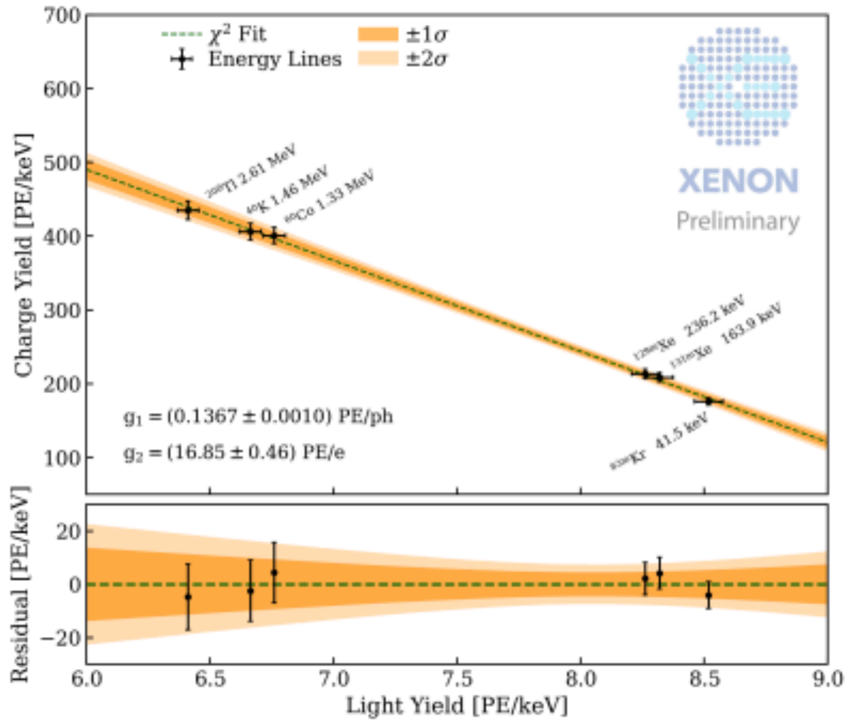
XENONnT maintains high electron lifetime thanks to its novel liquid phase purification

Calibration with Mono-energetic Electronic Recoils

SR0

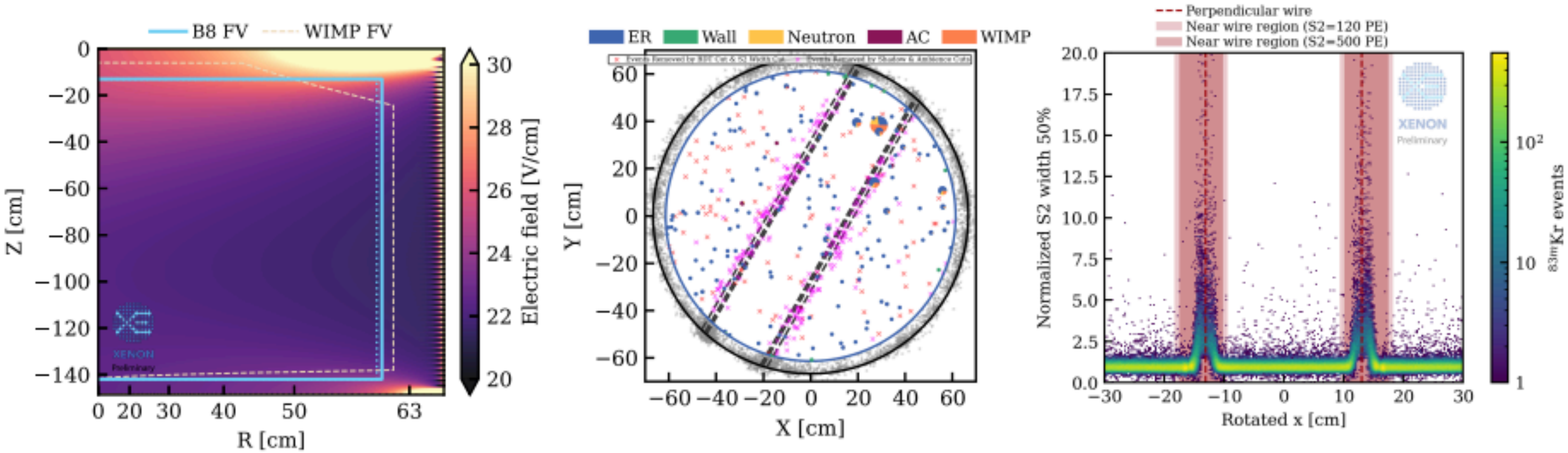


SR1



Science Run	g1 [PE/ph]	g2 [PE/e]
SR0	0.1515 ± 0.0014	16.45 ± 0.64
SR1	0.1367 ± 0.0010	16.85 ± 0.46

Fiducial Volume and Exposure



Science Run	Livetime [Years]	Fiducial Mass [Tonne]	Exposure [Ton-Year]
SR0	0.296	3.97	1.17
SR1	0.571	4.10	2.34
SR0+SR1	0.867		3.51

Events around the supporting wires are removed due to:

- high Background rate
- Insufficient modeling of S2

Other Backgrounds

OTHER SUBDOMINANT BACKGROUNDS

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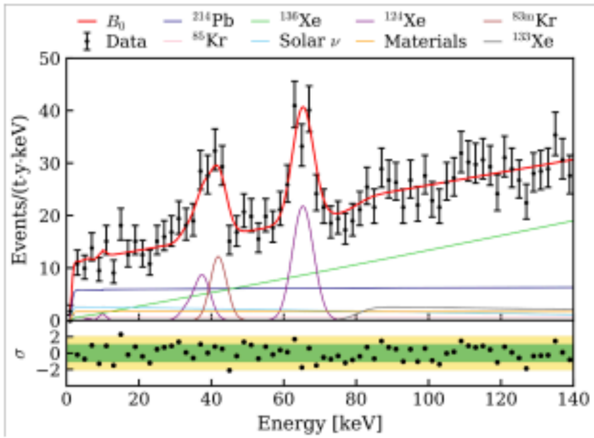
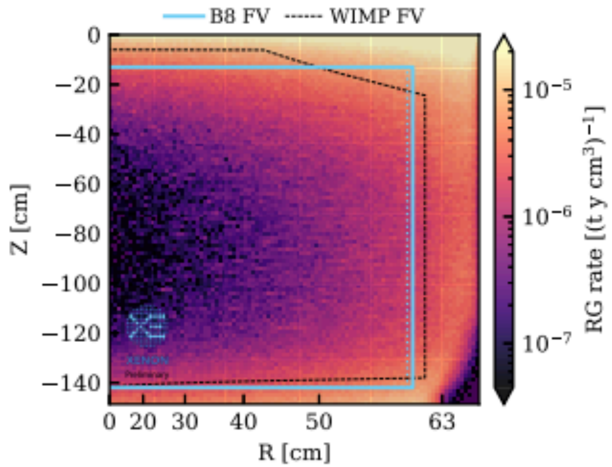




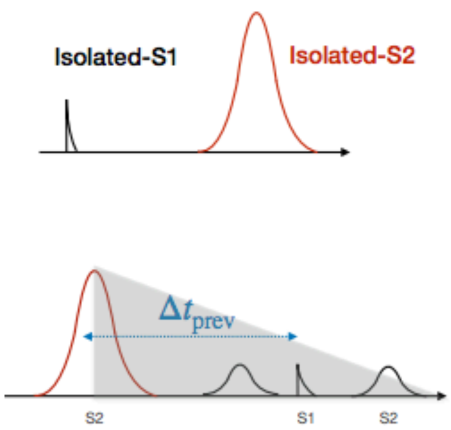
Science Run	Fiducial Mass [Ton]	Exposure [Ton-Year]
SR0	3.97	1.17
SR1	4.10	2.34

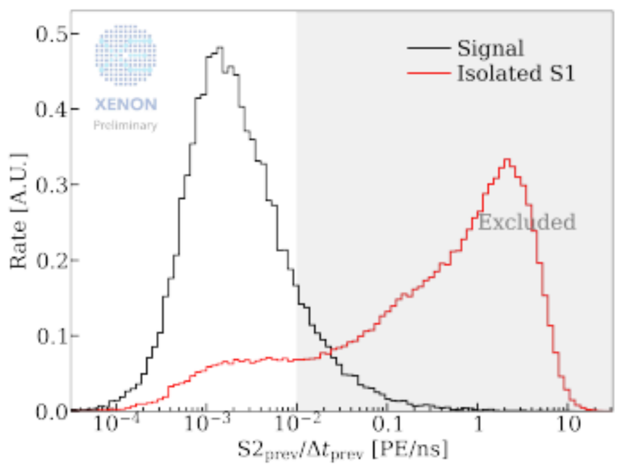
- **Electronic recoils**: Dominated by beta decays from ^{214}Pb
  - Assumed flat spectrum extrapolated from unblinded data
  - Conservatively assigned 100% uncertainty to yield model
  - ER background prediction:
    - SR0: 0.13 ± 0.13 Events
    - SR1: 0.56 ± 0.56 Events

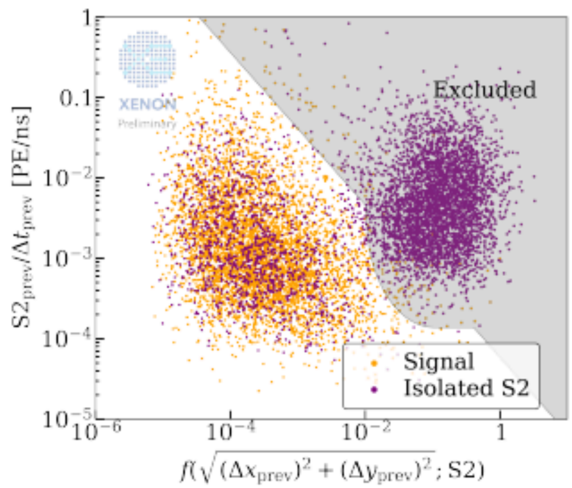
- **Radiogenic neutron**: spontaneous fission and (α,n) reactions
  - Modeled in a combination of data-driven approach and MC
  - Neutron background prediction:
    - SR0: 0.13±0.07 Events
    - SR1: 0.33±0.19 Events
- **Surface background**: ERs from ^{210}Pb plate out at detector walls
  - Data-driven model predicts < 0.3 Events → **negligible**

AC Background

Accidental Coincidence (AC) Background





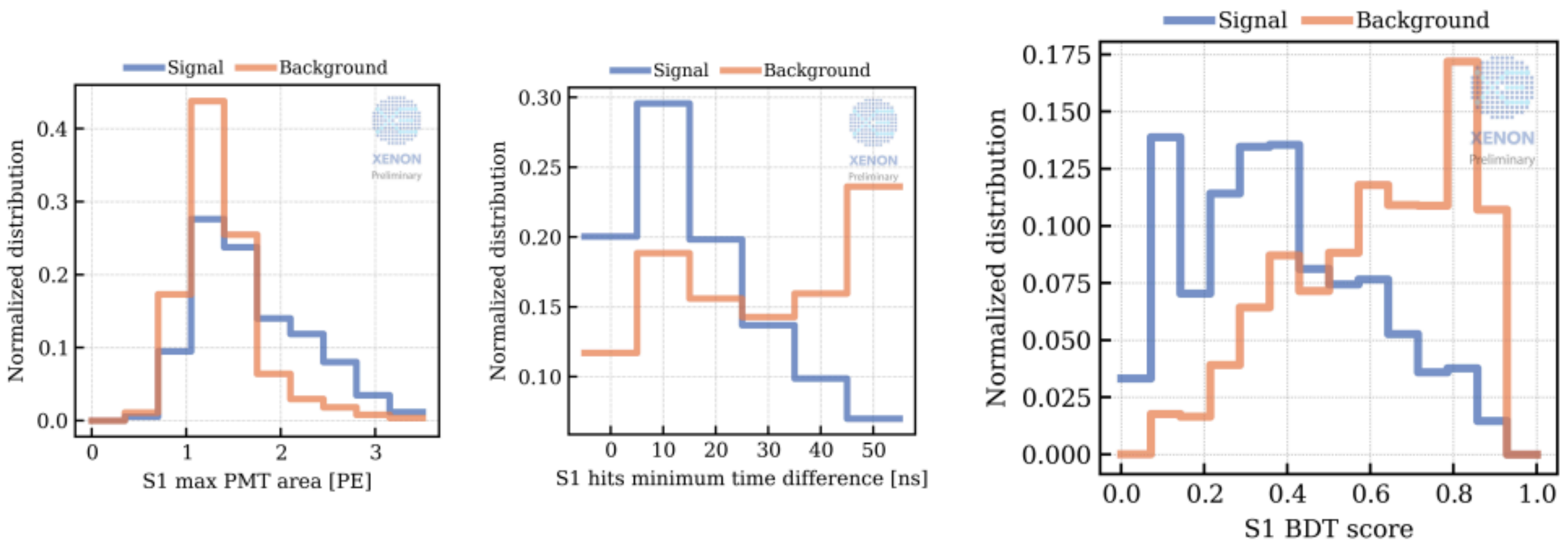


The accidental coincidence of Isolated-S1 and Isolated-S2 is a major background in this analysis

The AC background is highly correlated to high energy events in the TPC, and suppressed by some correlation analysis

AC Background S1 Discrimination

AC Discrimination by S1 Pulse Shape Analysis

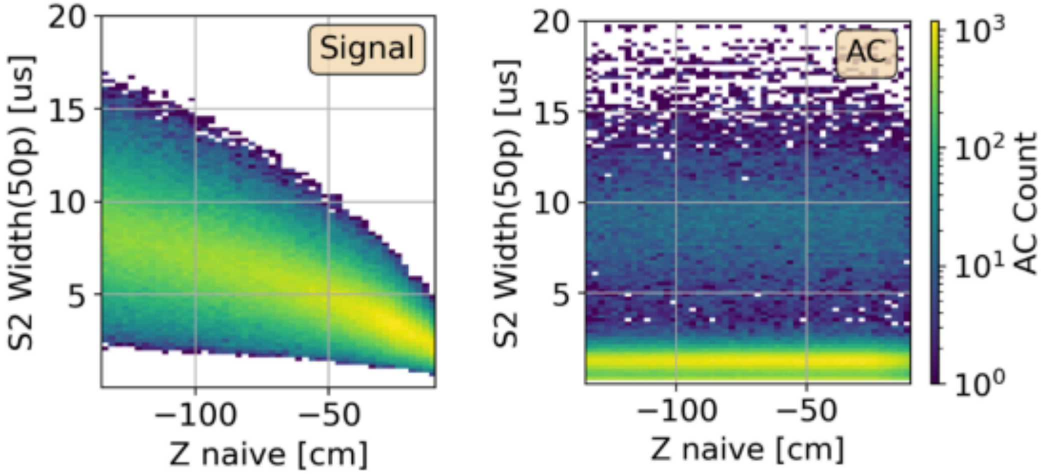


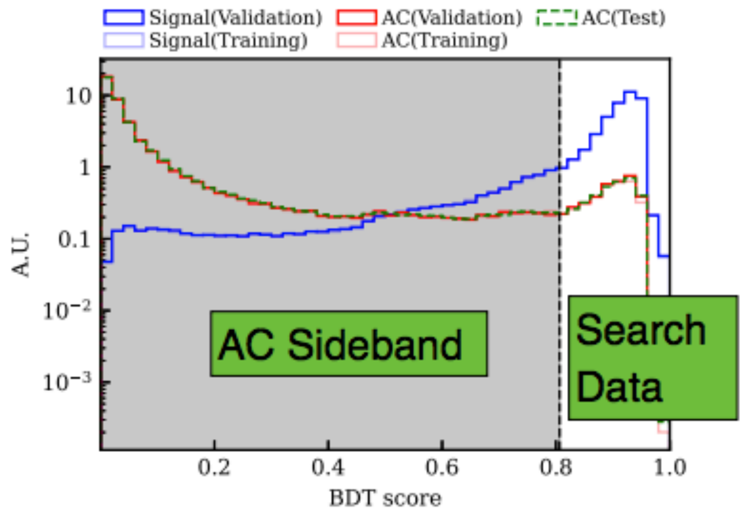
Isolated S1 peaks are primarily due to accidental pile-up of lone PMT hits

S1 Pulse shape and distribution pattern on PMTs are used for AC discrimination in this ananlysis

AC Background S2 Discrimination

AC Suppression by S2 Pulse Shape Analysis

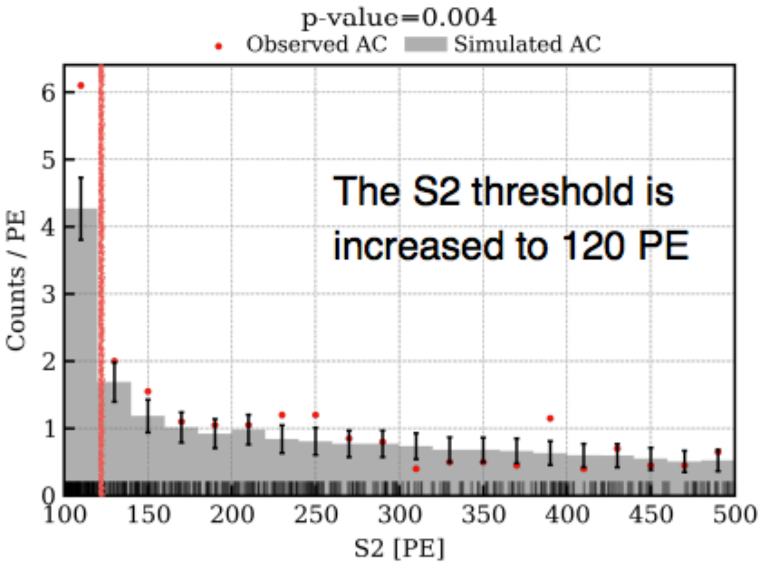




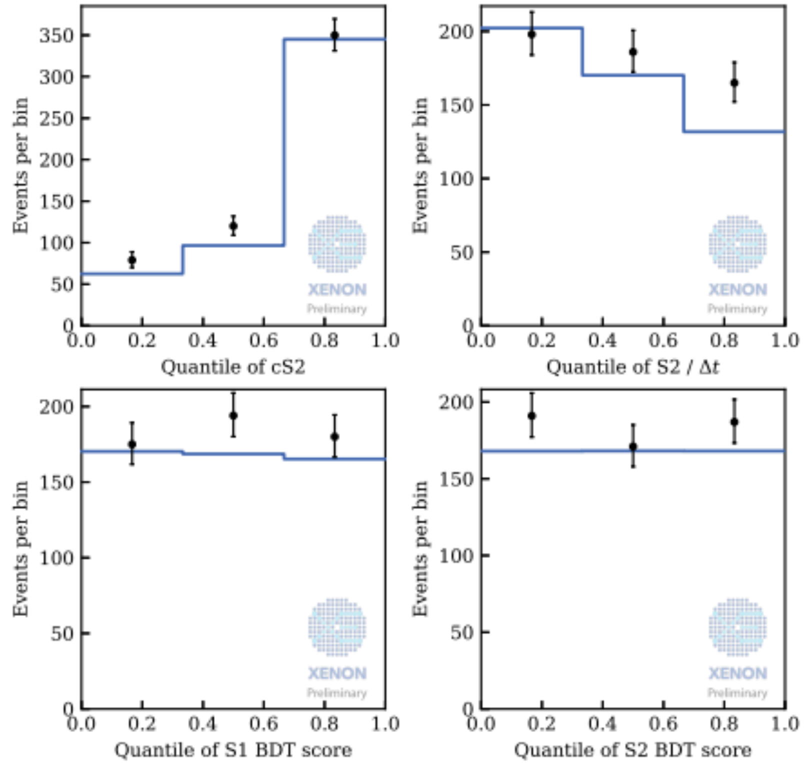
S2 pulse width is drift-time dependent, which is futher grouped as a BDT parameter for AC discrimination

The S2 BDT parameter is employed as an analysis dimension and to define the AC sideband

AC-Sideband Unblinding



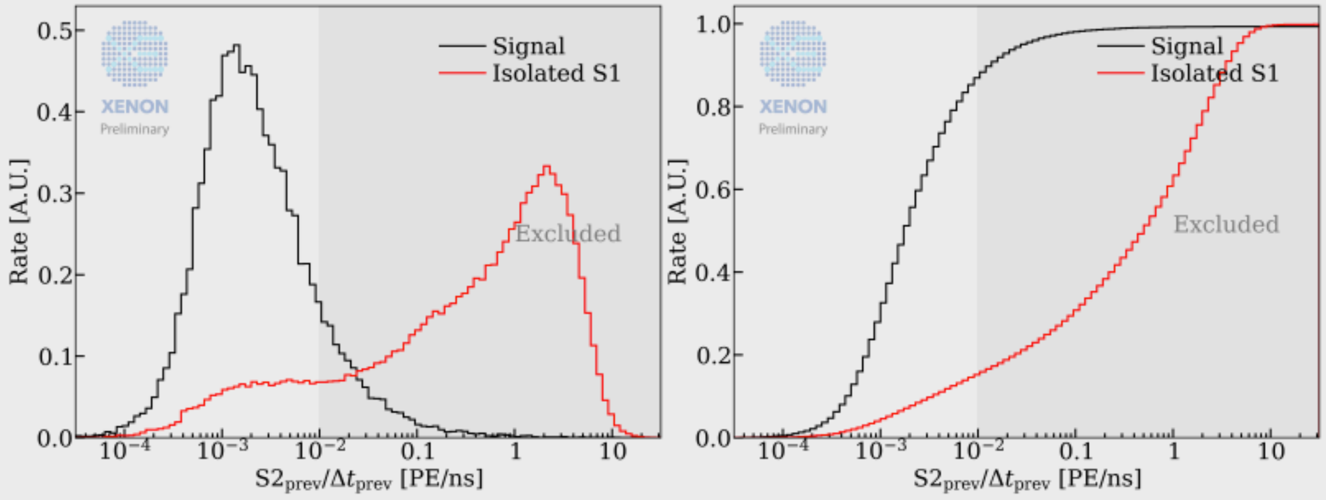
Science Run	Science Run	Science Run	Science Run	Science Run
SR0	122.7	121	0.33	-0.15 sigma
SR1	290.0	310	0.252	1.17 sigma



The remaining 7% difference is considered as a potential systematical uncertainty!

SR0 TimeShadow Cut

CEvNS TimeShadow Cut Impact on 2f Iso-S1 Peaks



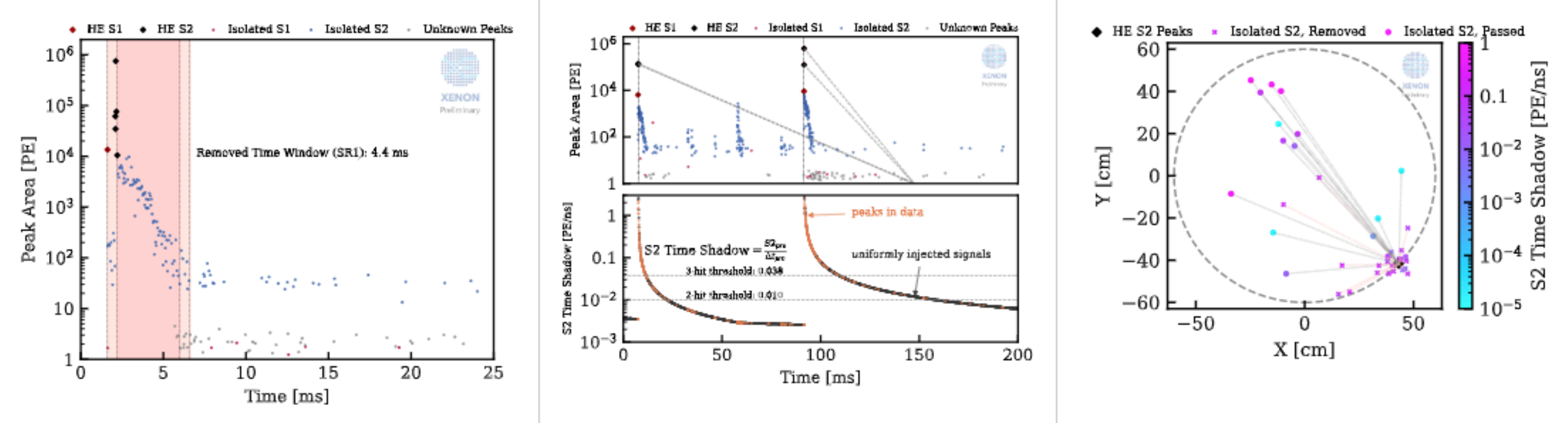
(Non-expert) Caption: Plot shows S2 Time Shadow distribution for a peak, which is the previous large(>1E4PE) S2 area divided by the time difference between them. Signal's peaks and previous S2 have no time correlation so their S2 Time Shadow is small, but for isolated S1s' the opposite is true. We can use this difference to distinguish between signal and isolated peaks. The isolated peaks here are 2-fold isolated S1 peaks(`tight_coincidence` == 2).

Person responsible: Dacheng Xu

Further information for Xe-members: Time shadow calculation used PeakShadow plugin. The TimeShadow distribution of the signal is data-driven. We can randomly select the time of potential signals because TimeShadow does not care about the features of the following suspicious peak except its time. The detailed design of the TimeShadow cut can be found at summary note.

SR1 TimeShadow Cut

Shadow Cuts Demonstration:



(Non-expert) Caption: Demonstration of the shadow cuts: 1.(Left) `TimeVeto` cut removes 1(2) maximum drift time in SR0(1) after S1 larger than 1000PE and S2 larger than 10000 PE. 2.(Middle) `TimeShadow` is defined as the maximum (large peak area)/(time difference); the bottom section shows the `TimeShadow` value at each moment. This `TimeShadow` is also an analysis dimension in the 4D inference. 3.(Right) `PositionShadow` combines the time and position correlation.

Person responsible: Kexin

Date: 2024/07/22

Further information for Xe-members: The selection of `TimeShadow` <10.1 PE/us (<38.22 PE/us) removed more than 80%(50%) 2(3)-hit isolated S1, accepting 87%(96%) 2(3)-hits B8 signal. For S2 peaks, the two-dimensional selection `PositionShadow` in time and position rejects 50% isolated S2s while accepting around 96% signals.