Into the Neutrino Fog with XENONnT

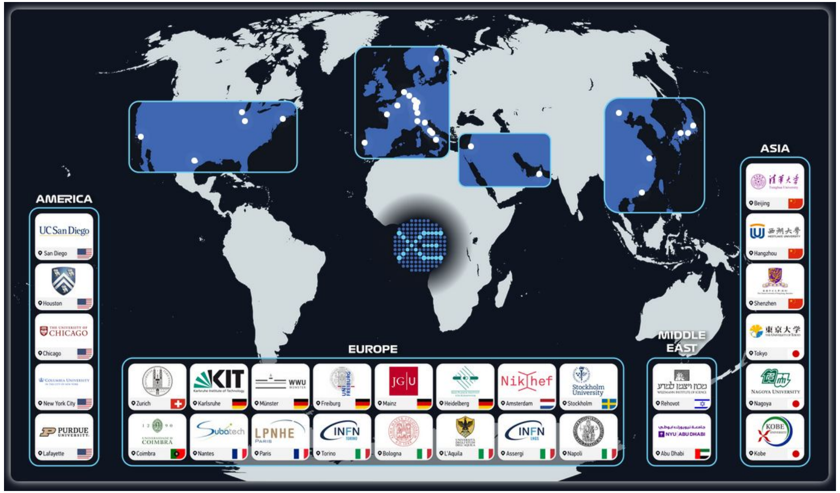
R. Biondi on behalf of XENON Collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

XENON

RICAP 2024 - 24th September 2024

The XENON Collaboration



- 29 Institutions Worldwide
- More than 200 Scientists

Main goal:

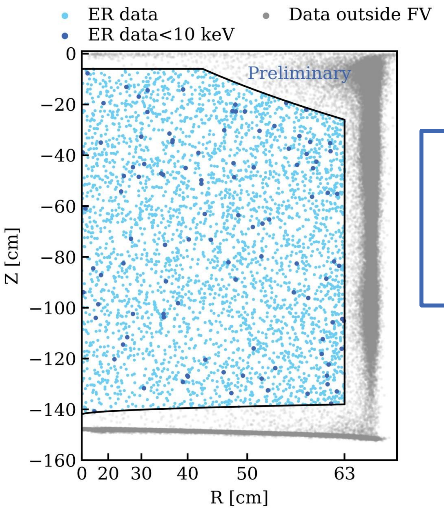
Detection of dark matter particles with a liquid xenon TPC

Last Collaboration Meeting March 11-14 2024 in LNGS

Xenonexperiment.org
Xenon_experiment
XENONexperiment
XENONexperiment

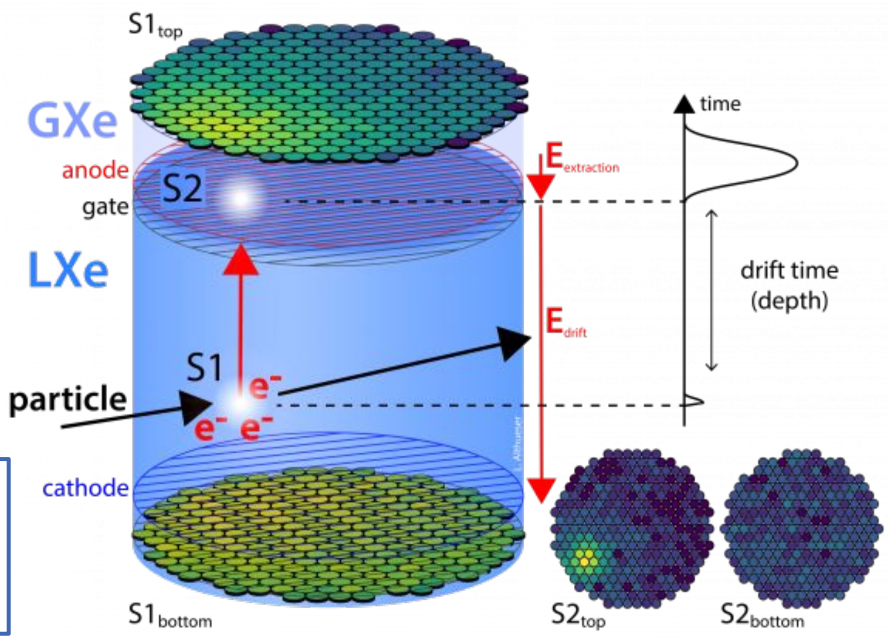
The TPC Detection Principle

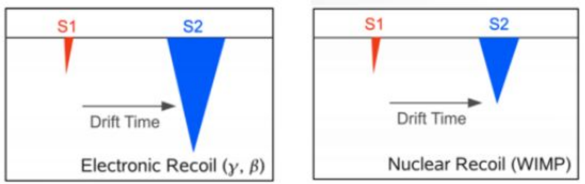
- Dual-phase (liquid+gas)
- Energy reconstruction
- 3D event reconstruction
- Fiducialization
- Event discrimination



WIMP Signal is expected to show up as **Nuclear Recoil**

$$E = W\left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right)$$

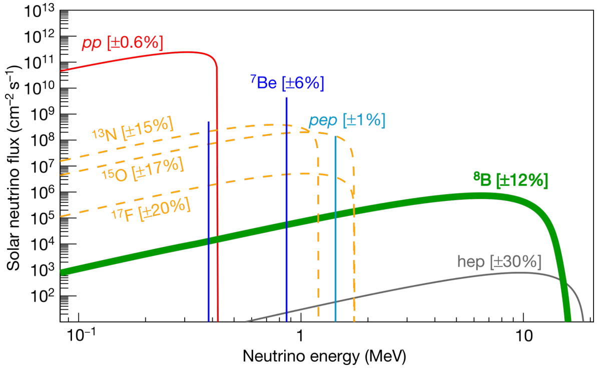


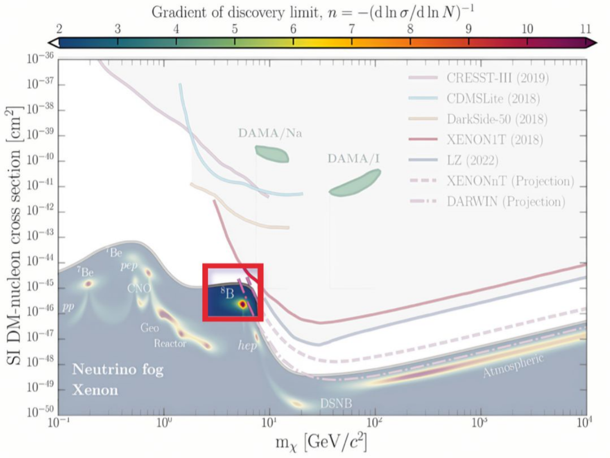


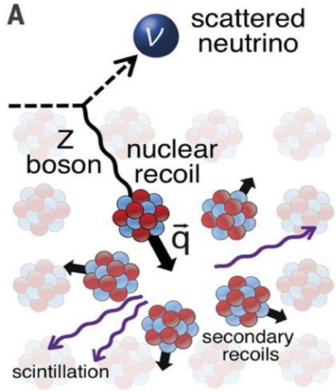
The Neutrino Fog

CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

- First measure by COHERENT (2017) from a spallation neutron
- Never measured in a xenon target
- ^{8}B CEvNS: Expected to have the largest detectable number of CEvNS events in xenon
- Signature indistinguishable from 5.5 GeV/c^2 WIMP with spin-independent $\sigma_{SI} = 4.4 \times 10^{-45}$ cm^2 nuclear recoil







D. Akimov et al, Science 357 (2017)

Ciaran A. J. O'Hare - Phys. Rev. Lett. 127, 251802

The XENON project at LNGS

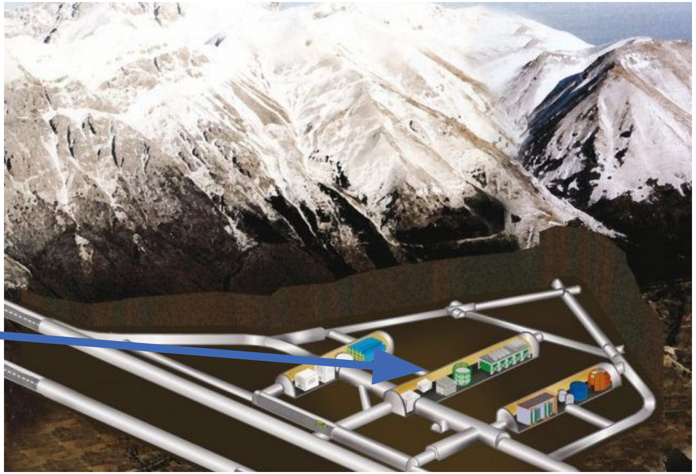
Laboratori Nazionali del Gran Sasso – INFN (Hall B)

1400 mt of rock: 3.800 m.w.e.

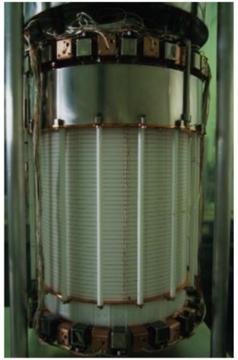
Muon flux ~ 1 m^{-2} h^{-1}

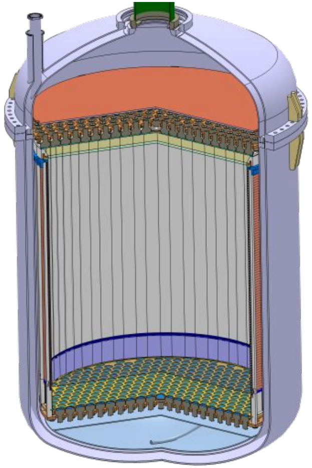
Suppression factor: 10^6

XENON1T



History and Future of the XENON project





	XENON10	XENON100	XENON1T	XENONnT	DARWIN - XLZD
Period	2005 - 2007	2008 - 2016	2012 - 2018	**2019 - 202?**	**202? - ...**
Dimensions	15 x 20 cm	30 x 30 cm	1 x 1 m	**1.5 x 1.3 m**	**2.6 x 2.6 m**
Active mass	14 kg	62 kg	2 tons	**5.9 tons**	**40 tons**
Sensitivity	~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	**~10^{-48} cm^2**	**~10^{-49} cm^2**

XENONnT

Fast upgrade exploiting the infrastructures from XENON1T

Larger TPC

Neutron Veto

Material selection and cleaning

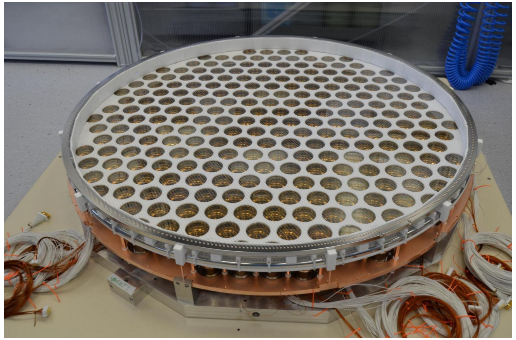
Rn distillation column

Rn-free pumps

Liquid-Xe Purification

New TPC

- Drift length 1.5 m (XENON1T had 1 m)
- Active **Xe mass 5.9 t** (2 t)
- Double the number of PMTs to 494
- Light detection efficiency: 36%
- Carefully **selected materials** to minimize background
- Field shaping rings with tunable potential

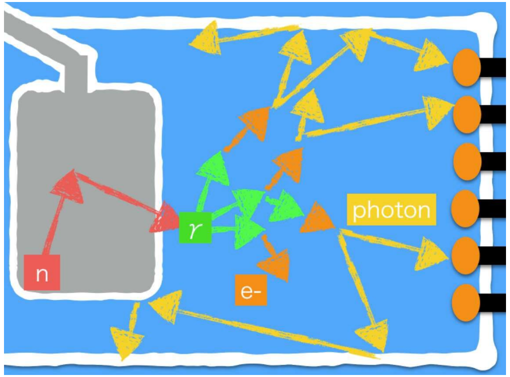


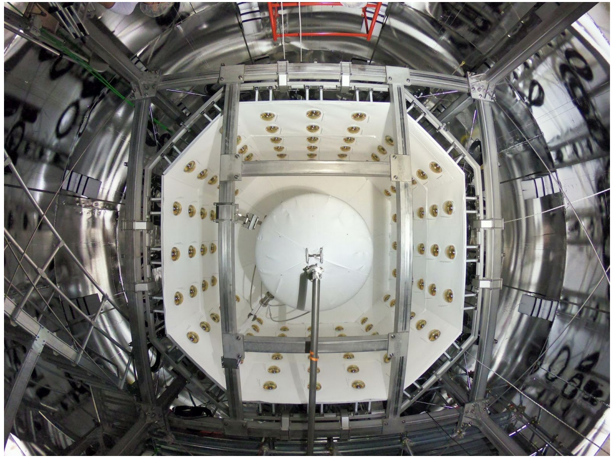
Commissioned in March 2020 during the lockdown due to COVID pandemic

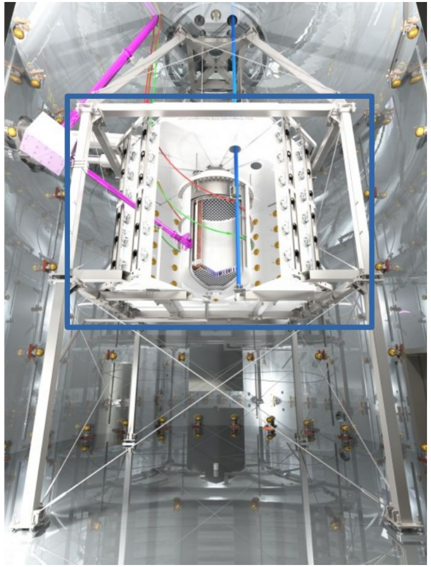
Neutron Veto

Water Cherenkov detector built around the cryostat with 120 PMTs inside an enclosure of reflective panels

To tag **neutrons events** which contribute to background in WIMP search







Running with pure water: **Measured tagging efficiency 68%**

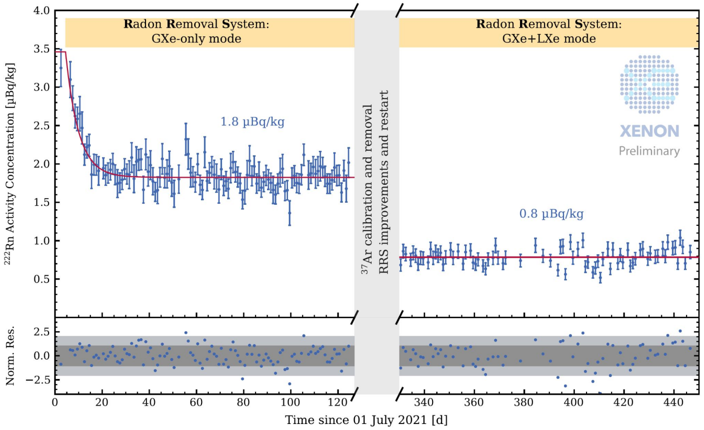
Currently operating with Gd salt (500 ppm) with tagging efficiency ~77%

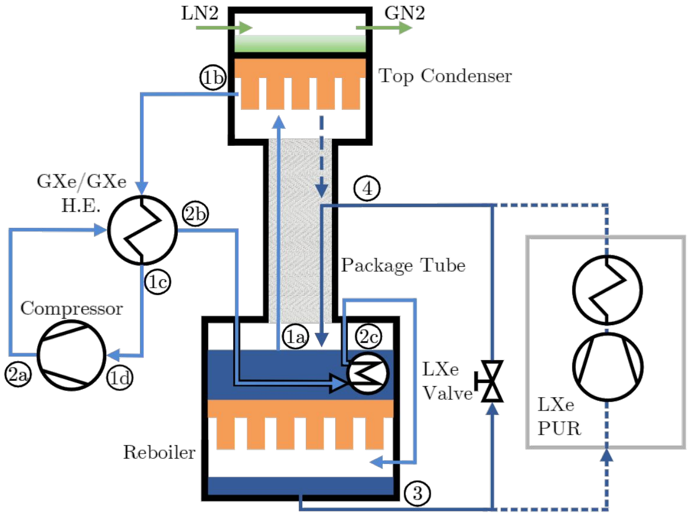
Rn Removal Column

ER background comes mainly from β-decay of ^{214}Pb from ^{222}Rn accumulating into LXe and GXe

High-flow **Radon distillation column**: 72 kg/h (200 slpm)

Radon as less volatile noble gas is trapped in the column until it decays (3.8 days)





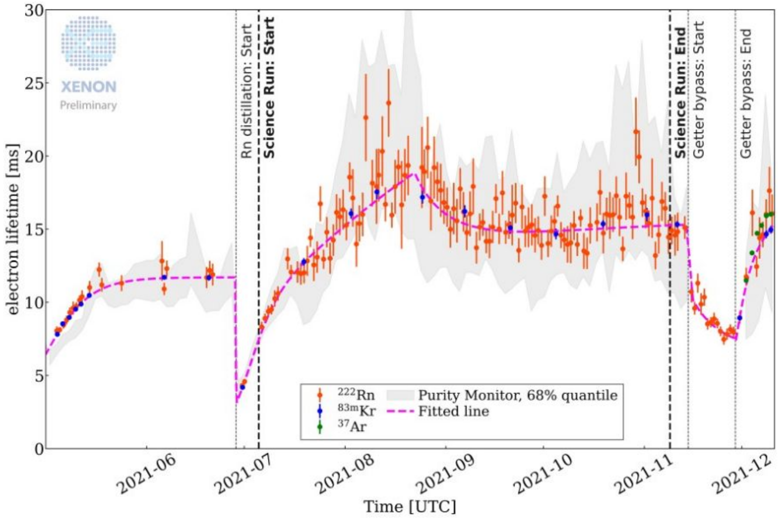
Performance:

- Pre-SR0 - No RRS: : 3.4 μBq/kg
- SR0 - GXe-only: 1.8 μBq/kg
- **SR1 - GXe + LXe: 0.8 μBq/kg**

Liquid Xe Purification System

Direct liquid circulation with cryogenic pump To purify faster the full inventory of LXe

- High flow: 2 liters LXe/min
- Replaceable filter units with low Rn emanation
- Online E-lifetime measurement by purity monitor



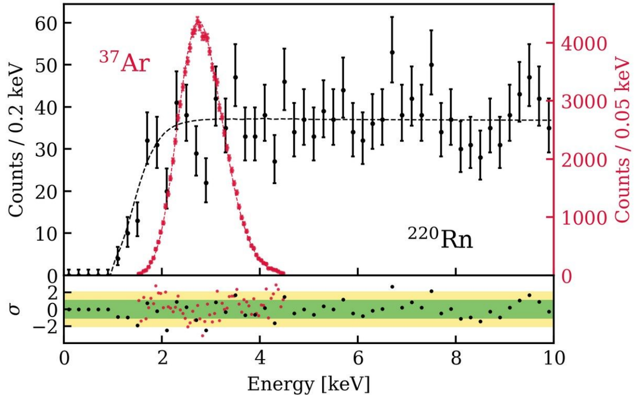
Achieved x10 better purity than XENON1T

Electron lifetime > 10 ms in science run

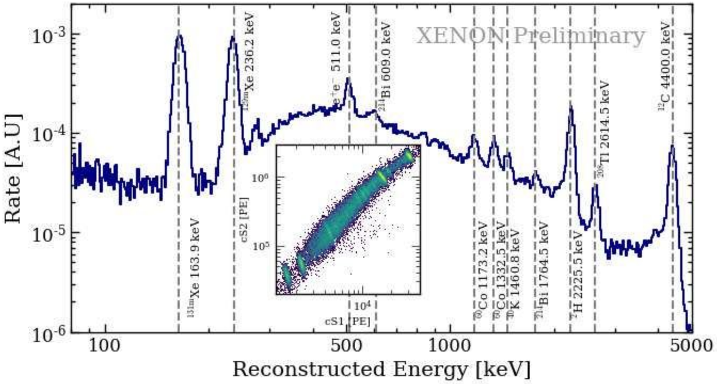
Calibration

Two **ER calibration** sources at low energies:

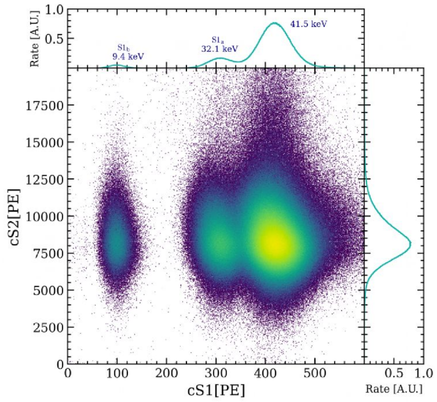
- **^{37}Ar:** mono-energetic peak at 2.82 keV, validates resolution model and energy reconstruction of peaks.
- **^{220}Rn:** its daughter ^{212}Pb provides a flat β-spectrum used to estimate cut acceptances and energy threshold



NR calibration with **AmBe** source:



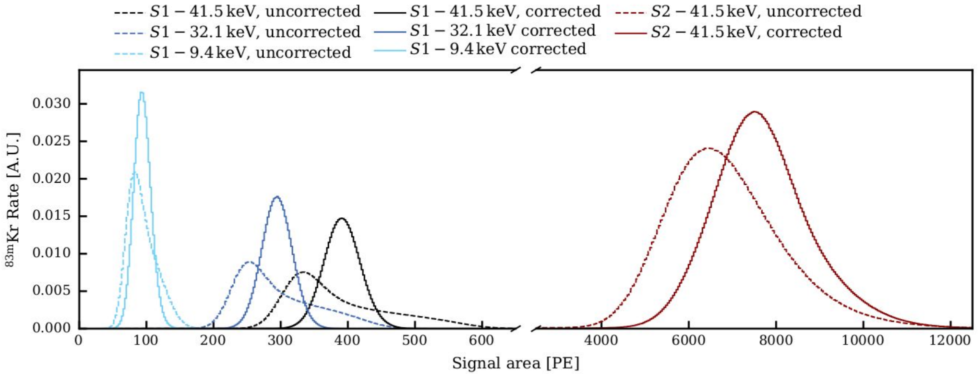
^{83m}Kr: bi-weekly calibrations: for corrections and e-lifetime

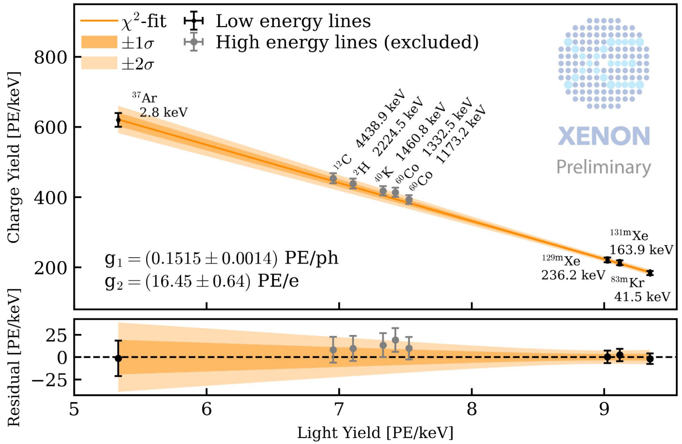


Corrections and Energy Reconstruction

S1 and S2 signals have to be corrected to take into account **position dependent response** of the detector, this is done via the periodical ^{83m}Kr calibration.

Corrected signals cS1 and cS2 are then used in the analysis





Energy reconstruction:

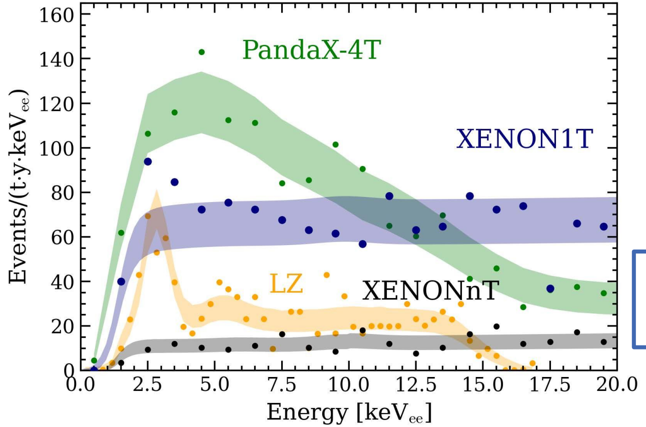
Using: ^{37}Ar, ^{83m}Kr, ^{131m}Xe, ^{129m}Xe calibration

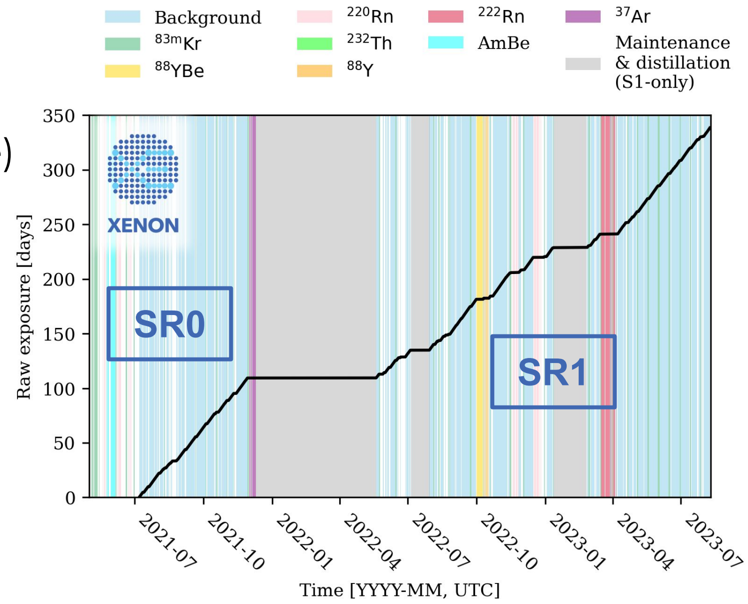
$$E = 13.7\ \text{eV} \left(\frac{cS1}{g_1} + \frac{cS2}{g_2} \right)$$

Datasets

SR0 and SR1 Science Data (2021-07 - 2023-08)

- Exposure: **3.51 ton x yr**
- Stable detector response: <1% (<3%) light (charge) yield variation
- High LXe 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)



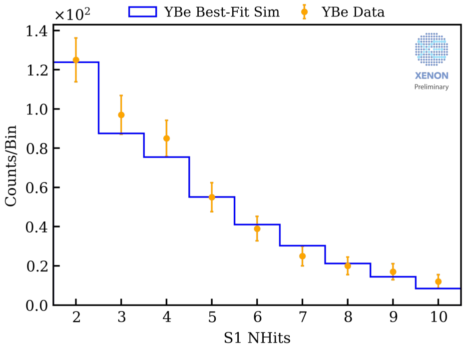


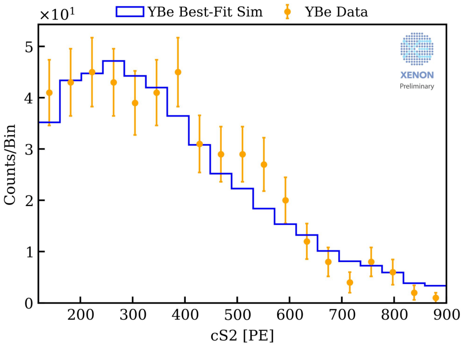
World leading low ER background in SR0, improved in SR1

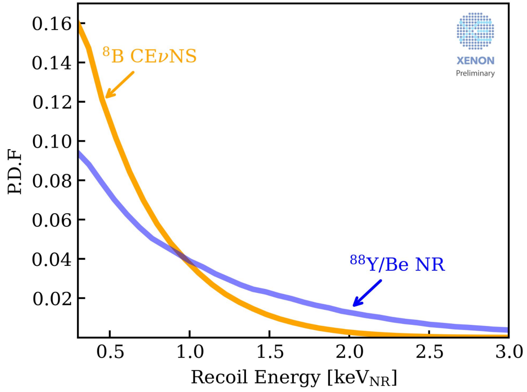
Calibration with YBe Neutron Source

^{88}YBe Low Energy NR Calibration with **152 keV neutrons** from photo-disintegration of ^{9}Be by γ-ray from ^{88}Y decay

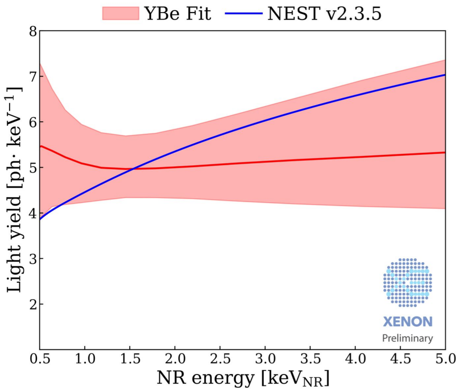
- Low energy NR yield model affects ^{8}B CEvNS detection efficiency
- Good simulation/data match
- Light/charge yield model constrained by ^{88}YBe data
- Yield model uncertainty leads to ~34% signal rate uncertainty

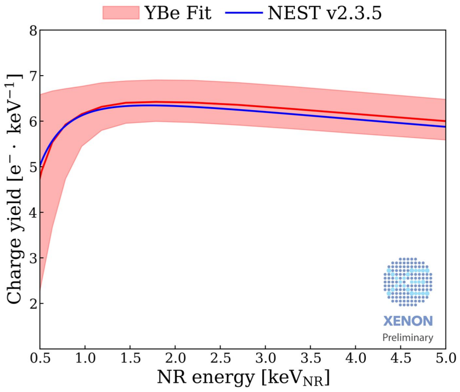






Recoil energy spectrum similar to ^{8}B CEvNS

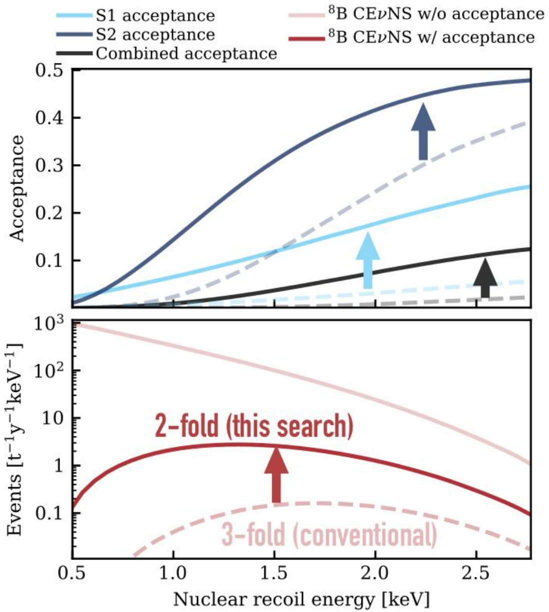


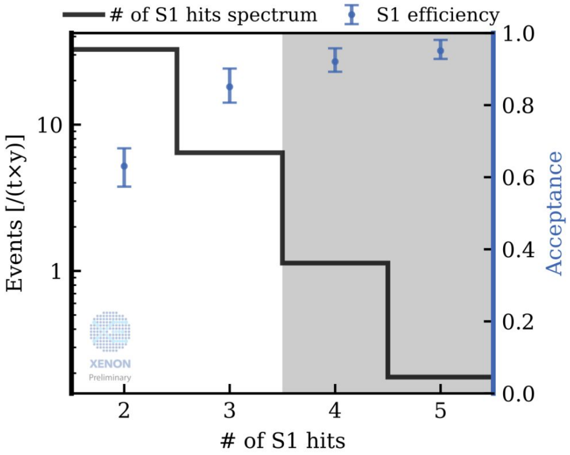


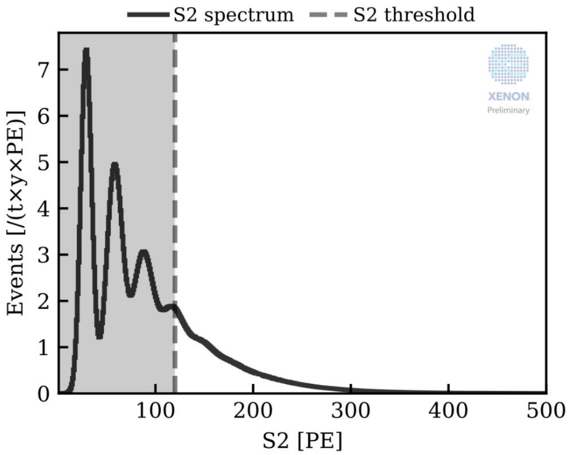
Energy Threshold and Region of Interest

ROI:

- **S1:** 2 or 3 hit
- **S2:** 120 - 500 PE







- Lowered S1(S2) threshold from conventional WIMP search analysis: 3 hits (200 PE)
- Relaxed S1 waveform shape requirement
- Lower S2 threshold is used to reject high isolated S2 background below it.

~x17 more Events Expected

Accidental Coincidence Background

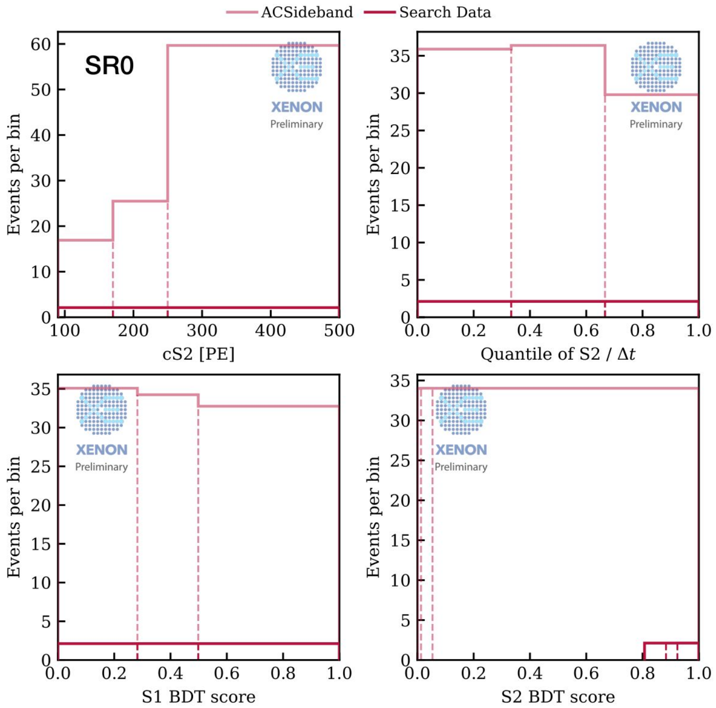
Random unphysical pairing of isolated S1 and S2

Isolated peaks are side products of **high energy interactions** (Physical mechanisms still under investigation)Isolated-S1(S2) Rate 15 Hz(150 mHz)

Suppression:

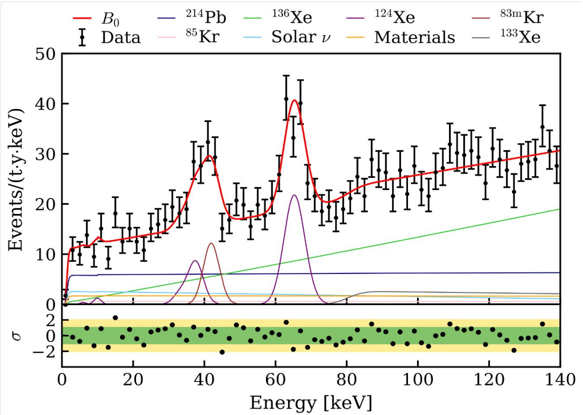
- Selection on space/time correlation to previous HE interactions (TimeShadow)
- Boosted Decision Tree selections:
  - S1 BDT: VUV photon spectrum + S1 pulse shape & spectrum
  - S2 BDT: S2 pulse shape compatible with diffusion law
- 3^4-bins 4D search space (cS2, S1 BDT, S2 BDT, TimeShadow)

Model Validated by **AC sideband** (events that failed S2 BDT)Fit and by ^{37}Ar L-shell 0.27 keV ER calibration



Expected # of AC events:
7.5 ± 0.7 for SR0 & 17.8 ± 1.0 for SR1

Other Backgrounds



Radiogenic Neutrons:
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

Phys.Rev.Lett. 129 (2022) 16, 161805

Electronic Recoils:
mainly β-decays from ^{214}Pb

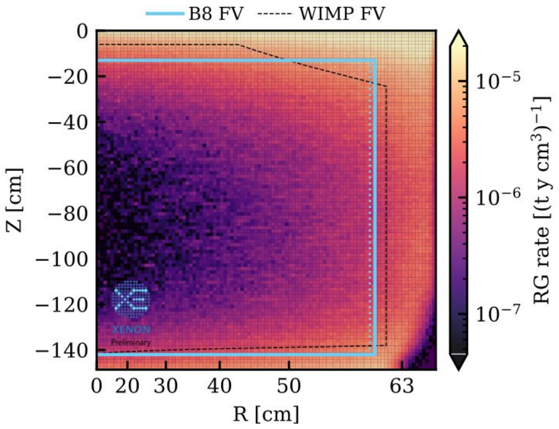
- Flat spectrum extrapolated from unblinded data
- Conservatively assigned 100% uncertainty to yield model
- ER background prediction:
  - SR0: 0.13 ± 0.13 Events
  - SR1: 0.56 ± 0.56 Events

Surface background:
ERs from ^{210}Pb plate out at detector walls

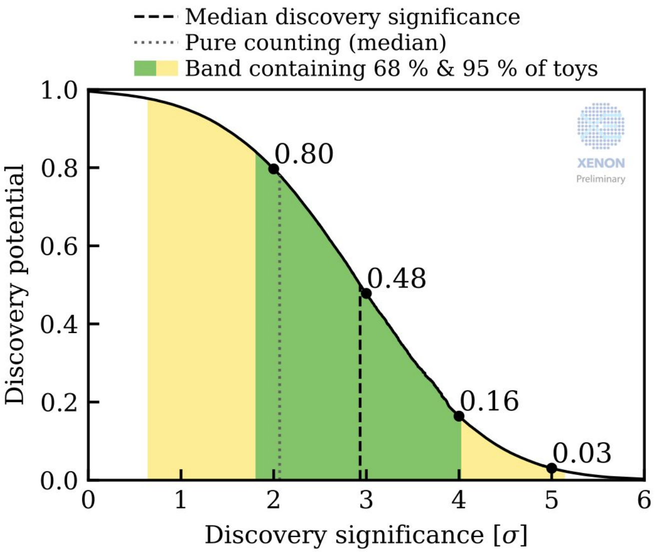
- Data-driven model predicts < 0.3 Events → **negligible**

Sensitivity and prediction

Total exposure: **3.51 ton year**



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



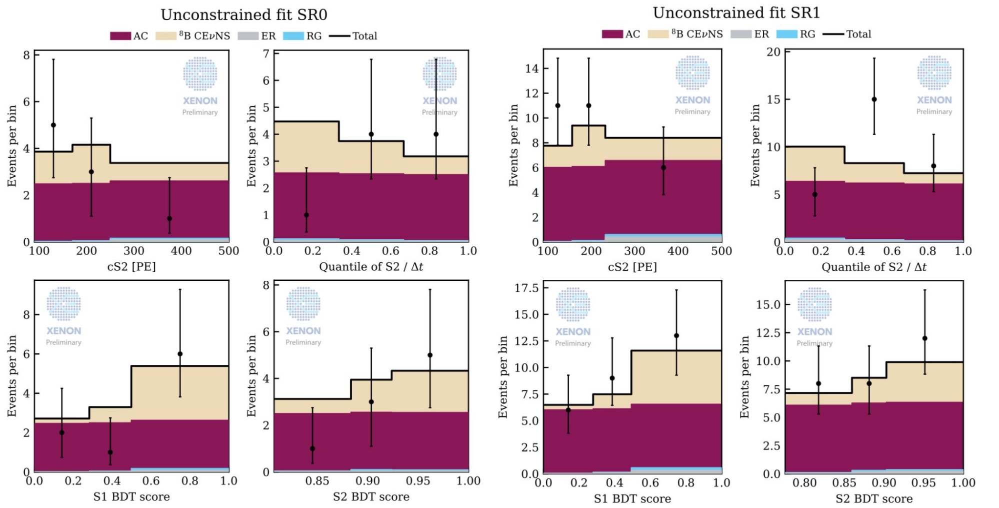
Component	**Rate [Events]**
AC - SR0	7.48 ± 0.52
AC - SR1	17.77 ± 1.23
ER	0.68 ± 0.68
NR	0.47 ± 0.32
Total Background	26.4 ± 1.5
^{8}B	**11.93 ± 3.1**

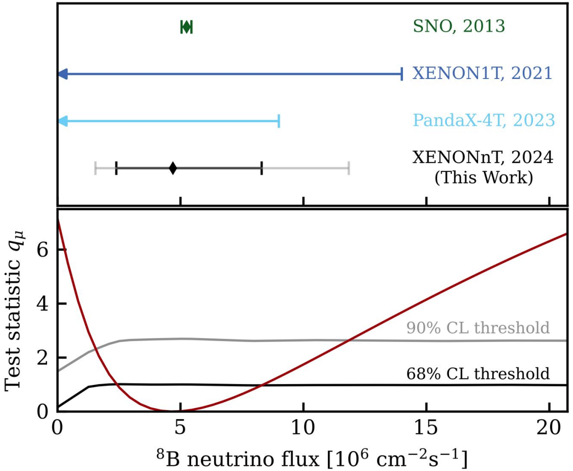
We to predicted a **48% probability** to detect solar ^{8}B neutrinos signal at **>3σ significance** using the full 4-D analysis

Results from Unblinding

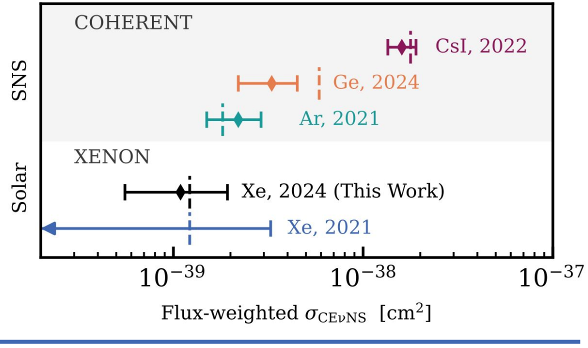
ArXiv: 2408.02877

- Data agrees with the signal + background expectation
- Flux-weighted σCEvNS in agreement with SM
- Flux measurement in agreement with SNO (2013)





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	

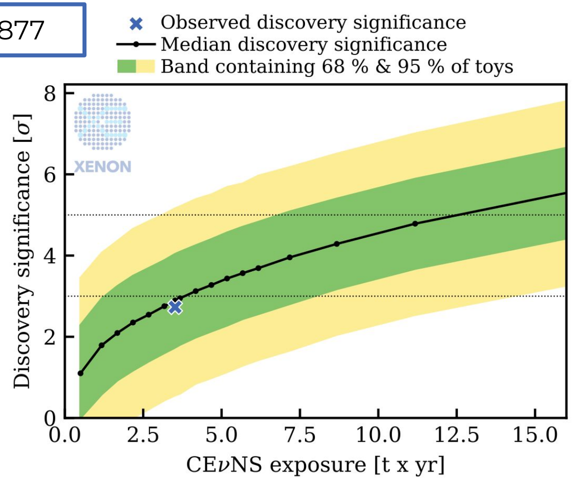


Summary and Outlook

XENONnT performed a blind search for 8B CEvNS

ArXiv: 2408.02877

- **2.73σ** Discovery significance of ^{8}B CEvNS
- Measurement of ^{8}B solar ν flux: $\mathbf{4.7^{+3.6}_{-2.3} \times 10^{6}\ cm^{-2}\ s^{-1}}$
- Measured neutrino flux-weighted CEvNS cross-section on Xe: $\mathbf{\sigma_{CEvNS} = 1.1^{+0.8}_{-0.5} \times 10^{-39}\ cm^{2}}$



A series of Firsts times:

- **FIRST** detection of astrophysical ν in a dark matter detector
- **FIRST** measurement of CEvNS process from astrophysical ν source
- **FIRST** measurement of CEvNS cross section on a Xe target

Data taking still on going (SR2): we expect to measure the solar ^{8}B neutrino signal at higher significance and to better constrain the neutrino flux

Thank You!

BACKUP

Low-ER excess in XENON1T

From: Phys. Rev. D 102, 072004

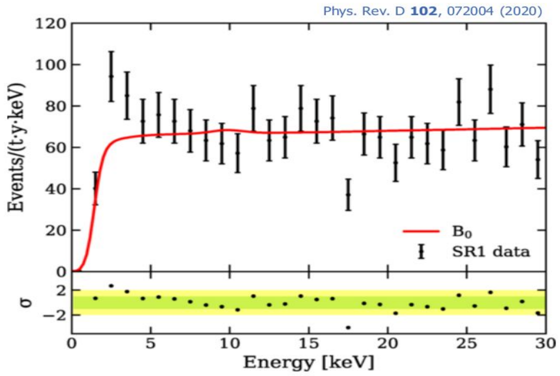
ER search in <30 keV range shown an excess of events over the expected background corresponding to a **3.3 σ fluctuation**

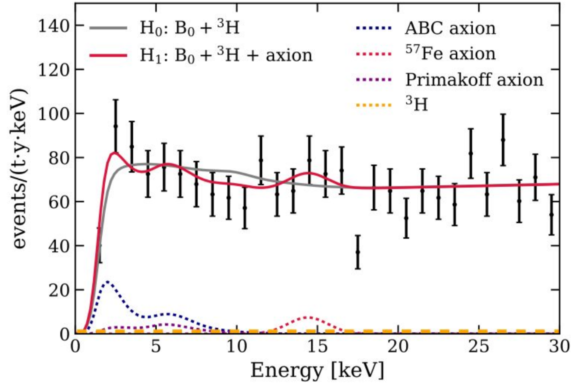
Hypothesis of ^{37}Ar leak is excluded:

- Removed by Kr distillation
- Limits on air leak from other contaminants (Kr, Rn)

Several hypothesis:

- Solar axions (3.4σ over bkg)
- Neutrino magnetic moment (3.2σ over bkg)
- Bosonic DM: ALPs, dark photons (3.0σ over bkg)
- β decay of Tritium
- New Physics?



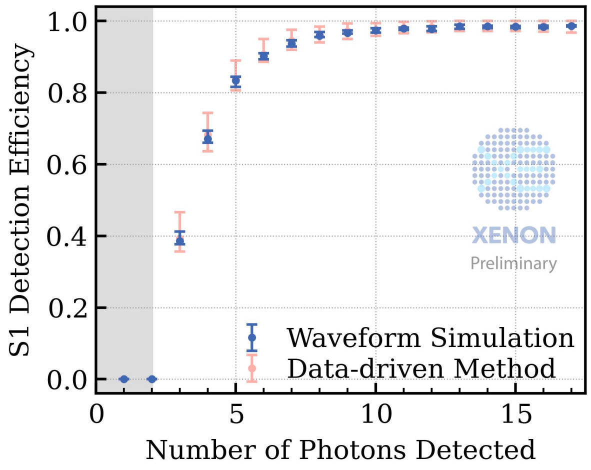


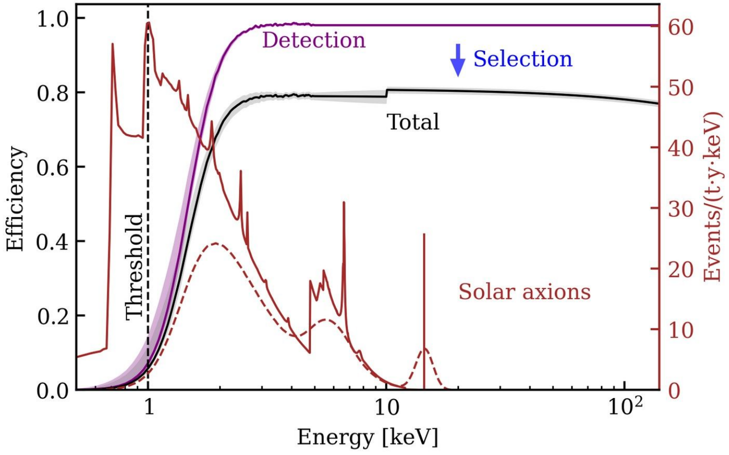
Efficiencies

Detection efficiency validated using **Monte Carlo** and **Data-Driven** methods

Good agreement between the two approaches

Total efficiency takes also **event-selection efficiency** into account





Tritium Enhanced Dataset (TED)

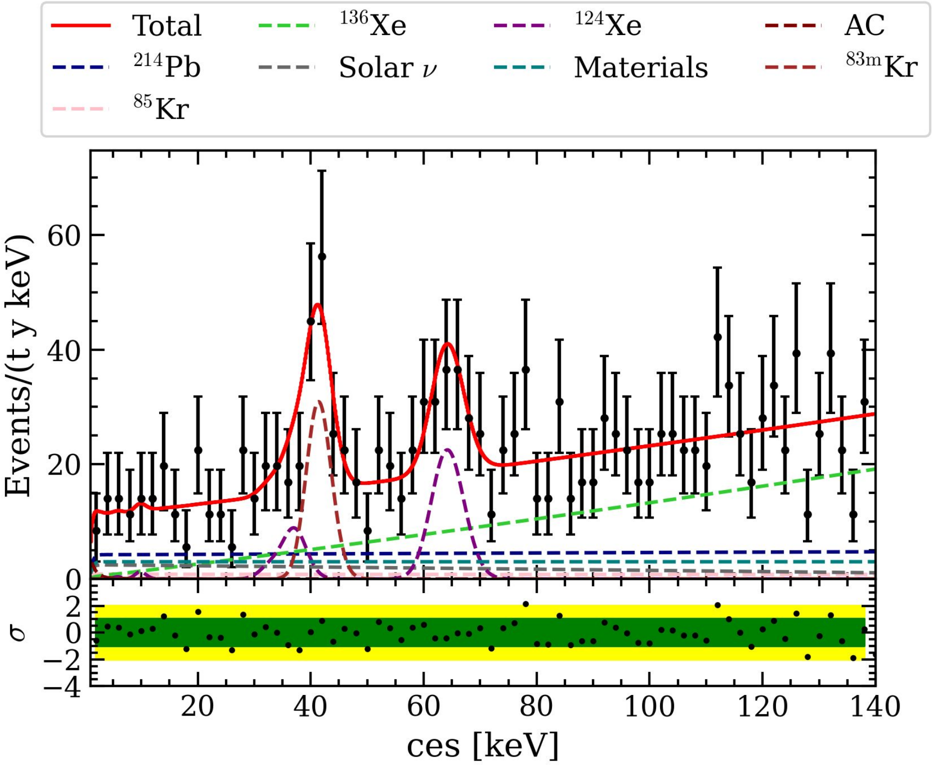
To Exclude presence of Tritium traces in the detector, XENONnT was operated **bypassing the GXe purification** for 14.3 days at the end of SR0

This would enhance the HT concentration in LXe by a factor 10-100

Data collected in this TED mode were **blinded**

After the unblinding, **no evidence was found for a tritium-like excess**

Tritium is therefore not included in the background model.



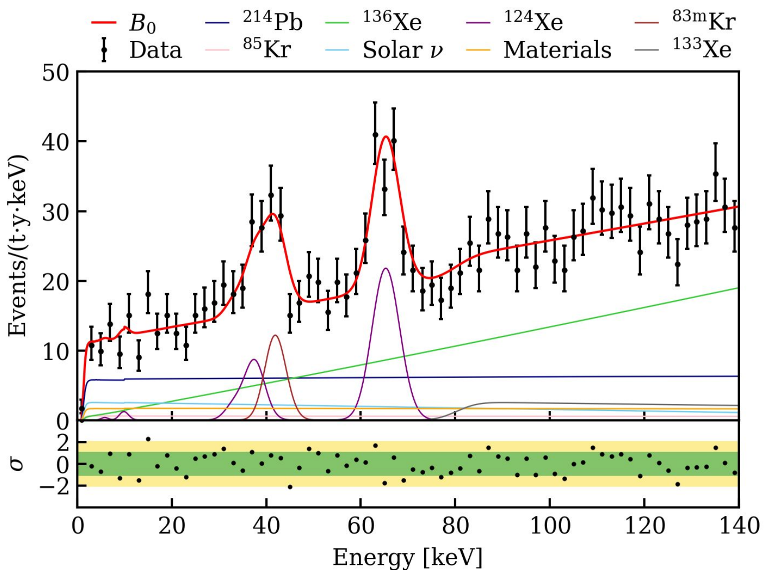
Low Energy ER Analysis

From: PRL 129, 161805 (2022)

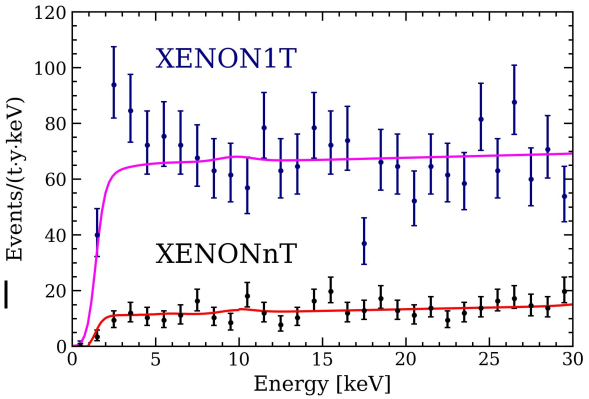
Full blind analysis

- Energy range: (1-140) keV
- Fiducial mass: (4.37±0.14) t
- Exposure: **1.16 tons years**

No excess observed



The excess observed in XENON1T could come from either tritium or statistical fluctuation



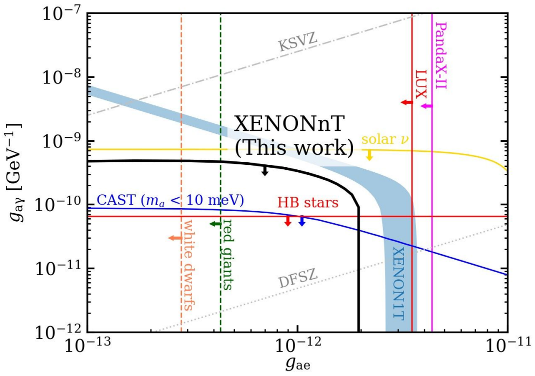
Background in (1,30) keV:

(15.2 ± 1.3 stat)events/(t*y*keV)

Factor ~5 reduction w.r.t. XENON1T

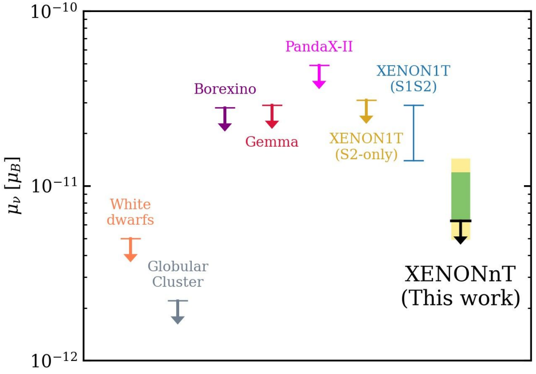
Limits on New Physics

Solar Axions



Limit on 14.4 keV peak for ^{57}Fe solar axions is < 20 events/(t*y)

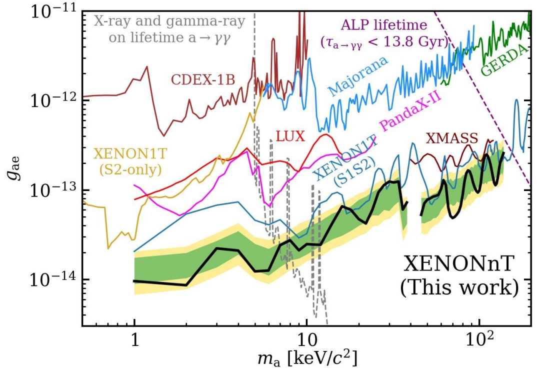
ν Magnetic Moment



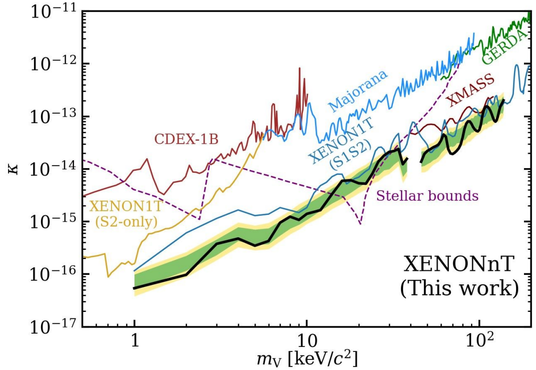
$\mu_\nu < 6.3\ 10^{-12}\ \mu_B$

The most stringent limit from direct detection experiment

Axion-like particles



Dark Photon



WIMPs search

From arXiv: 2303.14729

Background model:

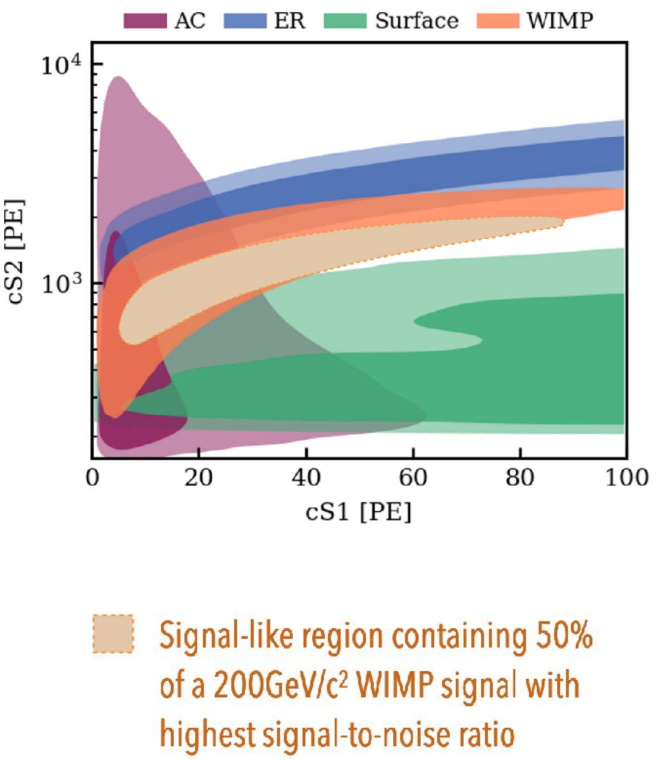
Electronic Recoil (ER): Mainly β decay of ^{214}Pb from ^{222}Rn

Accidental Coincidences (AC): random pairing of small S1 and S2 signals

Surface/Wall: ^{210}Pb plate-out on the PTFE wall of the TPC

Nuclear Recoil backgrounds (same shape as WIMP):

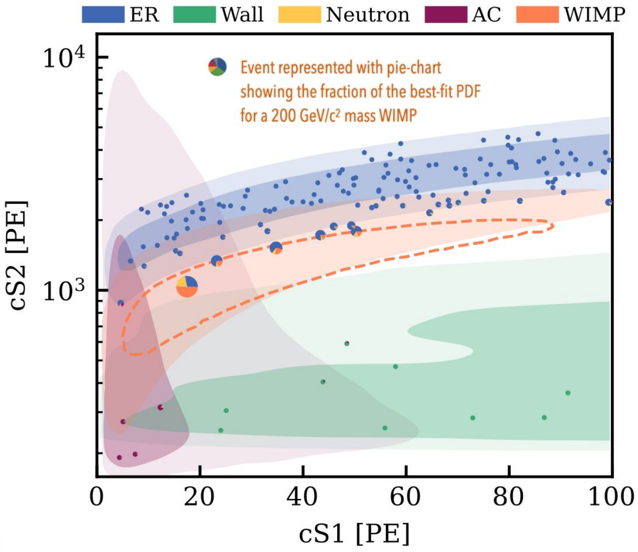
- CEvNS
- Neutrons



WIMPs Results

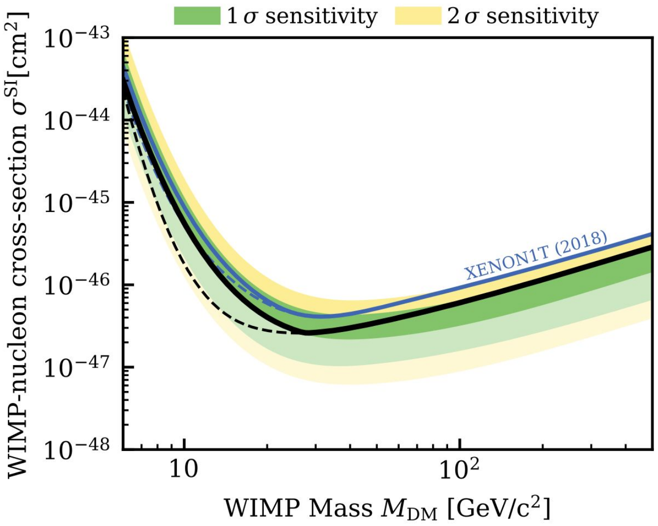
Full blind analysis

- Fiducial mass: (4.18±0.13) t (Same shape of ER, but smaller R < 61.35 cm)
- Exposure: **1.1 tons years**



No significant excess

XENONnT 90% C.L. Power-Constrained Limit To constrain large downwards fluctuations

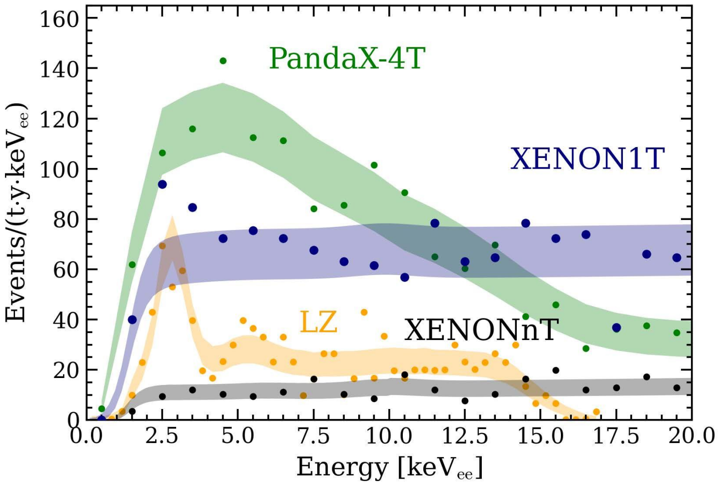


*Assuming a 200 GeV WIMP and a best-fit σ = 2.5 × 10^{-47} cm^2

Comparison with other LXe Experiments

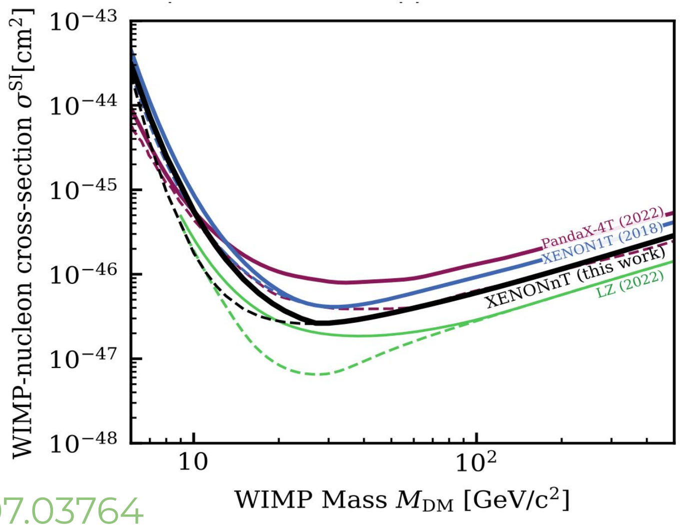
ER Background:

PandaX-4T PRL 129, 161804 (2022)
XENON1T PRD 102, 072004 (2020)
LZ arXiv:2207.03764
XENONnT PRL 129, 161805 (2022)



Spin-Independent WIMP-Nucleon cross section:

Same conservative power-constraint applied to results of other LXe experiments from non-blind analyses:



LZ, arXiv:2207.03764
XENON1T, PRL 121, 111302 (2018)
PandaX-4T, PRL 127, 261802 (2021)