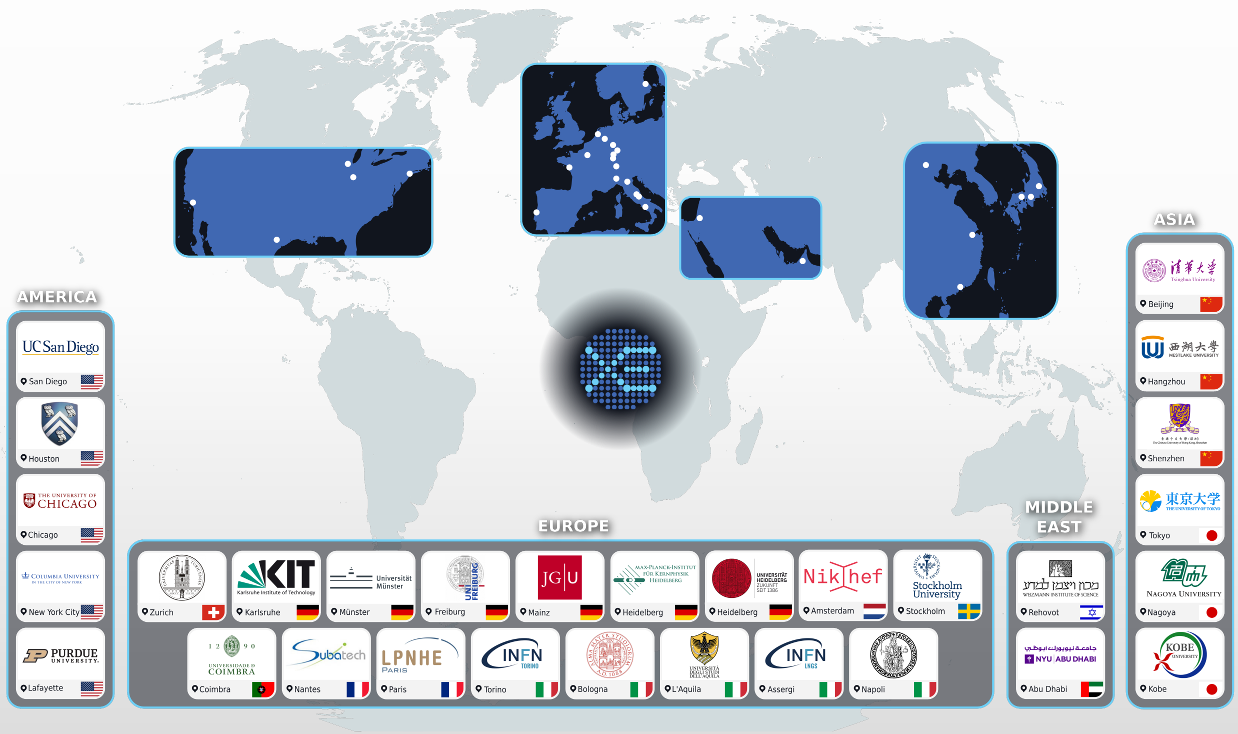
Latest results from the XENONnT Experiment

Federica Pompa (Subatech - CNRS/IN2P3)

On behalf of the XENON collaboration

The XENON Collaboration

~170 scientists, 30 institutions, 12 countries



Main Motivation:

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

Other studies:

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

How we do it:

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

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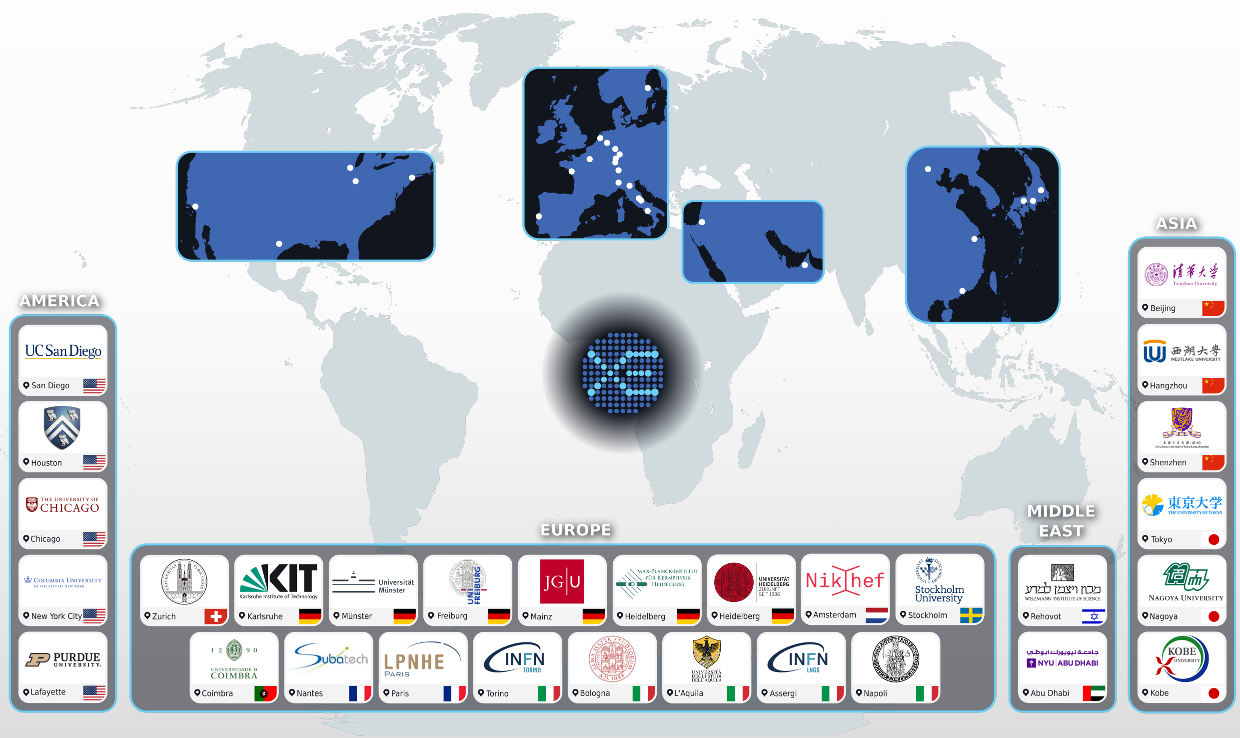


XENON program timeline

XENON10
25 kg LXe

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

XENON100
160 kg LXe

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

XENON1T
3200 kg LXe

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

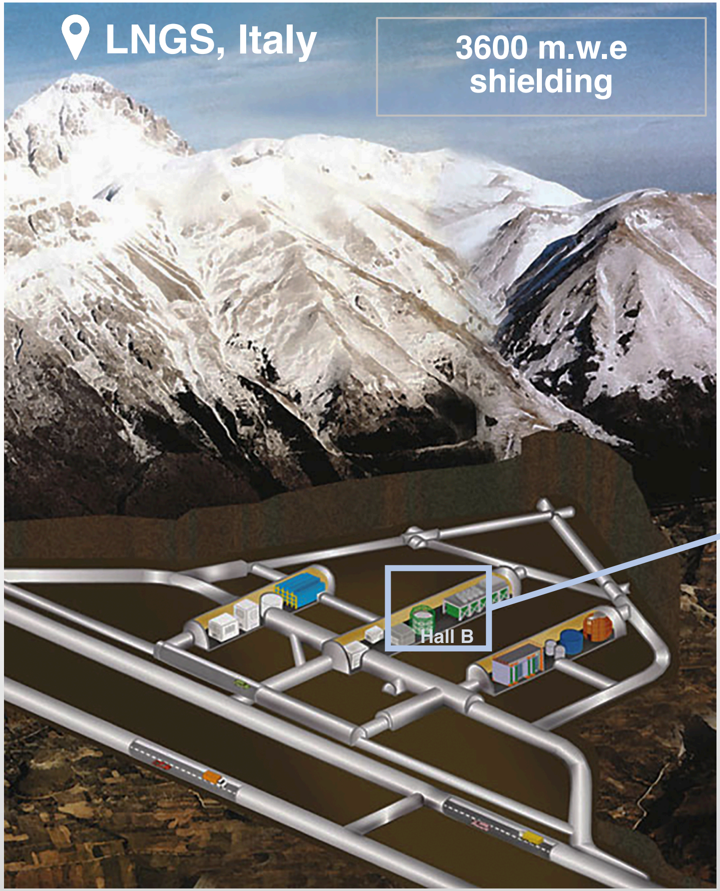
XENONnT
8600 kg LXe

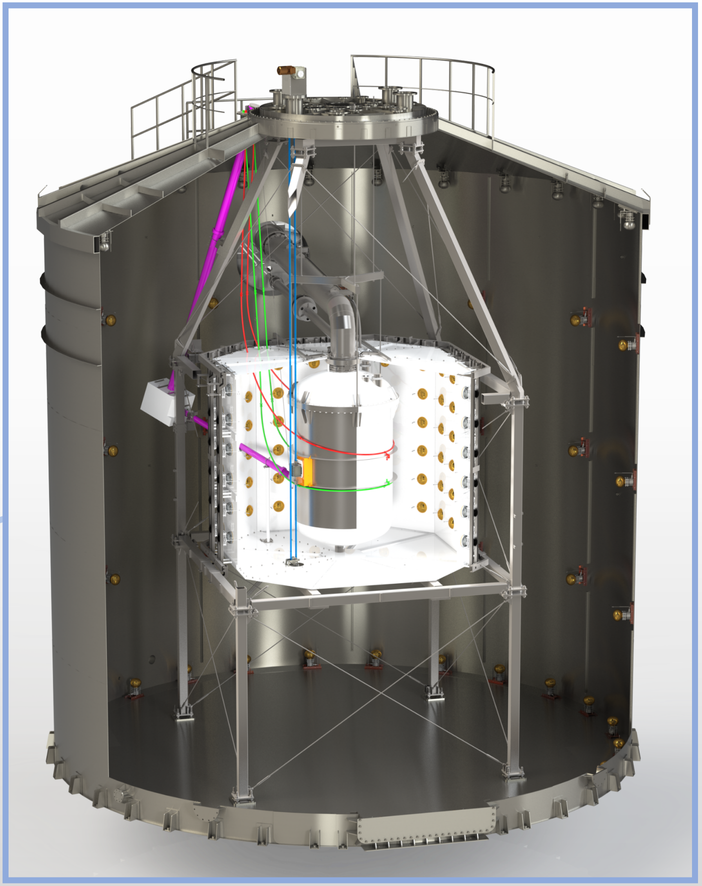
2020
300+ livedays
(ongoing)
BG: 0.04 / (t.d.keV)

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

Eur. Phys. J. C 84, 784 (2024)

XENONnT Experiment



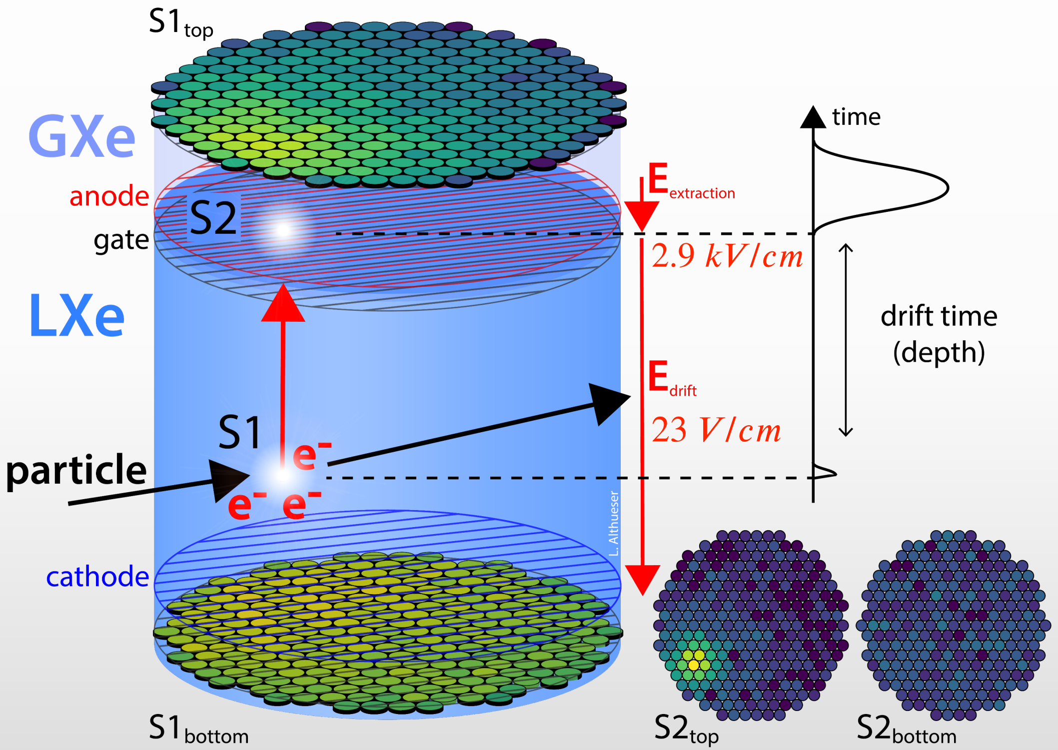


3 Nested Detectors

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)**. (arXiv:2412.05264 [physics.ins-det])
- Gd-doped Water Cherenkov **Muon Veto (MV)**. (2014 JINST 9 P11006)

Dual Phase TPC: Working Principle



- Particle interactions in LXe create both **prompt scintillation (S1)** and **delayed ionization** signals.
- Ionization electrons drifted upwards by **drift field** and extracted into gas phase by **extraction field**; leads to **electroluminescent light (S2)**.
- Signals collected in the top and bottom PMT 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.

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

Eur. Phys. J. C (2022) 82: 1104
Eur. Phys. J. C 77, 275 (2017)
2023 JINST 18 P07054

Eur. Phys. J. C 84, 784 (2024)

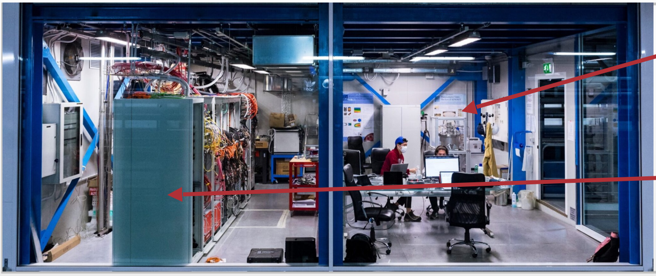
XENONnT Infrastructure

Rn Distillation

Continuous online distillation.

^{222}Rn (SR0): $1.9\ \mu Bq/kg$

^{222}Rn (SR1): $0.9\ \mu Bq/kg$

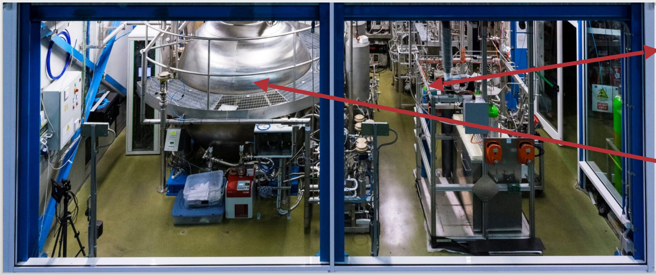


Kr Distillation

^{nat}Kr/Xe concentration < 50 ppq

nT DAQ

Shared between three detectors.

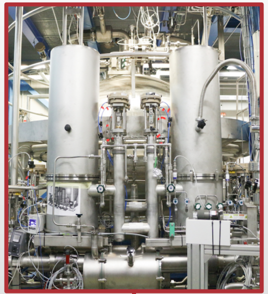


LXe Purification

Removes **electronegative** impurities.

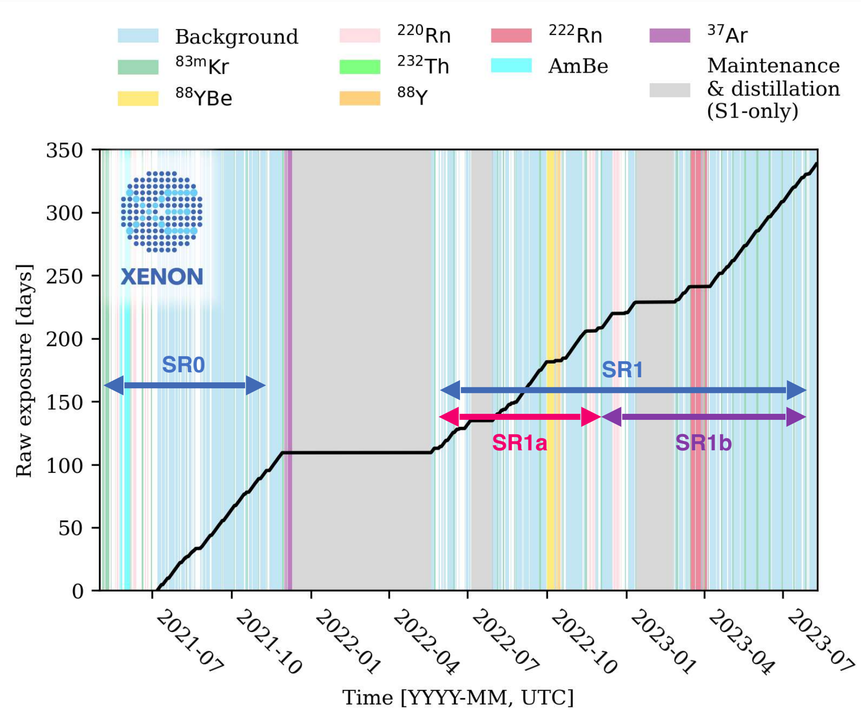
ReStoX

Fast **xenon recovery system** and storage, preserving purity.

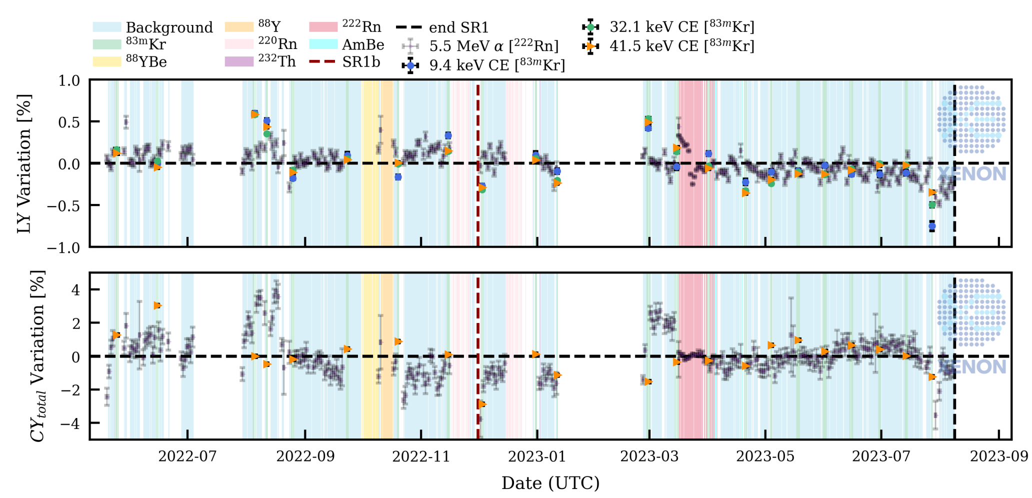


Eur. Phys. J. C (2022) 82: 860

XENONnT: Science Data

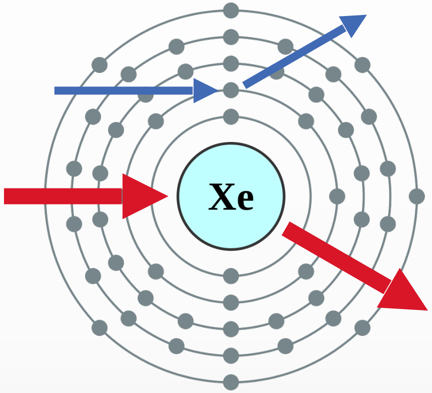


- Science data divided into various **Science Runs (SR)**. Exposure for science searches up to ~320 days.
- Very stable detector conditions. <1%(<3%) variation in Light (Charge) Yield.



Recoil Type Calibration: ER or NR

Electronic Recoils (ER)



Nuclear Recoils (NR)

NR

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

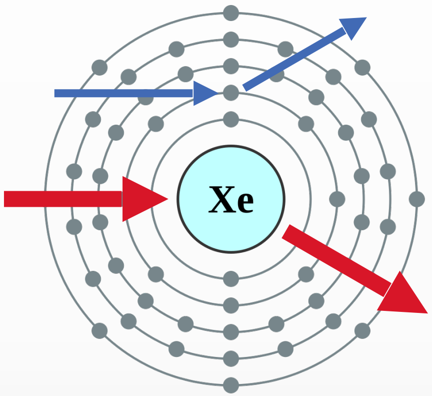
ER

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

✓ Signal ✗ Background

Recoil Type Calibration: ER or NR

Electronic Recoils (ER)



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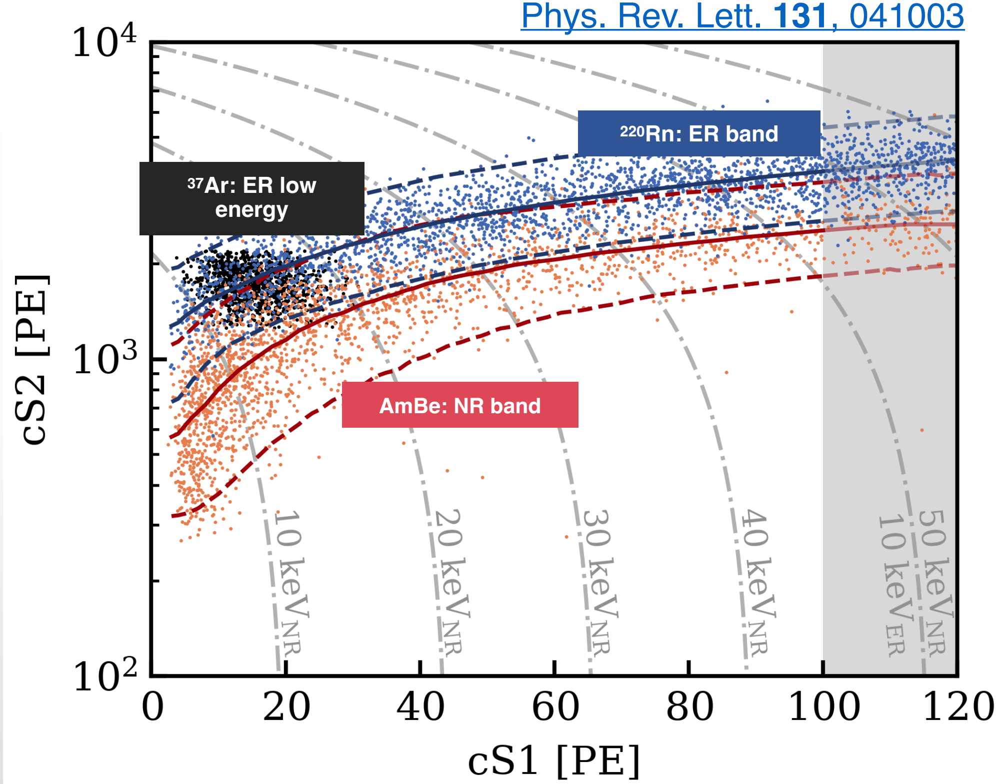
Phys. Rev. Lett. **131**, 041003



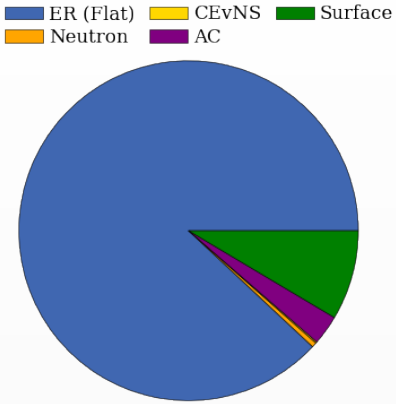
Discriminated via different S2/S1 ratio.

Other Calibrations
^{83m}Kr
TPC characterization and signal correction.
^{232}Th
High energy response.
YBe
Low energy NR response. arXiv:2412.10451 [physics.ins-det]

SR0+1: WIMP Search

Background expectations

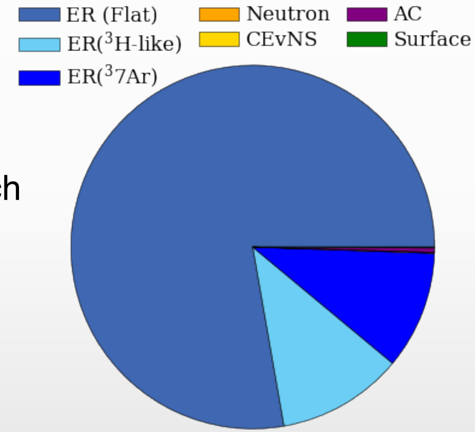
SR0



SR0 (95.1 days) - bkg rate: 1.60 events/day

- Updated neutron background model.
- Rest of the analysis unchanged.

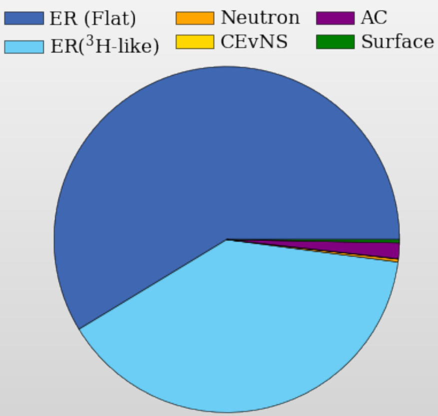
SR1a



SR1a (66.6 days) - bkg rate: 8.30 events/day

- High ER rate from accidental mixture of Kr-rich gas: high rate of ^{85}**Kr** and ^{37}**Ar**.
- Includes one month of cryogenic distillation.
- ^{3}**H-like** background: rate left unconstrained.
- Smaller fiducial volume.

SR1b



SR1b (119.9 days) - bkg rate: 2.14 events/day

- ER rate back to SR0 levels.
- ^{3}**H-like** component remains.
- Smaller fiducial volume.

Phys. Rev. Lett. **131**, 041003
arXiv:2502.18005 [hep-ex]

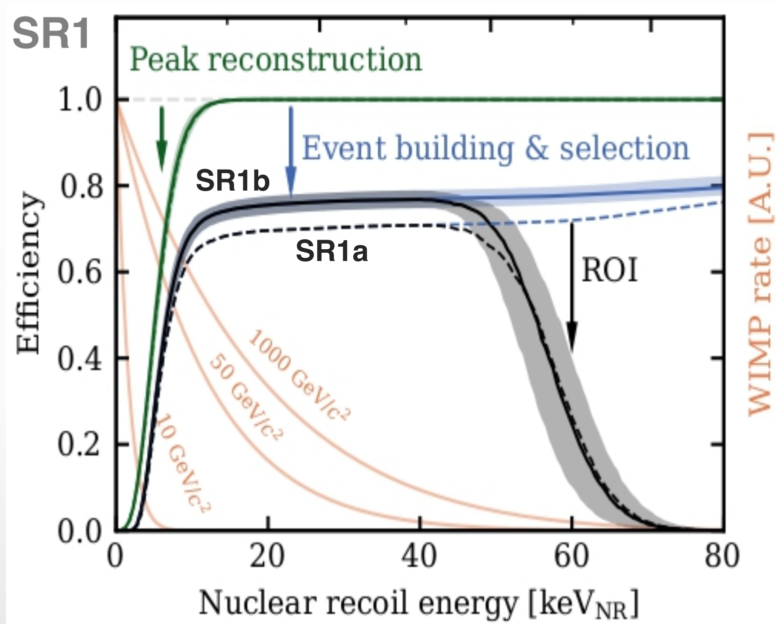
SR0+1: WIMP Search

Efficiencies

ROI :

cS1 < 100 PE

$cS2 \in [10^{2.1}, 10^{4.1}]$ PE



Peak reconstruction/Detection dominated by 3-fold requirement (3 PMTs to be in coincidence)

Event building: whether an event is successfully reconstructed: **SR1b > SR1a**

Selection: S1/S2 is signal-like, S2 consistent with e- diffusion, quality cuts

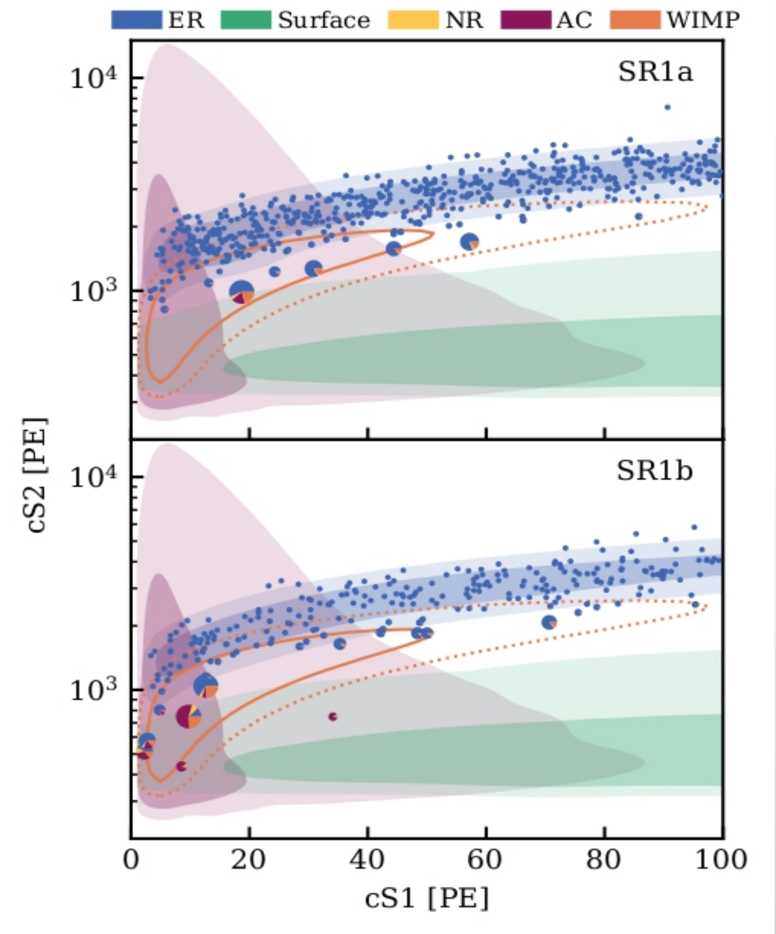
arXiv:2502.18005 [hep-ex]

SR0+1: WIMP Search

Fit to unblinded data

- Total exposure: **3.1 ty**
- Unbinned likelihood: separate terms for SR0, SR1a and SR1b.
- Shadowed dark (light) regions: 1σ (2σ) background probability density distributions.

No excess over background observed.



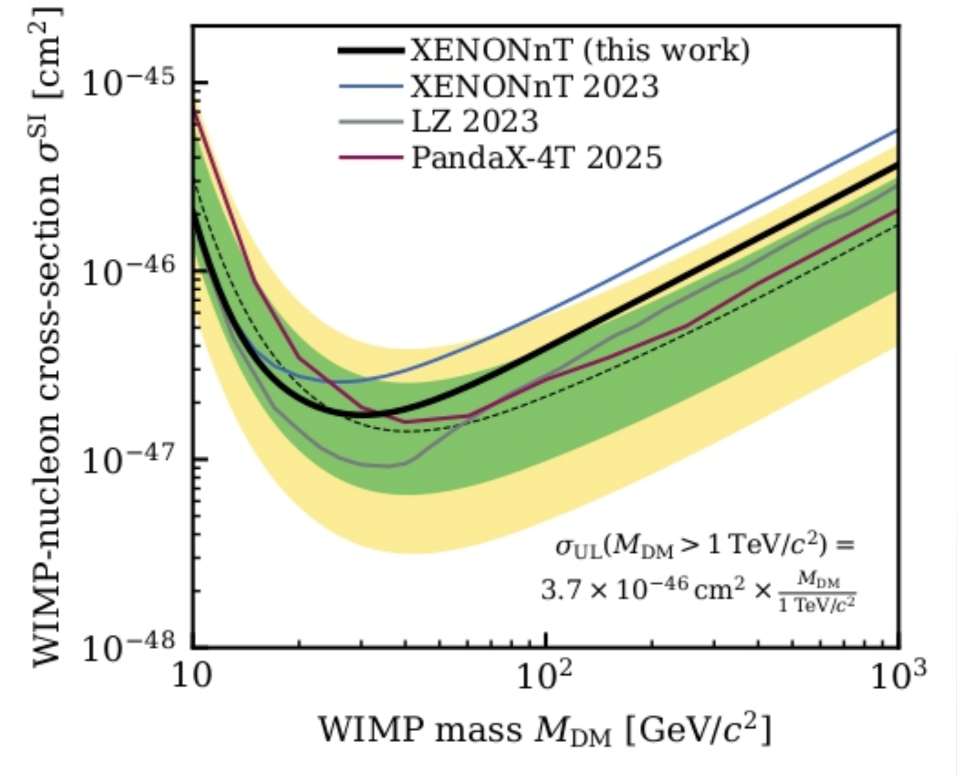
arXiv:2502.18005 [hep-ex]

SR0+1: WIMP Search

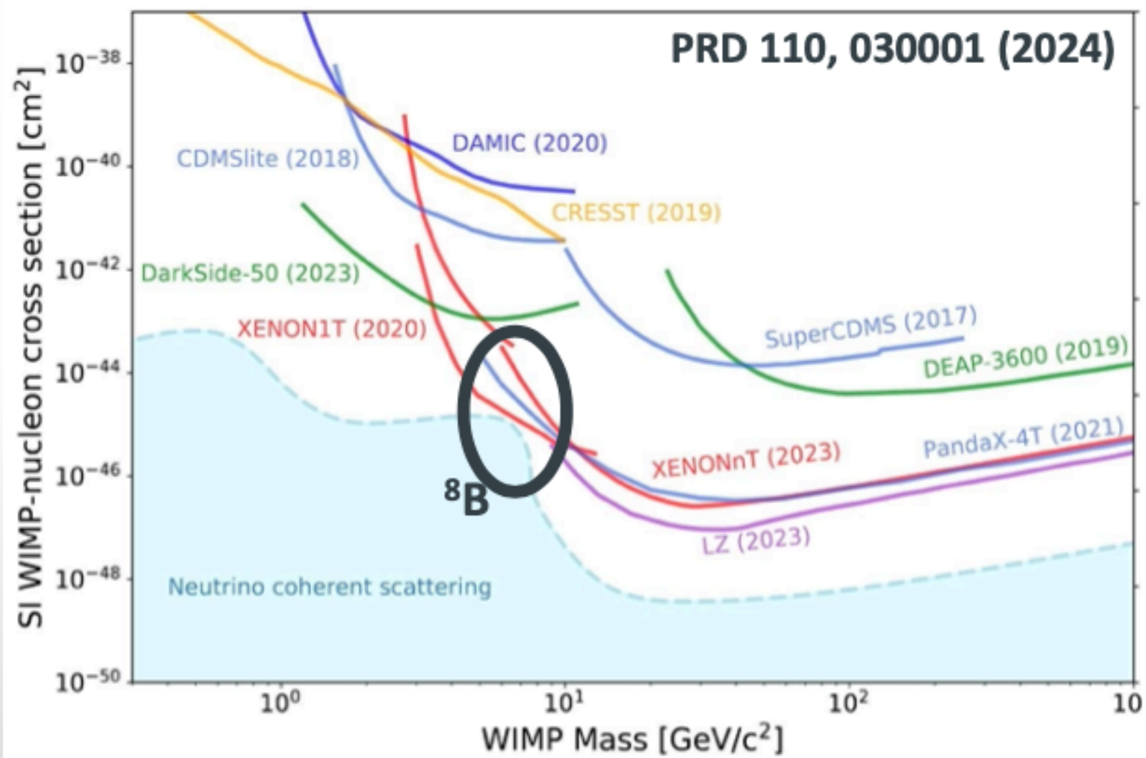
New **limits** set on **WIMP-nucleon cross section**.
Improvement from SR0 by a factor of **~1.5**

Best limit at WIMP mass of $30 GeV/c^2$.

Results consistent with other experiments.



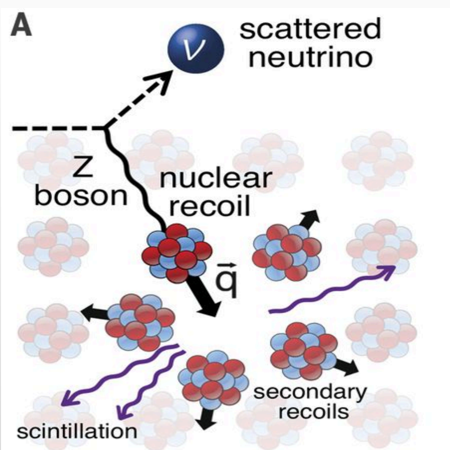
First step within the neutrino fog



SR0+1: CEvNS Search

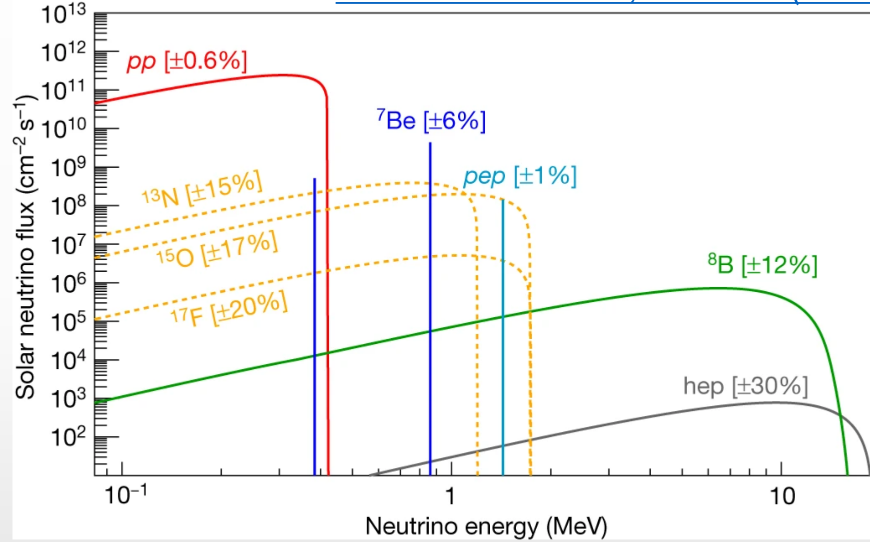
Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering

- 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.



D. Akimov et al, Science 357 (2017)

Nature volume 562, 505–510 (2018)



Solar neutrinos from ^{8}B is expected to have the highest number of detectable signals in XENONnT.

SR0+1: CEvNS Search

Fit to unblinded data

Phys. Rev. Lett. 133, 191002

Expected Background: 26.4 ± 1.4
Expected Signal: 11.9 ± 4.5

Observed Events: **37**

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

Total SR0+1 exposure: **3.51 tonne year**.

Inference with a 4-D binned likelihood.

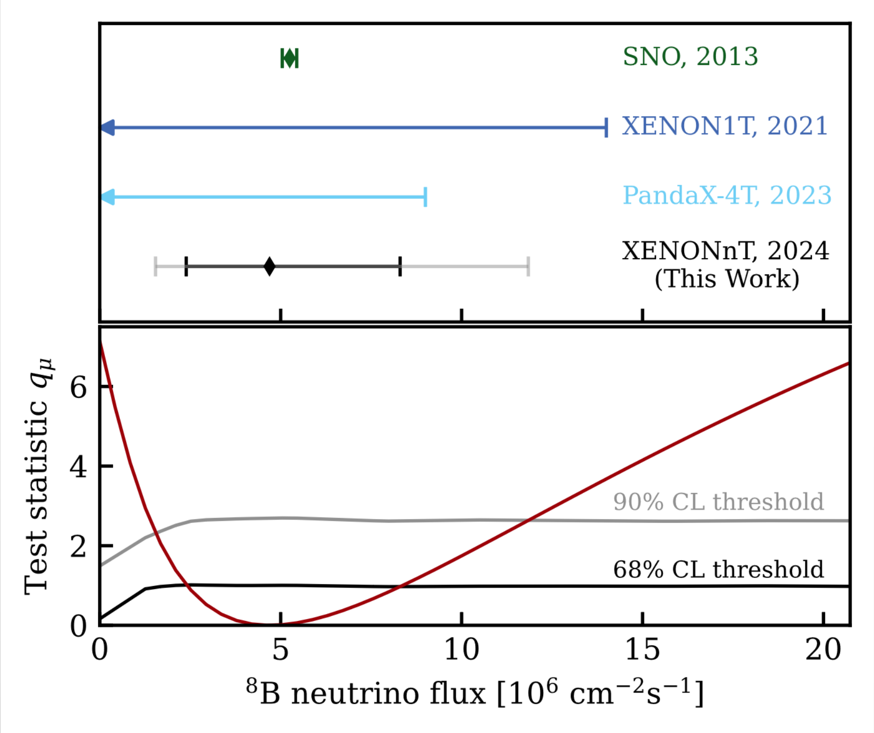
Observed ^{8}B CEvNS at a significance of 2.73σ.

First indication of CEvNS **from astrophysical neutrinos and in Xenon.**

SR0+1: CEvNS Search

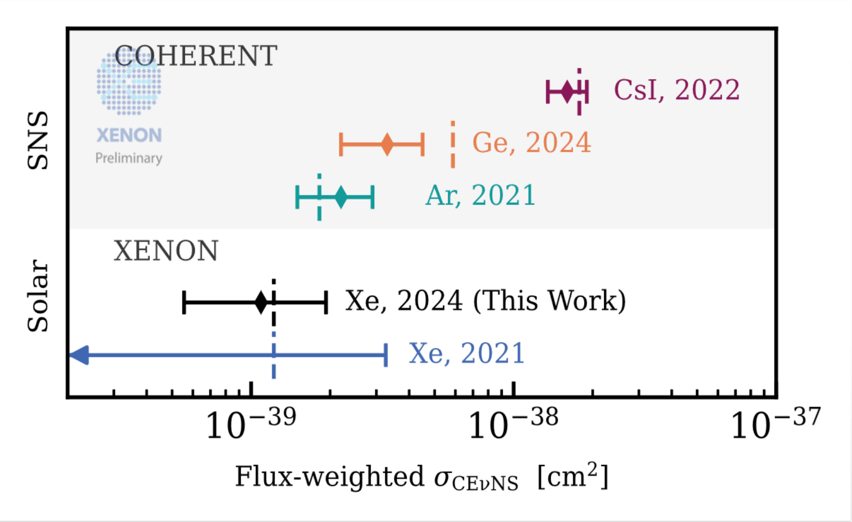
Phys. Rev. Lett. 133, 191002

Fit to unblinded data



Measured ^{8}B flux: $\left(4.7^{+3.6}_{-2.7}\right) \times 10^6\ cm^{-2}s^{-1}$.

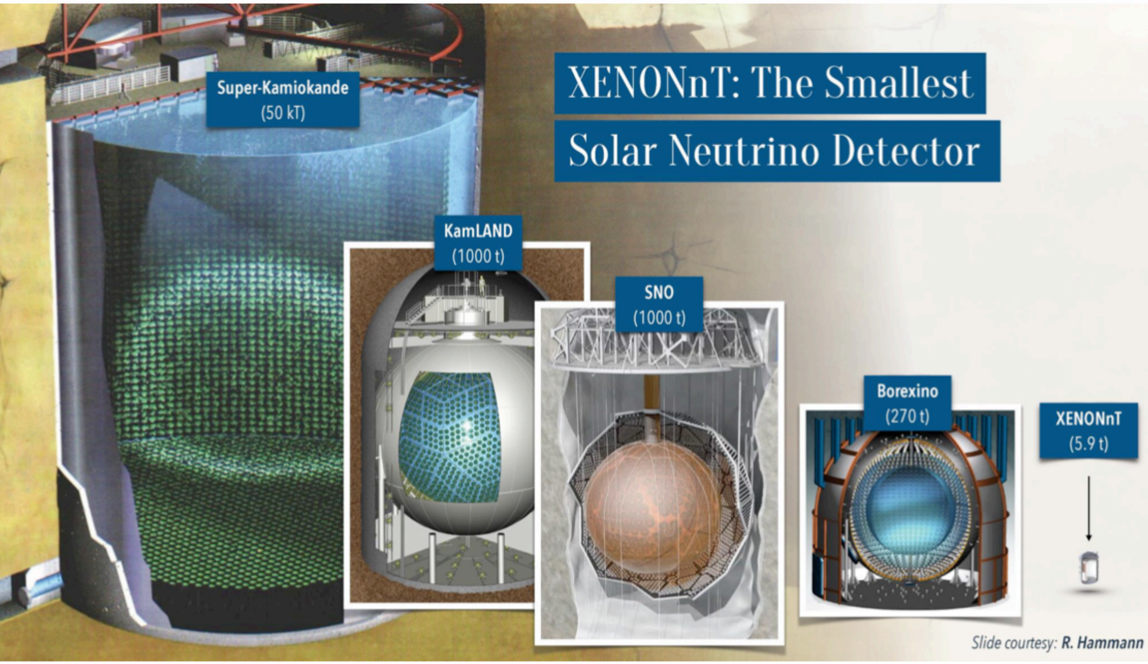
In agreement with other measurements.

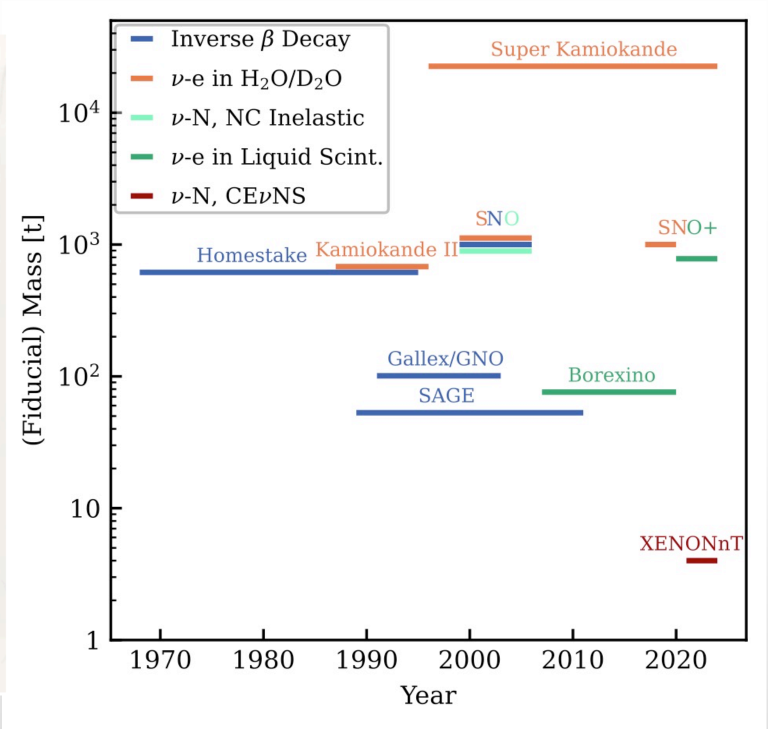


Fix the flux, and calculate cross section.

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

XENONnT : The Smallest solar neutrino detector





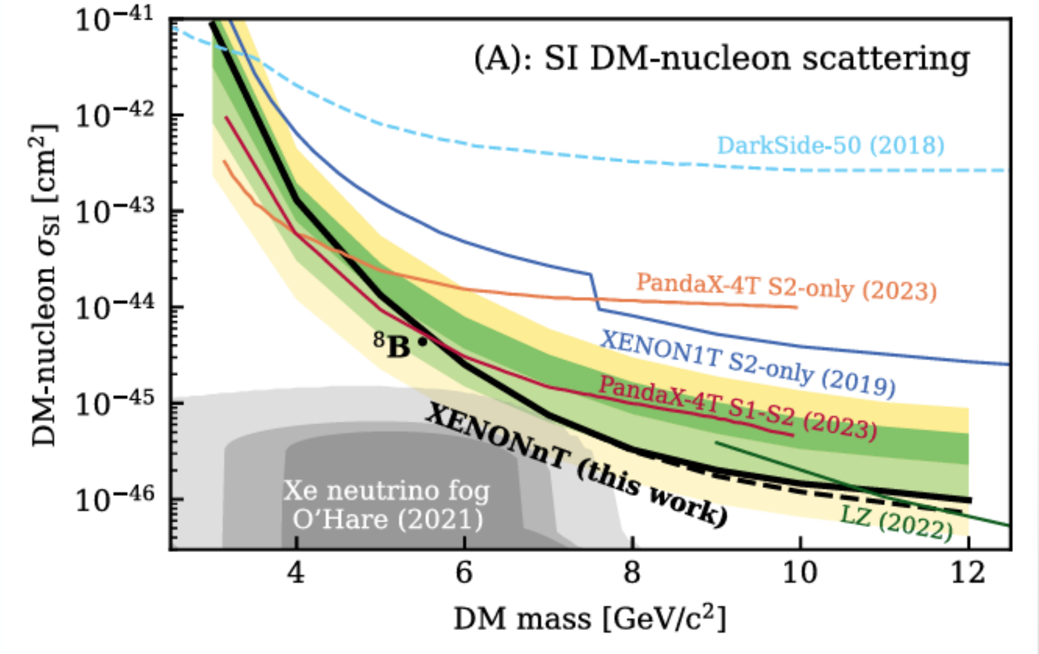
SR0+1: Low-mass WIMP Search

- Same dataset and analysis framework for CEvNS search is used.
- Background from ^{8}B **CEvNS**.
- **No excess** over background observed.

➢ New parameter space excluded.

➢ **First search into the neutrino fog.**

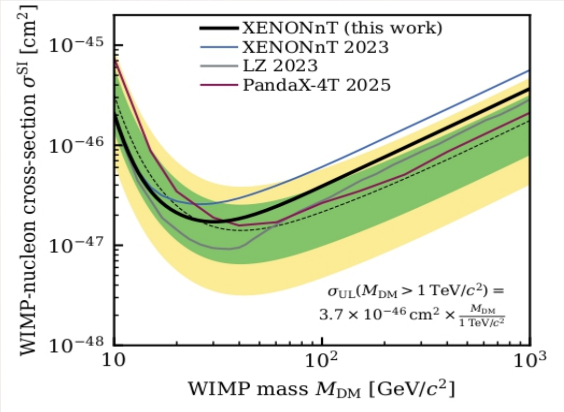
arXiv:2409.17868 [hep-ex]



^{8}B CEvNS: Nearly **indistinguishable** from a 5.5 GeV WIMP

Summary and Outlook

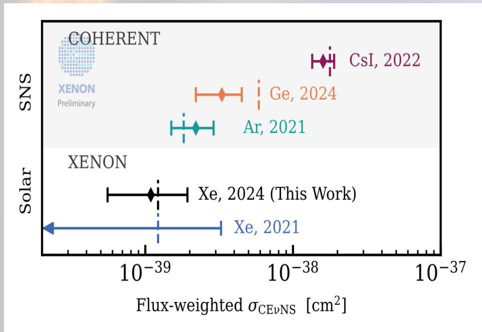
3-fold WIMP

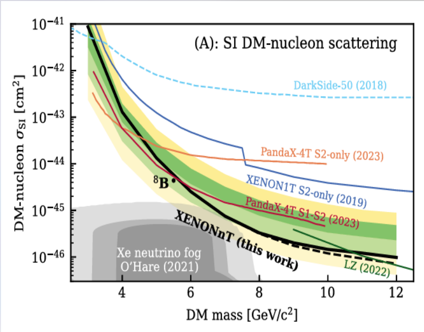


No excess observed in a **blind analysis**. Limit improved from SR0 by factor of **~1.5.**

Best limit: $1.7 \times 10^{-47} cm^2$ for WIMP mass of $30 GeV/c^2$

CEvNS and Low-Mass WIMP





Observed ^{8}B CEvNS at 2.73σ: 1st observation in Xenon and with astrophysical neutrinos.

"Highlights of the year" Physics Magazine 2024

Low Mass WIMPs: No excess observed. First search inside the neutrino fog.

Outlook

New results will come soon.

Gd-doping in n-Veto: Tagging efficiency **~77%**

XLZD

Xenon-**L**ux **Z**eplin-**D**arwin collaboration established to build the **next gen-LXe TPC** with upto 60t target mass.

XENON

[XENON Website: https://xenonexperiment.org/](https://xenonexperiment.org/)

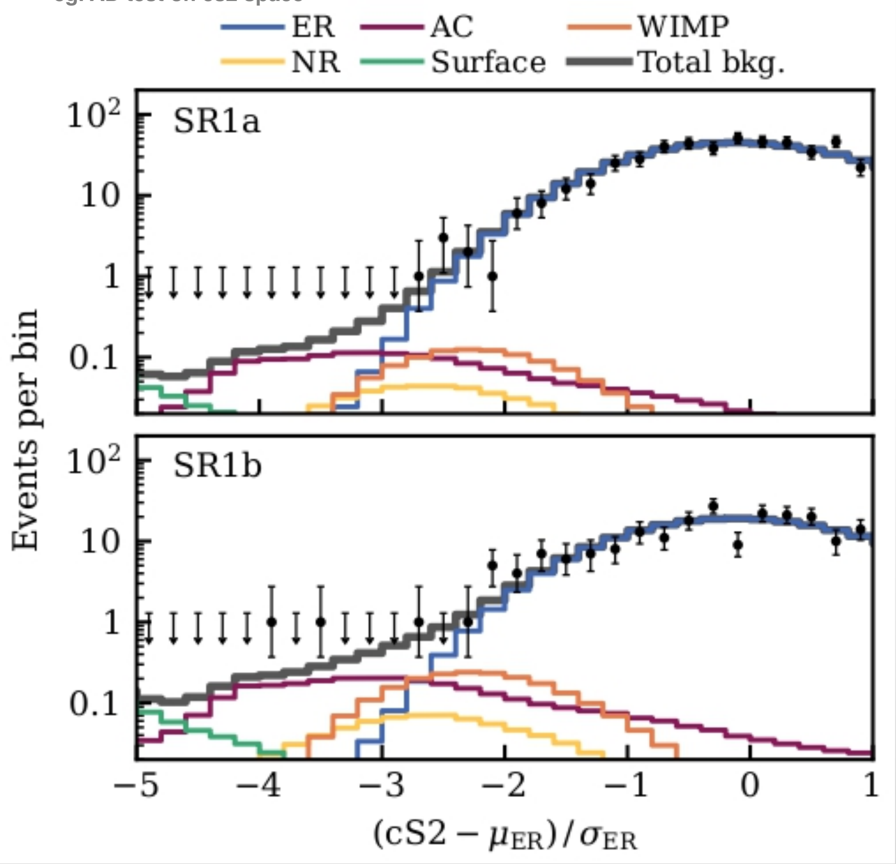
Backup Slides

arXiv:2502.18005 [hep-ex]

SR0+1: WIMP Search

Further tests

eg. AD test on cs2 space



After unblinding, further tests performed to identify mismodelling. **No evidence of mismodelling** observed.

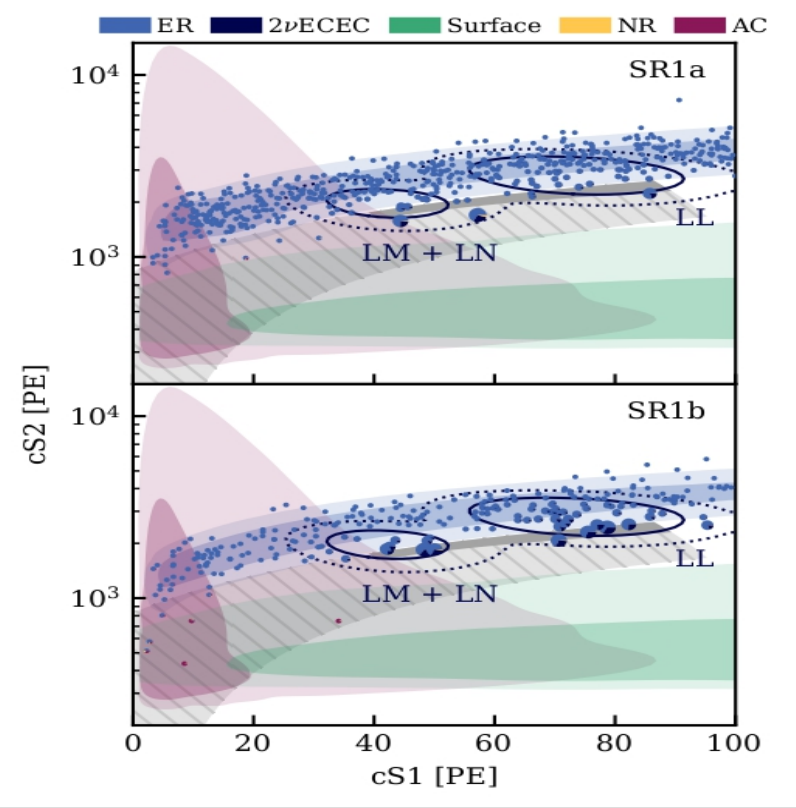
Tests for spatial homogeneity in XY: **No evidence of asymmetry in SR1.**

arXiv:2502.18005 [hep-ex]

SR0+1: WIMP Search

Charge yield of ^{124}Xe DEC

- Suppressed charge yield for ^{125}Xe L-shell EC (~0.9 Q_β) reported by XELDA (Phys. Rev. D 104, 112001).
- **No measurements** available at nT drift field.
- **^{124}Xe DEC** LL and LM+LN inside WIMP RoI with total of **(9.1 ± 1.4)** and **(4.5 ± 0.7)** events in SR0 and SR1.



!

Adding CY-suppression as nuisance parameter can absorb leakage from other backgrounds; **artificially lowering the limits.**

Perform **PLR test:** nominal model against model with unconstrained CY on SR1 data. Test size pre-defined to limit false WIMP discovery rate.

p_value = 0.09

Do **not reject** the nominal model.

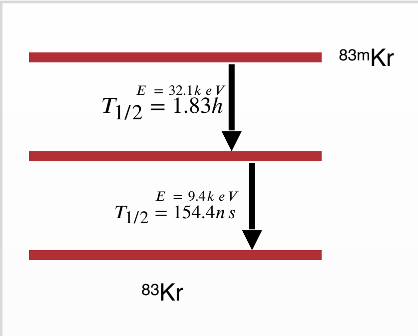
Best fit:

$$Q_{LL} = 0.8^{+0.08}_{-0.04}\, Q_\beta\,,\ Q_{LM} = 0.72^{+0.11}_{-0.04}\, Q_\beta$$

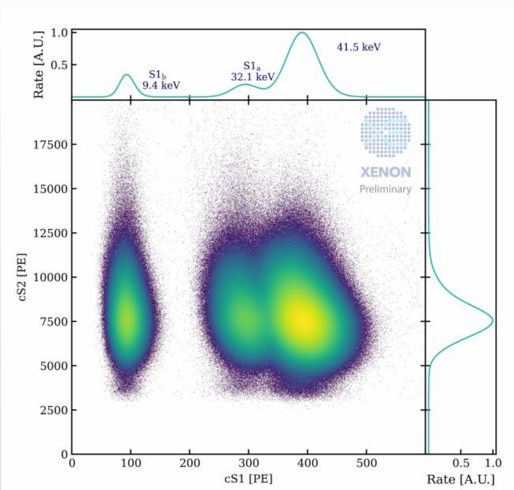
arXiv:2409.08778 [hep-ex]

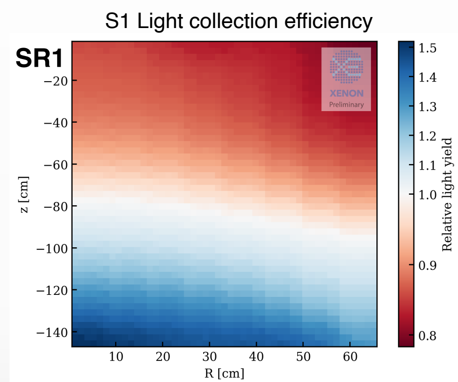
Corrections to Detector Effects

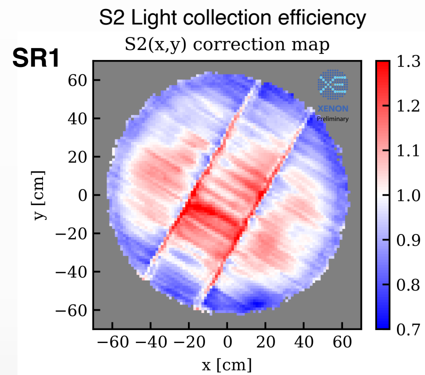
Calibrations using ^{83m}Kr

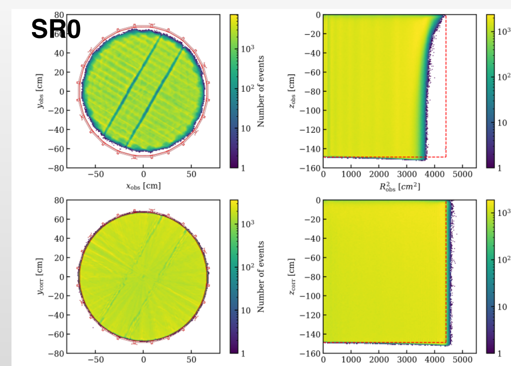


- Perform regular (~biweekly) calibration using internal calibration source.
- ^{83m}Kr **uniformly distributed** in the TPC





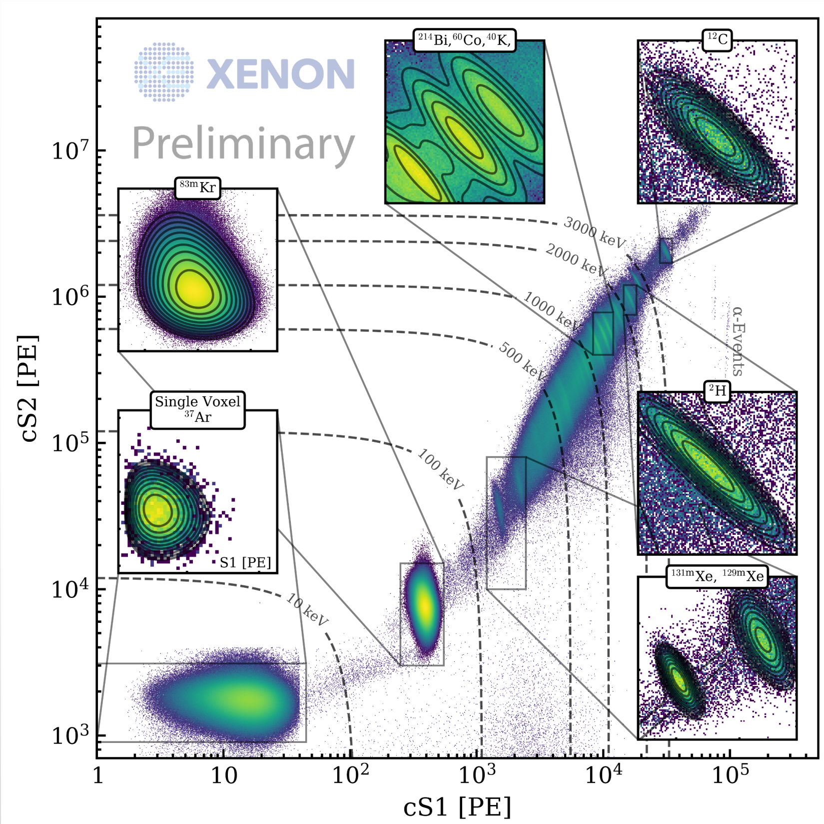


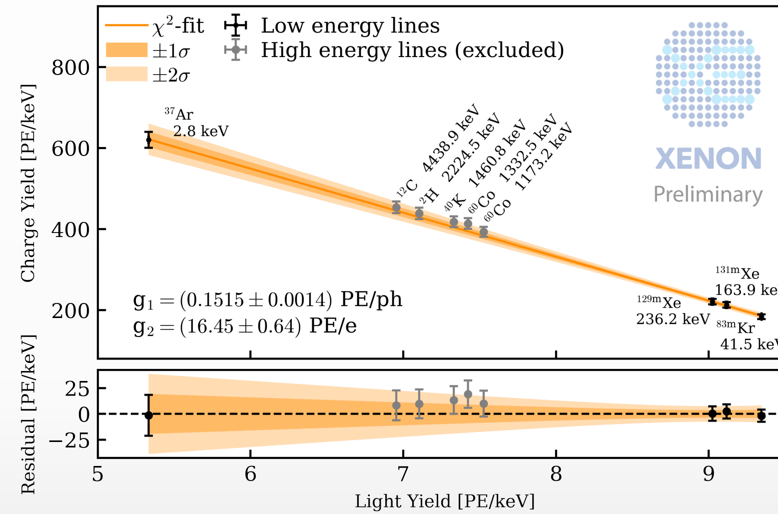


Field Distortion Correction

arXiv:2409.08778 [hep-ex]

Energy calibrations: g1, g2





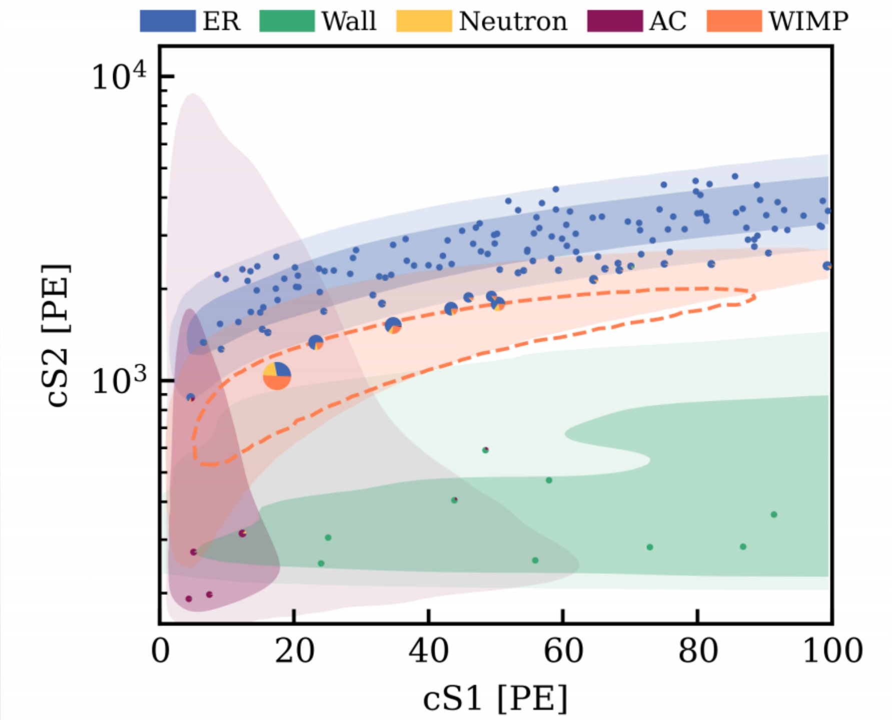
- g1,g2 calculated using monoenergetic peaks in cs1-cs2 space and the 'doke' plot.
- Combined energy scale: $E_{ces} = 13.7\ eV \times (cs1/g1 + cs2/g2)$

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

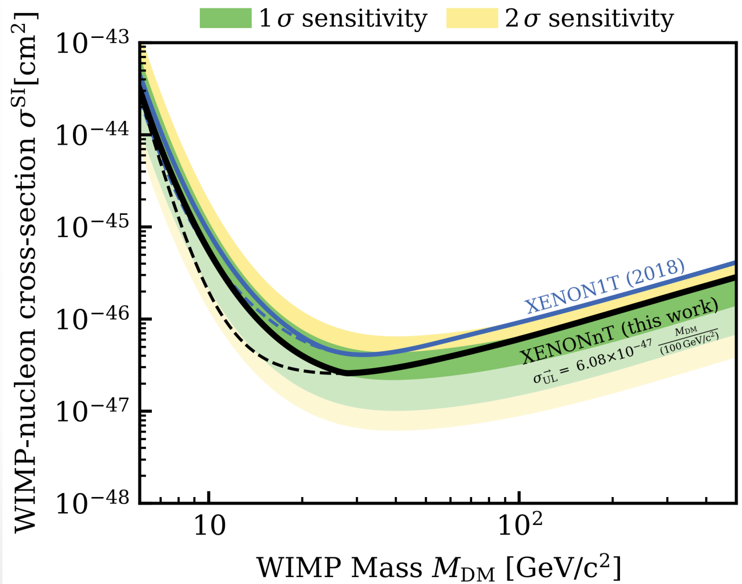
Recap : SR0 WIMP Results

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

Fit to unblinded data



Exposure: 1.09ty



No significant excess observed.

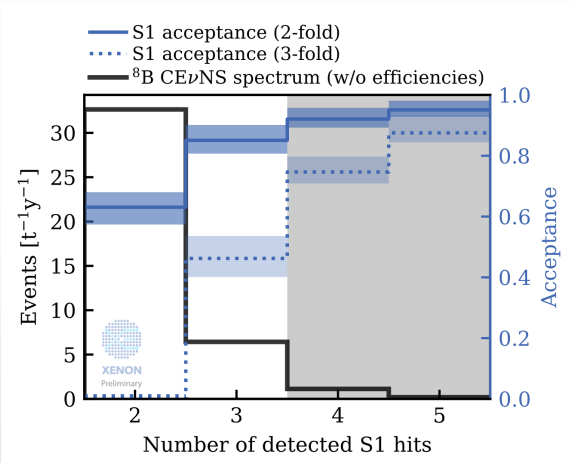
Best exclusion limit of $2.6 \times 10^{-47} cm^2$ at $28 GeV/c^2$

PCL to median sensitivity to avoid spurious limits

SR0+1: CEvNS Search

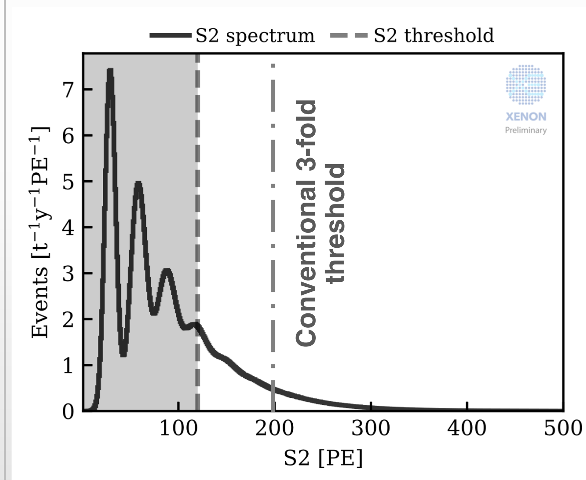
Lowering the threshold

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



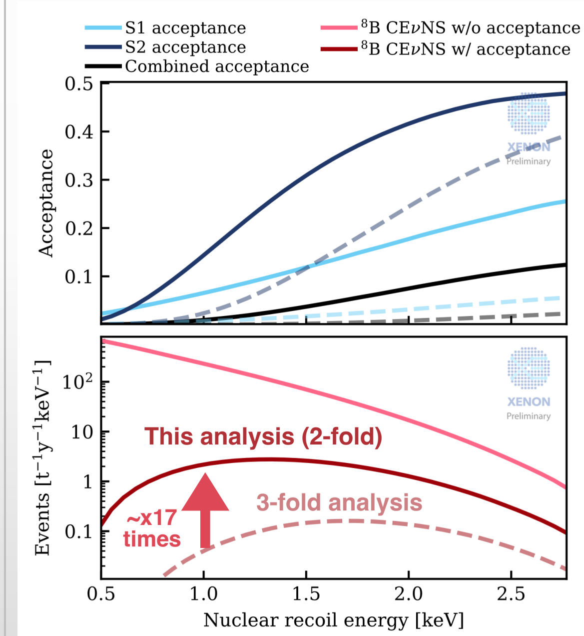
S1 ROI: 2 or 3 PMT coincidence.

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



S2 ROI: 150 – 500 PE.

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

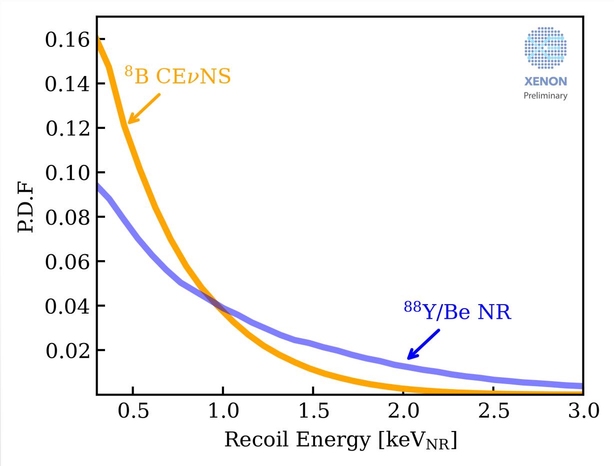


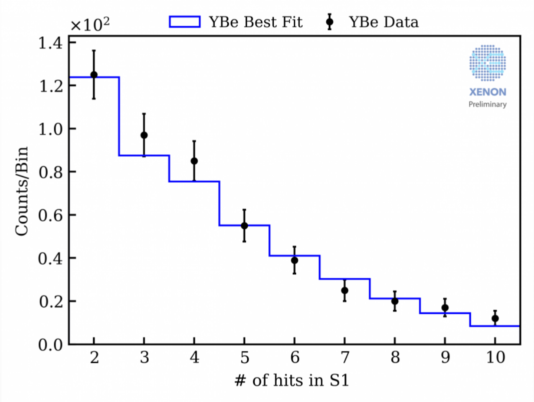
Phys. Rev. Lett. 133, 191002

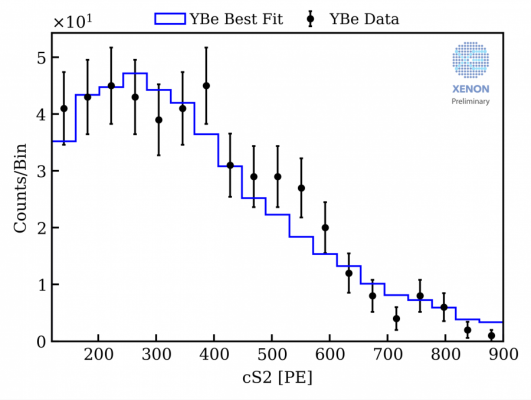
YBe Calibration: Low Energy NR Response

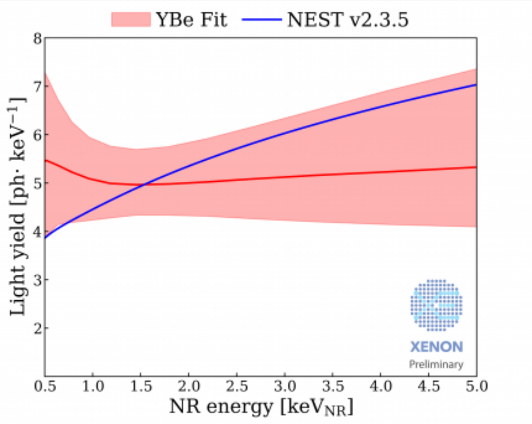
[arXiv:2412.10451 [physics.ins-det]]

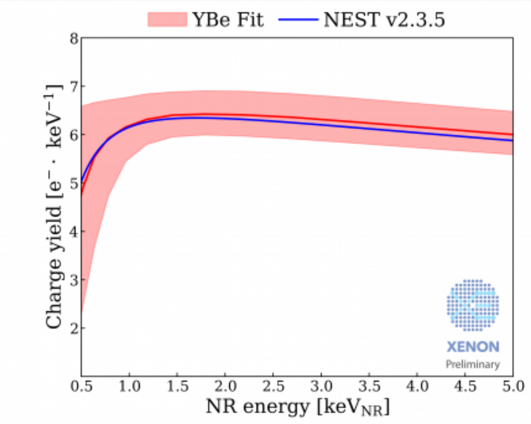
- **152 keV neutrons** produced by **photodisintegration of ^{9}Be due to γ from ^{88}Y** show similar recoil energy spectrum in TPC as ^{8}B CEvNS.











- **Good matching with model**. Fit the NEST model with the ^{88}YBe data to predict the light and charge yield in the ^{8}B CEvNS energy range at the XENONnT drift field (23 V/cm).

SR0+1: CEvNS Search

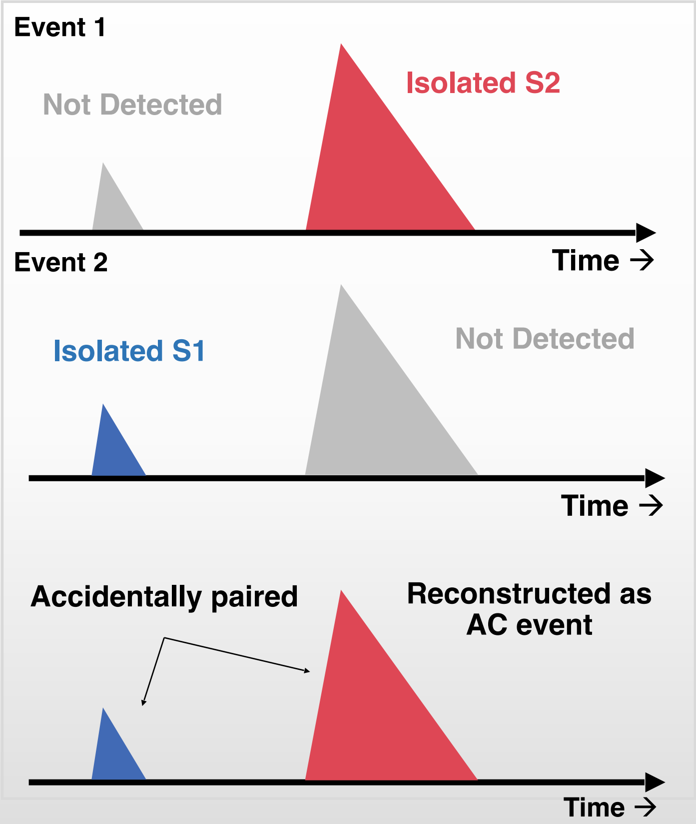
Accidental Coincidence Background (AC)

- ACs are accidental pairings of **Isolated S1** and **Isolated S2** signals. Major background near threshold.
- AC rate before mitigation:
  - ➢ Isolated S1 rate: ~15 Hz
  - ➢ Isolated S2 rate: ~150mHz
  - ➢ Raw AC rate: **~400 events/day**
- Mitigated using **analysis cuts** based on time and space information of peaks following a high energy peak.

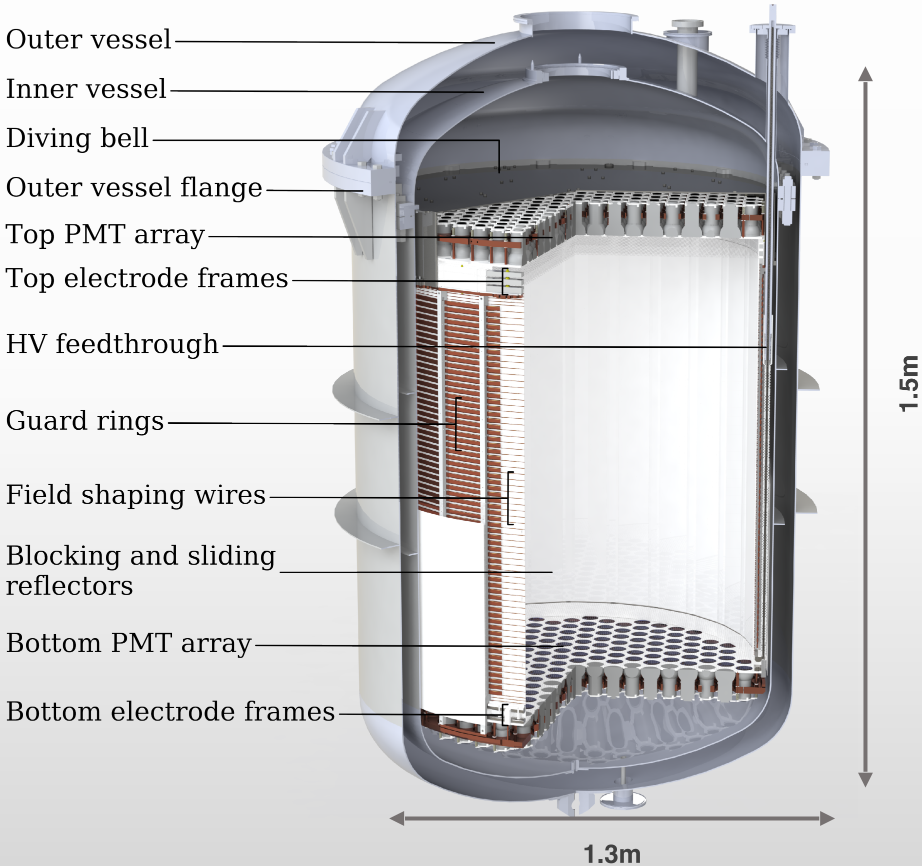
Expected AC Events after Mitigation:

SR0: 7.5 ± 0.7 | SR1: 17.8 ± 1.0

Phys. Rev. Lett. 133, 191002



XENONnT Time Projection Chamber



Total LXe

$V_{LXe\_total} = 8.5$ tonnes

Active LXe

$V_{LXe\_active} = 5.9$ tonnes

Drift Field

$E_{drift\_XnT} = 23$ V/cm

Extraction Field

$E_{extr\_XnT} = 2.9\ kV/cm$

Max drift time

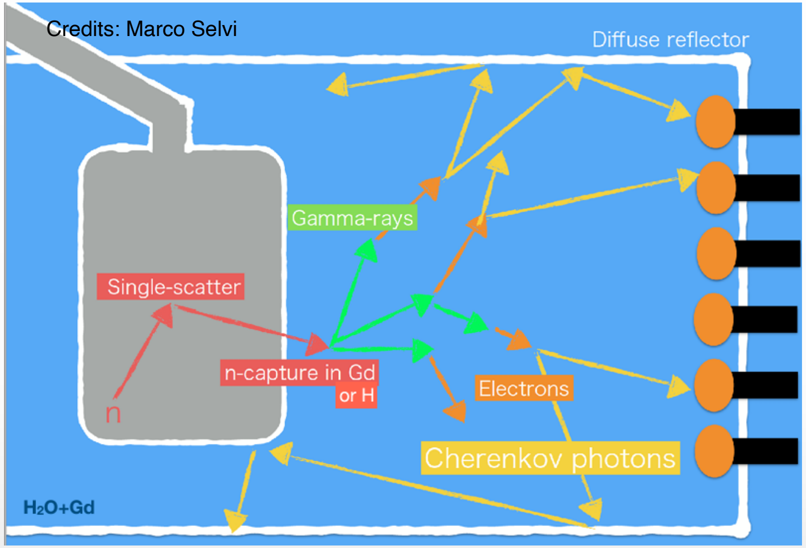
$t_{drift\_max} = 2.2\ ms$

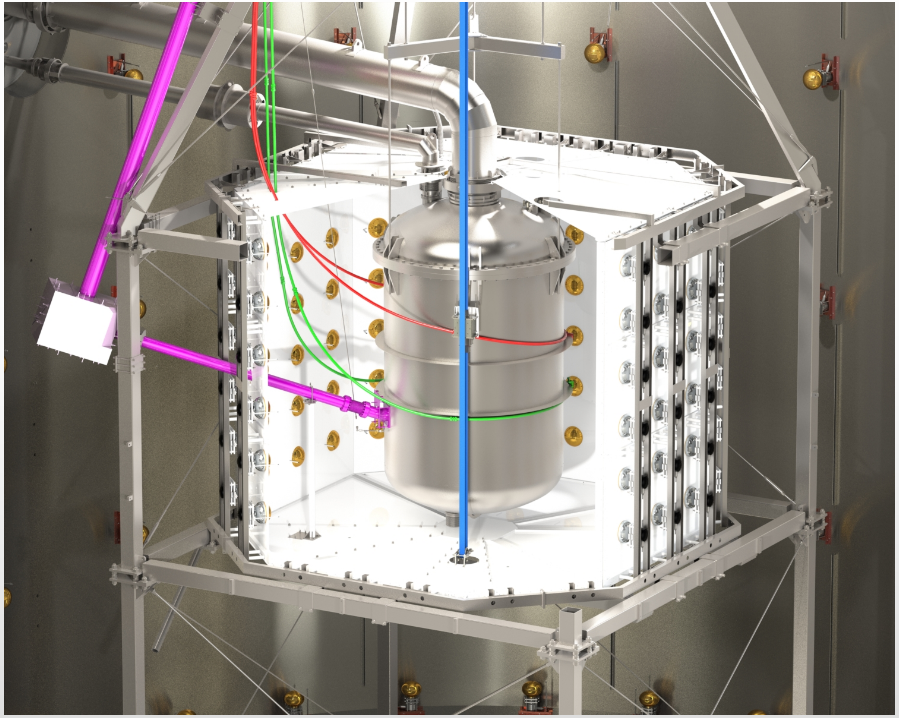
PMT Array

494 3" PMTs in total

JCAP11(2020)031

XENONnT Neutron Veto

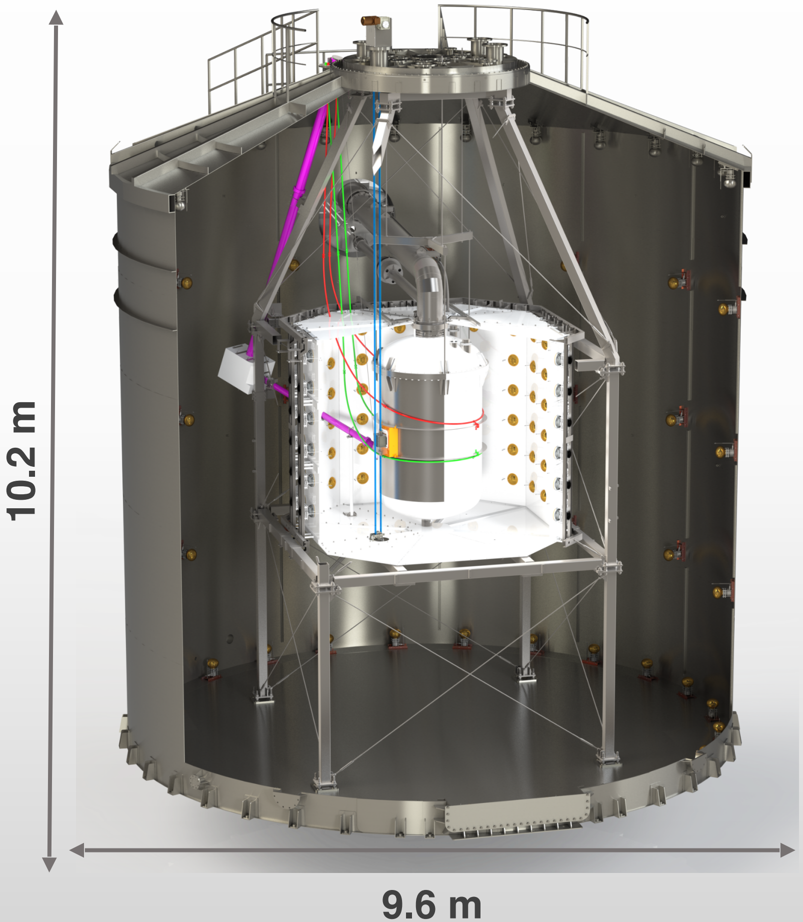




- 33 m³ demineralized water, optically separated from outer MV.
- 120 8” high-QE PMTs.
- $(53 \pm 3)\%$ **tagging efficiency** with water.
- With 500ppm **GdSO doping**, tagging efficiency increases to ~77%.

2014 JINST 9 P11006

XENON1T: Muon Veto

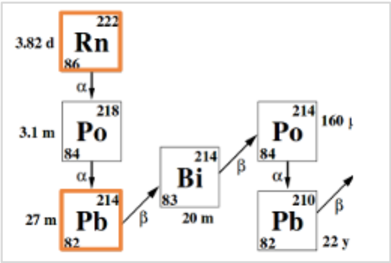


- Water Cherenkov detector.
- **700t** demineralized water.
- High reflectivity inner coating.
- 84 Hamamatsu 8” PMTs.
- **Active veto** against muon induced neutrons.
- Acts as passive shield against gamma rays and neutrons from the surrounding.

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

Online distillation for ^{222}Rn

- ^{222}Rn ($t_{\frac{1}{2}} = 3.8d$)emanates from detector material.
- Continuous online distillation utilizes the difference in **vapour pressure**.



- Purifies 1.8t (0.2t) of liquid (gas) xenon per day.

^{222}Rn activity

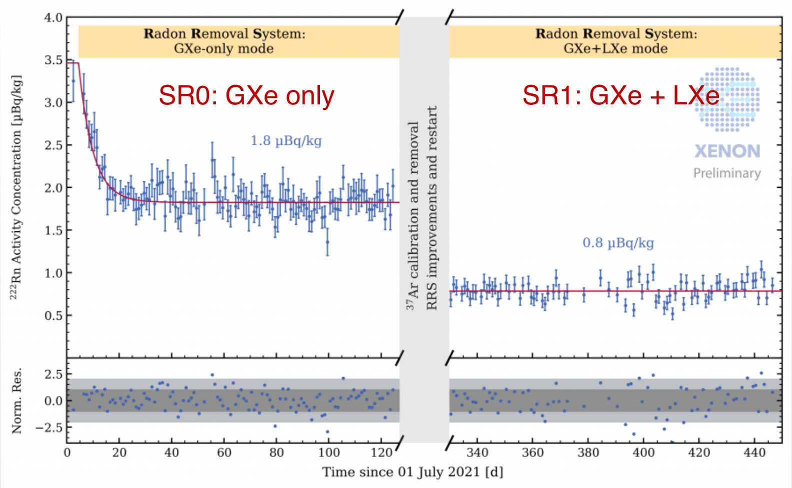
1T: $\sim 13\ \mu Bq/kg$

↓

nT SR0: $1.9\ \mu Bq/kg$

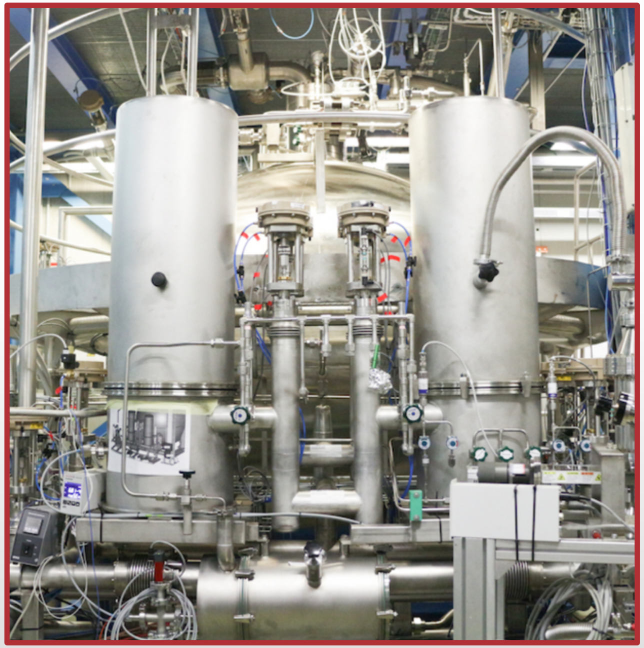
↓

nT SR1: $0.9\ \mu Bq/kg$



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

LXe Purification System



- **Electronegative impurities** attenuate light/charge signals:
  - ➢ Attach to drifting electrons (reduce S2 signal).
  - ➢ Absorb scintillation photons (reduce S1 signal).
- LXe Purification flow of 2 lpm; turnover of full inventory (8.6t) in 0.9 days.

electron lifetime

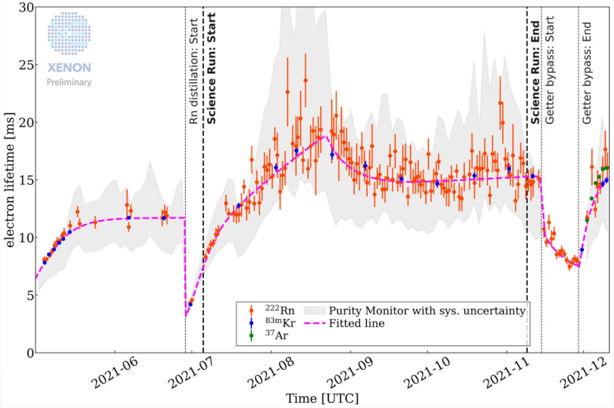
1T: ~0.65 ms

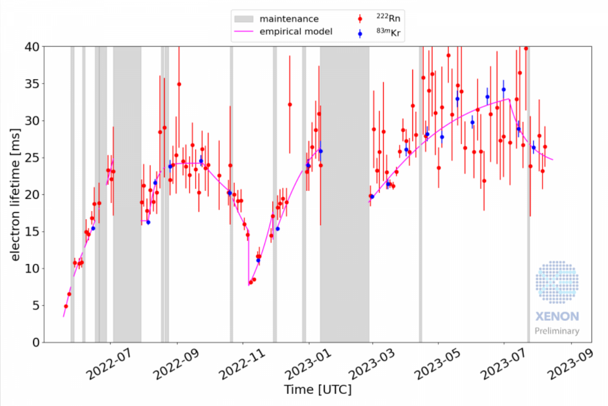
↓

nT SR0: $> 15\ ms$

↓

nT SR1: $\sim 20\ ms$





Recovery and Storage for Xenon: ReStoX

- Provide **quick recovery for Xenon** in case of emergency (like cooling loss) or for TPC maintenance reasons.
- **ReStoX-I** rated for upto **70 bar** and can store **7.6 tonnes** of Xe preserving its purity.
- **ReStoX-II** installed for XENONnT; can store **upto 10 tonnes** of Xe in liquid phase; entire inventory of Xenon even for longer extended shutdowns.

Insulated tower has a large area heat exchanger and can be cooled with liquid nitrogen.

Double-walled stainless steel sphere with inner vaccum sealed volume

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

^{85}Kr Distillation

- ^{nat}Kr traces (^{nat}Kr/Xe > 1ppb) exist in xenon **extracted from the air**, and is an ER background.
- Mitigated through **cryogenic distillation** of Xenon with a dedicated column before collecting science data.
- Online distillation can also remove radioactive Ar-37.
- Kr (**more volatile**) goes up and Kr-depleted Xe is collected from the bottom.
- ^{nat}Kr/Xe concentration <50 ppq achieved in nT.