

WIMP searches with the **XENONnT** Experiment

Ananthakrishnan Ravindran
On behalf of the XENON collaboration.



Co-funded by
the European Union

The XENON Collaboration



200+ Scientists

33 Institutions

13 Countries

Main Motivation

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

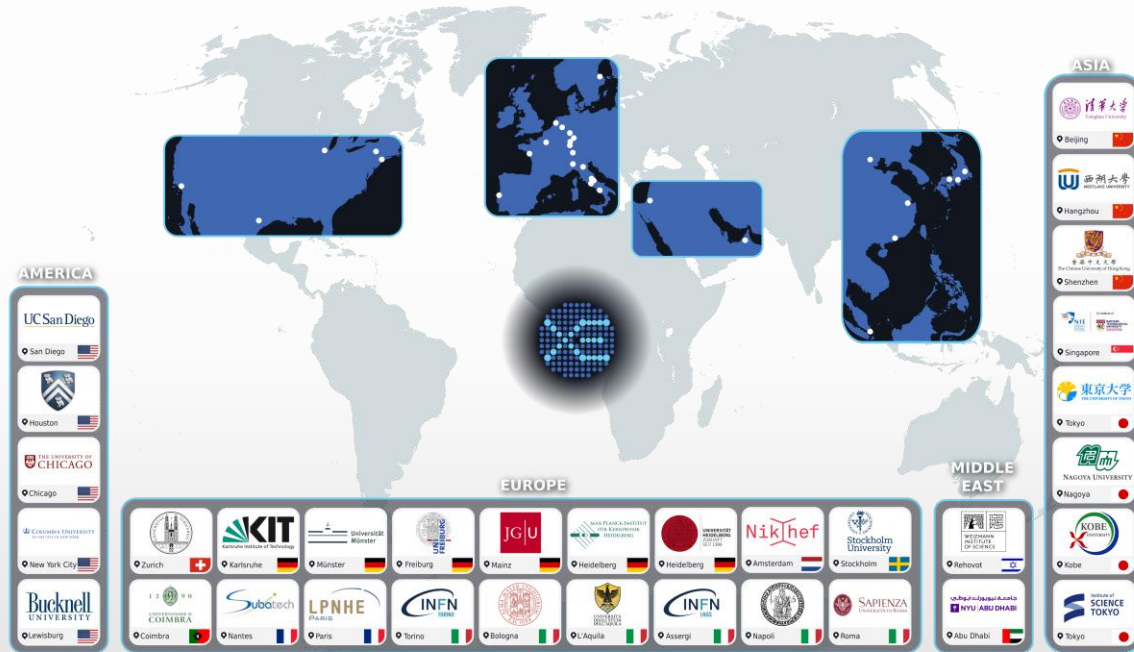
Other studies

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



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12 Countries

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)

XENONIT
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!!**

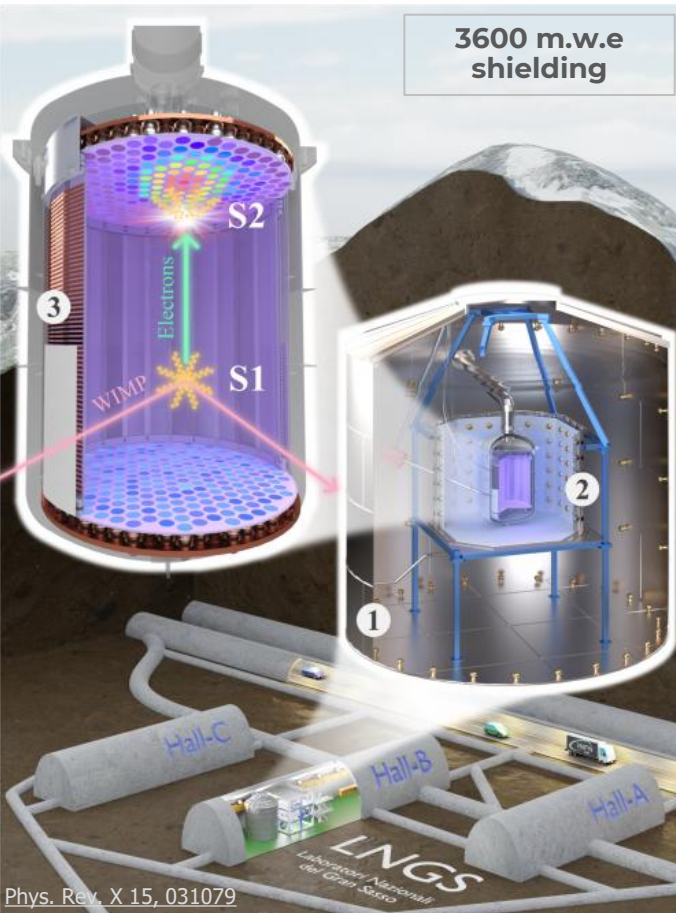


XENONnT Experiment

At LNGS, under the Gran Sasso Mountains

3 Nested Detectors

Sharing the same DAQ



1 Muon Veto

Gd-doped Water Cherenkov detector

~10 m x 10 m
diameter x height

84 8" PMTs

[2014 JINST 9 P11006](#)

2 Neutron Veto

Gd-doped Water Cherenkov detector

~4 m x 3 m
diameter x height

120 8" PMTs

[JCAP11\(2020\)031](#)

3 Time Projection Chamber

Time Projection Chamber (TPC)

~1.3 m x 1.5 m
diameter x height

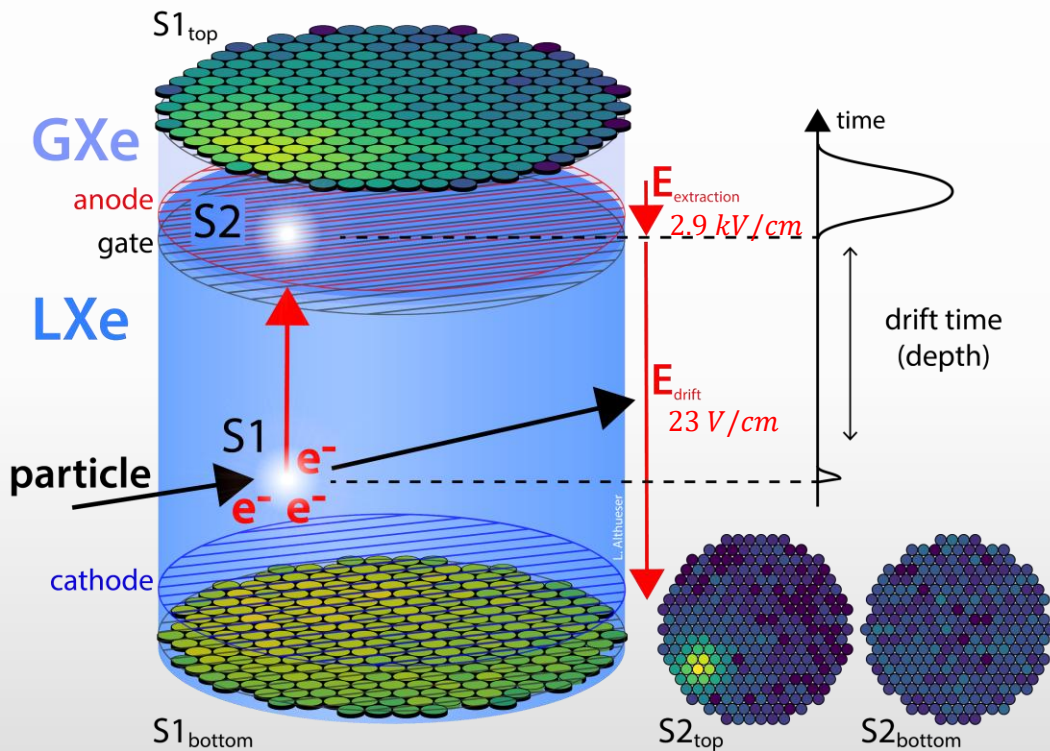
494 3" PMTs

[Eur. Phys. J. C 84, 784 \(2024\)](#)

Phys. Rev. X 15, 031079



Dual Phase TPC: Working Principle



- Particle interaction 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

x, y : S2 hit pattern
z: Drift time of e⁻

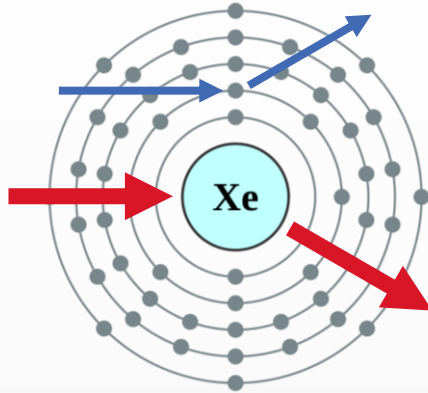
Energy Reconstruction

Combined S1 and S2 area; calibrated with known sources.



Recoil Type Calibration: **ER** or **NR**

Electronic Recoils (ER)



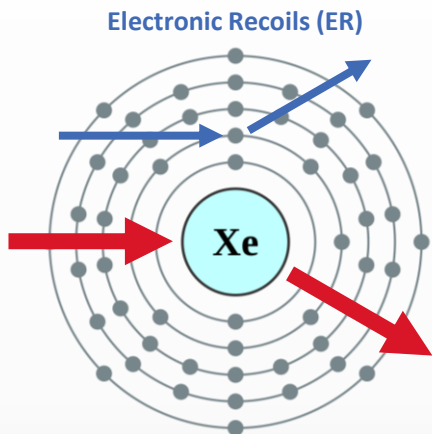
Nuclear Recoils (NR)

NR	✓	✗	Neutrons
	✓	✗	Neutrinos (CEvNS)
	✓		WIMPs

ER	✓	✗	Gamma & Beta
	✓	✗	$^{136}\text{Xe } 0\nu\beta\beta, 2\nu\beta\beta.$
	✓	✗	Neutrino elastic scattering.
	✓		Solar axions, ALPs.
	✓	✗	Signal Background



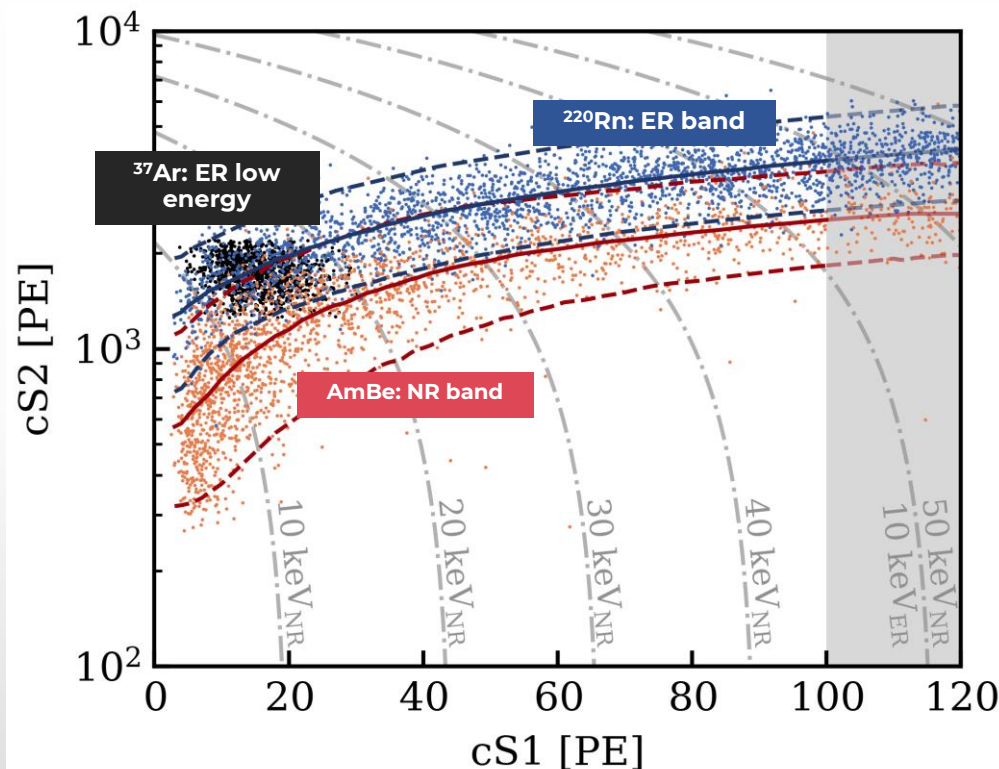
Recoil Type Calibration: ER or NR



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



Discriminated via different S2/S1 ratio.

Other Calibrations

^{83m}Kr

TPC characterization and signal correction.

^{232}Th

High energy response.

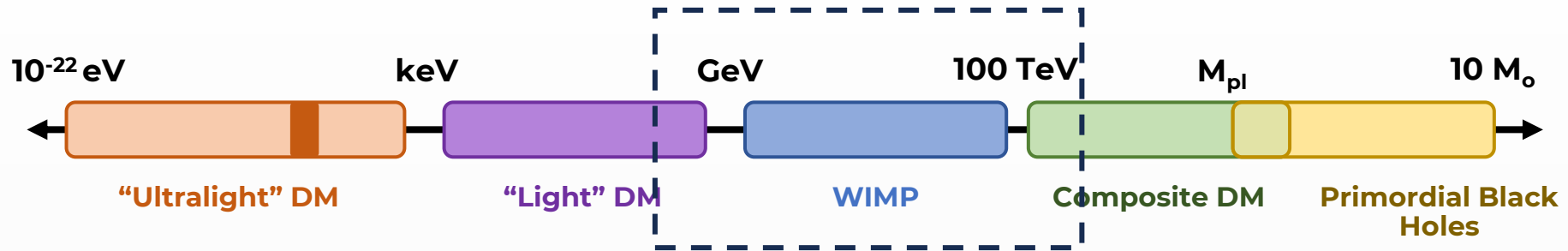
YBe

Low energy NR response.

[arXiv:2412.10451](https://arxiv.org/abs/2412.10451)
[physics.ins-det]

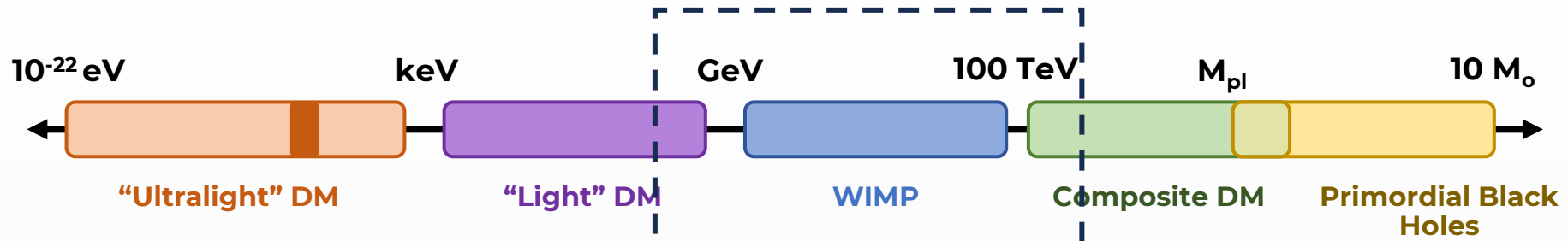


WIMP Landscape in XENONnT

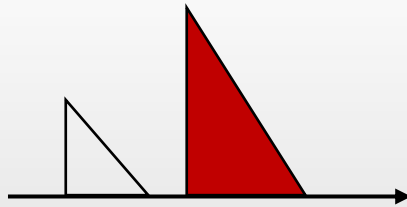




WIMP Landscape in XENONnT

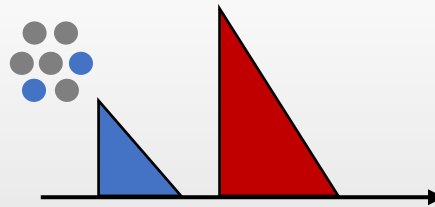


O(<1) GeV: S2-Only



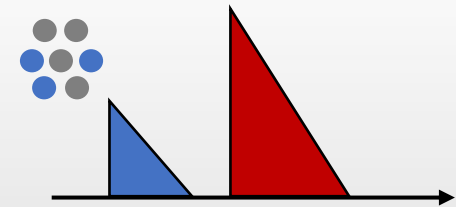
- Require no S1 signal.
- $E_{\text{th}}^{\text{NR}} \sim < 0.5 \text{ keV}$
- No access to "z"

O(1) GeV: 2-fold S1/S2



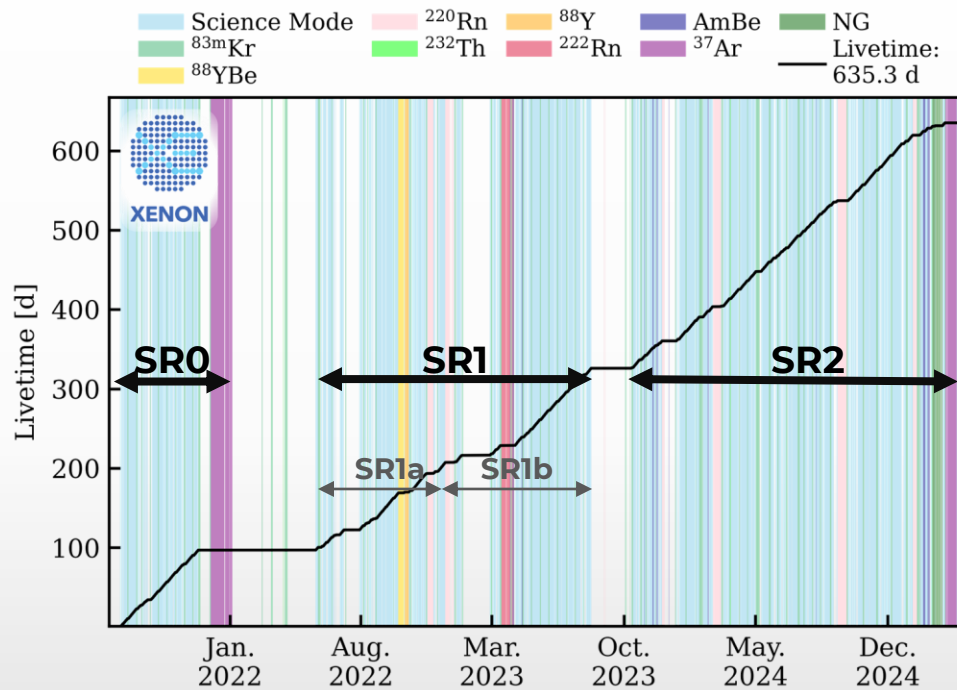
- S1 signal "seen" by 2 or 3 PMTs
- $E_{\text{th}}^{\text{NR}} \sim 0.5 \text{ keV}$
- Increased rate of accidental coincidences

O(>10) GeV: 3-fold S1/S2



- S1 signal "seen" by at least 3 PMTs
- $E_{\text{th}}^{\text{NR}} \sim 3.0 \text{ keV}$
- Low efficiency for low mass.

XENONnT: Science Data



Stable operation: ~650 live-days

<1%(<3%) variation in Light (Charge) Yield.

Continuous online Rn distillation

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

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

[Phys. Rev. X 15, 031079](#)

Kr Distillation

$^{\text{nat}}\text{Kr/Xe}$ concentration < 50ppq

[Eur. Phys. J. C 77, 275 \(2017\)](#)

LXe Purification

Electron lifetime > 20 ms

[Eur. Phys. J. C \(2022\) 82: 860](#)

Neutron tagging

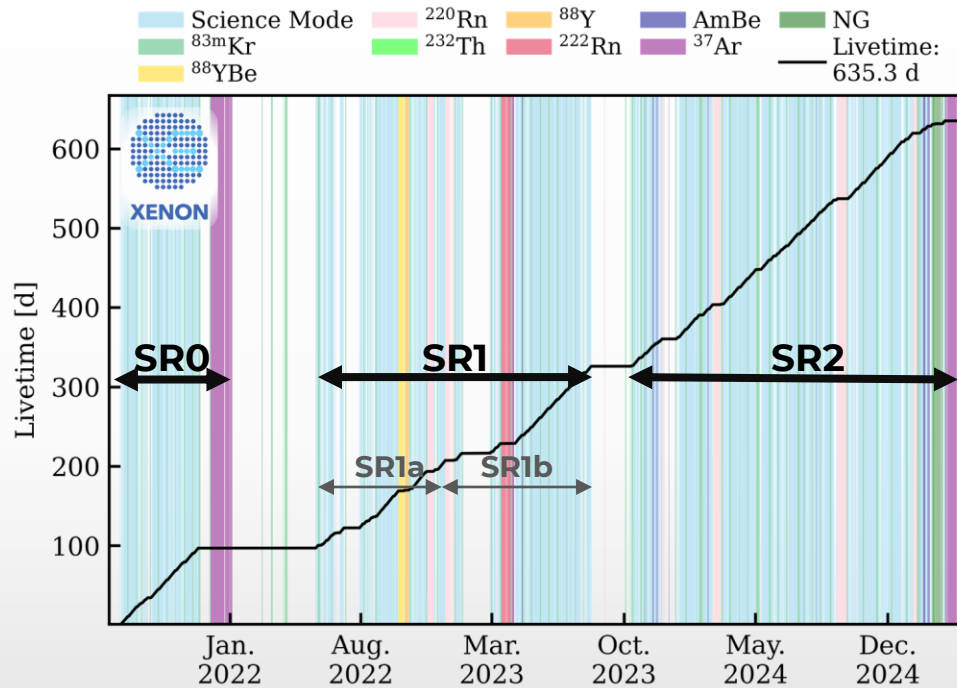
$(53 \pm 3)\%$ tagging efficiency in demi-water in SR01

77% tagging eff. in SR2 due to 500ppm Gd-loading

[EPJC 85 \(2025\) 695](#)

Major highlights

XENONnT: Science Data



WIMPs (3 – fold)

⁸B CEvNS and Low Mass WIMPs (2 – fold)

Low Mass WIMPs (S2 – Only)

pp ν

pp ν

See talk by
A. Elykov

Stable operation: ~650 live-days

<1%(<3%) variation in Light (Charge) Yield.

Continuous online Rn distillation

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

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

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[EPJC 85 \(2025\) 695](#)

Major highlights



“Classic” 3-fold **WIMP** Search

Backgrounds

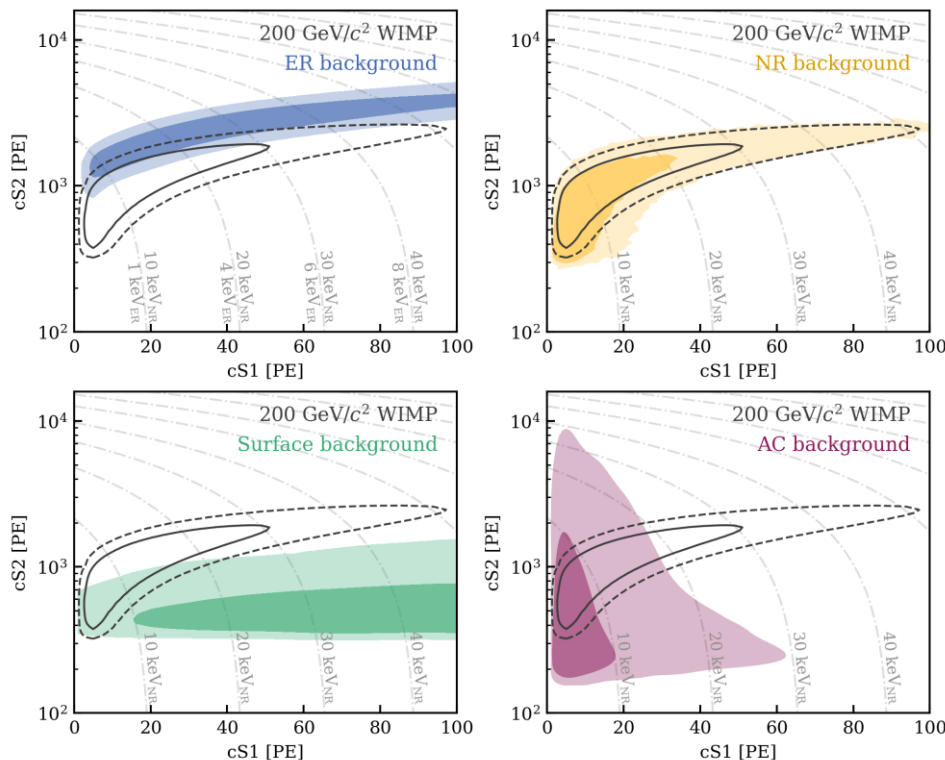
^{214}Pb , ^{85}Kr β -decays ^{124}Xe DEC, solar $\nu - e$ scatter.. :

Shape constrained by ^{220}Rn calibration data.

Rate constrained by fit to reconstructed spectrum in $[20, 140] \text{ keV}_{ER}$.

Plate-out effect from the PTFE walls: ^{210}Pb decay chain.

Rate constrained by a data-driven method and validated with events outside FV.



Radiogenic **neutrons**:

Constrained by sideband of multi-scatter events and single-scatter events tagged by n-Veto.

CEvNS events in RoI:

Constrained by neutrino flux and uncertainties in NR emission model.

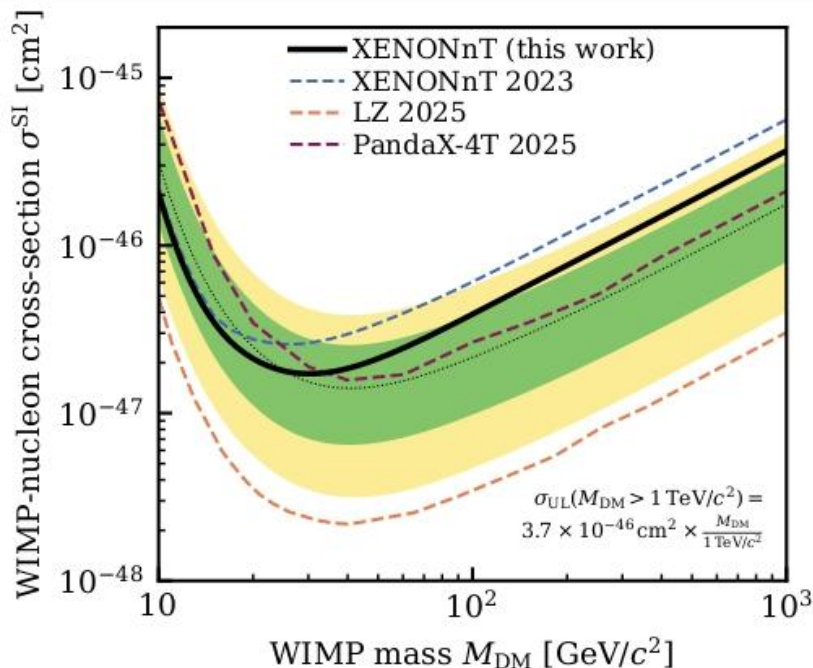
Accidental Pairing of random S1s and S2s.

Modelled by a data-driven method and validated on dedicated sidebands.

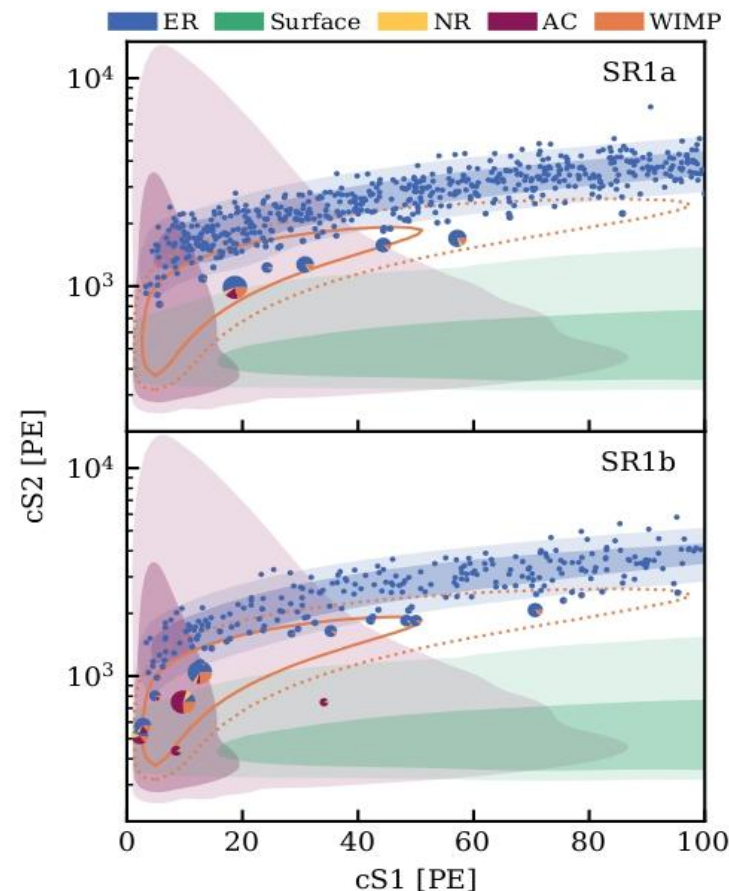


“Classic” 3-fold WIMP Search

Total exposure : 3.1 tonne years



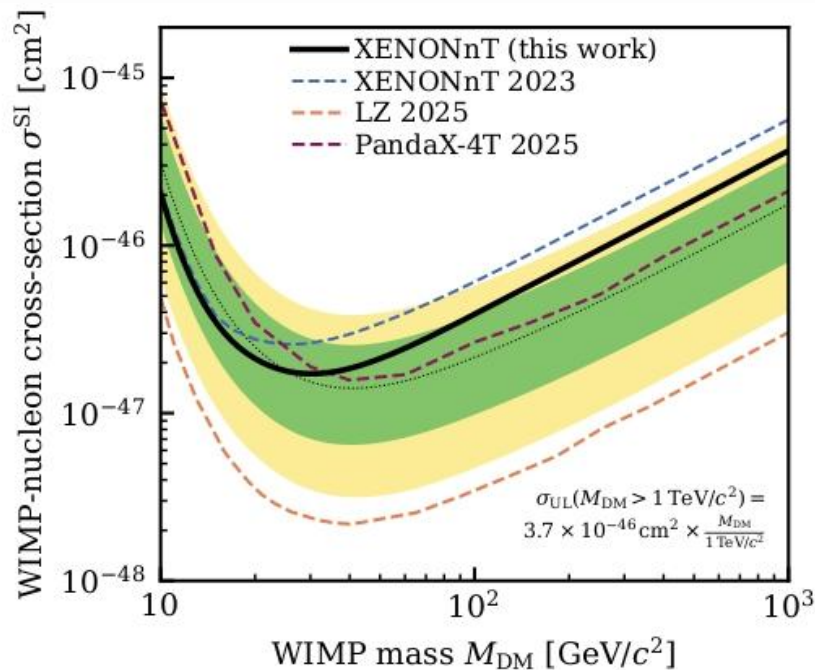
No significant excess observed





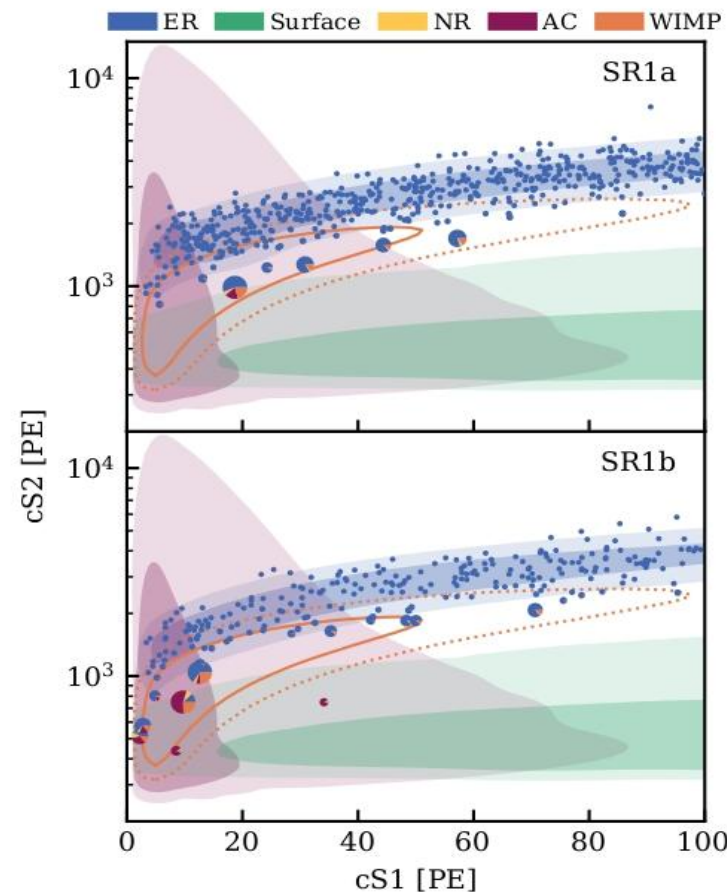
“Classic” 3-fold **WIMP** Search

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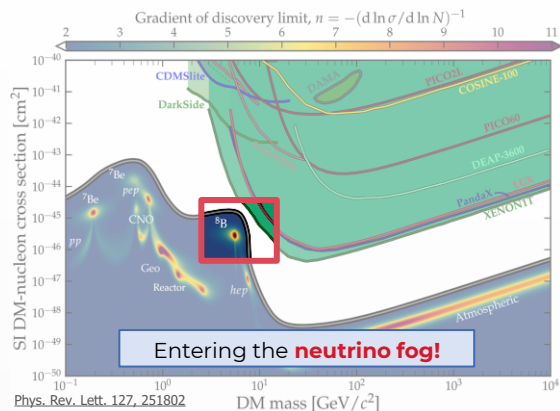
No significant excess observed

Soon: **SR0+1+2 WIMP** results with **~7 ty exposure**.

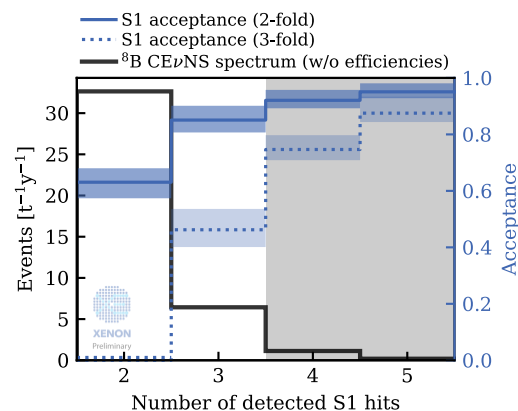




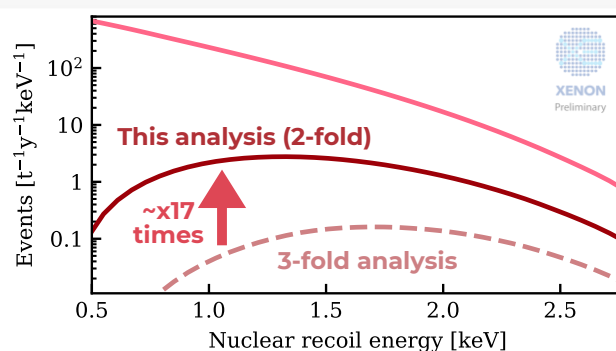
2-fold: CEvNS & Low-Mass WIMPs



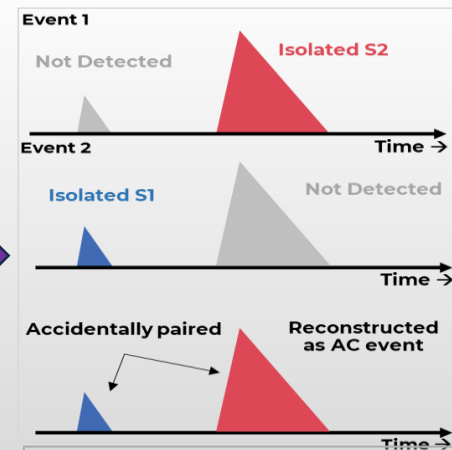
- LXe detectors start detecting WIMP-like neutrino signals.
 - **SR0+1 (2023):** 2.7σ indication.
 - **SR2 (2026):** **Doubled exposure** (6.77ty) and **additional 20% background reduction** due to improved peak classification: 3.3σ observation.



Reduced thresholds



Increased efficiency

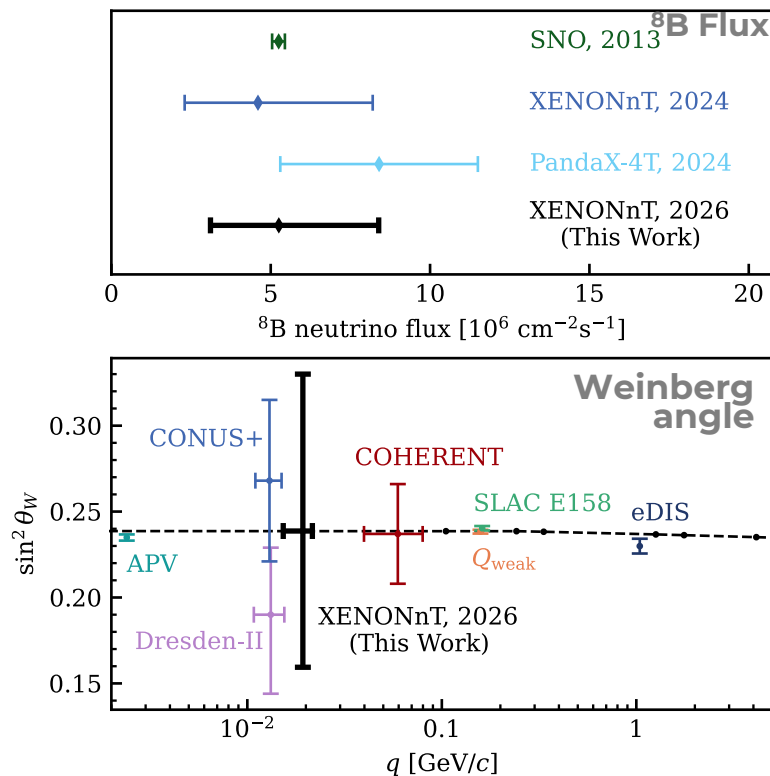


Increased backgrounds

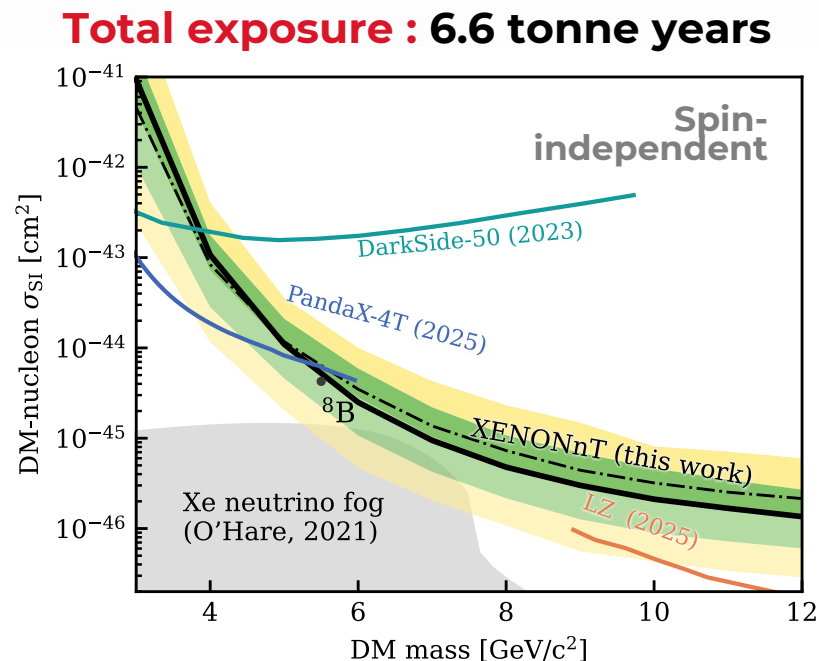


2-fold: CEvNS & Low-Mass WIMPs

Neutrino Results



WIMP Results

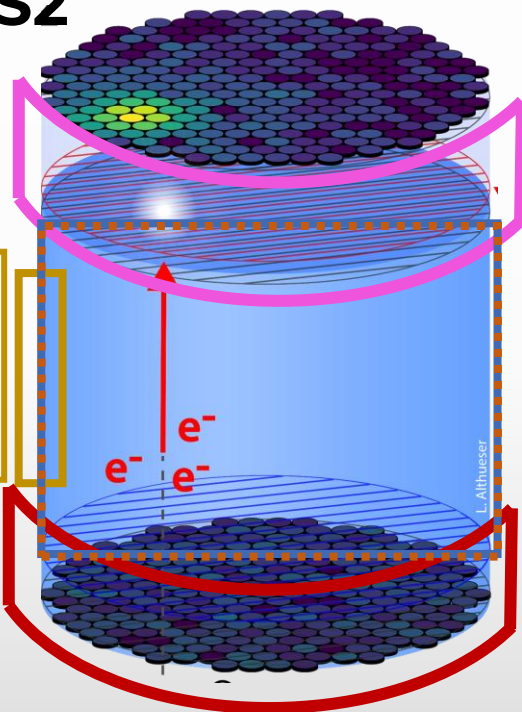


No significant excess observed



S2-Only: Low-Mass Dark Matter

S2



Gate Emissions: Small width due to shorter diffusion.
Negligible after Width Cut

All backgrounds are modelled with **data-driven** methods and are validated on dedicated sidebands.

Delayed Electrons:
Position & time correlated with large S2s

Targeted using **correlation based CNF and BDT** machines.

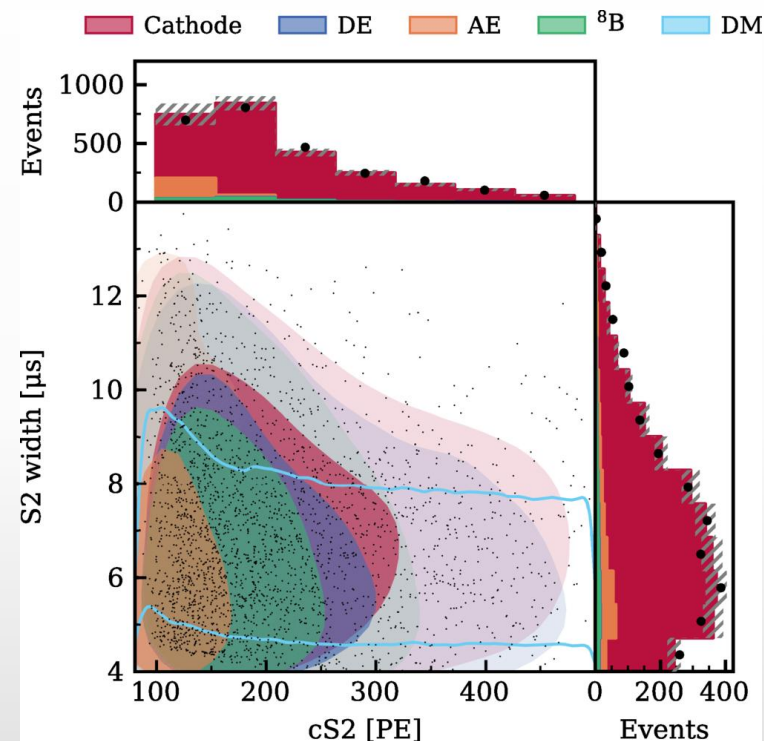
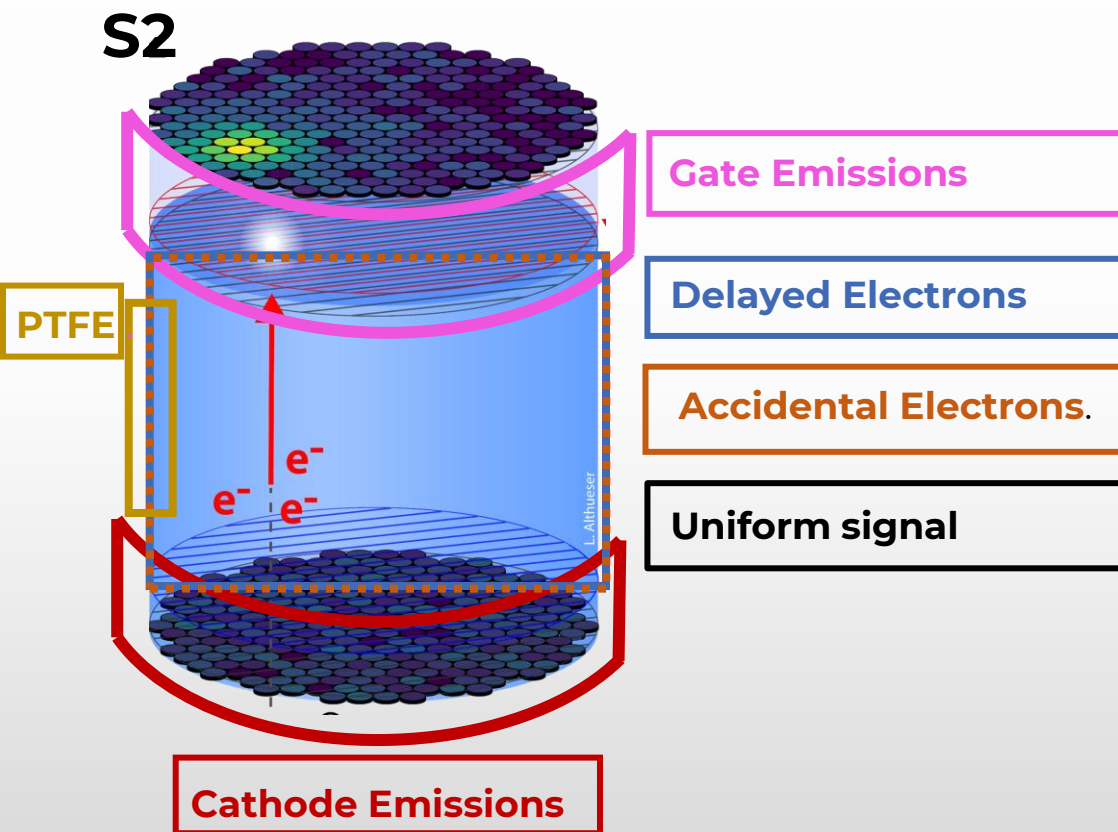
Accidental Electrons:
Random pileup of electrons; randomized hit patterns

Targeted using **the signal-likelihood of the pattern of hits** on top PMT array.

Cathode Emissions: Simulated from data-driven sidebands
Targeted cuts using **waveform based BDT** machine.



S2-Only: Low-Mass Dark Matter

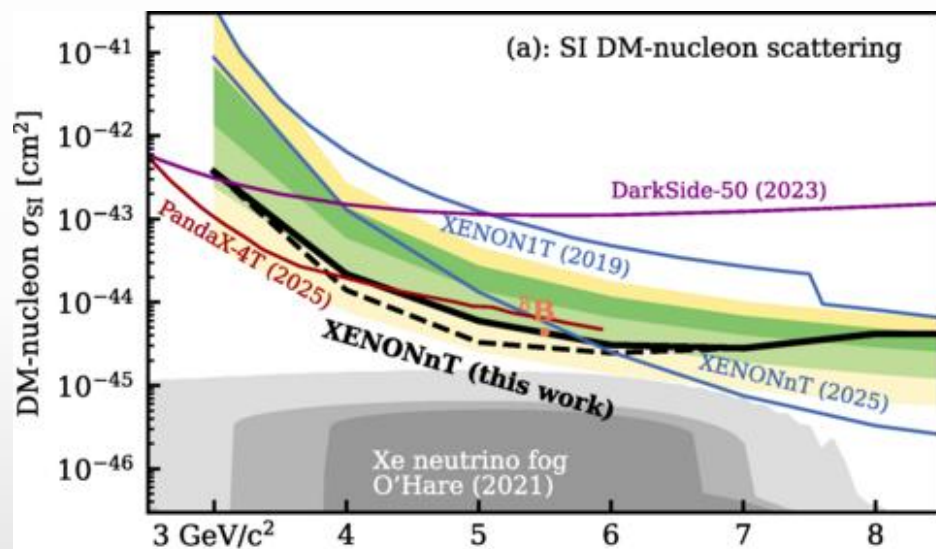


Total exposure :
7.8 tonne years



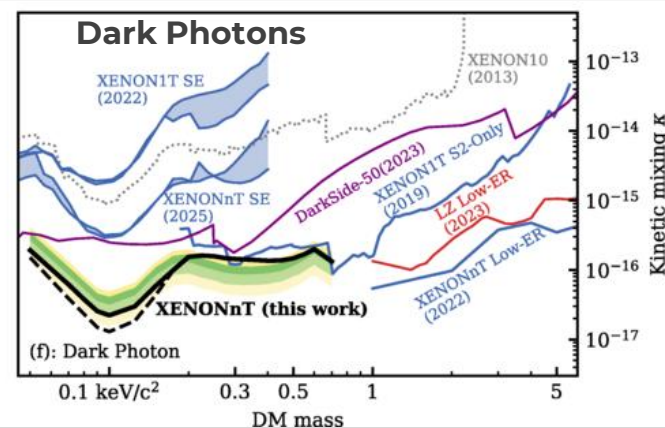
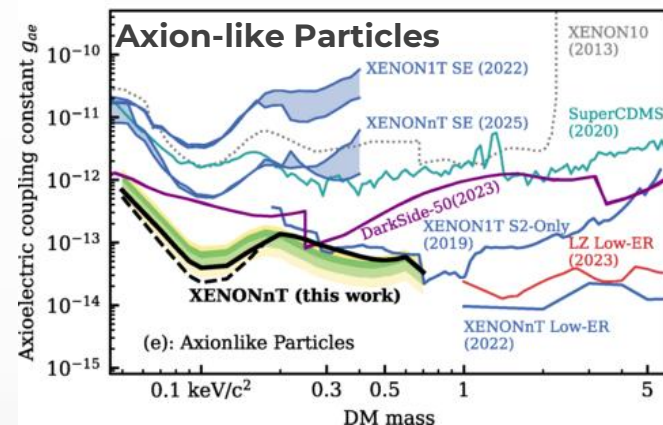
S2-Only: Low-Mass Dark Matter

Spin-independent DM-nucleon interaction



No significant excess observed

Leading limits

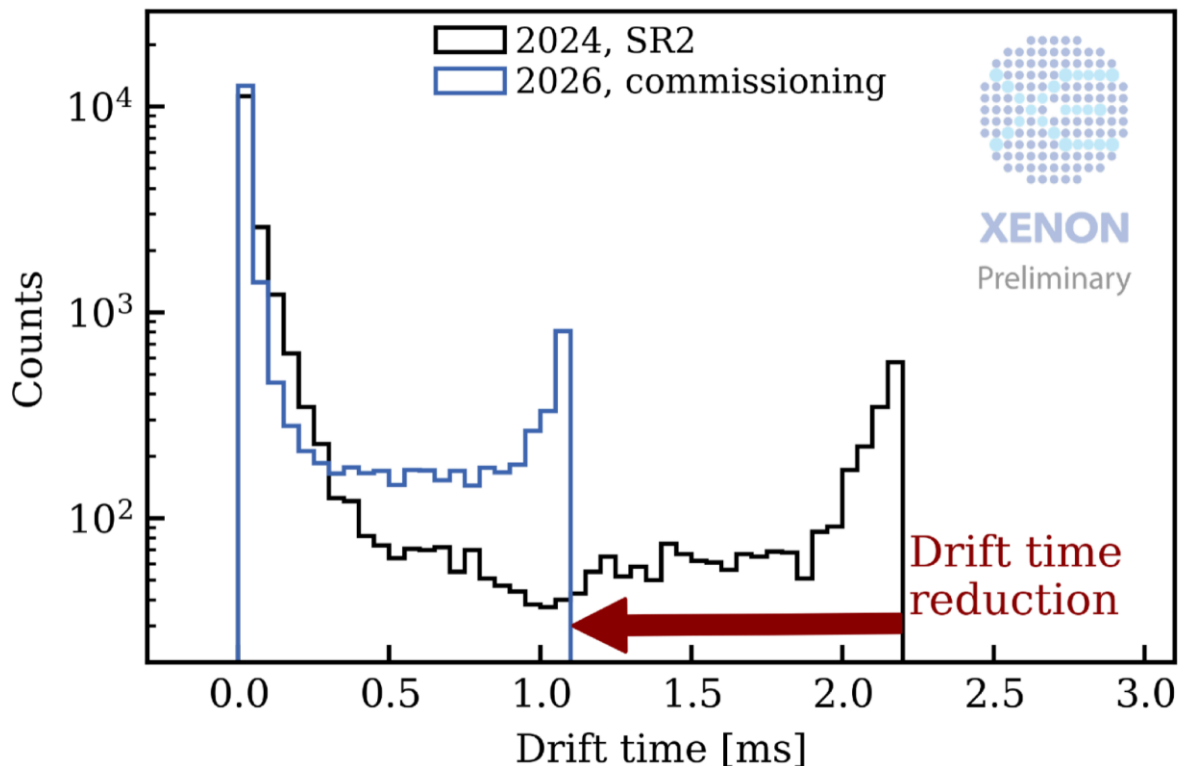


Outlook: Detector Upgrade



- New **hexagonal mesh** cathodes.
- **No more transverse wires** to hold up the gate.
- Replaced ~20 PMTs.
- Total downtime >1 year: **TPC operations: 5 weeks!**

Outlook: Detector Upgrade



Successfully Commissioned!

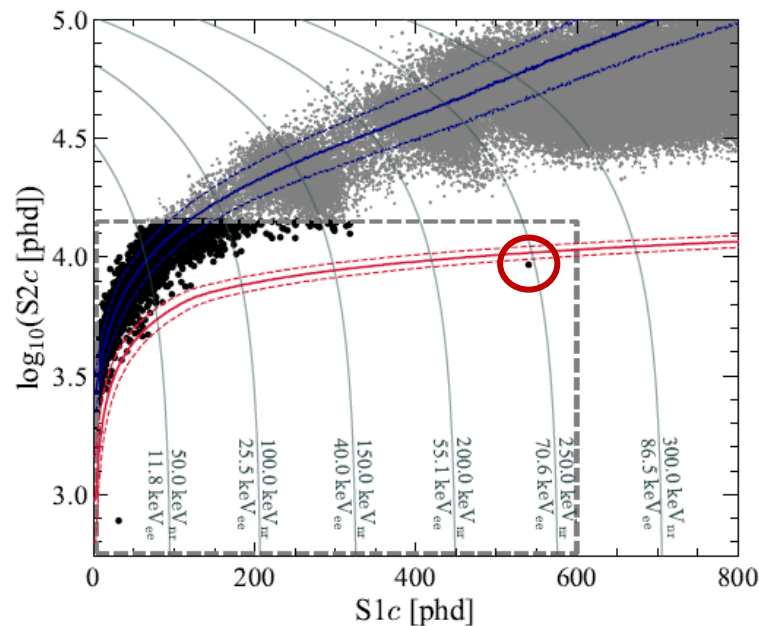
- New **hexagonal mesh** cathodes.
- **No more transverse wires** to hold up the gate.
- Replaced ~20 PMTs.
- Total downtime >1 year: **TPC operations: 5 weeks!**

XENON 2.0 is ready!

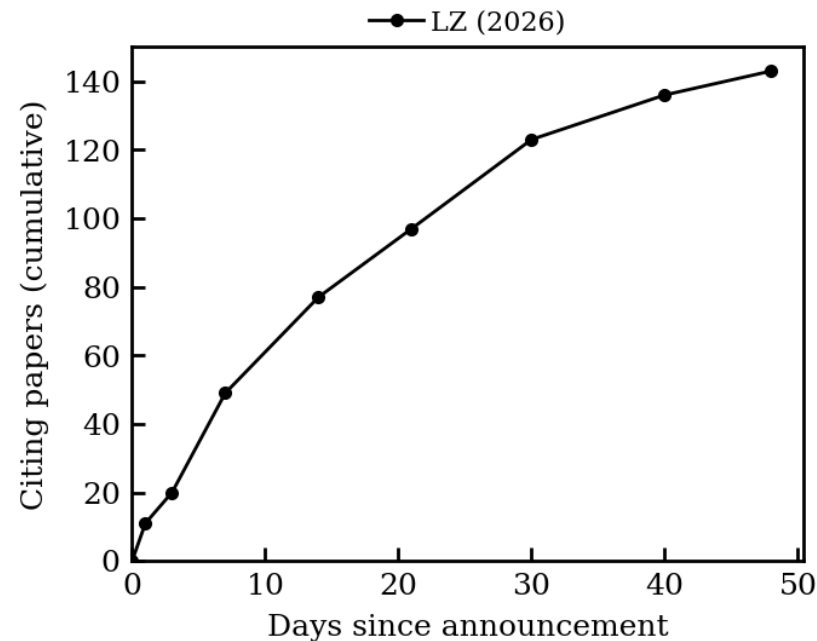
- Improved **drift** and **extraction field**.
- Better **ER/NR Separation**.
- Higher **n-tagging** (more Gd in n-Veto)



Outlook: Testing the “LZ Event”



- **1 event** in 2.84 ty exposure; **unblind analysis**.
- **$E = 248 \pm 23$ (stat) ± 23 (sys) keV**
- Bkg expectation in region ~ 0.01 events: **3.4σ** (2.6σ global)



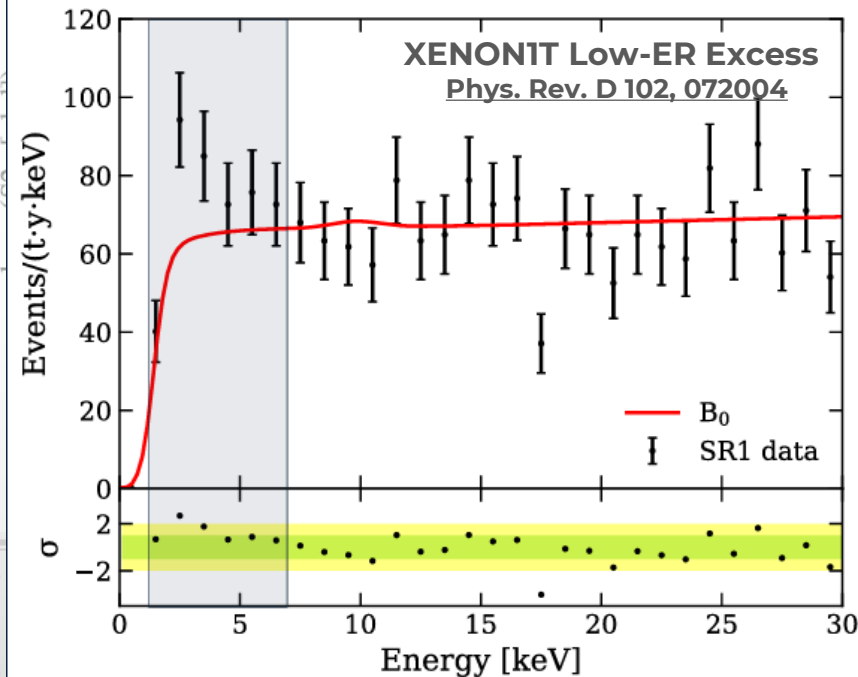
~150 papers in <2 months.

Journal club after this

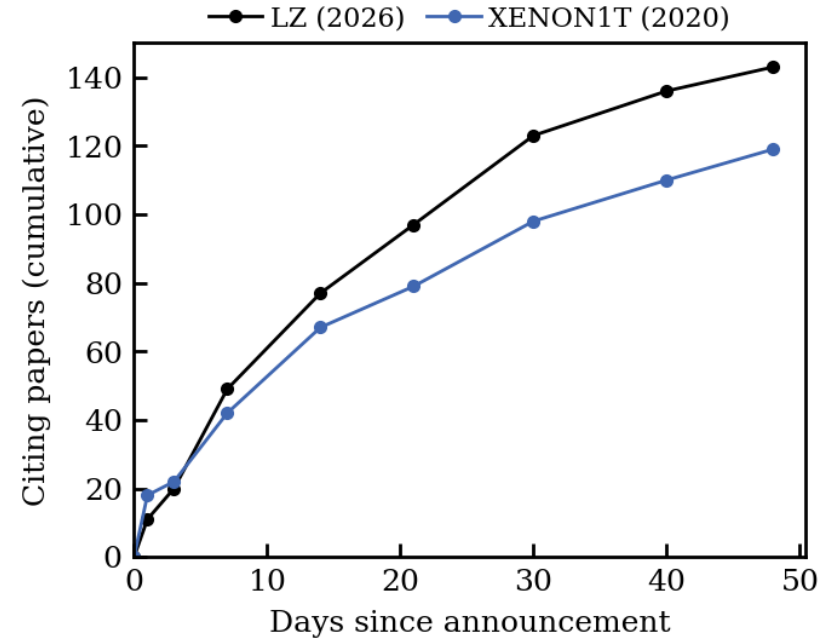
Outlook: Testing the “LZ Event”



Déjà vu..?



- Bkg expectation in region ~ 0.01 events: 3.4σ (2.6σ global)



XENONIT excess was **ruled out by XENONnT** 2 years and 350 more citations later

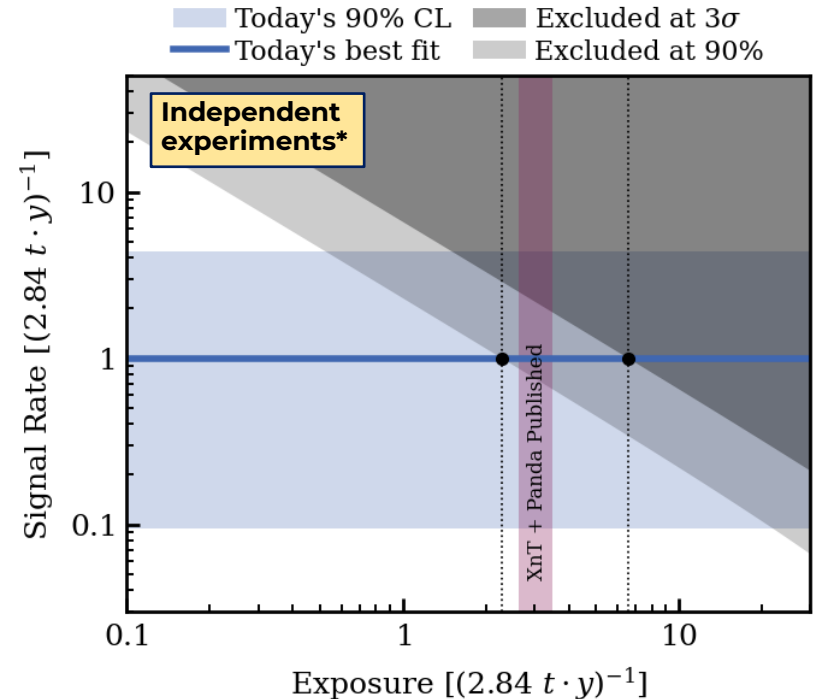
Outlook: Testing the “LZ Event”



But even if we don't see any more events,
Ruling out a 1 event excess will take time..

XENONnT, like all the other experiments, is **actively testing** this parameter space:

- Similar analysis was already in progress; now with extra care.
- XENON has **re-blinded** the region.
- **Modelling NR at high energy** necessary.
- ~650 live-days of exposure on disk in SR012. More data to be collected in SR3.



*Simple one-bin counting experiment.
(cS1, cS2 or spatial information will improve sensitivity)

A lot more science to come...



Thank you for your attention!



XENON

XENON Website: <https://xenonexperiment.org/>



Backup Slides

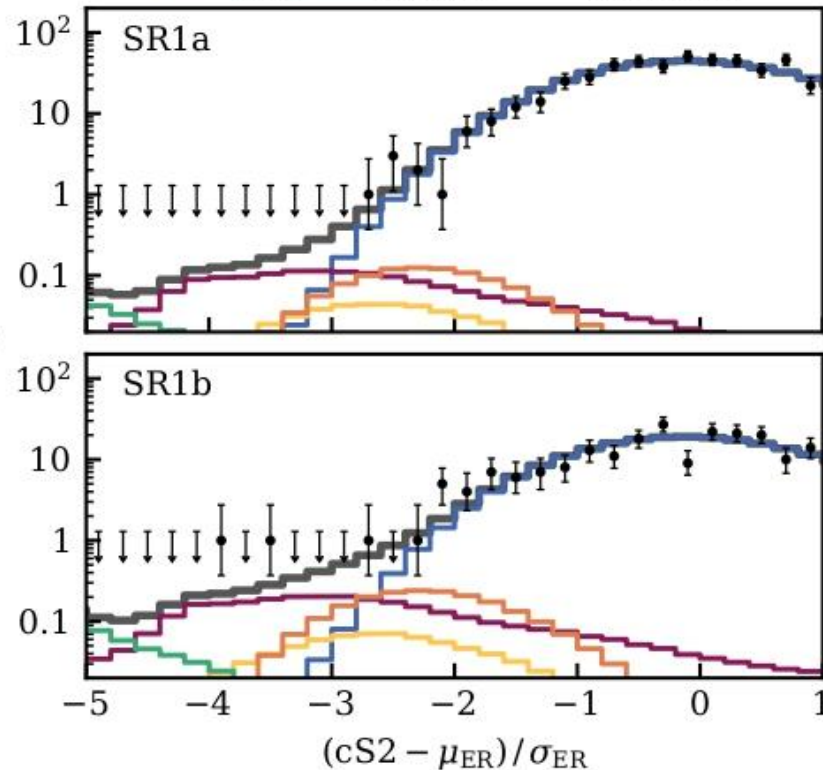


SR0+1: WIMP Search

Further tests

eg. AD test on cs2 space

— ER — AC — WIMP
— NR — Surface — Total bkg.



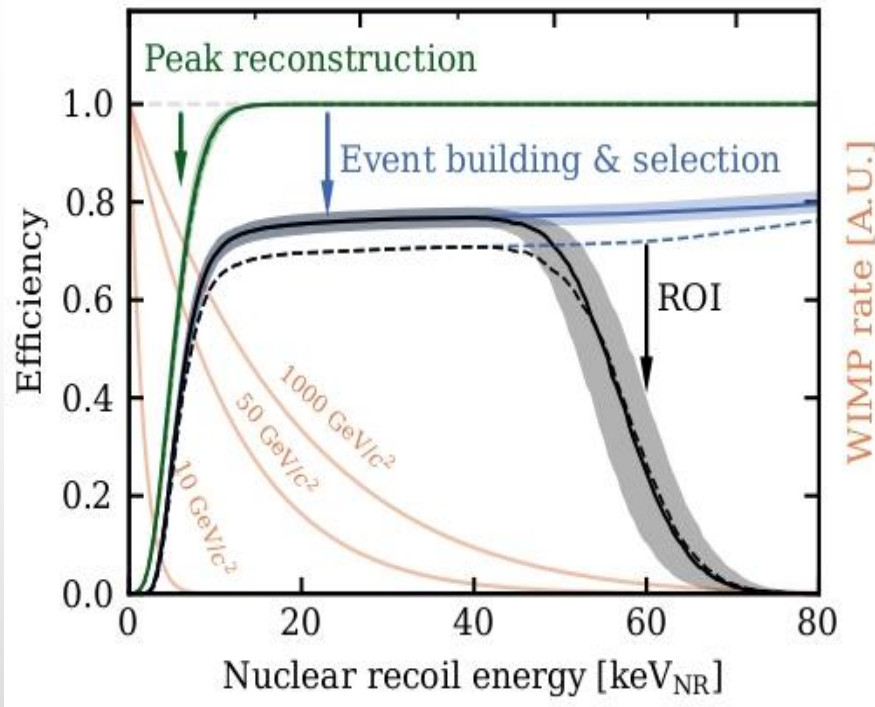
After unblinding, further tests performed to identify mismodelling. **No evidence of mismodelling** observed.

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



SR0+1: WIMP Search

Efficiencies



SR1a

SR1b

Peak Reconstruction

- Efficiency of an S1/S2 peak to be reconstructed.
- Dominated by 3-fold requirement (3 PMTs to be in coincidence)

Event building & Selection

- Efficiency in pairing S1s and S2s.
- Efficiency of the event selection cuts.

Region of Interest (RoI)

$$cs1 < 100 \text{ PE} \quad \& \quad cs2 \in [10^{2.1}, 10^{4.1}] \text{ PE}$$



SR0+1: **WIMP** Search

Backgrounds

SR0 (95.1 days)

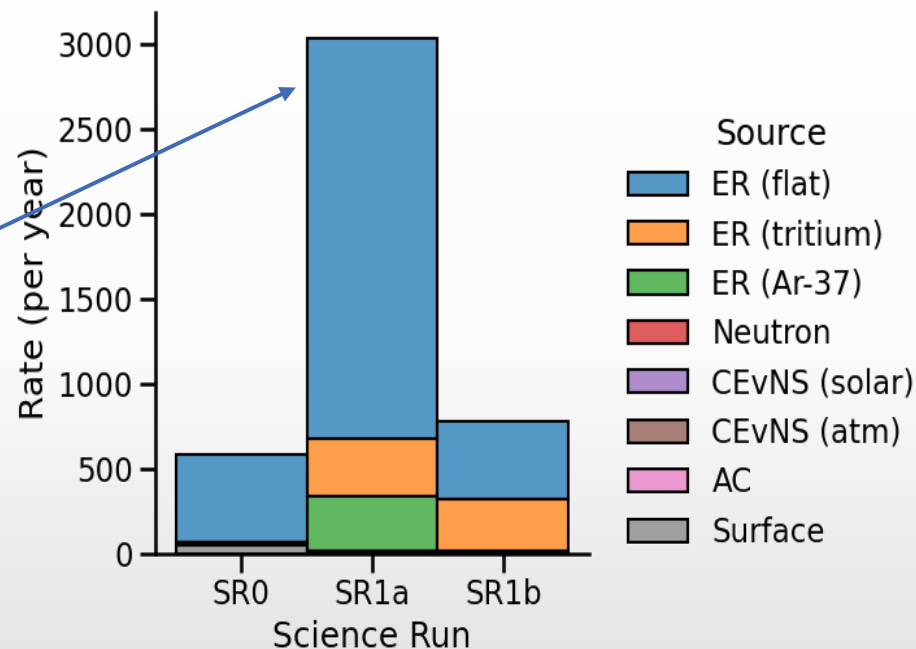
- Updated neutron background model.
- Rest of the analysis unchanged.

SR1a (66.6 days)

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

SR1b (119.9 days)

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

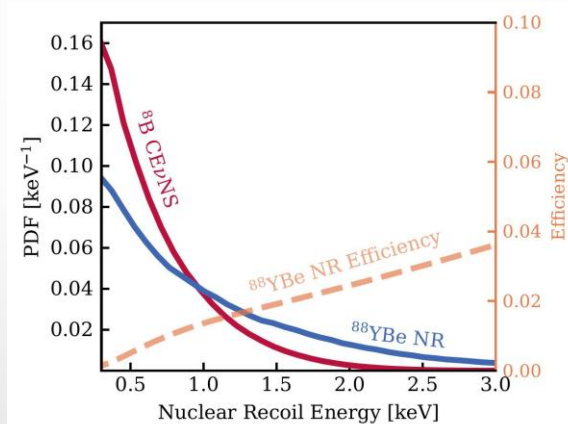


Total exposure :
3.1 tonne years

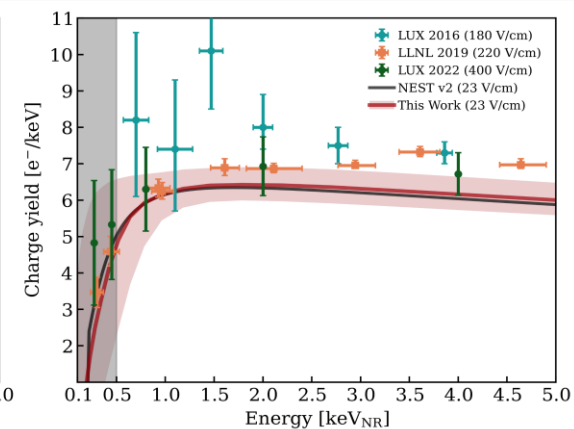
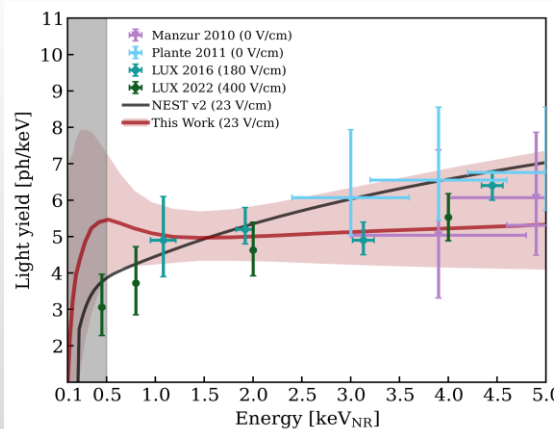
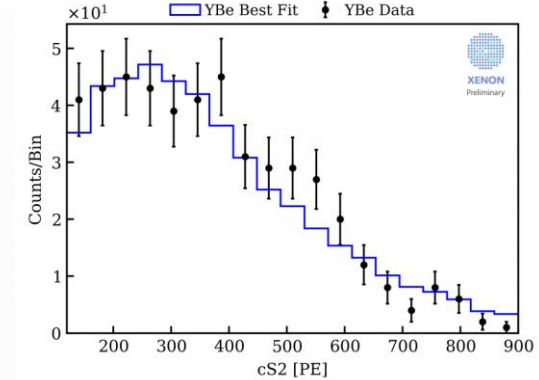
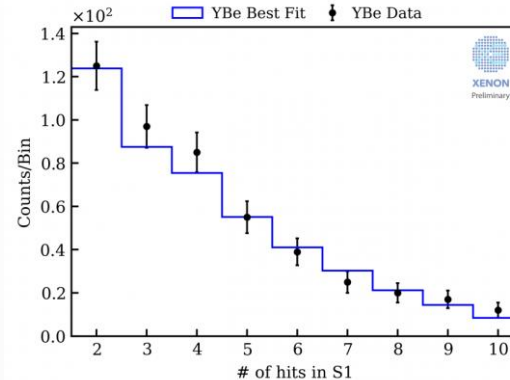


YBe Calibration

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



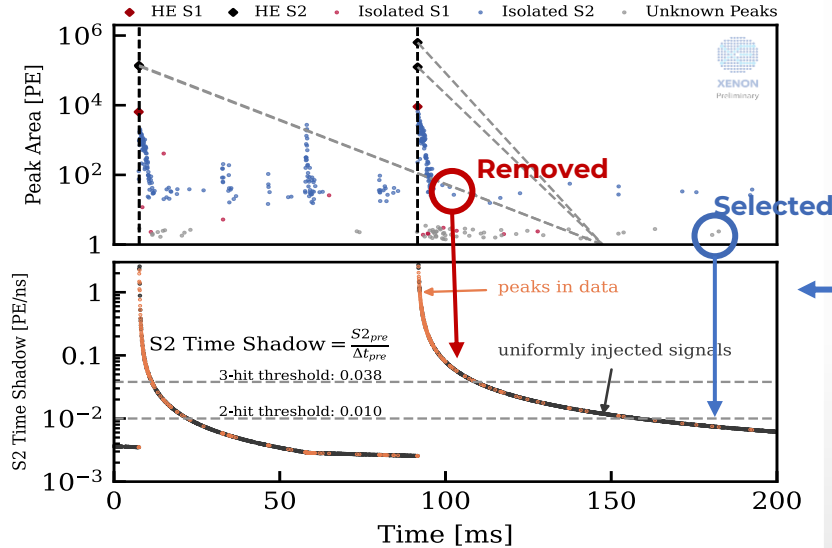
- Good matching with model.** Light and charge yield are constrained by fit of ^{88}YBe data on NEST model at 23 V/cm.





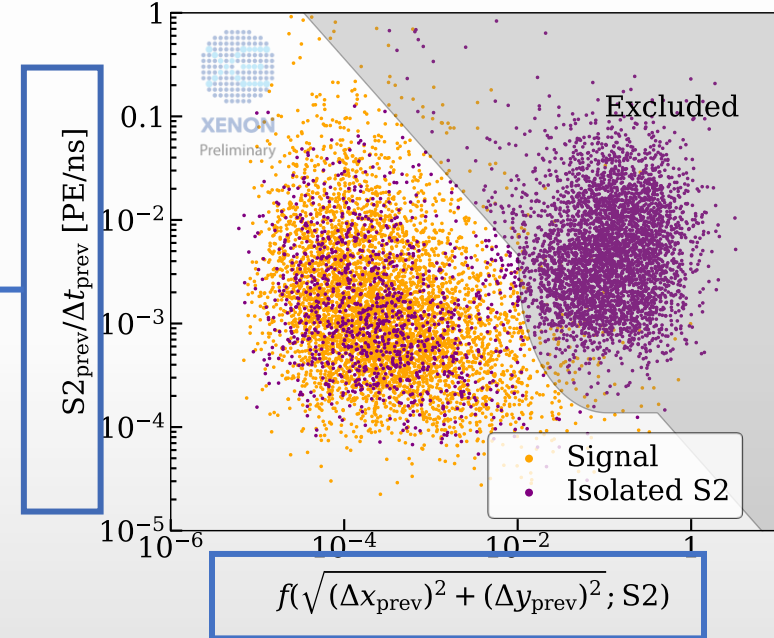
Time and Position Shadows

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-peaks** typically larger than of signal.

Position Shadow



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

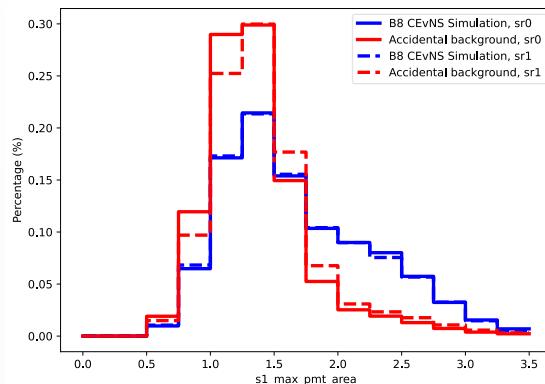
- Using the position information, **Iso-S2s** can be removed by combination of time and position shadow.



S1 BDT Features

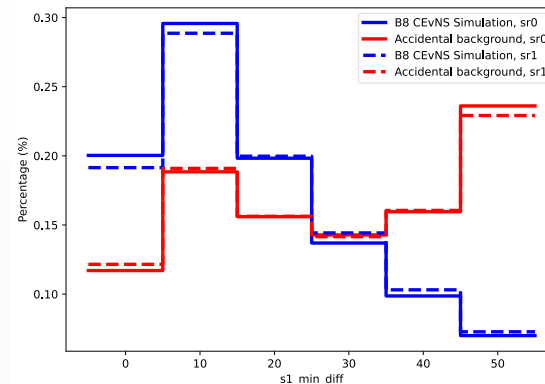
First: Max S1 hit area

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



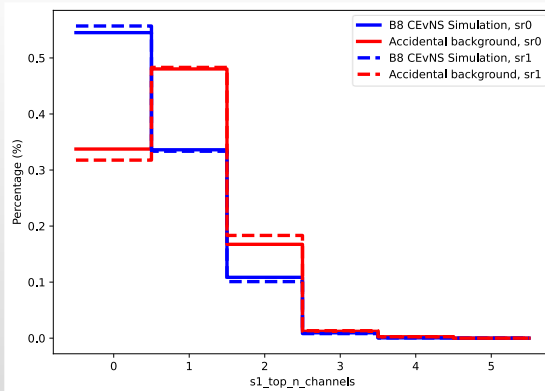
Second: Min time between S1 hits

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



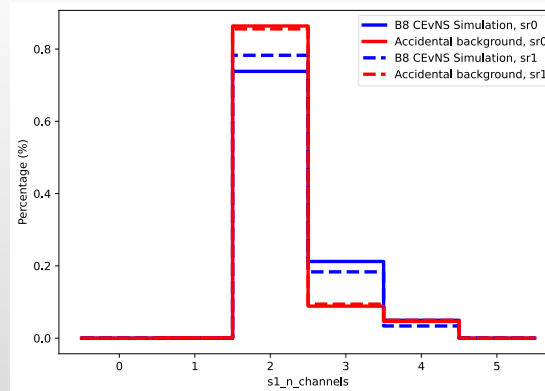
Third: No. of hits in top PMT array

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



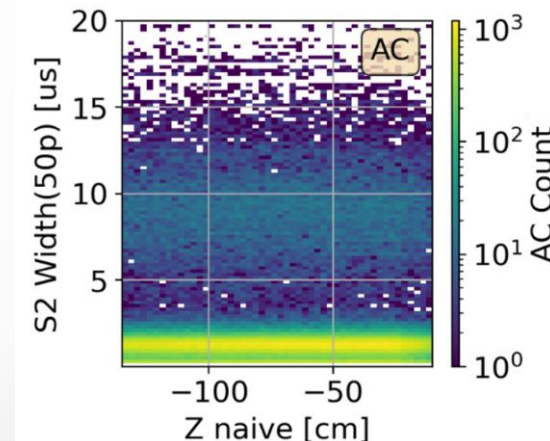
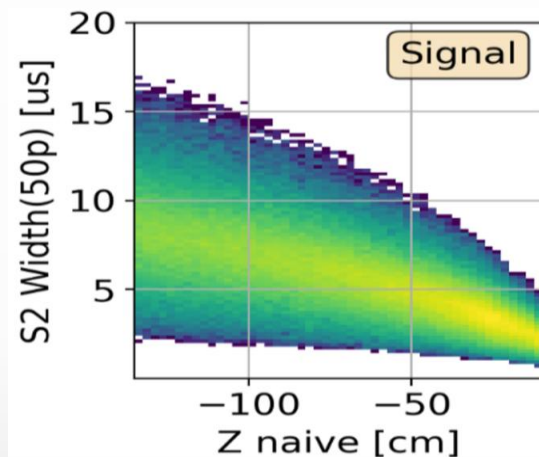
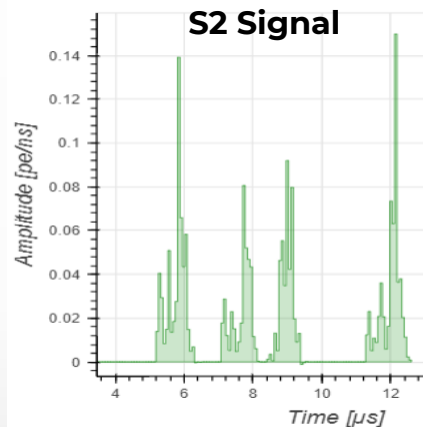
Fourth: Total no. of hits

Reproduces the full recoil spectrum.





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.



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)

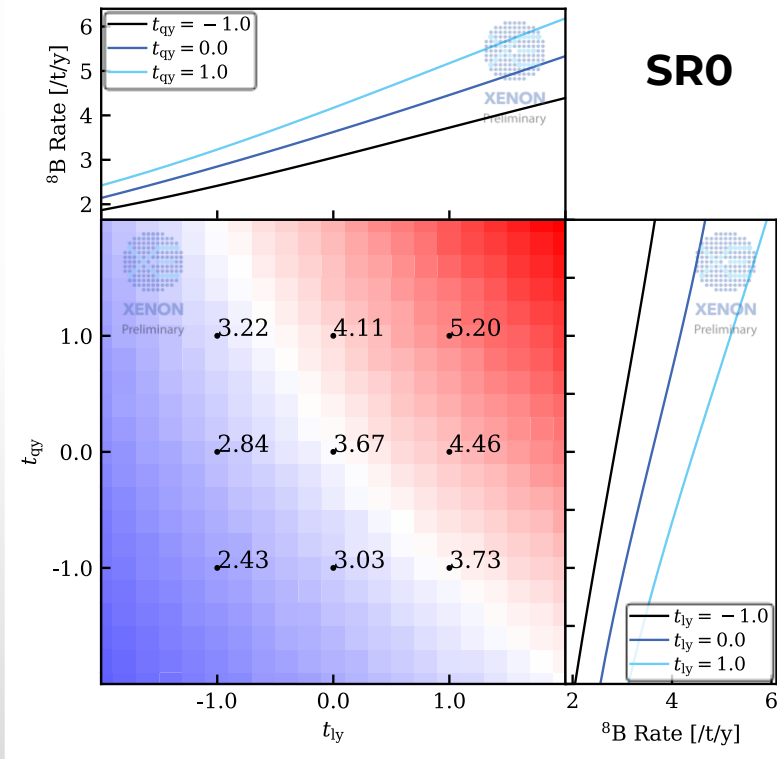
Uncertainty
band in fit

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

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

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

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

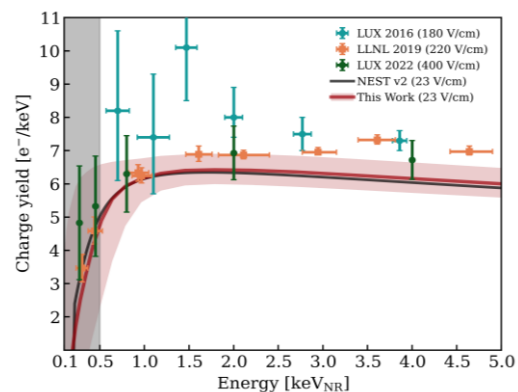
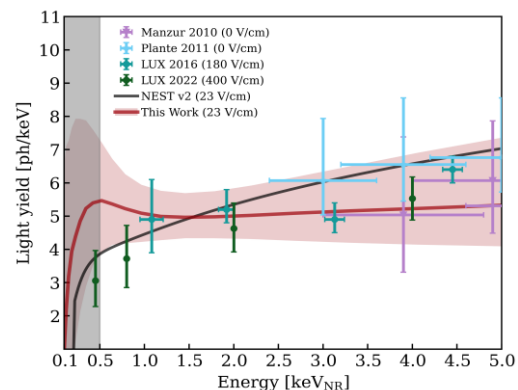


Expected ^8B rate at different light and charge yields.

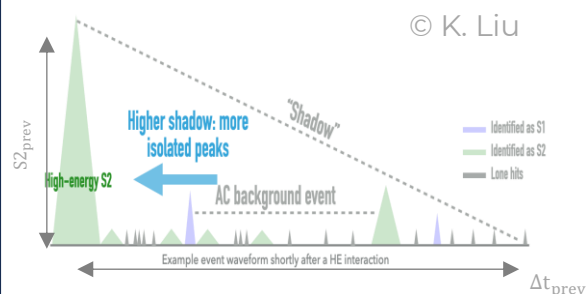


2-fold: CEvNS & Low-Mass WIMPs

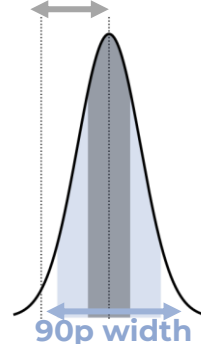
Model Low-Energy response using ^{88}YBe



Develop new methods to suppress AC background



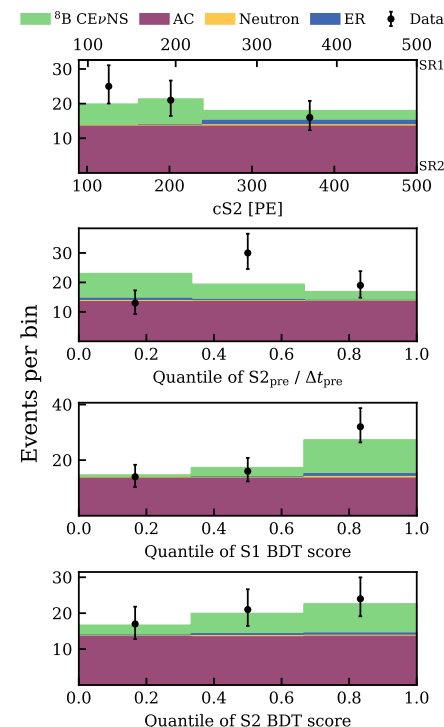
Rise time



Use time & space information from previous high energy peaks

Use S1/S2 waveform features to train a boosted decision tree (BDT)

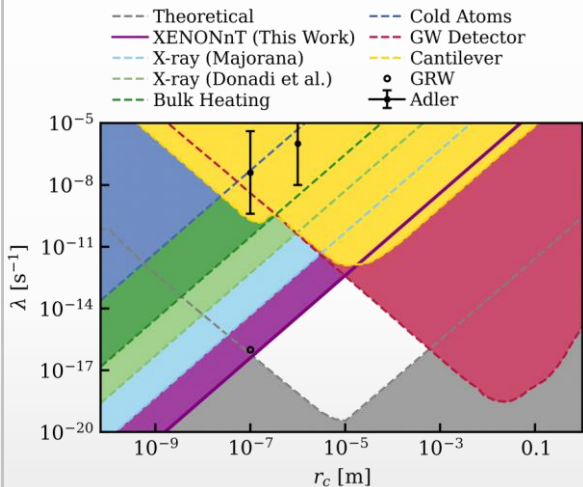
Multi-dimensional binned likelihood





Some other recent studies

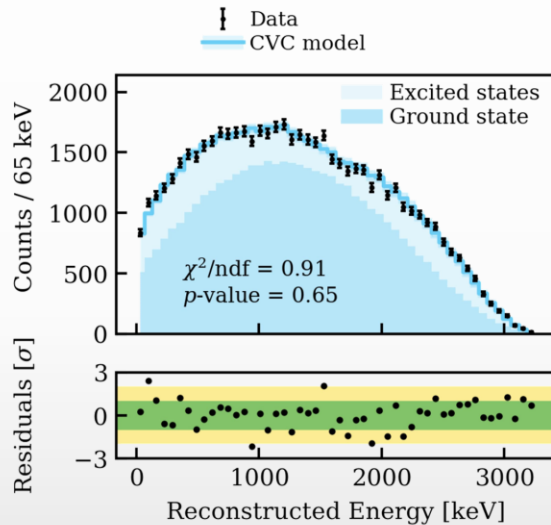
Spontaneous Wavefunction collapse



World leading limits on models addressing why macroscopic systems do not exist in superimposed position states.

[arXiv:2506.05507 \[hep-ex\]](https://arxiv.org/abs/2506.05507)

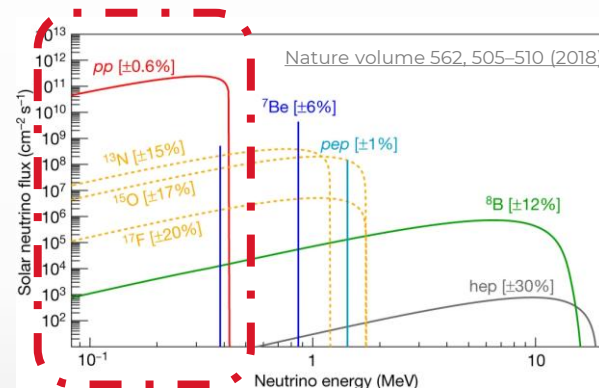
Spectral measurement: ^{214}Bi β^- decay to ^{214}Po g.s



Ultra low backgrounds allow for robust measurements of the $^{214}\text{BiPo}$ spectrum and to compare between models.

[arXiv:2510.04846 \[nucl-ex\]](https://arxiv.org/abs/2510.04846)

Measurement of Solar-pp neutrinos



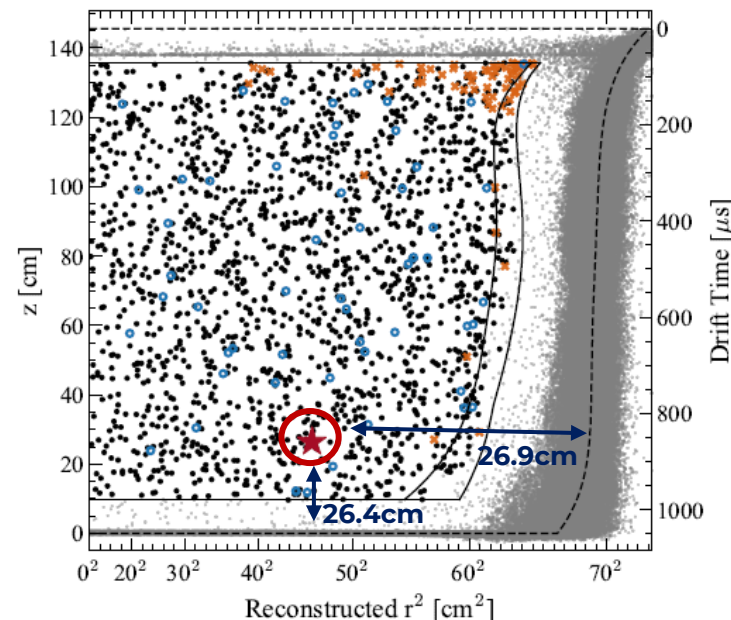
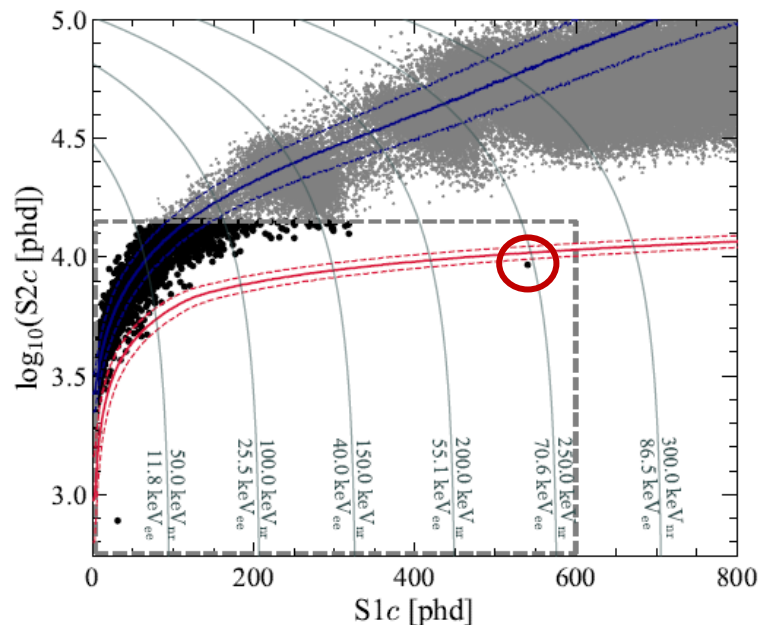
Low energy threshold ($<1 \text{ keV}_{\text{ER}}$) and reduced ER backgrounds allow **direct measurements of neutrinos** from the p-p fusion in the Sun.

Ongoing. Results soon.



Testing the “LZ Event”

LZ observed **1 event** at $E = 248 \pm 23$ (stat) ± 23 (sys) keV, for a background expectation ~ 0.01 events: 3.4σ local and 2.6σ global significance.



What we know

- 1 event in 2.84 ty exposure.
- Event slightly below NR band.
- Bkg expectation in region ~ 0.01 events.
- Does not show up in Bkg-dominated sidebands.
- Outside RoI for “classical” WIMPs
- Unblind Analysis.

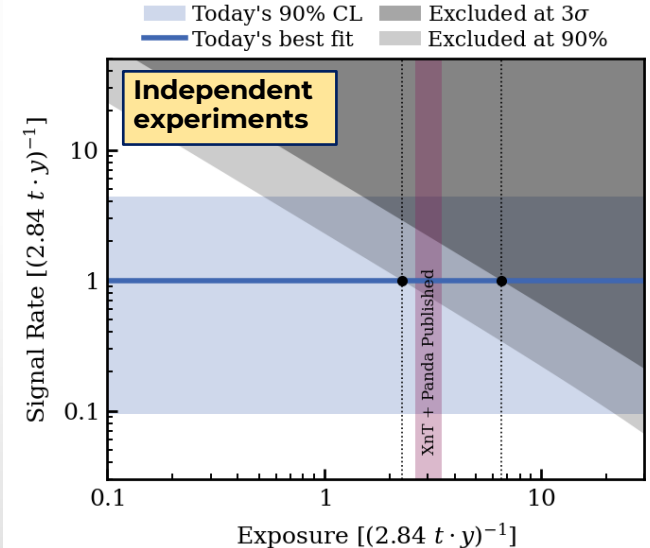
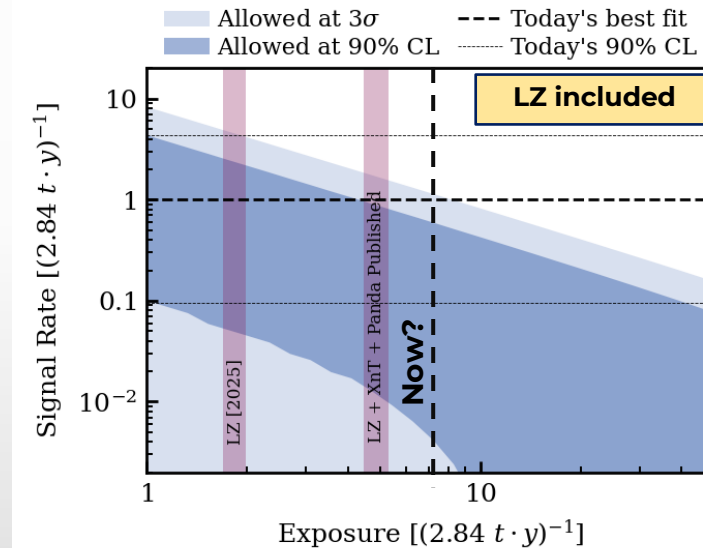


Testing the “LZ Event”

Even if we don't see any more events,
Ruling out a 1 event excess will take time..

We need (and have) more data to test. Published on-disk exposures:

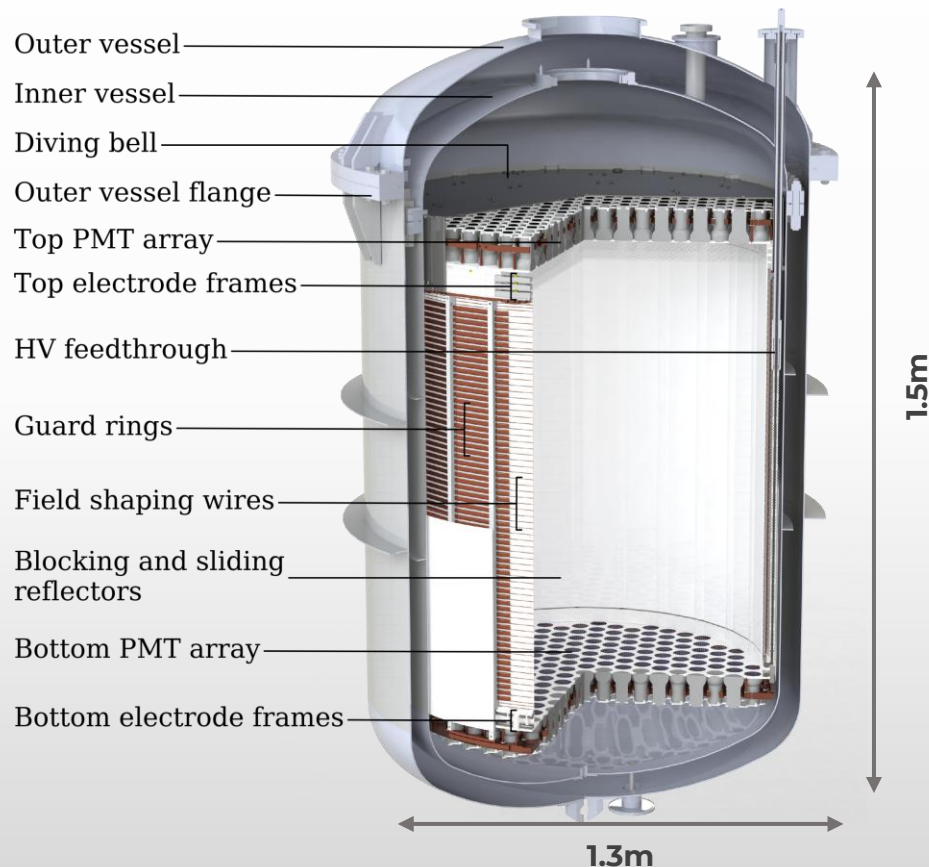
- LZ: **5.2 t.y** [2025]
- XENON: **7.2 t.y** [2026]
- Panda: **1.5 t.y** [2024]
- All experiments are actively looking at this region.



*Simple one-bin counting experiment.

(cS1, cS2 or spatial information will improve sensitivity)

XENONnT Time Projection Chamber



Total LXe

$$V_{\text{LXe_total}} = 8.5 \text{ tonnes}$$

Active LXe

$$V_{\text{LXe_active}} = 5.9 \text{ tonnes}$$

Drift Field

$$E_{\text{drift_XnT}} = 23 \text{ V/cm}$$

Extraction Field

$$E_{\text{extr_XnT}} = 2.9 \text{ kV/cm}$$

Max drift time

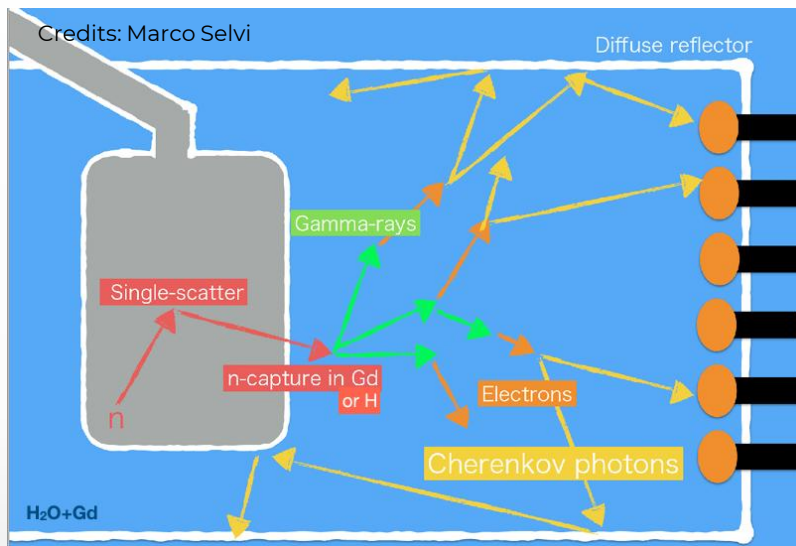
$$t_{\text{drift_max}} = 2.2 \text{ ms}$$

PMT Array

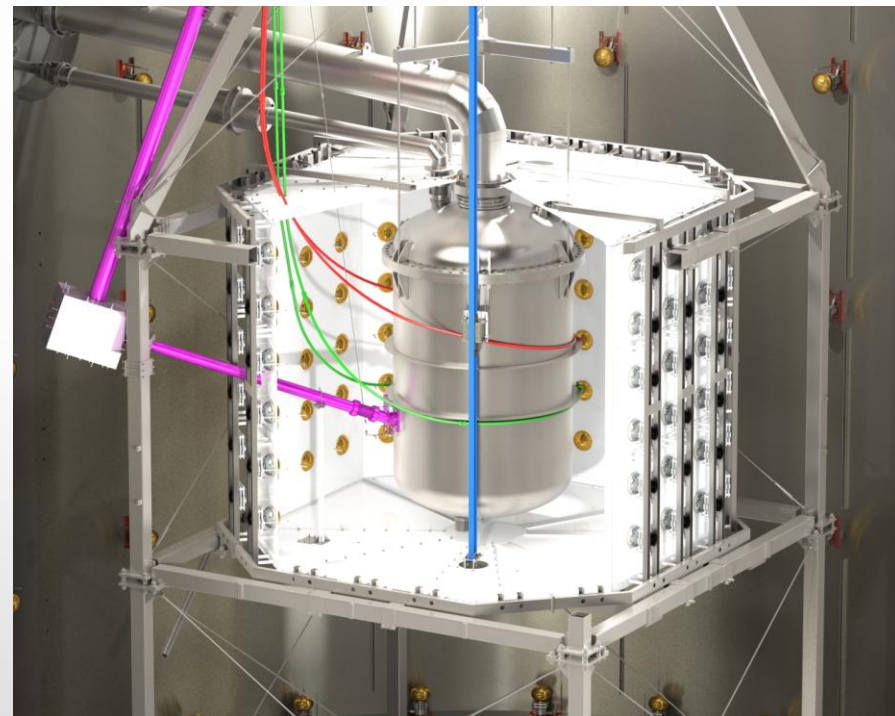
494 3" PMTs in total



XENONnT Neutron Veto

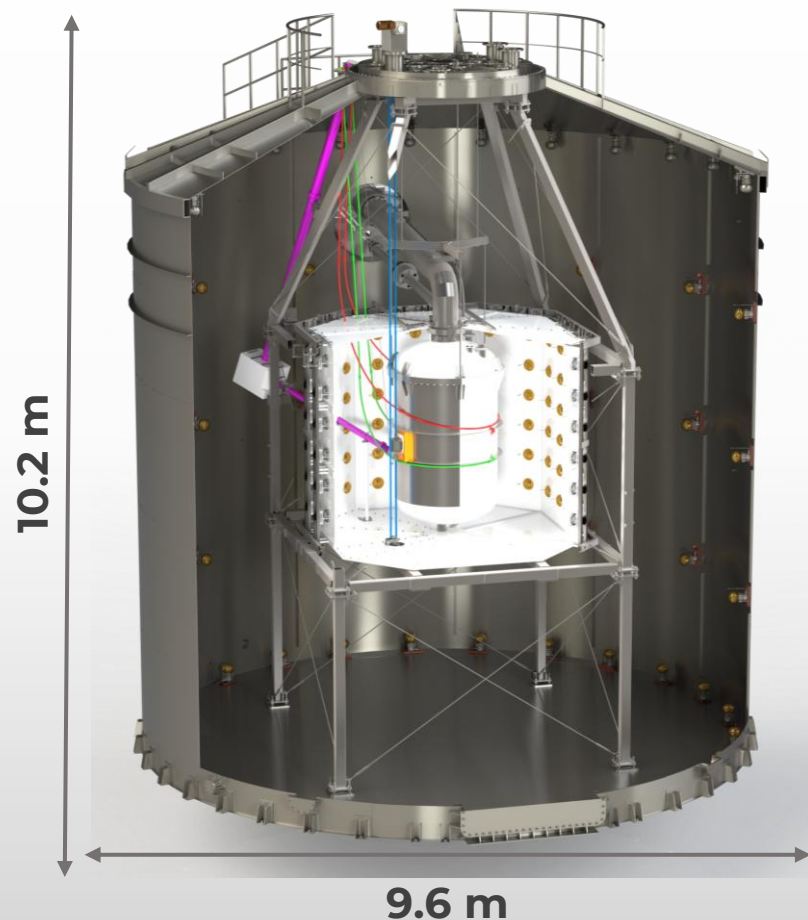


- 33 m³ demineralized water, optically separated from outer MV.
- 120 8" high-QE PMTs.
- $(53 \pm 3)\%$ **tagging efficiency** with water.
- With 500ppm **GdSO doping**, tagging efficiency increases to $\sim 77\%$.





XENONIT: 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.



XENONnT Infrastructure



Rn Distillation

Continuous online distillation.

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

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

Eur. Phys. J. C (2022) 82: 1104 arXiv:2502.04209 [physics.ins-det]



Kr Distillation

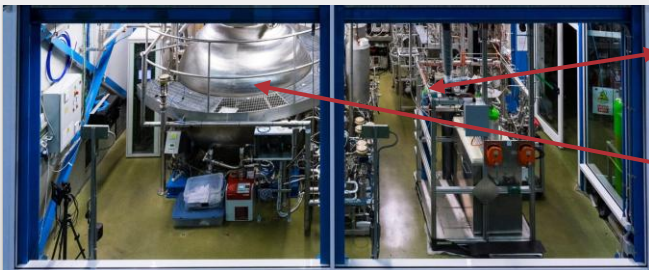
natKr/Xe concentration **$< 50 \text{ ppq}$**

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

nT DAQ

Triggerless DAQ. Shared between three detectors.

2023 JINST 18 P07054



LXe Purification

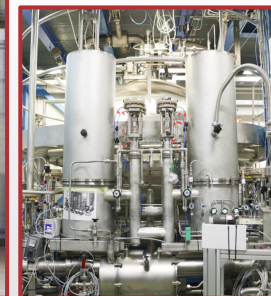
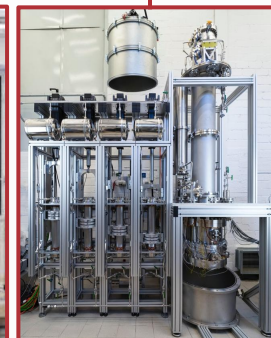
Removes **electronegative** impurities.

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

ReStoX

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

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



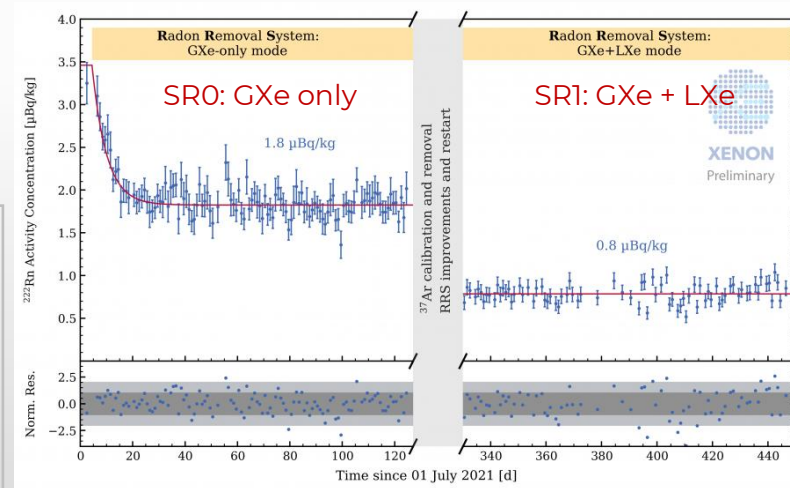
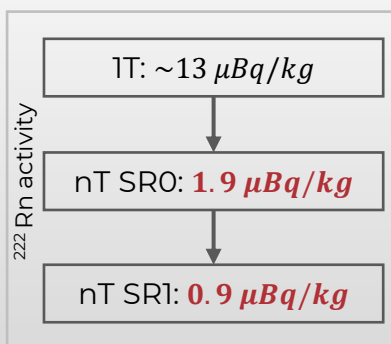
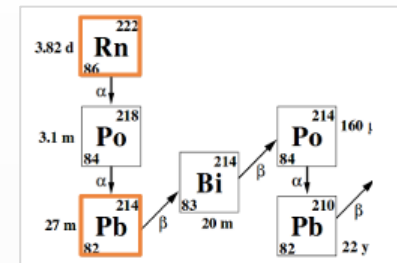
Outside the Service Building



Online distillation for ^{222}Rn



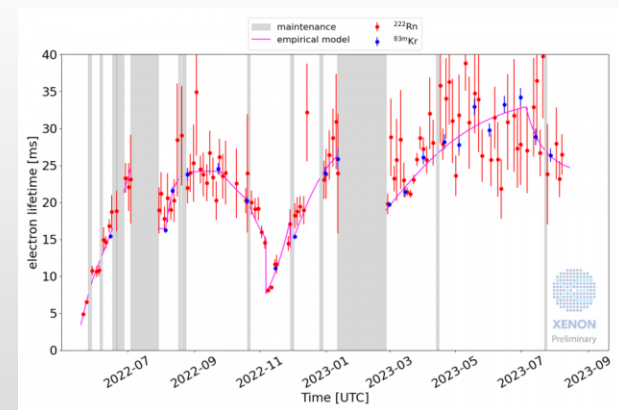
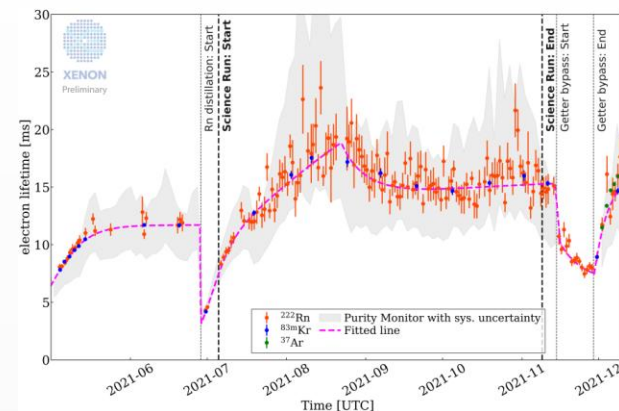
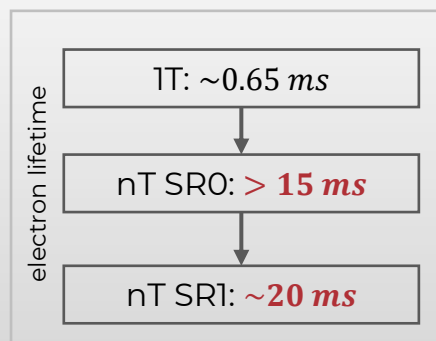
- ^{222}Rn ($t_{1/2} = 3.8d$) emanates from detector material.
- Continuous online distillation utilizes the difference in vapour pressure.
- Purifies 1.8t (0.2t) of liquid (gas) xenon per day.





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**.



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 vacuum sealed volume





^{85}Kr Distillation

- $^{\text{nat}}\text{Kr}$ traces ($^{\text{nat}}\text{Kr}/\text{Xe} > 1\text{ppb}$) 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.
- $^{\text{nat}}\text{Kr}/\text{Xe}$ concentration $< 50\text{ ppq}$ achieved in nT.

