

PERFORMANCE OF THE Gd-LOADED WATER CHERENKOV NEUTRON VETO OF XENONnT

IDM 2026

16th International Conference on
Identification of Dark Matter

Zaragoza

Spain
1–5 June 2026

EMANUELE ANGELINO
on behalf of the XENON collaboration

eangelino@uchicago.edu
University of Chicago



THE UNIVERSITY OF
CHICAGO



XENON PROJECT

DARK MATTER (DM) DIRECT SEARCH WITH LIQUID XENON

**@INFN LABORATORI NAZIONALI DEL
GRAN SASSO (LNGS) in Italy**

**Deep underground: 1.4 km rock / 3600 mwe
→ 10^6 μ reduction factor**

2005
XENON10
25 kg



2008
XENON100
160 kg



2016
XENONIT
3200 kg



2020
XENONnT
8600 kg



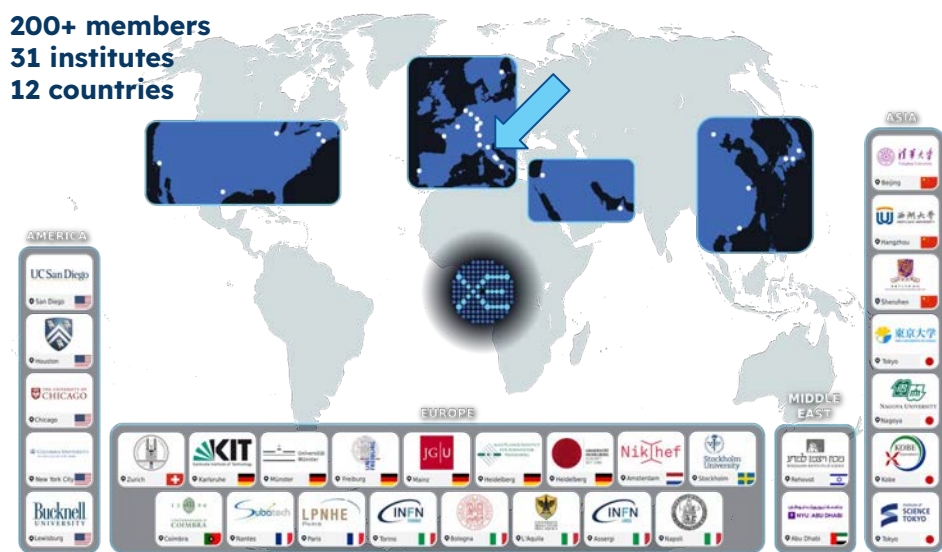
Gd-loaded water Cherenkov Neutron Veto of XENONnT

Emanuele Angelino

IDM 2026, Zaragoza, Spain

01/11

200+ members
31 institutes
12 countries



Collaboration Meeting 2025 @LNGS



XENON_nT EXPERIMENT

3 NESTED DETECTORS INSIDE
700 t WATER TANK (WT)



XENONnT EXPERIMENT



DUAL-PHASE Xe TIME PROJECTION CHAMBER (TPC)

- **5.9 t ACTIVE** mass (**8.6 t** in total), $\varnothing$ 1.3 m x h 1.5 m
- **494 3" PMTs**
- **RARE-EVENTS** searches via **NUCLEAR/ELECTRONIC RECOILS** (NR, ER)

[Eur.Phys.J.C 84 \(2024\) 8, 784](#)

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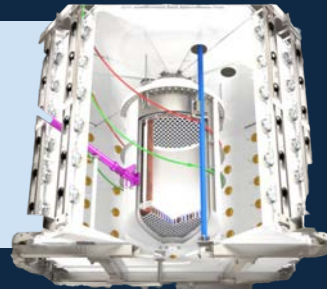
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Gd-WATER CHERENKOV NEUTRON VETO (NV)

- **33 m³** around cryostat, $\varnothing$ 2 m x h 3 m
- **120 8" PMTs**
- **RADIOGENIC NEUTRONS** from materials

[Eur.Phys.J.C 85 \(2025\) 6, 695](#)



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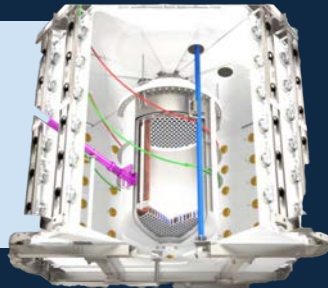
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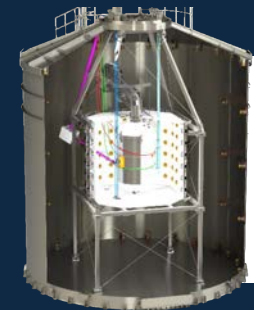
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[Eur.Phys.J.C 85 \(2025\) 6, 695](#)



Gd-WATER CHERENKOV MUON VETO (MV)

- **700 t water**, $\varnothing$ 10 m x h 10 m
- **84 8" PMTs**
- **MUON-induced NEUTRONS** (active veto), γ and neutrons from natural **RADIOACTIVITY** (passive shield)



**3 NESTED DETECTORS INSIDE
700 t WATER TANK (WT)**



XENONnT UPGRADES

FIDUCIAL MASS:
about 4 tonnes

EXPOSURE:
7 tonnes × year

FROM SR0 TO SR1:

**ONLINE RADON
REMOVAL SYSTEM**

1.8 → 0.9 uBq/kg

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

Reached **SOLAR PP
NEUTRINO** background
level (ER)

FROM SR1 TO SR2:

**Gd-LOADING INTO WATER
CHERENKOV NEUTRON VETO**

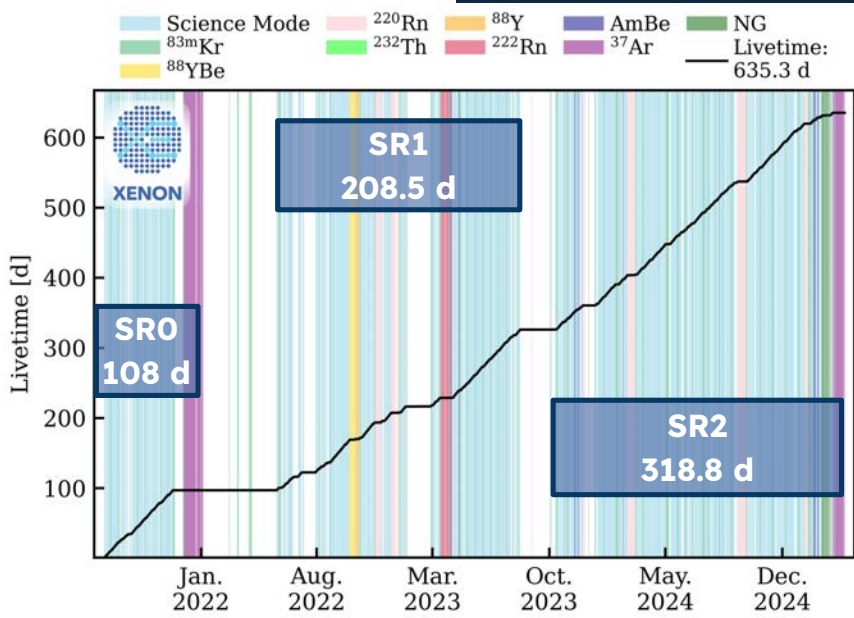
**REDUCED NEUTRON
BACKGROUND (NR)**
compared to previous
science runs

...FROM SR2 TO SR3:

**IN 2025 UPGRADED TPC with
NEW ELECTRODES**

COMMISSIONING NOW!

Improved **ER/NR
DISCRIMINATION**
with higher drift field



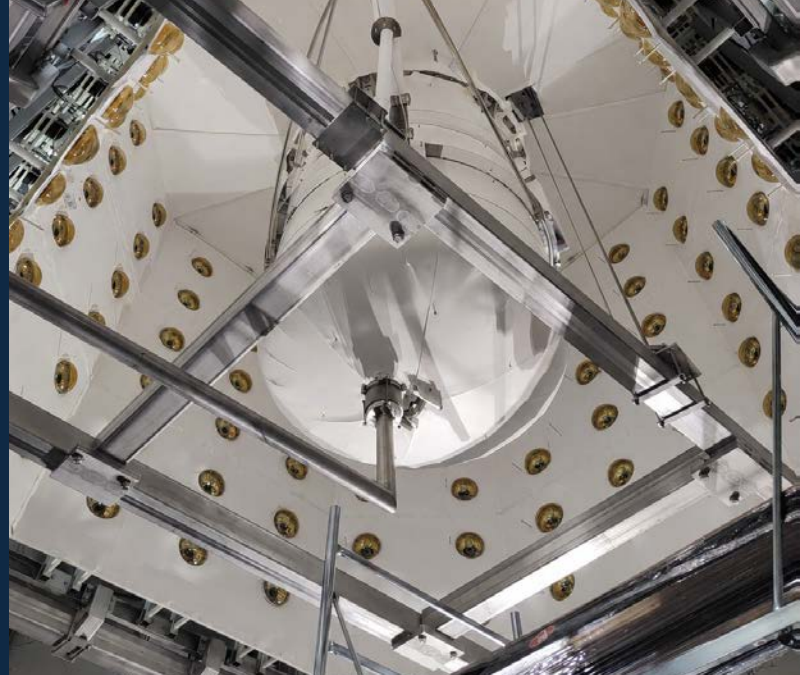
NEUTRON VETO

MAIN GOAL

TAGGING of **RADIOGENIC NEUTRONS** (from cryostat, PMTs, PTFE) inducing single scatter **NUCLEAR RECOILS (NR)** in TPC like **WIMPs**

DETECTOR DESIGN

- **CHERENKOV** light detected by **120 PMTs** at 1 m from cryostat
- high reflectivity **ePTFE PANELS** enclosing volume (33 m^3) with large **LIGHT COLLECTION** efficiency
- **LED** and **LASER** systems for PMT gain and optical properties monitor



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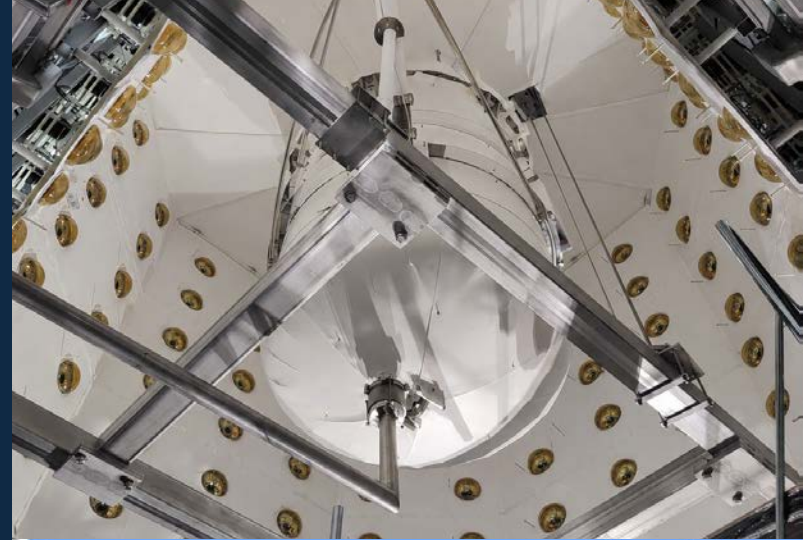
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PURE WATER IN SRO+SR1

H-capture: 2.2 MeV, 1 γ
 $\sigma \sim 0.33 \text{ b}$

Gd-LOADED WATER IN SR2

Gd-capture: 8 MeV, 3-4 γ
 $\sigma \sim 49000 \text{ b}$



Gd-WATER PLANT

PURE WATER ONLY

DEIONIZATION
via **ION-EXCHANGE RESINS**
(+ particle filtration)

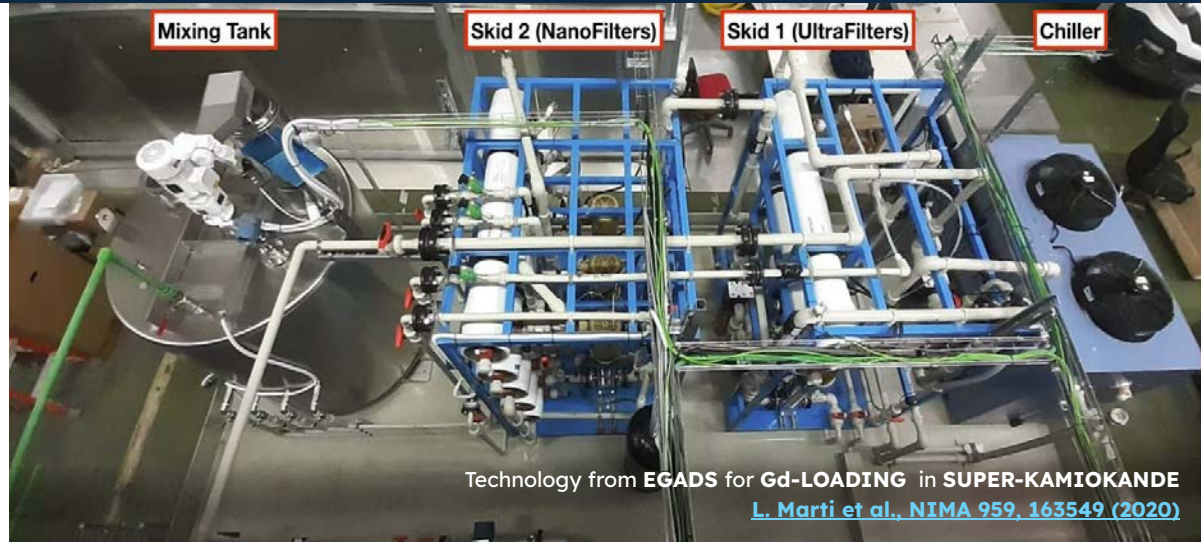
Gd-LOADED WATER

REMOVE impurities while
MAINTAINING Gd dissolved in water
exploiting **NANOFILTRATION**

NEED DEDICATED PLANT

- **INJECTION**
- **PURIFICATION**
- **RECIRCULATION**

Commissioned during **SRO+1**



Technology from **EGADS** for **Gd-LOADING** in **SUPER-KAMIOKANDE**
[L. Marti et al., NIMA 959, 163549 \(2020\)](#)

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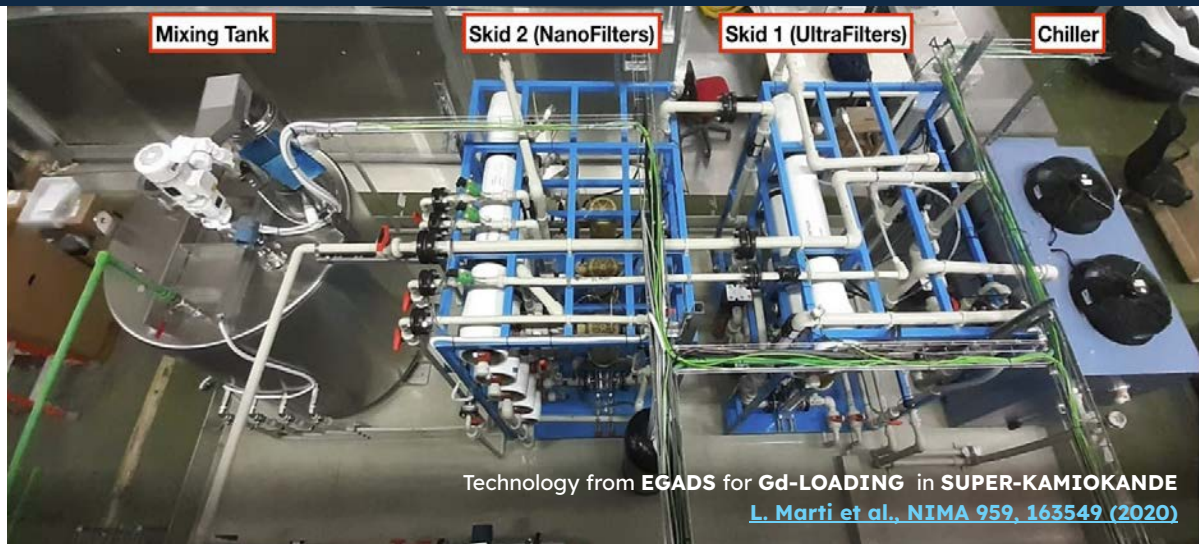
- **INJECTION**
- **PURIFICATION**
- **RECIRCULATION**

Commissioned during **SR0+1**

GADOLINIUM SULFATE Octahydrate
 $\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O}$ (**GdSO**)

inserted in steps during **SR2** data taking

0.02% Gd MASS CONCENTRATION
→ 500 ppm (350 kg) **GdSO**



Technology from **EGADS** for **Gd-LOADING** in **SUPER-KAMIOKANDE**
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NEUTRON CALIBRATION WITH AmBe

$^{241}\text{AmBe}$ SOURCE
CLOSE TO
CRYOSTAT (1 cm)

Events with **SAME** characteristics as
RADIOGENIC neutrons inducing NRs in
TPC and then **exiting** the cryostat



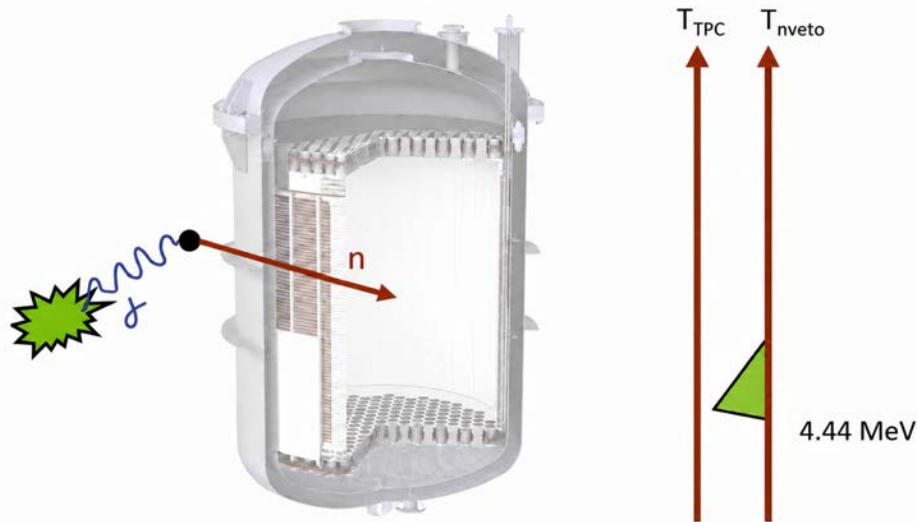
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PROMPT 4.4 MeV PHOTONS emitted with **NEUTRONS** (50% of cases) and **DETECTED** in NV act as triggers



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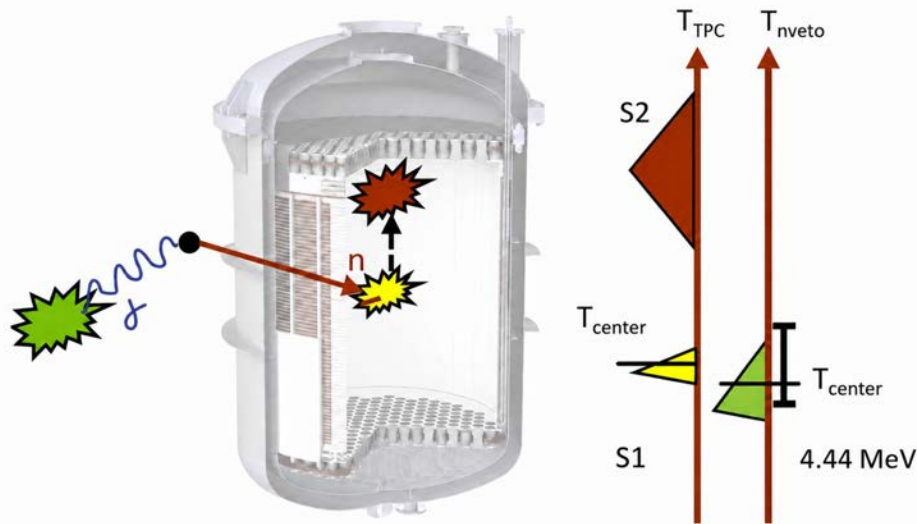
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COINCIDENT NR EVENTS selected in TPC within
100 ns provide a clean neutron selection



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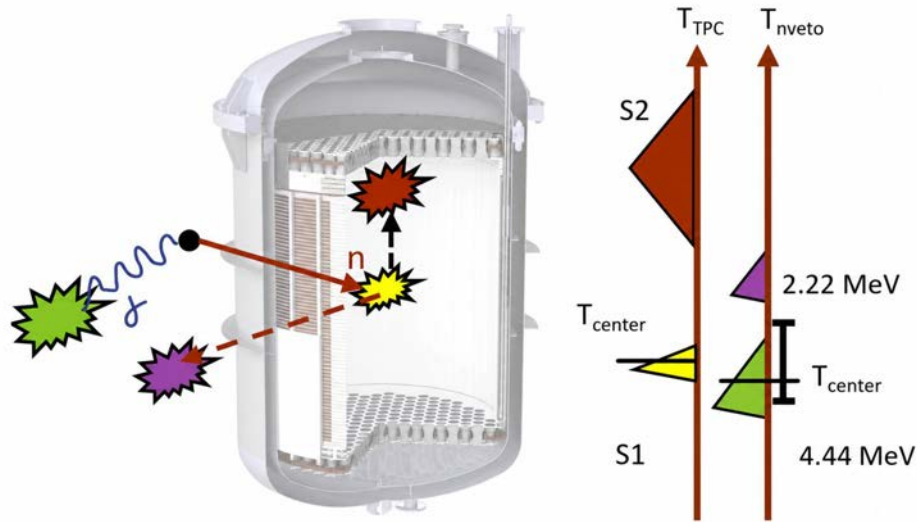
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NEUTRON CAPTURE signals searched in NV
within **O(1) ms** from NR in TPC to evaluate detector
performance



CALIBRATION CAMPAIGNS

- 0 ppm (pre-SR2)
- 50 ppm (insertion phase)
- 500 ppm (early SR2)
- 500 ppm (late SR2)

NEUTRON CAPTURES IN NV

**TIME
DIFFERENCE**
between NV
and TPC
signals

SHORTER CAPTURE TIME

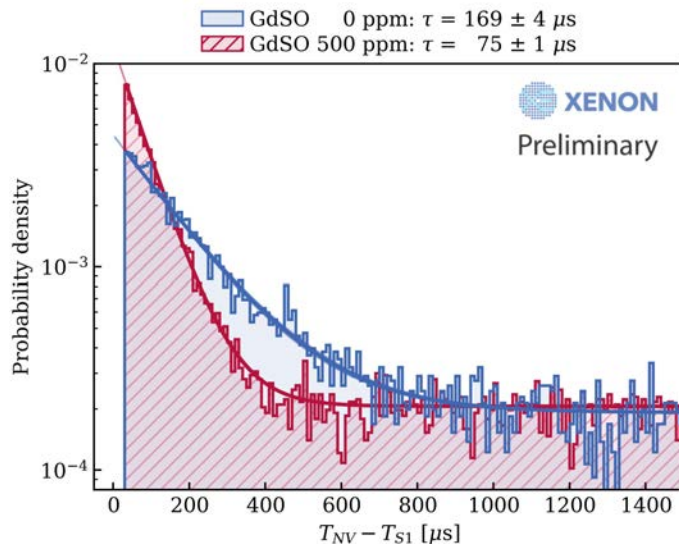
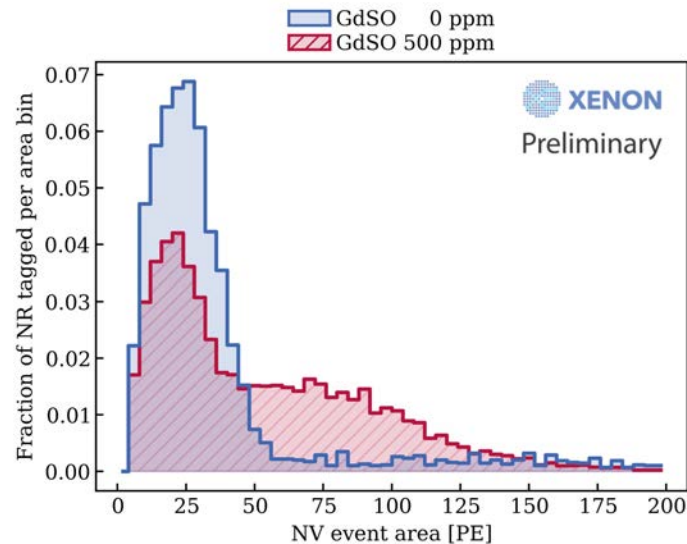
At 500 PPM GdSO, more than
factor 2 improvement:

169 μ s $\rightarrow$ 75 μ s

**NEUTRON
CAPTURE
AREA**
spectrum

LARGER SIGNAL AREA

- **H-CAPTURE** peak at ~ 20 PE
- **Gd-CAPTURE** peak at ~ 75 PE
- At 500 ppm, $\sim 60\%$ of capture on Gd



NEUTRON TAGGING EFFICIENCY

FRACTION of TPC NRs with detected **DELAYED NV SIGNAL** within fixed time **WINDOW**

NV events **THRESHOLD** and **TIME COINCIDENCE** chosen to maximize efficiency keeping **LOW** induced **DEADTIME** in TPC

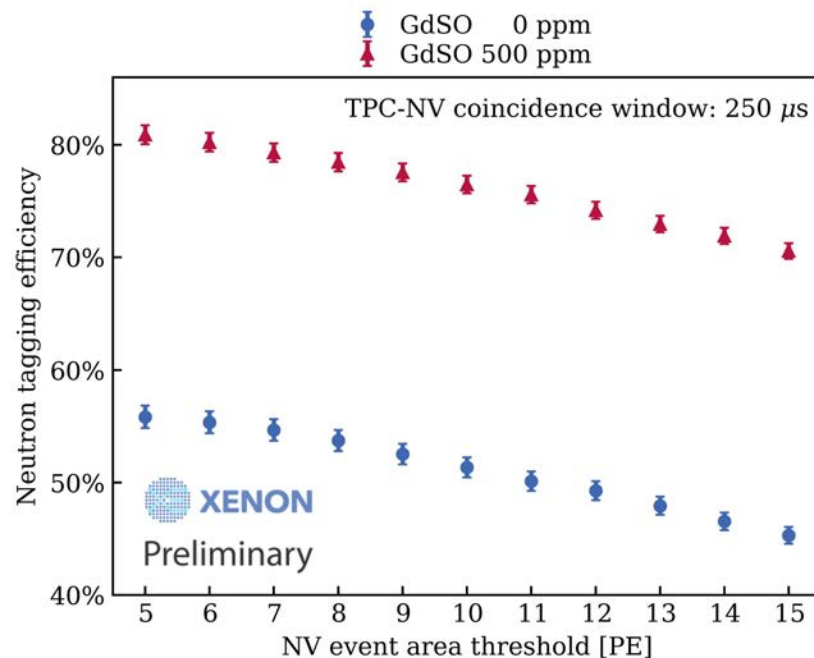
NV EVENT AREA: ≥ 5 PE
TIME WINDOW: 250 μ s

n-TAGGING EFFICIENCY:

55% $\rightarrow$ 81%

from 0 PPM to 500 PPM GdSO

NV-induced DEADTIME: 1.5%



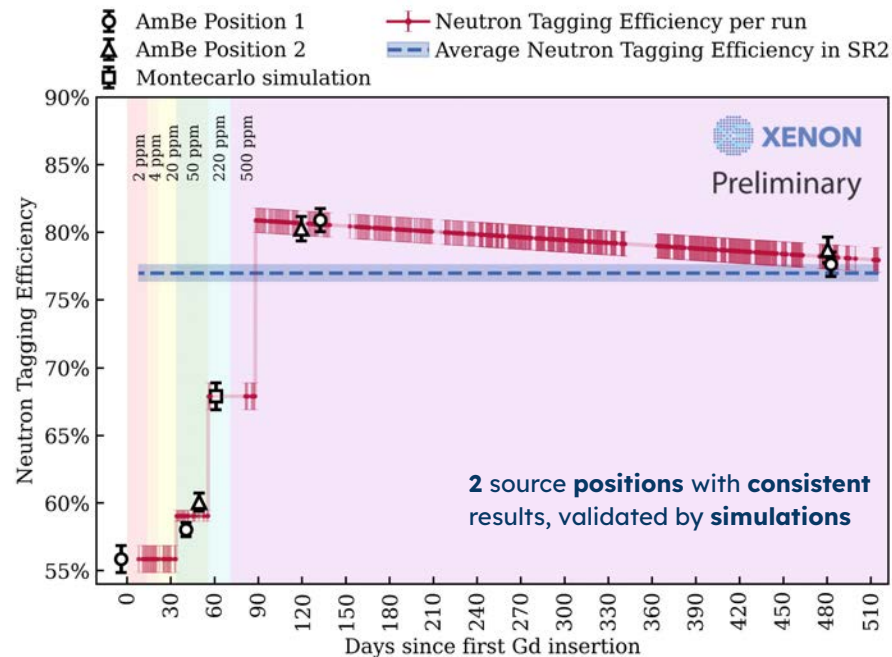
NEUTRON TAGGING EFFICIENCY IN SR2

INSERTION PHASE

significant efficiency
INCREASES in **STEPS**

500 PPM PHASE

slight decrease due to **NV OPTICAL
PROPERTIES** deterioration



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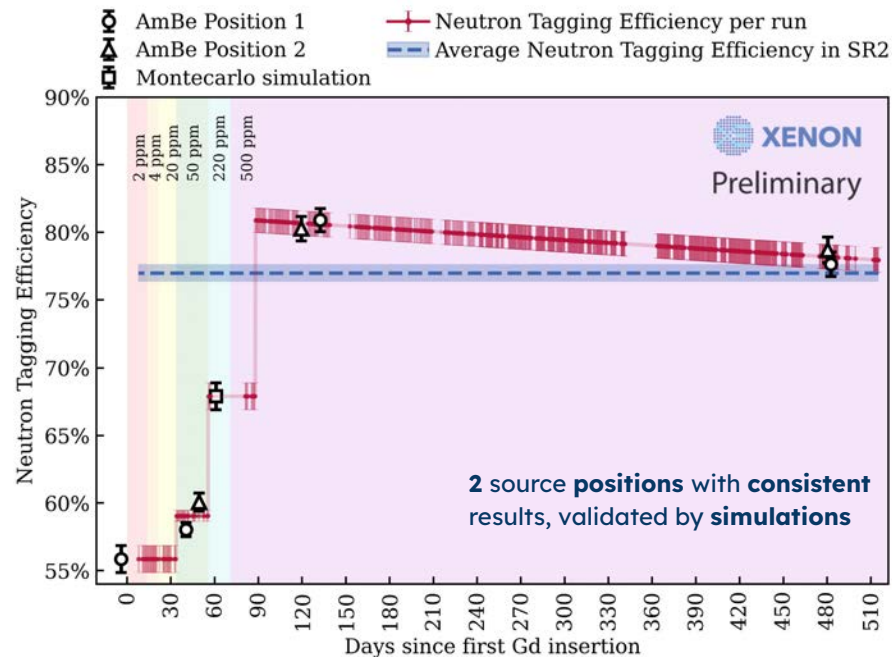
EFFICIENCY EVOLUTION

55% → 59% → 81% → 78%

pre SR2	50 ppm	500 ppm	500 ppm
		(early SR2)	(late SR2)

SR2 PERFORMANCE ESTIMATION

- **RUN-BY-RUN EFFICIENCY** obtained by **INTERPOLATION**
- **TIME-WEIGHTED** average



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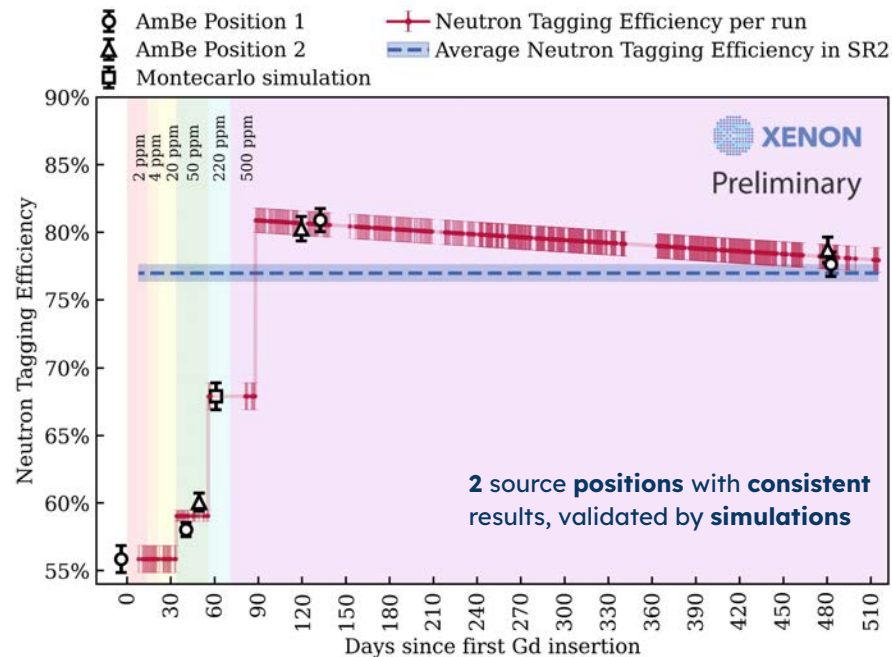
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AVERAGE TAGGING EFFICIENCY:

77 ± 1%

2x NEUTRON background **REDUCTION** in
SR2 compared to SR0+1

STATUS AND PERSPECTIVE

XENONnT 2025 UPGRADE

- NV **DISMOUNTED** during the 2025 **TPC UPGRADE**, reassembled in **2 MONTHS**
- **OPTICAL** properties **DETERIORATION** due to few **RUSTED** bolts (not stainless steel by accident) now **REPLACED**

DURING UPGRADE



AFTER UPGRADE



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CURRENT STATUS

PLANNED Gd IN SR3 : 0.2% in mass (3500 kg, 10x SR2)

➔ **~87% n-TAGGING EFFICIENCY**

ENHANCED WIMP SENSITIVITY with improved **ER/NR** discrimination and n-background **3x LOWER** than in **SRO+1**

Gd-WATER TECHNOLOGY VIABLE APPROACH FOR NEXT-GEN DETECTORS!

DURING UPGRADE



AFTER UPGRADE



FINAL INSIGHTS

Gd-WATER CHERENKOV NEUTRON VETO DESIGNED TO TAG RADIOGENIC NEUTRONS IN XENONnT

Gd-WATER PLANT NEEDED FOR INSERTION, PURIFICATION AND RECIRCULATION

IN SR2 WITH 0.02% Gd CONCENTRATION REACHED 77% NEUTRON TAGGING EFFICIENCY (53% IN SR0+1 WITH DEMI-WATER)

AFTER 2025 TPC UPGRADE, SR3 WITH 0.2% Gd CONCENTRATION TO REACH ~87% EFFICIENCY



¡Gracias por vuestra atención!

XENON OFFICIAL WEBSITE
www.xenonexperiment.org/

CONTACT XENON
xe-pr@lngs.infn.it



facebook.com/XENONexperiment/



instagram.com/xenon_experiment/



linkedin.com/company/xenon-experiment



More on XENONnT results:

- **New Dark Matter search results from XENONnT with combined science runs**
Maxime Pierre - 02/06/2026
- **Probing the neutrino fog with XENONnT**
Giovanni Volta - 02/06/2026
- **Rare Event Searches in the Electron Recoil Channel of the XENONnT Experiment**
Y.-T. Lin - 03/06/2026

@IDM 2026

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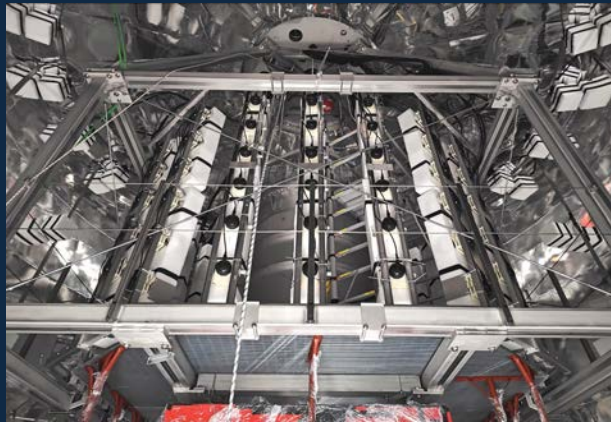
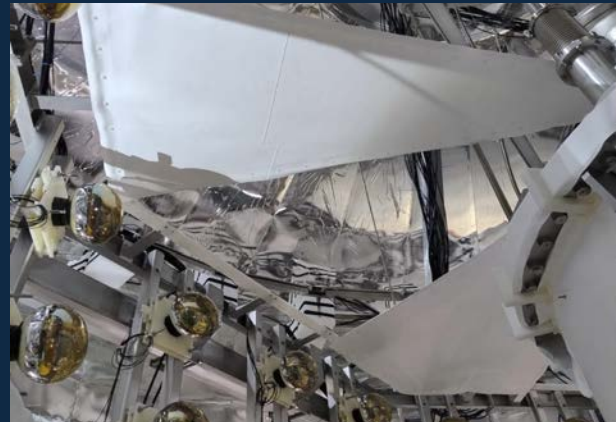
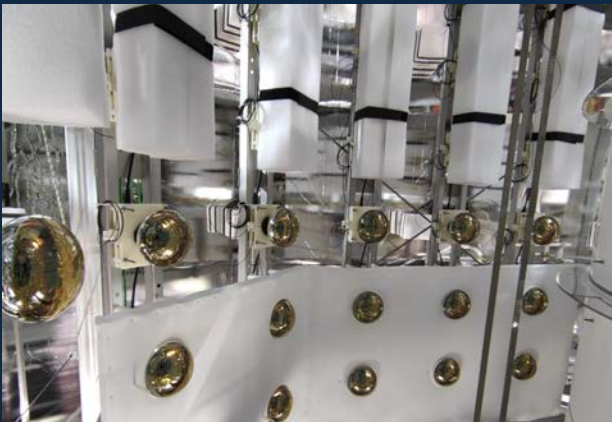
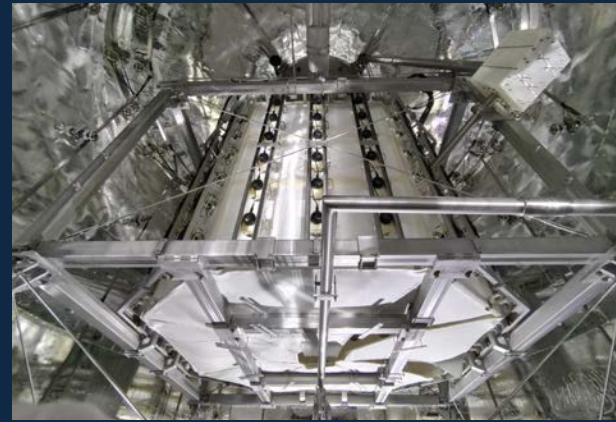


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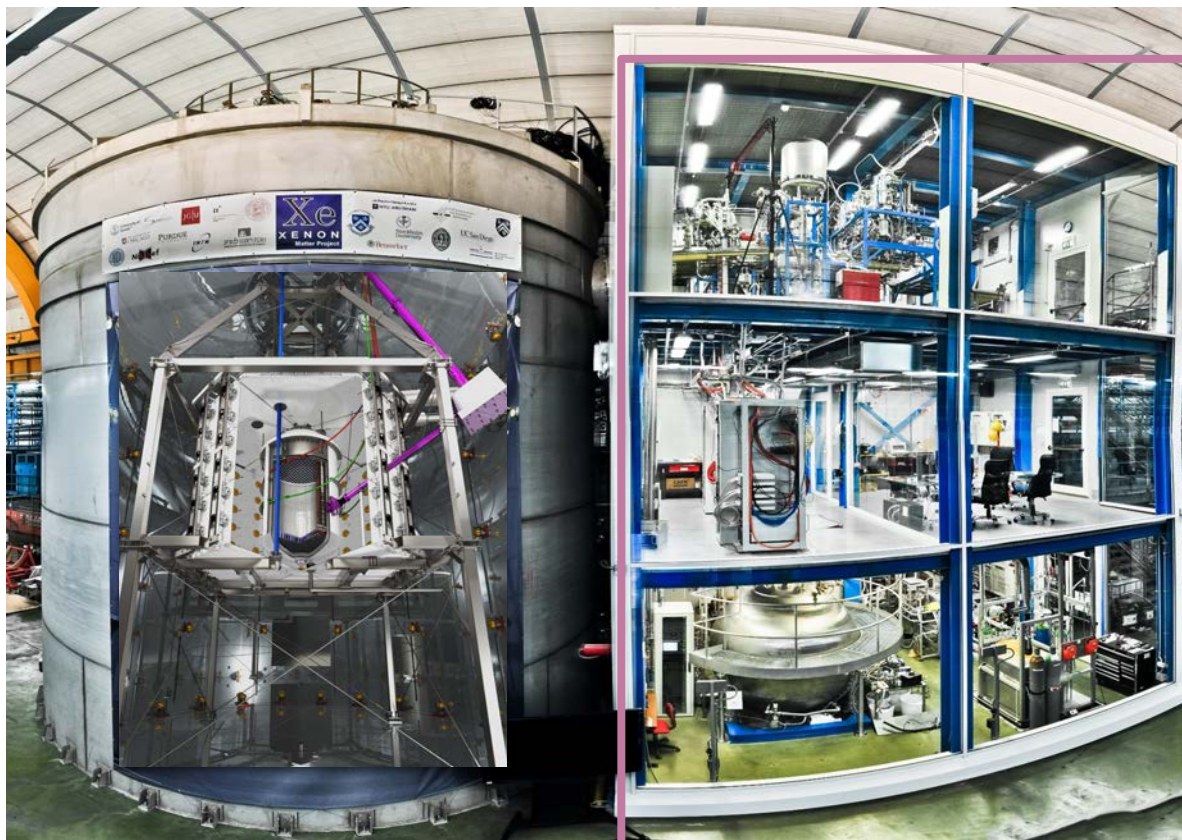


BACKUP
ВАСКОБ

NEUTRON VETO (RE)MOUNTING



XENON_nT EXPERIMENT



CRYOGENICS

GXe Purification
Calibration system

ELECTRONICS

Data Acquisition
Slow Control

RECOVERY & DISTILLATION

Kr Distillation Column
Rn Distillation Column
LXe Storage
LXe Purification

DUAL PHASE Xe TIME PROJECTION CHAMBER

Two detectable signals produced when a particle interact in LXe:

S1 Prompt scintillation in liquid xenon (LXe)

SCINTILLATION

S2 Secondary scintillation from **drifted electrons** in gaseous xenon (GXe)

IONIZATION

ENERGY RECONSTRUCTION

from combining **S1** and **S2** signals

3D POSITION RECONSTRUCTION

x-y (PMTs light pattern), z (drift time)

RECOIL TYPE

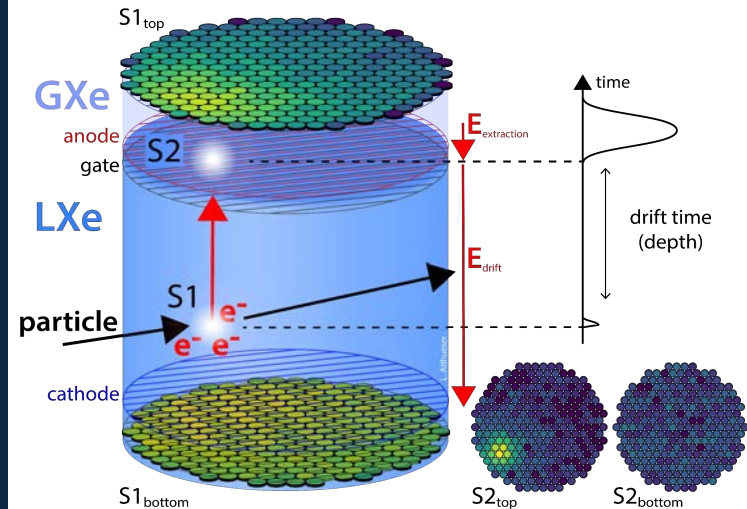
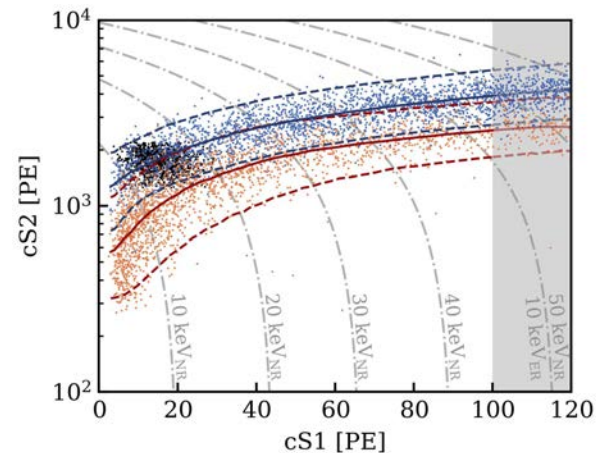
S2/S1 different for **Electronic Recoils (ER)** and **Nuclear Recoils (NR)**

ER

Electrons and photons from radioactivity, solar neutrinos (e^- elastic scattering), axions (?), dark photons (?) ...

NR

Neutrons, neutrinos (coherent elastic scattering off nuclei, CEvNS), WIMPs (?) ...



BACKGROUND IN XENONnT

Electronic Recoils:

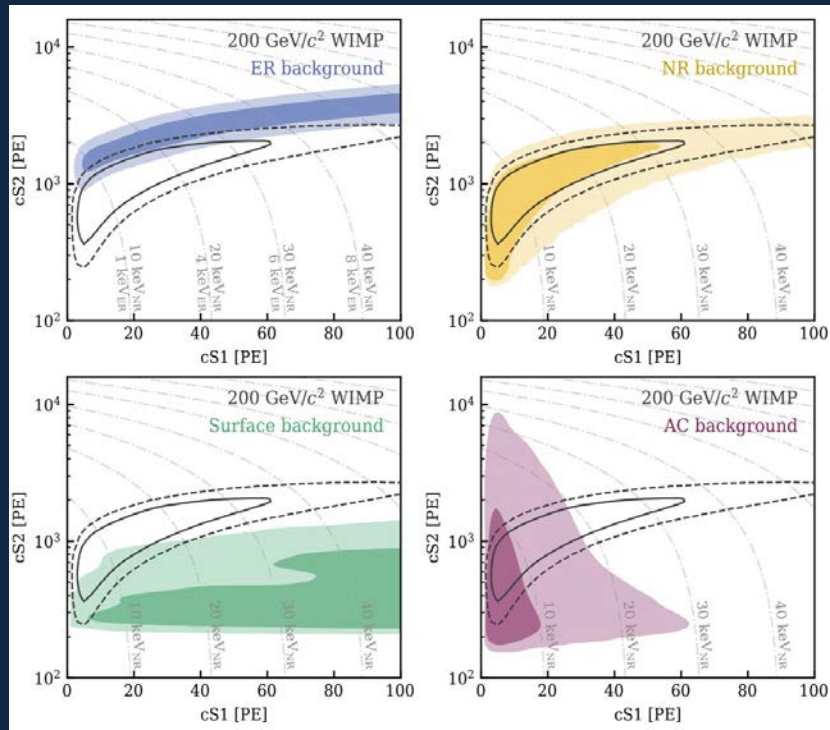
- ^{214}Pb from ^{222}Rn
- ^{85}Kr β -decays
- ^{124}Xe Double Electron Captures
- **solar-pp** $\nu - e$ elastic scattering

Modelled with ^{220}Rn calibration data and spectrum in $[20,140] \text{ keV}_{\text{ER}}$

Surface:

- ^{210}Pb (^{226}Ra chain) from **PTFE walls** due to plate-out effect

Suppressed by **fiducial volume** selection



[Phys.Rev.D 111 \(2025\) 6, 062006](#)

Nuclear recoils:

- **Radiogenic neutrons** from materials
- Solar or atmospheric **neutrinos** via **CEvNS**

Neutrons suppressed by **Neutron Veto** and **multi-scatter** events rejection

Accidental Coincidence (AC):

- Accidental pairing of isolated **S1-S2**

Removed by dedicated **machine-learning** based cuts

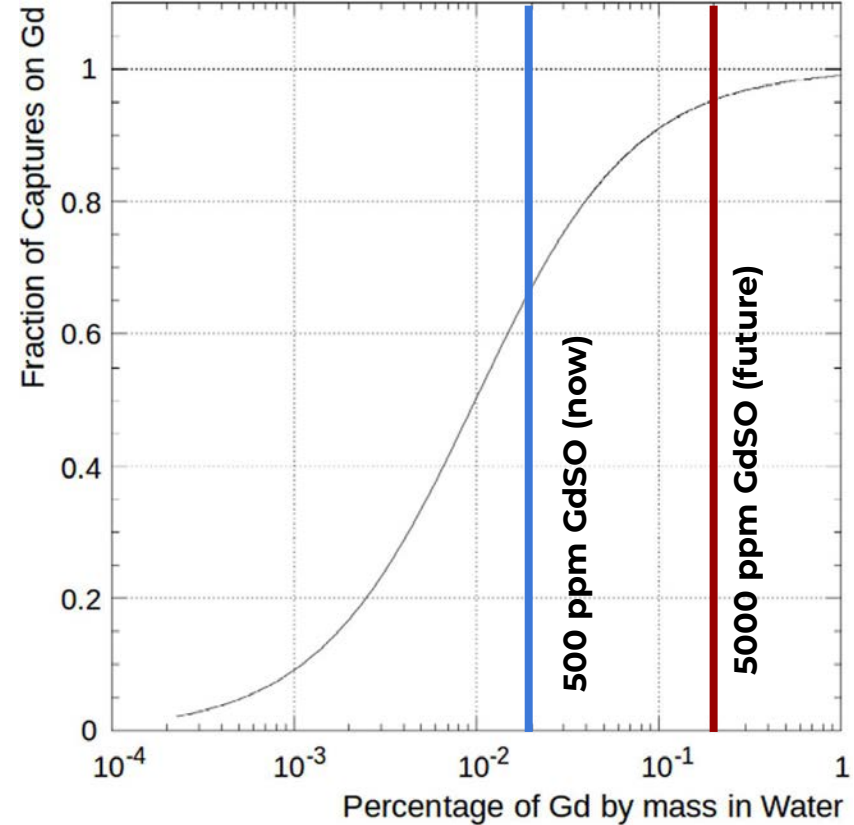
N-CAPTURE VS Gd-CONCENTRATION

Fraction of **neutrons** captured on **Gd** as a function of its **concentration** in water by **mass**

Currently, nVeto doped with **500 ppm GdSO** (**0.02% Gd mass** concentration), **tagging efficiency** increased up to **77%**,

Planned **XENONnT** nVeto with **3.5 t** of **GdSO** (**0.5% of GdSO, 0.2 % Gd mass concentration**), with **tagging efficiency** of **87%**

[L. Marti et al., NIMA 959, 163549 \(2020\)](#)



Gd-WATER PURIFICATION SYSTEM

PURE WATER ONLY

DEIONIZATION
via ION-EXCHANGE
RESINS
(+ particle filtration)

Gd-LOADED WATER

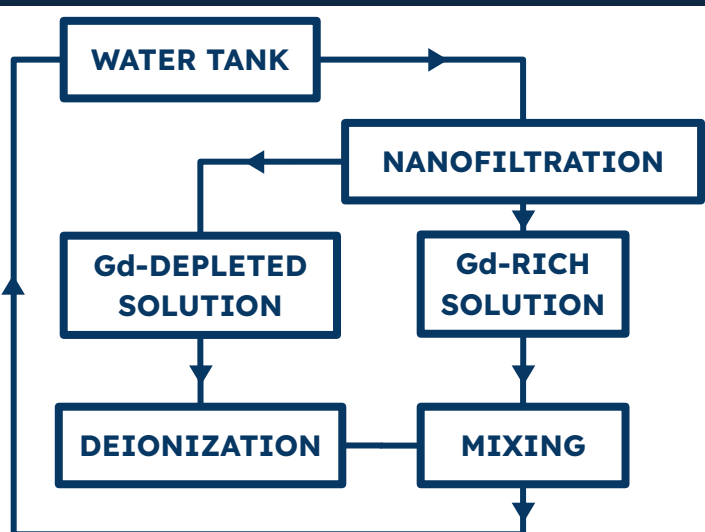
CHALLENGE
REMOVE impurities while
MAINTAINING Gd
dissolved in water

NEED DEDICATED PLANT

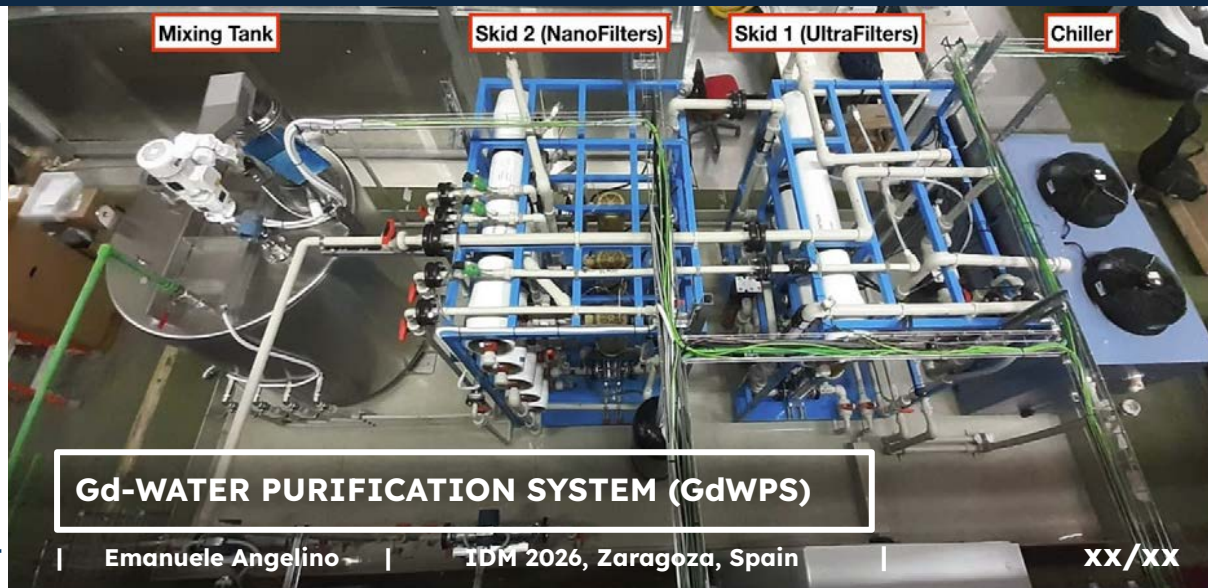
- INJECTION
- PURIFICATION
- RECIRCULATION

Commissioned during SR0+1

Developed with
technology from EGADS
for Gd-LOADING in
SUPER-KAMIOKANDE
[L. Marti et al., NIMA](#)
[959, 163549 \(2020\)](#)



Gd-loaded water Cherenkov Neutron Veto of XENONnT



Gd-WATER PURIFICATION SYSTEM (GdWPS)

Gd INSERTION

GADOLINIUM SULFATE
Octahydrate
 $\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O}$ (GdSO)

INSERTION
AT SR2
BEGINNING
(October 2023)

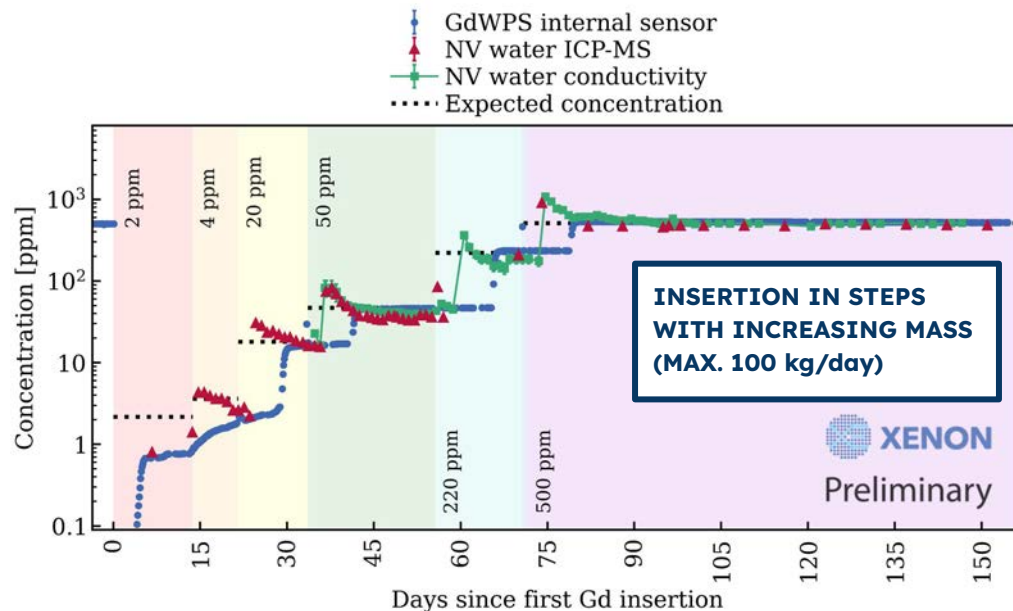
OPERATIONS performed smoothly during
SCIENCE DATA taking

REACHED 0.02% Gd MASS
CONCENTRATION

→ 500 ppm (350 kg) GdSO

Gd CONCENTRATION MONITORING

- **MASS SPECTROSCOPY** (offline, ICP-MS at Chemistry Lab)
- **CONDUCTIVITY** of water samples (offline, in situ)
- **GdWPS** conductivity **SENSORS** (online)



NEUTRON VETO OPTICAL MONITORING

Reflectivity Monitor (RM) and Diffuser Balls (DB) to monitor the optical performance of the NV:

- **RM:** 4 optical fibers pointing upward and downward, connected to a **375 nm** laser.
- **DB:** 4 quartz bulbs, providing **isotropic** light, illuminated by **448 nm** laser pulses.

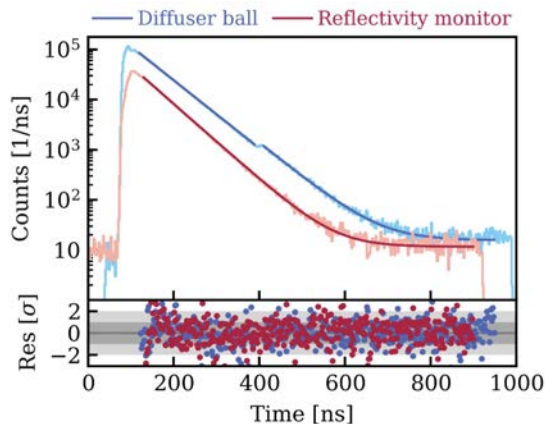
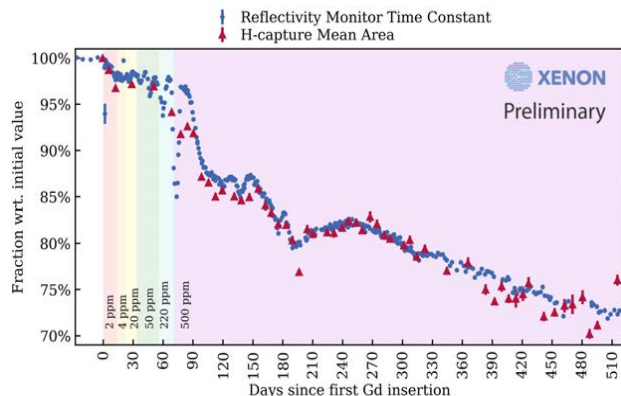
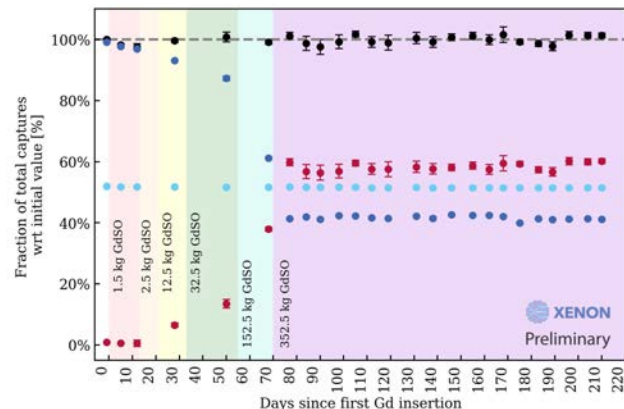
Time constants (τ) of the **arrival time** of **photons** determined by **optical** and **geometrical** properties of NV
Before Gd-sulfate insertion stable at 57 ns (RM) and 64 ns (DB).

AmBe calibration source far from cryostat (50 cm) to characterize NV:

- **2.2 MeV peak (H capture) → 1 Gaussian** with threshold
- **4.4 MeV peak (^{12}C de-excitation) → 1 Gaussian** with threshold
- **About 8 MeV peak (Gd capture) → 2 Gaussians** with threshold
- **High energy tail (higher level ^{12}C de-excitations or n captures on ^{56}Fe) → 2 Gaussians**

Mean area and amplitude correspond to mean collected light (that depends on **NV optical properties**) and **neutron captures**

About 60% of captures occurs on Gd. Given the large water buffer in this source position, total number of n-capture not changed with Gd



NEUTRON VETO OPTICAL BEHAVIOUR

Regular monitoring during SR2 of detector medium with:

**REFLECTIVITY
MONITOR**

PULSED LIGHT (375 nm)
probing photon
PROPAGATION TIME in NV

AmBe NEUTRON SOURCE
in NV center (50 cm from TPC)

2.2 MeV H-CAPTURE peak to
track **LIGHT COLLECTION
EFFICIENCY**

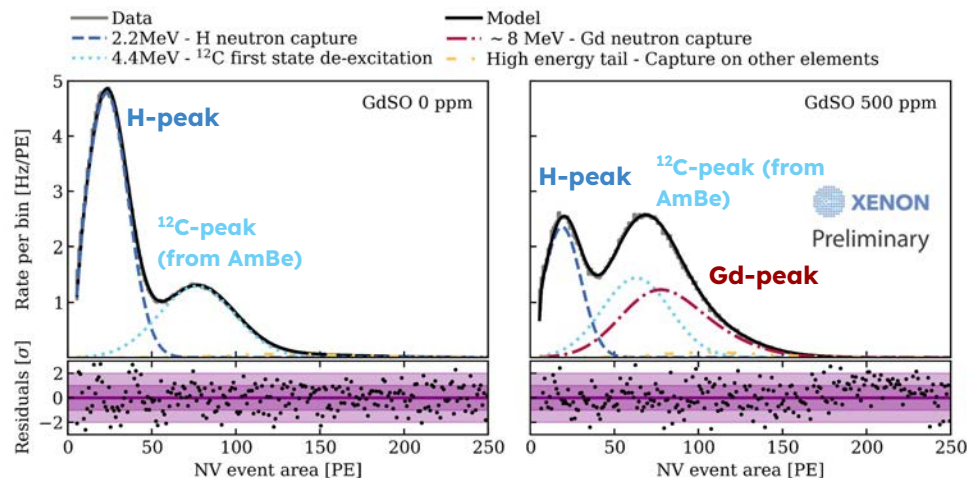
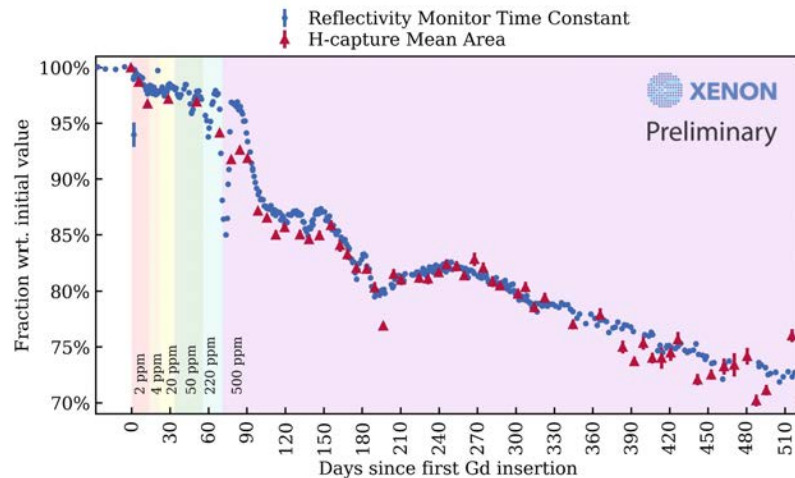
**OPTICAL
DEGRADATION**

After Gd insertion,
observables down to
70-75% wrt initial
value

During 2025 TPC upgrade found

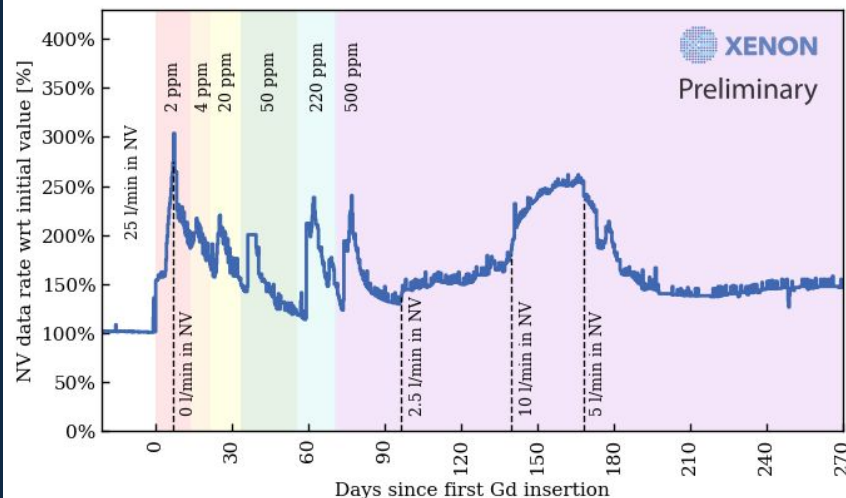
FEW RUSTED BOLTS
non-stainless steel (by accident)

caused deterioration of ePTFE
panels' **REFLECTIVITY**
→ **LESS COLLECTED LIGHT**



NEUTRON VETO RATE

- Raw NV DAQ rate increased after GdSO insertions
- Rate decreased as the system approached equilibrium
- Linked to concentration / flow transients
- Rate changes follow Gd concentration variations, not absolute concentration
- Increase mostly from single- or few-photon signals
- Likely weak light emission related to dissolved Gd and flow/concentration changes
- Suppressed by standard NV selection
- No impact on neutron-tagging performance
- Origin still under dedicated investigation



NEUTRON VETO IN SRO

Neutron background originated mostly from **PMTs**, **cryostat** and **PTFE** components

Signals in **TPC** can be attributed to **neutrons** from detector materials if, **differently** from **WIMPs**, **multiple-site** energy deposit occurred (**multiple scatter**)

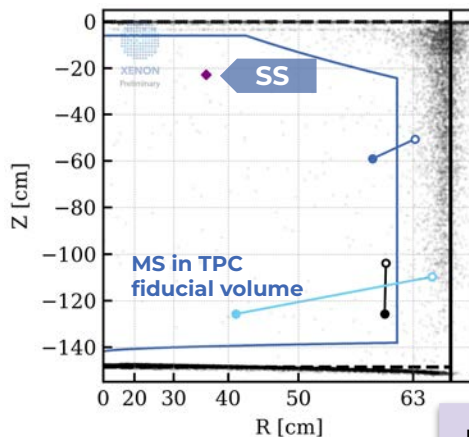
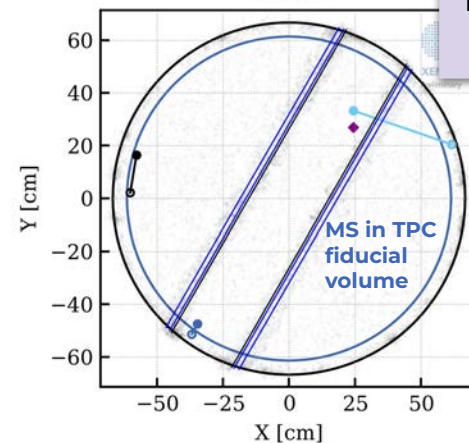
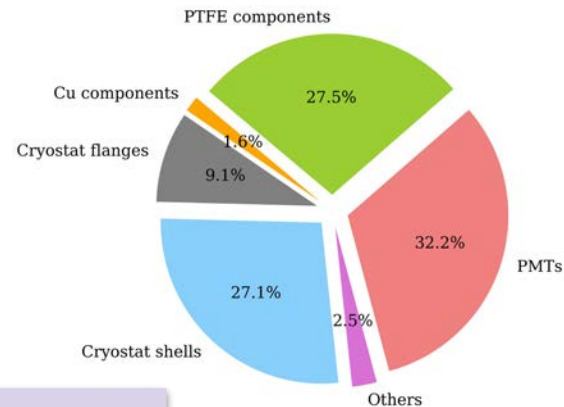
4 events in the **WIMP blinded** region tagged by **NV** and excluded: **3 multiple scatter (MS)** + **1 single scatter (SS)**

In **agreement** with **MS/SS** ratio of about **2.5** obtained from MC and AmBe calibration data

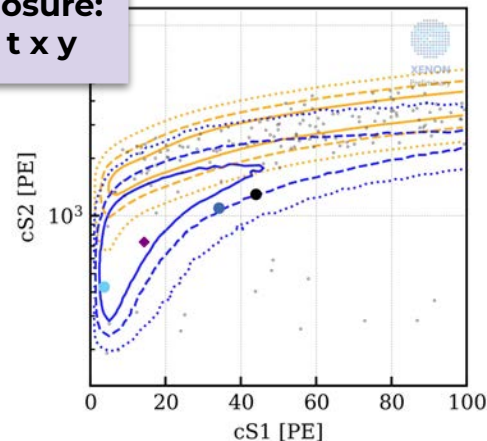
Considering **NV tagging efficiency** of **53%**, the **total neutron expectation** is $1.1^{+0.6}_{-0.5}$ events

This result is **6x higher** than **predictions** from **material screening** (ongoing **checks** to understand the discrepancy)

In SRO, NV had relevant role in **constraining** this specific **background** in a **data-driven** way

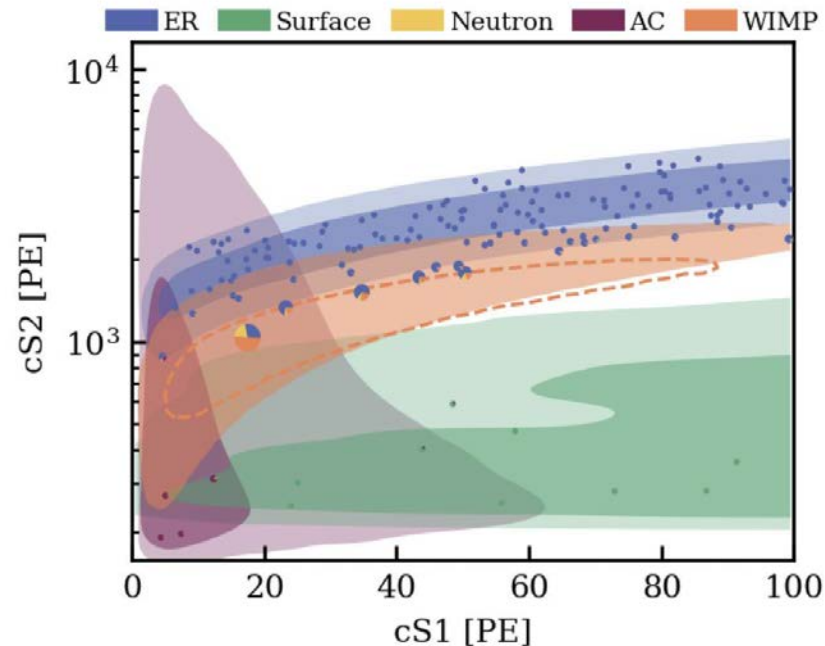


Exposure:
1.1 t x y



WIMP SEARCH IN SRO

- **152 events** in NR/ER search region
- **16** in NR **blinded** region
- **No significant excess**
- **Best fit** assuming a **200 GeV/c² WIMP** and $\sigma = 2.5 \times 10^{-47} \text{ cm}^2$



4.4 †
fiducial
volume

1.1 † x y
exposure

Pie-chart:

Event showing the **fraction** of the **best-fit PDF** for a **200 GeV** mass **WIMP** (assuming there are WIMPs)

Signal-like region:

containing 50% of a 200 GeV/c² WIMP signal with highest signal-to-noise ratio

	Nominal	Best fit	
	ROI	Signal-like	
ER	134	135^{+12}_{-11}	0.92 ± 0.08
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.16
CEνNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.006
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	0.32 ± 0.06
Surface	14 ± 3	12 ± 2	0.35 ± 0.07
Total background	154	152 ± 12	$2.03^{+0.17}_{-0.15}$
WIMP	...	2.6	1.3
Observed	...	152	3

WIMP SEARCH IN SRO + SR1

BLIND ANALYSIS for SR1:

- ^{222}Rn activity $< 1\text{uBq/kg}$ with Radon Removal System in high-flow mode
- longer exposure

SR1a:

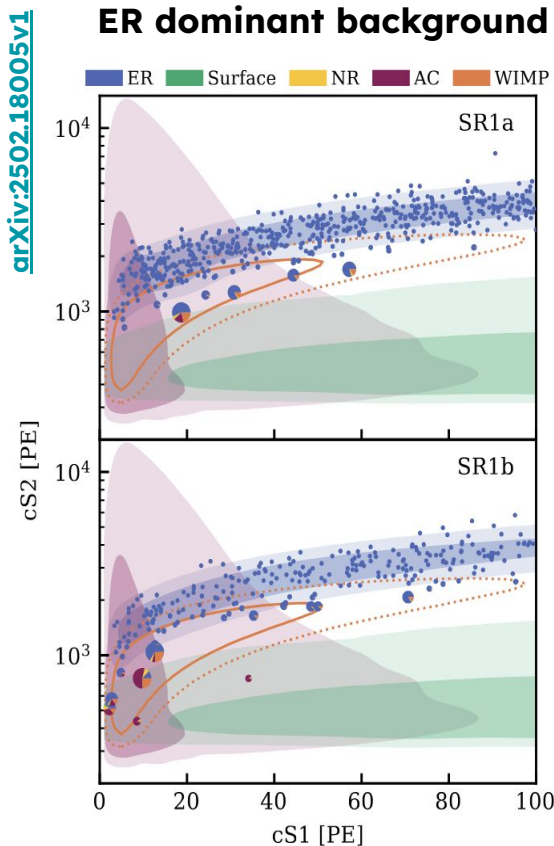
- higher ER rate from ^{85}Kr , ^{37}Ar , ^3H

SR1b:

- low ^{85}Kr , ^{37}Ar after cryogenic distillation
- ^3H still present

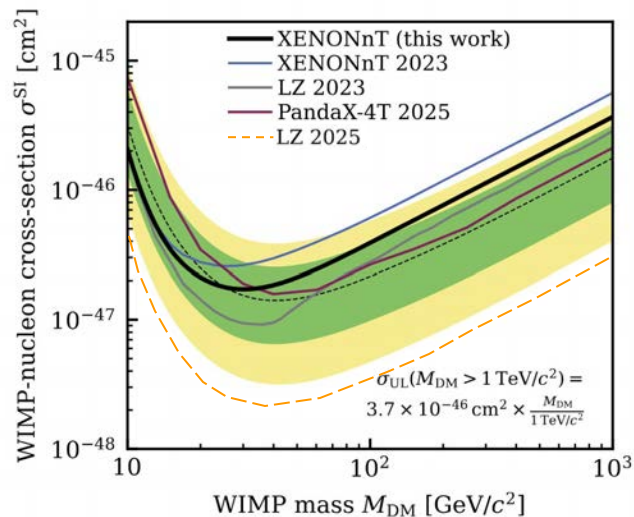
RE-ANALYSIS for SRO:

- Updated neutron background model



NO EXCESS OVER BACKGROUND

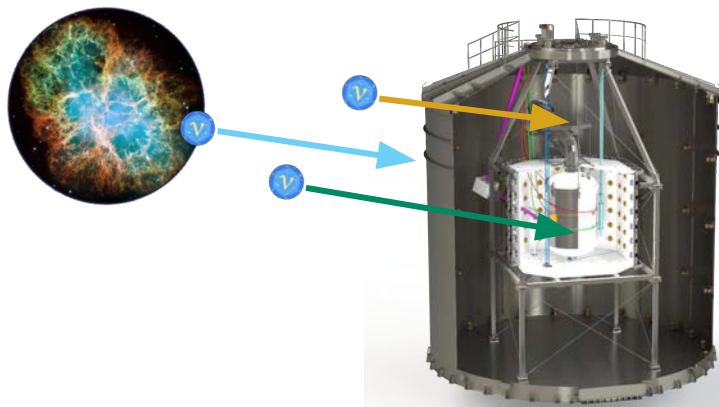
New limits on WIMP-nucleon cross section: $1.7 \times 10^{-47} \text{ cm}^2$ @ 30 GeV/c^2
factor 1.8 improvement wrt SRO:



WIMP SEARCH EVENTS IN SR0+SR1

	SR0		SR1a		SR1b	
	Nominal	Best fit	Nominal	Best fit	Nominal	Best fit
ER (flat)	134	136 ± 12	430 ± 30	450 ± 20	151 ± 11	154 ± 10
ER (^3H -like)	—	—	62	40 ± 30	101	80^{+18}_{-17}
ER (^{37}Ar)	—	—	58 ± 6	55 ± 5	—	—
Neutron	0.7 ± 0.3	0.6 ± 0.3	0.47 ± 0.19	0.45 ± 0.19	0.7 ± 0.3	0.7 ± 0.3
CE ν NS (solar)	0.16 ± 0.05	0.16 ± 0.05	0.010 ± 0.003	0.010 ± 0.003	0.019 ± 0.006	0.019 ± 0.006
CE ν NS (atm.+DSNB)	0.04 ± 0.02	0.04 ± 0.02	0.024 ± 0.012	0.024 ± 0.012	0.05 ± 0.02	0.05 ± 0.02
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	2.12 ± 0.18	2.10 ± 0.18	3.8 ± 0.3	3.8 ± 0.3
Surface	13 ± 3	11 ± 2	0.43 ± 0.05	0.42 ± 0.05	0.77 ± 0.09	0.76 ± 0.09
Total background	152	152 ± 12	553	550 ± 20	257	239 ± 15
WIMP (200 GeV/ c^2)	—	1.8	—	1.1	—	2.1
Observed	152		560		245	

SUPERNOVA NEUTRINO



SUPERNOVA NEUTRINO CHANNELS IN XENONnT

→ **TPC**, 6 t of LXe

$\nu_{e, \mu, \tau}, \bar{\nu}_{e, \mu, \tau}$ via **CEvNS** (charged and other neutral current are subdominant)

~ **100 expected** events from supernova at 10 kpc

→ **MUON & NEUTRON VETO**, 700 t ultra-pure water

$\bar{\nu}_e$ via **inverse beta** decay with H

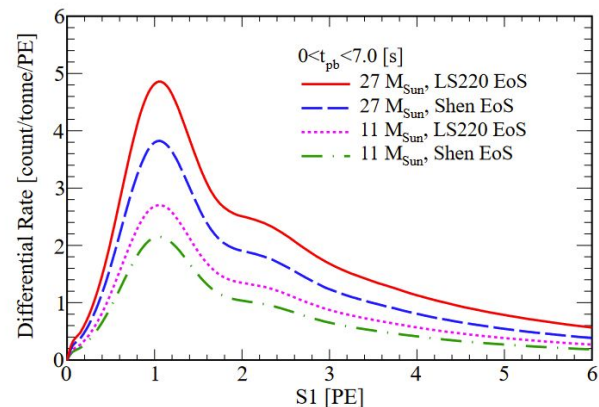
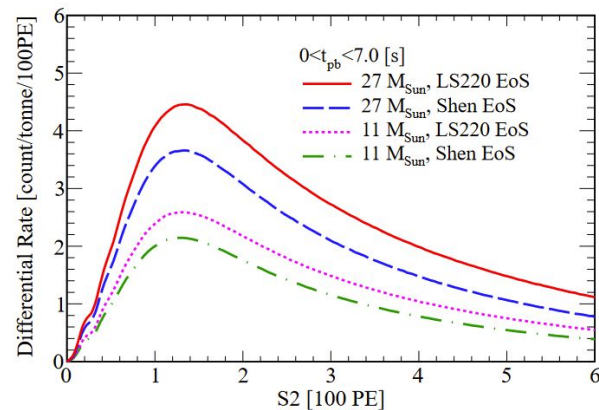
~ **70 - 200 expected** events from supernova at 10 kpc

PREDICTIONS IN XENONnT

Neutrinos deposit
around **O(1) keV**
in LXe

Background
stable in time,
can be reduced
with **specific**
selection (similar
to ^8B search)

Possible
improvements
using **coincident**
signals from
vetos



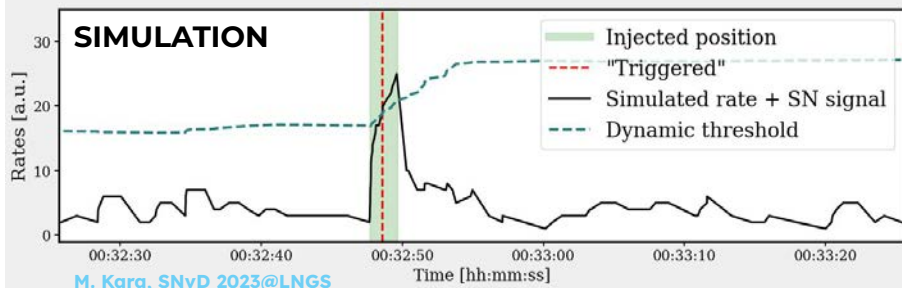
SUPERNOVA NEUTRINO

SENSITIVITY PROJECTIONS

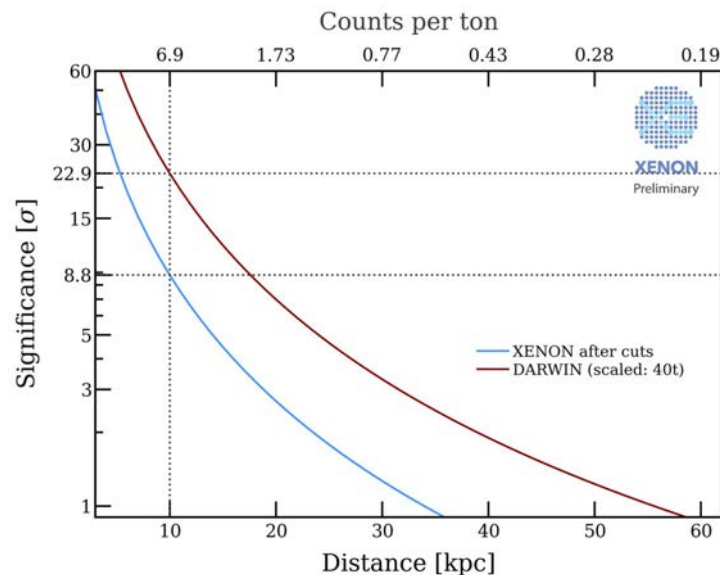
Cuts can **reduce background** down to **~ 3 Hz**, while **average signal** (SN at **10 kpc**) will result in **~ 45 events** in **~ 6 s** (~ 18 background events)

Triggerless DAQ allows **continuous** data taking and **increases in rate** with respect to a **dynamic threshold** can be monitored online

Considering signal evolution, time **window** can be **optimized**, resulting in **$\sim 8\sigma$ significance** (10 kpc)



M. Kara, SNvD 2023@LNGS



SNEWS INTEGRATION

XENONnT is **ready** to join the **Supernova Early Warning System (SNEWS)**

It will **receive** incoming **alerts** to check data and **send** possible **supernova observations**



THE END