First Results from XENONnT on Solar CEνNS

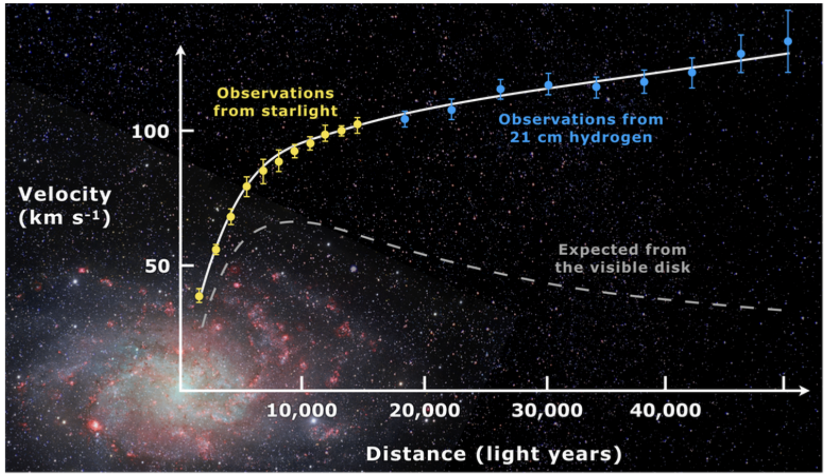
DMLab, 17 october 2024

Quentin Pellegrini

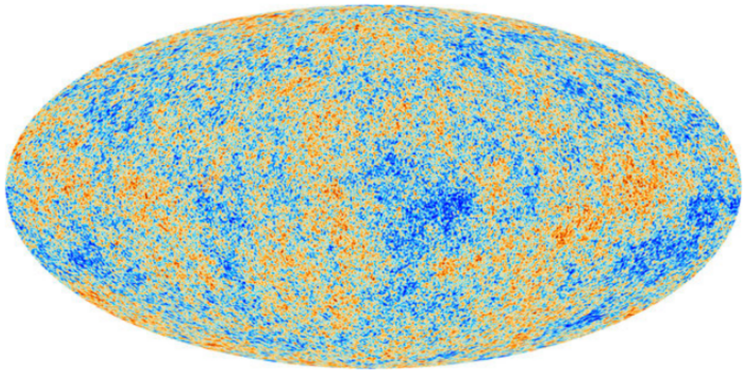
The XENON Program

XENON

M31 galaxy rotation curves

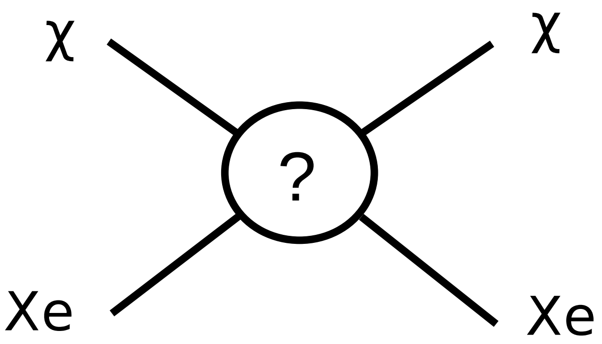


Planck CMB power spectrum of temperature anisotropy



XENONnT
2020–2027

⇒ DM makes up of **26.8%** of total mass-energy content of the universe

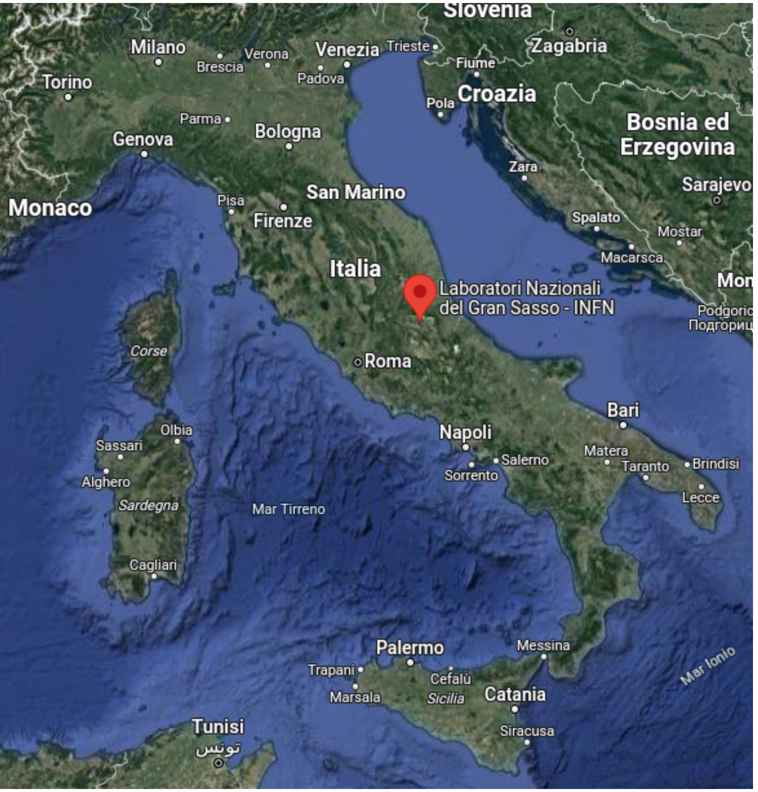


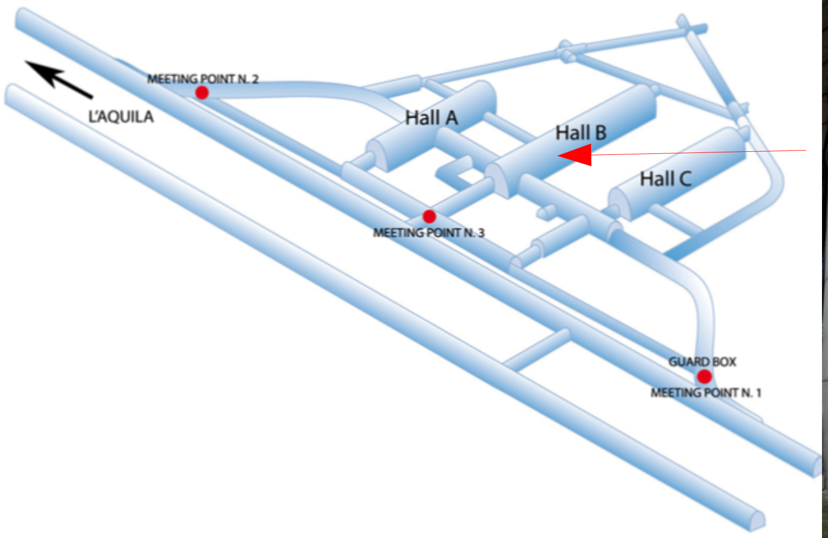
Direct dark matter detection
Weakly Interactive Massive Particle (WIMP or χ)

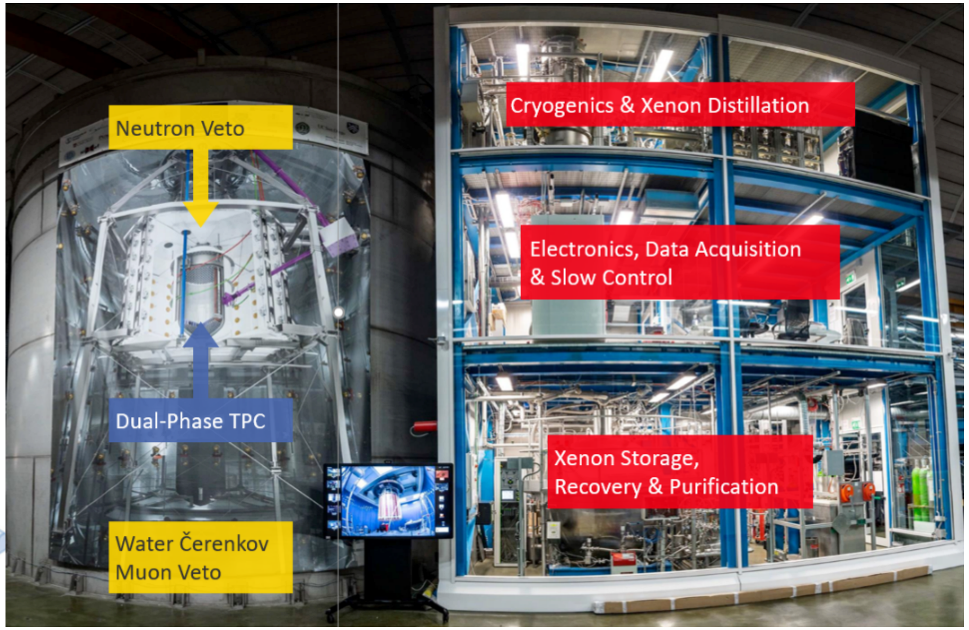
XENON collaboration

- 200+ scientists
- 29 institutions
- 12 countries

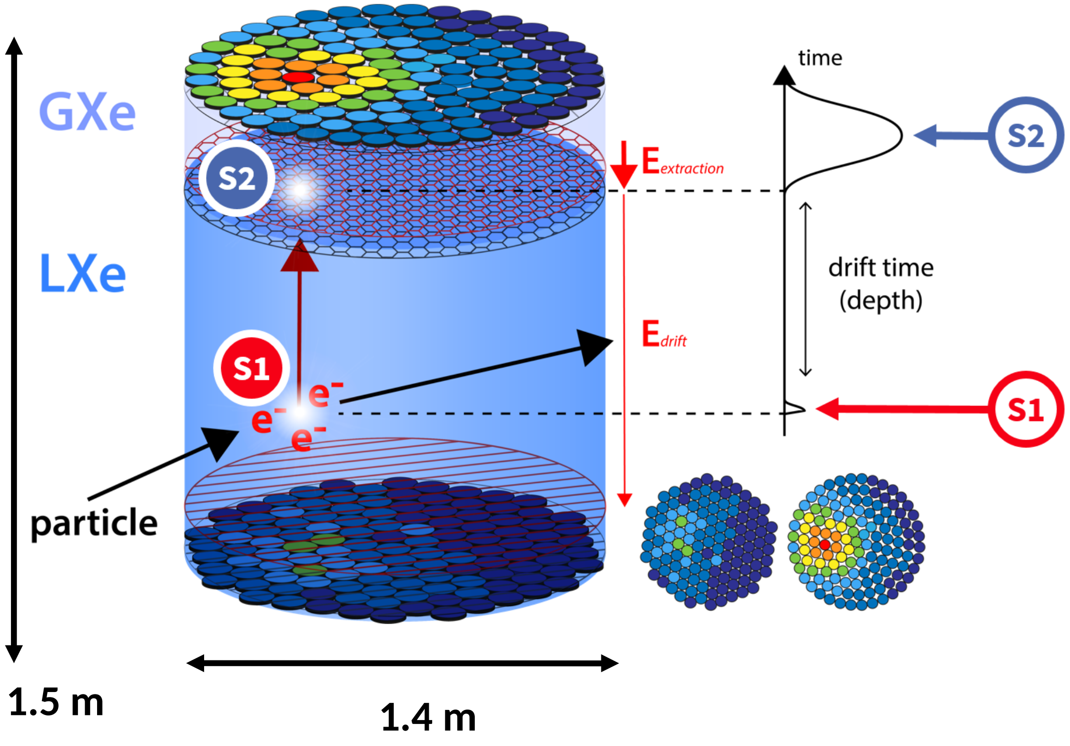
XENONnT


Slovenia
Milano
Verona
Brescia
Venezia
Trieste
Padova
Zagabria
Fiume
Torino
Pola
Croazia
Parma
Bologna
Genova
Bosnia ed Erzegovina
Zara
Sarajevo
Pisa
San Marino
Monaco
Firenze
Spalato
Mostar
Macarsca
Italia
Laboratori Nazionali del Gran Sasso - INFN
Podgorica
Corse
Roma
Bari
Olbia
Napoli
Sassari
Salerno
Matera
Taranto
Brindisi
Alghero
Sorrento
Lecce
Sardegna
Mar Tirreno
Cagliari
Palermo
Messina
Trapani
Cefalù
Marsala
Sicilia
Catania
Mar Ionio
Siracusa
Tunisi
تونس


MEETING POINT N. 2
L'AQUILA
Hall A
Hall B
Hall C
MEETING POINT N. 3
GUARD BOX
MEETING POINT N. 1


Neutron Veto
Cryogenics & Xenon Distillation
Electronics, Data Acquisition & Slow Control
Dual-Phase TPC
Xenon Storage, Recovery & Purification
Water Čerenkov Muon Veto

Detection principle



Dual Phase Time Projection Chamber (TPC)

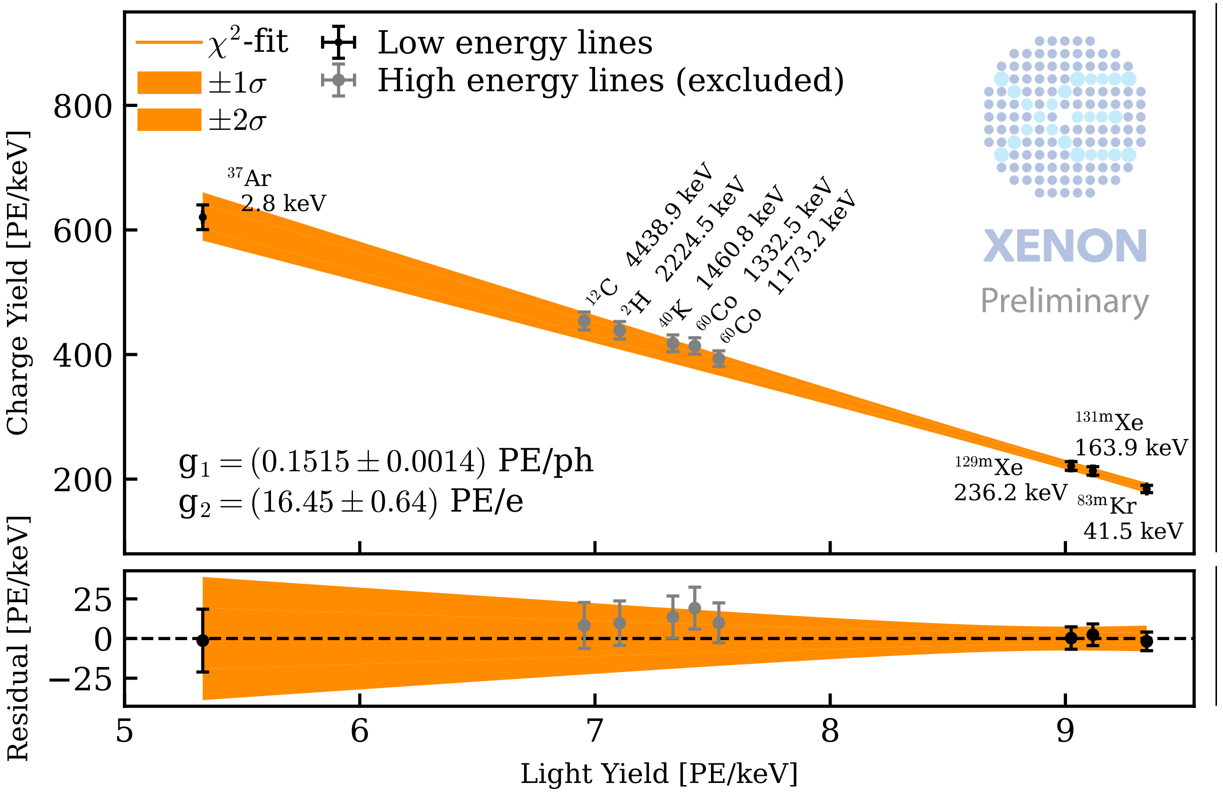
Position Reconstruction

- z → Drift time = t(S2) – t(S1)
- x, y → S2 signal

Energy Reconstruction

$$E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right) \qquad \frac{S2}{E} = -\frac{g_2}{g_1}\frac{S1}{E} + \frac{g_2}{W}$$

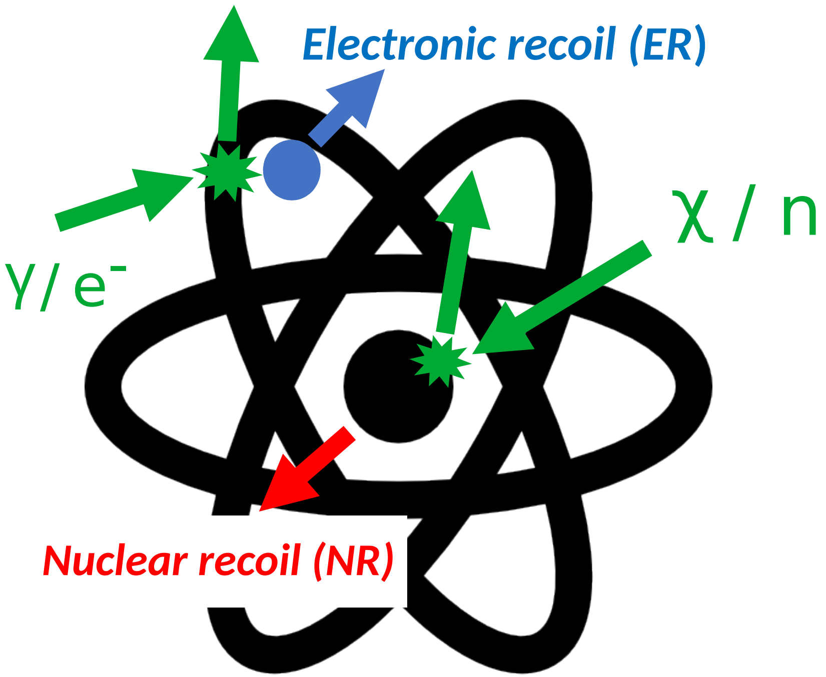
Mean quantum energy (13.5 eV) — *Detector gain constants* — *Charge Yield* — *Light Yield*



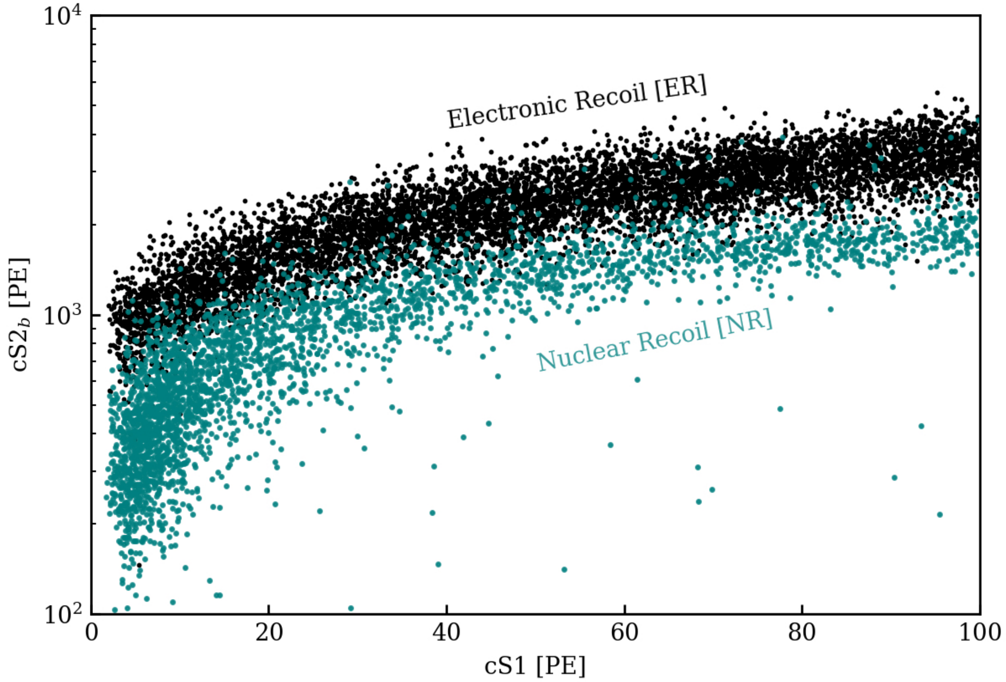
Detector gain constants fit

Particle discrimination

Weakly Interacting Massive Particle (WIMP or χ)
Solar Coherent Elastic Neutrino Nucleus Scattering (Solar CEvNS)

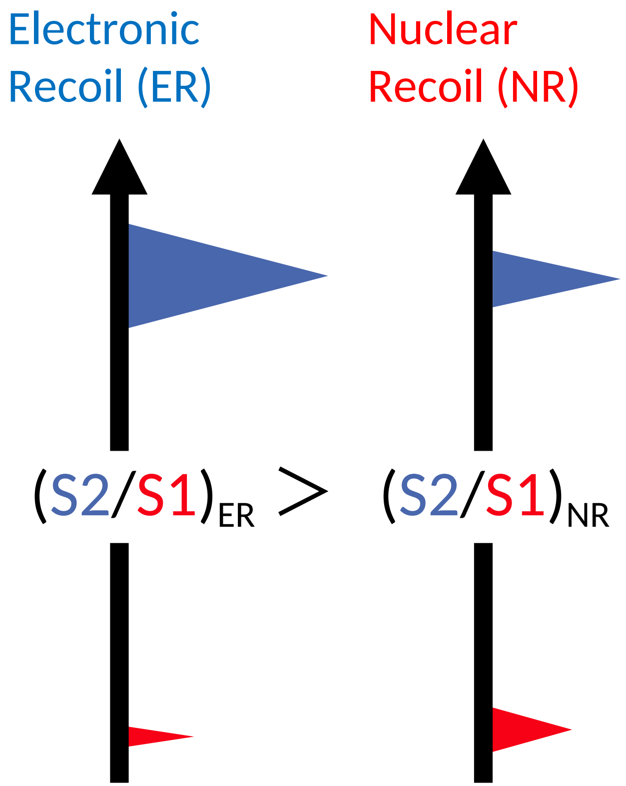


Liquid Xenon



WIMP
Solar CEvNS

ER

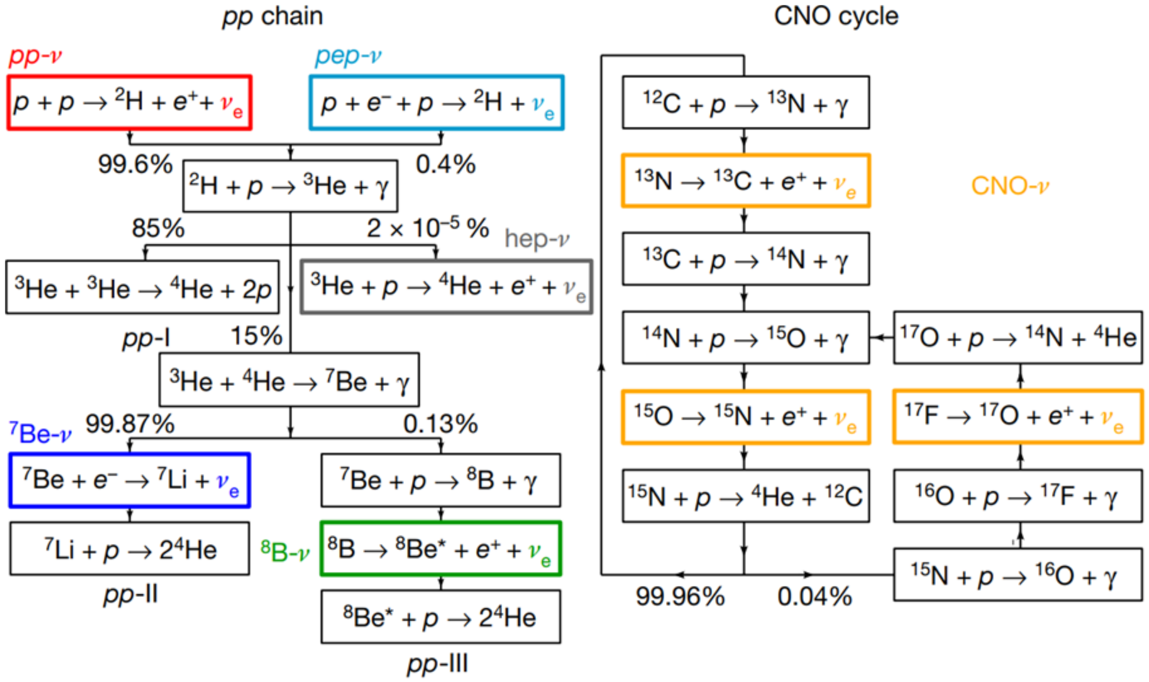


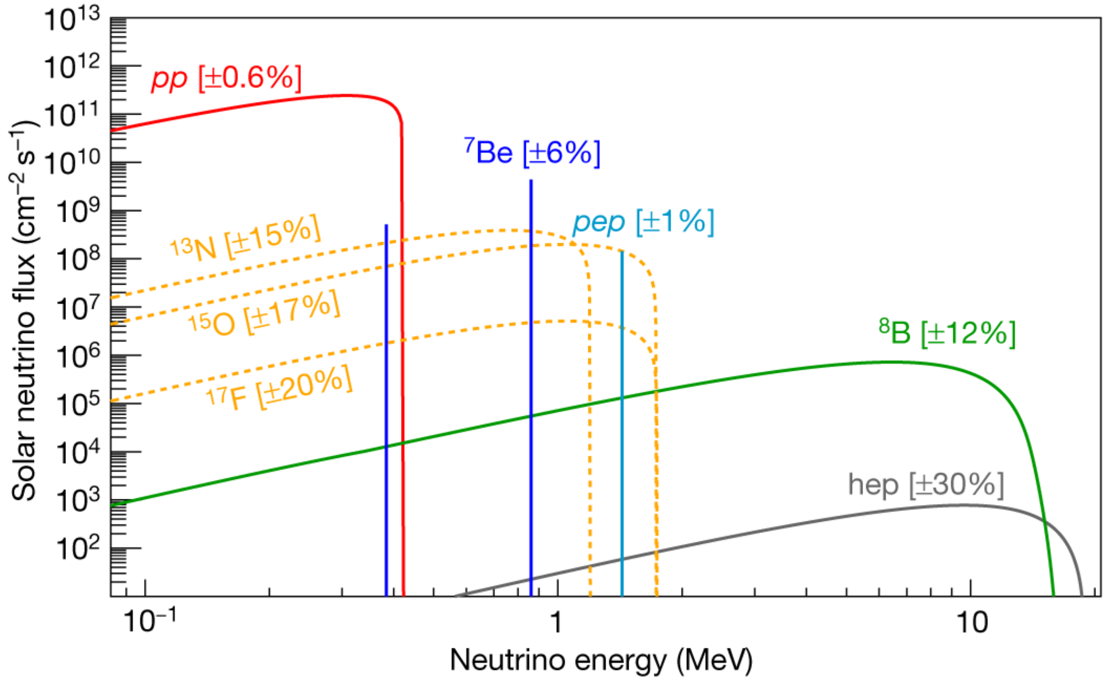
Solar neutrinos fluxes

XENON

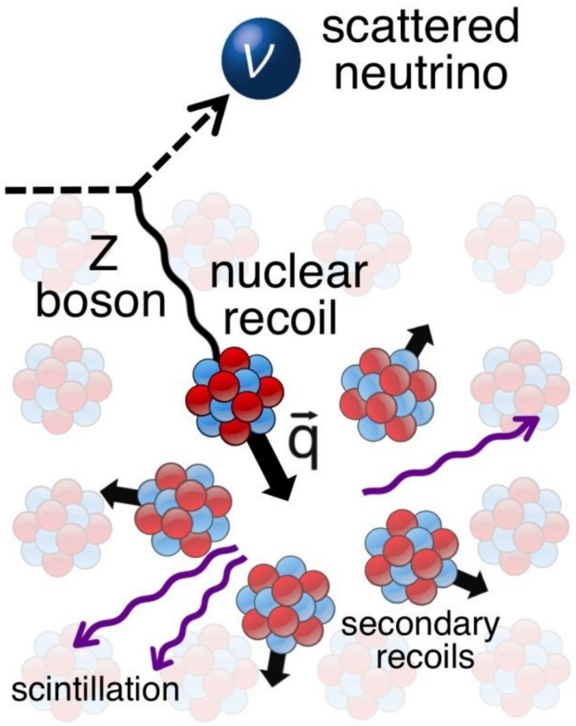
Nuclear reaction chains in solar core

$$4\,\mathrm{H}^{+} + 2\,\mathrm{e}^{-} \rightarrow {}^{4}\mathrm{He}^{2+} + \boxed{2\,\nu_e}$$





What is Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

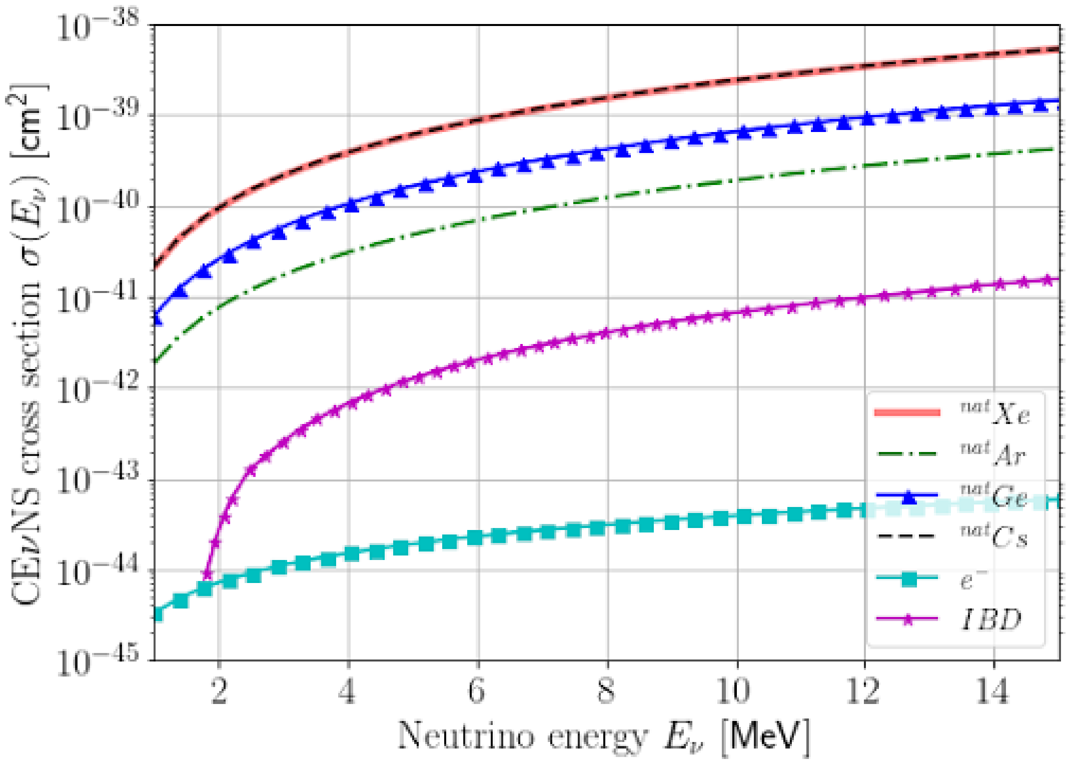


Standard Model Process

Coherence condition : qR< 1
Low-energy neutrinos (< 100 MeV)

$$\sigma_{CE\nu NS} \propto \mathrm{N}^2$$

Low-energy NR events



First observation of CEvNS at 6.7σ by COHERENT in 2017 at the Spallation Neutron Source (SNS)

COHERENT collaboration, D. Akimov et al., Observation of Coherent Elastic Neutrino-Nucleus Scattering, Science (2017) , [1708.01294]

XENONnT aims to detect world first astrophysical CEvNS signal

Solar neutrinos and DM experiments

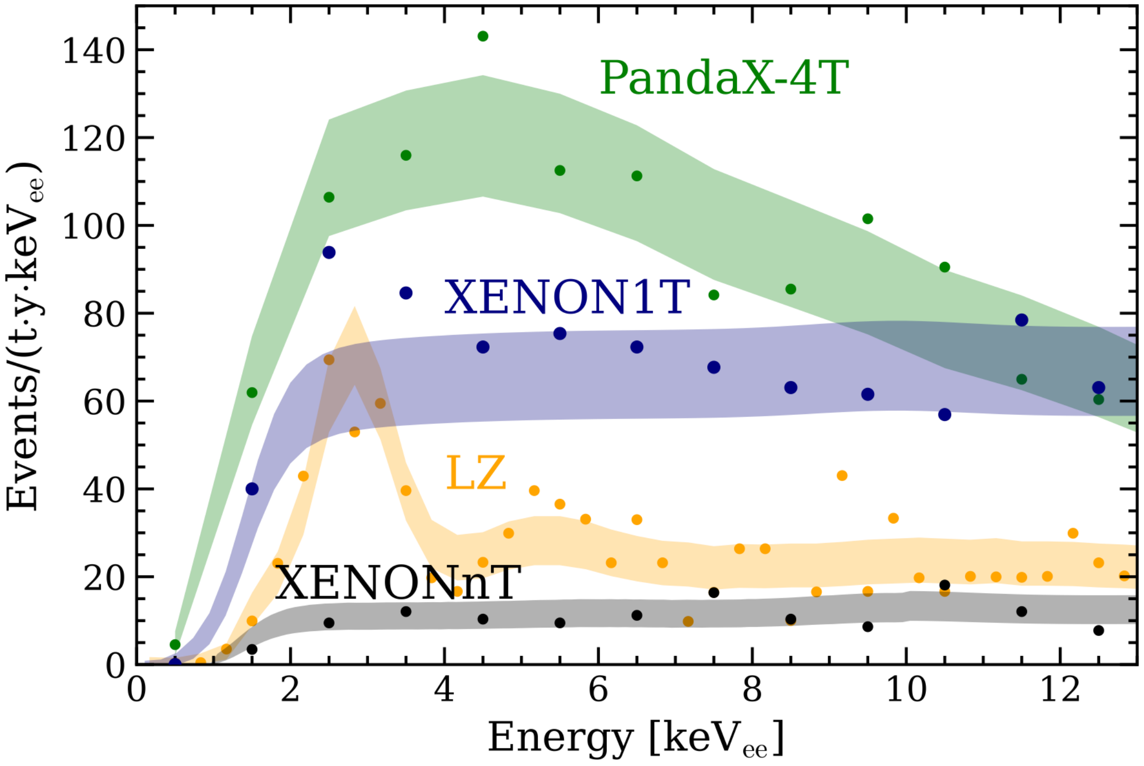
XENON

In LXe TPC experiments, Solar neutrinos interact mainly in two ways :

- Elastic electron scattering (ES) ⟶ ER signal
- Elastic coherent neutrino-nucleus scattering (CEνNS) ⟶ NR signal

Irreducible background for DM direct search

XENONnT ER study



Lowest ER background in low-energy region

Solar ES is the third most important background

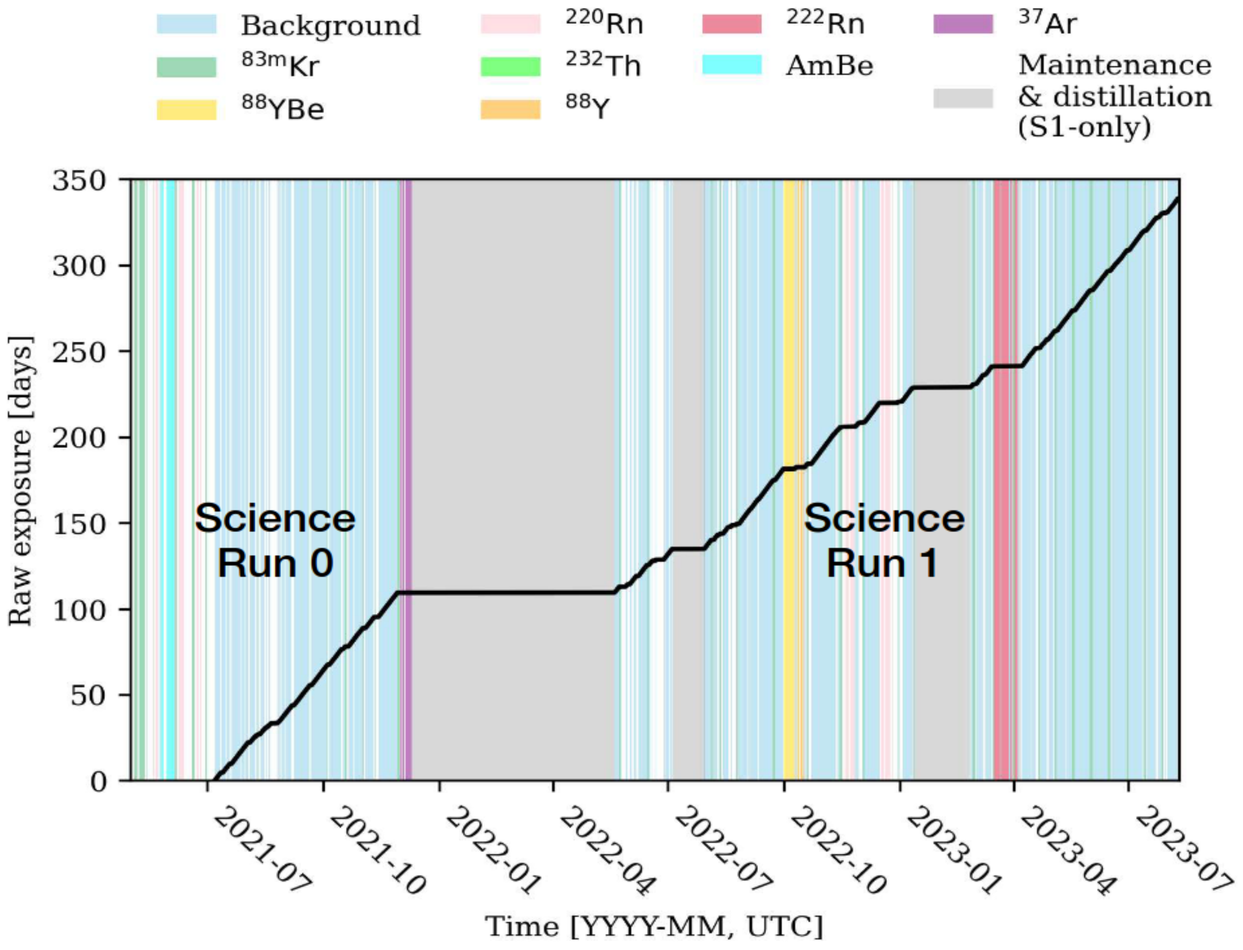
⟹ Solar pp Neutrino Elastic Electron Scattering Study

Potential improvement of solar neutrinos properties (PP flux, Pee, Weinberg angle, etc)

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

Science Runs

XENON



SR2 ongoing

Blind Analysis

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

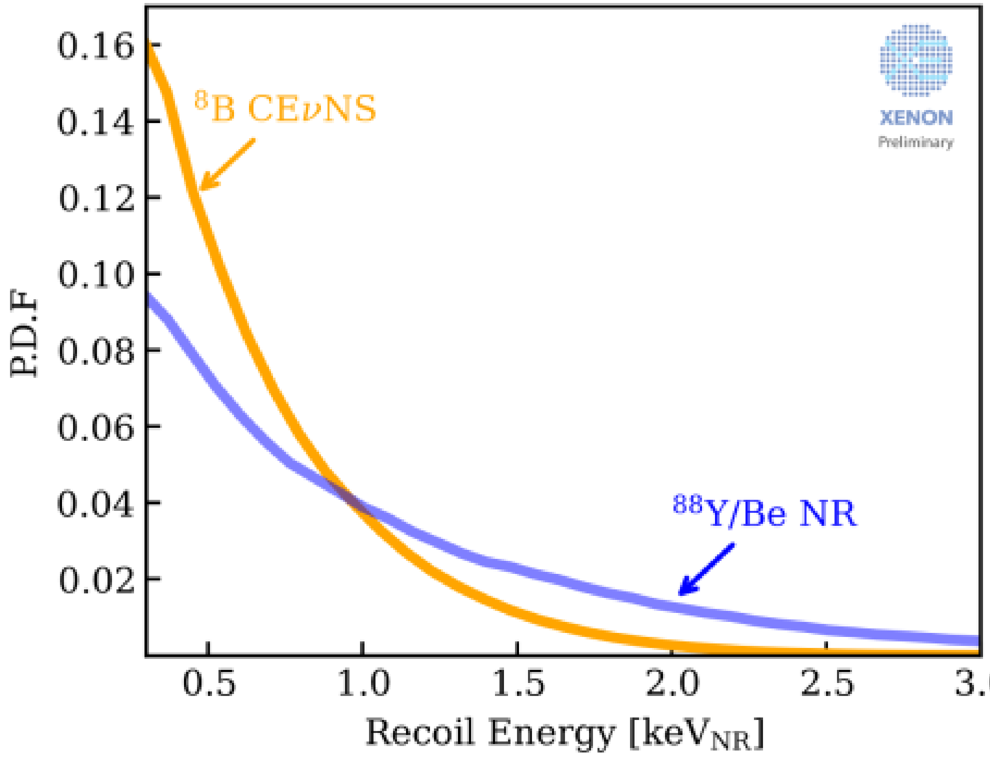
- Data taken between 2021-07 and 2023-08: ~340 days of **raw exposure**
- **Stable detector response**: <1% (<3%) light (charge) yield variation
- **High liquid xenon purity**: Electron lifetime ~20ms

NR Calibration & Yield

XENON

$$\gamma(^{227}Y) + {}^{9}\mathrm{Be} \rightarrow n + {}^{8}\mathrm{Be}$$

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



CEvNS Signal

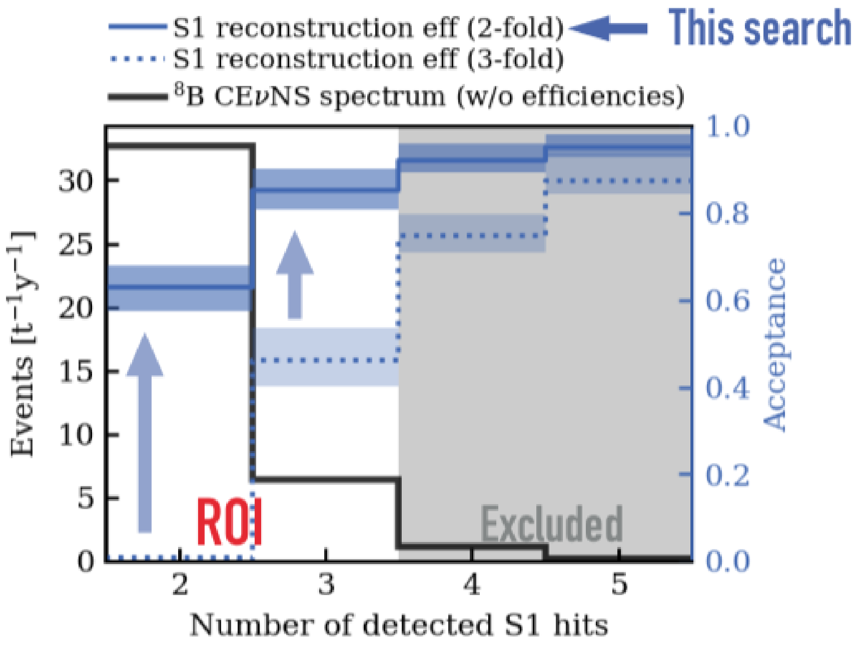
Boost sensitivity by lowering our energy threshold

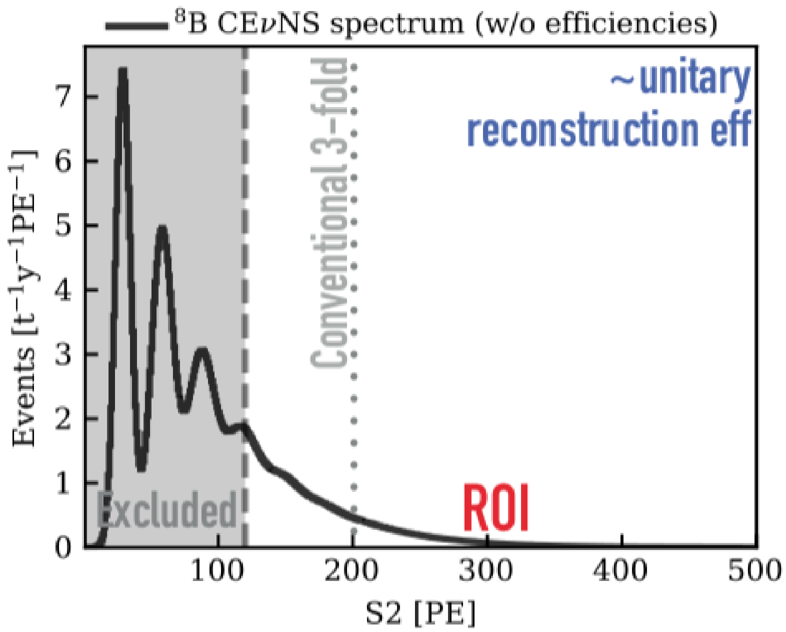
- ^{8}B event rate in the conventional WIMP “3-fold analysis" (SR0): ~1% detection efficiency → 0.2 events / (t x yr)
- Lowering our S1 and S2 threshold → improve our expected event rate to 3.7(3.3) events / (t x yr) in SR0(1)

Blinded Region of Interest

S1 ROI: 2 or 3 hits ; A hit corresponds to a recorded photon by PMT+DAQ+software

S2 ROI: [120 - 500] PE → Reject high rate of isolated S2 background signal





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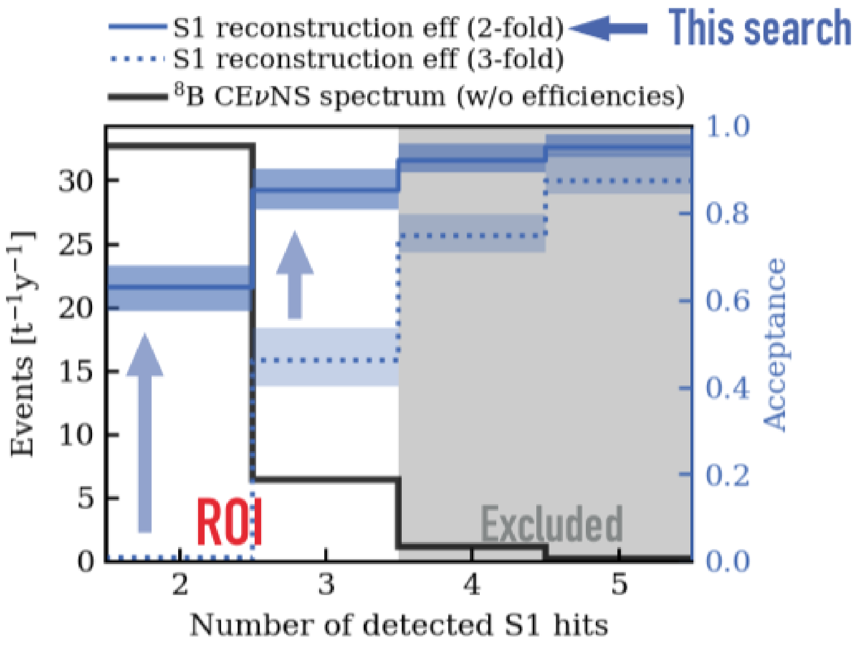
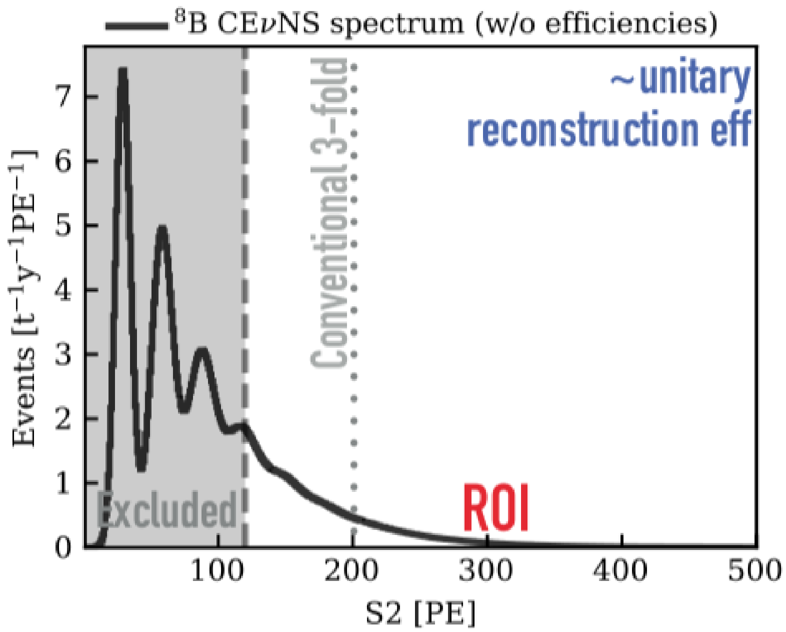
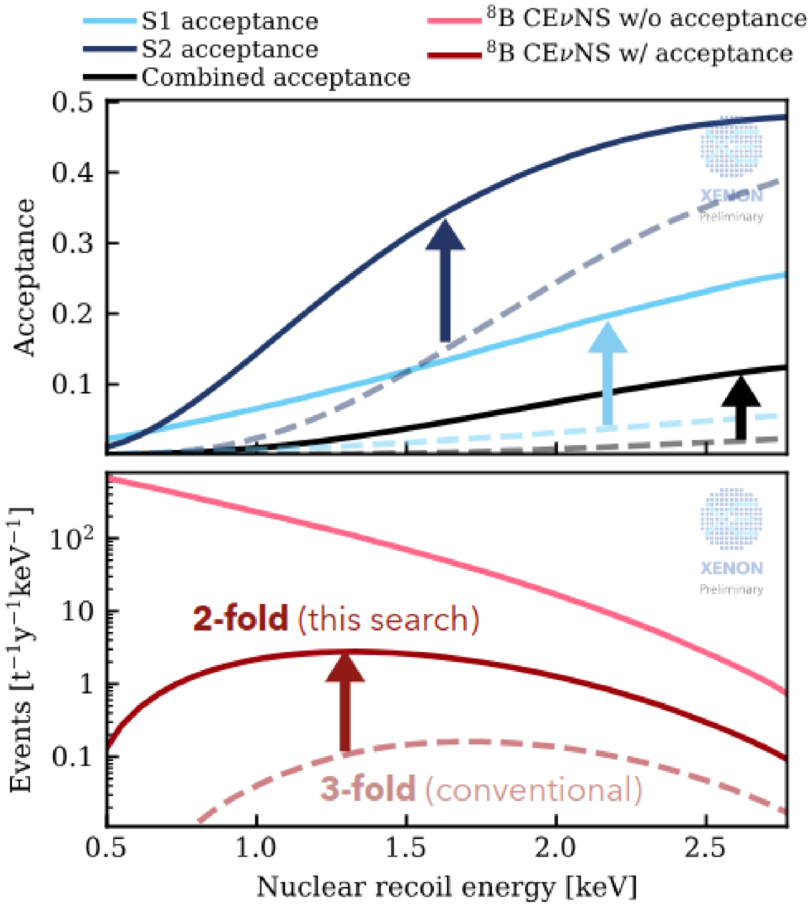
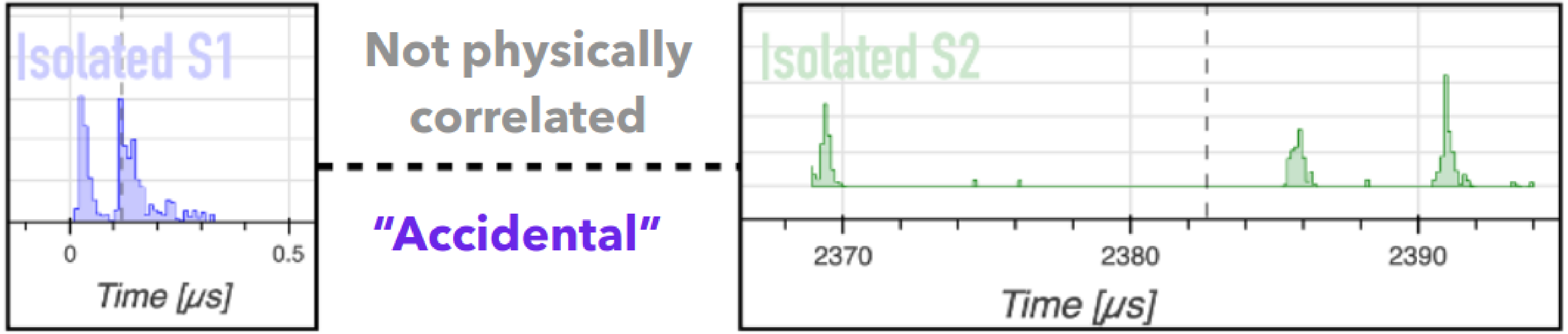




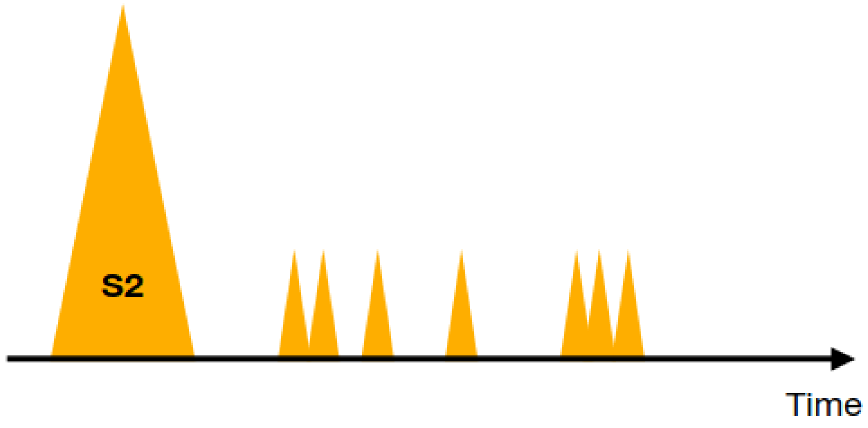


Backgrounds

Main Source: Accidental Coincidences



- Accidental Coincidence (AC): Random pairing of **isolated S1** and **isolated S2**, whose exact origin is under investigation. Current culprit:
  - ➡ **Isolated S1 signals**: from pile-up induced single PMT hits, misclassified single electrons,…
  - ➡ **Isolated S2 signals**: from few-electron pile-up events, notably following high-energy interactions,…

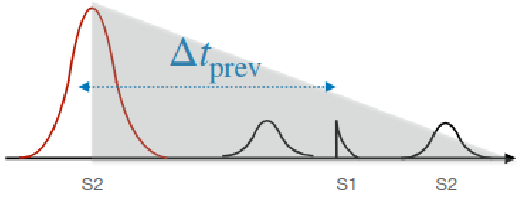


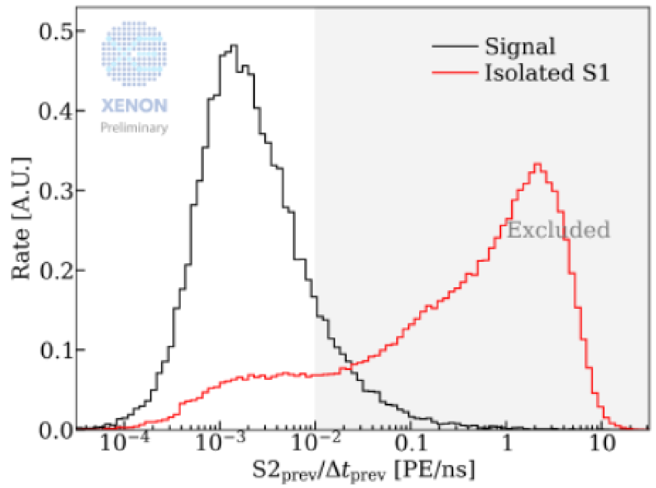
Backgrounds

Accidental Coincidences Suppression:

1- Time Shadow

- Use space/time correlation with previous high-energy interaction
  - ➡ **Isolated S1 rate**: 15 Hz → 2.3 Hz
  - ➡ **Isolated S2 rate**: 150 mHz → 25 mHz





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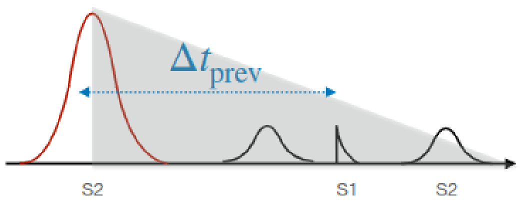

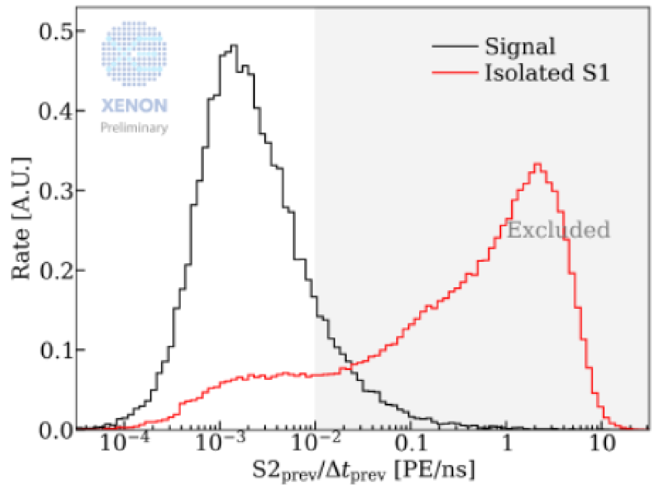

2- Two Boosted Decision Tree (BDT)

- **S1 BDT:** leverage S1 pulse shape and spatial distribution across the PMT arrays.
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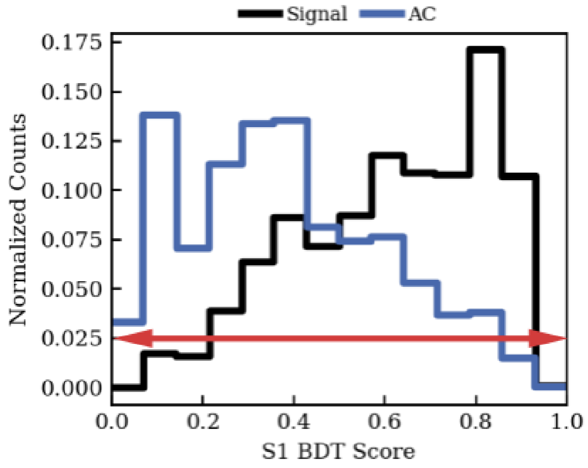
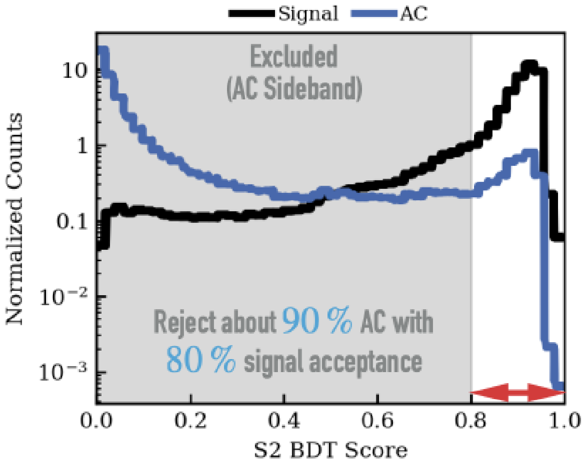




Expected # of AC events:

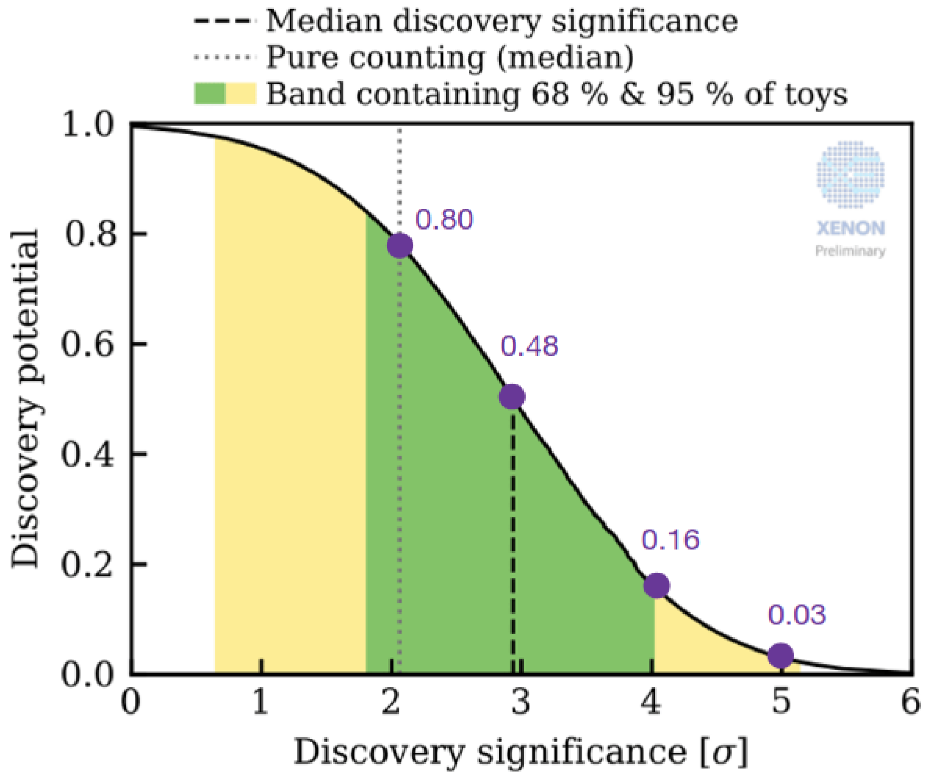
7.5 ± 0.7 (SR0) and 17.8 ± 1.0 (SR1)

CEνNS Prediction

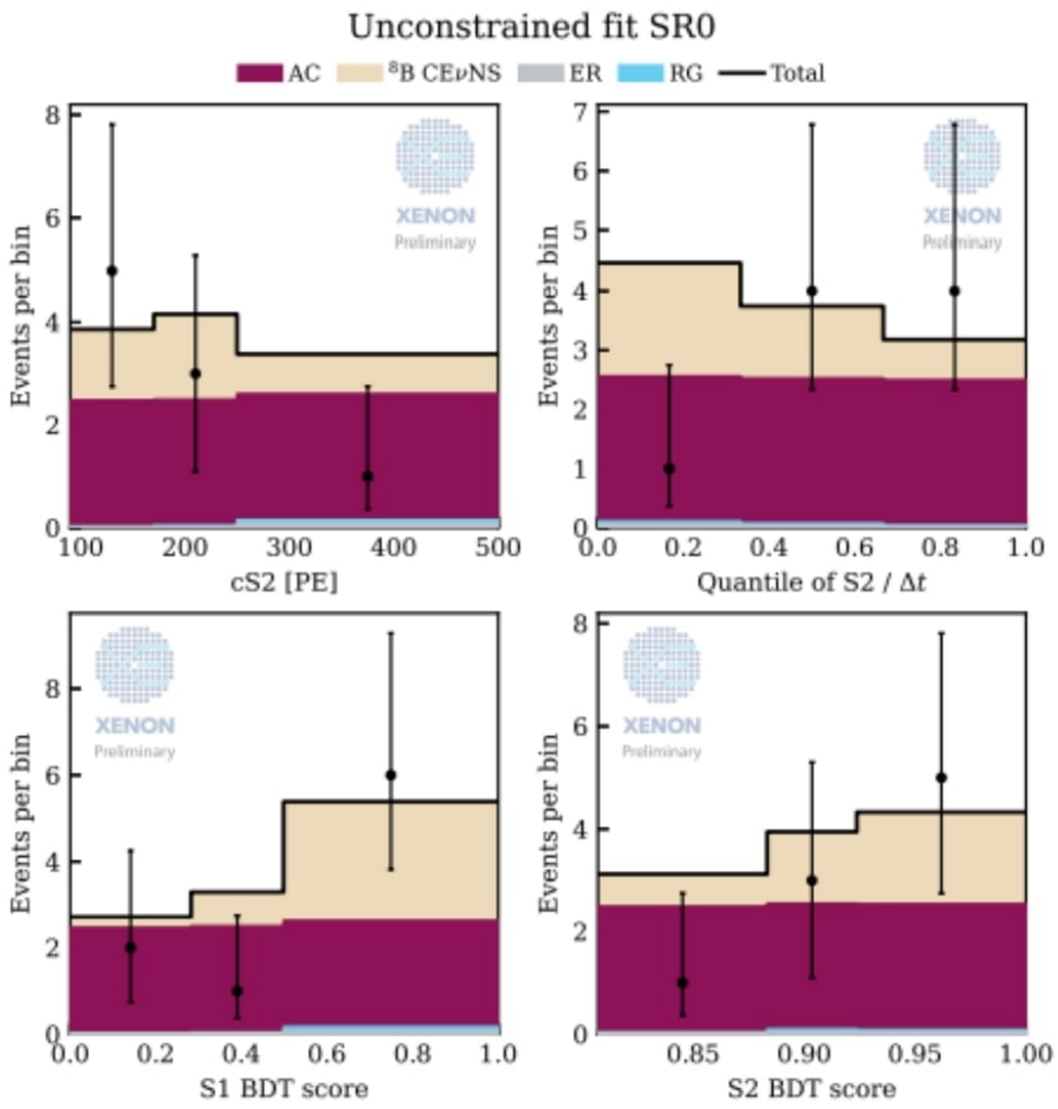
- Use both science run to perform a blinded analysis, with **316.16 days of livetime** and a fiducial mass of **4.0 (4.1) tonnes in SR0 (SR1)** leading to a **total exposure of 3.51 t x yr**
- Extended binned likelihood in 4D parameter space 3 x 3 x 3 x 3 = 81 bins (cS2, $S2_{prev}/\Delta t_{prev}$, S1 BDT, S2 BDT)

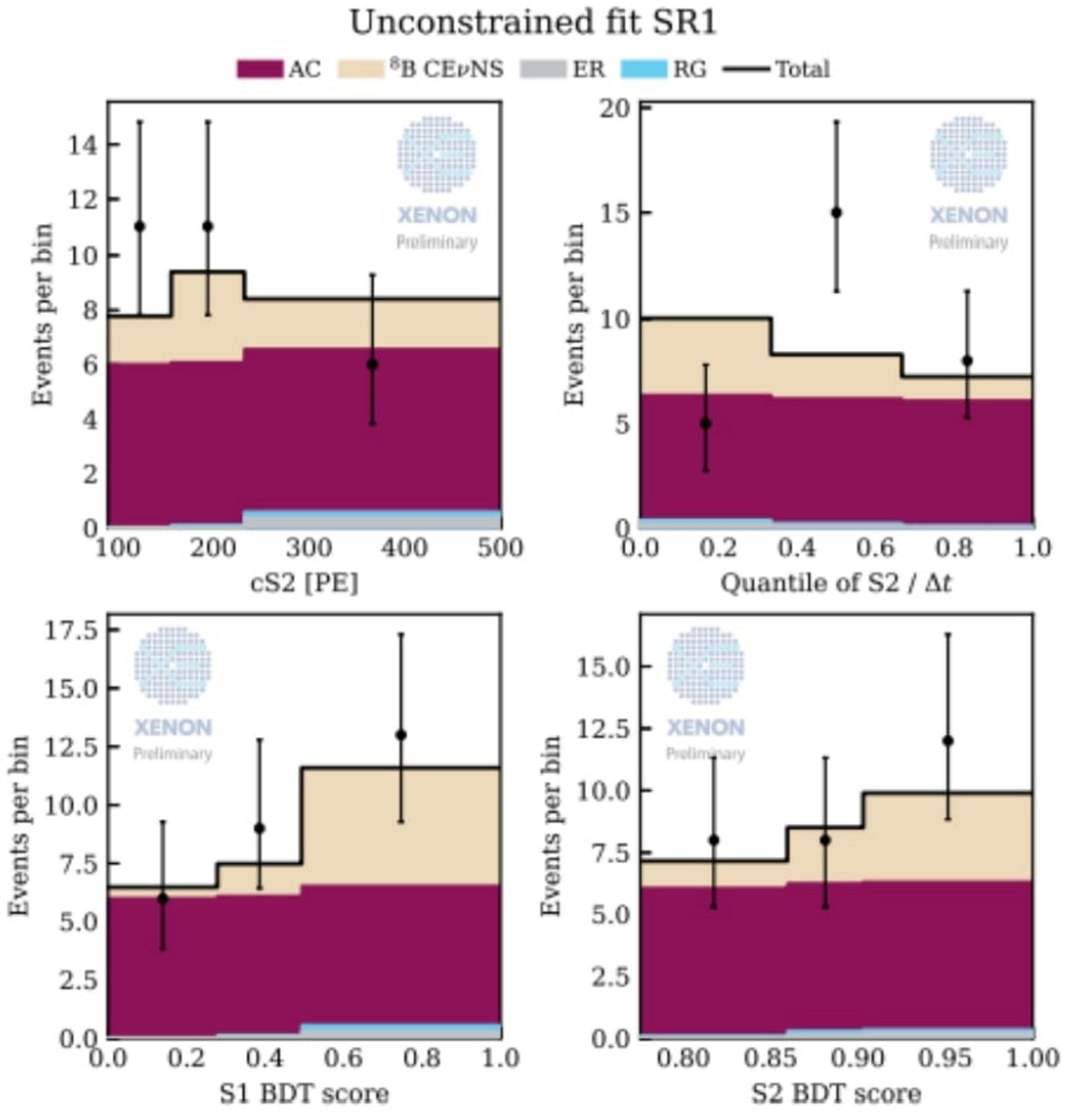
48% to observe > 3σ significance

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



Unbliding (07/03/2024)





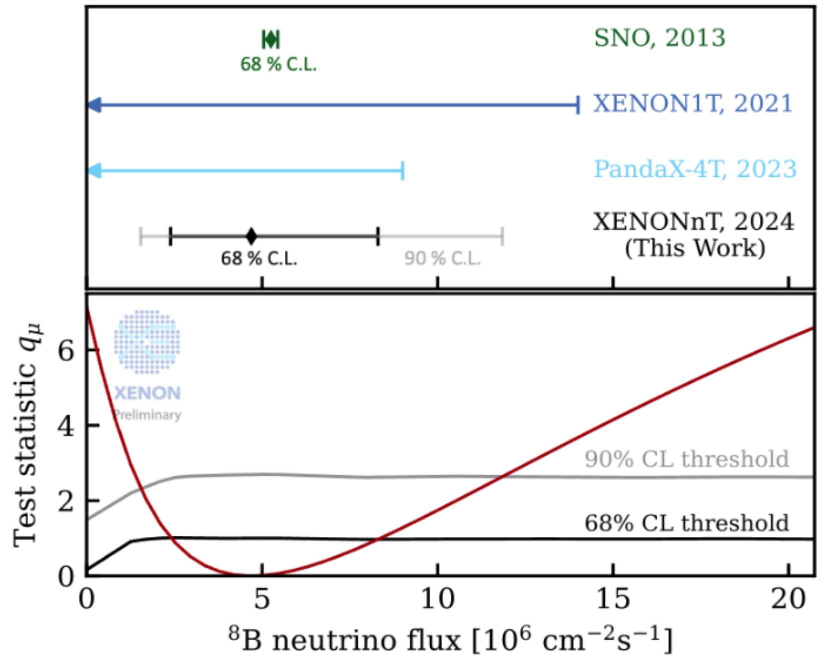
Unbliding (07/03/2024)

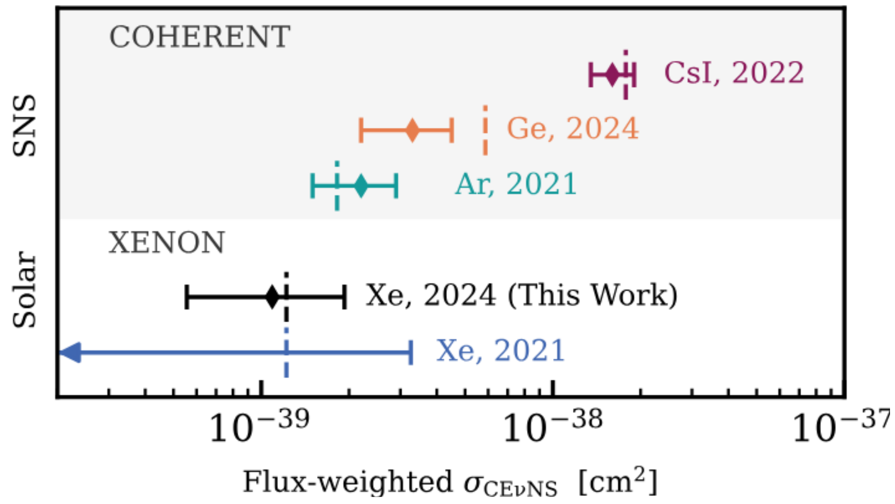
- **^{8}B neutrino flux**: $4.6^{+3.6}_{-2.3} \times 10^{6}$ cm^{-2} s^{-1} at 68% C.L. no tension with literature value
- With constrain from SNO flux → Measure the **flux-weighted CEνNS cross section**: $1.1^{+0.8}_{-0.5} \times 10^{-39}$ cm^{2}

Background only hypothesis rejected with 2.73σ significance

Strong evidence of CEνNS Interaction

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	





Conclusion

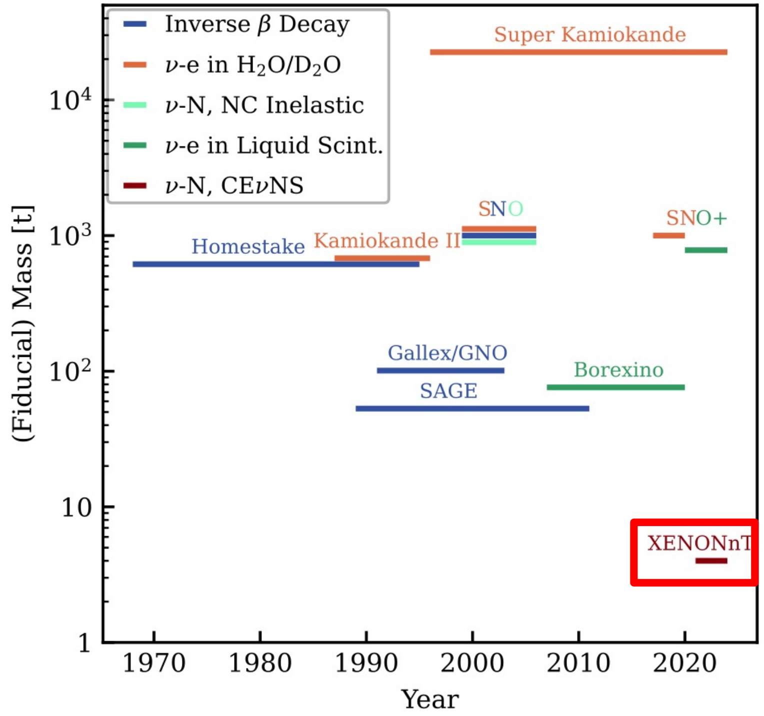
XENONnT performed a **blind search for ^{8}B CEvNS** with **3.5** ton-years

- 37 events found with a background expectation of 26 events
- **2.73σ** discovery significance

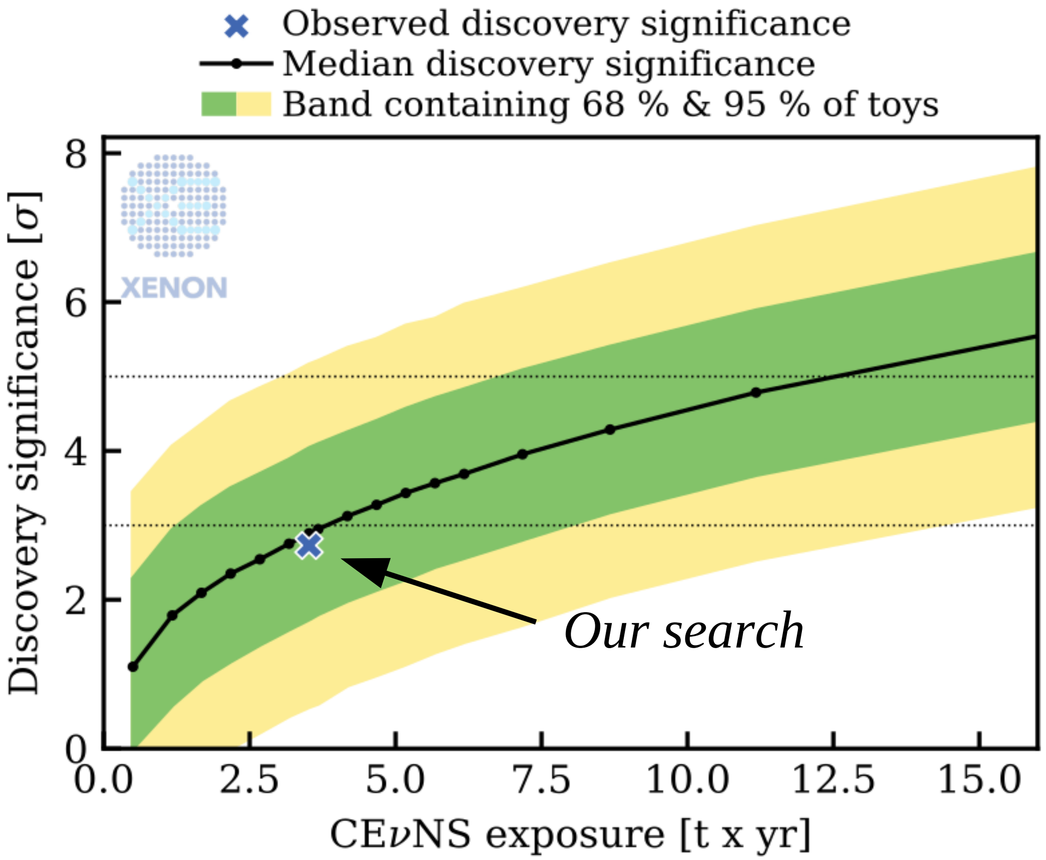
FIRST detected astrophysical ν in a **dark matter detector**

FIRST measured CEvNS signal from an **astrophysical source**

FIRST measured CEvNS signal on a **Xe** target

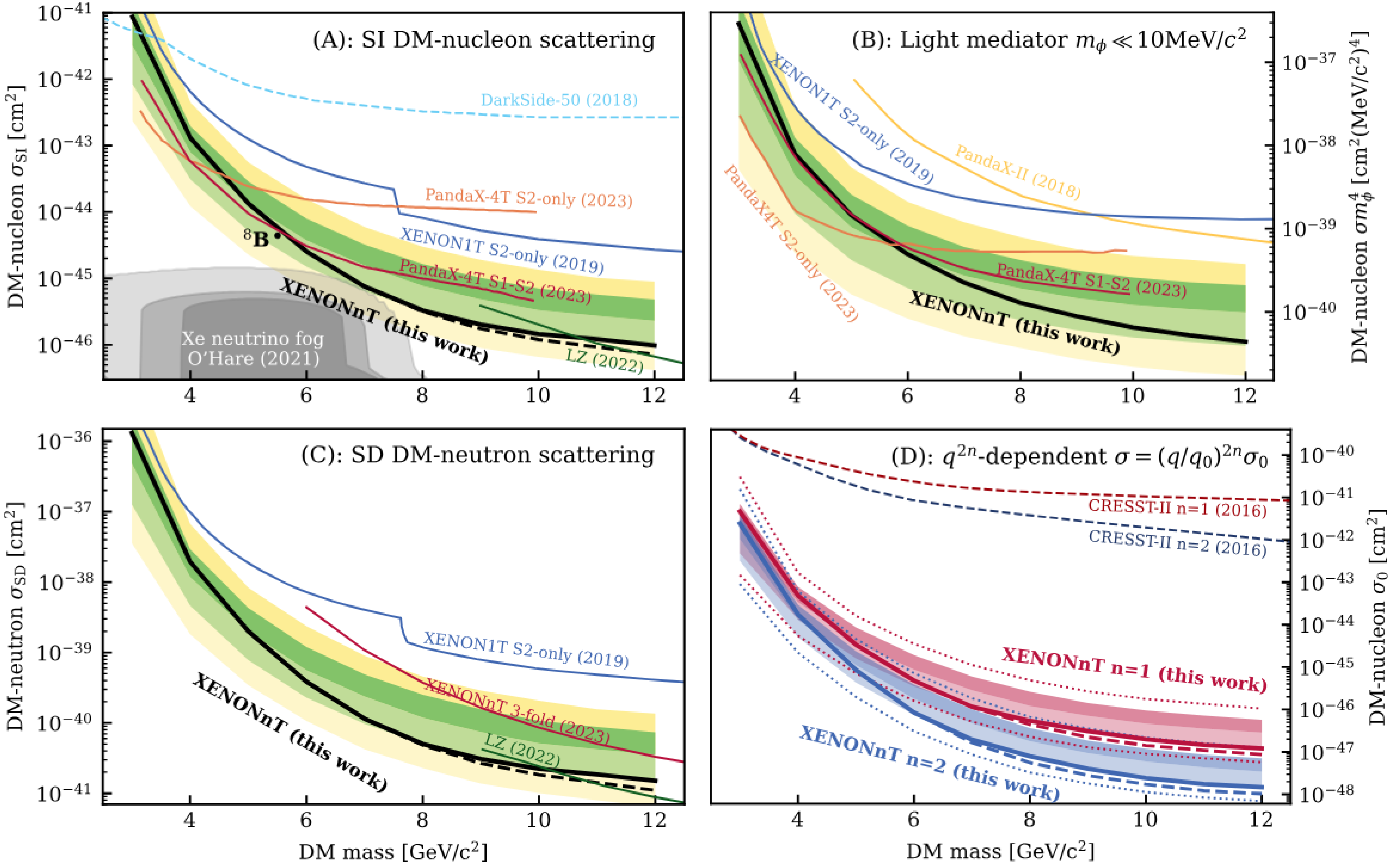


What's next?



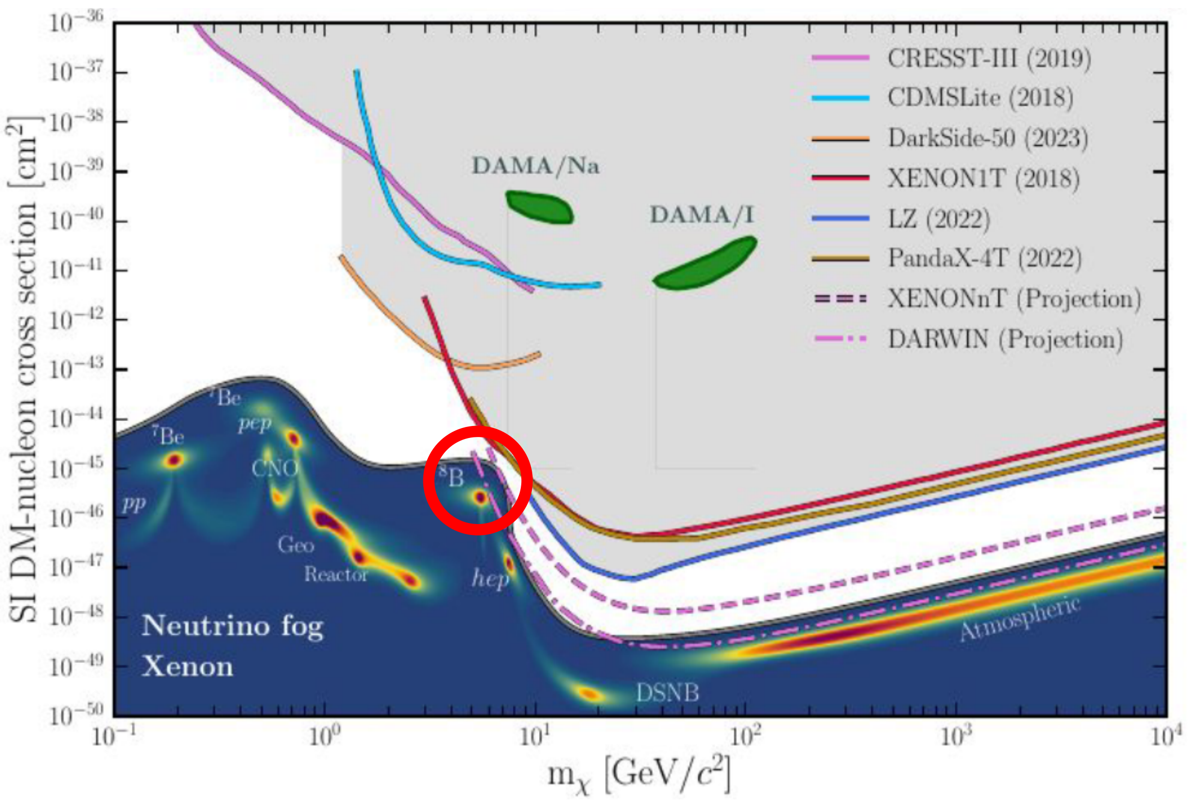
SR0+SR1+SR2 → >3σ « First Solar CEvNS Evidence»

Light DM



(A): SI DM-nucleon scattering
DarkSide-50 (2018)
PandaX-4T S2-only (2023)
XENON1T S2-only (2019)
PandaX-4T S1-S2 (2023)
8B
XENONnT (this work)
LZ (2022)
Xe neutrino fog
O'Hare (2021)
DM-nucleon σ_{SI} [cm^2]
(B): Light mediator $m_\phi \ll 10\mathrm{MeV}/c^2$
XENON1T S2-only (2019)
PandaX-II (2018)
PandaX4T S2-only (2023)
PandaX-4T S1-S2 (2023)
XENONnT (this work)
DM-nucleon σm_ϕ^4 [cm^2(MeV/c^2)^4]
(C): SD DM-neutron scattering
XENON1T S2-only (2019)
XENONnT 3-fold (2023)
LZ (2022)
XENONnT (this work)
DM-neutron σ_{SD} [cm^2]
(D): q^{2n}-dependent $\sigma = (q/q_0)^{2n}\sigma_0$
CRESST-II n=1 (2016)
CRESST-II n=2 (2016)
XENONnT n=1 (this work)
XENONnT n=2 (this work)
DM-nucleon σ_0 [cm^2]
DM mass [GeV/c^2]

DARWIN



DARWIN $\Longrightarrow$ expected 90 CEυNS per tonnes-year $\Longrightarrow>$ 3000 CEυNS per year in a 40 tonnes fiducial volume

J Aalbers et al 2023 J. Phys. G: Nucl. Part. Phys. 50 013001

Thank you for your attention

DMLab, 17 october 2024

Quentin Pellegrini

Backgrounds

Accidental Coincidences Suppression:

1- Time Shadow

- Use space/time correlation with previous high-energy interaction
  - ➡ **Isolated S1 rate**: 15 Hz → 2.3 Hz
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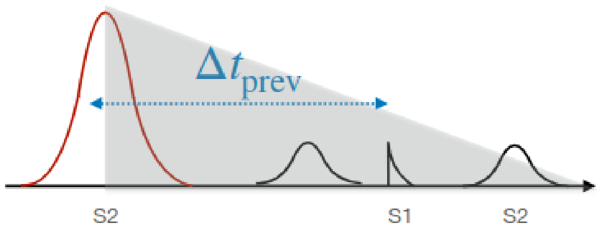

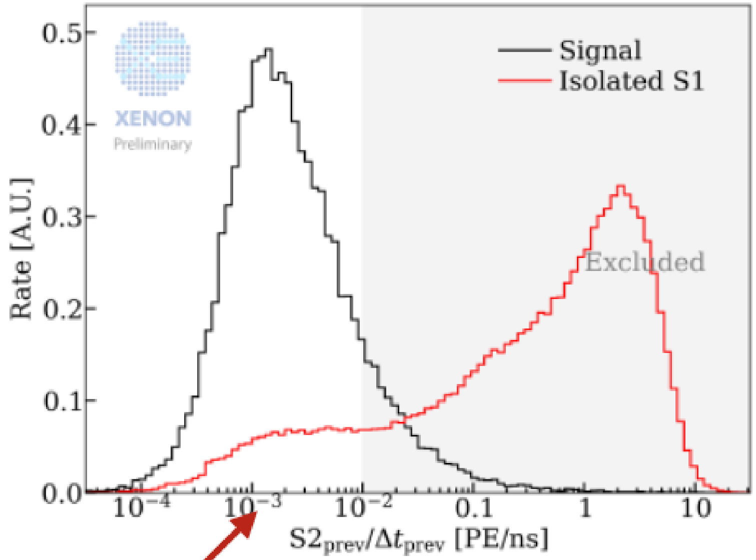

Those 3 dimensions are used in the inference

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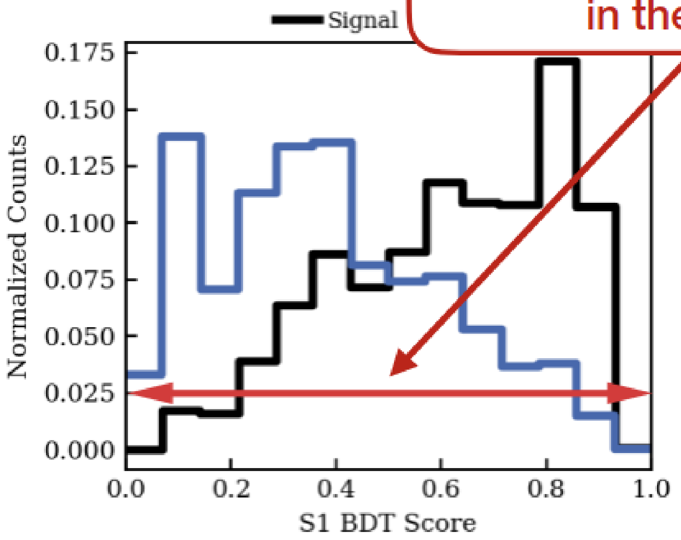

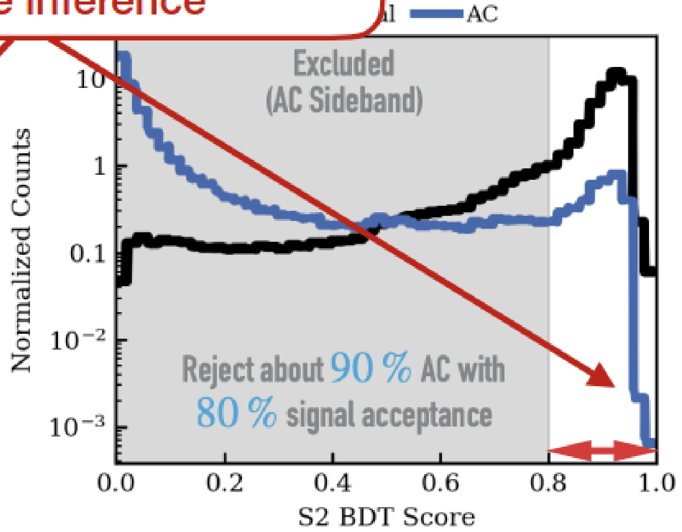

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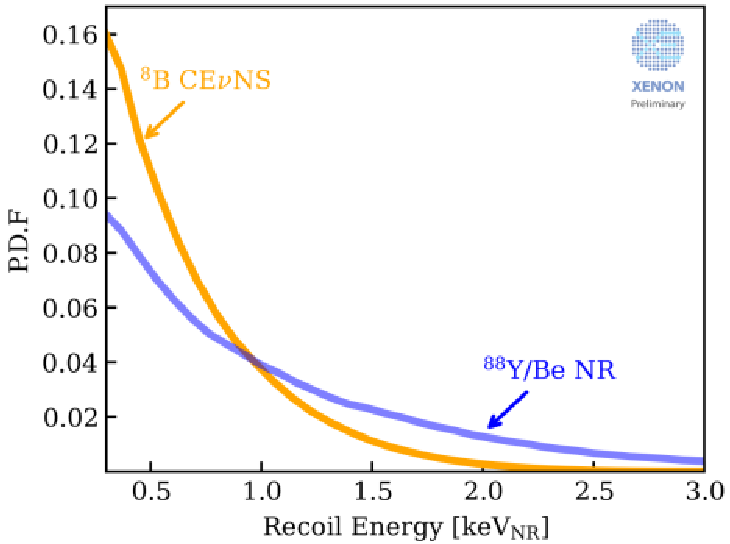
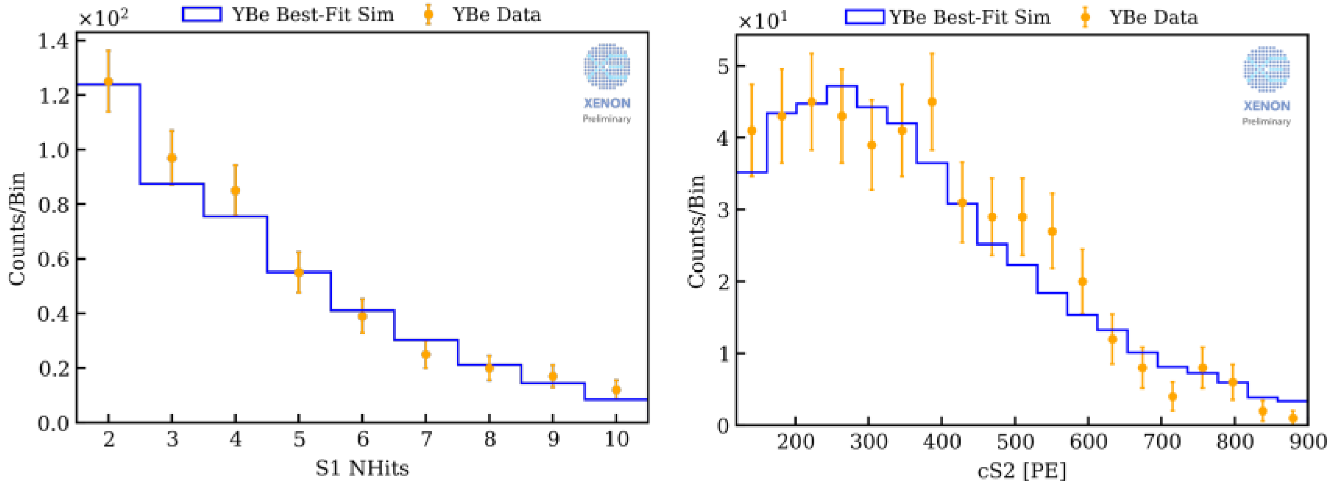
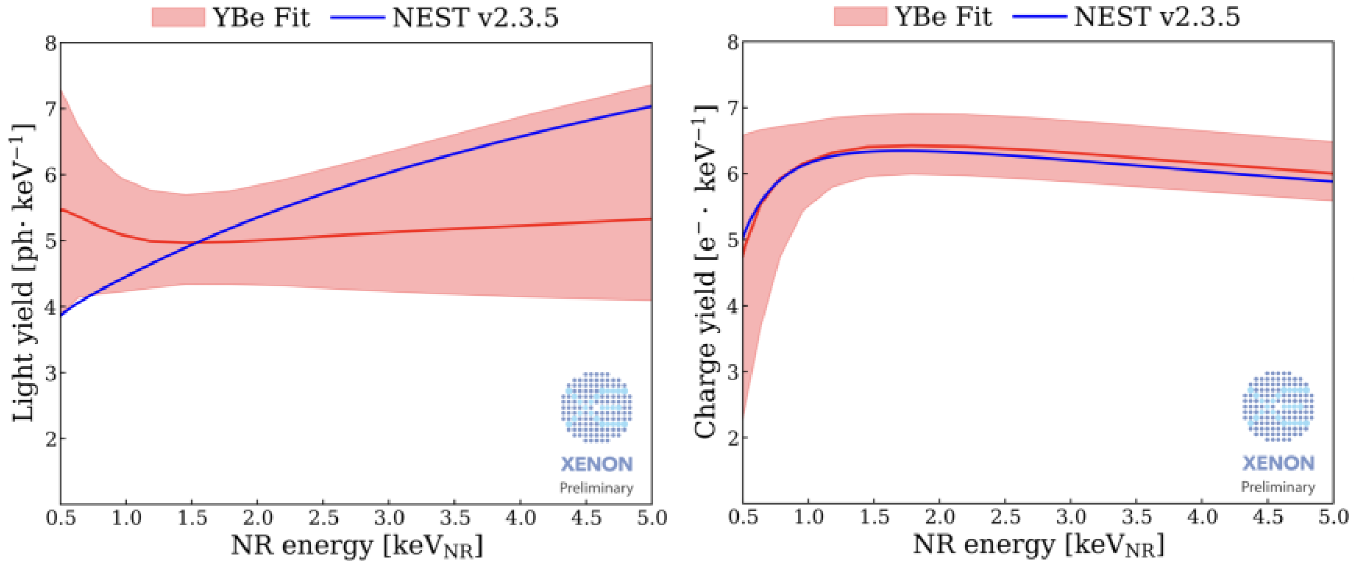
- Low energy NR yield model significantly affects ^{8}B CEνNS detection efficiency
- 152 keV neutrons from photo-disintegration of ^{9}Be by γ-ray of ^{88}Y
  - **Recoil energy spectrum similar to ^{8}B CEνNS**
- Good match between simulation and data
- **Light/charge yield model** are constrained by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



Publication in preparation





Astrophysical CEvNS and Dark Matter Search

XENON

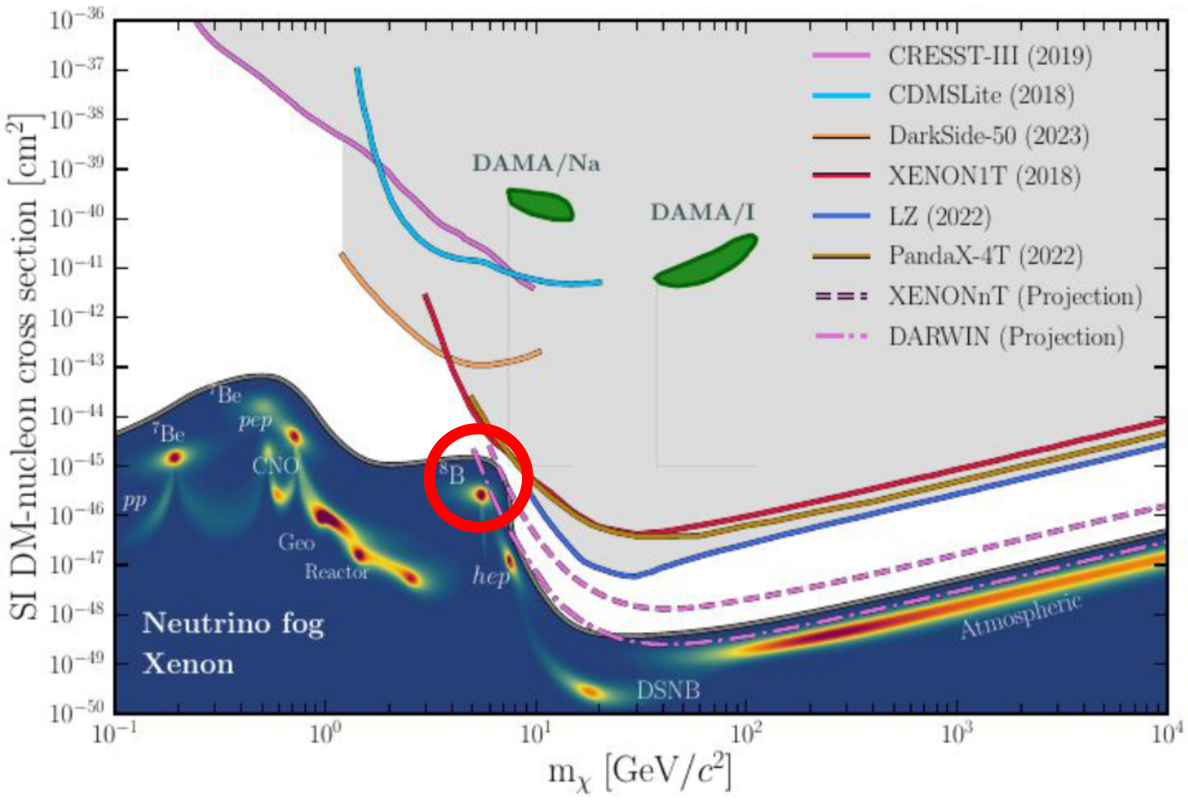
Astrophysical CEvNS

➡ Irreducible NR background

➡ WIMP Sensitivity limits, **Neutrino Fog (blue area)**

CEvNS and solar neutrinos

- **Background for Low-WIMP mass (< 10 GeV)**
- **Only ^{8}B-ν counts (pp III chain)**



Sensitivity of DM experiments in function of WIMP mass

Adapted from PRL 127, 251802 (2021)

XENONnT

XENON

3 Nested Detectors sharing the same DAQ

LXe - GXe time projection chamber

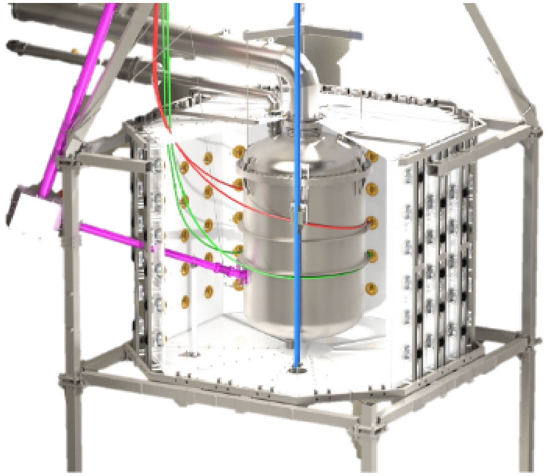
TPC

EPJ C 84 (2024) 138

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

Gd-doped water Cherenkov detector (NV)

NEUTRON VETO

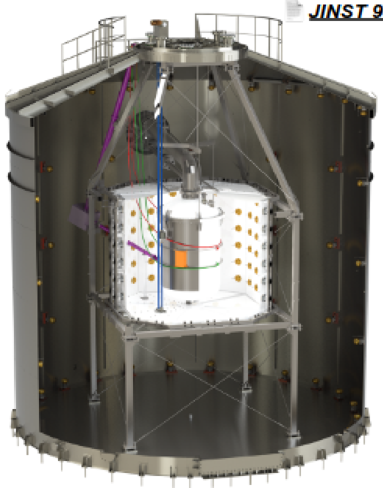


33 t water contained
~2 x 3 m diameter x height
120 PMTs (8" Hamamatsu R5912)
0.05% GdSO concentration (since 2023)
0.5% GdSO concentration (final goal)

Gd-doped water Cherenkov detector (MV)

MUON VETO

JINST 9 P11006



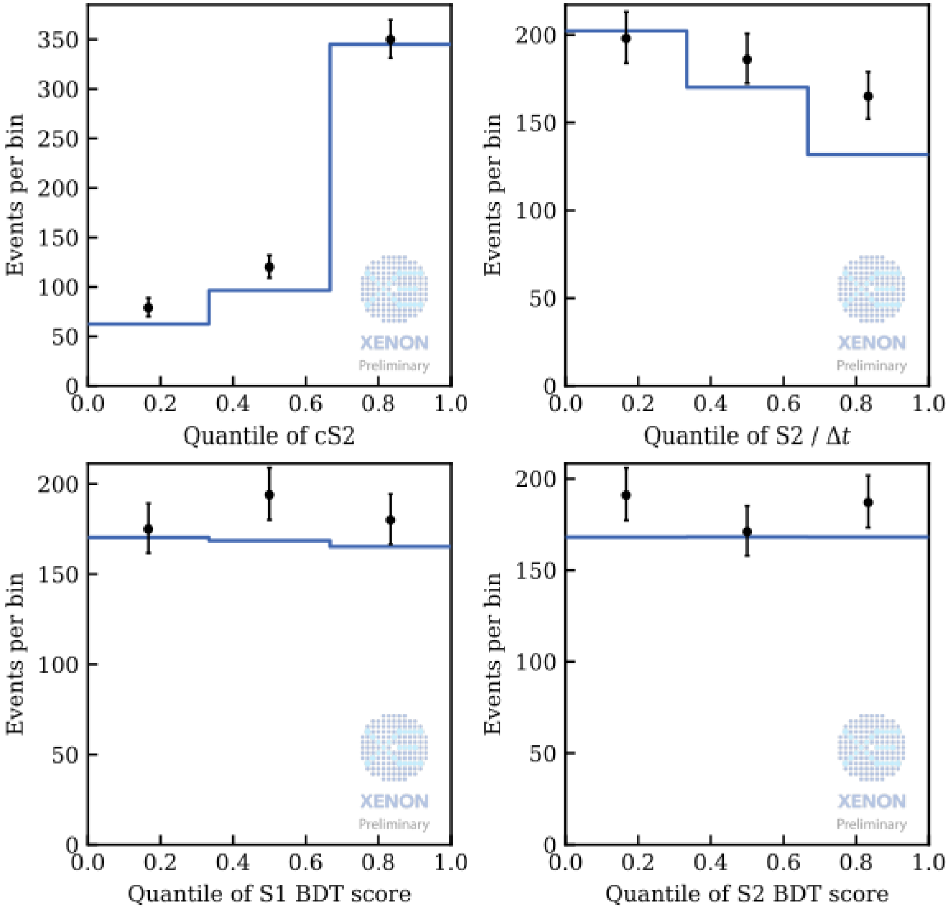
700 t water contained
~10 x 10 m diameter x height
84 PMTs (8" Hamamatsu R5912-ASSY)
Shares same water with NV but optically separated detectors

All detectors' materials very carefully selected for excellent radiopurity

AC Validation

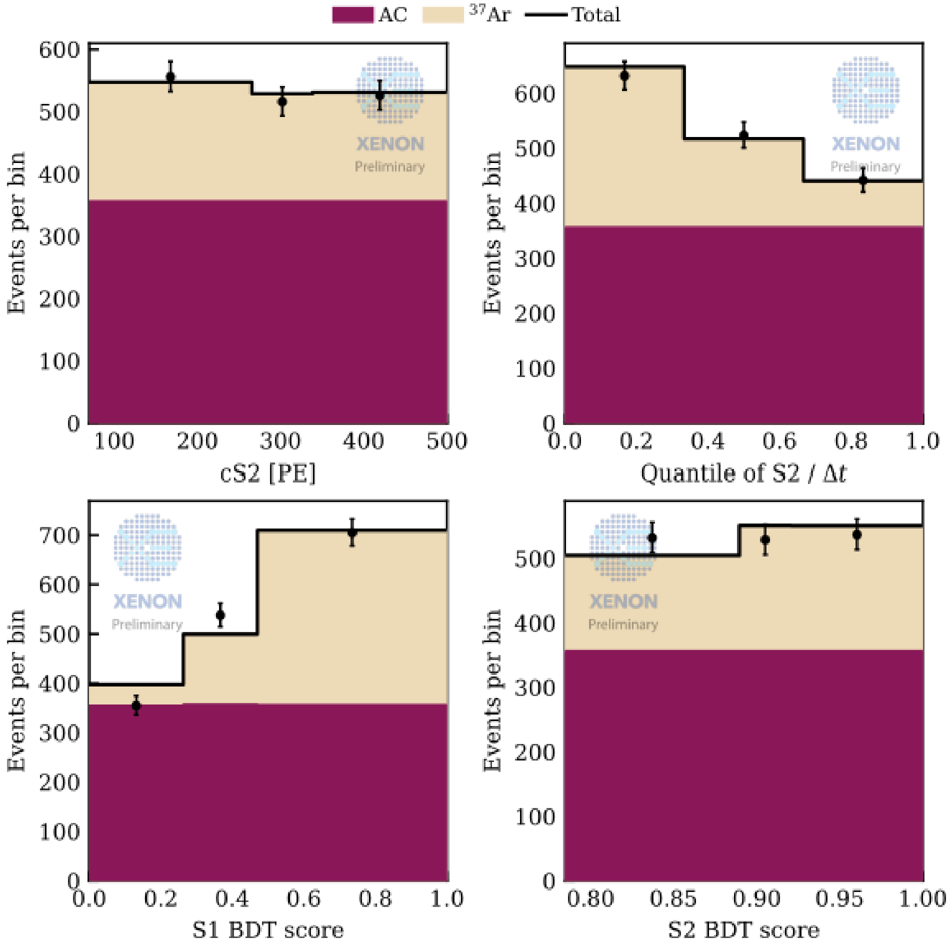
arXiv:2408.02877

AC SIDEBAND



Publication in preparation

37Ar L-shell EC



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

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