Latest results from the XENONnT dark matter experiment

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on behalf of the XENON Collaboration

THE XENON **COLLABORATION**

Paving the way for direct dark matter detection since 20 years

2005
XENON10
25 kg LXe

2008
XENON100
160 kg LXe

2016
XENON1T
3200 kg LXe

2020
XENONnT
8600 kg LXe

***200+** SCIENTISTS*

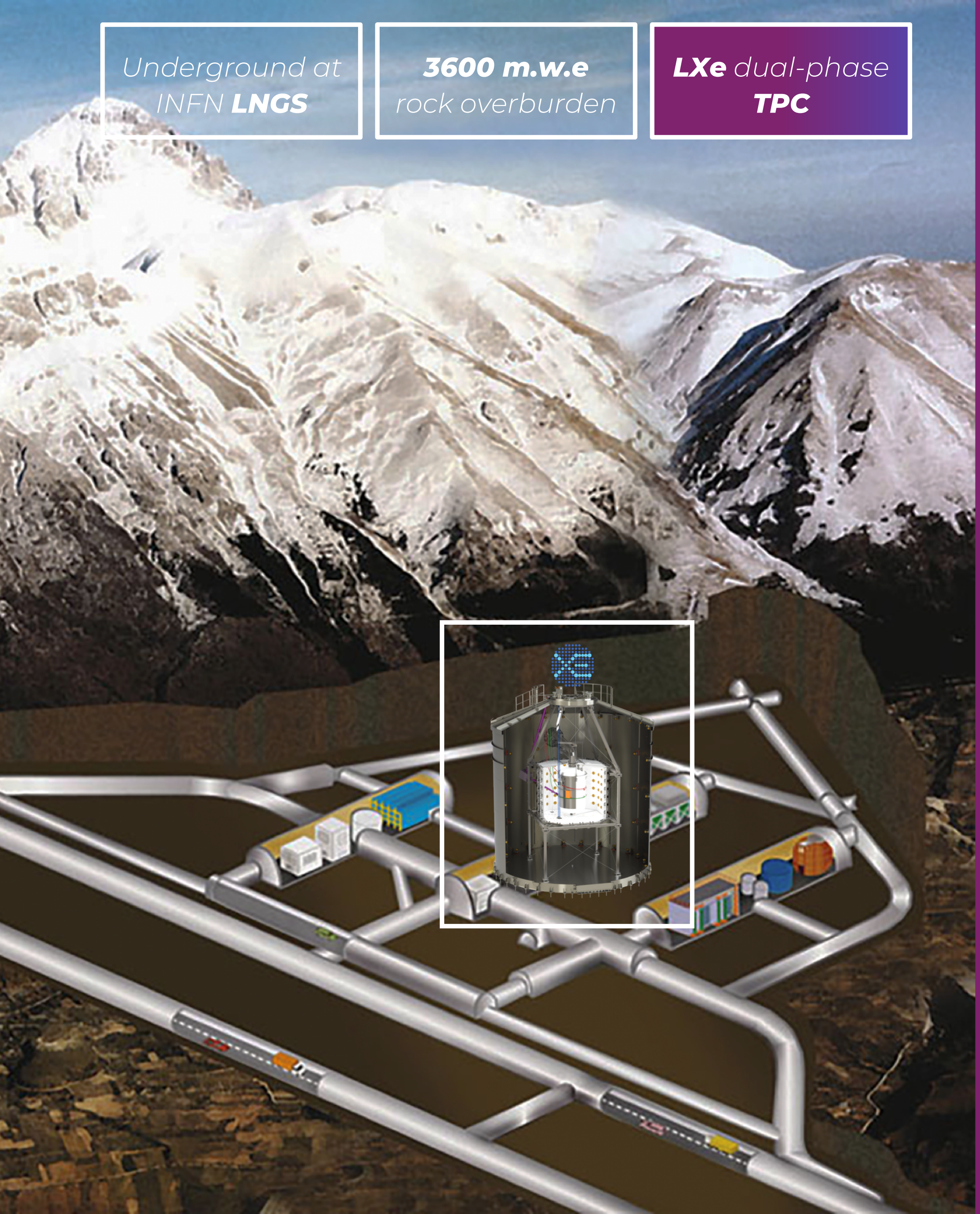
***29** INSTITUTIONS*

***12** COUNTRIES*

*Underground at INFN **LNGS***

3600 m.w.e *rock overburden*

LXe** dual-phase **TPC



THE XENON **PROJECT**

Direct DM search with LXe TPC

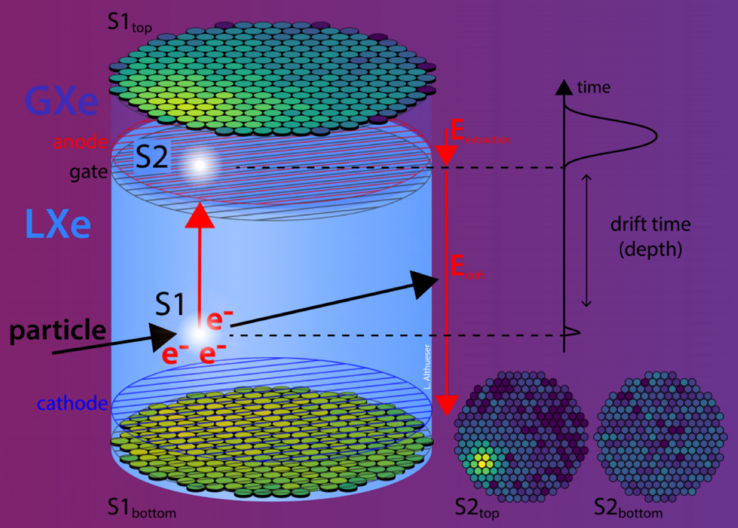
SCINTILLATION channel

S1 SIGNAL
prompt
LXe scintillation

Drift of ionization electrons

IONIZATION channel

S2 SIGNAL
secondary
GXe scintillation



ENERGY RECONSTRUCTION
from combined S1 and S2 signals

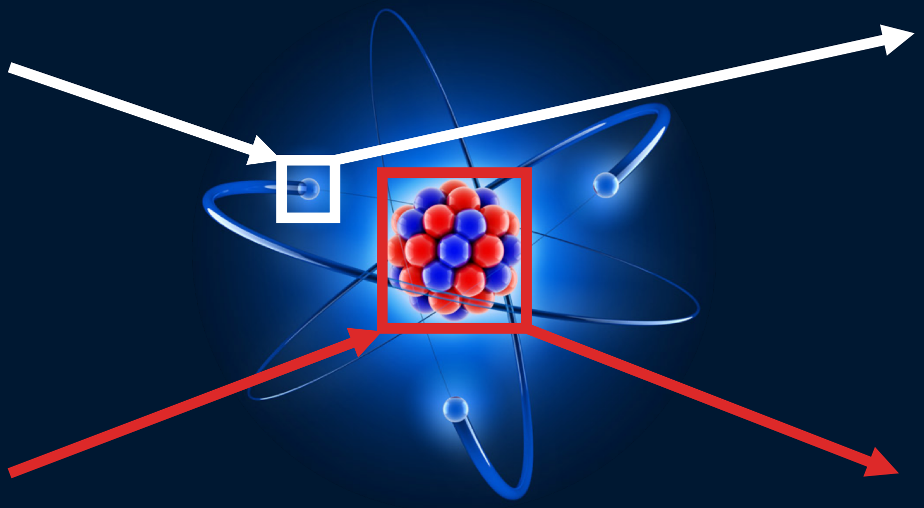
3D POSITION RECONSTRUCTION
(x,y) from S2 hit pattern
z from S1-S2 delay time

RECOIL TYPE

bkg | **Gamma**
bkg | **Beta**
bkg / ***sig*** | **Neutrino** elastic scattering
sig | **Solar axions, ALPs**

ER

electronic recoil



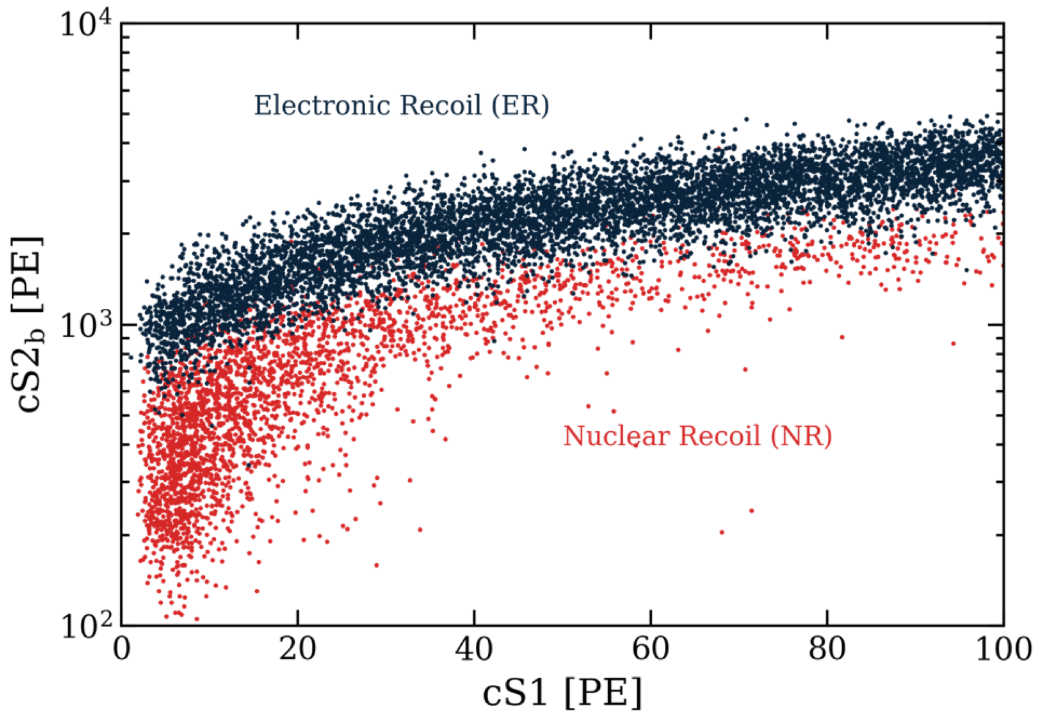
nuclear recoil

NR

bkg | **Neutron** elastic scattering
bkg / ***sig*** | Neutrino **CEvNS**
sig | **WIMP** dark matter

DISCRIMINATION

For ultra-low-background searches for ultra-rare events



In Hall B of underground LNGS

THE XENONnT EXPERIMENT

THE DETECTOR

PHYSICS RESULTS

WHAT'S NEXT

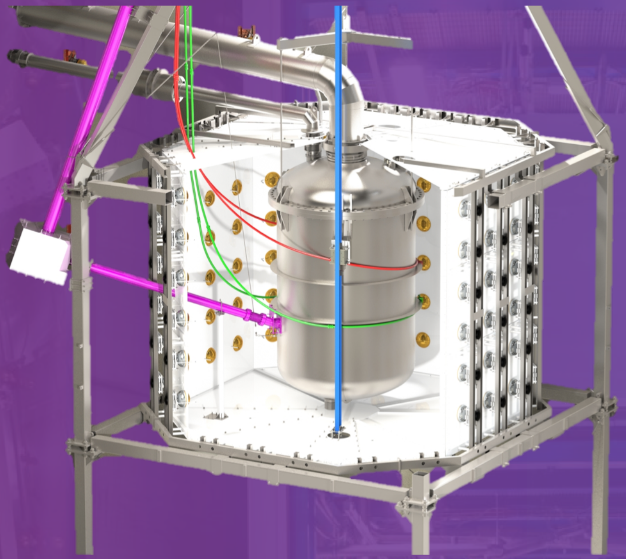
3 NESTED **DETECTORS**

Sharing the same DAQ JINST 18 P07054

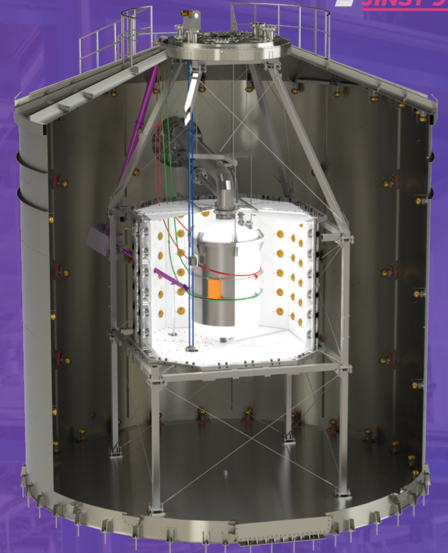
JINST 16 (2021) 08, P08033

LXe - GXe time projection chamber	*Gd-doped water Cherenkov detector (NV)*	*Gd-doped water Cherenkov detector (MV)*
TPC	**NEUTRON VETO**	**MUON VETO**

EPJ C 84 (2024) 138



JINST 9 P11006



TPC
- **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)

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)

MUON VETO
- **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 are very carefully selected for excellent radiopurity EPJ C77, 890 Eur. Phys. J. C (2022) 82:599

XENON **PURIFICATION**

Liquid purification and cryogenic distillation

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

^{222}Rn CRYO-DISTILLATION

Continuous online distillation

^{222}Rn conc. (SR0): **1.8 μBq/kg**

^{222}Rn conc. (SR1): **0.8 μBq/kg !**

Was the dominant bkg in XENON1T

EPJ C77, 275

^{85}Kr CRYO-DISTILLATION

^{nat}Kr/Xe concentration : **<50 ppt**

Made subdominant since XENON1T

ELECTRON LIFETIME

Removal of electronegative impurities

GXe and LXe purification systems

Electron lifetime achieved: ***>30 ms !***

Full TPC drift time: 2.2 ms

ER BACKGROUND LEVEL

Lowest background rate ever achieved in LXe-based dark matter detectors

LOW-ENERGY ER BACKGROUND RATE

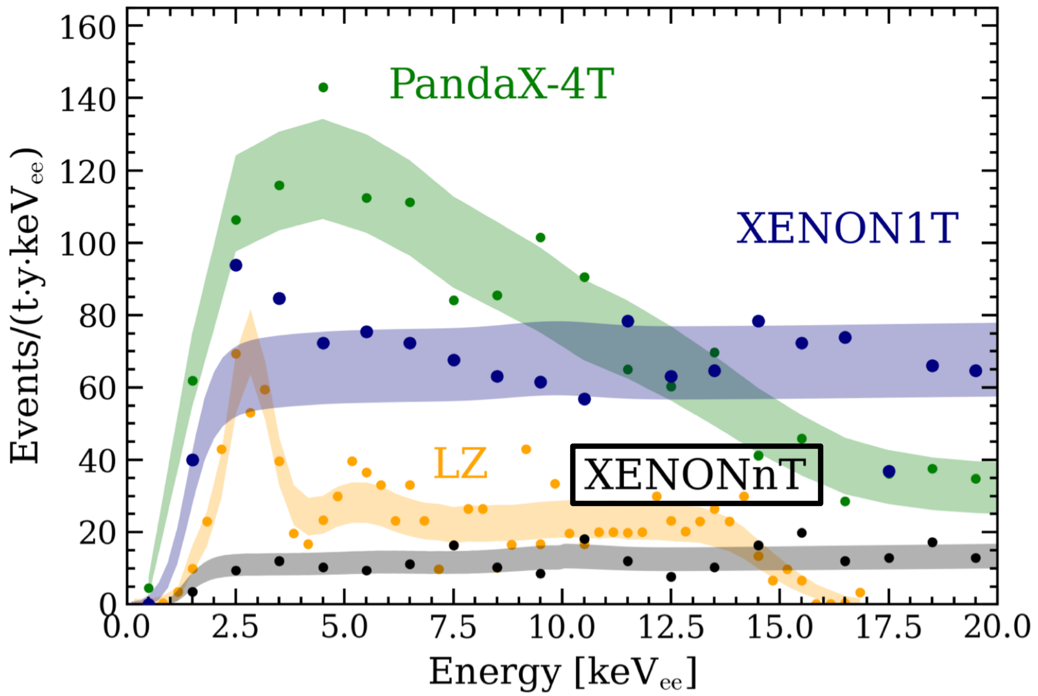
Relative improvement of XENON detectors

XENON10 .... *1*

XENON100 .... *5 · 10^{-3}*

XENON1T .... *2 · 10^{-4}*

XENONnT .... ***3 • 10^{-5}***



ER BKG RATE
16 ± 1
events / (t·y·keV)

XENONnT TIMELINE

2 scientific runs completed

CONSTRUCTION

Mar 2020 | TPC installation
Jun - Dec 2020 | NV installation
Cryostat filling (LXe)
MV/NV filling (water)
Jan – Jun 2021 | Commissioning

SCIENCE RUN 0

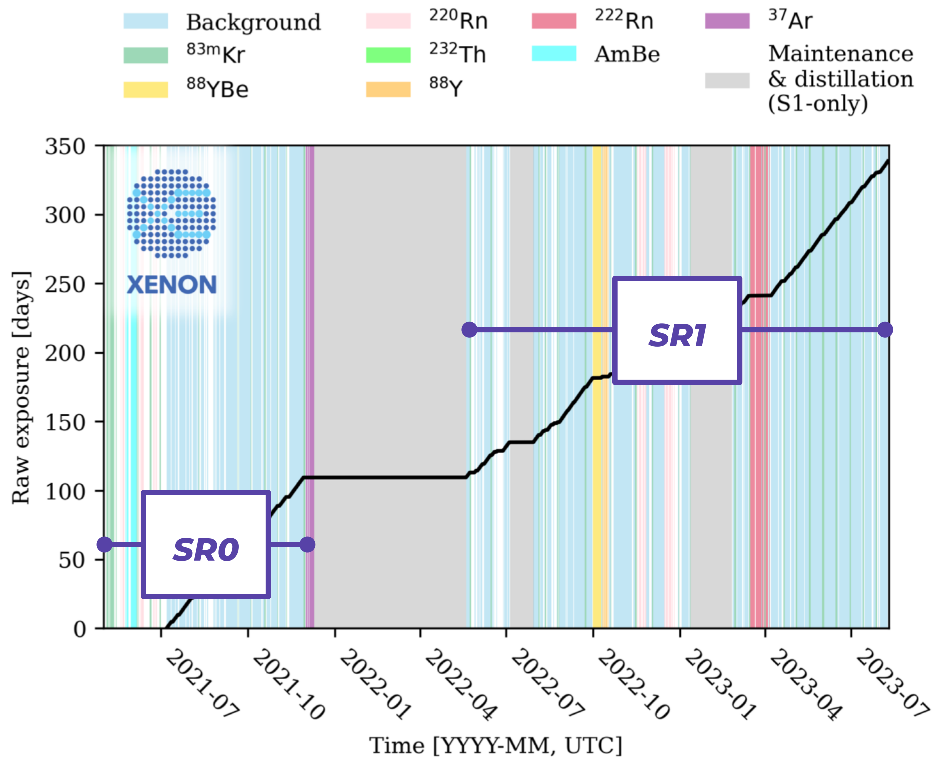
Jul 2021 | Start of SR0
Nov 2021 | End of SR0

SCIENCE RUN 1

May 2022 | Start of SR1
Aug 2023 | End of SR1

POST-SR1

2023 | GdSO insertion in water
2023 | Start of SR2



EXCELLENT STABILITY

PHOTOSENSORS
after 4 years of operation
478 of 494 PMTs still active (97%)
with stable gain

SIGNAL RESPONSE
stability of both light and charge yields within 1%

SCIENCE RUN 2
ongoing

PHYSICS **RESULTS** SO FAR

	a	χ	ν
	ER CHANNEL	**WIMP DARK MATTER**	**CEνNS**
	2022	*2023*	*2024*
DATA	***SR0***	***SR0***	***SR0 + SR1***
LIVETIME	***97.1*** *days*	***97.1*** *days*	***316.7*** *days*
FIDUCIAL MASS	***4.4*** *tonnes*	***4.2*** *tonnes*	***4.0*** *t (SR0) -* ***4.1*** *t (SR1)*
EXPOSURE	***1.1*** *tonne·year*	***1.1*** *tonne·year*	***3.5*** *tonne·year*
BLINDING	***BLINDED ANALYSIS***	***BLINDED ANALYSIS***	***BLINDED ANALYSIS***

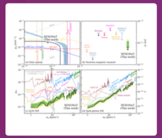
SEARCH FOR NEW PHYSICS IN **ER** DATA

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

THE RAREST PROCESS EVER OBSERVED

* **DEC** discovered by XENON1T in 2019
Half-life: **2 • 10^22 years**

Nature 568, 532-535 (2019)



NEW CONSTRAINTS ON BSM PHYSICS

SOLAR AXIONS
Couplings to gamma, electron, nucleon

NEUTRINO MAGNETIC MOMENT
$\mu_\nu < 6.3 \cdot 10^{-12}\ \mu_B$

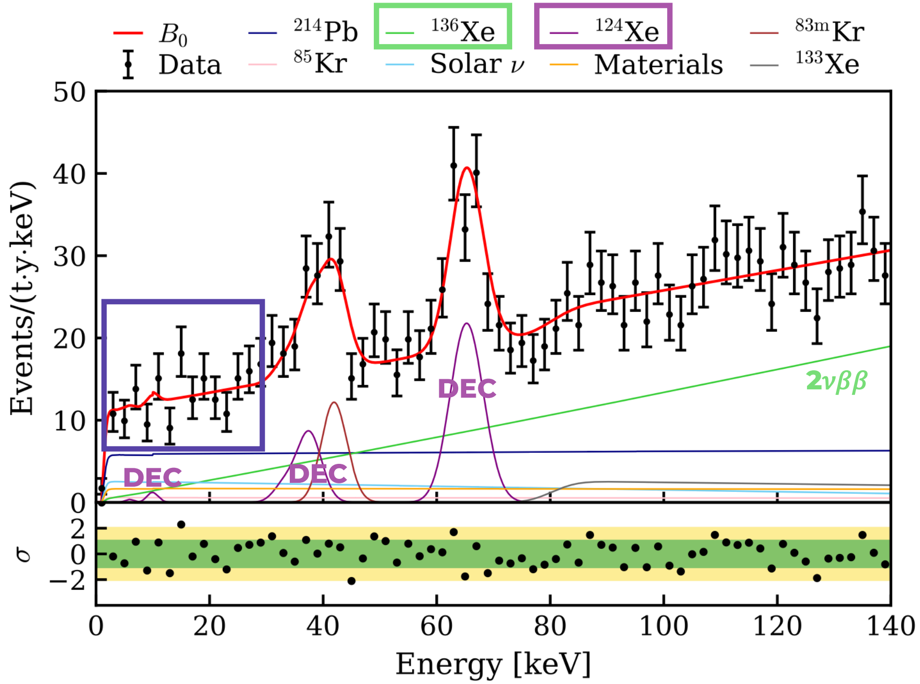
BOSONIC DARK MATTER
Dark photons, axion-like particles

ALL LEADING LIMITS
among non-astronomical observations

SPECTRUM DOMINATED BY DOUBLE WEAK PROCESSES!

^{136}Xe **2ν DOUBLE-β DECAY** (2νββ)
^{124}Xe **2ν DOUBLE ELECTRON CAPTURE DECAY** (DEC) *

Phys. Rev. C 106, 024328

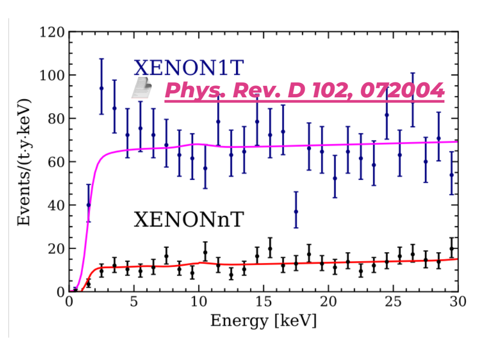


TESTING XENON1T EXCESS

EXCLUDED with **~4σ** significance

Most likely XENON1T had a tiny tritium contamination

XENONnT took steps to reduce tritium outgassing



FIRST SEARCH FOR **WIMP** DARK MATTER

[Phys. Rev. Lett. 131, 041003](#)

EXCLUSION LIMIT

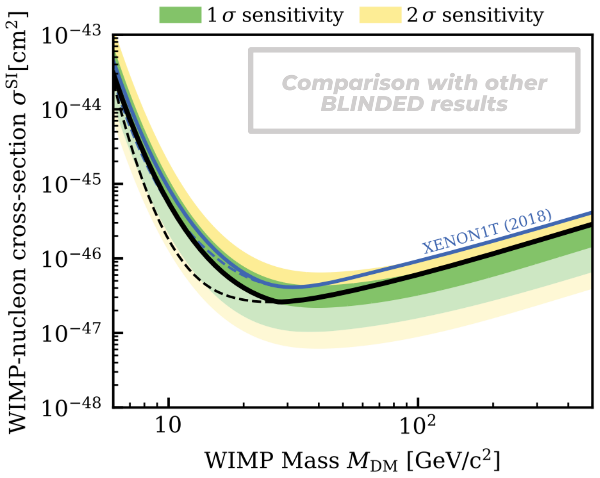
*Power-constrained limit (**PCL**) to median sensitivity*

[**Eur.Phys.J.C 81 (2021) 10, 907**](#)

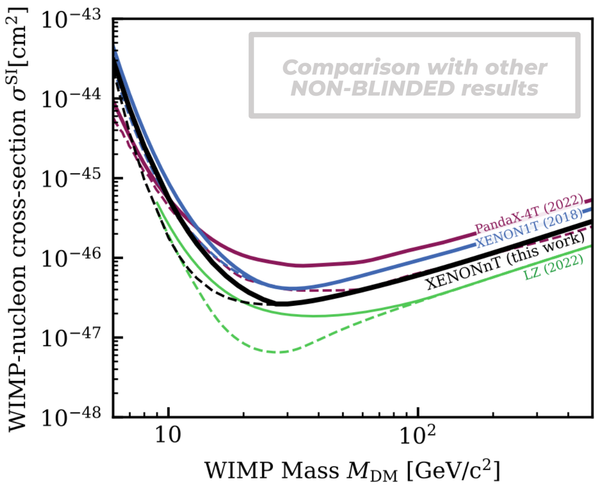
90% confidence level

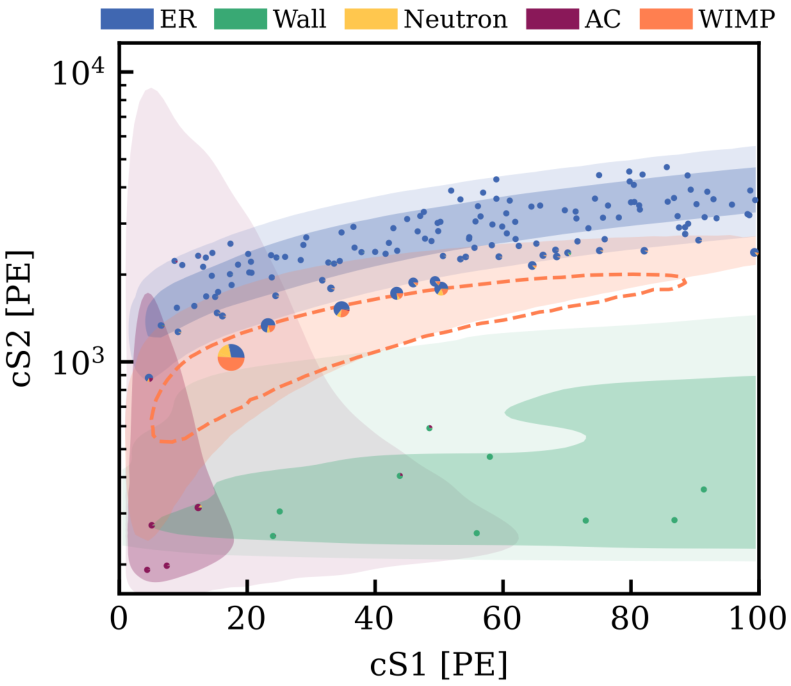
2.6 • 10^{-47} cm²
at 28 GeV/c²

Spin-independent WIMP-nucleon cross section



— PCL - - - - NO PCL





NO SIGNIFICANT EXCESS

Best-fit agrees with background

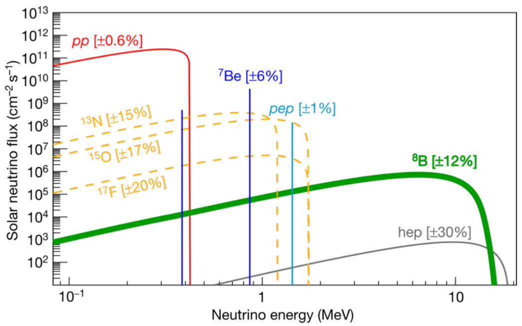
152 events in ER/NR region
16 events in NR blinded region

	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

SEARCH FOR CEνNS

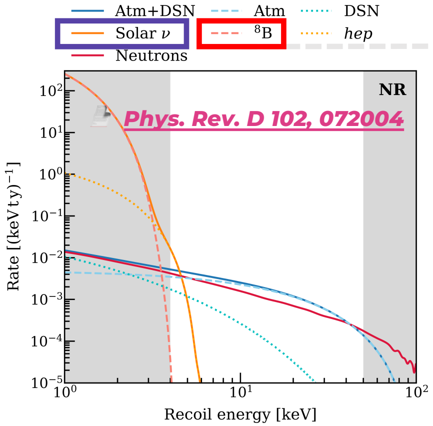
From solar ^8B neutrinos

SOLAR NEUTRINO FLUX



NUCLEAR RECOILS IN XENONnT

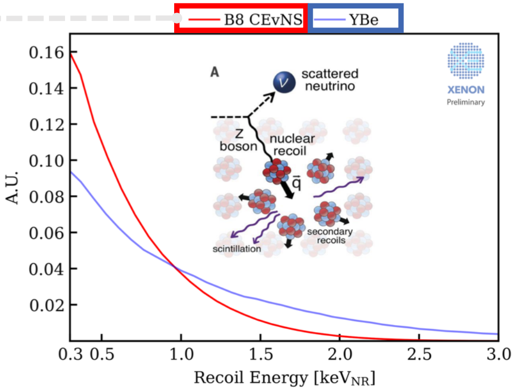
Solar neutrinos are at the edge of usual S1 threshold (3-fold) for WIMP search

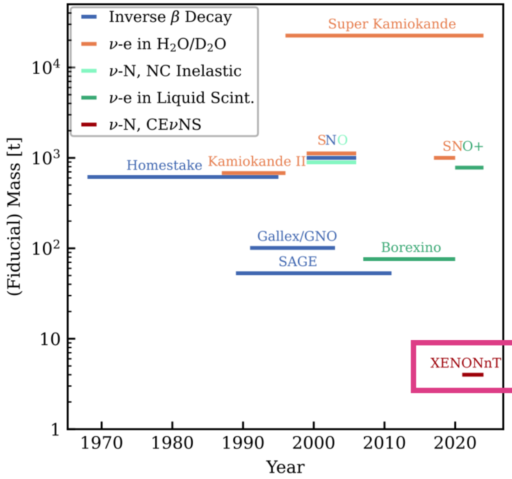


YBe CALIBRATION

Excellent MC-data match

Light and charge yields constrained in [0.5, 5] keV





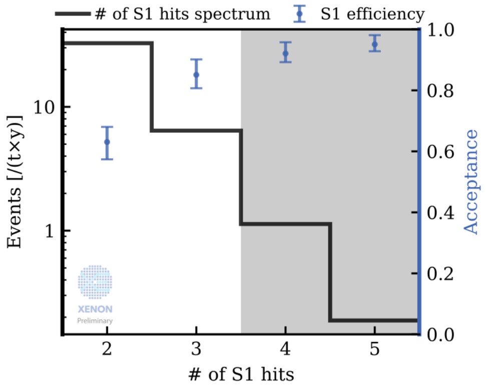
XENONnT AS SOLAR NEUTRINO DETECTOR

Joining the restricted club of experiments able to detect solar neutrinos, but with

MUCH SMALLER TARGET MASS
MUCH LOWER ENERGY THRESHOLD

S1 ROI [2, 3] hits

Lowered threshold 3 → 2-fold coincidence analysis



SEARCH FOR **CEνNS**

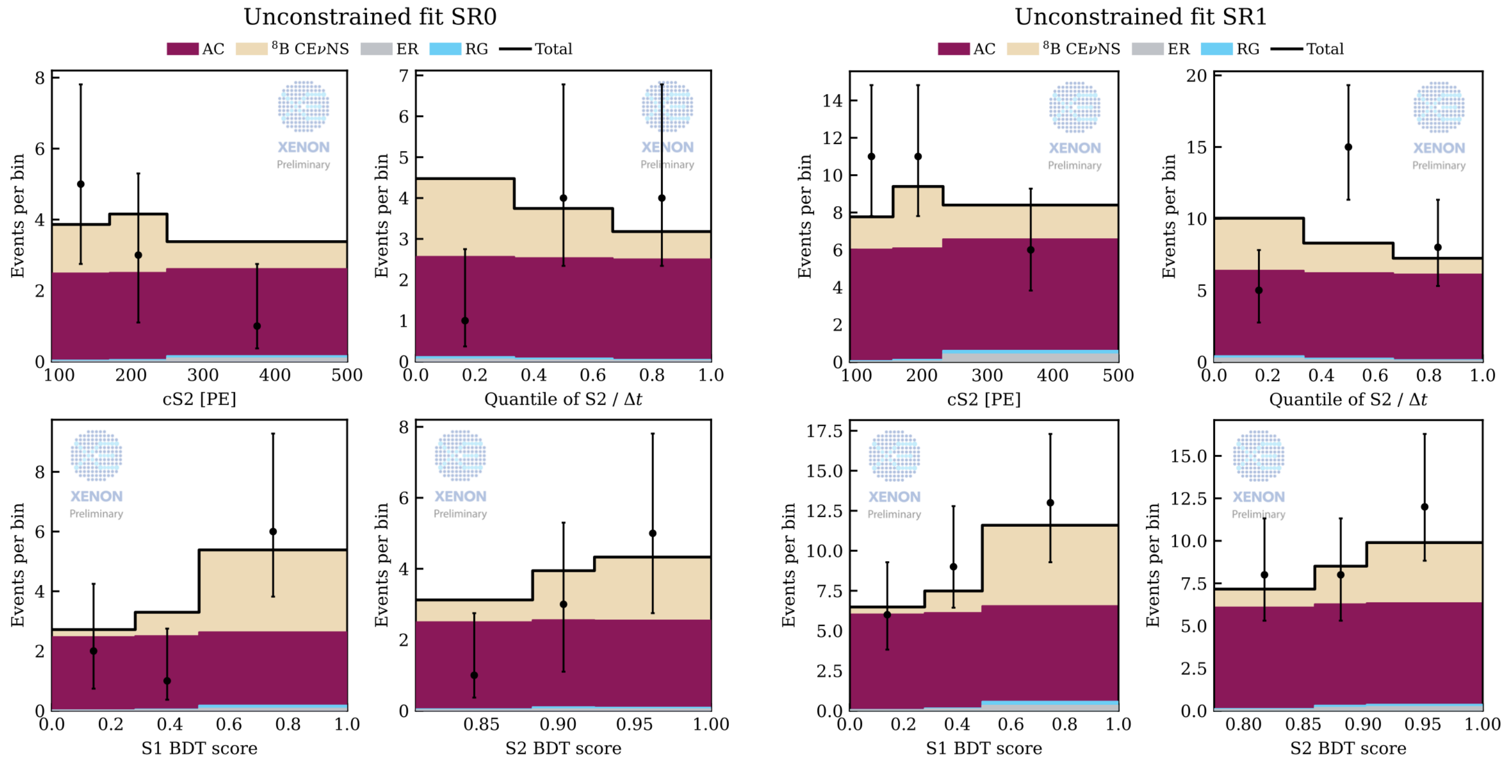
Data analysis and results

DATA AGREE WITH SIGNAL + BACKGROUND EXPECTATION

	NOMINAL EXPECT.	FIT BKG-ONLY	FIT SIG+BKG
ER	0.7 ± 0.7	0.74	0.54
NR	0.5 ± 0.3	0.50	0.45
(SR0) AC	7.5 ± 0.5	7.55	7.36
(SR1) AC	18 ± 1	18.26	17.90
TOTAL BKG	**26.4 ± 1.5**	**27.05**	**26.24**
^{8}B CEνNS SIGNAL	**12 ± 3**	**-**	**10.71**
SIGNAL + BKG	**38 ± 3**	**-**	**36.95**

37 OBSERVED EVENTS

No significant deviation of background and signal models parameters



4-dimensional analysis space for discrimination of the dominant background from accidental coincidence (AC) of isolated S1 and S2 signals.
Analysis validated with ^{37}Ar calibration data (L-shell electron capture, 0.27 keV).

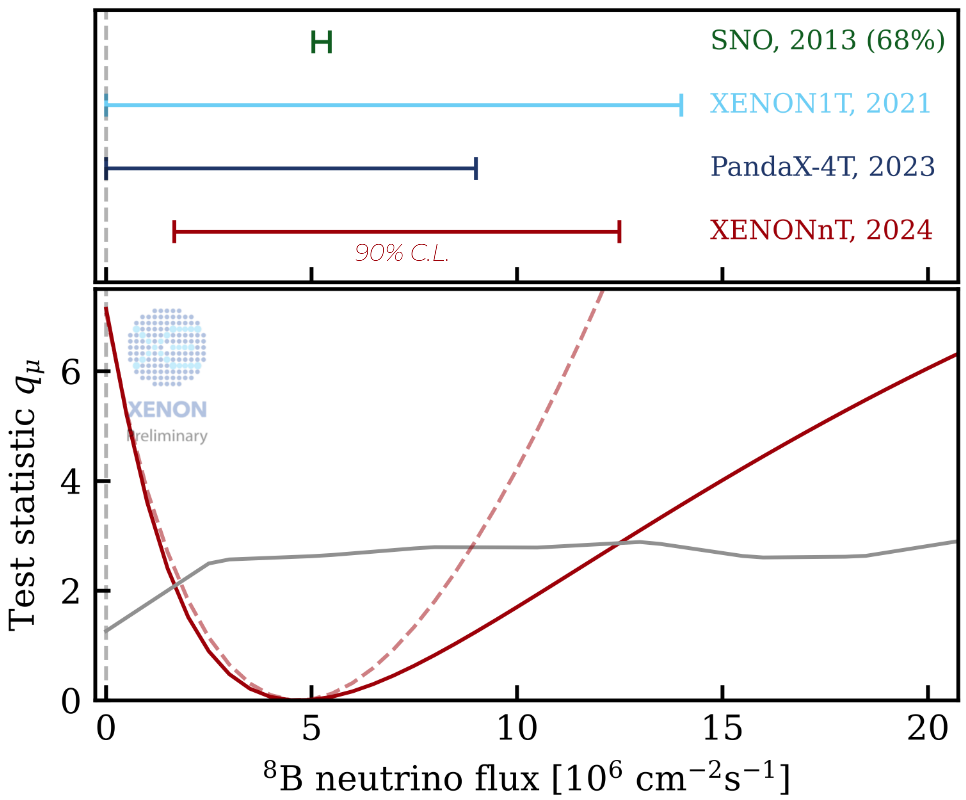
XENONnT MEASURED CEνNS

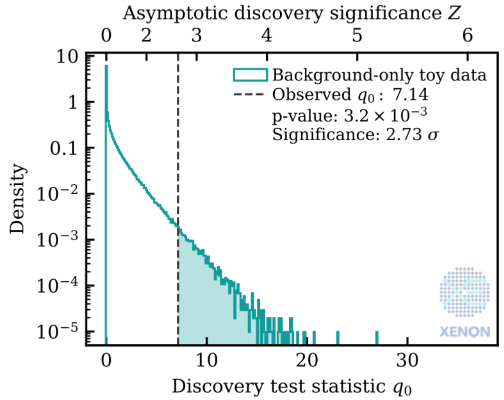
Paper in preparation

FIRST CEνNS MEASUREMENT FROM SOLAR NEUTRINOS

FIRST CEνNS MEASUREMENT WITH A Xe TARGET

FIRST DETECTION OF SOLAR NEUTRINOS BY A DARK MATTER EXPERIMENT

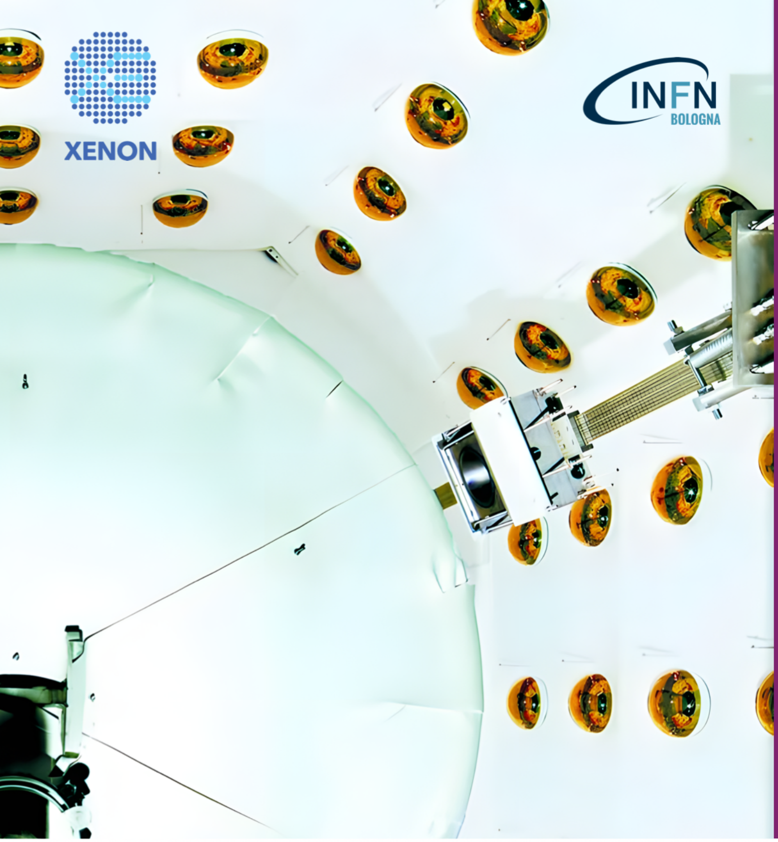




2.73 σ SIGNIFCANCE

for the rejection of the background-only hypothesis

With more exposure, we will measure ^{8}B solar neutrinos with higher significance and more precise constraint on their flux.



NV **Gd-DOPED** PHASE IN SR2

Further suppression of neutron background

Pure water in SR0 and SR1

500 ppm GdSO
current concentration

Dissolved 350 kg of Gd-sulphate in 2023

5000 ppm GdSO
final goal concentration

NEUTRON CAPTURES

on H	***2.2 MeV*** *single gamma*	***~200 μs*** *τ capture*
on Gd	***8 MeV*** *3-4 gammas*	***~75 μs*** *τ capture*

60% CAPTURES on Gd
with 500 ppm GdSO

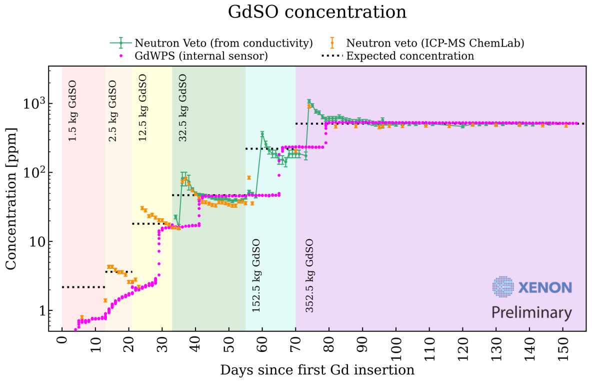
NV TAGGING EFFICIENCY

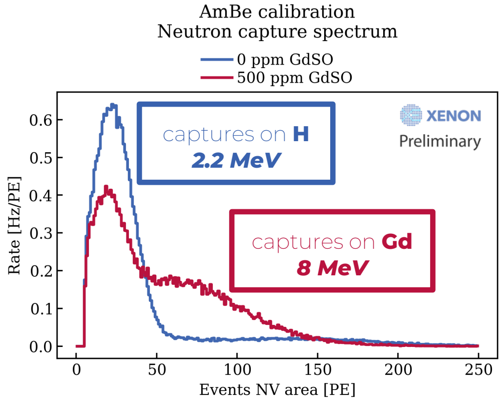
for 250 μs TPC-NV time coincidence window

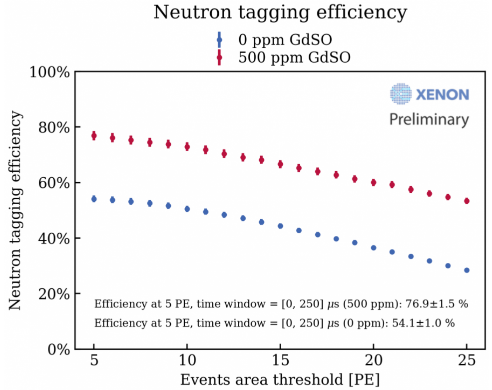
PURE WATER	***53%***
500 ppm GdSO	***77%***

FACTOR 2
NEUTRON BKG REDUCTION
SR0/SR1 → SR2

Transport system connection → Salt insertion → Stirrer activation

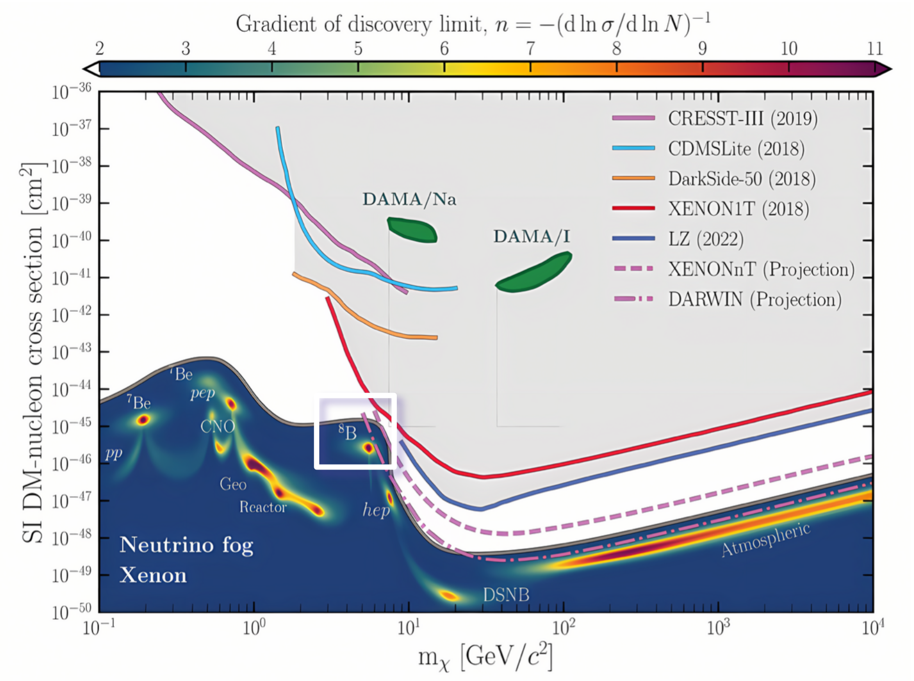






THE **FUTURE** OF XENONnT AND BEYOND

XENONnT *JUST GOT INSIDE* ***THE NEUTRINO FOG***



PHYSICS REACH OF LXe TPC

WIMP DARK MATTER
Standard 3-fold
Low mass 2-fold and S2-only

OTHER DM MODELS
Dark photons
ALPs
Planck mass
...

SOLAR NEUTRINOS
^{8}B, hep, ^{7}Be CEνNS
pp elastic scattering

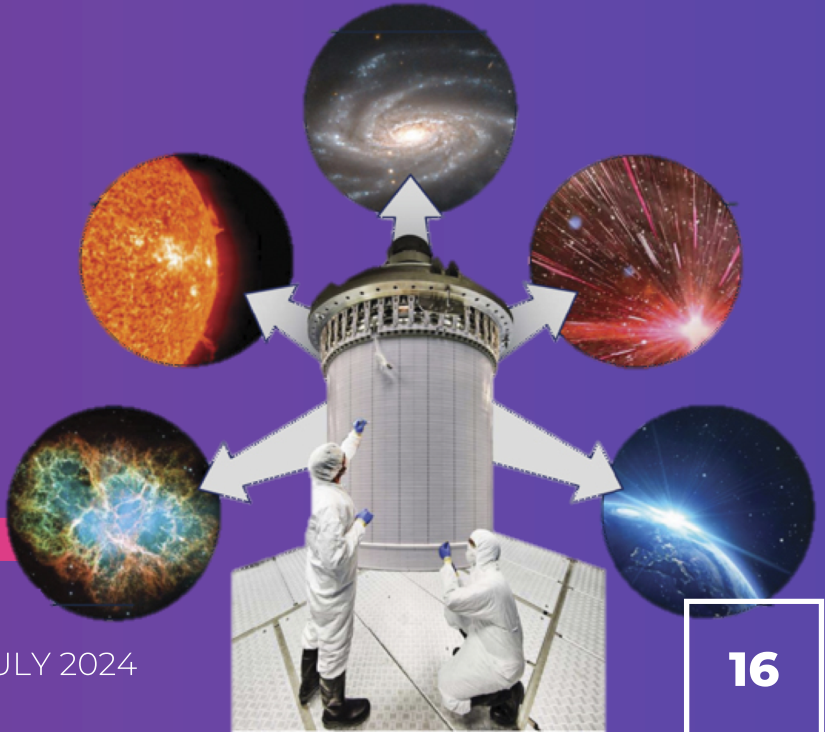
NEUTRINO NATURE
Neutrinoless double-beta decay
Double electron capture
Anomalous magnetic moment

ASTROPHYSICS
Supernova neutrinos (SNEWS)
Atmospheric neutrinos
GW multi-messenger

NEXT-GENERATION DETECTOR

~50 t *LXe TARGET*	***R&D*** *in progress*

Established XENON-LZ-DARWIN CONSORTIUM



QUICK SUMMARY

SR0–SR1 COMPLETED
SR2 ONGOING
> 3.5 t·y EXPOSURE

UNPRECEDENTED
ER BACKGROUND

SR0 ER SEARCHES
XENON1T EXCESS
EXCLUDED

SR0 COMPETITIVE
BLINDED LIMITS ON
WIMPs

FIRST OBSERVATION
OF ^{8}B SOLAR
NEUTRINO CEνNS

Gd-DOPED NV
MORE CHANNELS
TO EXPLORE

XENON WEBSITE
xenonexperiment.org

BACKUP SLIDES

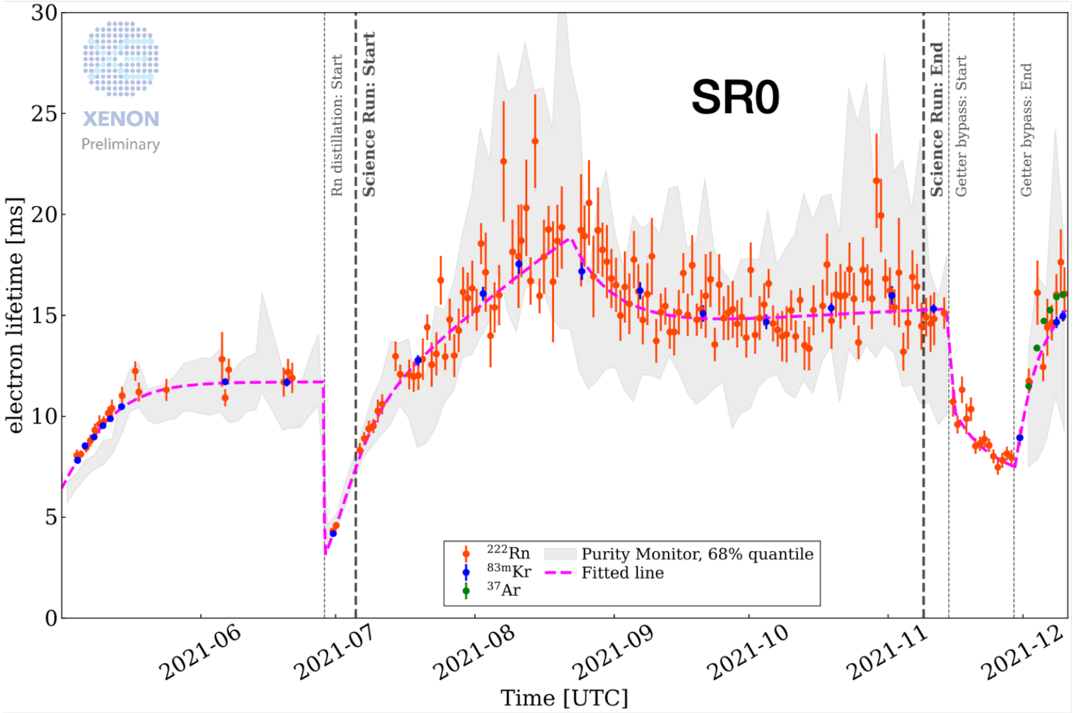
Are WIMPs ruled out?

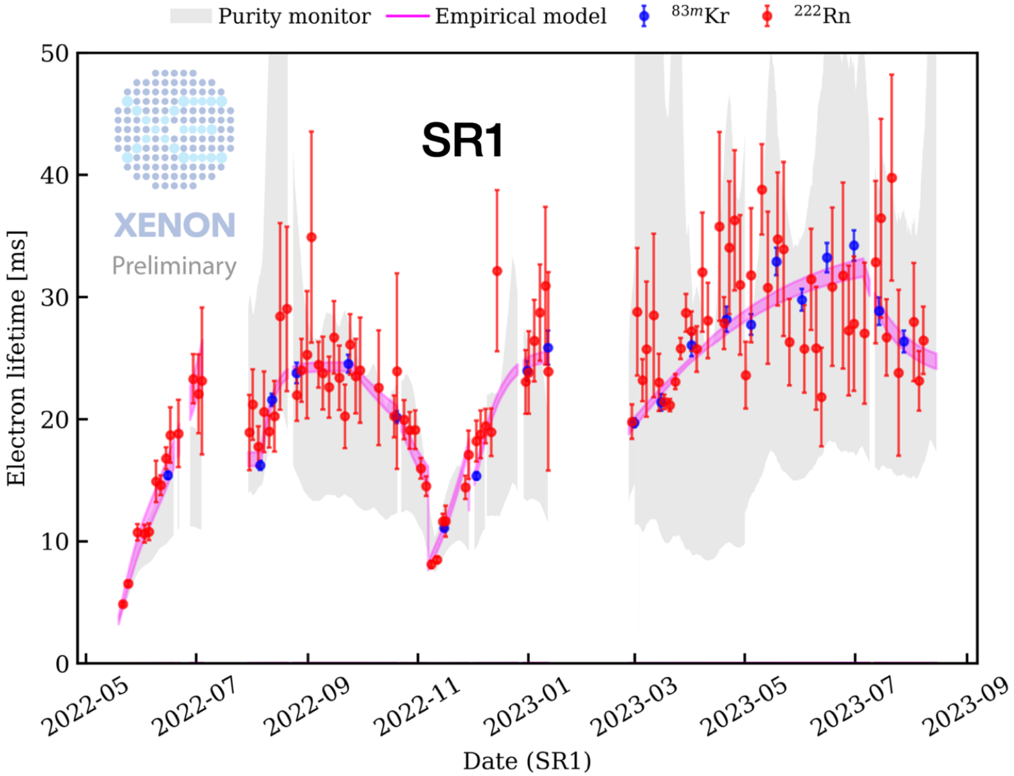
NO

absence of evidence ≠ evidence of absence

Credits: G. Bertone, ICHEP 2022

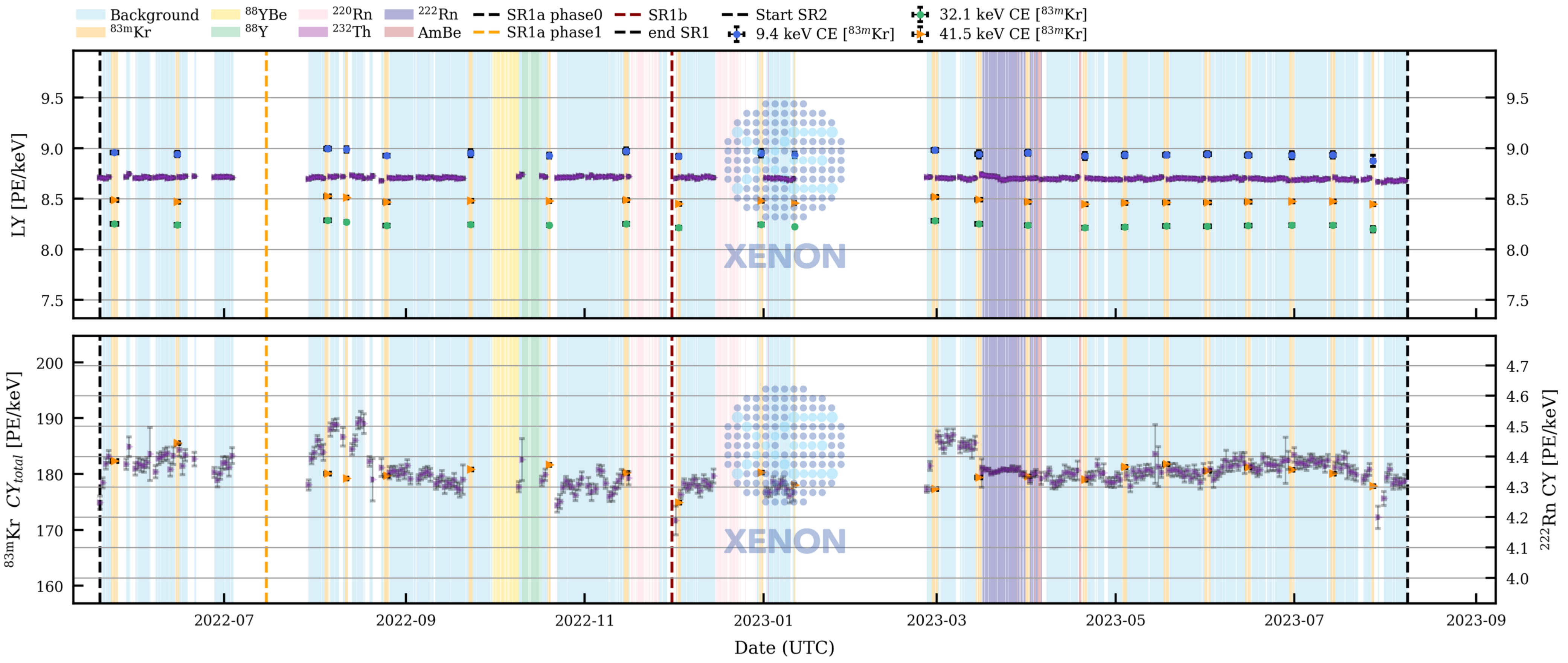
LXe PURITY IN XENONnT





Credit: Fei Gao, IDM 2024

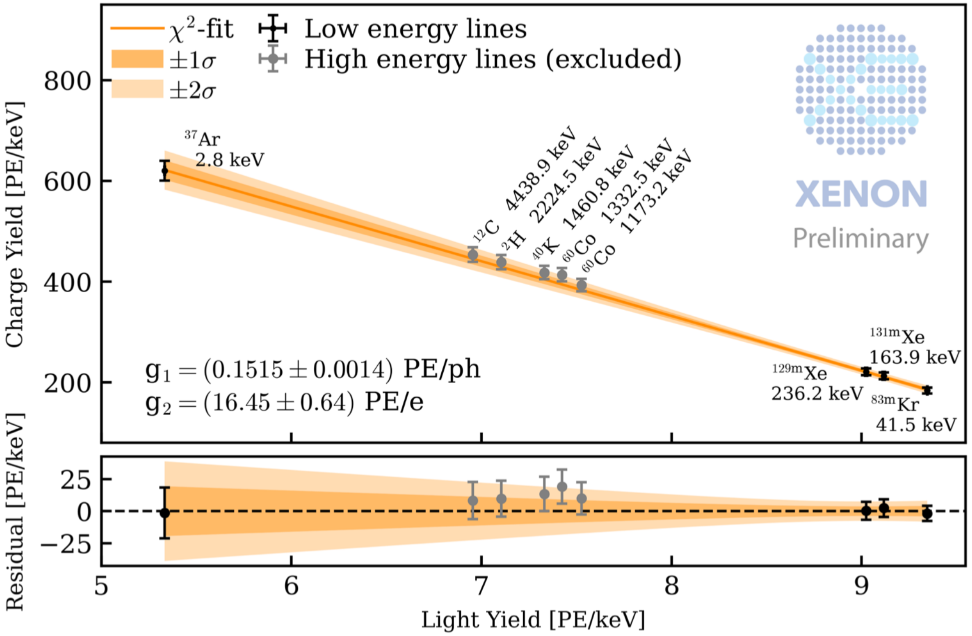
STABILITY OF XENONnT IN SR0 AND SR1



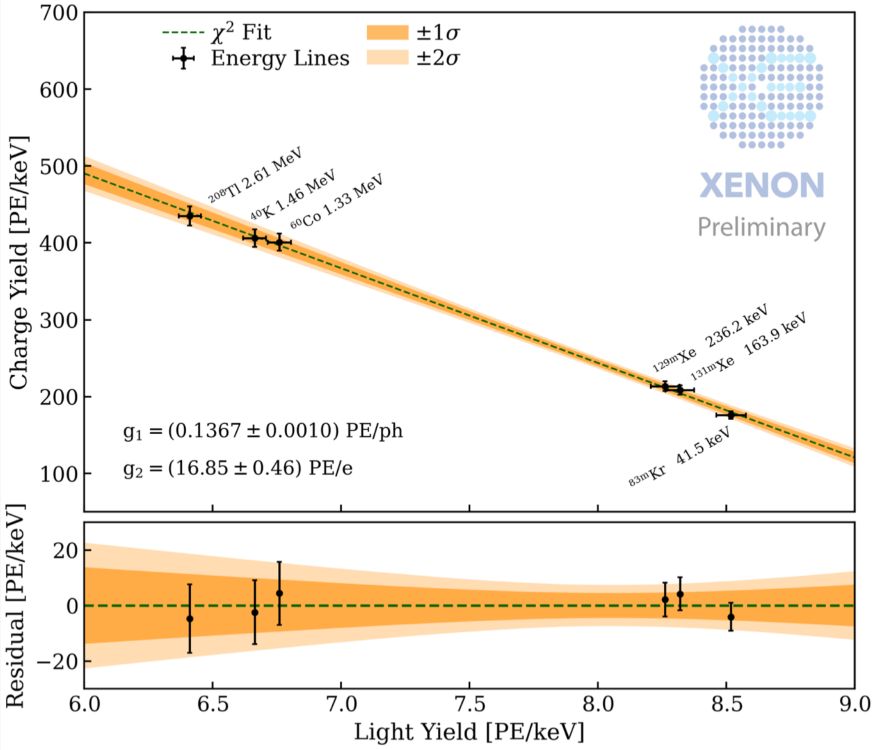
Credit: Fei Gao, IDM 2024

CALIBRATION OF TPC RESPONSE

SR0



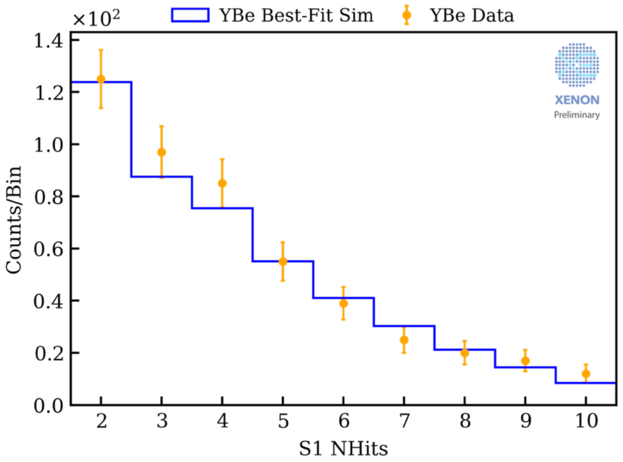
SR1

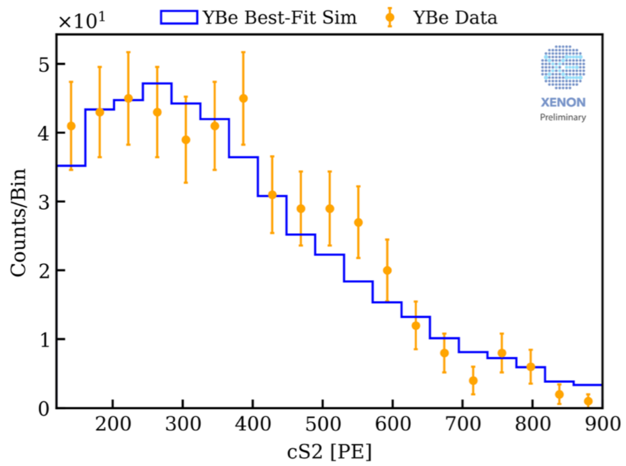


Science Run	g1 [PE/ph]	g2 [PE/e]
SR0	0.1515 ± 0.0014	16.45 ± 0.64
SR1	0.1367 ± 0.0010	16.85 ± 0.46

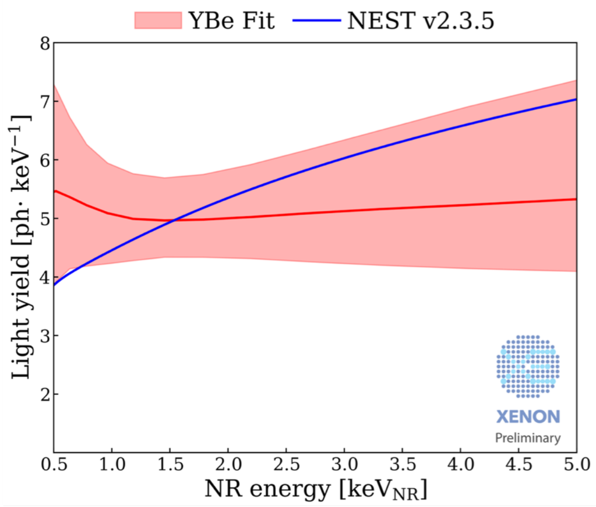
Credit: Fei Gao, IDM 2024

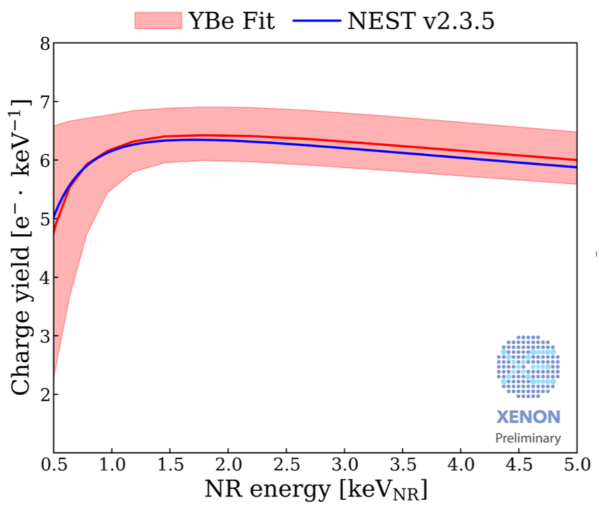
CALIBRATION OF Xe RESPONSE TO LOW ENERGY NRs





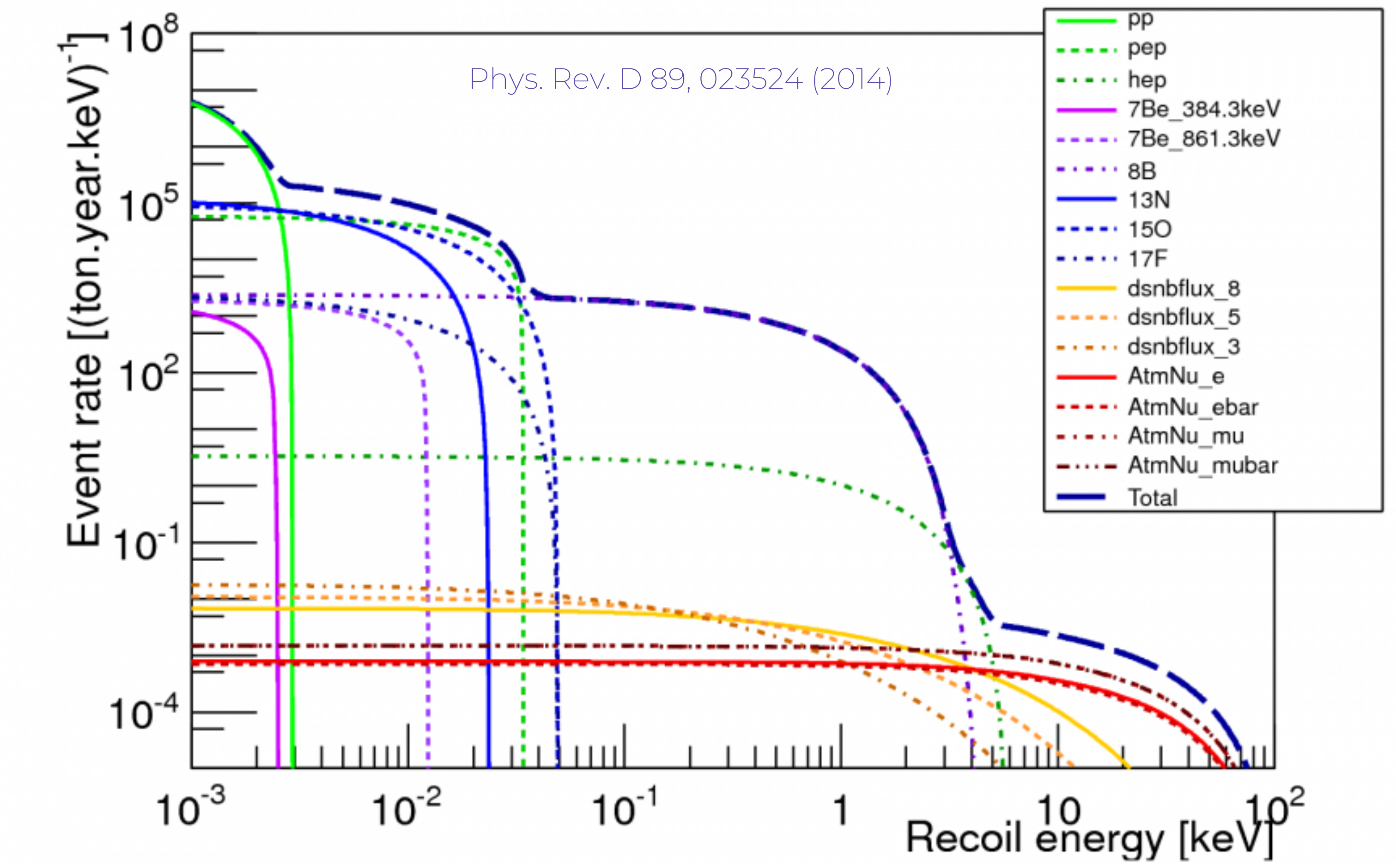
Excellent match between Data and Model



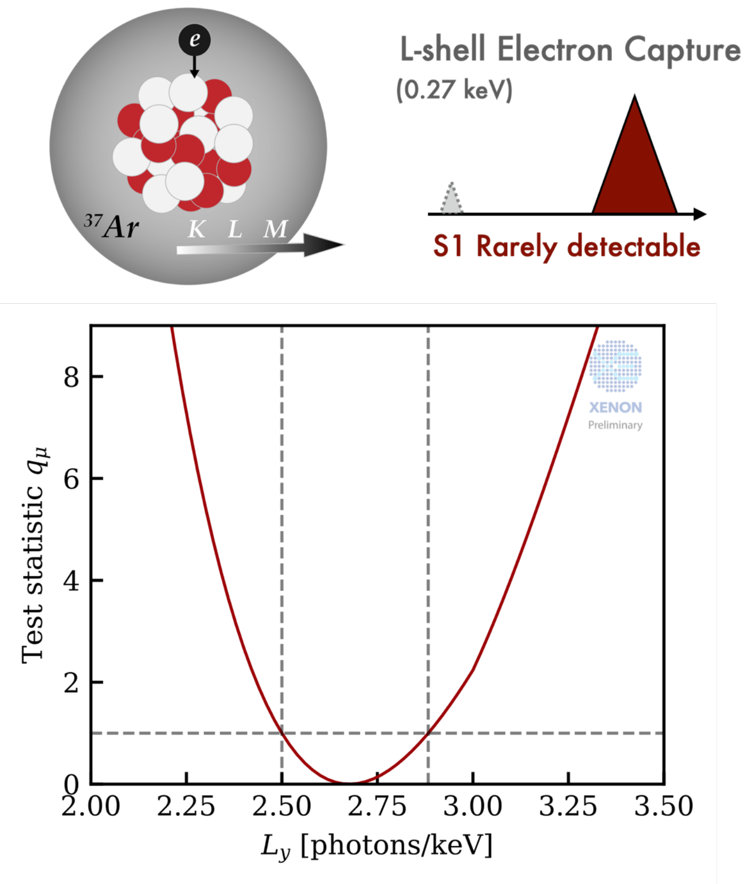


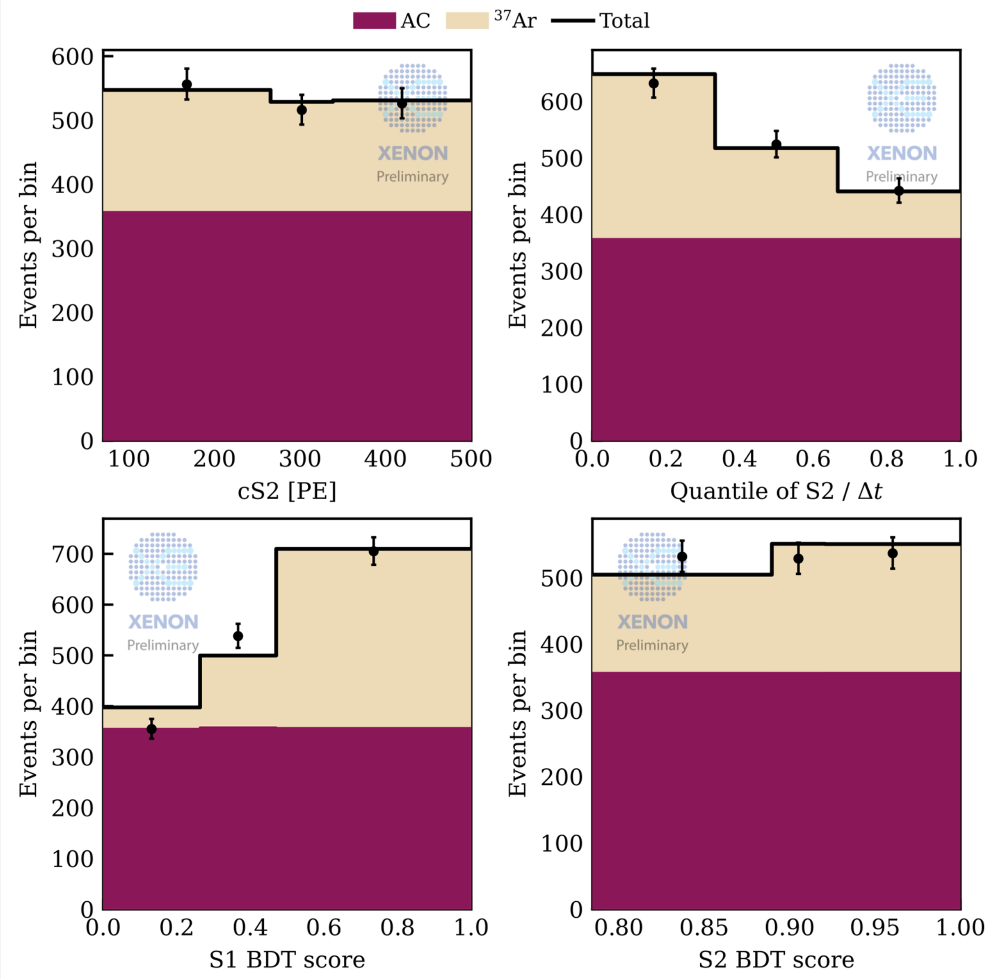
NEST model is constrained by YBe data to predict the light and charge yield in the ^{8}B CEvNS energy range at the XENONnT drift field

NEUTRINO-INDUCED NRs in Xe



CEvNS ANALYSIS VALIDATION WITH AR-37





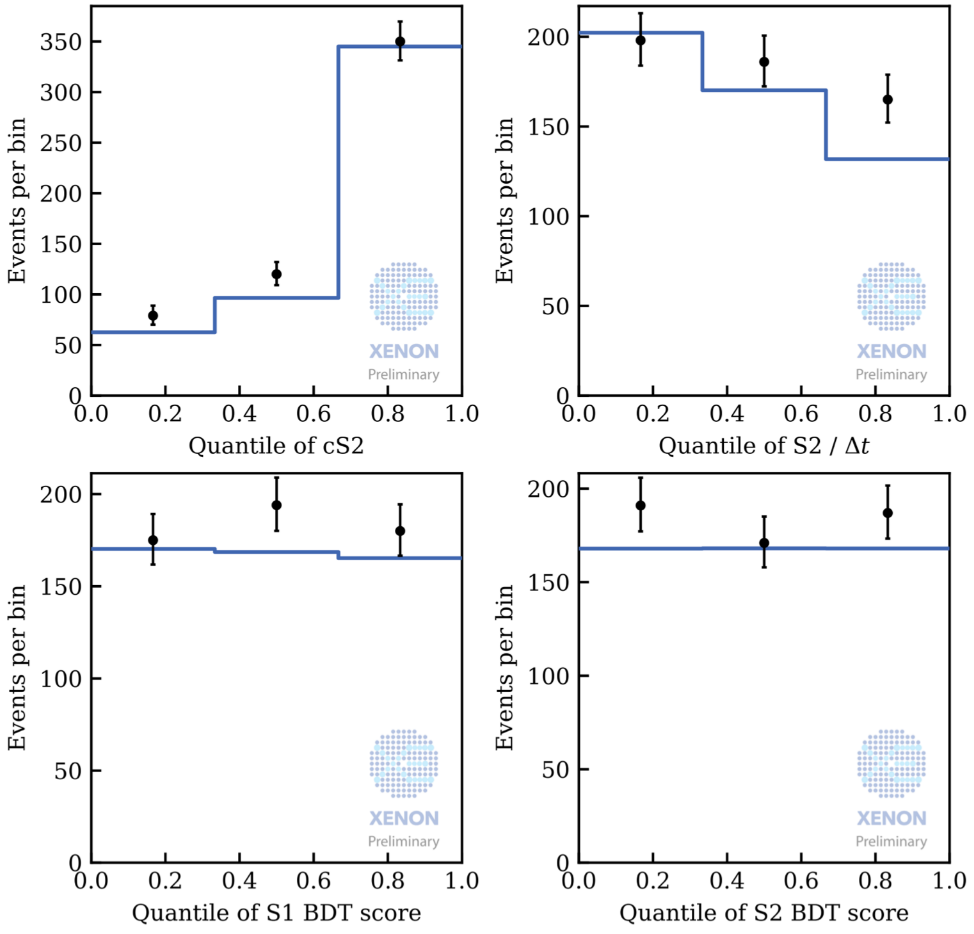
Credit: Fei Gao, IDM 2024

AC SIDEBAND UNBLINDING

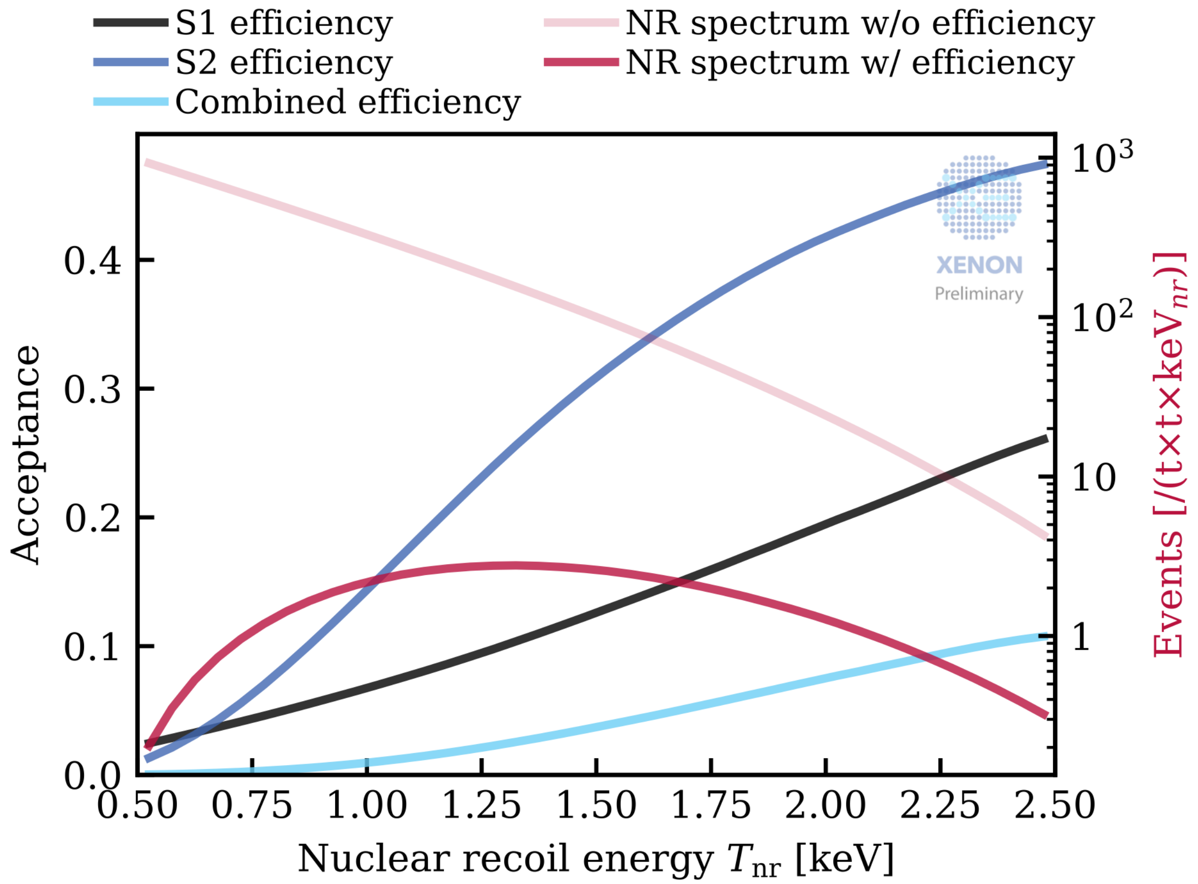
The S2 threshold is increased to 120 PE after sideband unblinding!

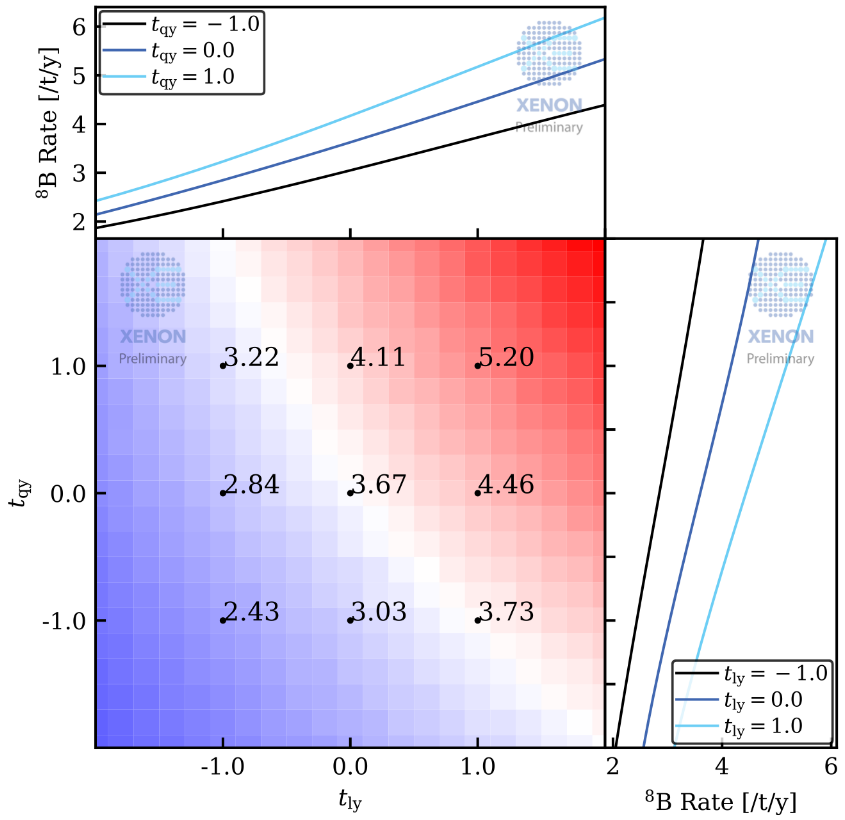
Science Run	Expectation	Observation	P-value (4D)	Deviation from expectation
SR0	122.7	121	0.33	-0.15 sigma
SR1	290.0	310	0.252	1.17 sigma

The remaining differences are considered potential systematical uncertainties! (<10%)



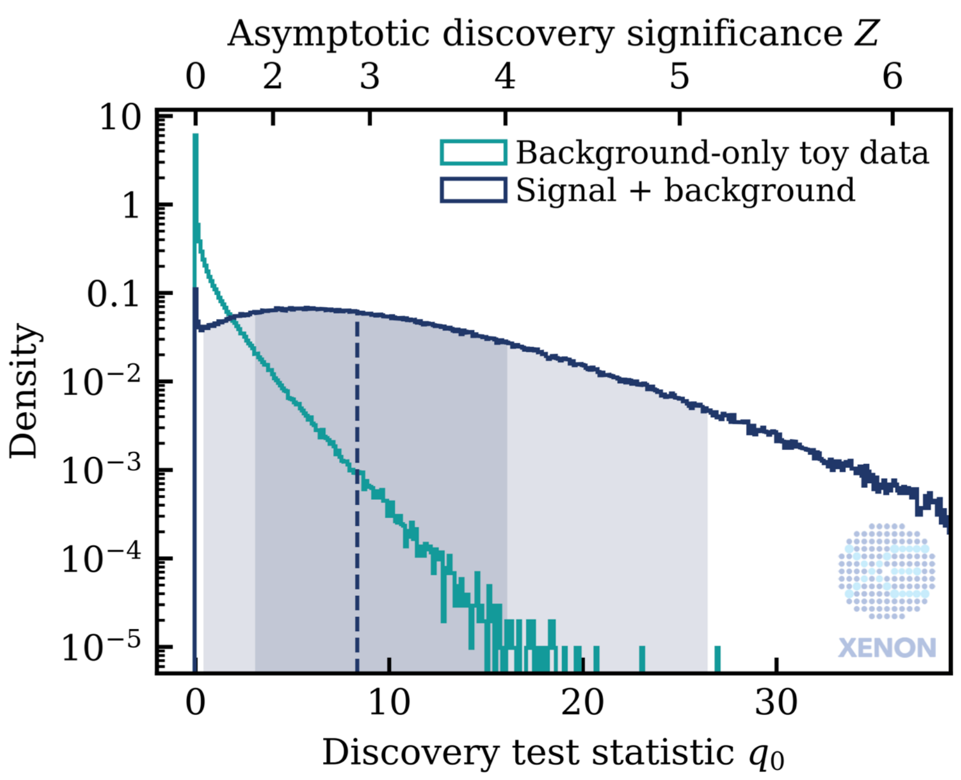
EFFICIENCY AND UNCERTAINTIES

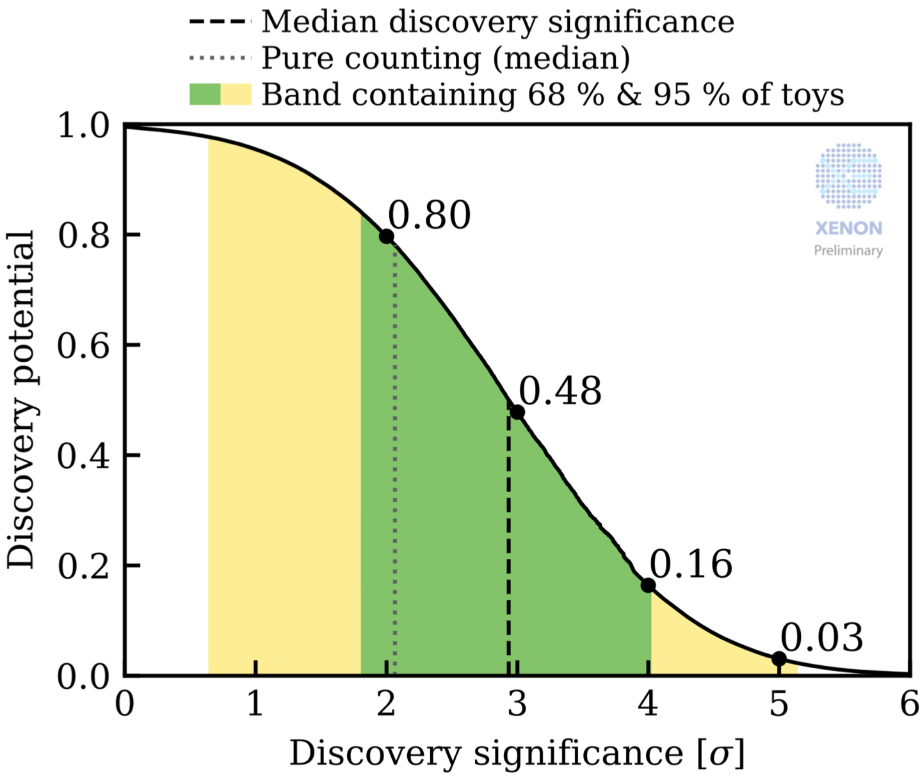




Credit: Fei Gao, IDM 2024

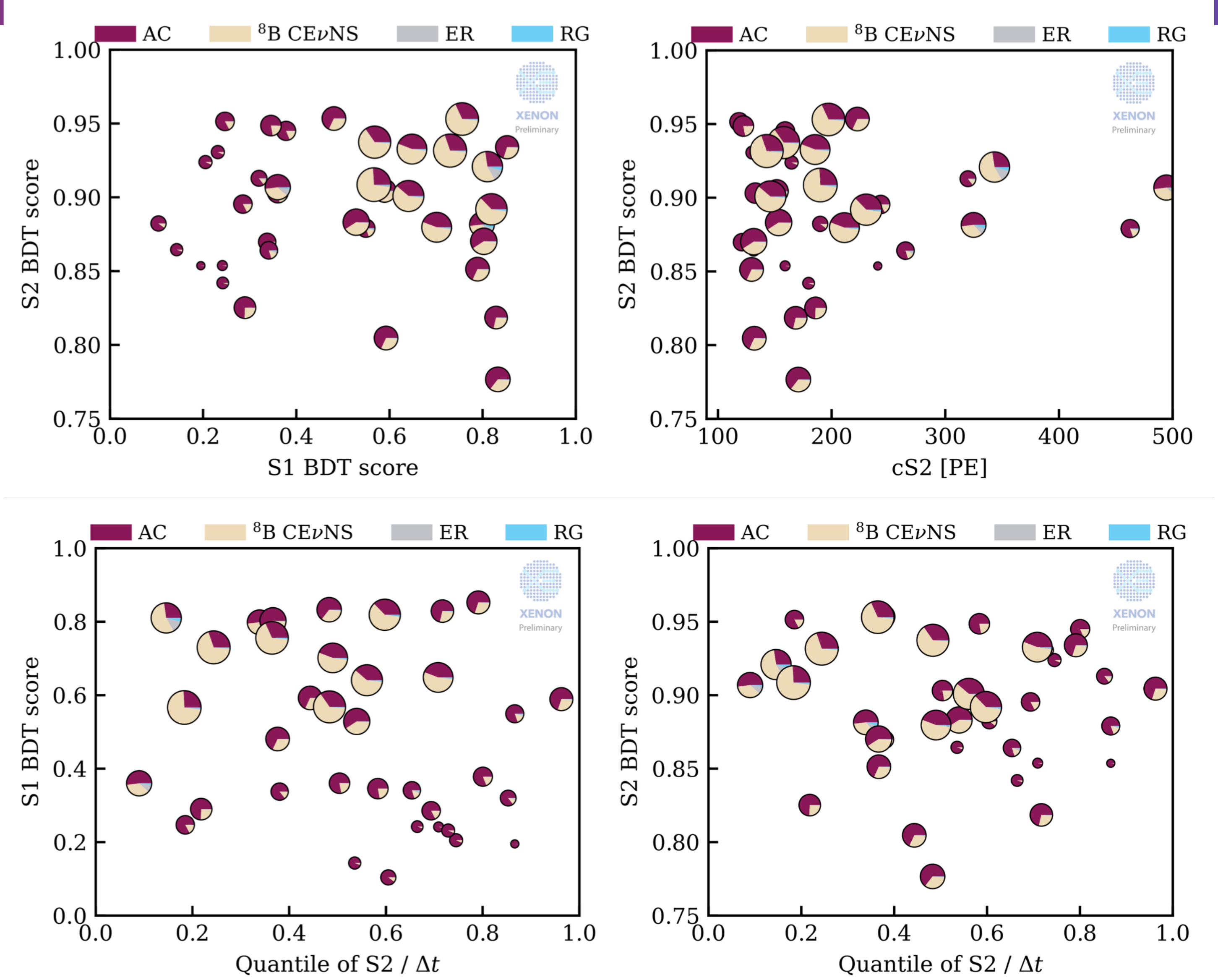
CEvNS DISCOVERY POTENTIAL

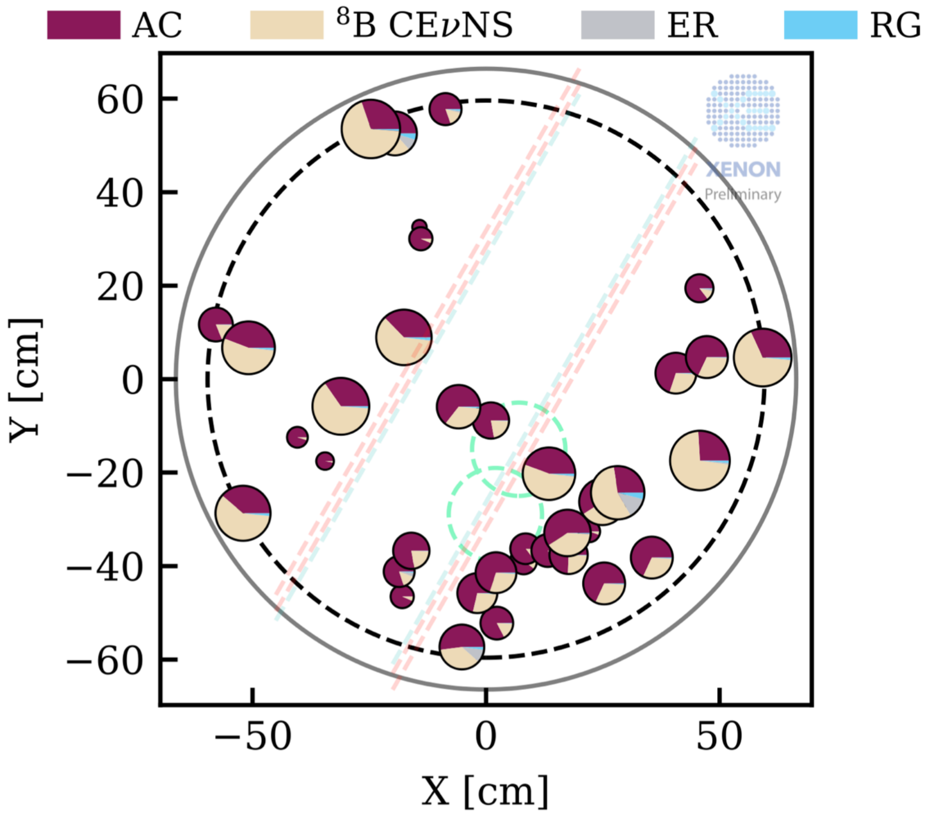


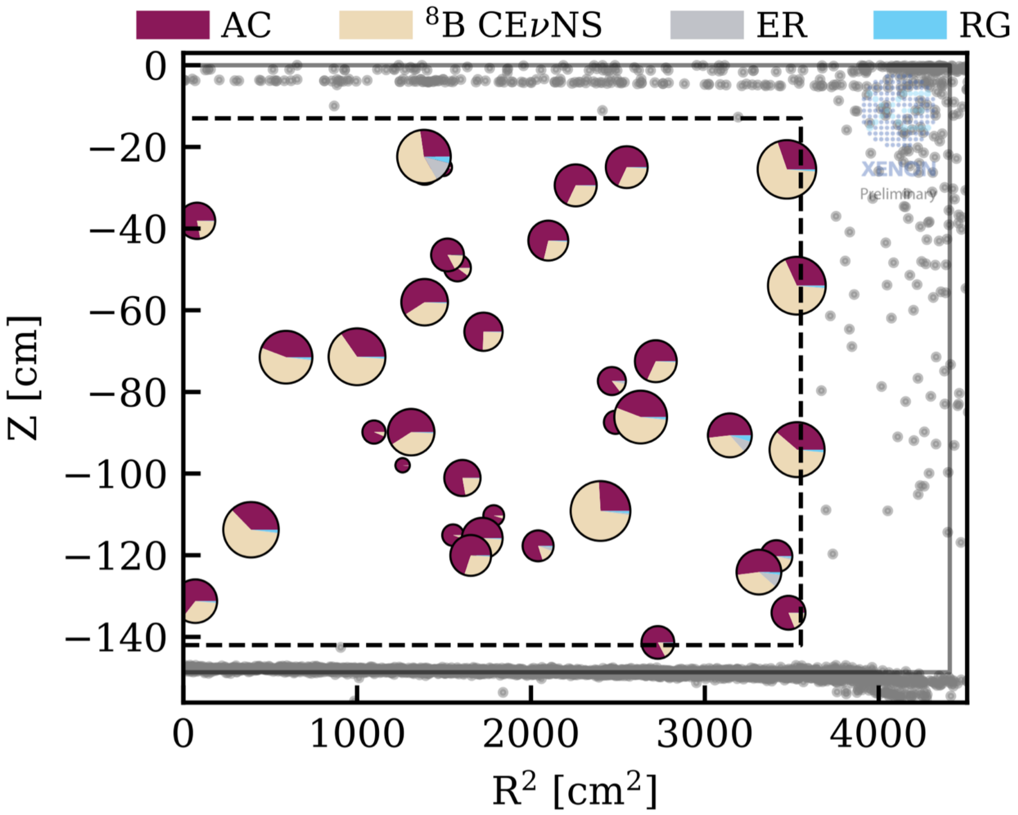


We expect to see solar ^{8}B neutrinos at >3(2) sigma significance with a probability of 0.48 (0.80), with a full 4-D analysis

UNBLINDED EVENTS

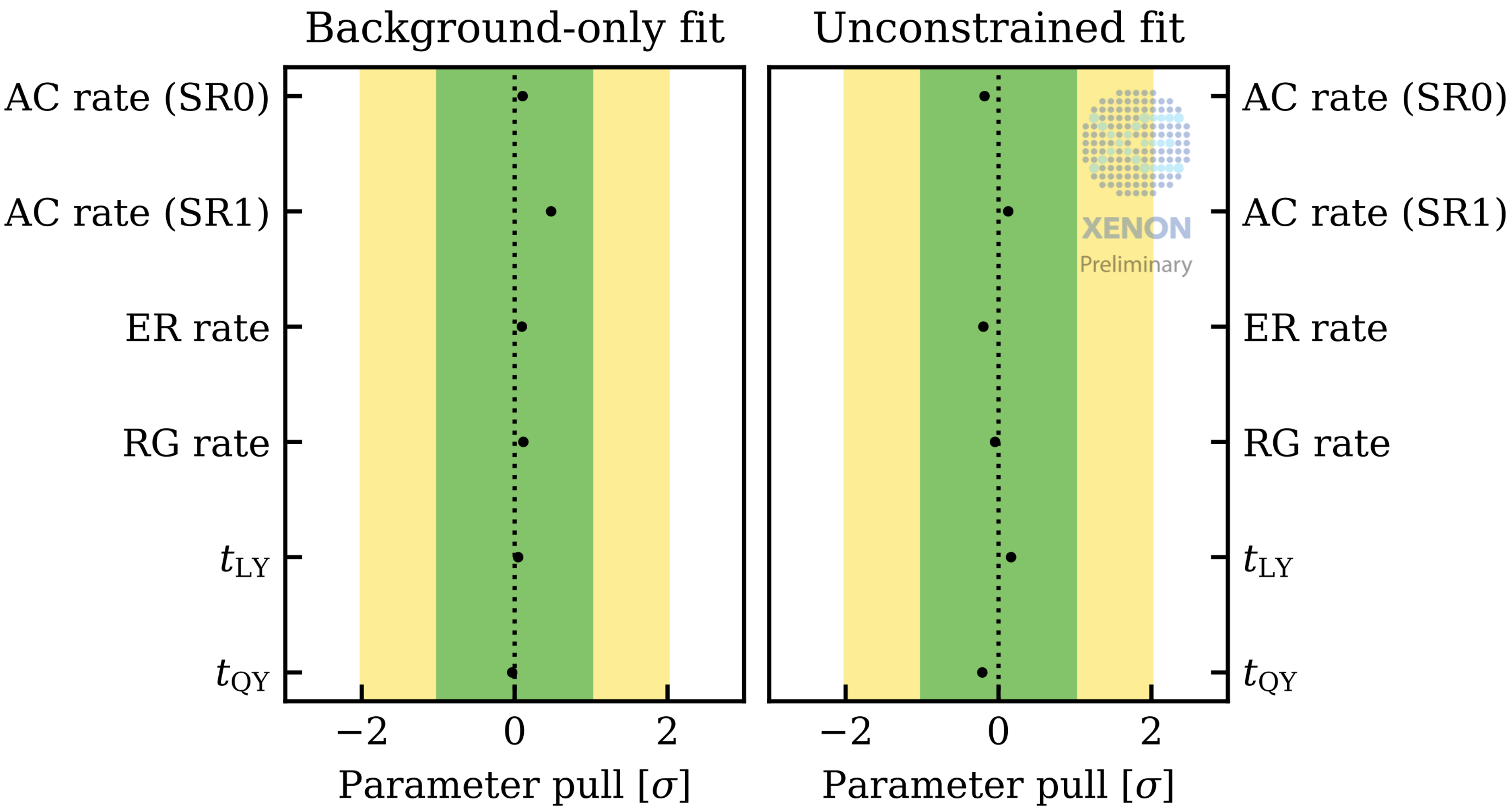






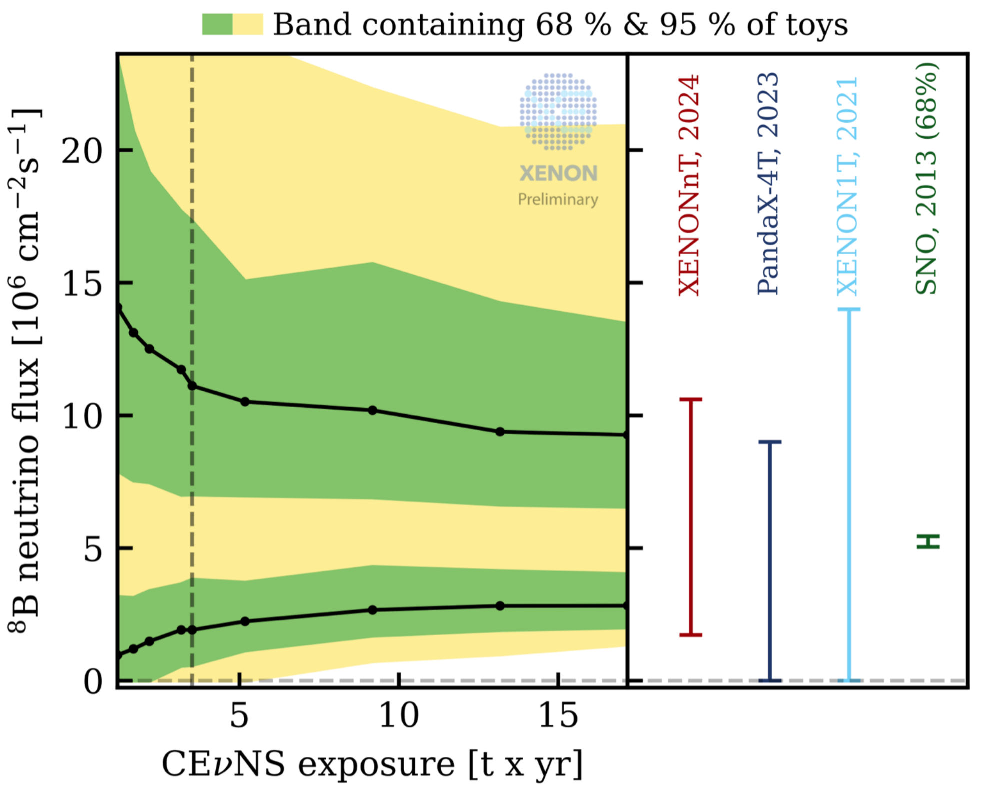
X, Y, and Z information are not considered in the likelihood analysis.

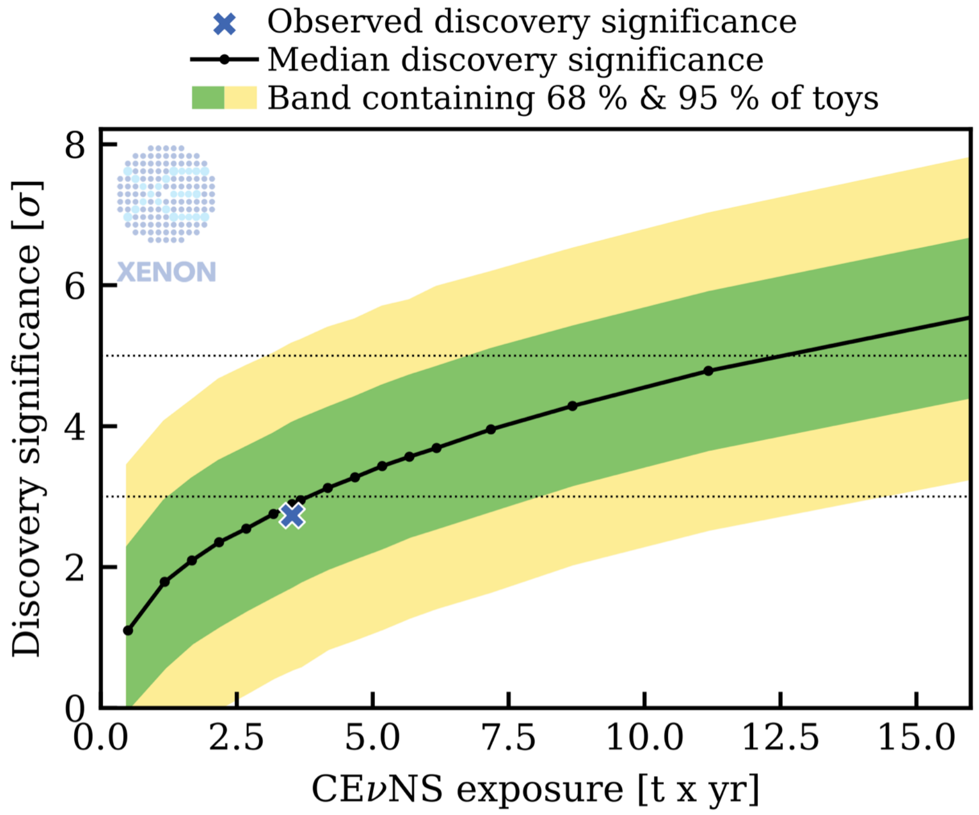
ANALYSIS PARAMETRS PULL



Credit: Fei Gao, IDM 2024

EVOLUTION OF SENSITIVITY TO CEvNS

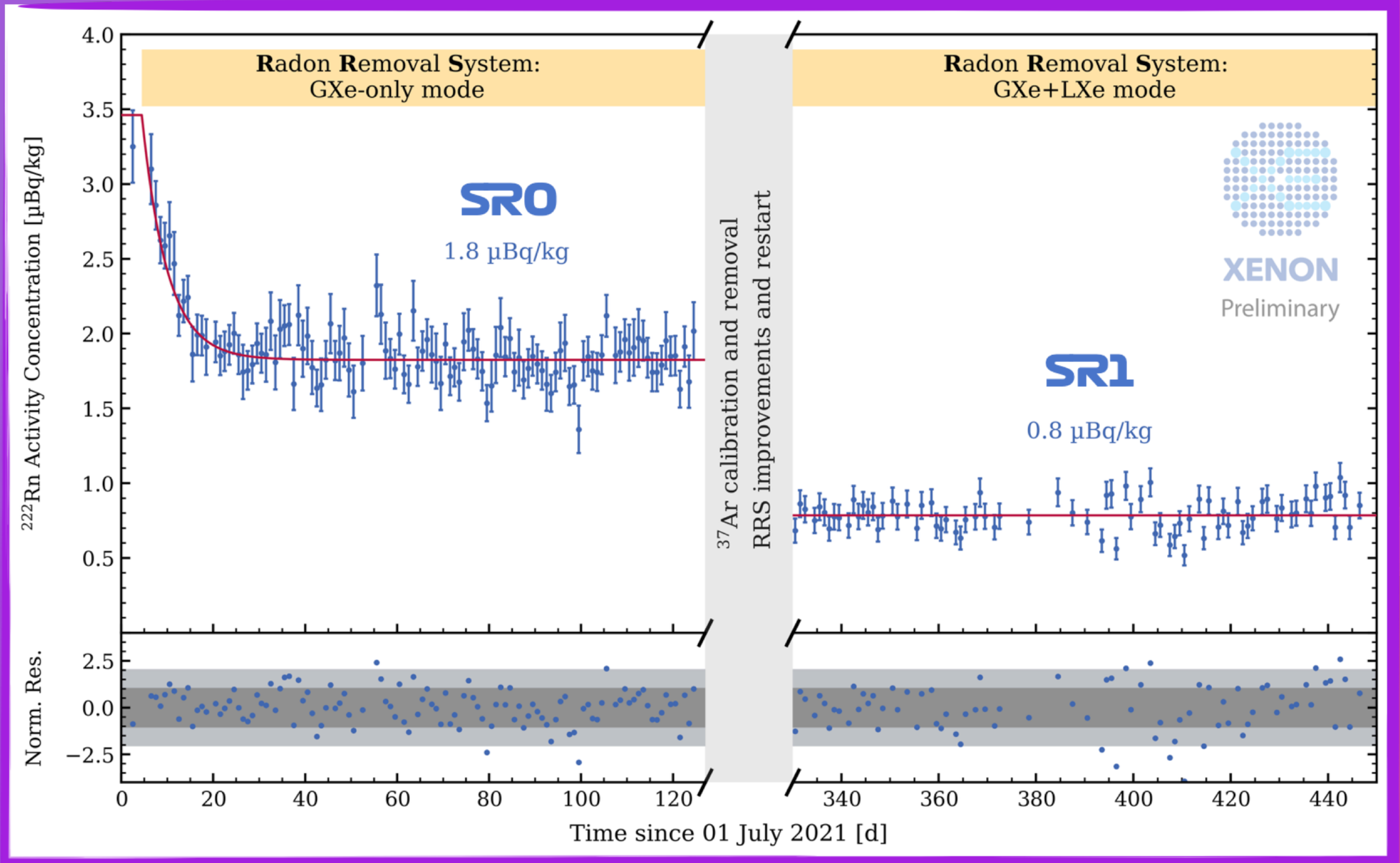




The improvements in flux measurement are limited by uncertainties of the LXe response to nuclear recoils.

Credit: Fei Gao, IDM 2024

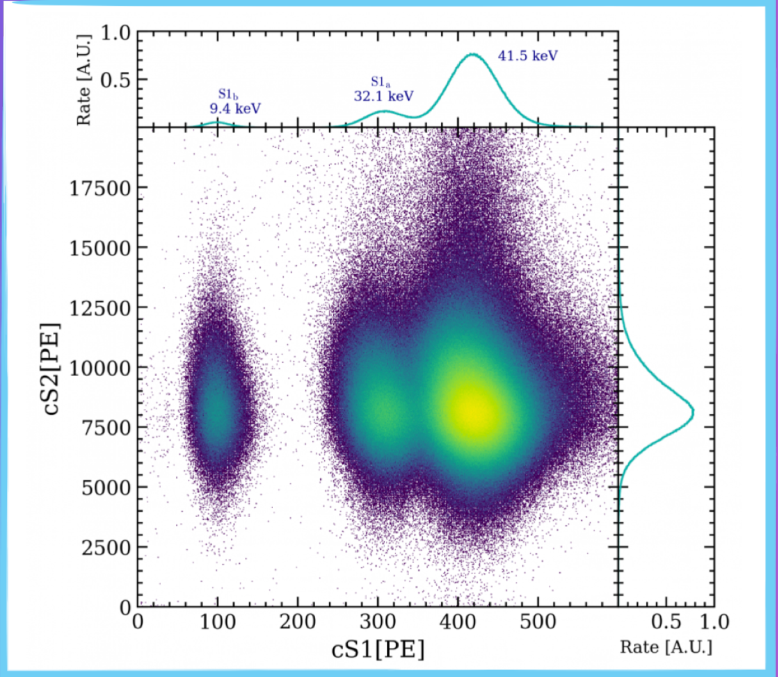
RN-222 LEVEL



Radon Removal System:
GXe-only mode
Radon Removal System:
GXe+LXe mode
SR0
1.8 µBq/kg
SR1
0.8 µBq/kg
XENON
Preliminary
37Ar calibration and removal
RRS improvements and restart
222Rn Activity Concentration [µBq/kg]
Norm. Res.
Time since 01 July 2021 [d]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2.5
0.0
−2.5
0
20
40
60
80
100
120
340
360
380
400
420
440

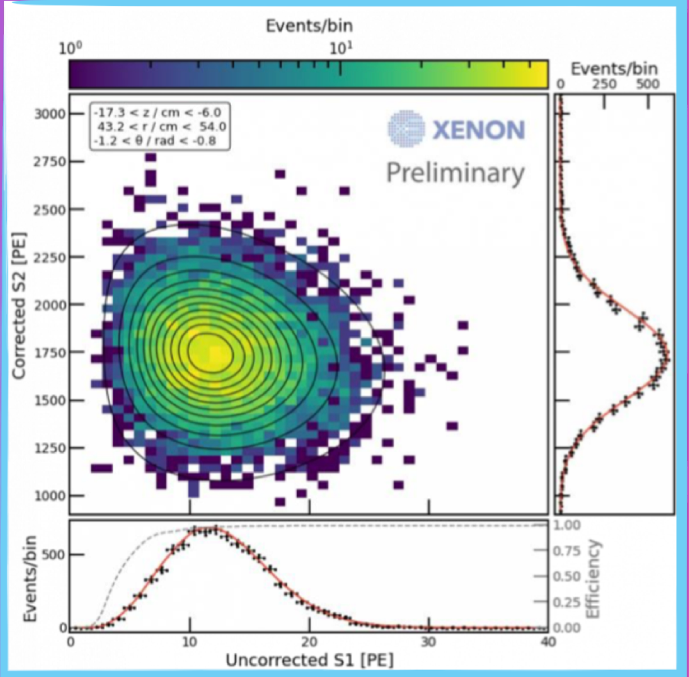
ER CALIBRATION SOURCES

KRYPTON-83m



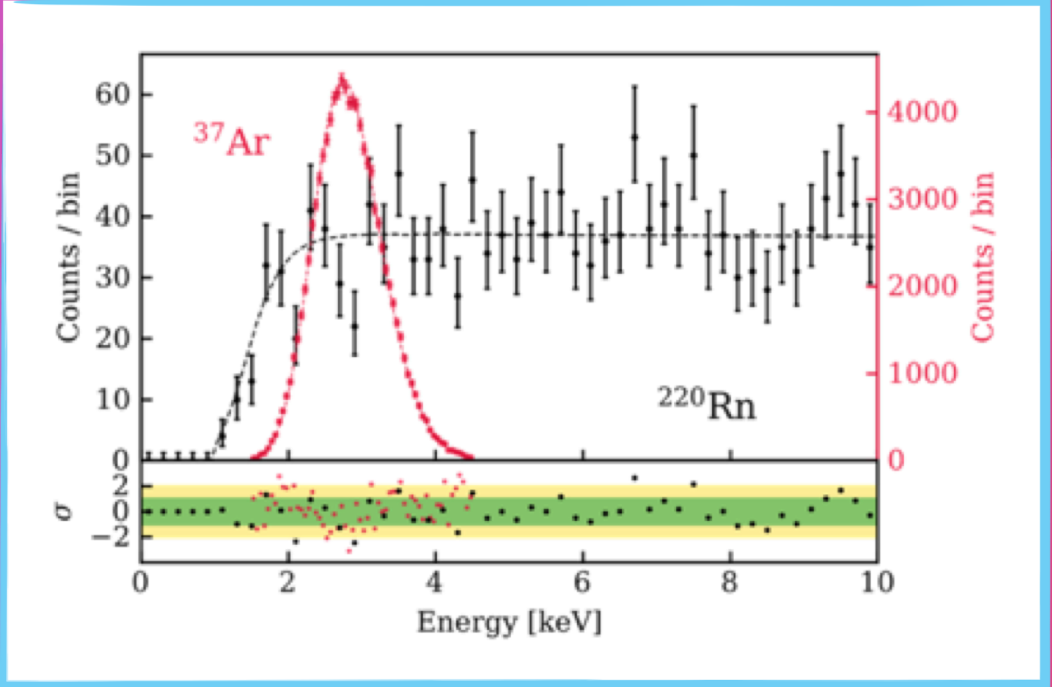
- Injected every 14 days
- Spatial corrections:
  S1 LCE, S2 LCE, drift field distortion
- Validation of drift field COMSOL simulation

ARGON-37



- Monoenergetic peak at 2.82 keV
- Low energy response and resolution with high statistics

RADON-220



- Flat beta spectrum from Pb-212
- Cut acceptances estimation
- Energy threshold validation
- Used to define the blinding region

ER – NR BANDS CALIBRATION

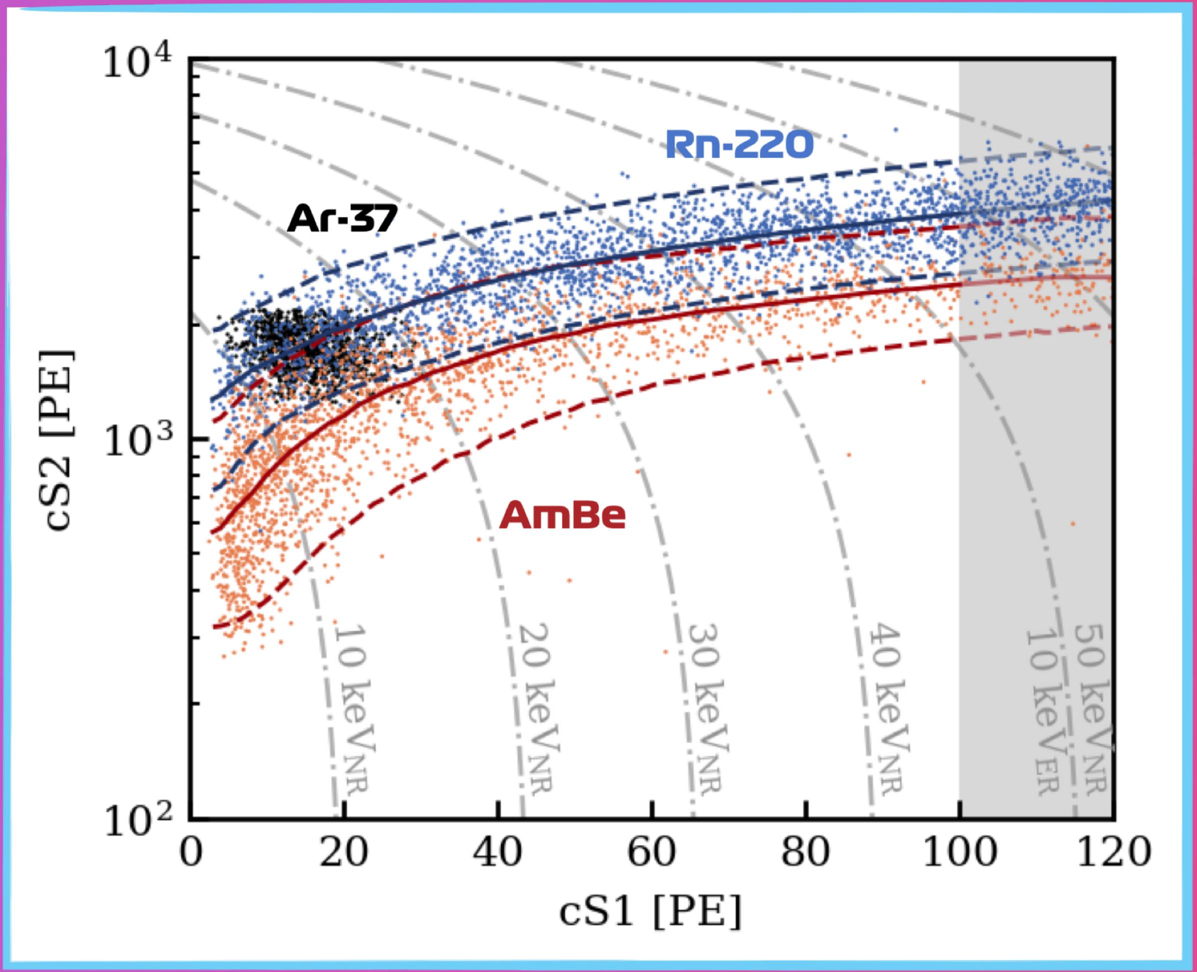
ER BAND

- Radon-220 (flat energy spectrum)
- Ar-37 (peak at 2.8 keV)

NR BAND

- AmBe (neutron source)

ER/NR bands separation
Fraction of ER events below NR median = 1.1%



LOW-ENERGY ER SEARCHES (SR0)

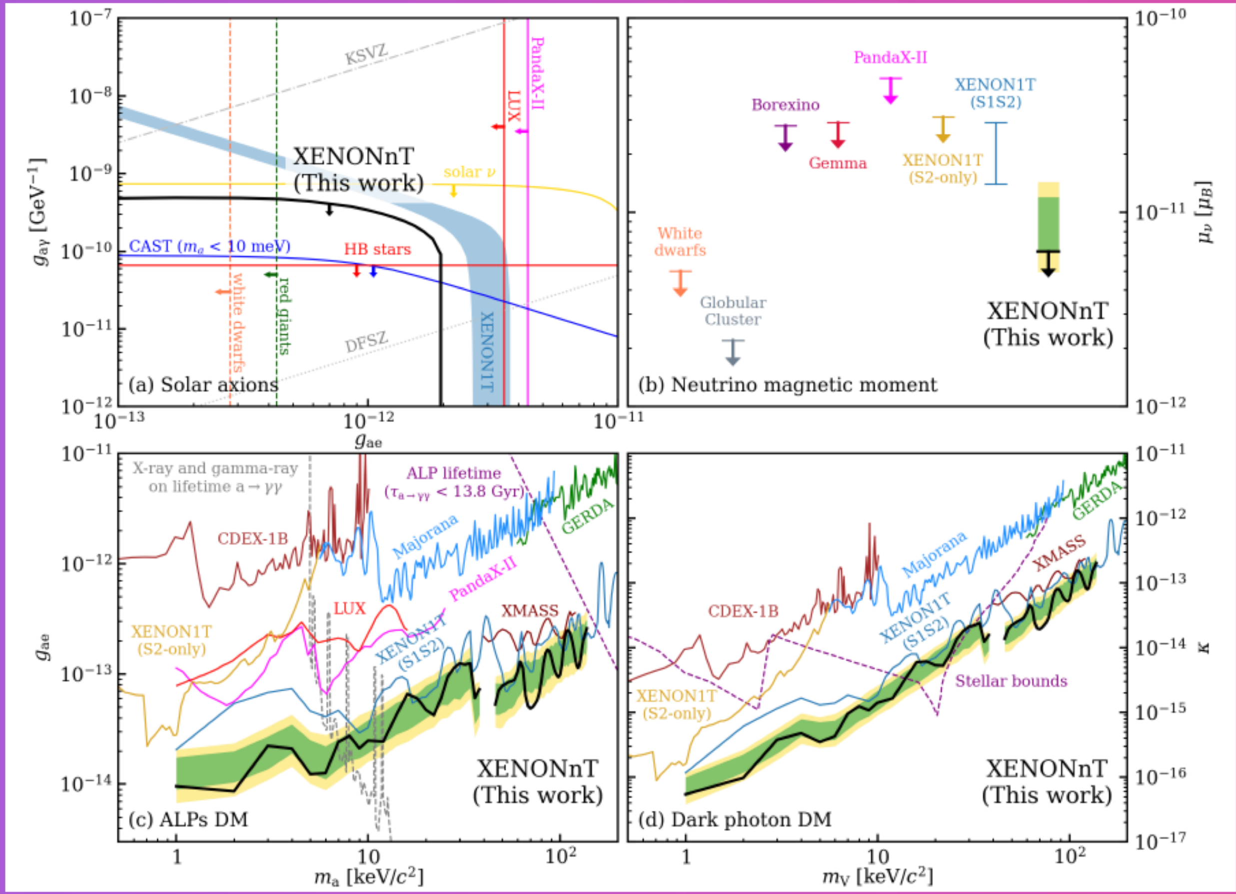
Search for New Physics in Electronic Recoil Data from XENONnT
XENON Collaboration, Phys. Rev. Lett. 129, 161805,arXiv:2207.11330 [hep-ex]

SOLAR AXIONS

- Significantly improved constraints on axion-gamma, axion-electron and axion-nucleon couplings

AXION-LIKE PARTICLES AND DARK PHOTONS

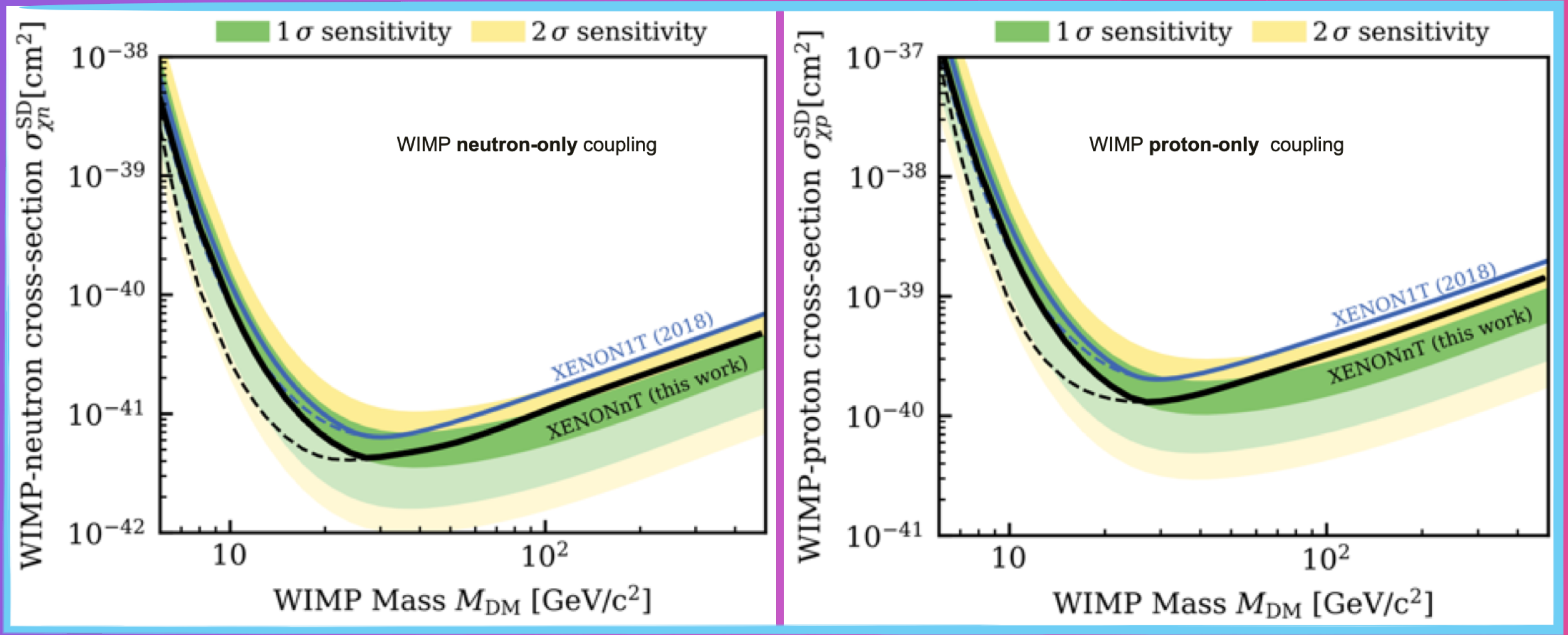
- Search for a peak found no significant excess
- New stringent limits in the range 1-140 keV
- No limits at 41.5 keV as the Kr-83m rate is left unconstrained



NEUTRINO MAGNETIC MOMENT

- $\mu_\nu < 6.3 \times 10^{-12} \mu_B$
- The most stringent limit in any direct detection experiment

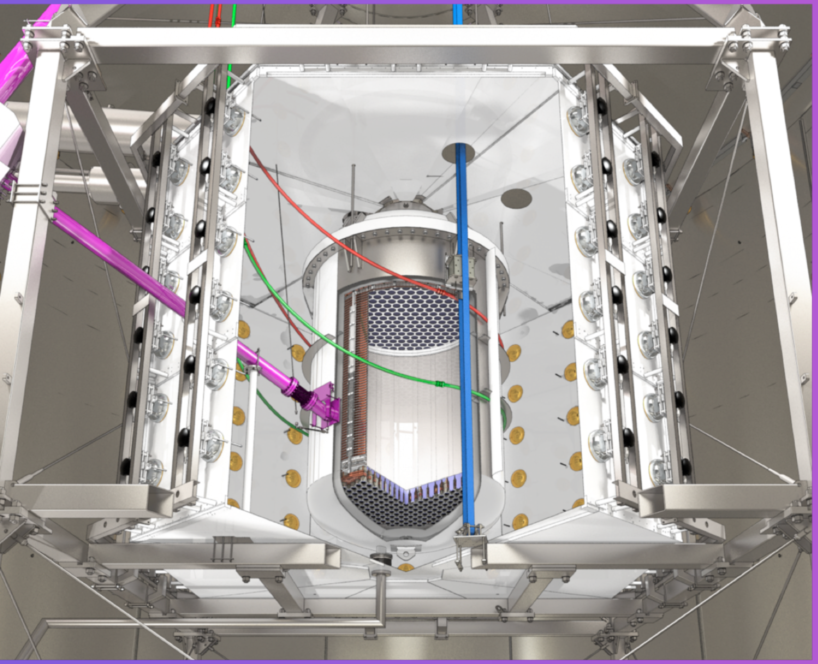
SD WIMP LIMITS (SR0)

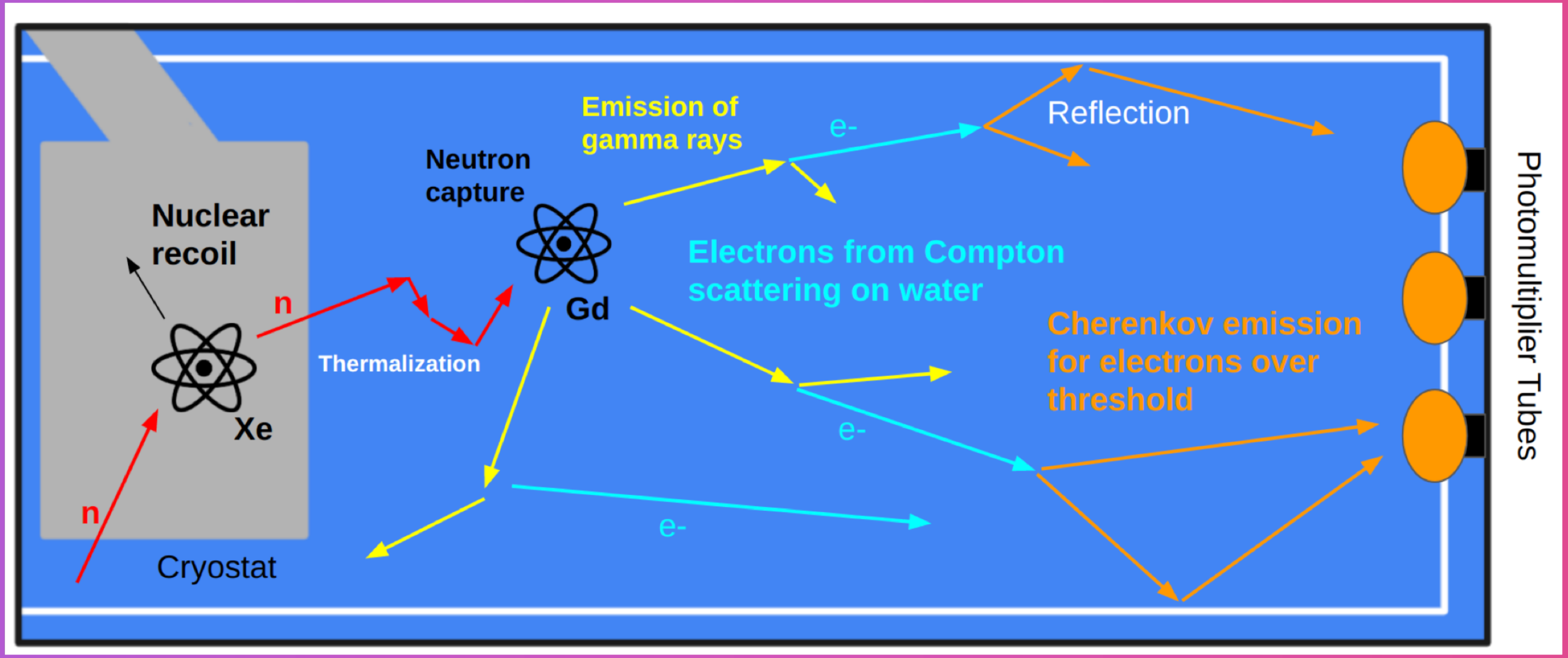


- Non-zero spin operator for ^{129}Xe and ^{131}Xe, due to unpaired neutrons
- In general, more sensitive to neutron-spin coupling

NEUTRON VETO

- Radiogenic neutrons scatter in the TPC (potential NR background event) and escape into the Neutron Veto
- Neutrons captured in water by H (~ 200 μs) → 2.2 MeV gamma emitted → Cherenkov light





High light collection efficiency required:

- 8" **high-QE** low-radioactivity PMTs
- ePTFE coating **>99% reflectivity**
- High water **transparency**

NEUTRON VETO CALIBRATION

AmBe calibration source placed close to cryostat (**same signature** of radiogenic **neutrons** from **detector materials**)

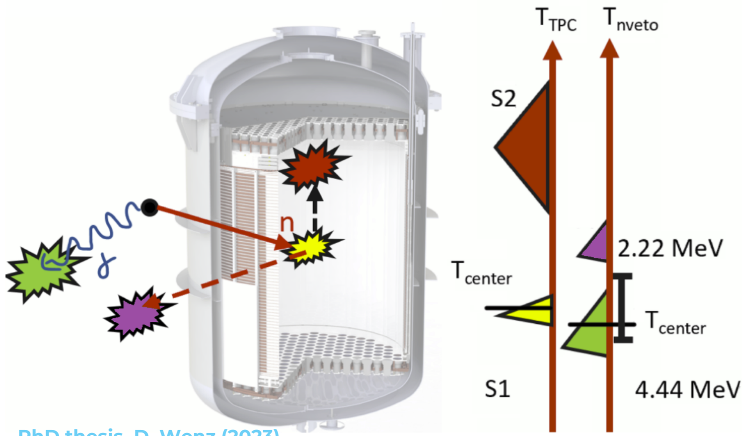
4.4 MeV gamma (γ) **emission** with **neutron** in about **50%** of cases

First **4.4 MeV** γ detected in **NV**, then coincidence requirement for **nuclear recoil** in **TPC**, hence search for **signals** from **neutron capture** in **NV**

Direct measurement of **neutron tagging efficiency**

After background subtraction, at **5-fold** coincidence, **5 PE** threshold, **600 μs** time windows: **(68 ± 3) %**

Average **capture time** in **demi-water** of about **180 μs**

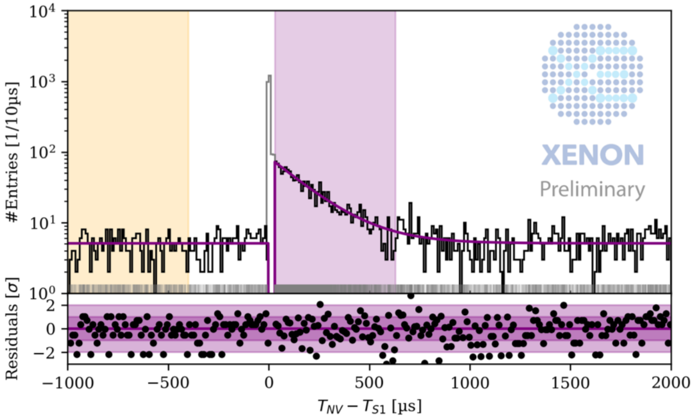


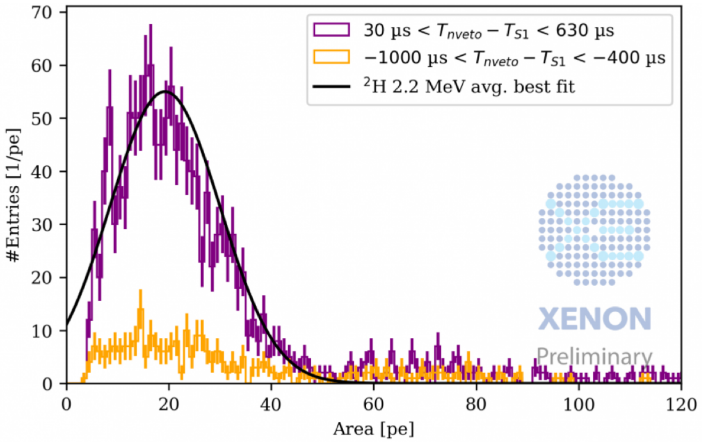
PhD thesis, D. Wenz (2023)

Highest neutron **detection efficiency ever measured** in a **water Cherenkov** detector

In Science Run 0, **time window** shortened to **250 μs** to **reduce** induced **dead time**

Then, neutron **tagging** efficiency is **(53 ± 3) %** with **1.6% livetime loss**





NEUTRON VETO IN SR0

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**)

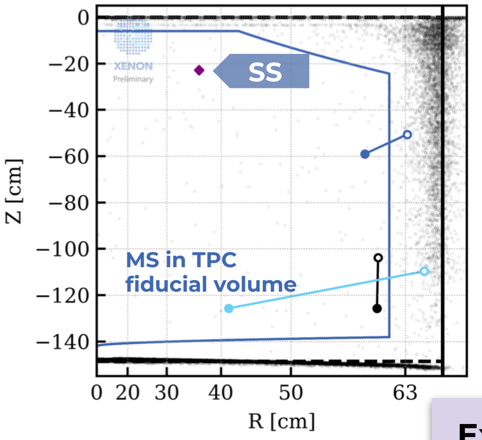
4 events in the **WIMP blinded** region tagged by **NV** and excluded: **3 multiple scatter (MS)** + **1 single scatter (SS)**

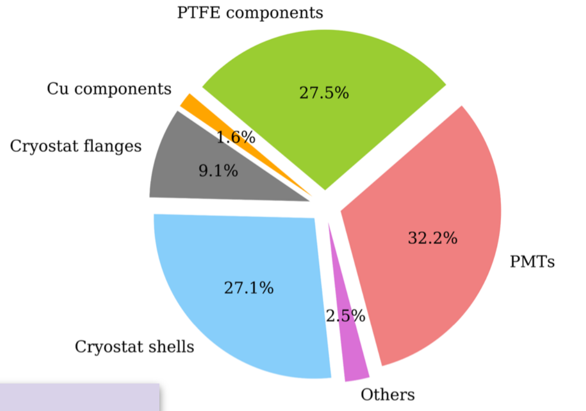
In **agreement** with **MS/SS** ratio of about **2.5** obtained from MC and AmBe calibration data

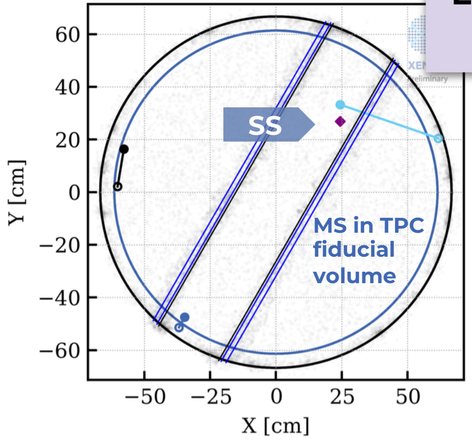
Considering **NV tagging efficiency** of **53%**, the **total neutron expectation** is **$1.1^{+0.6}_{-0.5}$** events

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

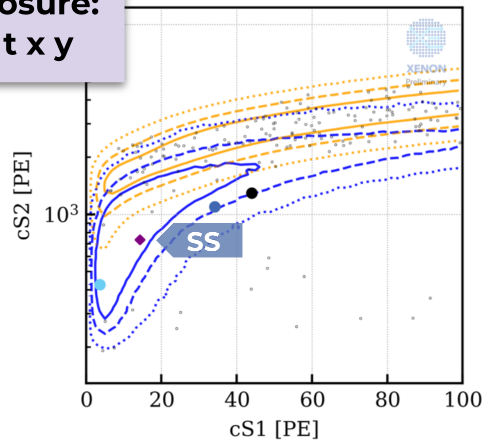
In SR0, NV had relevant role in **constraining** this specific **background** in a **data-driven** way







Exposure:
1.1 t x y

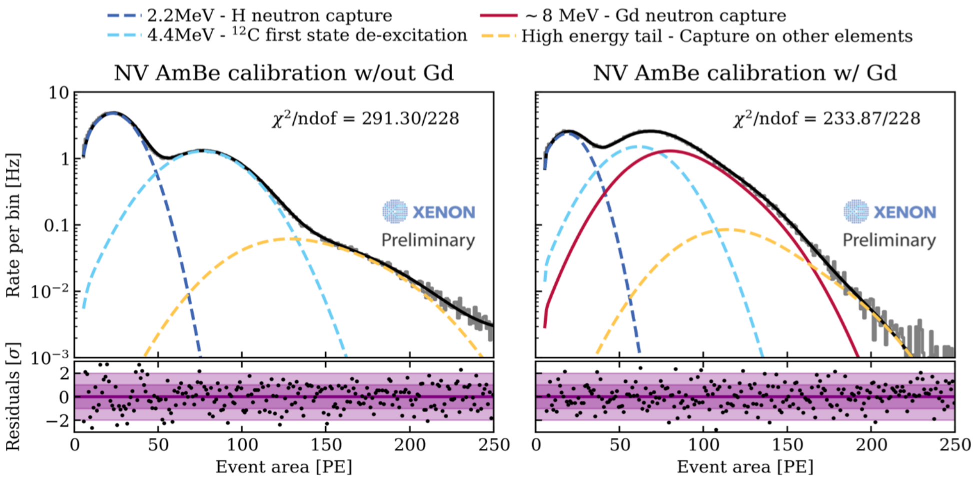


NV PERFORMANCE AFTER Gd INSERTION

AmBe calibration **source far** from **cryostat** (**50 cm**) to characterize NV **response** along time, **area spectrum** can be **modeled** with:

- **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**



With **GdSO dissolved** in water, **mean collected light**, monitored with **periodic** calibrations, is reduced by about **20%** (→ **4% less H** captures)

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