Nantes Université cnrs IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom THE UNIVERSITY OF MELBOURNE Subatech XENON

16TH PISA MEETING ON ADVANCED DETECTORS

XENONnT Dark Matter Experiment: Recent Status and Latest Results

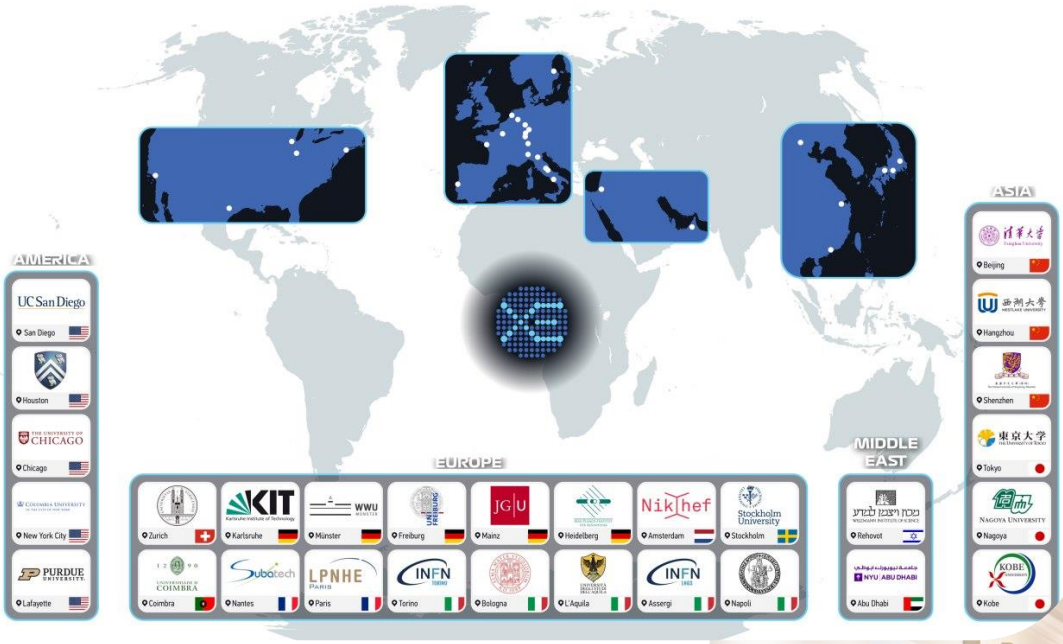
Marina Bazyk

on behalf of XENON collaboration

bazyk@subatech.in2p3.fr

30 May, 2024

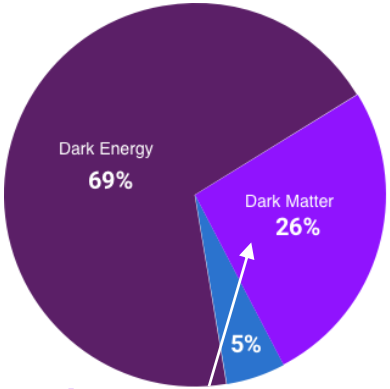
XENON collaboration



12 countries
27 institutions
~200 scientists

How do we detect Dark Matter?

XENONnT: direct detection of DM @ low-energy recoil with Xe target



Dark Matter:

- Several candidates/models exist
- Observations – astrophysical & cosmological:
  DM – component of the Universe (~26%)
  DM is non-luminous & non-baryonic

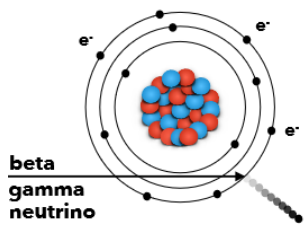
WIMP

- Weakly Interacting Massive Particles (WIMPs)
- Masses ~ few GeV/c^2 to tens TeV/c^2
- Non-relativistic

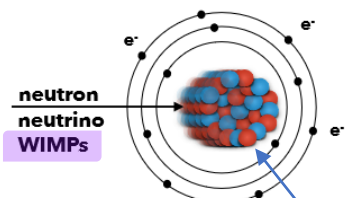
Direct Detection of WIMP:

- Low interaction strength with normal matter expected
- Elastic collision: WIMP-nucleon interaction
- **Direct detection** – Nuclear Recoil

Electronic Recoil (ER)



Nuclear Recoil (NR)



E_{recoil} = 1 – 100 keV

XENONnT Physics Program is very rich:

- Primary goal – DM, but thanks to low backround:
- 0$\nu\beta\beta$, CEvNS, solar neutrinos, etc, …

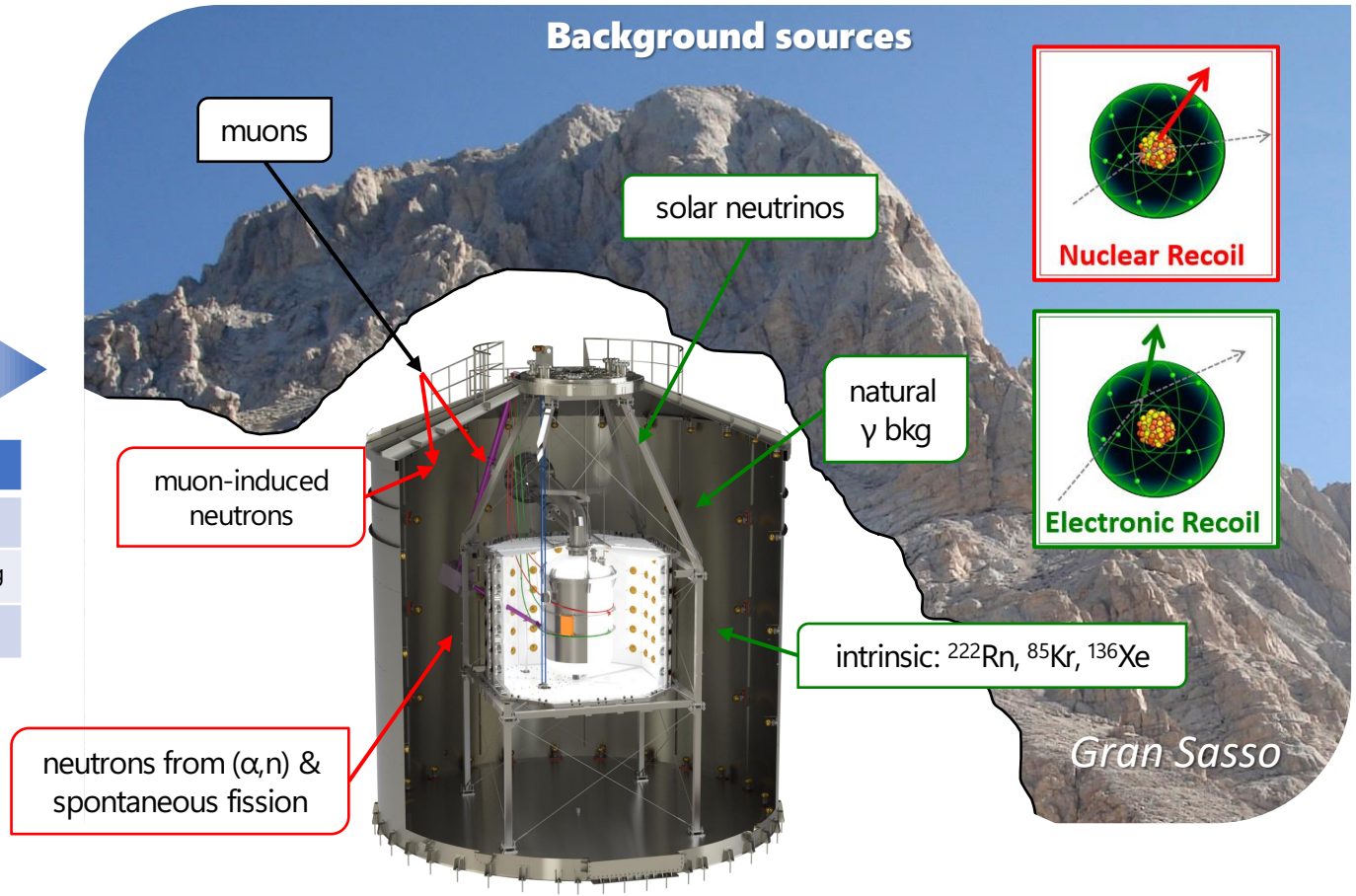
XENONnT experiment

Primary goal: Direct detection searches for **WIMPs**

WIMP detection

- Elastic collision
- Nuclear recoil
- Energy$_{recoil}$ 1 – 100 keV
- Rare event
  [expected ~1 event/year]
- *Very low background required*

Background origin	How to handle
cosmic rays	underground lab
intrinsic contamination	radio-pure materials, clean assembling
external backgrounds	shielding coupled to veto detectors



The XENON Project

*Laboratori Nazionali del Gran Sasso (LNGS), **Italy***

Evolution:

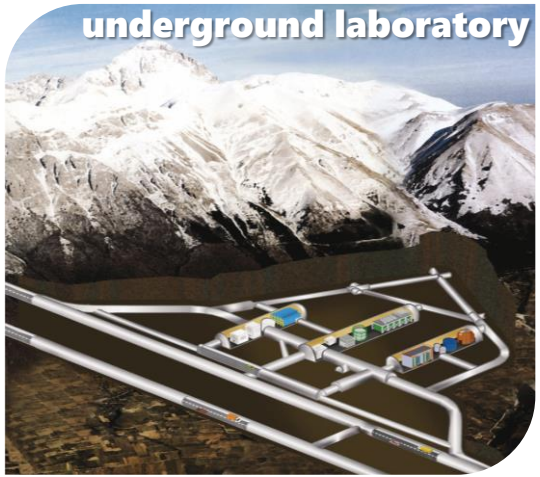
You are here

	XENON10	XENON100	XENON1T	XENONnT
Mass:	15 kg	161 kg	3.2 t	8.5 t
Exposure:	0.87 kg × yr	48 kg × yr	1 t × yr	20 t × yr
BG ER rate: [events / (t·y·keV)]	~2M	~1800	~82	~15.3
TPCs:				

Time

XENONnT experiment

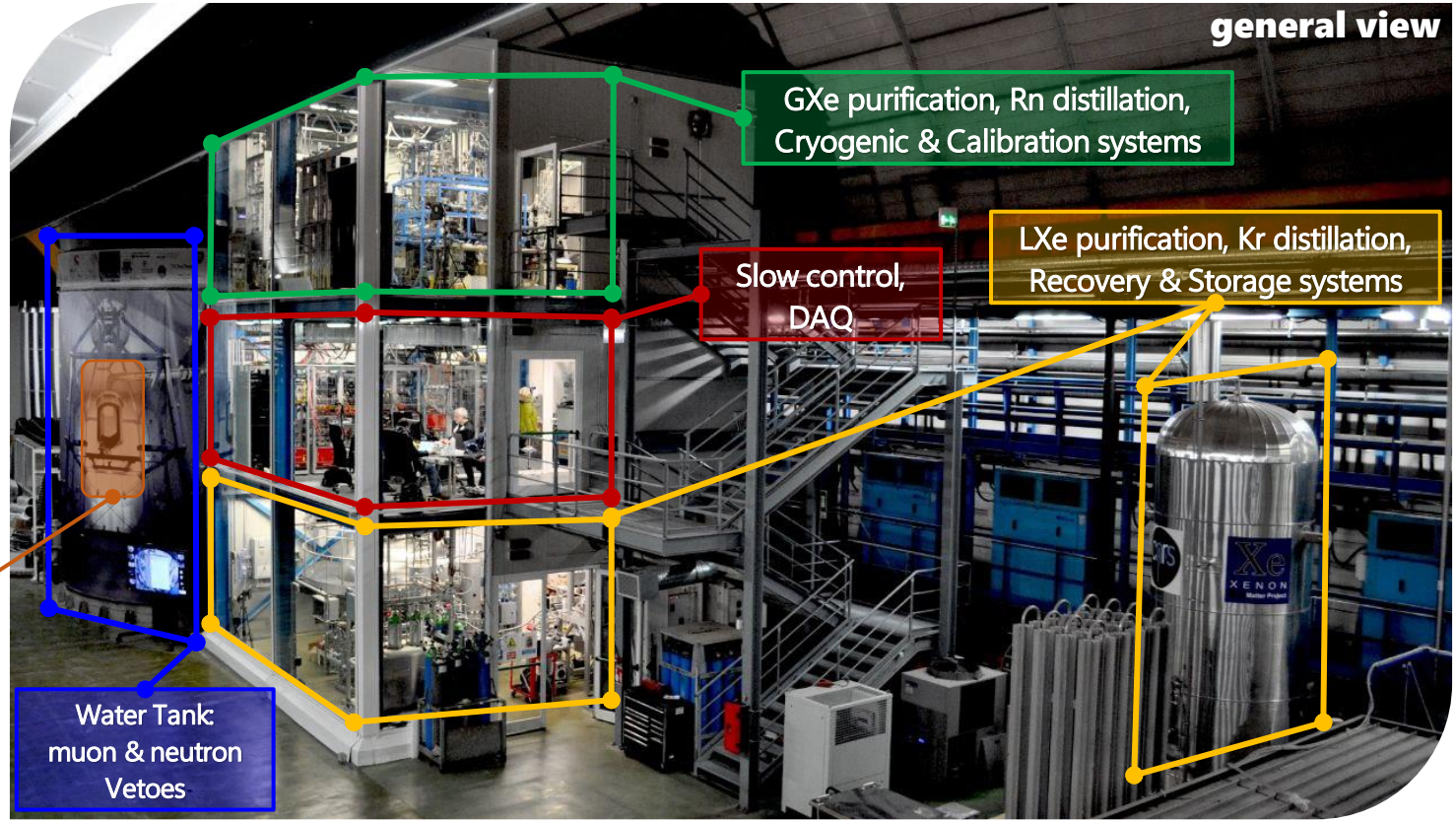
*Laboratori Nazionali del Gran Sasso (LNGS), **Italy***



Rock shielding
[1.5 km rock – 3600 m.w.e]

Main detector

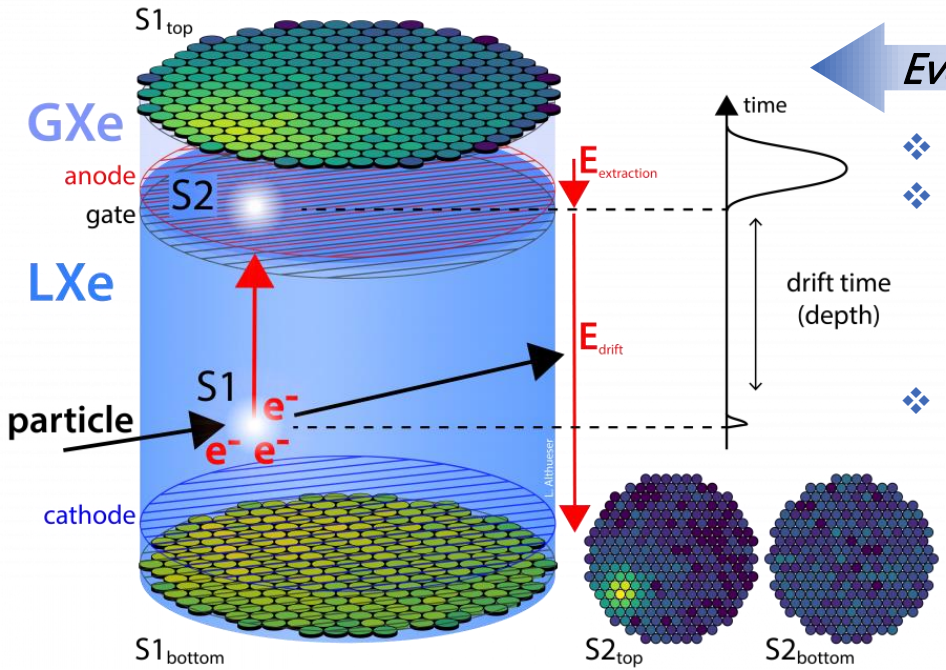
Dual-Phase Time Projection Chamber



Main detector

XENONnT TPC: detection

Working Principle



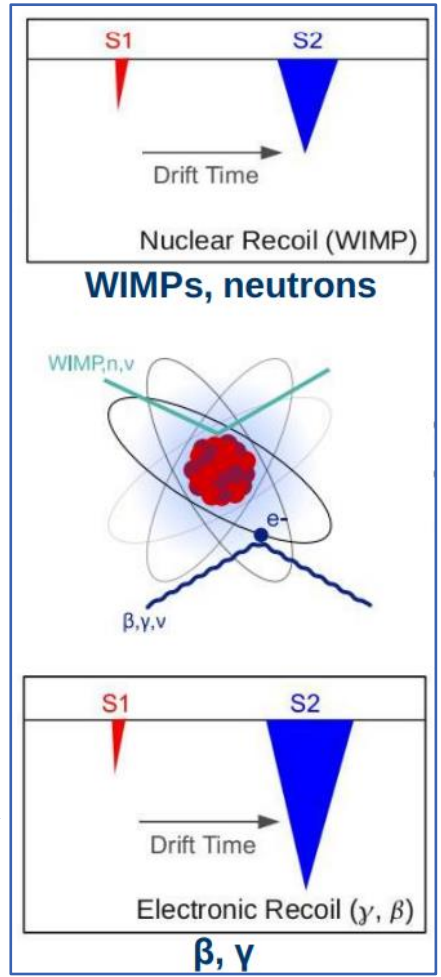
Event 3D position reconstruction

- X & Y – from S2 top PMTs pattern
- Z – from drift time

- **Energy reconstruction:**
  E [keV] ~ cS1/g1 + cS2/g2
  g1 & g2 – from calibration peaks

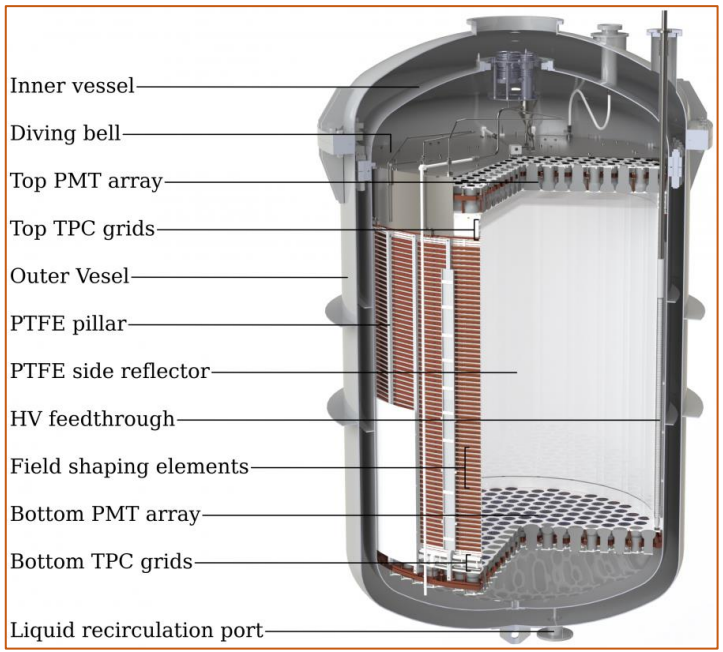
Particle discrimination in S1 & S2

- Prompt scintillation light: signal S1
- Secondary light in GXe from drifted e^- : ionization signal S2



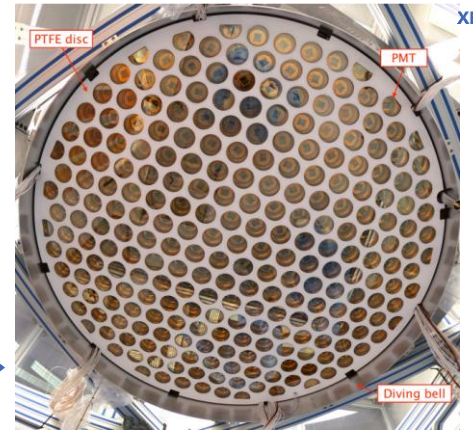
Main detector

XENONnT TPC: design



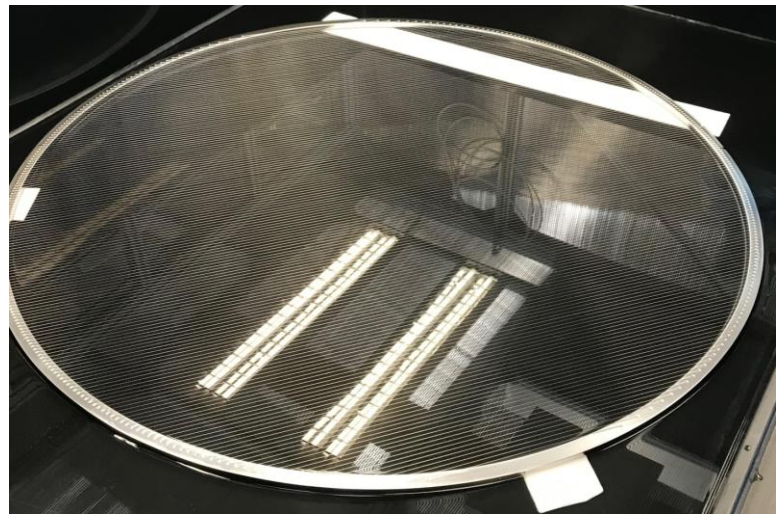
- Dual-phase TPC: **liquid & gaseous Xe**
- Double wall vessel: 8.5 t **of LXe** [total]
- Sensitive volume: 5.9 t **of LXe** [active target]
- Active region: **1.9 m** high, **1.3 m** wide
- Enclosed by PTFE [Teflon]

494 3-inch PMTs [top and bottom]



*3 parallel-wire **electrodes** [cathode, gate & anode]*

*2 additional parallel-wire **electrodes** [PMTs shielding]*



LXe purification, Kr distillation, Recovery & Storage systems

GXe purification, Rn distillation, Cryogenic & Calibration systems

Purification systems

Gaseous and Liquid Xe purification:

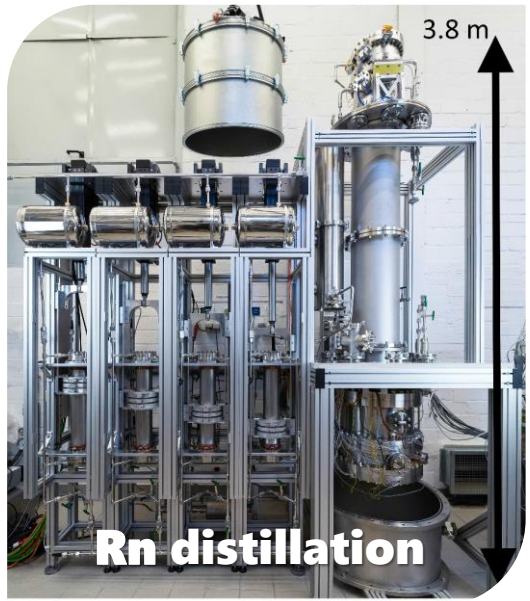
continuous removal of e-negative impurities

- 8.5 t of Xe **continuously** purified
- high **LXe flow** of 2 liters/min (≈350 kg/h)
- Getter pills or Q5-filter
- Average electron lifetime: 15 ms

Radon and Krypton removal:

^{85}Kr and ^{222}Rn

- source of radiation **background**
- **cryogenic online distillation columns**
- ^{nat}Kr/Xe ~ 50 ppq (mol/mol)
- ^{222}Rn activity: < 1 µBq/kg

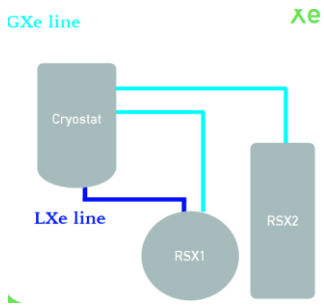


ReStoX systems

Recovering and Storage of XENON

- 7.5 t of Xe capacity
- sphere, D = 2.1 m
- double-wall, vacuum insulated

- XENONnT utilizes both ReStoX
- Linked between each other & main cryostat
- GXe or LXe can be stored

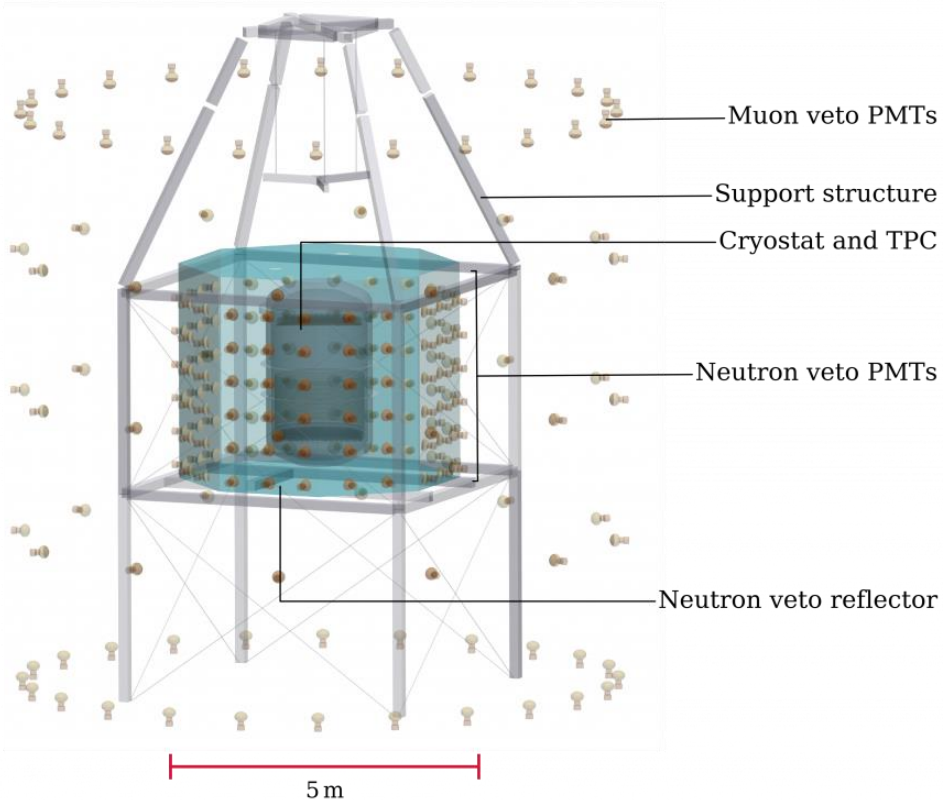


- 10 t of Xe capacity
- cylinder, H = 5.5 m, D = 1.45 m
- Xe recovery rate: > 1 t/h
- foam insulated

Water Tank: Muon & Neutron Vetoes

Muon and Neutron veto

Suppression nuclear induced background



Active water Cherenkov

Muon veto:

- 10.2 m height 9.6 m diameter
- 84 x 8-inch **PMTs**
- Demineralized water, 700 t
- Passive γ and neutron shield

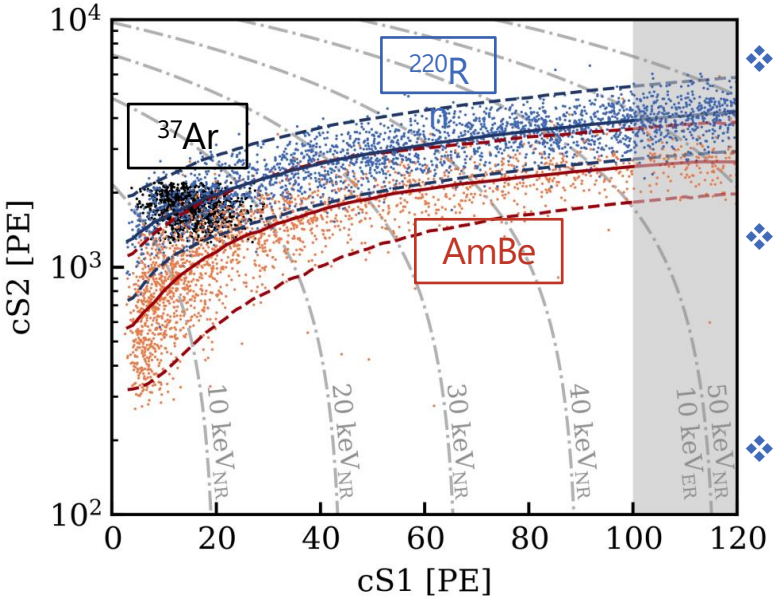
Neutron veto:

- Optically separated inner region
- **Gd**-doped water
- 33 m^3 volume
- 120 x 8-inch **PMTs**

Main detector

XENONnT TPC Calibration

Electronic Recoil [**ER**] & Nuclear Recoil [**NR**] Calibration:



❖ ^{220}Rn:

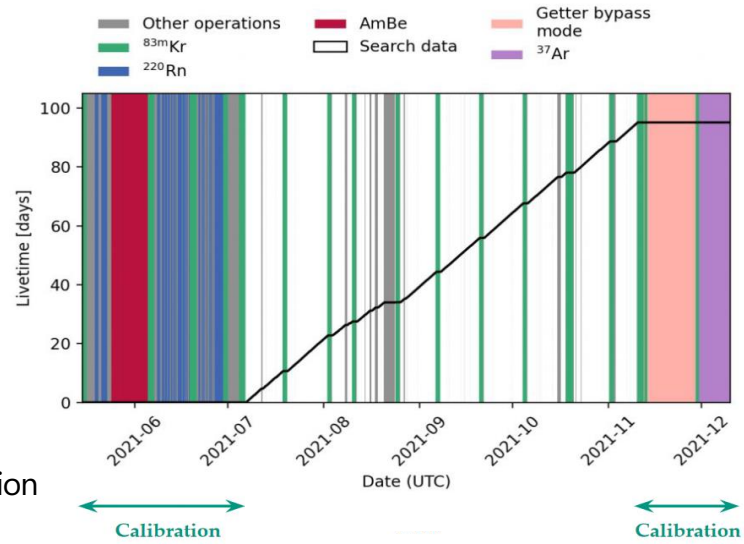
- modeling ER response
- validation of cuts acceptance

❖ AmBe:

- neutrons: modeling NR response
- neutron veto characterization

❖ ^{37}Ar:

- low energy response calibration
- peak reconstruction



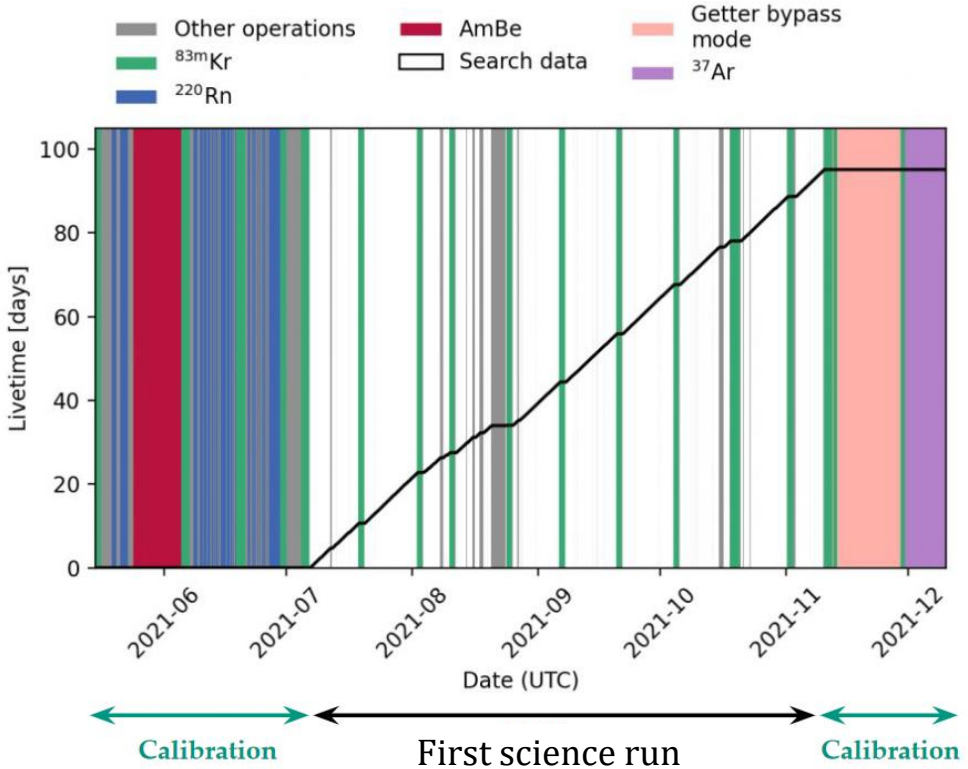
^{83m}Kr:

- TPC response characterization
- low energy response calibration

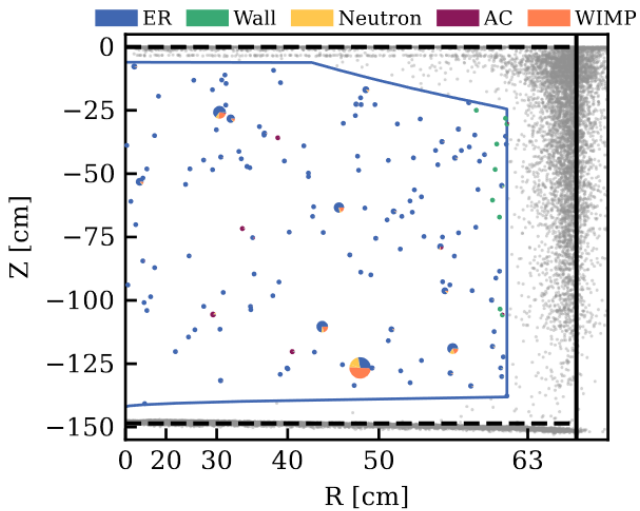
[not shown in the left figure]

XENONnT – First Science Run

*First Science Run: **July 6 – November 10, 2021***



- Livetime: **95.1** days
- Fiducial mass: **4.18 ± 0.13** t
- Exposure time: **1.1 t × year**
- Blinded **data analysis**



Fiducial volume in R-Z space [blue line]
Spatial distribution of the search data [see next sides]

XENONnT, arXiv:2303.14729

Detection Efficiency & Data Selection

First Science Run: ***July 6 – November 10, 2021***

Detection Efficiency

- 3-fold PMT coincidence for S1 signal
- Full waveform simulation & data-driven methods

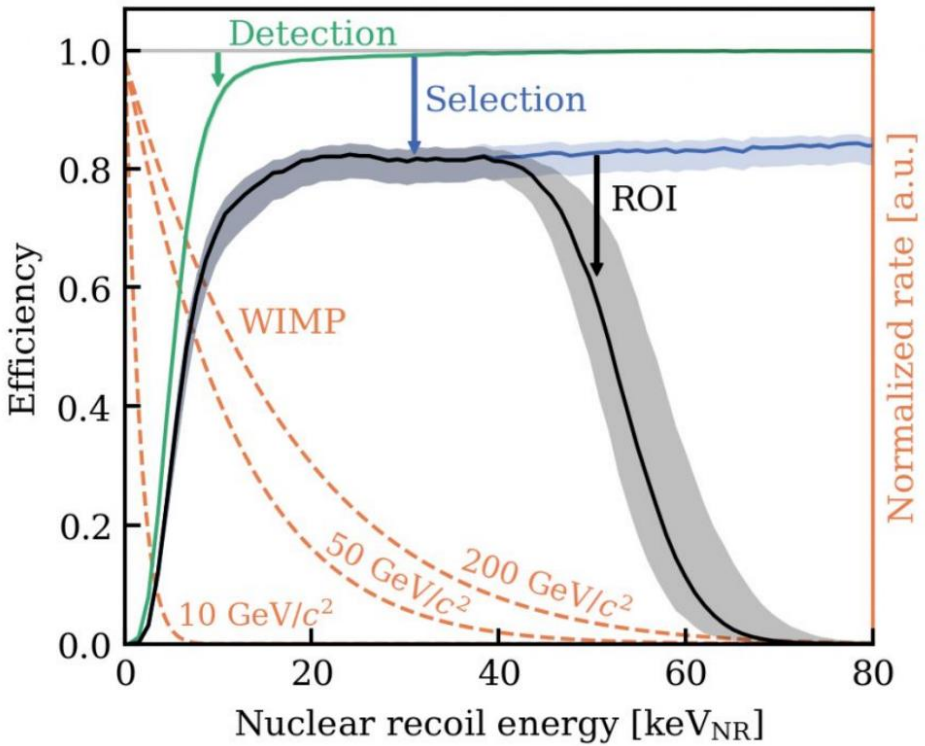
Selection Efficiency

- Data quality selection: remove unphysical & multi-site events

Region of Interest [ROI]

- Fully contains WIMP spectra

Total efficiency at least 10% from 3.3 keV_{NR} – 60.5 keV_{NR}



XENONnT, arXiv:2303.14729

Background model used

*First Science Run: **July 6 – November 10, 2021***

Electronic Recoils [ER]:

- dominated by β-decays of ^{214}Pb [daughter of ^{222}Rn]
- ^{85}Kr background, solar neutrino-e$^-$ scattering & γ-rays from detector materials

Accidental Coincidences [AC]:

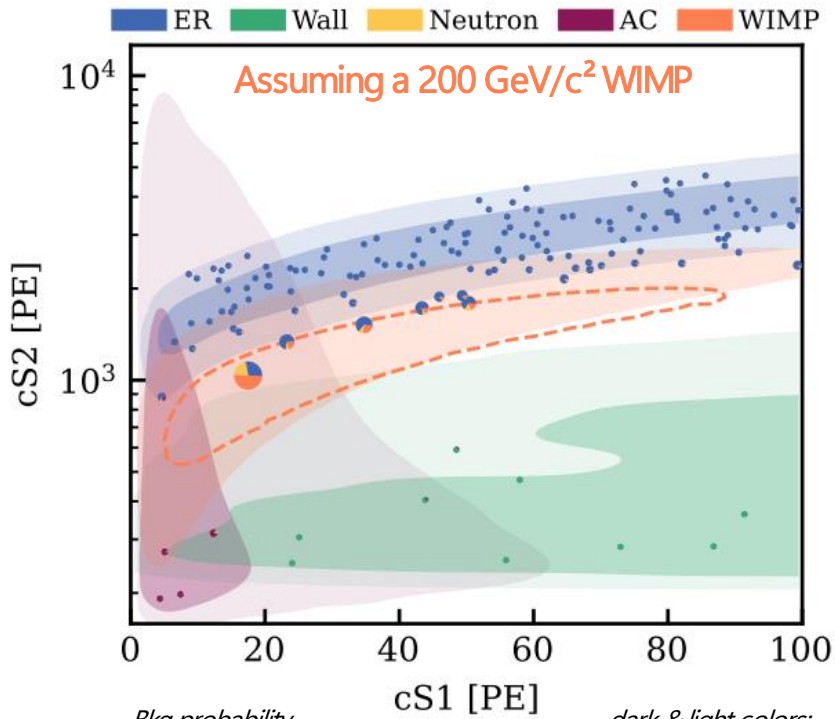
- random pairing of S1 & S2 signals
- suppressed by a dedicated anti-AC cut [based on data-driven models]

"Wall":

- ^{210}Pb from PTFE walls of the TPC
- suppressed by fiducial volume

Nuclear Recoils [NR]:

- radiogenic neutrons from spontaneous fission & (α, n)-reactions
- radiogenic neutron rate prediction from NV tagging: ~ 1.1 events
- CEνNS from ^{8}B solar neutrinos
- Cosmogenic neutrons – negligible



Bkg probability density distributions

dark & light colors: 1σ & 2σ contours

XENONnT, arXiv:2303.14729

**Expected number of events per component – data is available [not included in this slide]*

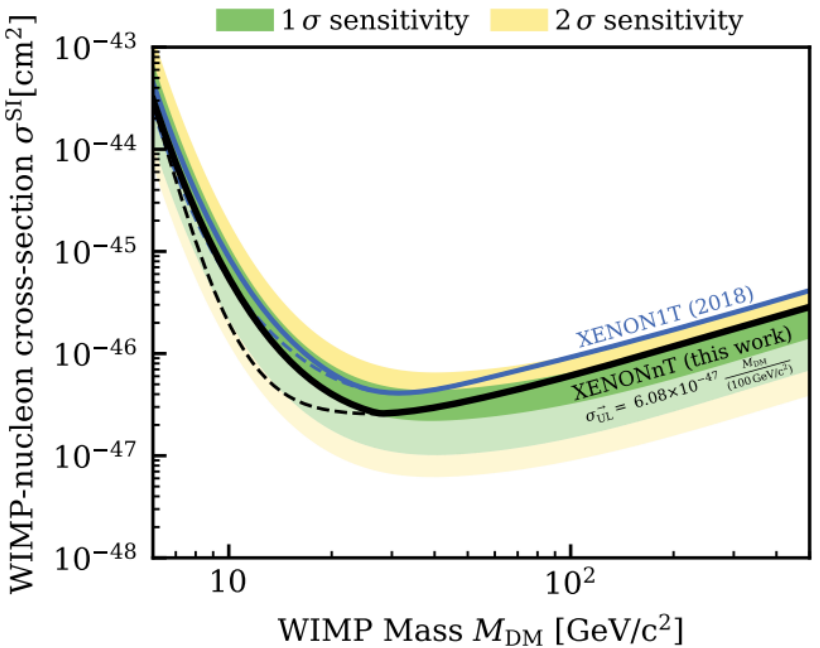
WIMP searches – first results

*First Science Run: **July 6 – November 10, 2021***

- 152 events in ROI*, 16 in blinded region
- No significant excess during the run

- **New upper limit** with 90% confidence level on spin-independent WIMP-nucleon interaction
- Minimum upper limit: 2.58×10^{-47} cm^2 (90% C.L.) at 28 GeV/c^2

- Low-energy ER background level of (15.8 ± 1.3) events/(t·y·keV)
  ~5 times lower than XENON1T
- 1.7 times sensitivity improvement w.r.t XENON1T at a WIMP mass of 100 GeV/c2

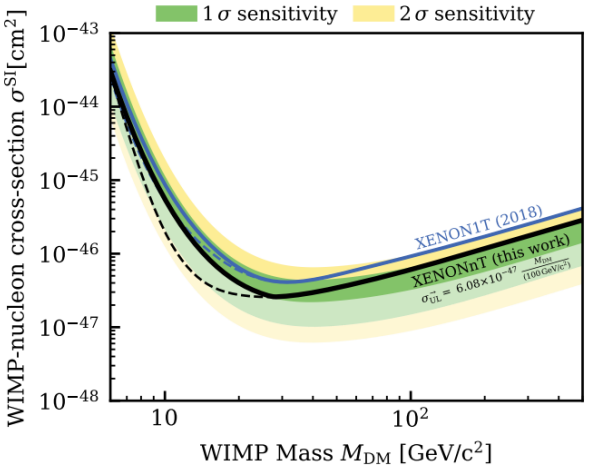


XENONnT, arXiv:2303.14729

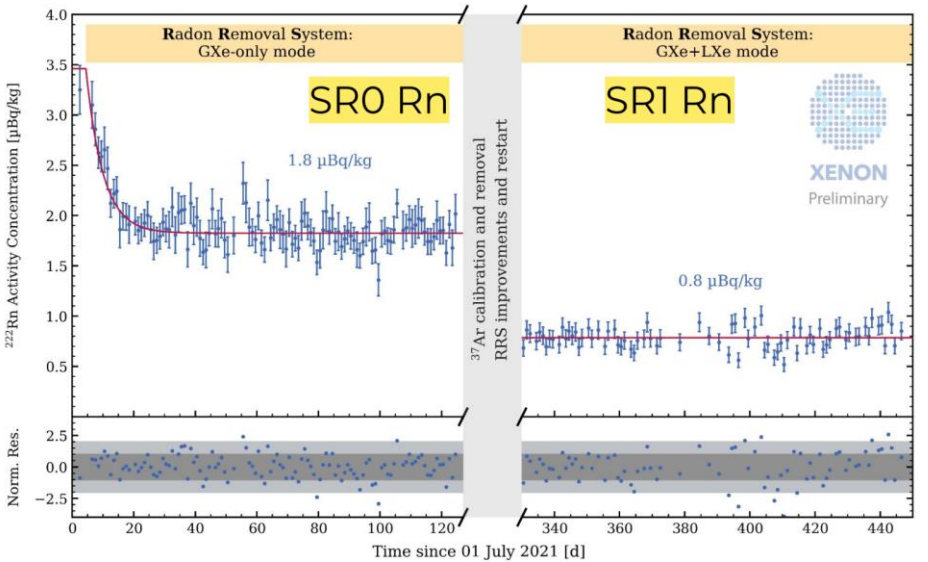
Summary & Outlook

After four years, XENONnT continues to perform well

- **First Science Run** "SR0": blinded Dark Matter search done
- Unprecedented low background has been achieved
  - **New upper limit** with 90% C.L. for SI WIMP-nucleon interaction



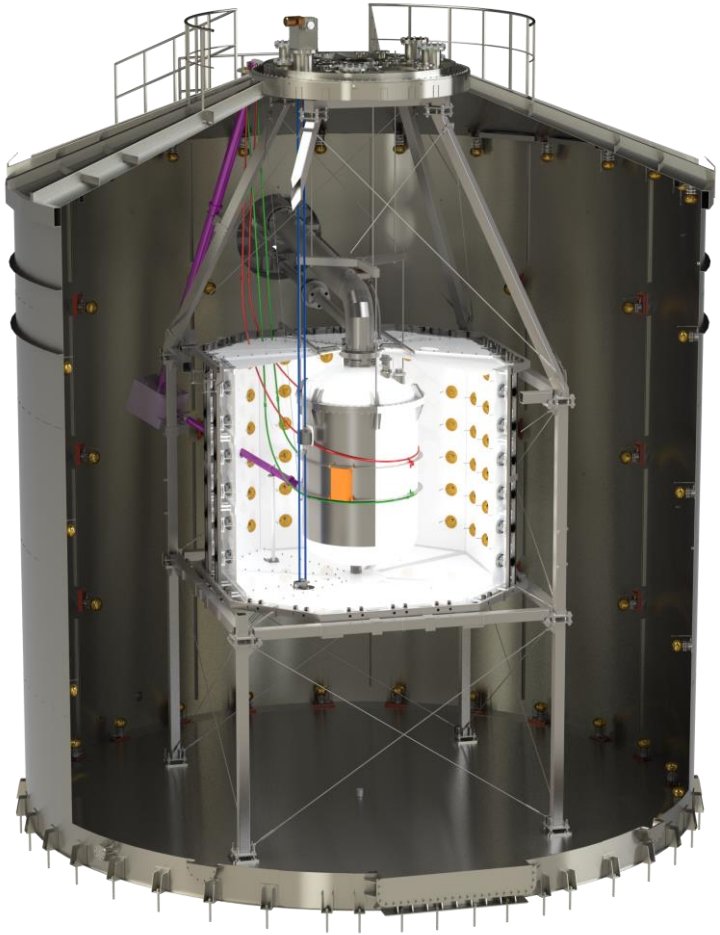
- Gd **loading for NV: done** to increase neutron tagging efficiency [53%→87%]
- **Second Science Run** "SR1":
  - **further reduction of** ^{222}Rn

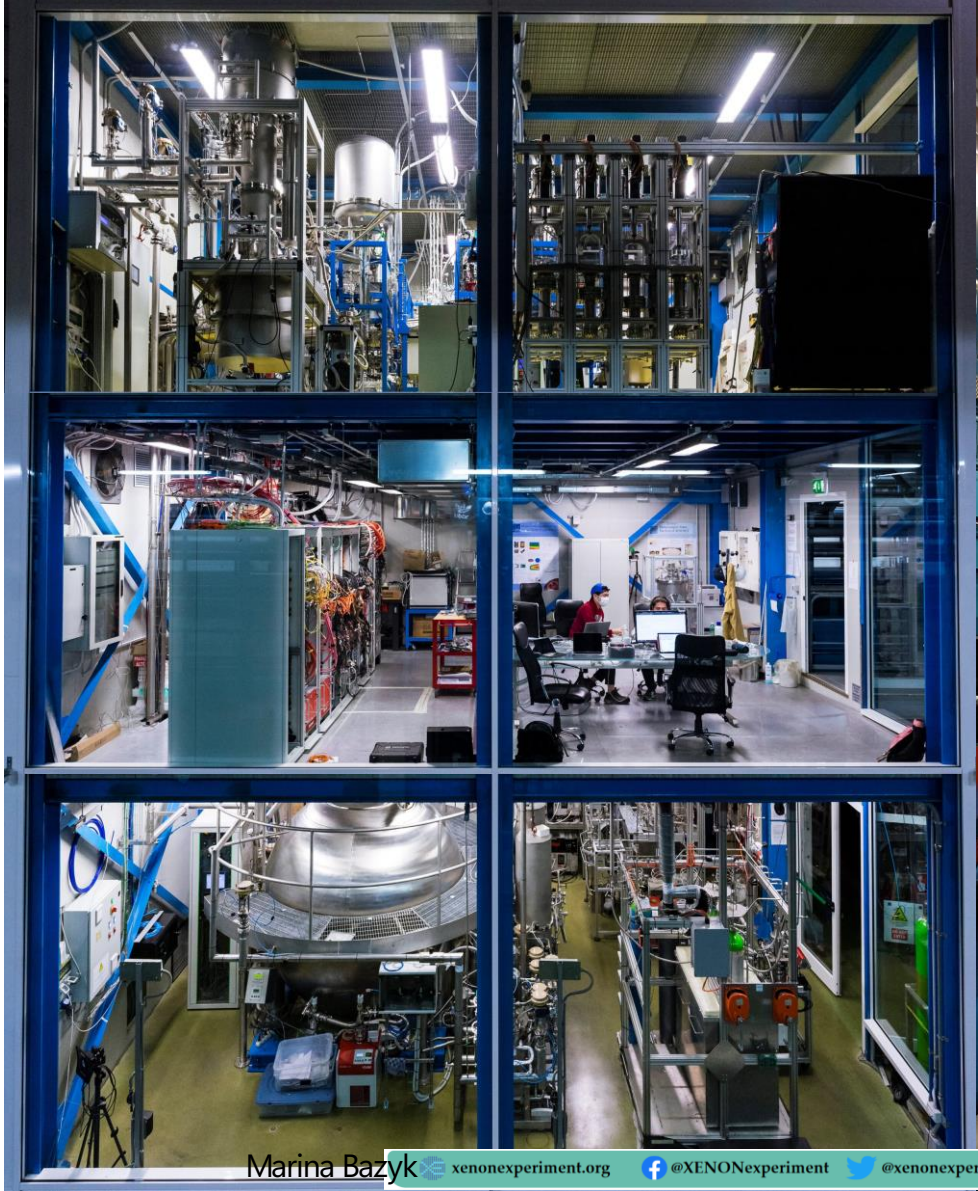


XENONnT continue data taking.

Stay tuned: new results coming soon!

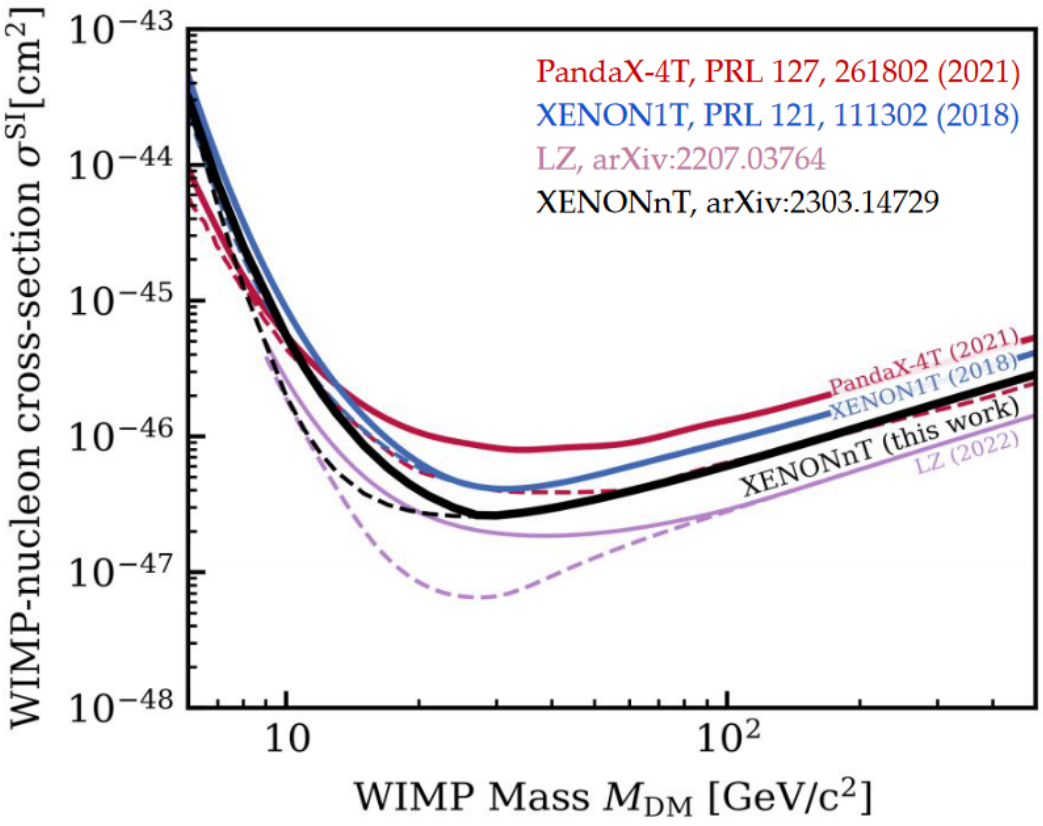
xenonexperiment.org @XENONexperiment @xenonexperiment @xenon_experiment





Thanks for your attention!

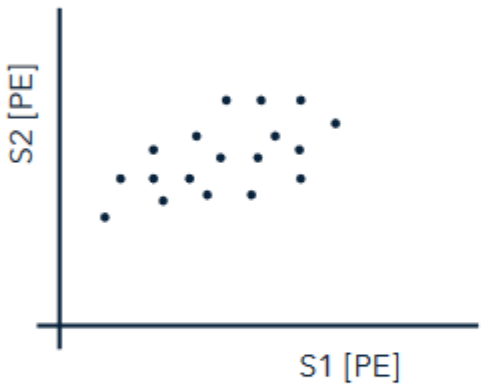
Back-up 0 – Comparing ton-scale experiments



Back-up 1 – energy reconstruction

Combined energy reconstruction from S1 and S2:

2D analysis

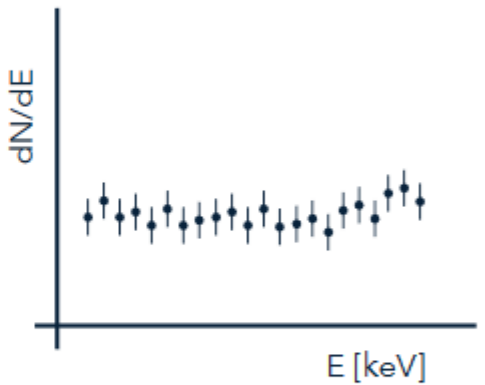


$W = 13.7$ eV/quantum

$$E = W(n_{ph} + n_e)$$

$$E = W\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

1D analysis



- Energy reconstruction based on detector-dependent parameters:
  - g1: photon detection efficiency.
  - g2: charge amplification factor.

→ Determined through severals calibrations

Back-up 2 – bkg model & values

Table:

	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

Figure:

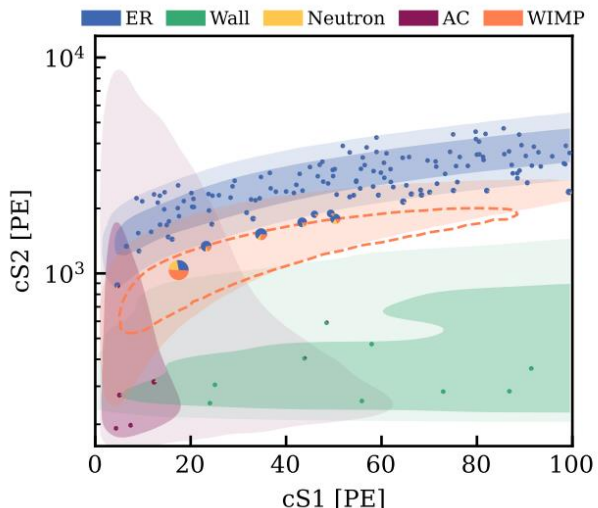


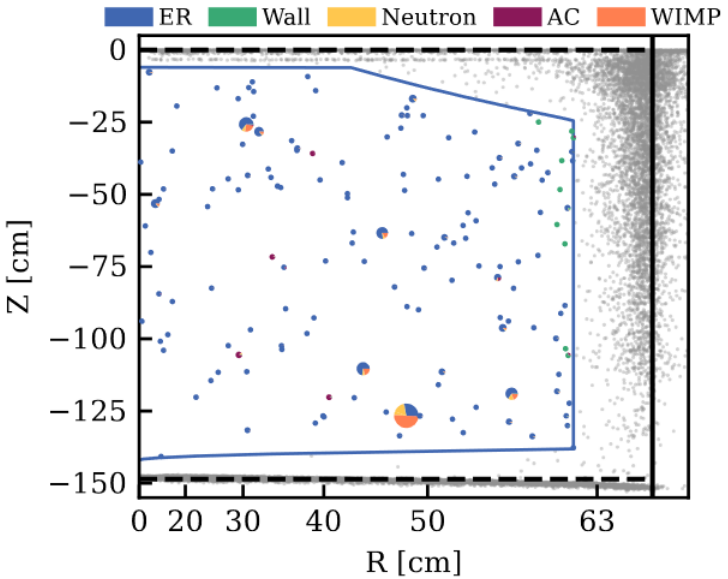
Table:

- Expected number of events for each model component and observed events. The "**nominal**" **column** shows expectation values and uncertainties, if applicable, before unblinding. The nominal ER value is the observed number of ER events before unblinding.
- Other columns show **best-fit expectation values** and uncertainties for a free fit including a 200 GeV/c^2 WIMP signal component. The best-fit signal cross-section is 3.22×10^{-47} cm^2.
- In addition to the expectation values in the full ROI, we include the expectation values in a **signal-like cS1,cS2 region containing the 50% of signal in with the best signal-to-background ratio**. This region is indicated in the Figure with an orange dashed contour. The best-fit and pre-unblinding values agree within uncertainties for all components which include an ancillary constraint term.

Figure:

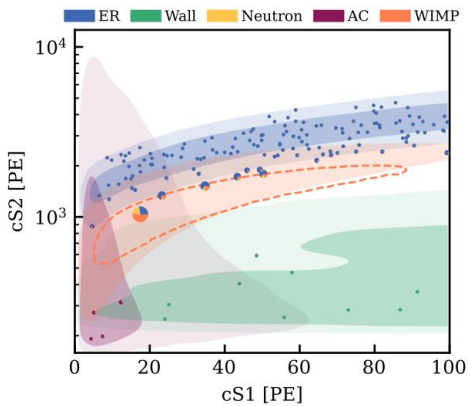
- >DM search data in the cS1-cS2 space. Each event is represented with a pie-chart, showing the fraction of the best-fit model, including the expected number of 200 GeV/c2 WIMPs (orange) evaluated at the position of the event. The size of the pie-charts is proportional to the signal model at that position.
- >Background probability density distributions are shown as 1σ (dark) and 2σ (light) regions as indicated in the legend for **ER** (blue), **AC** (purple) and **surface** (green, "wall"). The **neutron** background (yellow in pies) has a similar distribution to the **WIMP** (orange filled area showing the **2σ** region).
- >The orange dashed contour contains a signal-like region which is constructed to contain 50% of a 200 GeV/c2 WIMP signal with the highest possible signal-to-noise ratio.

Back-up 2.1 – bkg & search data R-Z distribution



Fiducial volume in R-Z space [blue line]
Spatial distribution of the search data

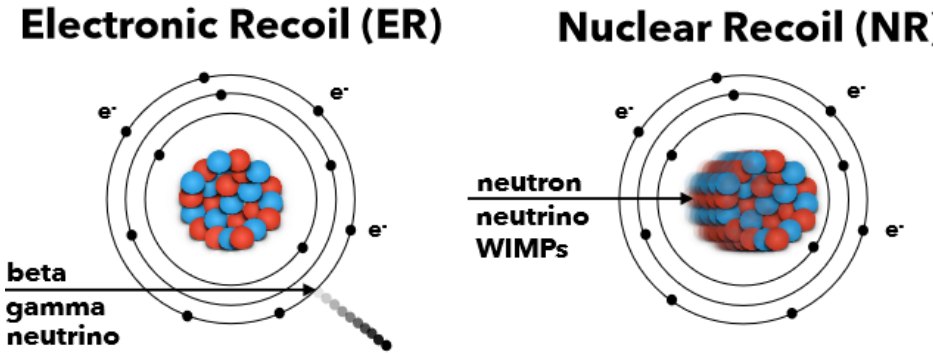
- **Spatial distribution** of the search data in the 4.18 t fiducial volume (blue line).
- Each event is represented with a pie-chart, showing the fraction of the best-fit PDF including a 200 GeV/c2 WIMP evaluated at the position of the event, color-coded as in ***figure below***.
- Events reconstructed outside of the fiducial volume are colored in gray.
- Black dashed lines depict the boundaries of the sensitive volume given by the cathode and gate positions.
- The TPC radius is indicated by a vertical black line

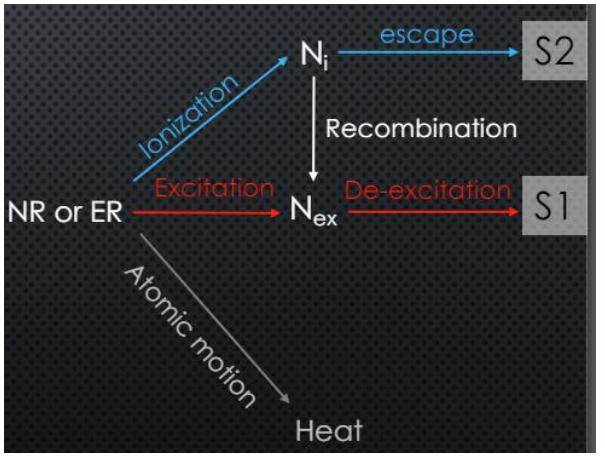


Bkg probability density distributions

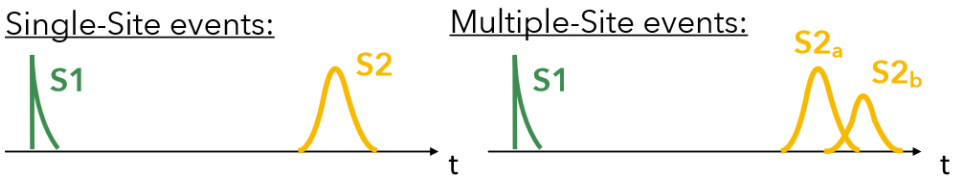
dark & light colors: 1σ & 2σ contours

Back-up 3 – Signals from Xe





1. Production of **excited Xe**: (↑ n_{γ_UV})
2. … and **ionized Xe**: (↑ n_{e^-})
3. **Recombination** of ionized Xe: (**↑ n_{γ_UV}**) and (**–↓ n_{e^-}**)
4. Generation of 2 anti-correlated **signals: n_{γ_UV}** (**light**) and **n_{e^-}** (**charge**)



Back-up 4 – ReStoX