

Universität
Münster

Searching for Dark Matter and Rare Events with **XENONnT**

IUVSTA Workshop 109
APPEC Tech Forum Vacuum & Cryogenics
Industry meets Academia

Lutz Althüser – 25.11.2025
On behalf of the **XENON** collaboration
On behalf of the **LowRad** team
Low Radon and **low** internal **Rad**ioactivity

living.knowledge



XENON Collaboration

~200 Members
 29 Institutions



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 San Diego 
- 
 Houston 
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 Chicago 
- 
 COLUMBIA UNIVERSITY
 IN THE CITY OF NEW YORK
 New York City 
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 UNIVERSIDADE DE COIMBRA Coimbra 	 Subatech Nantes 	 LPNHE PARIS Paris 	 INFN TORINO Torino 	 UNIVERSITÀ DEGLI STUDI BOLOGNA Bologna 	 UNIVERSITÀ DELL'AQUILA L'Aquila 	 INFN LNGS Assergi 	 UNIVERSITÀ DI NAPOLI NAPOLI Napoli 

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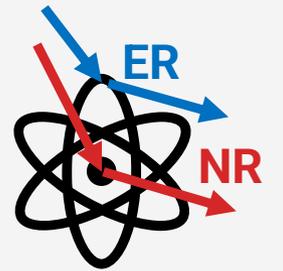
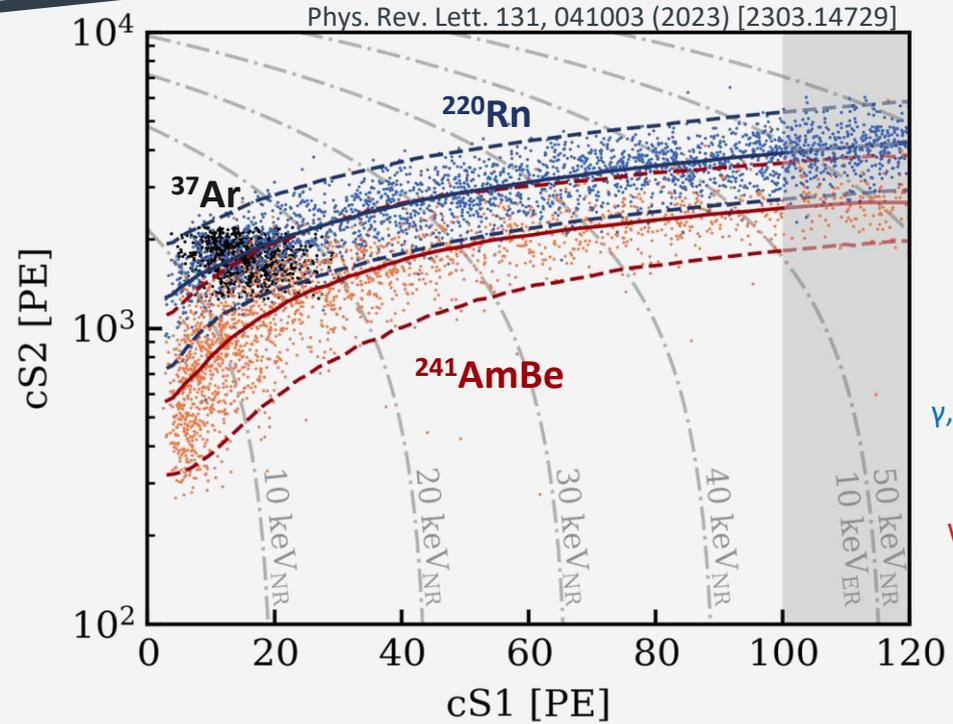
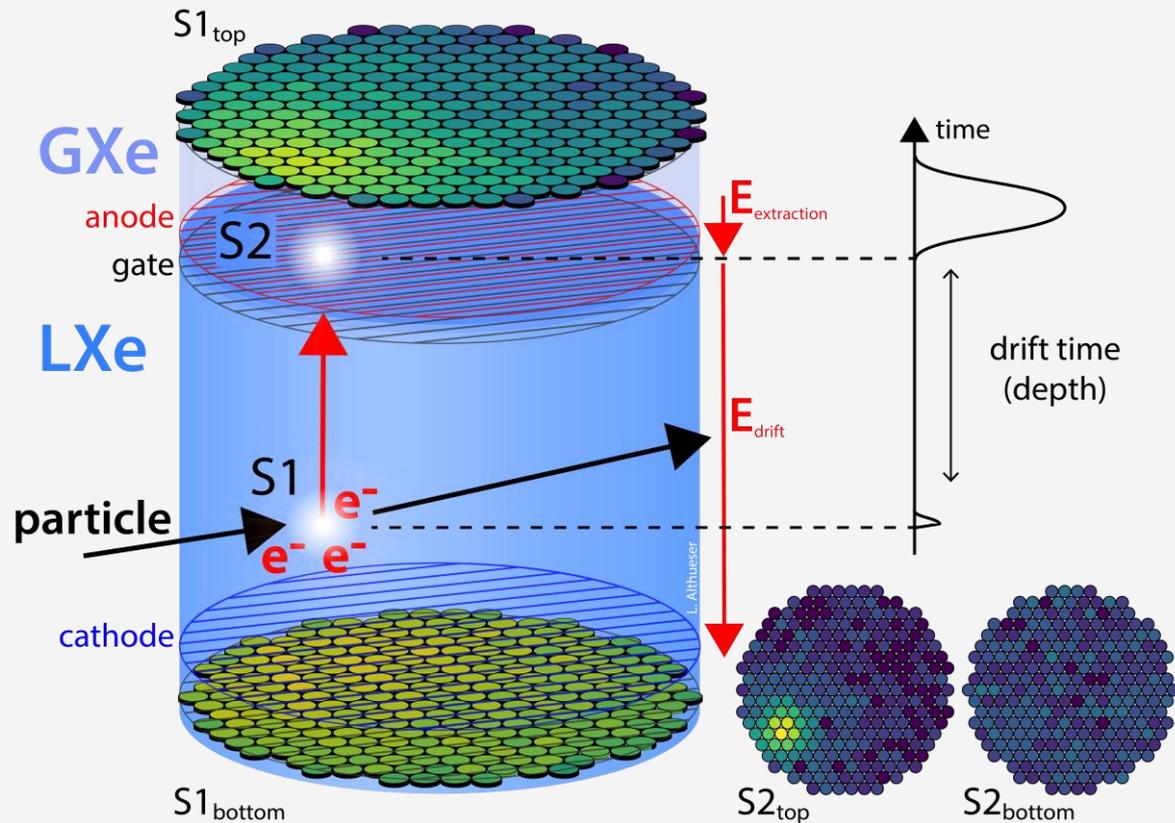
XENON Dark Matter Project

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



- **XENONnT** experiment
- Located @LNGS in Italy
- Depth of 3600 m water equivalent
- Muon Veto and Neutron Veto (~700 t ultrapure water, prepared for Gd-loading)
- Time Projection Chamber with **5.9 t** of LXe in the active region and 8.6 t in total in the system

Detector Calibration and Response Modelling



ER (Electronic Recoils)
 γ , β backgrounds, dark photon

NR (Nuclear Recoils)
 WIMP DM, neutrons, CEvNS

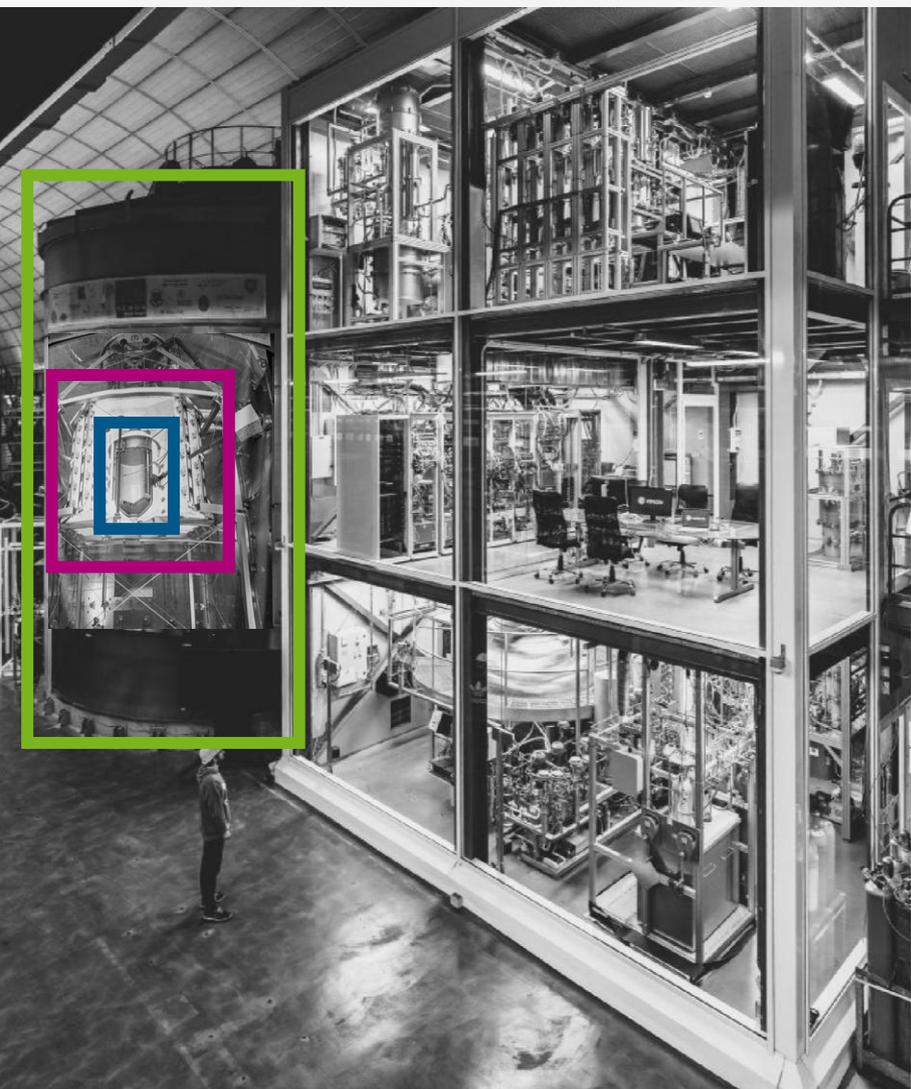
ER response model

- For data blinding, detector response validation
- ^{212}Pb from ^{220}Rn (flat β -spectrum) for **cut acceptances and threshold**
- ^{37}Ar , (mono-energetic 2.8 keV peak, $t_{1/2} = 35$ d) as high statistics anchor for the **low-energy response and resolution models**

NR response model

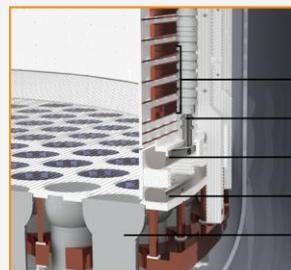
- $^{241}\text{AmBe}$, external source with **clean NR selection** via coincident tagging with the neutron Veto

XENONnT Detectors

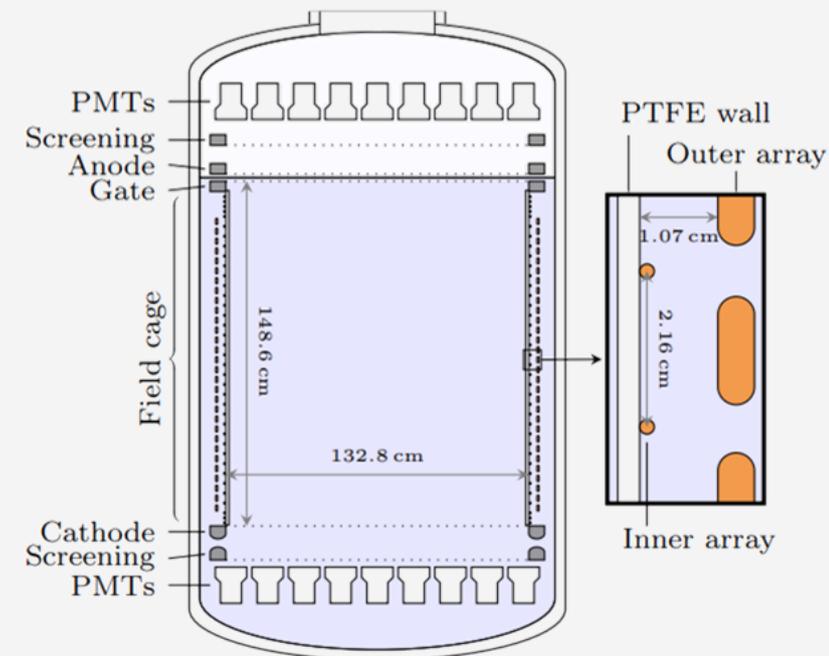


Dual-phase LXe TPC

- 1.3 m (\varnothing) x 1.5 m
- 8.5 t LXe in total (2.5x XENON1T)
- 5.9 t LXe instrumented (3x XENON1T)
- 494 3-inch PMTs (2x XENON1T)



- Guard Rings
- HV Feedthrough
- Cathode Grid
- Bottom Screening Grid
- Photomultiplier Tube (PMT)

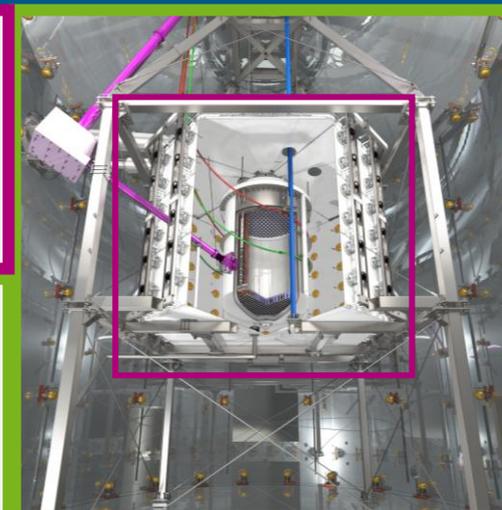


Muon Veto (MV)

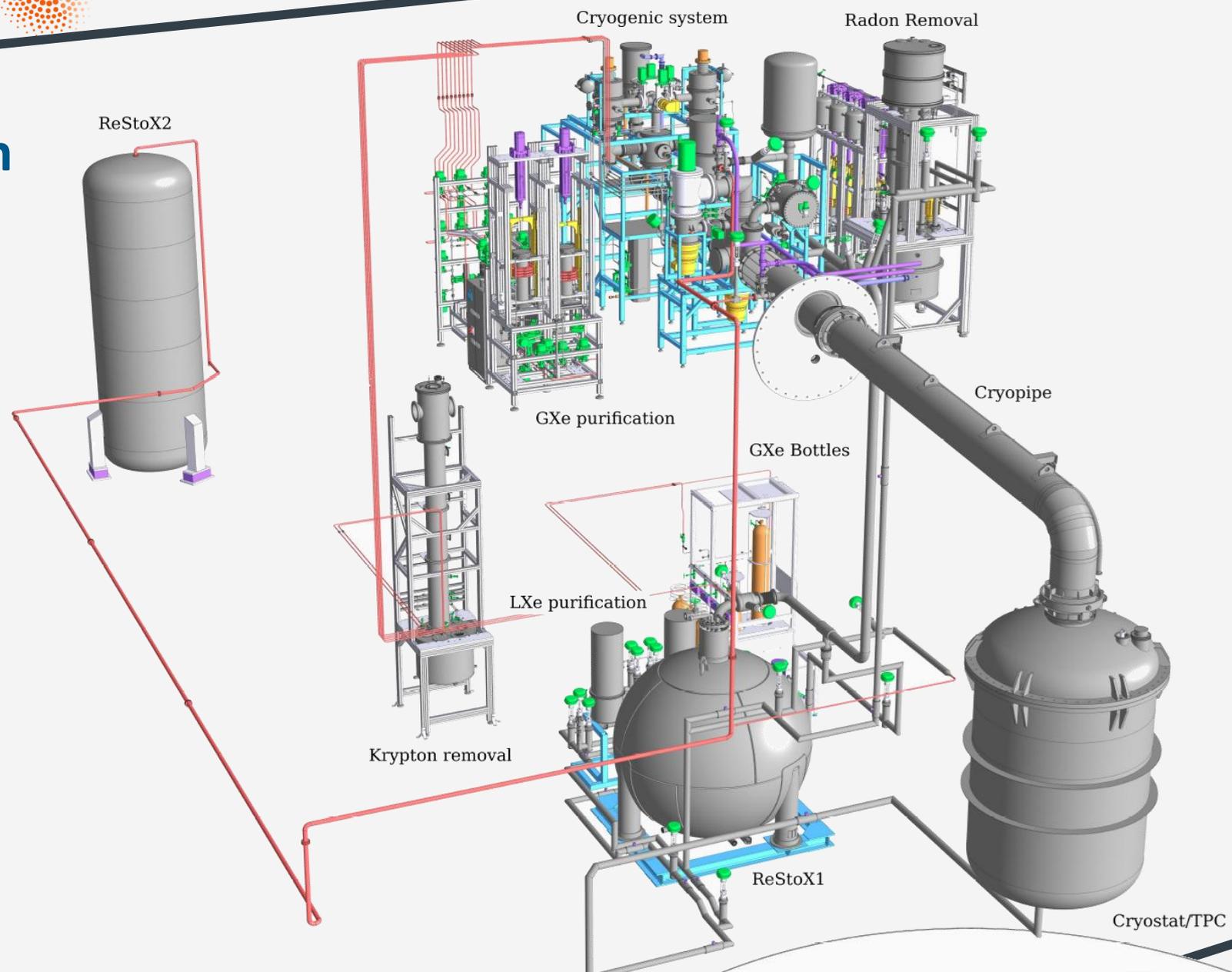
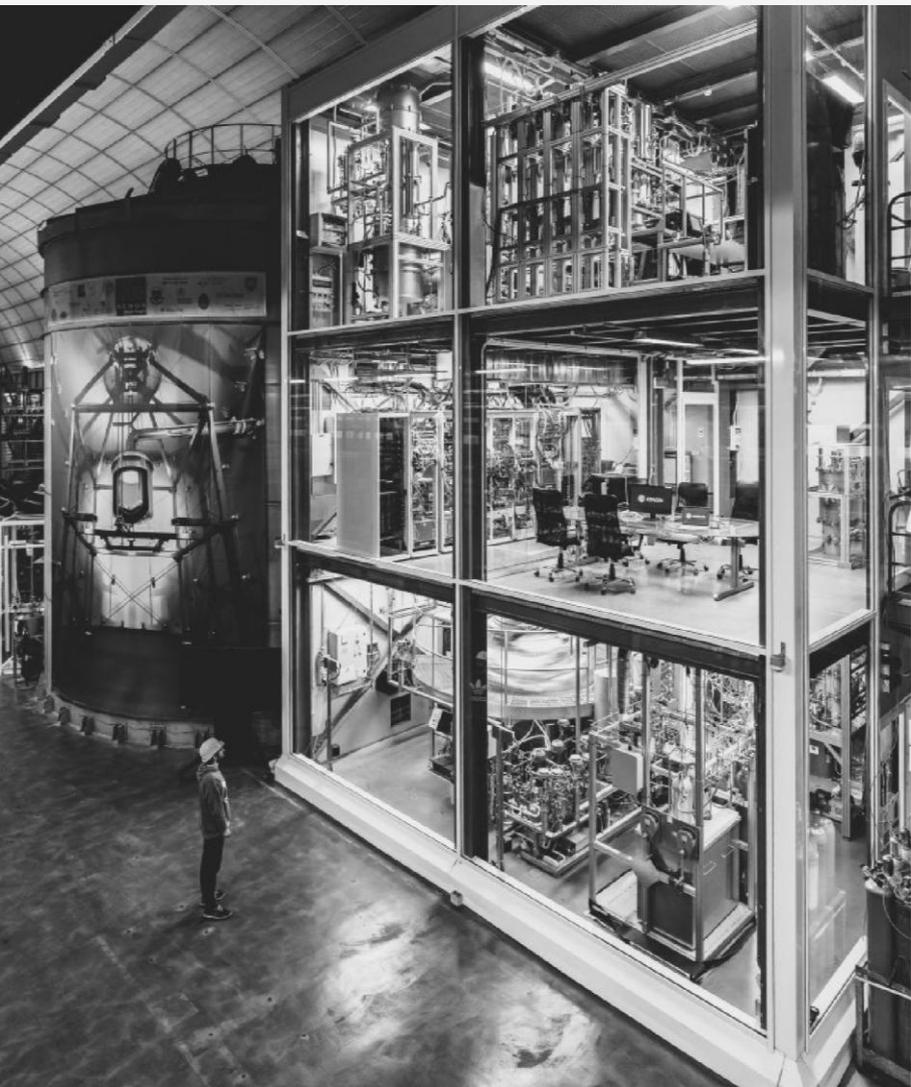
- Water Cherenkov detector
- 700 t ultra-pure water
- 84 8-inch PMTs

Neutron Veto (NV)

- Gd-loaded water Cherenkov detector
- 120 8-inch PMTs



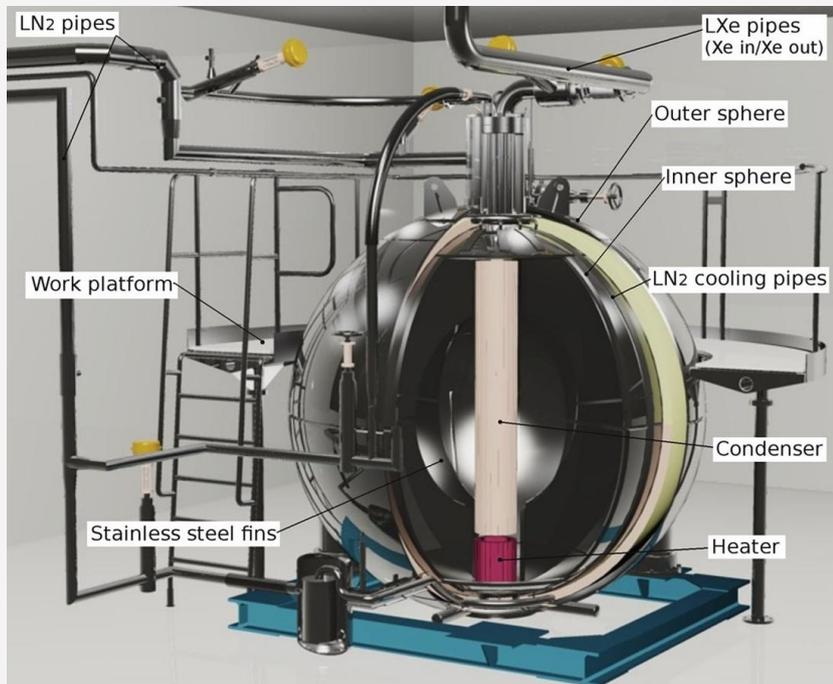
XENONnT Cryogenics System



Recovery and Storage for Xenon (ReStoX)

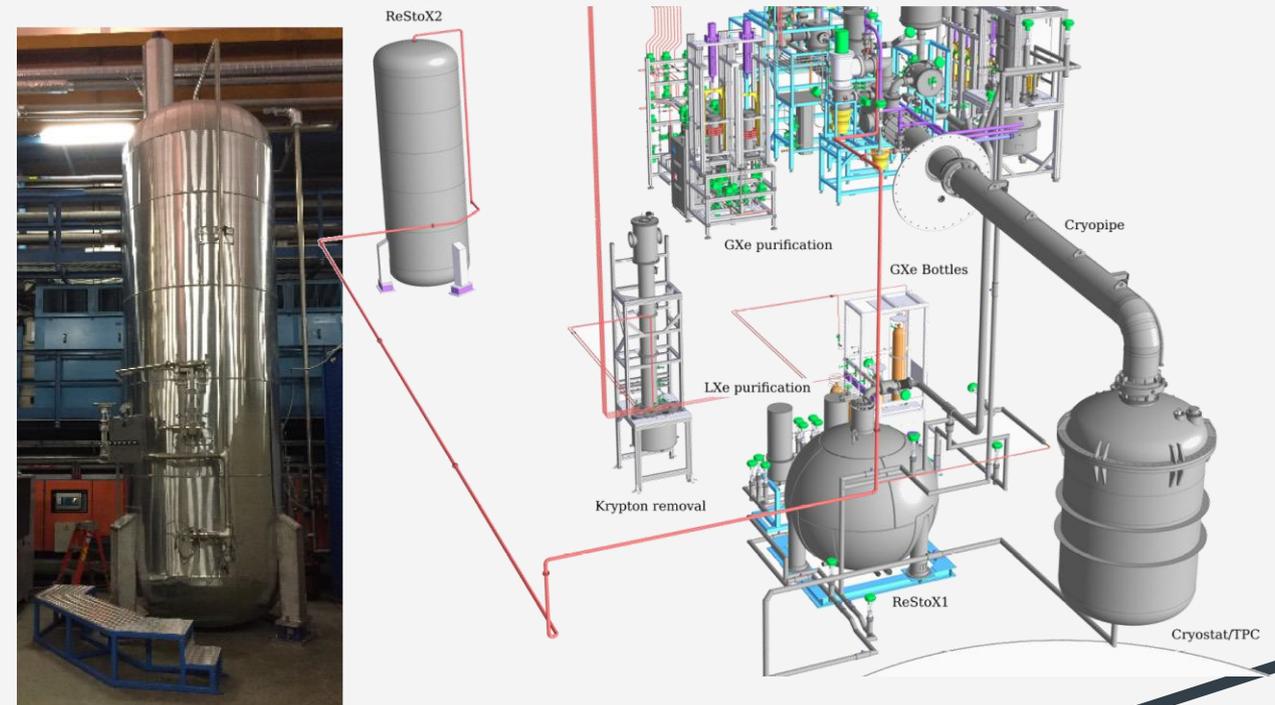
ReStoX 1

- 2.1 m diameter sphere, 73 bar maximum pressure
- Build for XENON1T and used for XENONnT
- Capacity of 7.6 tonnes (LN₂: 35 kg/d)
- Recovery speed of 50 kg/h (LN₂: 25 kg/h)

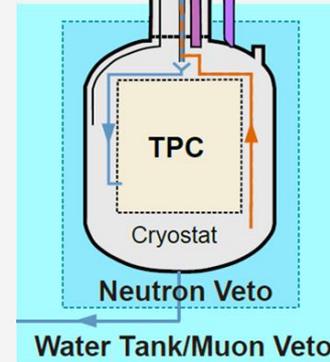
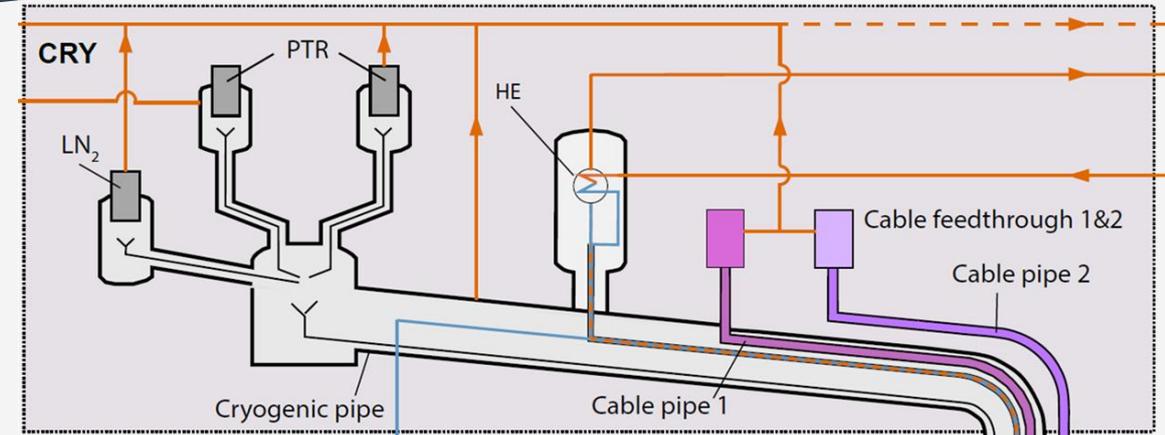
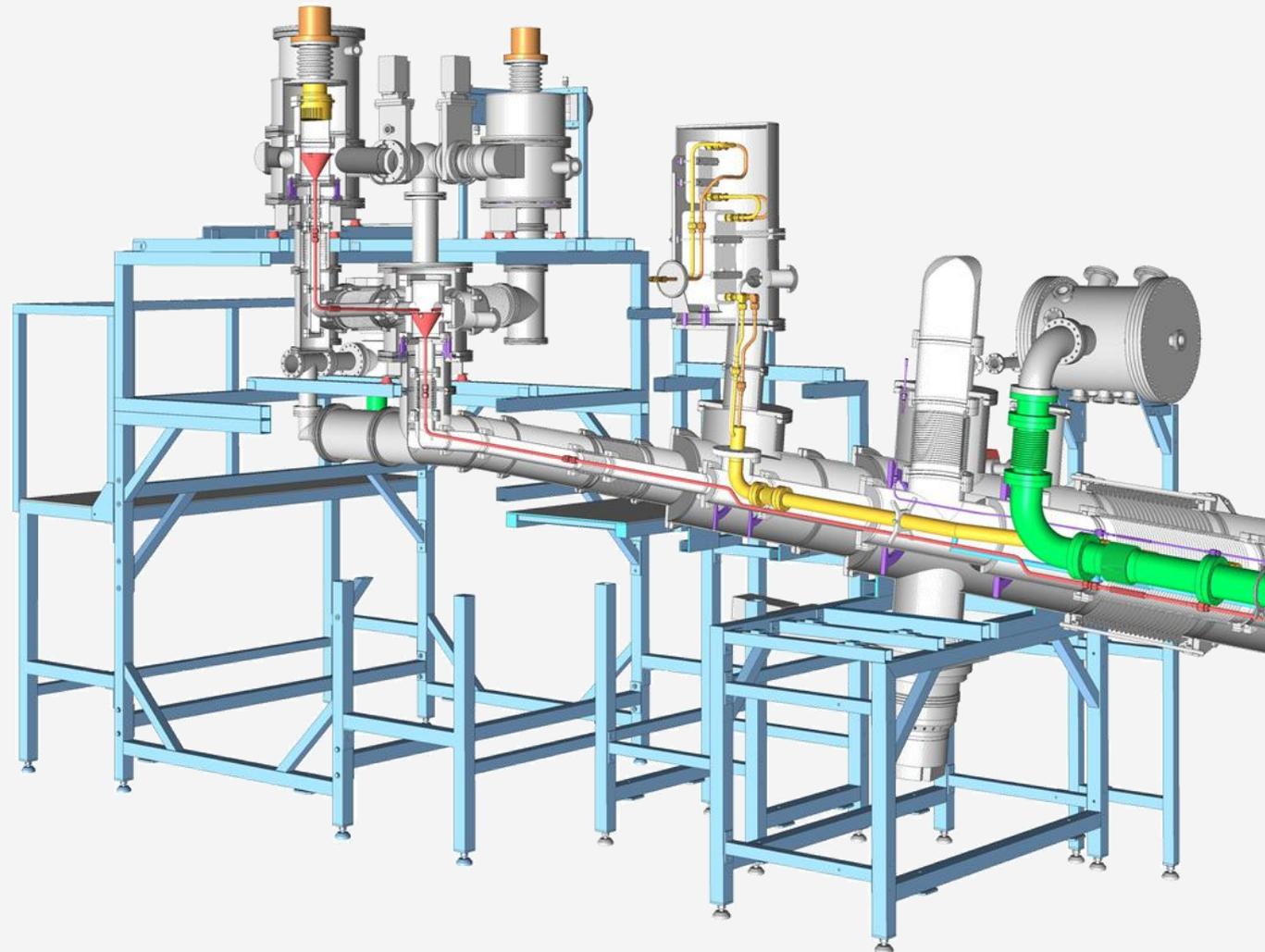


ReStoX 2

- 1.45 m diameter, 5.5m height, 71.5 bar maximum pressure
- Build for XENONnT to enable fast recovery
- Capacity of 10 tonnes (LN₂: 0 kg/d)
- Recovery speed of 1 tonne/h (LN₂: 8 tonne)



XENONnT Cryogenics System



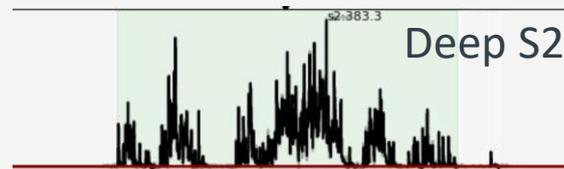
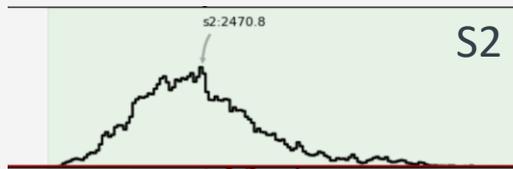
Cooling/Liquefaction

- Heat load <200 W (including purification systems)
- Redundant **Iwatani PC150 pulse tube refrigerators** with 250 W @ 177 K (LXe temperature)
- One PTR can be serviced while the other is in operation
- **Backup LN₂ cooling system** with custom LN₂/LXe heat exchanger reaching >500 W

Electronegative Impurities in XENON

Ionization Electrons attach to electronegatives

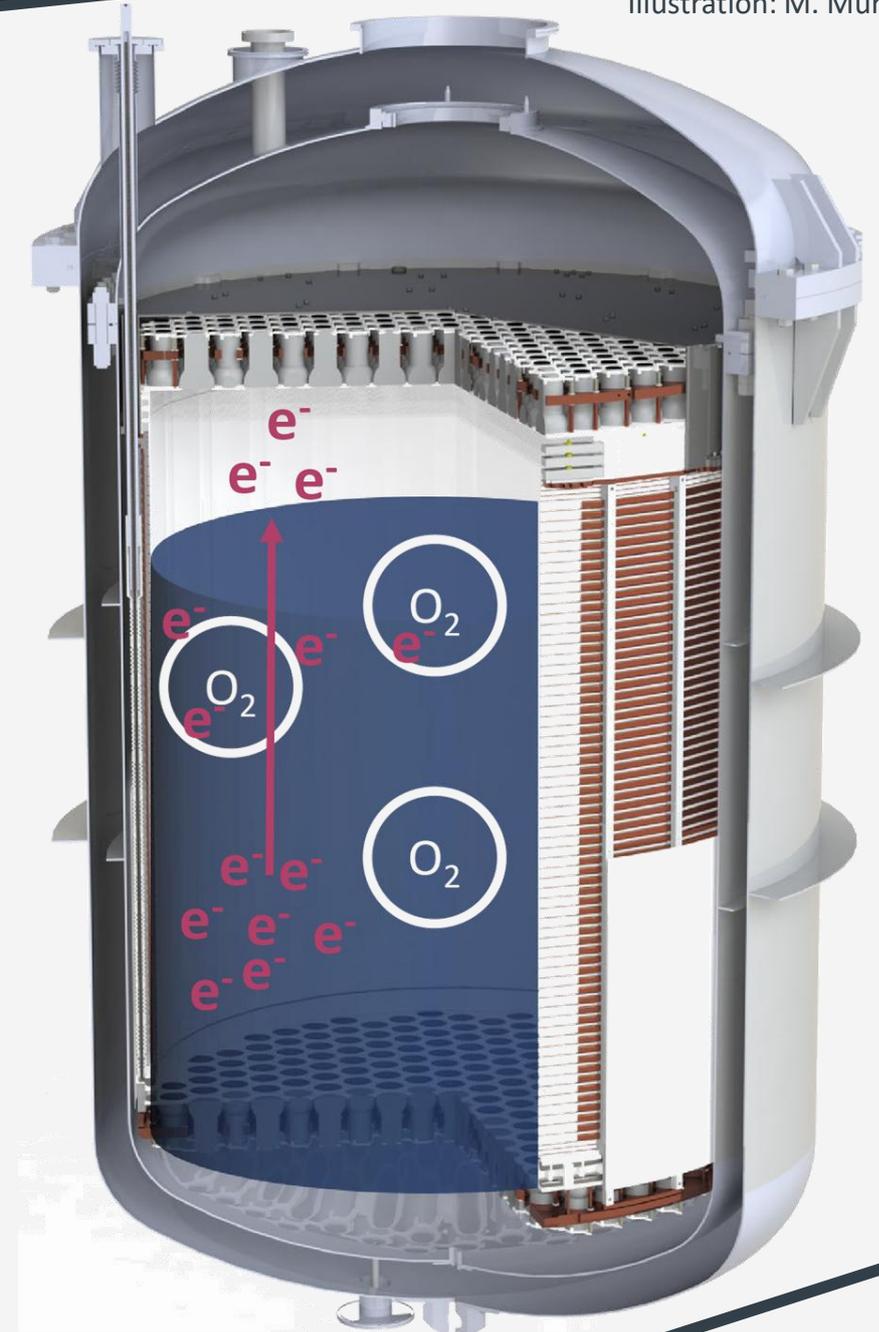
- Drifting electrons attach to impurities along the drift
- S2 size is reduced, lower sensitivity for small signals
- Distorted S2 signals from deep interactions



Xenon purity is expressed as electron lifetime τ_e

- Time over which the number of drifting electrons N_e is reduced by a factor $1/e$ due to attachment
- Attachment depends on specific rate constant k_i and concentration C_i

$$N_e(t) = N_e(0)e^{-t/\tau_e} \quad \tau_e = \frac{1}{\sum k_i C_i} = \frac{1}{\sum k_{O_2} C_{O_2}}$$



Removal Model for Electronegatives

O₂ mole fraction

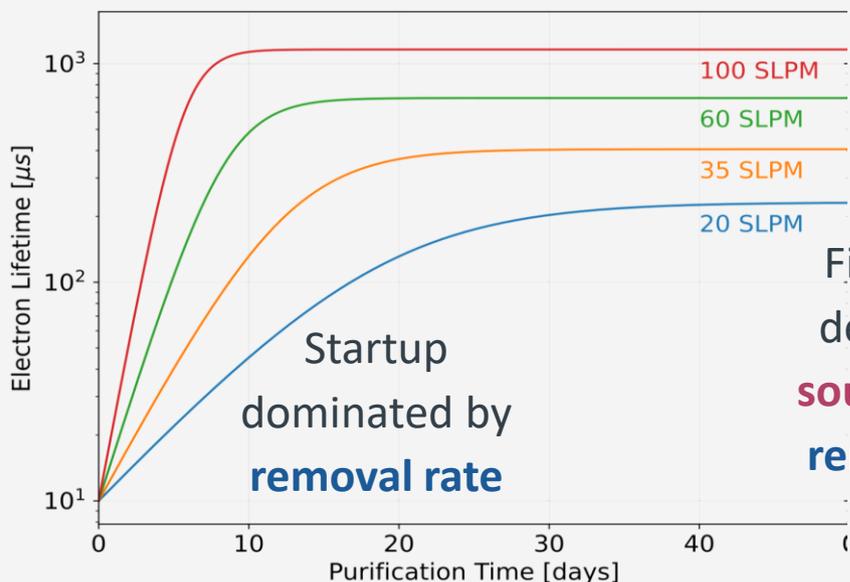
Removal term

(total mass, removal efficiency, flow rate)

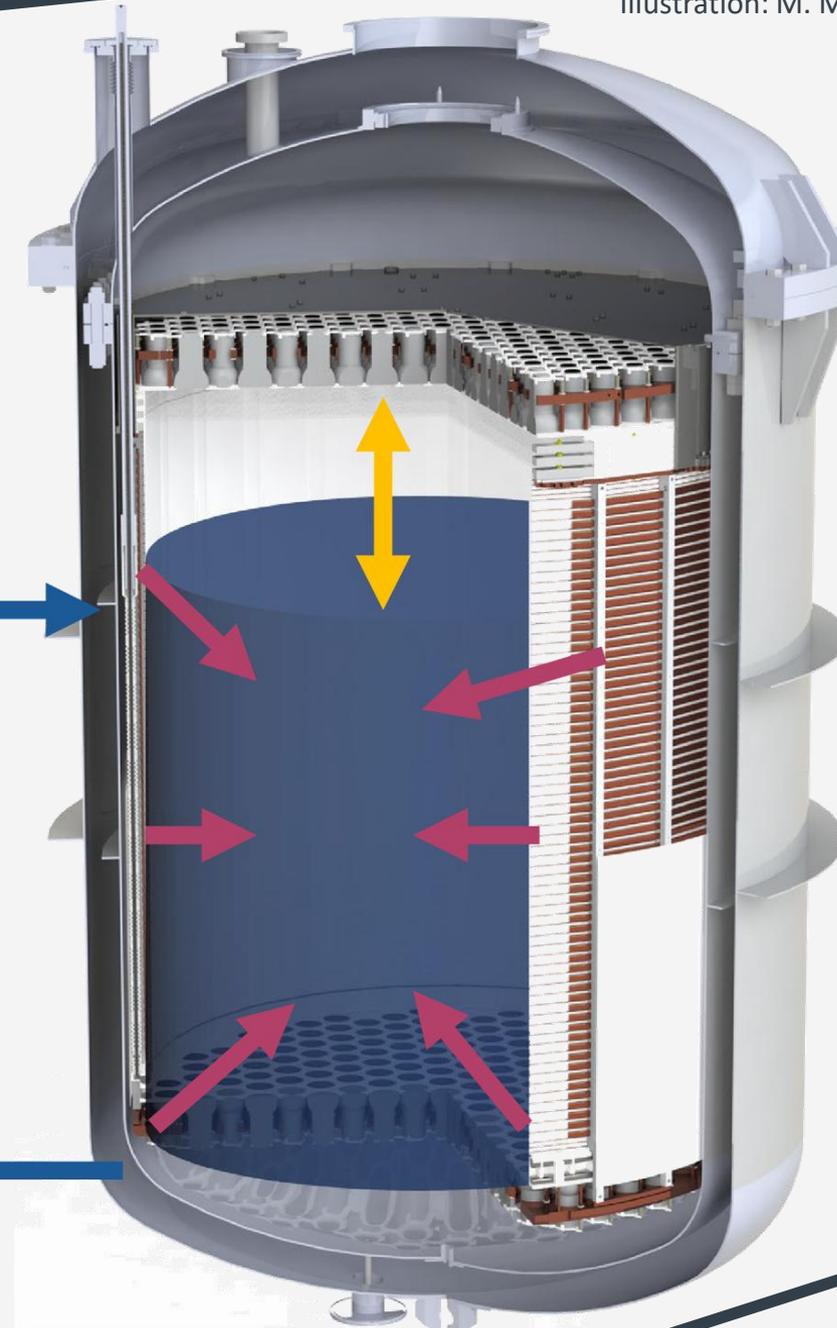
$$n \frac{dx}{dt} = \Lambda - \frac{n\epsilon}{\tau_P} x + (\text{GXe/LXe migration})$$

Source term

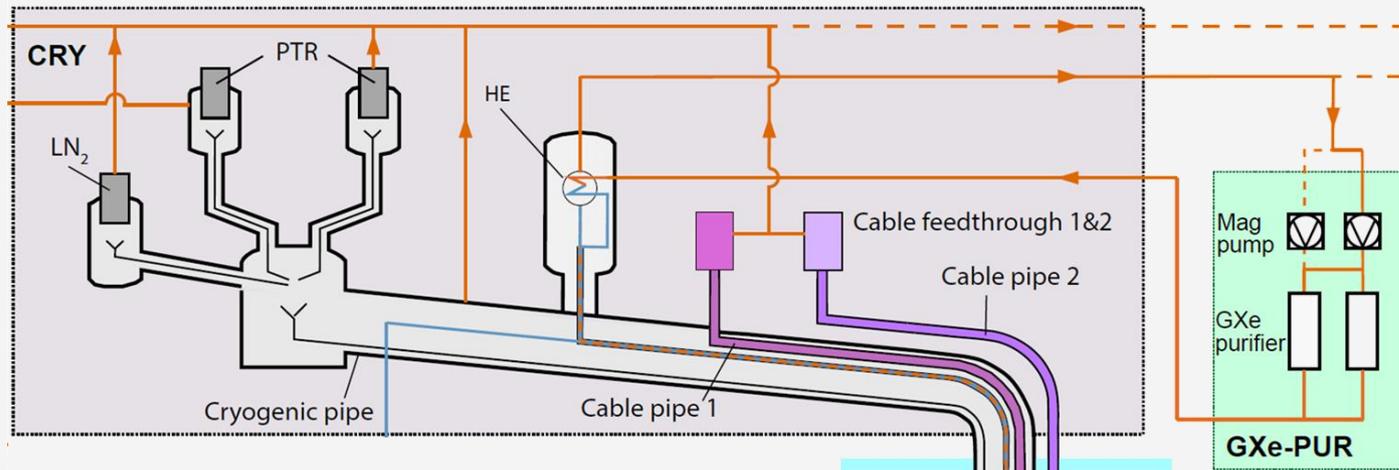
(surface desorption)



Purification System

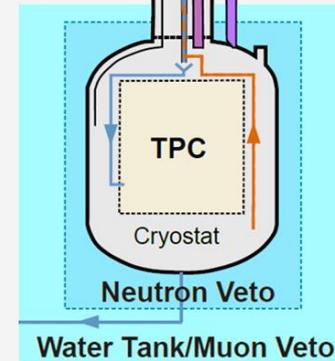


Gaseous Xenon Purification in XENONnT

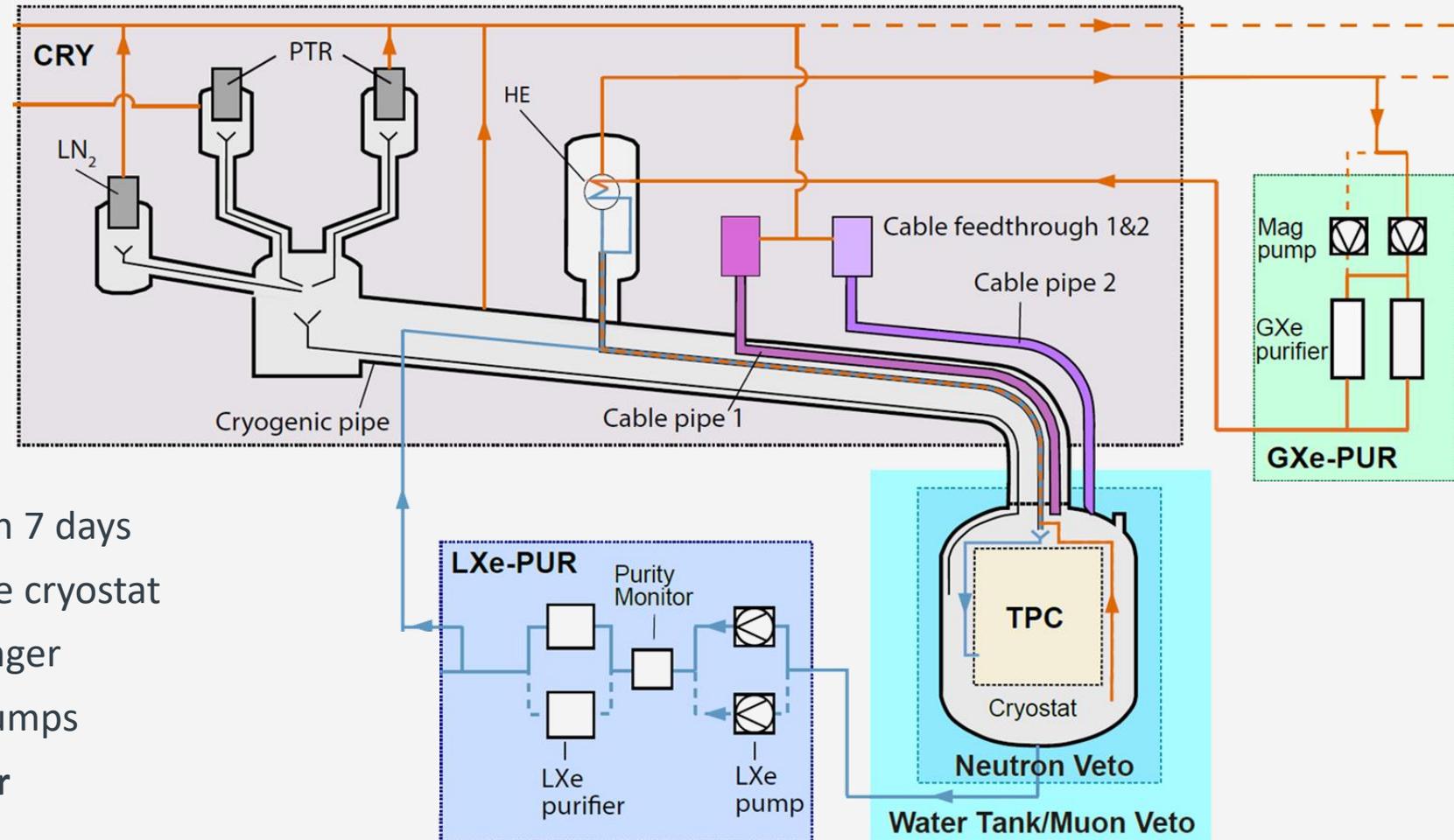


Upgraded XENON1T Purification

- 2x SAES heated getter (PS4-MT50-R) with Hydrogen Removal Units (HRUs) (tritium removal)
- 2x Custom-developed magnetically-coupled piston pumps (radon-free, 1.9 bar ΔP at 100 slpm)
- Limited by the GXe pump flow of 60 – 100 slpm
- Handles the injection of radioactive sources for calibration
- Developed for a **turn-around time of 7 days for 3.2 tonne**



Liquid Xenon Purification in XENONnT



- **Goal:** <0.1 ppb O₂-equivalent conc. in 7 days
- LXe extracted from the bottom of the cryostat
- Sub-cooled by a LXe-LN₂ heat exchanger
- Pumped using two redundant LXe pumps
- **Purified by custom-designed purifier**
- Volumetric flow rate of **1-4 LPM**
- **Turn-around time of 0.9 days for 8.6 tonne**

Liquid Xenon Purification in XENONnT

Pumped using two redundant LXe pumps

- Barber Nichols Pump (BNCP-32C-000)
- **Magnetically-coupled shaft partial emission centrifugal cryogenic liquid pump**
- Satisfies requirements of cleanliness, efficiency, low heat influx, and liquid flow rate
- Minimal down time during annual pump maintenance

Two custom-designed redundant LXe purifiers

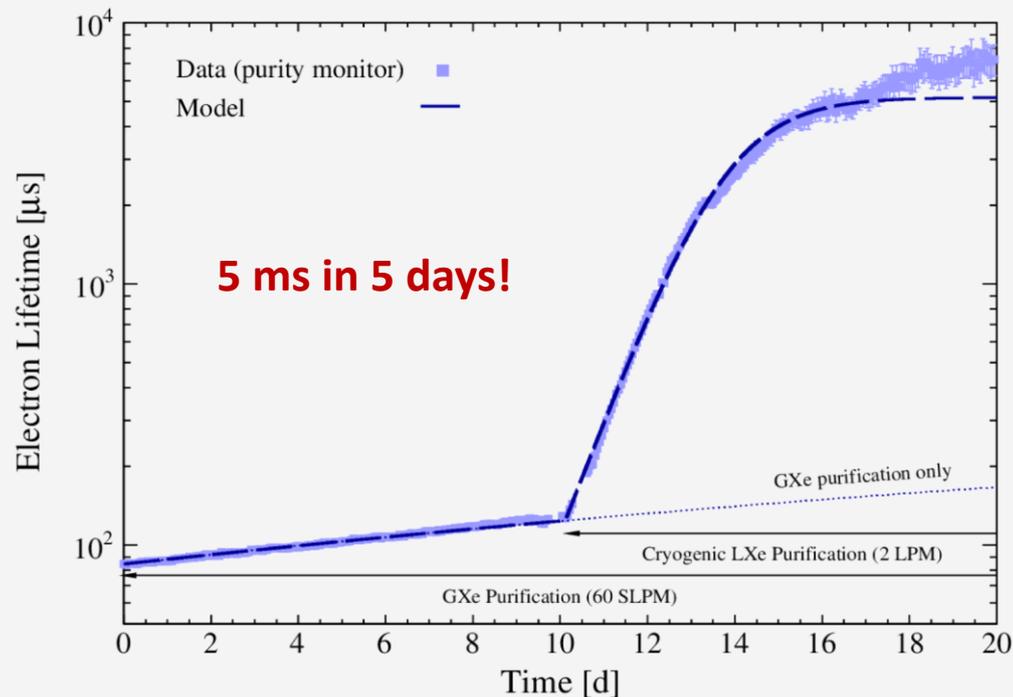
- Independent vacuum insulation enclosures
- **In-situ regeneration** while other unit is in operation
- High efficiency **Engelhard Q5 purifier (high Rn)** at low purity
- Lower efficiency **SAES St707 filter (low Rn)** normal operation
- Purity can be kept >1 year without regeneration



Liquid Xenon Purification in XENONnT

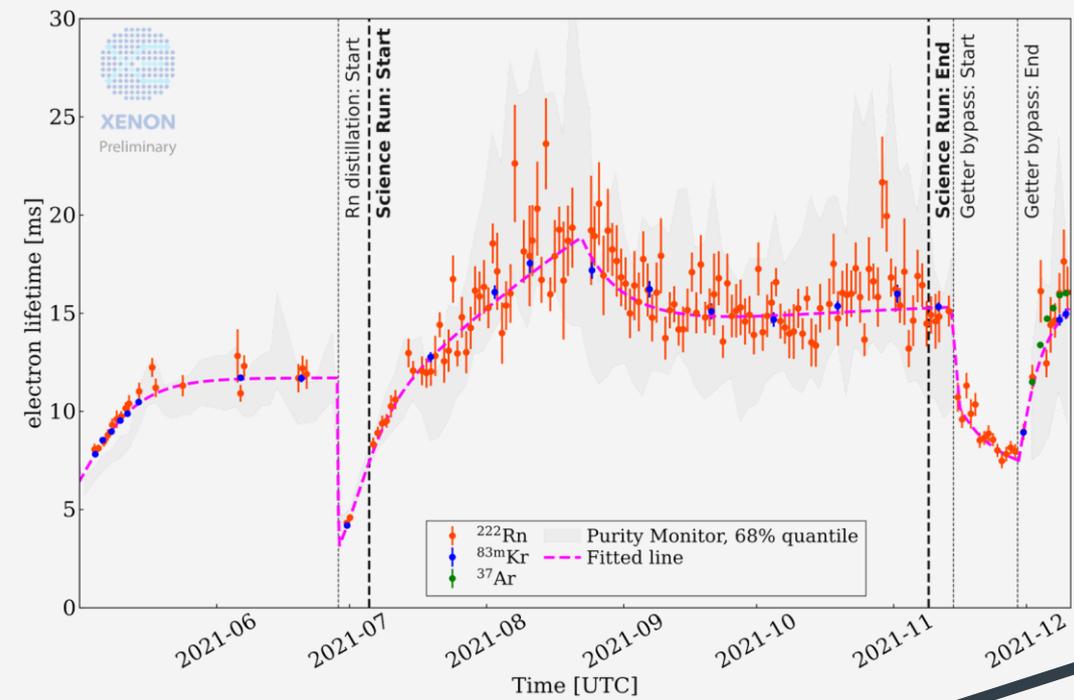
Purification Strategy

- Initial purification with high-efficiency purifier (Q5) to clean xenon bulk, but with high radon emanation
- Switch to lower efficiency purifier (St707) to maintain purity with low radon emanation during science data taking



Performance during science data taking

- Flow rate of 2 LPM
- Turn-around time of 0.9 days for 8.6 tonne
- Achieved electron lifetime up to 20 ms
- About 90% of the electrons survive the full drift (1.5 m)



Status and Exposure

1st Science Run (SR0)

Search for New Physics in Electronic Recoil Data from XENONnT
Phys. Rev. Lett. 129, 161805 (2022)

First Dark matter Search with Nuclear Recoils from the XENONnT Experiment
Phys. Rev. Lett. 131, 041003 (2023)

WIMPs

2nd Science Run (SR1)

First indication of Solar ^8B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT
Phys. Rev. Lett. 133, 191002 (2024)

CEvNS

First Search for Light Dark Matter in the Neutrino Fog with XENONnT
Phys. Rev. Lett. 134, 111802 (2025)

Light Dark Matter

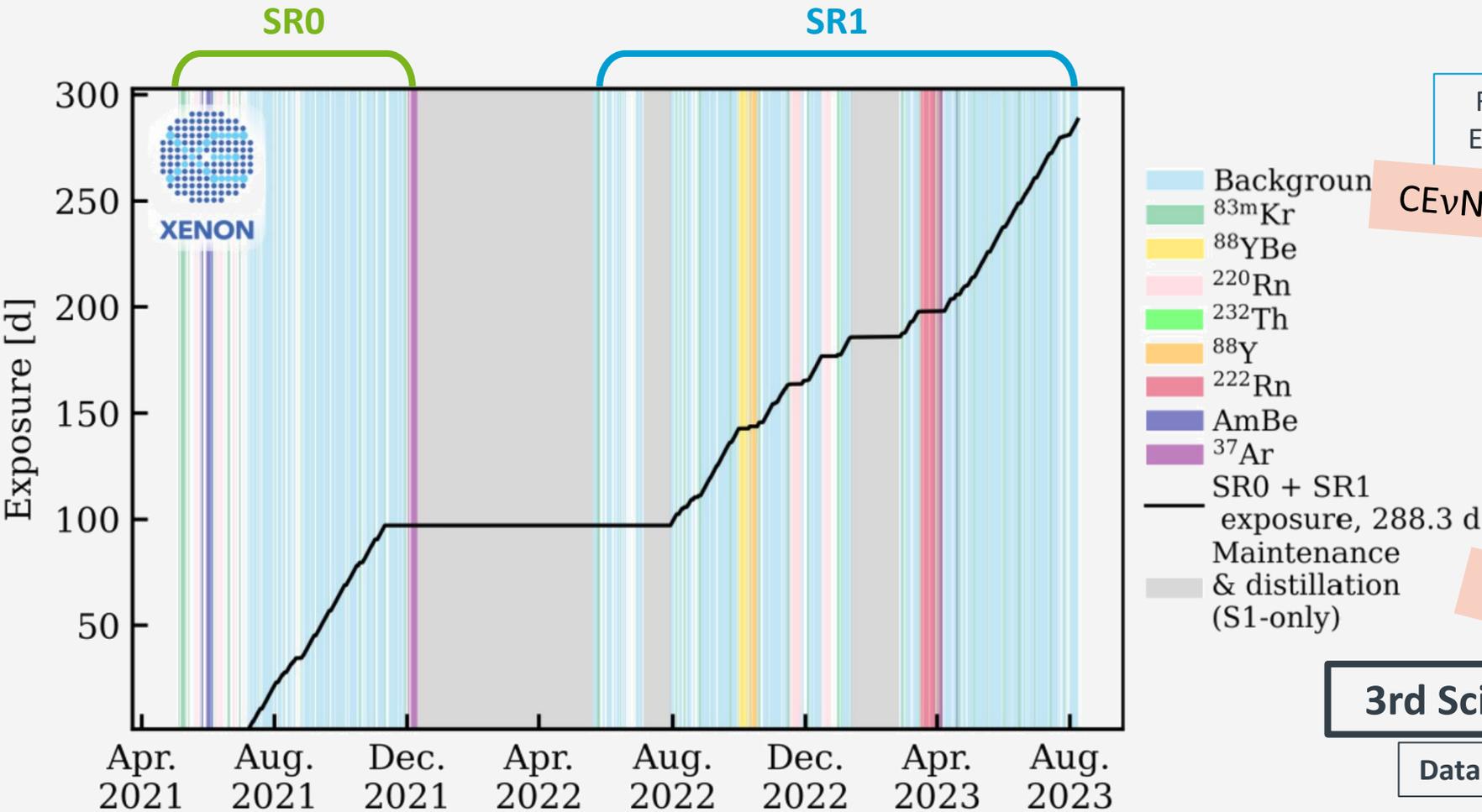
Search for light dark matter in low- ϵ ionization signals from XENONnT
Phys. Rev. Lett. 134, 161004 (2025)

WIMP Dark Matter Search using a 3.1 tonne x year Exposure of the XENONnT Experiment
arXiv:2502.18005 (2025)

WIMPs

3rd Science Run (SR2)

Data analysis ongoing!



XENONnT SR0+SR1 WIMP Search (updated)

Blind analysis

3.1 tonnes x years exposure

SR0 (95 days, 0.26 years)

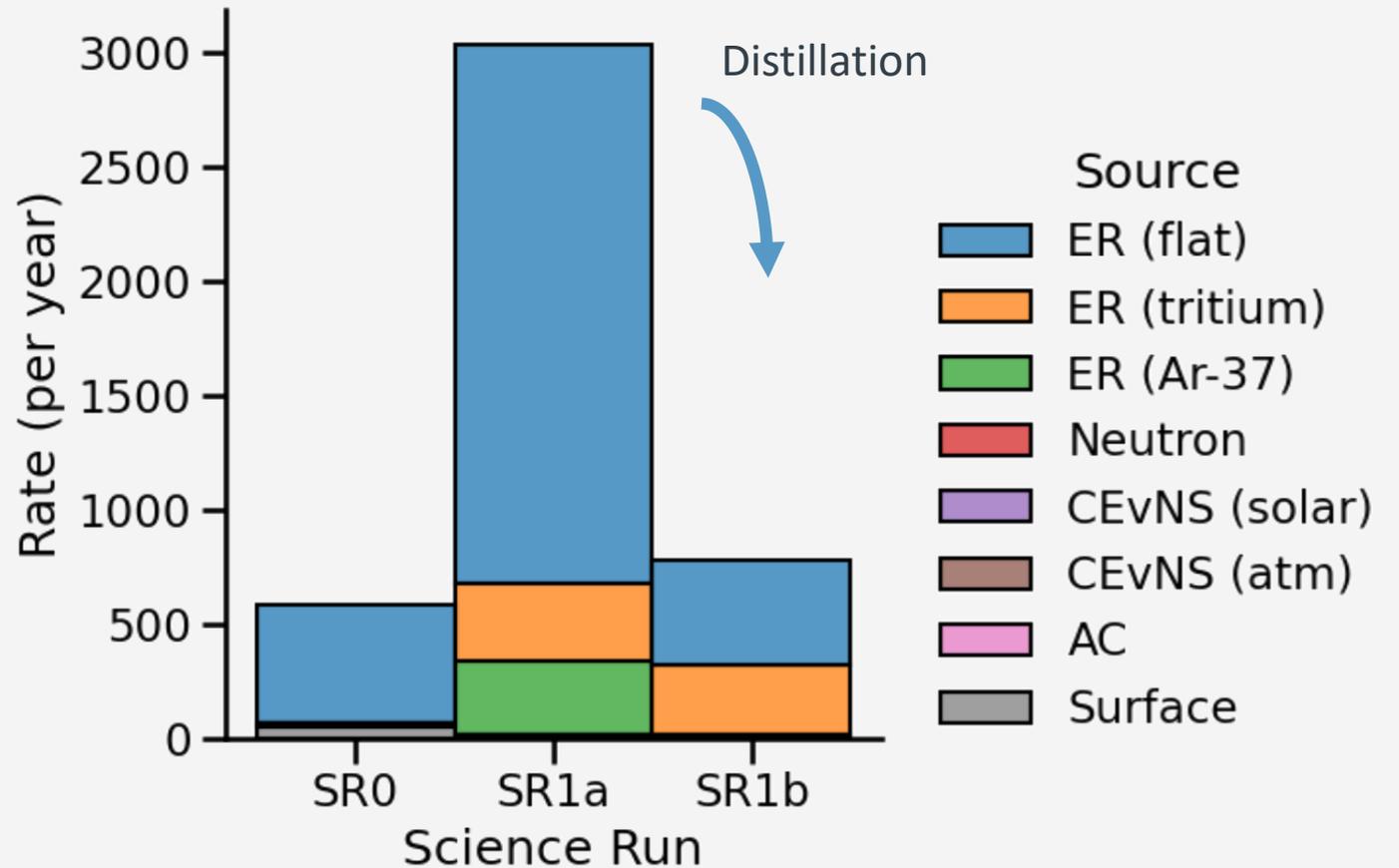
- Updated neutron background model

SR1a (67 days, 0.18 years)

- **High rate of ^{85}Kr and ^{37}Ar**
- Accidental injection of small amount of commercial-grade purity xenon leftover from previous operations (not distilled)
- **Tritium-like** background

SR1b (120 days, 0.33 years)

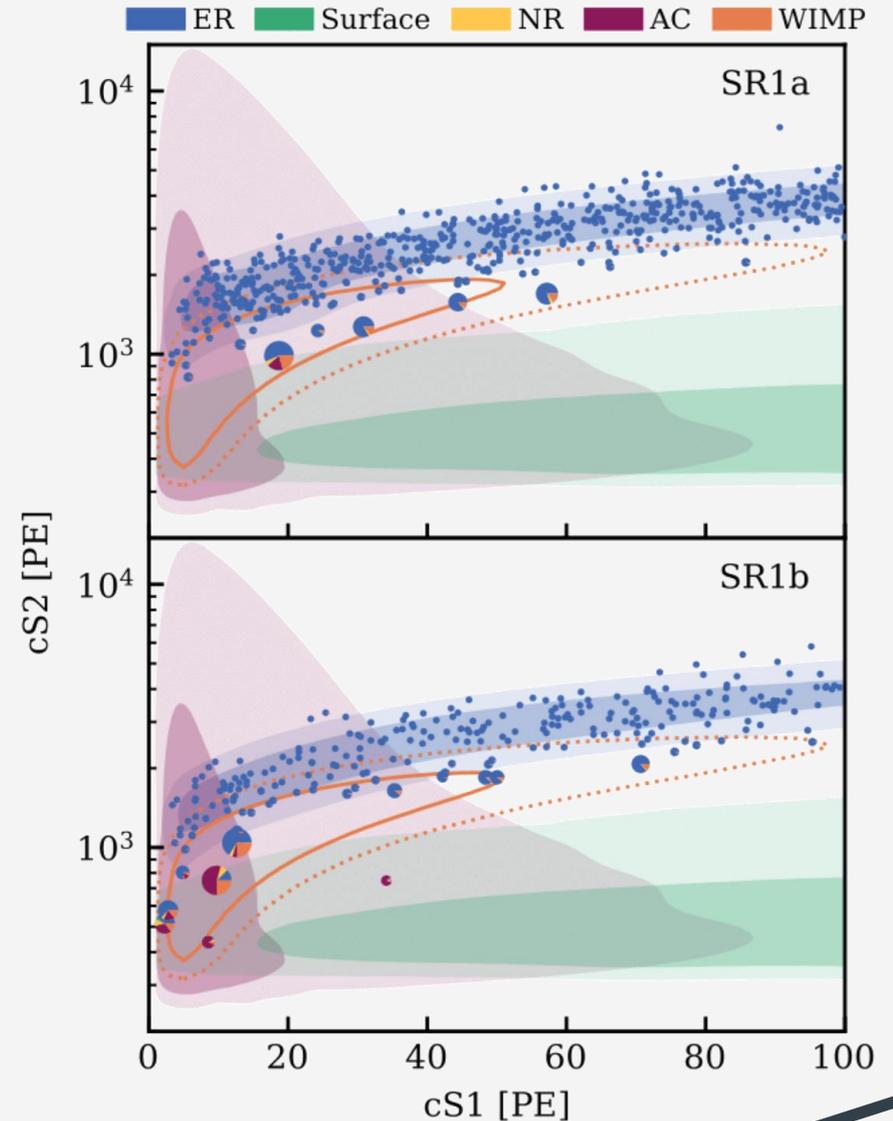
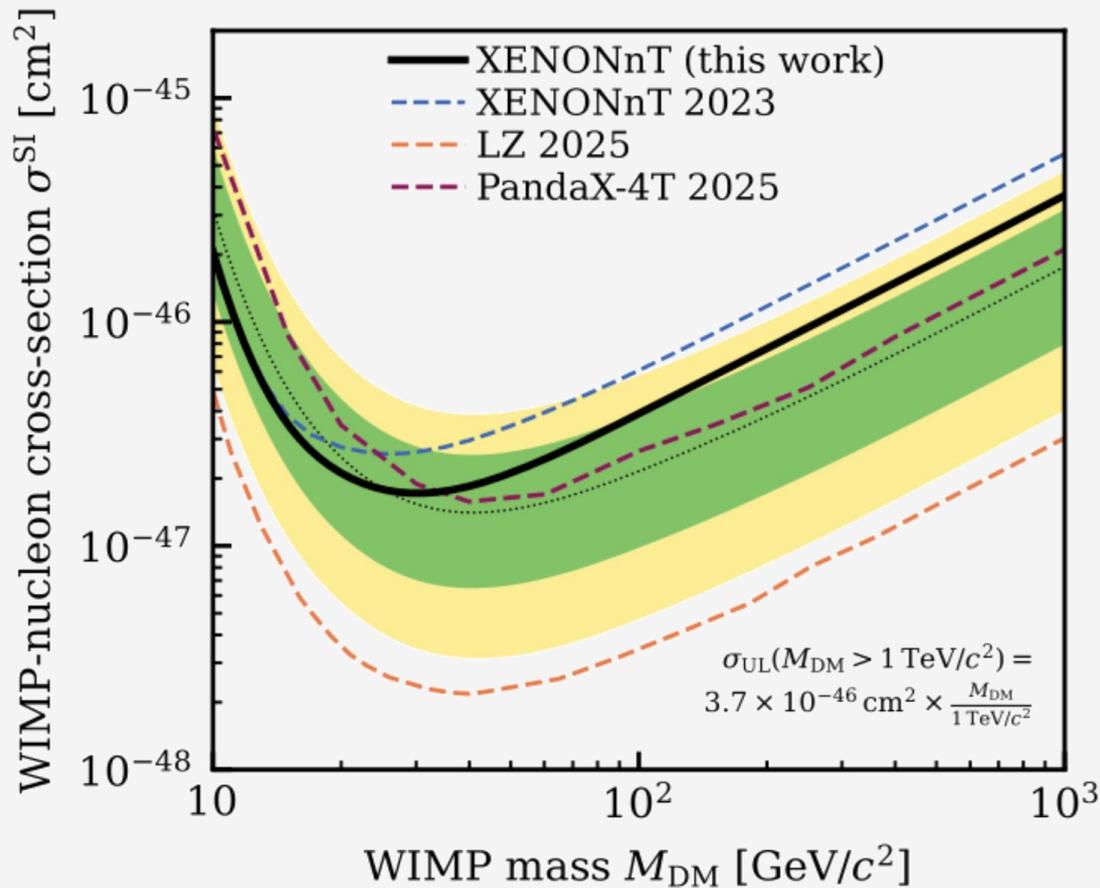
- ER rate back to SR0 level (distillation)
- Tritium-like backgrounds remains



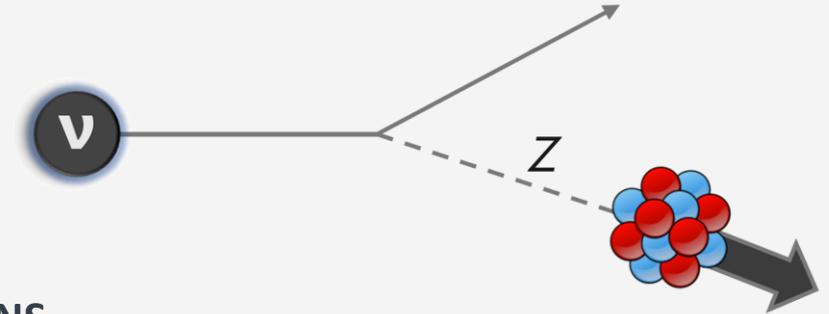
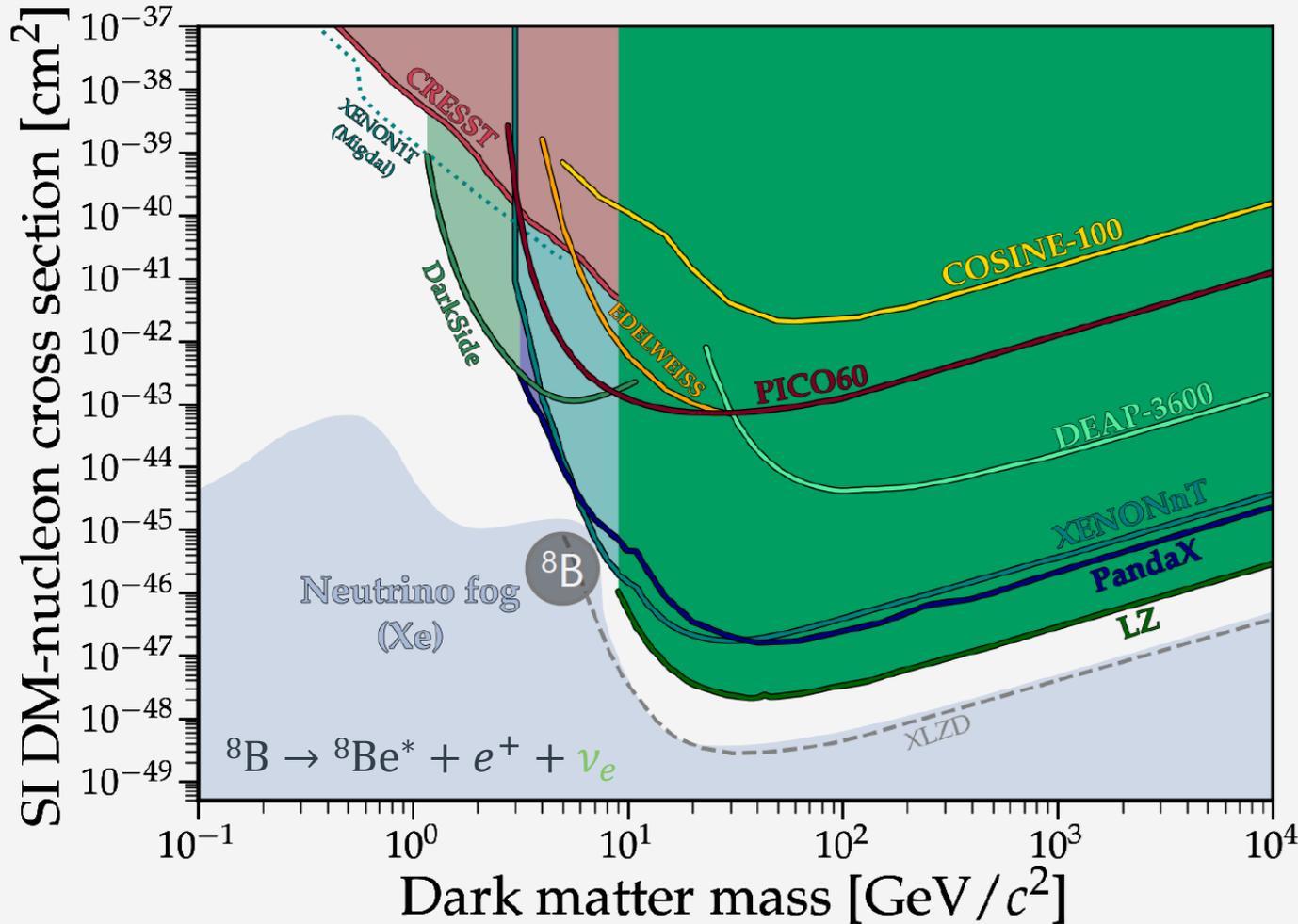
XENONnT SR0+SR1 WIMP Search (updated)

Blind analysis

3.1 tonnes x years exposure



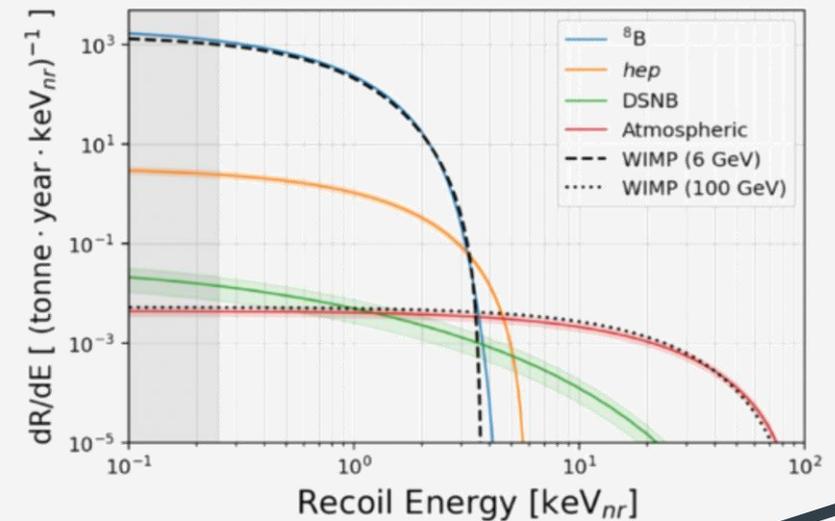
Searching through the Neutrino Fog



CEvNS

Coherent Elastic neutrino-Nucleus Scattering

- Mimic WIMP single scatter NR signal
- Irreducible background from solar & atmospheric neutrinos



XENONnT SR0+SR1 CEvNS Search

First indication of solar ⁸B events

- Discovery significance: **2.73σ** from SR0 + SR1
- **Measured ⁸B flux:** $(4.7^{+3.6}_{-2.6}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$
- Fix flux: **First measurement of CEvNS cross-section in xenon**
- Significance to be increased with further XENONnT data
- Latest measurement **turns into background** for further dark matter searches

Expected background:

$$26.4^{+1.4}_{-1.3}$$

Expected signal:

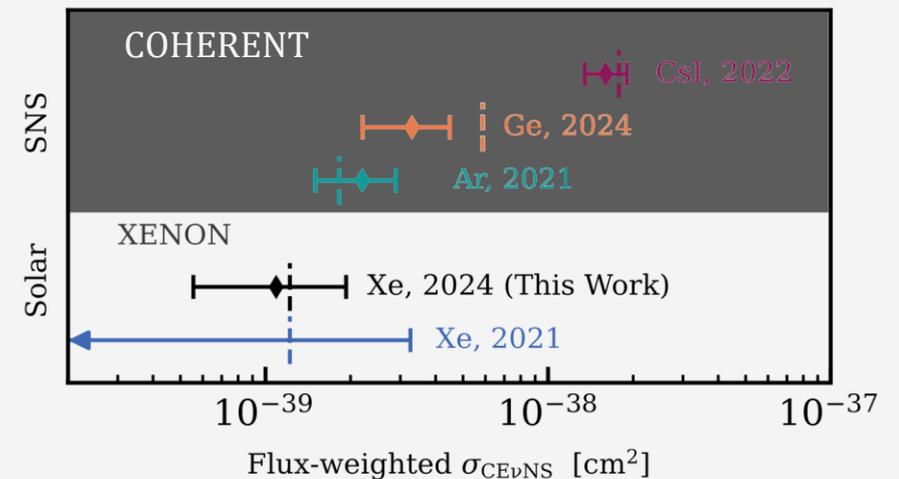
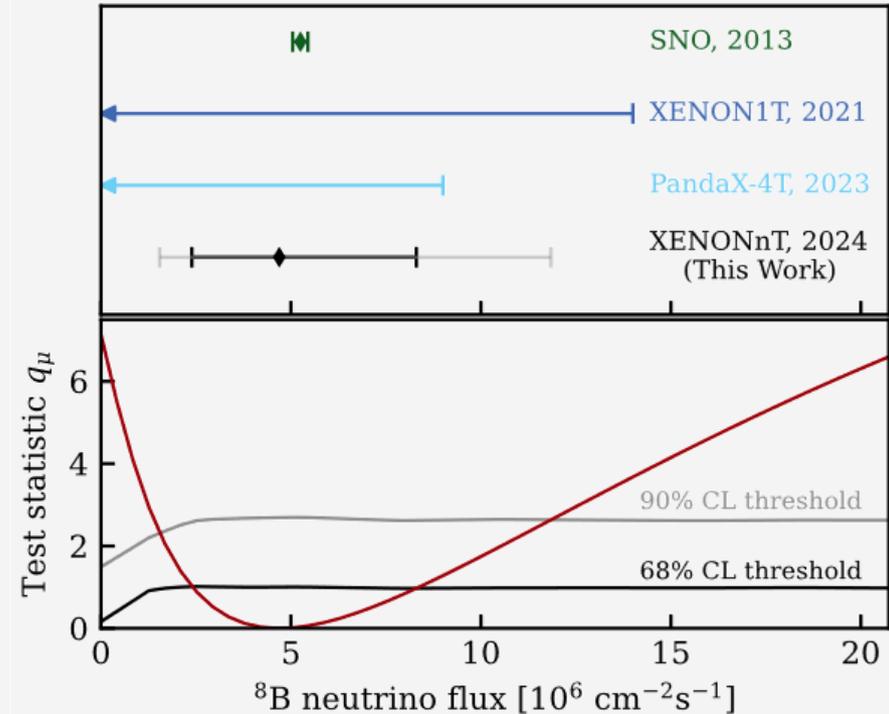
$$11.9^{+4.5}_{-4.2}$$

Observed:

37

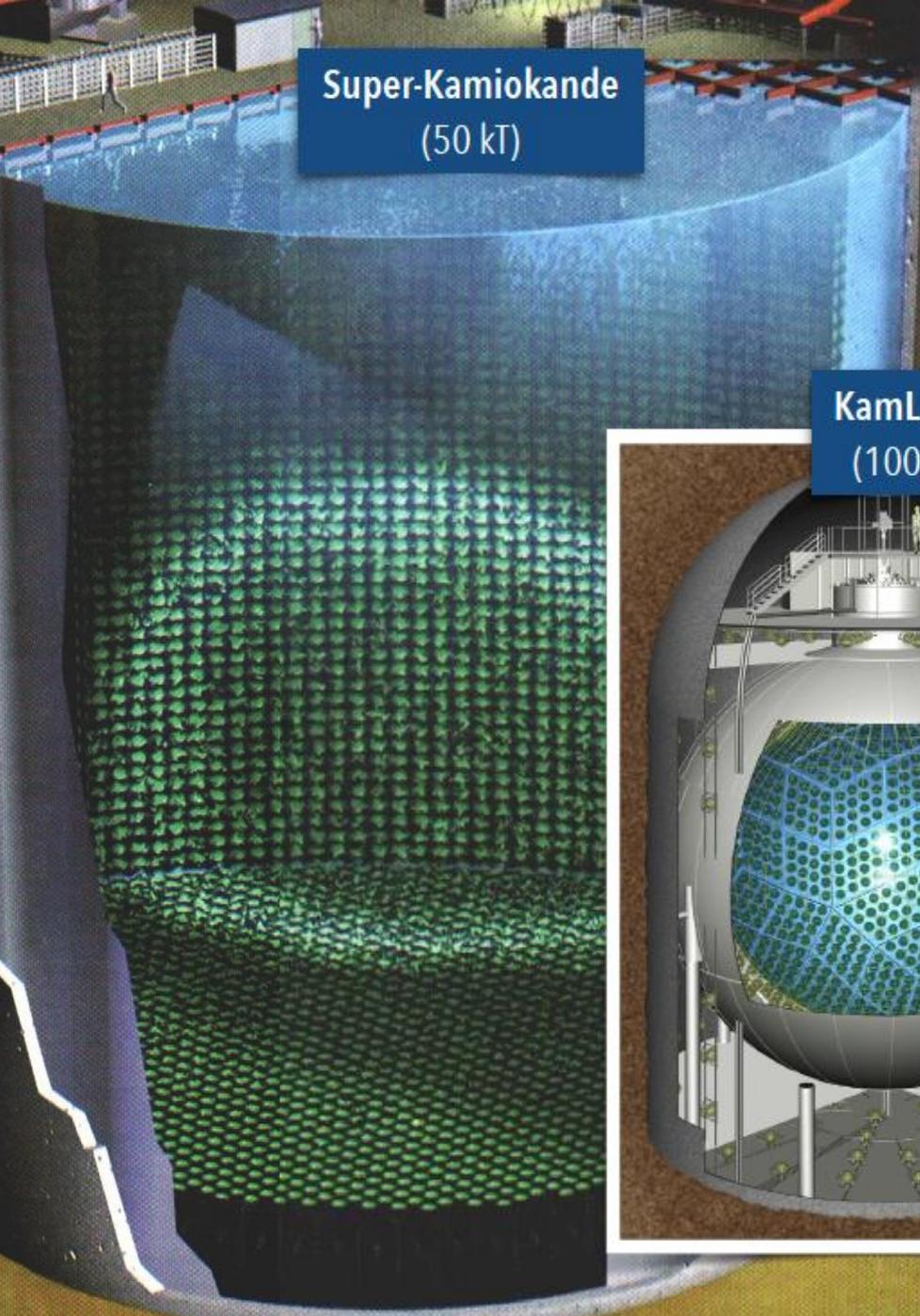
Best-fit number of ⁸B signal events

$$10.7^{+3.7}_{-4.2}$$

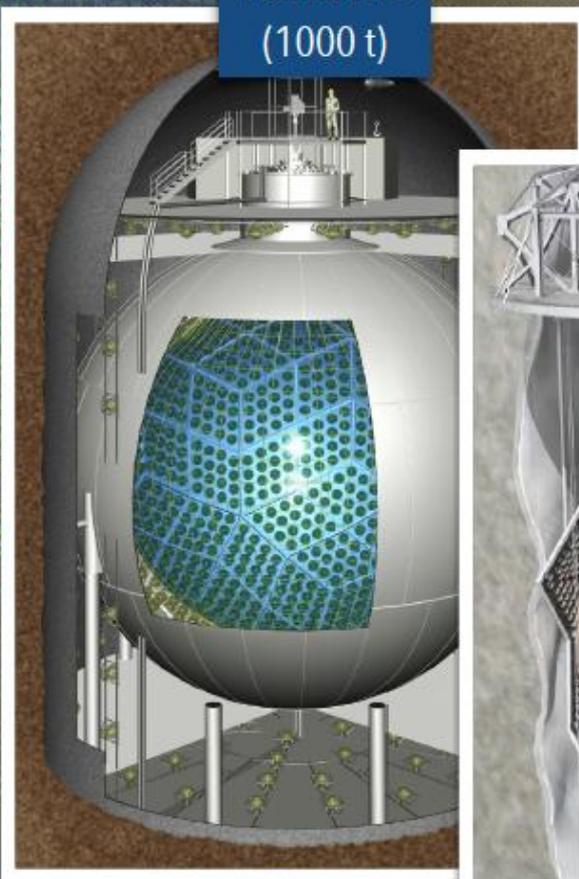


XENONnT: The Smallest Solar Neutrino Detector

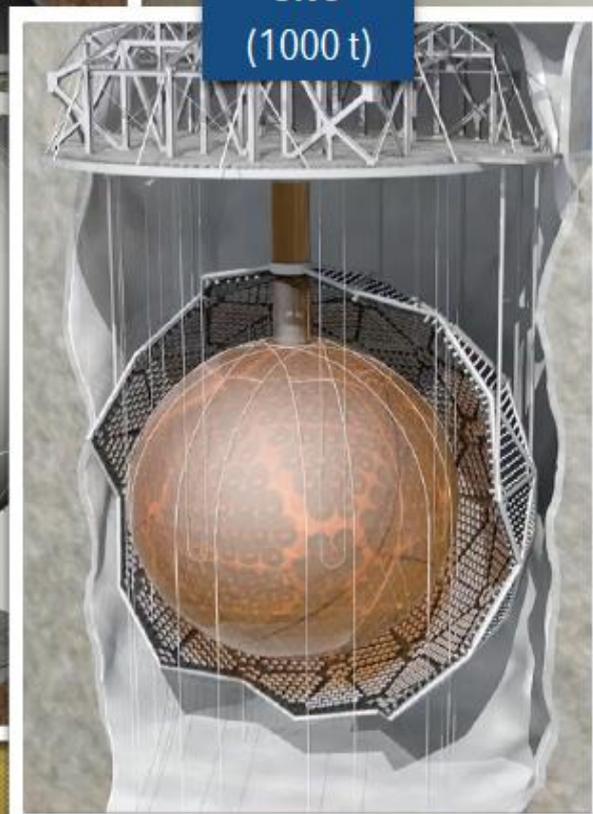
Super-Kamiokande
(50 kT)



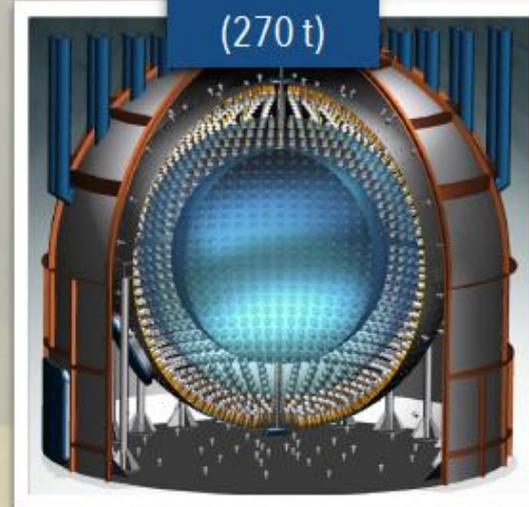
KamLAND
(1000 t)



SNO
(1000 t)



Borexino
(270 t)



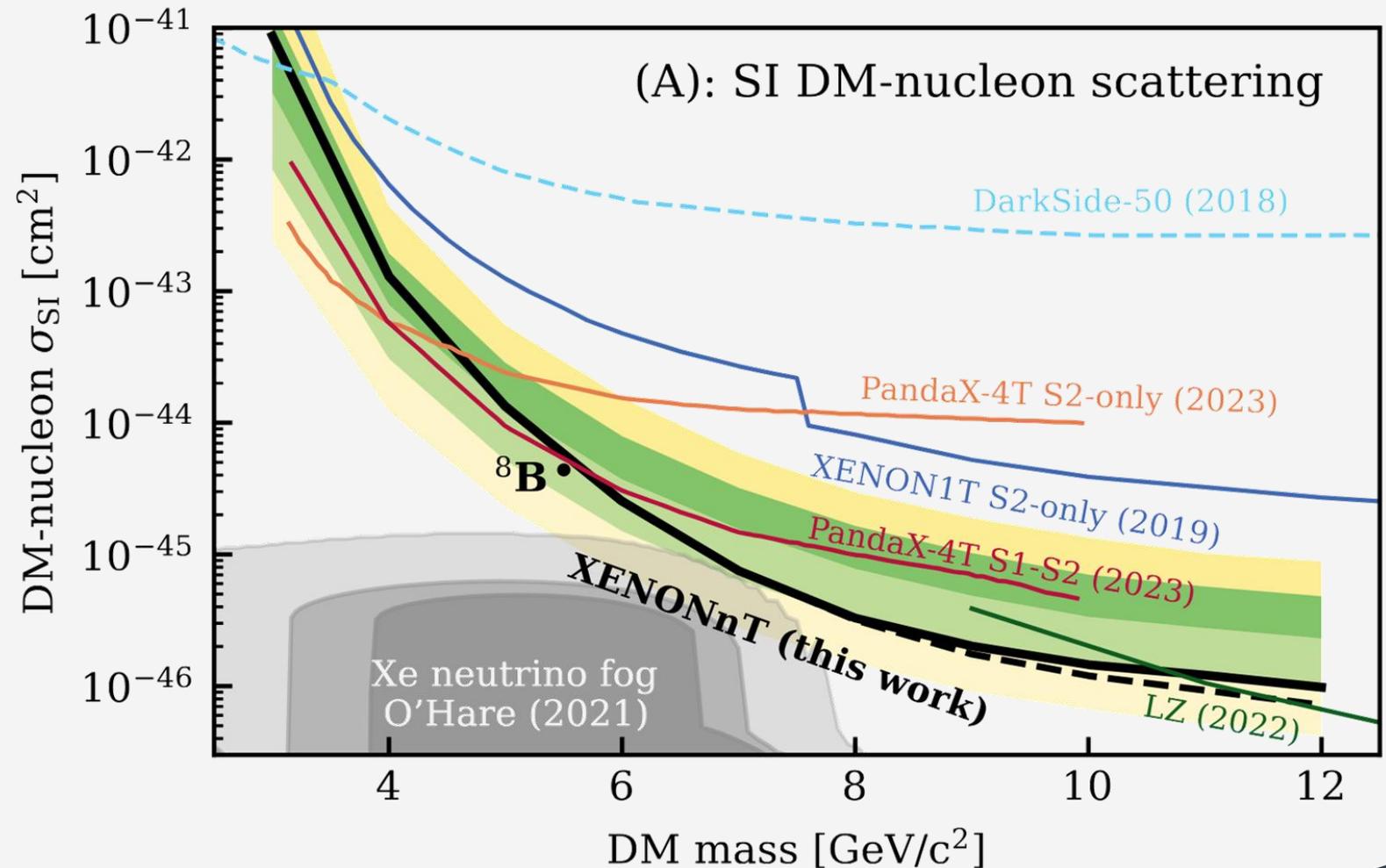
XENONnT
(5.9 t)



Light WIMP Search

- Use same dataset & analysis for WIMP search at low masses
- CEvNS now as background
- No excess found
- Excluded new parameter space in the low mass range

→ First step into the neutrino fog



Summary and Outlook



XENONnT Science results

- New limits from SR0+SR1 WIMP search
- First observation of ^8B via CEvNS
- First Dark Matter search in the neutrino fog

Prospects for the future

- XENONnT SR2 data analysis ongoing
- Detector upgrade ongoing (stronger drift field, discrimination, ...)
- Next generation of LXe experiments on the way (XLZD)

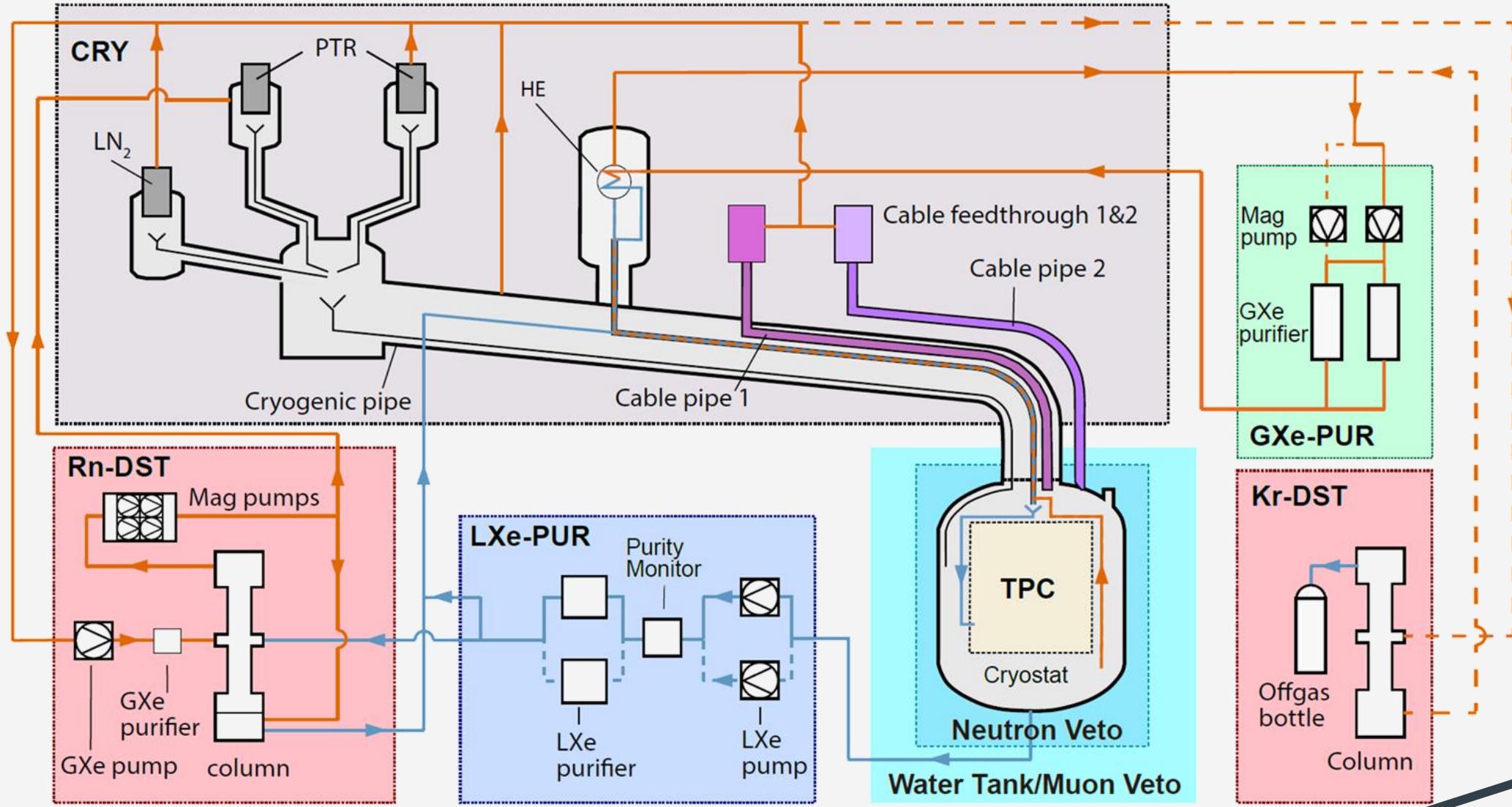


xenonexperiment.org

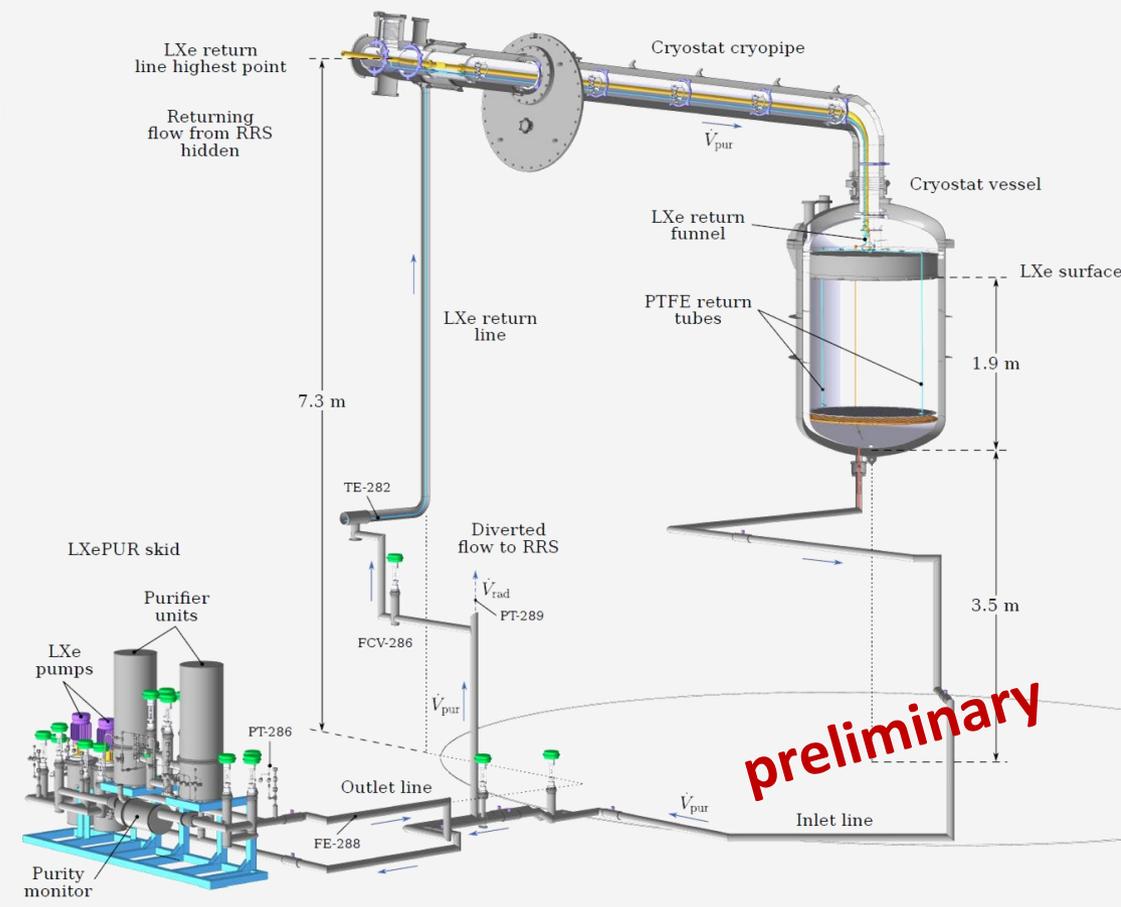
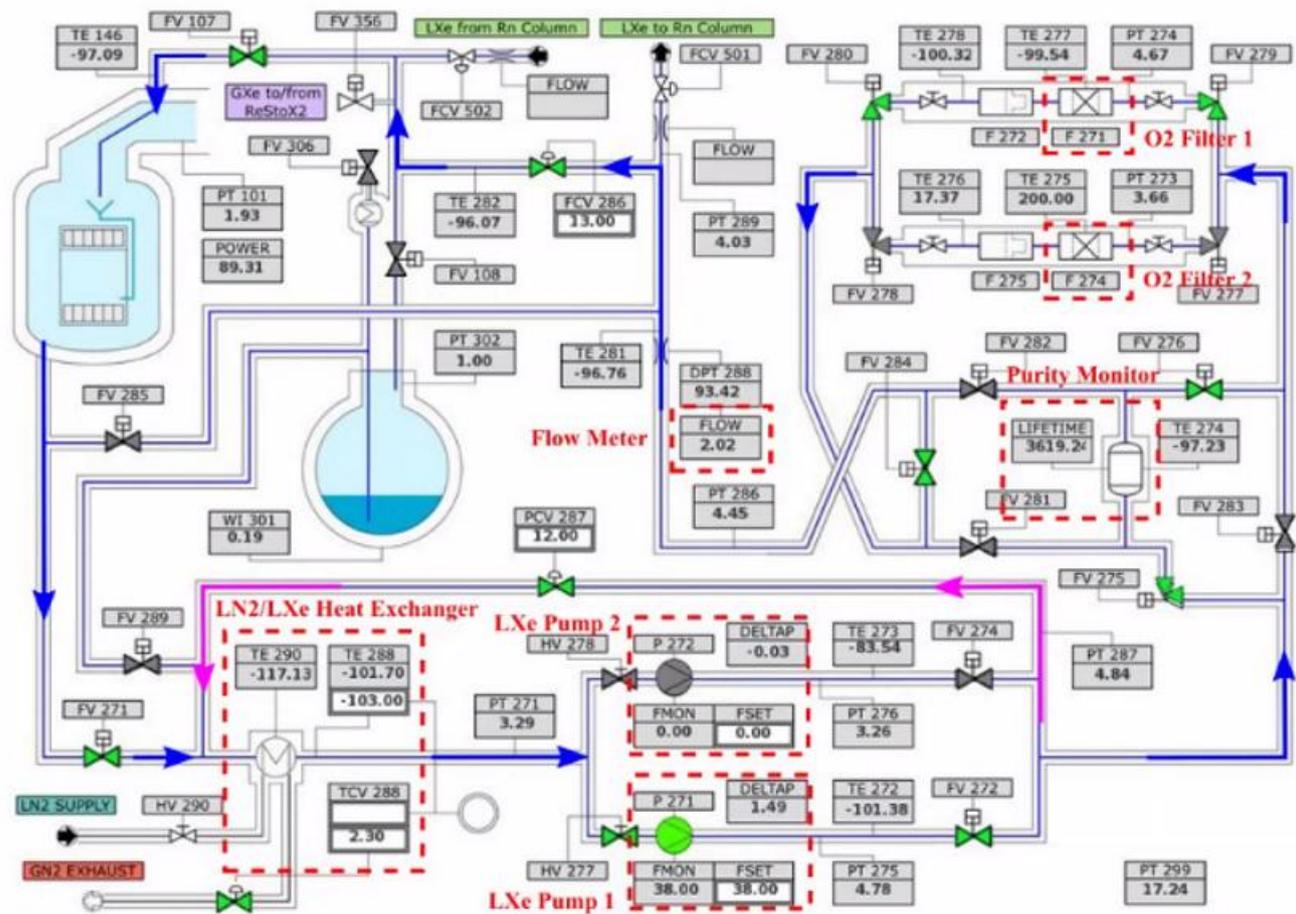


XENON-LZ-DARWIN

XENONnT Cryogenics Overview

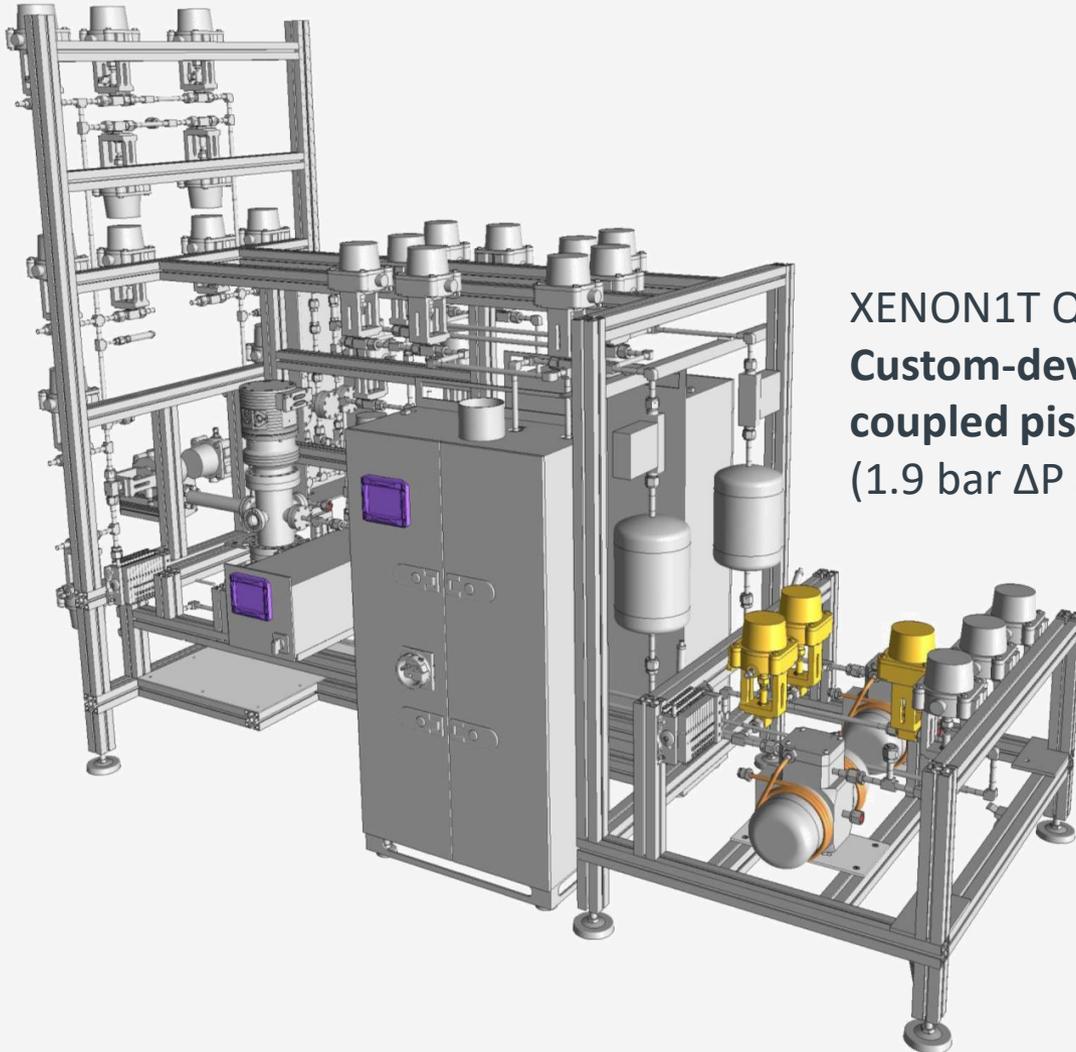


LXe Purification Overview



preliminary

Gaseous Xenon Purification for XENON1T (upgraded for XENONnT)



XENON1T Q-Drives replaced by **Custom-developed magnetically-coupled piston pumps** (radon-free) (1.9 bar ΔP at 100 slpm)



Sorbents – Engelhard Q5 / BASF Cu-0226-S

- CuO on alumina substrate
- Spheres with diameter 0.6 – 1.2 mm (14x20 mesh)
- Large specific surface (200 m²/g)
- Activated via reduction reaction $\text{CuO} + \text{H}_2 \rightarrow \text{Cu} + \text{H}_2\text{O}$
- Achieved by flowing mixture 5% H₂ + 95% Ar through bed
- Mostly O₂ removal via $2 \text{Cu} + \text{O}_2 \rightarrow 2 \text{CuO}$
- High sorption capacity (0.5 mg O₂/g sorbent)
- High radon emanation rate (100's mBq/kg)
Eur. Phys. J. C 82, 599 (2022)
- Used in LAr purification systems

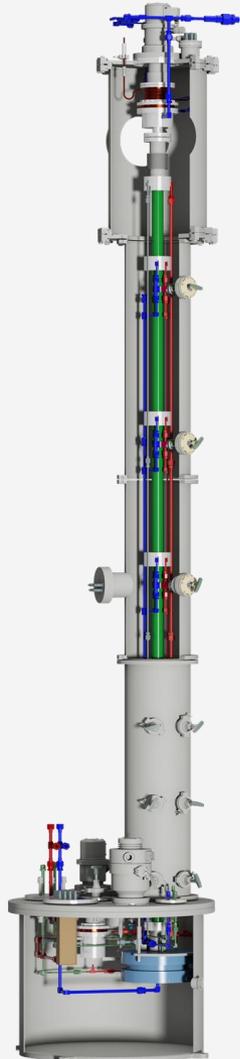


Sorbents – SAES St707

- Non evaporable getters (NEG) alloy of Zr (70%), V (24.6%), Fe (5.4%)
- Pills used in SAES MonoTorr (Entegris Gatekeeper) heated getter gas purifiers (rare gas version)
- Irreversibly sorbs H_2O , O_2 , CO , CO_2 , CH_4 , N_2 , (H_2 reversibly)
- Low radon emanation rate (100 $\mu\text{Bq}/\text{kg}$)
Eur. Phys. J. C 82, 599 (2022)
- Sorption capacity is high (best) at temperatures $>200^\circ\text{C}$



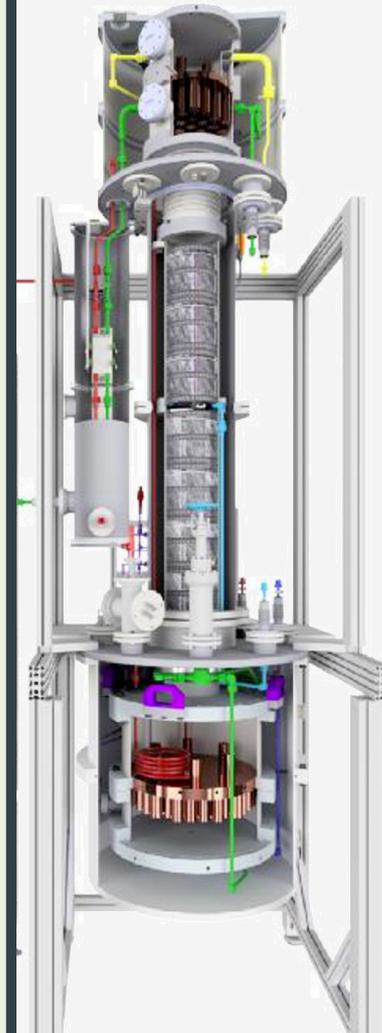
Krypton and radon removal @XENONnT



Krypton distillation

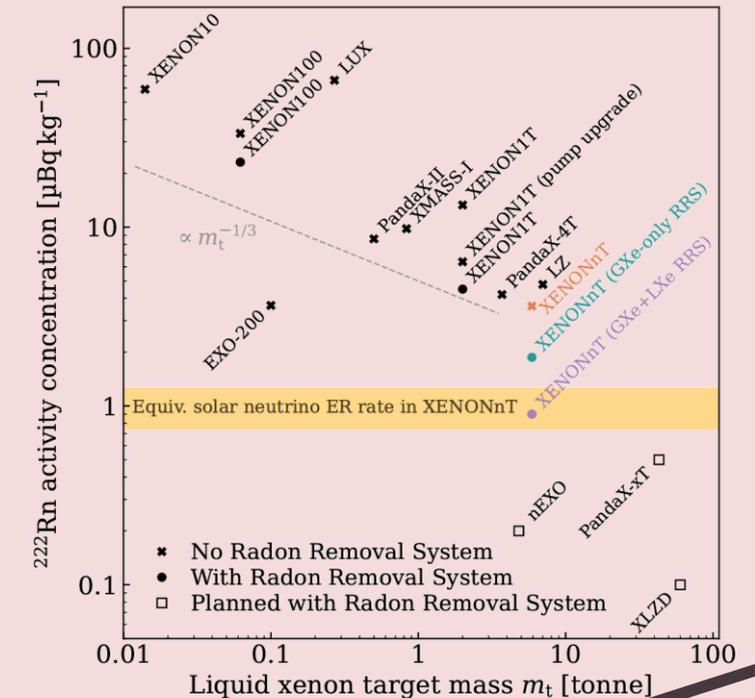
- **Offline distillation demonstrated**
 $\text{natKr/Xe} < 0.026 \times 10^{-12}$ (26 ppq)
- **Online distillation @XENON1T**
 $\text{natKr/Xe} < (360 \pm 60) \times 10^{-15}$ (ppq)
- **Offline + online distillation @XENONnT**
 $\text{natKr/Xe} < (56 \pm 36) \times 10^{-15}$ (ppq)
 - Processed 6 t commercial xenon offline
 - Additional 3 weeks of online distillation
 - Further online distillation campaigns (Ar)
- **Xe recovery: 99%** (1% offgas)
- **1 day of Kr distillation generates ~0.7 kg offgas**
- **Need for online distillation**
 - Kr can re-enter
 - ^{37}Ar calibrations

DARWIN: $< 0.05 \times 10^{-12}$ (0.05 ppt)

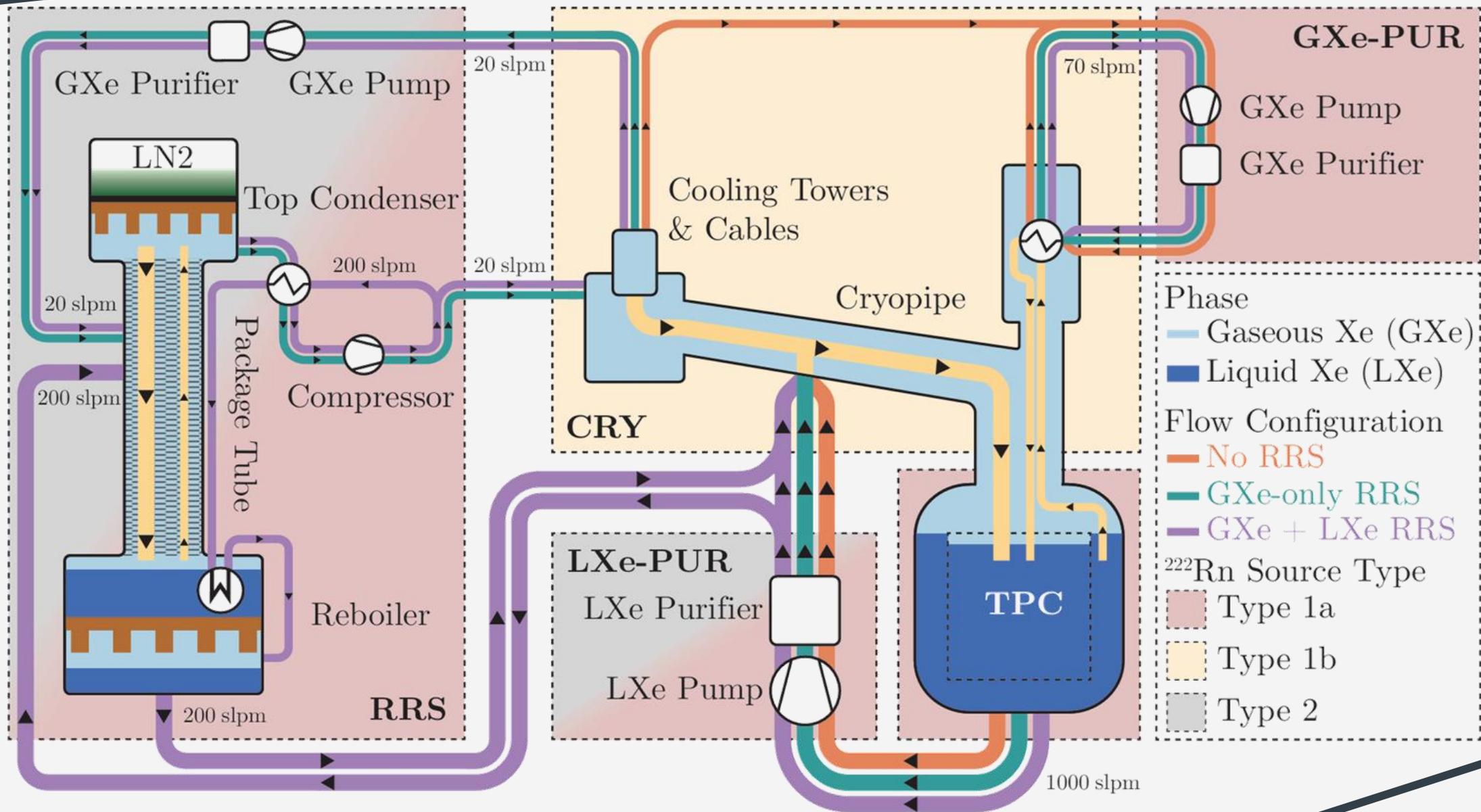


Radon distillation

- SR0 – GXe-only: 1.8 $\mu\text{Bq/kg}$
- SR1 – **GXe + LXe: 0.9 $\mu\text{Bq/kg}$**
with 200 slpm GXe + 25 slpm LXe



DARWIN: $\sim 0.1 \mu\text{Bq/kg}$ (10^{-26})



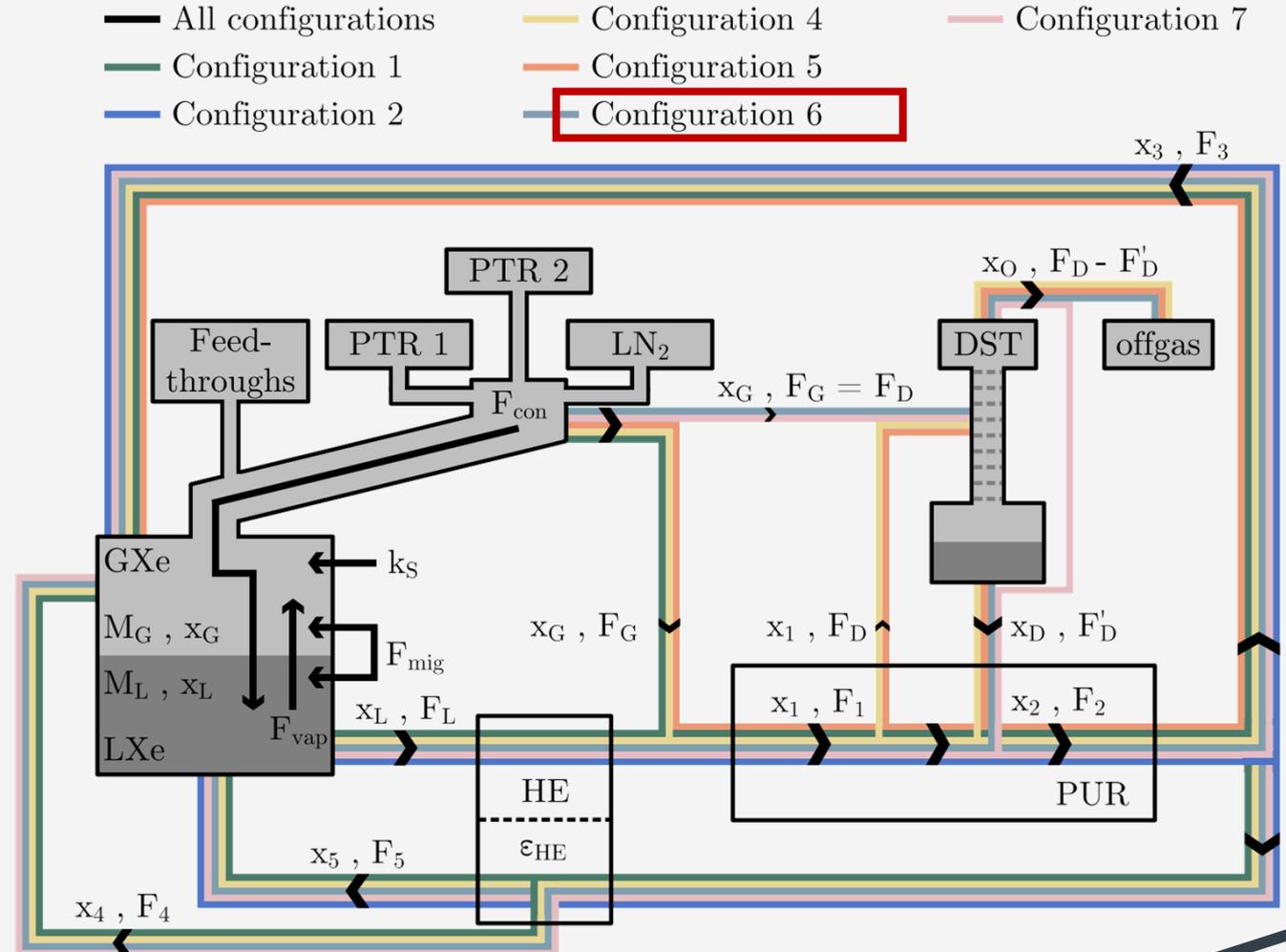
Online krypton removal for XENON

Requirements for ^{85}Kr removal system:

- Needs to be **removed once**
- Kr can re-enter via (tiny) air leaks

Online Kr removal method

- Make use of the TPC as single stage DST
- Remove Kr from GXe, disturb equilibrium
- Kr migrates from LXe to GXe
- 1% offgas (0.85 kg/d | 6 kg/week), $\tau_{\text{eff, Kr}} = 6 \text{ d}$



Background Modeling

ER Background

- Dominant: Radon (^{214}Pb β decay)
- Subdominant: ^{85}Kr (cryogenic distillation)

Surface Background

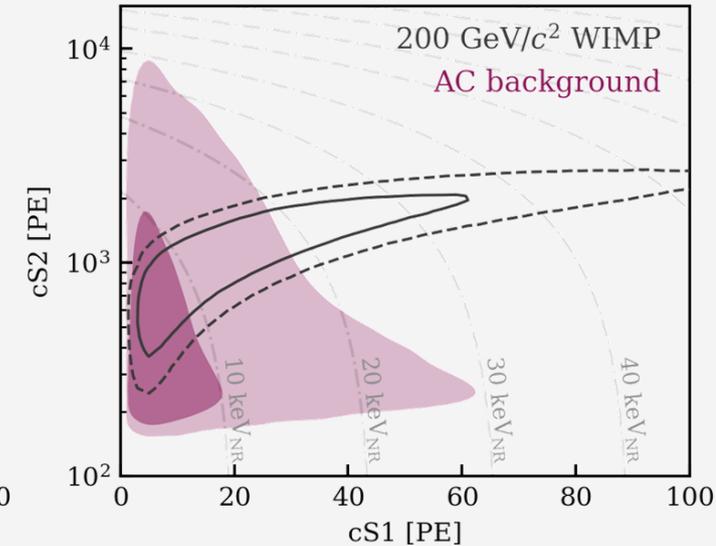
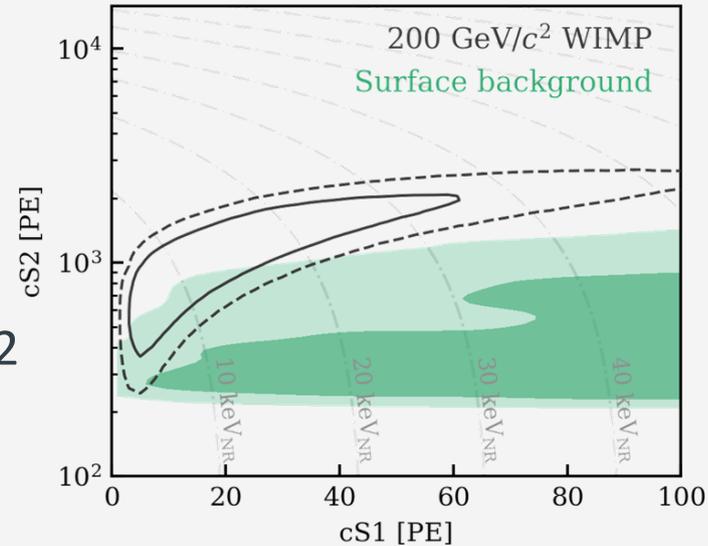
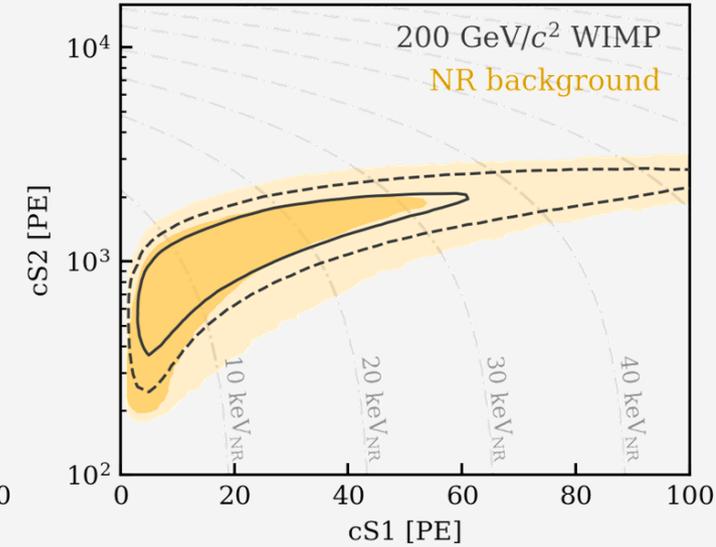
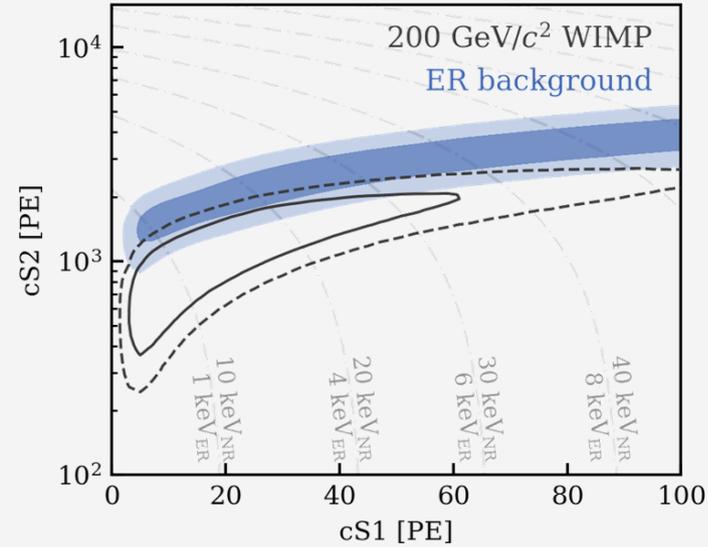
- ^{210}Pb plate-out at the PTFE walls
- Reduced by fiducial volume cut

Accidental Coincidences (AC)

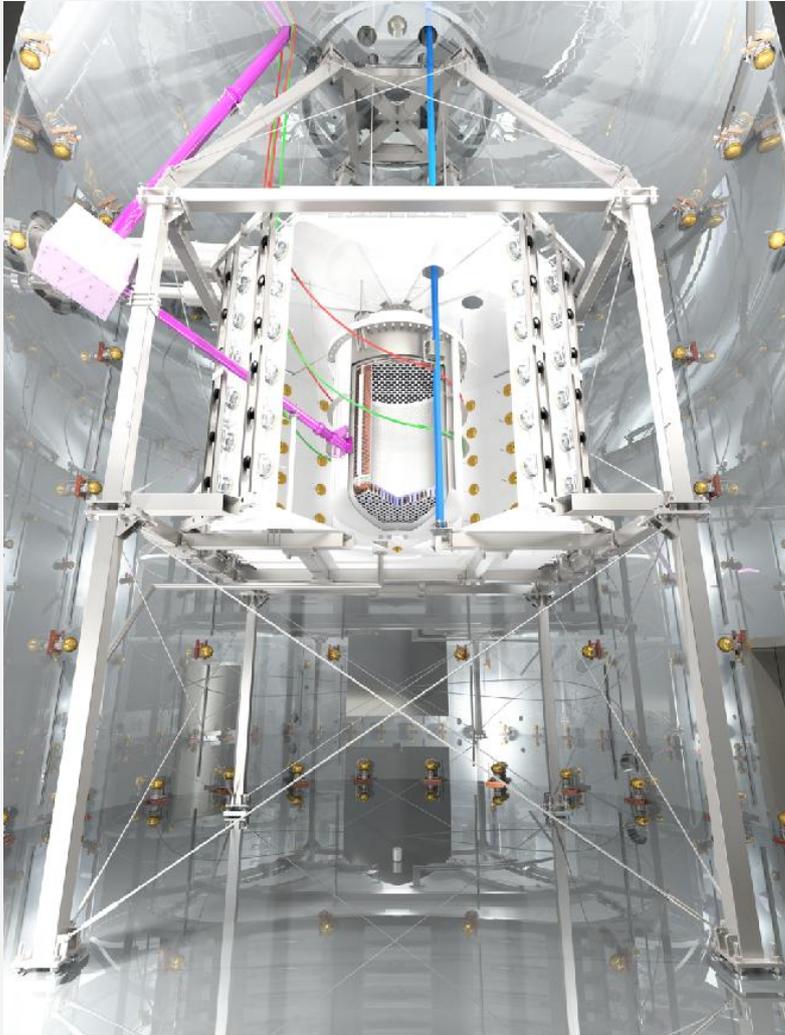
- Random pairing of isolated S1s and S2s
- Suppression with gradient BDT cut based on S2 shape and position information

NR Background

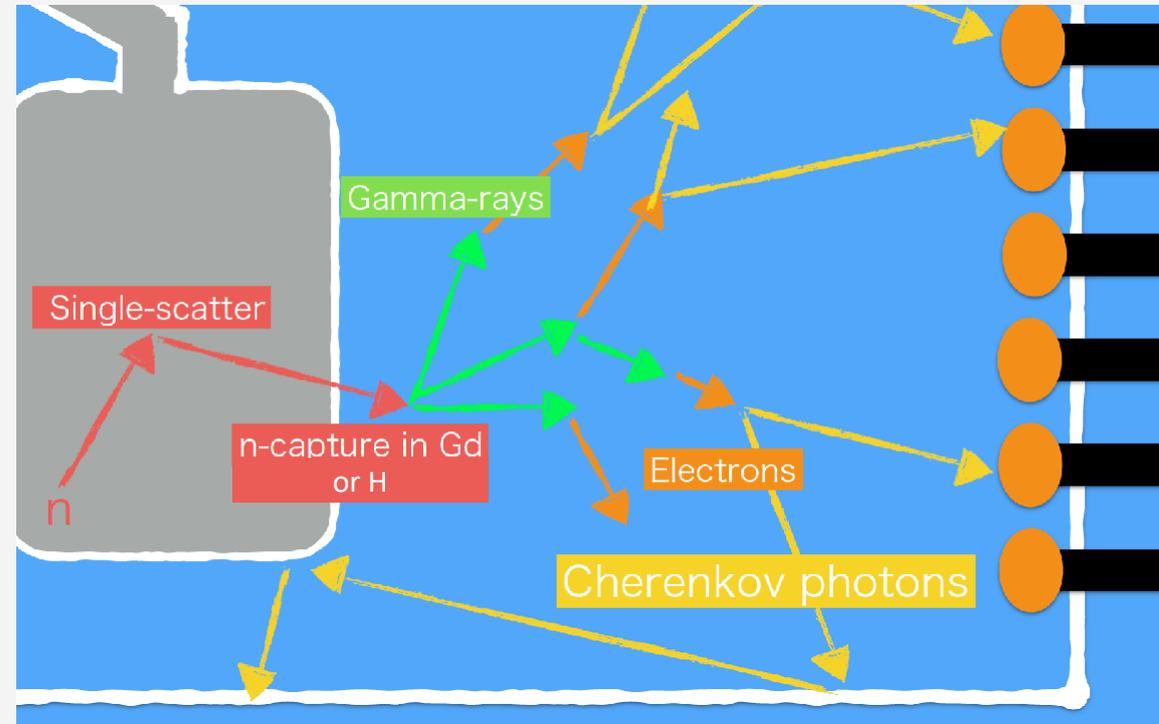
- Radiogenic neutron rate constrained by NV tagging
- CEvNS constrained from solar ^8B neutrino flux (subdominant)



The XENONnT neutron veto



- Used in **SR0** with **demineralized water**
- Reaching **53% neutron tagging efficiency in SR0** mode (reduced TPC dead time)
- Achieved 68% n-tagging eff. in calibrations with $^{241}\text{AmBe}$
- Data-driven prediction of the neutron background in SR0



Neutrino Fog

