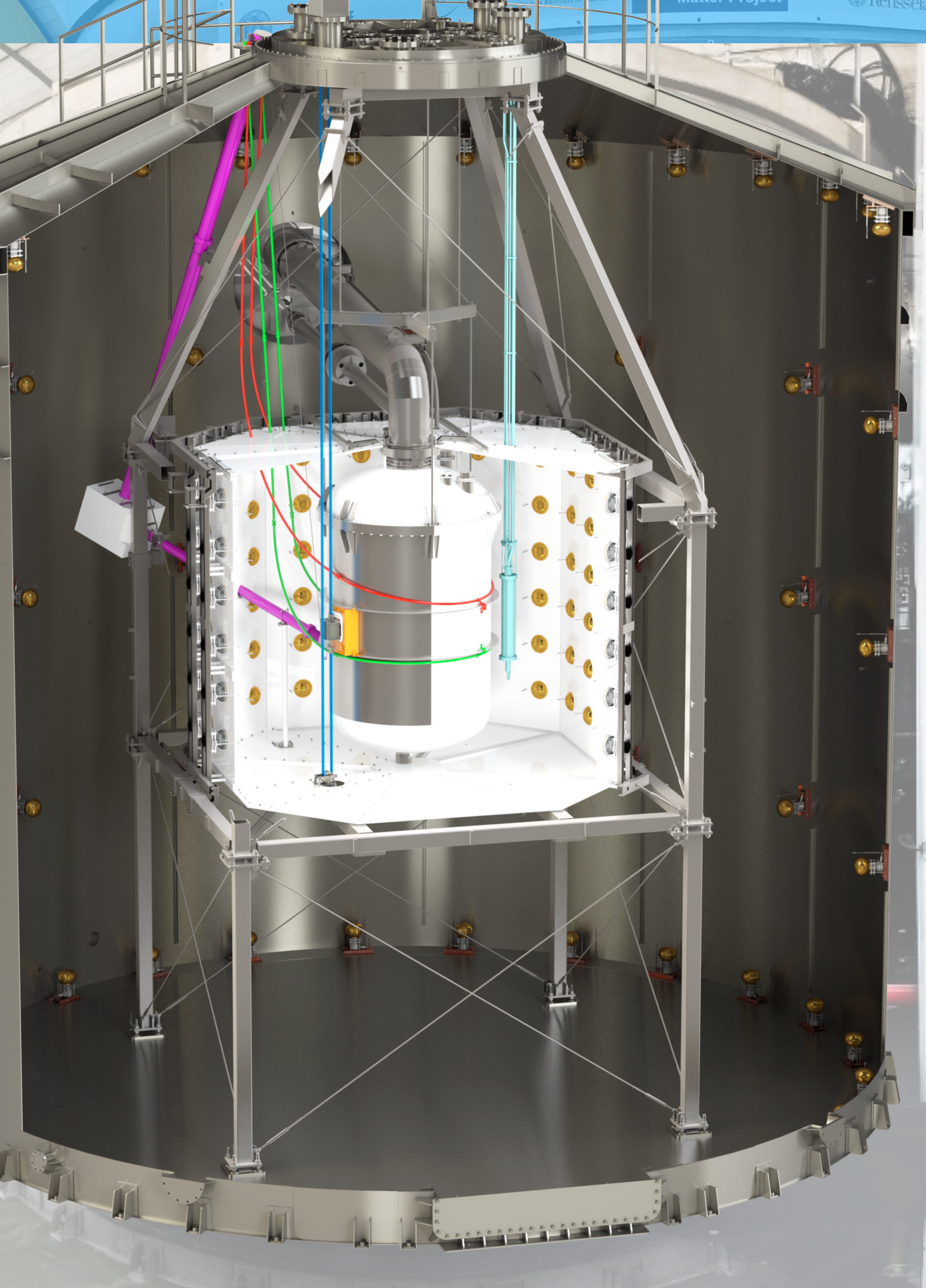

The XENONnT Neutron Veto: performance without & with Gd-doping

Marco Selvi - INFN Bologna
selvi@bo.infn.it

On behalf of the XENON Collaboration

IDM2024 @L'Aquila - 8 July 2024

XENONnT: main upgrades

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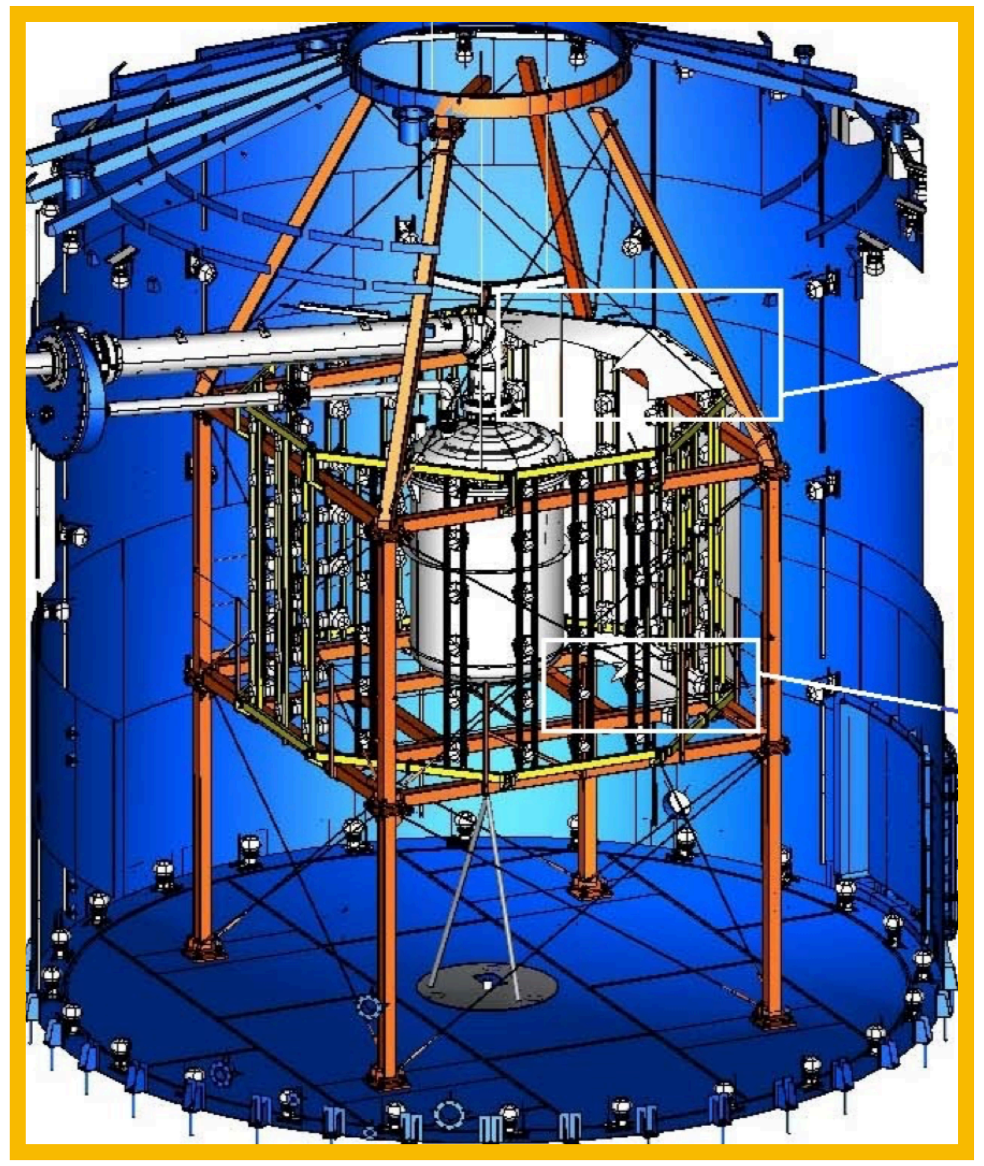
Larger TPC

Total 8.5 t LXe
5.9 t in TPC
~ 4 t fiducial
248 → 494 PMTs

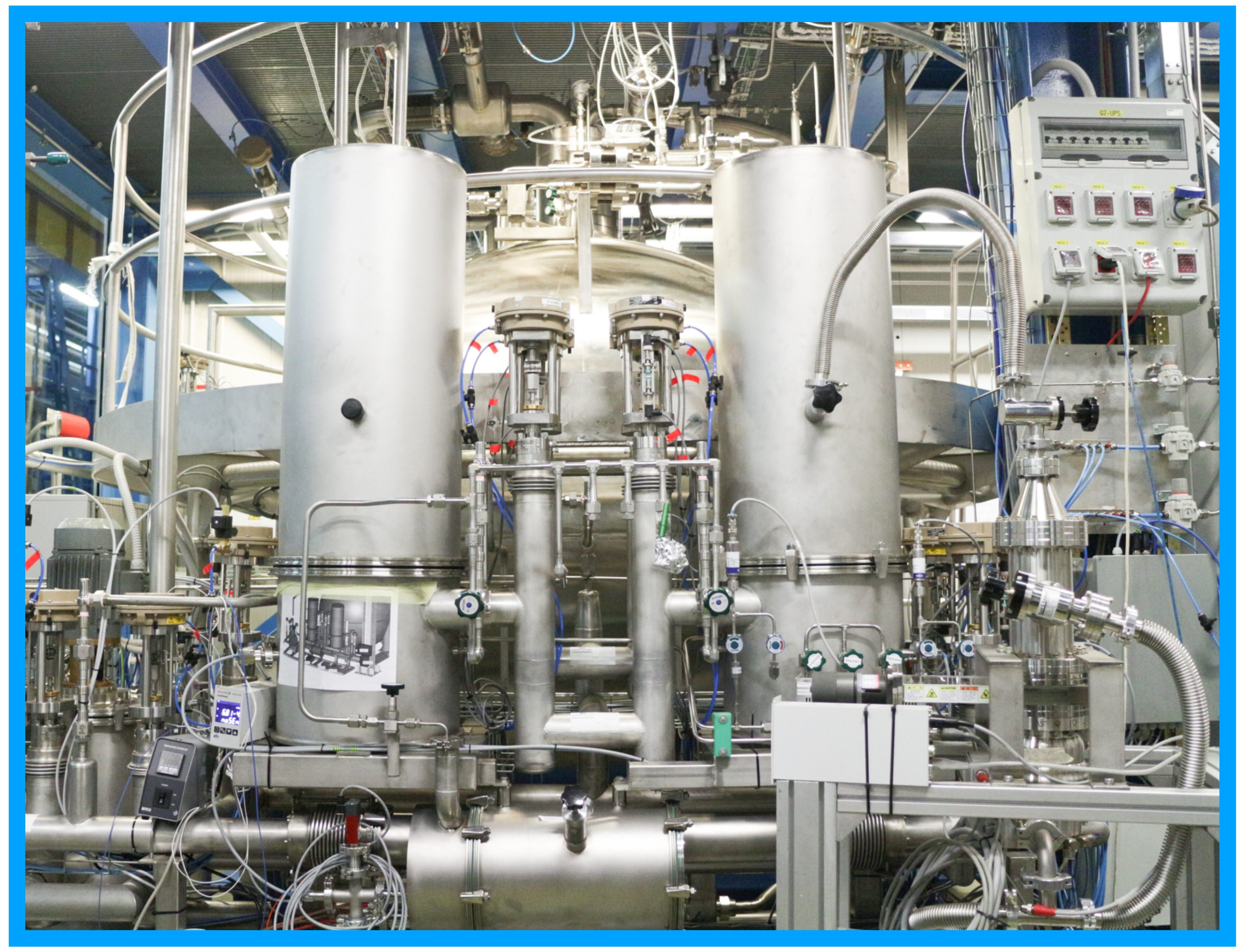


Neutron veto

Inner region of
existing muon veto
optically separated
120 additional PMTs
Gd in the water tank
0.5% $Gd_2(SO_4)_3$

^{222}Rn distillation

Reduce Rn (^{214}Pb) from
pipes, cables,
cryogenic system
New system,
PoP in XENON1T



LXe purification

Faster xenon cleaning
5 L/min LXe
(2500 slpm)
XENON1T ~ 100 slpm

XENONnT: main upgrades

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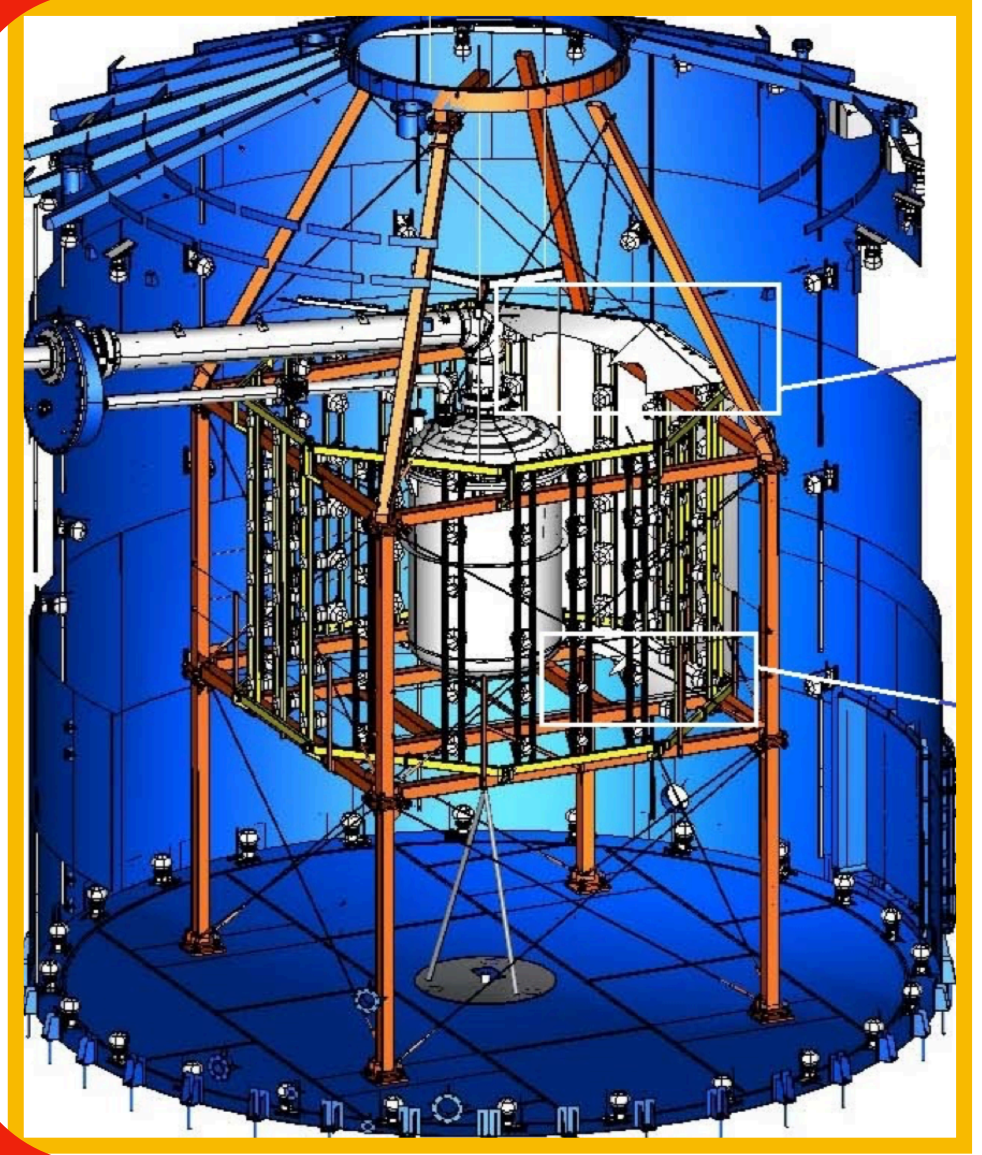

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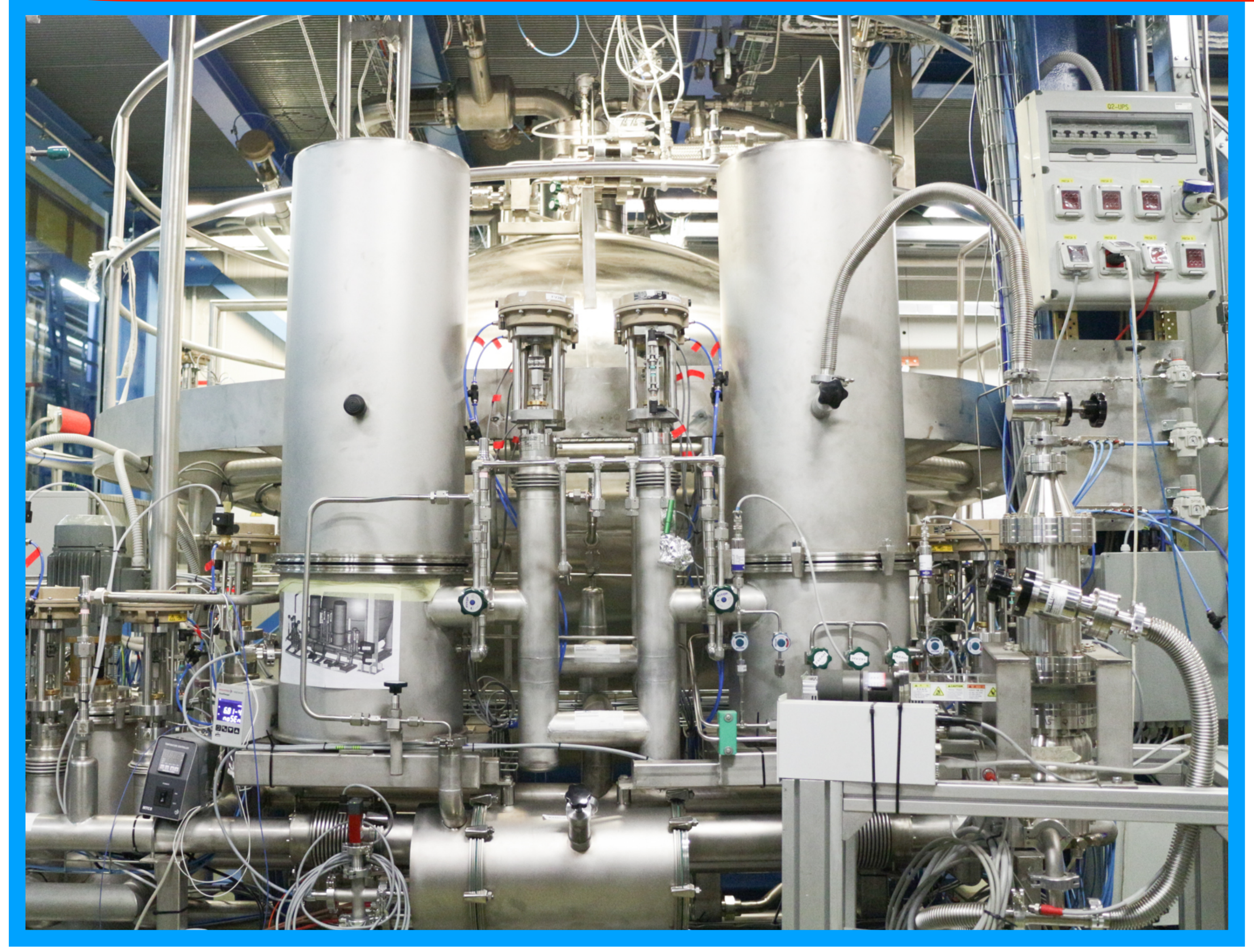

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XENONnT Neutron Veto concept

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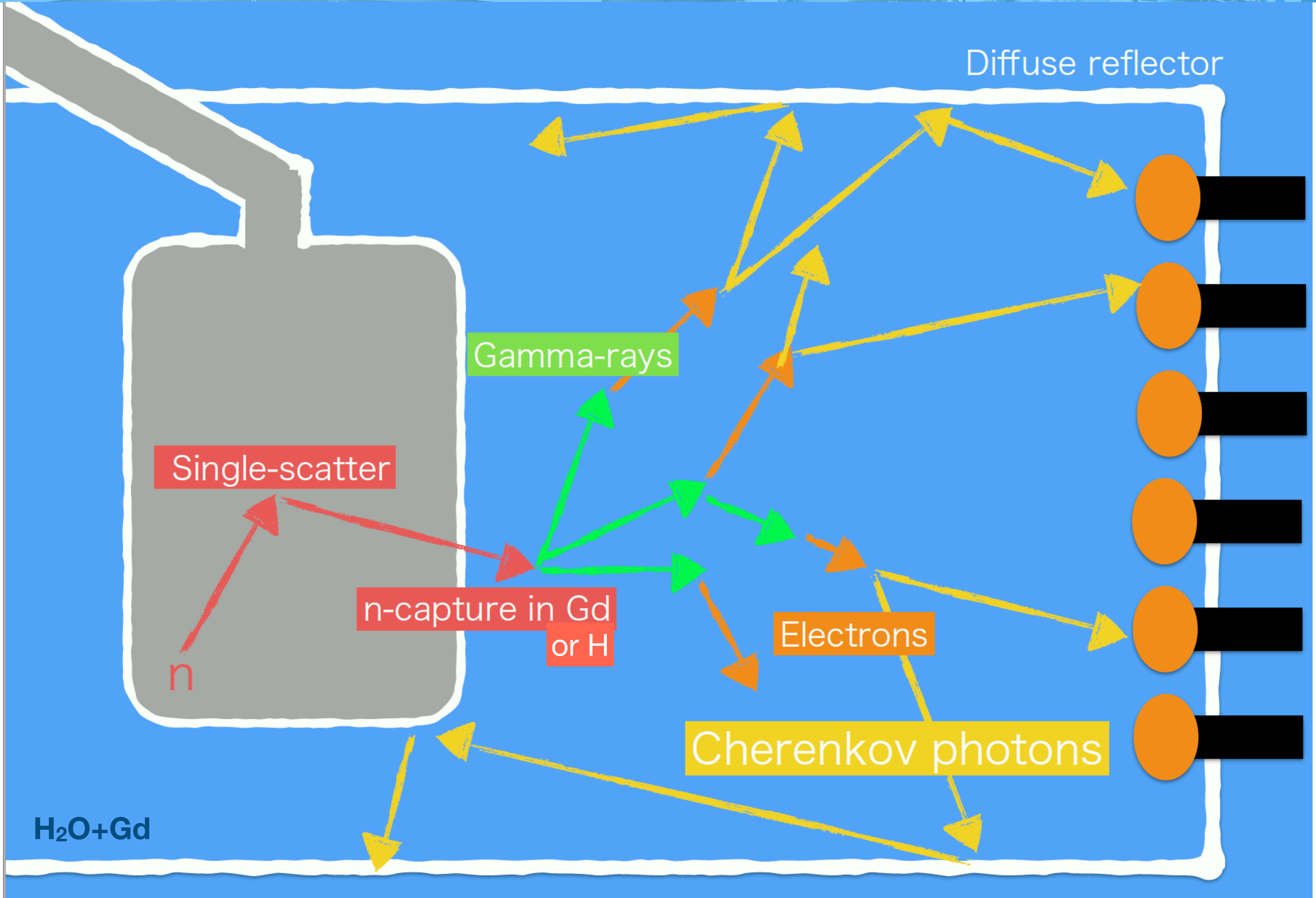


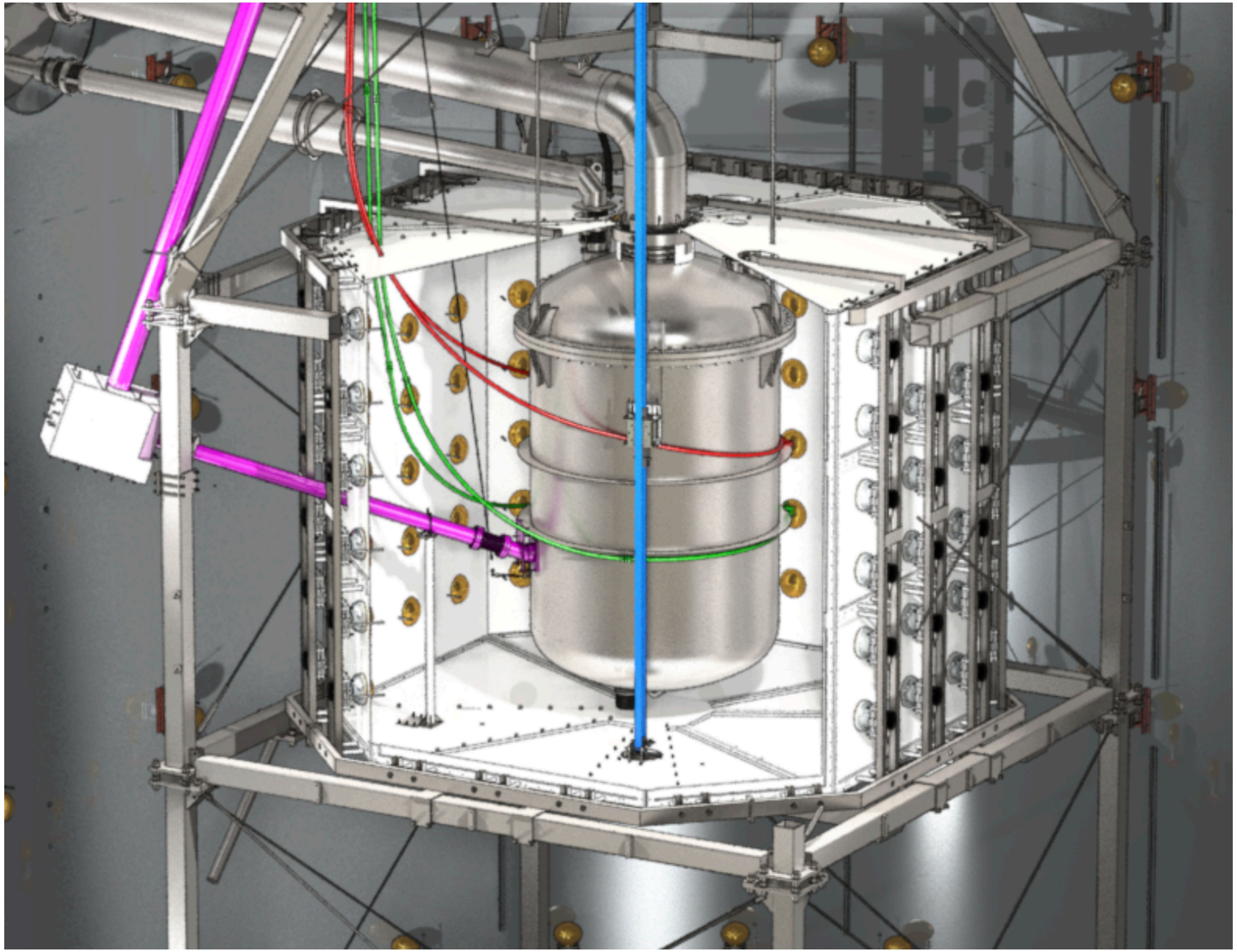
Gd-loaded Water: 0.2% of Gd in mass -> 3.4 t of Gd-sulphate-octahydrate; (technology from EGADS-SK)

Cherenkov light is detected by 120 8” high-QE low-radioactivity PMTs (Hamamatsu R5912) installed in water 1m away from the cryostat;

High-reflectivity ePTFE panels confine an inner nVeto region (33 m^3) with large light-collection efficiency;

LED calibrations for PMT gain, laser calibrations for transparency monitor.

First Science Runs with demineralzed-water,
The current one with Gd-doped water.



XENONnT timeline

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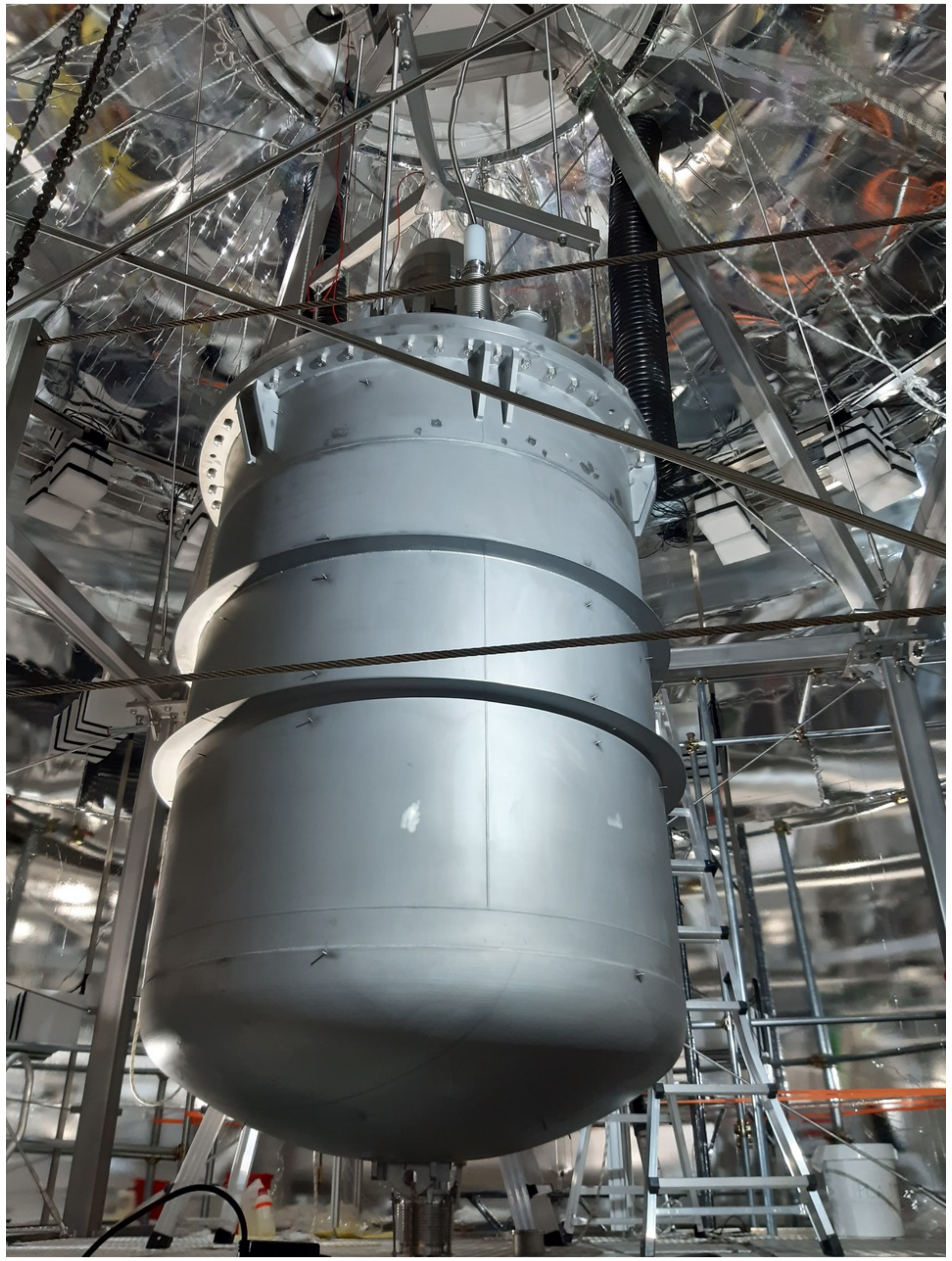


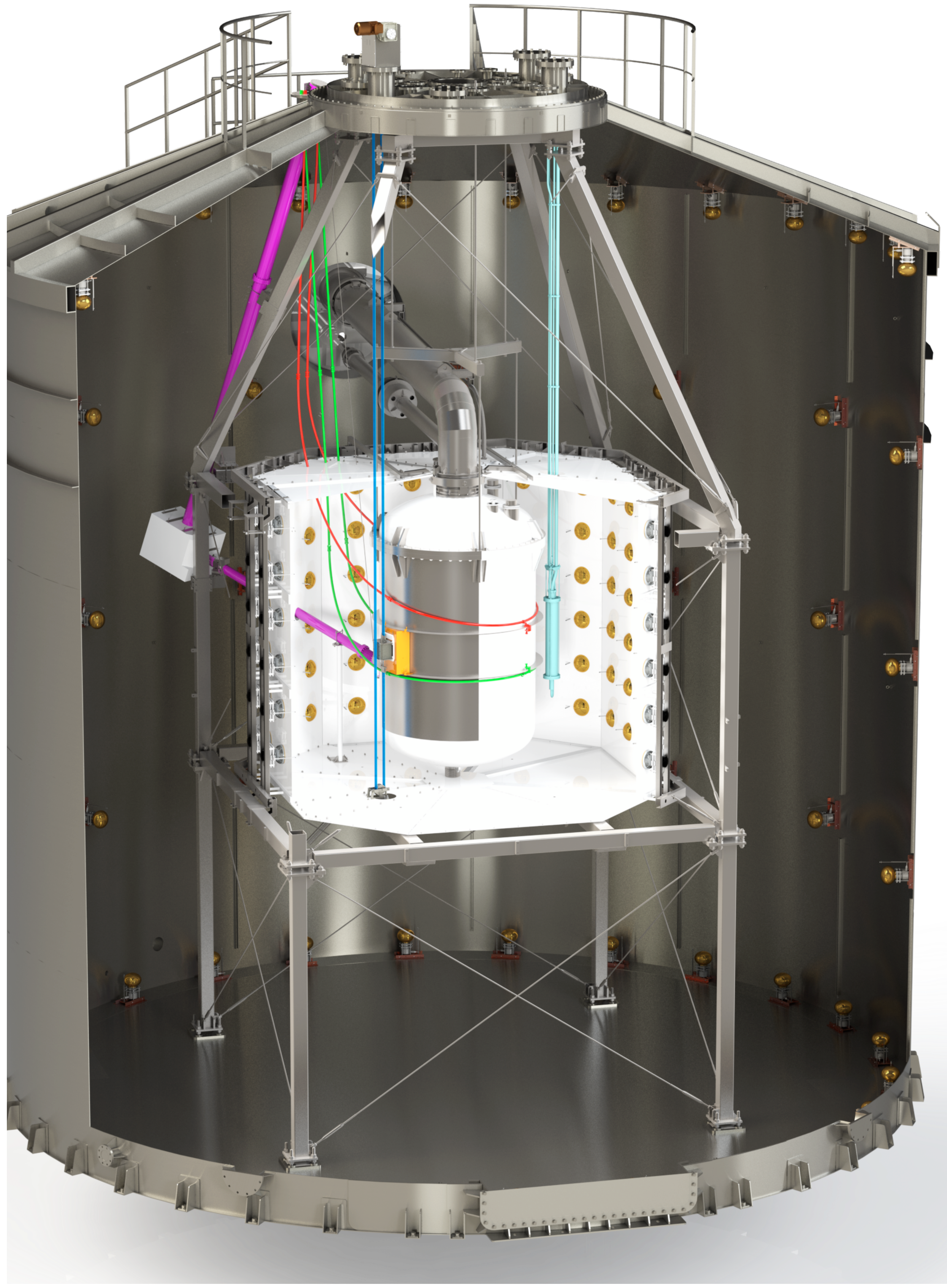
March 2020
Installation of the TPC underground at LNGS, a few days before the first COVID19 lockdown

July-December 2020
Installation of the nVeto
Filling of the cryostat with LXe
Water Tank closed and filled with demi-water

January-June 2021
Commissioning, commissioning, commissioning…

July-November 2021
Science Run 0

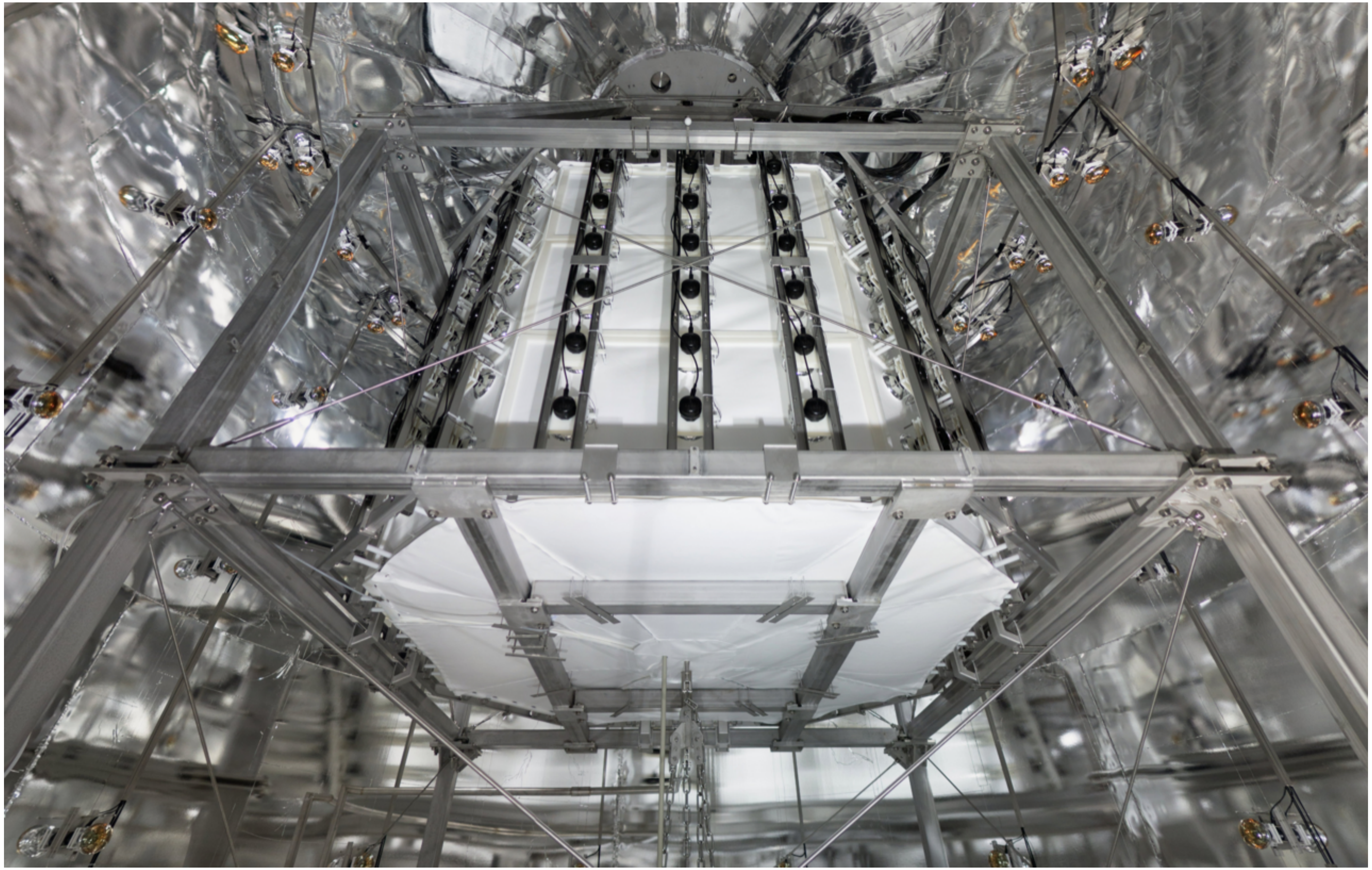
in 2022
Refurbishment of Rn Distillation Column
Start of Science Run 1
Commissioning of the GdPlant with demi-water
Search of new physics with ER:
PRL 129, 161805 (2022)



in 2023
First insertion of Gd-Sulphate in the GdPlant
First results on WIMP search with NR: PRL 131, 041003 (2023)
First insertion of Gd-Sulphate in the Water Tank. Start of Science Run 2.

XENONnT Neutron Veto: some pictures

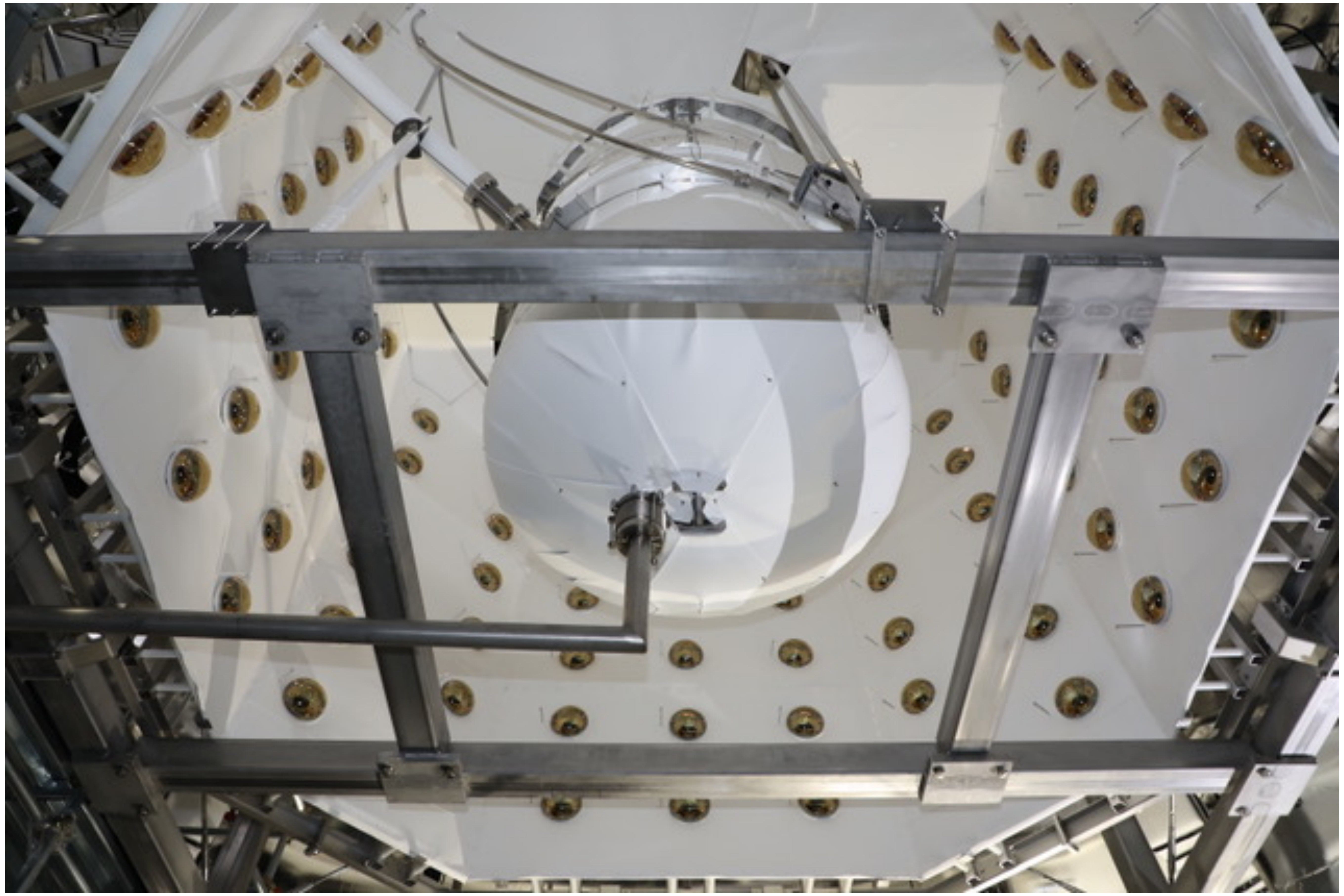
Marco Selvi | selvi@bo.infn.it



...a Baptistery inside the Cathedral

XENONnT Neutron Veto: some pictures

Marco Selvi | selvi@bo.infn.it



https://www.nature.com/articles/d41586-020-02741-3

Neutron calibration with AmBe

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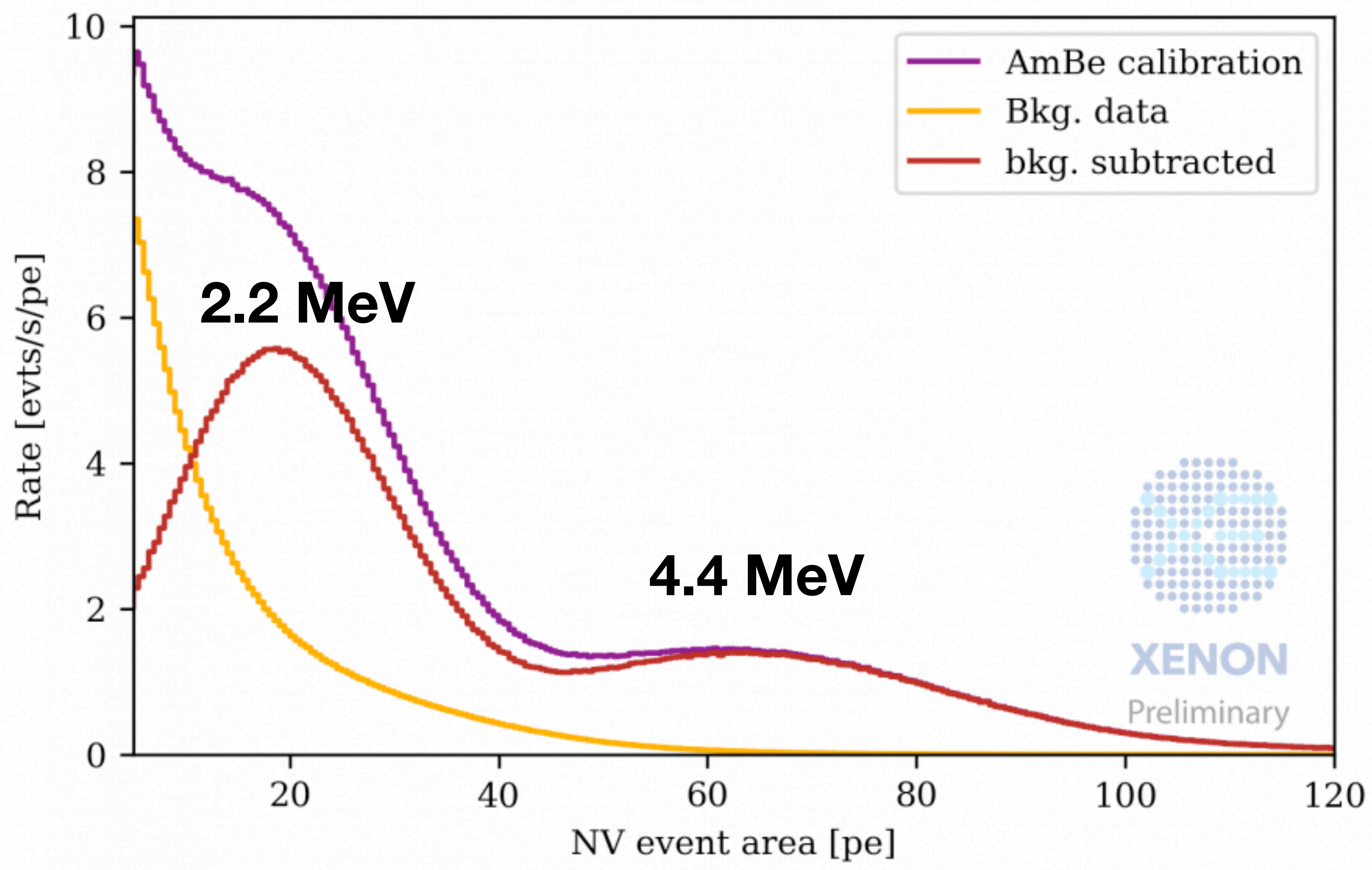
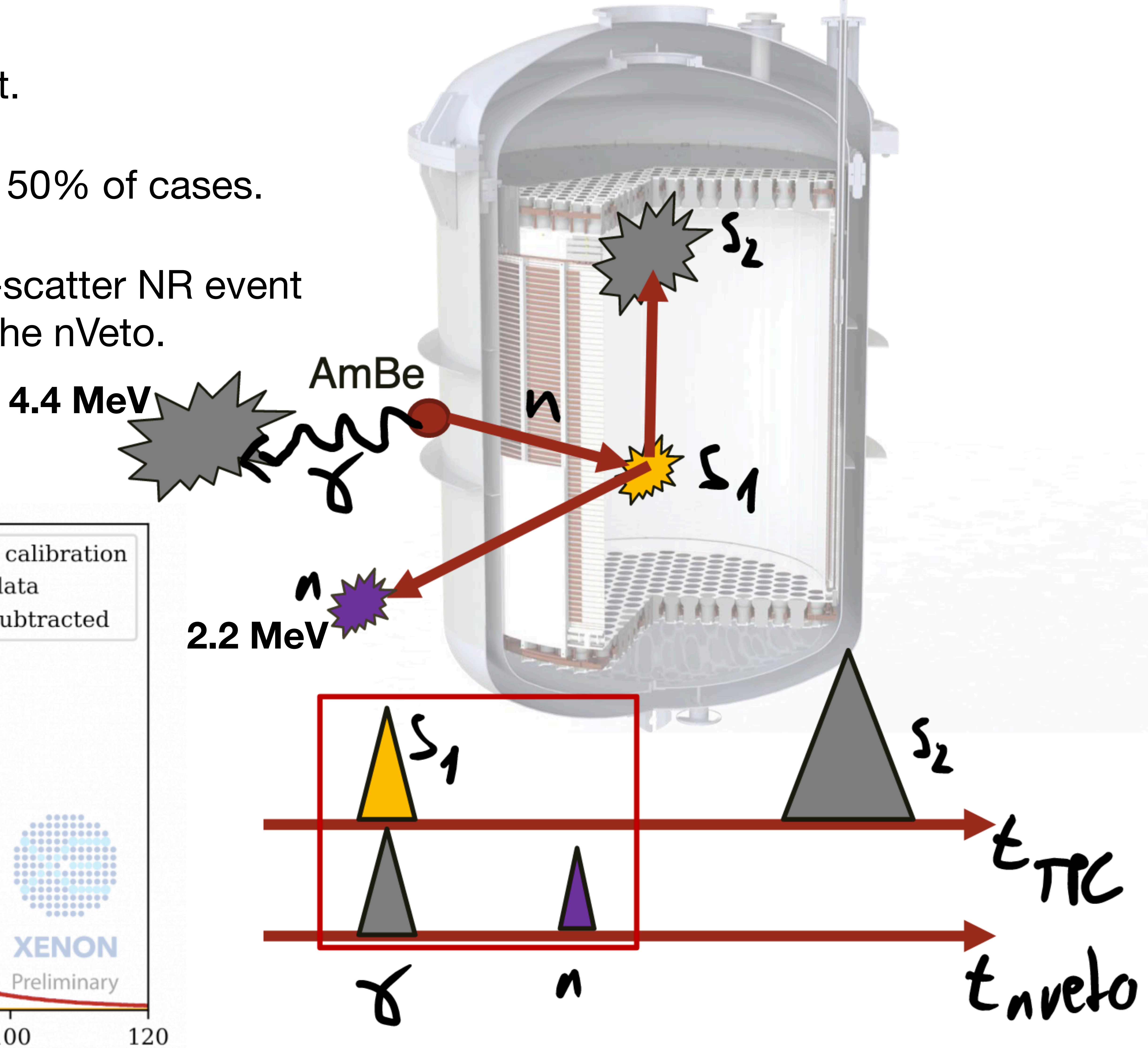
- Neutron calibration with AmBe source placed close to the cryostat.

- AmBe emits a 4.4 MeV gamma together with the neutron in about 50% of cases.

- Detect the 4.4 MeV gamma, require the coincidence with a single-scatter NR event in the TPC, and look for the 2.2 MeV gamma of neutron capture in the nVeto.

- Direct measurement of the neutron tagging efficiency of the nVeto (the event pattern is the same of dangerous neutrons produces by detector's materials)





Neutron calibration with AmBe

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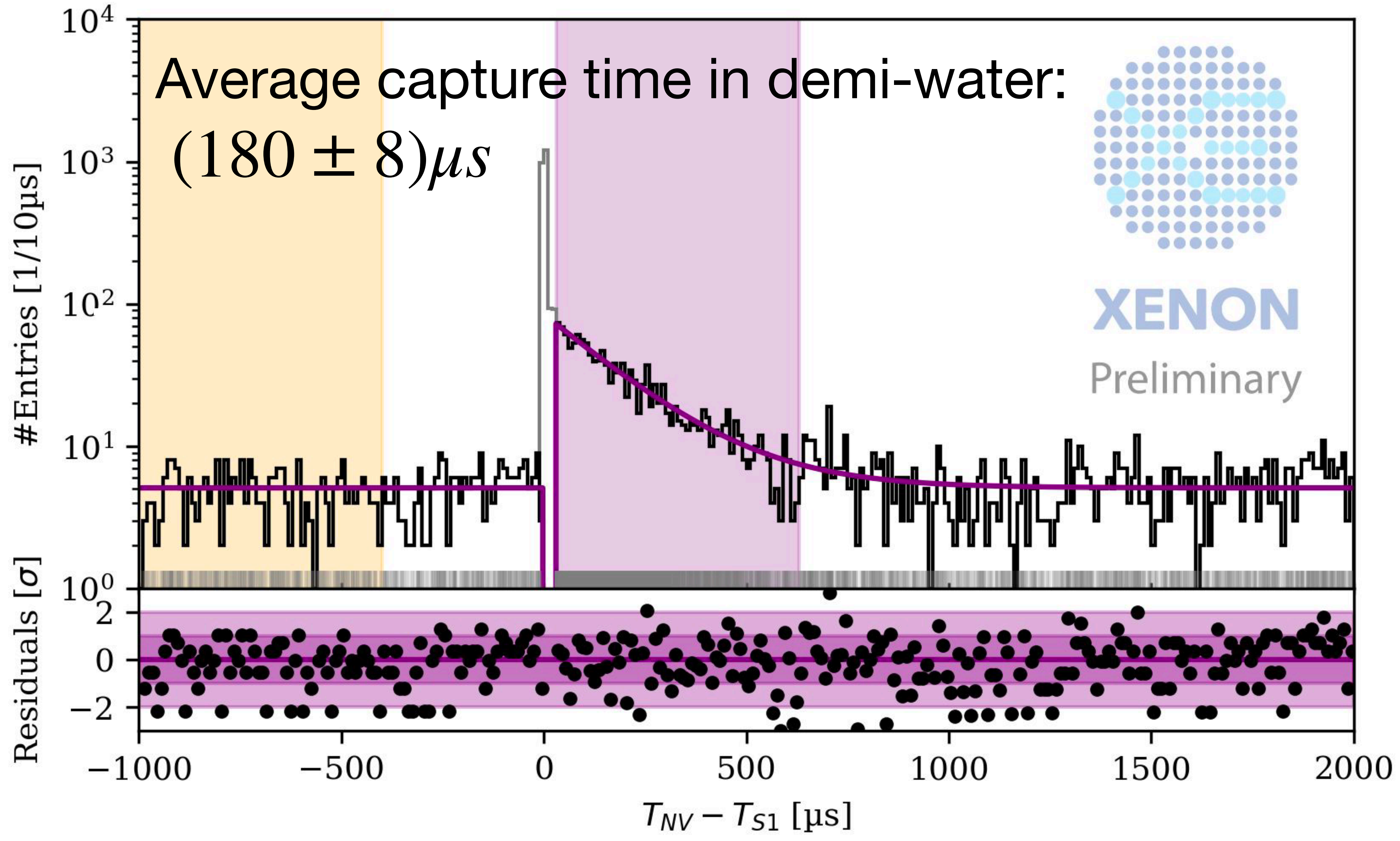

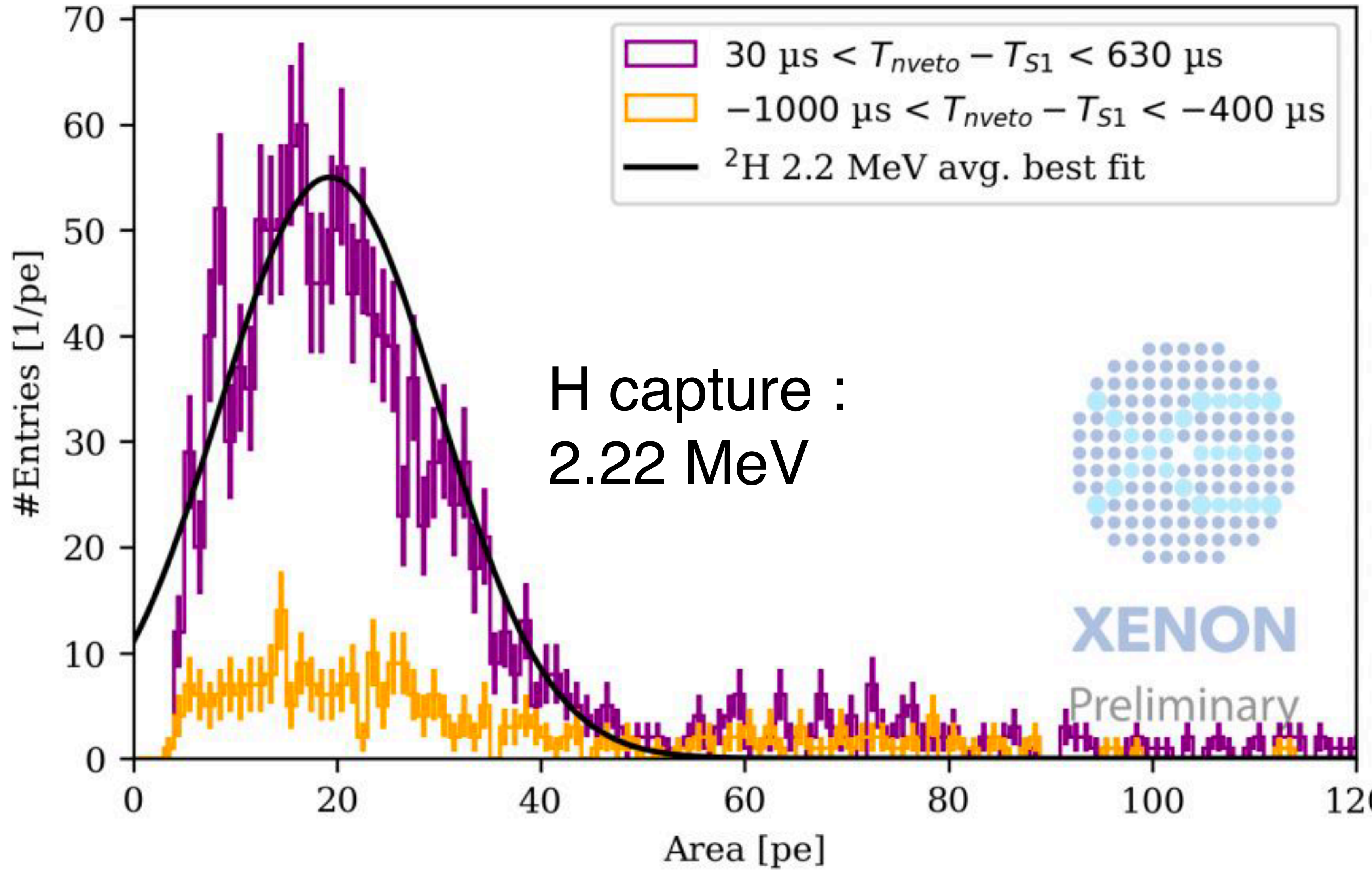

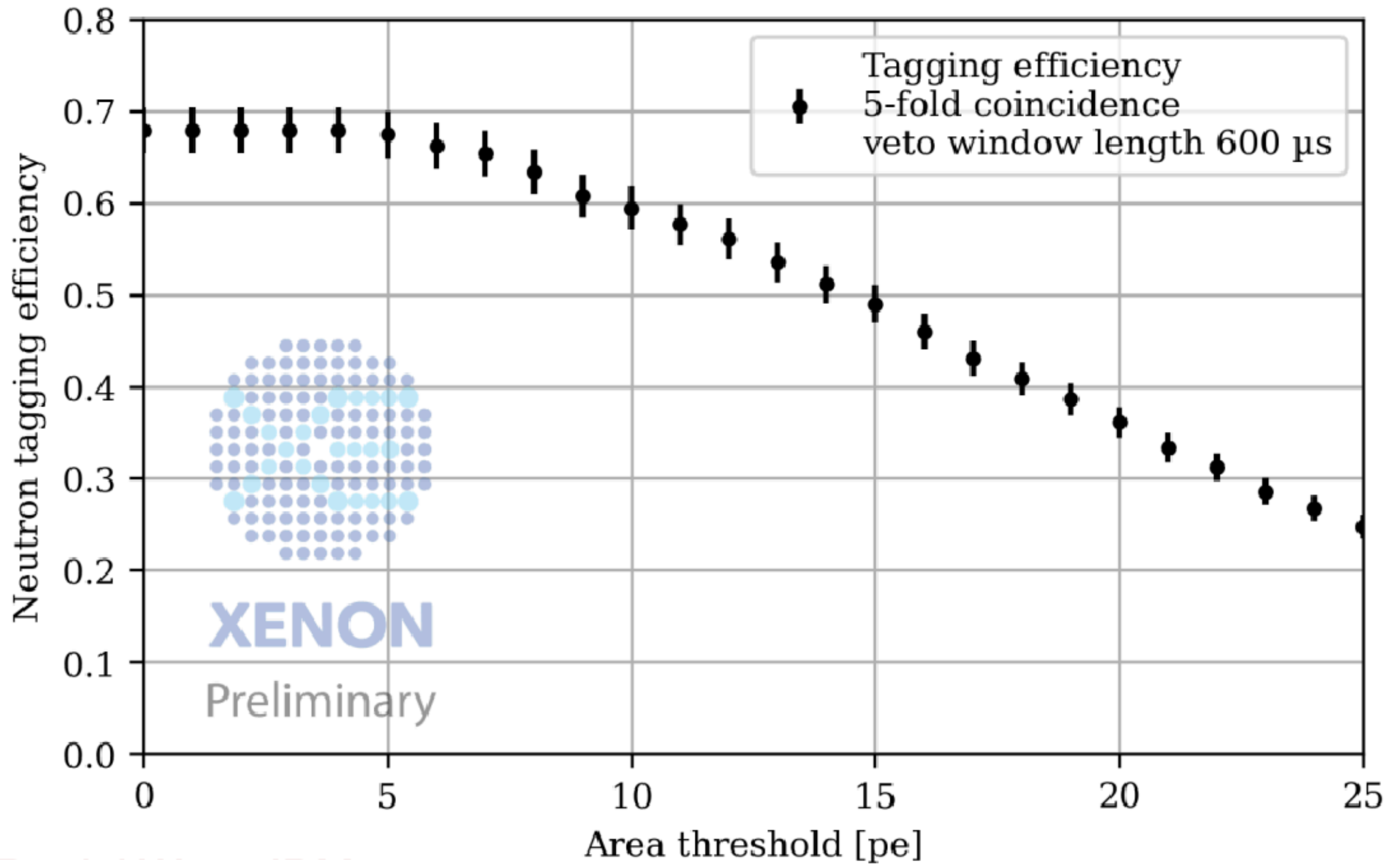

- The 2.2 MeV gamma peak corresponds to about 20 detected pe.

- Neutron Tagging efficiency (after background subtraction): $(68 \pm 3)\ \%$
(at 5-fold coincidence, 5 pe threshold, 600 us time window)

To our knowledge, this corresponds to the highest neutron detection efficiency ever obtained in a water Cherenkov detector (paper in preparation).

In Science Run 0 we decided to shorten the time window to 250 us, to reduce the induced dead time.
The efficiency becomes $(53 \pm 3)\ \%$, and the live-time lost is 1.6%.

Neutron Veto in Science Run 0

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In the search for **Nuclear Recoil** events, the nVeto has been used to tag multiple and single scatter NR events in the TPC, to obtain a data-driven estimation of the neutron background.

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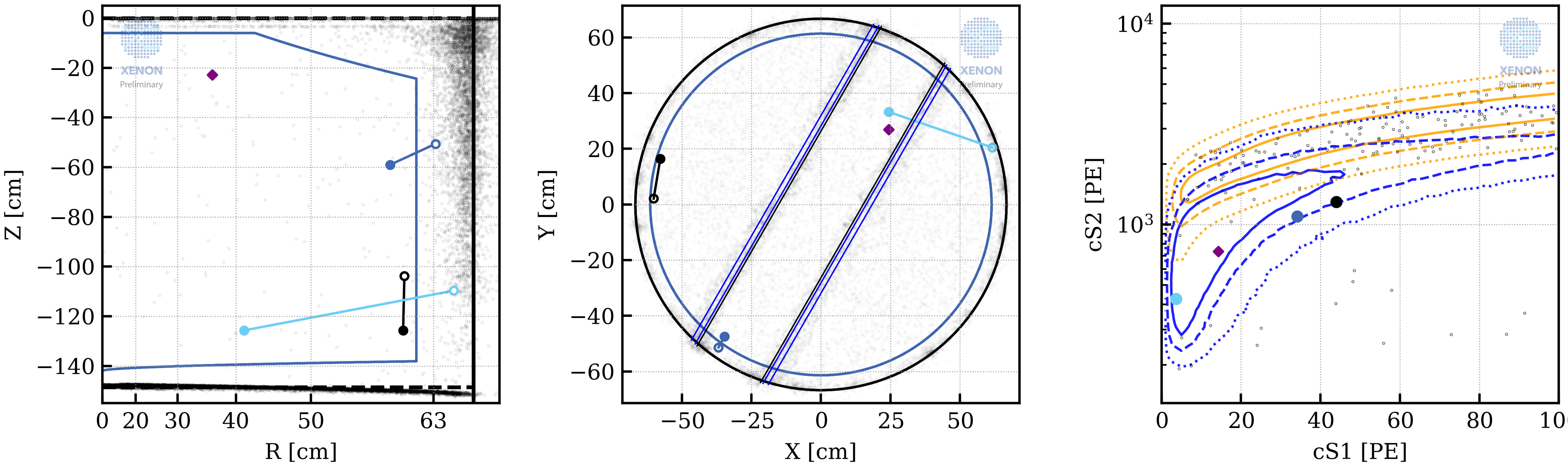
In the search for **Nuclear Recoil** events, the nVeto has been used to tag multiple and single scatter NR events in the TPC, to obtain a data-driven estimation of the neutron background.



Considering the 3 multiple scatter + 1 single scatter events, **nVeto-tagged,** with the primary S2 inside the fiducial volume, and the MS/SS ratio of ~ 2.2, obtained from MC and validated with AmBe data + the 53% nVeto tagging efficiency, **we obtained the neutron background prediction of** (1.1 ± 0.5) **neutron-induced events in SR0**.

This measurement is x6 larger than MonteCarlo predictions, based on material screening: checks are ongoing to explain the discrepancy.

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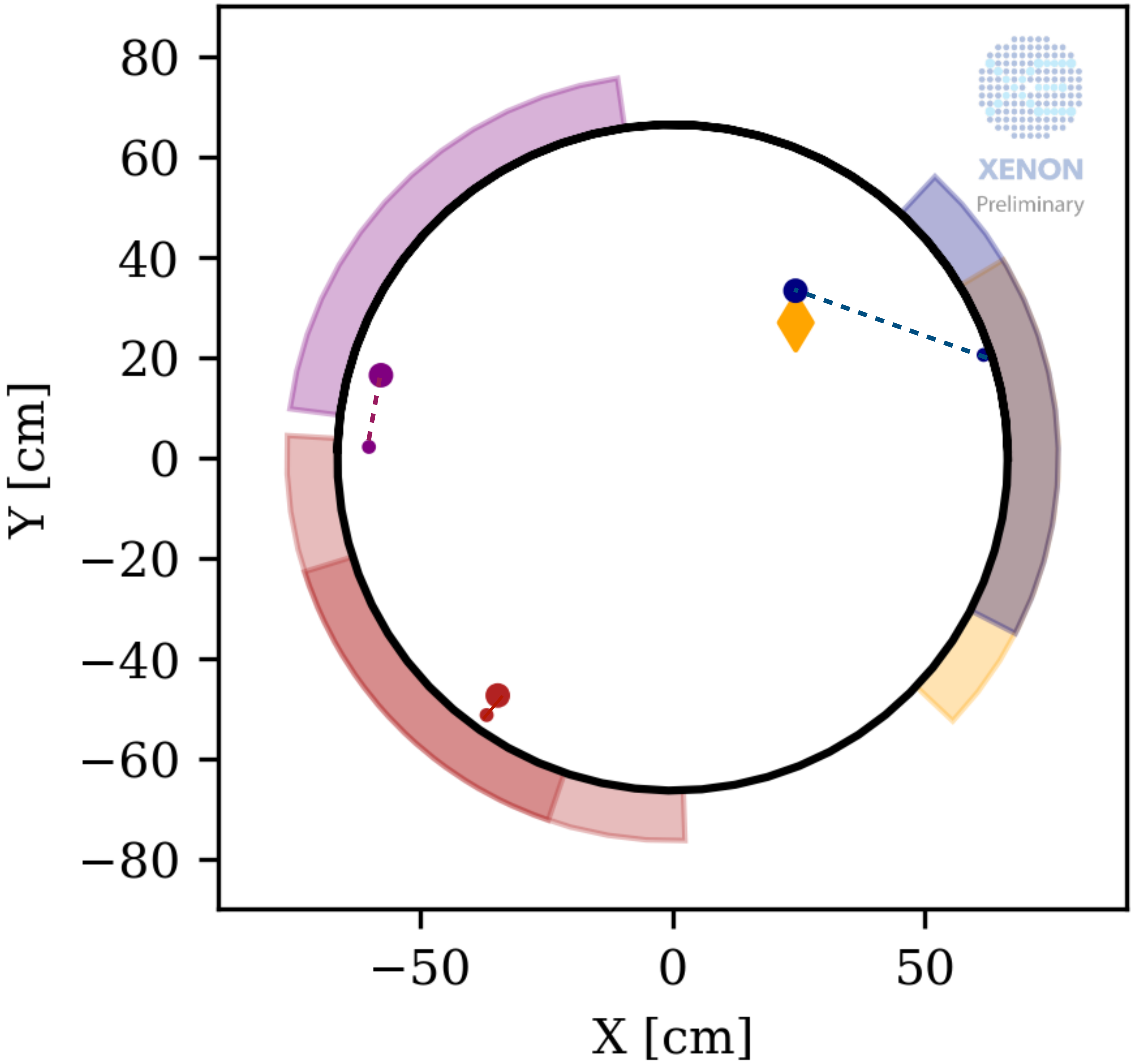
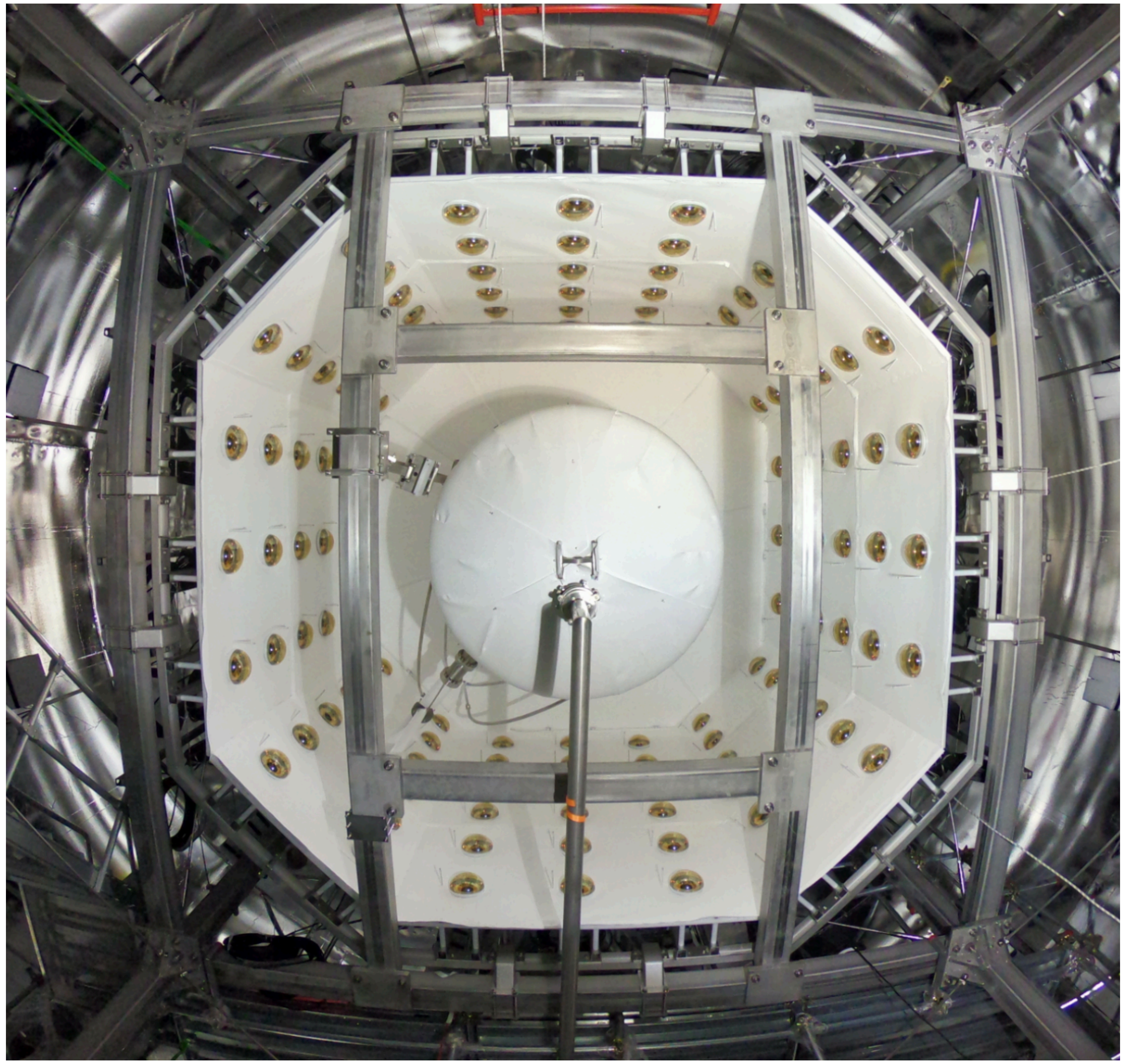
- The angular position of events in the Neutron Veto can be obtained by the first hits in the PMTs

- Agreement between position in the TPC and the Neutron Veto





Neutron Veto in Science Run 0

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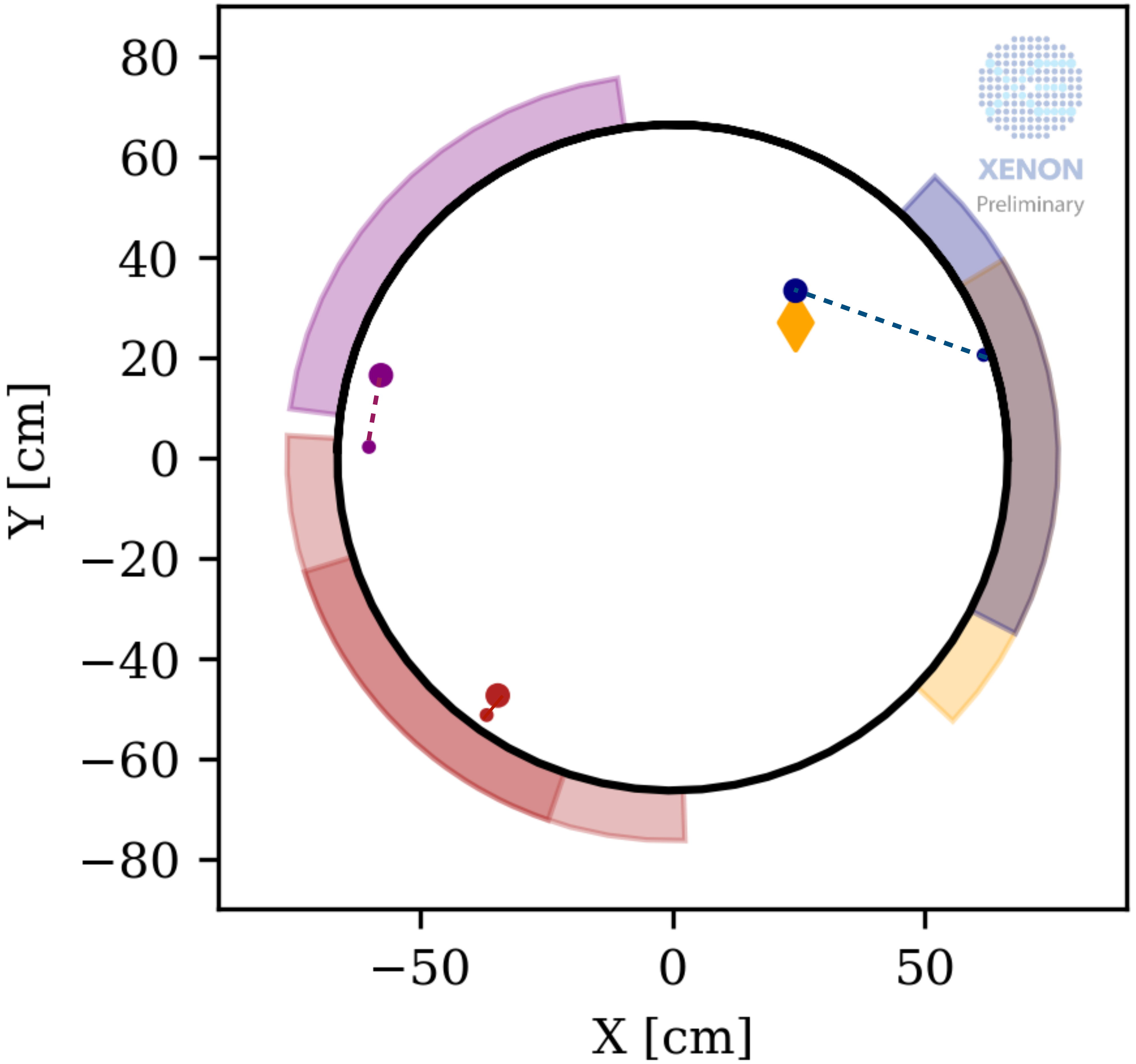

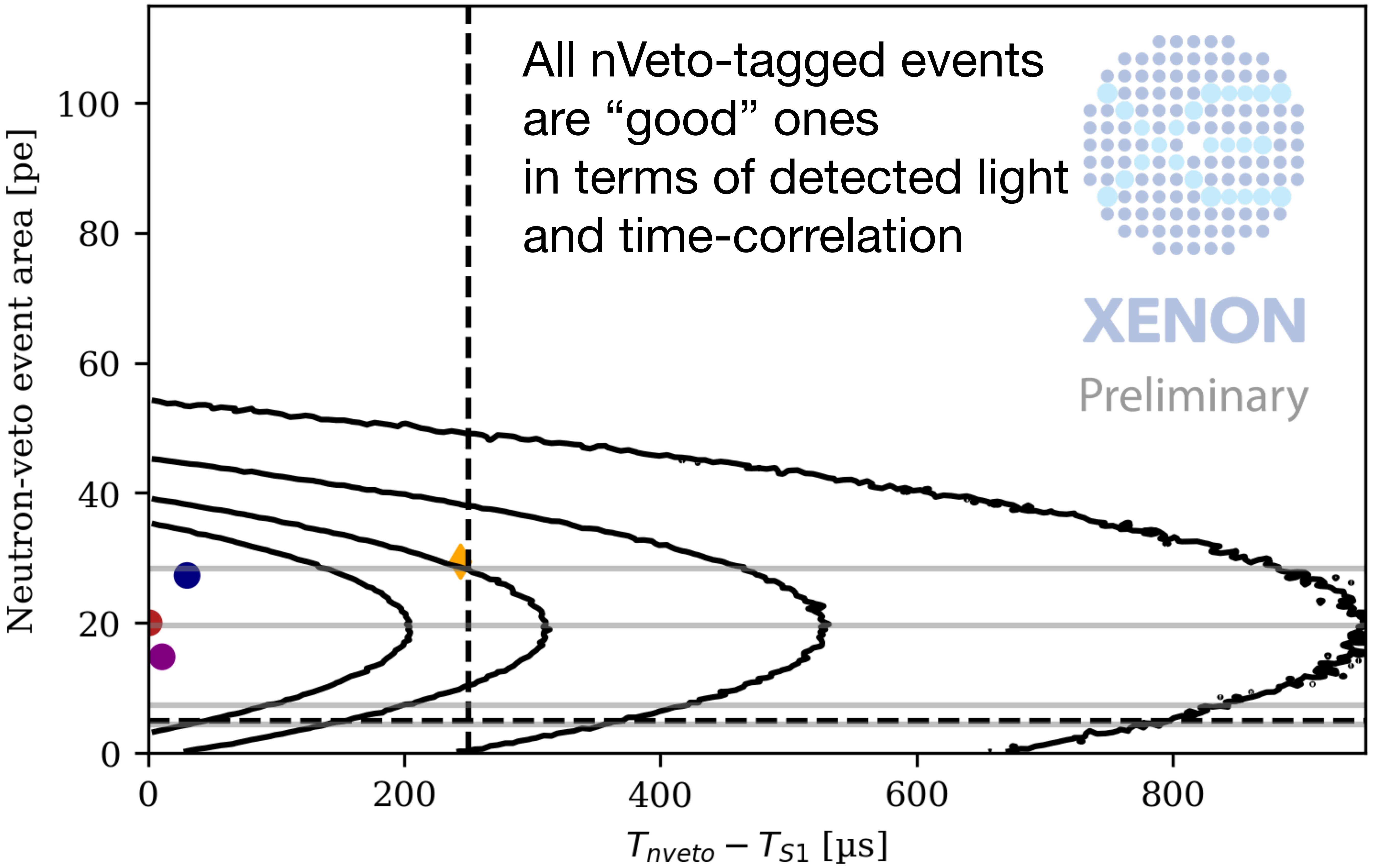

(Current) nVeto 2nd phase with Gd-doped water

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To further improve the neutron veto performances, in fall 2023 we doped water with Gd-Sulphate-Octahydrate salt, at 0.02% concentration of Gd in mass (350 kg of GdSO).

	Neutron capture cross section	Gamma Energy	Mean capture time
H	0.33 b	Single, 2.2 MeV	200 us
Gd	49000 b	3-4 gammas, 8 MeV in total	75 us

Monte Carlo prediction for neutron tagging efficiency with Gd: **77%**

-> Reducing the neutron background by a factor **2** with respect to Science Run 0.

A novel purification plant for Gd-Water was installed, developed with technology from the EGADS project.

L. Marti et al., NIMA 959, 163549 (2020)

The Gd-Water Purification Plant

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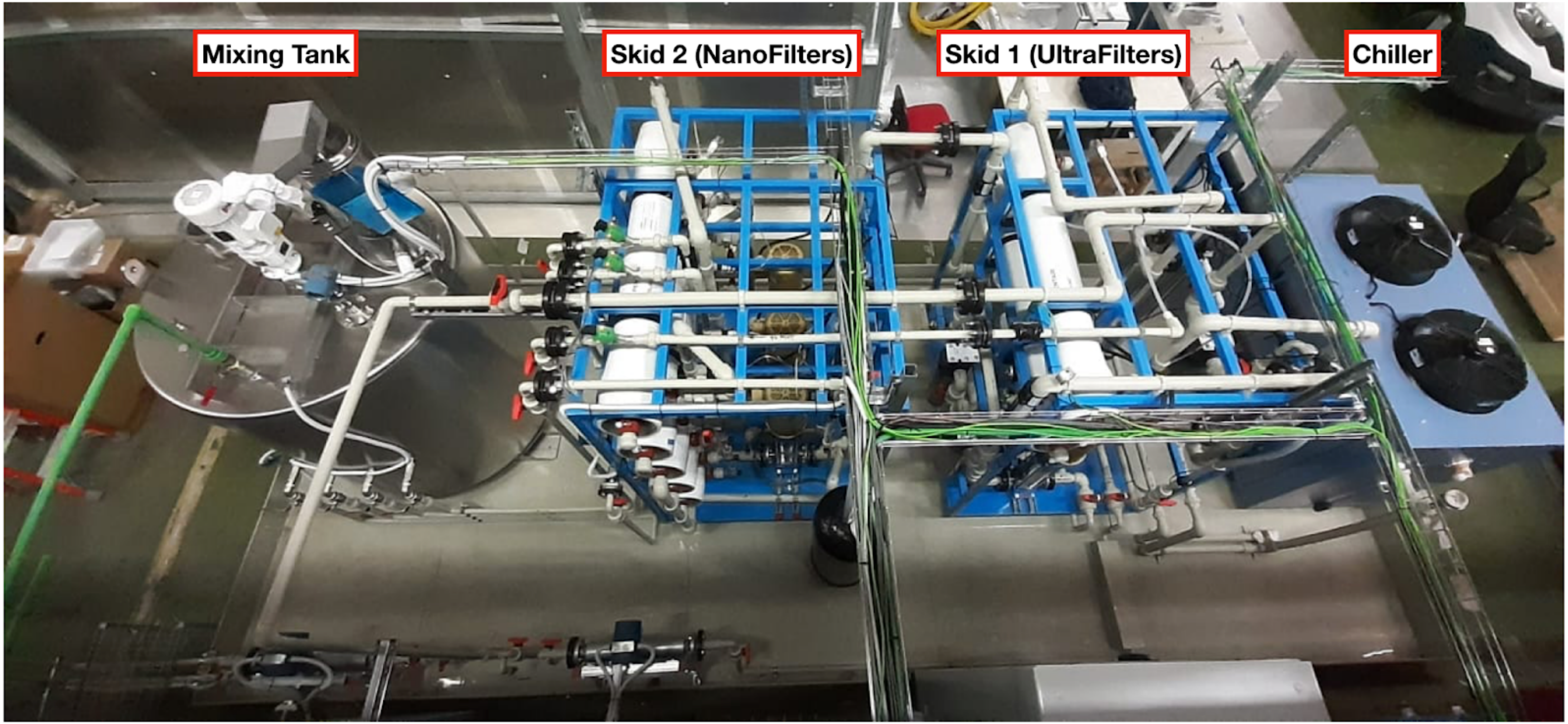

The Gd-Water Purification Plant

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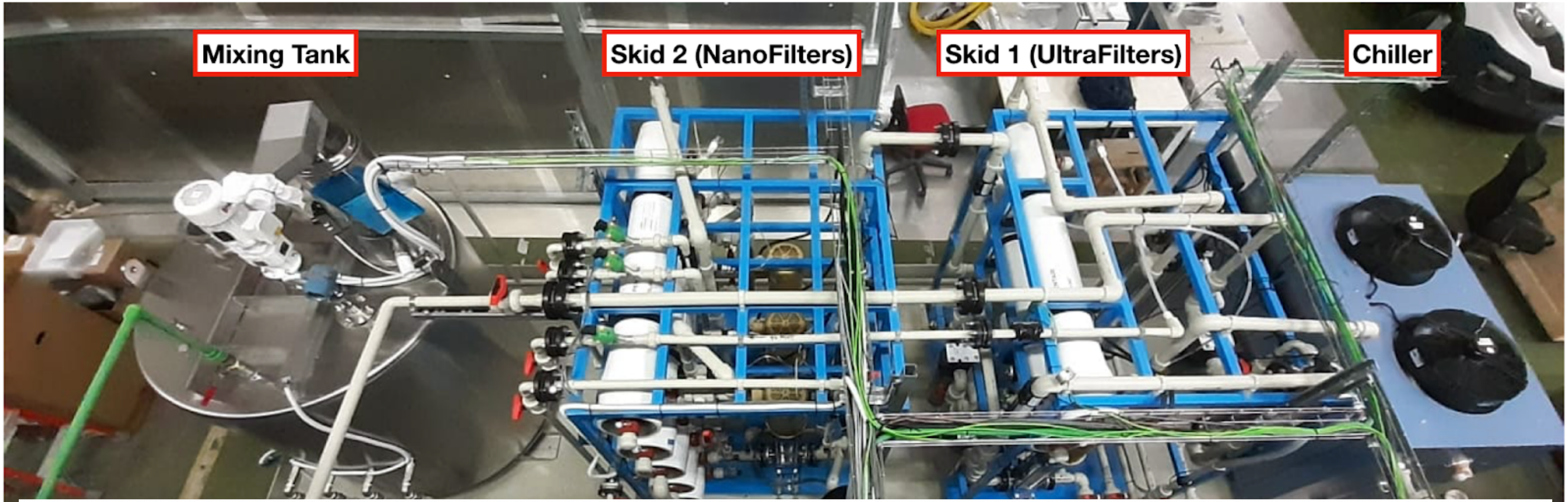
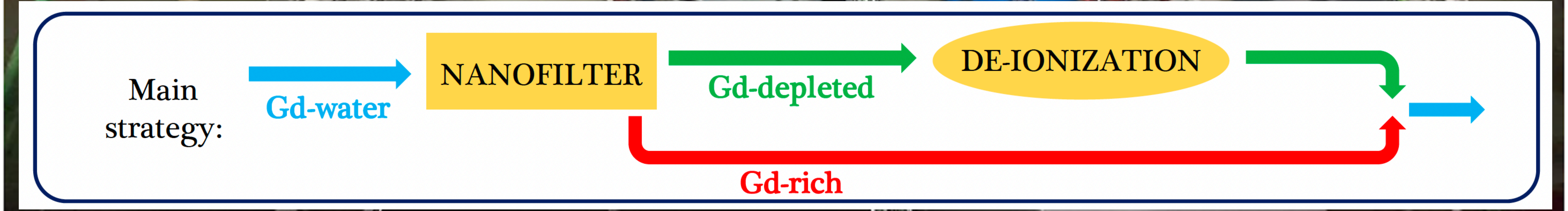
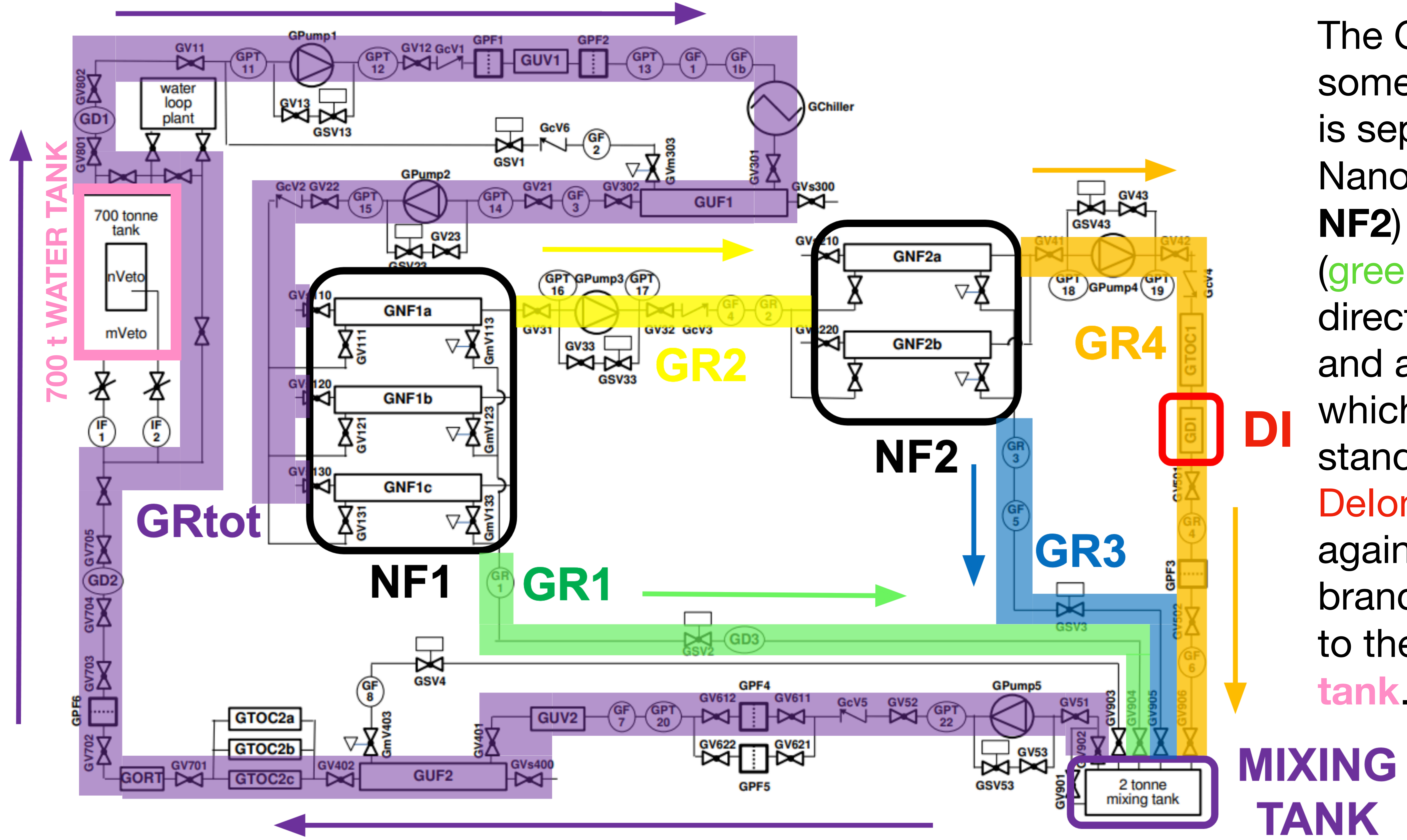




XENONnT: GdPlant P&ID



The Gd-Water solution, after some preliminary treatment, is separated via NanoFiltration (**NF1** and **NF2**) into a Gd-rich part (green and blue) sent directly to a Mixing Tank, and a Gd-depleted part which is first purified via a standard water treatment as DeIonization, then mixed again with the other branches, before returning to the main 700 t water tank.

GdSalt insertion

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Transport system connection → Salt insertion → Stirrer activation

The GdSalt is transported underground in a sealed container, and transferred in the mixing tank with a pneumatic tool. Defining the procedure with LNGS has been a crucial milestone both on the technical and authorisation point of view.

GdSalt insertion

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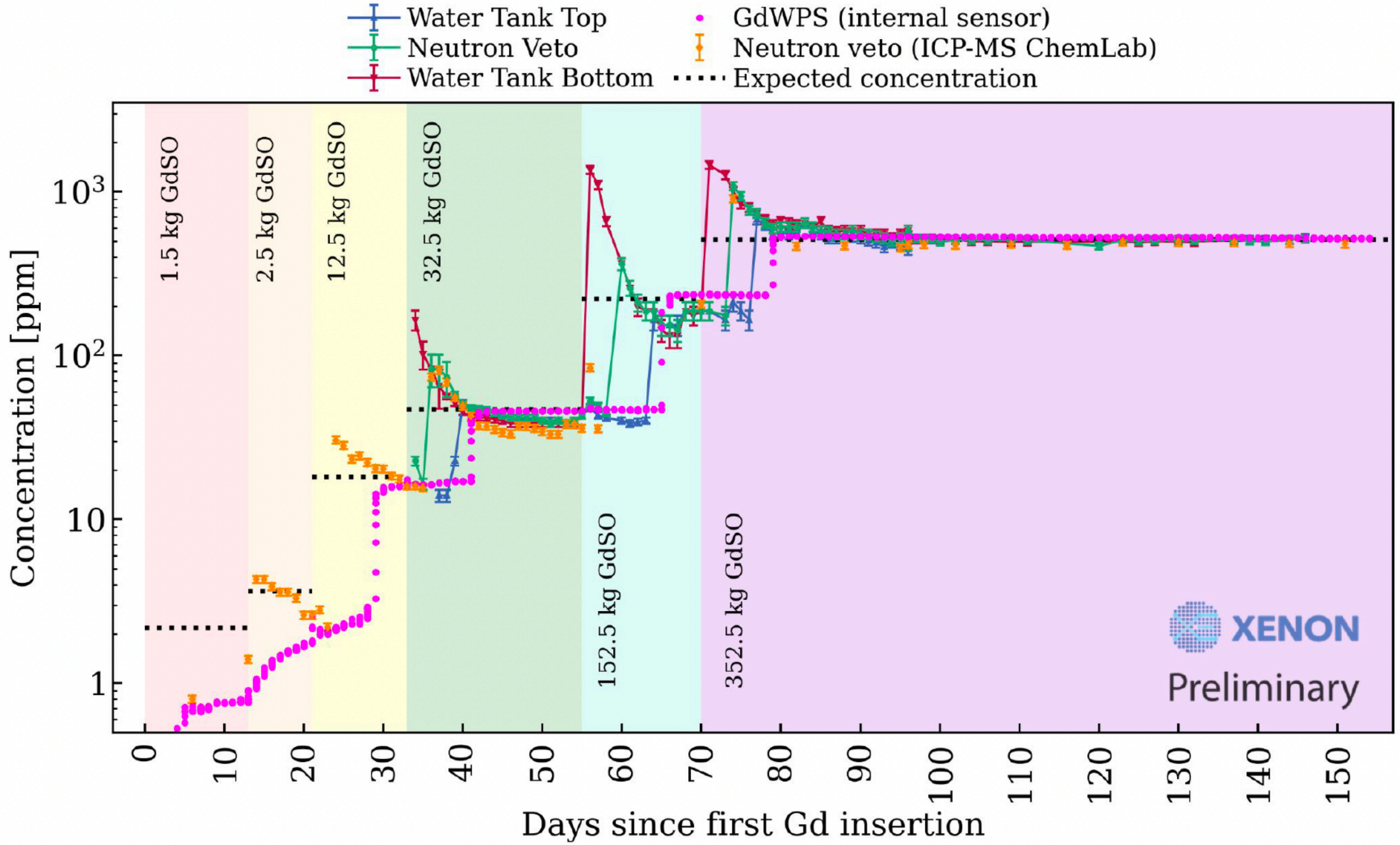
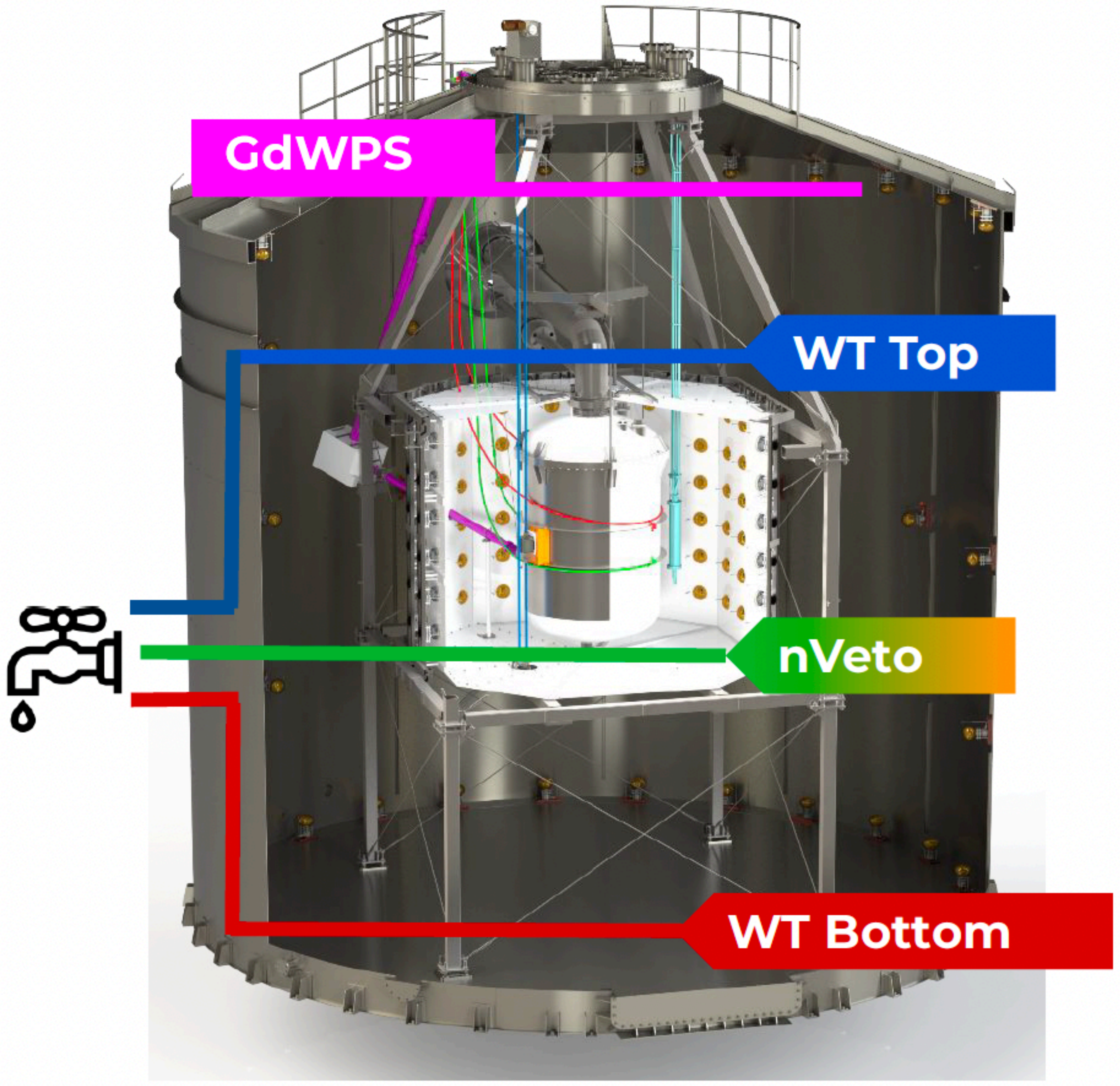
Gd-sulfate **concentration** in the **system** can be estimated with **direct** measurements of **Gd** via mass spectrometry (**ICP-MS** at **LNGS chemistry lab**), **conductivity** of small **samples** from **WT** (performed in situ) **and conductivity** measured by **GdWPS** inner sensor (online)





nVeto performance with GdWater

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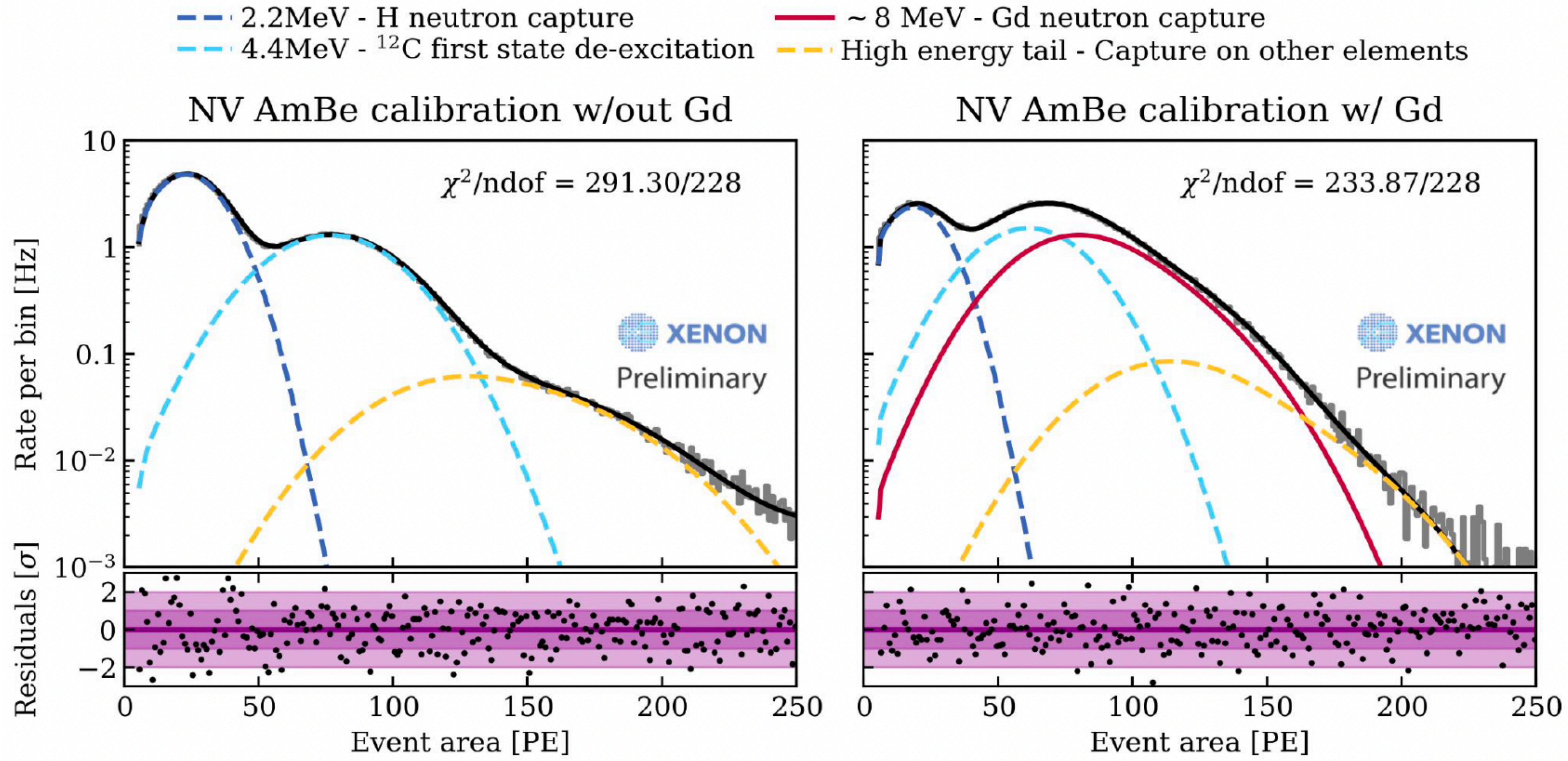
AmBe calibration **source far** from **cryostat** (**50 cm**) to characterize NV **response** along time, **area spectrum** can be **modeled** with:

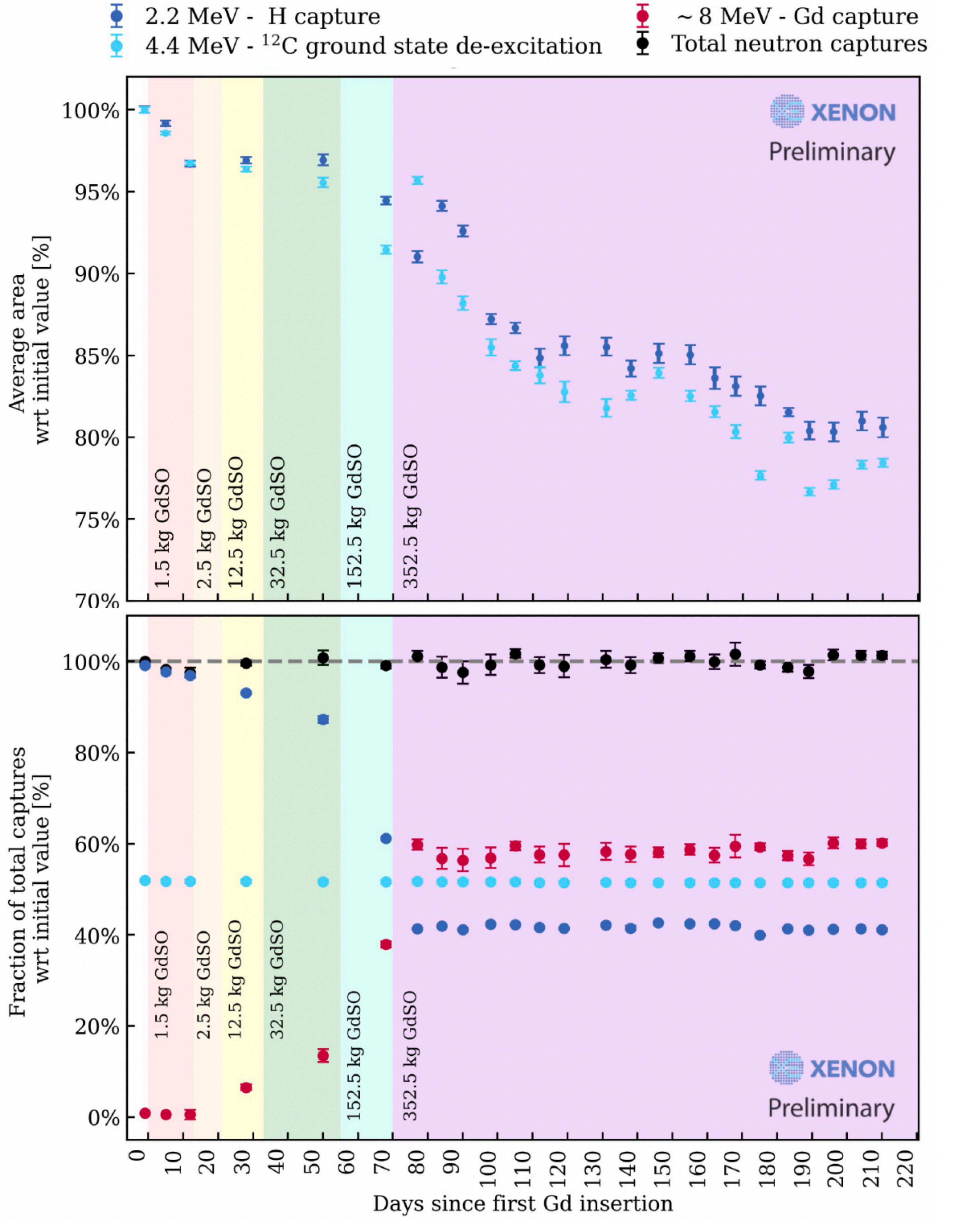
- **2.2 MeV peak** (**H** capture) → **1 Gaussian** with threshold
- **4.4 MeV** peak (**^{12}C de-excitation**) → **1 Gaussian** with threshold
- About **8 MeV** peak (Gd capture) → **2 Gaussians** with threshold
- **High energy tail** (higher level **^{12}C** de-excitations or n captures on **^{56}Fe**)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



nVeto performance with GdWater

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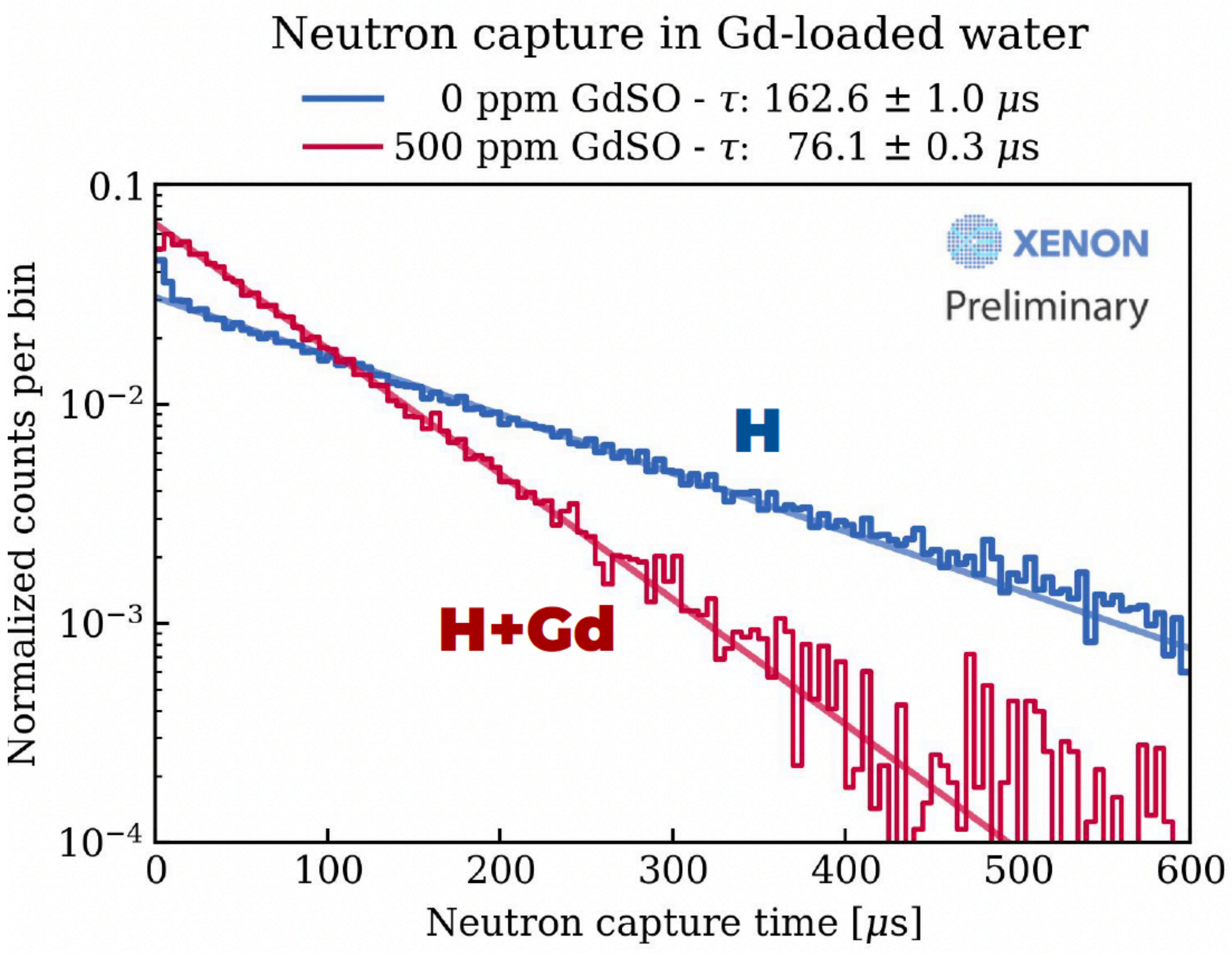
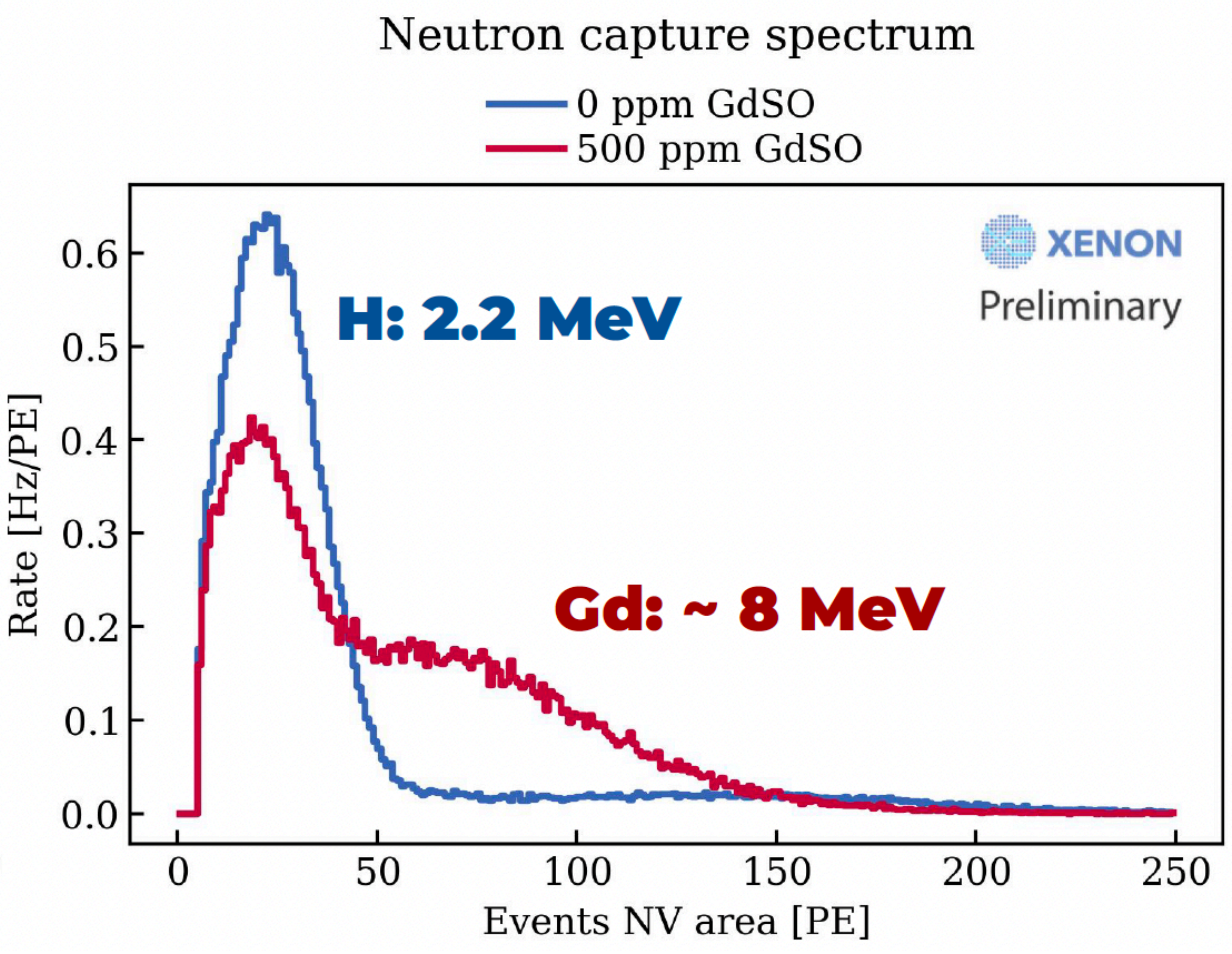
AmBe calibration with **source close** to **cryostat** (**~ 1 cm**) → events with **same** characteristics of **neutron** emitted from **detector materials**

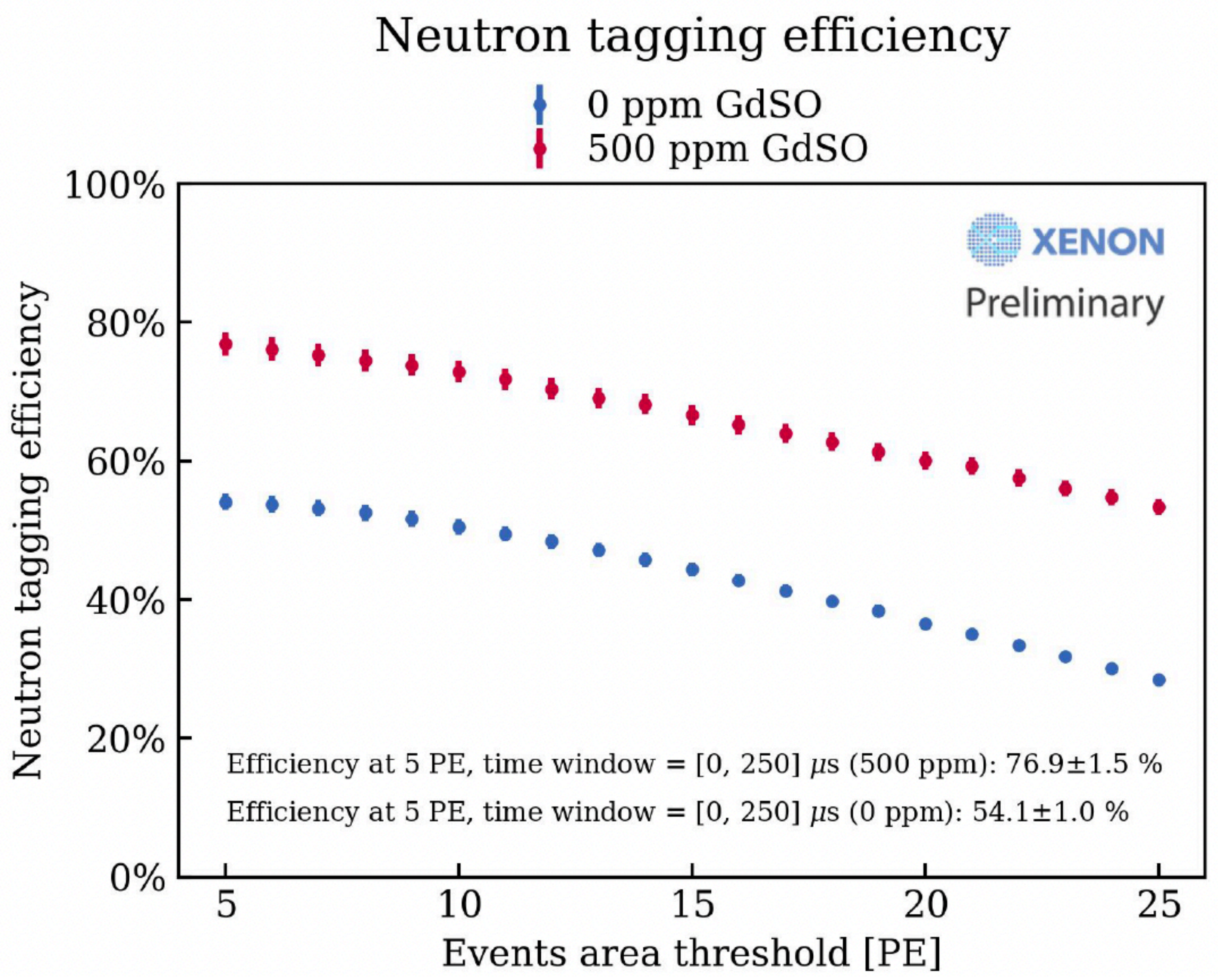
Neutron **capture time** and **area spectrum** can be **estimated** by using **NV** only (**self-trigger**), by looking for NV events **following 4.4 MeV** signals from AmBe source in NV

At 500 ppm GdSO, **average** neutron **capture time** around **77 μs** (2x **shorter** than in **demi-water**) and **larger** average **area**, with a **10% increase** in neutron **captures.**

Tagging efficiency is estimated by **requiring coincidence** with **nuclear recoils** detected in the **TPC**
Neutron tagging efficiency with **500 ppm** of GdSO, in a **250 us** time-window, is about **77%** (about **53%** in SR0):
→ a **factor 2** neutron **background reduction** wrt SR0 with demi-water







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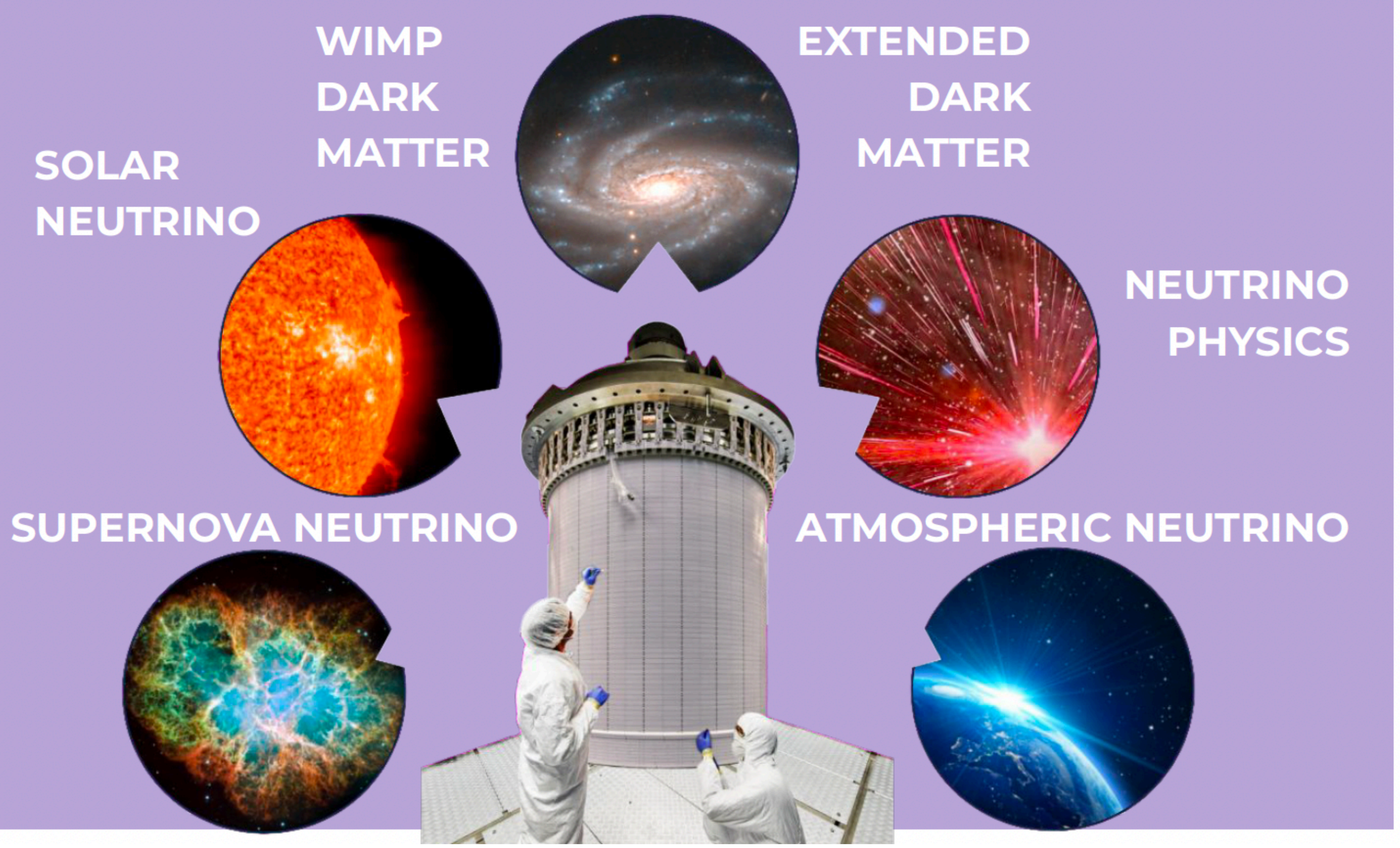
NEXT-GENERATION LXe EXPERIMENT

Dual-phase Xe TPC with **~60** t of active **LXe**, from the **joint** efforts of **XENON**, **LZ** and **DARWIN** collaboration into the **XLZD consortium**

Multi-purpose observatory for **dark matter, neutrino** and **rare events**, probing **WIMPs** down to **neutrino floor**

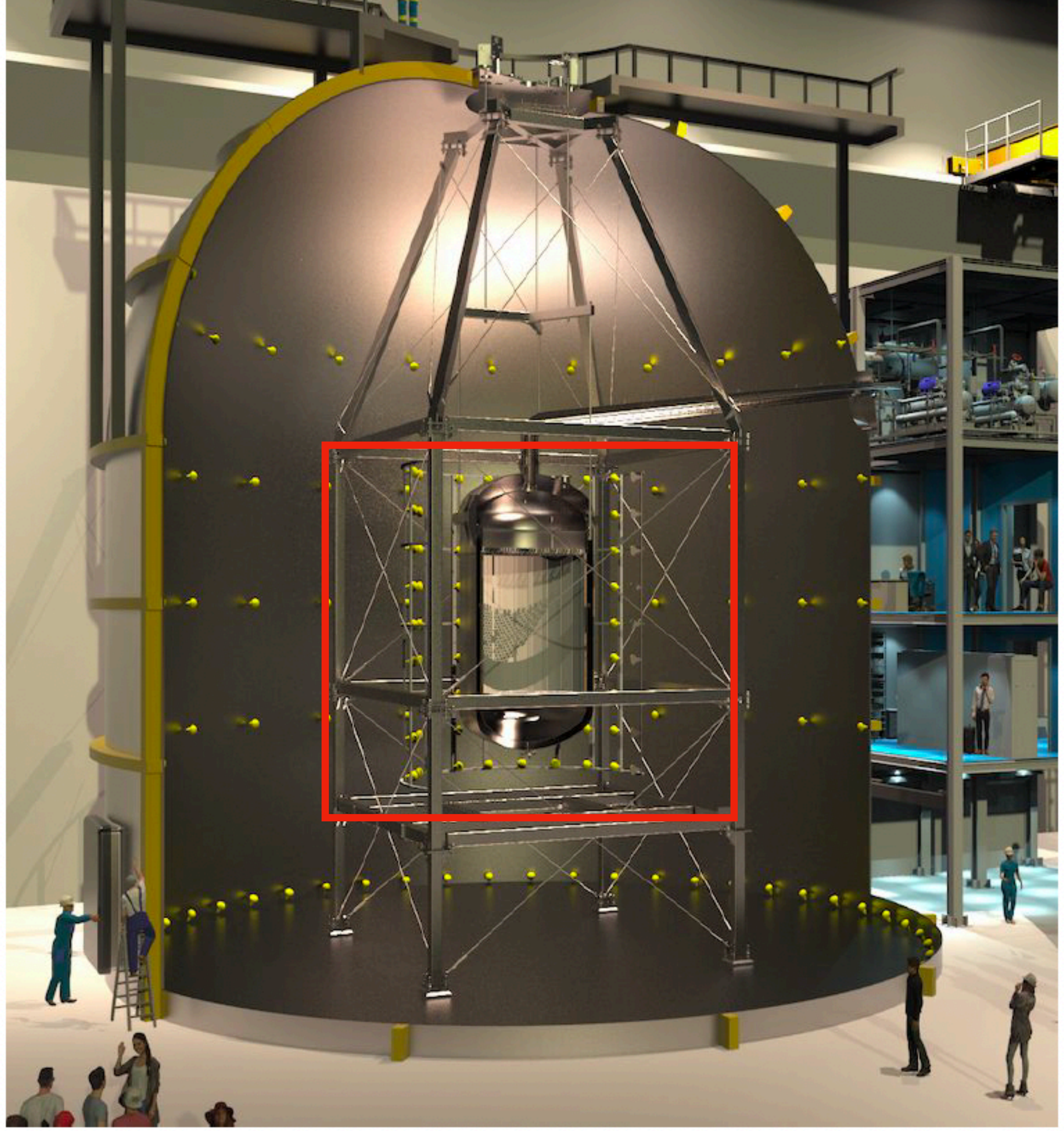


J. Phys. G: Nucl. Part. Phys. 50 013001

Gd-doped Water Cherenkov Neutron Veto can be a viable technology also for the next-gen LXe experiment XLZD.

Increasing the Gd-salt concentration, the n-tagging efficiency can be improved up to 90%

Planning the future DARWIN/XLZD observatory, T. Pollman, TAUP 2023



XENONnT neutron veto: Conclusions

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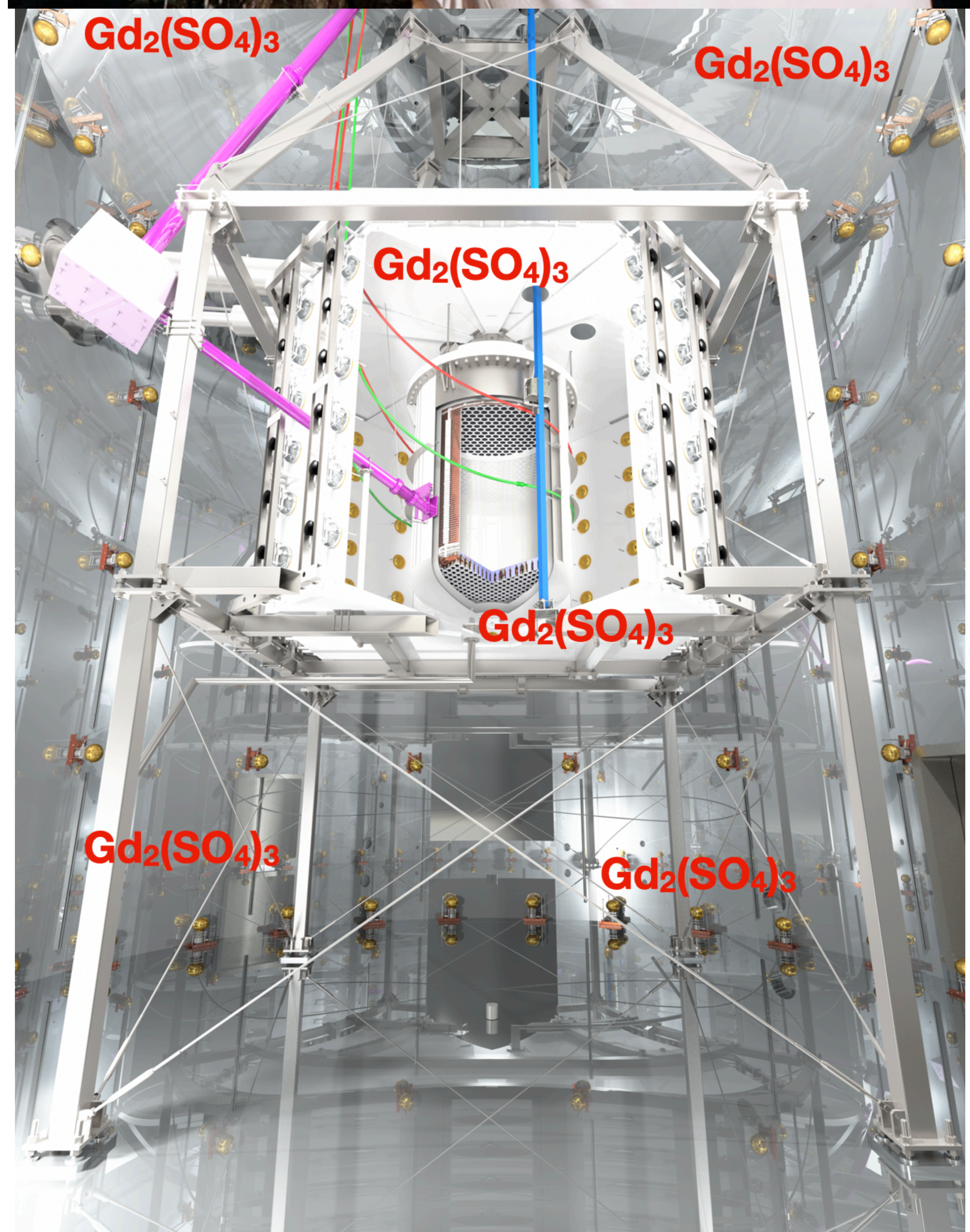
The XENONnT Neutron Veto was built in 2020, commissioned in 2021 and operated with demi-water in the first Science Runs.

The calibration with AmBe neutron showed a very good **neutron tagging efficiency of 68%**, the highest ever measured in a water Cherenkov detector.

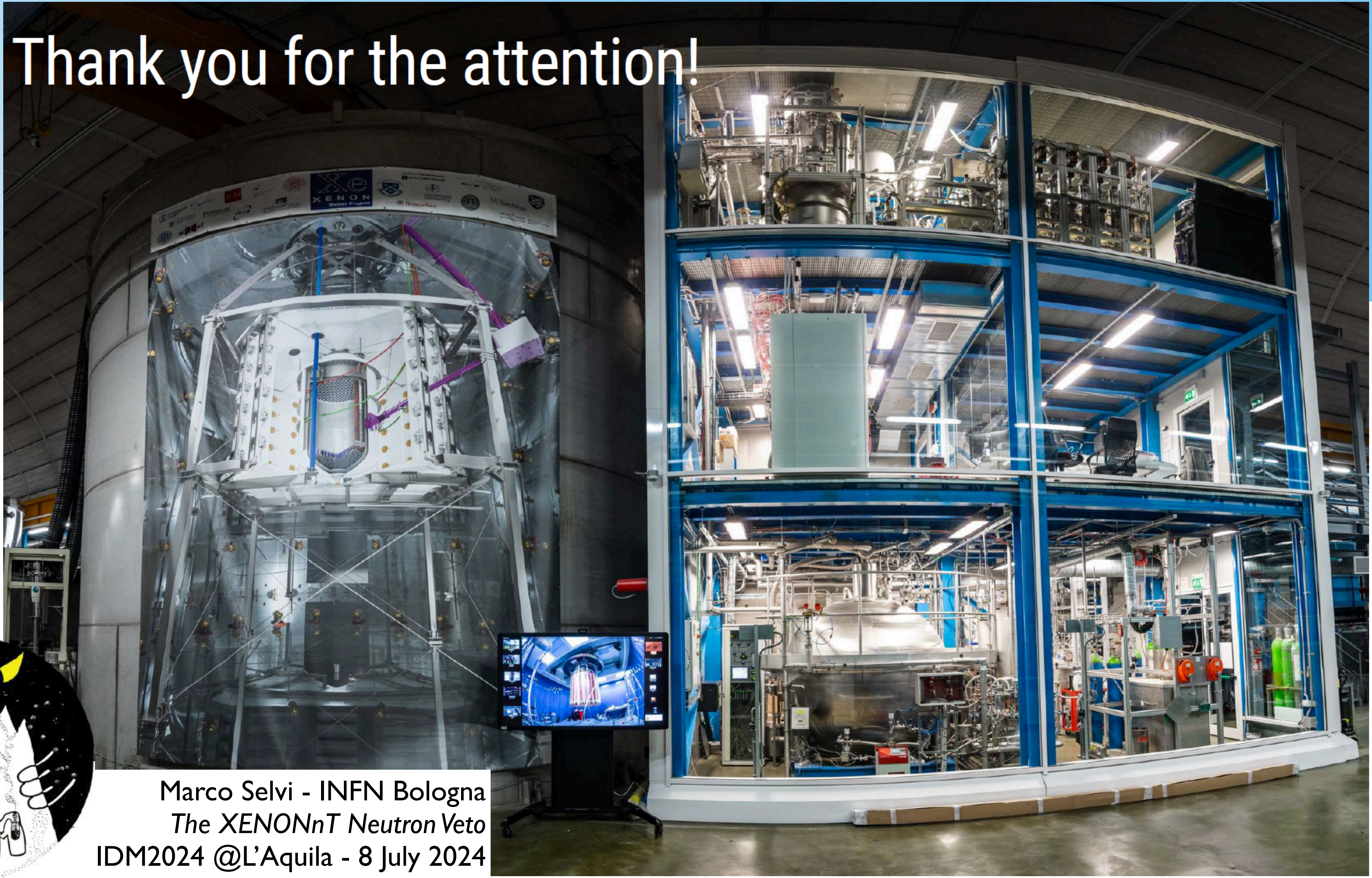
The system allowed to reduce the neutron background in Science Run 0, and to constrain it in a data-driven way.

Since 2023, we doped the water with 500 ppm of Gd-salt, improving the **efficiency up to 77%**, reducing the neutron background by another factor 2 (further improvements are still doable, by increasing the Gd concentration).

The Gd-loaded Water Cherenkov Neutron Veto is one of the options for the **XLZD** outer detector.



Thank you for the attention!



Marco Selvi - INFN Bologna
The XENONnT Neutron Veto
IDM2024 @L'Aquila - 8 July 2024

Backups

XENONnT Neutron Veto: PMTs and DAQ

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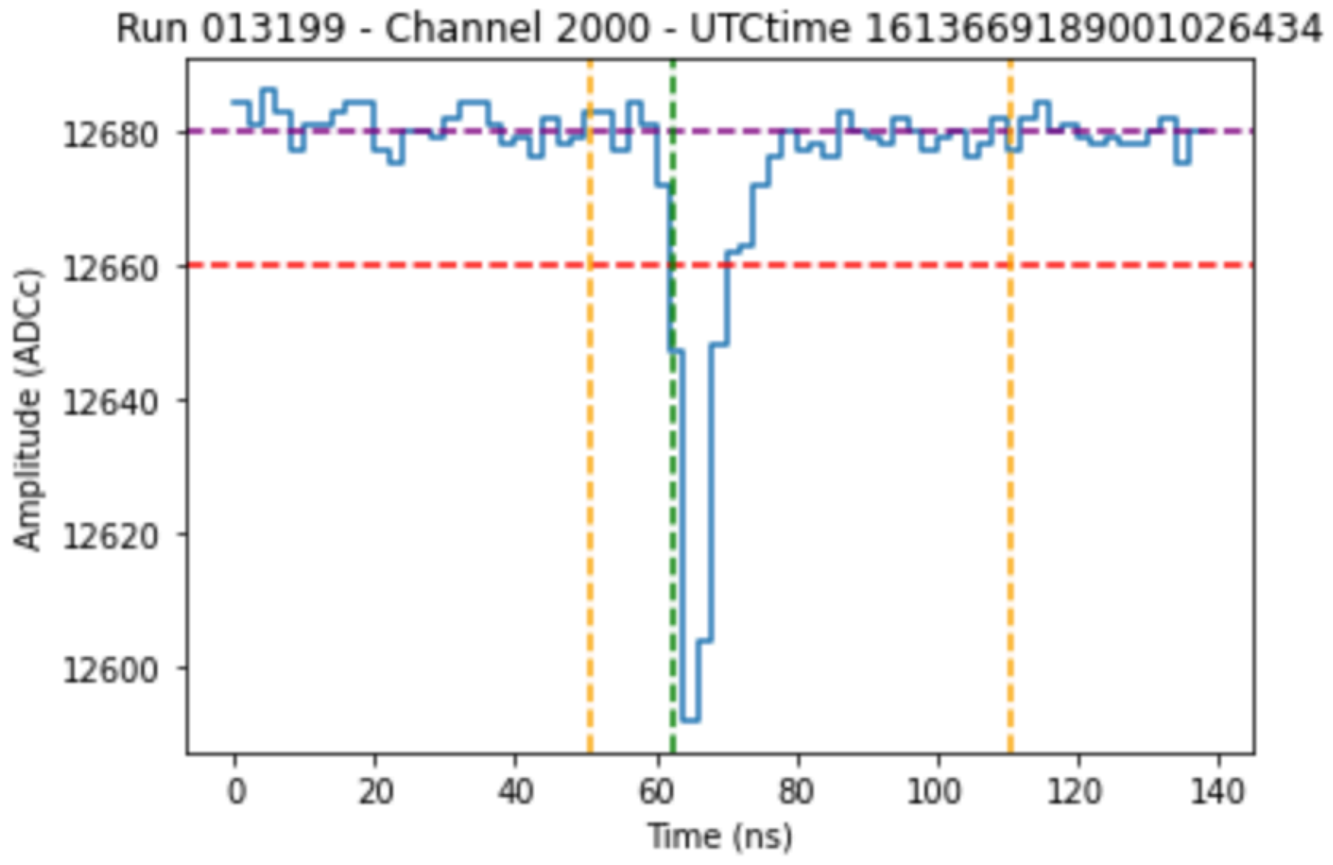
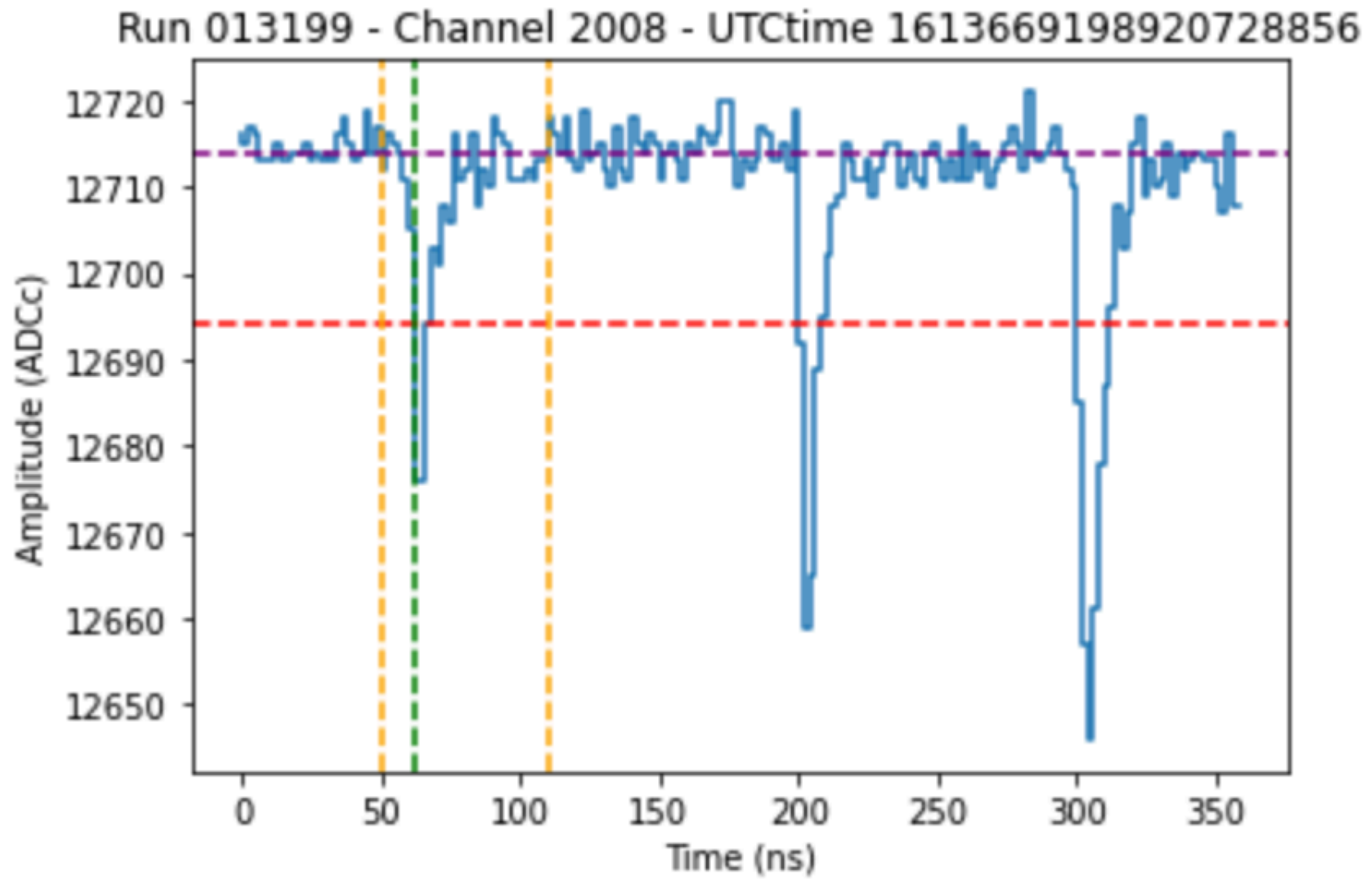
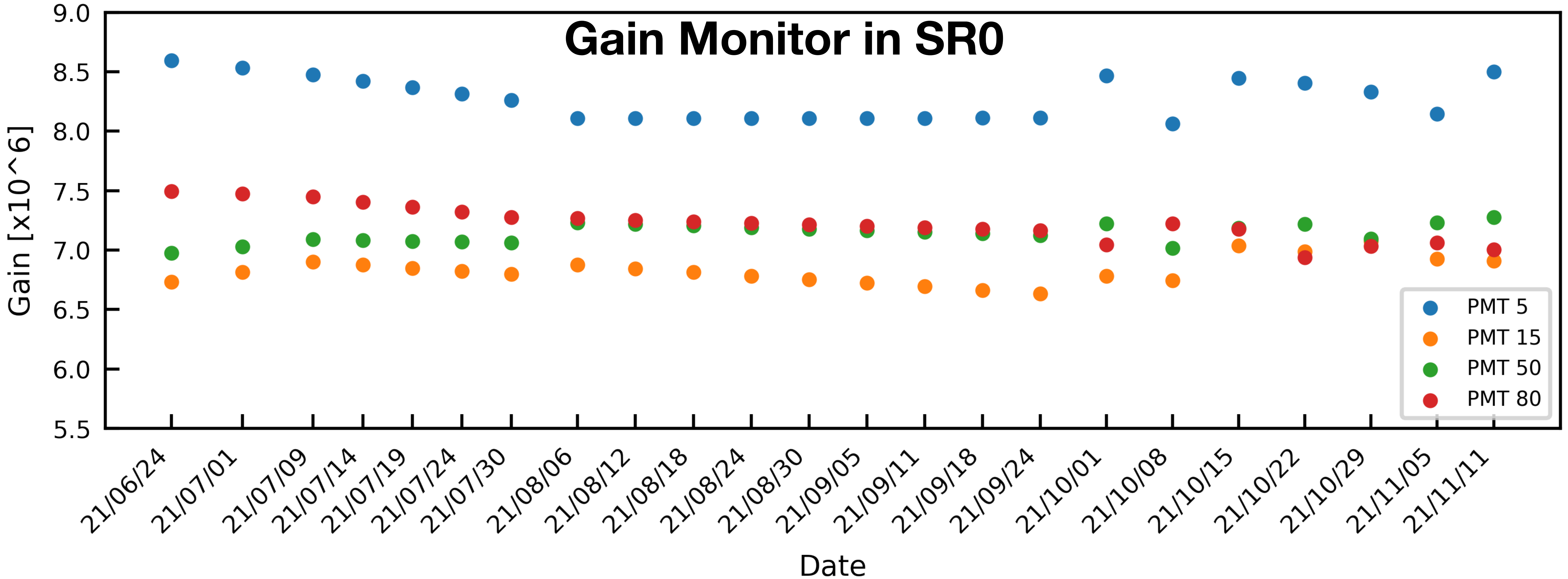
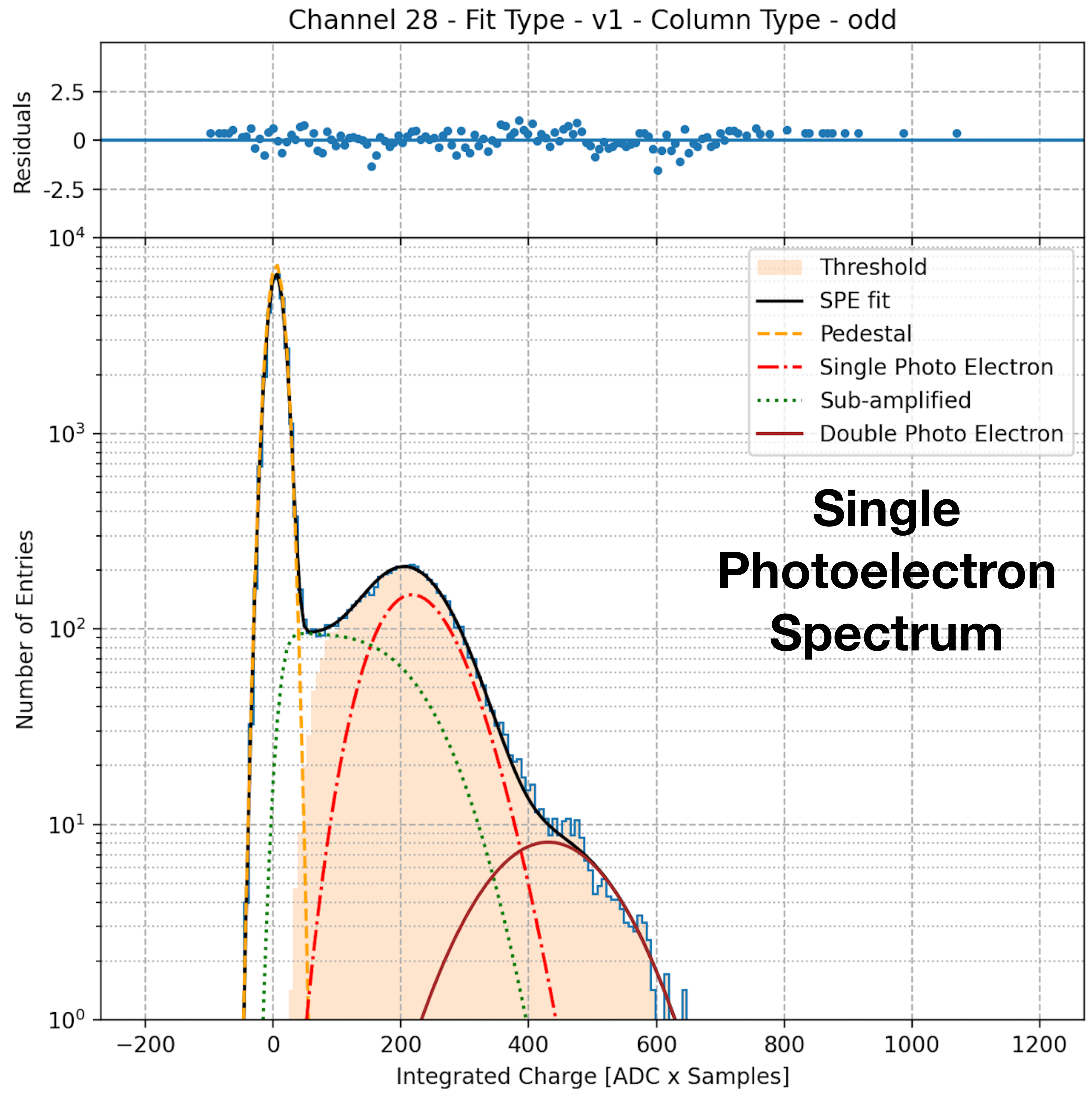
- Digitizers CAEN V1730: 2 ns sampling, 14 bit resolution.
- Data Acquisition in Self-Trigger mode, Threshold 15 ADC counts.
- All 120 PMTs and channels are working very well, with RMS of baseline <3.

Example Waveforms









- PMT gains are monitored via weekly LED calibrations.
- Gains were stable within 5% for the whole Science Run 0

XENONnT Neutron Veto: background rate

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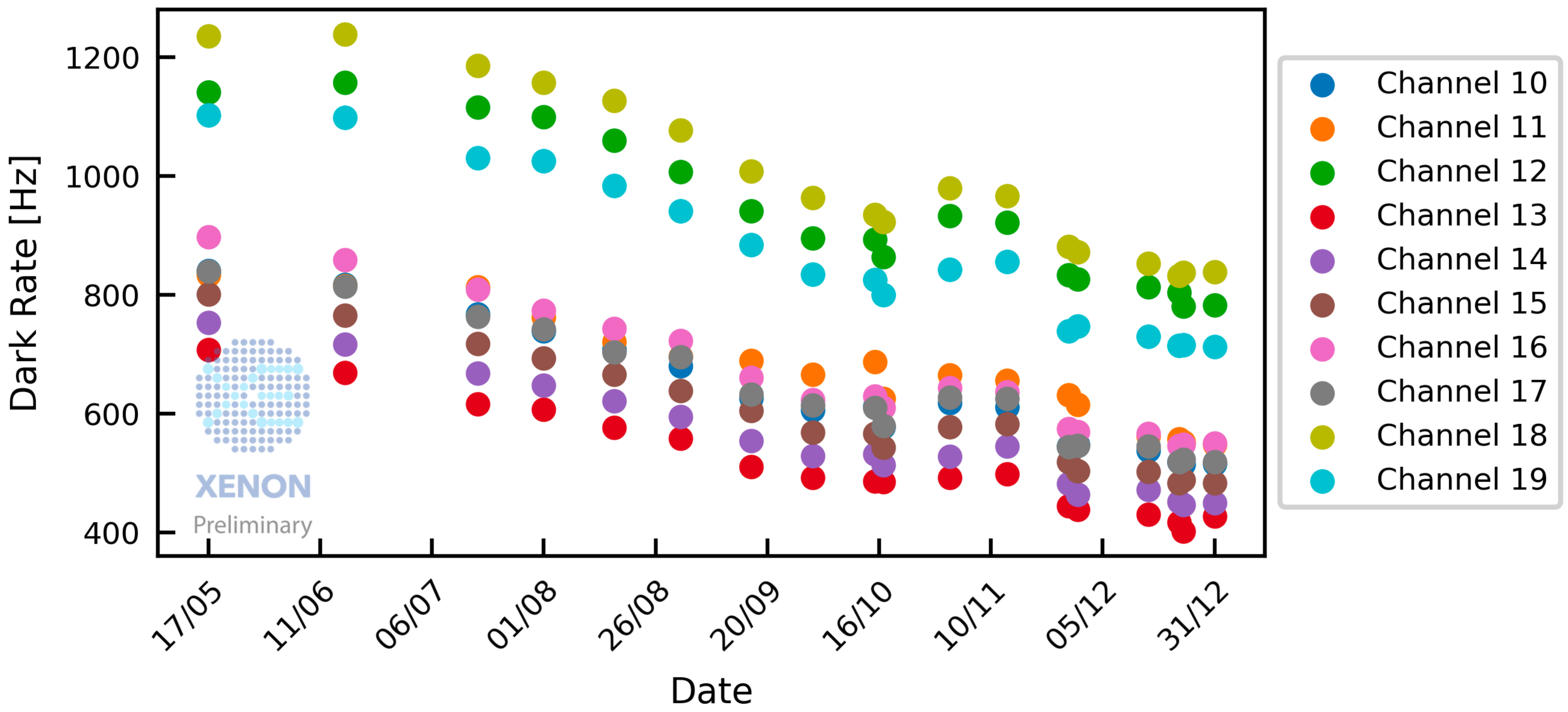
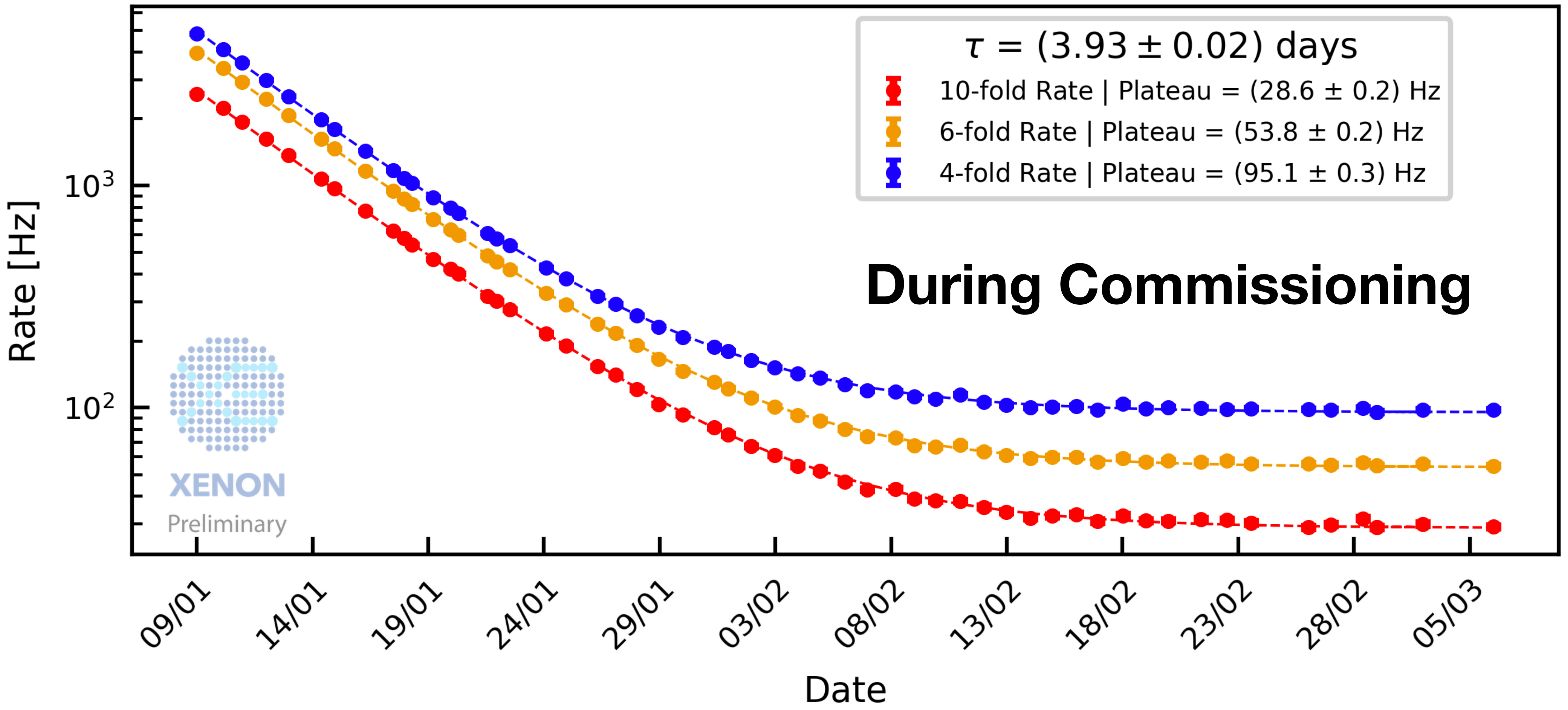
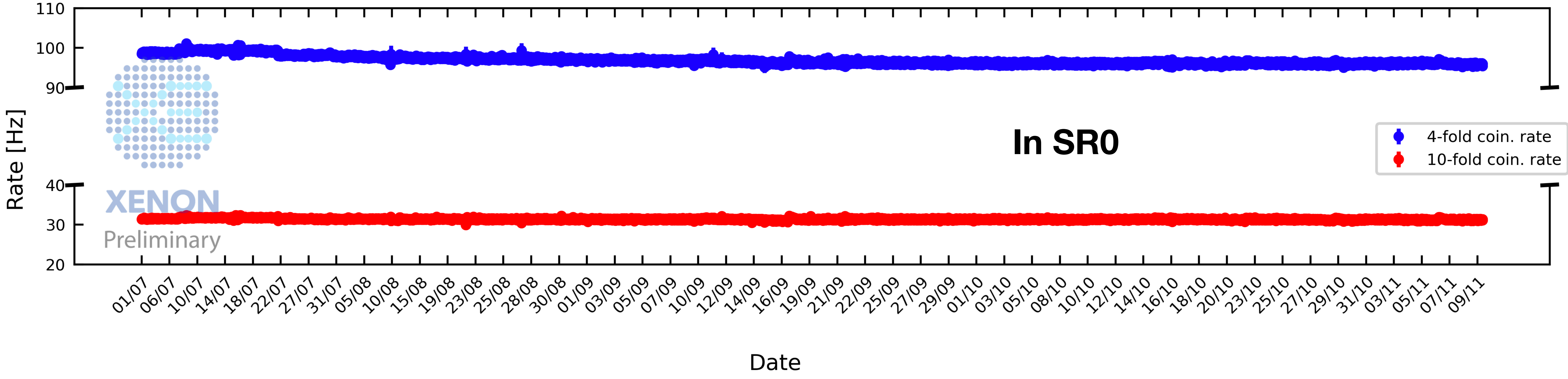
PMT dark rate during SR0



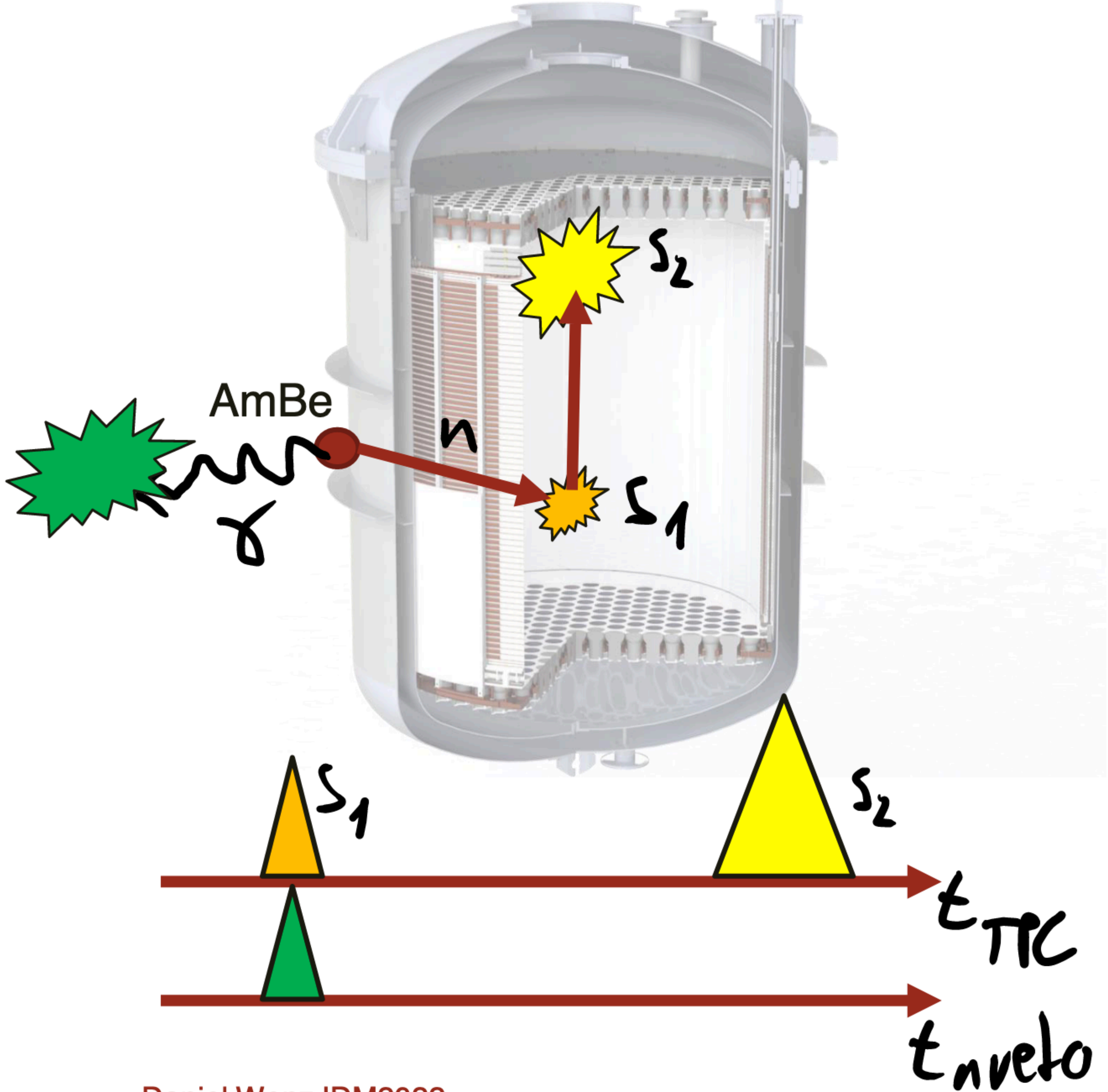
nVeto coincidence rate (inside 300 ns)



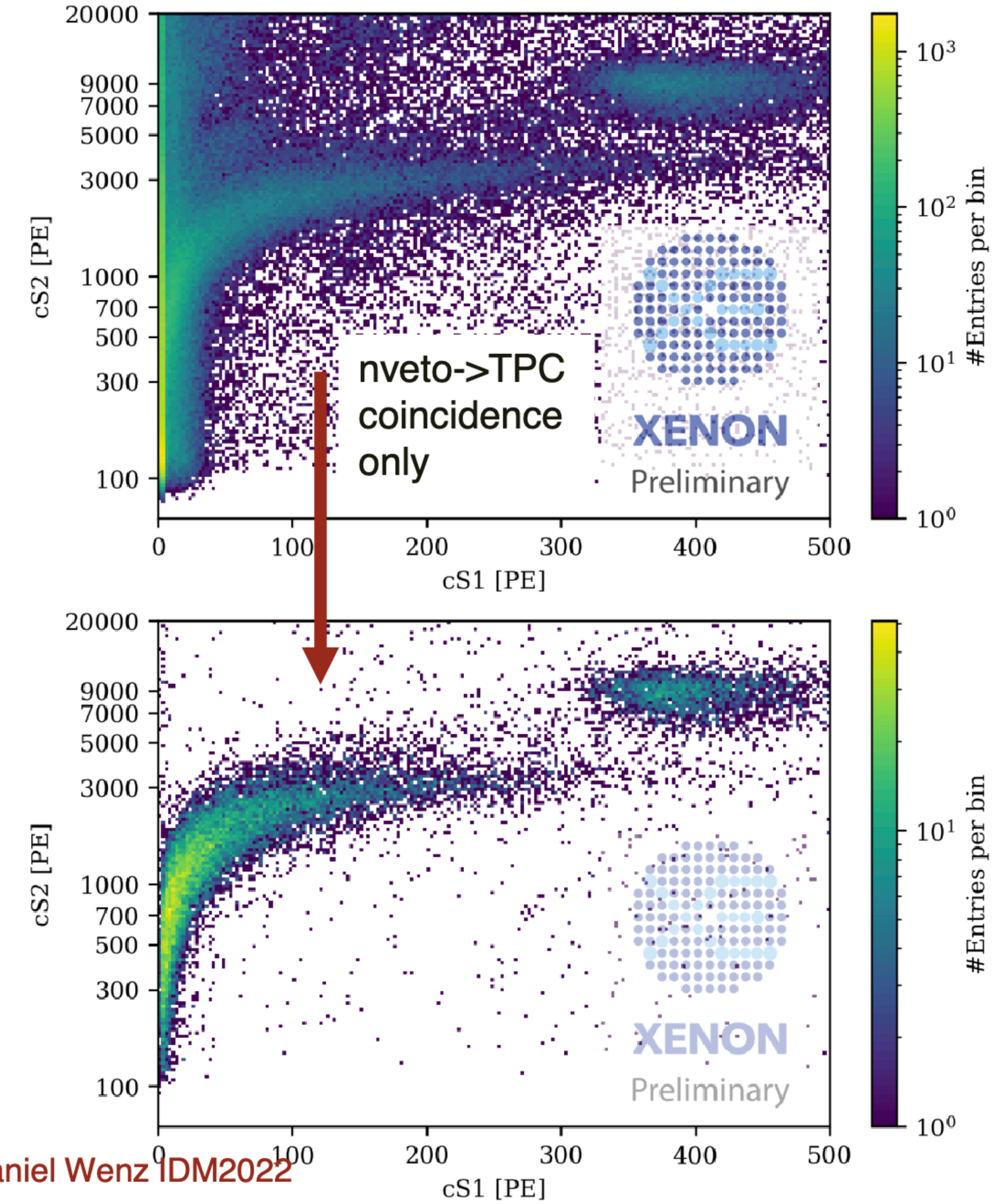


- Low dark rate in each PMT: O(1kHz)
- Initial decrease of coincidence rate due to Rn-decay in water
- Plateau at <100 Hz with a 4-fold requirement (due to gammas from the radioactivity of the materials close to the nVeto)
- Deadtime induced in the TPC due to accidental coincidences with the nVeto = 100 Hz x 500 us -> 5%

nVeto-tagged events clean-up the NR band



Daniel Wenz IDM2022



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Neutron calibration with AmBe

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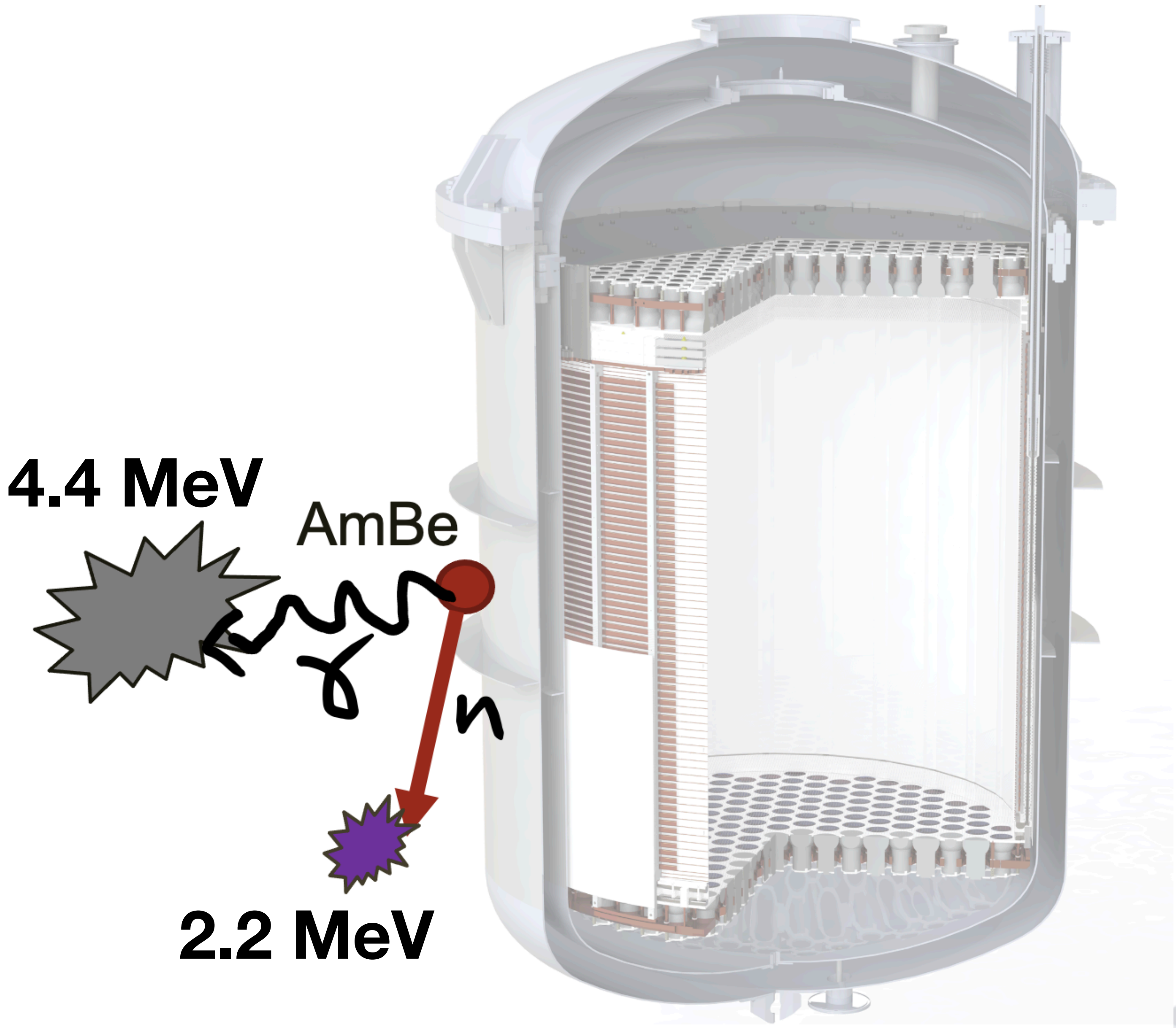
Neutron detection efficiency

- Neutron calibration with AmBe source placed close to the cryostat.

- AmBe emits a 4.4 MeV gamma together with the neutron in about 60% of cases.

- Detect the 4.4 MeV gamma in the TPC or nVeto,
and look for the 2.2 MeV gamma of neutron capture in the nVeto.

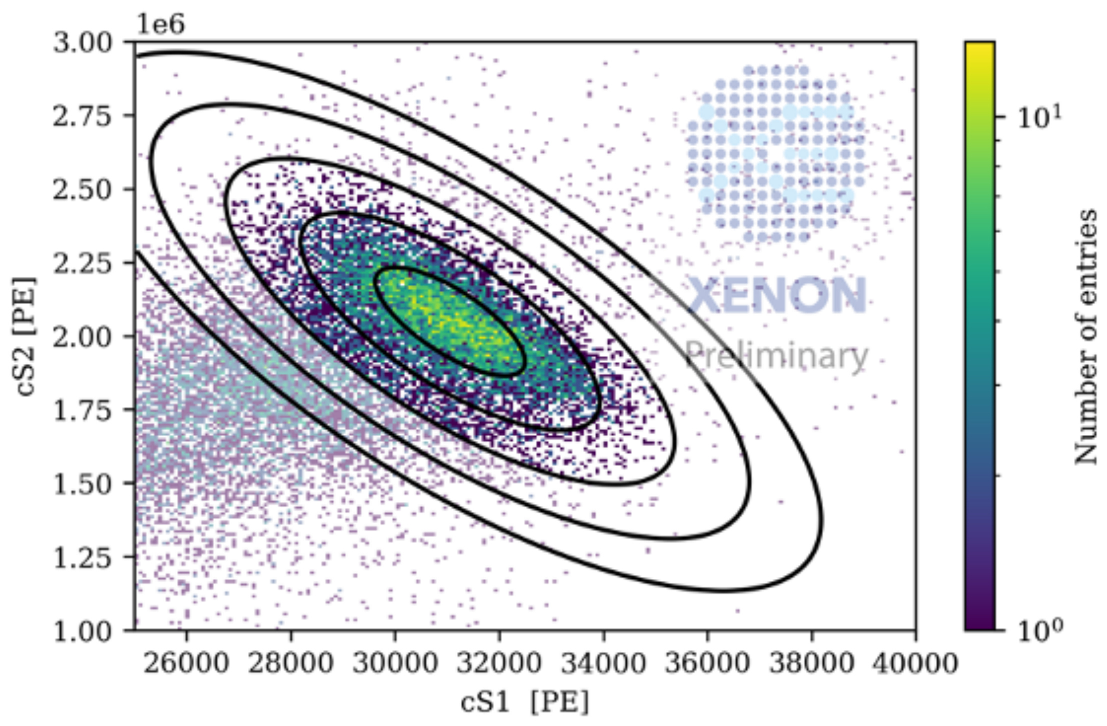
- Direct measurement of the neutron detection efficiency of the nVeto

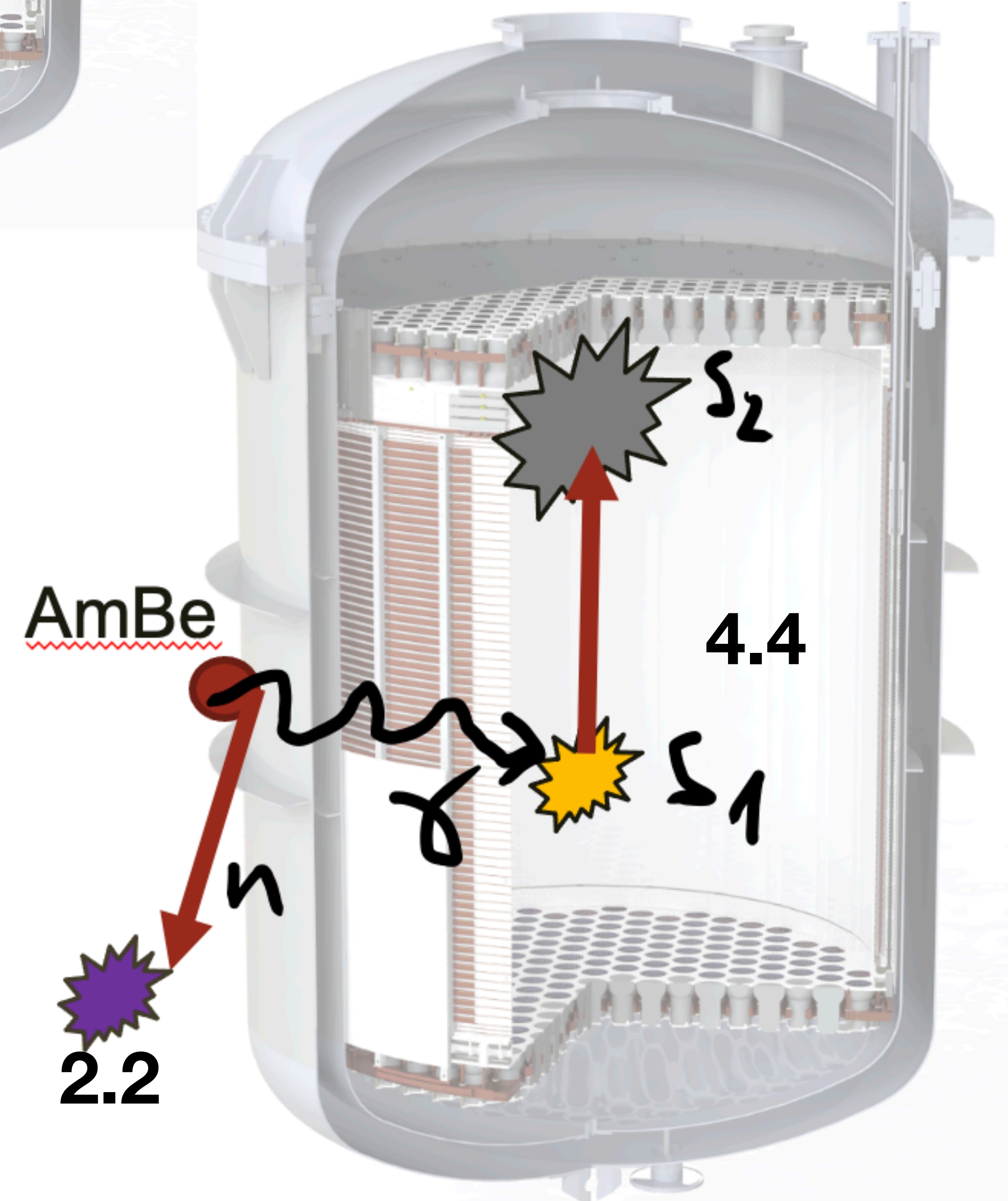


"Number of neutrons detected | selection"
―――――――――――――――――――――――
"Number of 4.4 MeV gamma detected in the TPC"

➡ $(80.2 \pm 1.3)\ \%$ @ 5-fold coincidence, 5 pe threshold and 600 μs window

➡ To our knowledge highest detection efficiency ever measured in a water Cherenkov detector.





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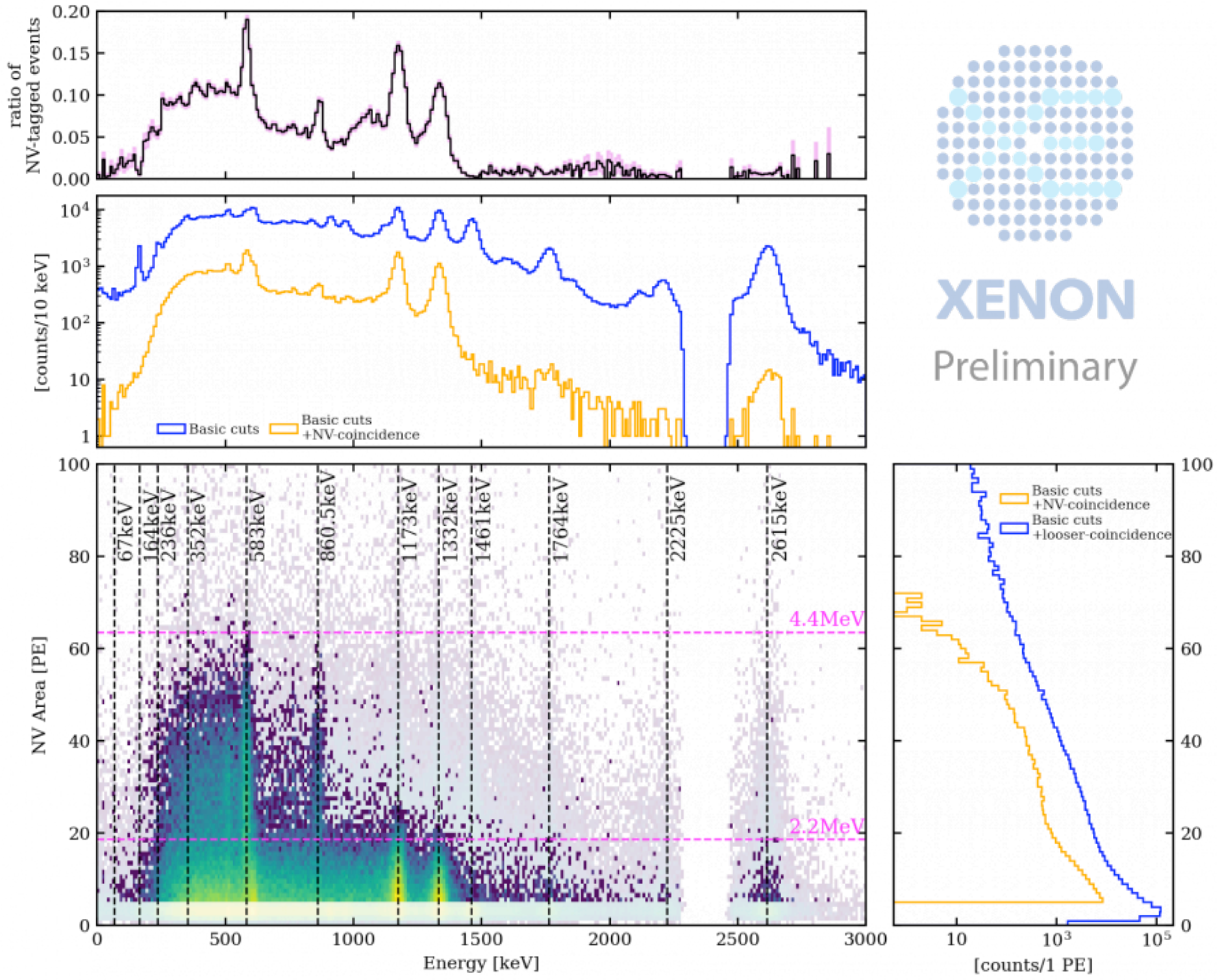
In the search for **Electronic Recoil** events, the nVeto has been used to tag part of the gammas from material radioactivity, as ^{60}Co and ^{208}Tl, that present some energy deposit in the nVeto together with the one in the TPC.

- Reduction about 10% for ER background from materials.

- Clear and effective demonstration of the low energy threshold of the neutron veto.



Performances with GdWater

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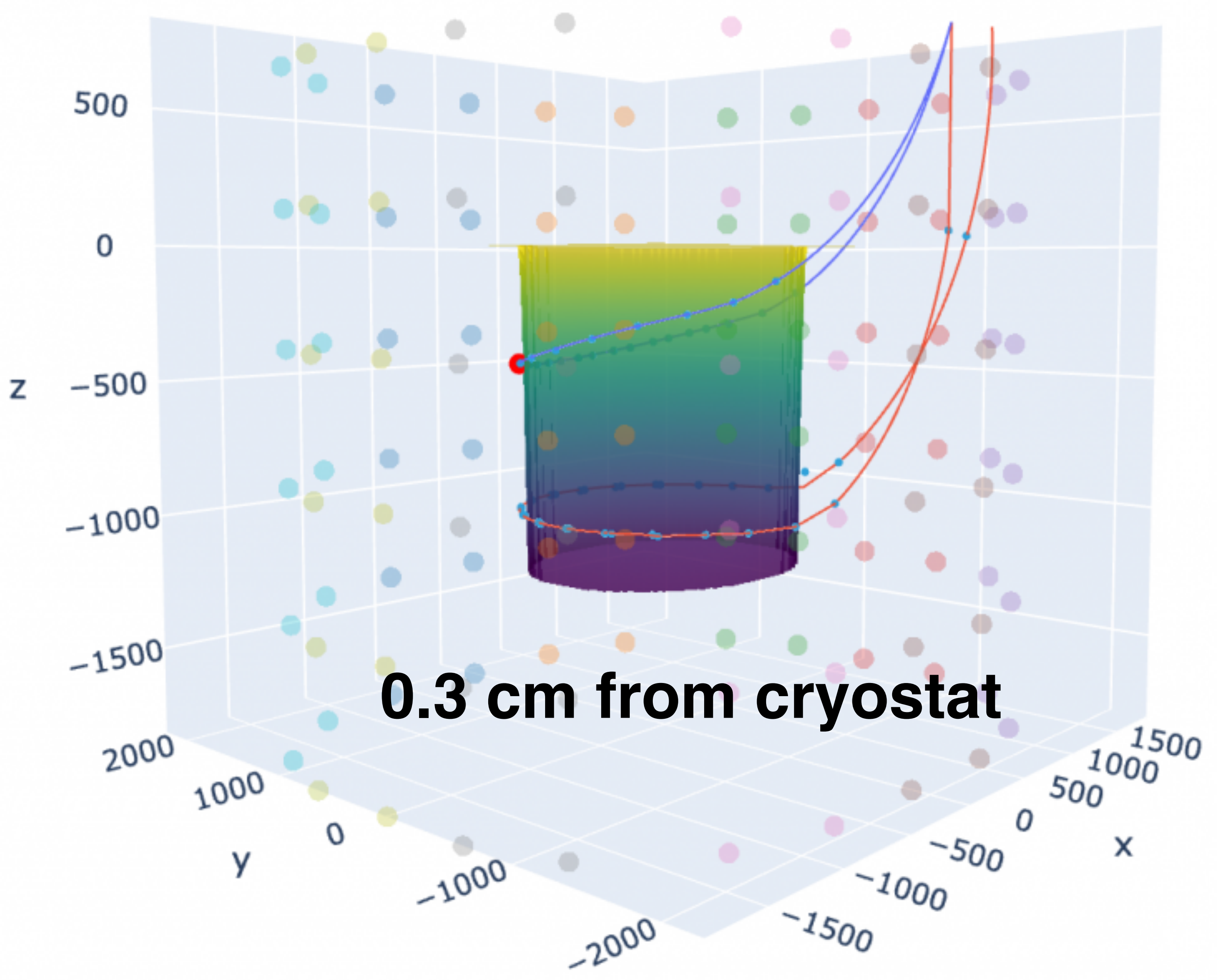

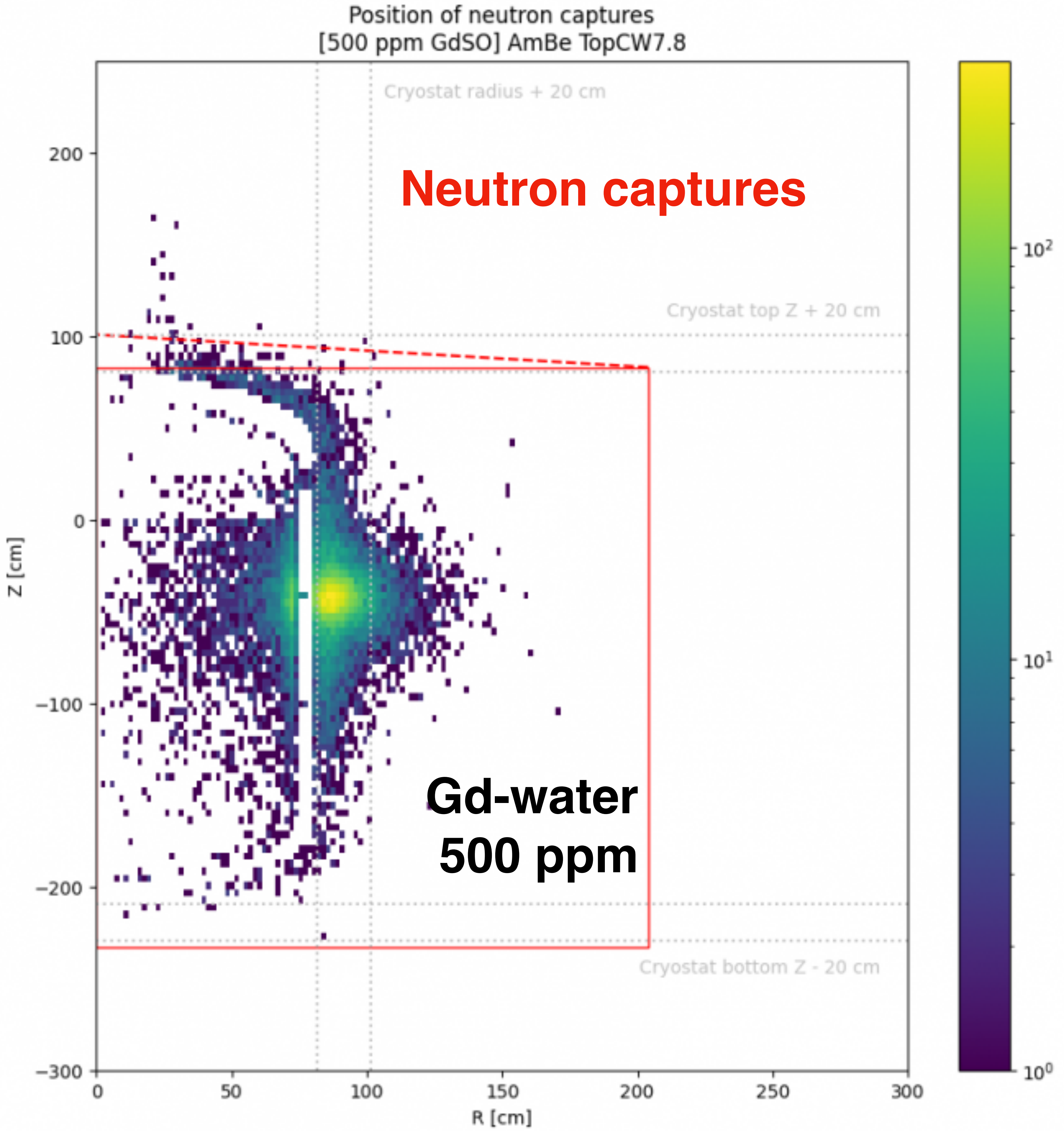

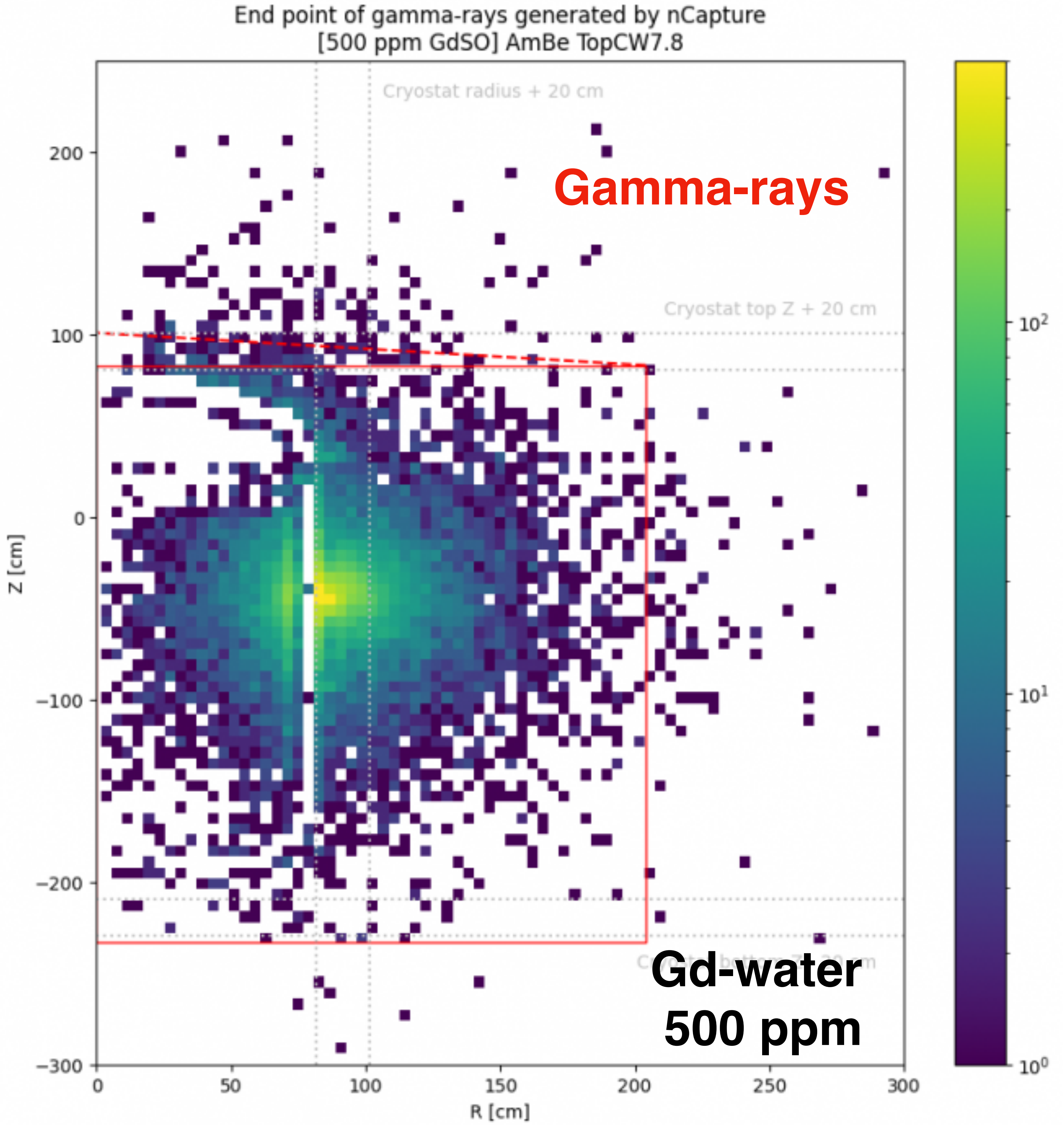

Neutron Veto performances: transparency monitor

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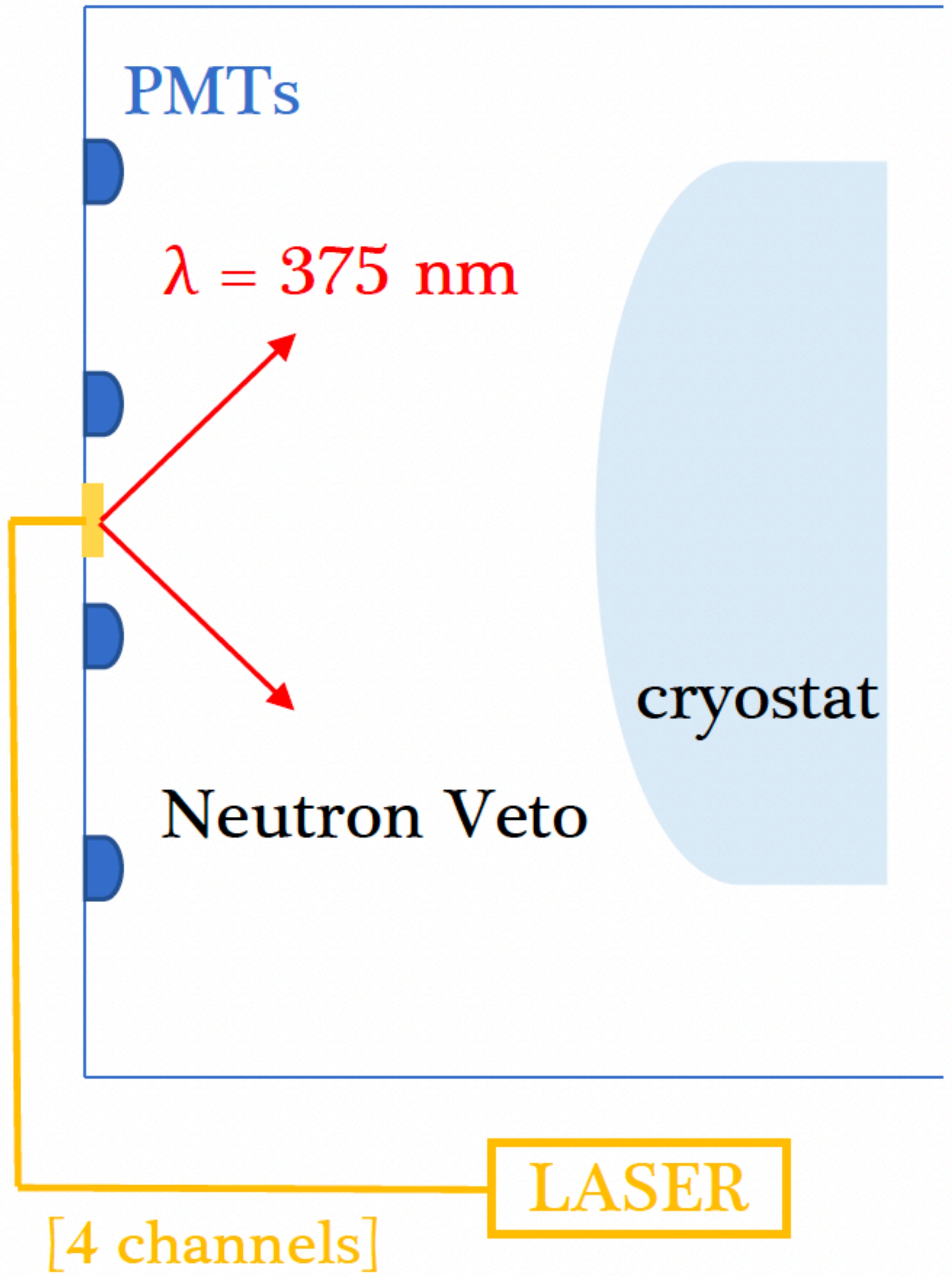
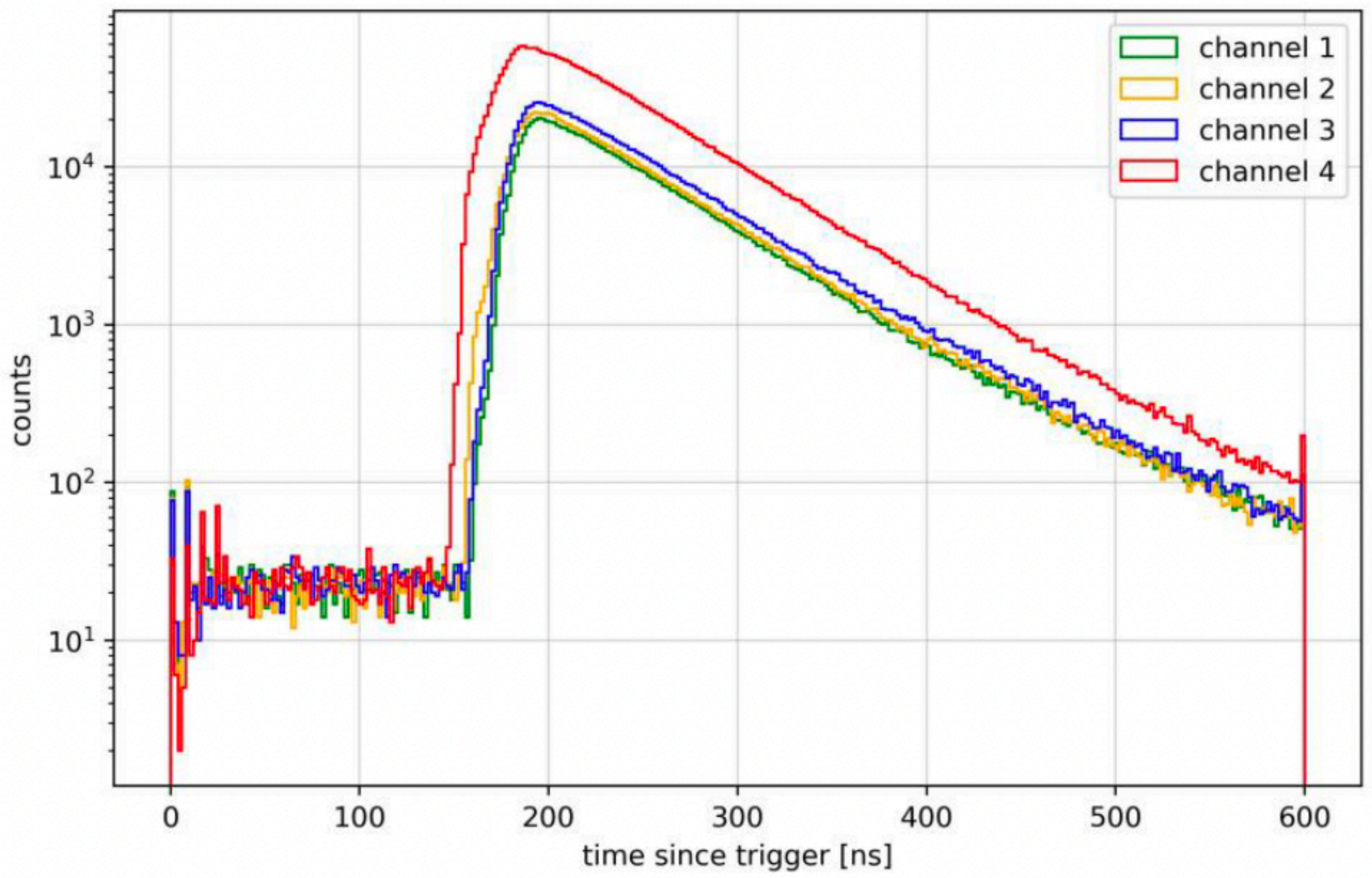
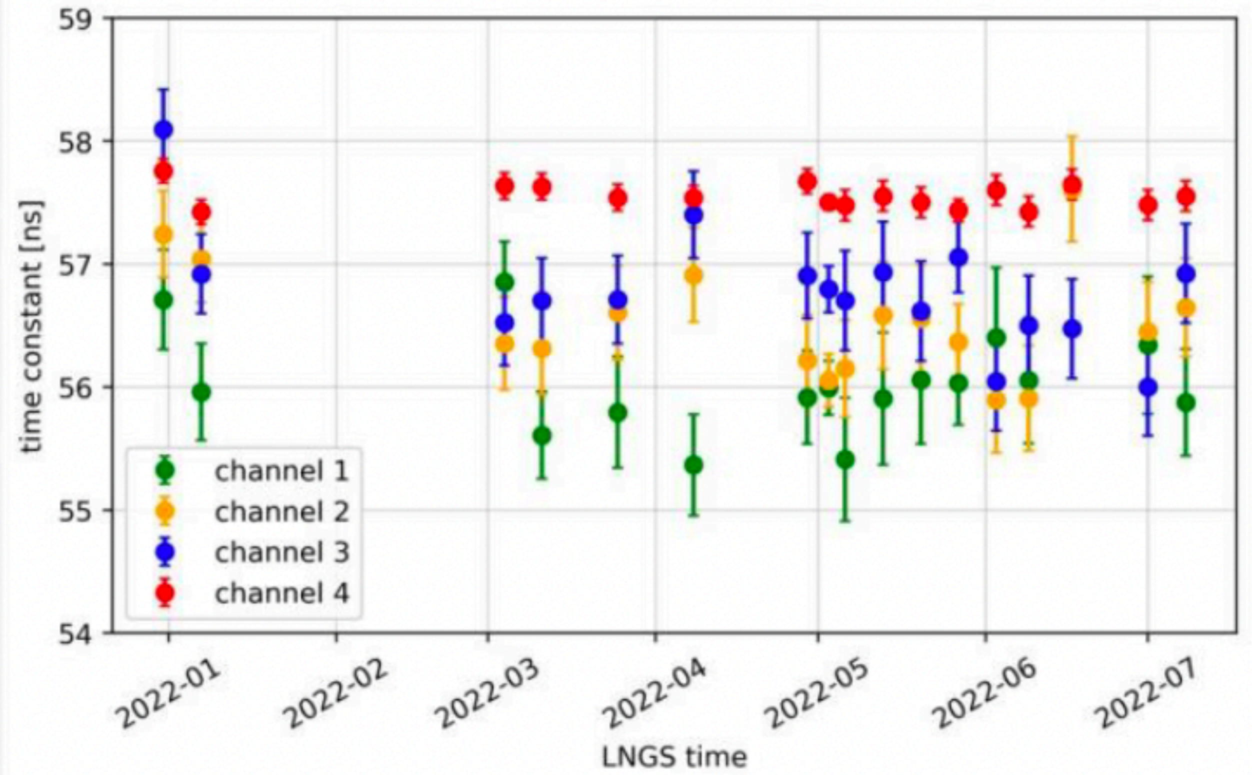


PMT hits timings are recorded; the distribution is **exponential:**



Time constant τ stable over time: (57 ± 1) ns

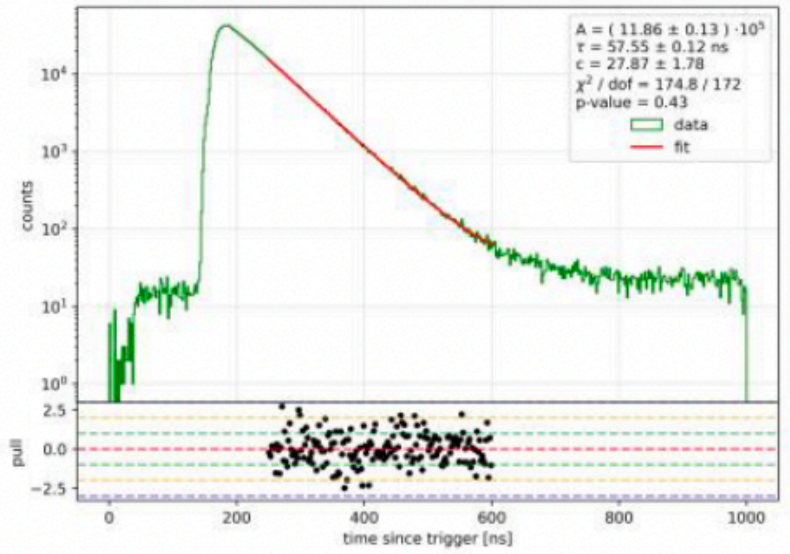


- measure of the **optical properties**
- depends on water **transparency** and wall **reflectivity**

Selection cuts in:
- number of PMTs
- hits area in photoelectrons

3-parameter **fit:**

$$f(t) = Ae^{-t/\tau} + c$$



GdSalt insertion: effect on the transparency

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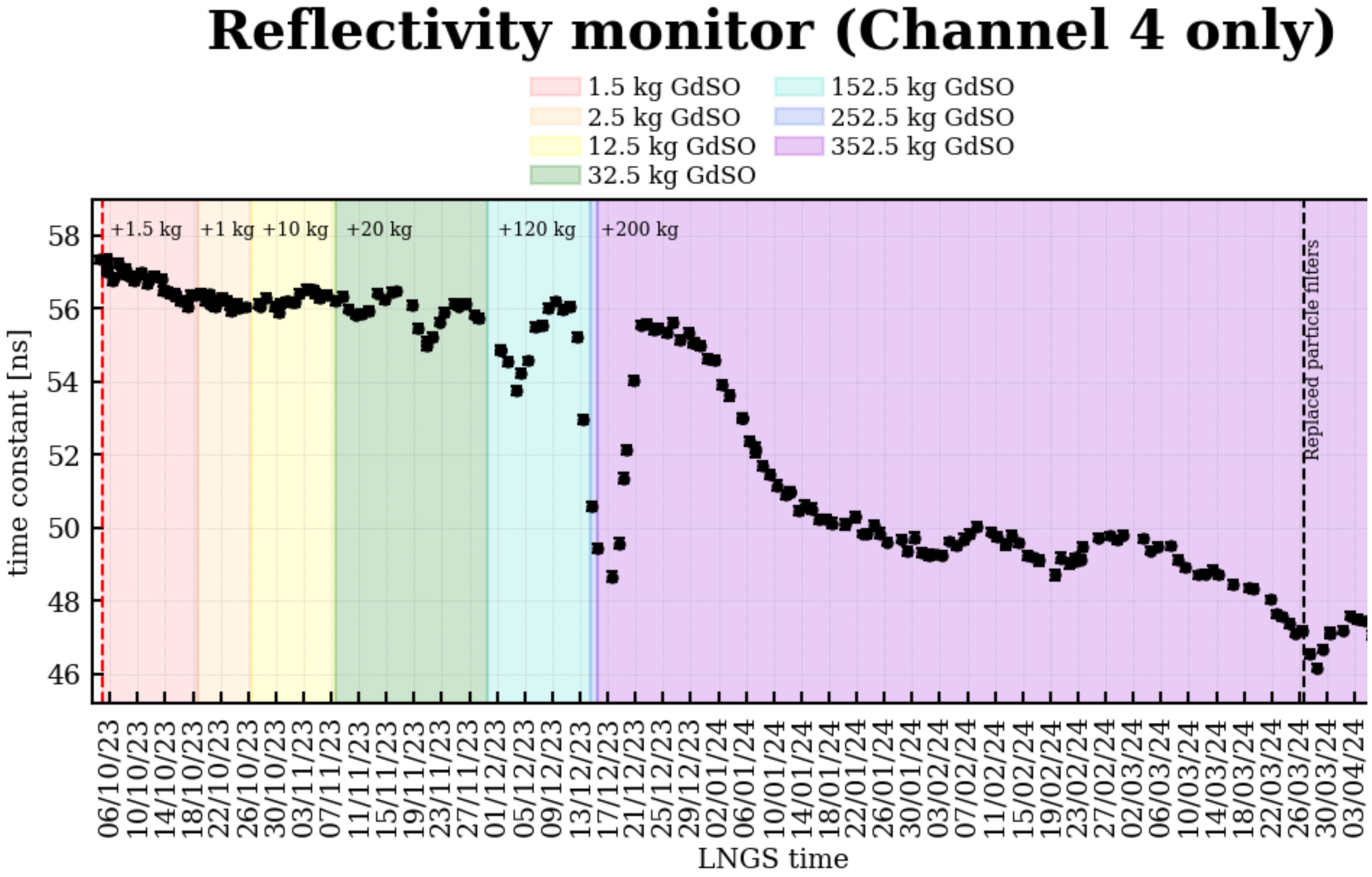

As expected, we observe a reduction in the water transparency with GdSO, by -15%.

(Next) nVeto 3rd phase with high-conc Gd-water

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To further improve the neutron veto performances, we doped water with Gd-Sulphate-Octahydrate salt, at 0.2% concentration of Gd in mass (3.5 t of GdSO).

	Neutron capture cross section	Gamma Energy	Mean capture time
H	0.33 b	Single, 2.2 MeV	200 us
Gd	49000 b	3-4 gammas, 8 MeV in total	30 us

Monte Carlo prediction for neutron tagging efficiency with Gd: **85%**

-> Reducing the neutron background by a factor **3** with respect to Science Run 0.

A novel purification plant for Gd-Water is needed, developed with technology from the EGADS project.

L. Marti et al., NIMA 959, 163549 (2020)