



# The XENONnT Neutron Veto

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Design

Construction

Performance



Dark Matter

The XENON Dark Matter Experiment

The Neutron Veto

Topics

1

2

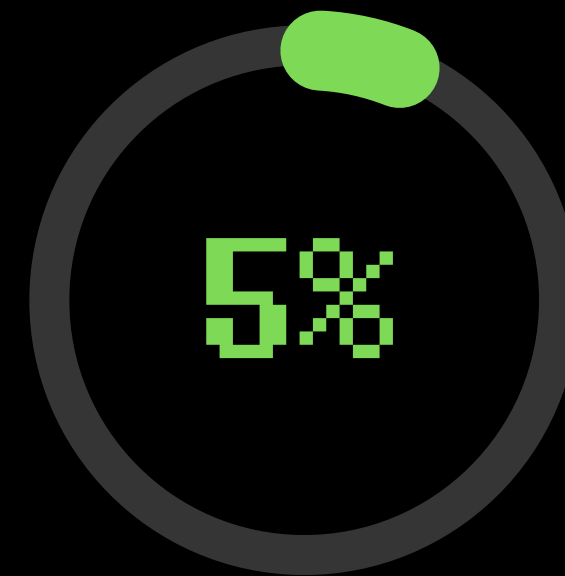
3



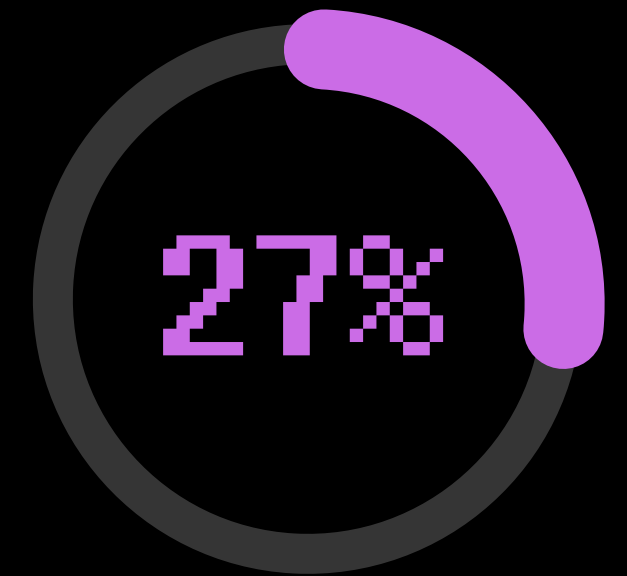
# Dark Matter



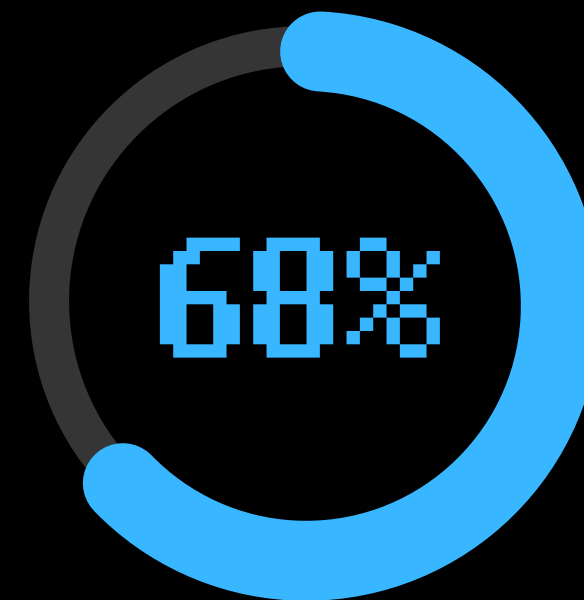
Ordinary (baryonic) matter



Dark Matter



Dark Energy



# Dark Matter

## Evidences

Astronomical and Cosmological

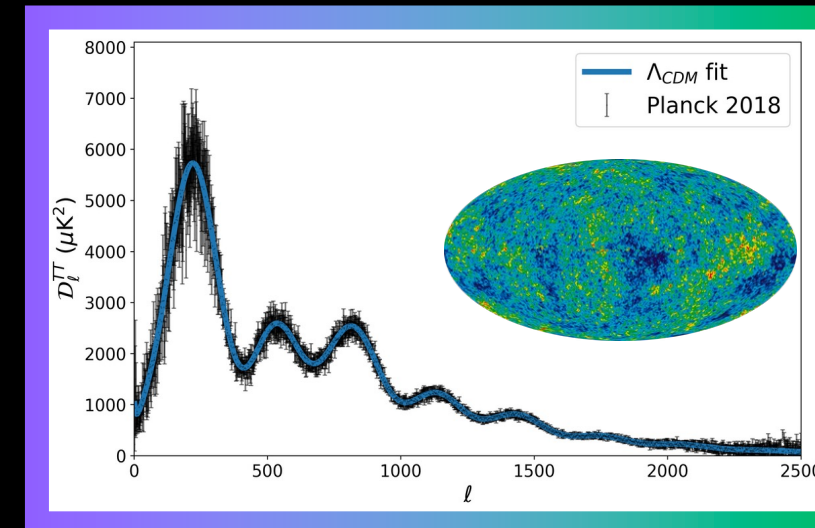
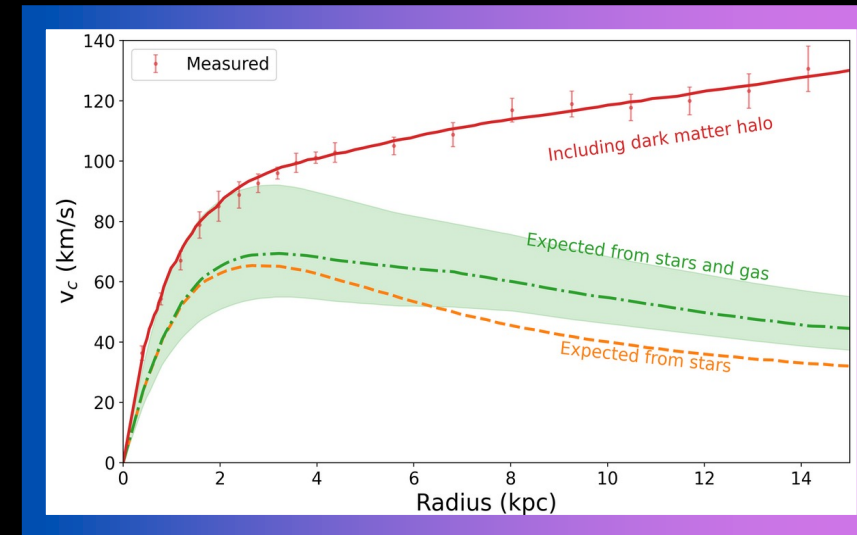
Galactic Rotation Curve

Large Scale Structure

Cosmic Microwave Background

Gravitational Lensing

Bullet Cluster



## Candidates

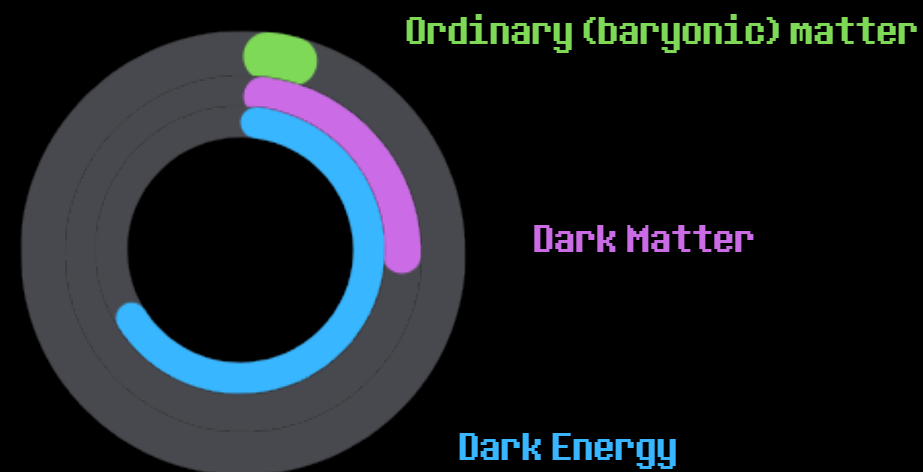
Sterile Neutrinos

Axions

Weakly Interacting Massive Particles (WIMPs)

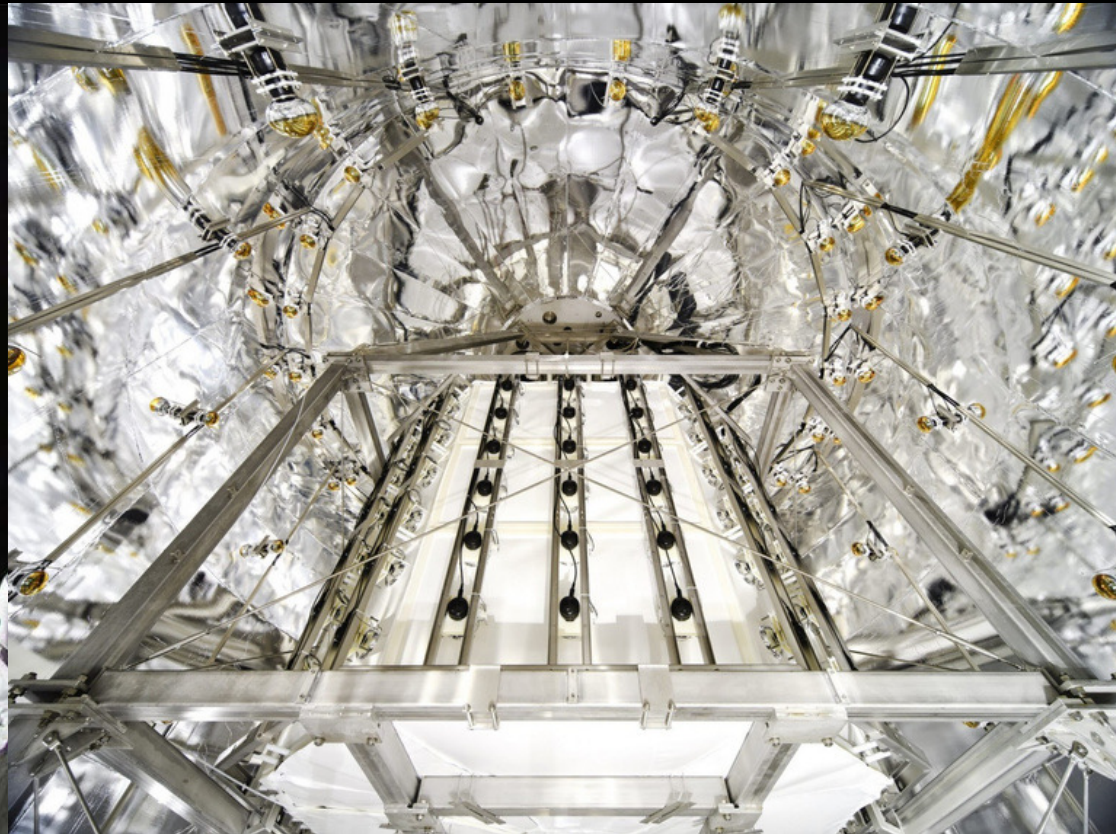
Light Dark Matter (SubGeV DM)

Dark Photon





Indirect Detection

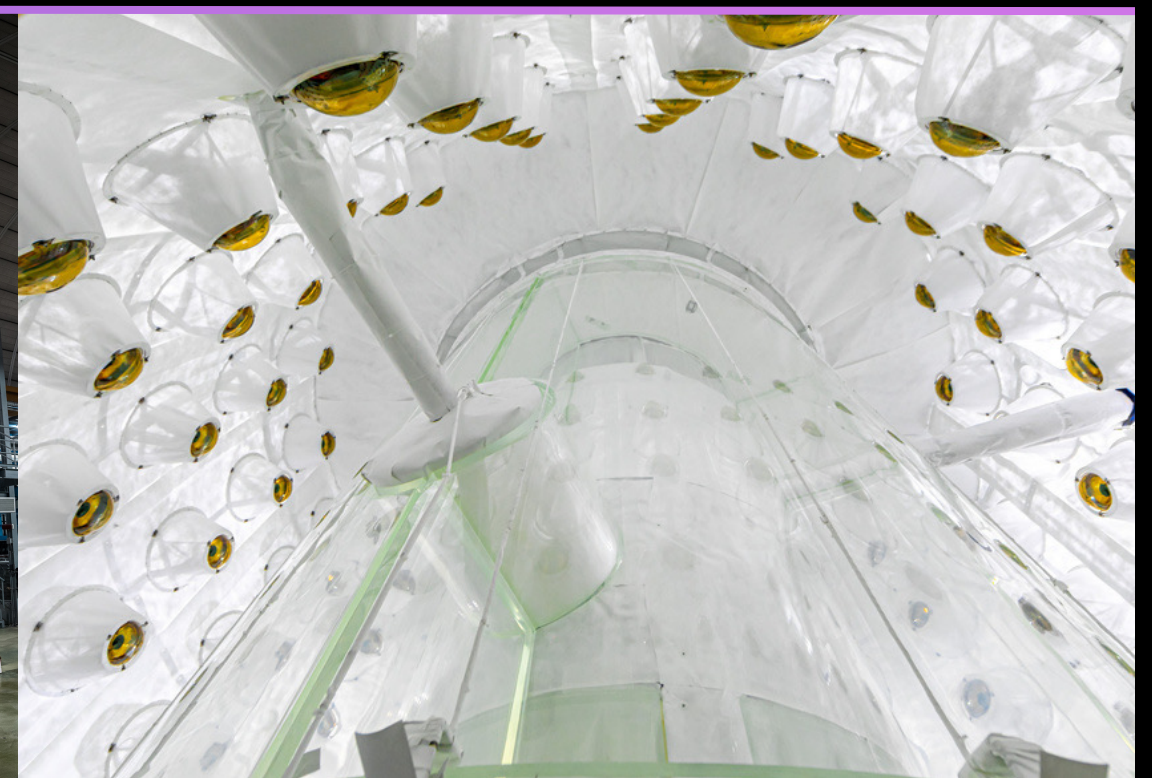


Direct Detection



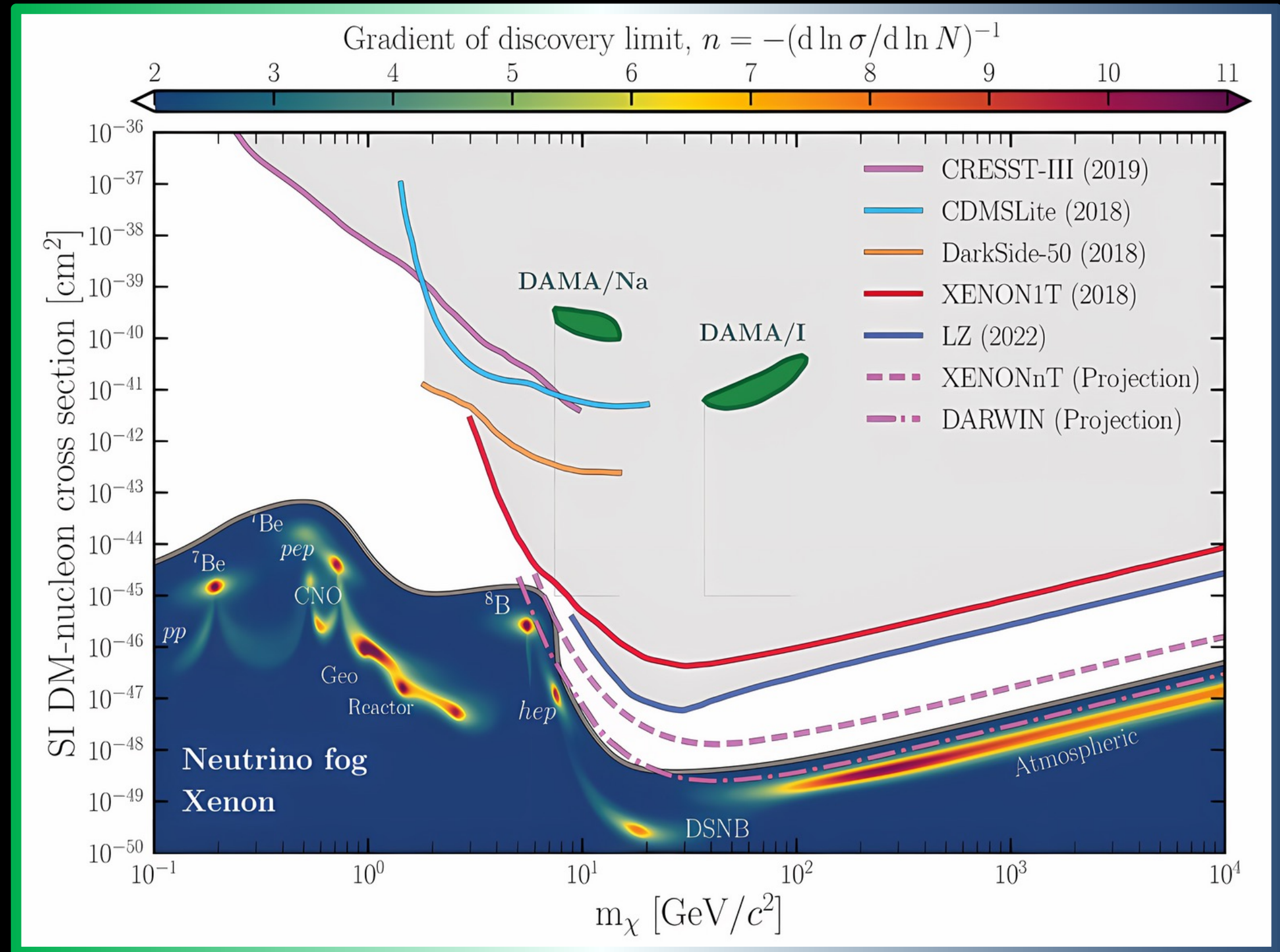
Production at collider

# Detection techniques



# Direct Detection

- XENONnT
- Darwin / XLZD
- LZ
- DarkSide-50
- DarkSide-20k
- DAMA
- XENON1T
- PandaX-4T
- CRESST
- DEAP-3600
- SuperCDMS
- NEWS







# XENON

**Enlightening the Dark**



# The Collaboration

About 200 scientists from over 25 institutions across the world form the international XENON collaboration, representing more than 25 different nationalities.

## Location

The XENON Dark Matter project is born with the aim of Direct Search for Dark Matter with Liquid Xenon Deep Underground at the INFN **Laboratori Nazionali del Gran Sasso, Italy.**

With its 1.4 km of rock, the mountain provides a reduction of the cosmic ray flux of a factor  $10^6$

# The XENON Project



# The history **so far**

**XENON10**  
**2006**



14 kg Xe target  
 $\sim 10^{-45} \text{ cm}^2$   
2M background ER/(keV t y)

**XENON100**  
**2008**



62 kg Xe target  
 $\sim 10^{-45} \text{ cm}^2$   
1800 background ER/(keV t y)

**XENON1T**  
**2016**



2 t Xe target  
 $4 \times 10^{-47} \text{ cm}^2$   
82 background ER/(keV t y)

# The history **so far**

**XENONnT**  
2020

8.5 t Xe target  
 $1.4 \times 10^{-48} \text{ cm}^2$  \*  
16.1 background ER/(keV t y)

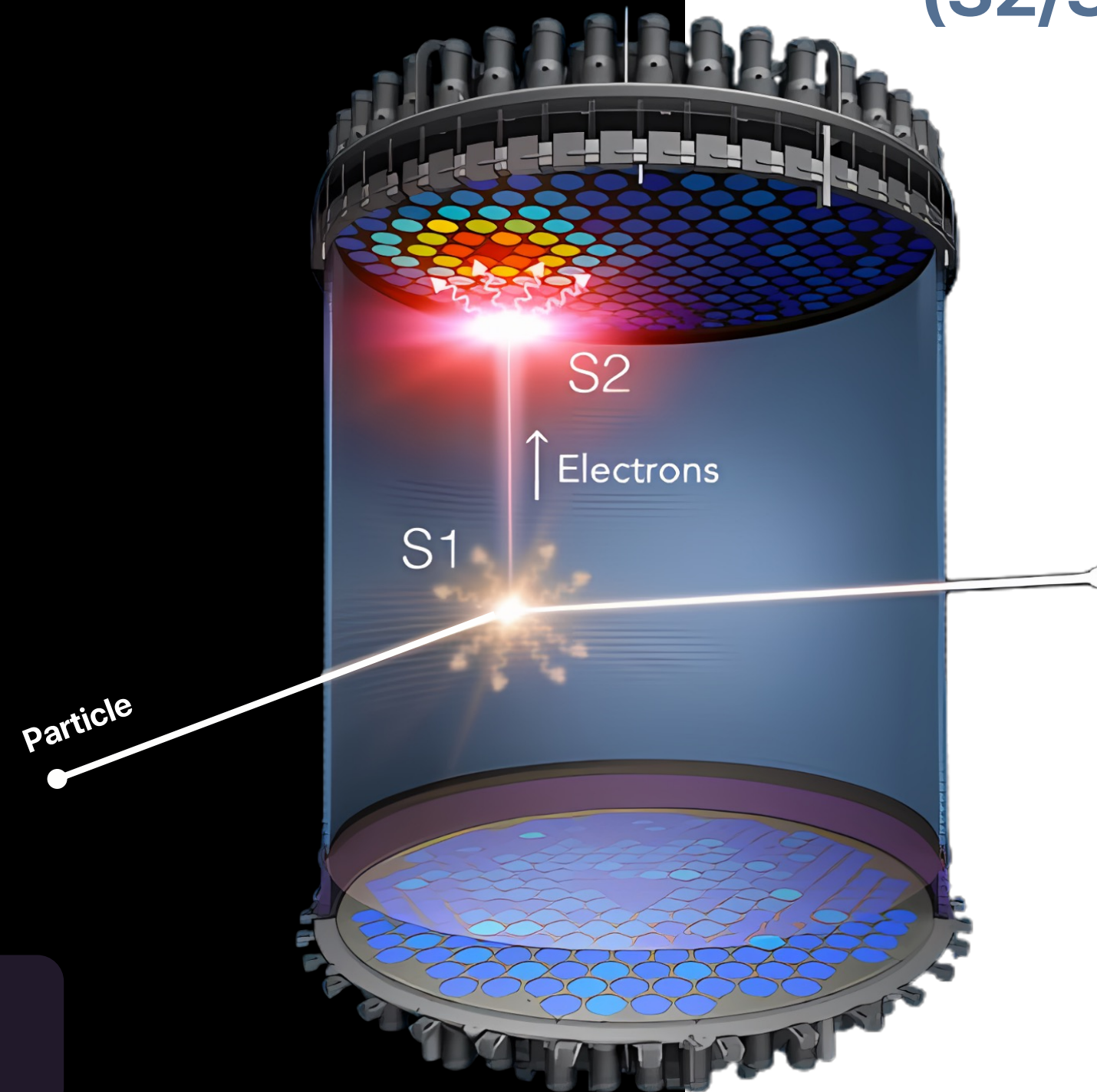
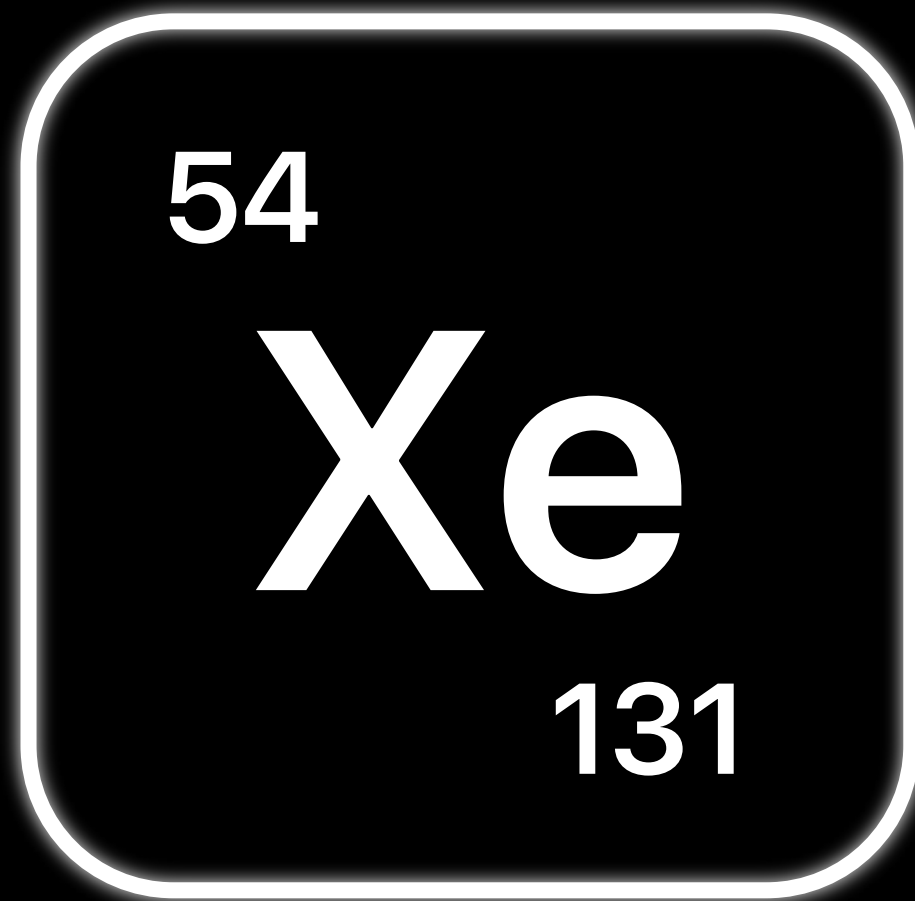


**Darwin/XLZD**  
Future



\*(projected for 20 t y exposure)

# Dual Phase TPC Detection Principle



Interaction

$$(S2/S1)_{ER} > (S2/S1)_{NR}$$

High density provides excellent  
**Self-shielding**  
d=2.96 g/cm<sup>3</sup>

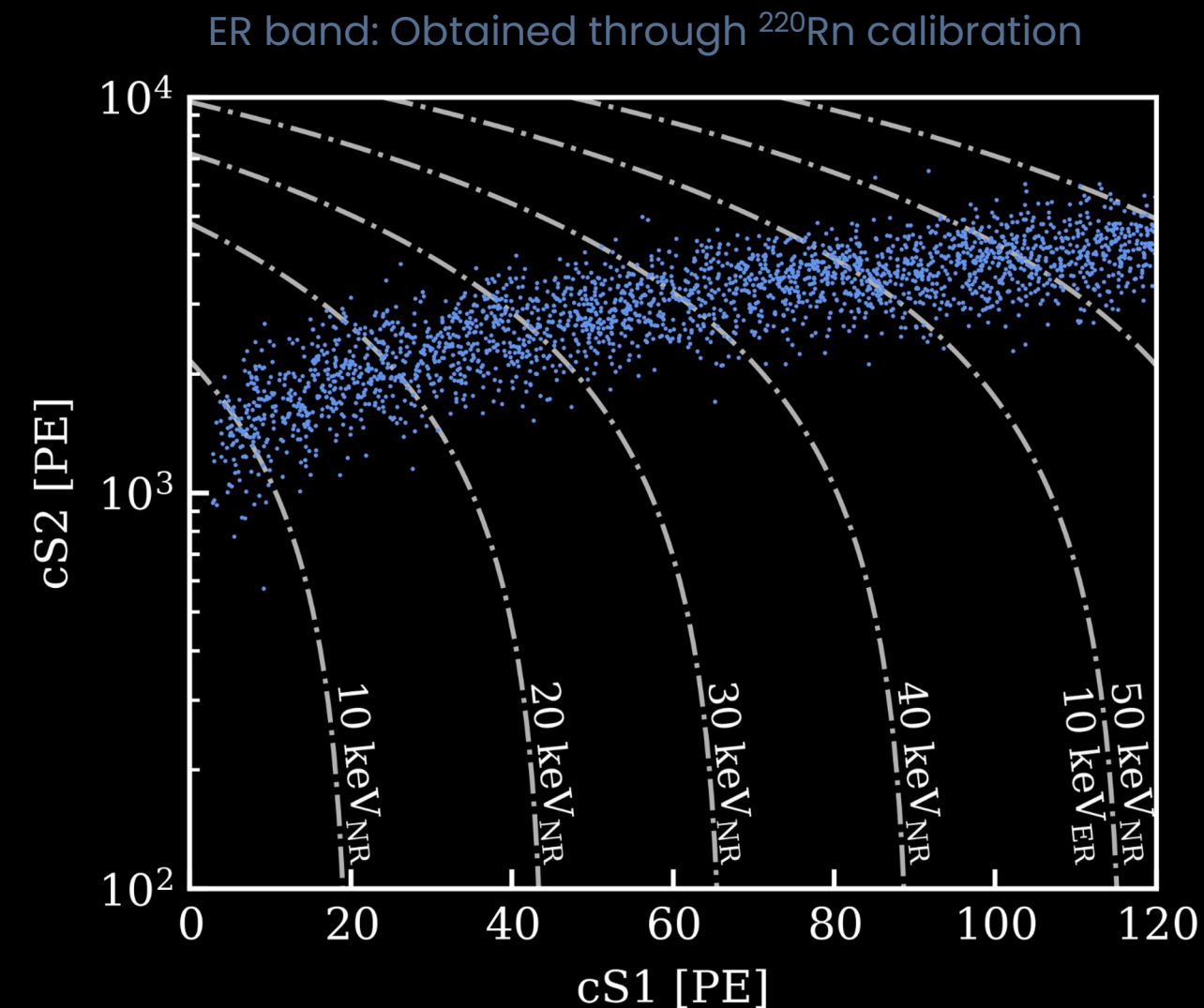
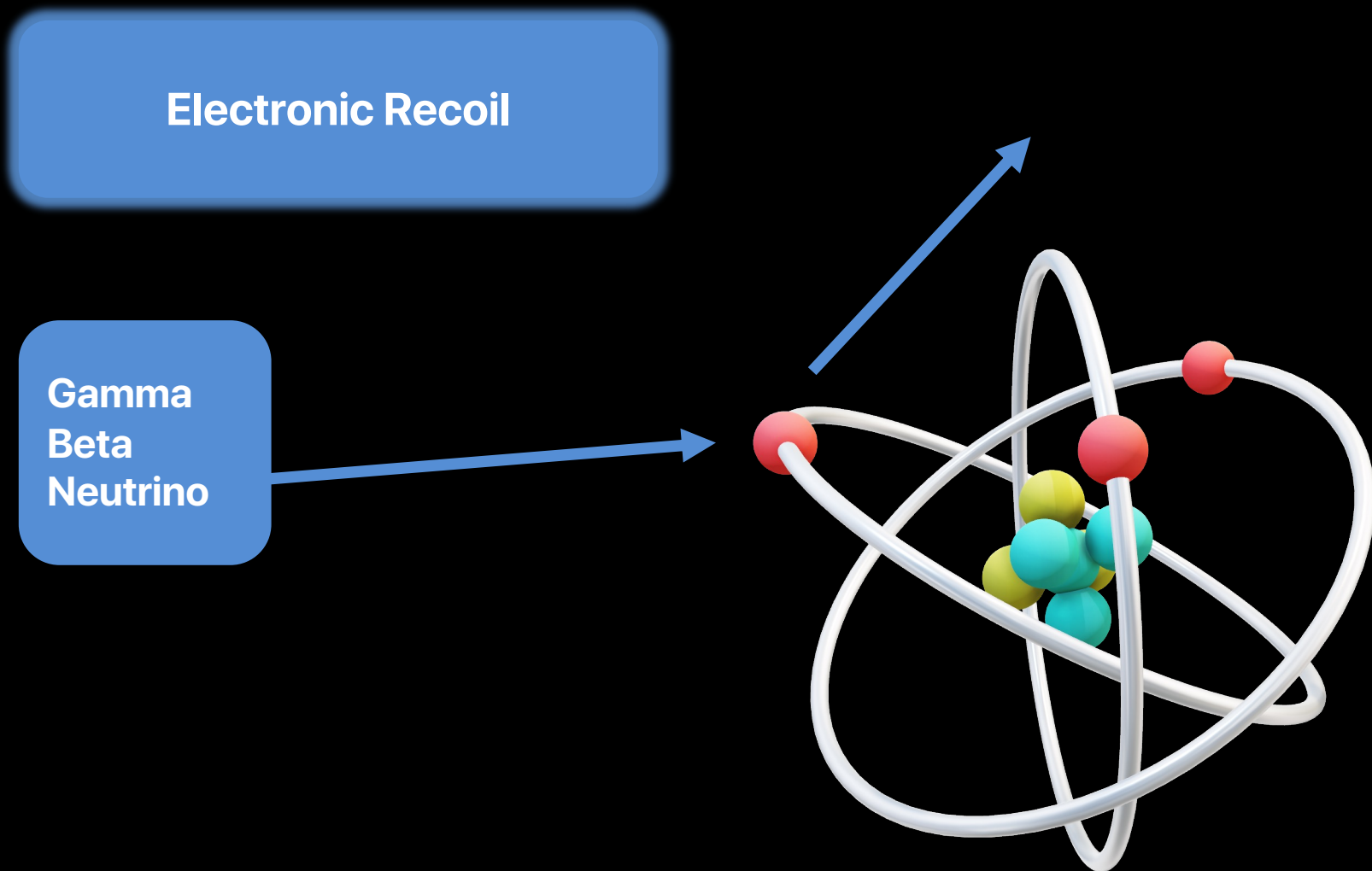
High atomic number enhance  
**Spin independent**

LXe can be liquefied at T = 161 K  
**Compact detectors**  
designs

Non-zero spin isotopes  
**Spin dependent**

- Energy Reconstruction
- 3D Event Reconstruction
- Volume fiducialization

# Dual Phase TPC Detection Principle



## Backgrounds:

**Radon** : Due to its 3.8 d half-life, the emanation of  $^{222}\text{Rn}$  from detector materials results in a distribution of  $^{222}\text{Rn}$  and its decay products within the whole LXe volume. **This is the largest contribution in the energy ROI**

**Krypton** : The xenon target contains natural krypton and therefore traces of the radioactive isotope  $^{85}\text{Kr}$ . Its contribution depends on the  $^{\text{nat}}\text{Kr}$  concentration and is estimated to be **a factor 5 lower than Radon.**

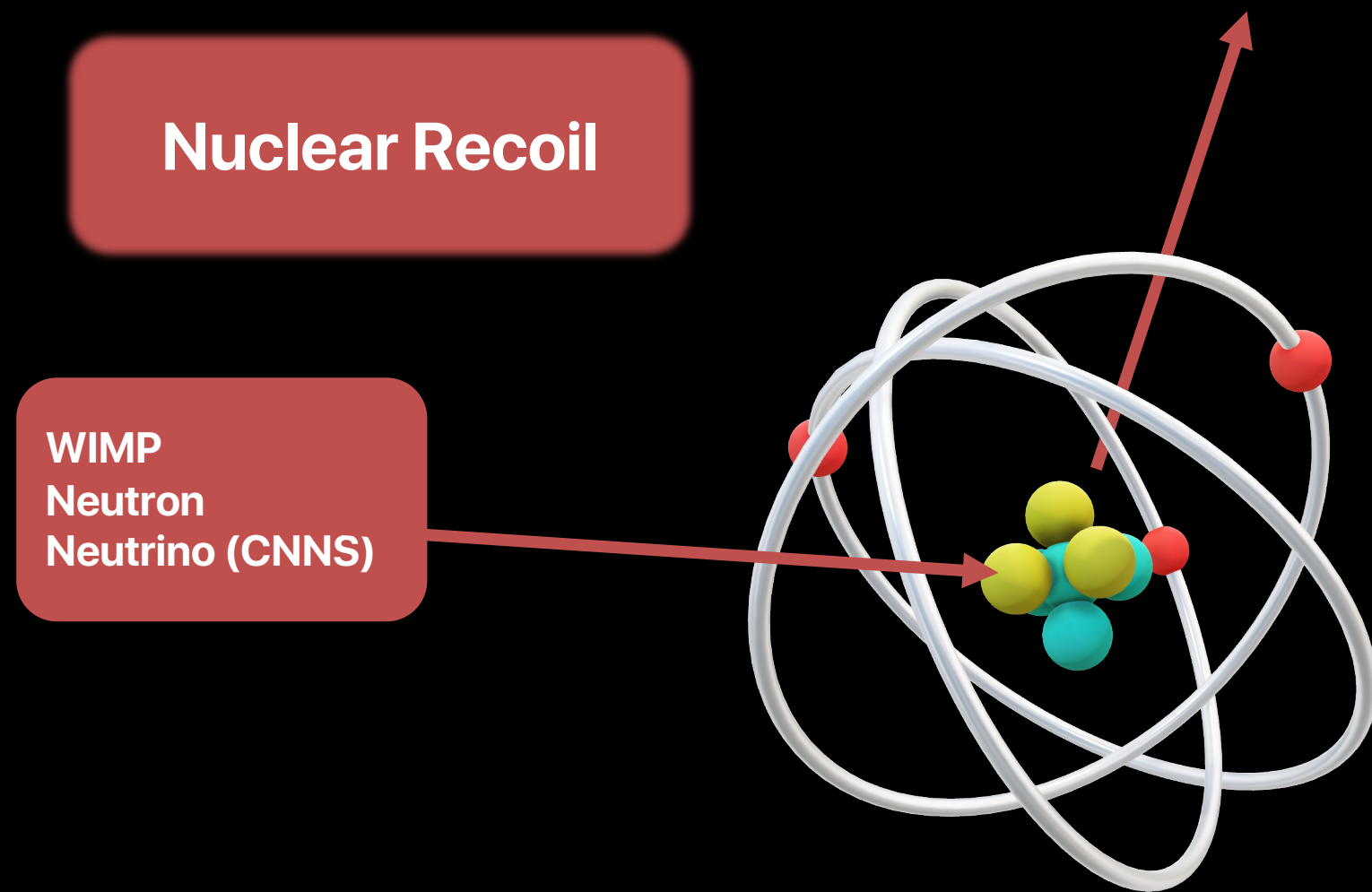
**Xenon** : Unstable xenon isotopes are distributed uniformly within the target volume.

**Solar neutrinos** : Solar neutrinos can elastically scatter off atomic electrons of the LXe target yielding low-energy ER signals. **It is the second largest source of ER background in XENONnT**

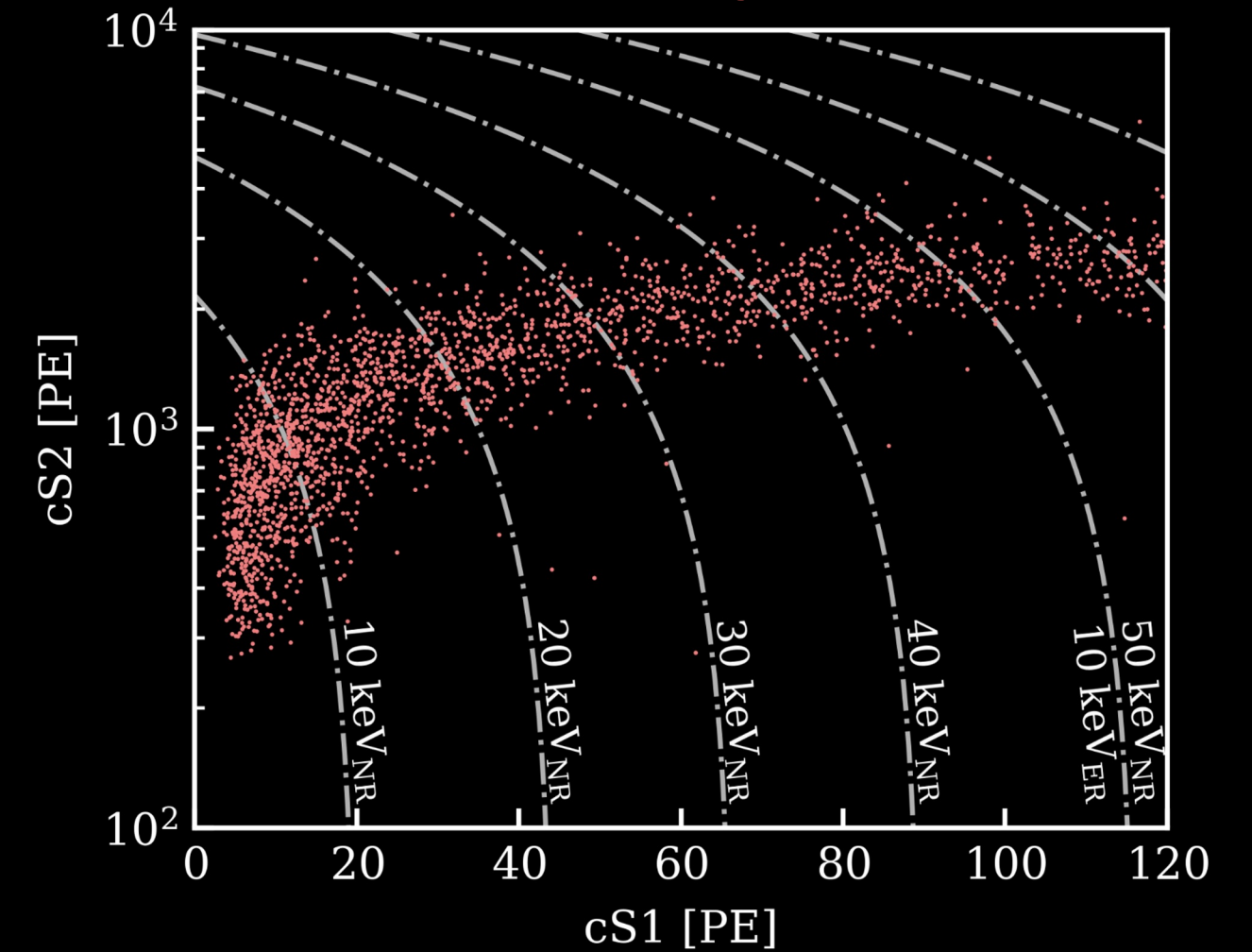
Source	Rate $[(\text{ty})^{-1}]^*$
Detector Radioactivity	$25 \pm 3$
$^{222}\text{Rn}$	$55 \pm 6$
$^{85}\text{Kr}$	$13 \pm 1$
$^{136}\text{Xe}$	$16 \pm 2$
$^{124}\text{Xe}$	$4 \pm 1$
Solar neutrinos	$34 \pm 1$
Total	$148 \pm 7$

\*MC predictions from [arxiv.org/2007.08796](https://arxiv.org/2007.08796)

# Dual Phase TPC Detection Principle



NR band: Obtained through AmBe calibration



## Backgrounds:

**Radiogenic Neutrons** : Radiogenic neutrons are produced through spontaneous fission (SF) or  $(\alpha, n)$  reactions in detector materials. Largest contribution even after being reduced with a novel Neutron Veto.

**Cosmogenic Neutrons** : Neutrons induced by cosmic muons interacting in the rock and concrete surrounding the detector can be tagged using the active muon veto in the water tank. Negligible Contribution

**CEvNS neutrinos** : Neutrino interactions from solar, atmospheric and diffuse supernova (DSN) neutrinos contribute to the NR background through CEvNS. Solar neutrino backgrounds limit the sensitivity to WIMPs with masses of a few  $\text{GeV}/c^2$ . In contrast, the NR spectra induced by atmospheric and DSN neutrinos affect the sensitivity to heavier WIMPs.

Source	Rate $[(\text{ty})^{-1}]^*$
Neutrons	$(4.1 \pm 2.1) \times 10^{-2}$
CEvNS (solar $\nu$ )	$(6.3 \pm 0.3) \times 10^{-3}$
CEvNS (atm + dsn $\nu$ )	$(5.4 \pm 1.1) \times 10^{-2}$
Total	$(1 \pm 0.2) \times 10^{-1}$

\*MC predictions from [arxiv.org/2007.08796](https://arxiv.org/2007.08796)

# XENON infrastructure

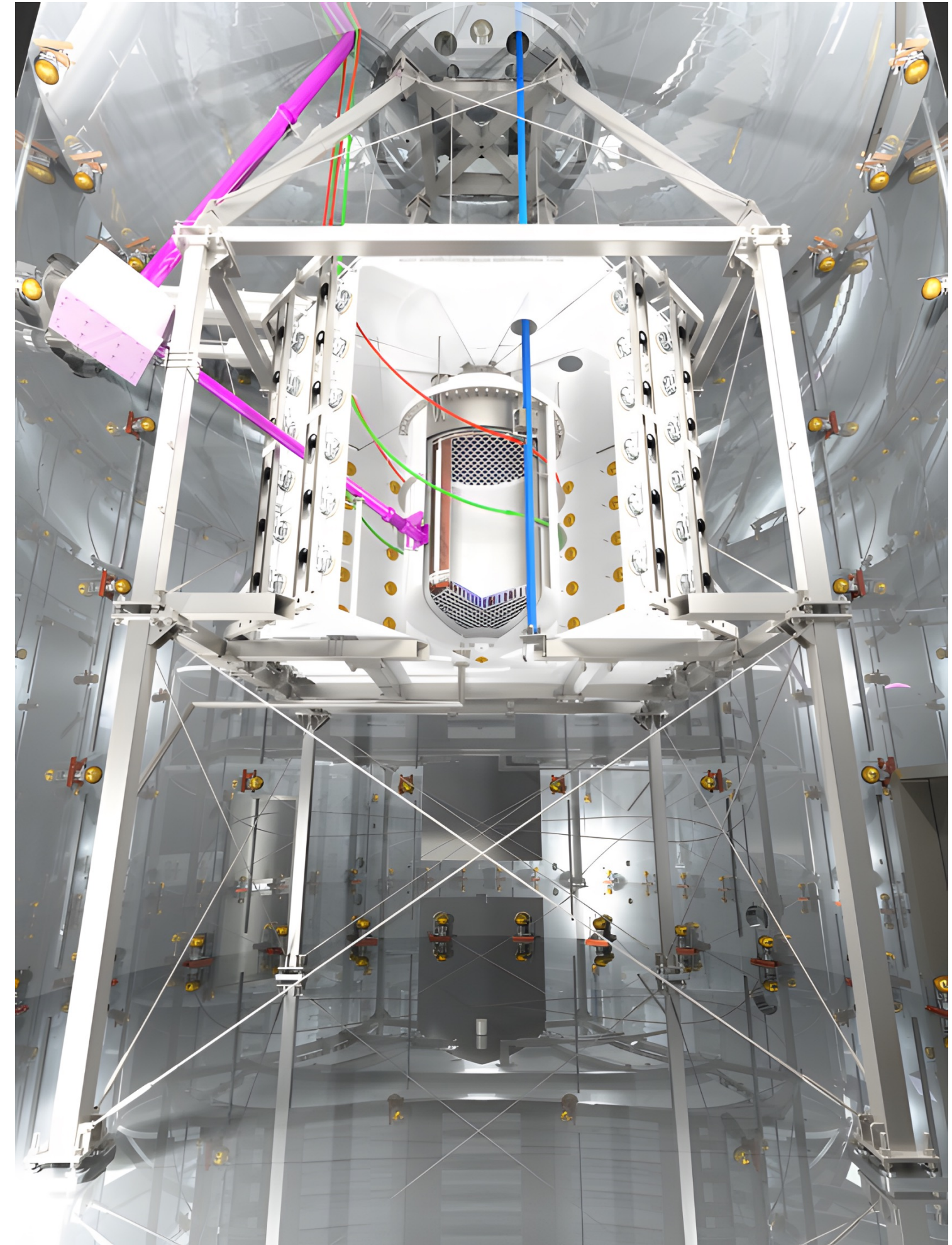
The experiment's infrastructure can be split into a **service building** that hosts almost all of the xenon handling systems, and a **water tank** that contains three nested detectors: the Neutron Veto, the Muon Veto and the TPC.



## Scalability

The entire infrastructure was designed with XENONIT with the idea that an upgrade (XENONnT) could be easily implemented, utilizing as much of the existing setup as possible.

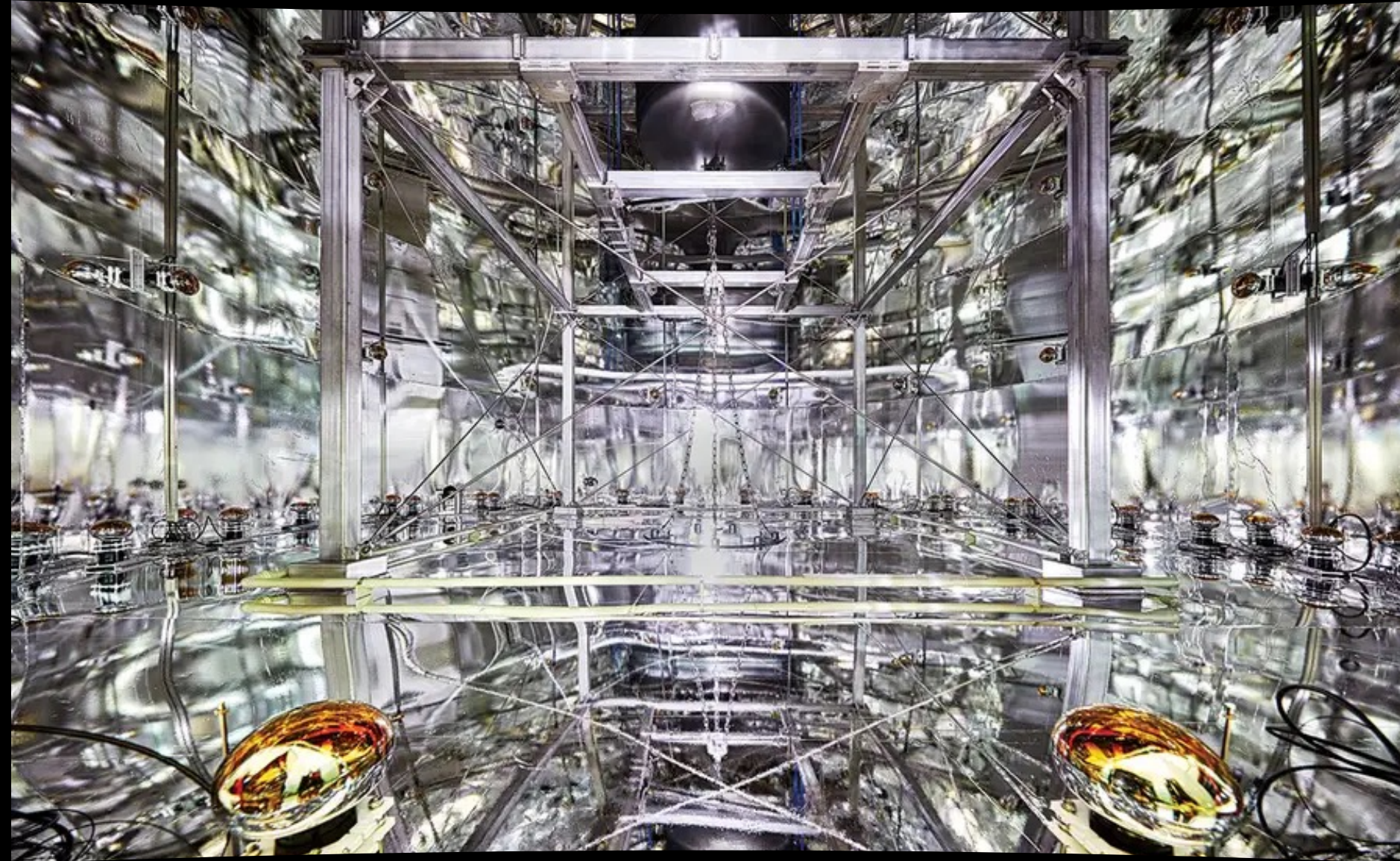
## The Experiment



Instrumented with 84 PMTs

Gd loaded Water Cherenkov detector

Passive Water Shield against environmental radioactivity



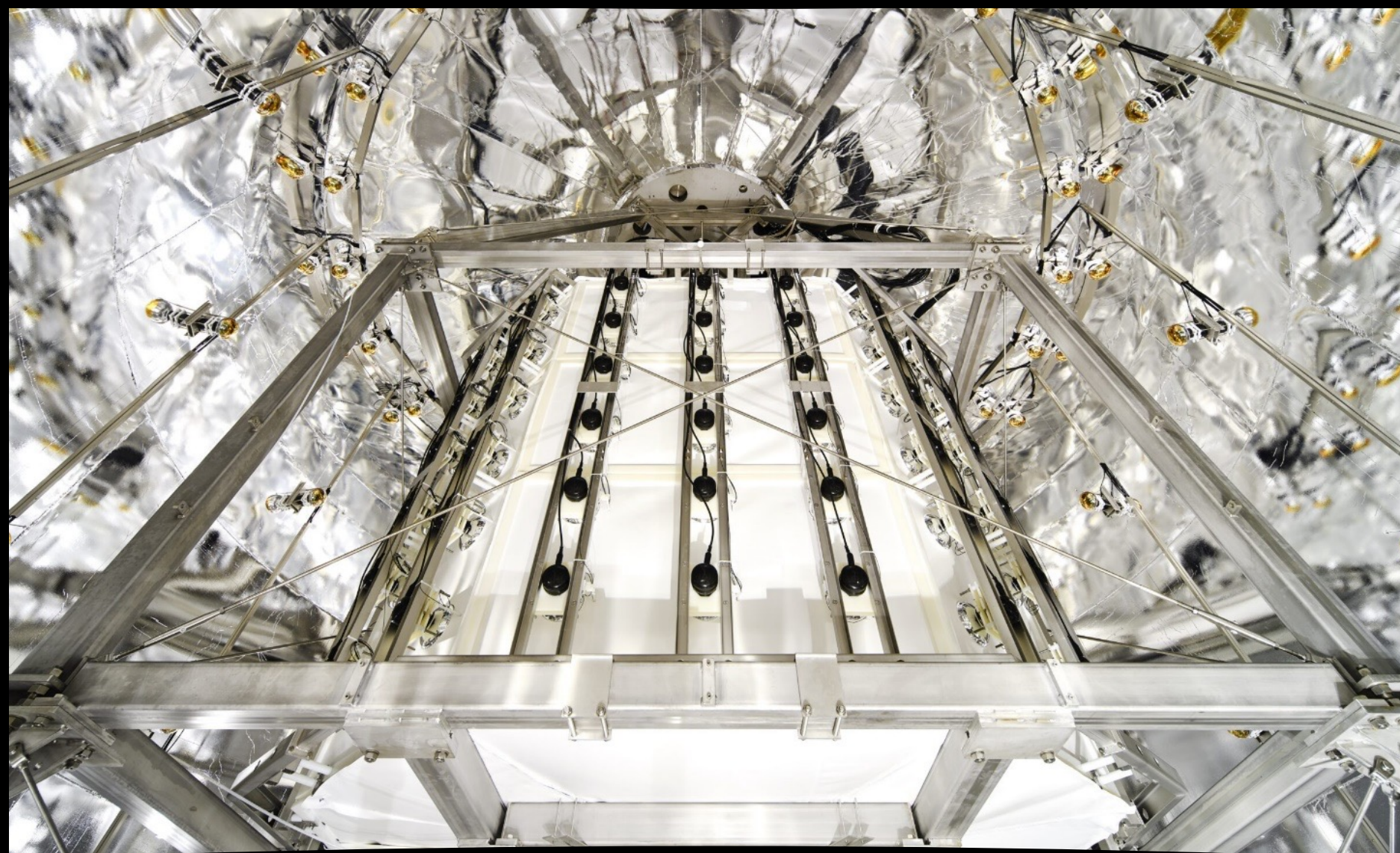
# The Muon Veto

# Main Research Topic

Instrumented with 120 PMTs



Gd loaded Water Cherenkov detector



Optically separated from the MV by high reflectivity ePTFE panels



# The Neutron Veto

Instrumented with 494 PMTs



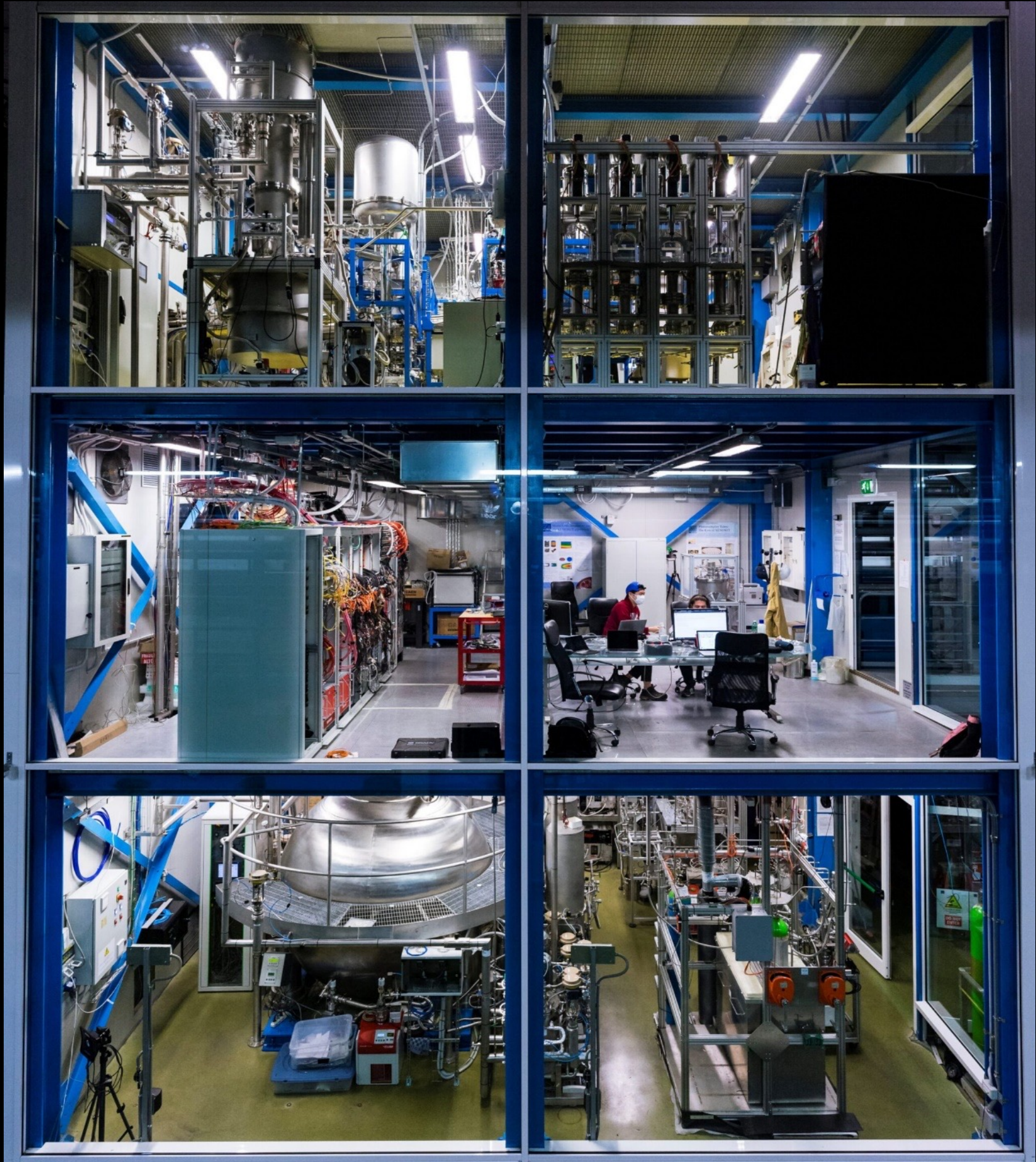
8.5 tons of Xe

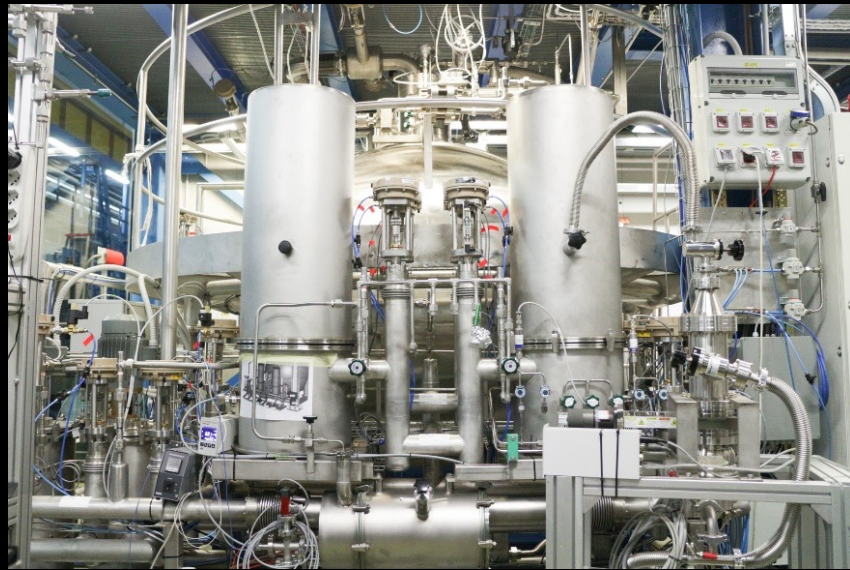


5.9 tons as active target mass

## Cryostat & TPC

# Service building





- Removing electronegative impurities
- LXePUR: Up to 16 tonne/day

Electron lifetime: ~15 ms

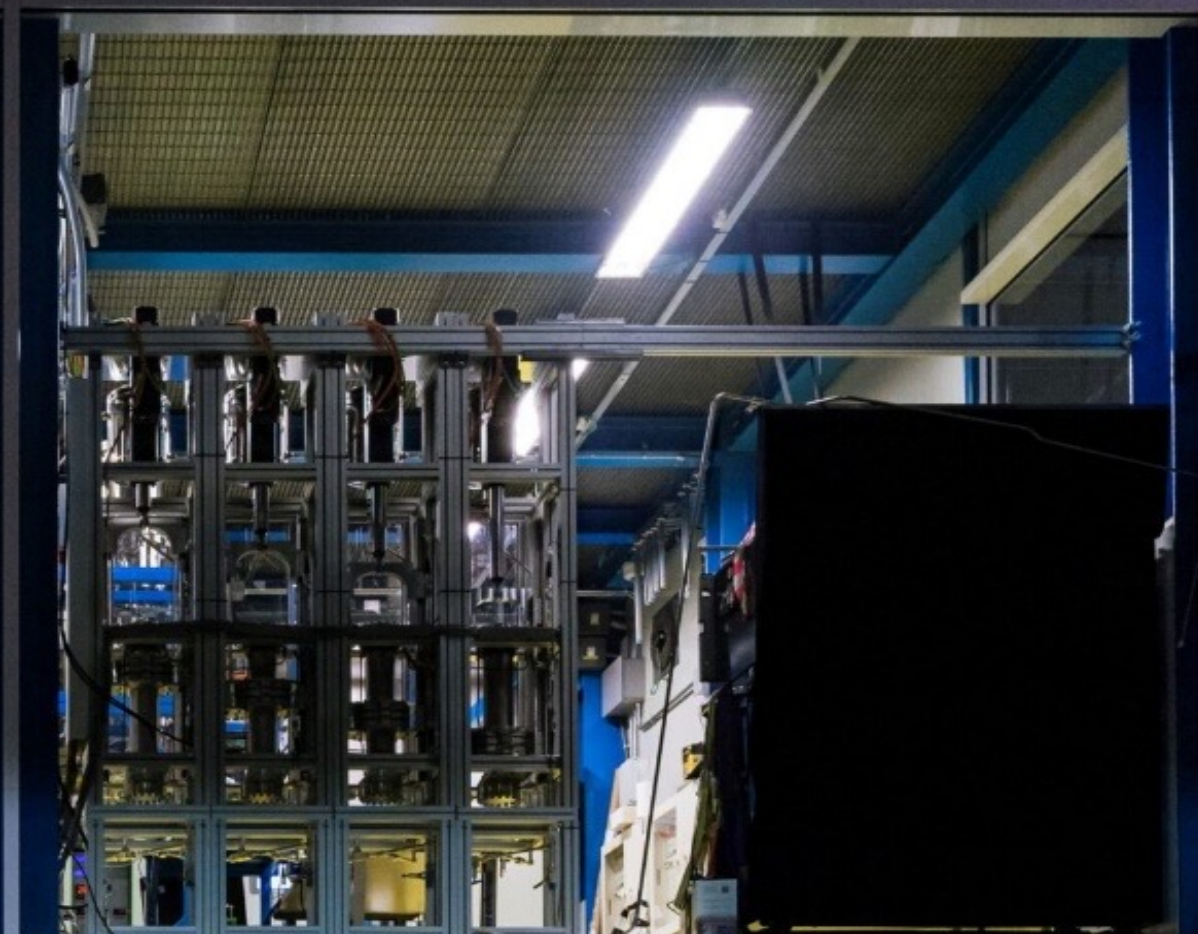


- $^{222}\text{Rn}$  (major ER background)
- Continuous distillation at 70 kg/h

$^{222}\text{Rn}$  suppressed to  $\sim 0.8 \mu\text{Bq/kg}$

## Service building Lv 2

LXe purification system



Radon removal system



- Triggerless Data Acquisition
- All data above per-channel threshold stored long term
- Open-source & faster processing Software
- Advanced computing structure
  
- Distributed SCADA system
- Real-time monitoring and control of all the experiment

## Service building Lv1

Slow Control



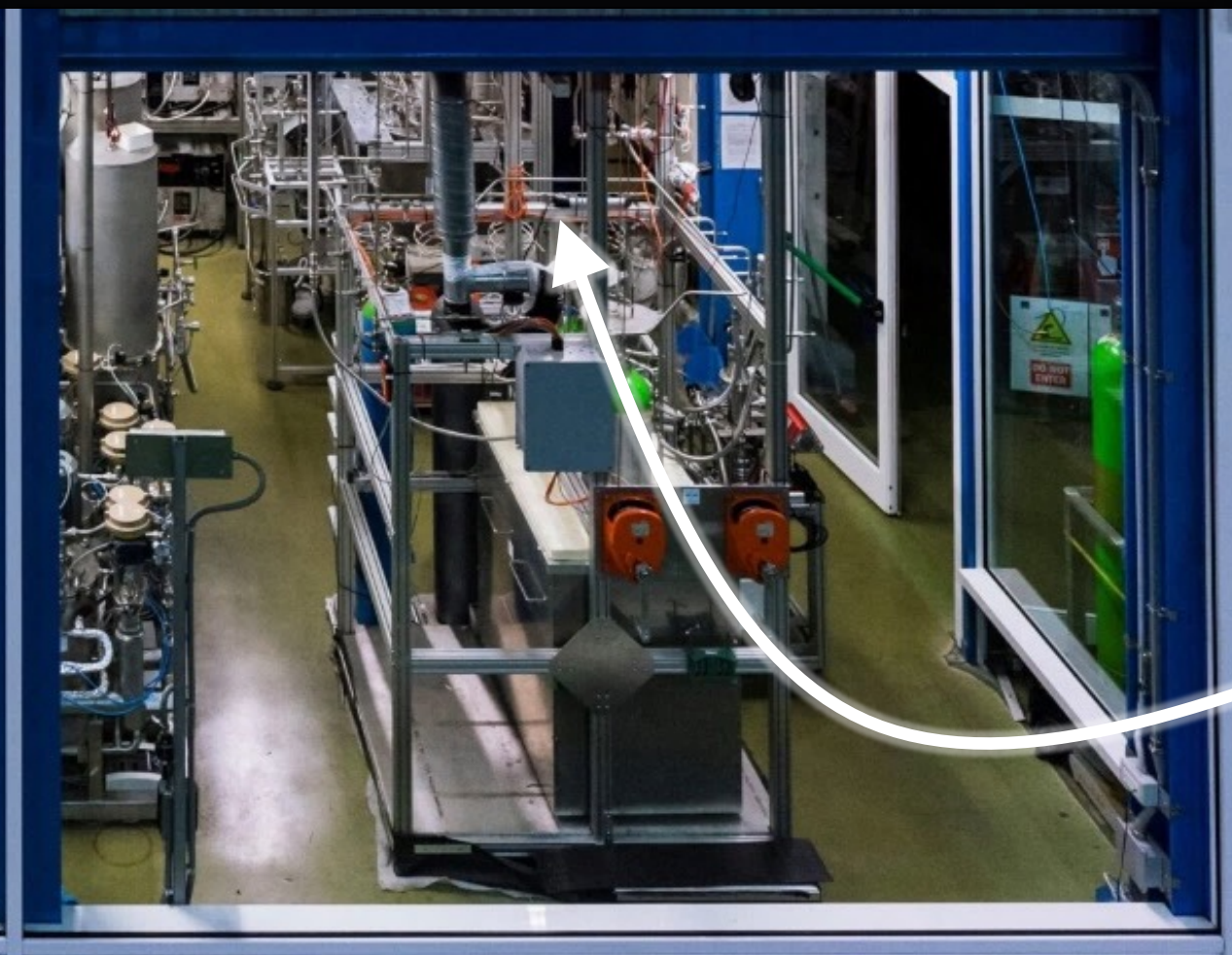
DAQ

- Cryogenic storage and recovery system for LXe
- Can keep up to 8 tons (we have ReStoX 2).

- $^{85}\text{Kr}$  removed by cryogenic distillation

ReStoX

Service building Lv0



Kr removal system



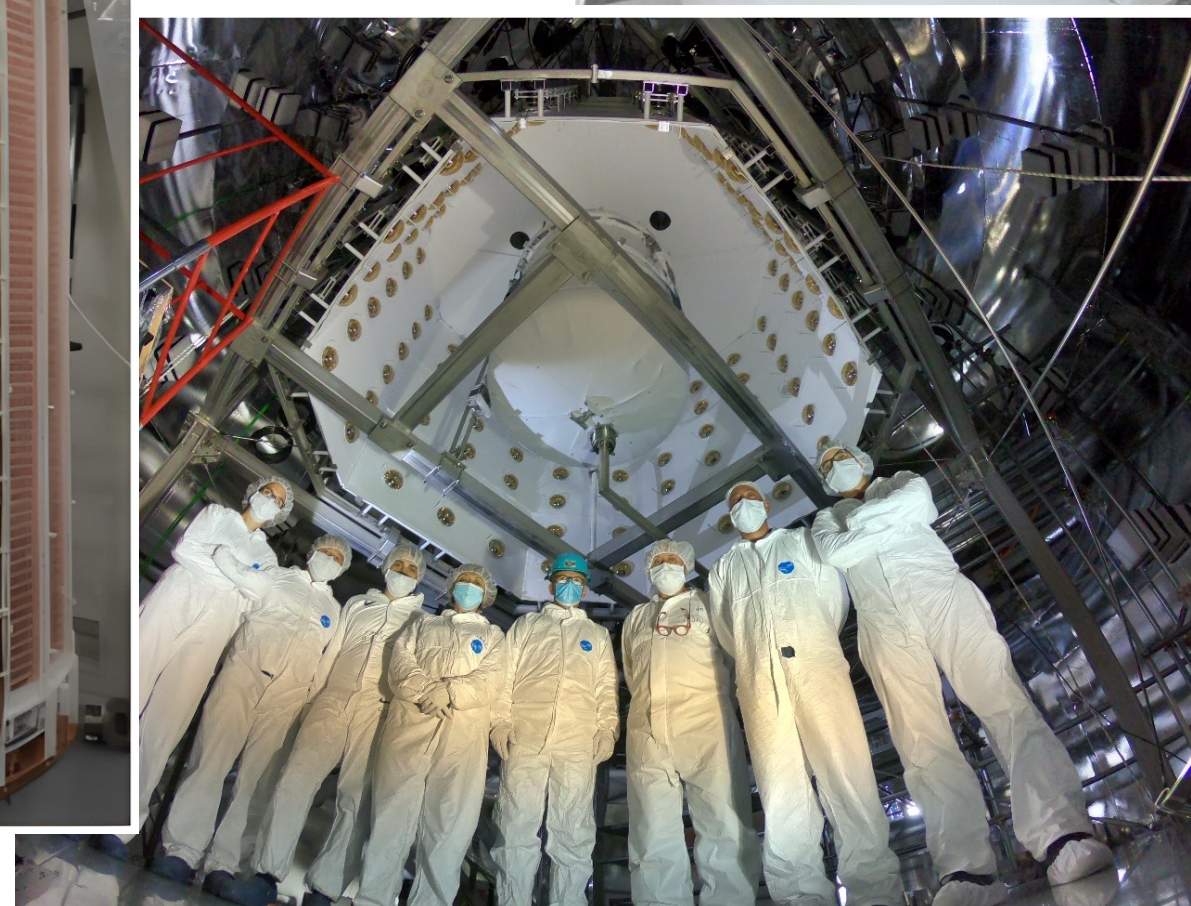
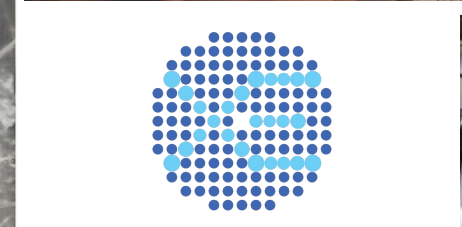
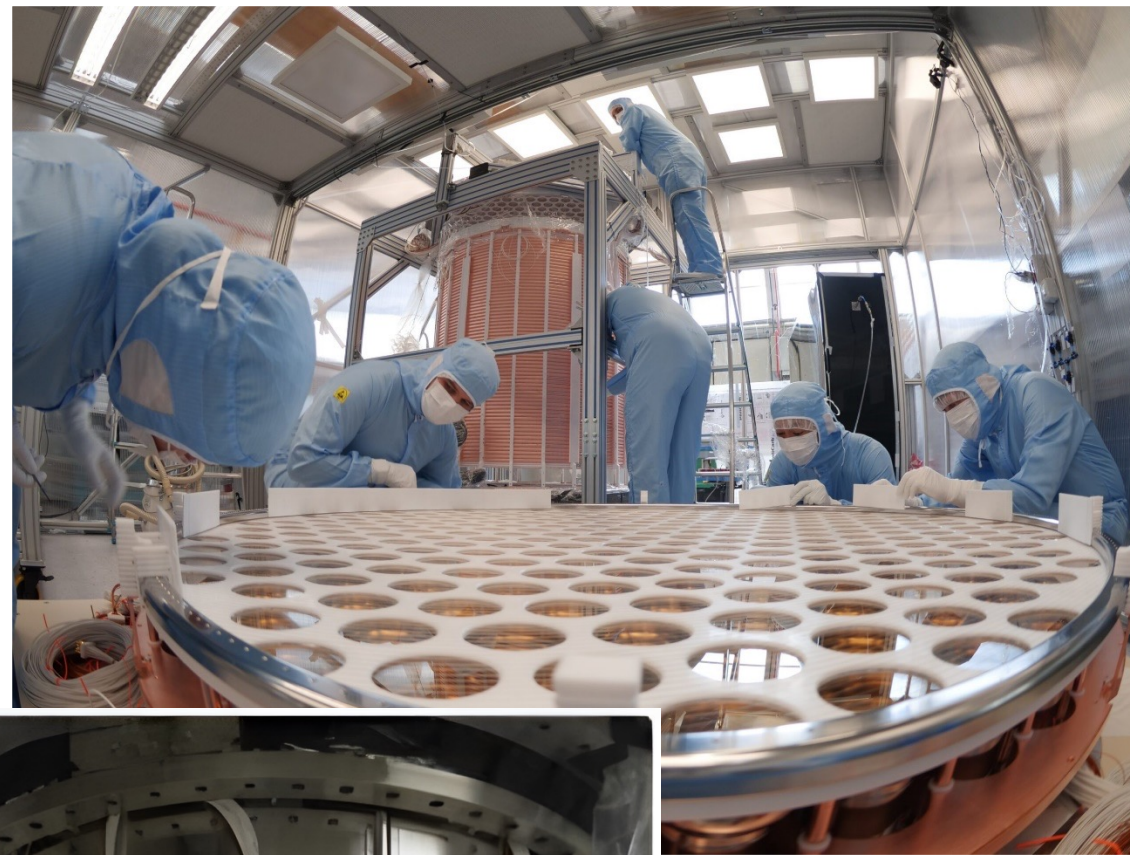
# Construction 2020

## Commissioning

## Science Run



# Timeline



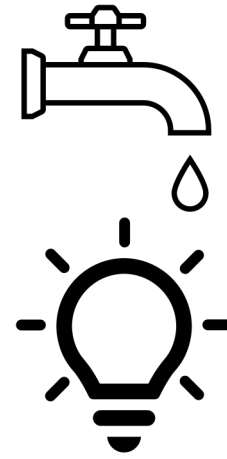
# Construction

# Commissioning 2021

# Science Run



# Timeline



- Filling of the Water Tank
- Setup and configuration of optical calibration devices
- Preliminary detector calibrations
- Tuning of PMT parameters
- Detector stability



Short circuit between the cathode and the bottom screening mesh

- Cathode HV: -2.75 kV
- Gate HV: 0.3 kV - Anode HV: 4.9 kV
- Drift field: 23 V/cm (goal: 200 V/cm)

Lower extraction efficiency  
Lower SE gain



Construction

Commissioning

Science Run

2022

Science Run 0

- Published results for
- Low ER analysis in 2022
- WIMP analysis in 2023

Search for Dark Matter

First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment

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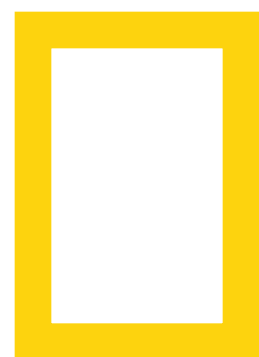
2024  
Science Run 2

Ongoing  
NV – Gd Phase

2023

Science Run 1

After a few refurbishments and optimizations. Completed in August 2023.



Timeline



RESEARCH  
ACTIVITY

The XENONnT

**Neutron Veto**

# The XENONnT NEUTRON VETO

Gadolinium loaded Water Cherenkov instrumented with 120 PMTs. Optically separated from the Muon Veto by means of high-reflectivity ePTFE panels.



# Why we need it

## Radiogenic Neutrons

emitted by detector materials (e.g. cryostat, PMTs, PTFE, ...) are one of the **most challenging background** for a DM direct search experiment as they can scatter off LXe ... **can scatter** off LXe atoms **in the TPC in the same way as WIMPs**

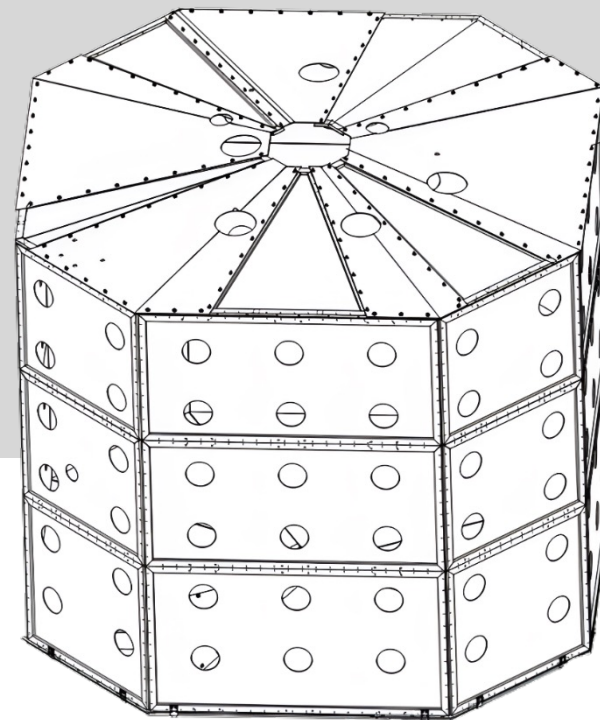
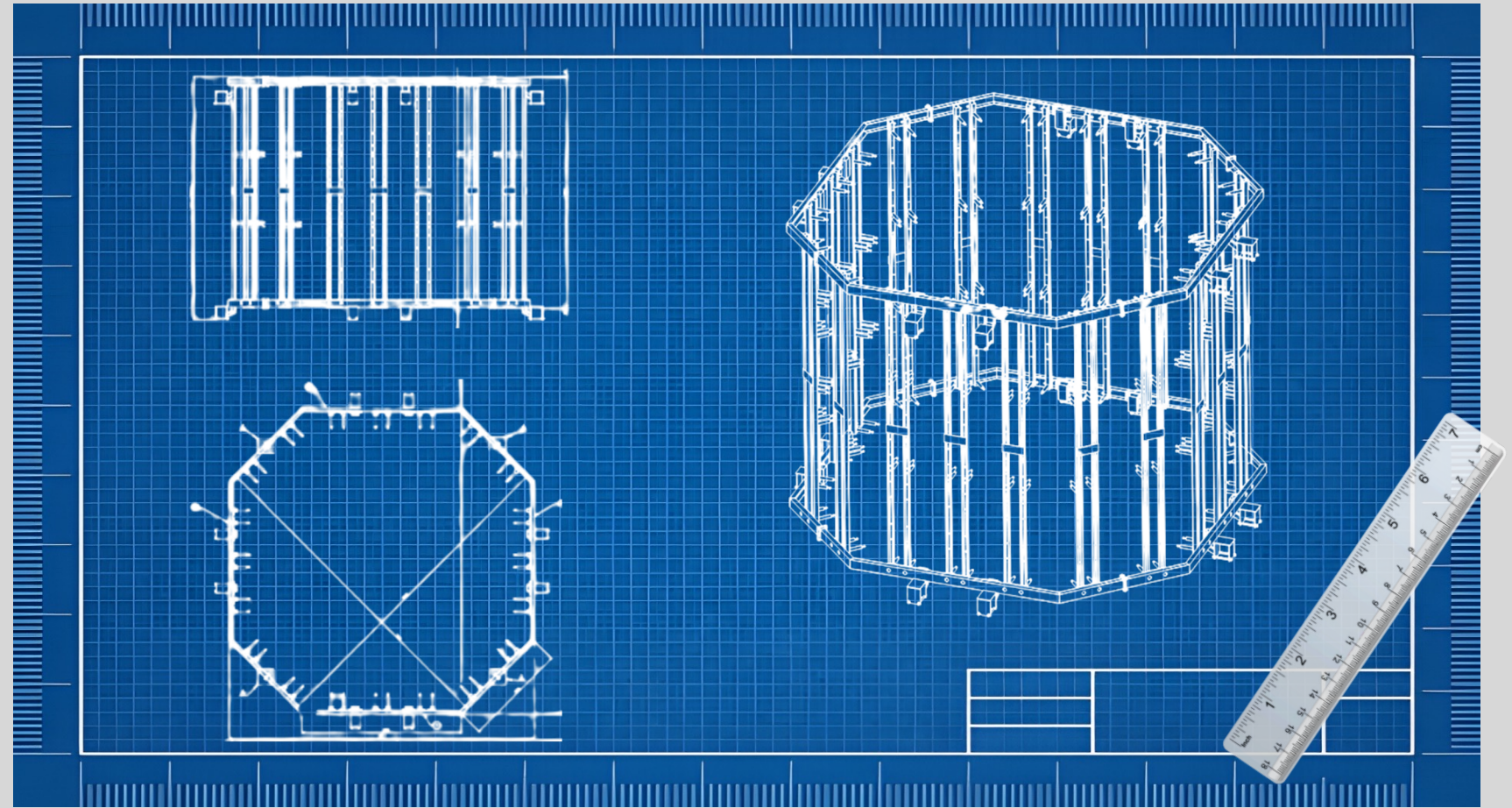
The Neutron Veto aims to **tag the neutrons** that go out from the TPC (after a single scatter interaction).

It exploits the neutron capture process on water+Gd

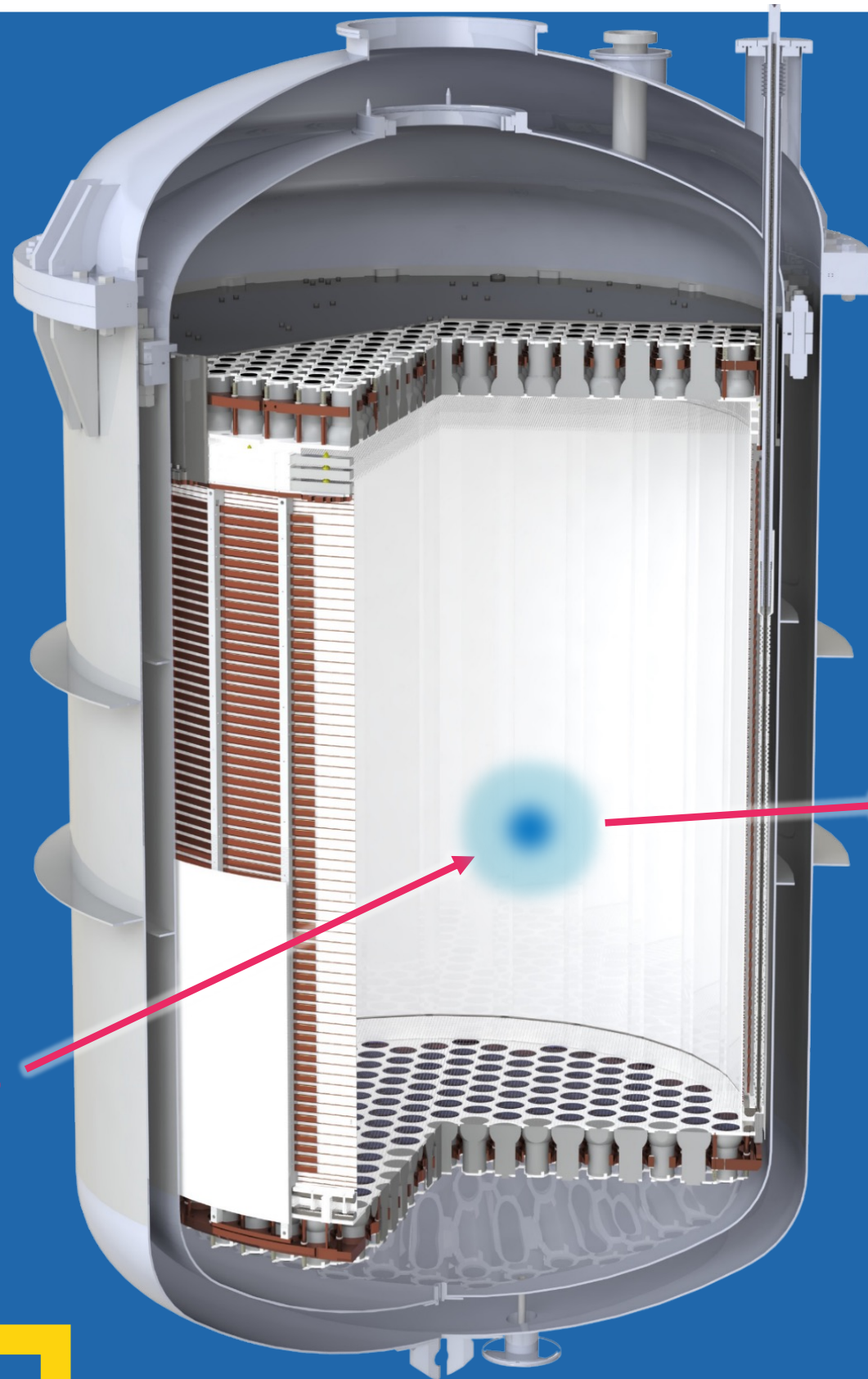


# Design

## Octagonal shaped Stainless steel Support Structure



**ePTFE reflector panels** with holes for the PMTs and for the interferences with the other detectors.



64  
**Gd**  
Gadolinium

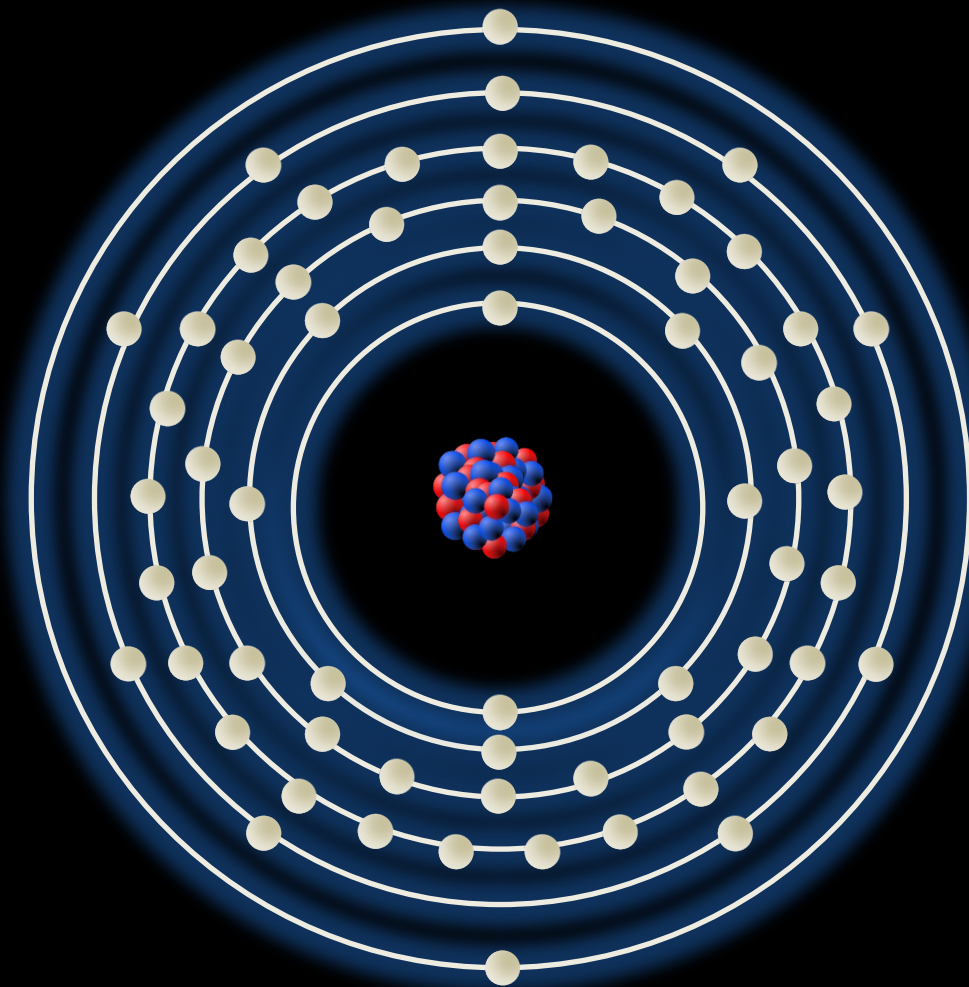
1  
**H**  
Hydrogen

# Detection Principle

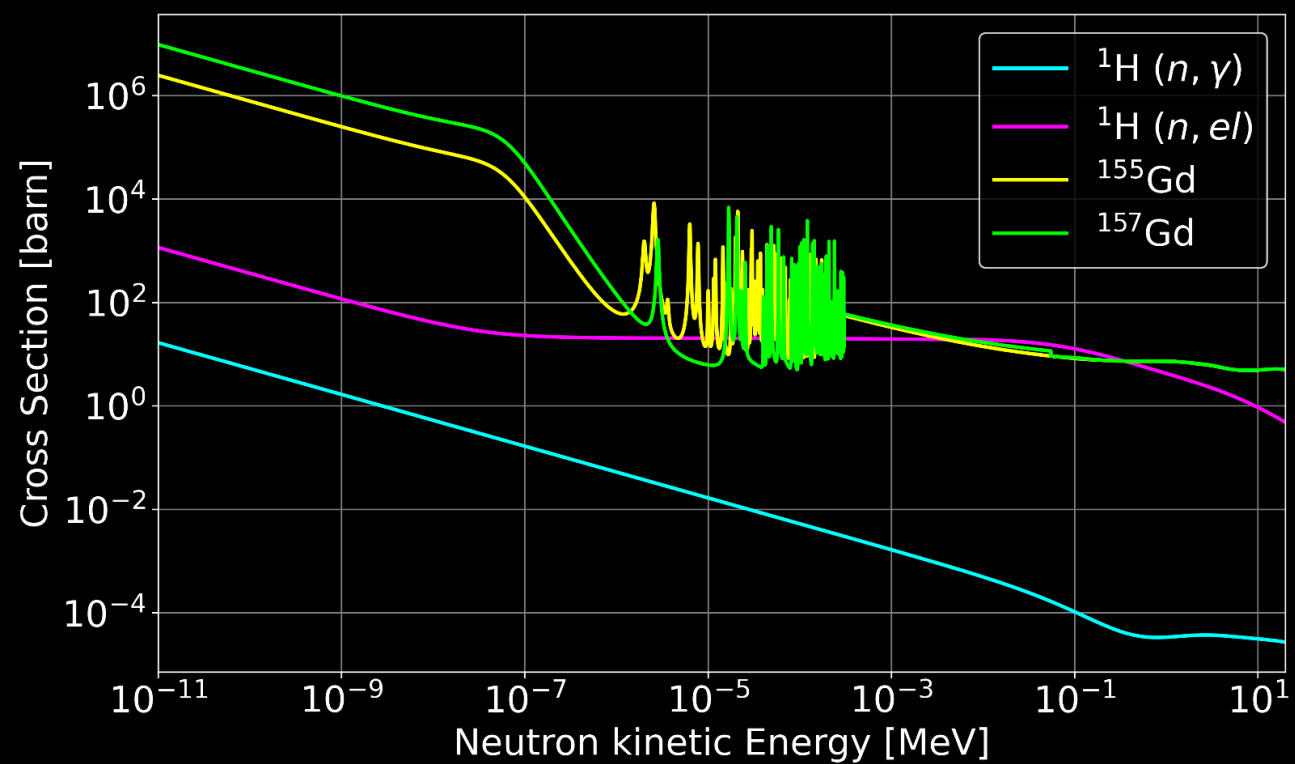
64

Gd

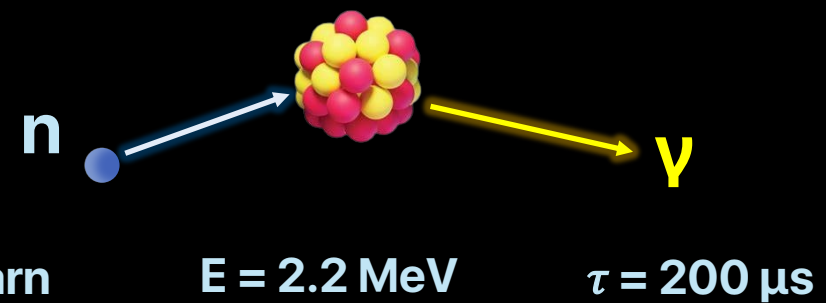
Gadolinium



Neutron Capture cross-section

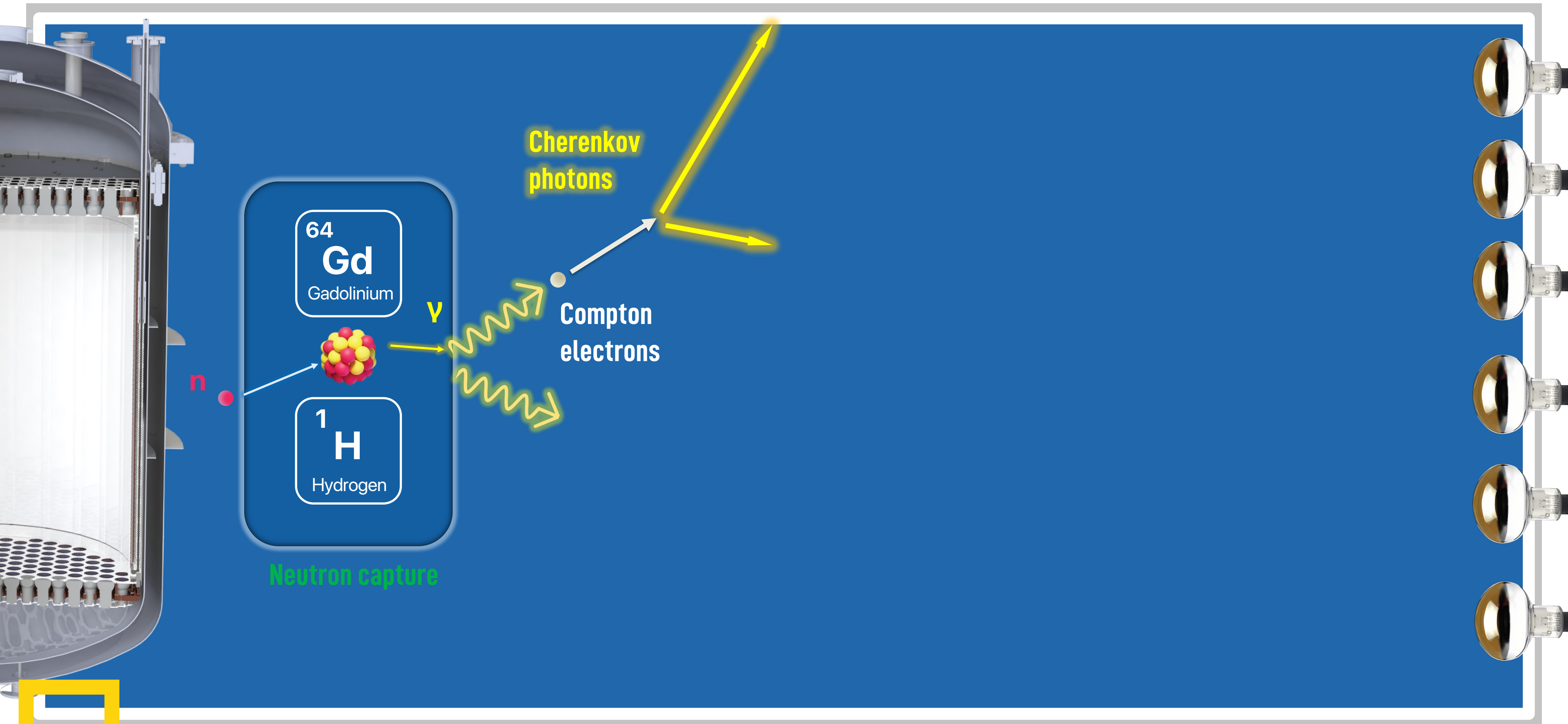


Gd -155 = 61k barn  $E = 8.5 \text{ MeV}$   $\tau = 30 \mu\text{s}$   
Gd -157 = 255k barn  $E = 7.9 \text{ MeV}$

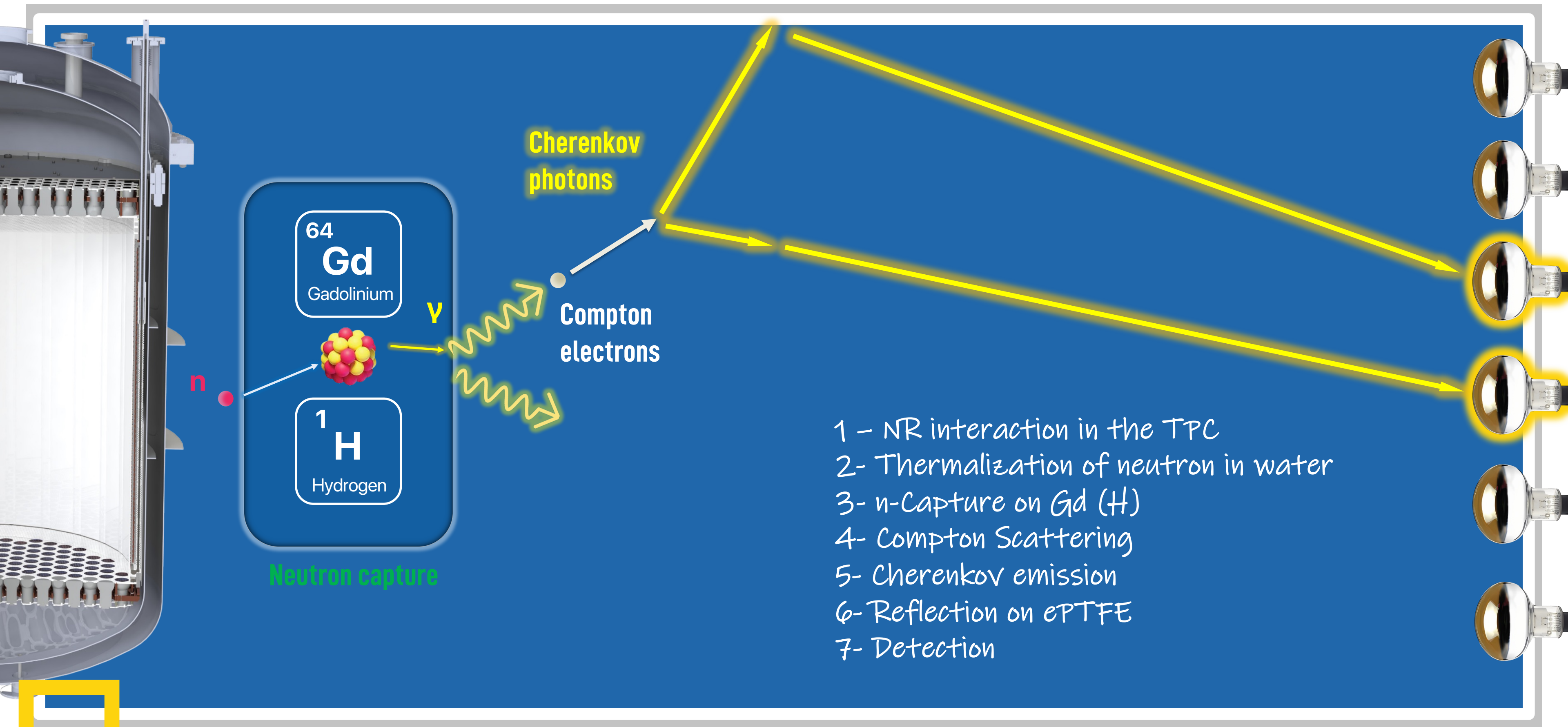


# Detection Principle

## Why Gadolinium



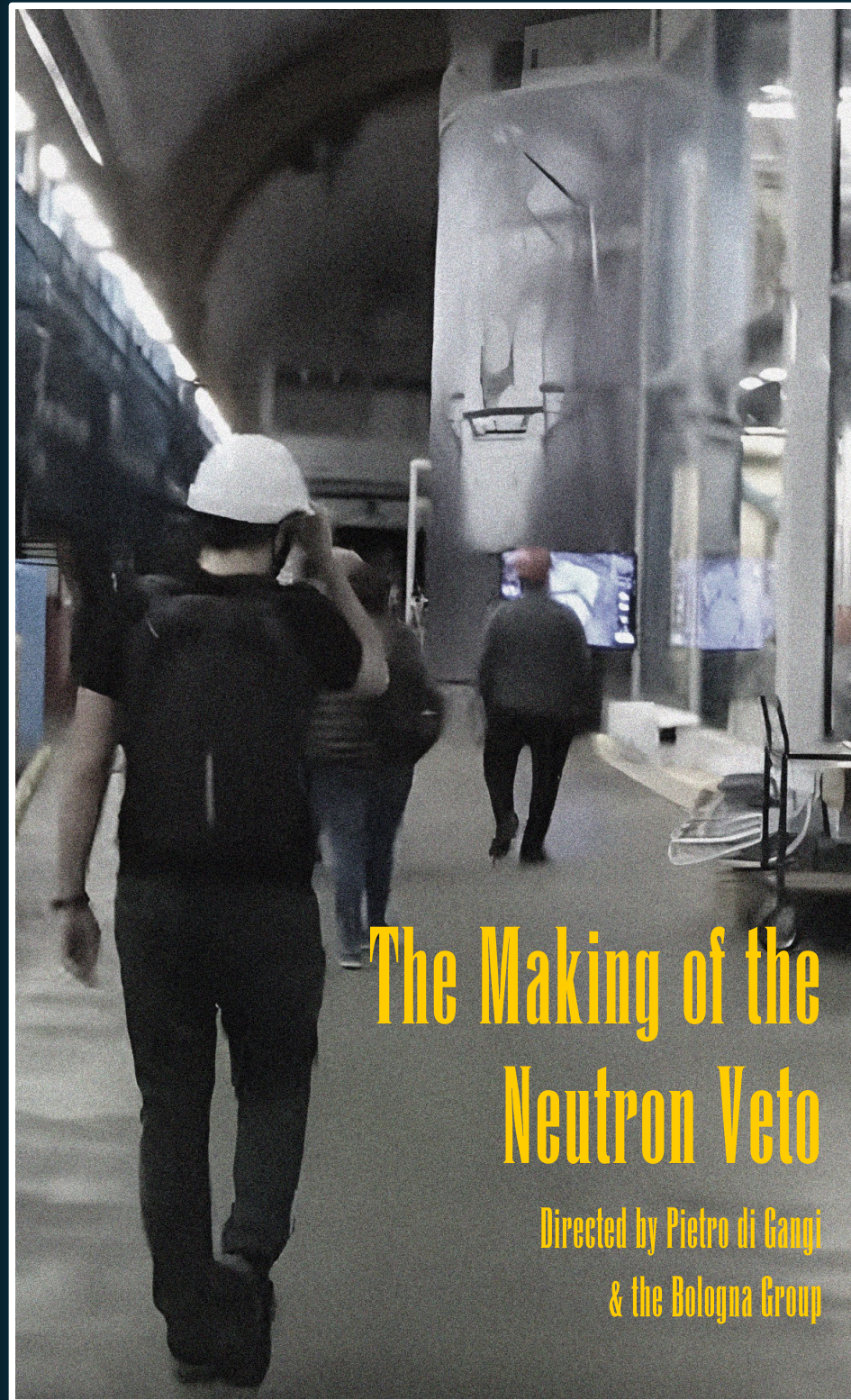
# Detection Principle



# Detection Principle



# Construction of A Gadolinium loaded water cherenkov detector

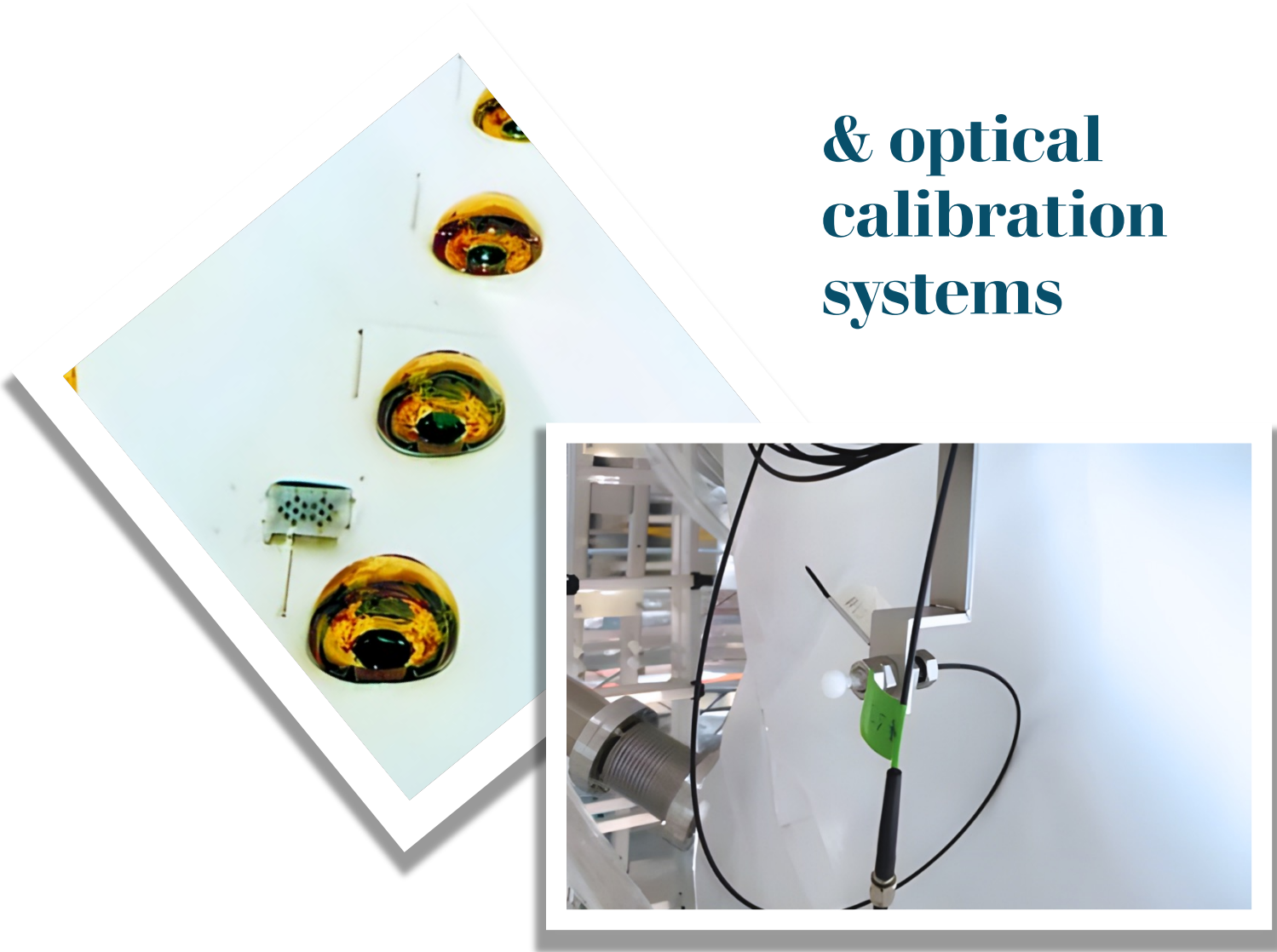


# A Gadolinium loaded water cherenkov detector instrumented with 120 PMTs

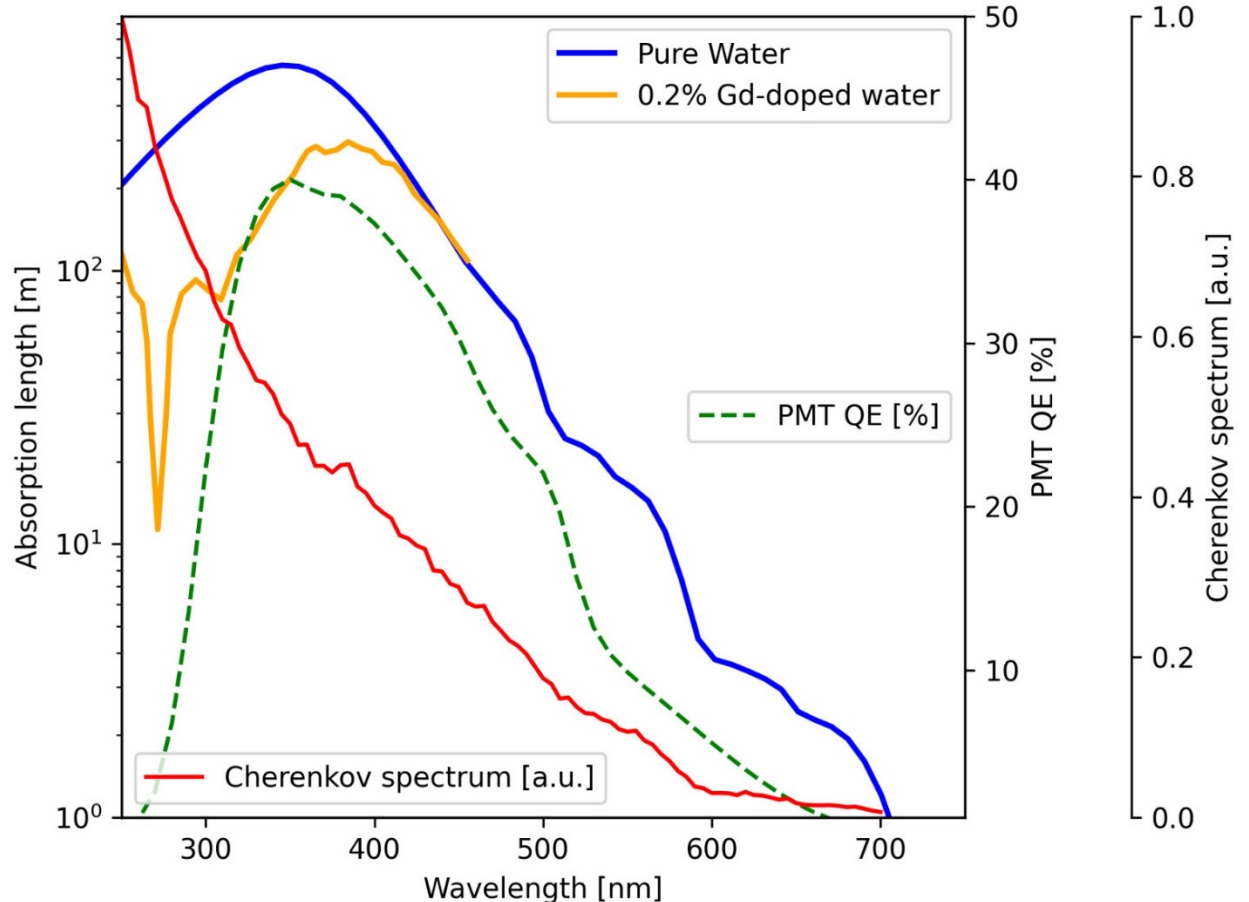
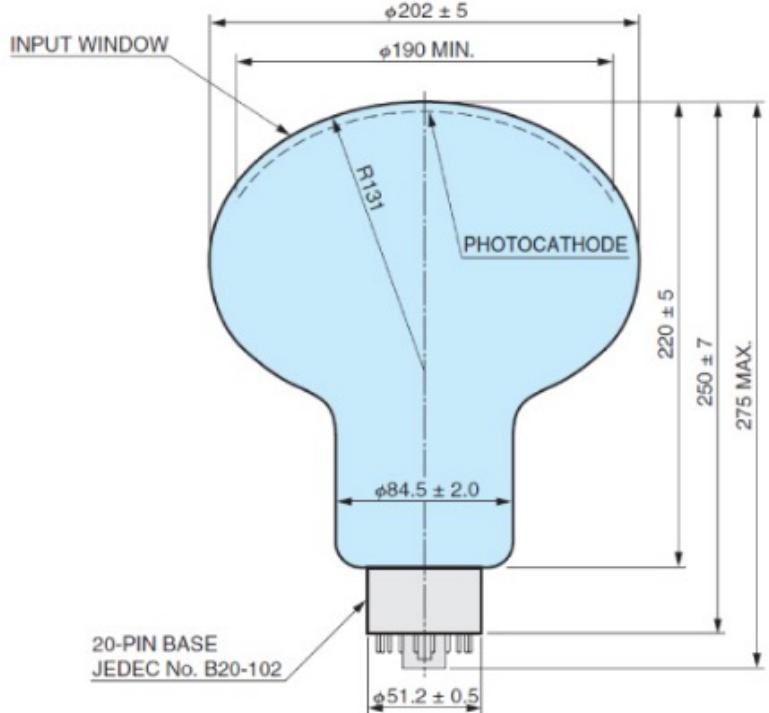


## Hamamatsu R5912

- 8-inches photocathode
- High Quantum Efficiency
- Low Radioactivity



& optical calibration systems



**Optical Fibers**  
Coupled to LEDs

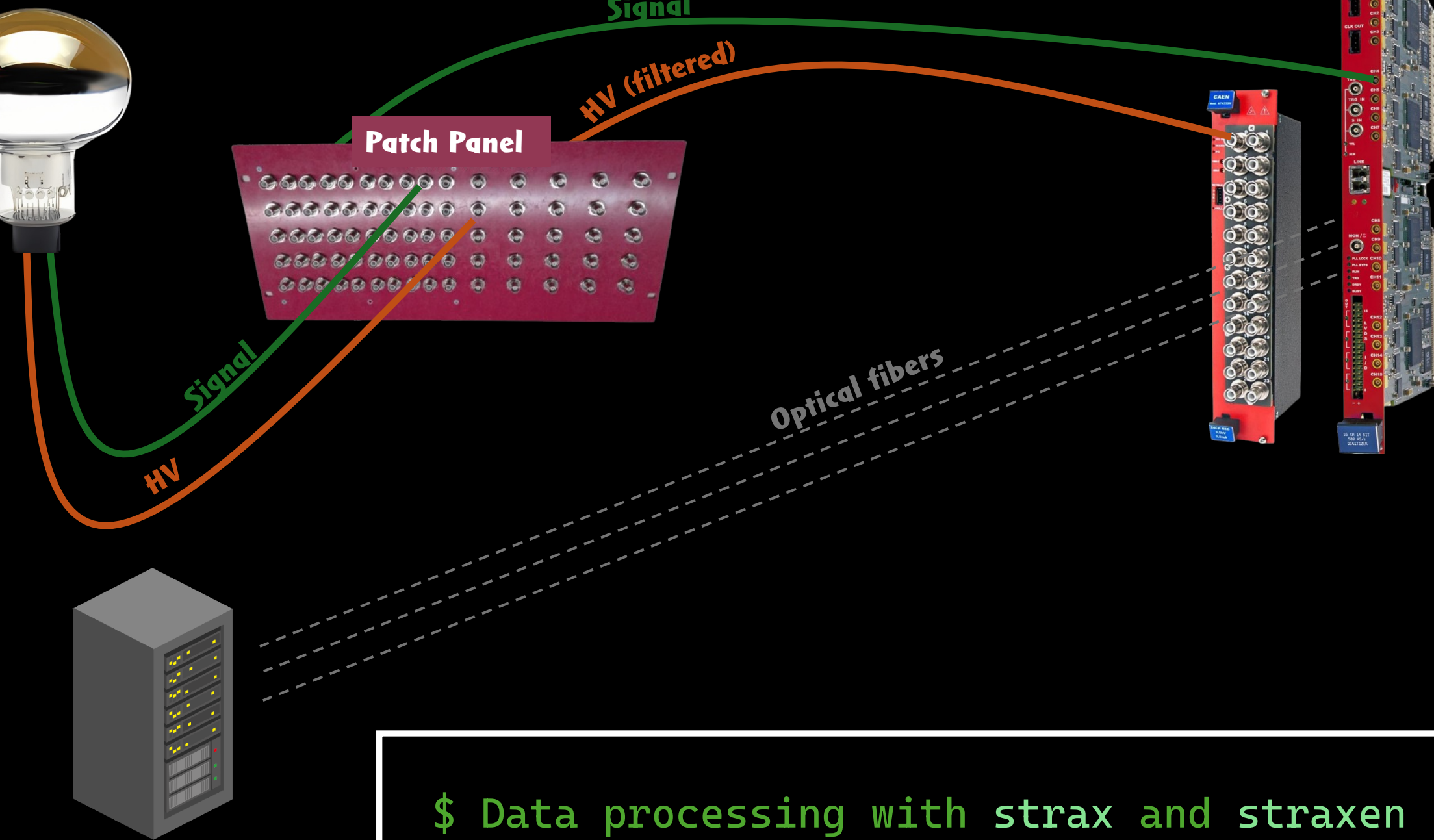
Used to calibrate the PMTs

**Reflectivity Monitor**  
Coupled to LASER (375 nm)

Used to monitor NV optical properties

**Diffuser Ball**  
Coupled to LASER (448 nm)

# DAQ and Data Processing pipeline



Servers  
Event Builders

**Digitizer CAEN v1730**  
**Self-triggered DAQ Mode**

**14-bit - 500 MS/s**

**2 Vpp dynamic range**

**Self-triggered DAQ Mode**

Standard DAQ mode for Science Runs

Light calibration - Pulsers

**External trigger DAQ Mode**

**\$ Data processing with strax and straxen**

```
$ straxen> raw_records : Stores waveforms
```

```
$ straxen> raw_records/hitlets: Stores hit information (Area, Amplitude) of all hits passing the Software Trigger.
```

The hitfinder algorithm identify as hit consecutive samples above a ADC-count threshold.

The Software Trigger requires 3 hits in a window of 600 ns.

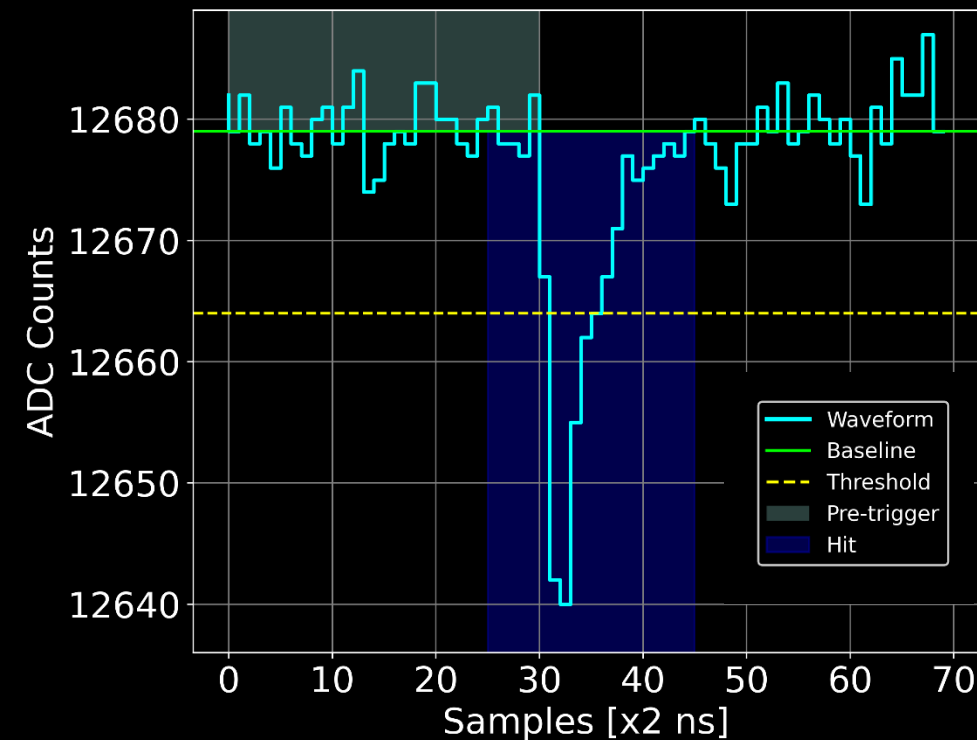
```
$ straxen> hitlets_nv/events: the surviving hits are clustered within a tighter window of 200 ns.
```

# DAQ and Data Processing pipeline

```
$ straxen> raw_records :
```

```
$ raw_records :
```

- Time
- Channel
- Waveform
- Baseline (Digitizer)



```
$ Data processing with strax and straxen
```

```
$ straxen> raw_records : Stores waveforms
```

```
$ straxen> raw_records/hitlets: Stores hit information Software Trigger. The hitfinder algorithm identify as hit consecutive samples above a ADC-count threshold. The Software Trigger requires 3 hits in a window of 600 ns.
$ straxen> hitlets_nv/events: the surviving hits are clustered within a tighter window of 200 ns.
```

```
$ straxen> hitlets : at least 3 signal in 600 ns
```

```
$ straxen> events : at least 2 signal in 200 ns
```

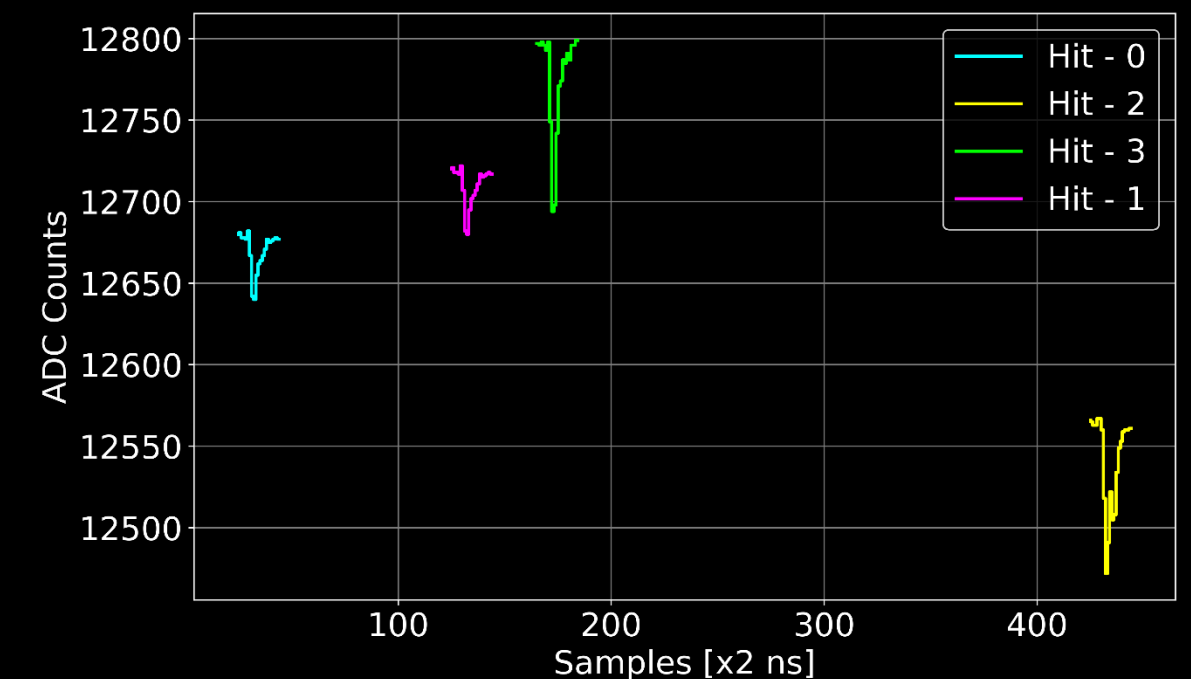
```
$ hitlets :
```

- Time
- Channel
- Amplitude
- Area [pe]

```
$ events :
```

- Time/Endtime
- Area (total) [pe]
- N\_contributing\_pmts
- Center time

```
4 hitlets and 1 event with 3 hits
```





Neutron Veto

# Low Level Analysis

■ **PMT Calibration** ..... **01**

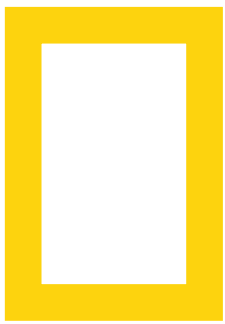
Dark Rate & Noise

Gain and SPE Response

■ **Detector Performance** ..... **02**

nFold Coincidence Rate

Reflectivity Monitor



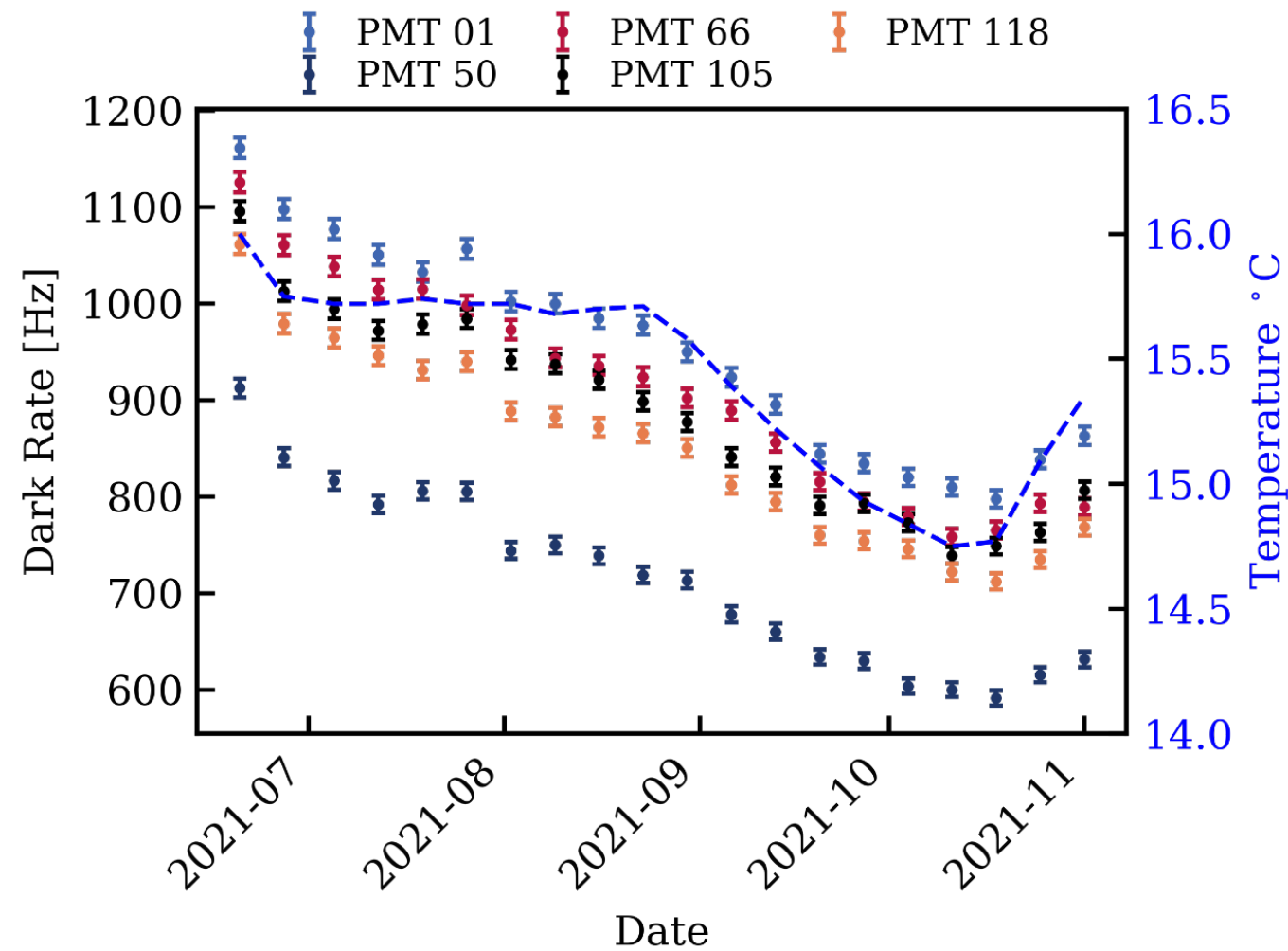
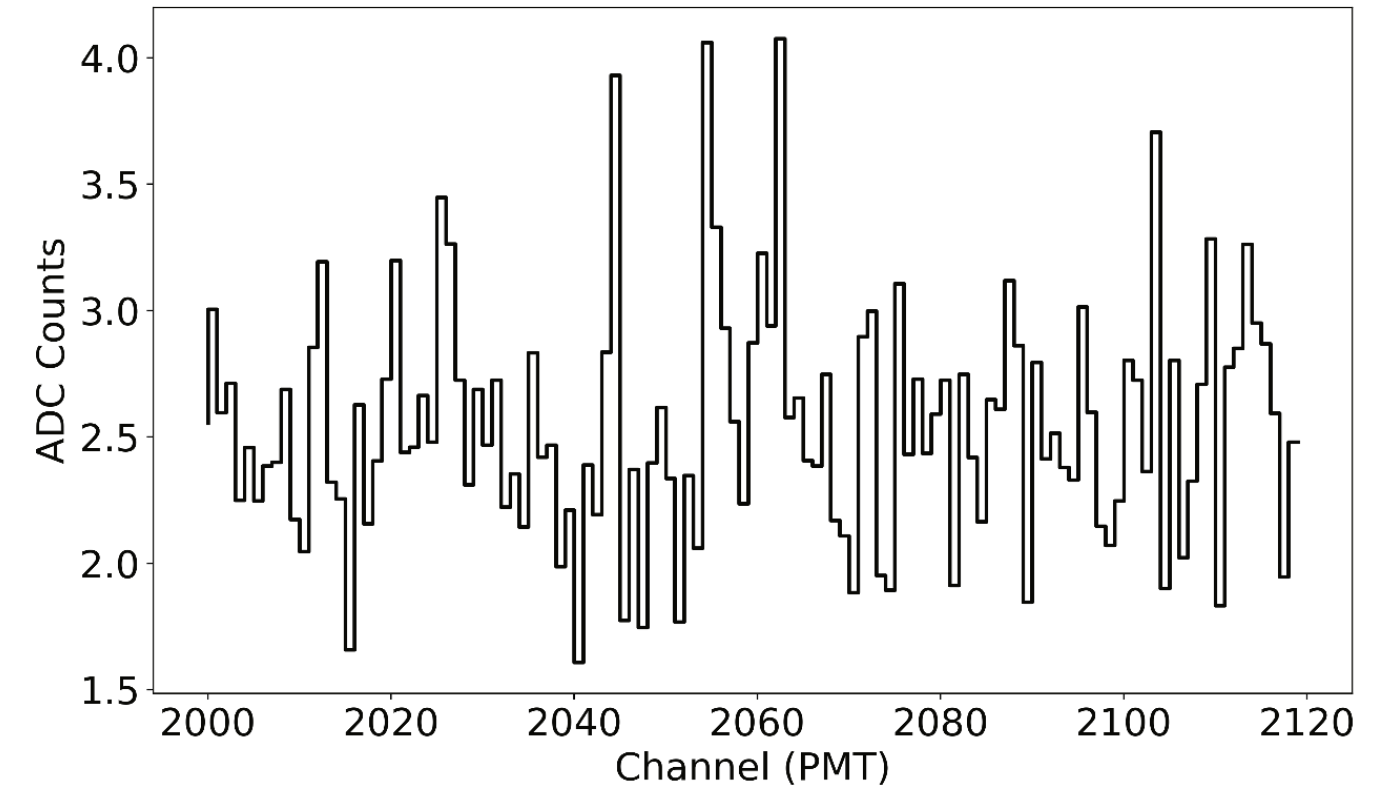
# Low Level Analysis

# Dark Rate & Noise



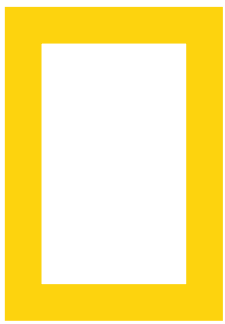
## Baseline

The baseline for each channel is calculated from the first 26 samples of the acquired waveforms.  
An average value for the std is  $\approx 2.5$  ADC counts.



## Temperature dependence

The Temperature dependence is compatible with the known temperature dependence of thermionic emission by alkali photocathodes, but **has a negligible impact on the efficiency of the NV** due to the high PMT coincidence requirement for neutron tagging



# Low Level Analysis

## Gain and SPE

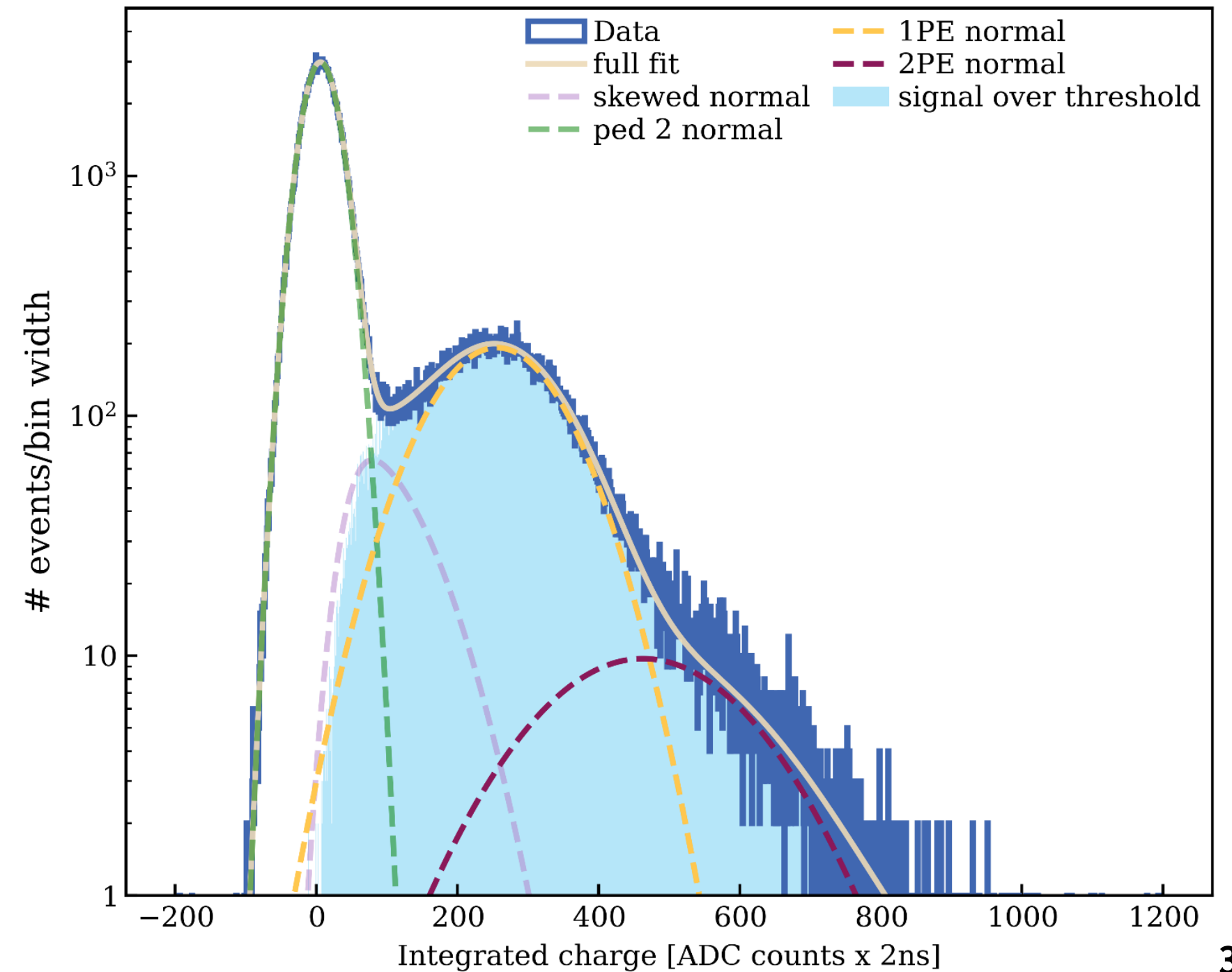
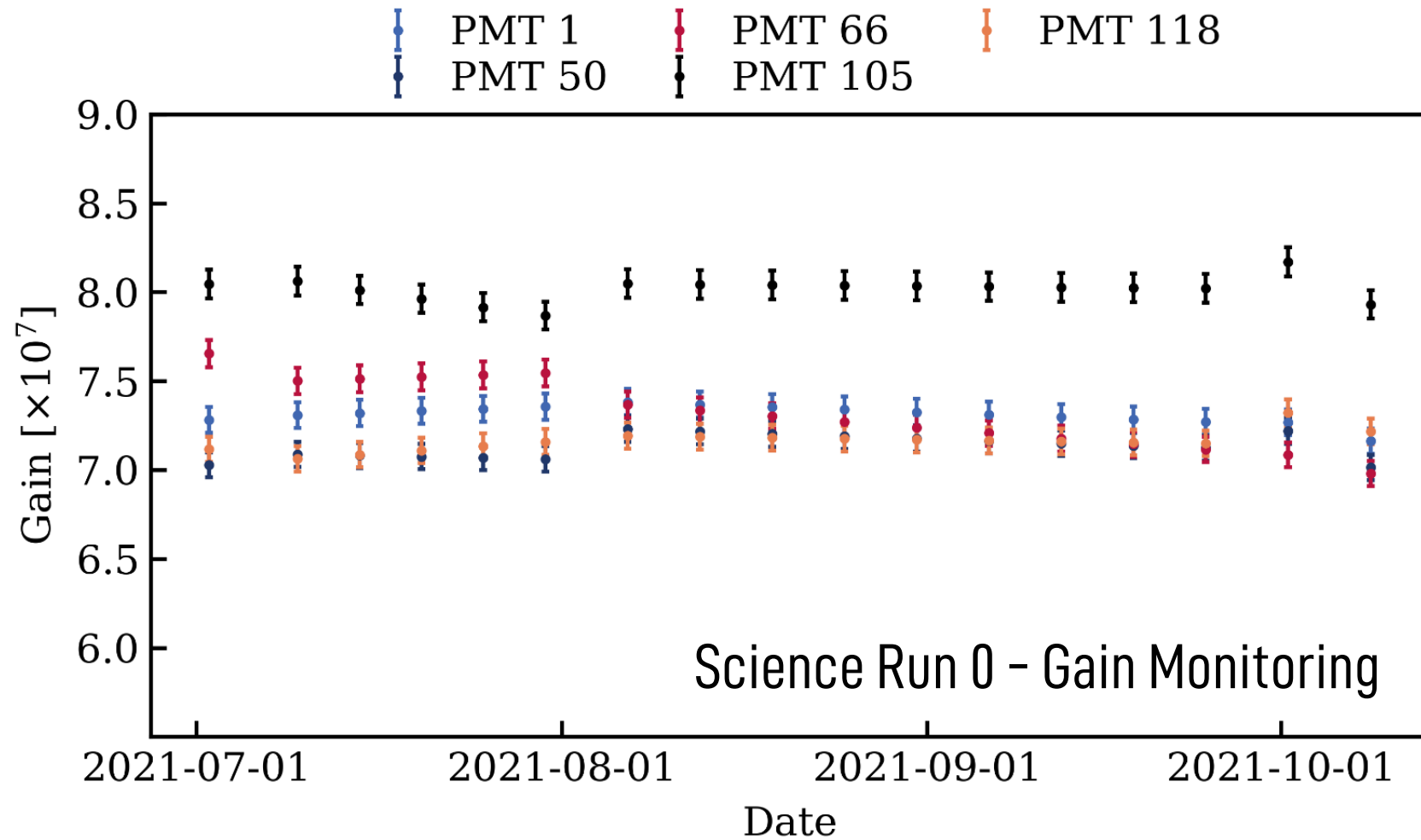


$$P_{\text{SPE}} = f_{\text{FA}} \cdot \mathcal{N}(\mu_{\text{FA}}, \sigma_{\text{FA}}) + (1 - f_{\text{FA}}) \cdot \mathcal{N}(\xi, \omega) \cdot \left[ 1 + \text{Erf} \left( \alpha \frac{(x - \xi)}{\sqrt{2}\omega} \right) \right]$$

### SPE Model V0

### Gain

From the fit of the spectra, both PMT gain and SPE acceptance are determined. The gain is defined as the mean value of the overall SPE component. Typical gain values are  $\sim 7 \times 10^6$  with a stability better than 5%.



# SPE Model VI

More details in the Appendix

■ 1PE: continuous Poissonian ( $f_{1PE}$ ) + 'rounded box' ( $f_{1PE\_SA}$ ):

$$f_{1PE} = \frac{\mu_{1PE}/\sigma_{1PE}^2 \cdot e^{-(\mu_{1PE}/\sigma_{1PE})^2} \cdot (\mu_{1PE}^2/\sigma_{1PE}^2)^{(x-\mu_{base})\mu_{1PE}/\sigma_{1PE}^2}}{\Gamma(1. + (x - \mu_{base})\mu_{1PE}/\sigma_{1PE}^2)}$$

$$f_{1PE\_SA} = \frac{(1. + \text{Erf}(x - \mu_{base} - \mu^L)/\sigma^L) \cdot (1. - \text{Erf}(x - \mu_{base} - \mu^R)/\sigma^R)}{4 \cdot (\mu^R - \mu^L)}$$

**backscattering**

In literature different phenomena are considered to fill the gap between the full 1PE peak and the pedestal: backscattering of the primary PE, collection inefficiency at 1st dynode (bad trajectory), trapping of secondary electrons in dynode material, nonuniformity of the secondary emission, etc.

Due to backscattering a fraction [0:1] of the PE Energy can be available to produce secondary electrons in a fraction  $k$  of the events. As a result the probability to generate  $m$  electrons is modified

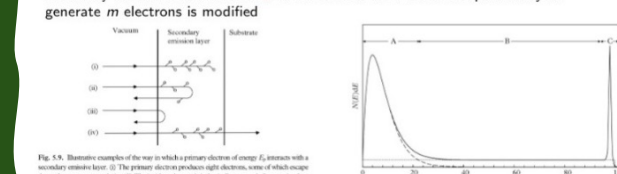


Fig. 5.8. Schematic diagram of the way in which a primary electron of energy  $E_0$  strikes with a secondary electron layer. (a) The primary electron produces eight electrons, some of which escape the surface as true secondaries. (b) The incident electron is totally reflected after exciting four electrons, some of which escape as true secondaries. (c) The incident electron is totally reflected after exciting four electrons, some of which escape as true secondaries. (d) The incident electron is totally reflected after exciting four electrons, some of which escape as true secondaries. (e) The incident electron has sufficient initial energy to traverse the secondary electron layer into the substrate, where there is the chance of generating or collecting secondaries.

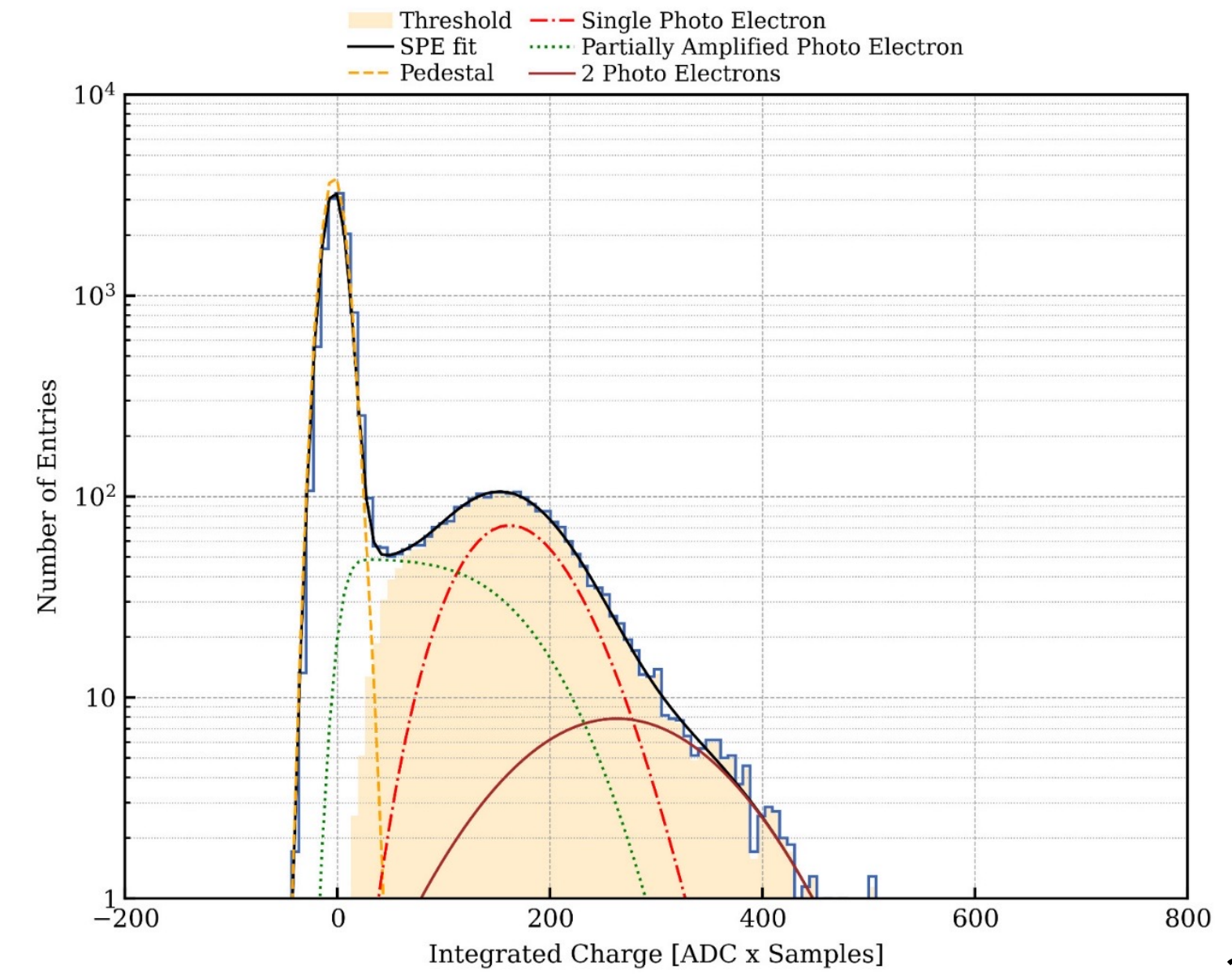
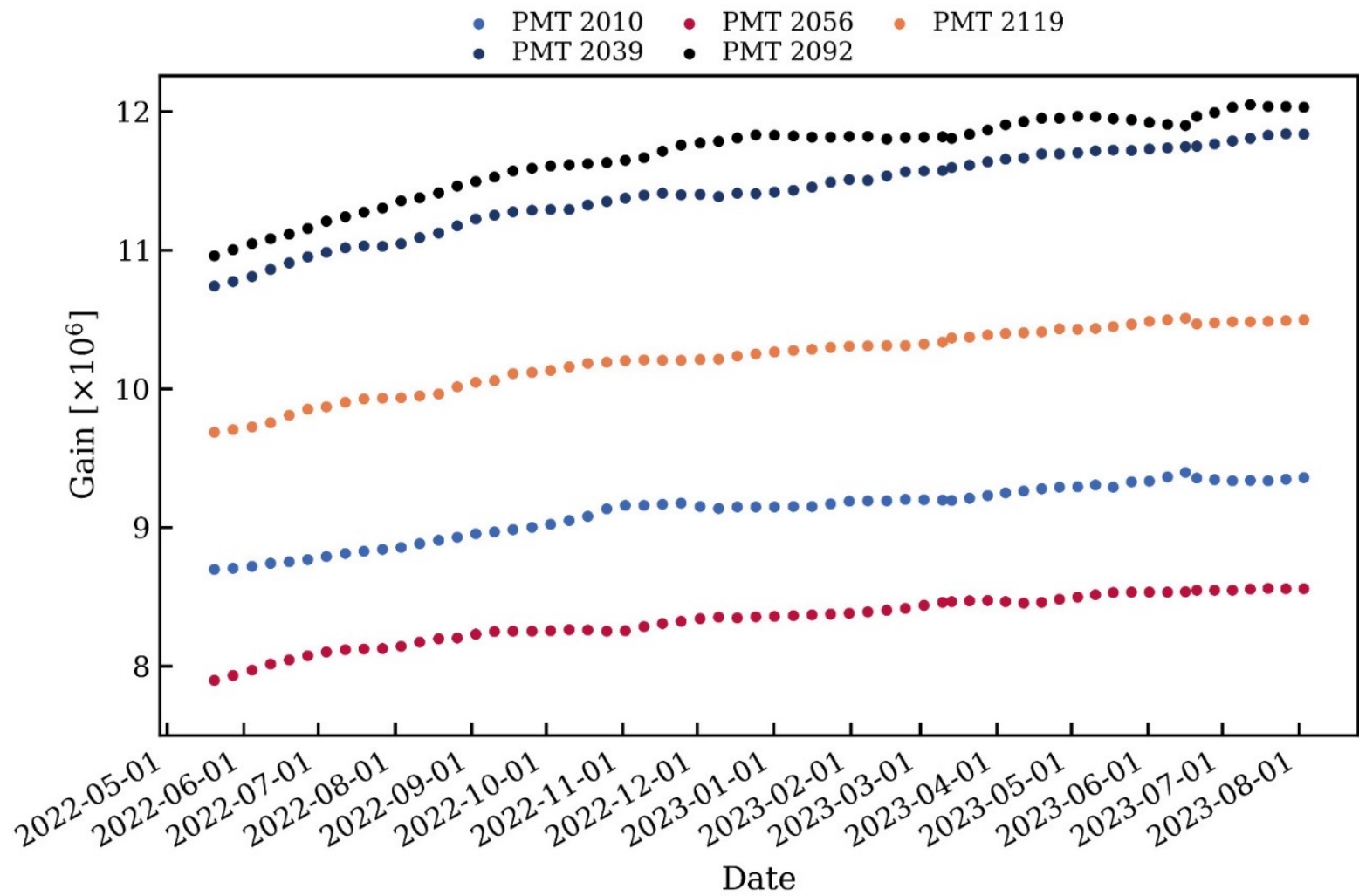
Fig. 5.9. The energy distribution of electrons created by a surface backscattered by primary electrons of energy  $E_0 = 100$  eV. The processes involved in the three regions A, B, and C are explained in the text, and in the diagrams of Fig. 5.8.

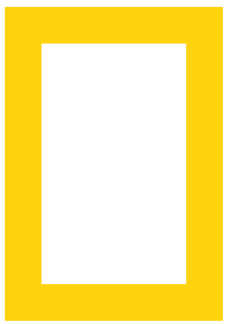
A.G.Wright, The photomultiplier handbook, cap.5. Also contains many reference therein. In particular Dekker, A. J. (1958). Secondary electron emission. Solid State Phys. 6, 251 - 311.

## SPE Acceptance

$$\varepsilon = \frac{N - \int [\mathcal{F}_{2PE}(x) + \mathcal{F}_{3PE}(x)] dx}{\int \mathcal{F}_{1PE}(x) dx}$$

## Science Run 1 - Gain Monitoring





# Low Level Analysis

## nFold Coincidence Rate



### Analysis:

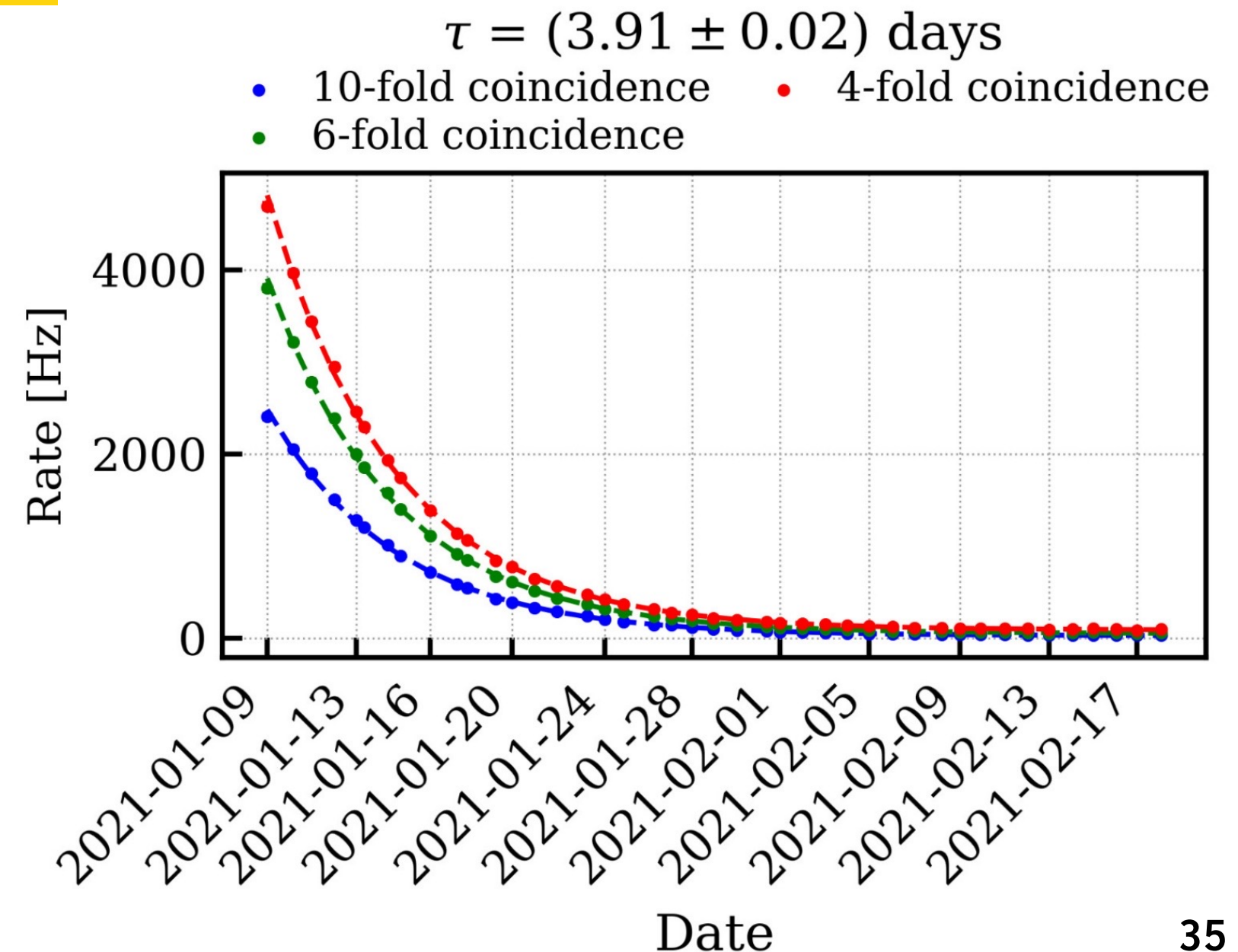
In the events datatype on self-triggered data we have the `n_contributing_pmts`;

The analysis consists in monitoring the rate, highlight trends and spot bad runs.

During the Science Runs we have used it as a **Data Quality cut**.

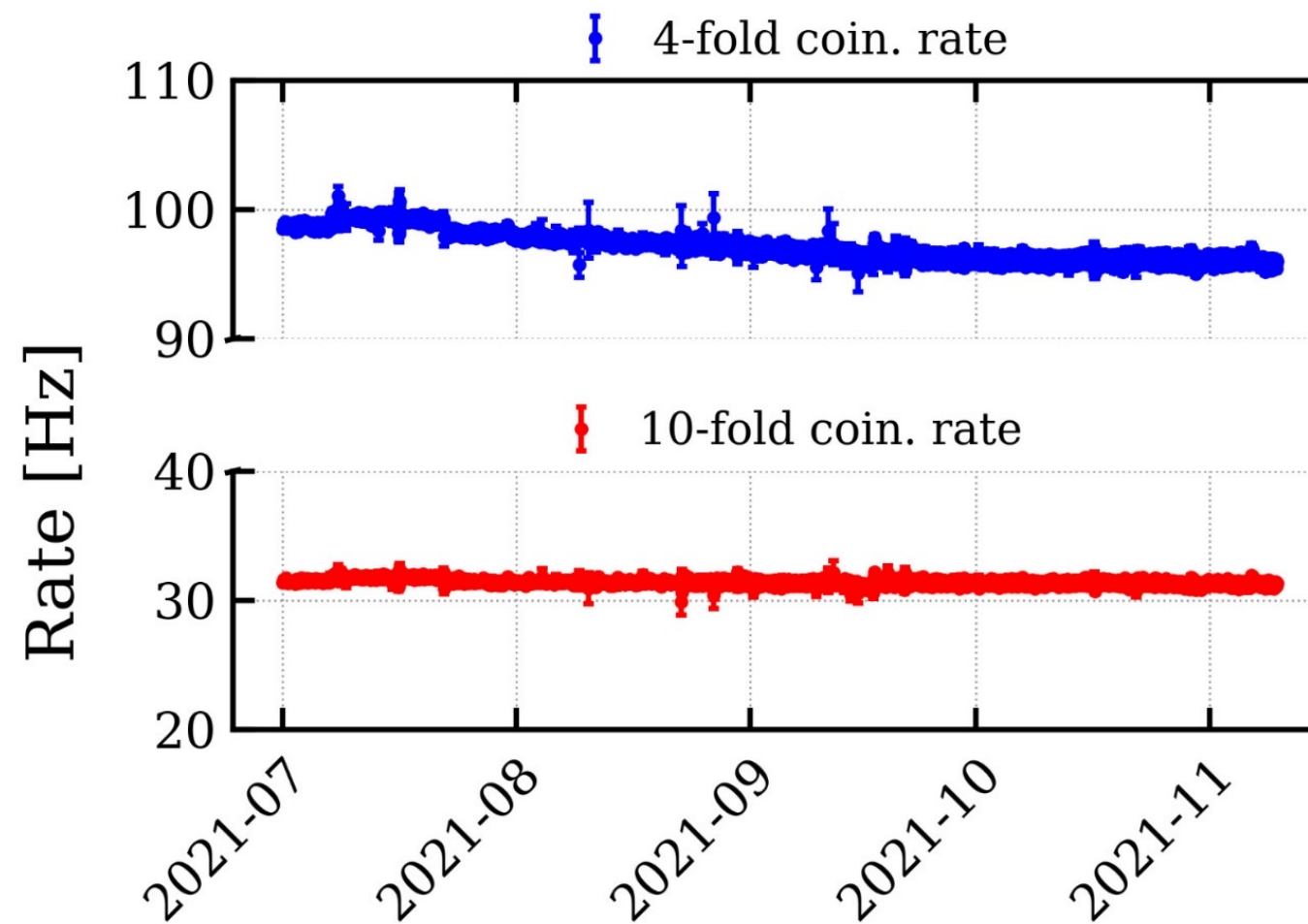
### Commisioning

The exponential trend observes as soon as we filled the water tank, has been fitted with an exponential function on top of a flat component. The time decay constant is in agreement with the decay of  $^{222}\text{Rn}$  present in water sourced directly from the Gran Sasso rock.



# Science Run 0

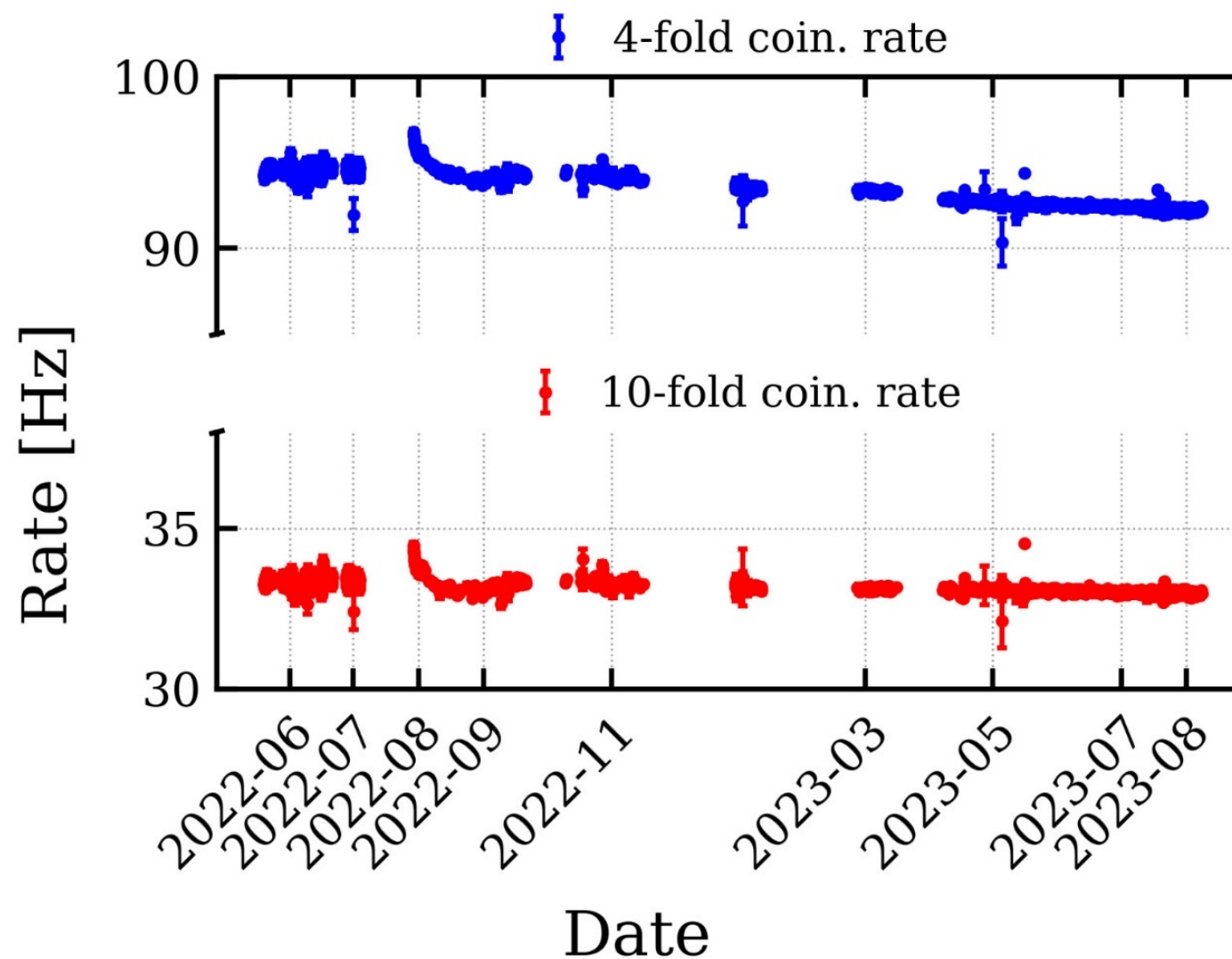
Data quality: No runs to be discarded from the analysis



The slightly decreasing trend in the 4-fold coincidence rate has been related to the dark rate trend

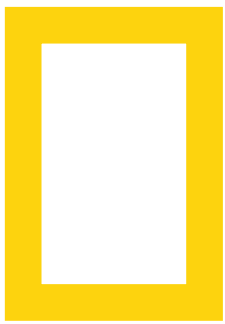
# Science Run 1

Data quality: Few outliers; Holes in the plot related to calibrations (No science data)



All the visible patterns are due to dark rate fluctuations

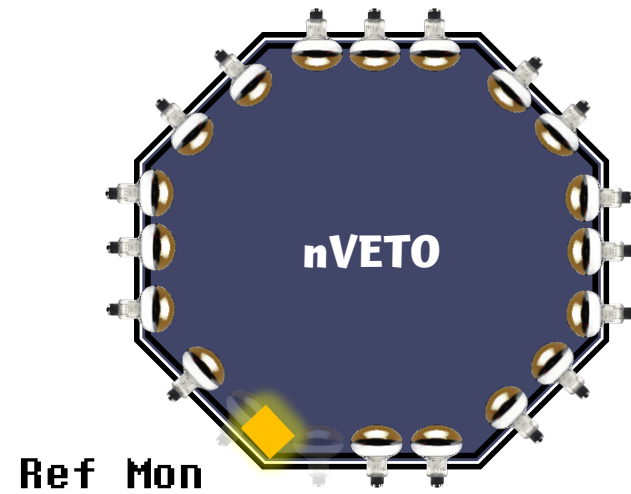
# Science Run 2



Neutron Veto

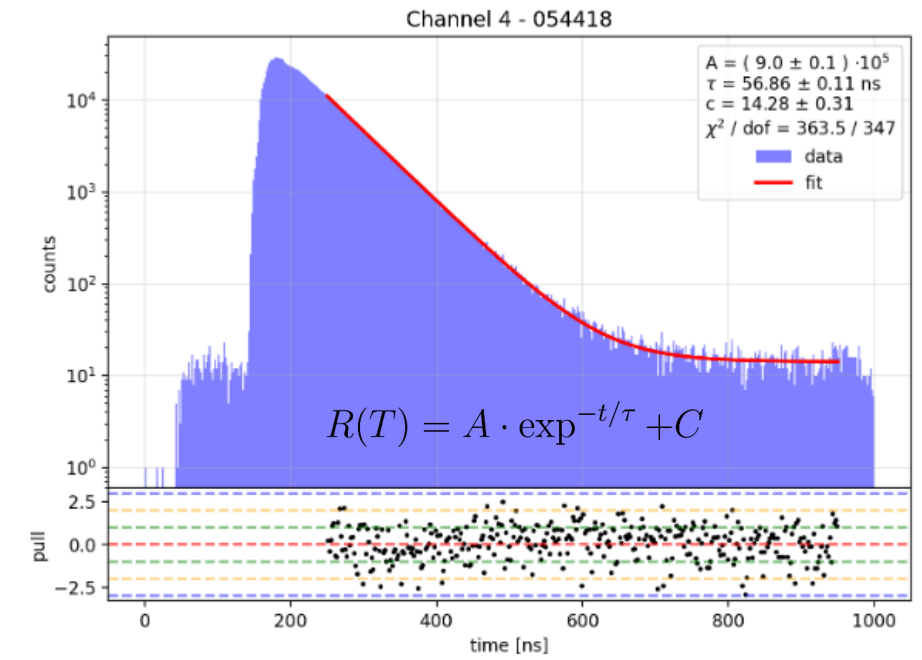
# Low Level Analysis

# Reflectivity Monitor



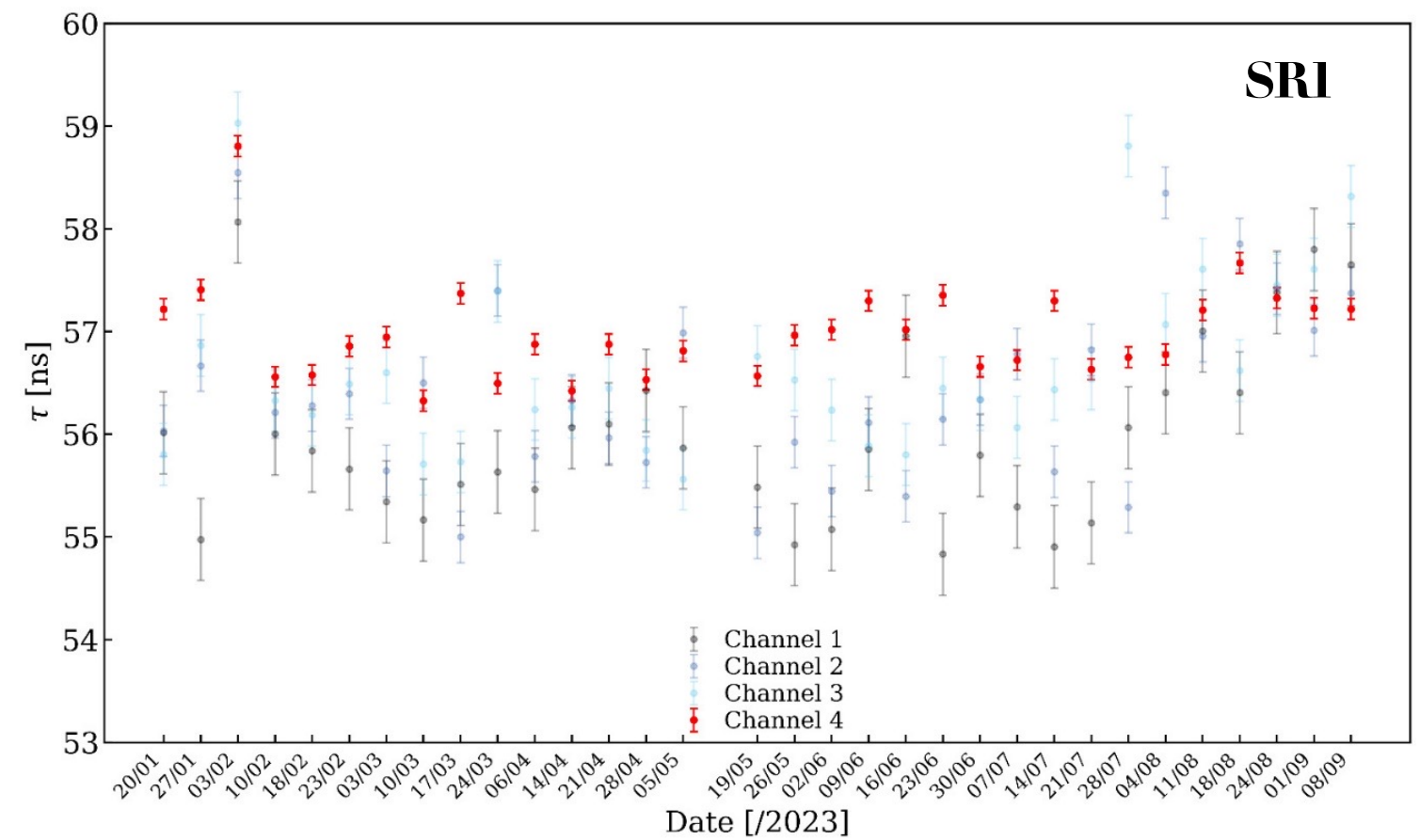
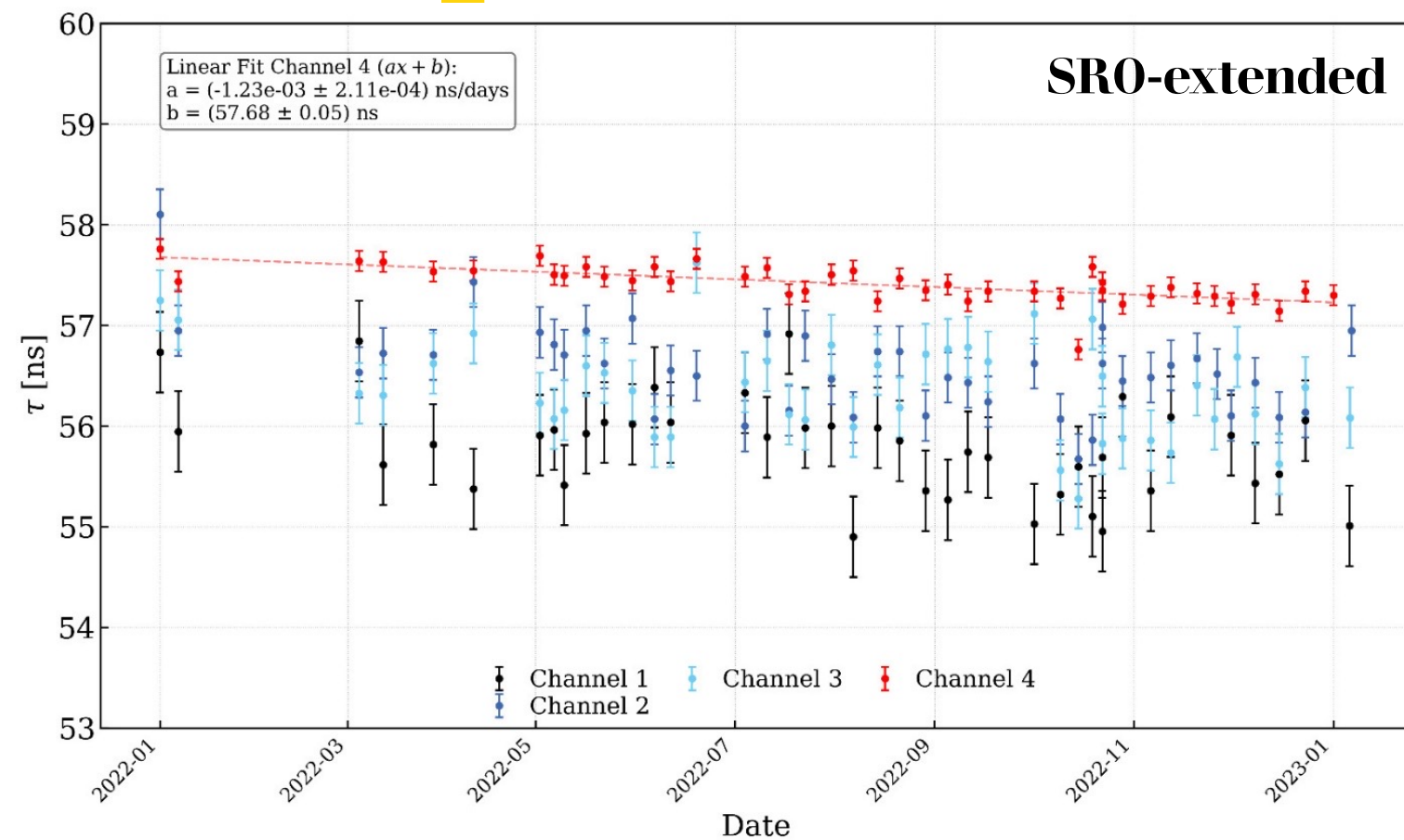
## Analysis:

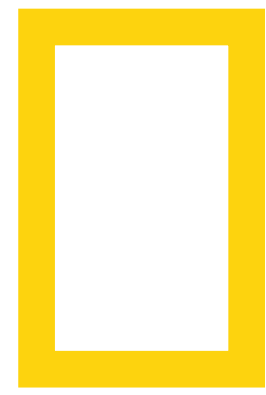
Once the dedicated plugin as been developed, the analysis consists of studying the time distribution of the hits wrt the trigger time



## Monitoring:

The tau of the time distribution is related to the optical properties of the nVeto (water transparency and wall reflectivity)





Neutron Veto

# Calibration

■ **AmBe Calibration** ..... **01**

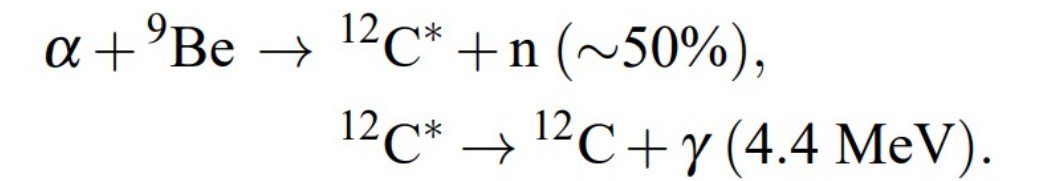
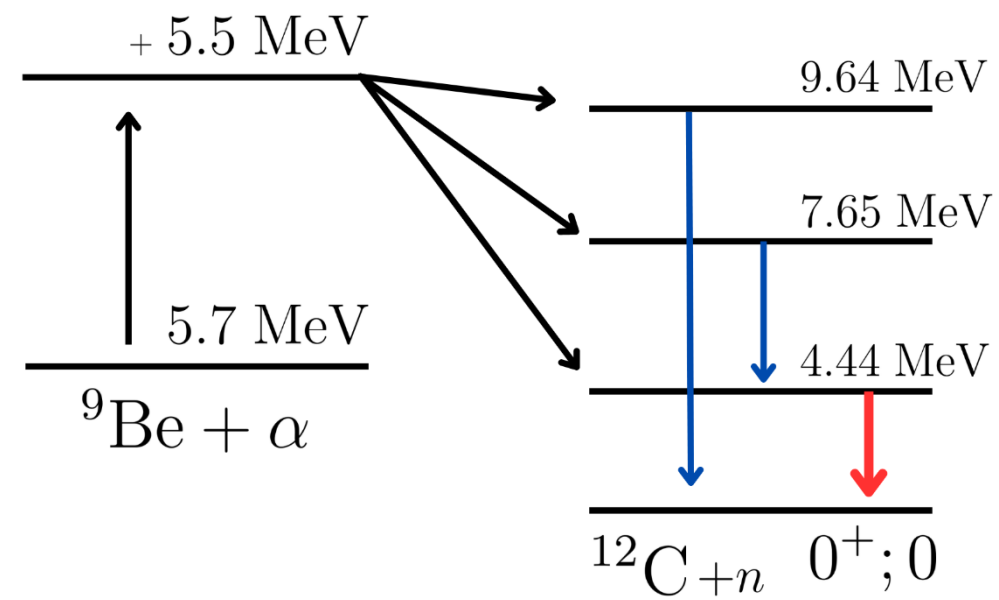
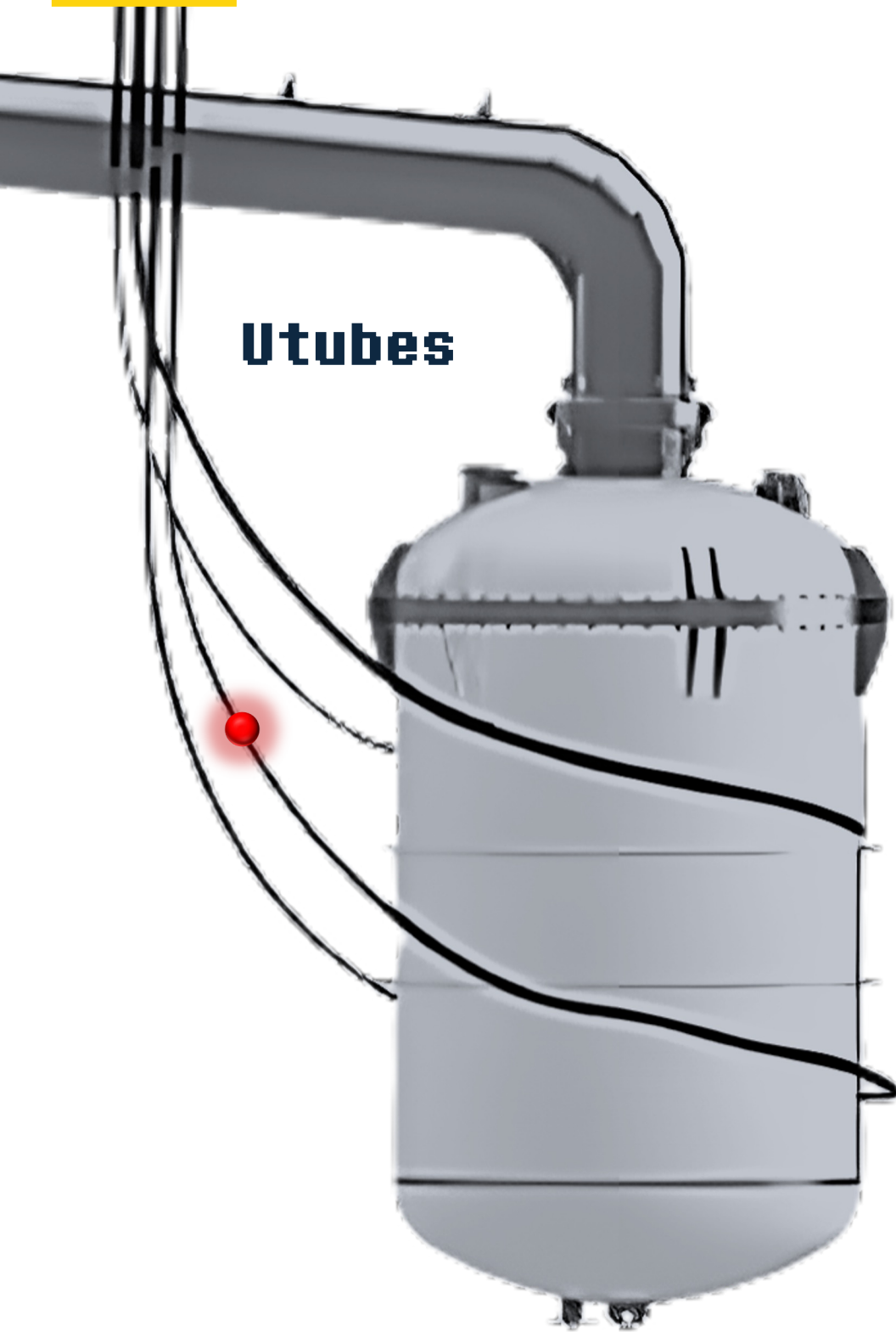
Source

Detection Efficiency

Tagging efficiency

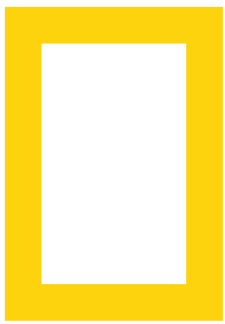
# Calibration

## Americium Beryllium Source



**During SR0 and SR1 we performed AmBe calibrations in order to:**

- Calibrate the single scatter nuclear recoil response of the TPC;
- Estimate the efficiency of the nVeto to detect and tag neutron signals



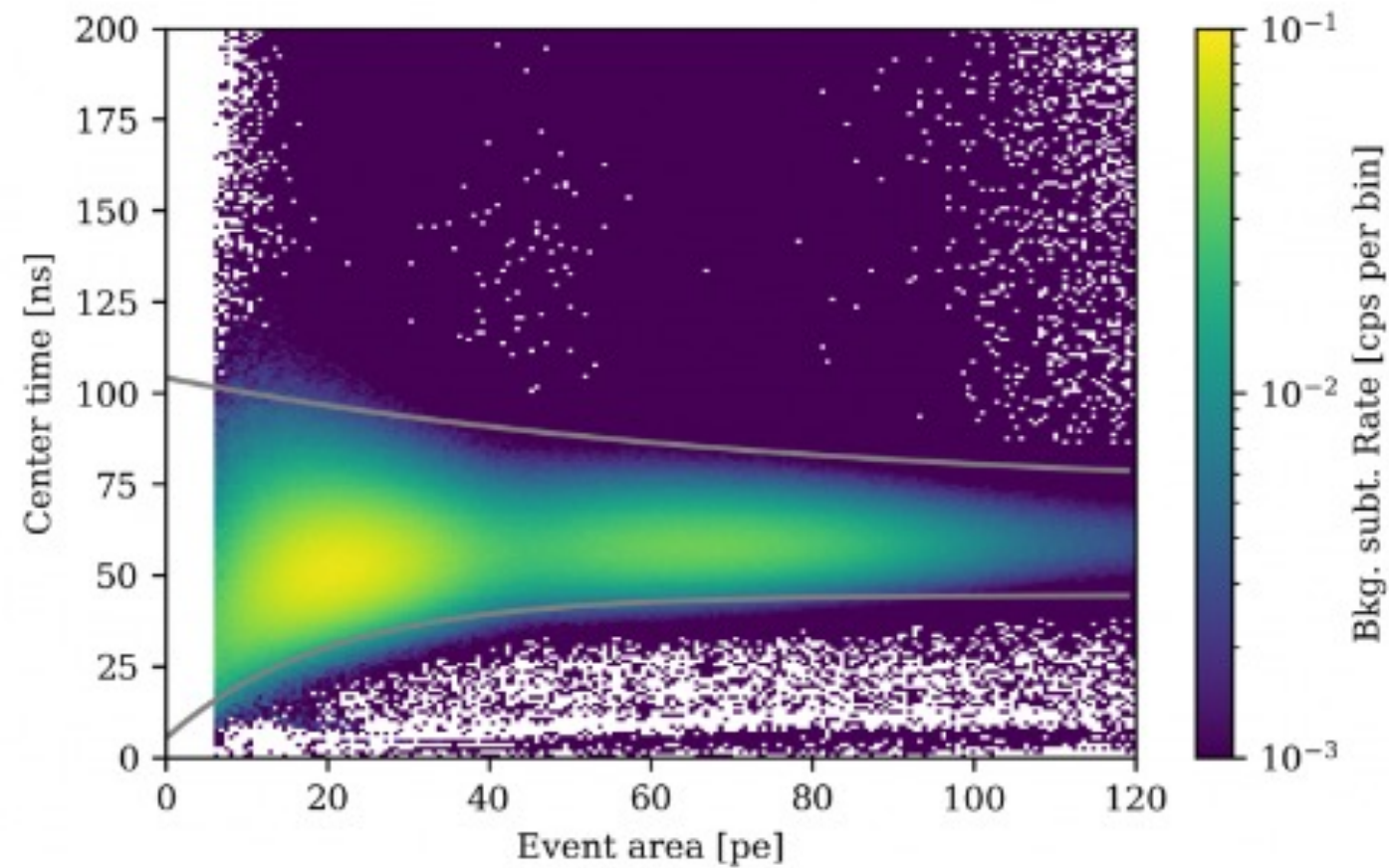
# Calibration

# Spectrum

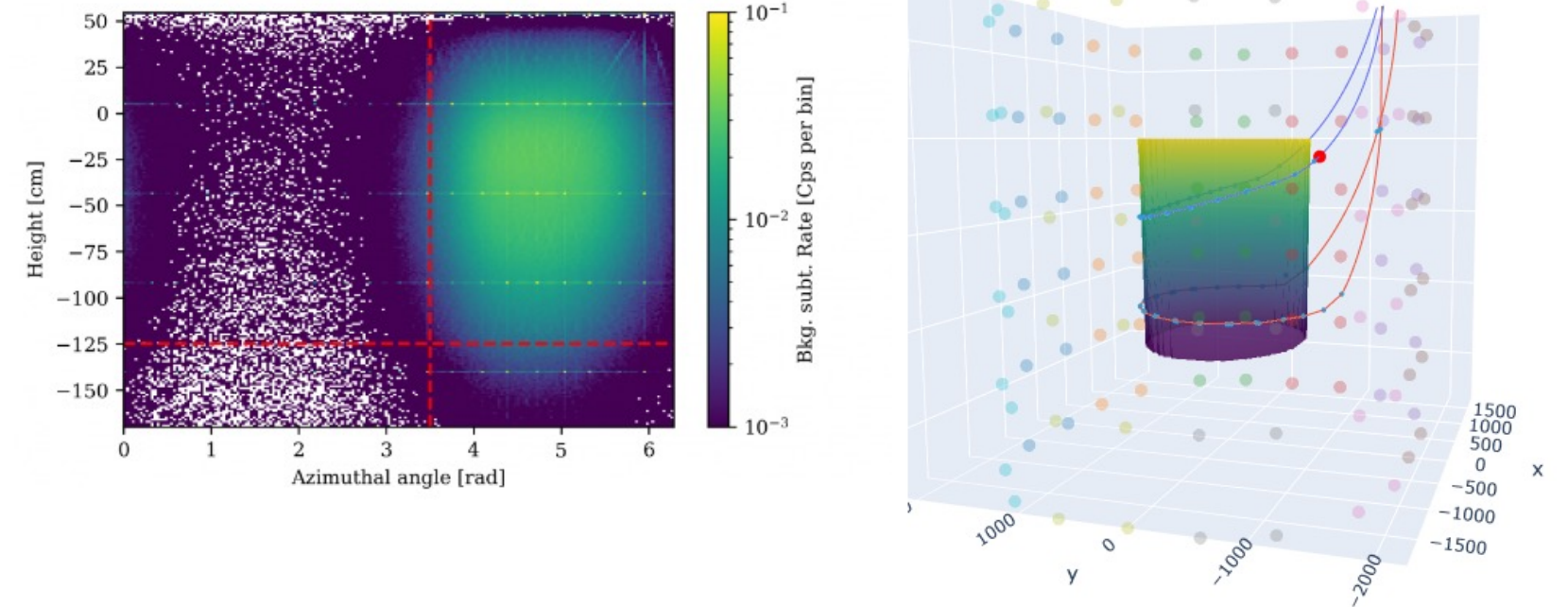
## Center Time:

The center time is the average of the times of the hits contributing to the event weighted by the area of the hits.

## Area vs Center Time (after background subtraction)



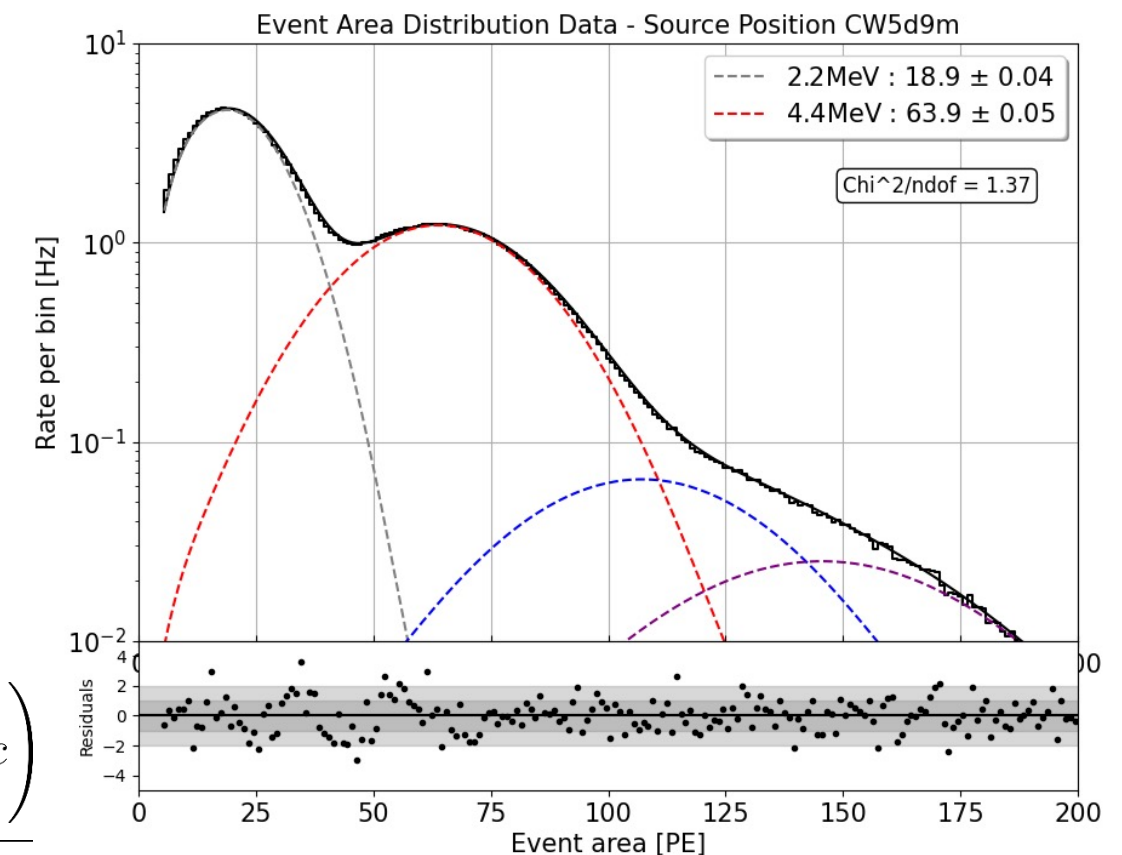
## Source Position : Top tube – clockwise – 5d9m.



## Charge Spectrum

From the charge spectrum of the AmBe runs, after the background subtraction) we estimate the resolution of the NV in detecting the 2.2 MeV.

In SRO conditions the H-capture peak is around 20 pe, while the 4.4 MeV Gamma is around 65 pe.



$$f(x; A_1, A_2, A_3, A_4, \mu_1, \mu_2, \mu_3, \mu_4, \sigma_{th}, \mu_{th}, s, o, c) = N_{cdf}(x, \mu_{th}, \sigma_{th}) \cdot \left( \sum_{i=0}^4 N(x, A_i, \mu_i, \sigma(\mu_i, s, o)) + c \right)$$

$$\sigma(\mu, s, o) = \sqrt{\mu \cdot s + o}$$

# Calibration

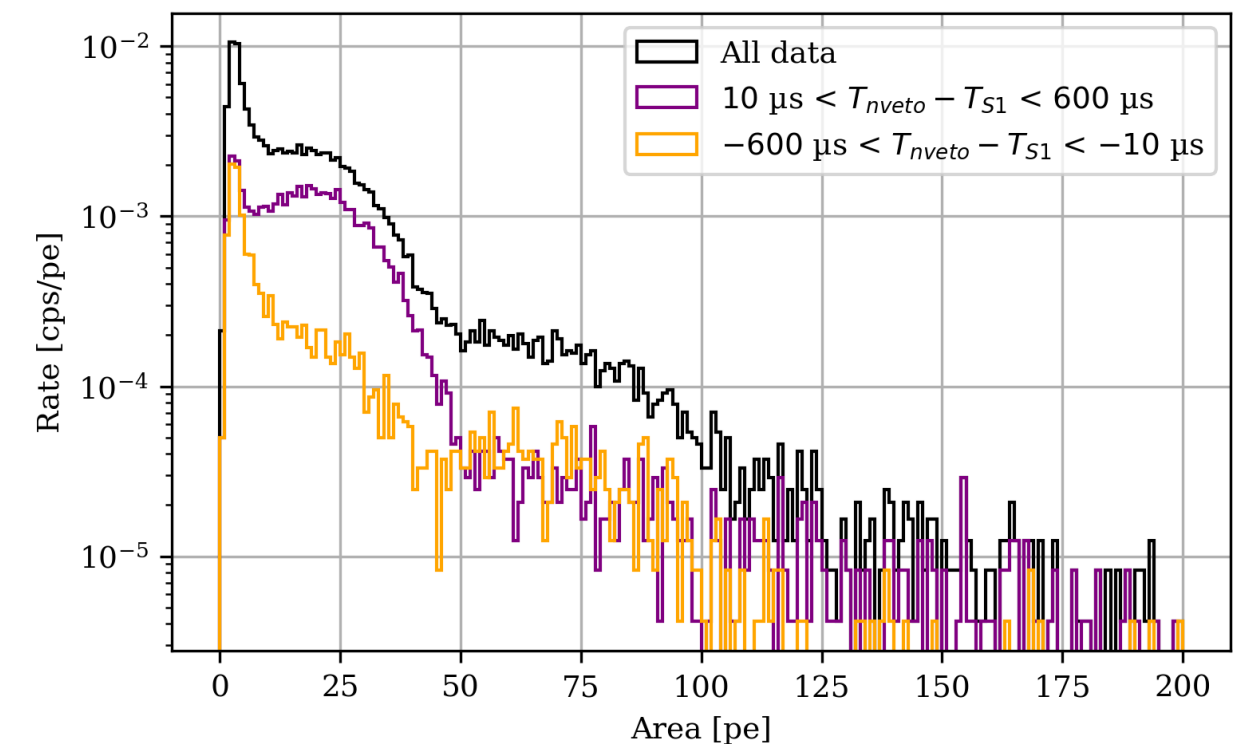
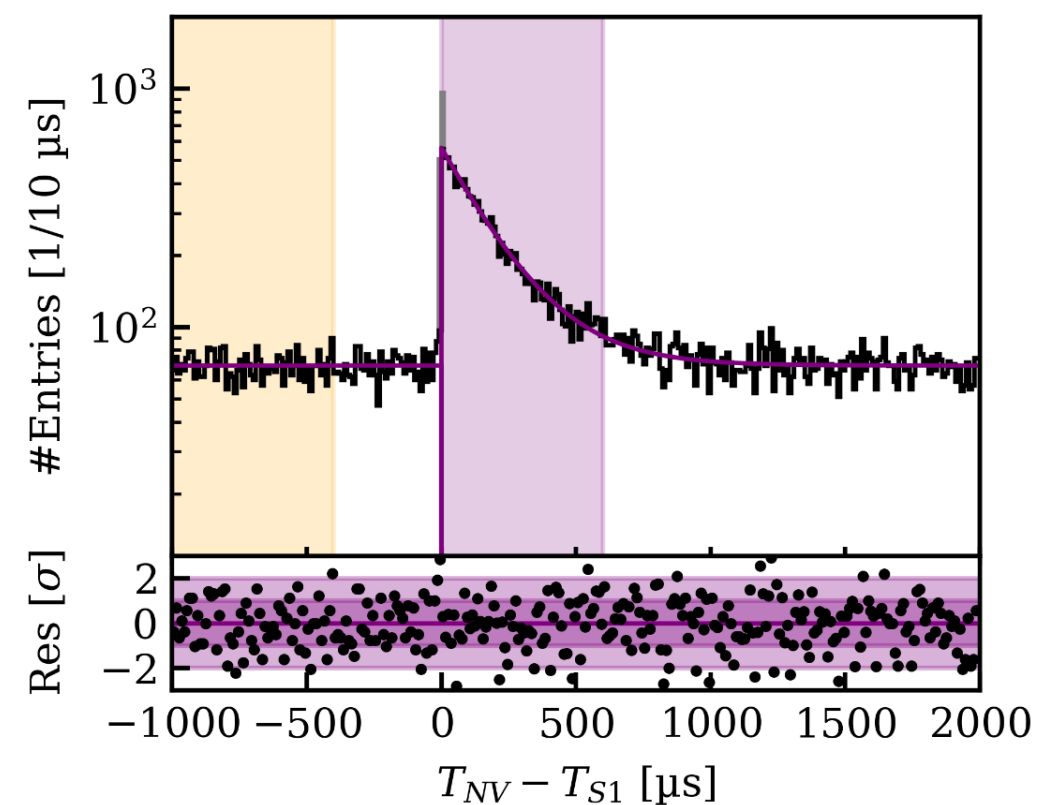
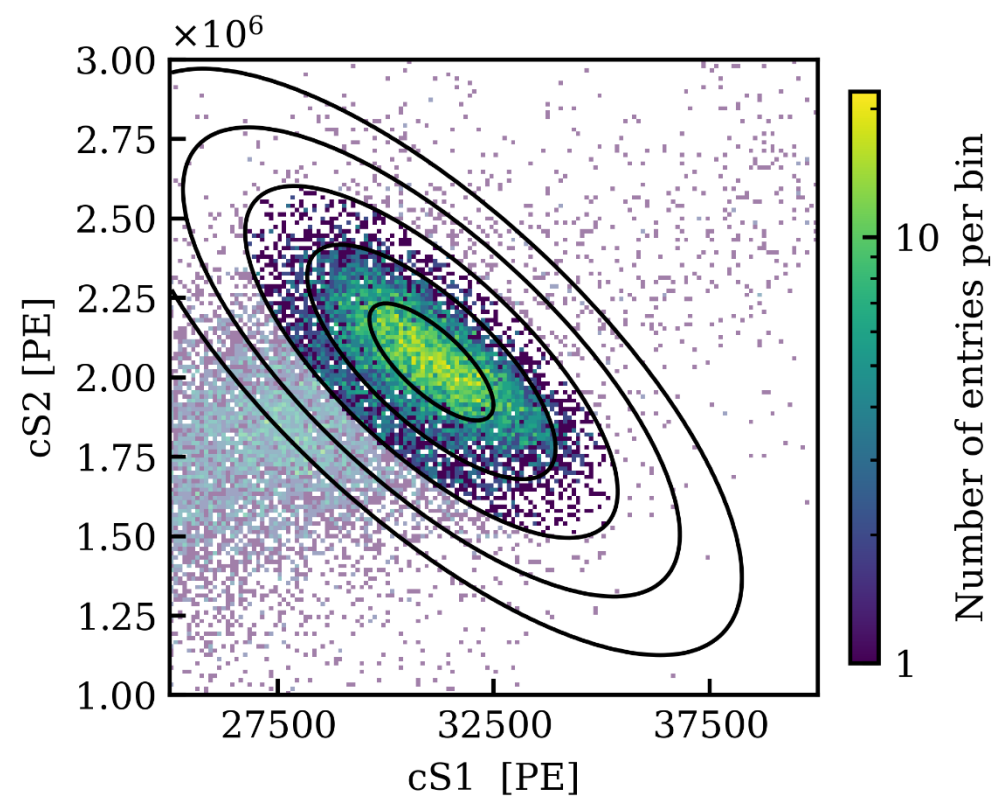
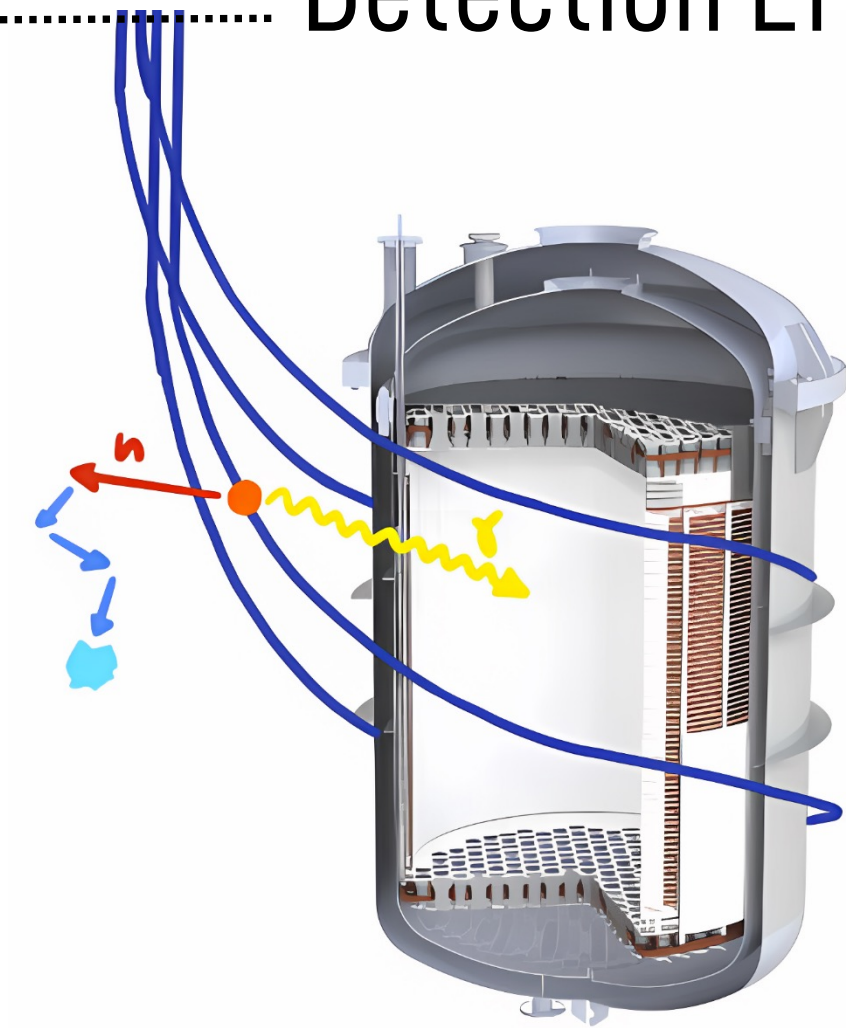
# Detection Efficiency

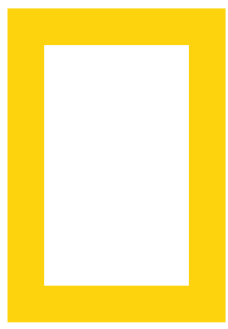
## Detection Efficiency:

$$\eta = \frac{\text{Number of neutrons seen by the nVeto}(A_{th}); \text{given } \gamma \text{ seen by the TPC}}{\text{number of } \gamma \text{ seen by the TPC}}$$

## Step of the analysis

- 1 - Background-free selection of 4.4 MeV gammas in the TPC
- 2 - Definition of **Background region** and **ROI** in the event time distribution
- 3 - Subtract ROI and bkg area spectra
- 4 - Evaluation of Detection efficiency efficiency (Area threshold)

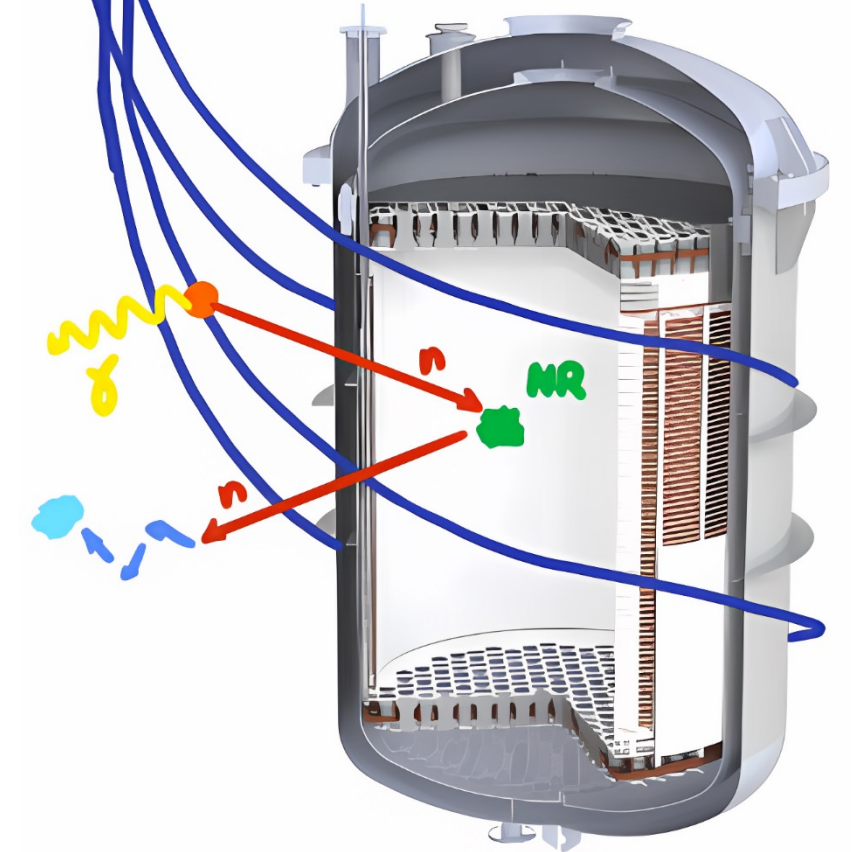




# Calibration

# Tagging Efficiency

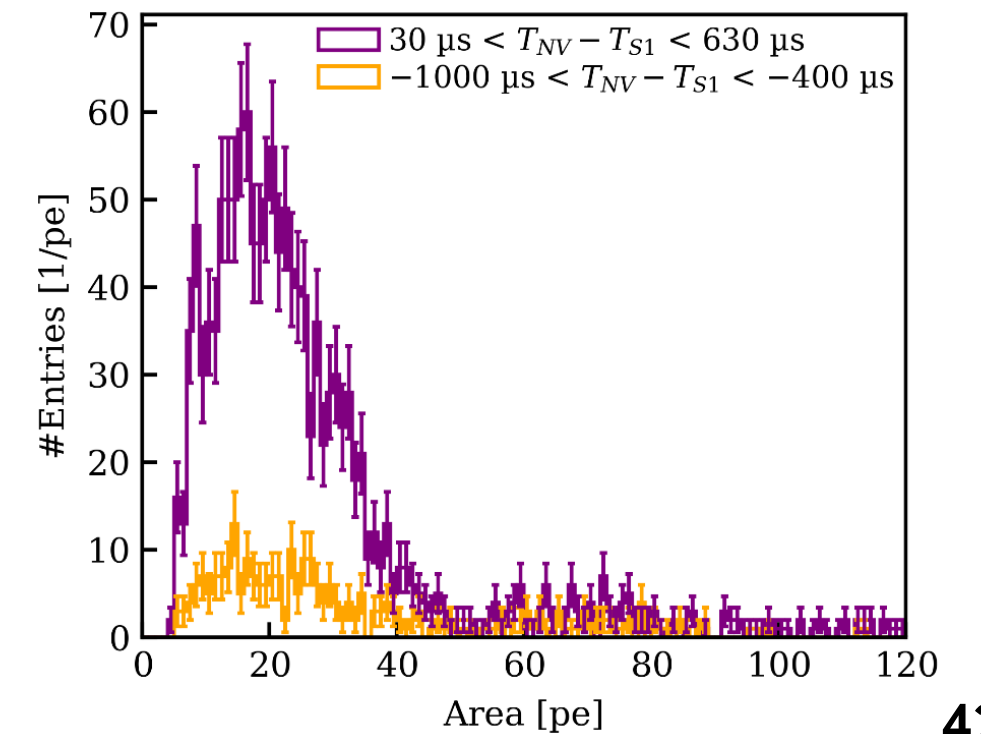
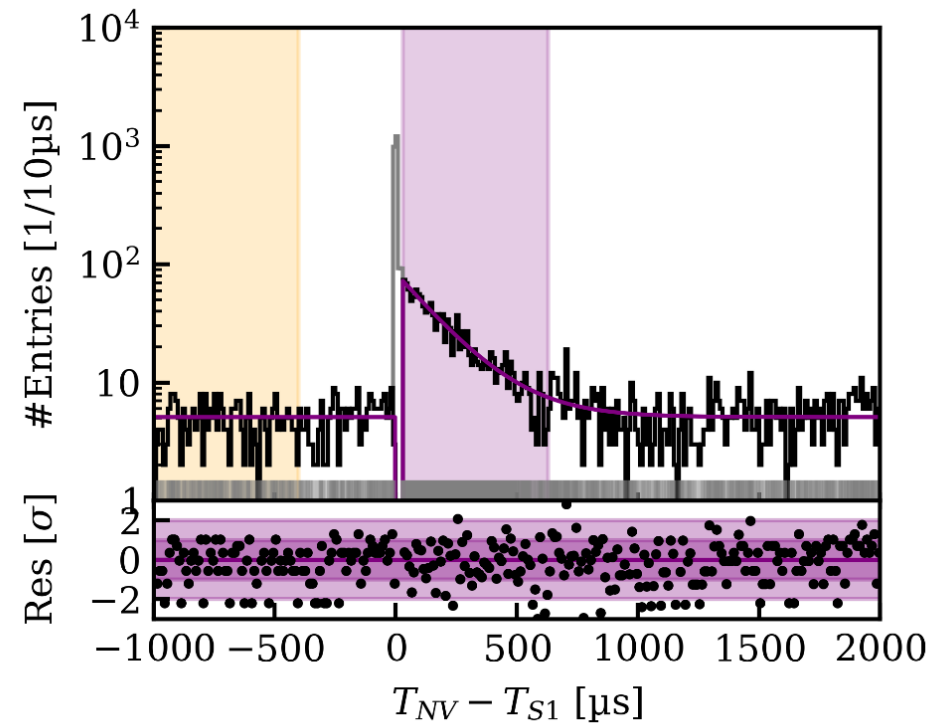
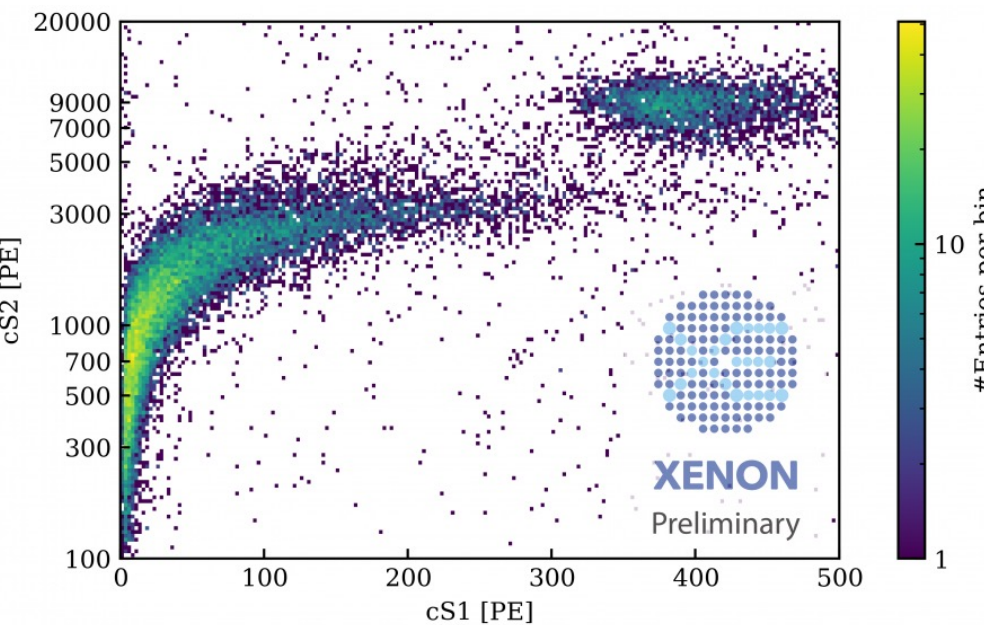
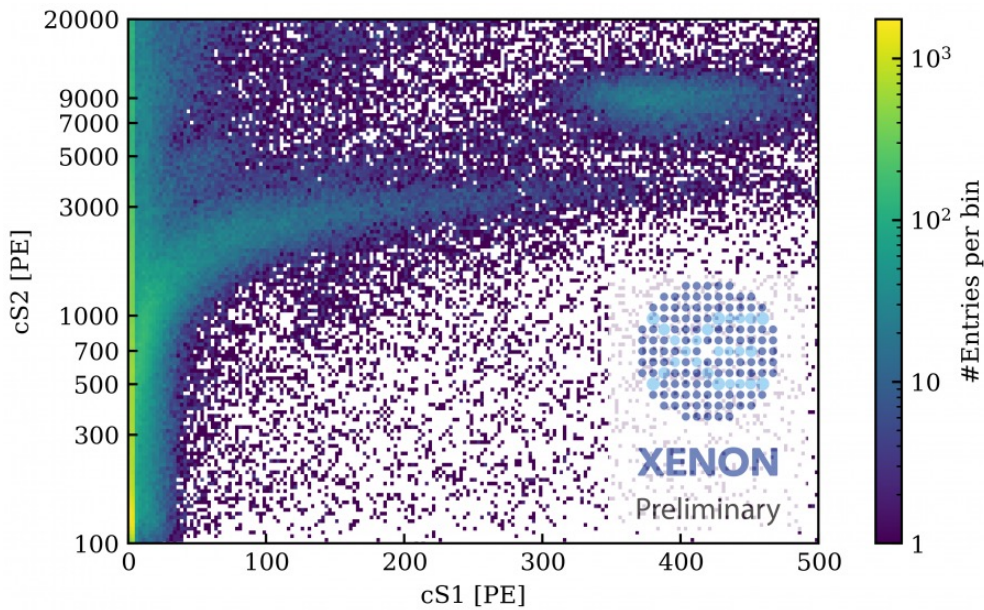
**Tagging Efficiency:** =  $\frac{\text{number of neutrons}}{\text{number of triggering NR}}$



## Step of the analysis

- 1 - Search of coincident events
- 2- Definition of **Background region** and **ROI**
- 3- Subtract ROI and bkg area spectra
- 4- Evaluation of Tagging efficiency (Time window / Area threshold)

Spectrum of selected NR events (NV-TPC coincidence)



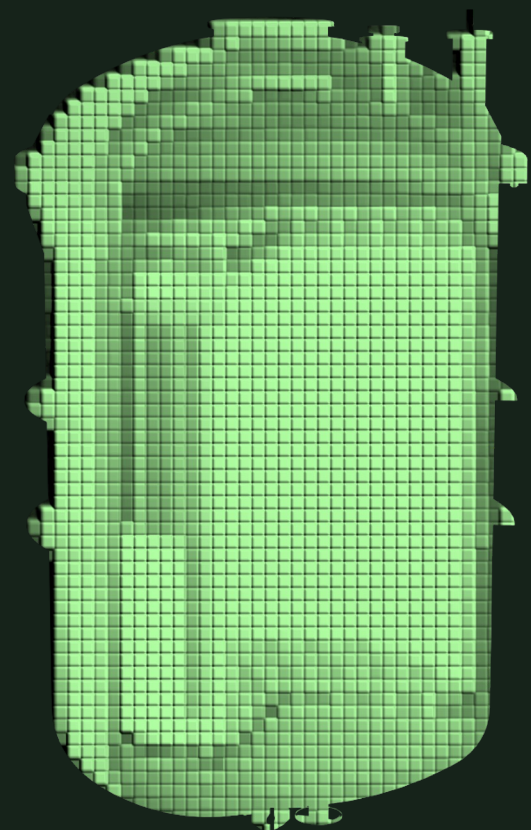
Neutron Veto's  
**HIT - SIMULATOR**

A fast and efficient simulator for NV hitlets and events.

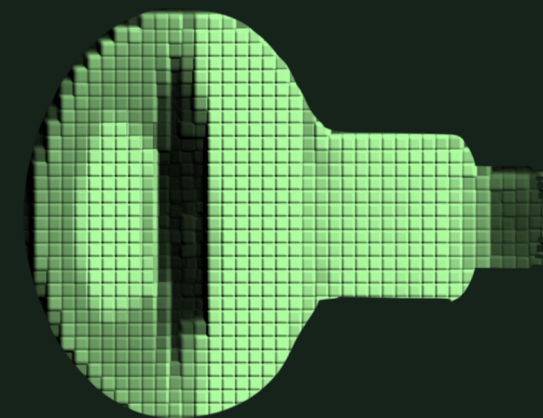


Neutron Veto's

# HIT - SIMULATOR



EPIX



HITSIM

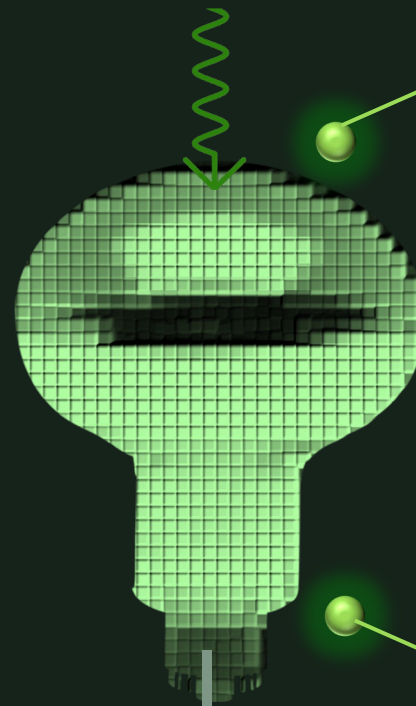
Geant4: takes care of all the physics process and particles propagation;

EPIX: Start processing-chain of TPC simulated data;

HitSim: Designed as a fast and efficient simulator for NV hitlets and events

# Neutron Veto's HIT - SIMULATOR

HITSIM



SURVIVING PROBABILITY

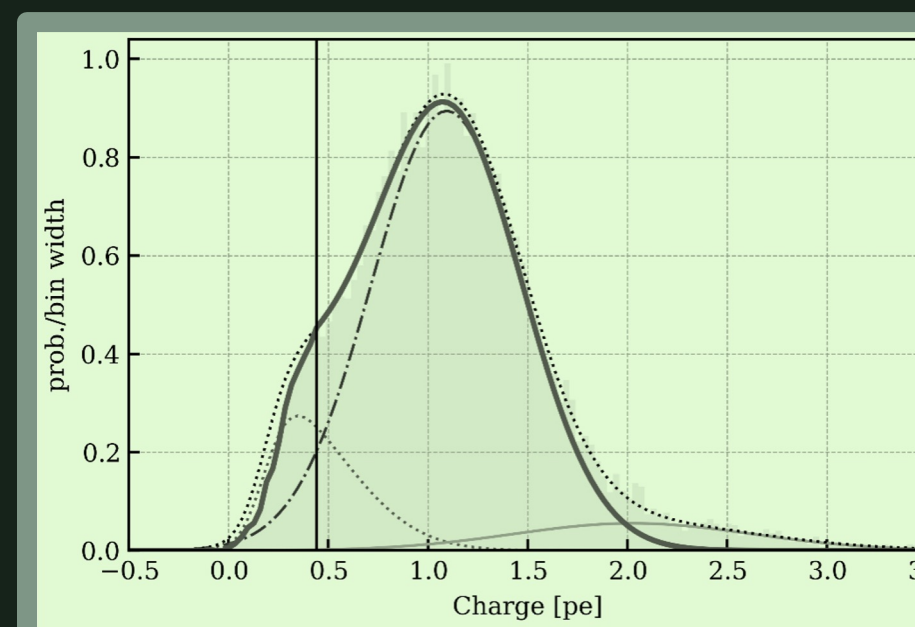
$$p_{det}(\lambda) = \text{Binom}(n = 1, p = \text{QE}_i(\lambda) \cdot \text{SPE}_{\text{Acc.}} \cdot \text{eCE})$$

- QE: Quantum efficiency - Wavelength & PMT dependent (120 curves)
- SPE Acceptance: Calculated from SPE PDF (120 values ~ 95%)
- eCE : Effective Collection Efficiency - scaling (MC-Data match)

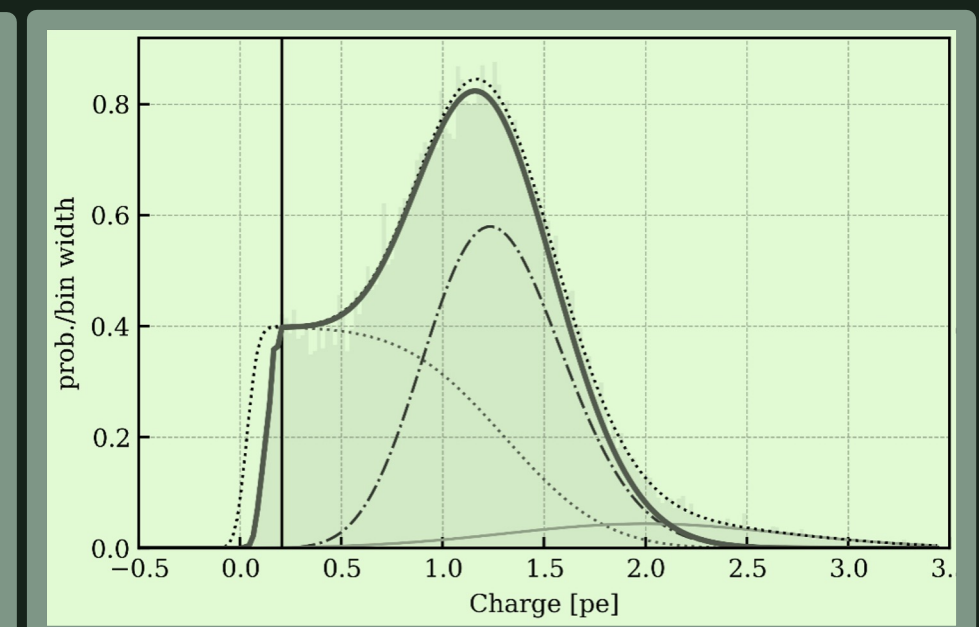
$$(\text{eCE})_{\text{SR0}} = 75\% - (\text{eCE})_{\text{SR1}} = 87\%$$

CHARGE SAMPLING

SR0 Model



SR1 Model

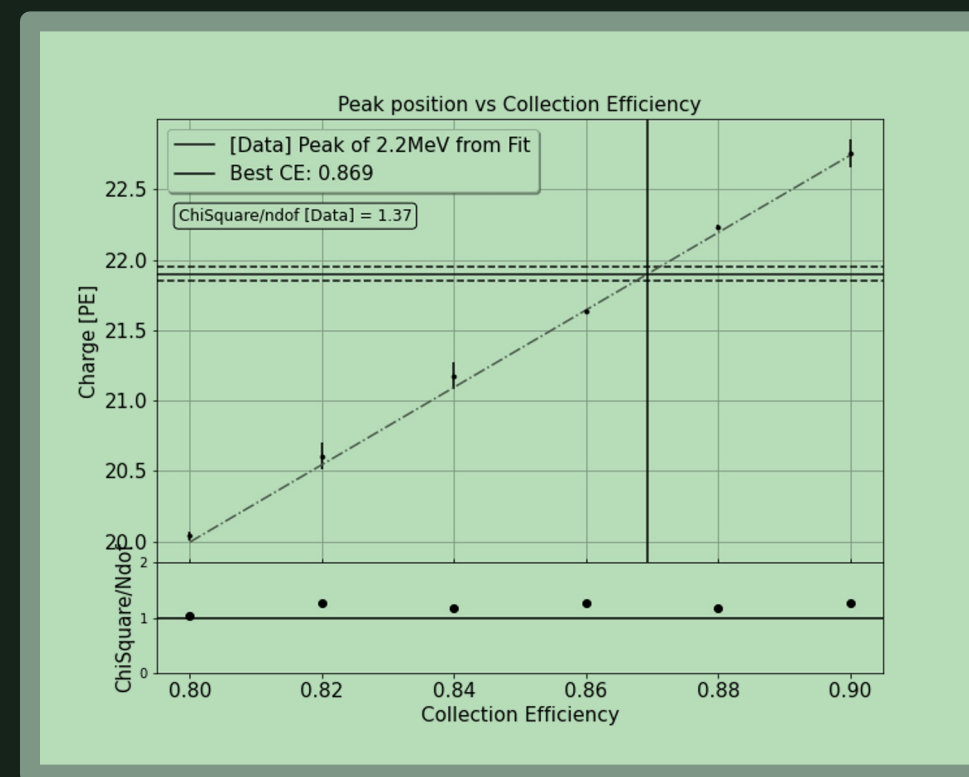


- Hit distribution over time (source rate)
- Signal clusterization
- Hitlets generation
- Event generation

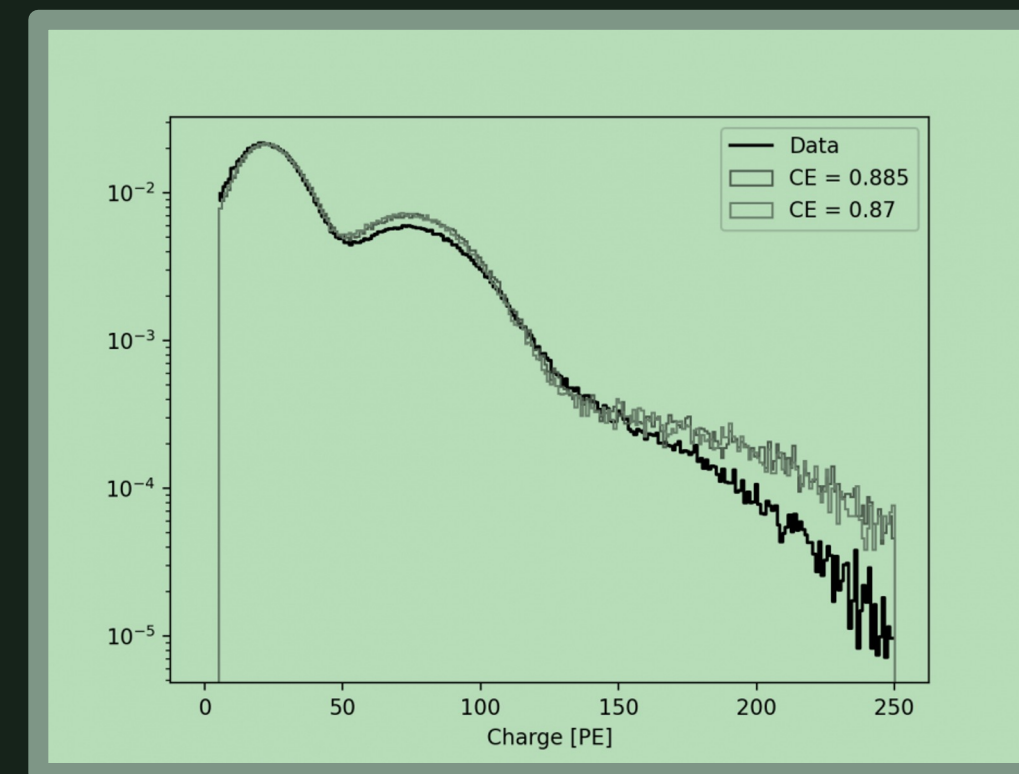
# Neutron Veto's **HIT - SIMULATOR**



## MC - DATA MATCHING



$$(eCE)_{SR0} = 75\% \quad (eCE)_{SR1} = 87\%$$



### Hitlet Simulator purpose:

The development of the hitlet simulator as allowed us to predict the tagging efficiency varying the Gd concentration, as well as to perform other studies e.g. neutron inelastic scattering, neutron captures outside the water.

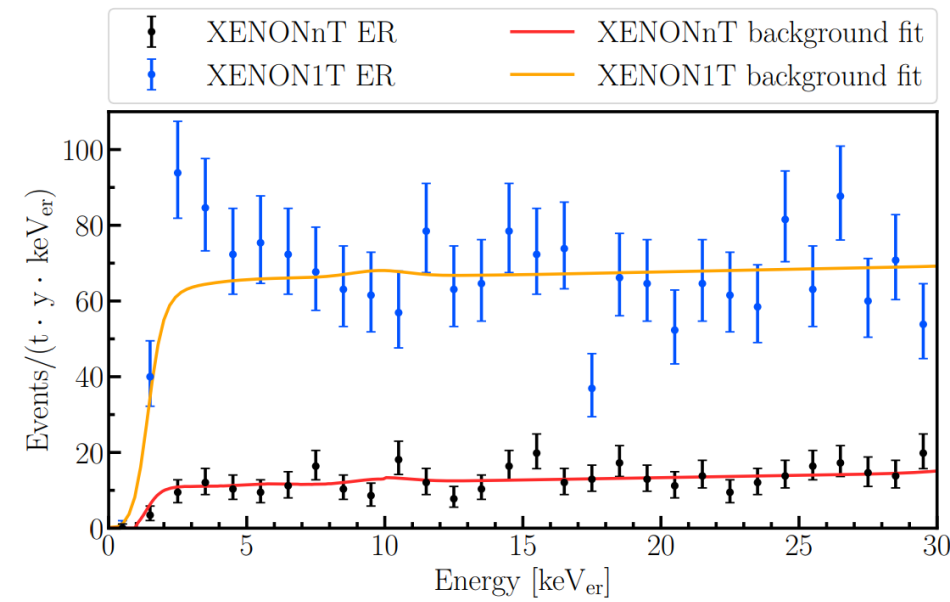




SR0

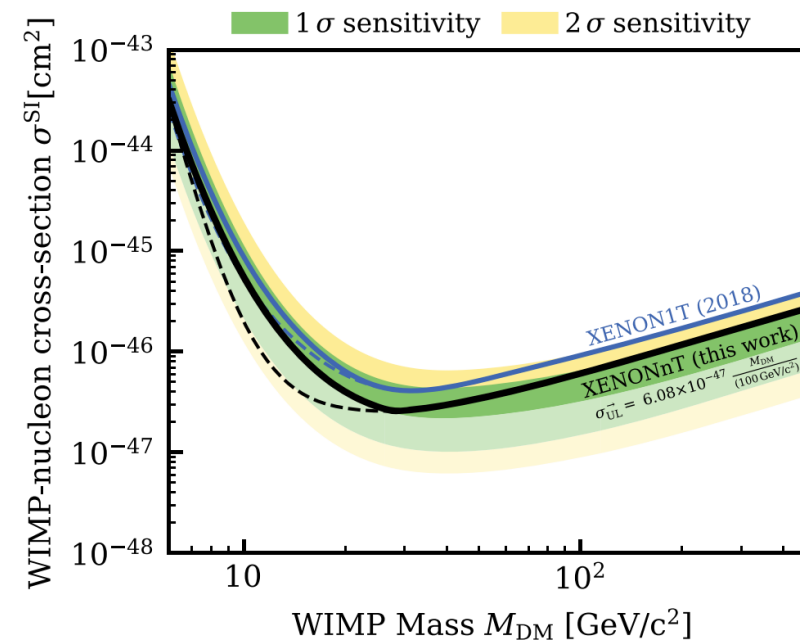
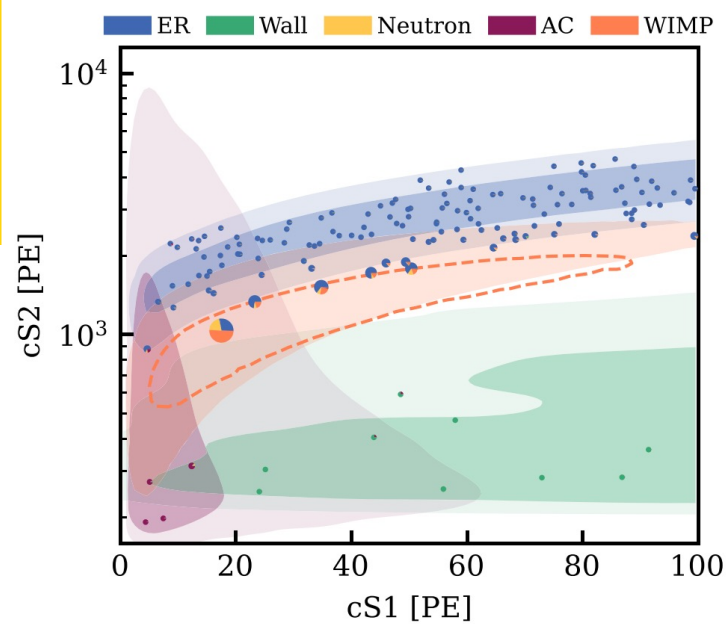
SR1

SR2



**Search for new physics in ER Data**

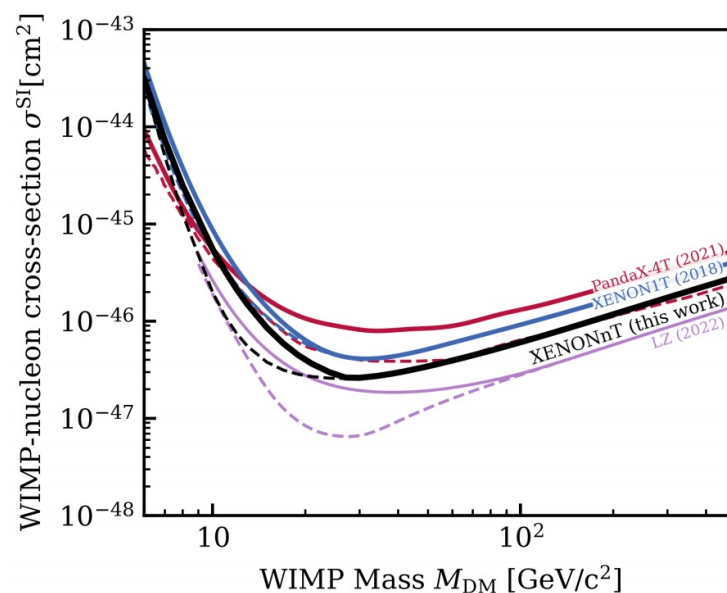
The XENONnT ER background is  $\sim 5\times$  lower than that of XENON1T. No excess with respect to the background model is observed in the XENONnT data.



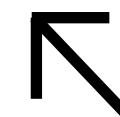
**First Dark Matter search with NR Data**

The analysis for WIMP discovery revealed no significant. The most stringent upper limit observed is  $2.58 \times 10^{-47} \text{ cm}^2$  at a WIMP mass of  $28 \text{ GeV}/c^2$ , at a 90% confidence level.

After the unblinding, the ROI contained a total of 152 events, with 16 of these located in the blinded WIMP search area.



	Nominal		Best fit	
	ROI		Signal-like	
ER	134	$135^{+12}_{-11}$	$0.92 \pm 0.08$	
Neutrons	$1.1^{+0.6}_{-0.5}$	$1.1 \pm 0.4$	$0.42 \pm 0.16$	
CEvNS	$0.23 \pm 0.06$	$0.23 \pm 0.06$	$0.022 \pm 0.006$	
AC	$4.3 \pm 0.9$	$4.4^{+0.9}_{-0.8}$	$0.32 \pm 0.06$	
Surface	$14 \pm 3$	$12 \pm 2$	$0.35 \pm 0.07$	
Total background	154	$152 \pm 12$	$2.03^{+0.17}_{-0.15}$	
WIMP	...	2.6	1.3	
Observed	...	152	3	

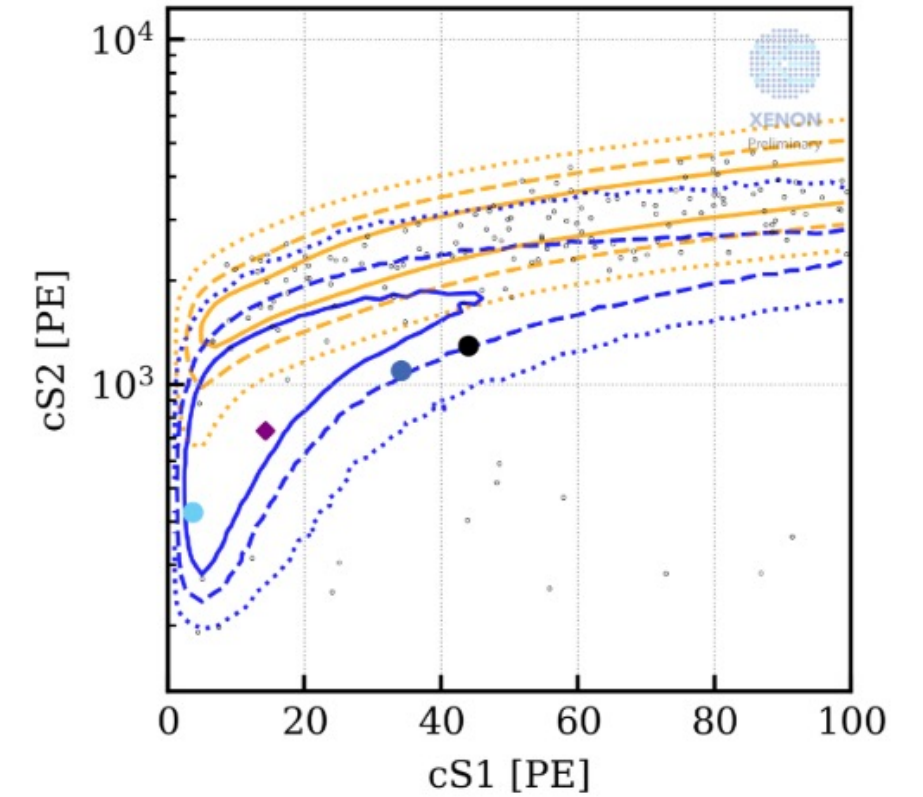
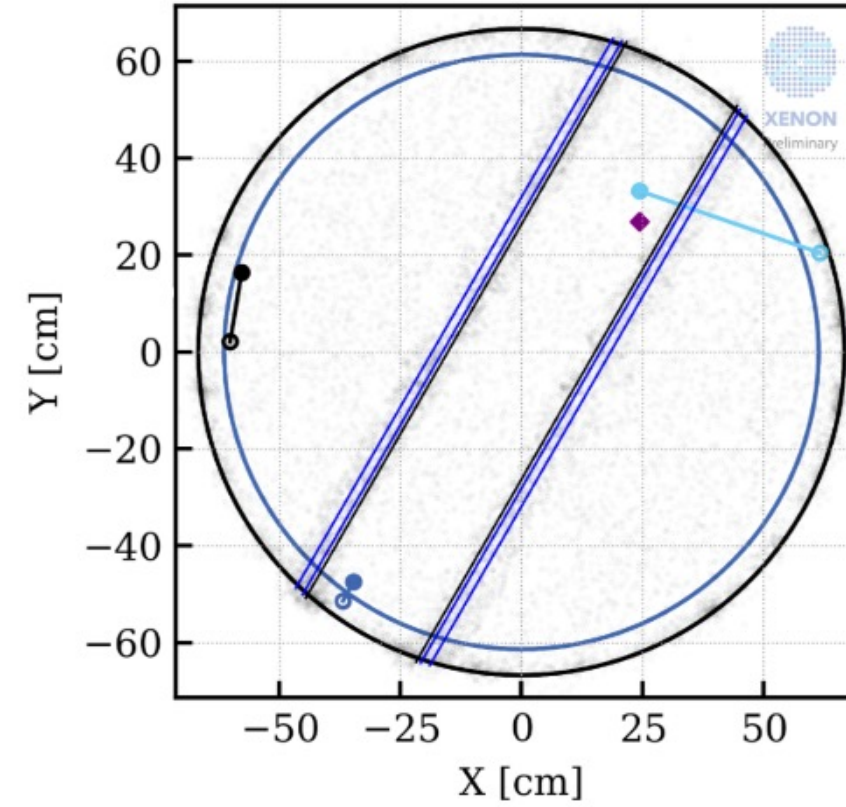
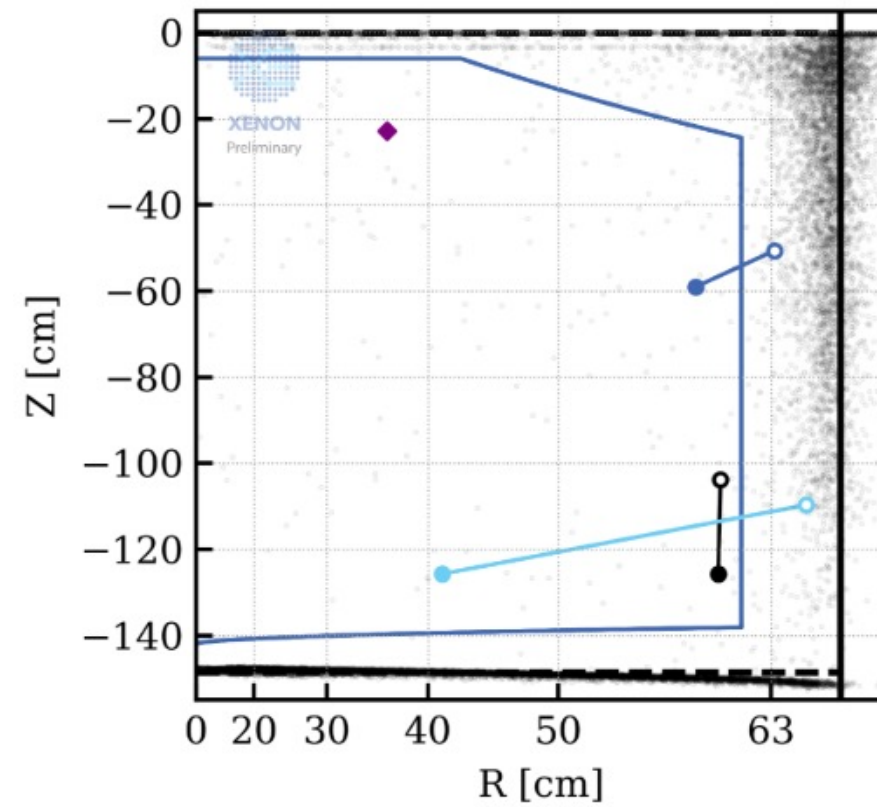


Fiducial Volume :  $(4.18 \pm 0.13) \text{ t}$   
 Livetime : 97.1 days  
 Total exposure of  $(1.09 \pm 0.03) \text{ t x y}$   
**Neutron Veto : Demi Water**

Science Run 0

## Impact of the Neutron Veto

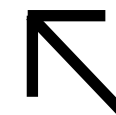
In the search for Nuclear Recoil events, the nVeto has been used to tag multiple and single scatter NR events in the TPC, to obtain a data-driven estimation of the neutron background.



### Neutron Background prediction:

Considering the 3 MS events plus 1 SS that are tagged by the nVeto, where the primary S2 within the FV, and considering the MS/SS ratio = 2.5 obtained from MC validated with AmBe data, as well as the 53% nVeto tagging efficiency, we obtained a neutron background prediction of  $(1.1 \pm 0.5)$  neutron-induced events in SR0

This is x6 times larger than MC predictions based on material screening; The origin of the higher-than-expected neutron background in SR0 has been found to originate from the inner vessel's top flange and is now included correctly in SR1 neutron model



Fiducial Volume :  $(4.18 \pm 0.13)$  t  
 Livetime : 97.1 days  
 Total exposure of  $(1.09 \pm 0.03)$  t x y  
**Neutron Veto : Demi Water**

Science Run 0

SR0

SR1

SR2



## Preliminary Results

The SRI+SR0 exposure will be used in a combined WIMP search to achieve a 3.6 tonne-year exposure

### Three science analyses ongoing (data still blinded):

- A search for low energy NR from CEvN scattering of solar neutrinos
- A search for WIMP-nucleon elastic scattering
- A search for low-energy ERs from elastic scattering of solar pp neutrinos

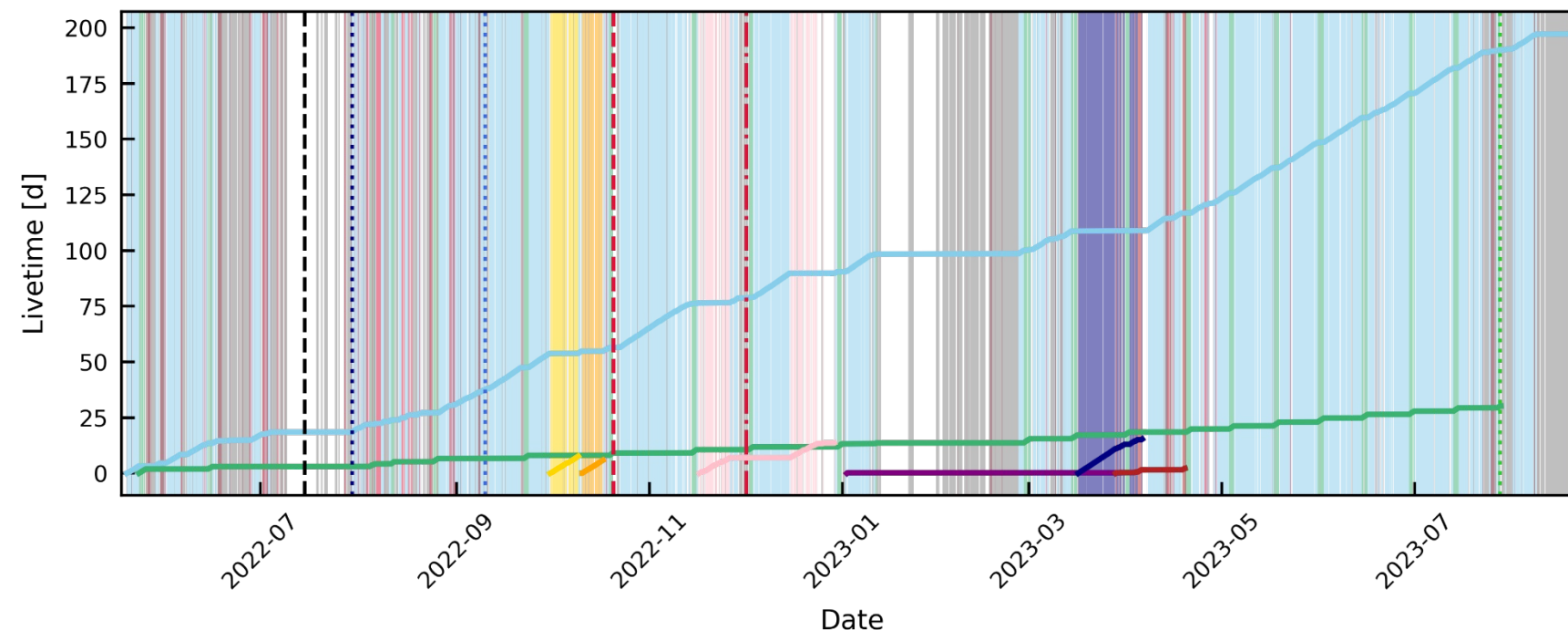
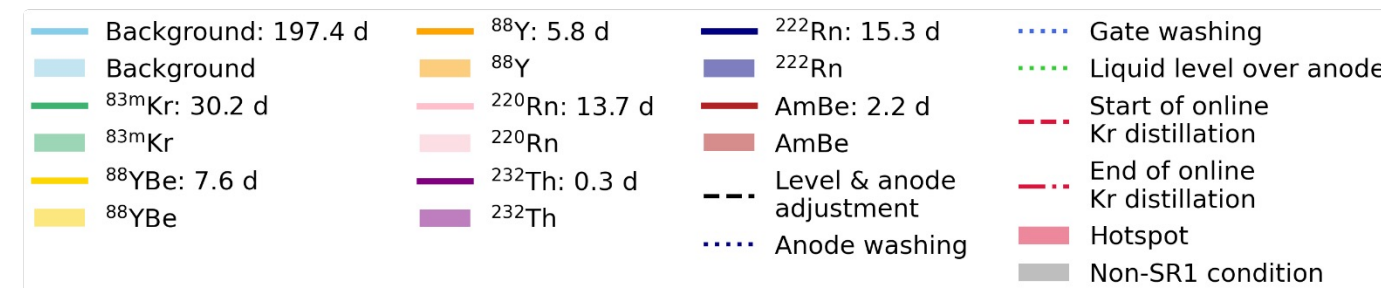
## Improved performances wrt SR0

maintenance on the radon distillation columns leading to an unprecedentedly low level of  $< 1 \mu\text{Bq/kg}$ .

Enhancement of NV PMTs  
Increased the HV of the PMTs (+200V) to improve the SPE Acceptance.

### Increased Tagging Efficiency

$(56 \pm 2) \%$  -  $250 \mu\text{s}$  **(+5%)<sub>SR0</sub>**  
 $(70 \pm 2) \%$  -  $600 \mu\text{s}$



Fiducial Volume : tbd  
Livetime : 189 days  
Total exposure of  $\sim 2.5 \text{ t} \times \text{y}$   
**Neutron Veto : Demi Water**

Science Run 1

SR0

SR1

SR2





# What's new?

	Neutron capture cross-section	$\gamma$ energy	Mean capture time
H	0.33 b	Single $\gamma$ , 2.2 MeV	200 us
Gd	49000 b	3-4 $\gamma$ , 8 MeV in total	30 us*

For a 0.2% Gd mass concentration

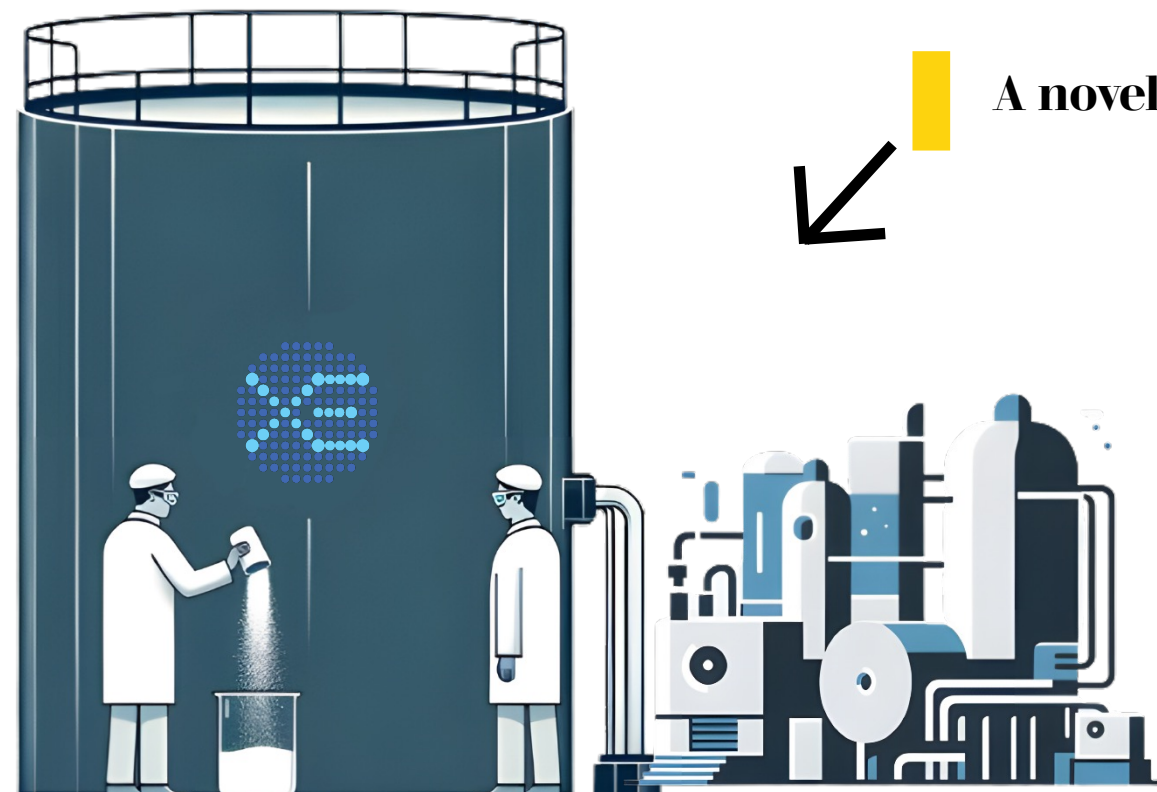
SR0

## The main news is the Gd-doping of the Neutron Veto:

- Gadolinium Sulfate Octahydrate ( $Gd_2(SO_4)_3 \cdot 8H_2O$ ) injected into WT through GdWPS in various steps
- Reached 0.02 % Gd mass concentration which corresponds to 350 kg of GdSO (500 ppm GdSO)
- With Gd, expected neutron tagging efficiency of about 77%

SR1

SR2



A novel purification plant for Gd-water.



Start Date: 12/10/2023

Fiducial Volume : tbd

Lifetime : to-date 100 days

Total exposure of -- t x y

**Neutron Veto : Gd-Water**

Science Run 2

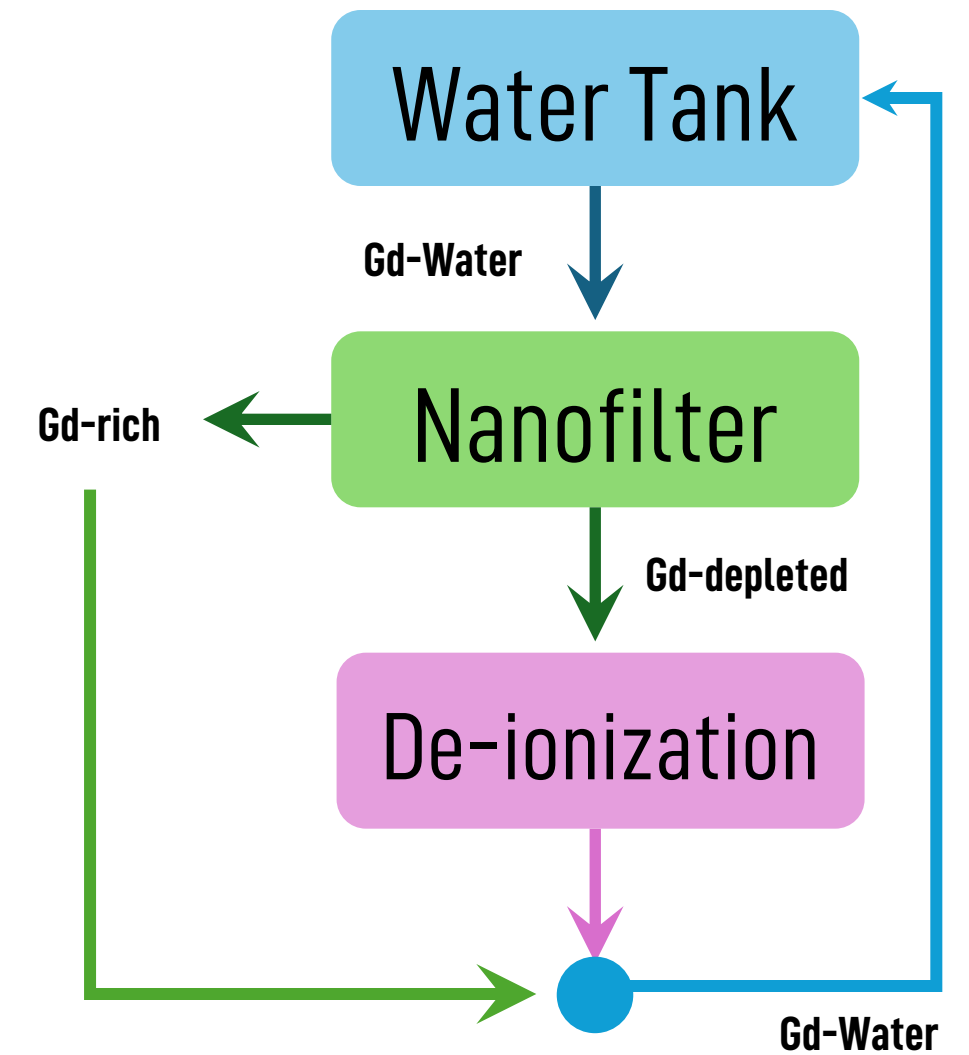
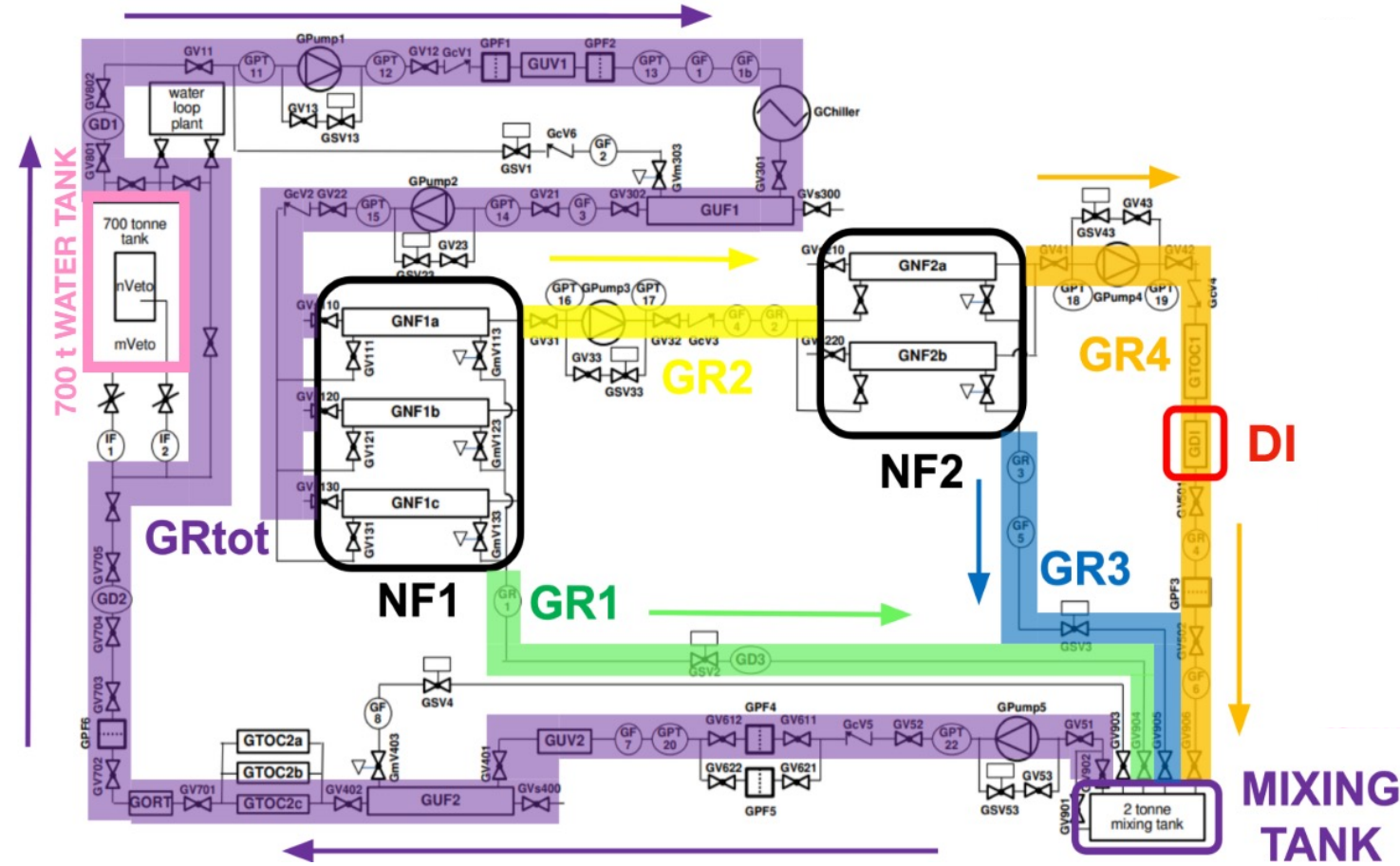


# The GdWPS

SR0

SR1

SR2



## EGADS

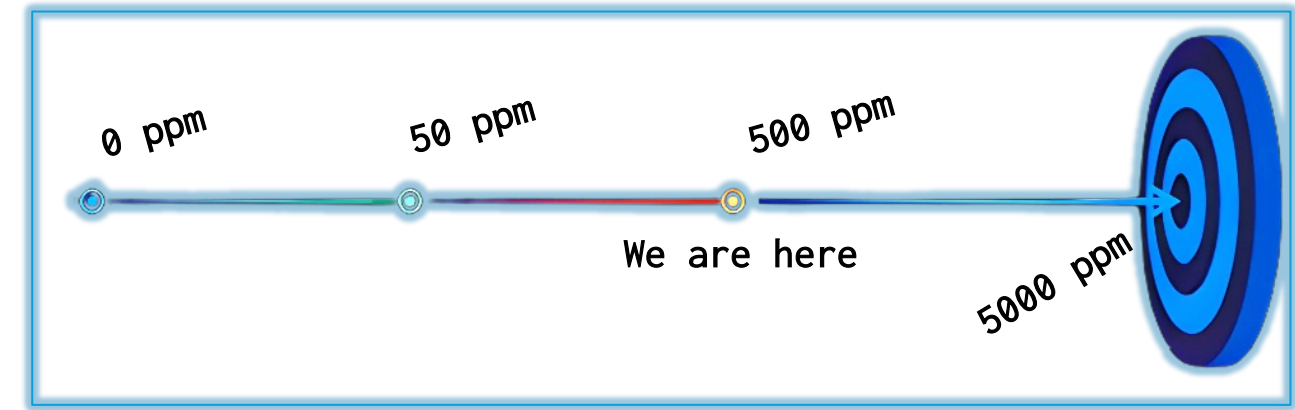
The design and operational strategy of the GdWPS were inherited from the EGADS (Evaluating Gadolinium's Action on Detector Systems) facility, located in the Kamioka mine. Its primary purpose was to establish that incorporating Gd into the SK detector would be both safe and effective.



# Plan for Gd injection

## How much Gd do we need?

By design we plan to reach a concentration of 0.2%.  
 Currently we are at 0.02% with which the fraction of Gd capture is about 60% .

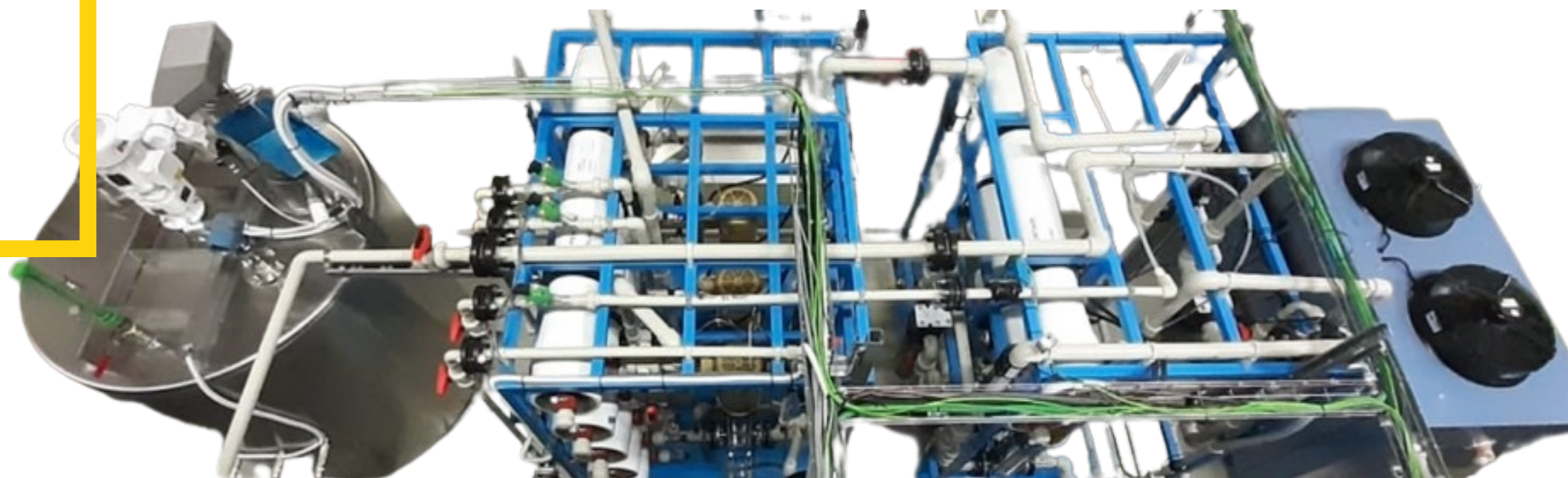
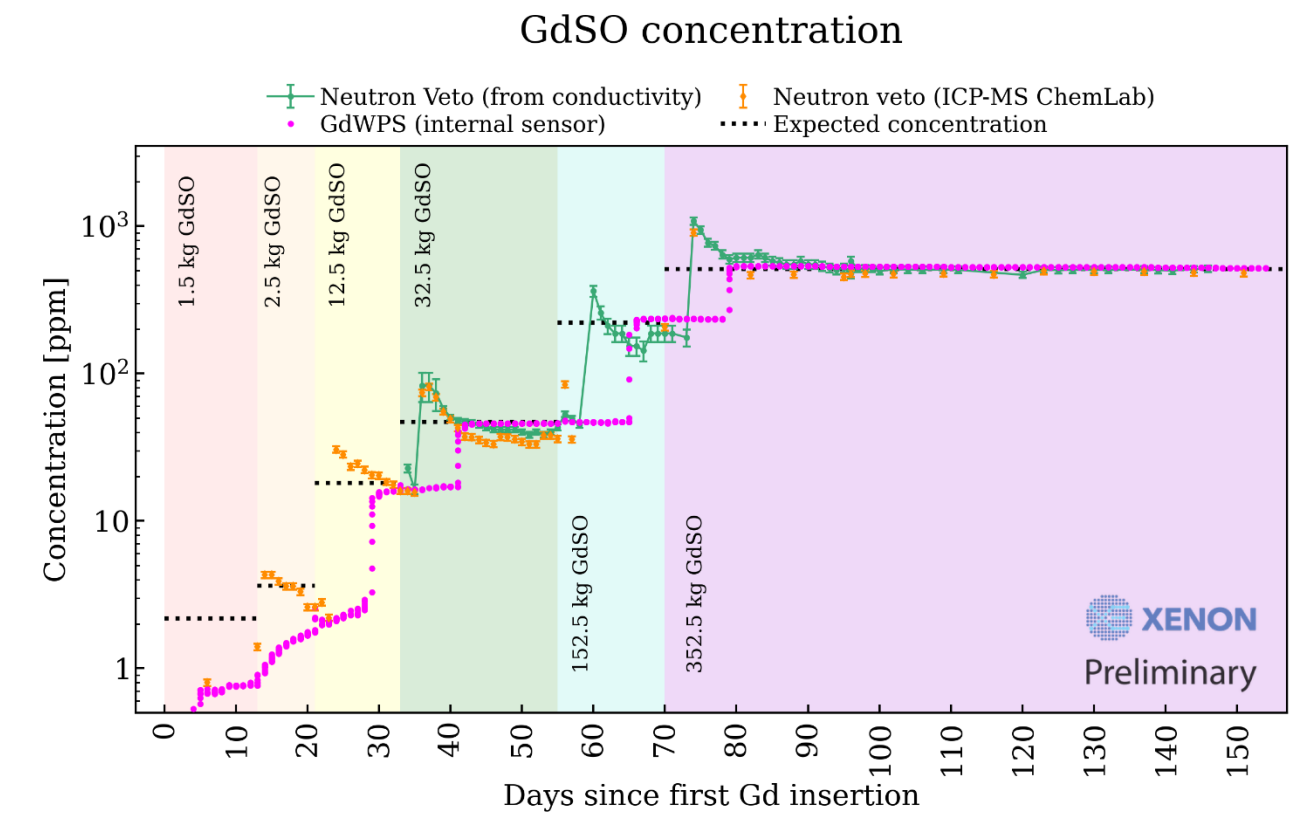
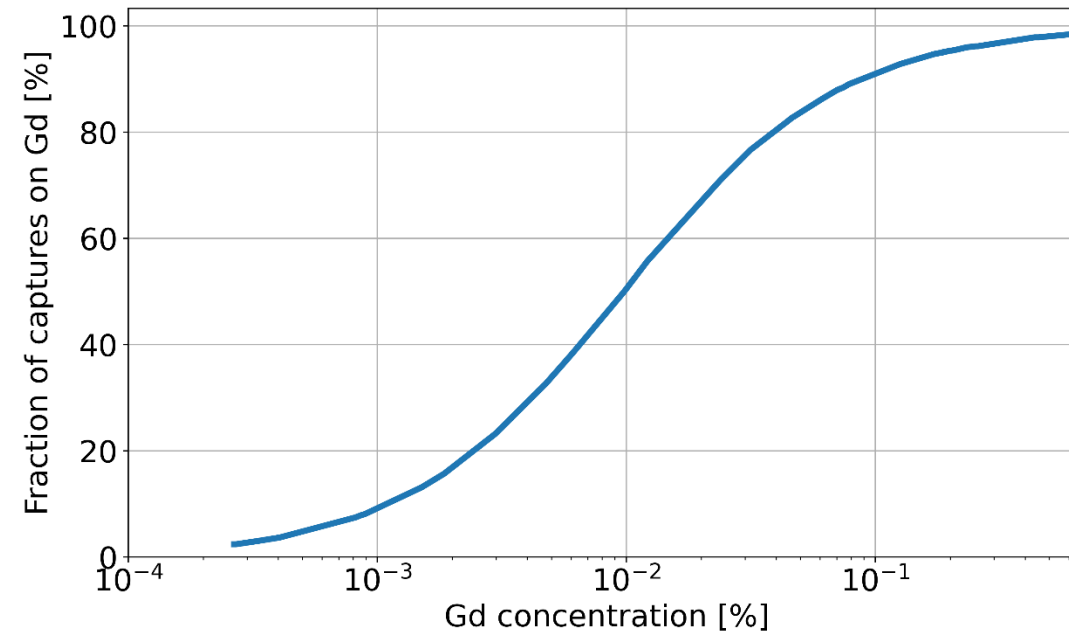


Target Concentration

SR0

SR1

SR2



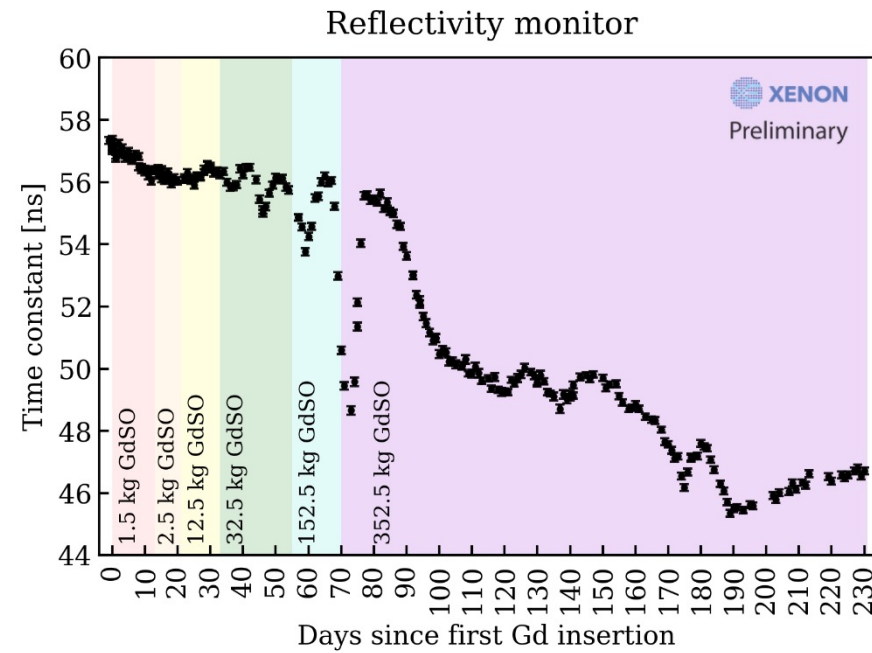


# Impact of Gd Concentration of 500 ppm

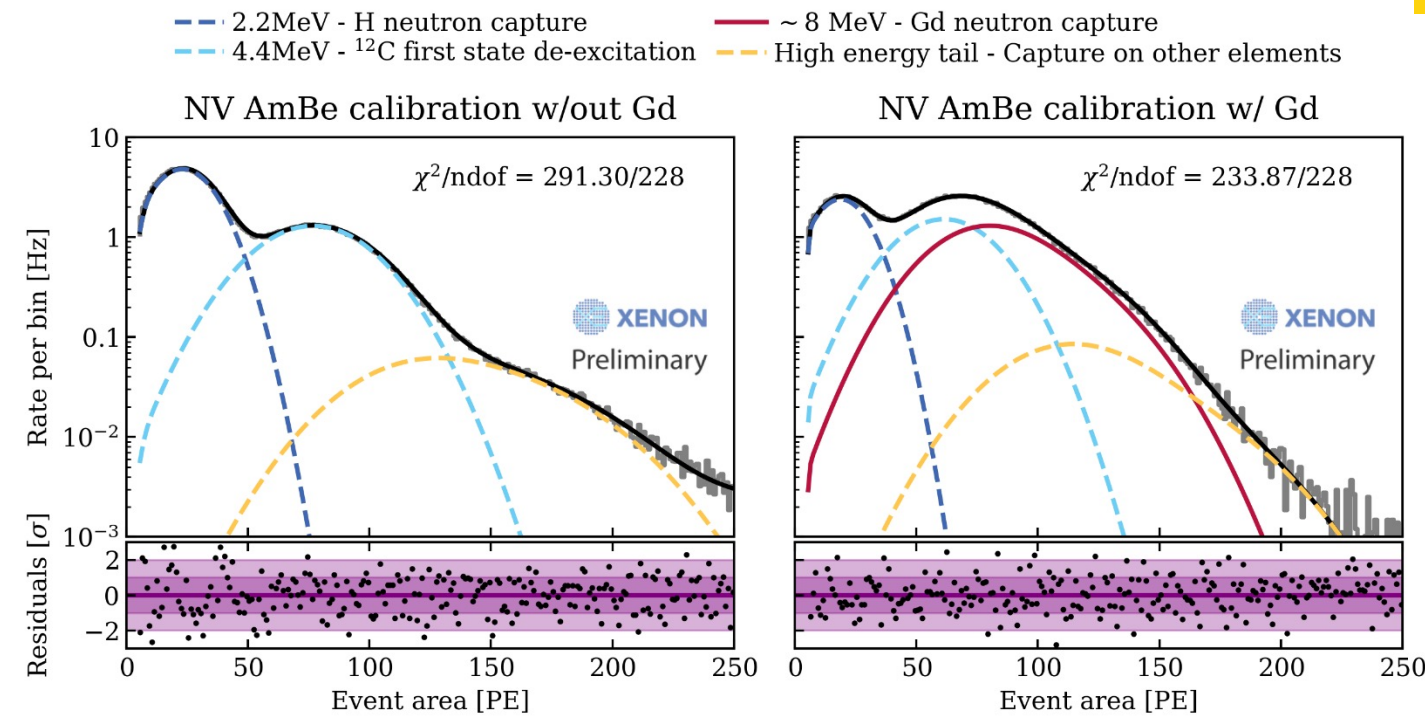
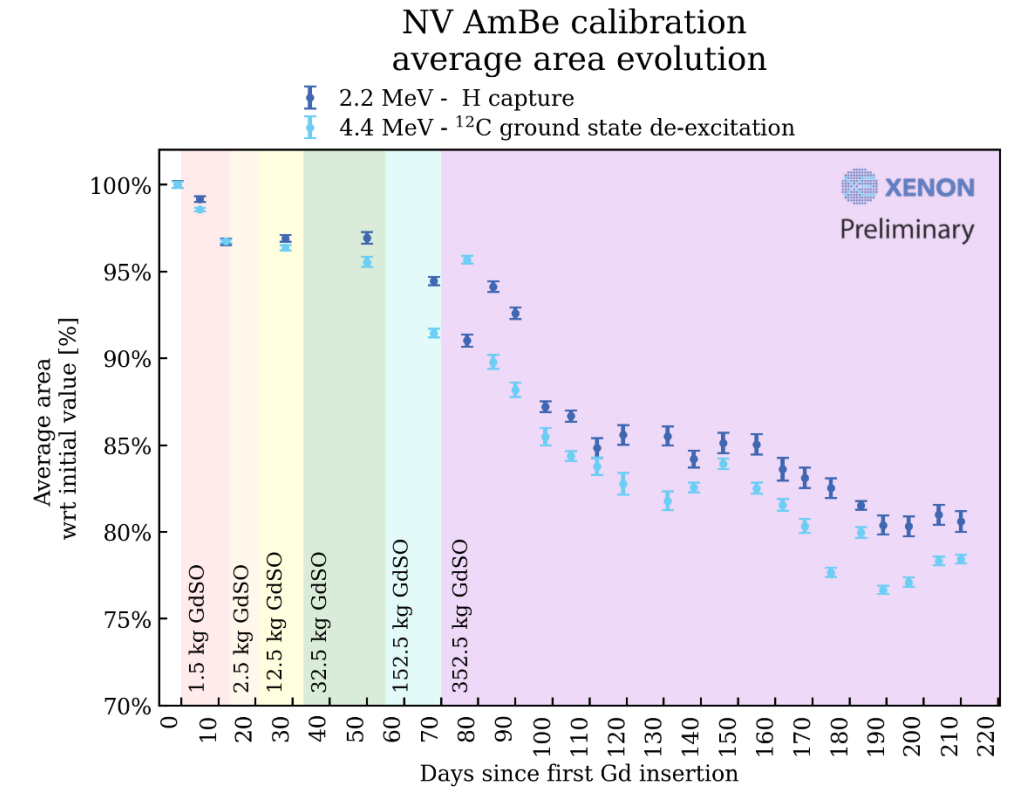
SRO

SR1

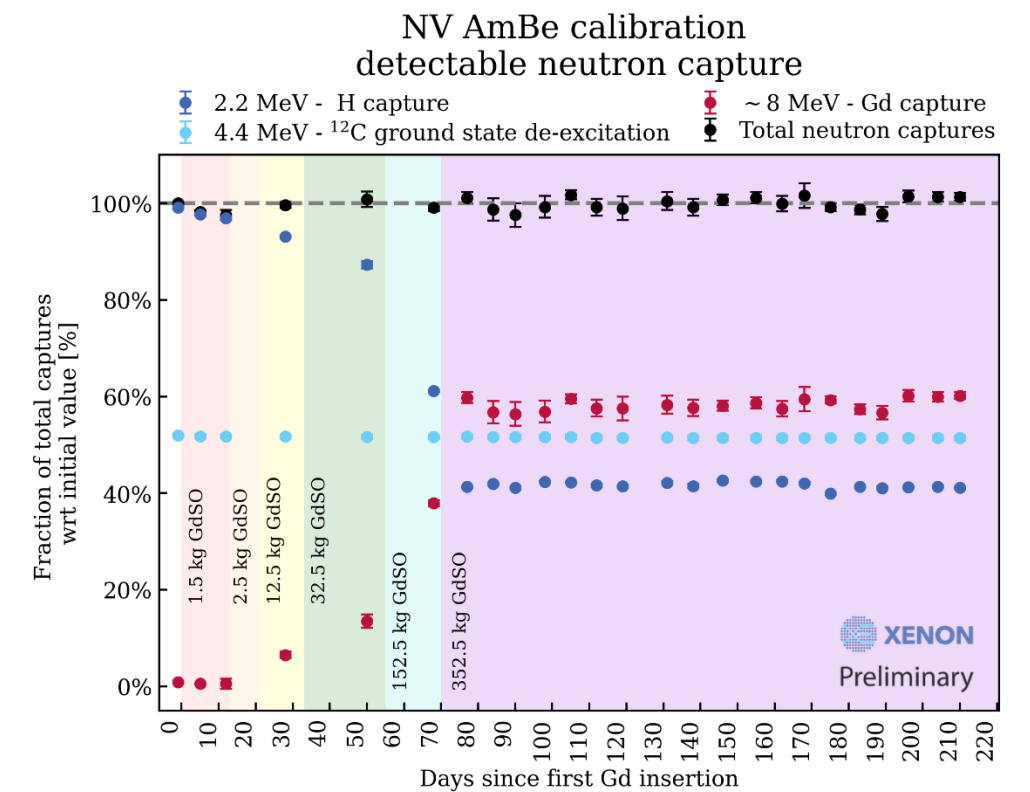
SR2



**Optical Properties:**  
As soon as we dissolved GdSO in water we observed a degradation of the optical properties monitored with the reflectivity monitor. This is reflected in a shift of the 2.2 MeV and 4.4 MeV peak towards lower area.



**However:**  
The total number of n-capture does not change.





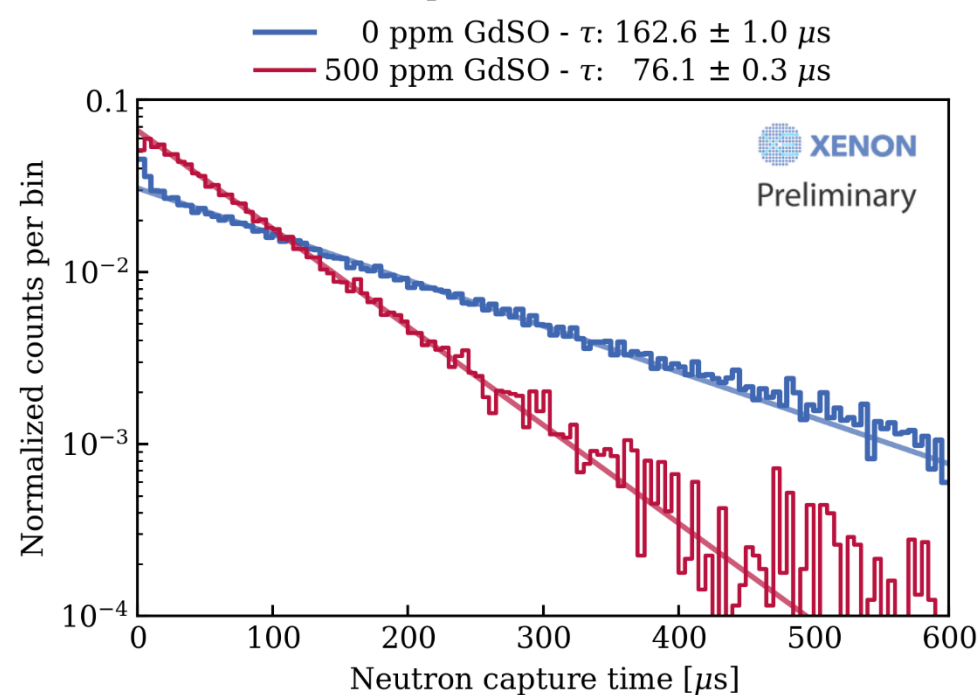
SR0

SR1

SR2



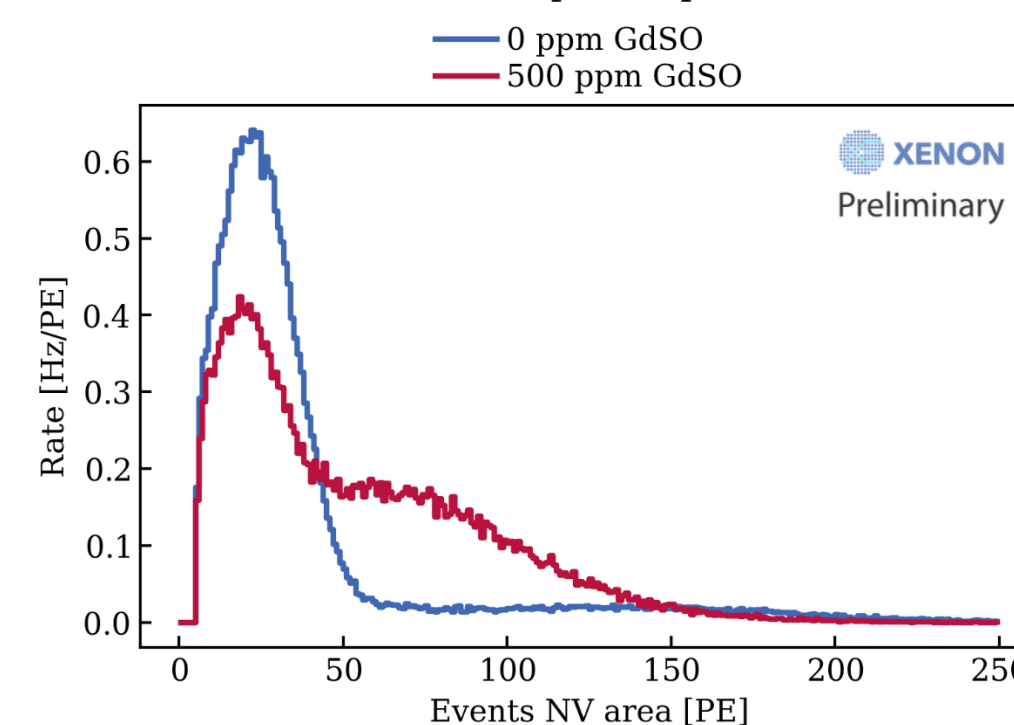
AmBe calibration  
Neutron capture in Gd-loaded water



### Neutron Capture Time

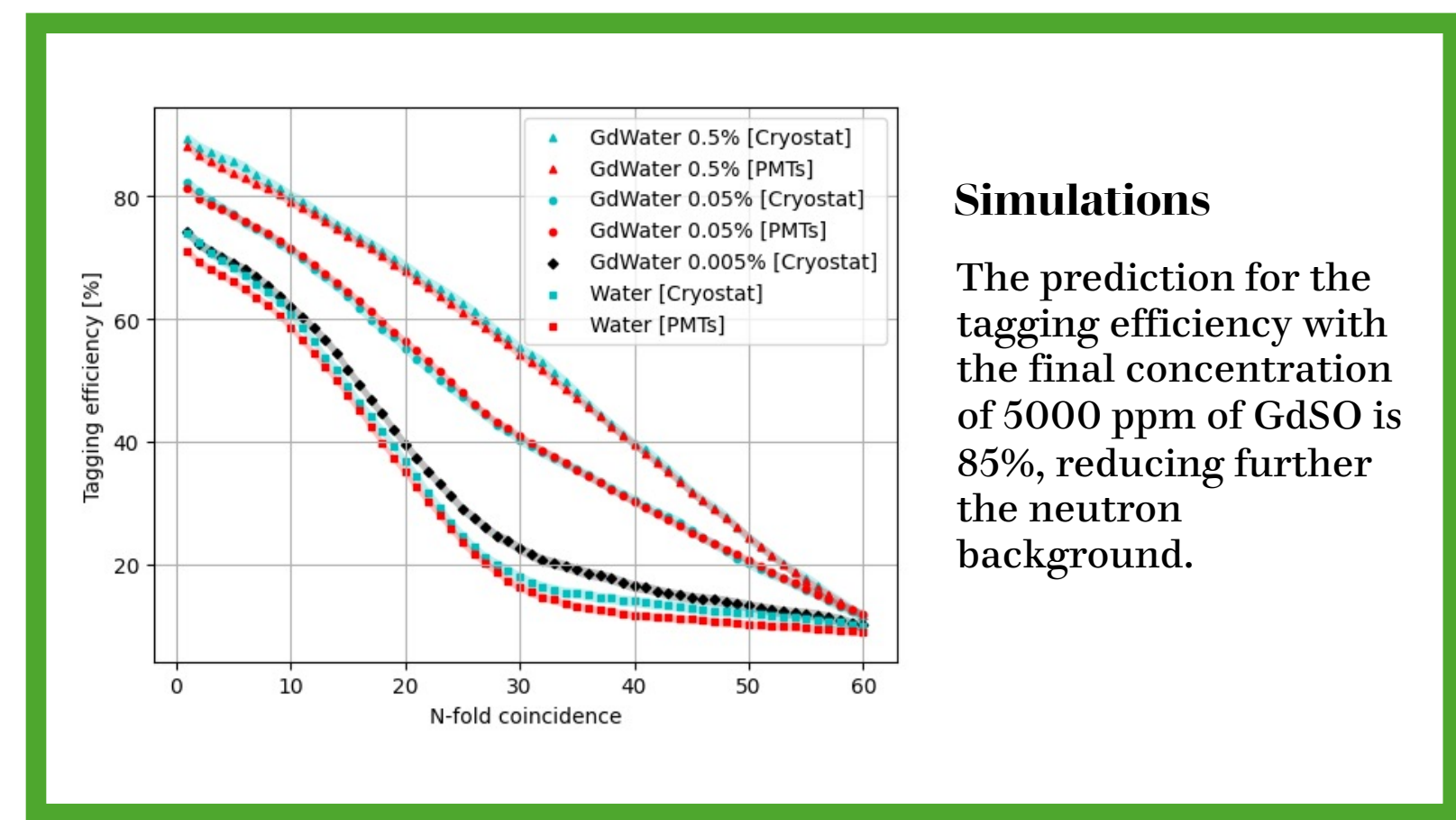
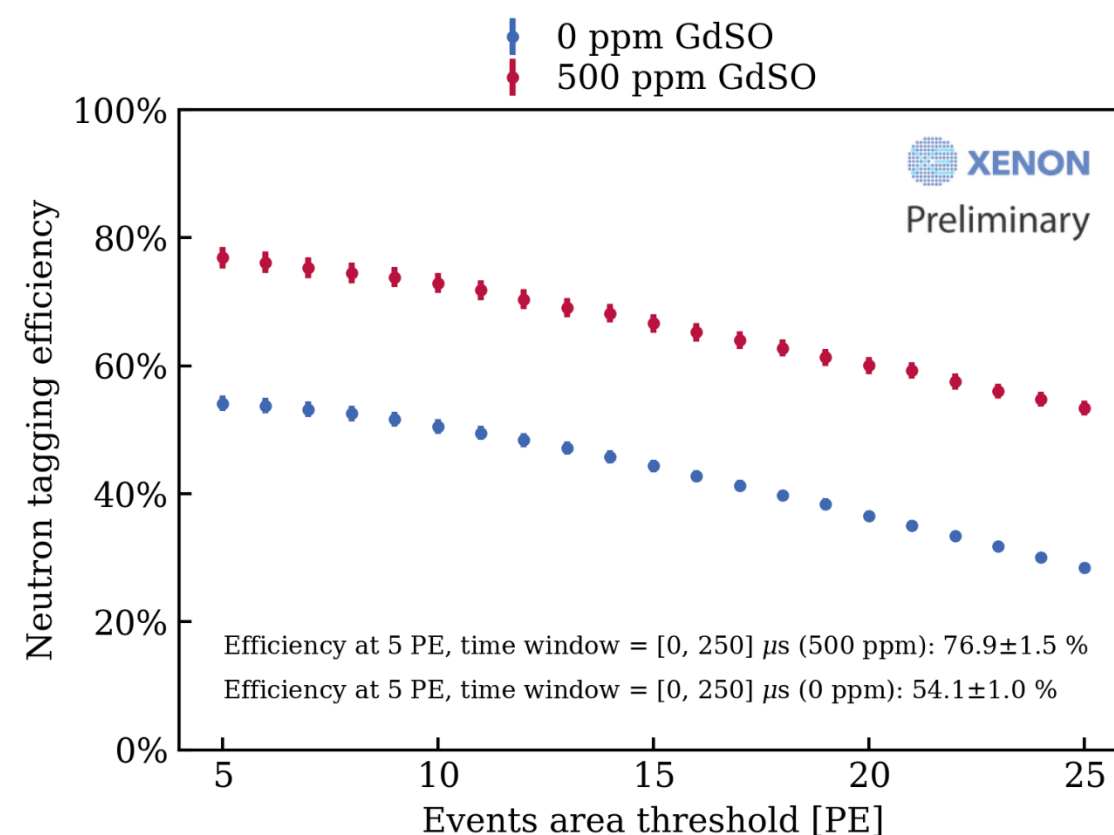
Results to be 2x shorter than in demi water. The larger area associated to Gd captures increase of 10% the neutron captures.

AmBe calibration  
Neutron capture spectrum



### Neutron tagging efficiency

with 500 ppm of GdSO, in a 250 us time window, is about 77% (compared to 53% in SR0):  
**a factor 2 neutron background reduction** wrt SR0 with demi-water



### Simulations

The prediction for the tagging efficiency with the final concentration of 5000 ppm of GdSO is 85%, reducing further the neutron background.

# SUMMARY

## The XENONnT Experiment

The XENON Dark Matter Project at LNGS uses a dual-phase xenon TPC to detect WIMPs. The latest phase, XENONnT, built in 2020, features an enlarged TPC with 5.9 tons of liquid xenon and a new Gadolinium-loaded water Cherenkov Neutron Veto. The experiment is currently taking data in the so-called Science Run 2 after the first two science runs have been successfully completed.

## The Neutron Veto

The NV has been the focus of my PhD research, from its design to data analysis. It addresses one of the key challenges in DM detection, i.e. distinguishing WIMP-induced NRs from backgrounds. Neutrons from detector materials can mimic WIMP signals, affecting the detection sensitivity. The NV mitigates this by tagging the radiogenic neutrons.

The NV is a Gd-loaded water Cherenkov detector which has demonstrated excellent performance already in its water-only phase (SR0 and SR1). The performances are parametrized by the Tagging Efficiency, which has been estimated to be  $(56 \pm 3)\%$  [SR1] with a  $250 \mu\text{s}$  coincidence window, having a negligible impact on the TPC downtime.

The NV excellent performances are the results of the PMT characteristics [ High Gain, Low Dark Rate & noise level -> Low DAQ threshold] and the excellent optical properties of the ePTFE.

## The Gadolinium phase

In SR2 we have dissolved Gd-sulphate for a concentration of 500 ppm [0.02% Gd mass] in the Water Tank. This has enhanced the NV tagging efficiency, reaching a value of  $(77 \pm 3)\%$  [SR2] with a  $250 \mu\text{s}$  coincidence window. The capture time is reduced of a factor 2. MC simulations built around a dedicated NV simulator, predict a reduction of a factor 2 in the neutron background compared to SR0.

## Results and Future prospects

XENONnT, despite the hardware problems on the electrodes, has produced competitive results in the WIMP search with the SR0 data analysis. Thus, the SR1 analysis is very promising. The future prospect is to have an NV with the nominal Gd Concentration of 5000 ppm to lead the ground to the next project, Darwin, which could opt for the same technology to reduce the neutron background.

Follow the project on : <https://xenonexperiment.org/> & all the main social networks

# THANK YOU

