Optimization of the Light Detection System of the ICARUS detector

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on behalf of the ICARUS Collaboration

Imaging Cosmic And Rare Underground Signals

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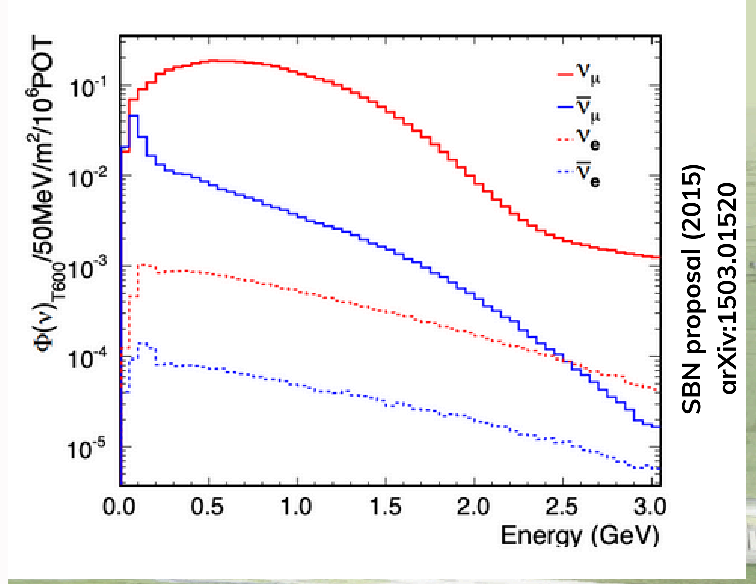
Siciliae Studium Generale 1434

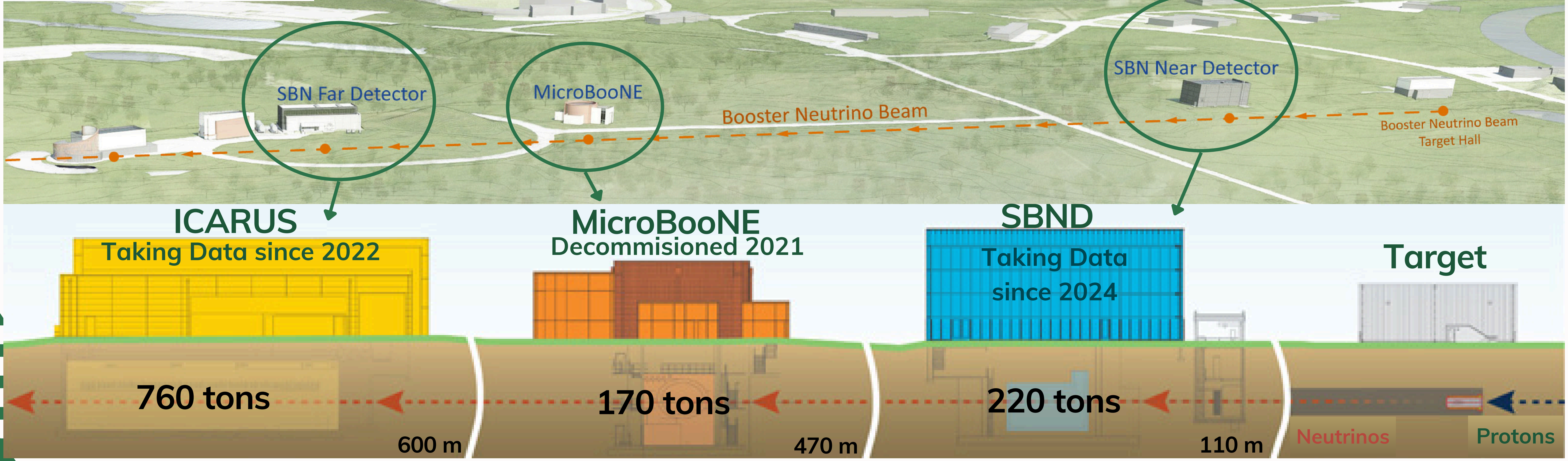
The Short-Baseline Neutrino Program

Short-Baseline → $L/E \leq 1 m/MeV$

LAr -TPC detectors



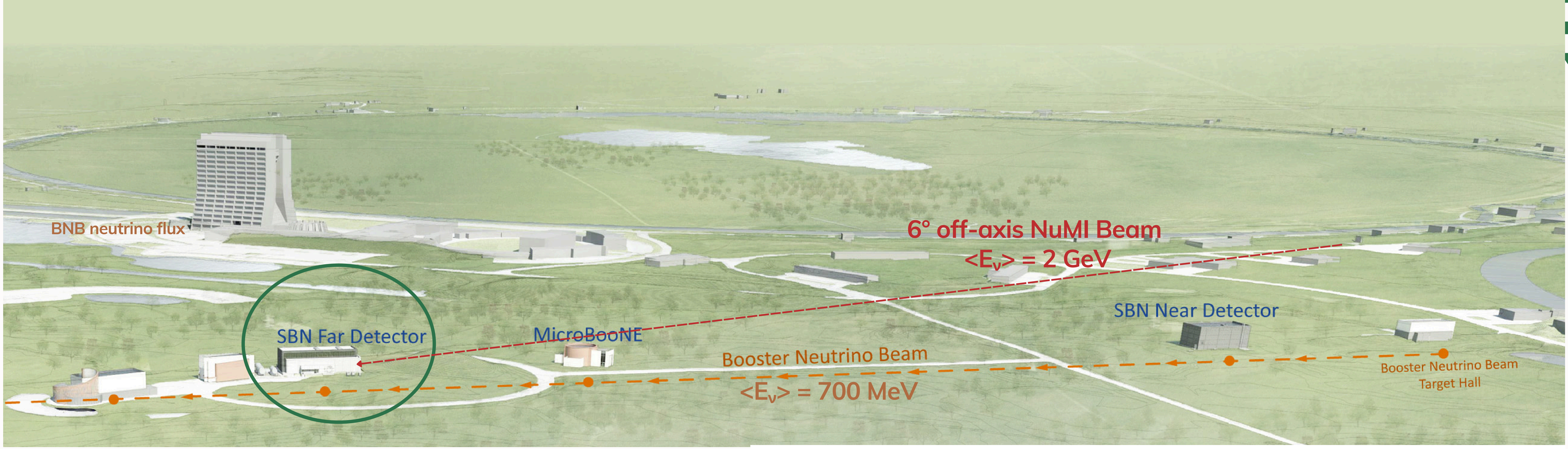
Detector	Distance	Active LAr Mass	Total LAr Mass
SBND	110 m	112 ton	220 ton
MicroBooNE	470 m	87 ton	170 ton
ICARUS	600 m	476 ton	760 ton



The Short-Baseline Neutrino Program

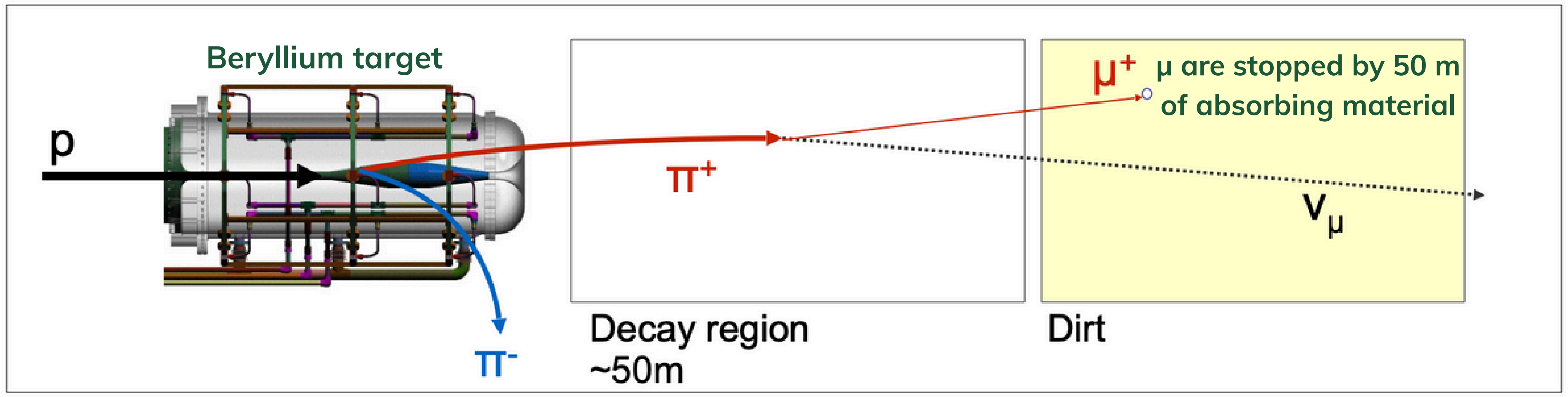
Short-Baseline → $L/E \leq 1$m /MeV

Two beams: Booster Neutrino Beam and NuMI (only for ICARUS)



Collected Protons on target (Pot)	BNB (FHC) *positive focussing*	NuMI (FHC) *positive focussing*	NuMI (RHC) *negative focussing*
RUN1 (Jun 9 - Jul, 2022)	0.41×10^{20}	0.68×10^{20}	-
RUN2 (Dec 22 - Jul, 2023)	2.06×10^{20}	2.74×10^{20}	-
RUN3 (Mar - Jul, 2024)	1.36×10^{20}	-	2.82×10^{20}
RUN4 (Dec 10, 2024 - Jul 12, 2025)	2.58×10^{20} *	-	-
TOTAL	6.41×10^{20}	3.42×10^{20}	2.82×10^{20}

*RUN4 data updated in mid May 2025

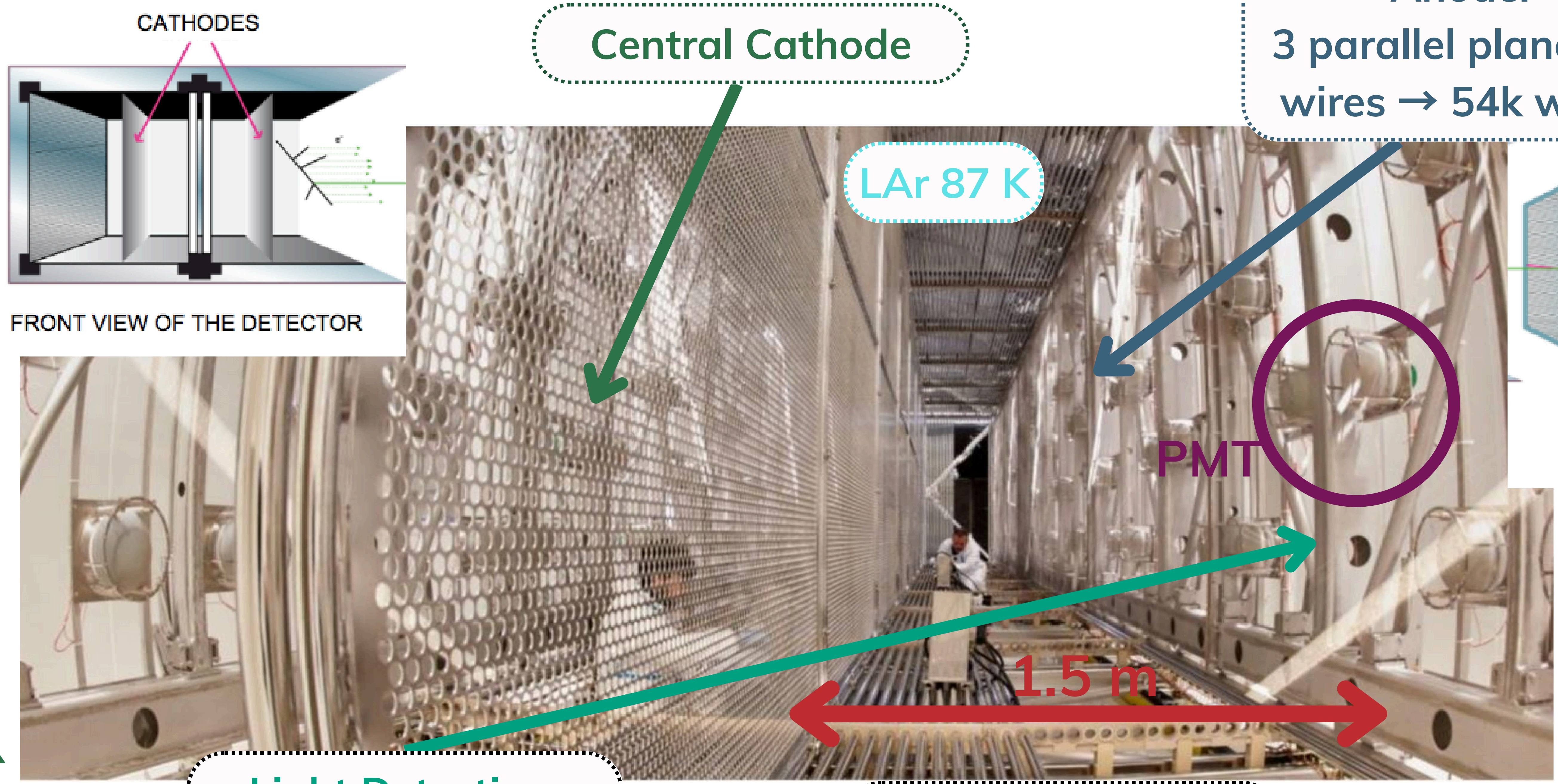


$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\qquad$ $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

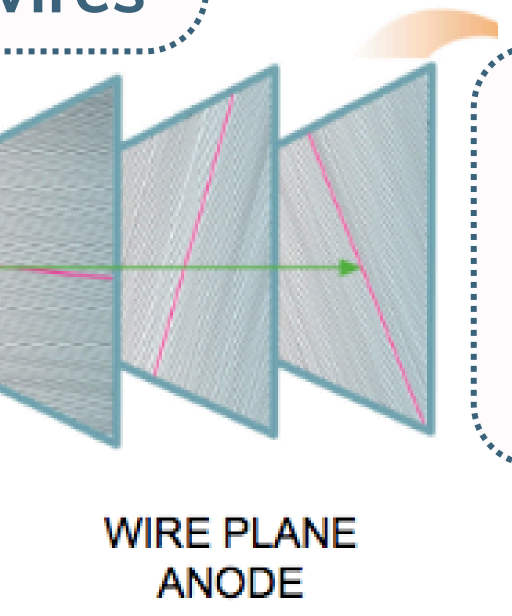
The ICARUS-T600 detector

It is made up of two identical T300 cryostats, each containing two LAr TPC with a shared cathode

Central Cathode



Anode:
3 parallel planes of wires → 54k wires



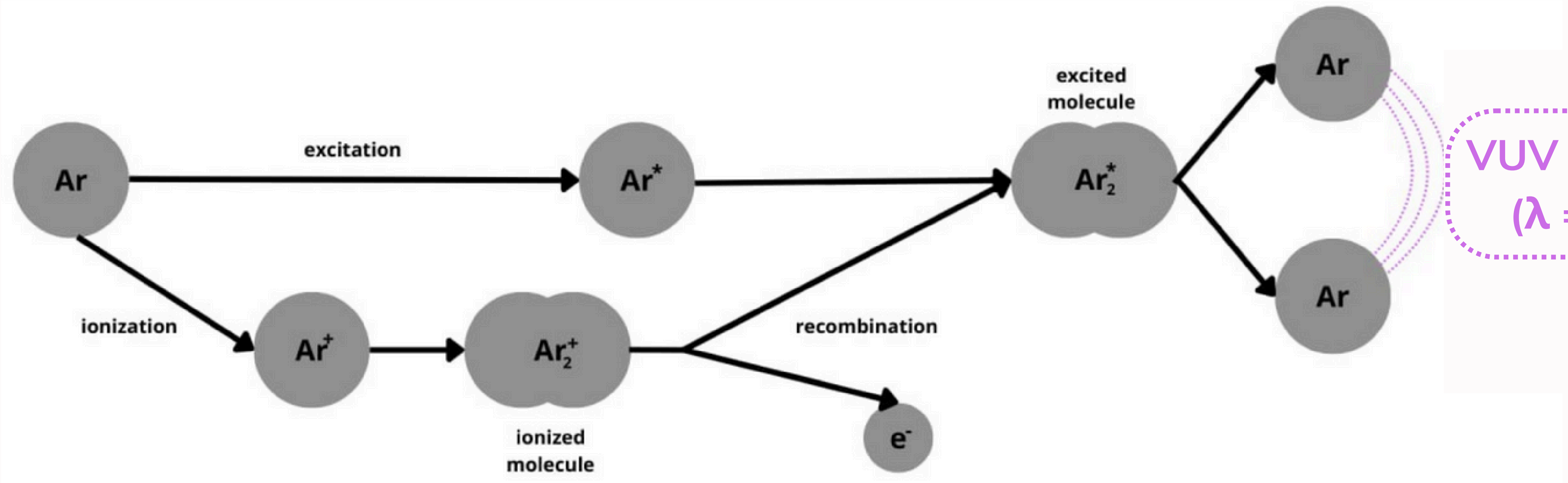
Anode:
0°, ±60°
two Induction and one Collection

3D reconstruction of the trace with a resolution of ~1 mm^3

Light Detection System

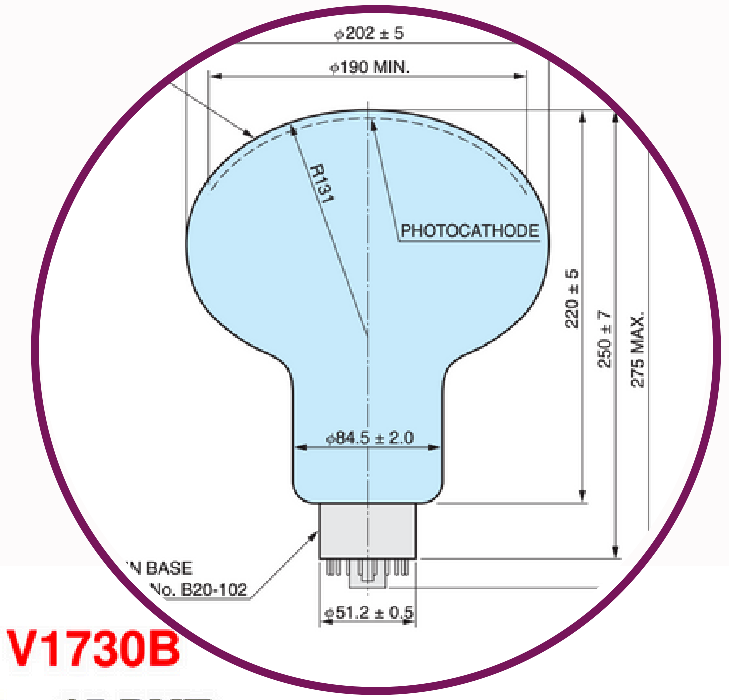
$E = 500$ V/ cm
$t_{drift} = \sim 0.96$ms

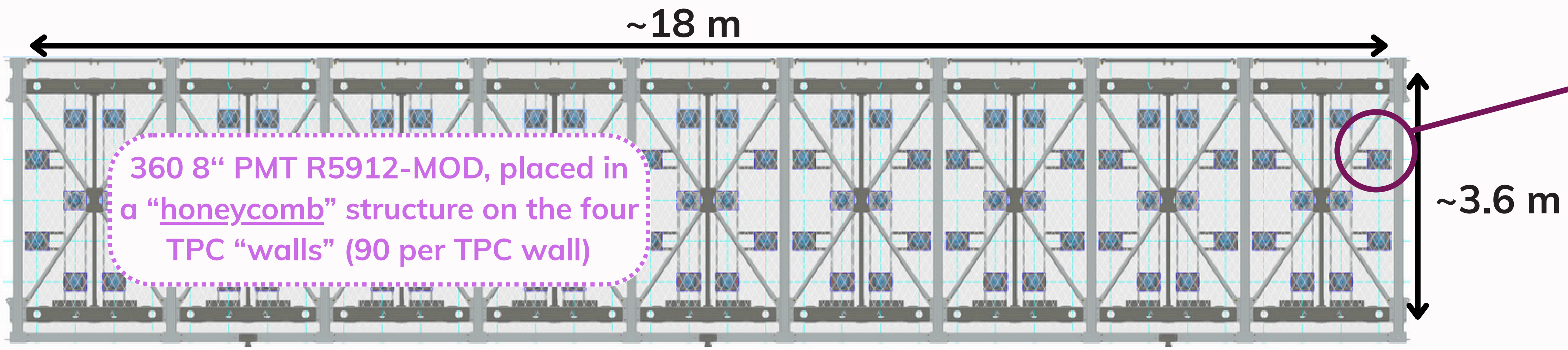
ICARUS Light Detection System



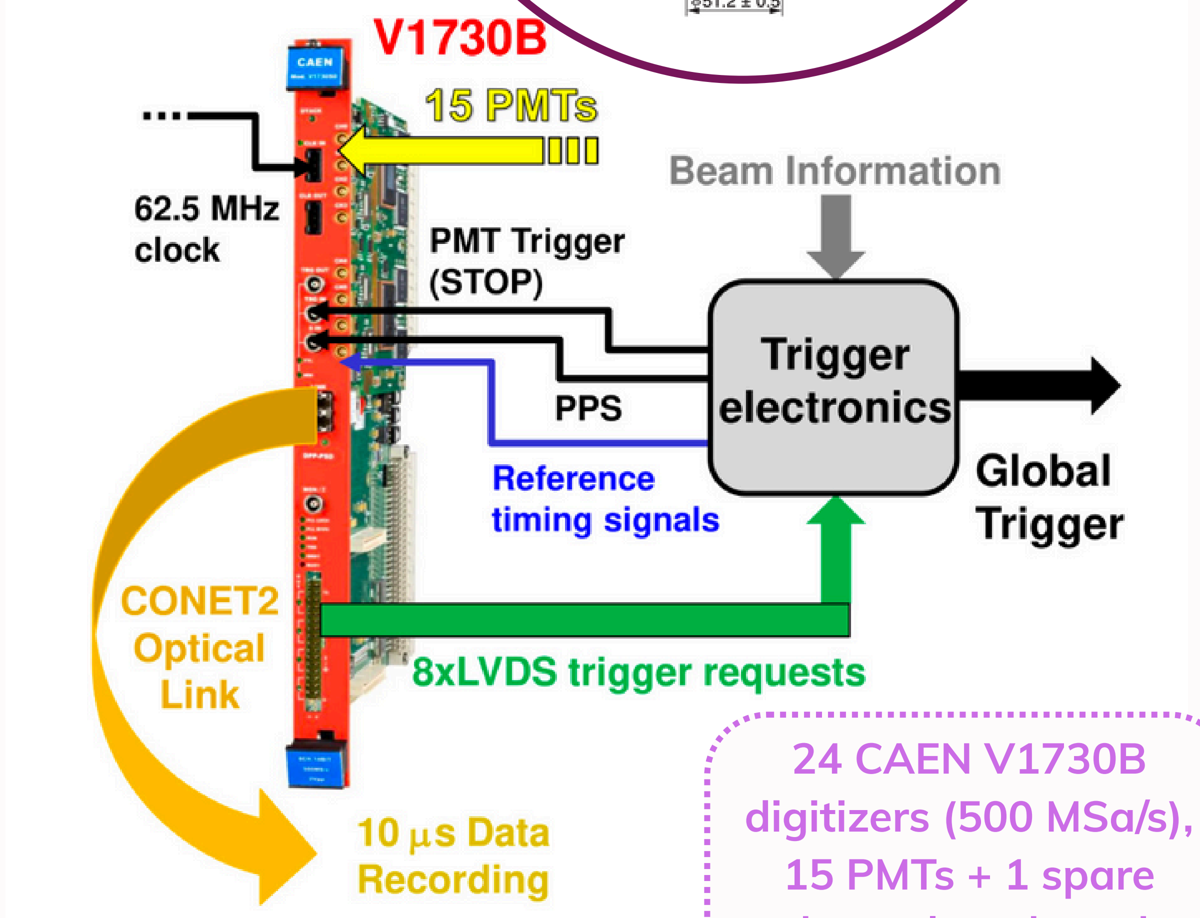
VUV Scintillation (λ = 128 nm)

PMTs have a peak sensitivity at λ = 420 nm: coated with Tetra-Phenyl Butadiene (TPB) as WLS





360 8“ PMT R5912-MOD, placed in a “honeycomb” structure on the four TPC “walls” (90 per TPC wall)



24 CAEN V1730B digitizers (500 MSa/s), 15 PMTs + 1 spare channel per board.

Gaols

- identify the occurrence time t_0 of each interaction inside the TPCs with O(ns) precision → **within 2 ns beam spills**
- improve spatial resolution of the events reconstruction along the longitudinal direction with O(m) precision.
- fundamental element for the **trigger system** for events and for cosmic ray veto (in anti-coincidence with Cosmic Ray Tagger signals).

PMT gain loss @ FNAL

Preliminary measurements on PMT gain
~15% gain loss in 250 days (1.80 %/month)

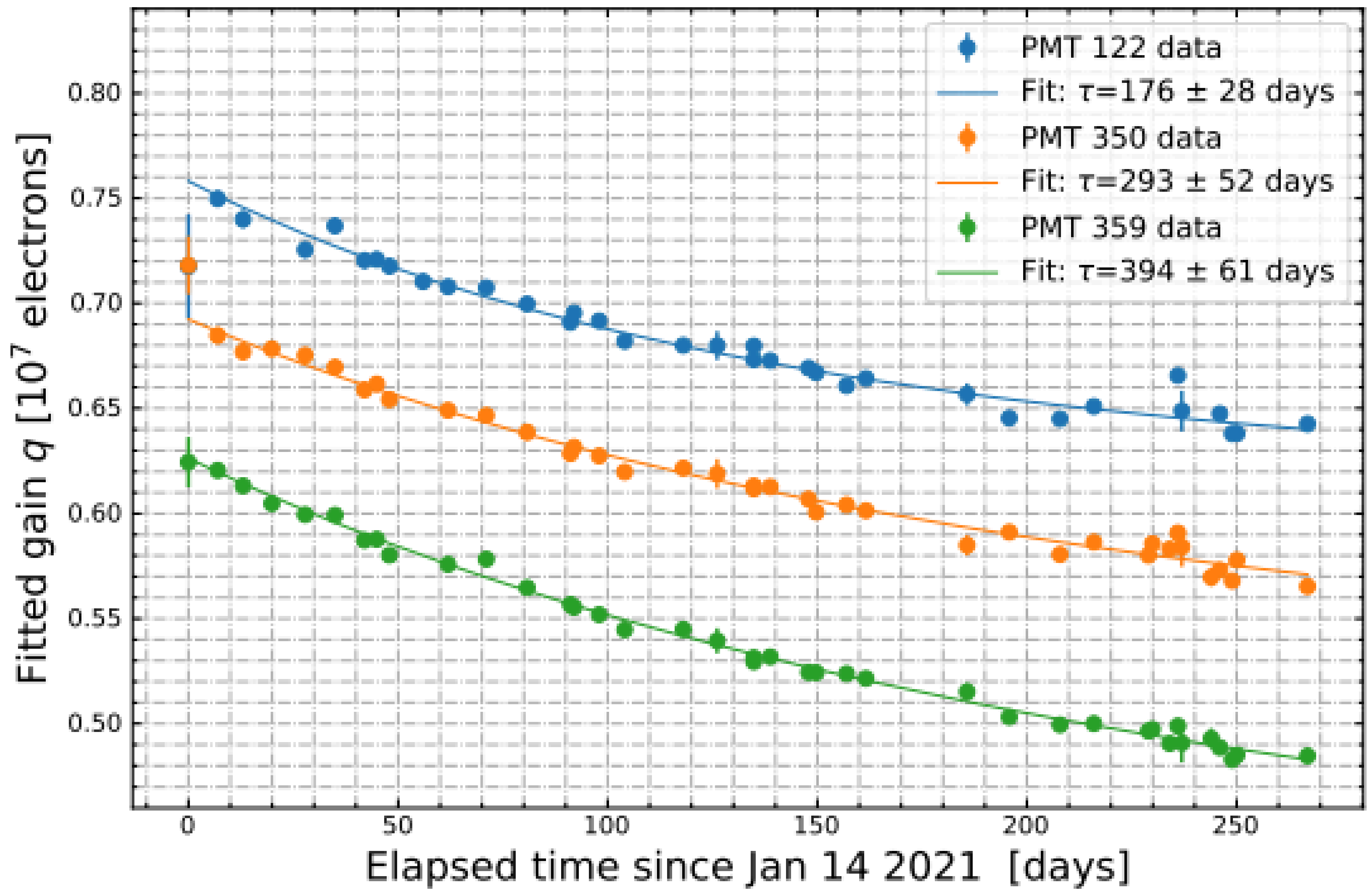
Estimated output charge in 6000h: 7 C

PMT gain test @ INFN Catania

Using the CSN1-INFNCT climatic chamber

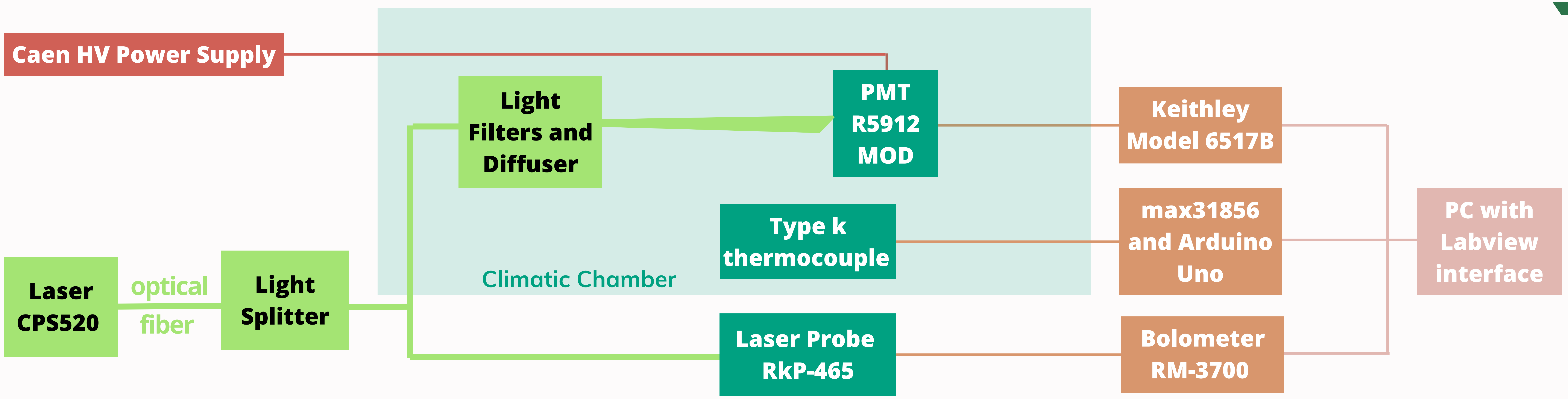
Implementation of an experimental setup to perform a stress test of the PMT in current mode. (max. anodic current ~28 μA)

It is required a long-lasting data acquisition (50-70 hours), to allow the collection of 5-7 C of anodic charge



Gain evaluated by Single Electron Response (S.E.R.) using Argon backgrounds photons (Optical Pulse)

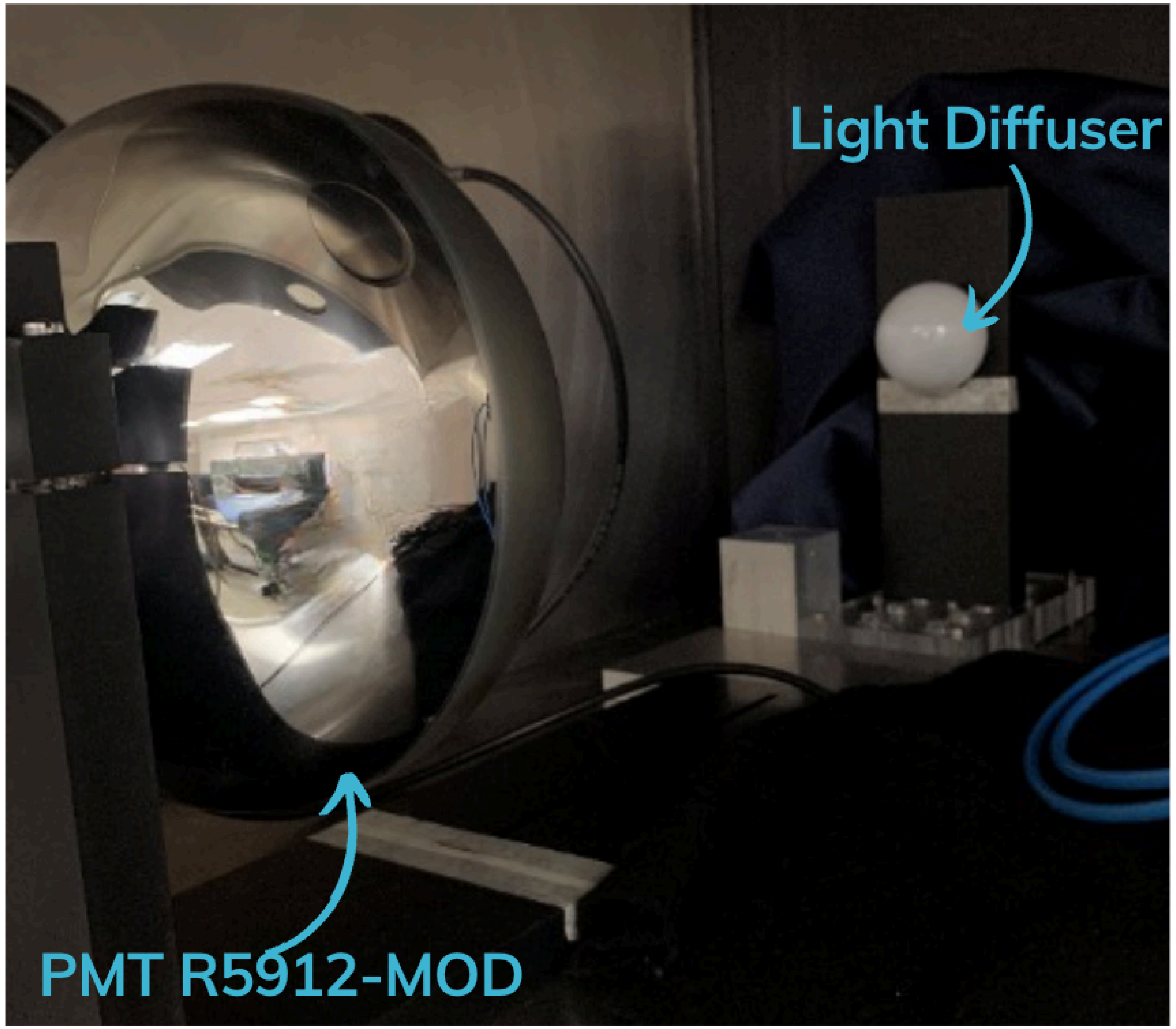
Experimental Set-Up

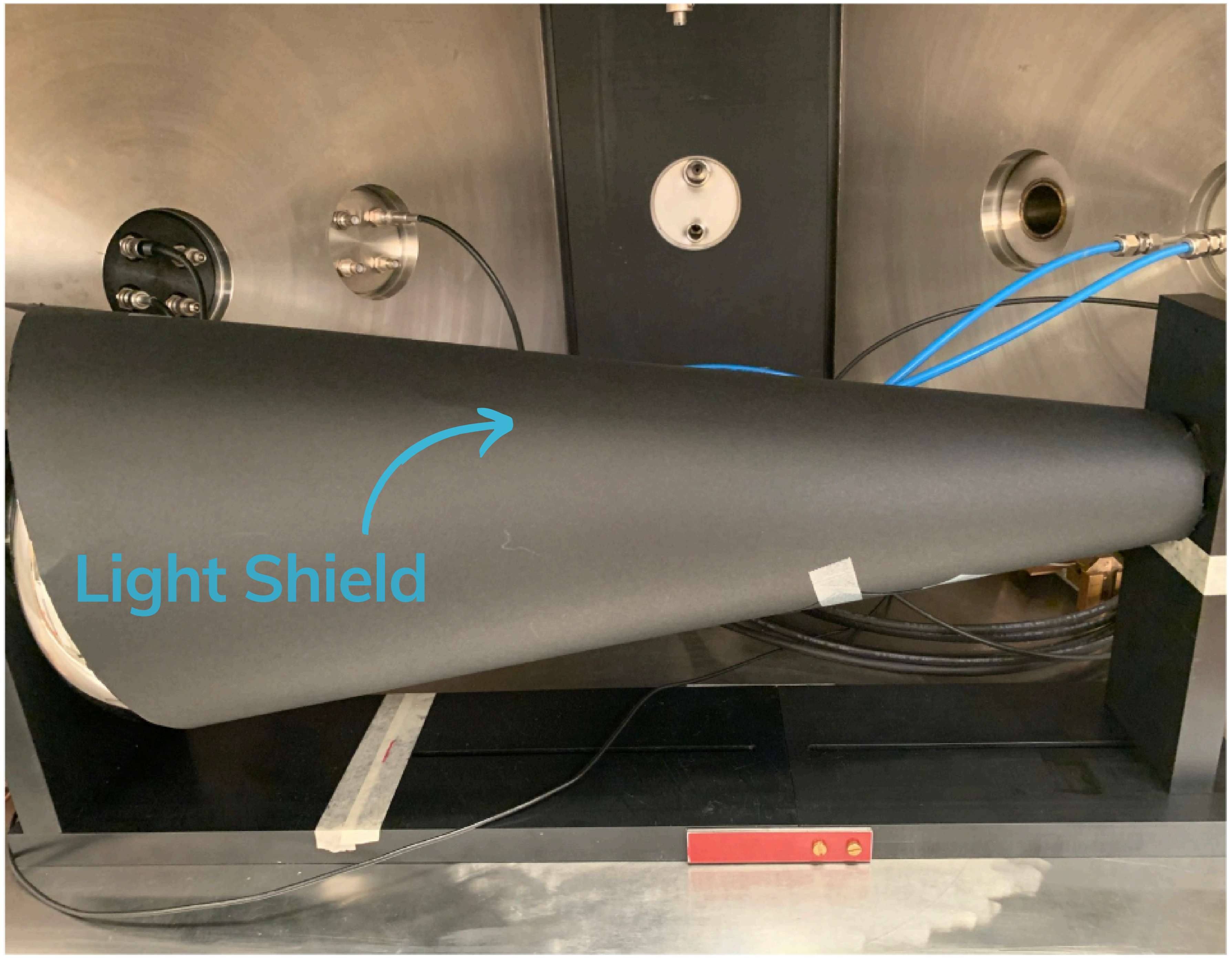


Preliminary tests were carried out to verify the *distance from the phototube* and the suitable attenuation to obtain an anode current of ~28 μA.

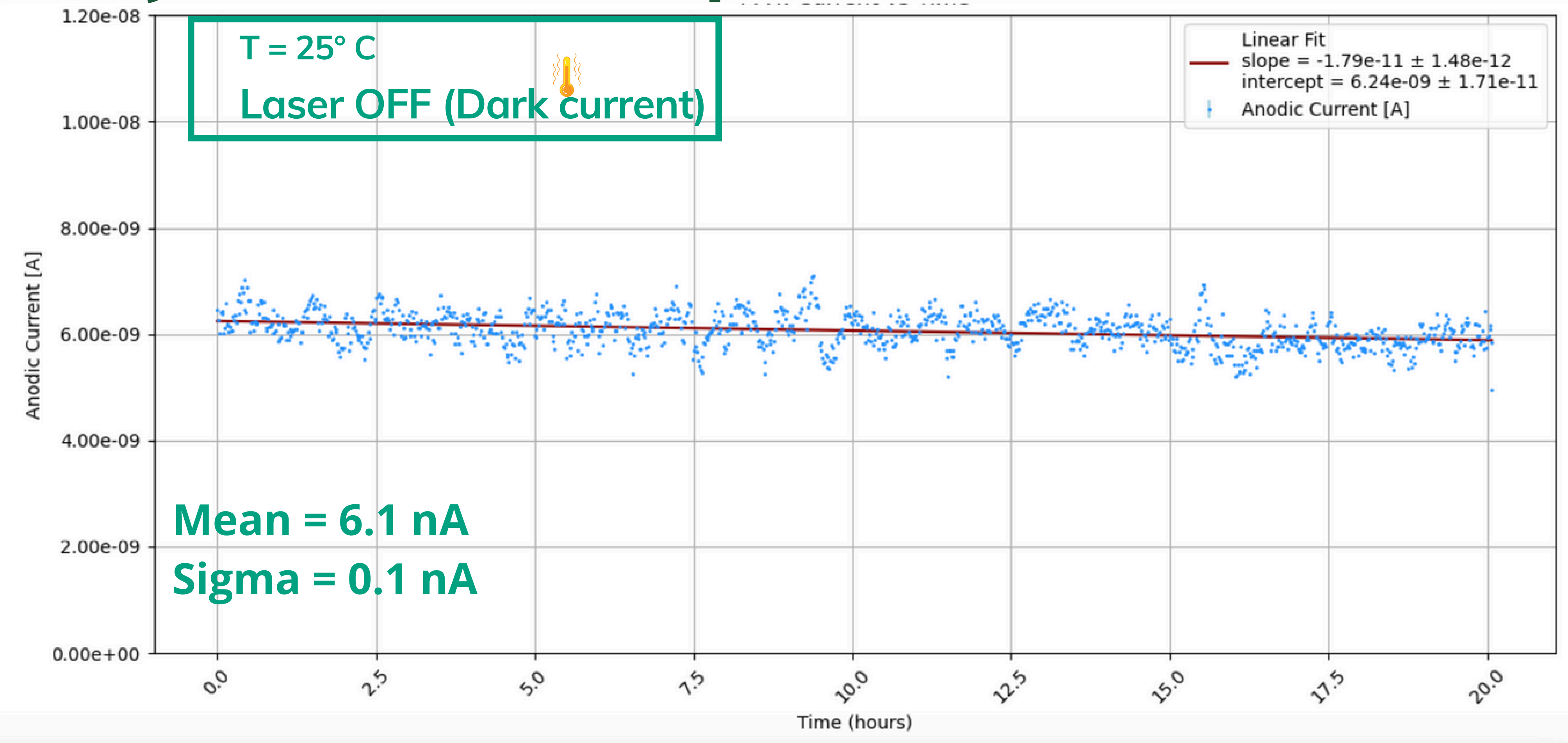
PMT without TPB coating; a laser beam (λ = 520 nm); PMT peak sensitivity 420 nm.

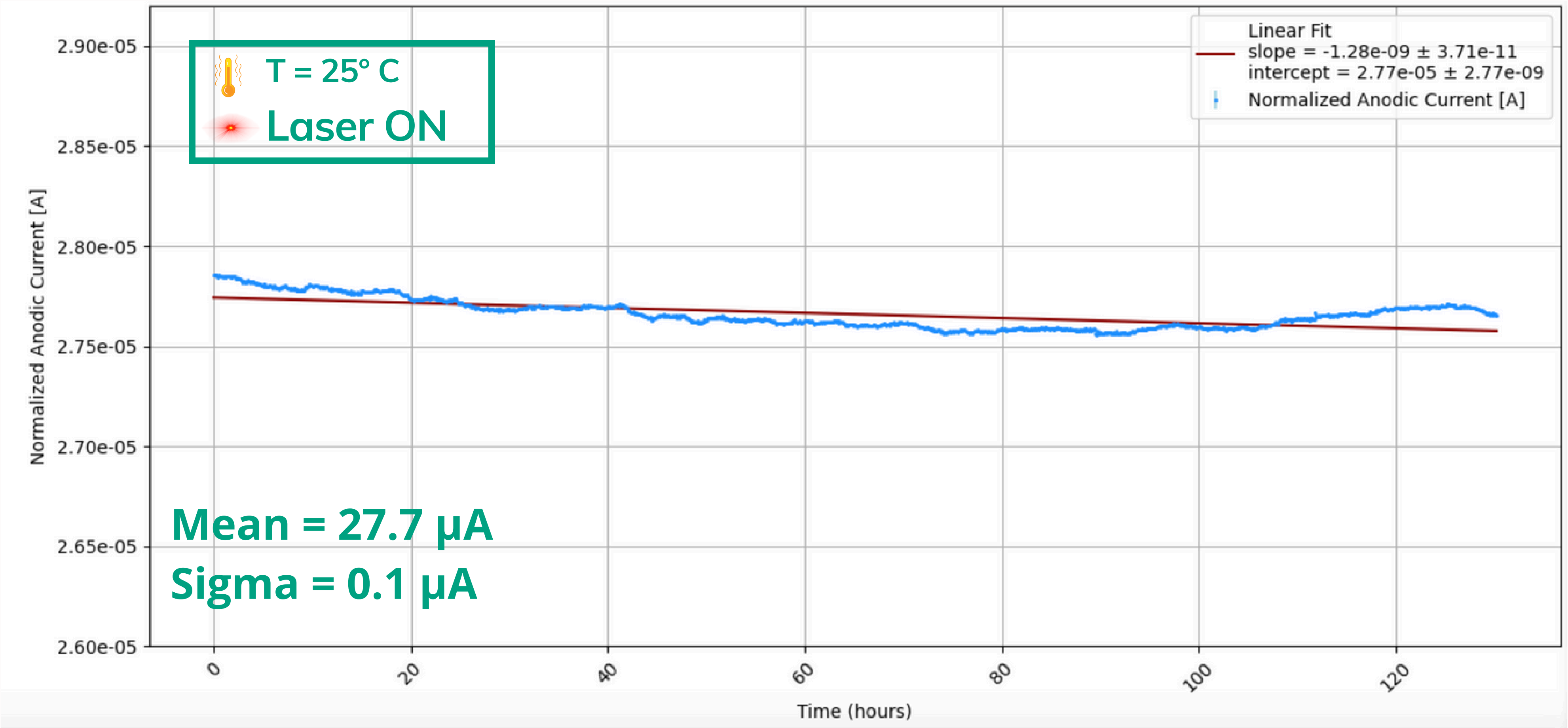
Experimental Set-Up





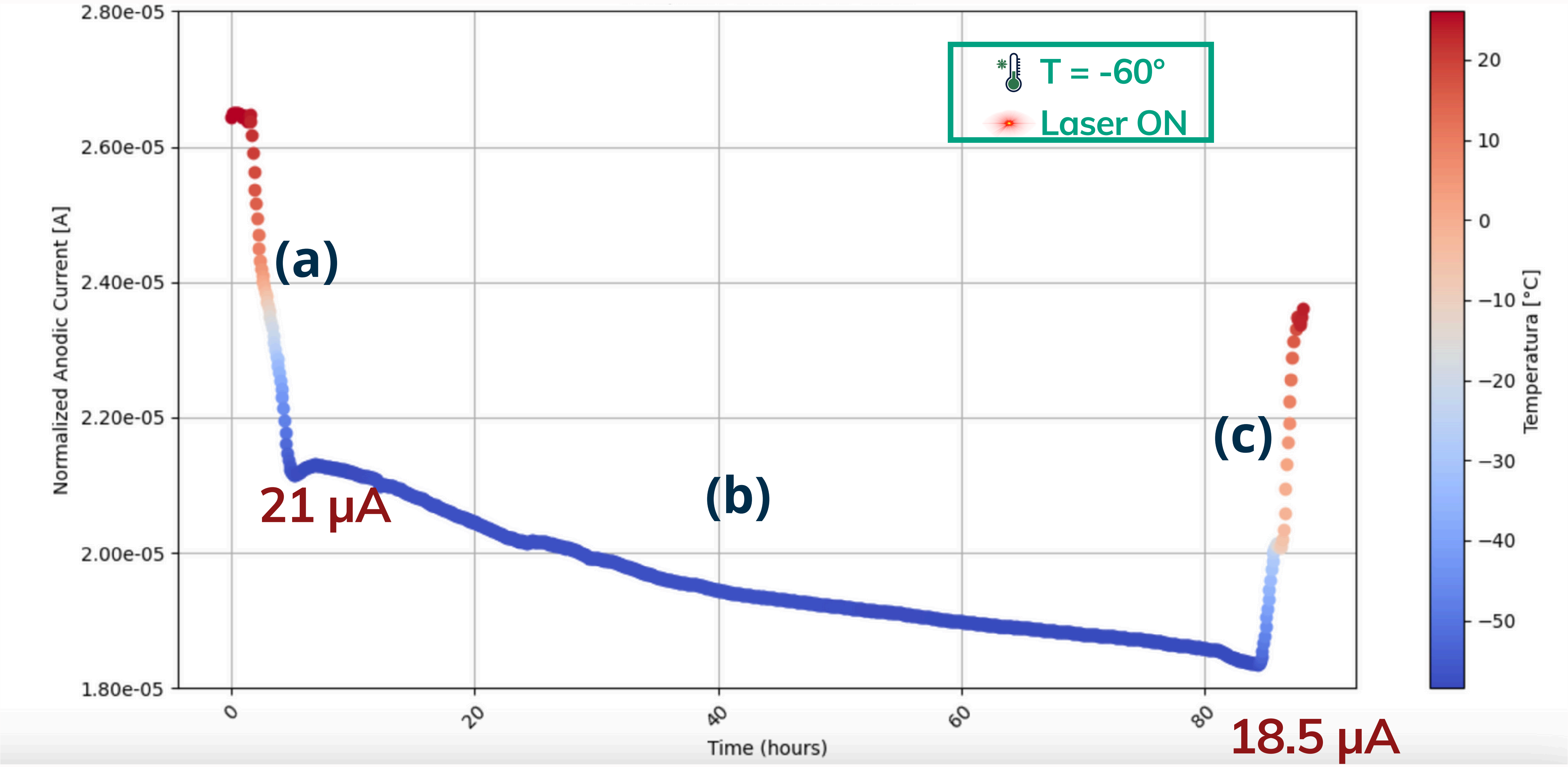
PMT stability at room temperature





No loss at room temperature.

Gain loss at low temperature: a typical behaviour



The gain loss in (a) is recovered during (c): it is a reversible loss and the rate is 6×10^{-8} A /°C.
During phase (b), we observe a permanent loss:
no gain recovery is obtained by bringing the PMT back to room temperature.

During each cooling we identified three phases:

- (a) gain loss during cooling from room temperature
- (b) gain loss at a fixed low temperature;
- (c) gain increase during temperature raising.

Permanente loss at low temperature (even higher than LAr)

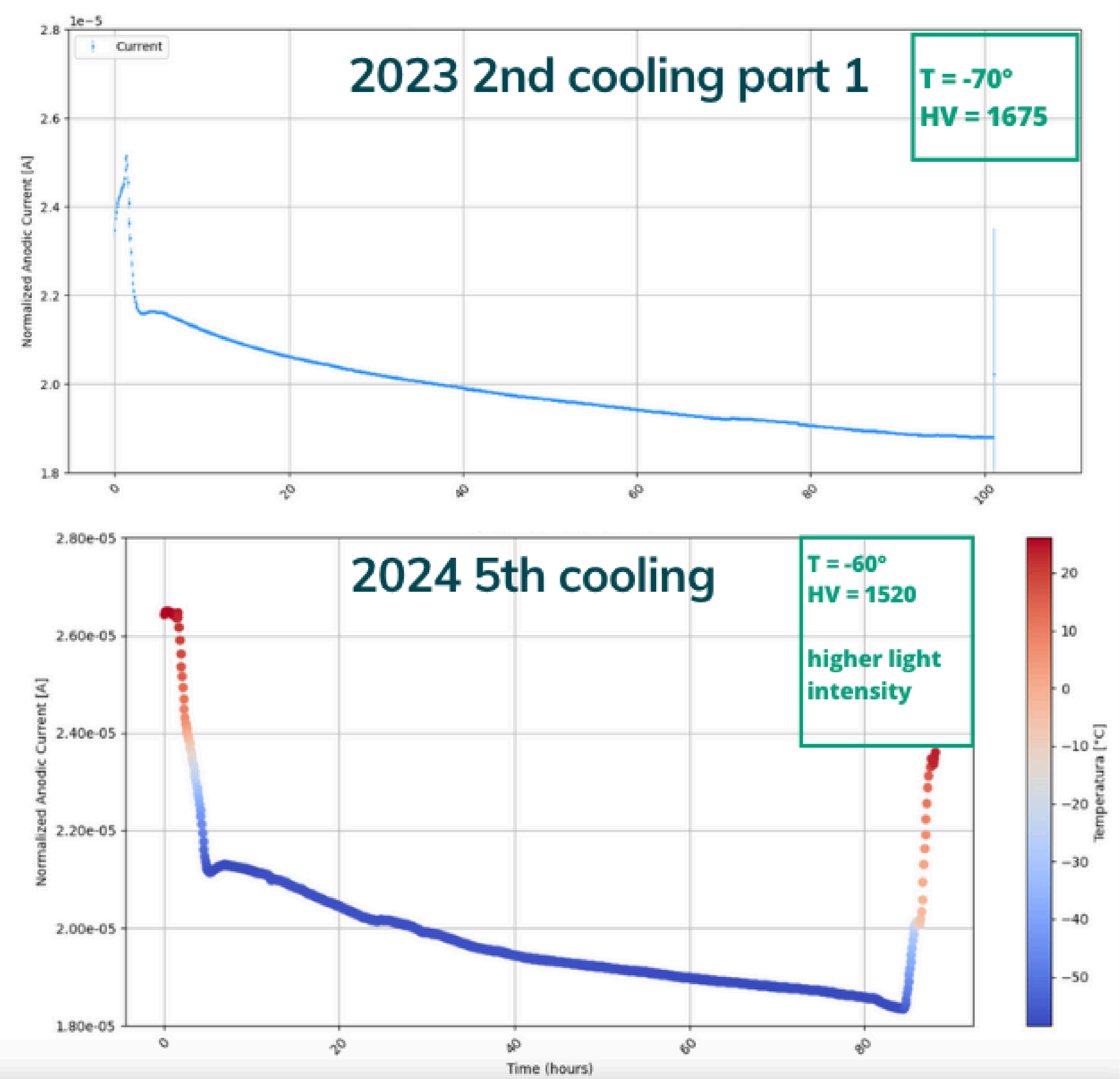
Summary of measurement

		Temperature (°C)	Duration (h)	HV (V)	Gain loss (%)	Anodic Charge (C)	Gain loss / charge (%/C)
2022/2023	1st Cooling	-74	20	1575	7.29 %	1.89	3.86 %
	2nd Cooling part 1	-70	95	1575	12.50 %	6.81	1.84 %
	2nd Cooling part 2	-70	20	1675	3.05 %	2.11	1.45 %
	3rd Cooling	-66	150	1675	16.60%	16.60	1.00 %
2024	4th Cooling	-60	45	1520	19.68%	3,49	5.41%
	5th Cooling	-60	80	1520	13.39 %	4.20	3.18%
	6th Cooling	-60	63	1520	8.88 %	3.87	2.29 %

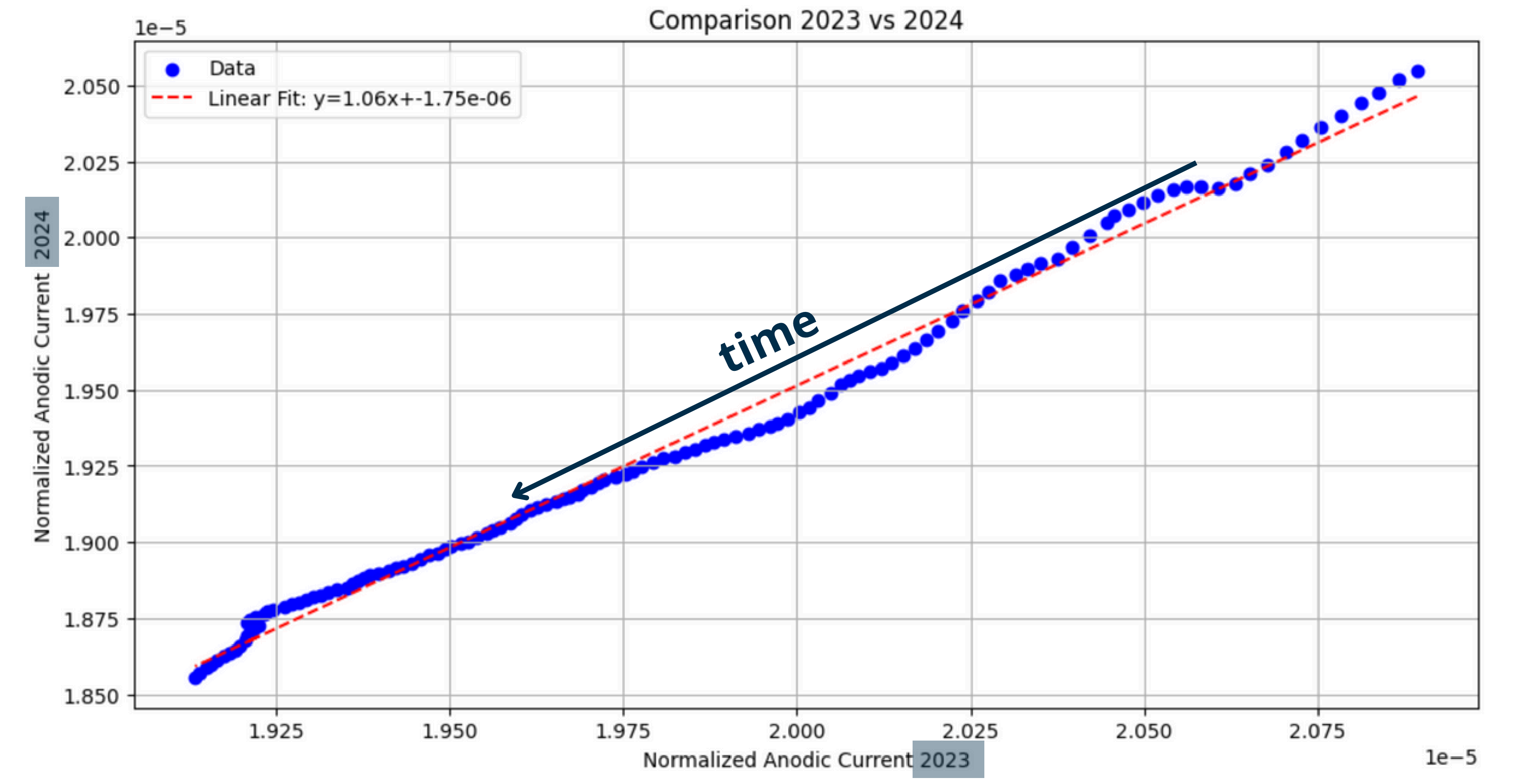
Dependance on the amount of light and HV.

For subsequent measurements under the same conditions, the loss decreases.

Reproducibility



1st and 4th cooling start from ~28 μA anodic current.



PMT gain loss @ FNAL

From January to November 2021 (Commisioning)

Preliminary measurements on PMT gain ~15% gain loss in 250 days (1.80 %/month)

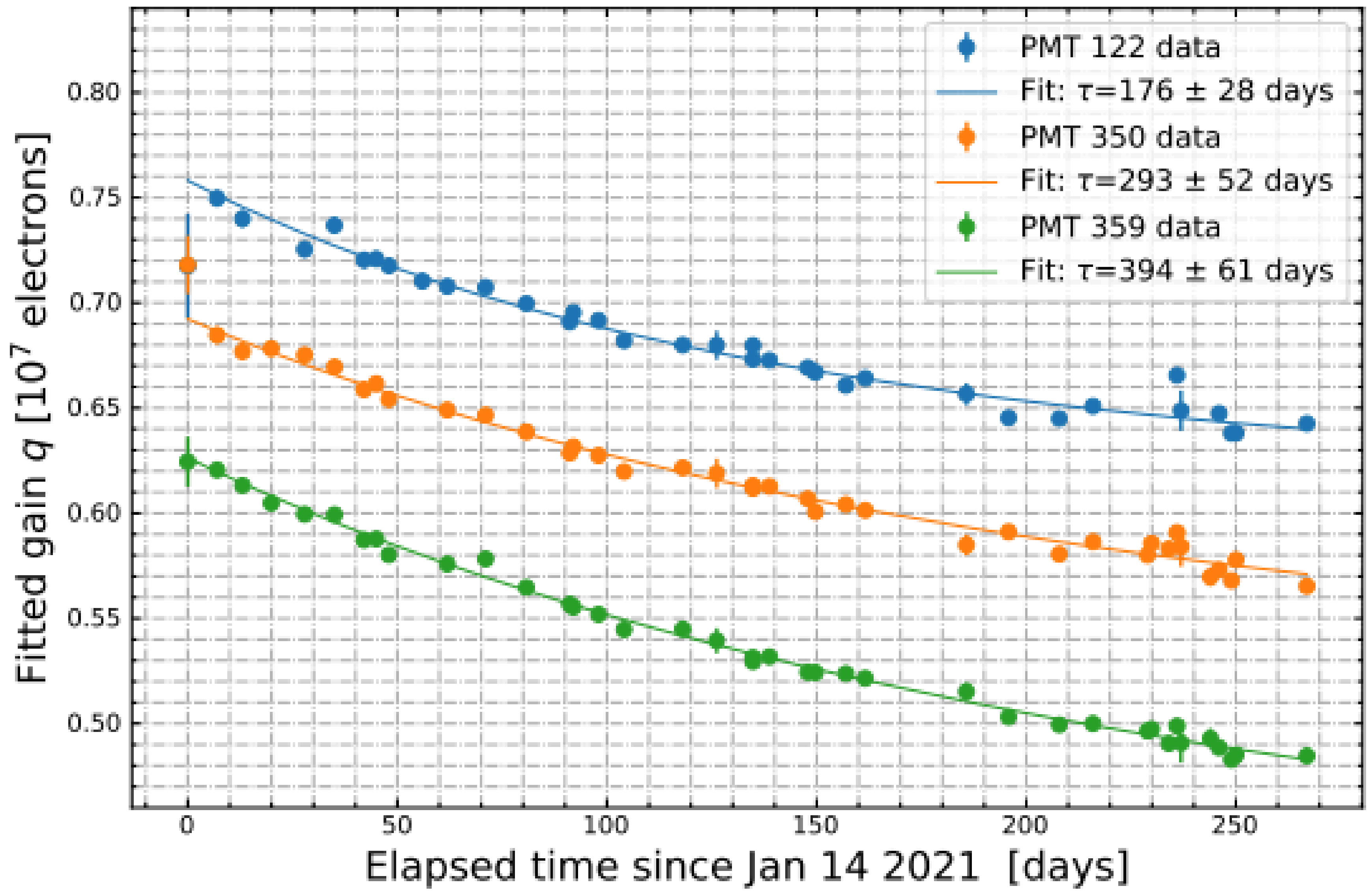
RUN 1-2: 2022/23

Installation of 2.85-meter concrete overburden (June 2022):
PMTs were equalized in gain at 0.46 × 10 ± 2.1% and showed a gain loss rate of 0.64 %/month.

RUN 3-4: 2023/24

Installation of **new signal cables** and the overall **reduction in the PMT voltage.** current average gain is 0.39 × 10 ± 0.7% and the gain loss rate is 0.31 %/month.

Estimated output charge in 6000h: 7 C



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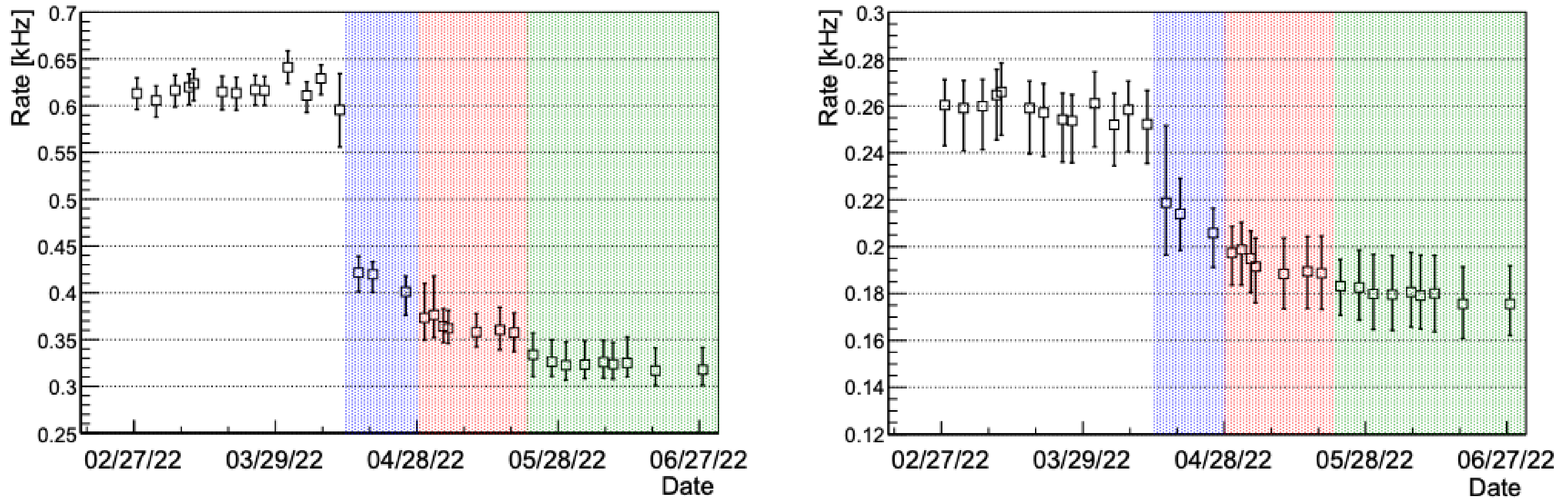

A. Aduszkiewicz et al 2025 JINST 20 T04002

Cosmic γ's and and neutrons are suppressed by ~2.85 m thick concrete overburden installed on top of the CRT

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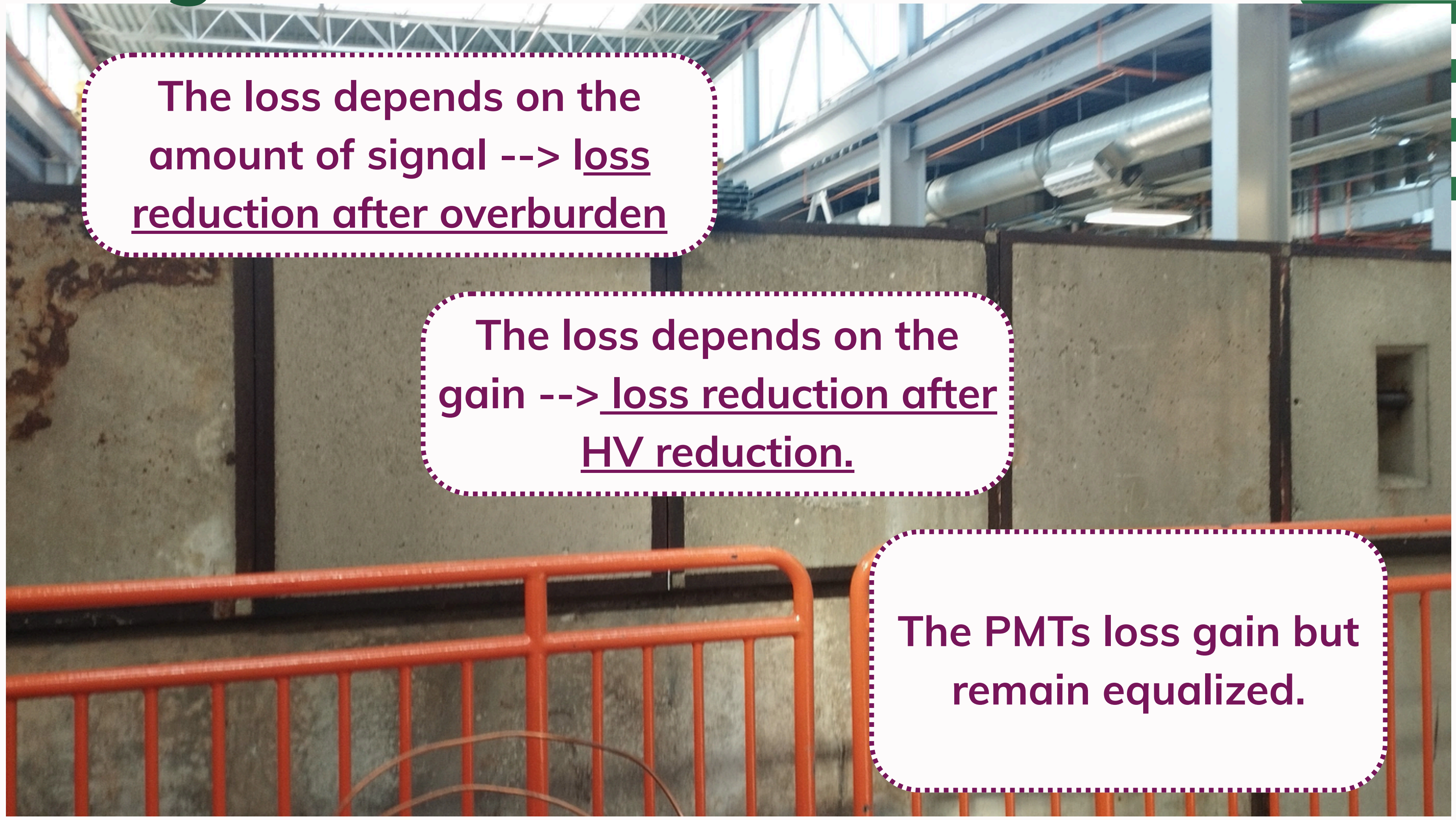
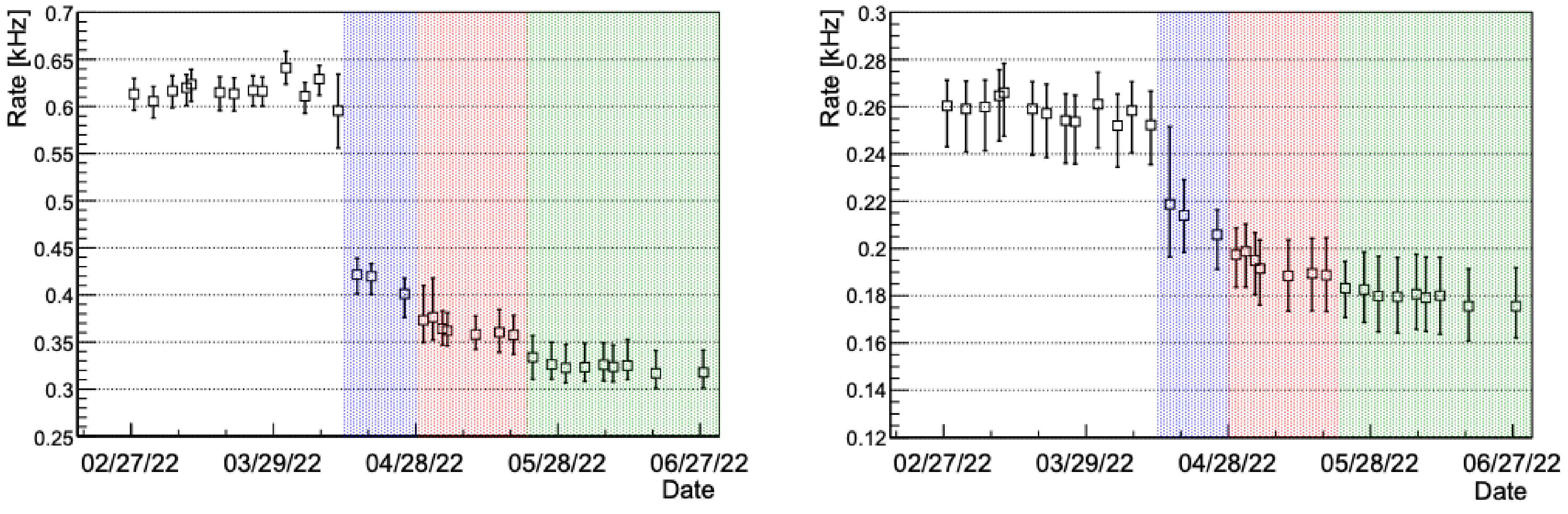


The loss depends on the amount of signal --> <u>loss reduction after overburden</u>

The loss depends on the gain --> <u>loss reduction after HV reduction.</u>

The PMTs loss gain but remain equalized.



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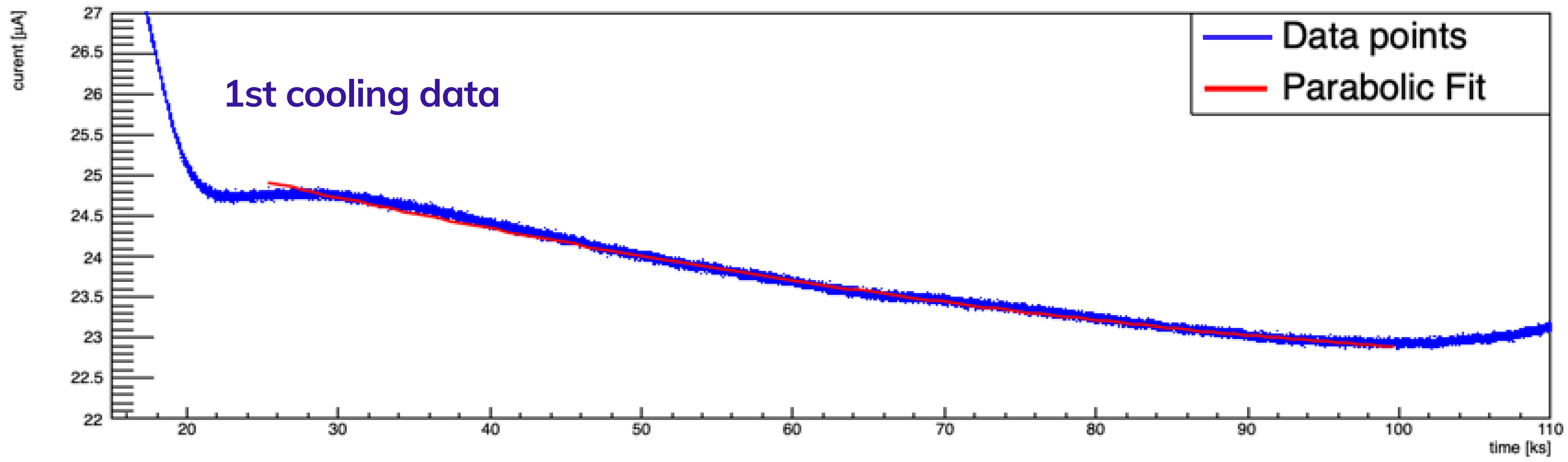
SPR waveform for RUN2 (old 37-m-long RG316/U cablese) and RUN3 (new 28-m-long WL-195N cables)

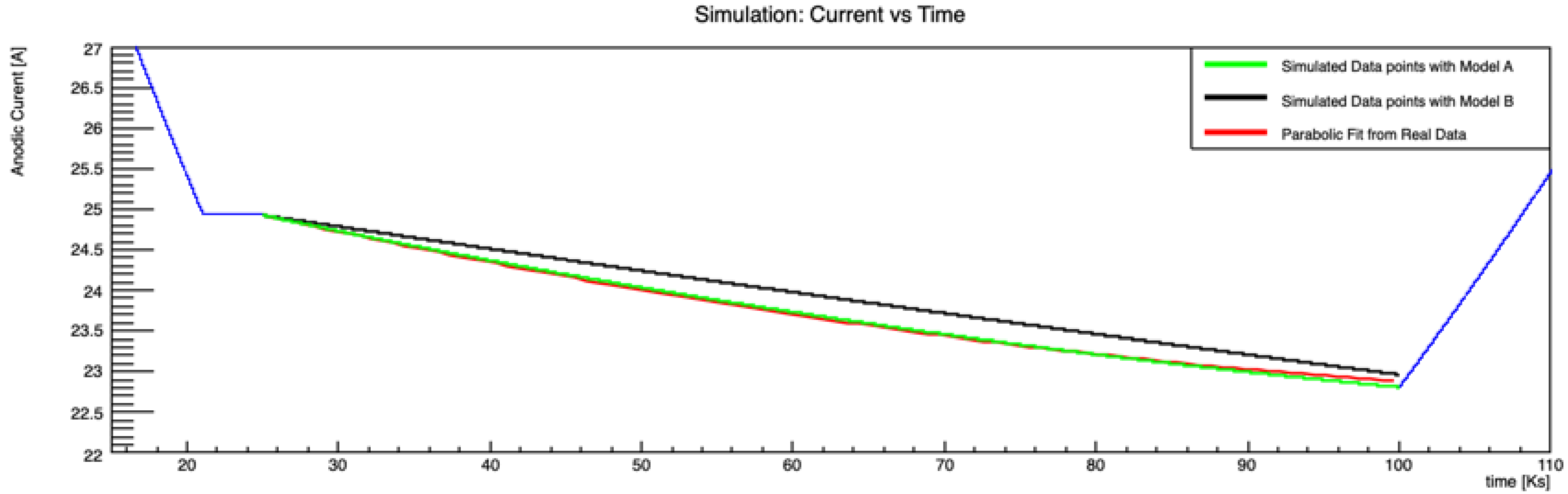
shorter tail in RUN3, as expected, due to the use of the new cables

In RUN3, an average increase in signal amplitude was observed, indicating a higher amplitude and shorter duration, leading to an overall improvement in signal resolution .

A Simple Model

$$G = \prod_{i=1}^{n} A_i V_i^{\alpha_i} = \prod_{i=1}^{n} A_i (\epsilon_i V)^{\alpha_i}$$





The simulation uses the known voltage divider data and real PMT Gain data (1.11×10^7) to model the dynode multiplication chain.

Model A the coefficient A decrease proportionally to the current in each dynode.

Model B the coefficient α to decrease proportionally to the current in each dynode.

only the last dynodes in the chain impact on the total gain loss

Key findings

Indications from FNAL loss:

1. The loss depends on the amount of signal --> loss reduction after overburden
2. The loss depends on the gain --> loss reduction after HV reduction.
3. The PMTs loss gain but remain equalized.

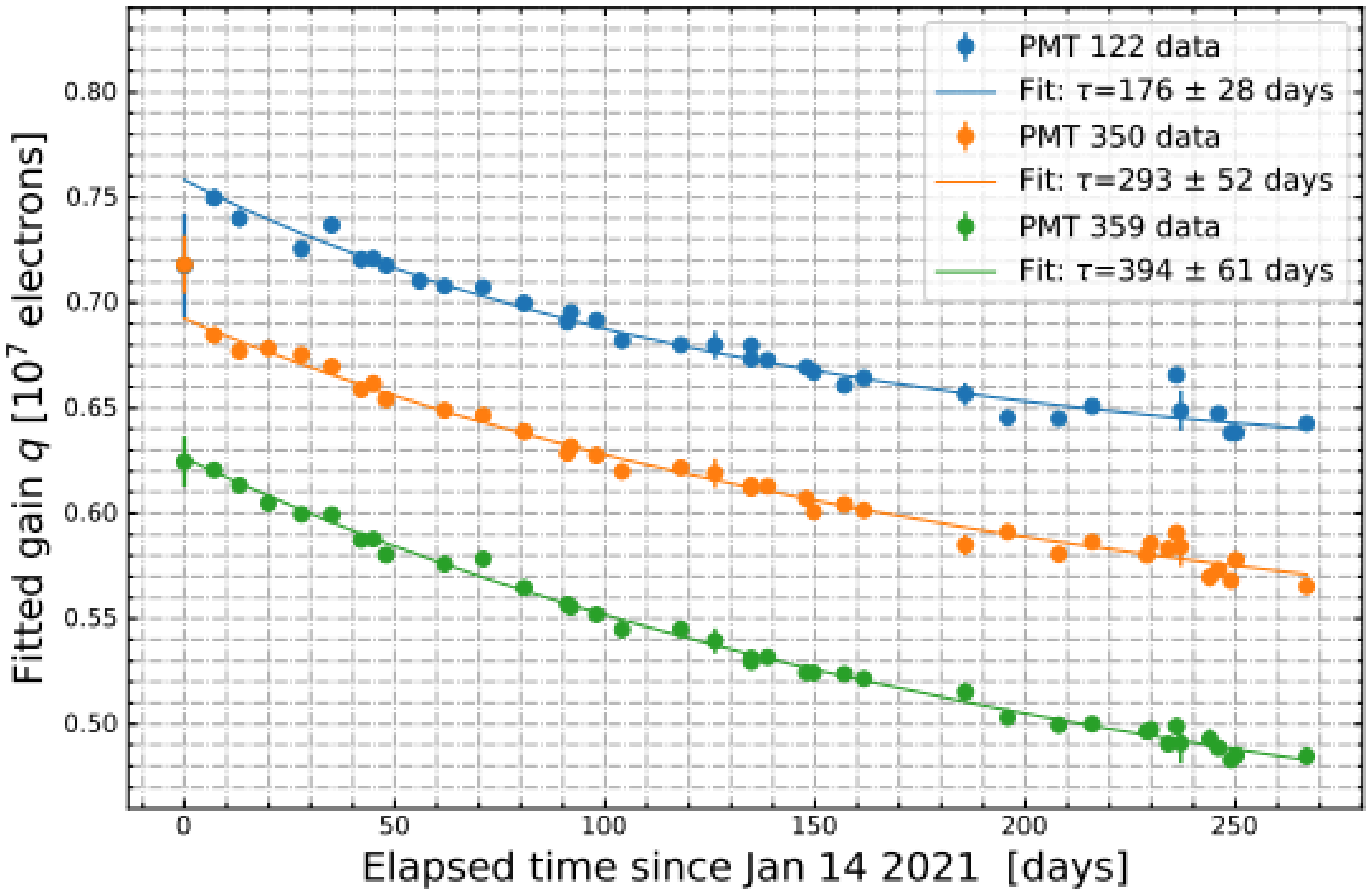
From Catania test:

1. The same loss is observed even at higher the temperature and it is a permanent loss.
2. We also see dependance on the amount of light and HV.
3. No loss at room temperature. NEW
4. For subsequent measurements under the same conditions, the loss decreases. NEW

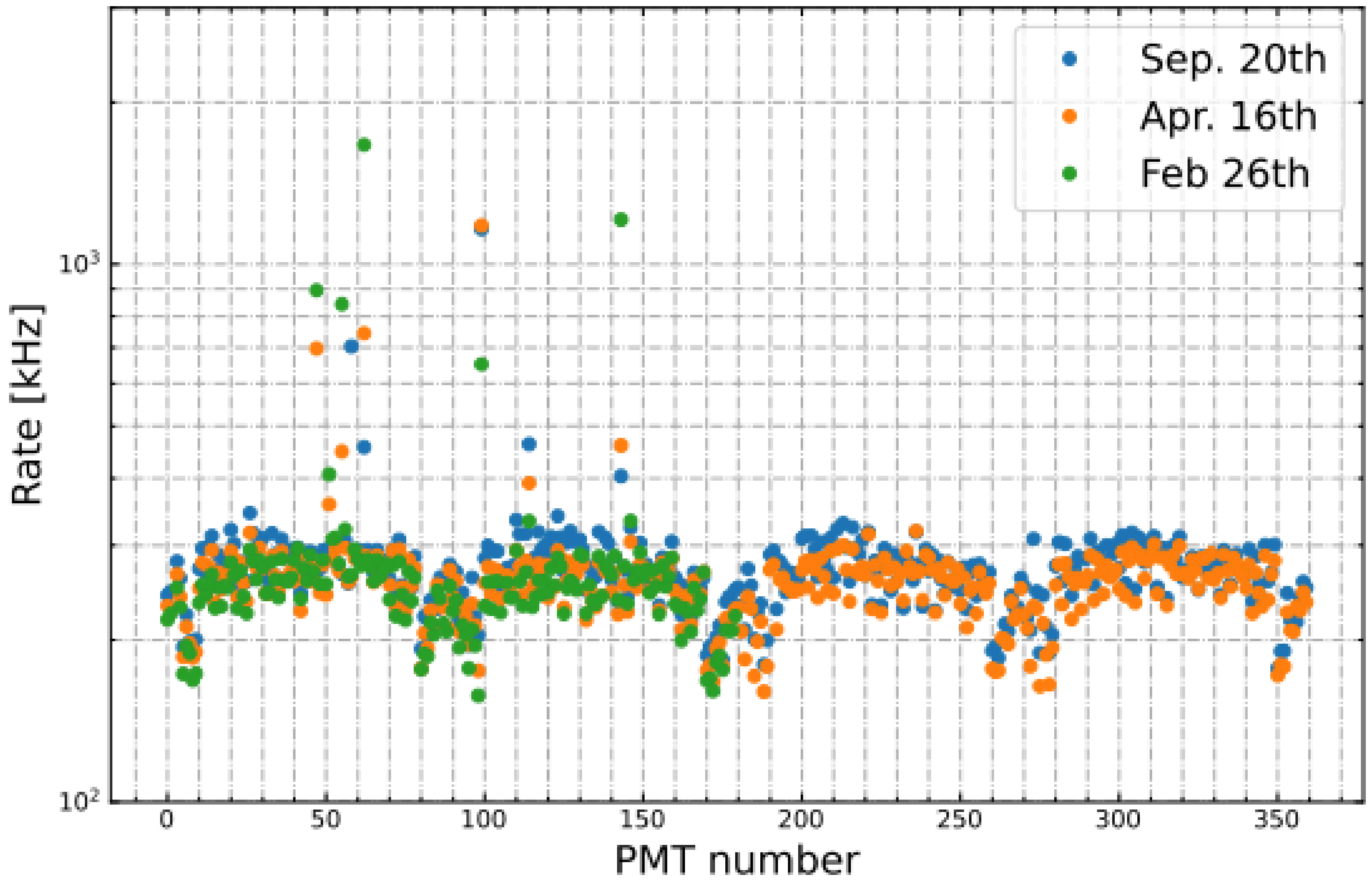
Based on Hamamatsu guidelines and on simulation the dynodes current-dependent degradation seems a reasonable cause for the effects.

THANKS for your ATTENTION

Backup



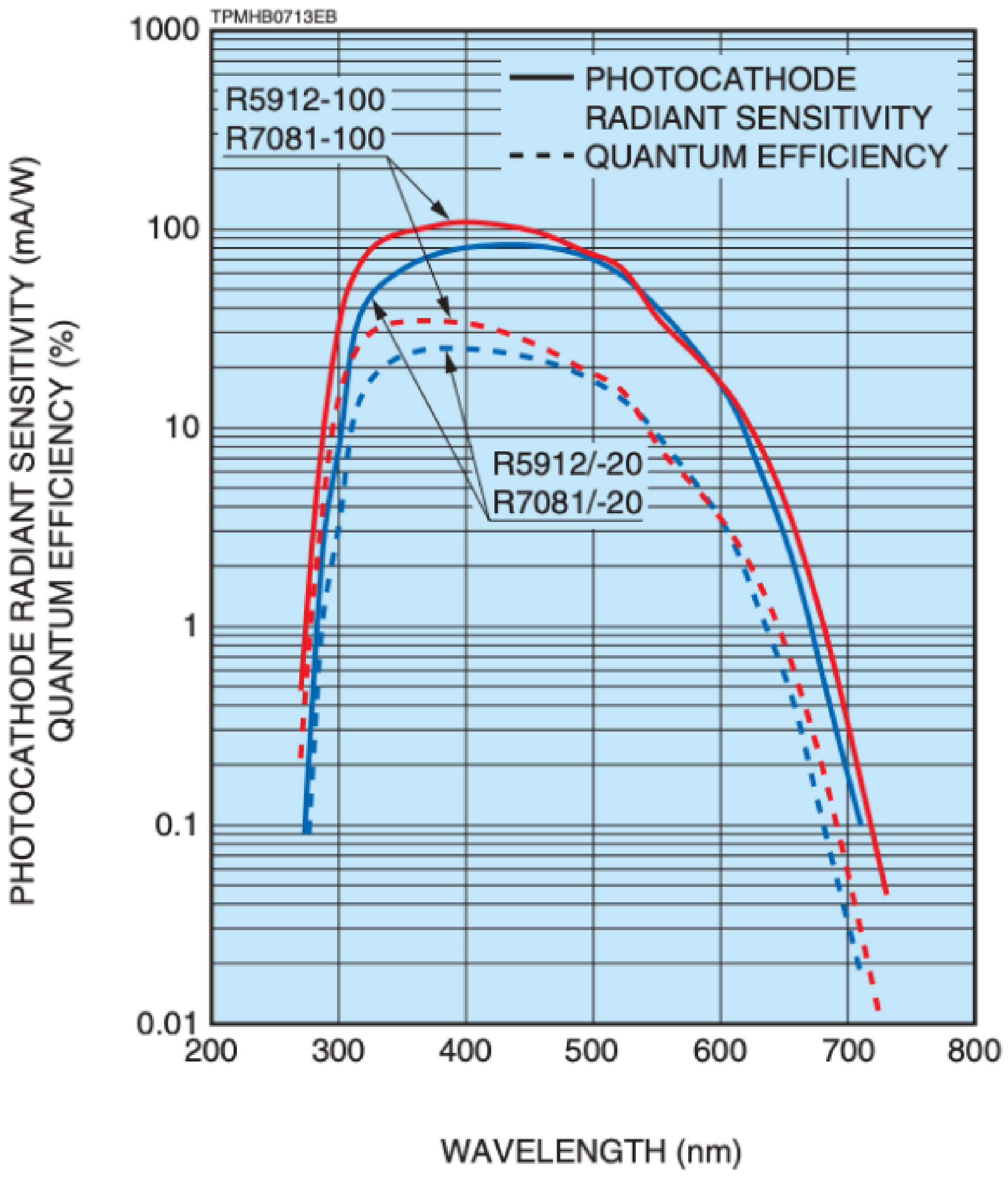
PMT 122 data
Fit: τ=176 ± 28 days
PMT 350 data
Fit: τ=293 ± 52 days
PMT 359 data
Fit: τ=394 ± 61 days
Fitted gain q [10^7 electrons]
Elapsed time since Jan 14 2021 [days]



Sep. 20th
Apr. 16th
Feb 26th
Rate [kHz]
PMT number

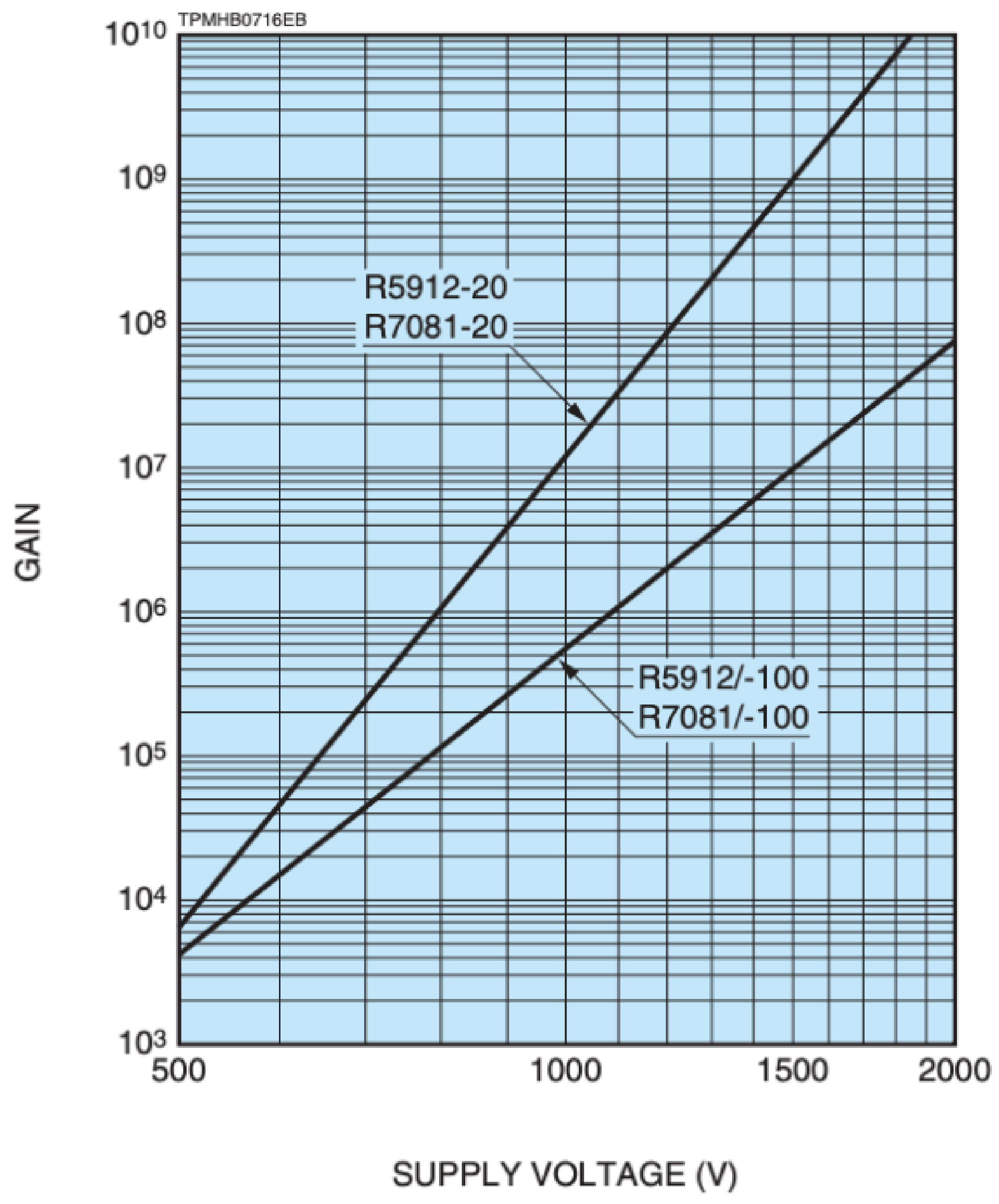
SPECTRAL RESPONSE

●R5912/-20/-100
●R7081/-20/-100



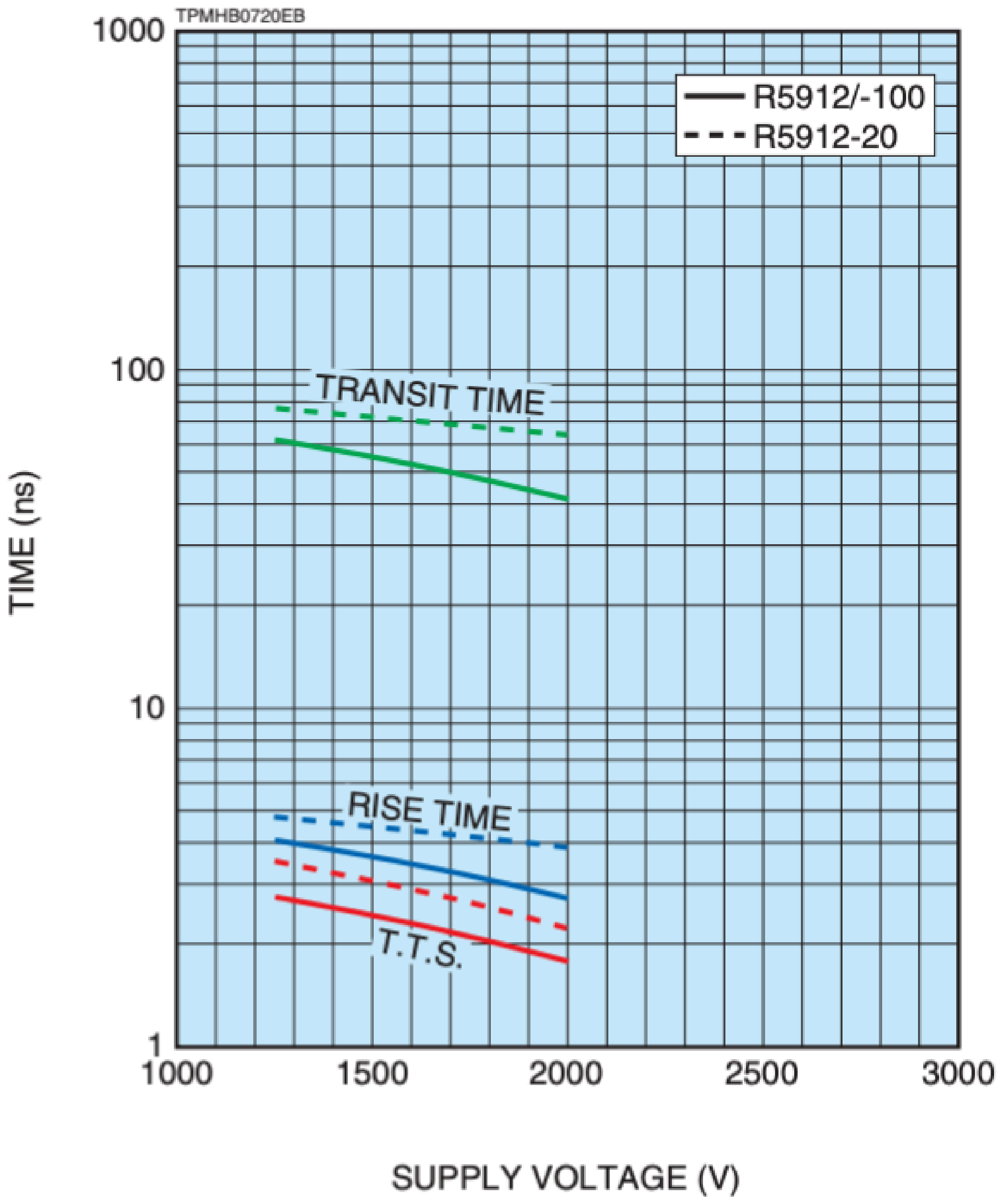
GAIN

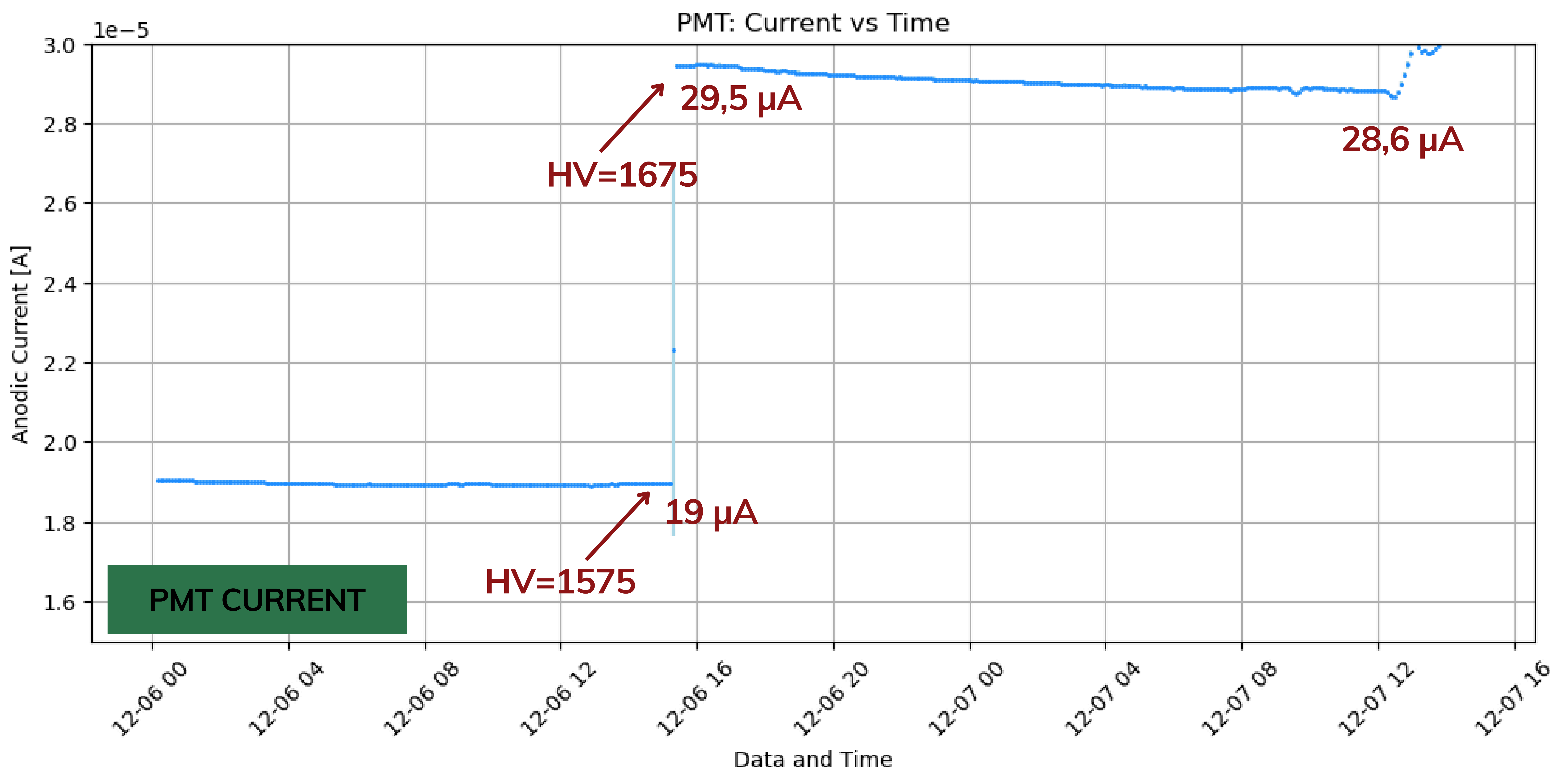
●R5912/-20/-100
●R7081/-20/-100



TYPICAL TIME RESPONSE

●R5912/-20/-100

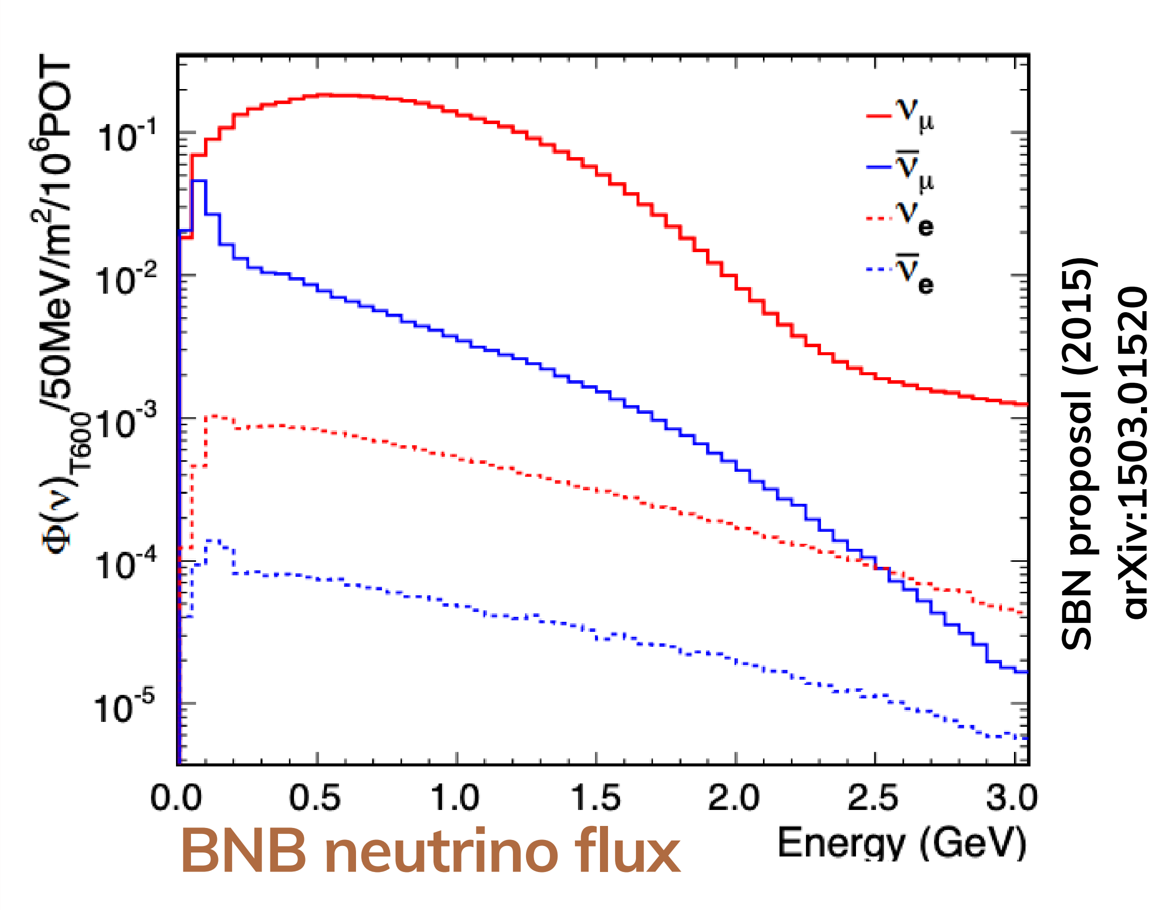



PMT: Current vs Time
1e−5
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
Anodic Current [A]
29,5 µA
HV=1675
28,6 µA
19 µA
HV=1575
PMT CURRENT
12-06 00
12-06 04
12-06 08
12-06 12
12-06 16
12-06 20
12-07 00
12-07 04
12-07 08
12-07 12
12-07 16
Data and Time

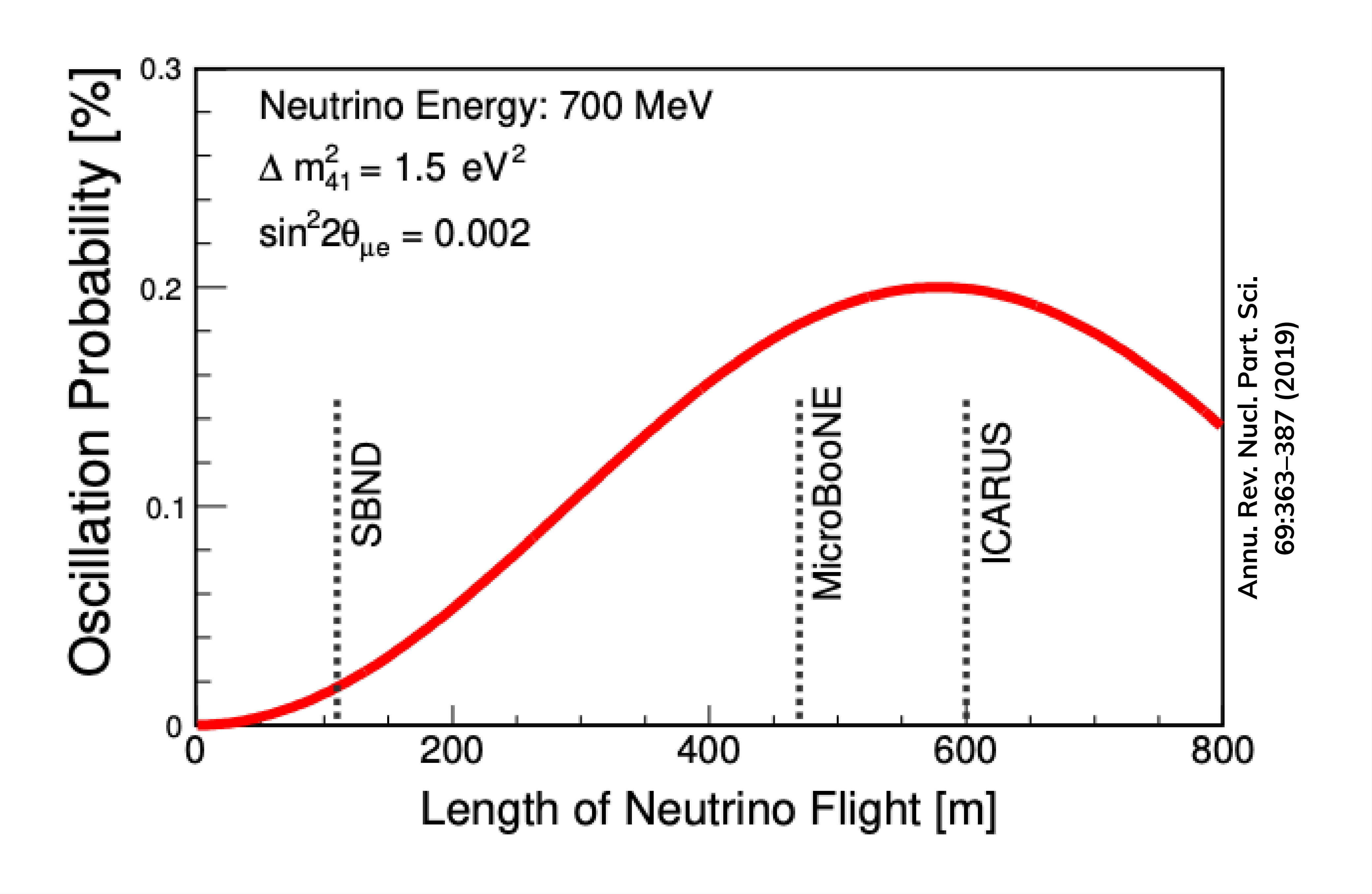
Neutrino Oscillations Overview

The probability that a $|\nu_\alpha\rangle$ flavour neutrino is detected as another flavour $|\nu_\beta\rangle$ at the time t in a vacuum is, **in a two-neutrino oscillation approximation:**

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$



BNB neutrino flux

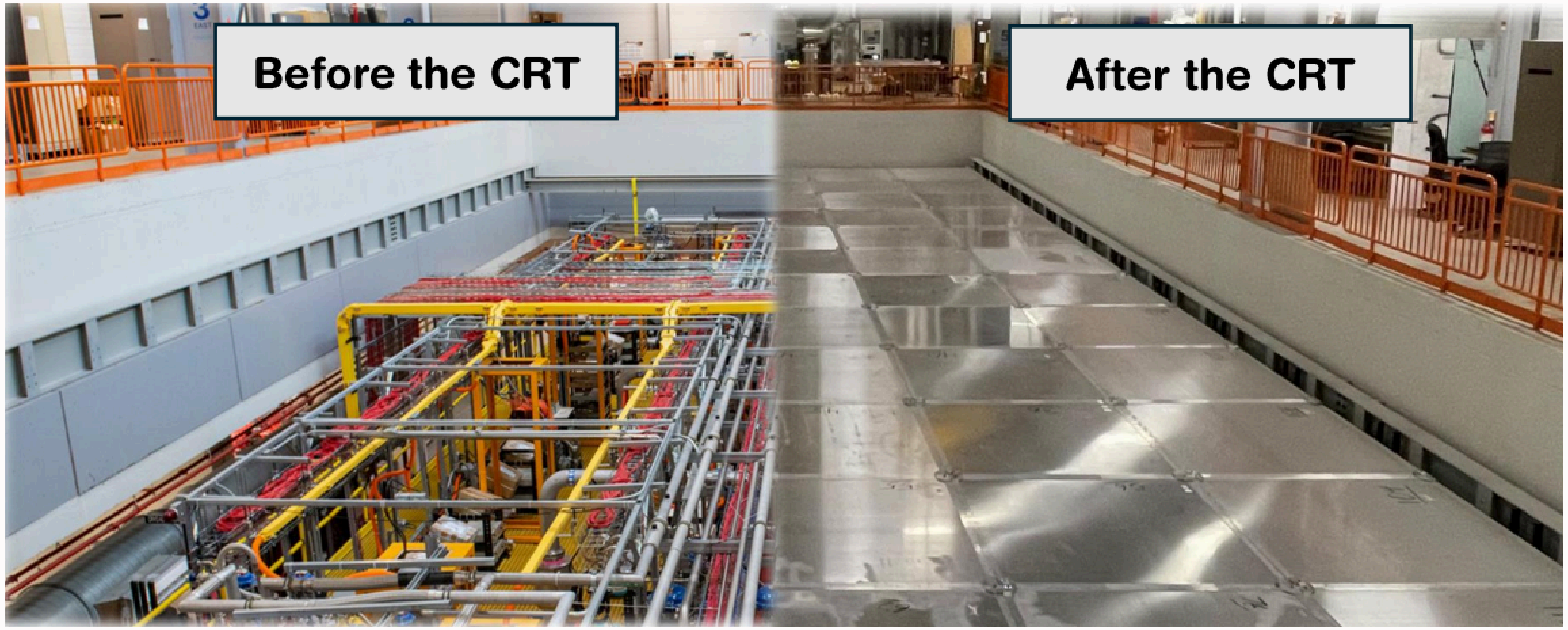


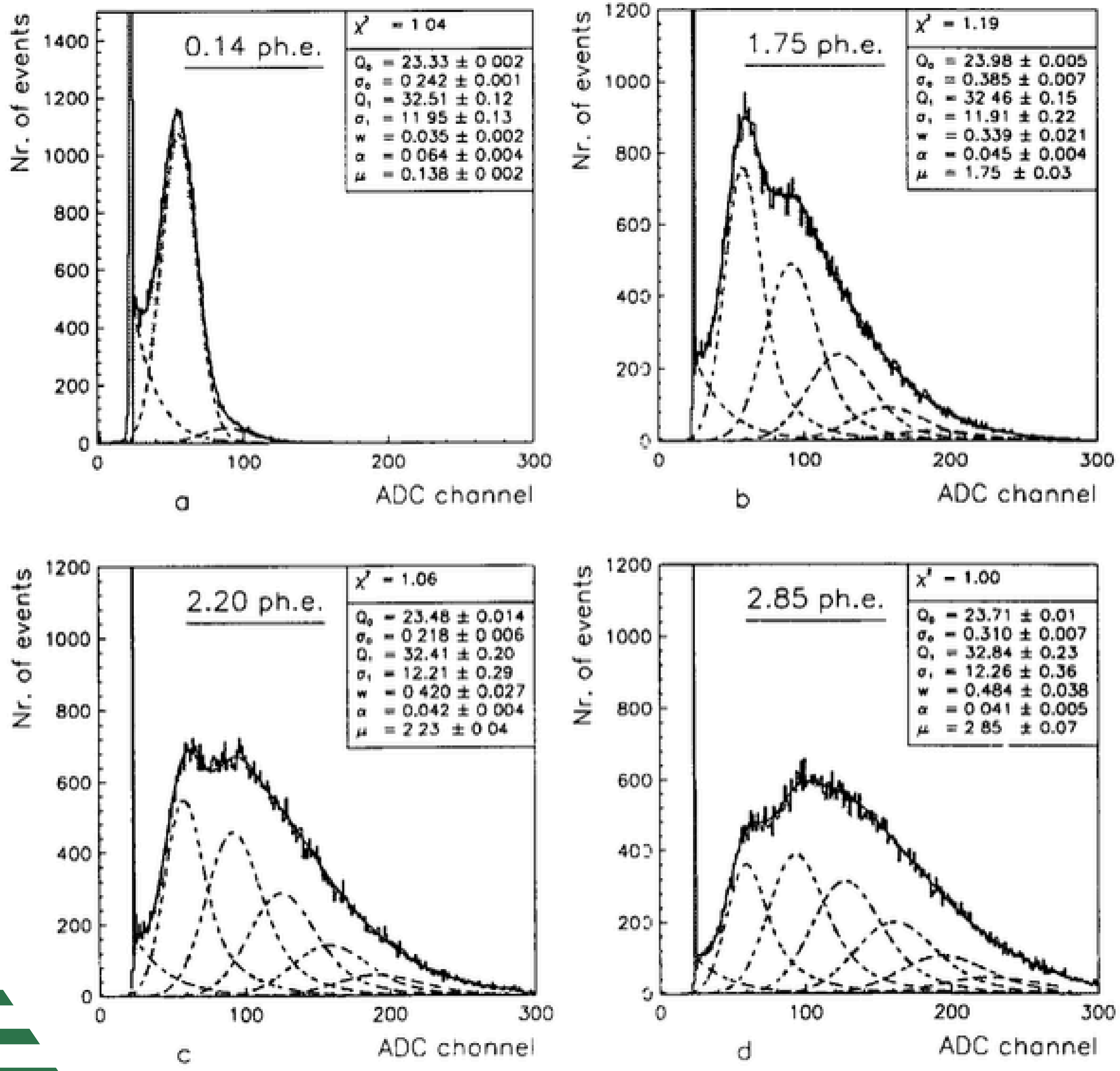
ICARUS: $L/\langle E_\nu \rangle$ ~ 600 m/ 700 MeV -----> Δm^2~ O(1 m /MeV)

ICARUS Cosmic Ray Tagger

- The Cosmic Ray Tagger system (CRT) encloses the detector: **a double layer of scintillator bars (~1000 m^2)** tagging incoming cosmics with ~95% efficiency.
  - Completion of the CRT installation in Dec 2021

- The expected rate of cosmics and neutrinos is:
  - 1 ν every 180 / 53 spills for BNB (1.6 μs) / NuMI (9.6 μs);
  - 1 cosmic μ every 55 / 6 spills for BNB (1.6 μs) / NuMI (9.6 μs).





Nucl. Instrum. Meth. A 339, 468 (1994)

photopeak

$$S_{ideal}(x) = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-nq)^2}{2n\sigma^2}\right]$$

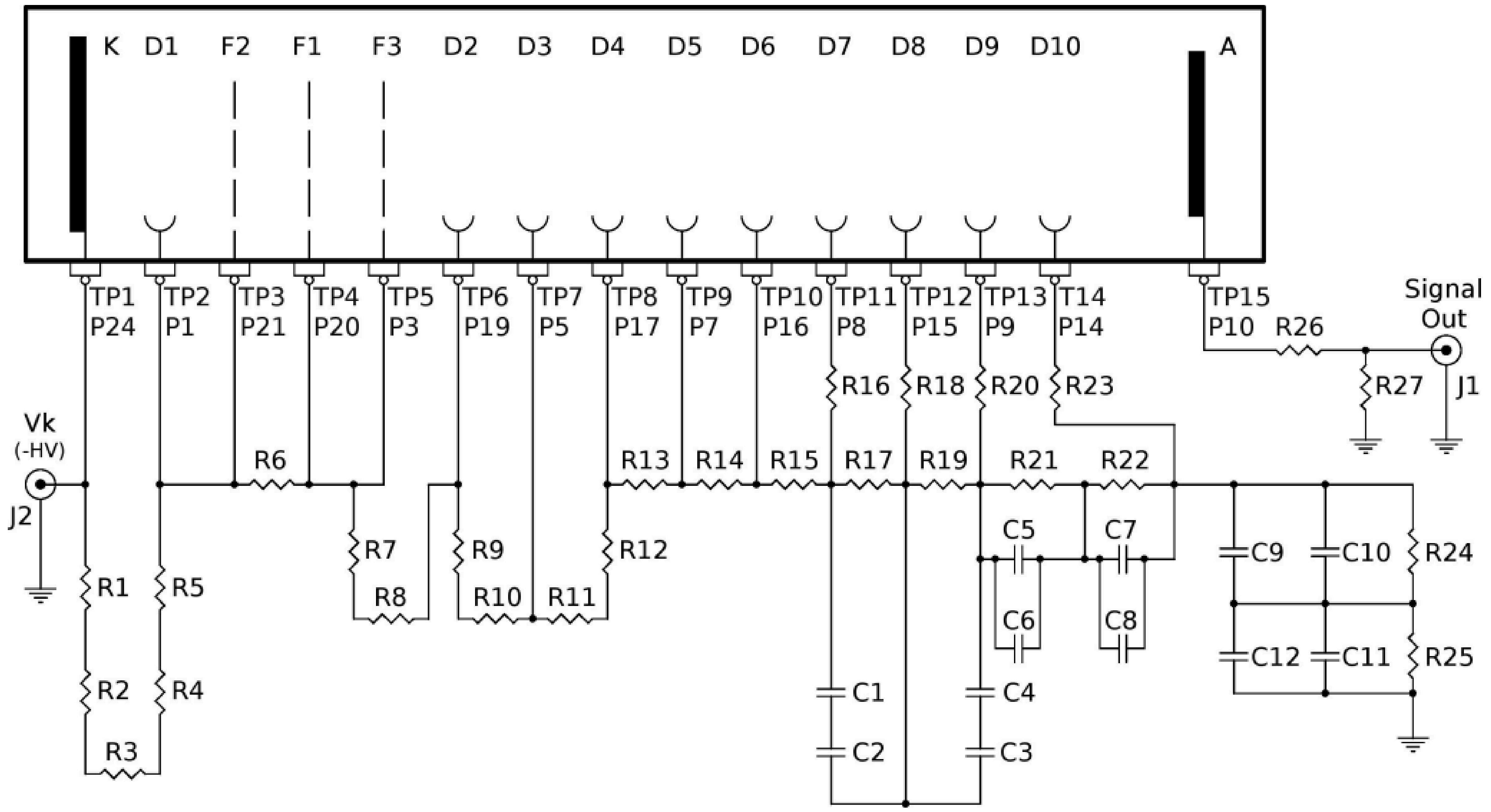
$$\underset{\text{REAL}}{\cancel{S_{ideal}}}(x) = \sum_{n=0}^{\overset{N}{\cancel{\infty}}} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-nq)^2}{2n\sigma^2}\right]$$

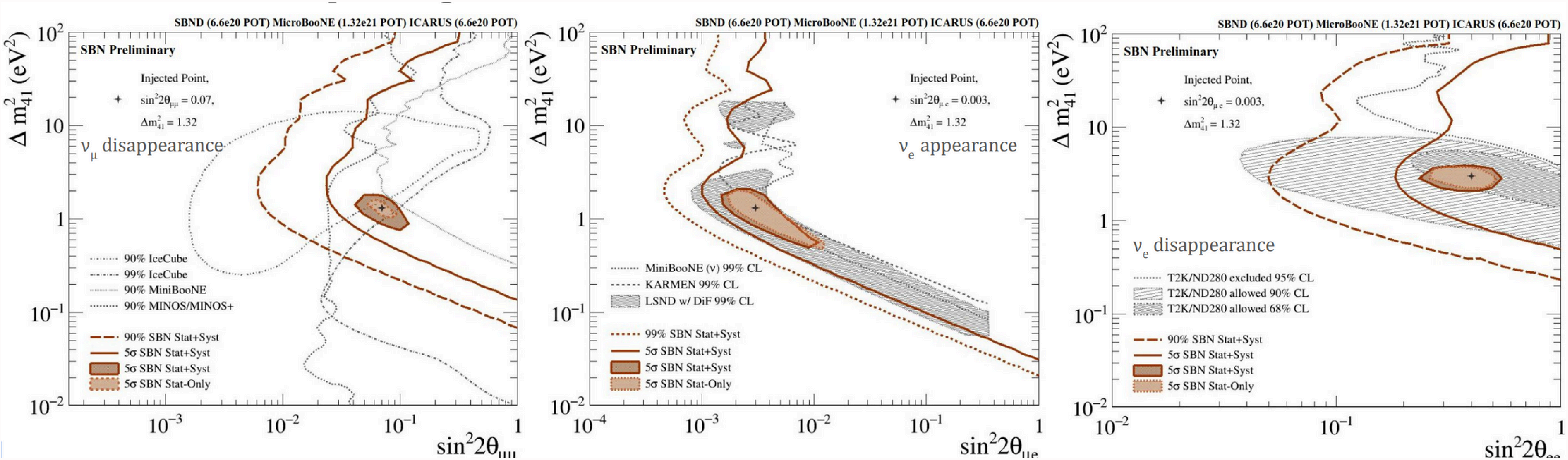
+

pedestal given by electronic noise, which is present even in the absence of a light source.

$$G = \prod_{i=1}^{n} A_i V_i^{\alpha_i} = \prod_{i=1}^{n} A_i (\epsilon_i V)^{\alpha_i}$$

Electrodes	Ratio
K-D1	16.8
D1-F2	0
F2-F1	0.6
F1-F3	0
F3-D2	3.4
D2-D3	5
D3-D4	3.33
D4-D5	1.67
D5-D6	1
D6-D7	1.2
D7-D8	1.5
D8-D9	2.2
D9-D10	3
D10-A	2.4




SBND (6.6e20 POT) MicroBooNE (1.32e21 POT) ICARUS (6.6e20 POT)
SBN Preliminary
Injected Point,
sin²2θμμ = 0.07,
Δm²41 = 1.32
νμ disappearance
90% IceCube
99% IceCube
90% MiniBooNE
90% MINOS/MINOS+
90% SBN Stat+Syst
5σ SBN Stat+Syst
5σ SBN Stat+Syst
5σ SBN Stat-Only
Δ m²41 (eV²)
sin²2θμμ
SBND (6.6e20 POT) MicroBooNE (1.32e21 POT) ICARUS (6.6e20 POT)
SBN Preliminary
Injected Point,
sin²2θμe = 0.003,
Δm²41 = 1.32
νe appearance
MiniBooNE (ν) 99% CL
KARMEN 99% CL
LSND w/ DiF 99% CL
99% SBN Stat+Syst
5σ SBN Stat+Syst
5σ SBN Stat+Syst
5σ SBN Stat-Only
Δ m²41 (eV²)
sin²2θμe
SBND (6.6e20 POT) MicroBooNE (1.32e21 POT) ICARUS (6.6e20 POT)
SBN Preliminary
Injected Point,
sin²2θμe = 0.003,
Δm²41 = 1.32
νe disappearance
T2K/ND280 excluded 95% CL
T2K/ND280 allowed 90% CL
T2K/ND280 allowed 68% CL
90% SBN Stat+Syst
5σ SBN Stat+Syst
5σ SBN Stat+Syst
5σ SBN Stat-Only
Δ m²41 (eV²)
sin²2θee

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$