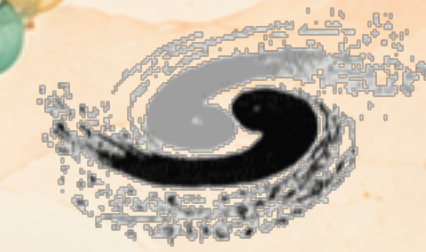




THE SMALL PMT SYSTEM OF THE JUNO EXPERIMENT



L. Labit,
University of Strasbourg - IPHC
on behalf of the JUNO Collaboration



中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Chinese Academy of Sciences



NUCLEI &
PARTICLES

PARTICLES

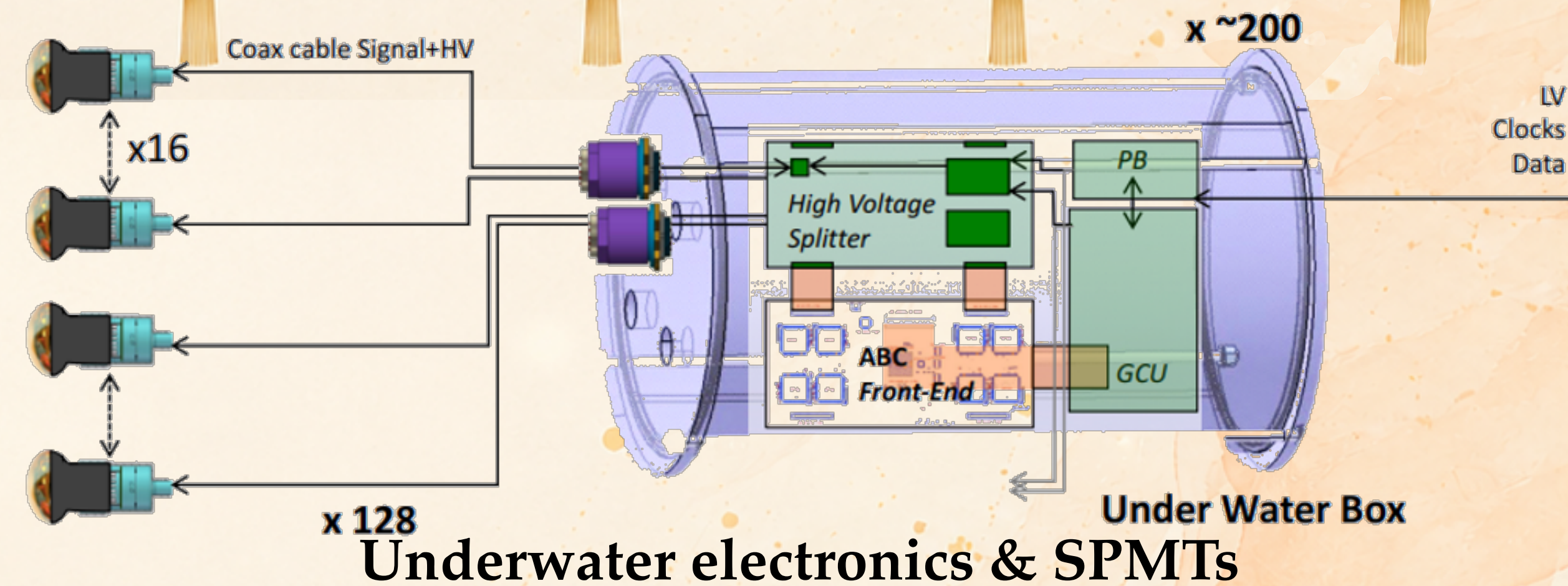
OVERVIEW

SMALL PMT SYSTEM OVERVIEW



- Main goal is to characterise the Large PMT **instrumental non-linearity**
 - Need a secondary array of PMTs in single photo-counting regime
- Physics potential includes
 - solar oscillation parameters, proton decay, SuperNovae, ...
- The system consists of :
 - 25 600 3-inch PMTs
 - dedicated underwater front-end electronics

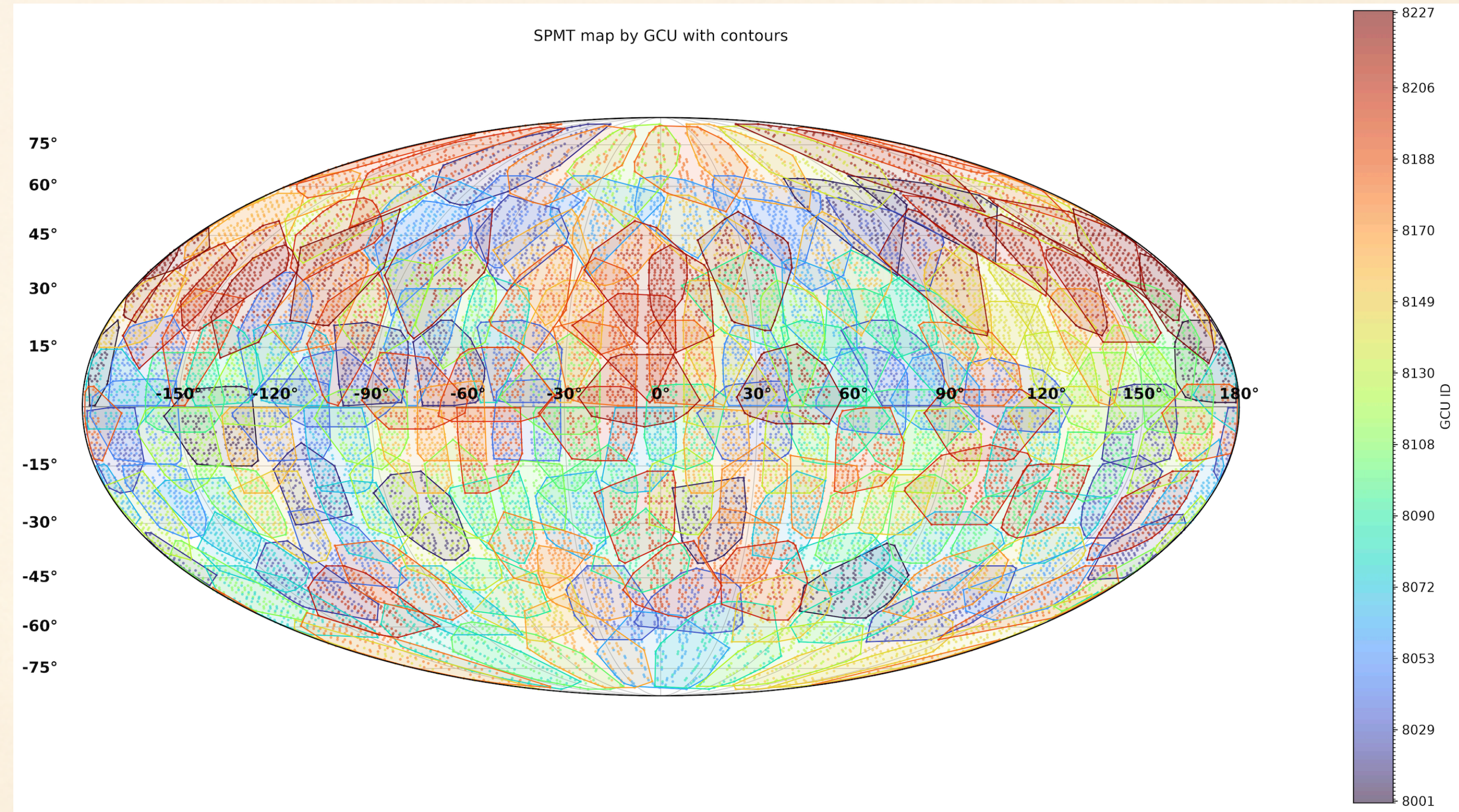
CPC 46 (2022) 123001, CPC 47 (2023) 113002



LPMT surrounded by SPMTs

SMALL PMT SYSTEM OVERVIEW

- PMTs deployed with 5 & 10 meter cables (low-amplitude signals)
→ Overlapping electronics coverage to avoid **blind spots** in case of electronics malfunction



SPMT coverage by electronics

HARDWARE STATUS

SPMT PRODUCTION & INTEGRATION

- 26 000 3-inch PMTs produced by Hainan Zhangchuang (HZC)
→ continuous performance tests over 2 years to ensure JUNO's requirements are met

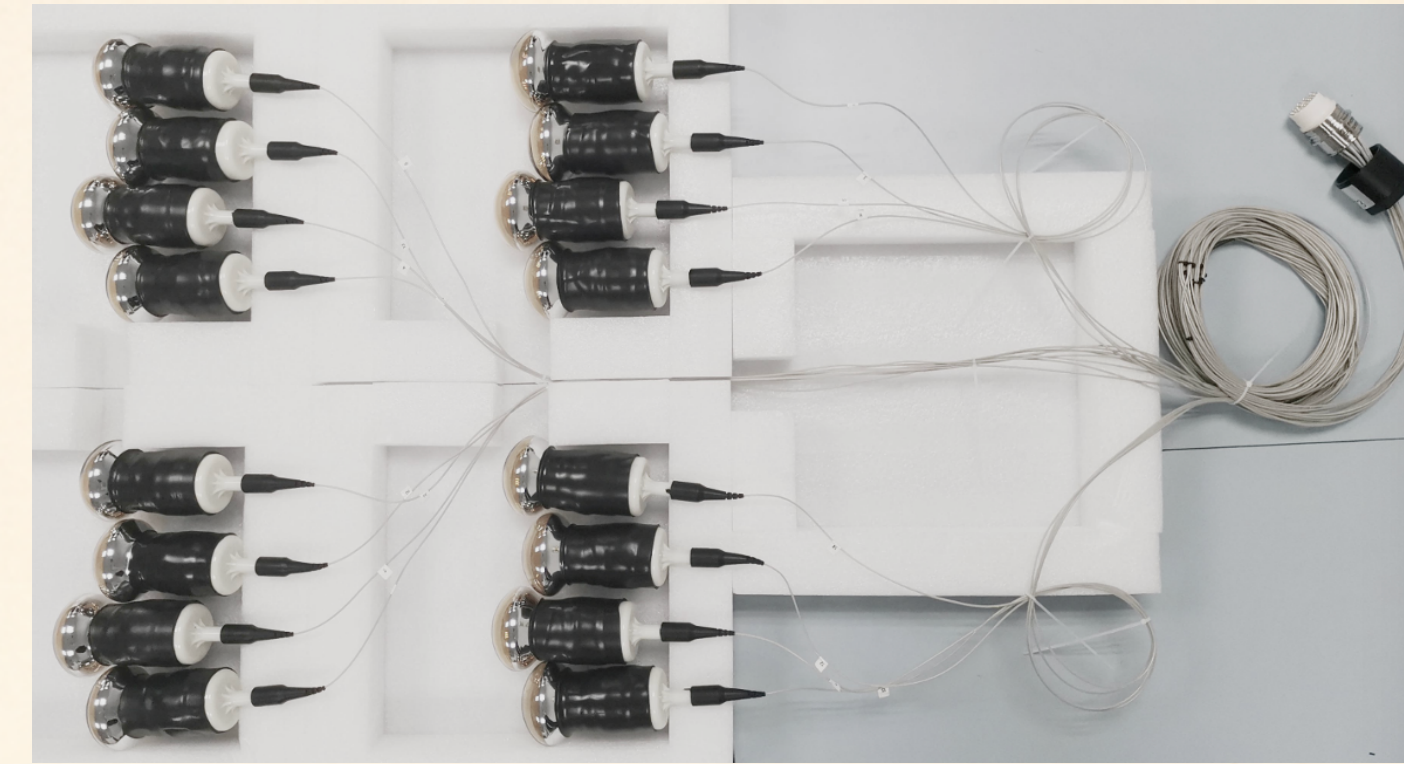
NIM, A 1005 (2021) 165347

- PMTs grouped in sets of 16 to the same Axon connector
→ 1600 groups of PMT

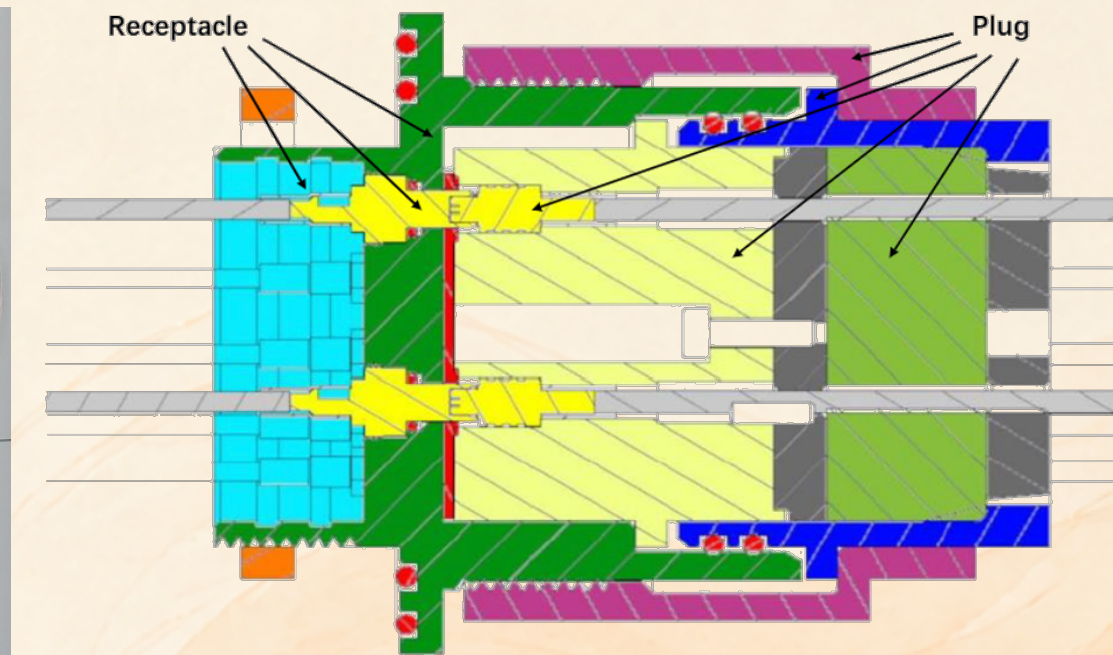
- Instrumented PMTs (HV divider, cable, connectors) qualified at Guangxi University

NIM, A 1086 (2026) 171301

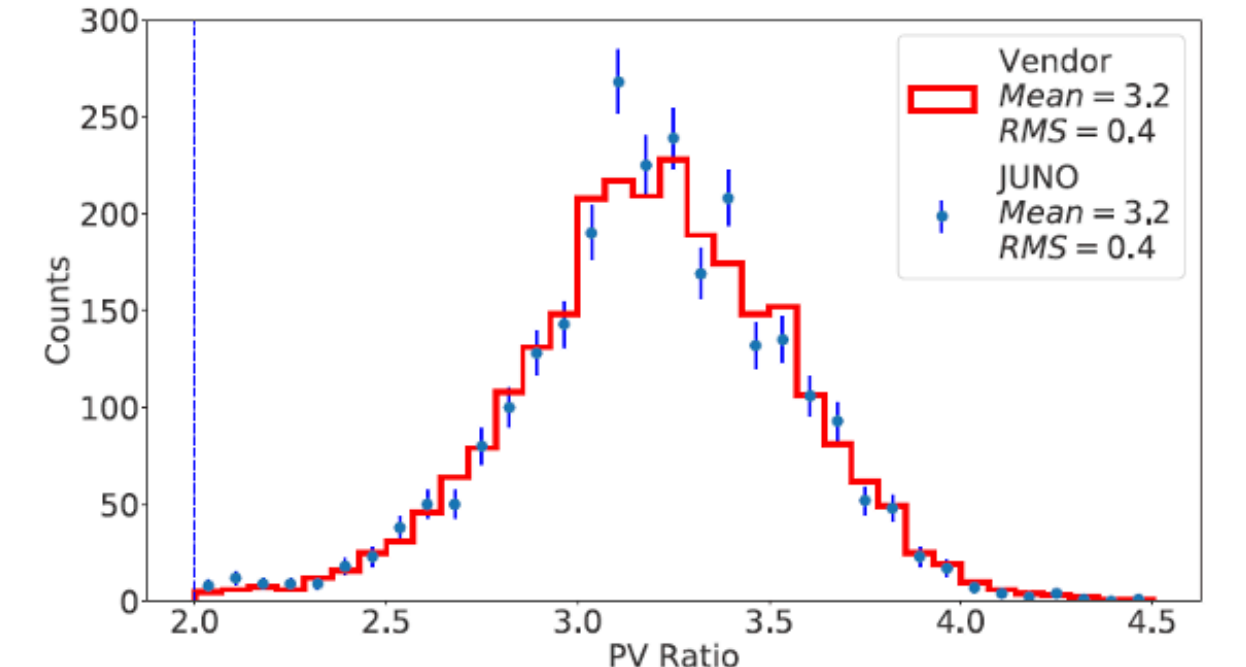
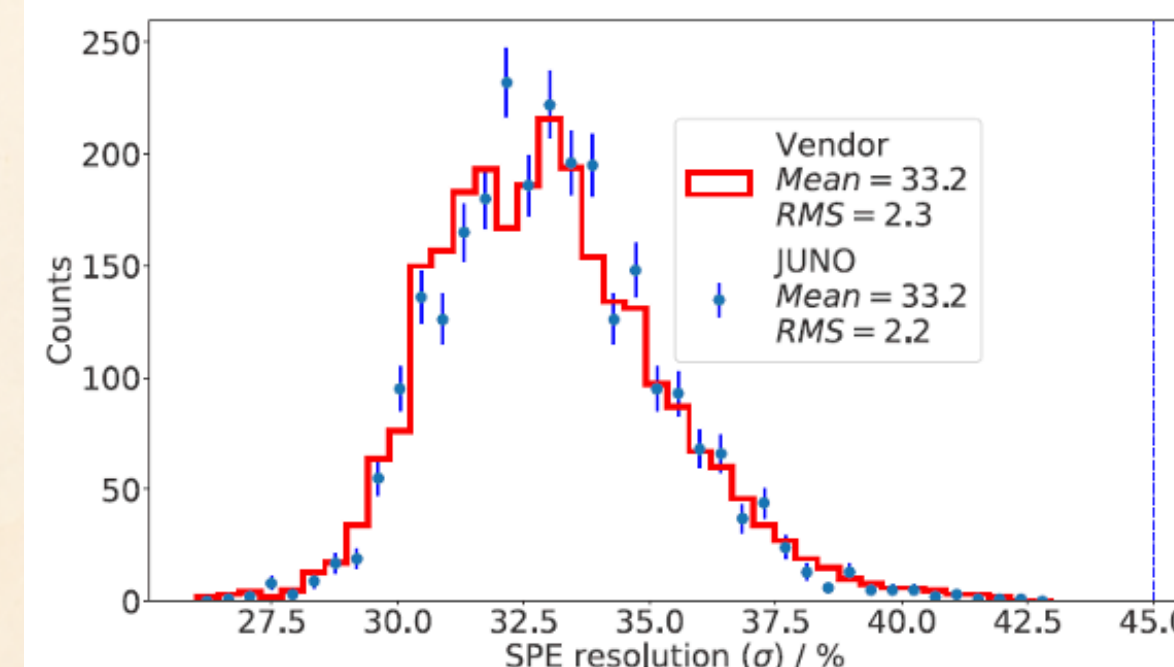
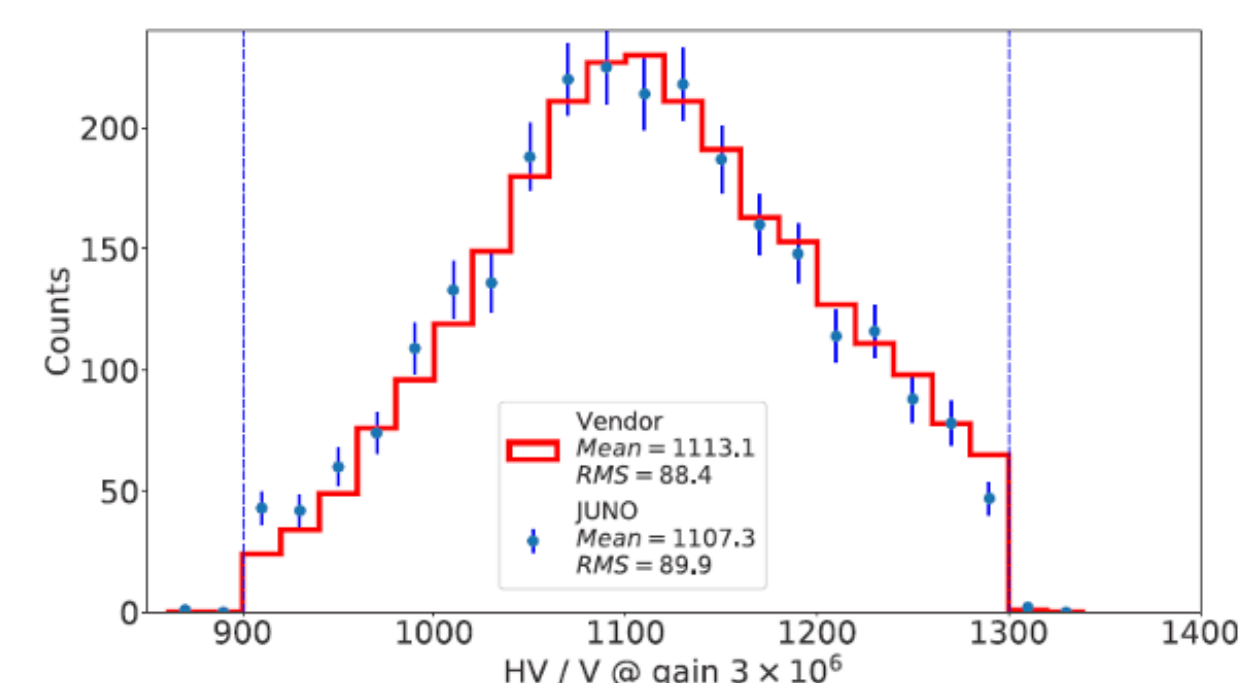
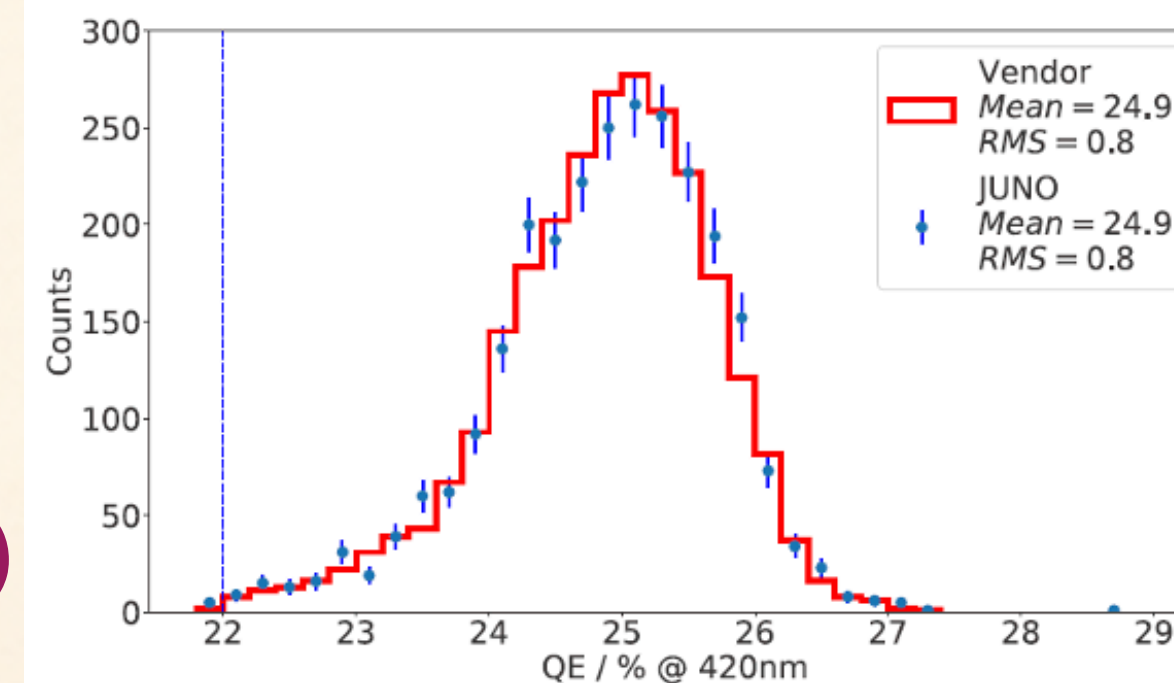
→ performance consistent with bare PMTs meeting JUNO's requirements



Group of 16 PMTs & connector



Schematic of Axon connector

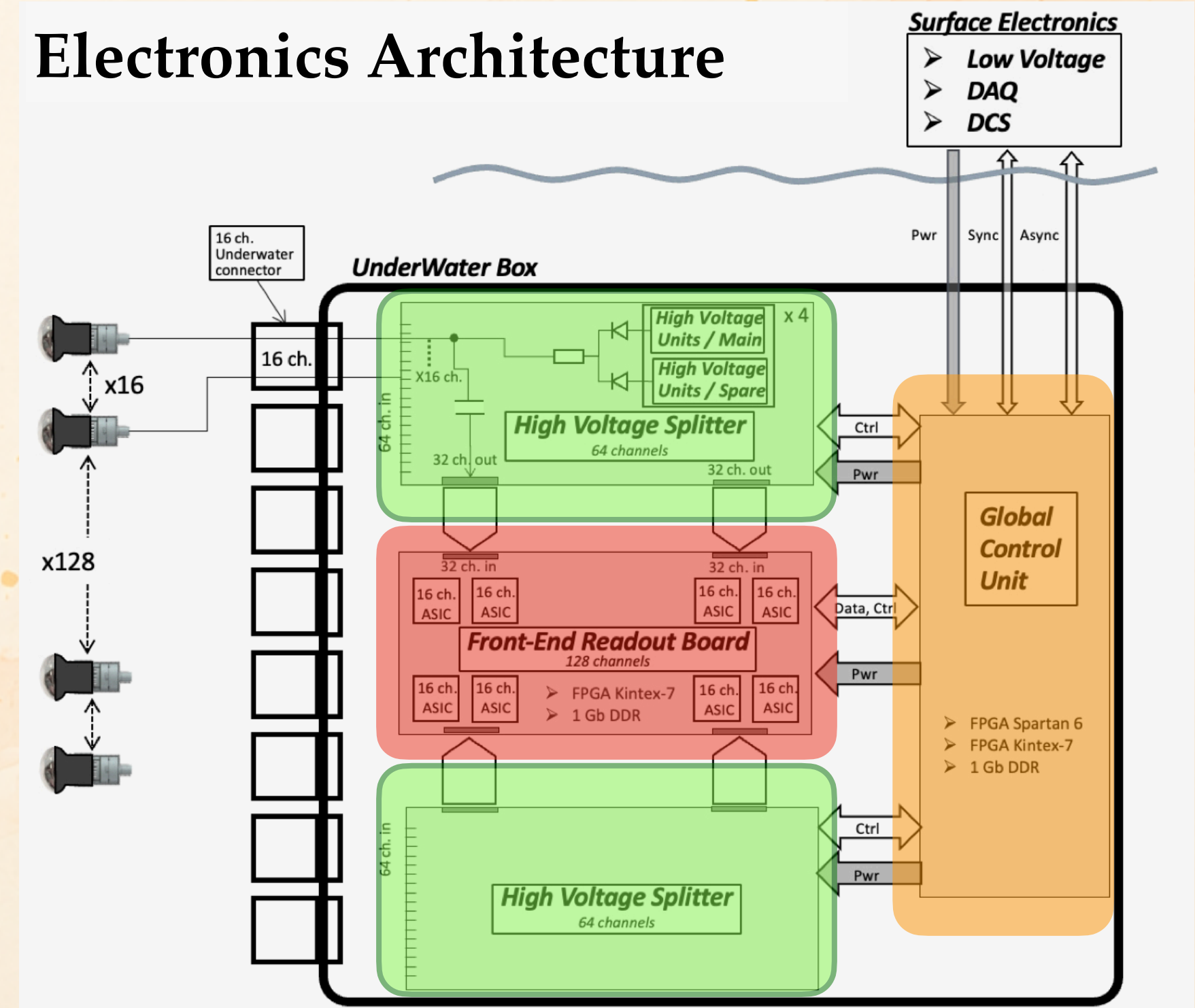
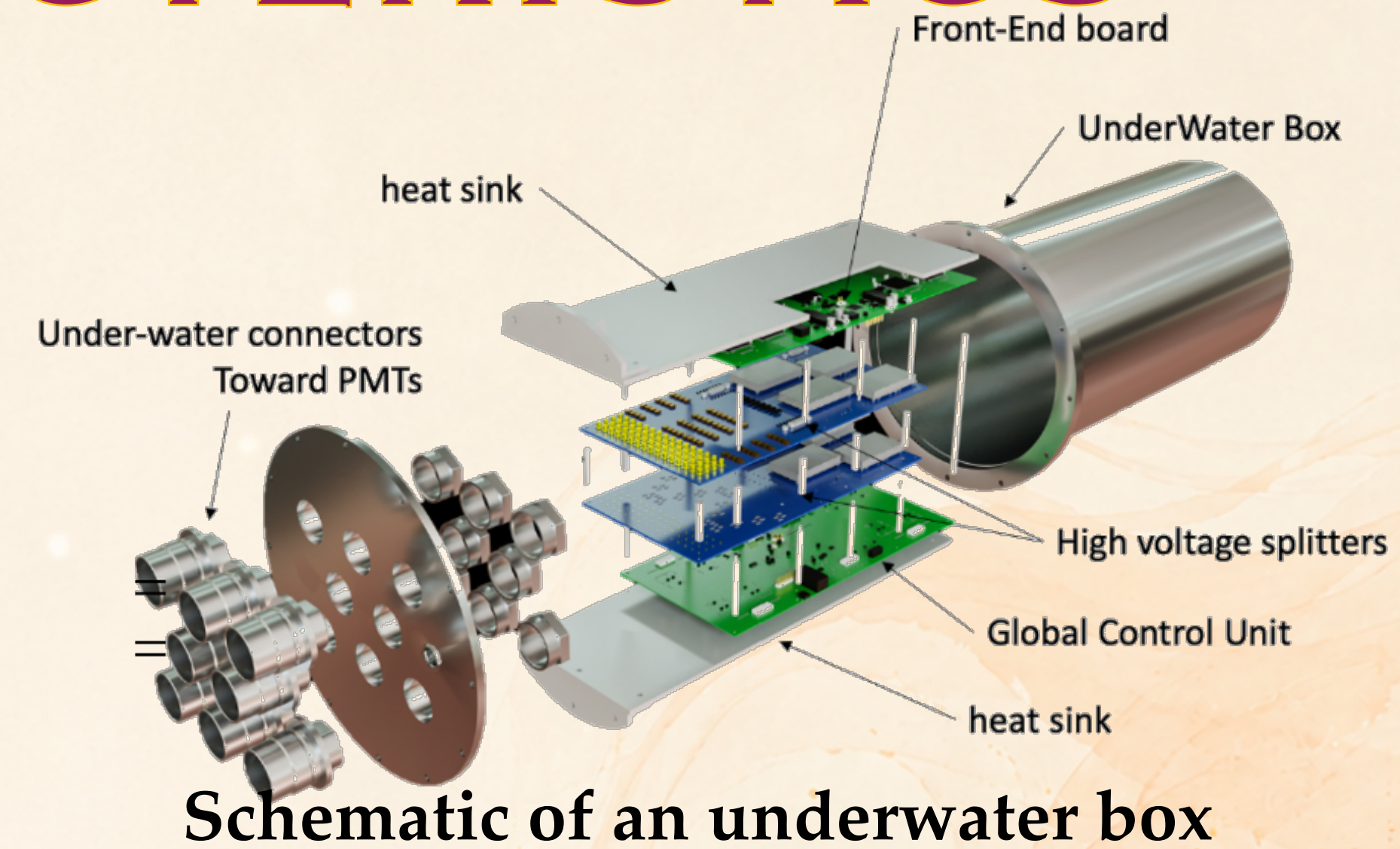


Bare vs Instrumented performance

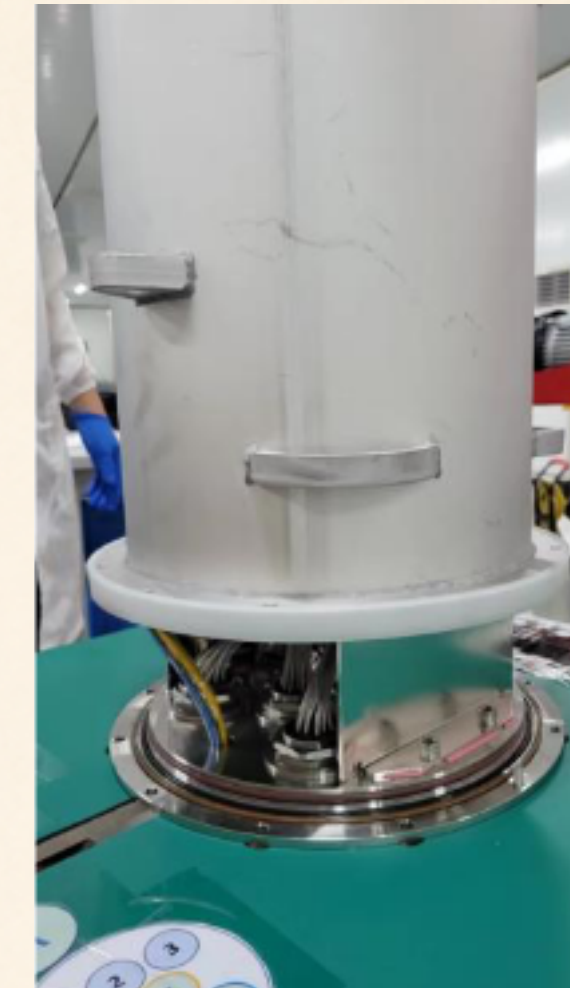
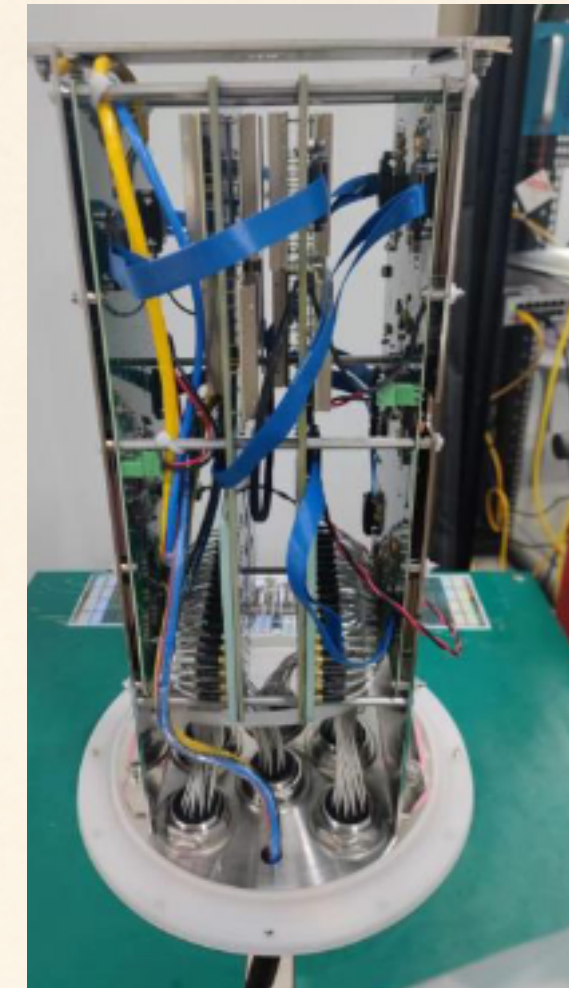
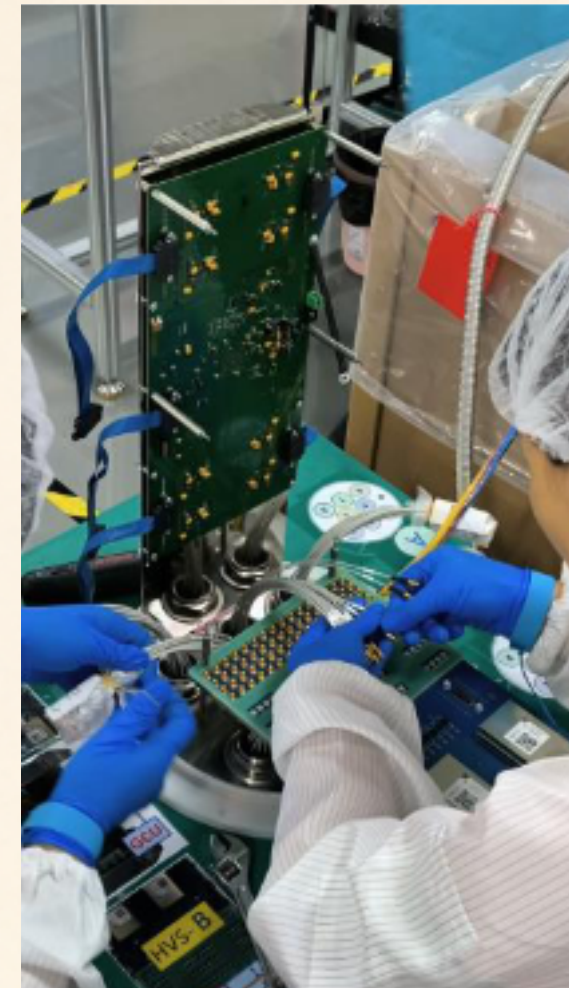
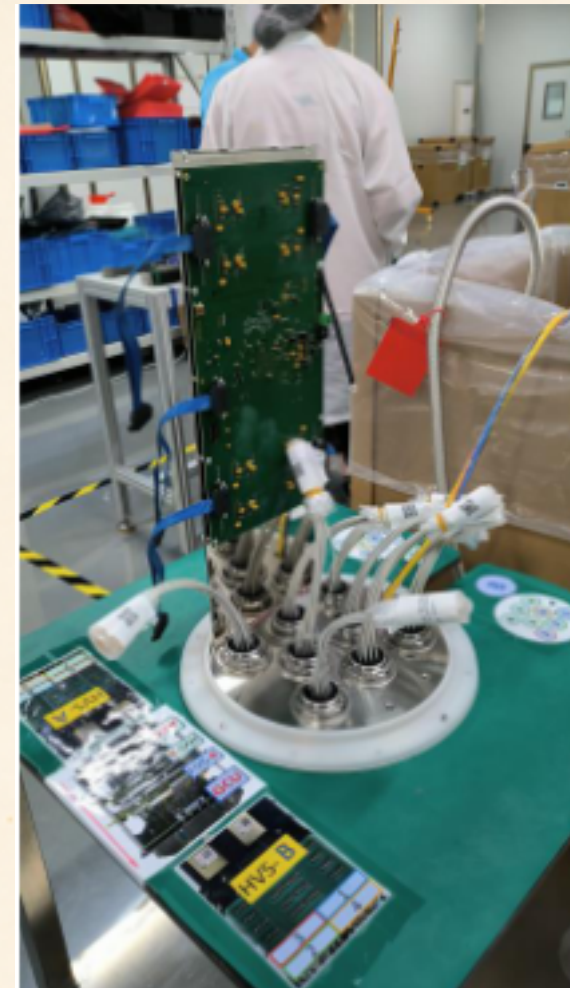
ELECTRONICS CHARACTERISTICS

- Requirement : digitise single photo-electron (PE) signal ~ 2 mV amplitude with trigger threshold lower than 0.33 PE
→ CATIROC ASIC developed by OMEGA laboratory
2021 JINST 16 P05010
- CATIROC's performance :
→ 16 independent self-triggering channels with pre-amplifier
→ charge & time measurements (time granularity ~ 250 ps)
→ common programmable trigger threshold
→ 2 hits / channel can be digitised within $\sim 9 \mu s$

- Electronics architecture [arXiv:2604.25835](https://arxiv.org/abs/2604.25835)
→ 2x64 channels HV Splitter boards powering PMTs and decoupling signal from high-voltage
→ ABC front-end board: reads out and formats data from 8 CATIROC chips (Q/T pairs from 128 channels)
→ GCU board powering ABC board, sending clock and transferring data from ABC to DAQ
⇒ Electronics performance validated at LP2I Bordeaux & IHEP



ELECTRONICS INTEGRATION



Receptacle
assembly

ABC
mounting

2 HV splitter
mounting

GCU
mounting

Closing
underwater
box

Leakage test

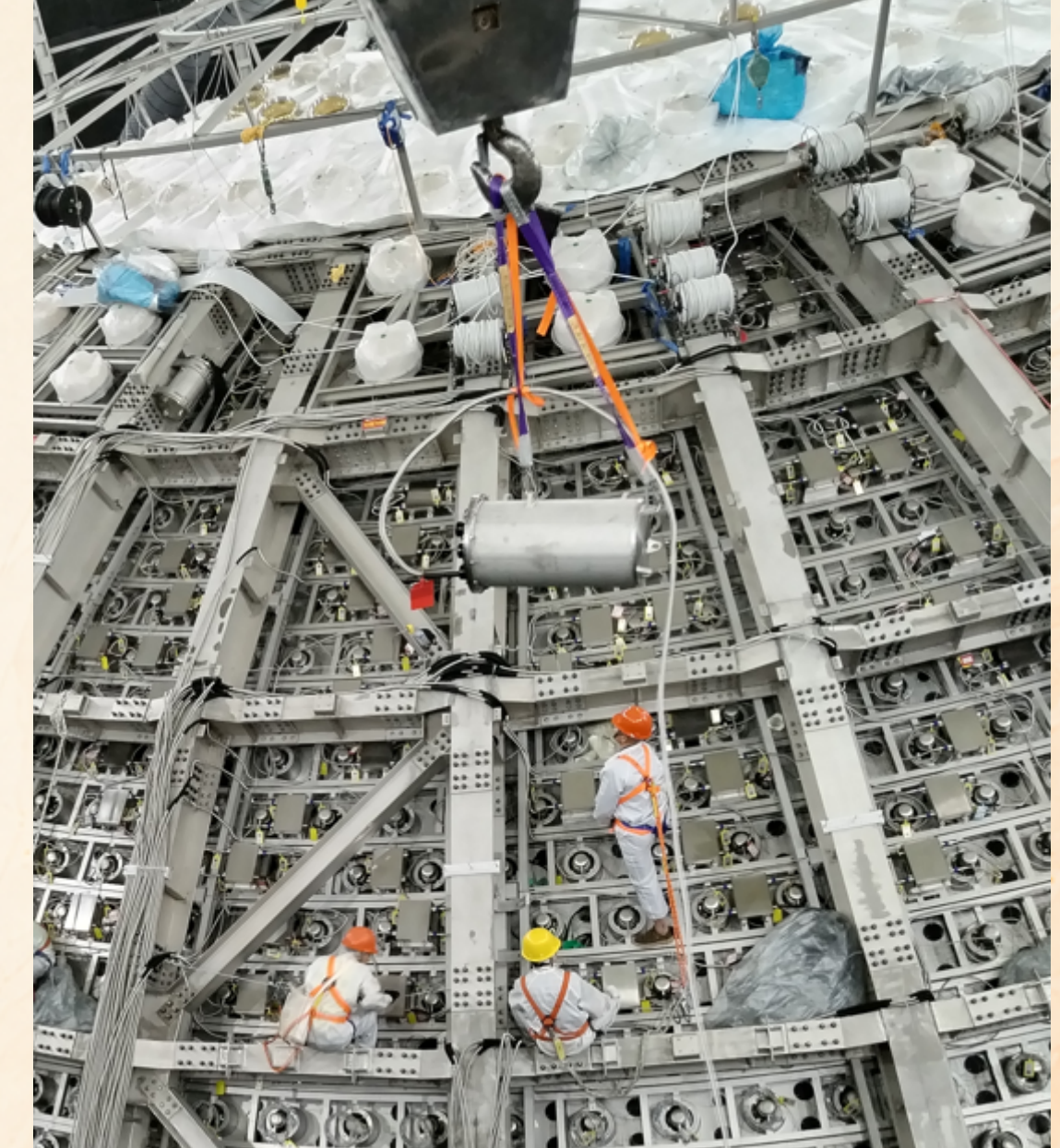
- 200 + 4 spare sets of electronics assembled at JUNO
- **Operational test** for all channels with PMTs
- **Leakage tests** for all integrated underwater boxes with custom SF₆ gas system

RDTM 10 (2026) 2

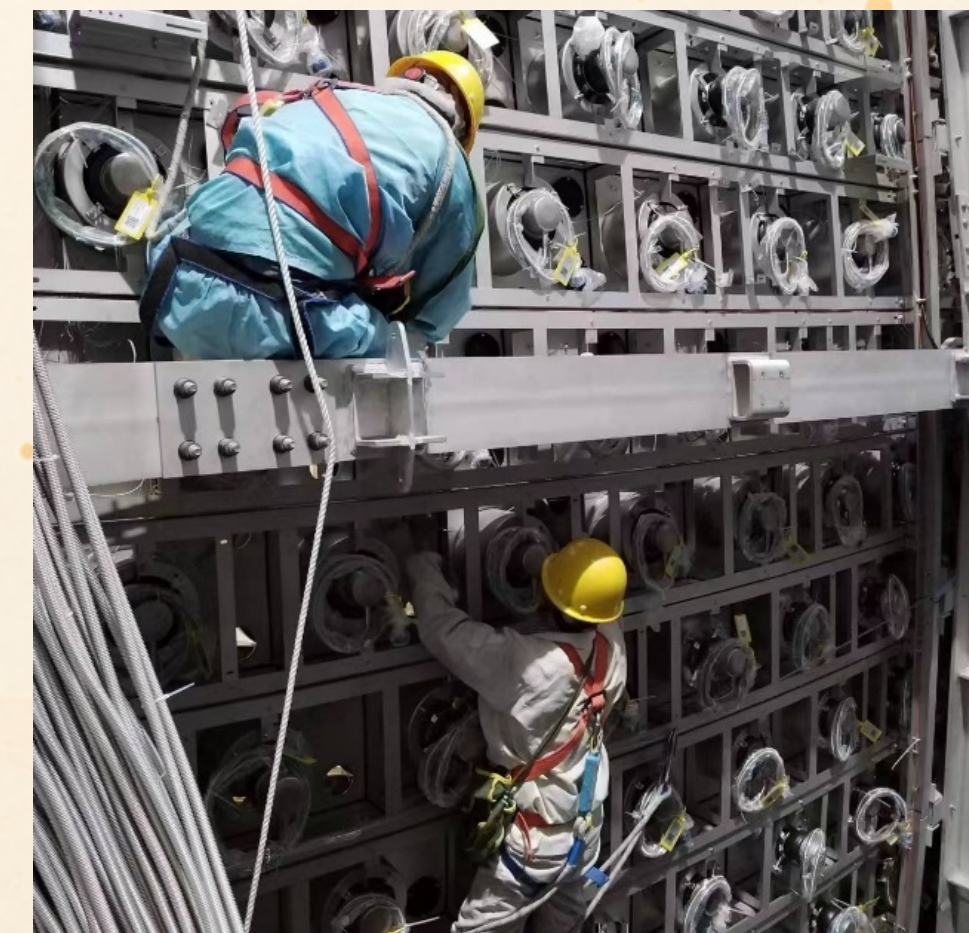
SPMT SYSTEM INSTALLATION

- SPMT installation over 2 years : early 2023 to 5th December 2024
- Installation of 25 587 PMTs and 200 electronic underwater boxes
 - Installation speed : average 101 PMTs/day by 1 or 2 group of workers (3 - 6 workers)
 - Cable and cleanliness was checked one by one
- A WeChat App was developed to scan QR code to ensure installation position for each PMT and electronics box

Underwater box lifting and installation



PMT installation



SPMT
MID:
GJ-N57-06(3/6)
PID:
N-57-020.5-U
CID: 12 Type: L

QR code on PMT



Module
MID:
GJ-N57-06(3/6)
PID:
N-057-020.5-U
CID: 12

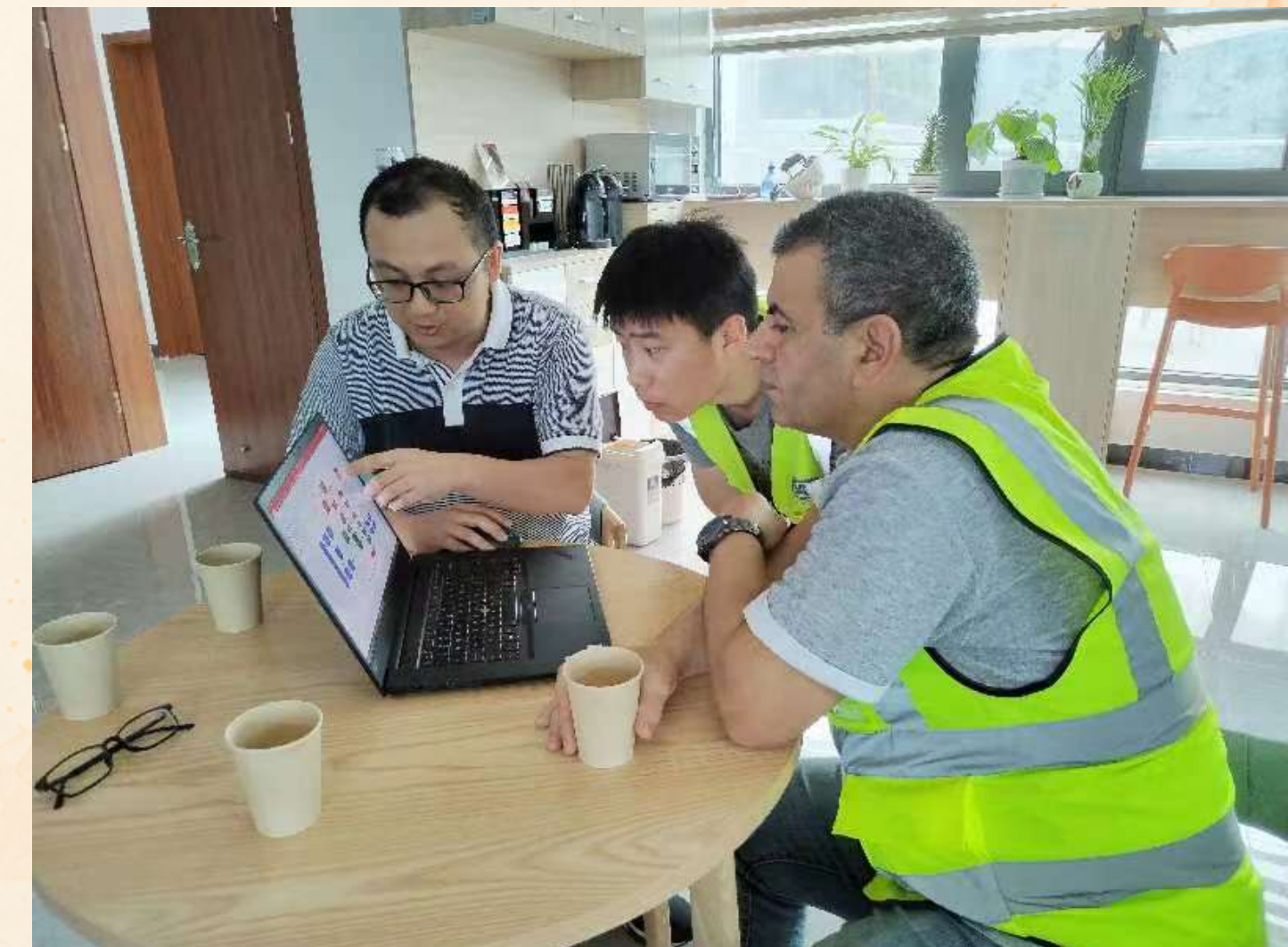
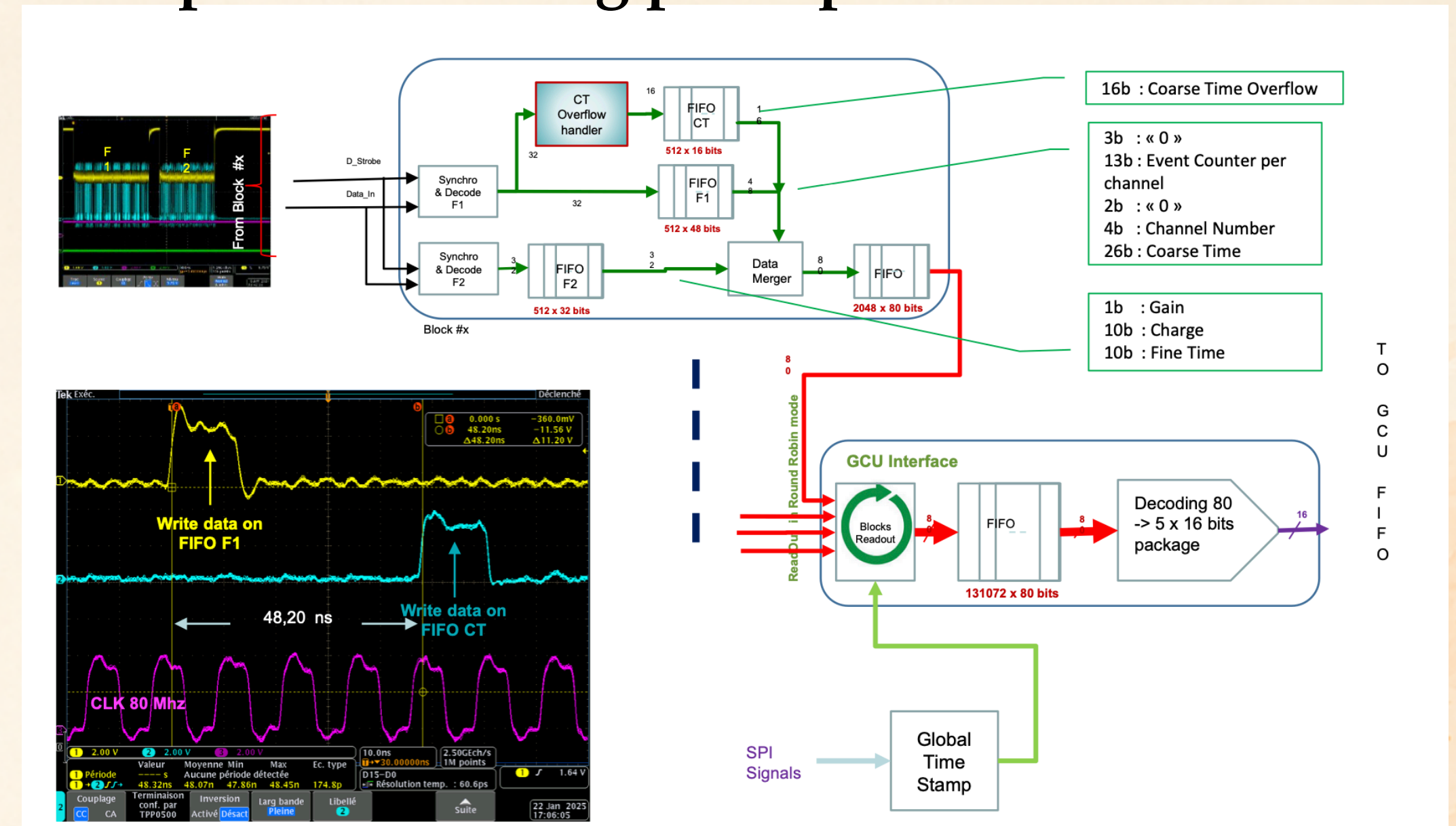
QR code on installation position



FIRMWARE DEVELOPMENT

Simplified working principles of ABC firmware

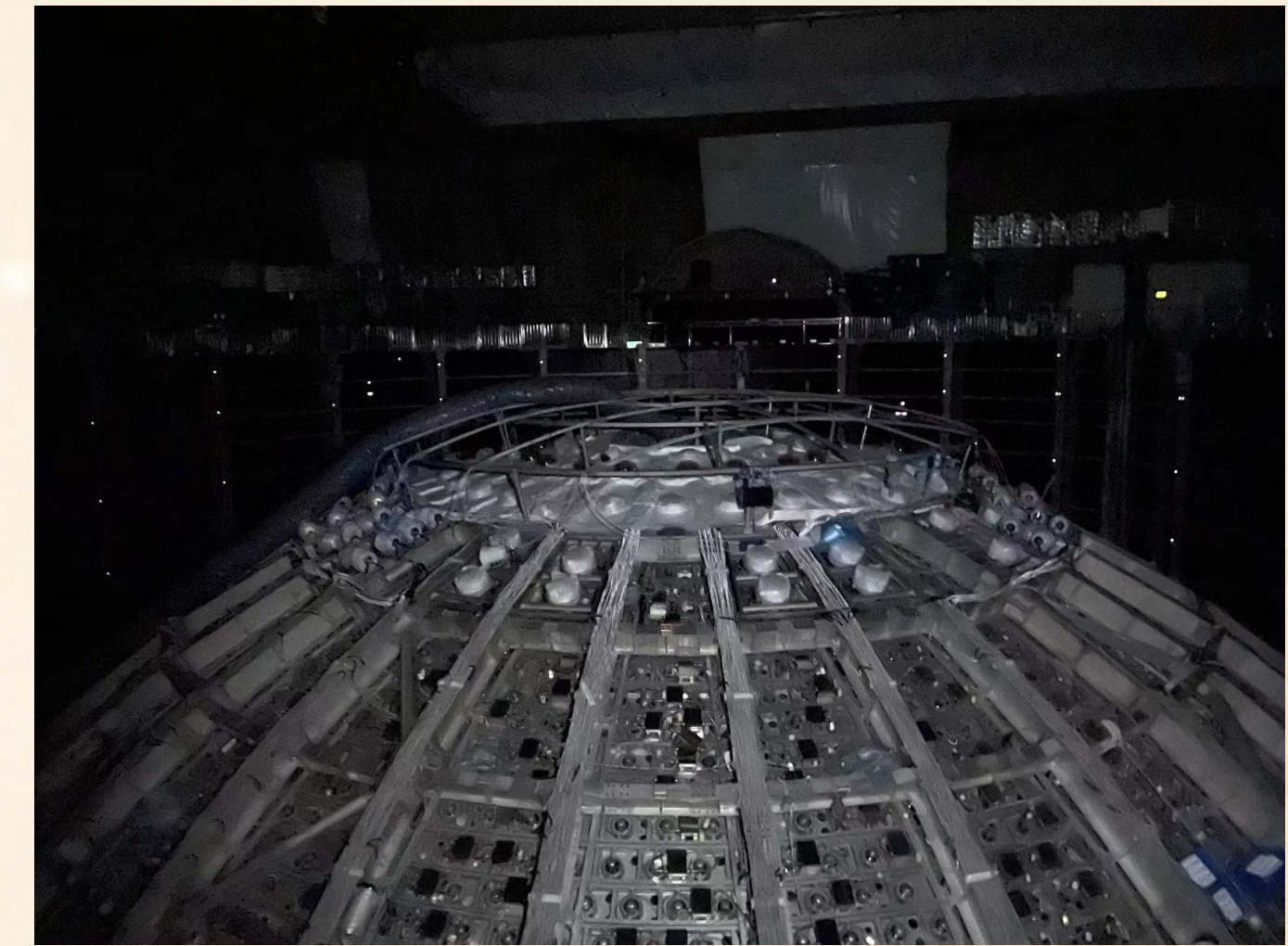
- Challenge : handling **parallel** charge and time datastream of 128 channels and complex communication along the electronic chain
- Joint development of 2 dedicated firmwares
 - ABC firmware by LP2I Bordeaux
 - GCU firmware by IHEP
- **Functional firmwares** successfully implemented during commissioning



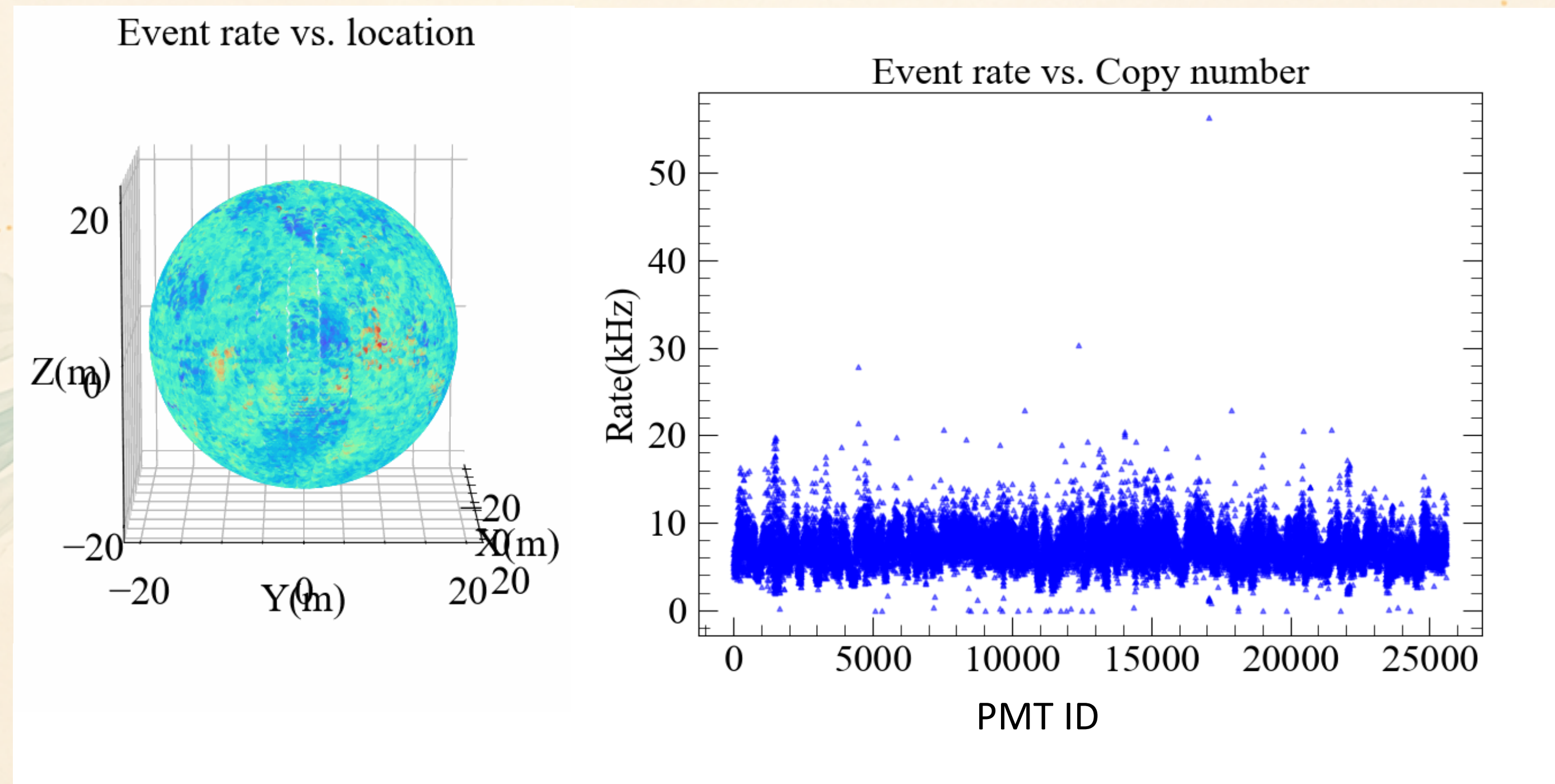
J. Hu, Z. Chu (IHEP) & A. Rebi (LP2I Bordeaux)
talking about the firmwares

SPMT COMMISSIONING: DRY PHASE

- 10 light-off tests during installation (before water filling)
 - check response of the PMTs and **electronic chain** after installation
 - **problematic channels identified** (damaged cables, misconnection) and **fixed**
- Average dark count rate during installation ~ 7 kHz
- Hit rate **uniform** over the whole detector

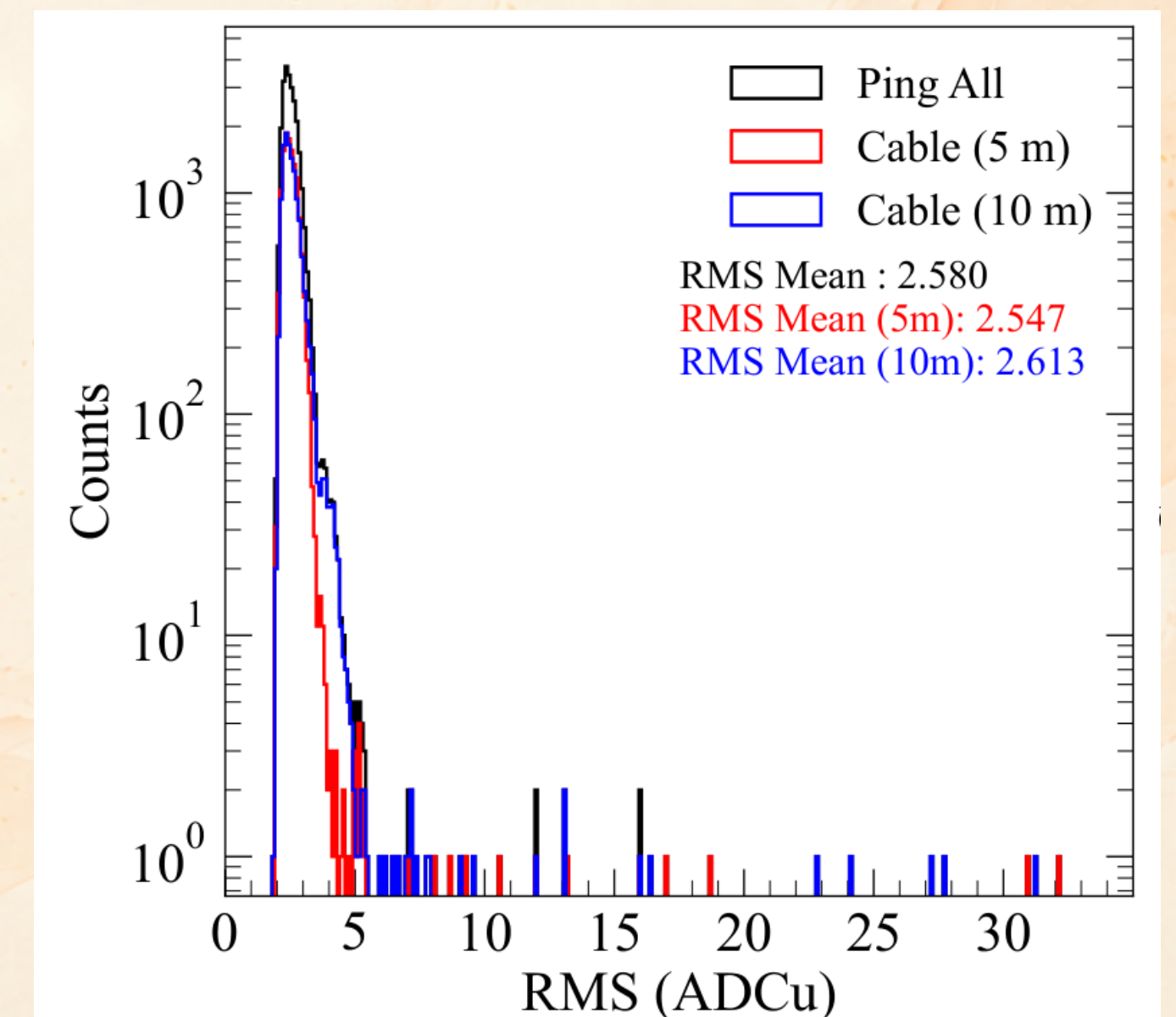
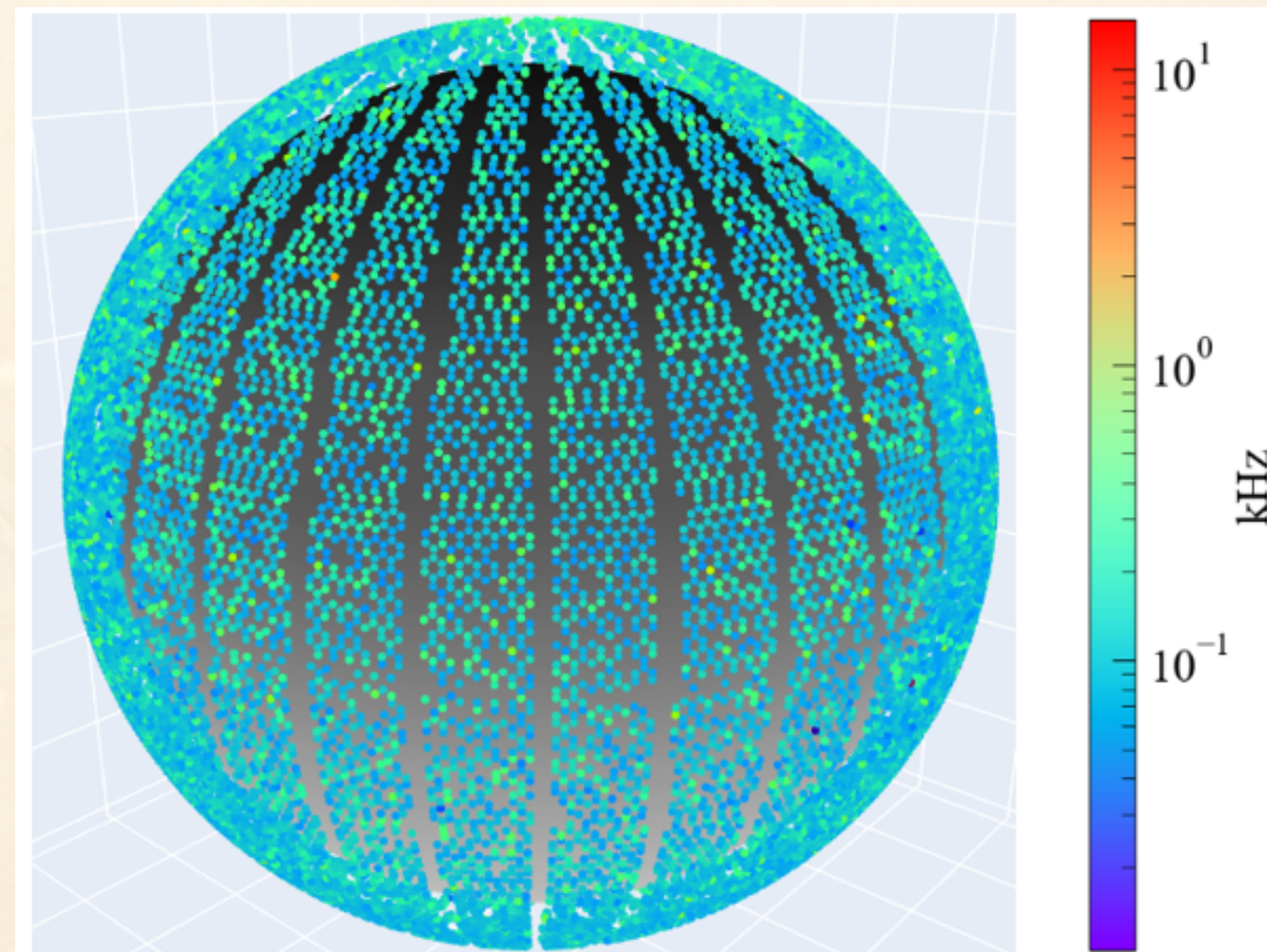
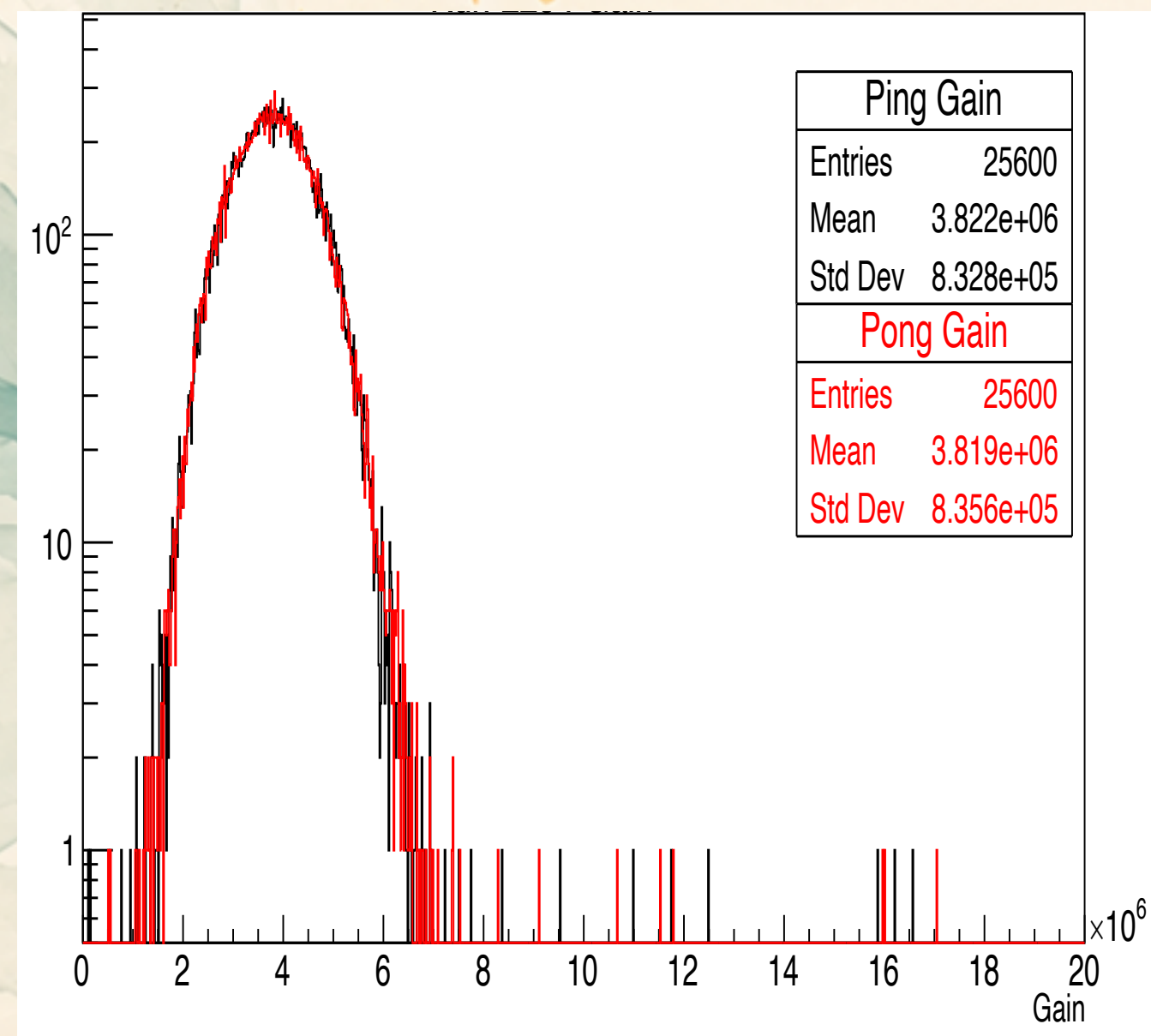


JUNO in the dark



SPMT COMMISSIONING: WATER PHASE

- 44 days of water filling from Dec. 18th 2024 to Feb. 1st 2025
- PMT dark count rate **reduced to ~530 Hz** after covering of the detector
- Charge pedestal RMS ~2.6 ADCu about 0.05 PE
→ **low electronic noise**

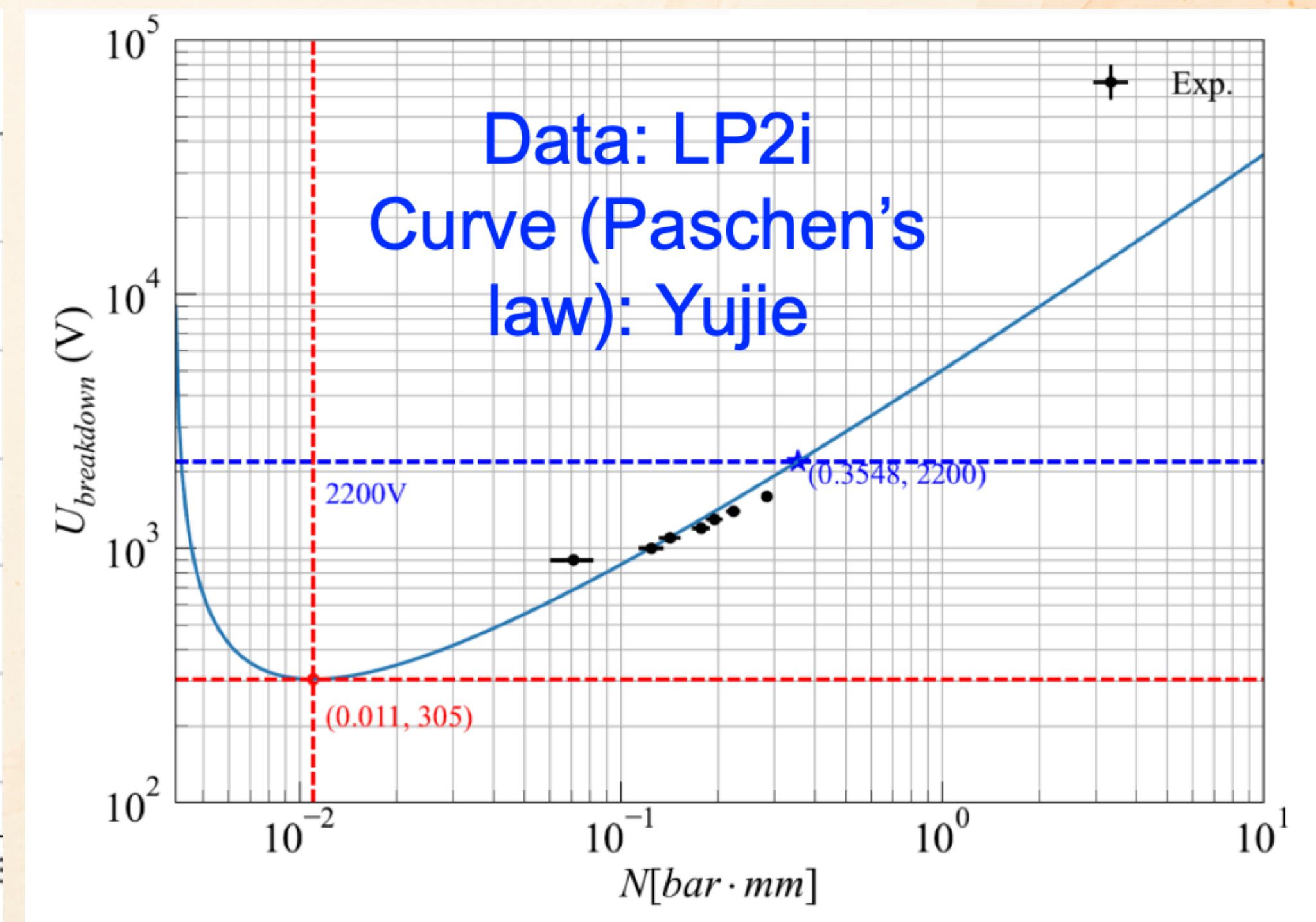
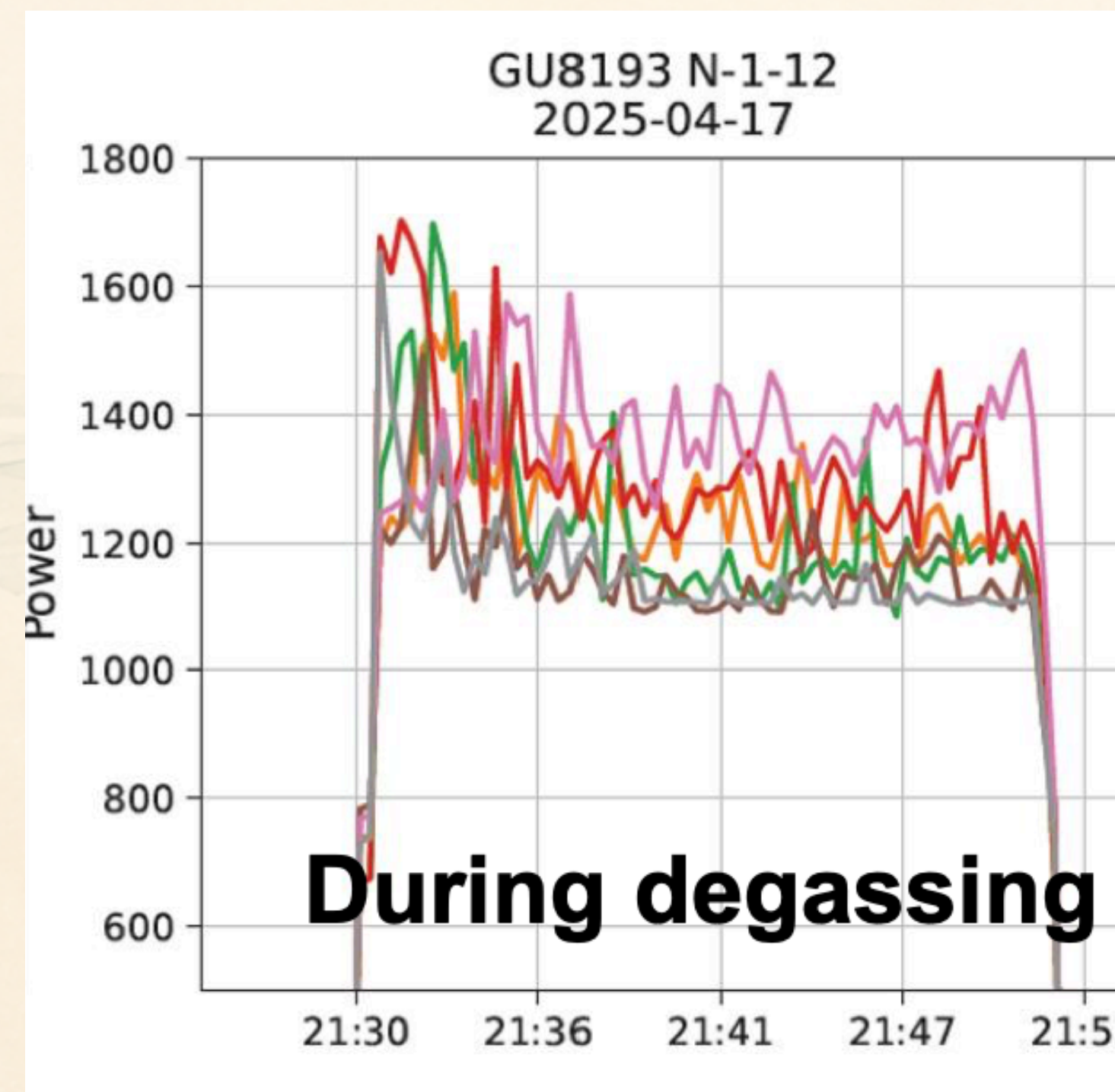


SPMT CONNECTOR DEGASSING ISSUE

- Underwater connector **watertight** but **not gas-tight**
→ gas diffused out of the connector in degassed water leading to **pressure decrease** and **HV breakdown**
- Effect characterised by **Paschen's law**



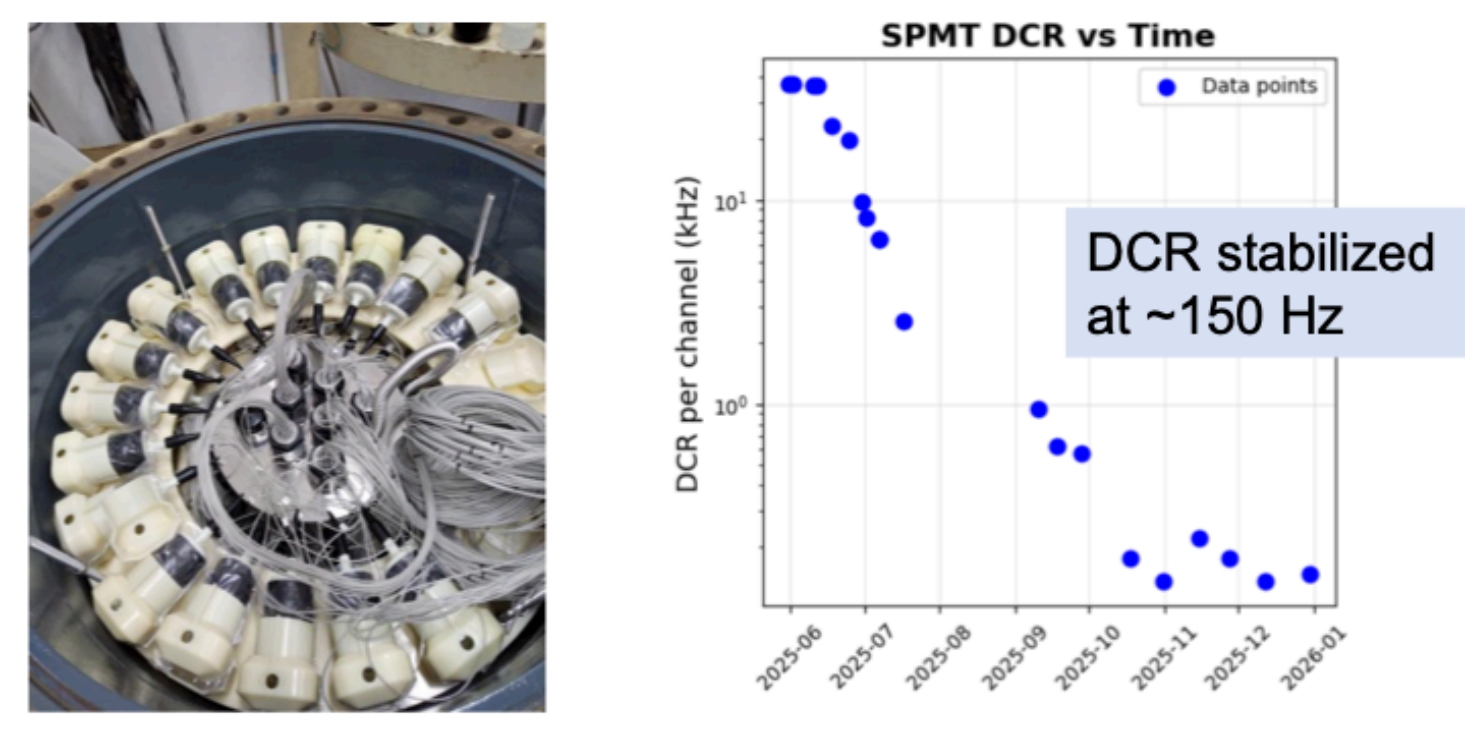
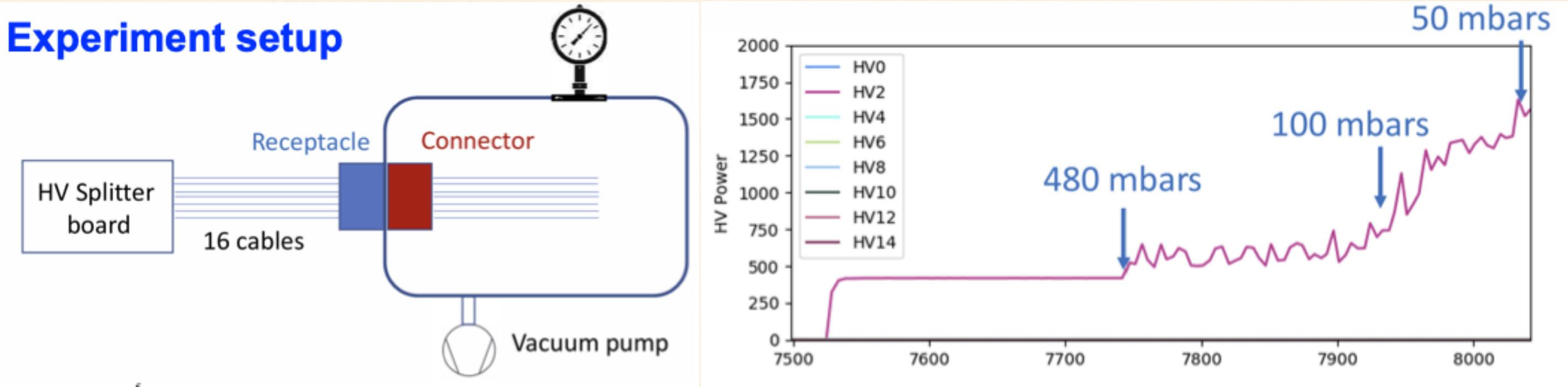
16-PMT connector



DEGASSING ISSUE : DEDICATED TESTS

HV breakdown at 480 mbar at 1230 V

- **Dedicated tests** were performed at LP2I Bordeaux & IHEP to comprehend the issue
- Connector tested in **low pressure dry** conditions
 - Same HV power pattern as observed in JUNO
 - Consistent with Paschen's law
- Connector tested in **high pressure** (0.4 MPa) gased water
 - data taken every 2 weeks over 7 months with **no evidence** of HV breakdown
- Electronics stress test in HV breakdown regime
 - HV breakdown **damages protection diode** on HV splitter first then CATIROCs

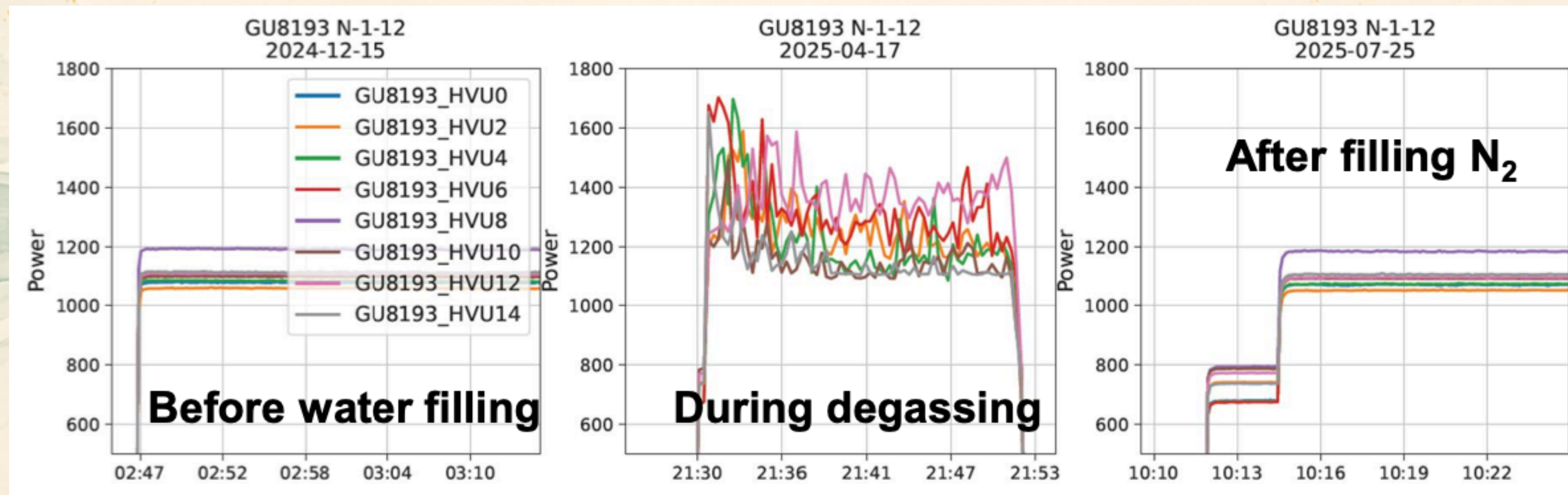


TEST CONDITION	DURATION	RESULT
HVS ONLY	16 HOURS	3/32 PROTECTION DIODE DAMAGED
DAMAGED HVS + CATIROC	1 HOUR	1/1 CATIROC DEAD

DEGASSING ISSUE : SOLUTION

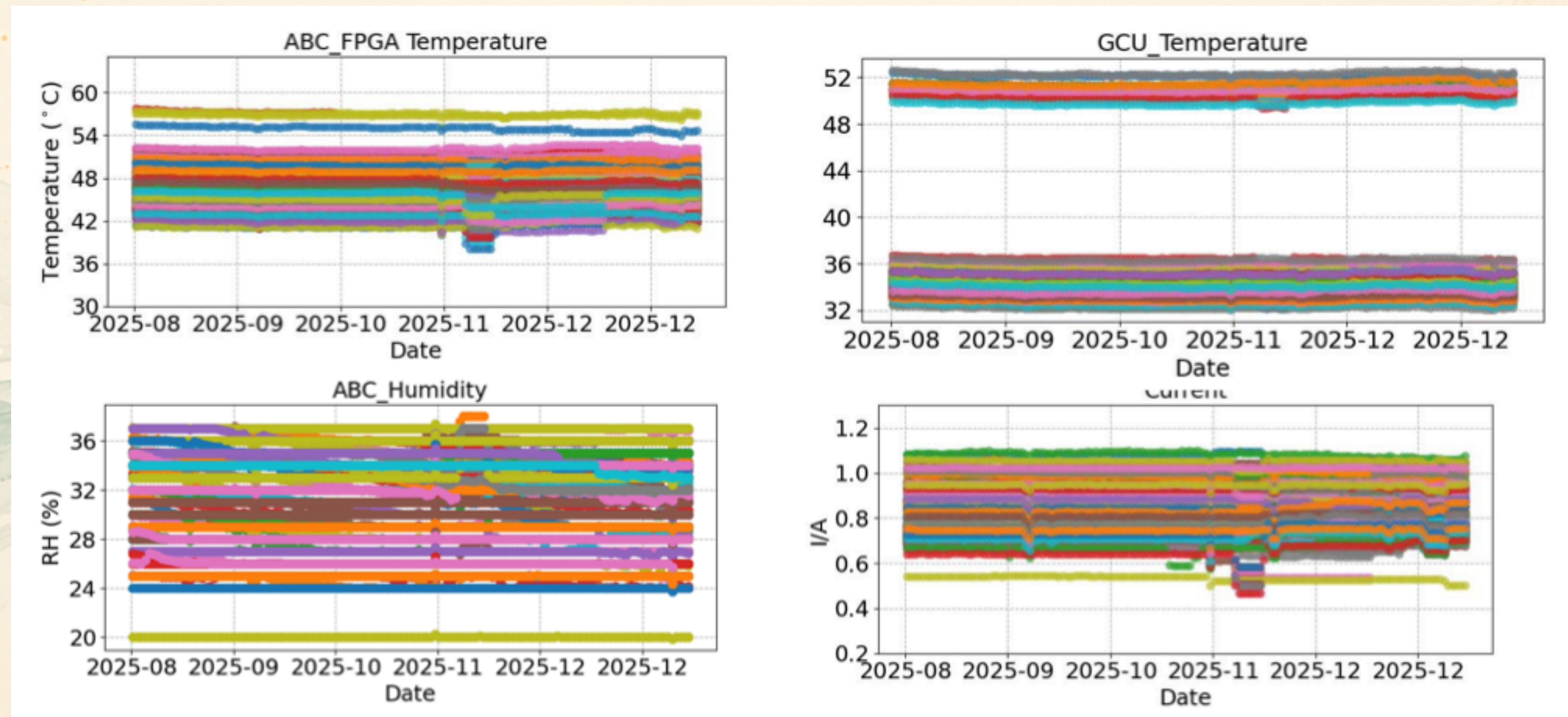
- Resolved after 2 months of N₂ gas filling in water circulation system
→ N₂ in water diffuses back to connector
- Close monitoring of HV power to avoid further breakdown
- 90 / 1600 (6%) CATIROCs can no longer be configured
→ consistent with dead CATIROCs from stress test
- 222 / 1600 (14%) CATIROCs can be configured but no data received
→ consistent with dead protection diode
- ~20 000 channels still alive but only 13 000 **most stable** channels selected into physics analysis

⇒ Lesson learned : do NOT use air insulated connectors in degassed water



ELECTRONICS MONITORING

- **Stable** temperature and humidity for 199/200 ABCs (1 ABC lost connection in March 2025)
- **Stable** temperature and low voltage for 200 GCUs
- **No water leak** in underwater boxes



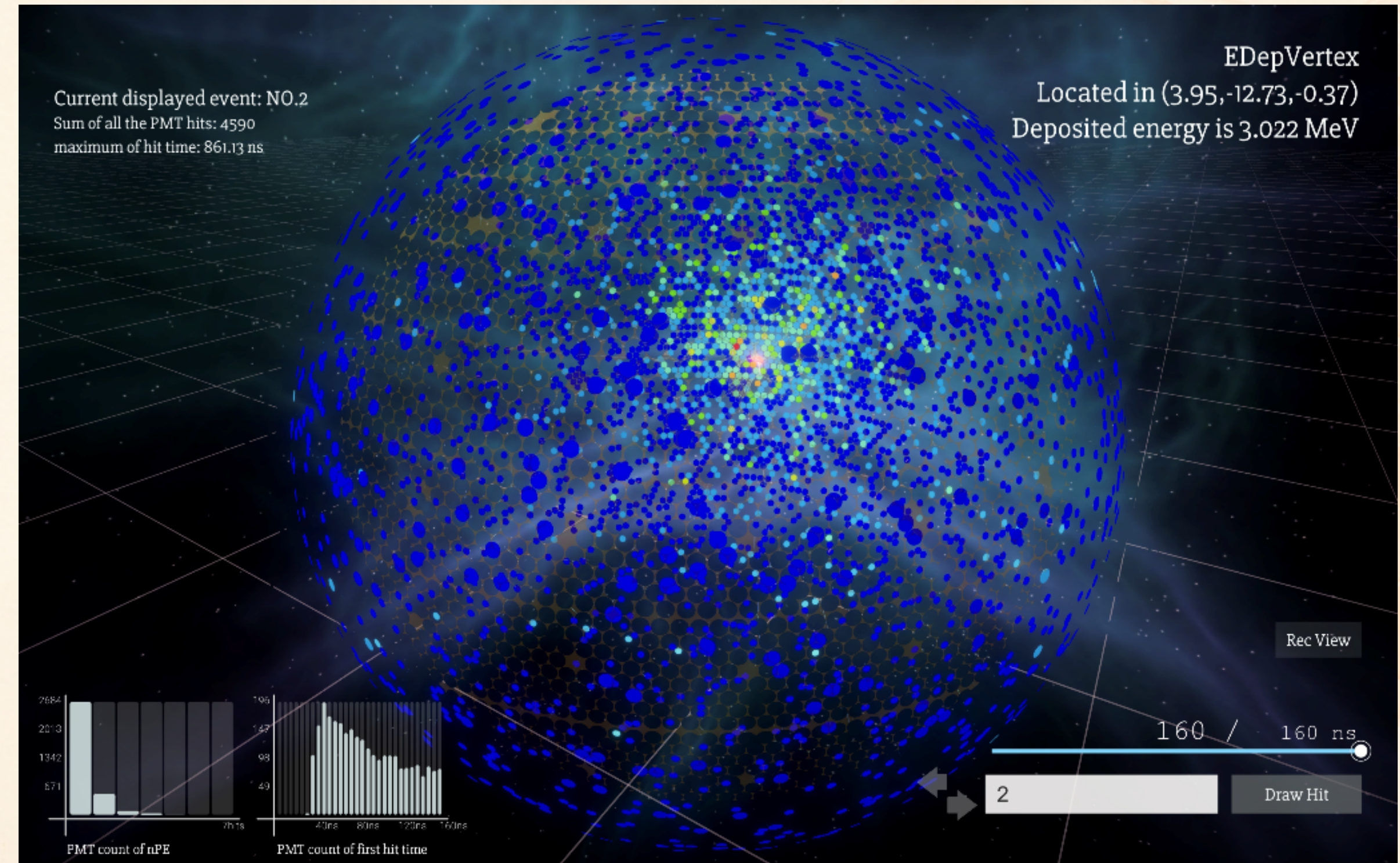


PHYSICS ANALYSIS

SPMT SIMULATION STATUS

- Geometry :
 - all 25 600 PMT **positions** with connection to the chosen 200 underwater boxes
- PMT **parameters** :
 - Quantum efficiency, measured dark noise and transit time spread
- Electronics :
 - CATIROC **features** : dead-time, charge acceptance, undershoot
- **Calibration** package :
 - Convert ADC charge and time to number of PE and ns

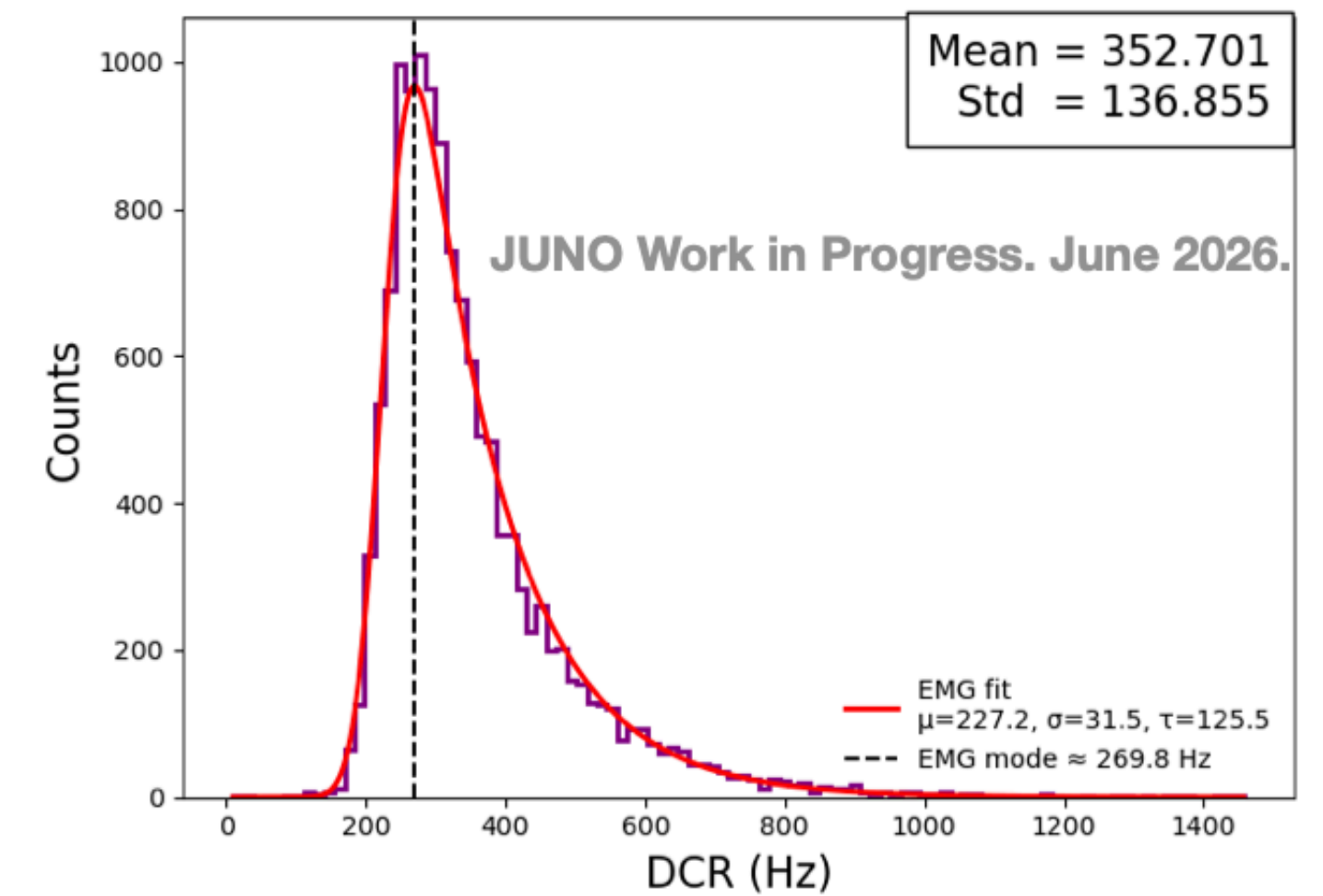
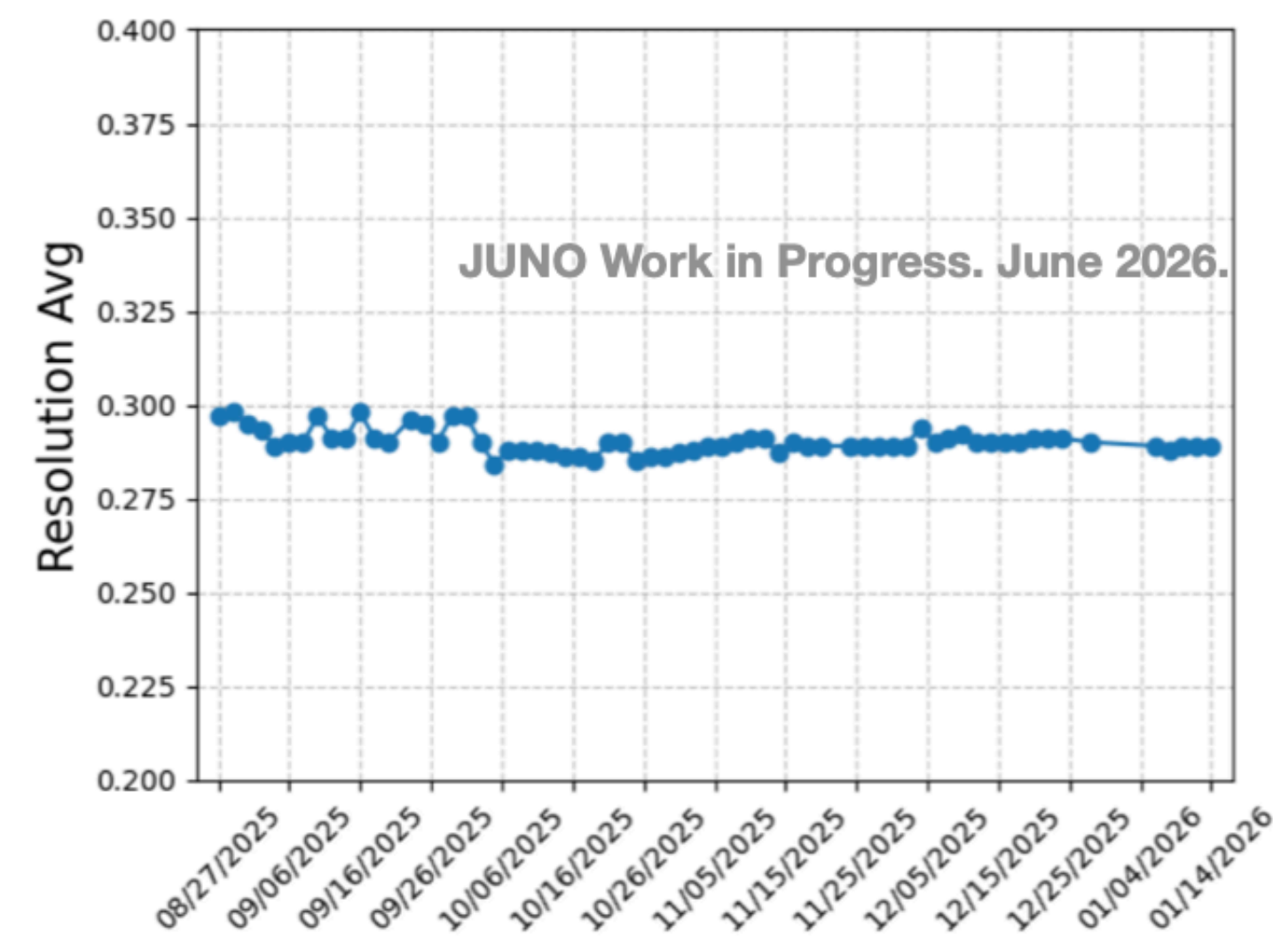
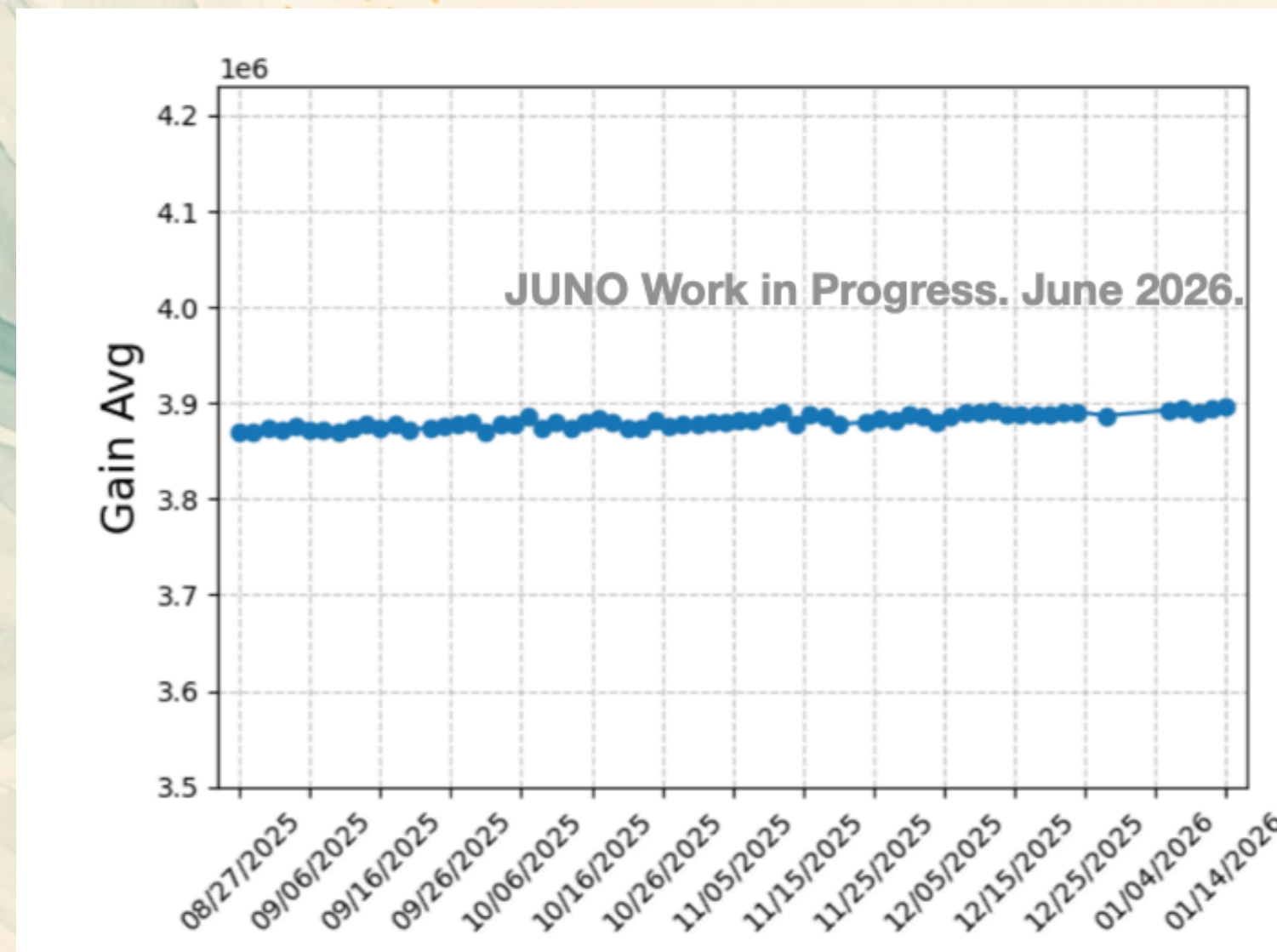
⇒ SPMT simulation is **implemented in SNIPEr**, JUNO's official software based on GEANT4



Event Display

SPMT PERFORMANCE IN PHYSICS RUN

- Run averaged gain and PMT charge resolution are stable over analysed physics runs
 - Gain $\sim 3.9 \times 10^6$
 - PMT charge resolution $< 30\%$
 - Average dark count rate ~ 350 cps
 - ⇒ System still in good shape for physics analysis



LPMT NON-LINEARITY CONSTRAINT

- SPMT constraint on LPMT instrumental non-linearity

→ based on Poisson occupancy

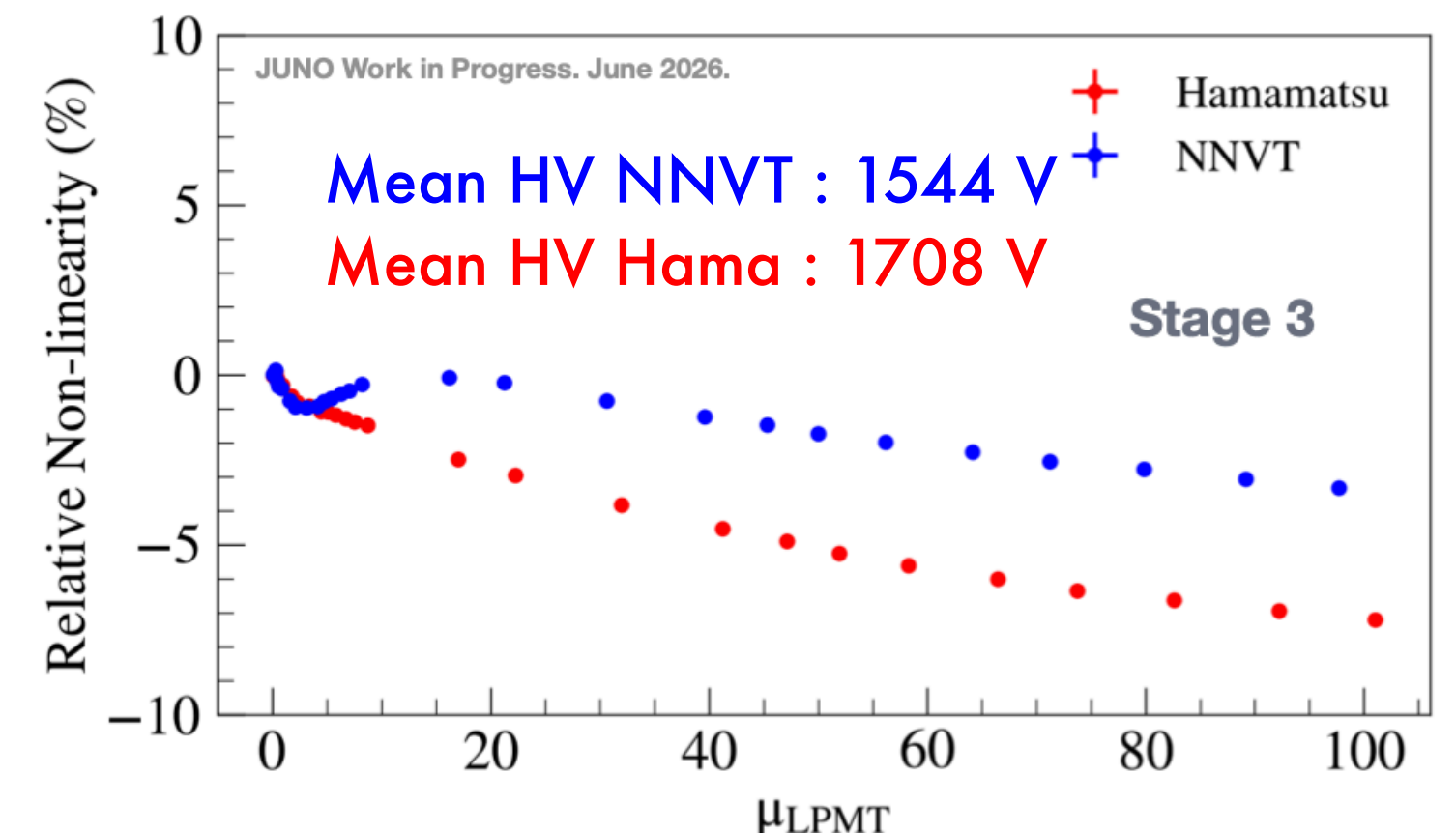
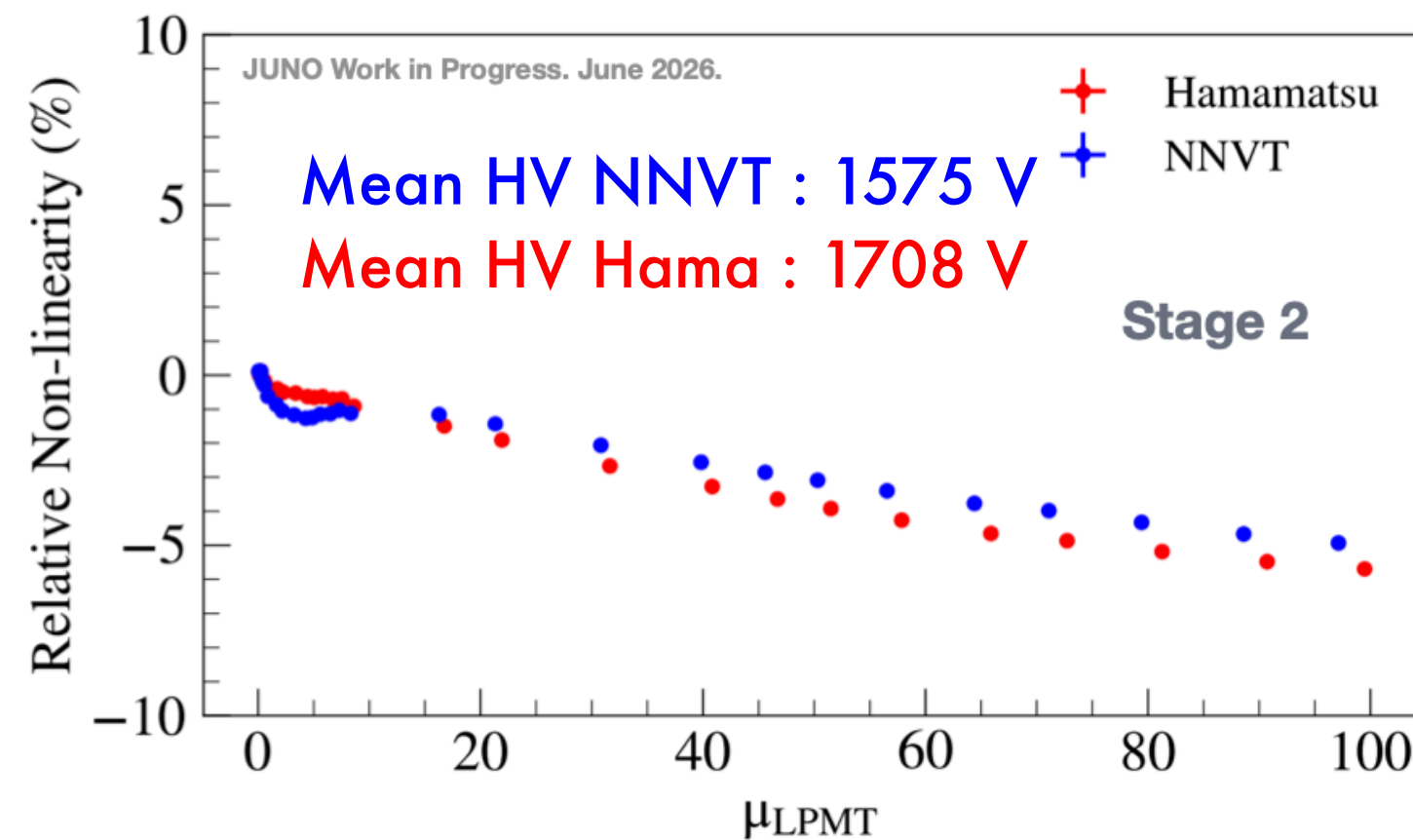
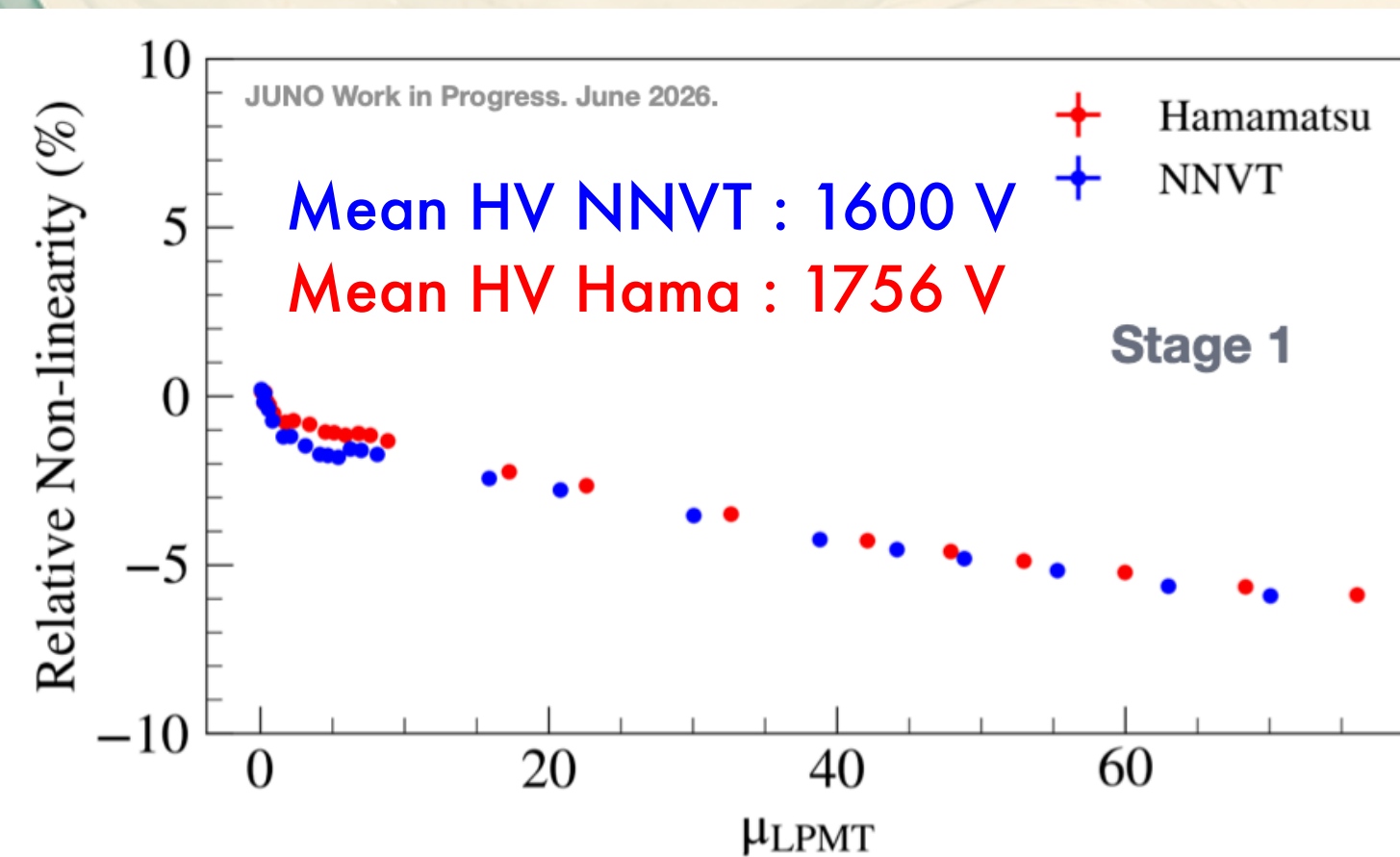
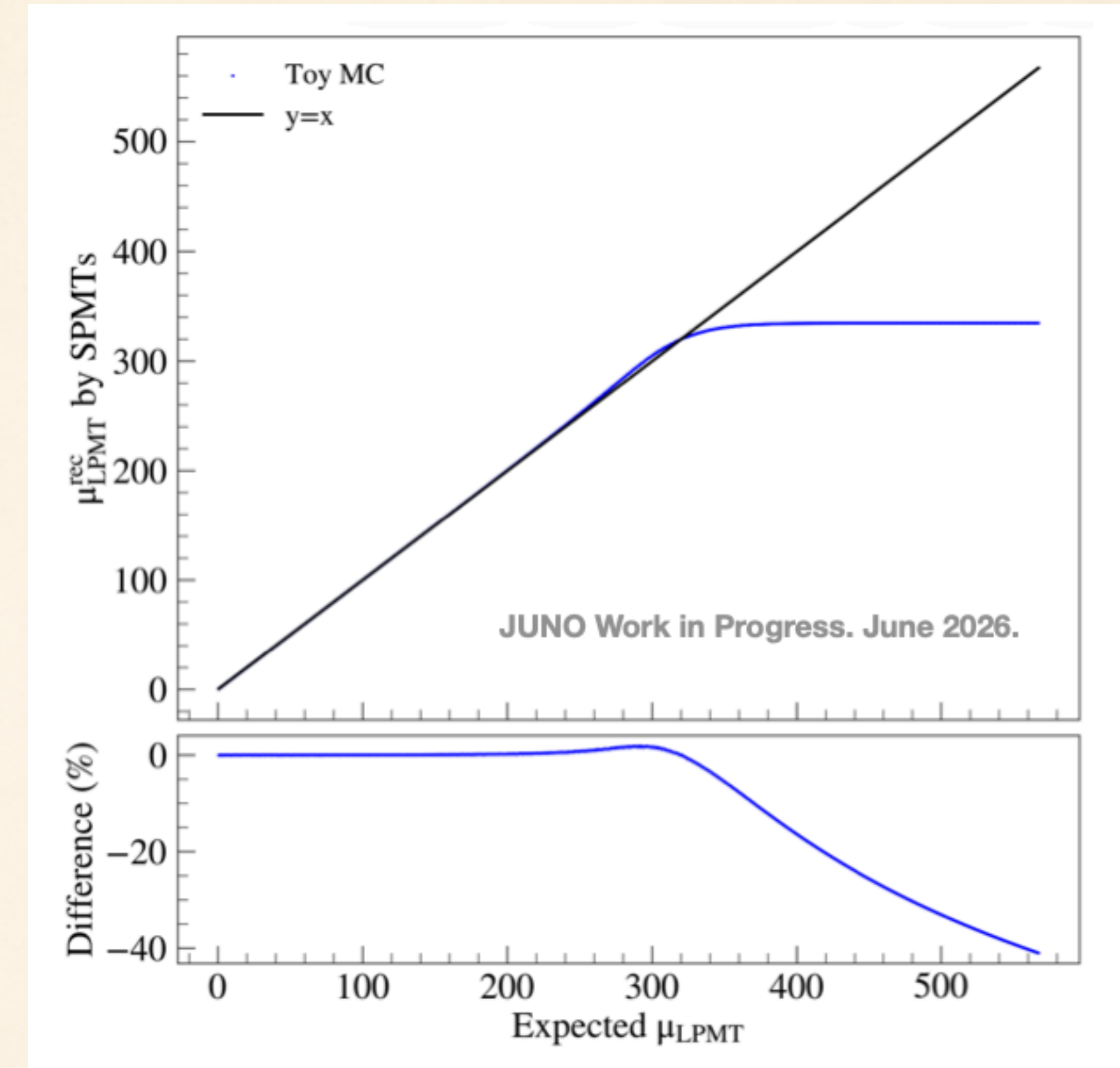
$$\mathcal{P}_{\text{unfired}} = \frac{N - N_{\text{fired}}}{N} = e^{-\mu_{\text{spmt}}}$$

$$\Rightarrow \mu_{\text{spmt}} = -\ln(\mathcal{P}_{\text{unfired}})$$

$$\mathcal{R}(\mu_{\text{LPMT}}) = \frac{\mu_{\text{lpmt}}}{\mu_{\text{spmt}}}$$

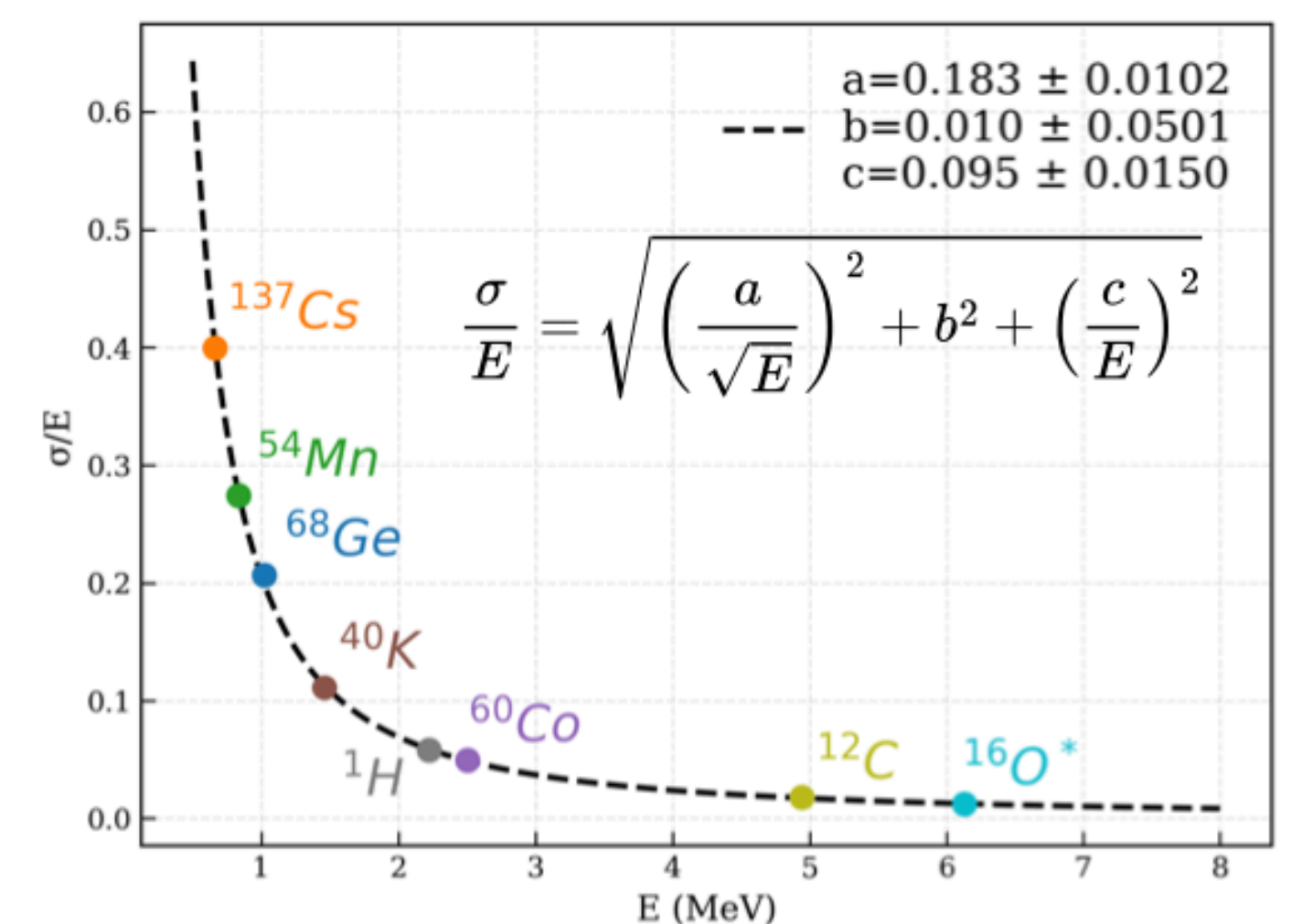
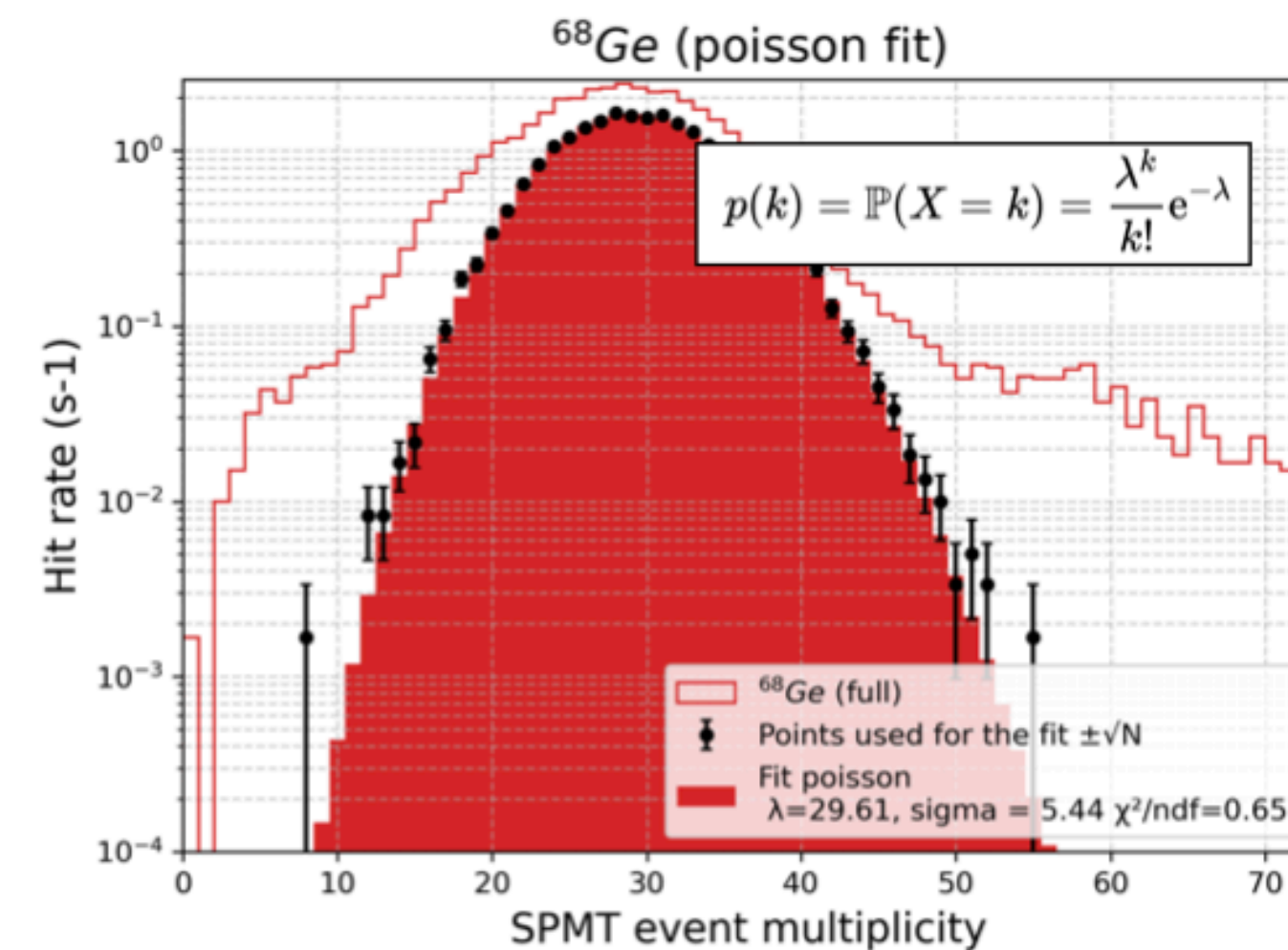
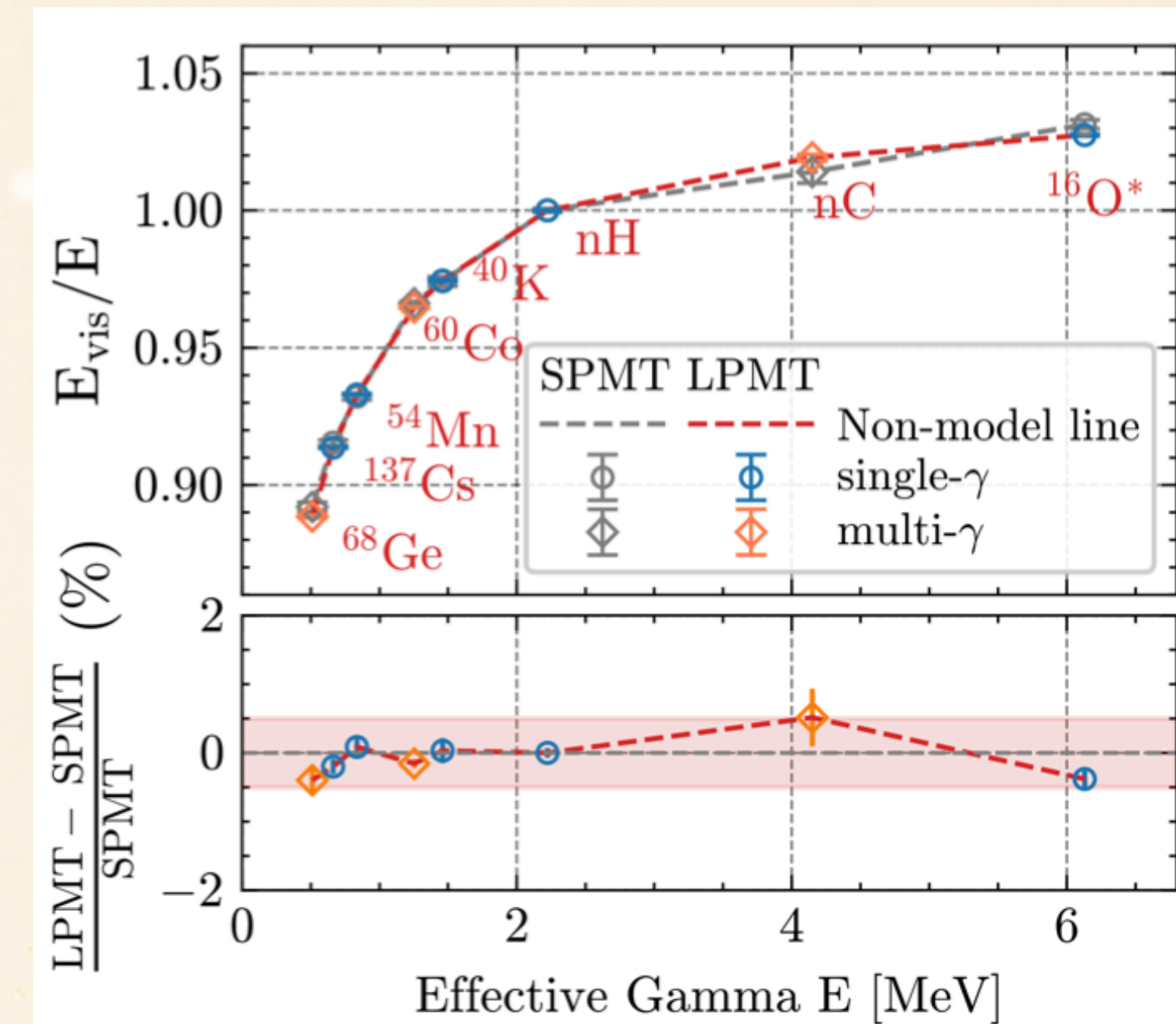
→ constant $\mathcal{R}$ indicates linear LPMT response

- Occupancy strategy valid up to $\mu_{\text{LPMT}} \simeq 300$
- LPMT instrumental non-linearity depends on applied HV but remains $\lesssim 5\%$



SPMT INDEPENDENT ENERGY MEASUREMENT

- Liquid scintillator non-linearity agreement between LPMT and SPMT at $\pm 0.5\%$
- Energy measurement with SPMT only
→ Energy resolution $\sim 20\%$ at 1 MeV driven by :
photo-statistics (a), non-uniformity (b), dark count rate (c)



CONCLUSION

The JUNO small-PMT system has been **produced, integrated, installed, and commissioned.**

- The main commissioning issue, connector degassing in degassed water, is now **understood** and **mitigated** by N₂ injection and HV-power monitoring
- Despite this issue, ~20,000 channels remain **operational**, with the 13 000 most stable channels selected for **physics analysis**
 - Ongoing **efforts to raise** the number of channels included in the physics analysis
- The system shows **stable performance** in physics runs:
 - gain $\sim 3.9 \times 10^6$
 - PMT charge resolution $< 30\%$
 - average dark count rate ~ 350 cps
- The SPMT system provides an **independent single-photoelectron** measurement, enabling **constraints** on LPMT **instrumental non-linearity** and an independent energy measurement
 - ⇒ The JUNO small-PMT system is ready to contribute to the JUNO physics analyses