



The 3-inch PMT system of the JUNO experiment

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on behalf of the JUNO Collaboration



JUNO: an instrumental challenge

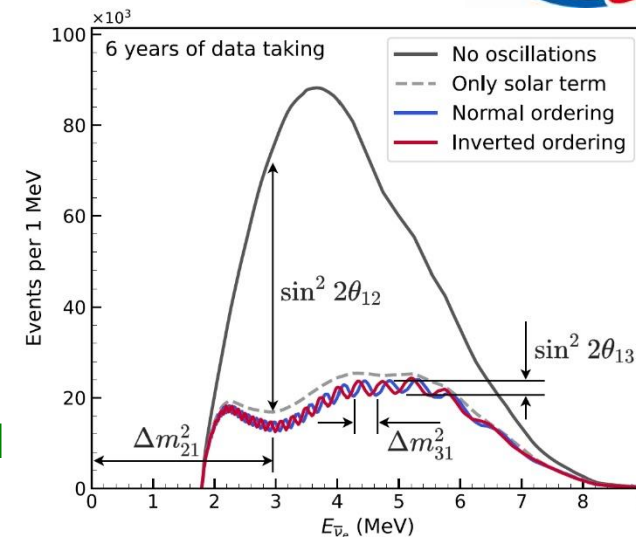


- Resolving the neutrino mass ordering in JUNO requires an **energy scale uncertainty better than 1%** and an unprecedented **energy resolution of 3% at 1 MeV**

$$\frac{\sigma_{E^{rec}}}{E_{vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{vis}}\right)^2}$$

Statistical fluctuation of detected photoelectrons (PE)

Non-statistical fluctuation (detector's spatial non-uniformity, PMT dark noise,...)



- Very challenging performances:**

- High light yield and transparency of the liquid scintillator
- High photo-cathode coverage
- High quantum and detection efficiencies

- Two photodetection arrays in JUNO:**

- 17612 20-inch PMTs (LPMT system)
- 25600 3-inch PMTs (SPMT system)



Motivation for the SPMT system



LPMT system (20-inch)

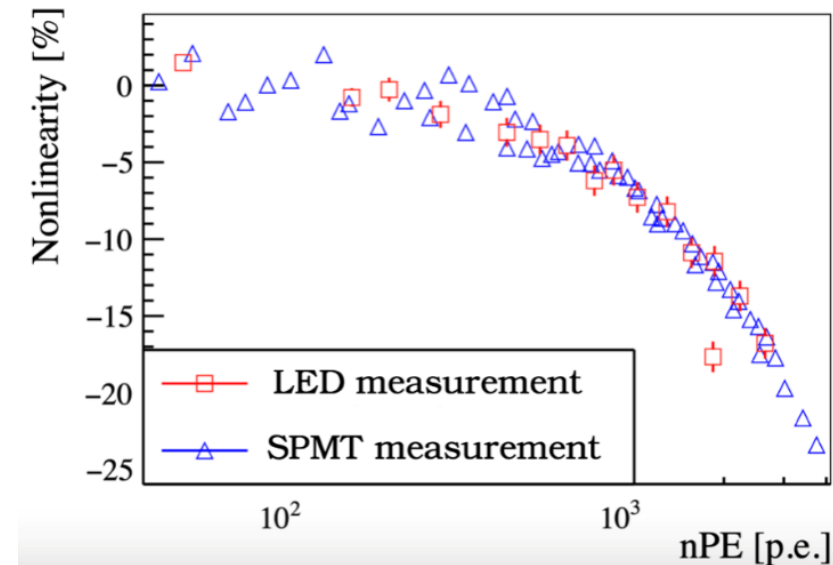
- 75% photo-cathode coverage and ~ 1600 PE/MeV \rightarrow drive the energy resolution
- Large dynamic range [1-100] photoelectrons for reactor antineutrinos [0-10] MeV \rightarrow possible instrumental non-linearity



SPMT system (3-inch)

- Operates in single photon-counting regime (1 hit = 1 PE) for reactor antineutrinos [0-10] MeV \rightarrow help to calibrate instrumental non-linearity
- Very good Time Transit Spread (TTS) of 1.6 ns \rightarrow help for vertex and muon track reconstructions
- 3% additional photo-cathode coverage and ~ 40 PE/MeV

Large PMT non-linearity

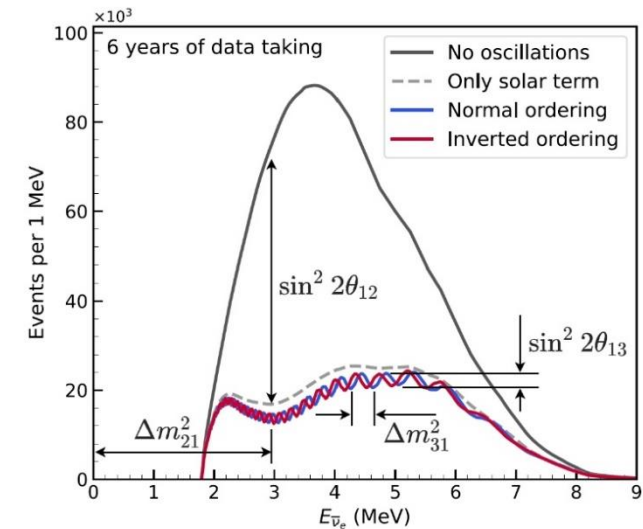
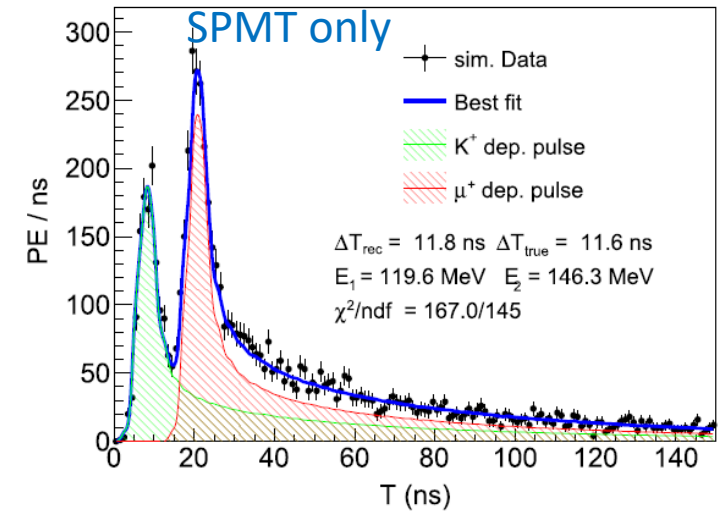


Enhanced physics capabilities with SPMTs



CPC 47, 113002 (2023)

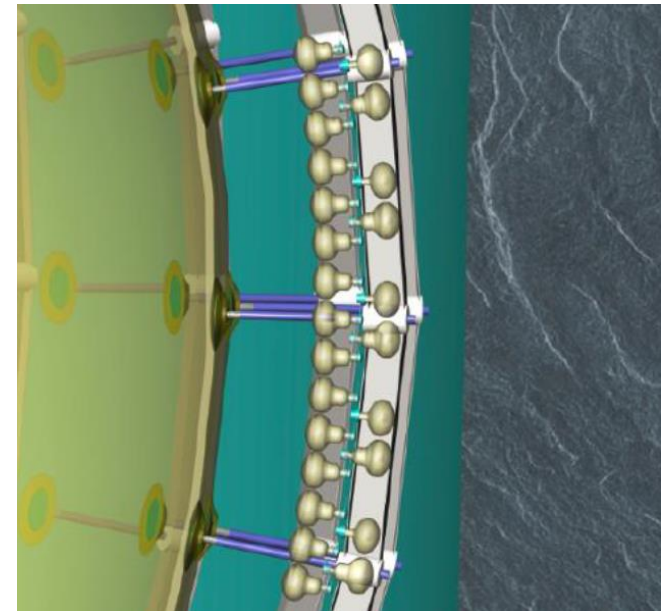
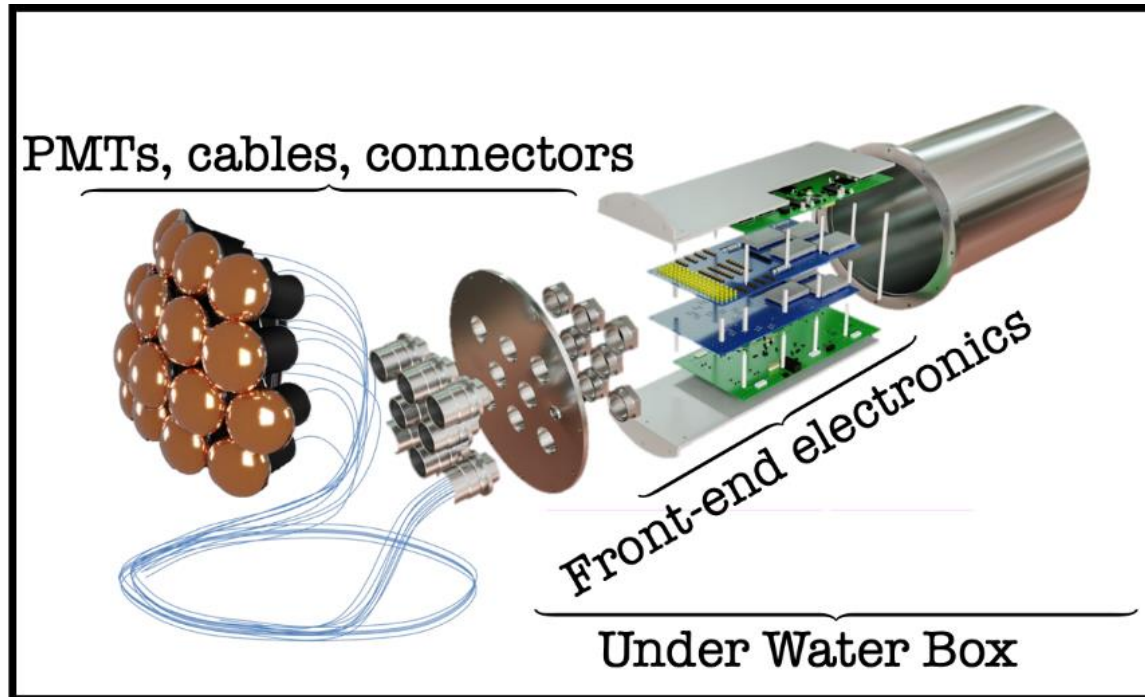
- Proton decay search: $p \rightarrow \bar{\nu} + K^+$
- Semi-independent measurement of θ_{12} and Δm_{21}^2
- High rate supernova neutrino detection
- Improve reconstruction and extend dynamic range



Overview of the SPMT system



- 25600 3-inch PMTs interlaced in the holes between the 20-inch PMTs
 - Each front-end electronics handles 128 PMTs grouped by 16 PMTs
- 200 Under Water Boxes (UWB) needed

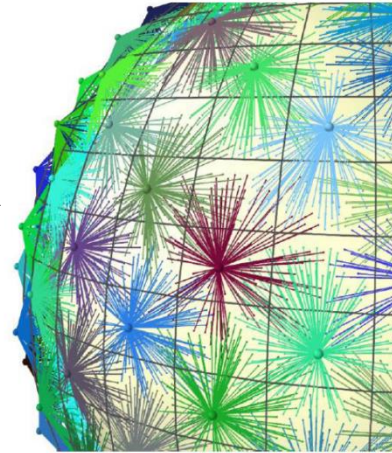


Overview of the SPMT system

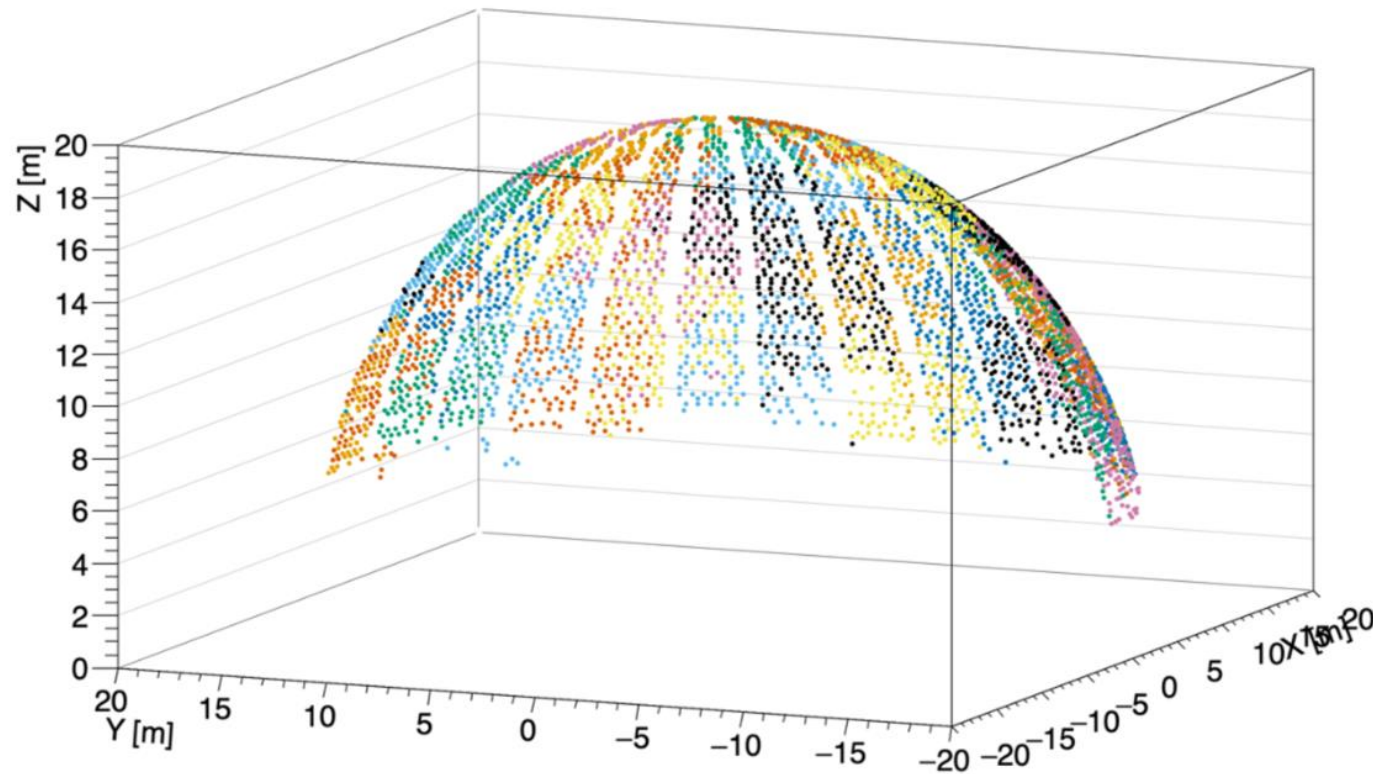


Requirements:

- Deployment of PMTs with maximum 10 m cable length (low amplitude signal)
- At least ~50% overlapping in the electronics coverage in any given PMT area to avoid a blind spot in case of UWB failure



Channel positioning

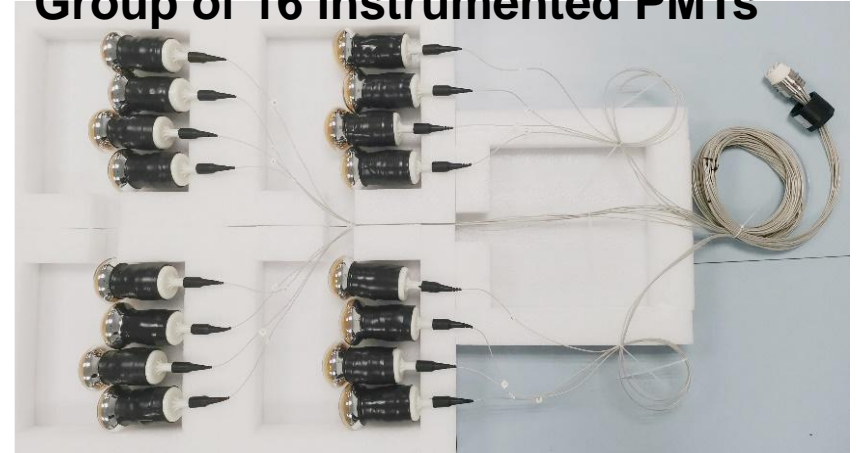


Instrumented PMT performances

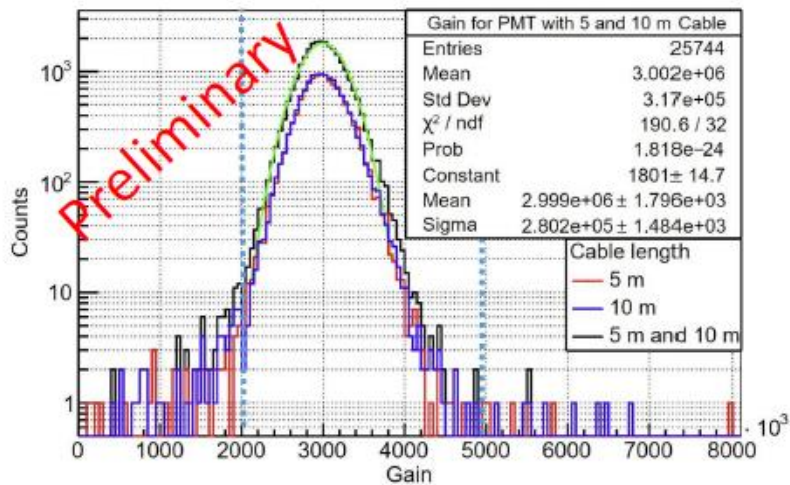


- 3-inch PMTs grouped by 16 to the same connector
→ 1600 groups of PMTs
- Instrumented PMTs (divider, potting, cable and connectors) qualified at Guangxi University (GXU)
→ Very good performances, consistent with bare PMTs measured at HZC Photonics (PMT manufacturer)

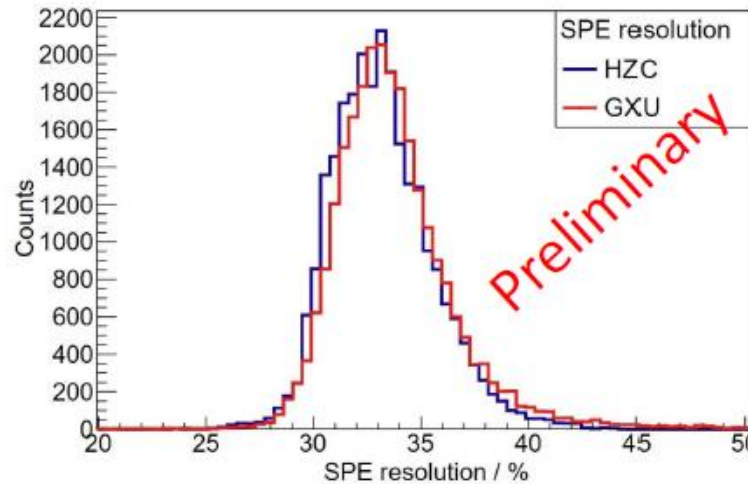
Group of 16 instrumented PMTs



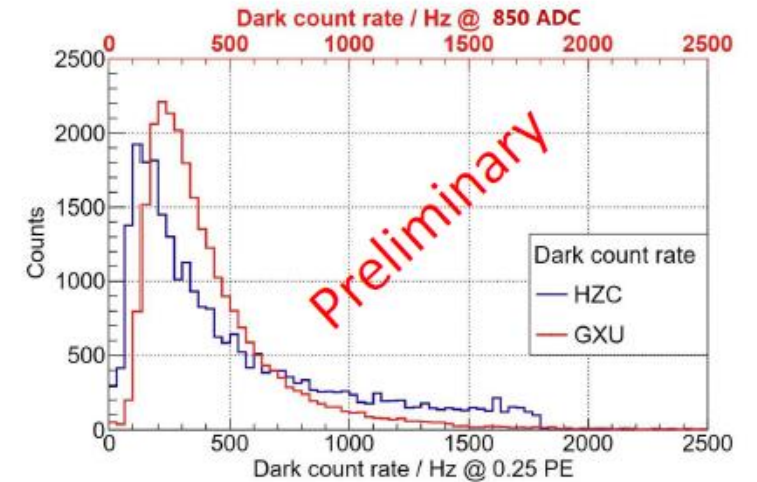
PMT gain $\sim 3.10^6$



Single PE resolution $\sim 33\%$



Dark rate at 0.25 PE threshold



→ 20288 PMTs already sent from GXU to JUNO site for installation

SPMT electronics challenge



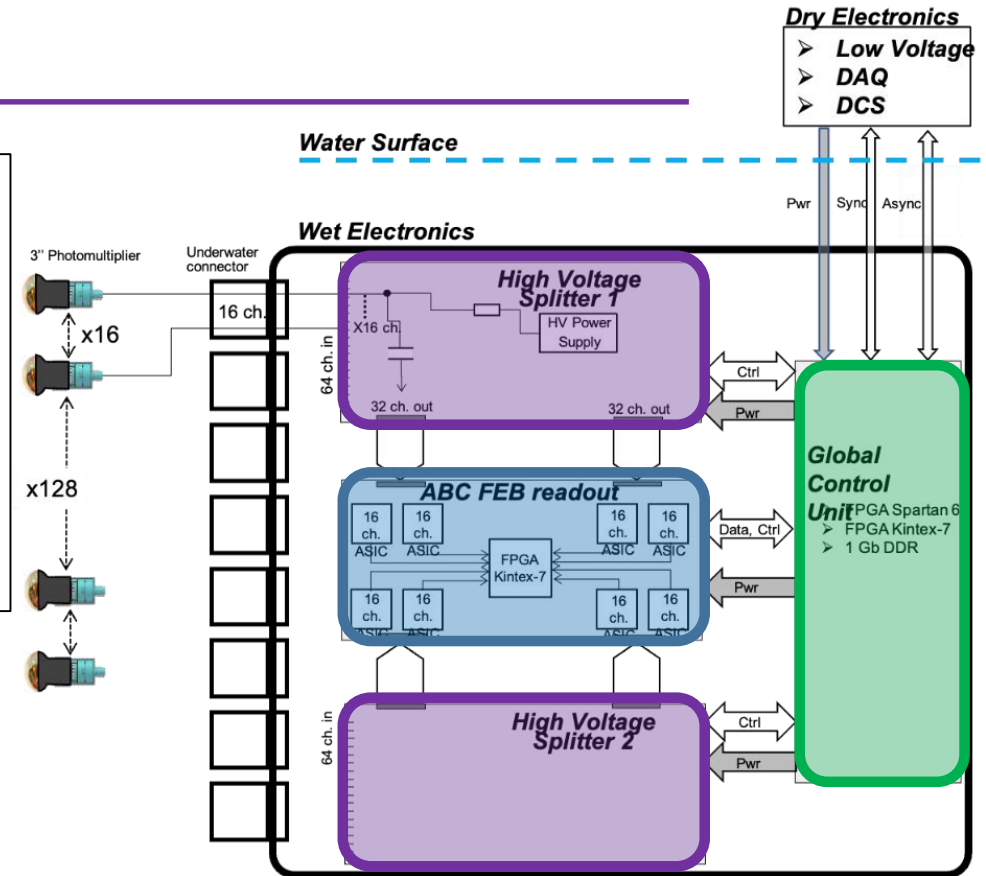
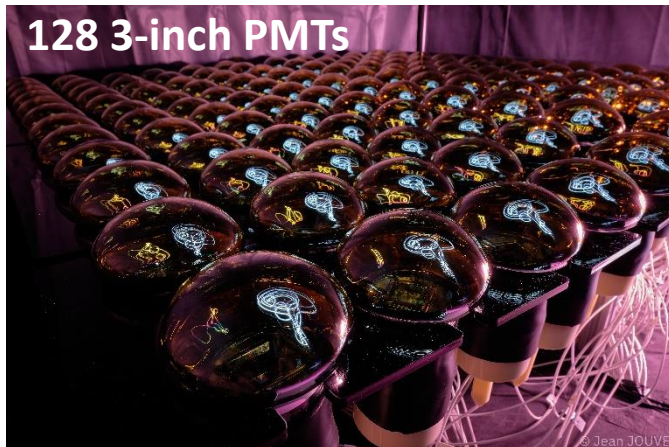
- **Challenge:** to digitize a single PE signal of ~ 2 mV amplitude with a trigger threshold lower than $1/3^{\text{rd}}$ of PE \rightarrow need a very low noise front-end electronics
- **Solution:** CATIROC chip developed by the OMEGA laboratory (France)
 - charge and time measurements
 - 16 independent channels auto-triggering on the single PE
 - pre-amplifier for each channel
 - programmable trigger threshold (common to all channels)
- **Performances :**
 - Mean noise ~ 0.03 PE for PMT gain at 3×10^6
 - Time resolution ~ 150 ps
 - Only 2 hits can be digitized within a ~ 9 μs time window



SPMT electronics architecture

- **2x64 channels HV Splitter boards** powering PMTs and decoupling the signal from high-voltage
- **ABC front-end board:** reads out and formats the data from 8 CATIROC chips (Q/T pairs from 128 channels)
- **GCU board** powering ABC board, sending the clock and transferring data from ABC to DAQ

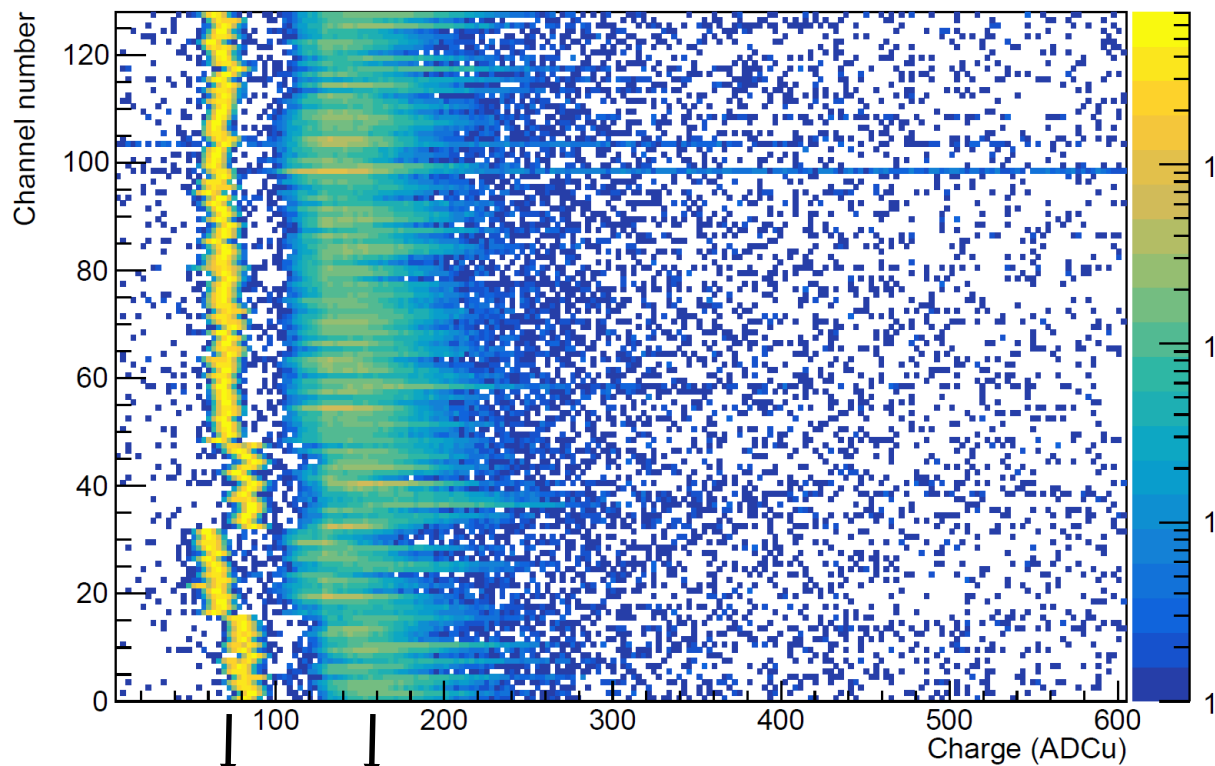
→ performances tested and validated with 3-inch PMTs and full electronic chain at IHEP and LP2i Bordeaux



SPMT electronics performances

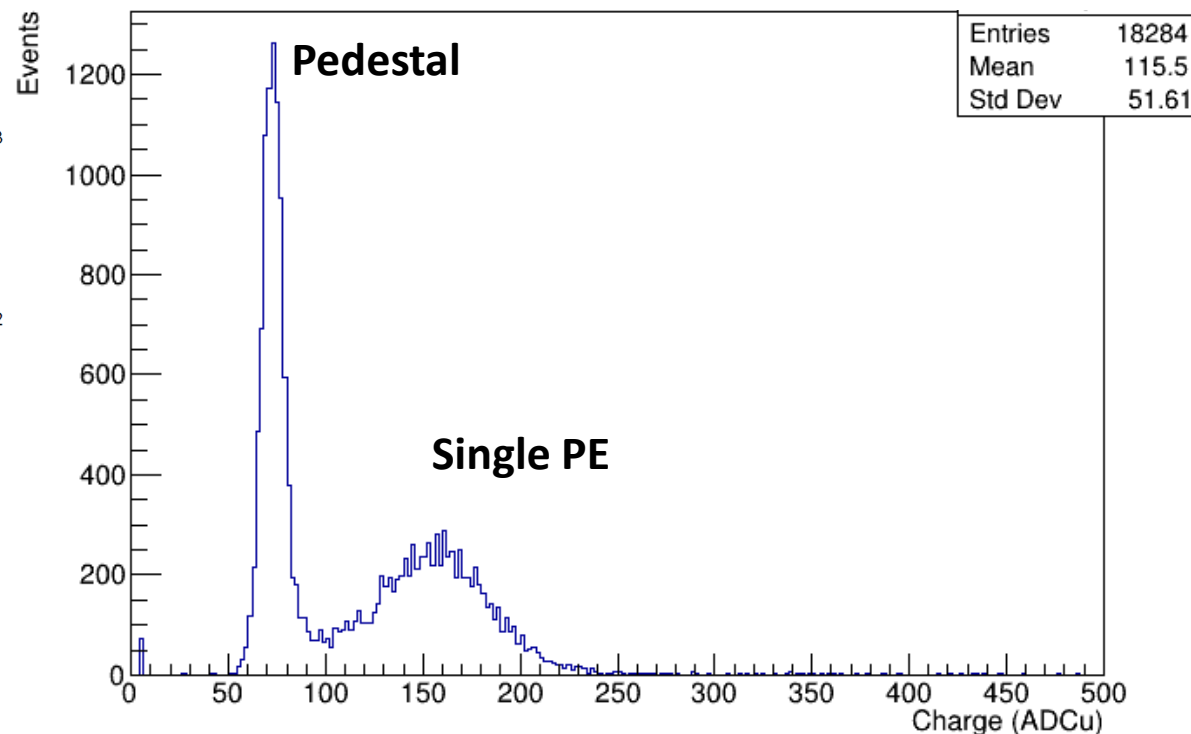


Charge measured over 128 channels



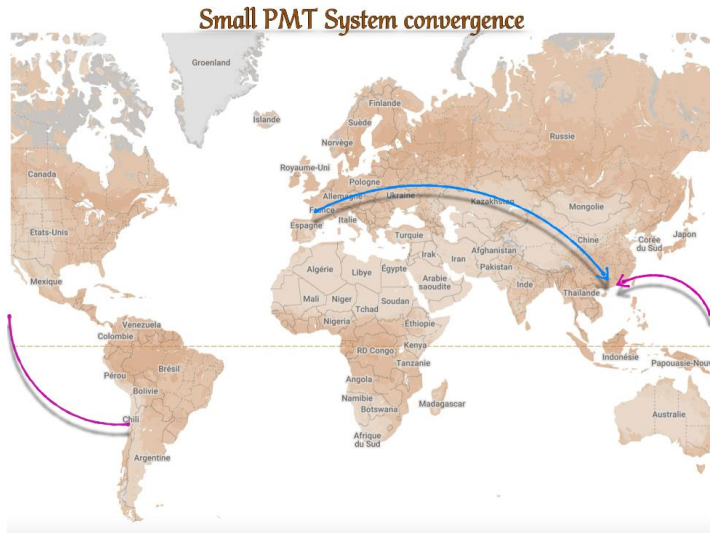
Pedestal events
Single PE events

Charge spectrum for 1 channel

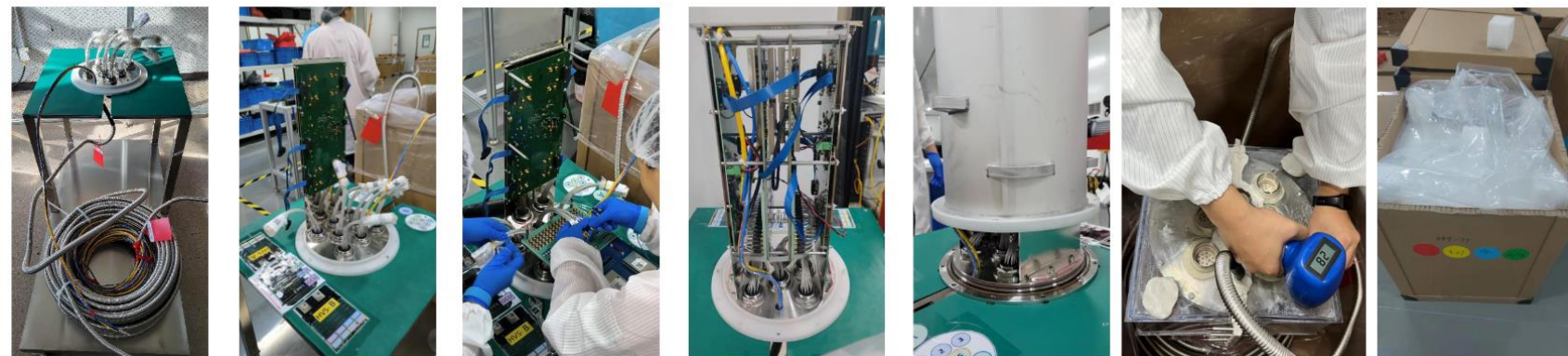


→ Single PE events well-separated from pedestal events

SPMT electronics integration at JUNO site



- Front-end electronics components sent to JUNO site
 - 220 front-end readout boards from France
 - 440 high voltage splitter boards from Chile
 - 220 GCU boards from China
- 208 electronics (JUNO+TAO+spares) mounted and tested successfully → 26624 channels OK
- 7 months of integration achieved in April 2023



→ the French team joined the chinese effort in 2023 for the electronics integration and commissioning

PMT and electronics installation status

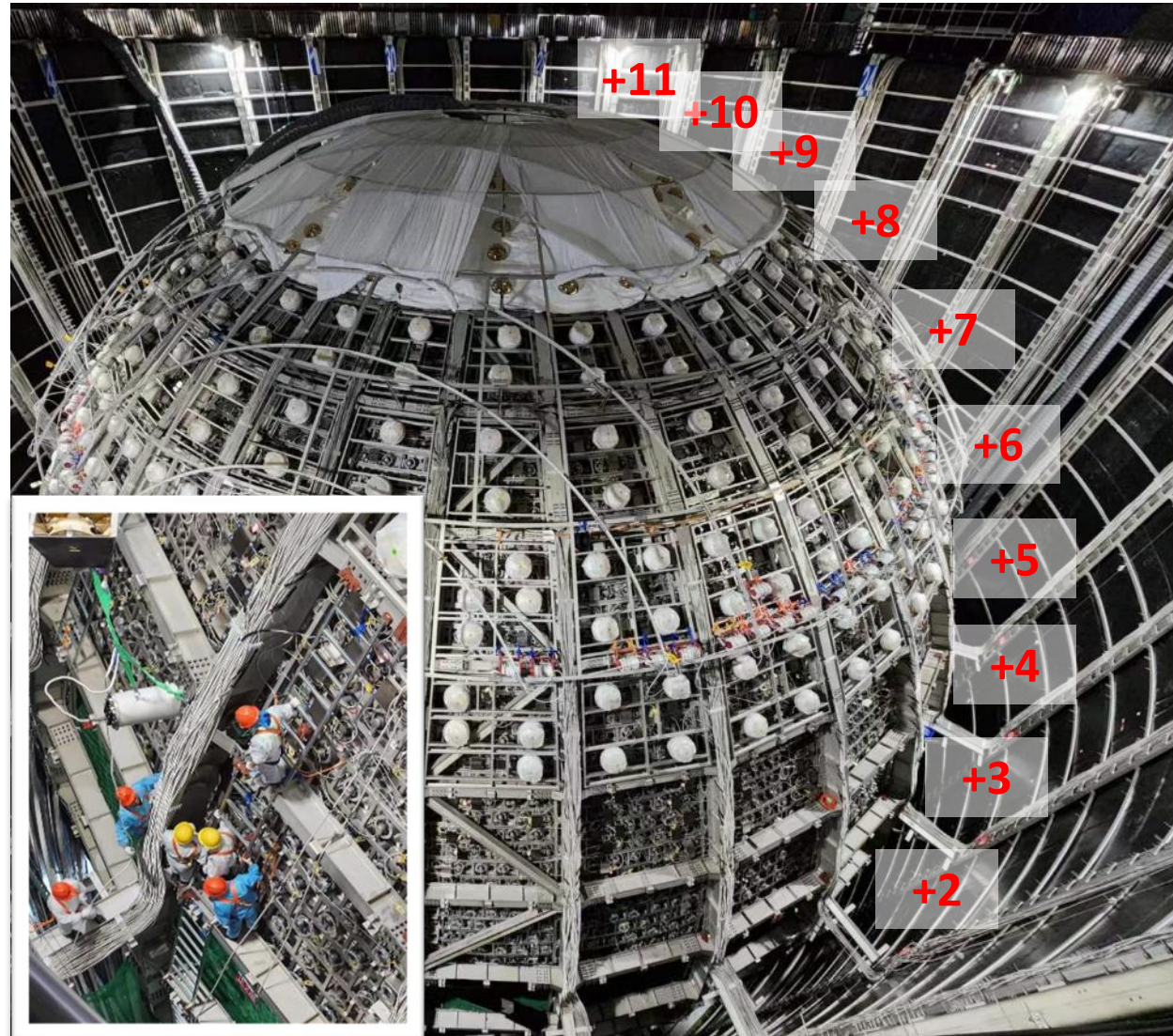


- PMT installation from top to bottom started early 2023

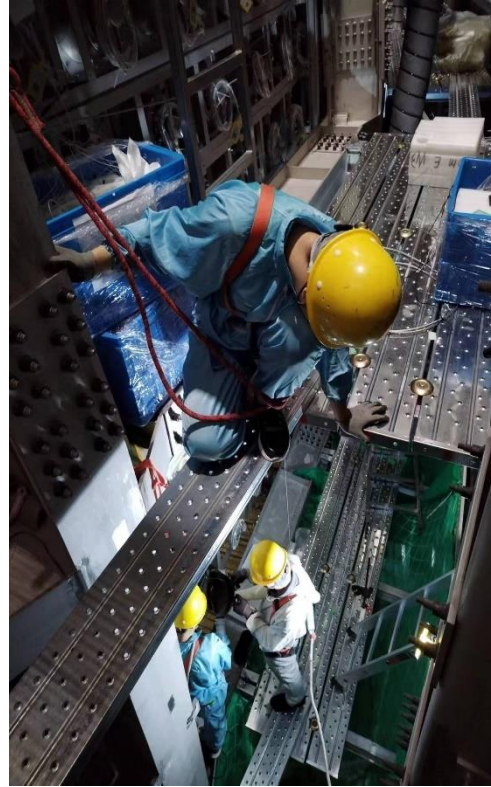
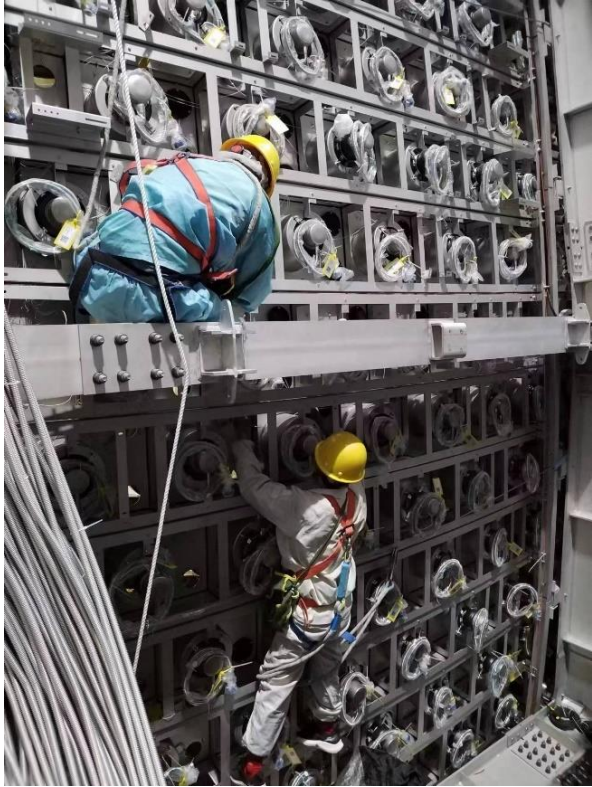
Status on 2024, June 3rd:

- **PMTs:** 13194 over 25600 (51.5%)
- **UWB electronics:** 101 over 200 (50.5%)

→ Installation to be completed by end of 2024



PMT and electronics installation



- Installation speed: ~80-160 PMTs/day
 - PMT installation reached the lower hemisphere
- huge efforts from the chinese teams to drive the installation

SPMT commissioning



- **Motivation:** to operate the full chain after installation and verify the PMTs and electronics response

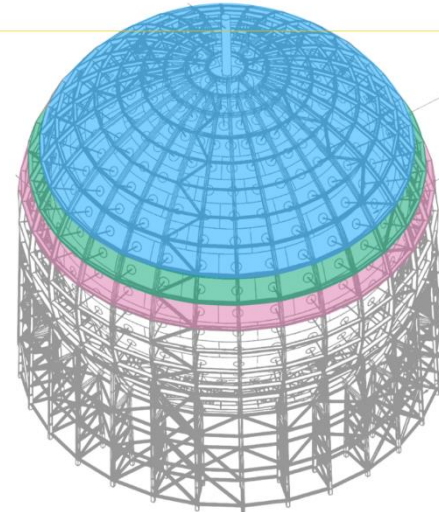
- **Light-on tests:** to check the response of the electronics after installation

→ 100% of installed electronics OK

- **Light-off tests:** to check the response of the PMTs connected to electronics after installation

- Problematic channels identified on the truss (cables, connector gaskets), some of them fixed

→ More than 99% of PMT channels OK



SPMT connected

SPMT installed

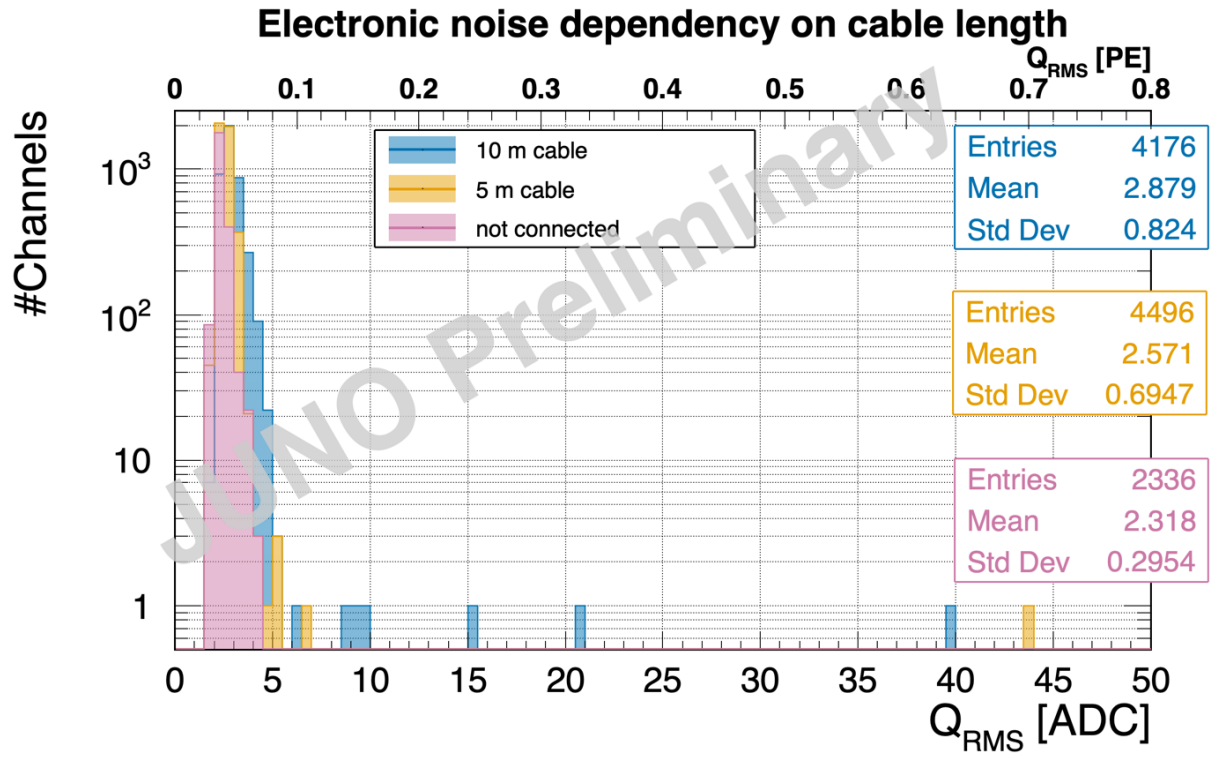
Under Water Box



SPMT commissioning: noise level



- Light-on tests performed early February 2024 with 11008 channels from 86 UWBs

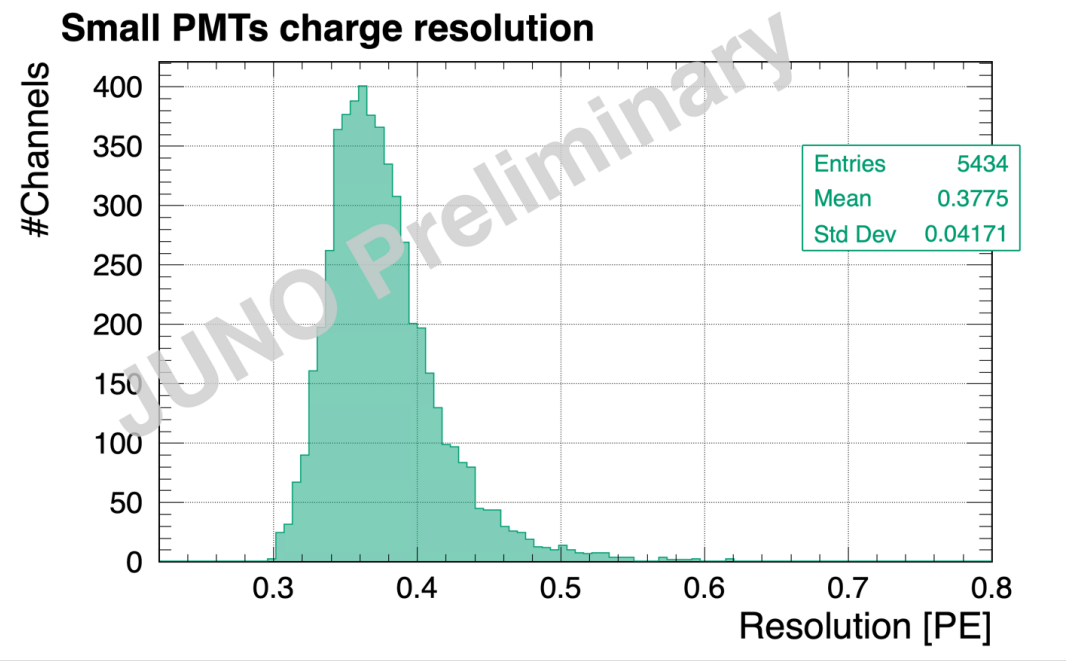
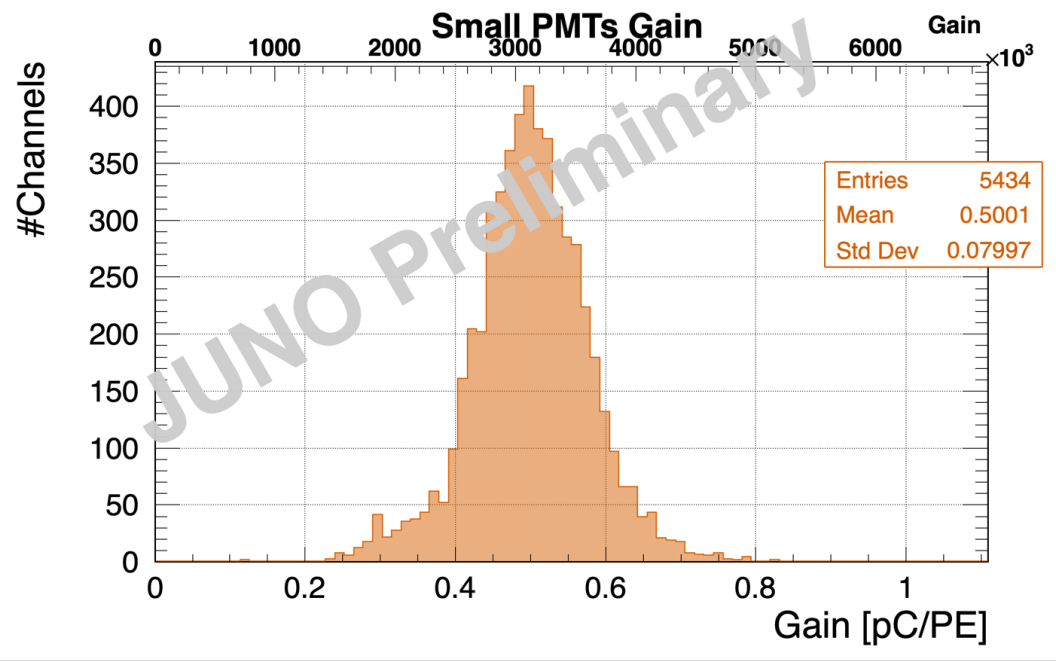


- Noise level measured with 10 m and 5 m cables length, and with no PMT connected
 - Very few noisy channels (>0.25 PE) due to badly connected cables identified and fixed
 - Mean noise ~ 0.05 PE, much lower than the nominal trigger threshold of 0.33 PE
- very low electronic noise !

SPMT commissioning: PMT performances



- 5th light-off tests end of February 2024 with 8672 PMTs connected to 43 UWBs

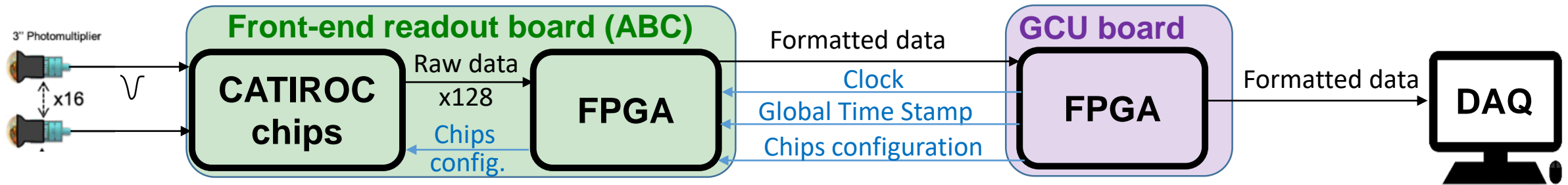


- Mean PMT gain is $\sim 3.1 \times 10^6$, consistent with the nominal value (3.0×10^6)
- Mean SPE resolution is $\sim 38\%$, greater than the nominal value (33%) \rightarrow to be investigated

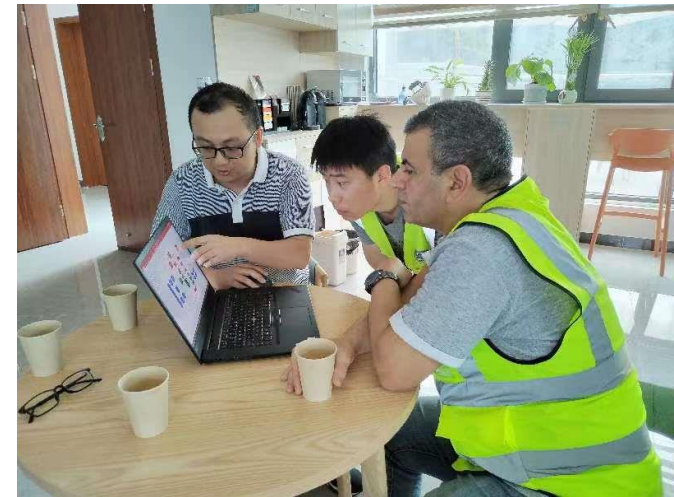
SPMT firmwares status



- **Challenge:** handling Q/T information from 128 channels and managing the complex data transfer and communication along the whole SPMT electronic chain



- Joint development of the two firmwares by LP2i Bordeaux (**ABC**) and IHEP (**GCU**)
 - Functionnal firmwares successfully used for the 5th light-off tests
- Final SPMT firmwares completion and validation by end of 2024



SPMT simulation status



Geometry:

- 25600 PMT positions with connection to the chosen 200 UWBs

PMT parameters:

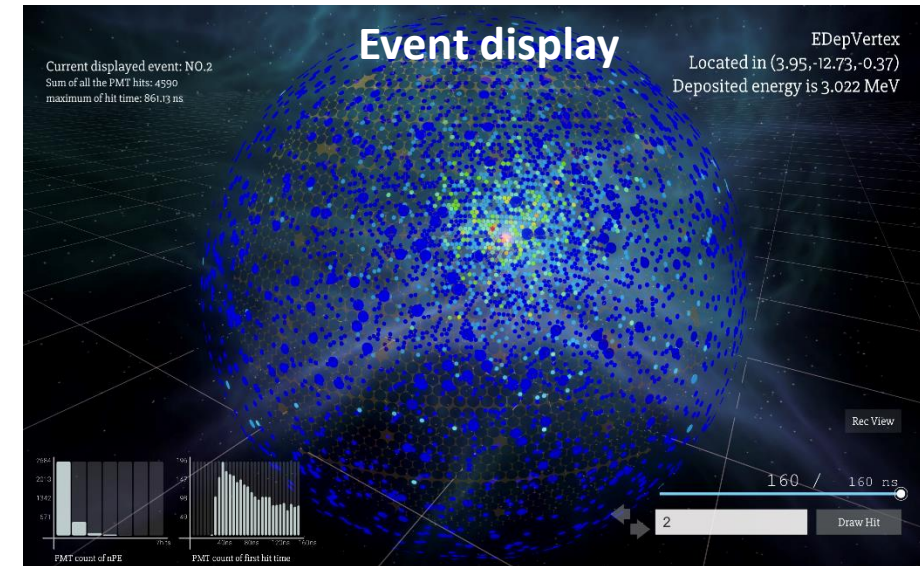
- QE at 420 nm and dark noise values measured for the whole production as well as a mean value for TTS

PMT + electronics simulation:

- PMT features (waveform, dark noise, TTS) and ASIC features (dead-times, charge acceptance,...)

Calibration:

- Package to convert the ADC charge into a number of PE



→ all implemented in SNIKER, the JUNO detector simulation software based on GEANT4

- **SPMT system:**
 - Single photon-counting regime to pinpoint slight instrumental non-linearity from LPMTs
 - Enhanced physics capabilities (Proton decay, θ_{12} and Δm_{21}^2 measurement, Supernova)
- **Installation status:**
 - 13194 3-inch PMTs over 25600 (51.5%)
 - 101 UWBs over 200 (50.5%)
- **Commissioning status:**
 - 100% of the electronics and >99% of the PMTs are functional
 - Very low noise measured (<0.05 PE)
 - Good PMT performances so far (gain and charge resolution)
 - Good ABC and GCU firmware performances from 5th light-off tests
- **Simulation status:** PMT and electronics features implemented

→ Installation completion of the SPMT system by the end of 2024 and first commissioning data in water phase very soon... stay tuned !

SPMT teams for the FCPPL project



- **IHEP:** Miao HE, Xiaoshan JIANG, Zheng WANG, Jilei XU, Zhimin WANG, Lei FAN, Jun HU, Zhe NING, Yunhua SUNYangfu WANG, Meihang XU, Xiaoping JING, Chuanya CAO, Diru WU, Ziliang CHU
- **Guangxi University:** Hongbang LIU, Yongbo HUANG, Xiwen LIU
- **LP2i Bordeaux:** Frédéric PERROT, Cédric CERNA, Cécile JOLLET, Abdel REBII, Loïc LABIT, Matthieu LECOCQ, Cédric HUSS, Frédéric DRUILLOLE, Selma CONFORTI & Stéphane CALLIER (OMEGA)
- **SUBATECH:** Mariangela SETTIMO

Thank you !