TRIUMF

Princeton Physics

SFU SIMON FRASER UNIVERSITY

GSSI GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

PD24

- Recent progress and new developments in photon-detectors such as SiPMs, MCPs, APDs, PMTs, Hybrid PMTs and digital photon-sensors
- Front-end, DAQ and trigger electronics
- Applications in particle and astroparticle physics, nuclear physics, nuclear medicine and industry

Photodetector system of the JUNO experiment

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on behalf of the JUNO Collaboration

INFN
Istituto Nazionale di Fisica Nucleare

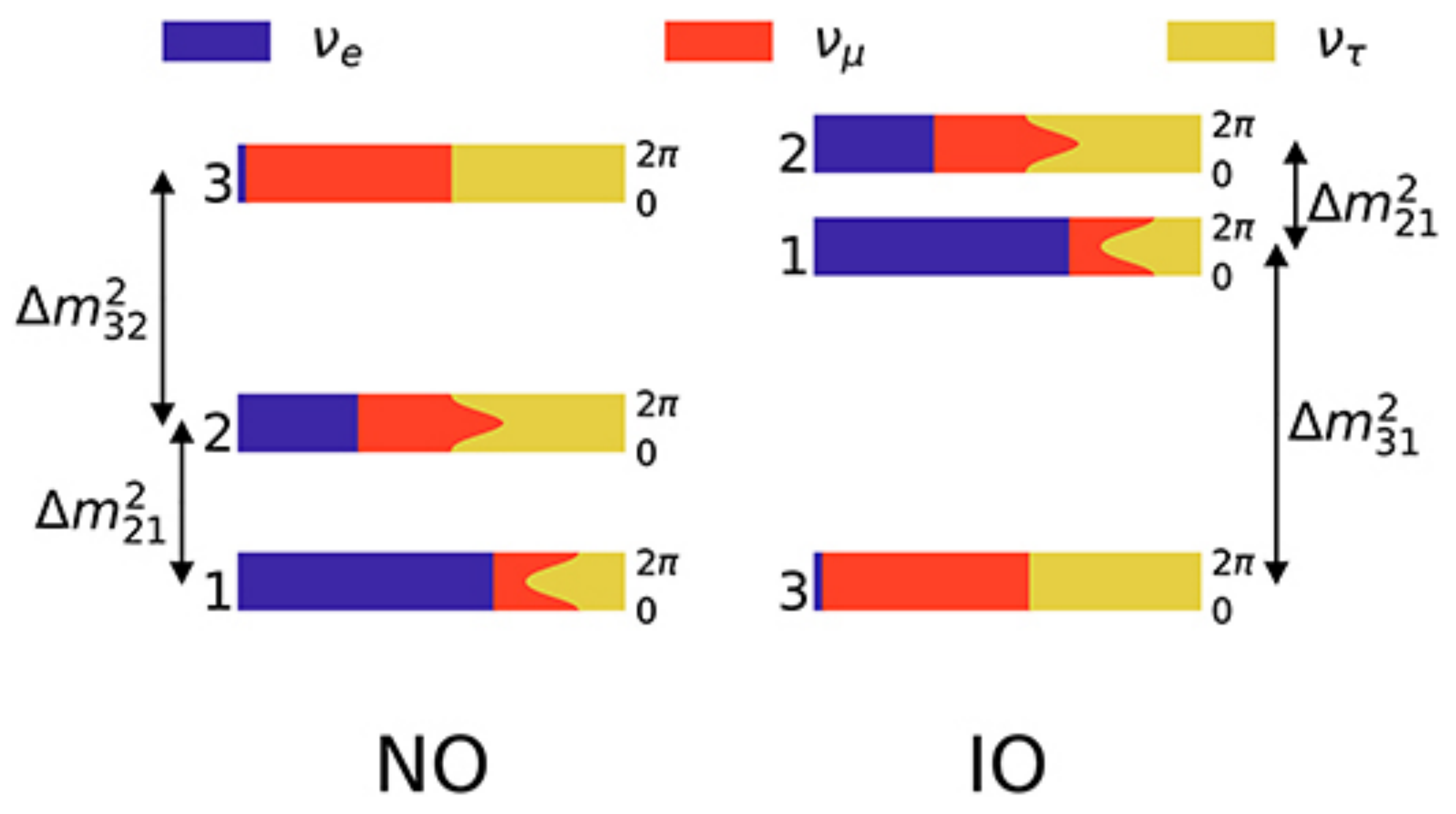
JUNO

PD24 - Vancouver 19.11.2024

JUNO: Jiangmen Underground Neutrino Observatory

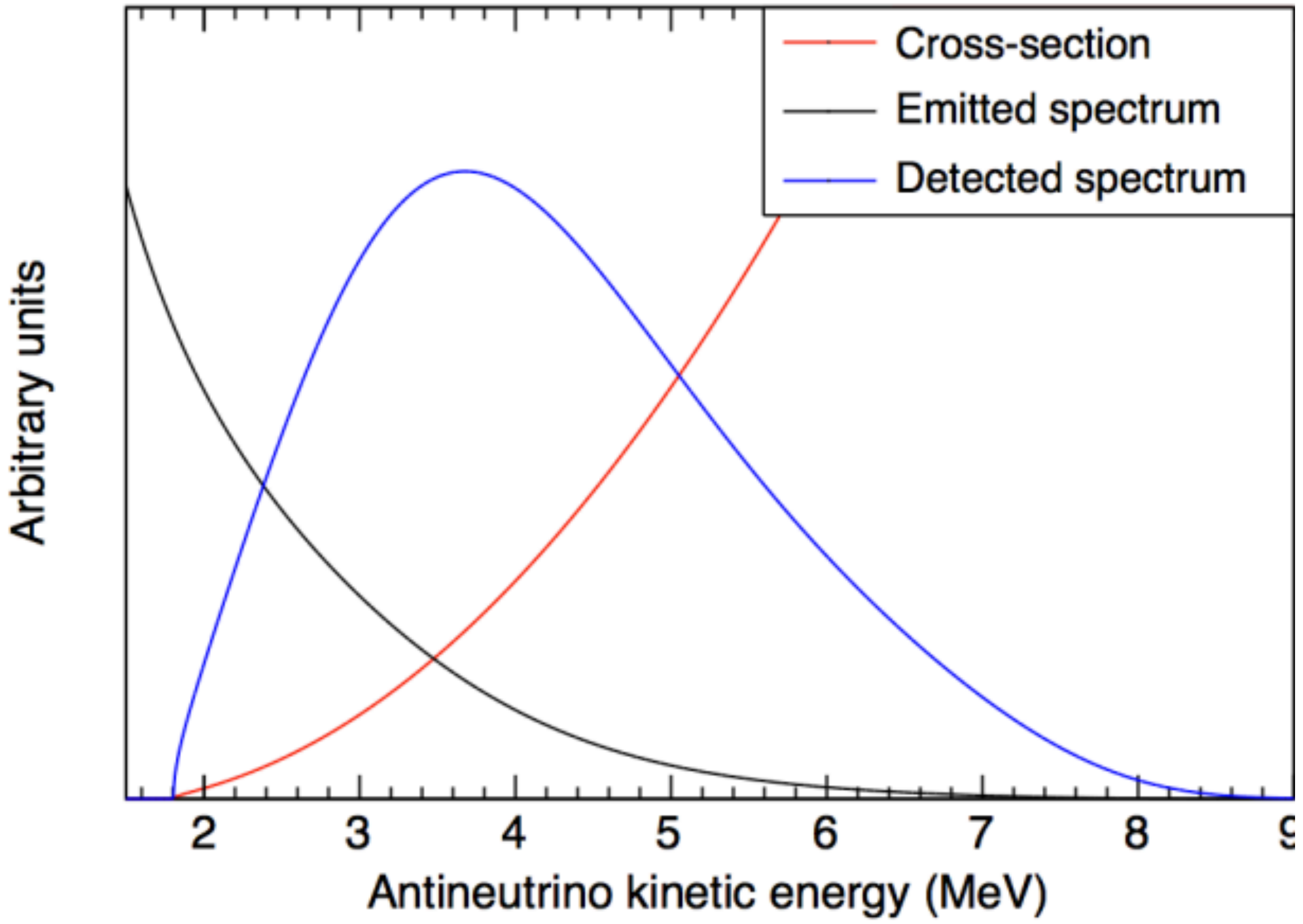
JUNO is a **20 kton** multi-purpose underground **liquid scintillator detector.**

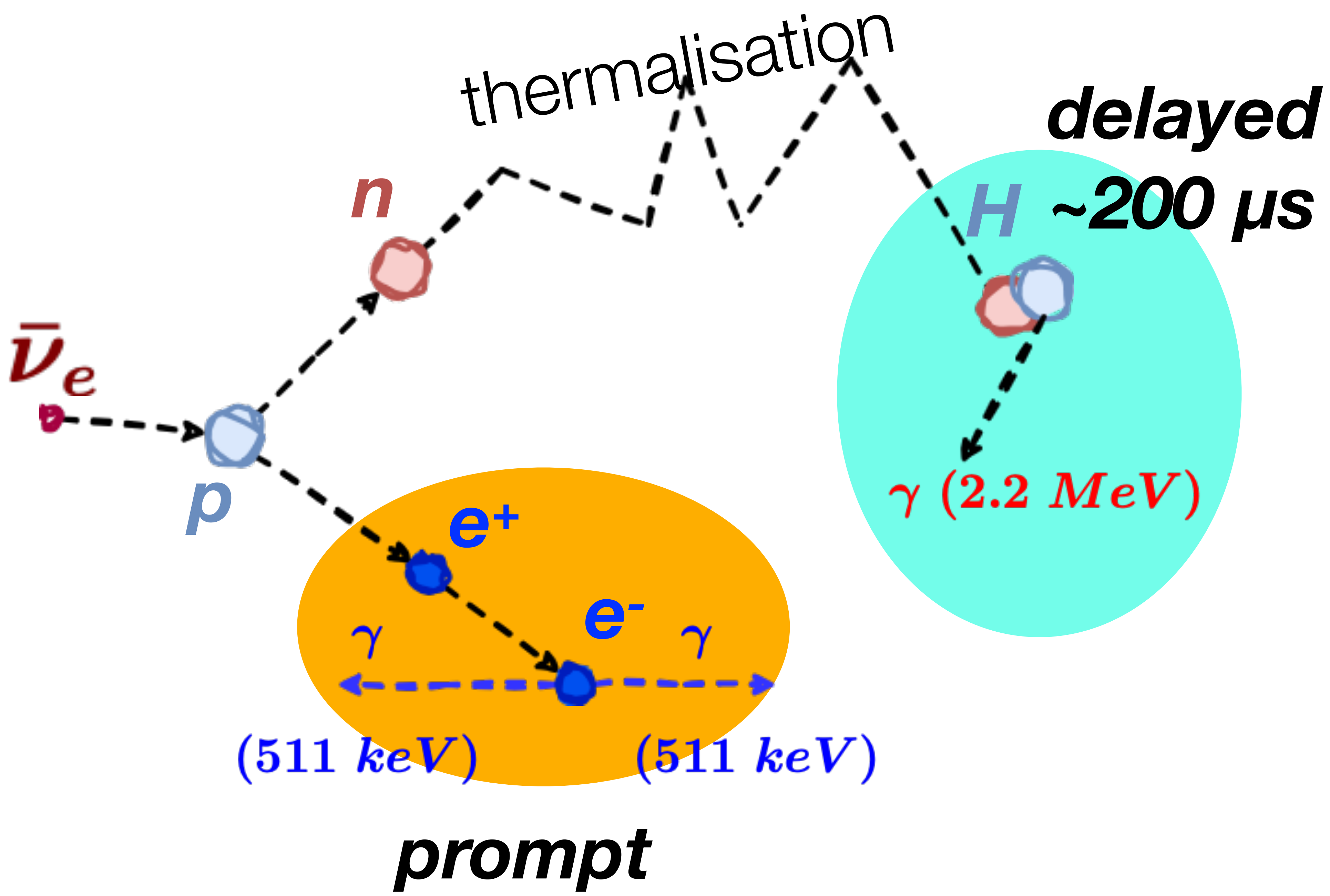
Main goal is the measurement of **Neutrino Mass Ordering** using **reactor neutrinos**



Reactor anti-neutrinos

Nuclear reactors are **extremely intense**, **well understood** and $\bar{\nu}_e$-**pure** source



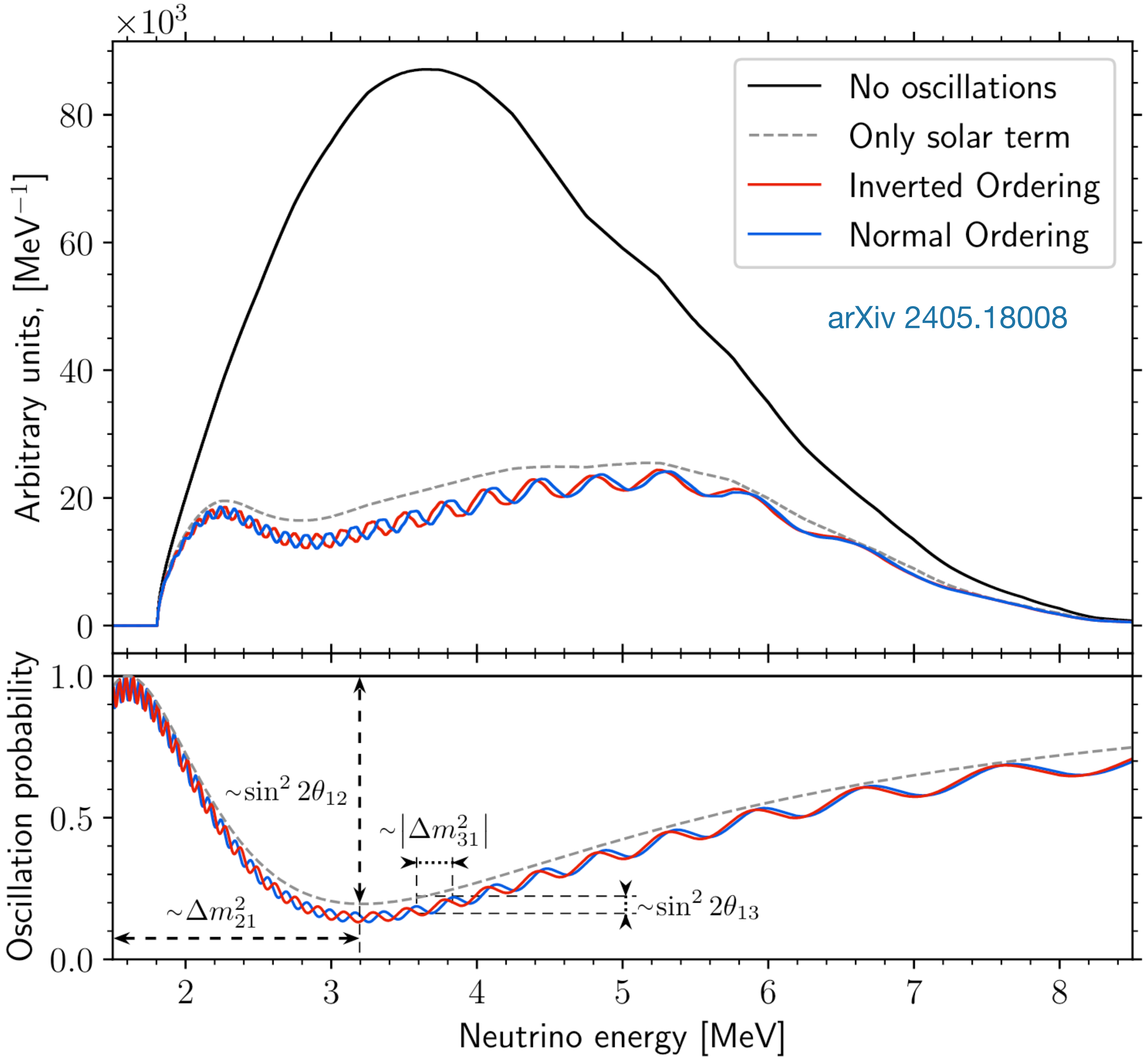


- Typical flux ~ 2 x 10^{20} $\bar{\nu}_e$/sec/GW_{th}
- Reactor neutrino allows for a **wide range of experimental baseline** (few m to 100 km) to explore **different oscillation feature**

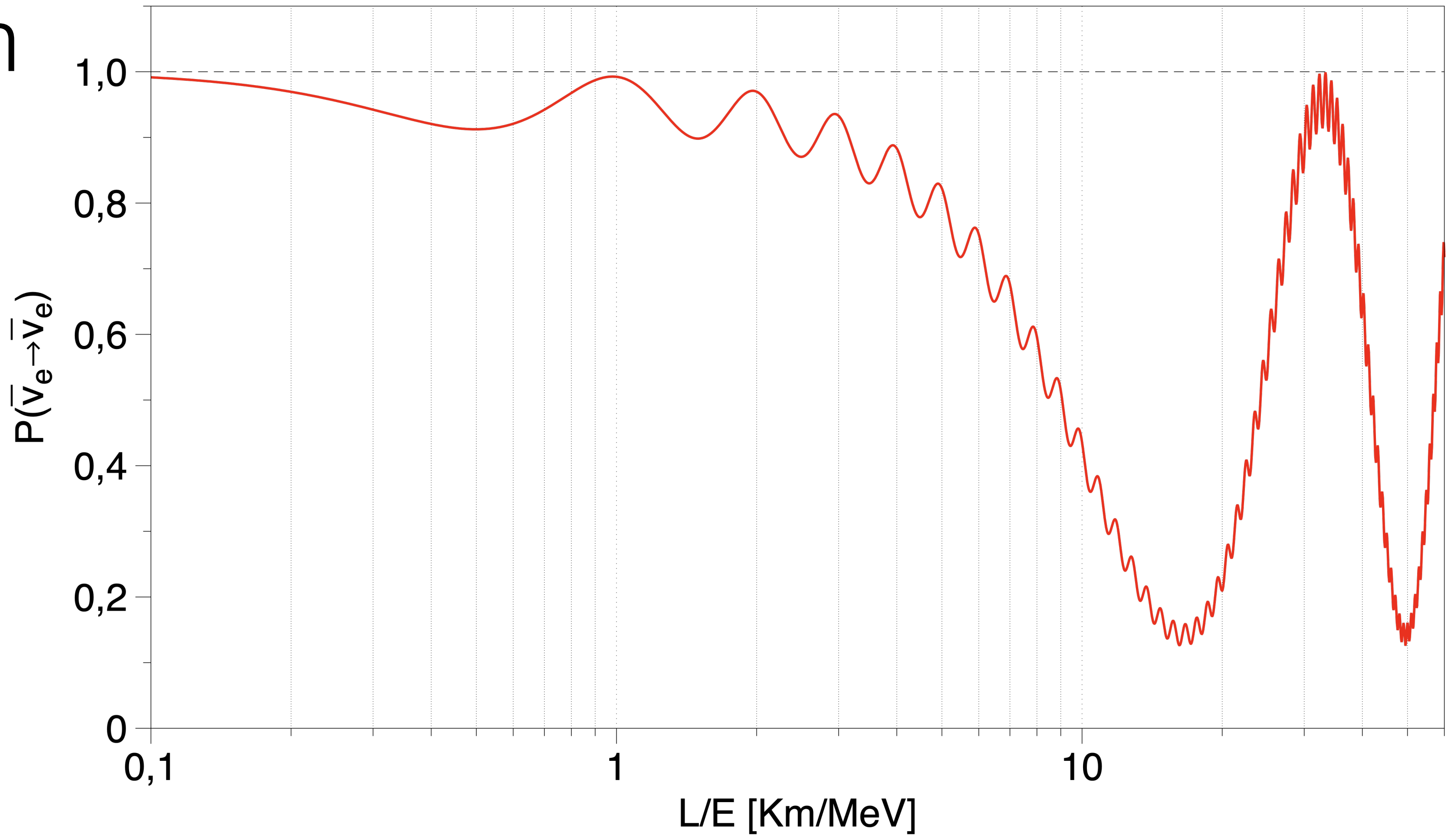
- Detection via Inverse Beta Decay
- Prompt-delayed coincidence: energy, time, space
- Neutrino energy: $E_{\bar{\nu}_e} \sim E_{prompt} + 0.78\ MeV$

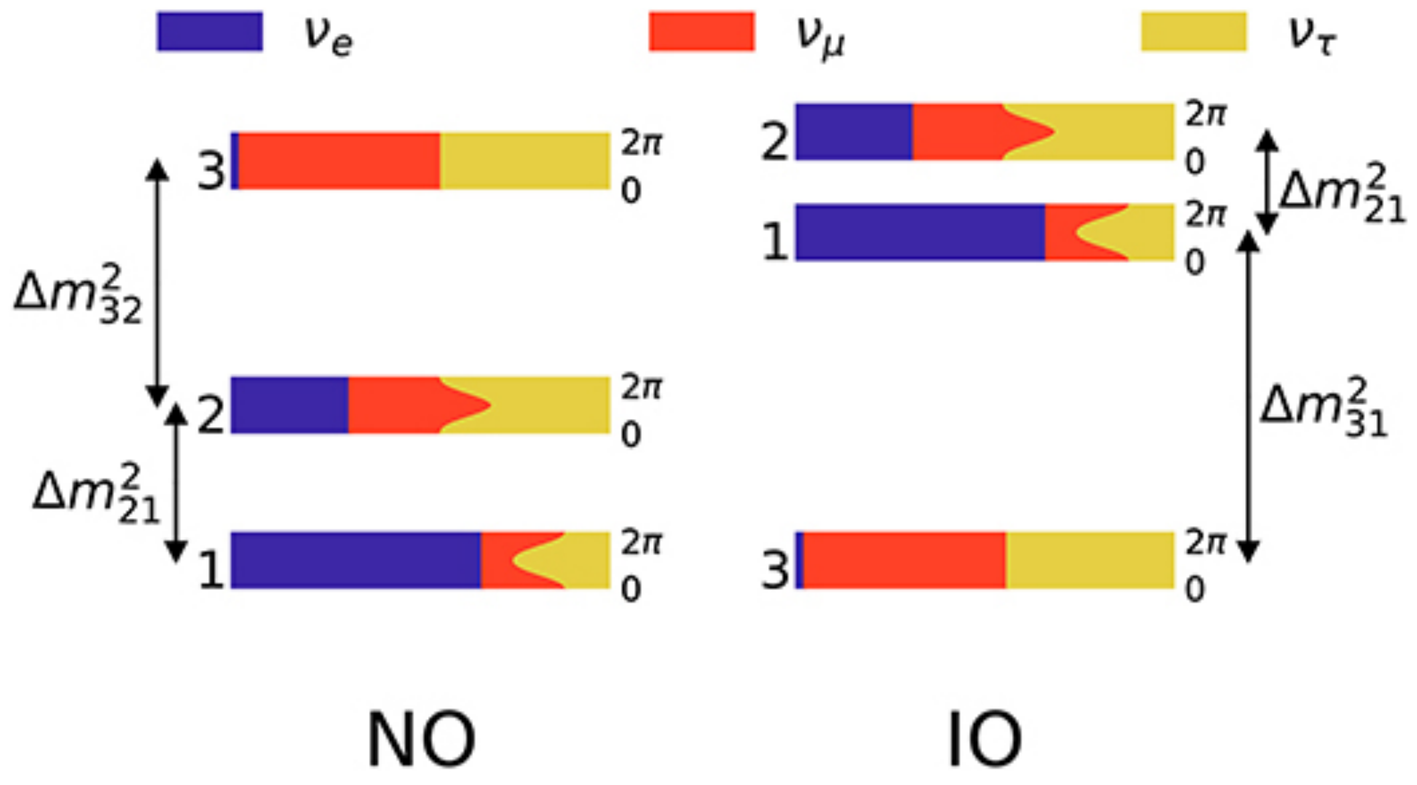
JUNO experiments main goal

Measure the reactor neutrino spectrum at 52.2 km from NPPs (first “solar” minima) to resolve the fast oscillation driven by the interference between Δm^2_{31}, Δm^2_{32} and extract NMO



arXiv 2405.18008

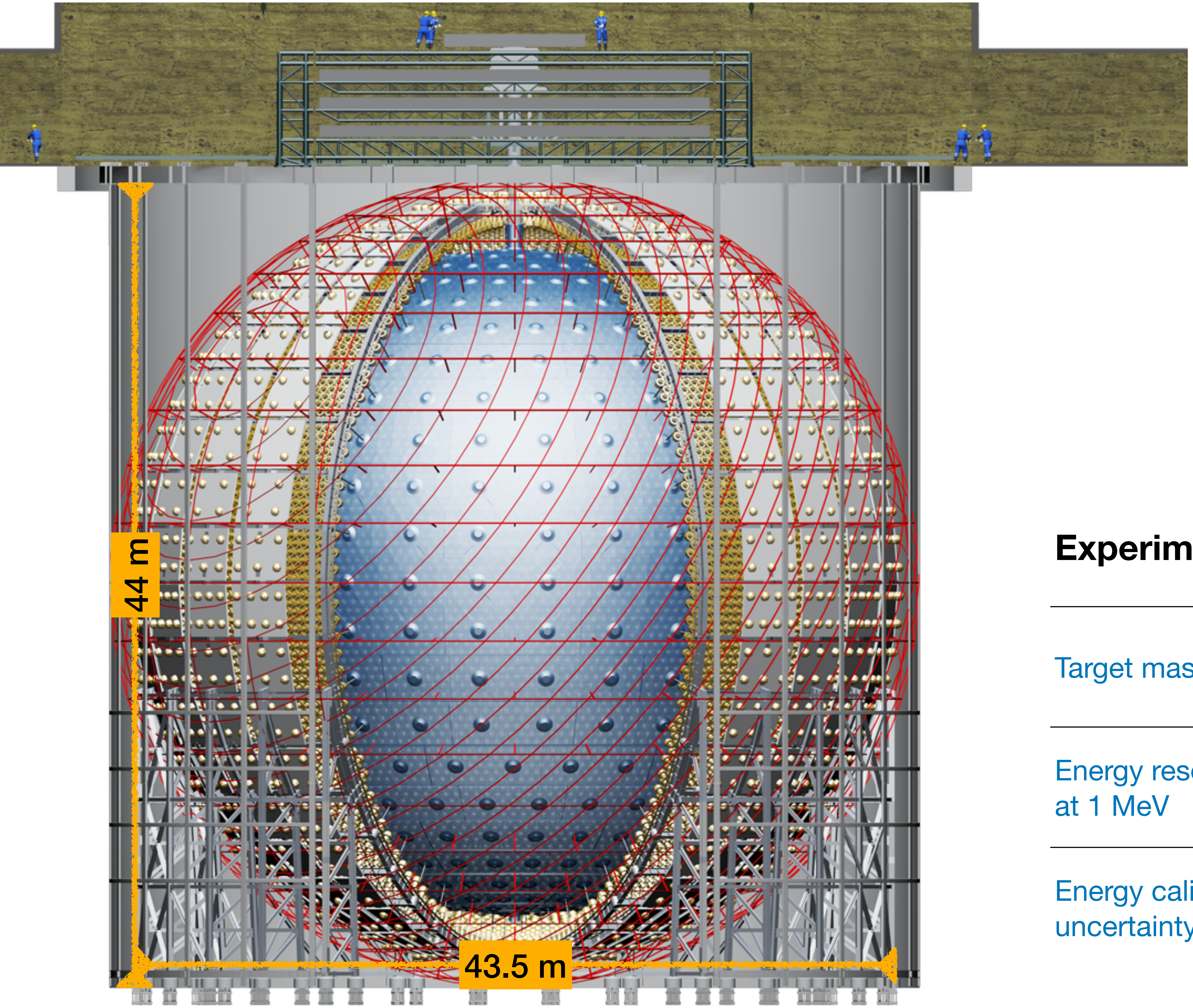




Requirement of the experiment

- **Large target mass:** 20 kton liquid scintillator (LS)
  - ✓ Large statistics
- **Excellent energy resolution:** 3% at 1 MeV
  - ✓ Large photocathode coverage
  - ✓ High photon detection efficiency
- **Highly transparent liquid scintillator**
- **Control of energy scale and systematics**
  - ✓ Calibration and quality control of PMTs

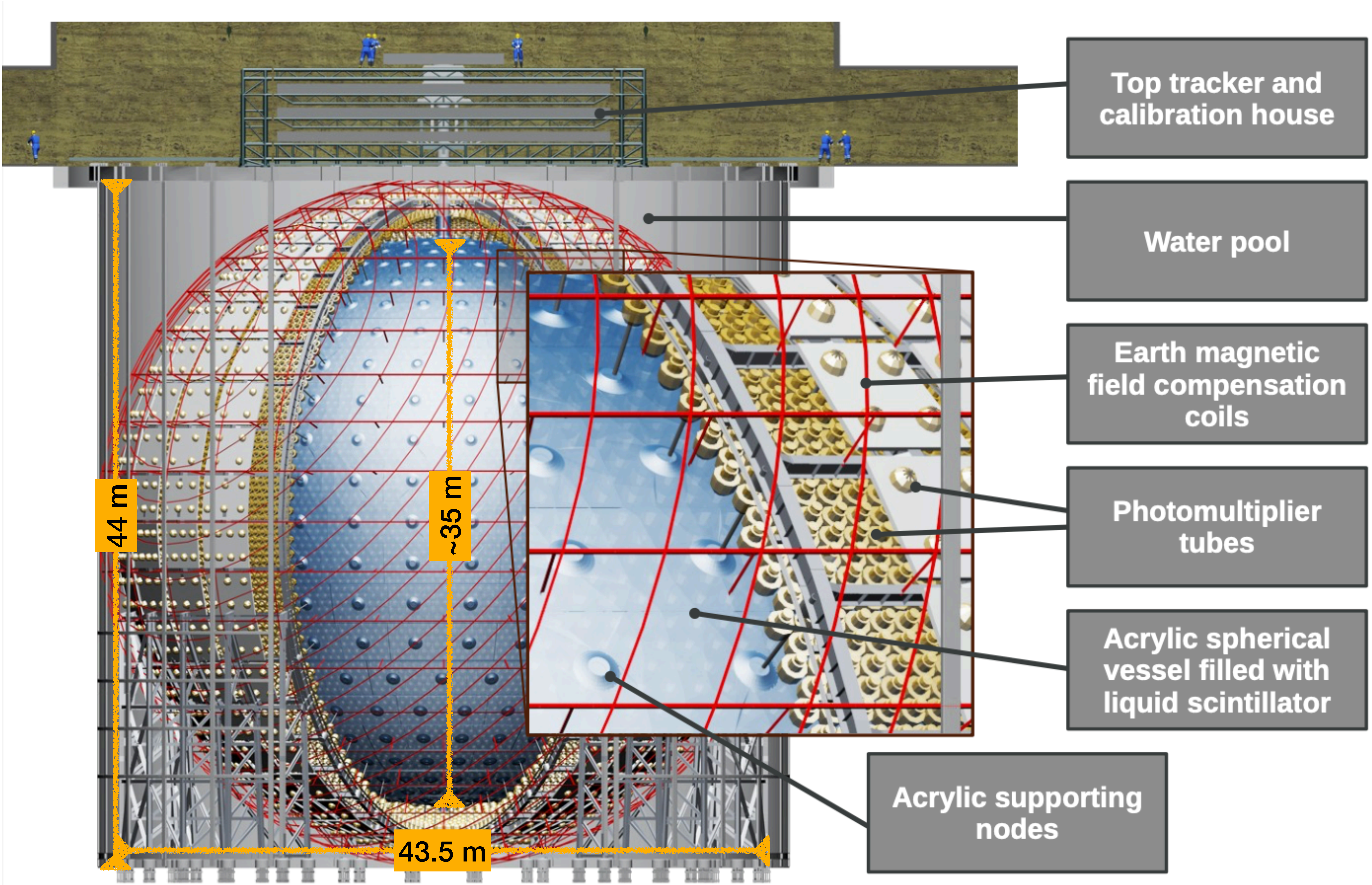
JUNO detector design



- Huge homogenous calorimeter
- **20 kton** Liquid Scintillator
  - ✓@ 52 km from NPP ~2.3 reactor IBD/day/kton
- **Precise and accurate energy reconstruction**
  - ✓Energy resolution: **< 3% @ 1 MeV**
  - ✓Energy calibration: **< 1%**

Experiment	**DayaBay**	**Borexino**	**KamLAND**	**JUNO**
Target mass [t]	20	300	1000	20000
Energy resolution at 1 MeV	~8.5%	~5%	~6%	< 3%
Energy calibration uncertainty	0.5%	1.0%	2.0%	< 1%

JUNO detector design



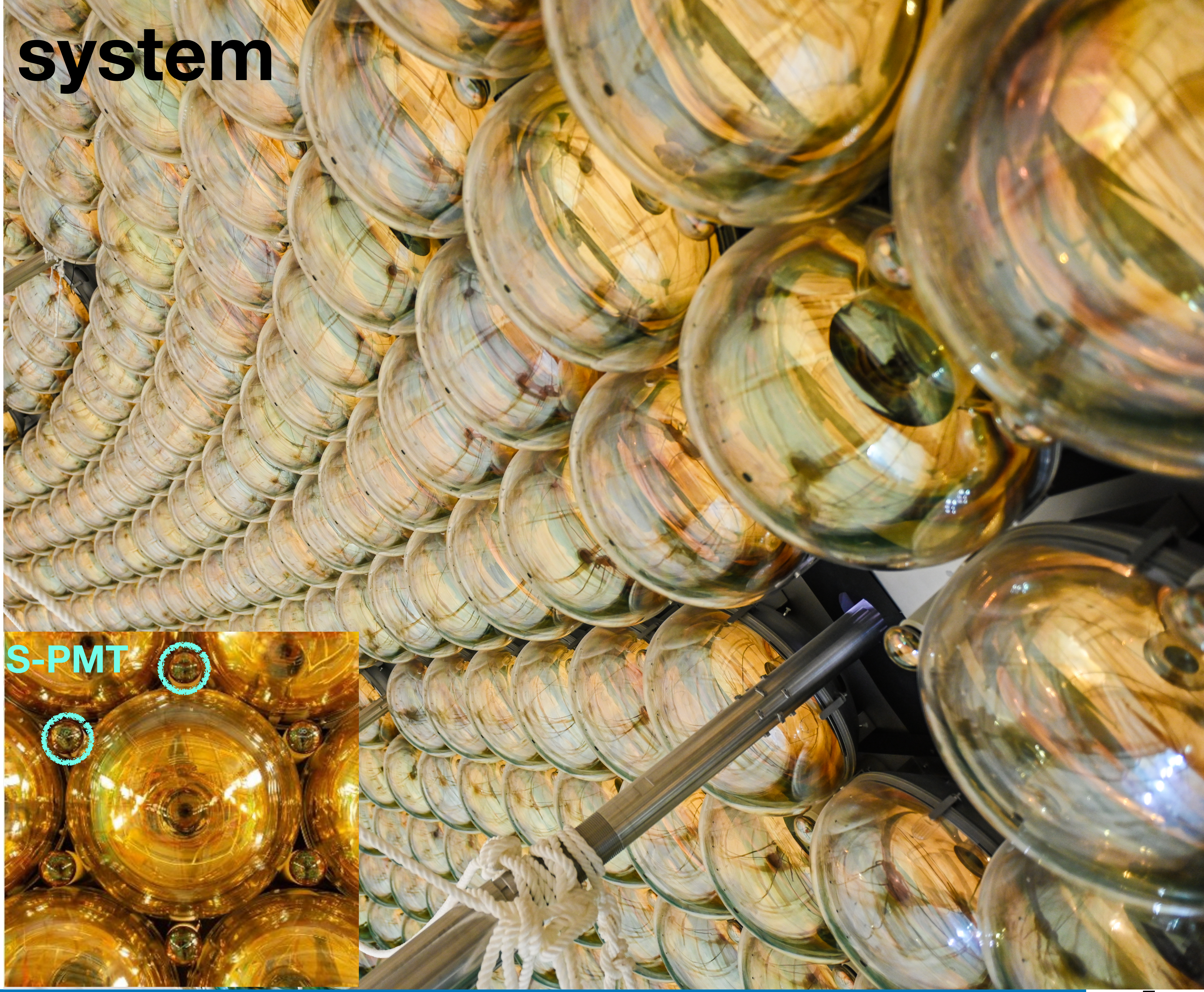
Photomultipliers system

To ensure **high photon statistics** to reach required energy resolution and mitigate possible systematics JUNO is equipped **with 2 PMT system:**

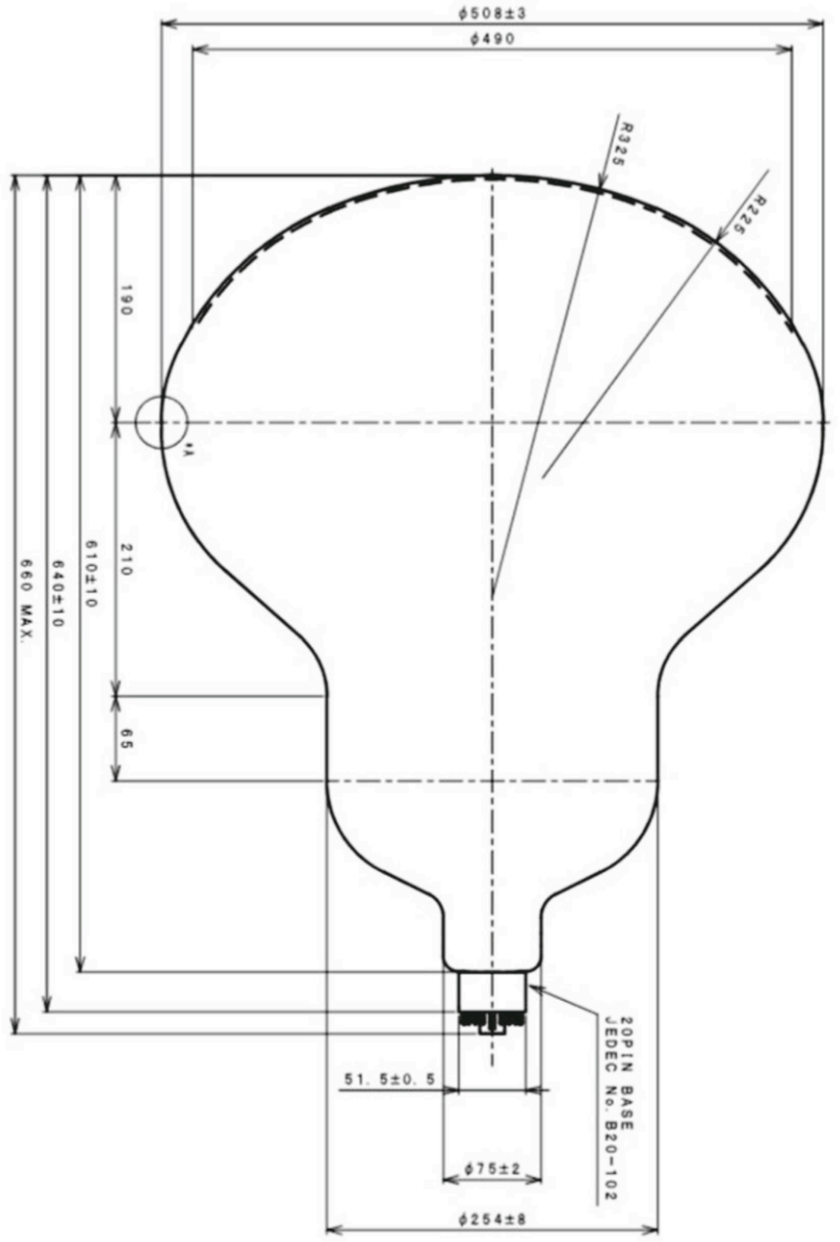
20" PMTs and **3" PMTs**

	20" PMT		3" PMT
	Hamamatsu	NNVT	HZC
Quantity	5000	12612 + 2400	25600
Charge collection	Dynode	**MCP**	Dynode
Photo detection efficiency	**28.5%**	**30.1%**	25%
Dynamic range [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

- ✓ Photocathode coverage **~78 %**
- ✓ light level of **1660 pe/MeV**

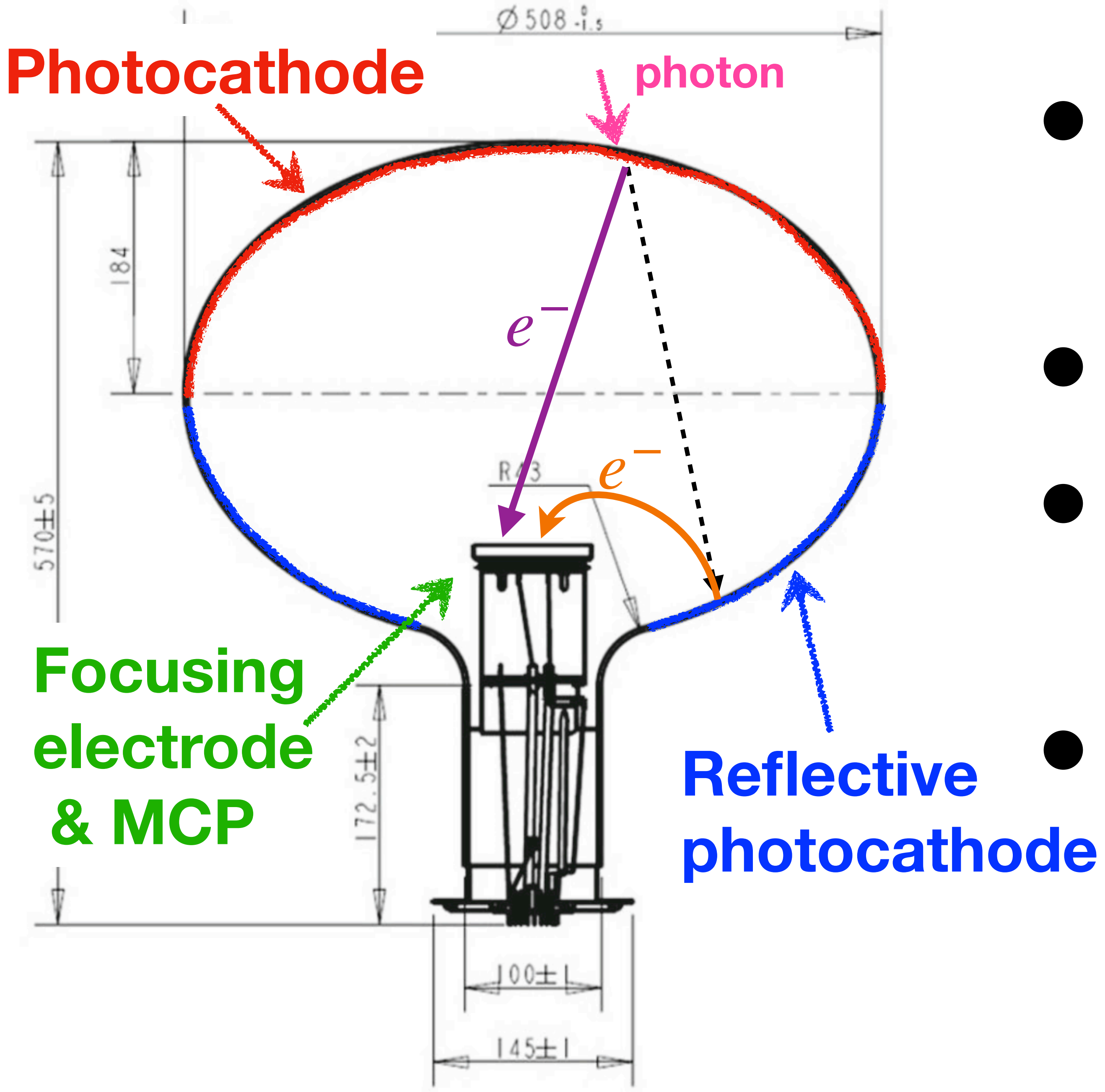


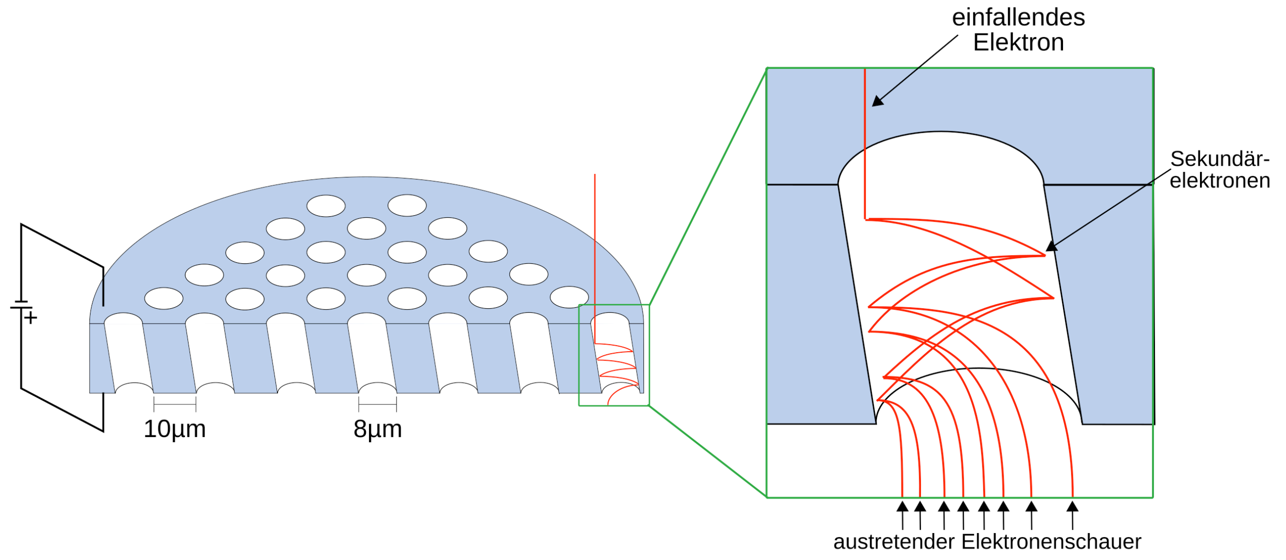
20” PMTs



- Hamamatsu Photonics **R12860-50 HQE** (SBA)
- Box and linear-focused dynode PMT
- **Excellent time resolution** for vertex reconstruction
- High detection efficiency
- **5000 PMTs** in the central detector only

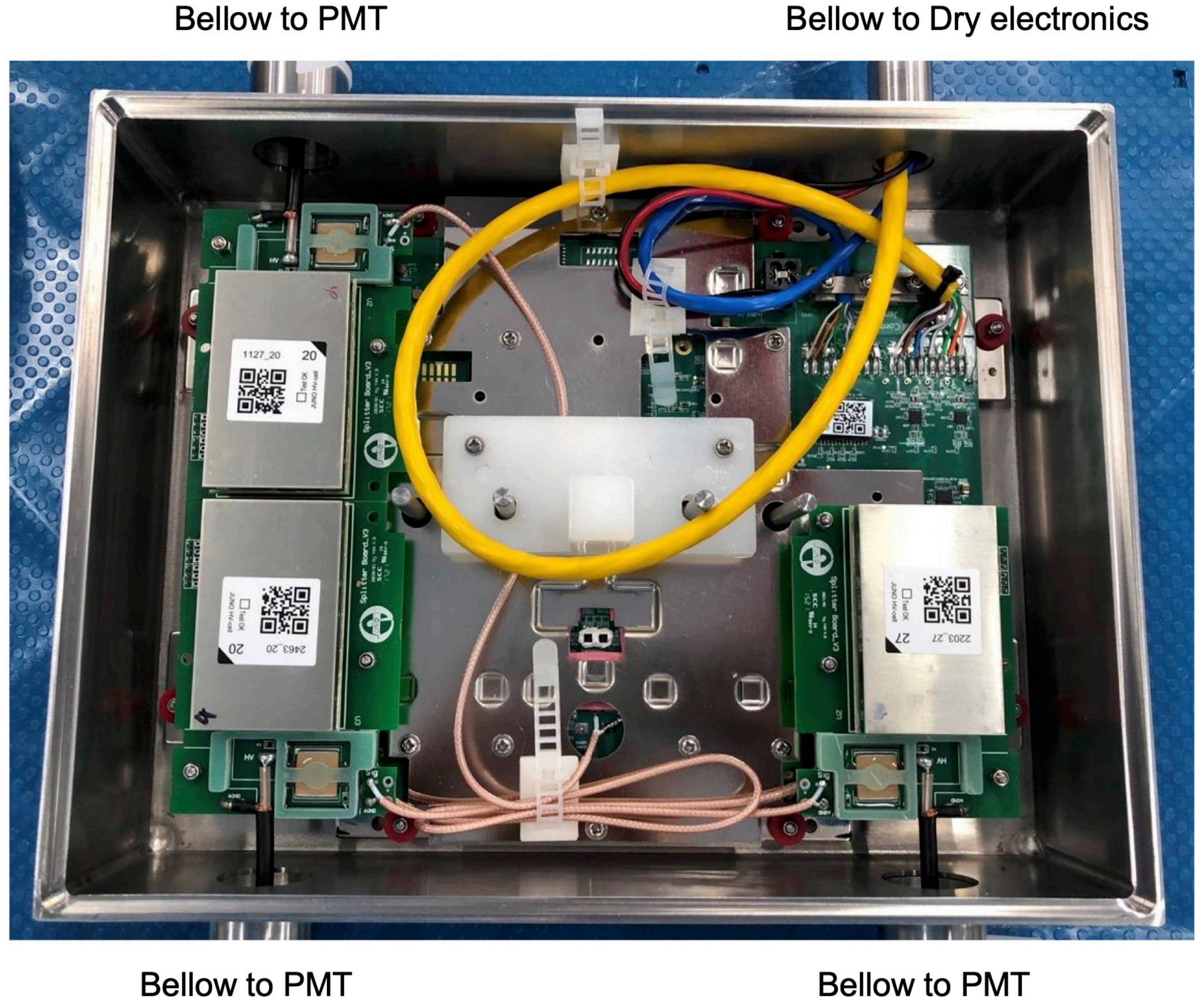
- **IHEP & NNVT jointly developed** technologies & prototypes
- **Microchannel plate** (MCP) technology for amplification
- Optimised collection efficiency via **transmission** + **reflection** photo cathode
- **12612** in the central detector + **2400** in the veto

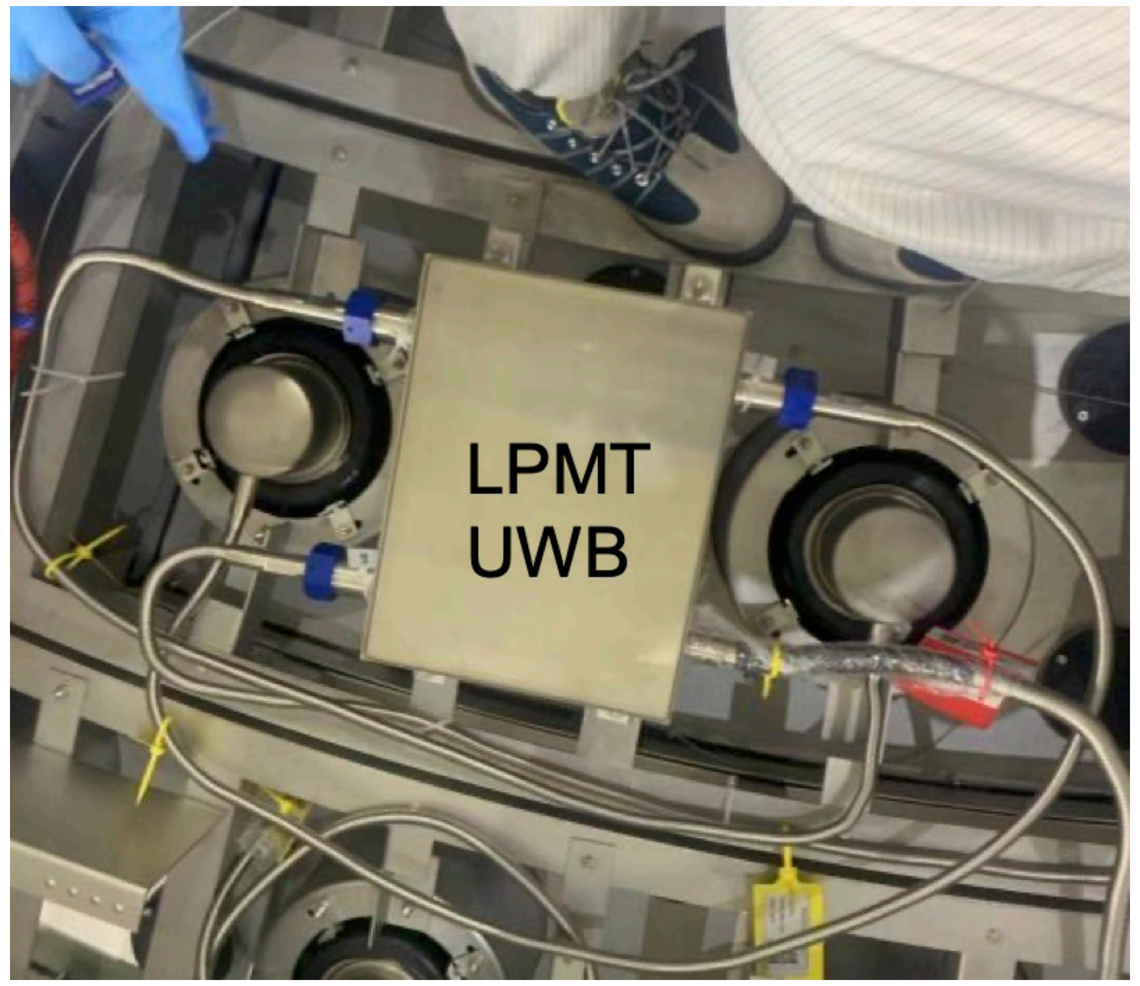


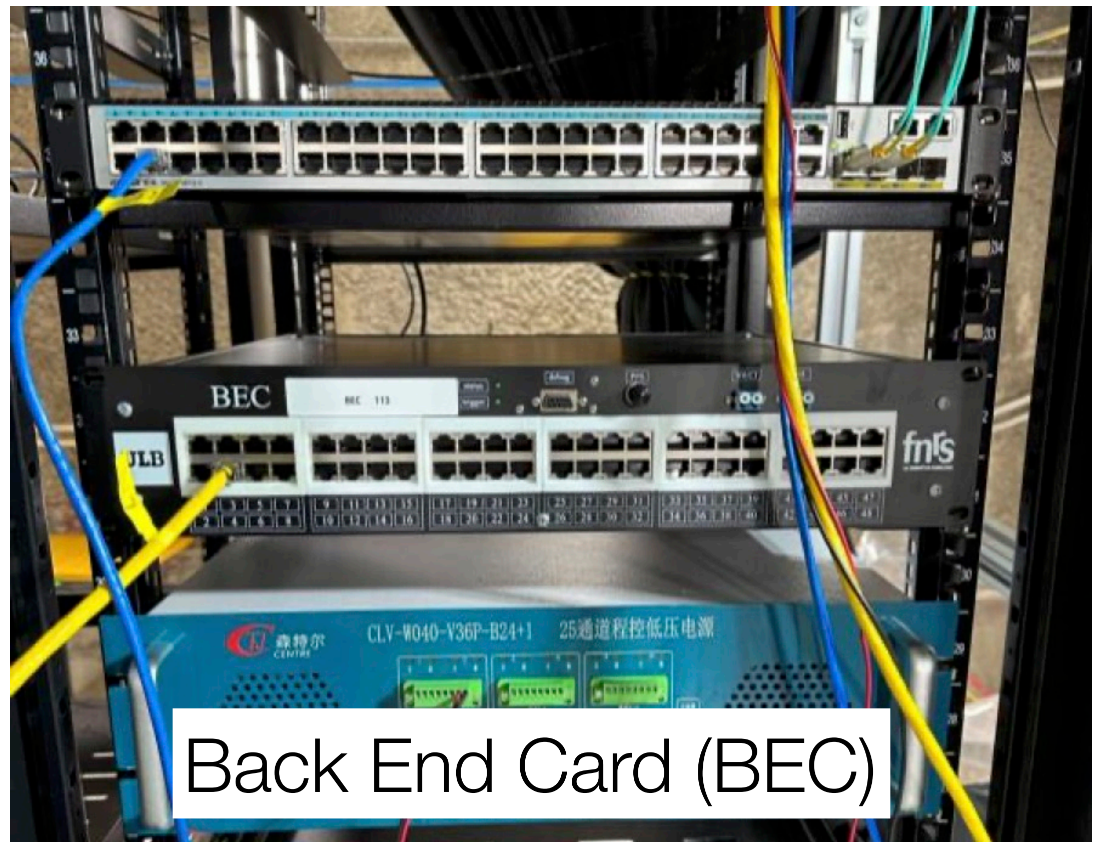


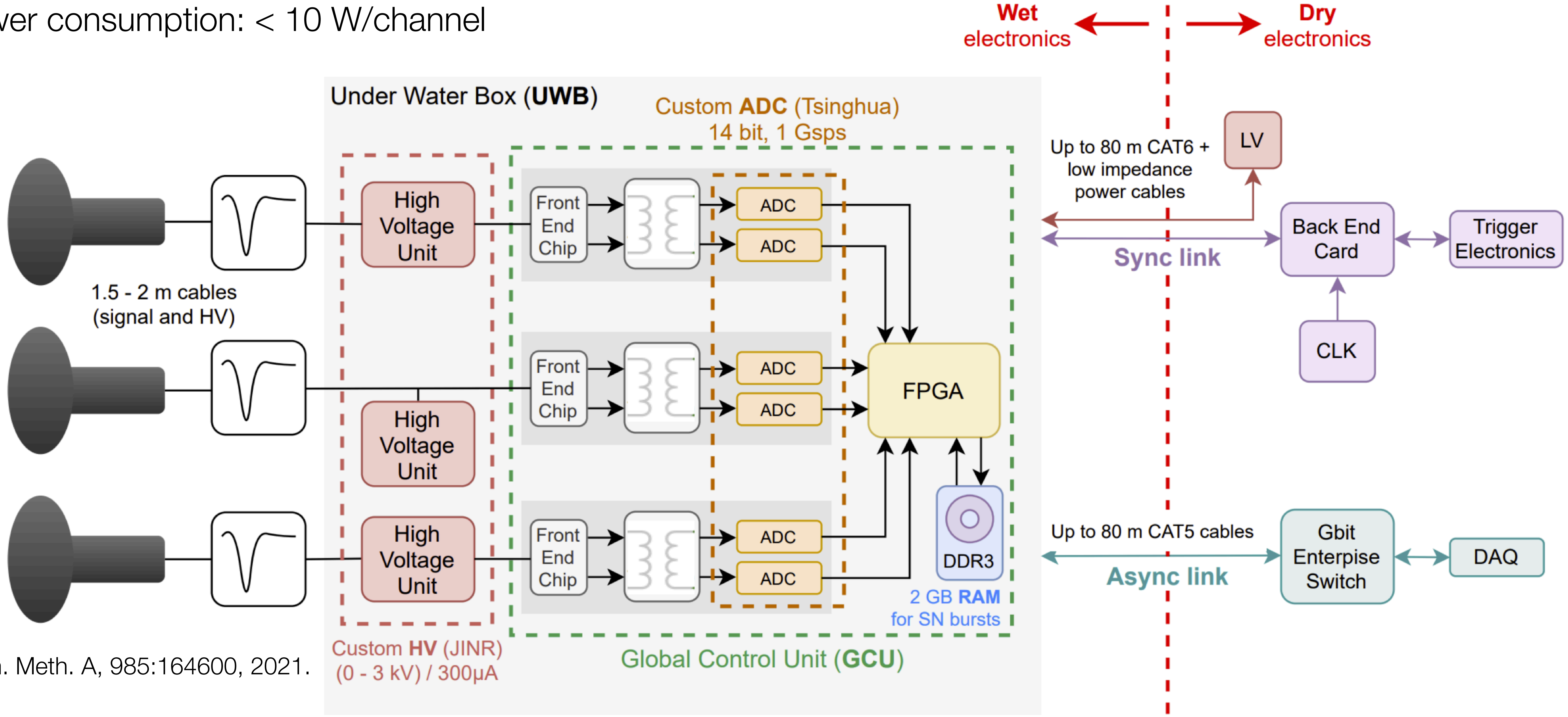
20” PMT Electronics

- 1 Gsps, 12-14 bits ADC
- Energy resolution 10% @ 1-100 pe, 1% @ >100 pe
- **Large dynamic range: 1-4000 pe**
  - Low gain (8:1) 0~7.5V (0-4000 pe)
  - High gain (1:1) 0~960 mV (0-128 pe)
- Excellent **photon time stamp**
- Global and self-trigger support
- **Negligible dead-time** for supernova event
- Aerospace-grade reliability: **< 0.5% underwater electronics failure in 6 years**
- Power consumption: < 10 W/channel



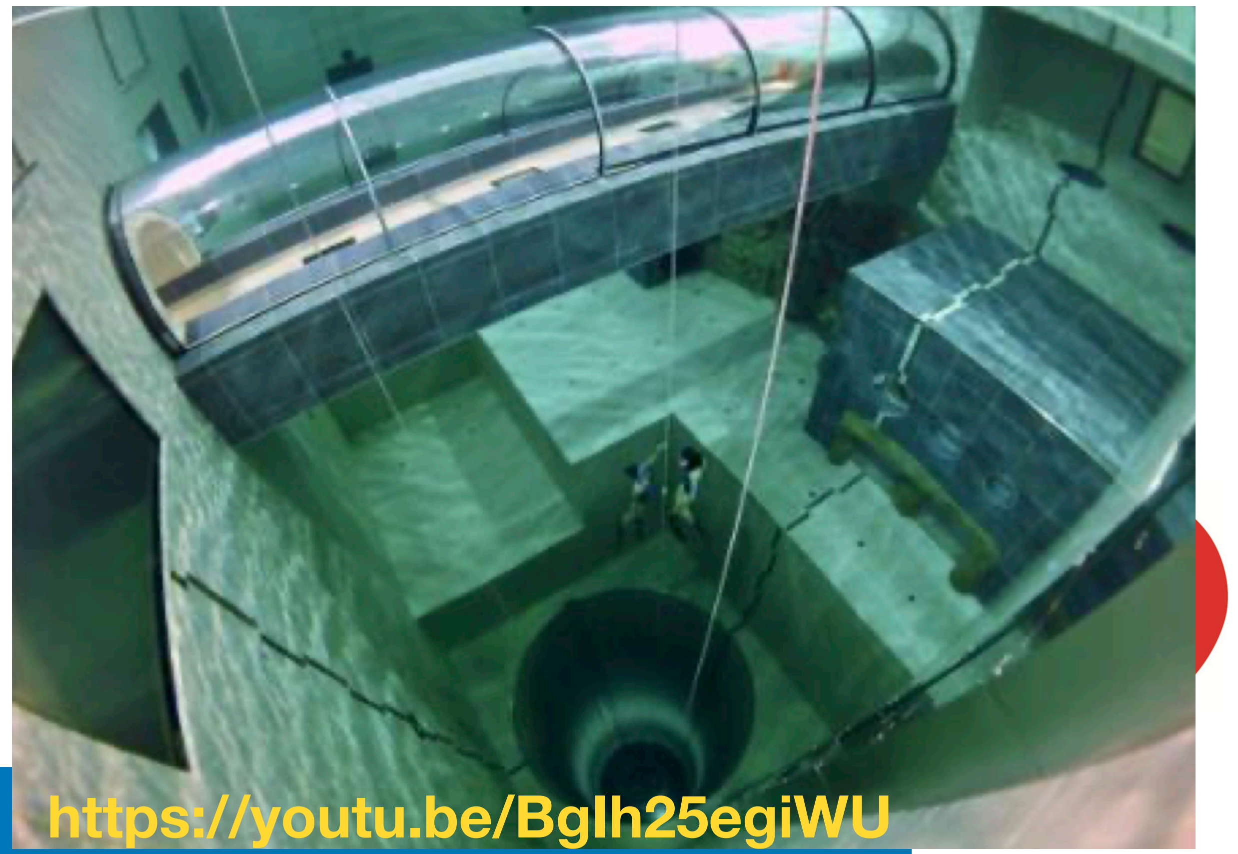






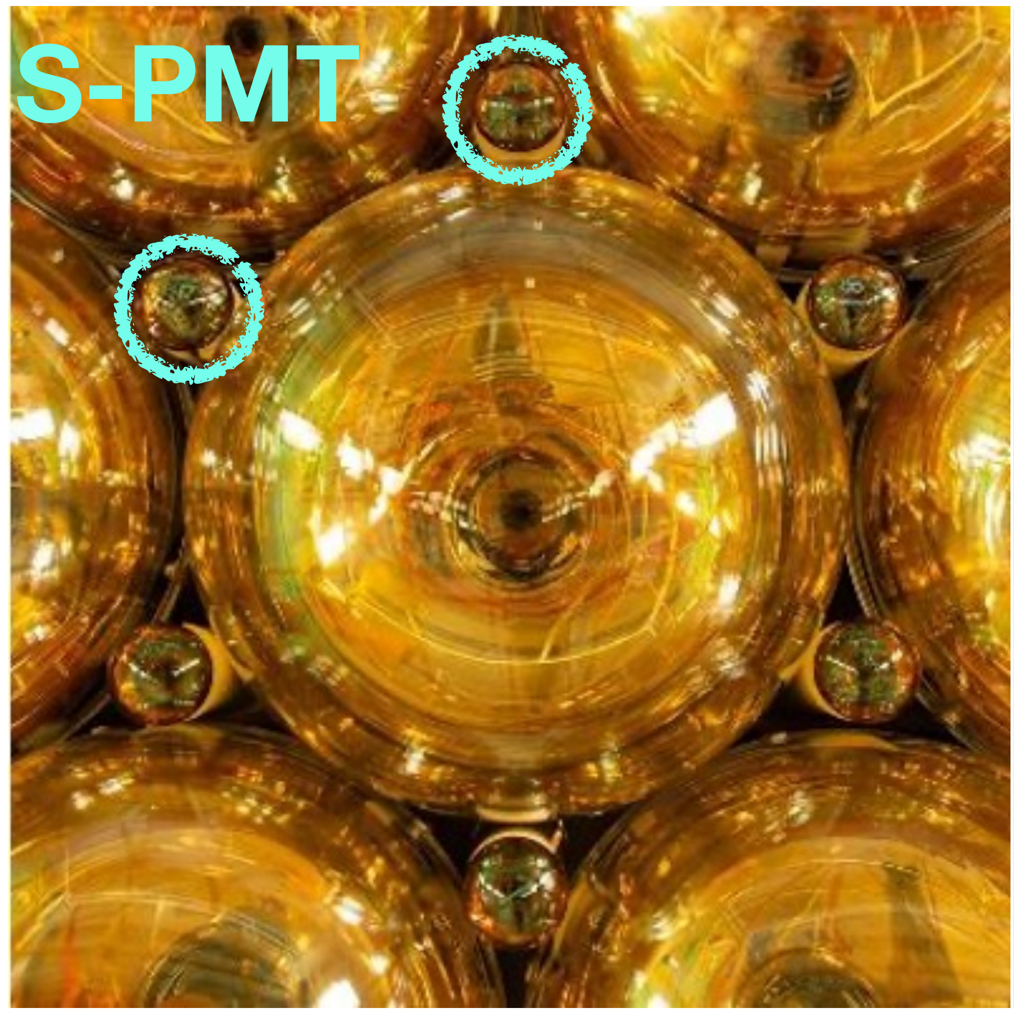
Nucl. Instrum. Meth. A, 985:164600, 2021.

Waterproof and cooling test at -40 m



https://youtu.be/BgIh25egiWU

3” PMT Electronics

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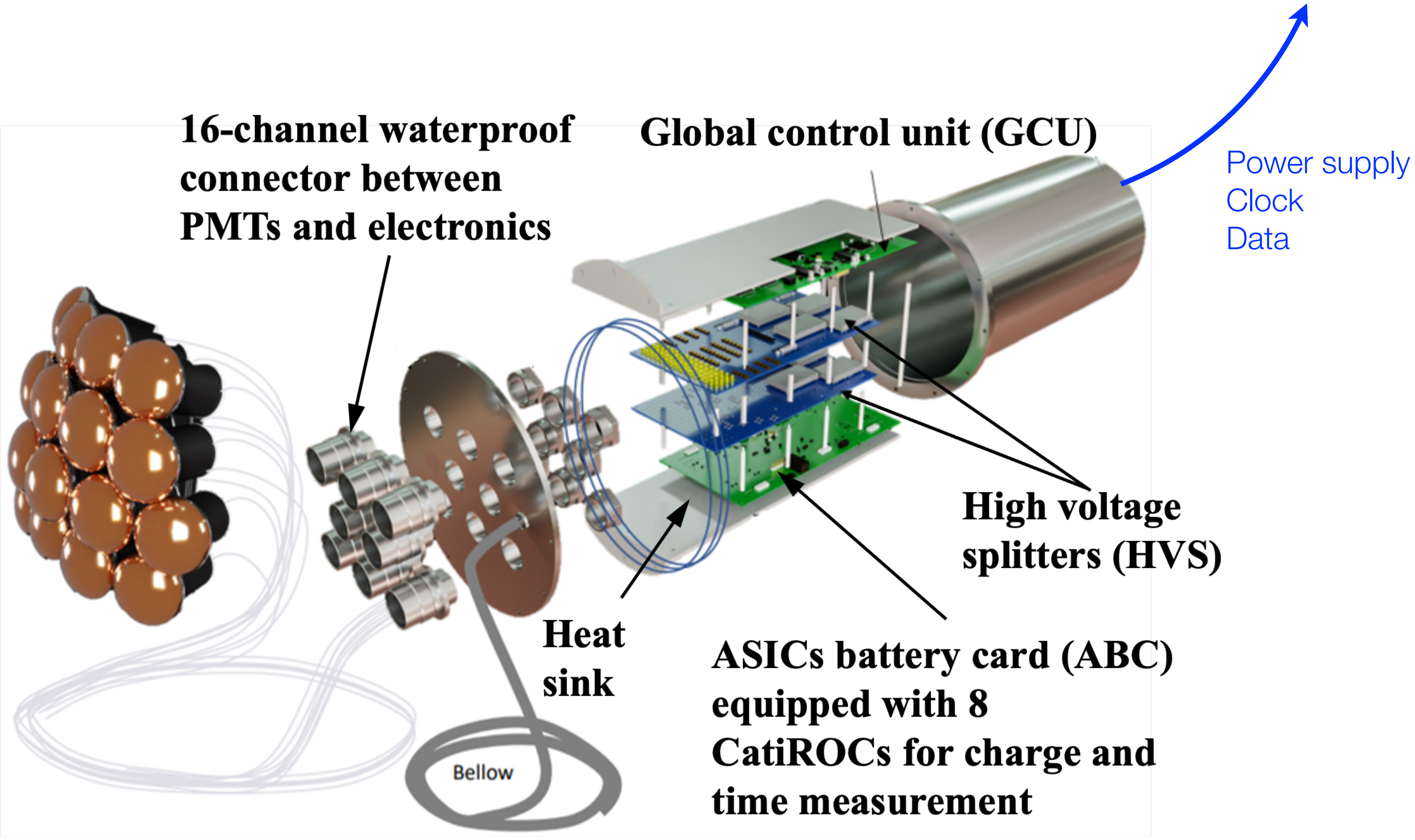

16-channel waterproof connector between PMTs and electronics

Global control unit (GCU)

Power supply
Clock
Data

High voltage splitters (HVS)

Heat sink

ASICs battery card (ABC) equipped with 8 CatiROCs for charge and time measurement

- Calibrating charge non-linearity of 20” PMTs and their electronics
  - ✓ **photon-counting vs. waveform deconvolution**
  - ✓ more in Akira Takenaka talk of this workshop
- **Extend JUNO energy and rate range**: muons, nearby supernova
- Semi-independent measurement of $\theta_{12},\ \Delta m^2_{21}$

SPMT Under Water Box

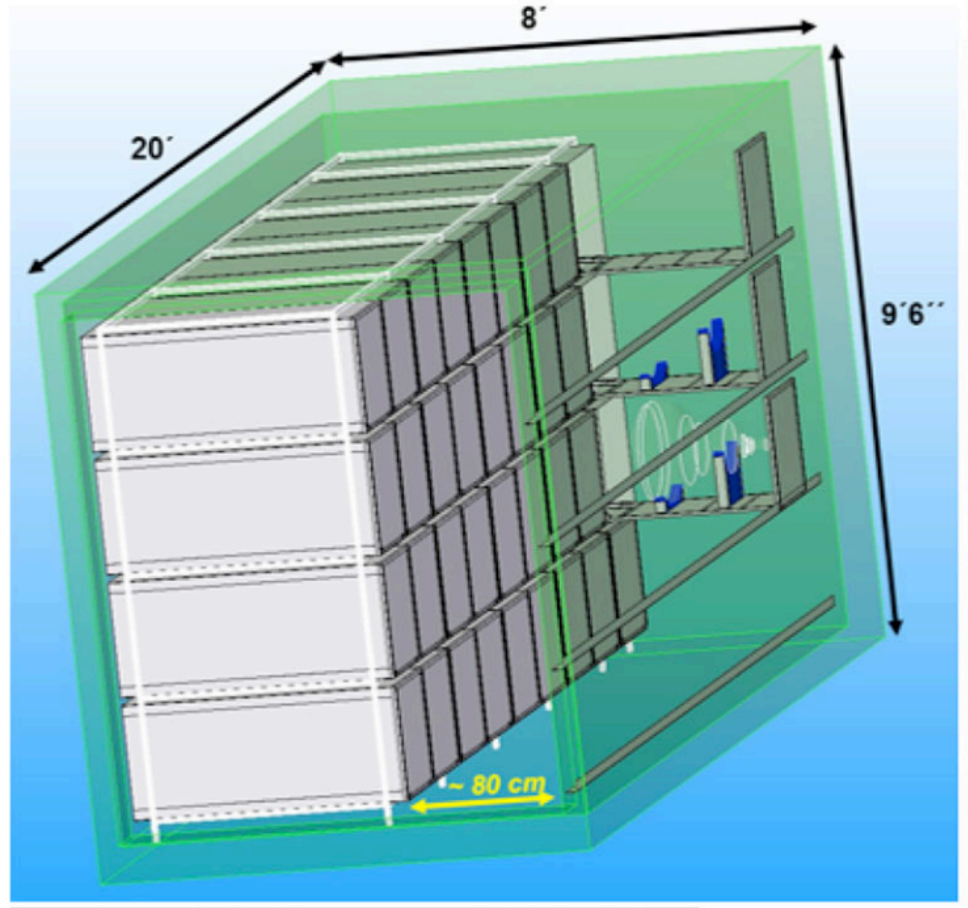
- 128 ch. PMTs,
- 8 connectors, 16PMTs/connector
- 8 High voltage modules + 8 spares
- 2 High voltage splitter boards
- 1 Front-End + digitalisation Electronics (ABC)
- 1 Global Control Unit (GCU)

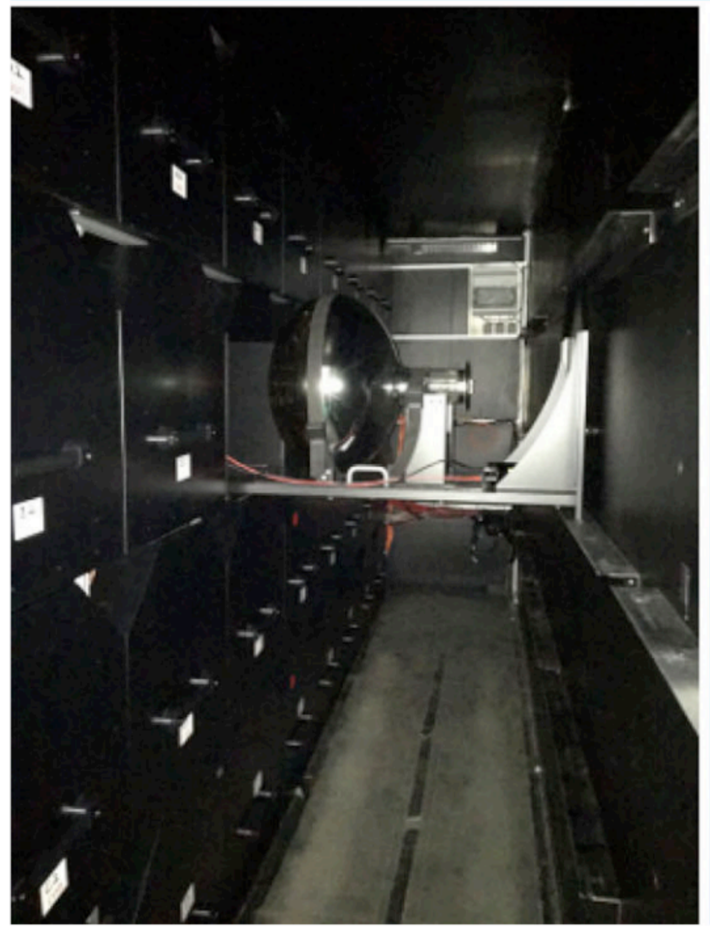
2021JInst..16P5010J

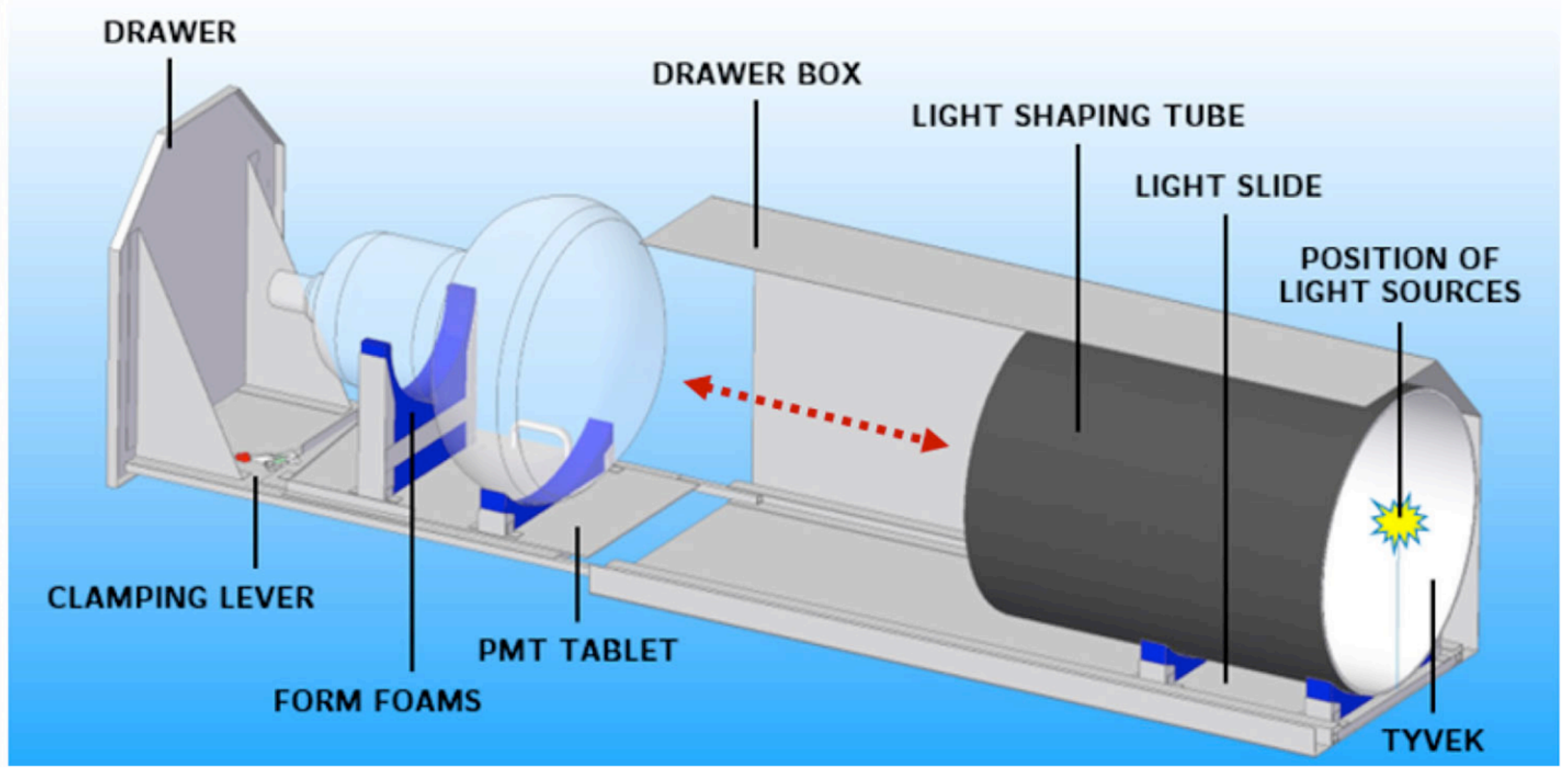
20” PMT testing & characterisation

Eur. Phys. J. C (2022) 82:1168

To ensure the required quality all 20” PMTs have been tested and selected base on stringent criteria







Parameter	**HPK R12860-50** Average (limit)	**NNVT GDB-6201** Average (limit)
QE	30.3% (≥ 27%)	28.5% (≥ 26.5%)
CE	95.6%	98% (≥ 96%)
Effective area ratio	96% (93%)	97% (≥ 96%)
Gain	107	107
HV (for a 107 gain)	2000 V (≤ 2500 V)	2500 V (≤ 2800 V)
QE uniformity	5% (≤ 15% inside 70) 20% (≤ 30% inside 80)	(≤ 8 10%)
TTS (FWHM)	2.7 ns (≤ 3.5 ns)	12 ns (≤ 15 ns)
P/V ratio	3 (≥ 2.5)	3.5
Pre-pulse ratio (80 ns window main pulse 160 p.e.)	0.8% (≤ 1%)	0.5% (≤ 1%)
After-pulse ratio (0.5 ~ 20 µs window main pulse 160 p.e.)	10% (≤ 15%)	10% (≤ 15%)
Dark count rate (0.25 p.e., 22 C)	10 kHz (≤ 50 kHz)	≤ 50 kHz (if 24% ≤ PDE < 27%) ≤ 60 kHz (if 27% ≤ PDE < 28%) ≤ 80 kHz (if 28% ≤ PDE < 29%) ≤ 100 kHz (if 29% ≤ PDE)
Glass radioactivity	238U: < 400 ppb 232Th: < 400 ppb 40K: < 40 ppb	238U: < 75 ppb 232Th: < 75 ppb 40K: < 30 ppb
Pressure tolerance	≥ 0.8MPa	> 1MPa
Dimension tolerancea	508 (±3 mm) (diameter) < 10 mm (height)	508 (±3 mm) (diameter) < 10 mm (height)
Lifetime	≥ 20 years	≥ 25 years

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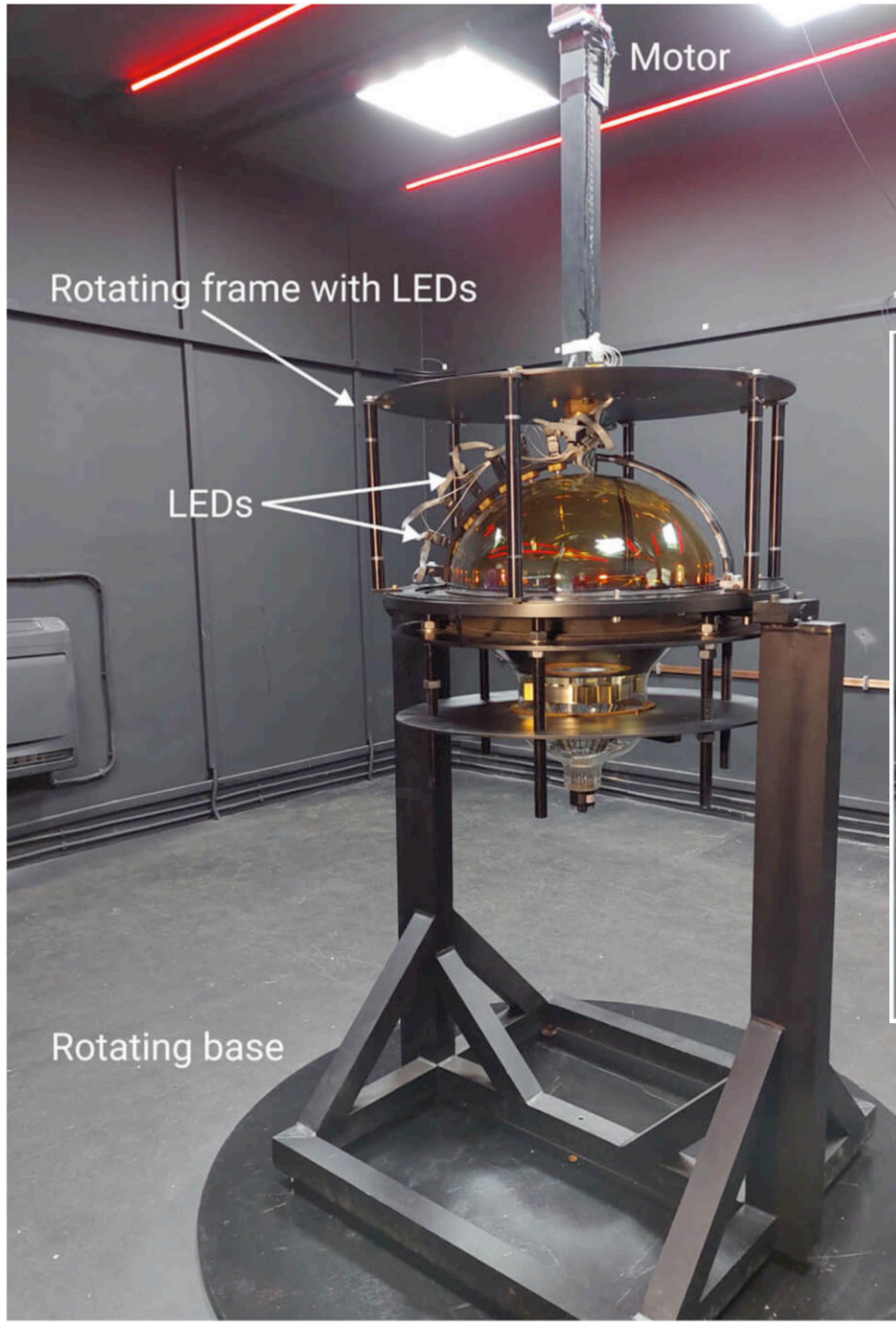
20” PMT testing & characterisation

Two dark rooms with rotating stage to scan the surface of the PMTs

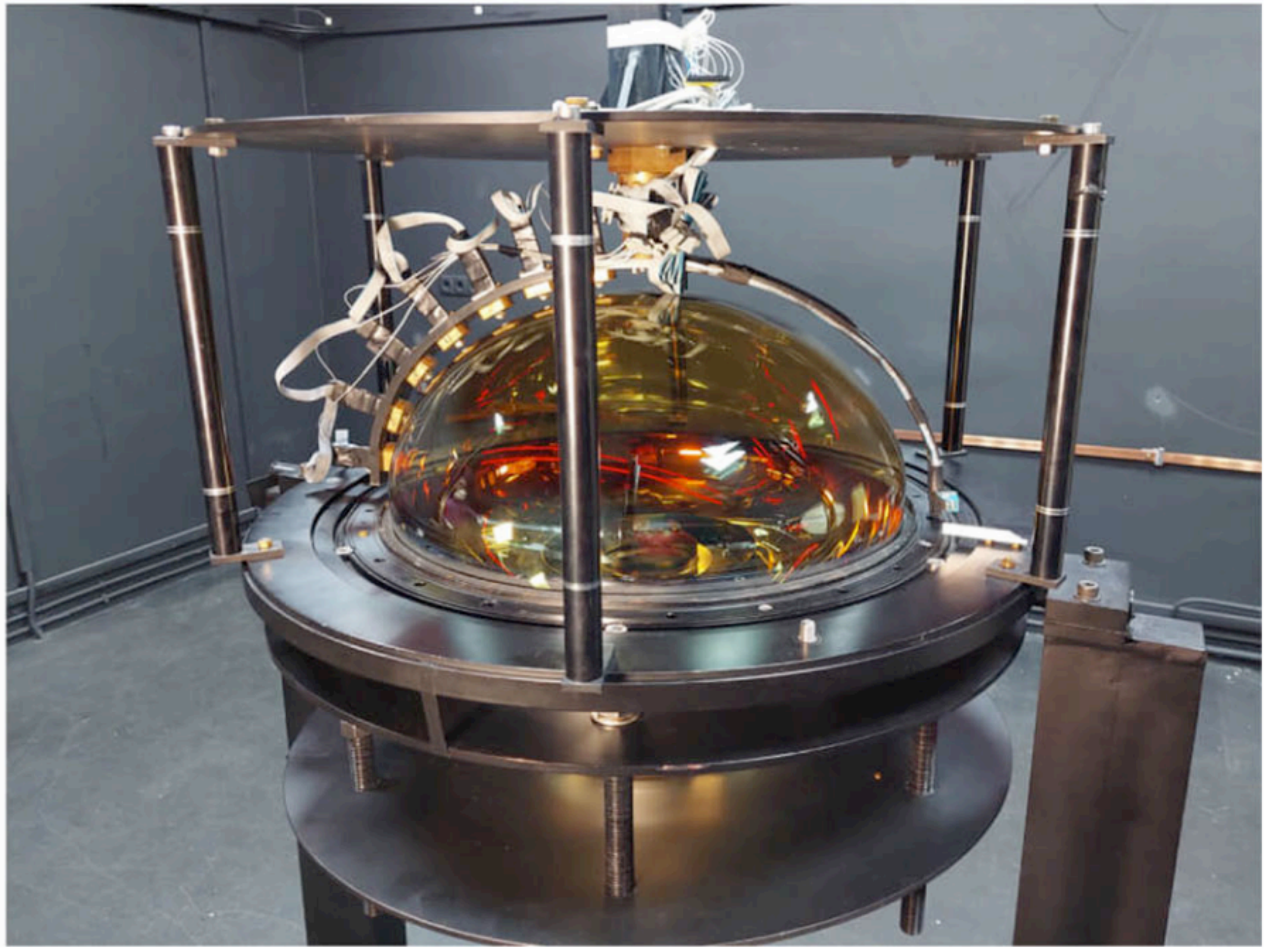
Scan on **5% of the PMTs**

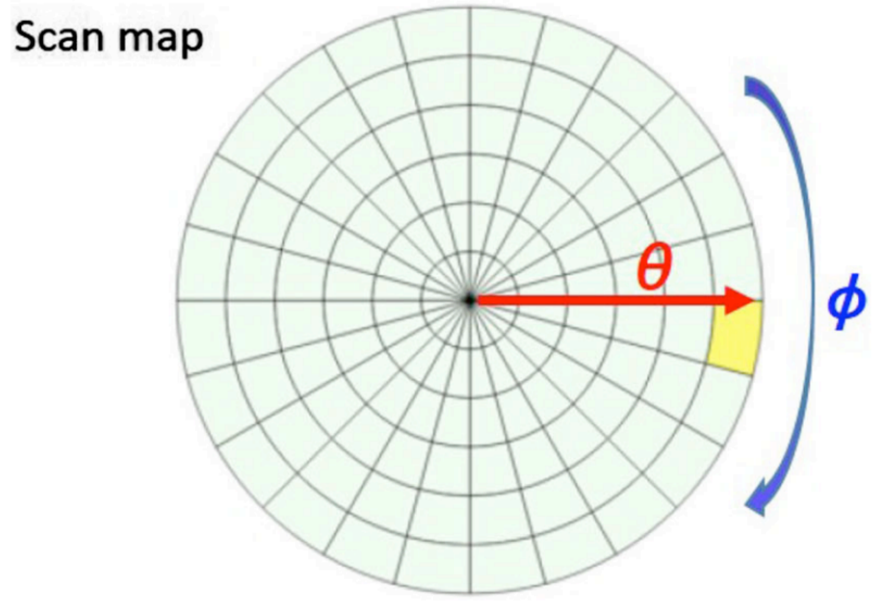
Helmholtz coils to suppress to test the magnetic field sensitivity in the range ± 50 μT.



7 LED to cover the zenith angle

Rotating stage to azimut angle





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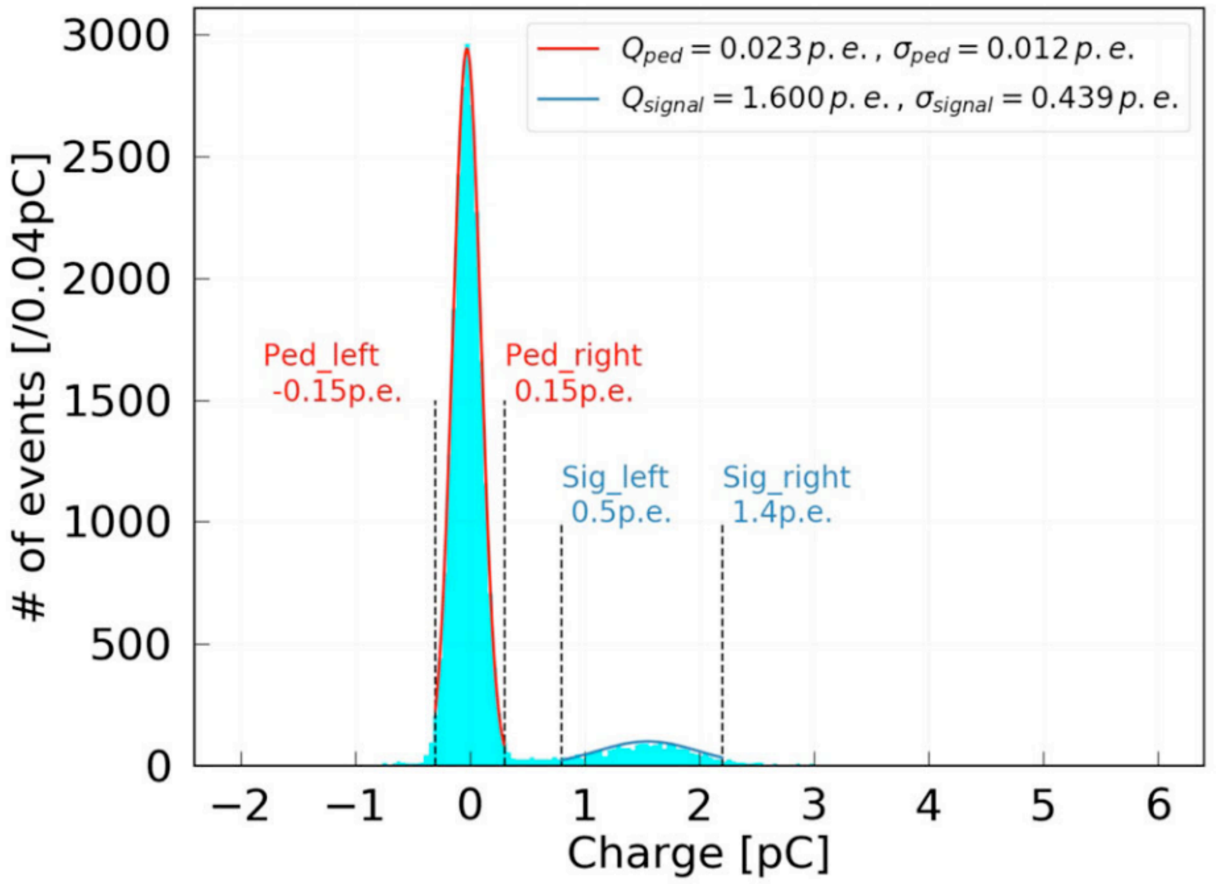
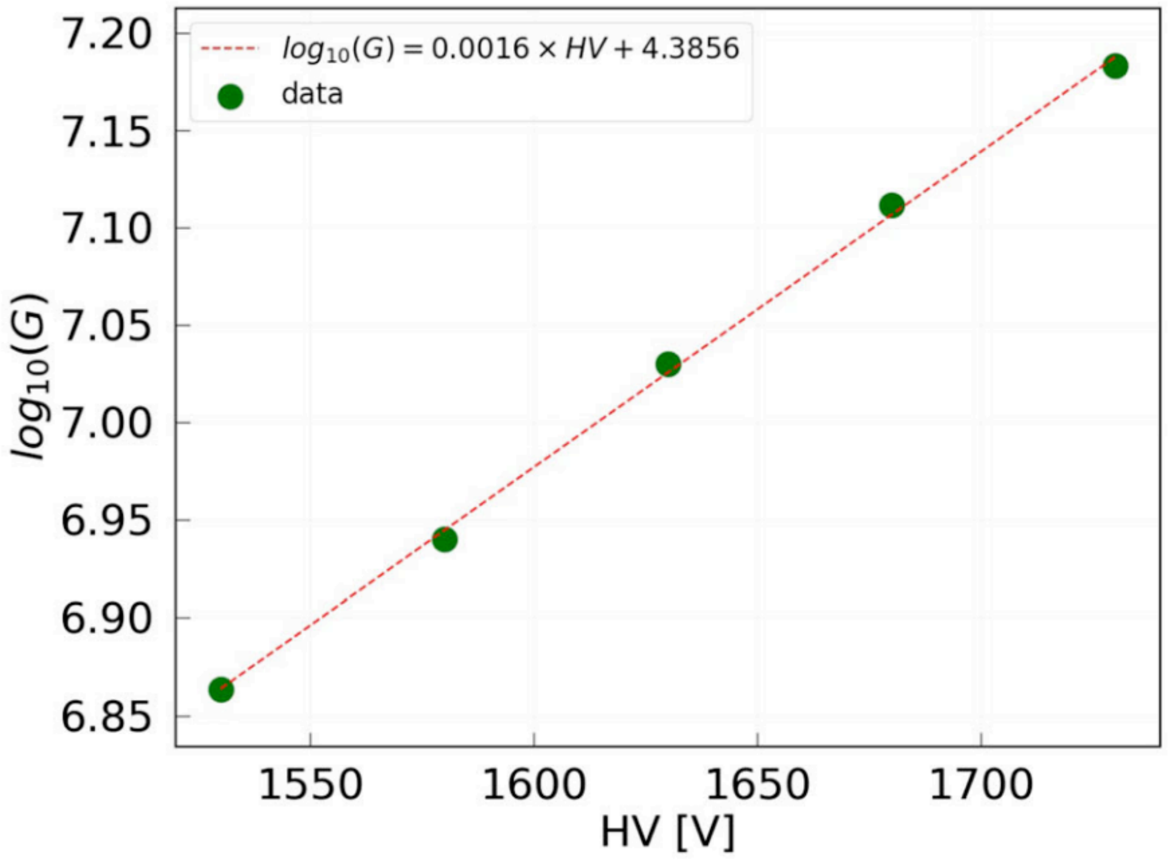
20” PMT gain and HV optimisation

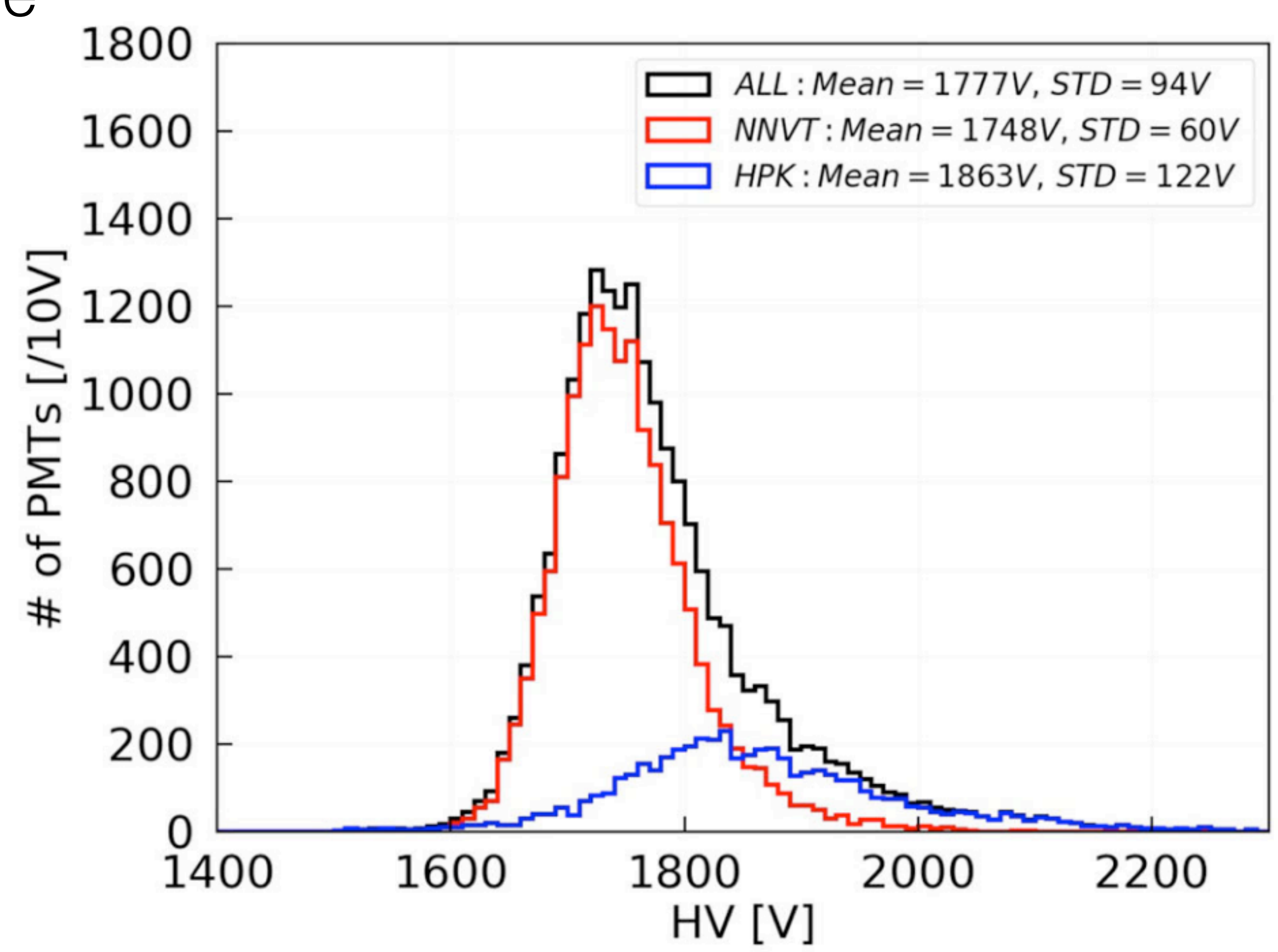
With a mean illumination μ = 0.1 pe

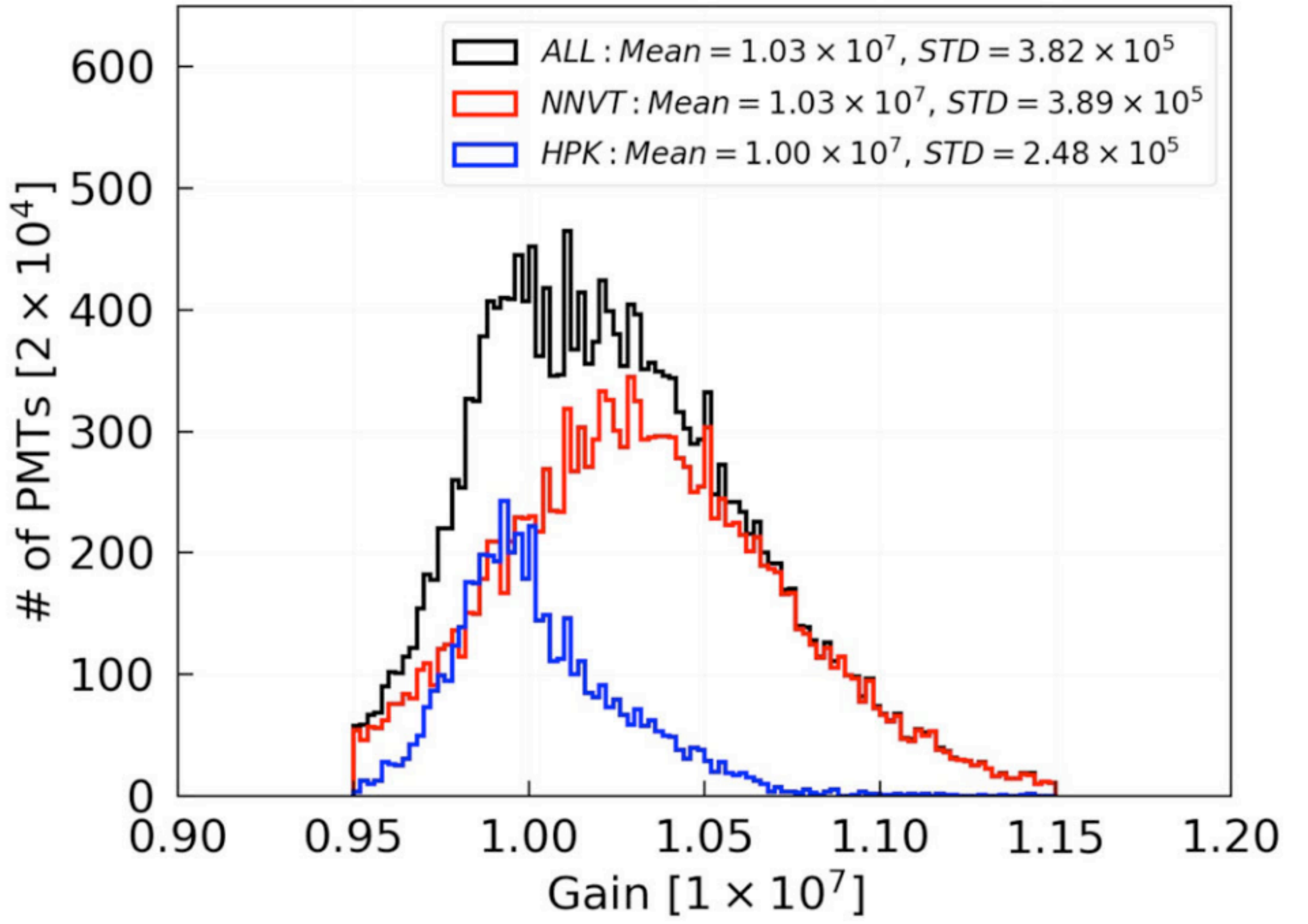
HV at which the gain G is 1 x 10^7

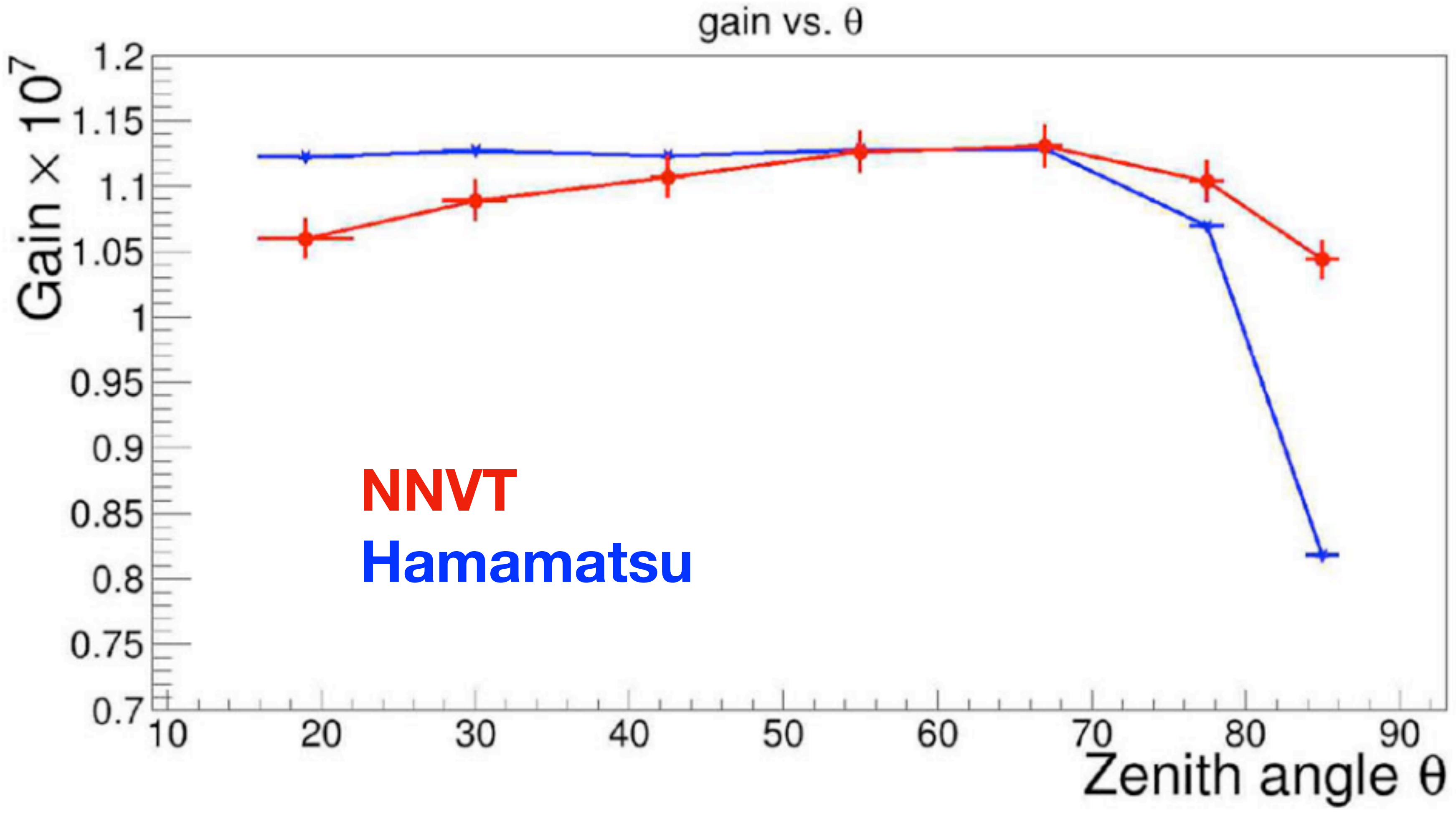
$$G = \frac{Q_{sig} - Q_{ped}}{e}$$

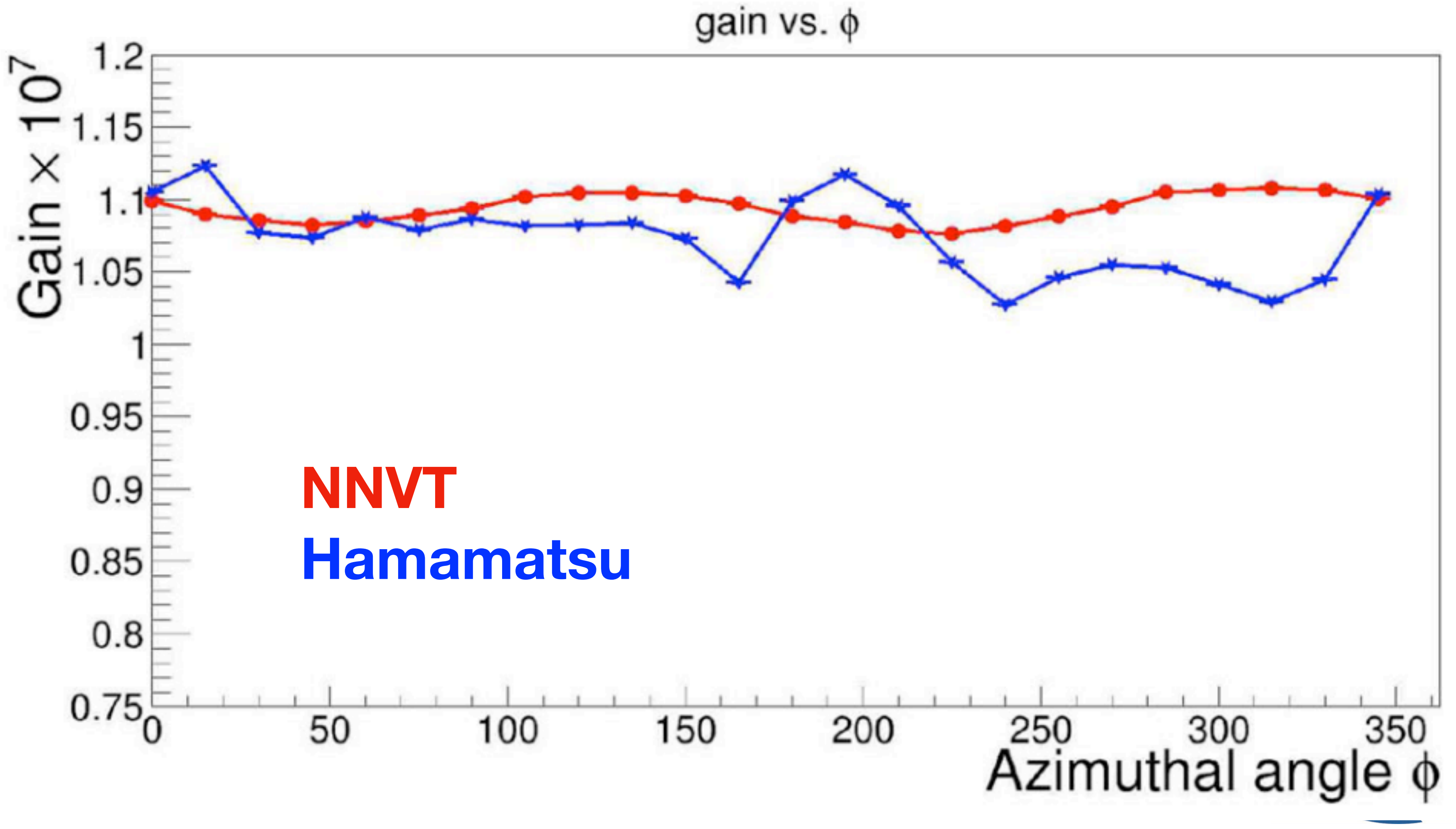












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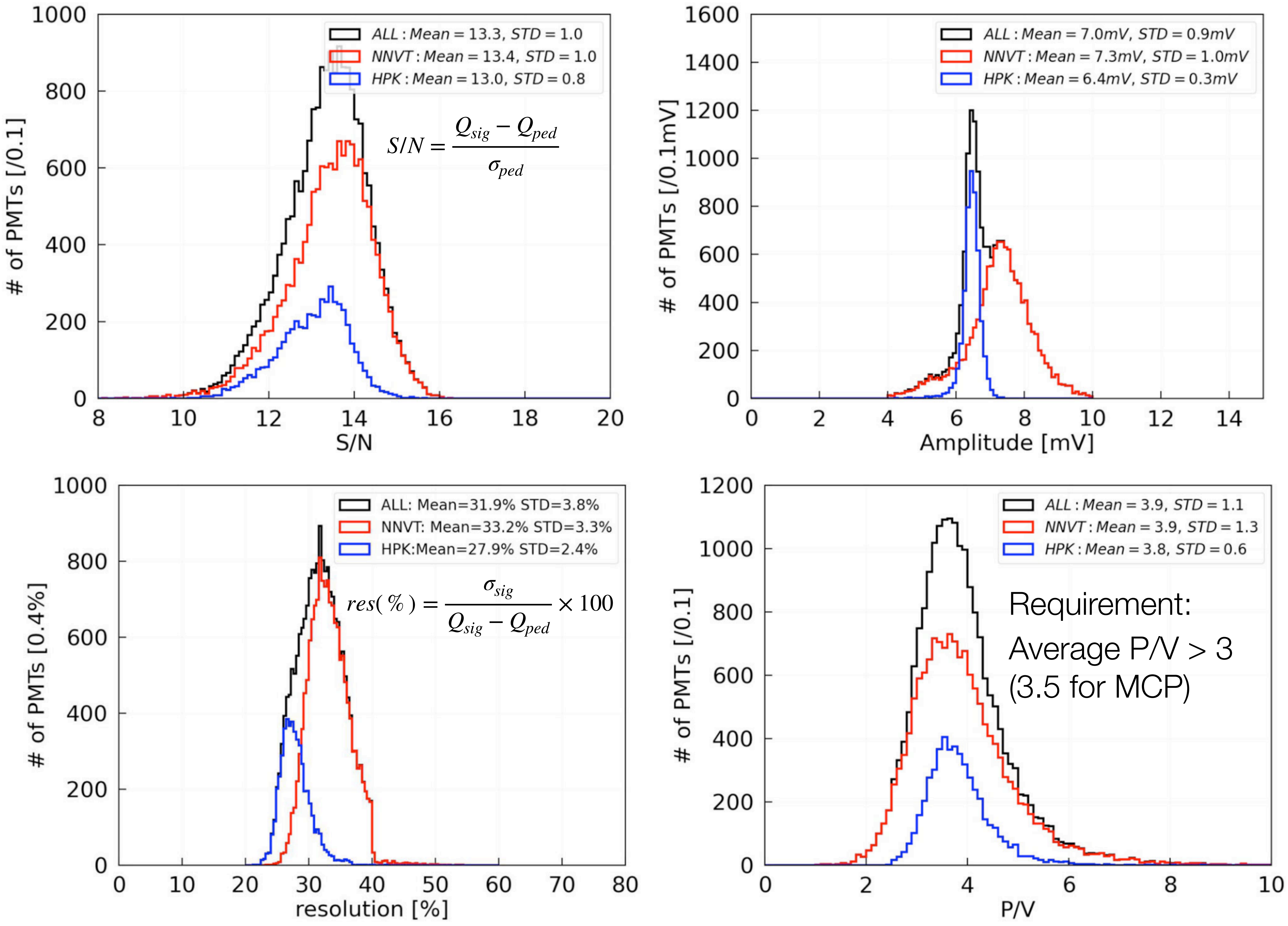
20” PMT single photoelectron features

At the operating voltage (G=10^7) **20k waveforms** per PMT have been acquired with a mean illumination of **μ = 0.1 p.e.** to extract the SPE characteristics



$$S/N = \frac{Q_{sig} - Q_{ped}}{\sigma_{ped}}$$

$$res(\%) = \frac{\sigma_{sig}}{Q_{sig} - Q_{ped}} \times 100$$

Requirement:
Average P/V > 3
(3.5 for MCP)

For MCP the SPE is not really Gaussian distributed due to long tail, but the resolution is anyway a good parameter to measure the relative spread of charge response.
res < 40% for central detector

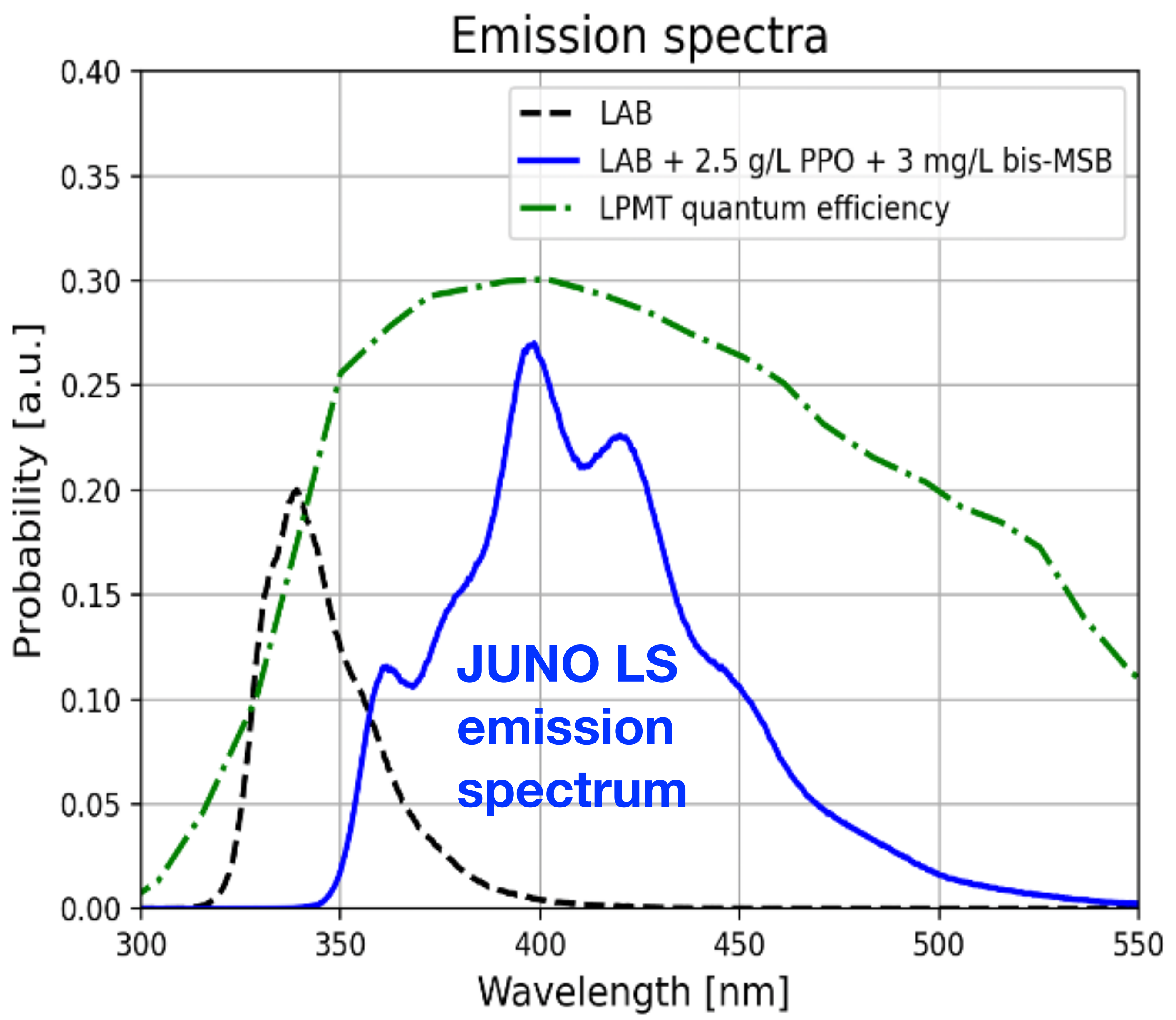
20” PMT testing & characterisation

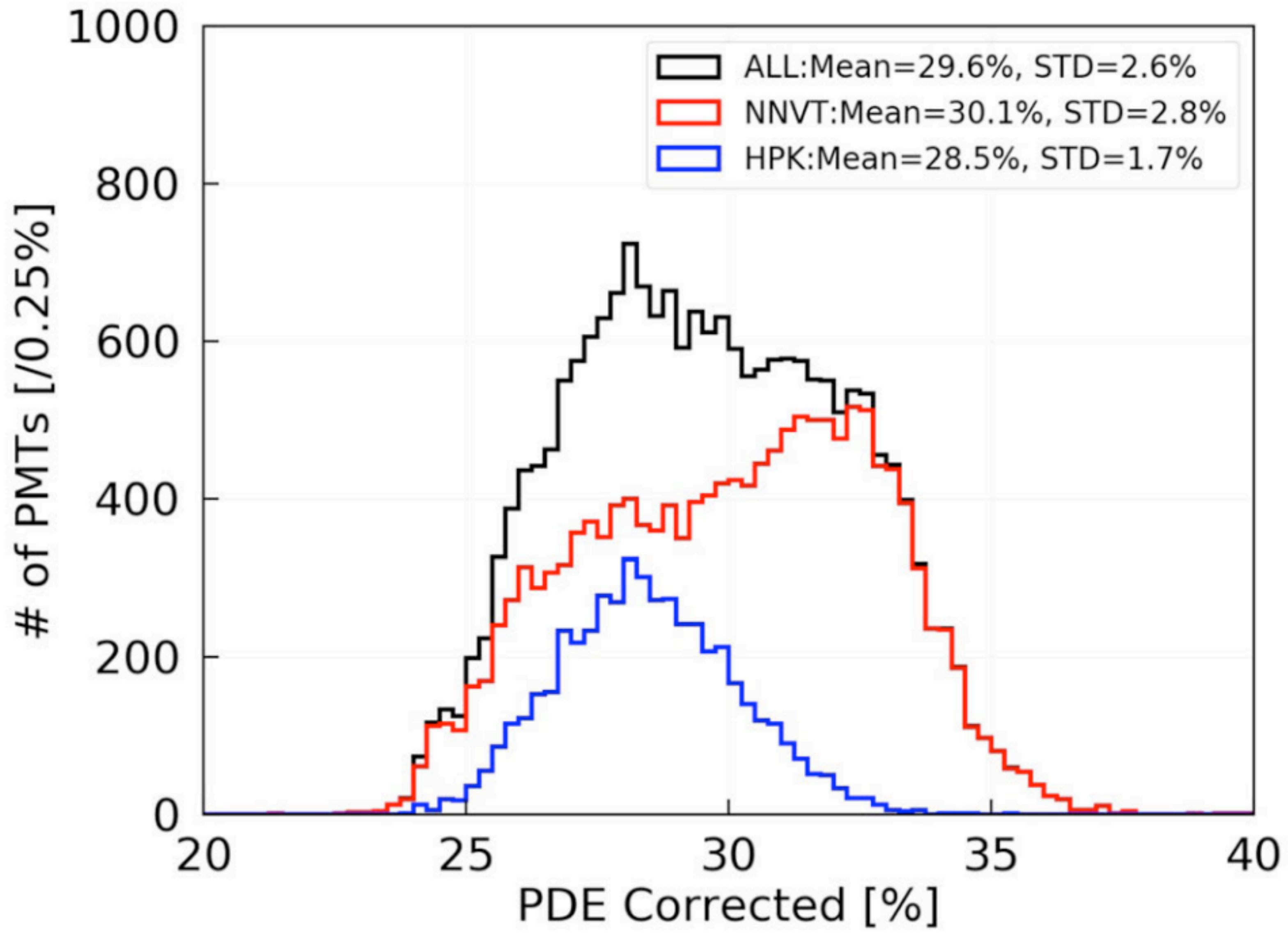
Eur. Phys. J. C (2022) 82:1168

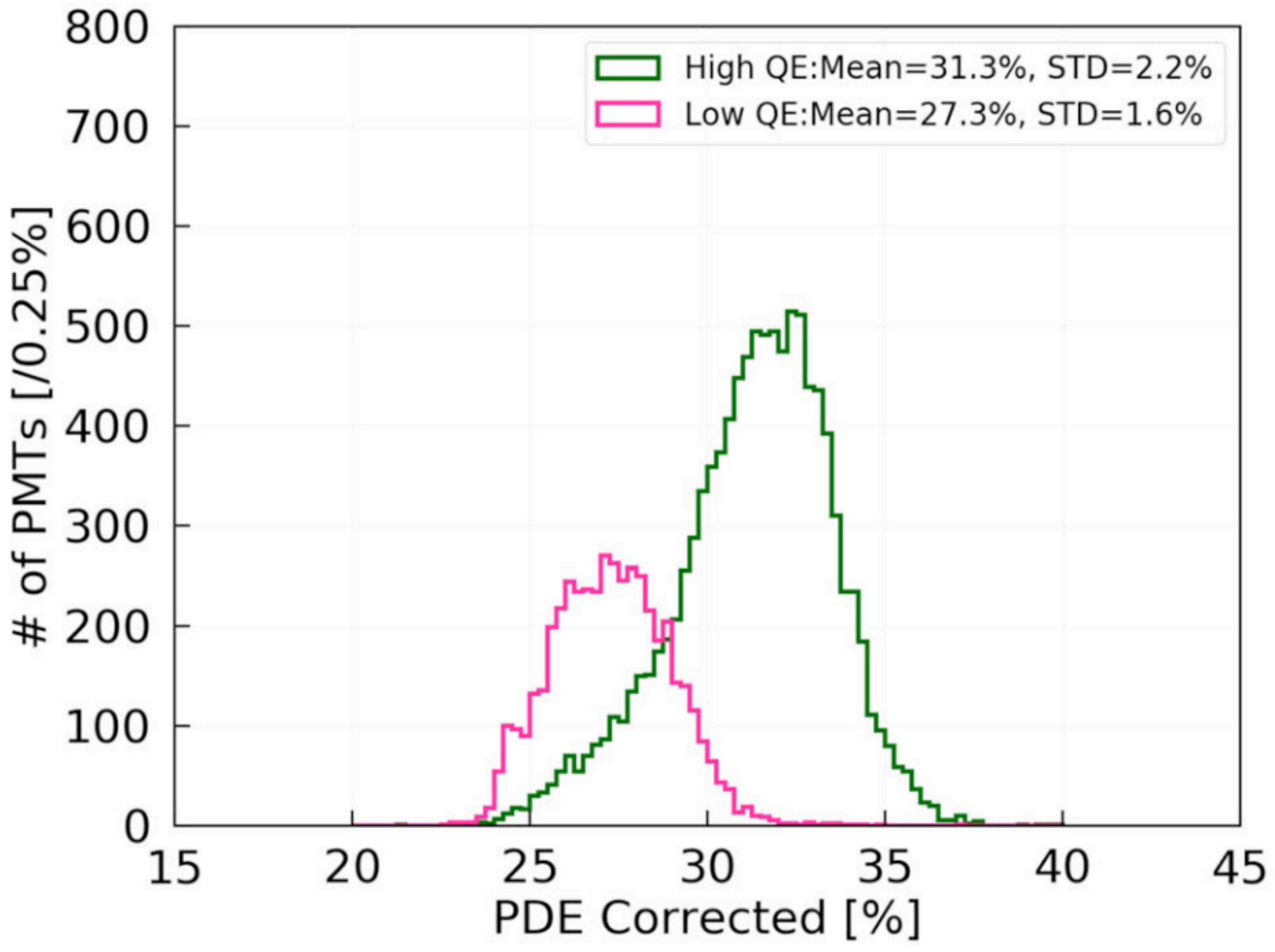
PMTs have been selected, among other parameters, on the Photon Detection efficiency @ 420 nm to be > 24 % (<PDE> > 27 %)

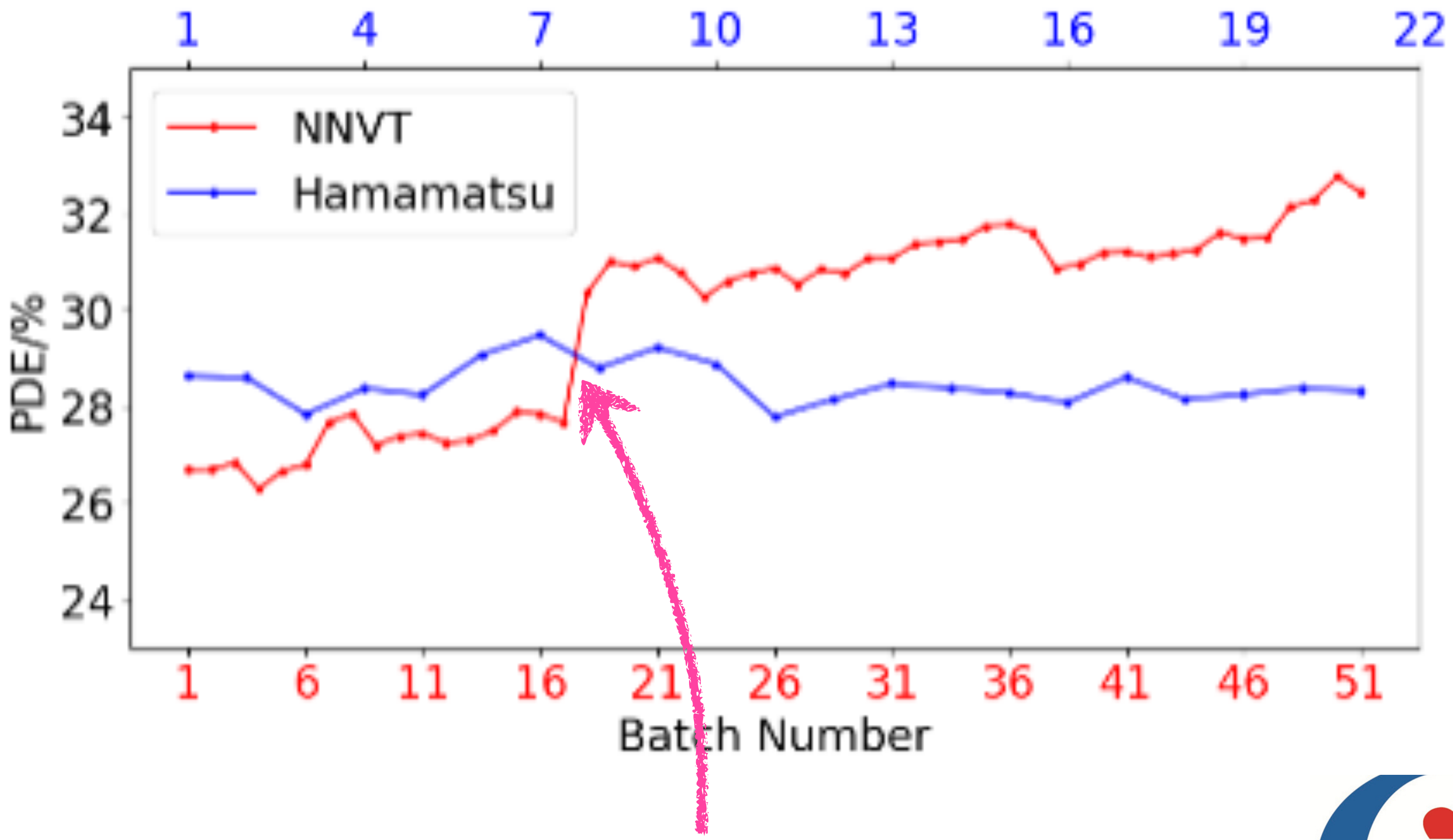
$$PDE(\lambda) = QE(\lambda) \times CE \times EAR$$

EAR = effective area ratio,
relative area where CE > 95.6%





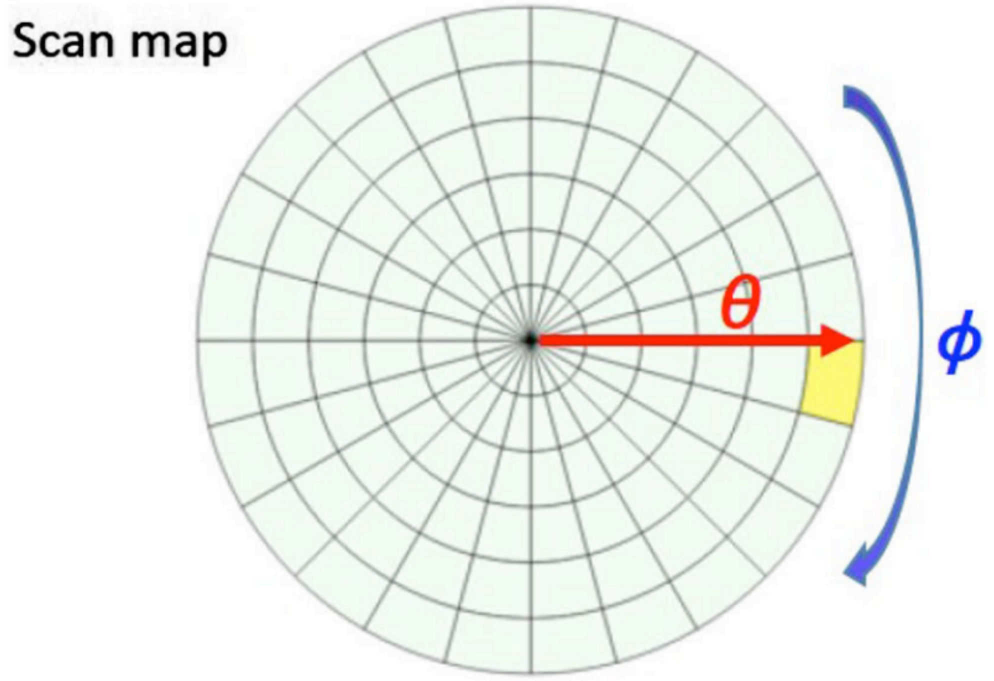




Improvements in PMT production

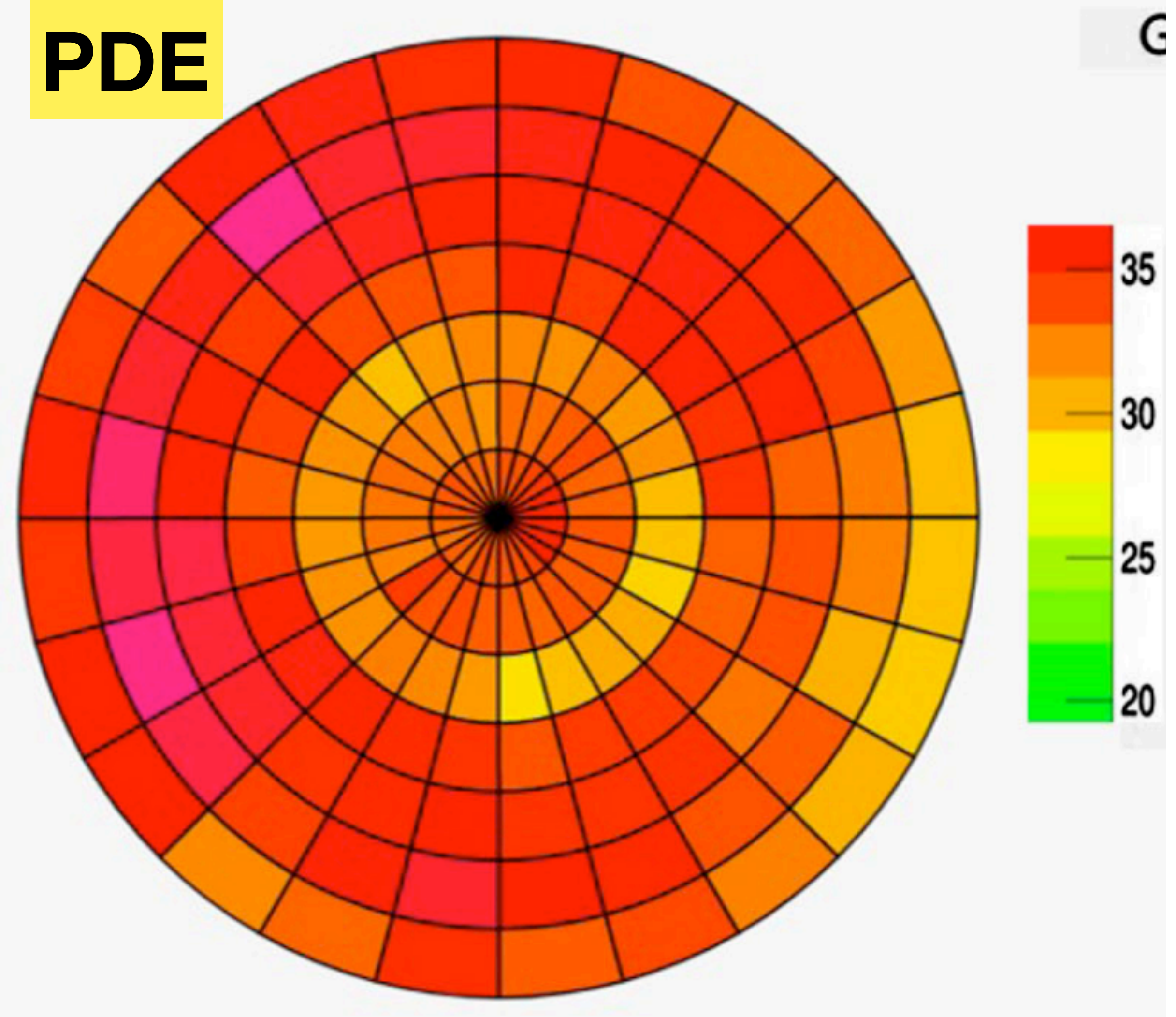
Mean PDE
- NNVT = **30.1%**
- Hamamatsu = **28.5 %**
- ALL = **29.6%**

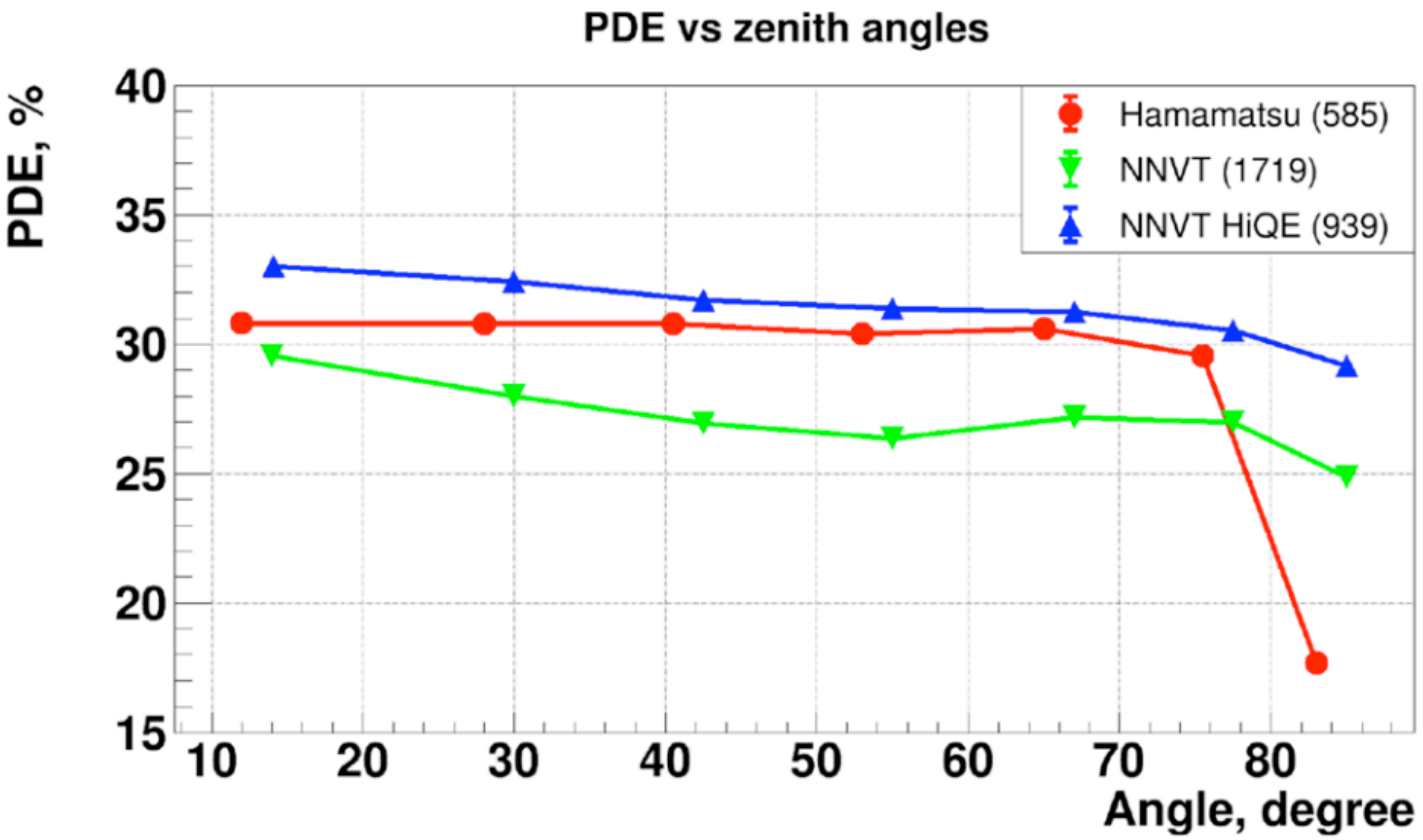
20” PMT testing & characterisation

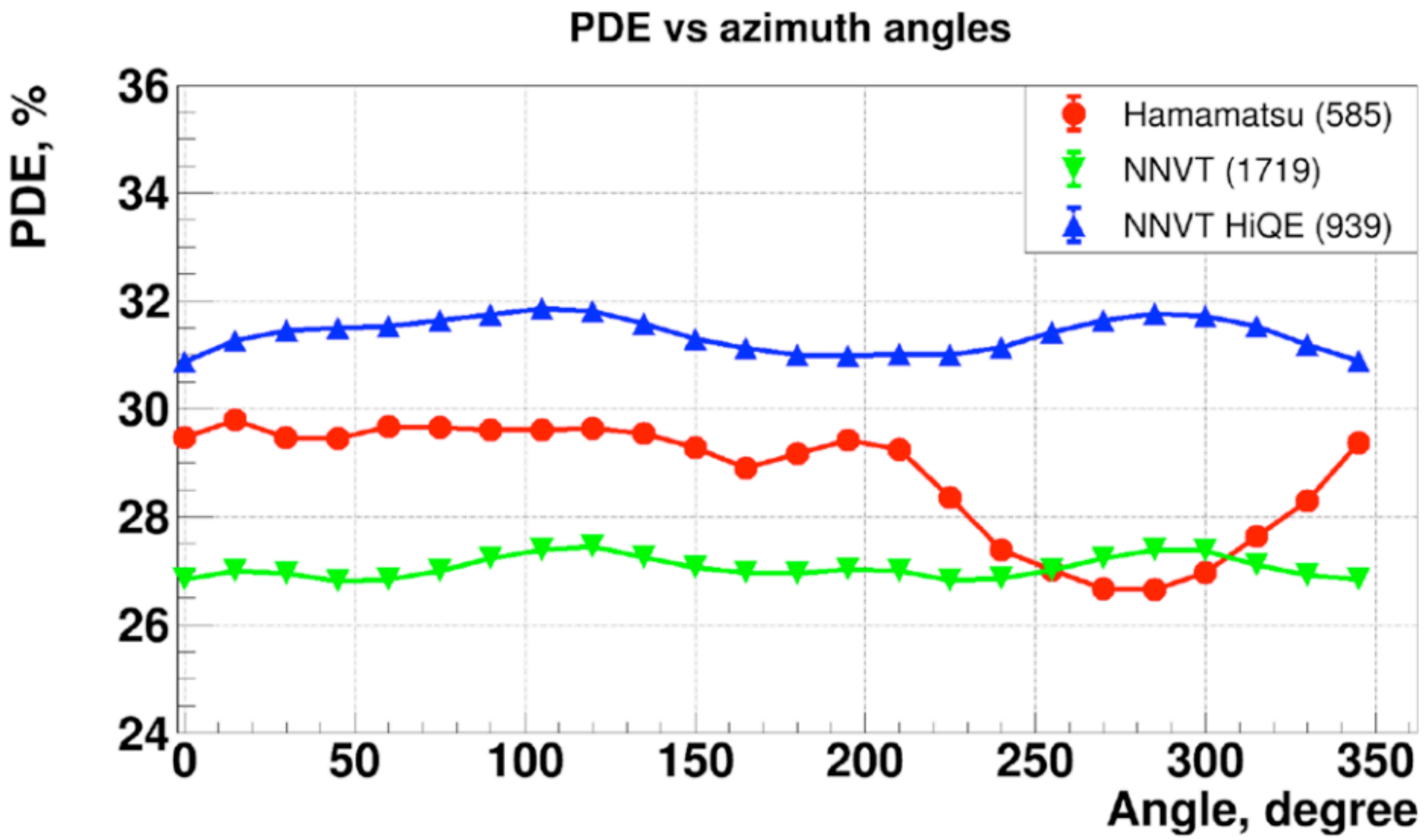


About 3000 20” PMTs have been scanned to measure the uniformity of their response.

Very uniform PDE both in zenith and azimuthal.







20” PMT Dark Count Rate

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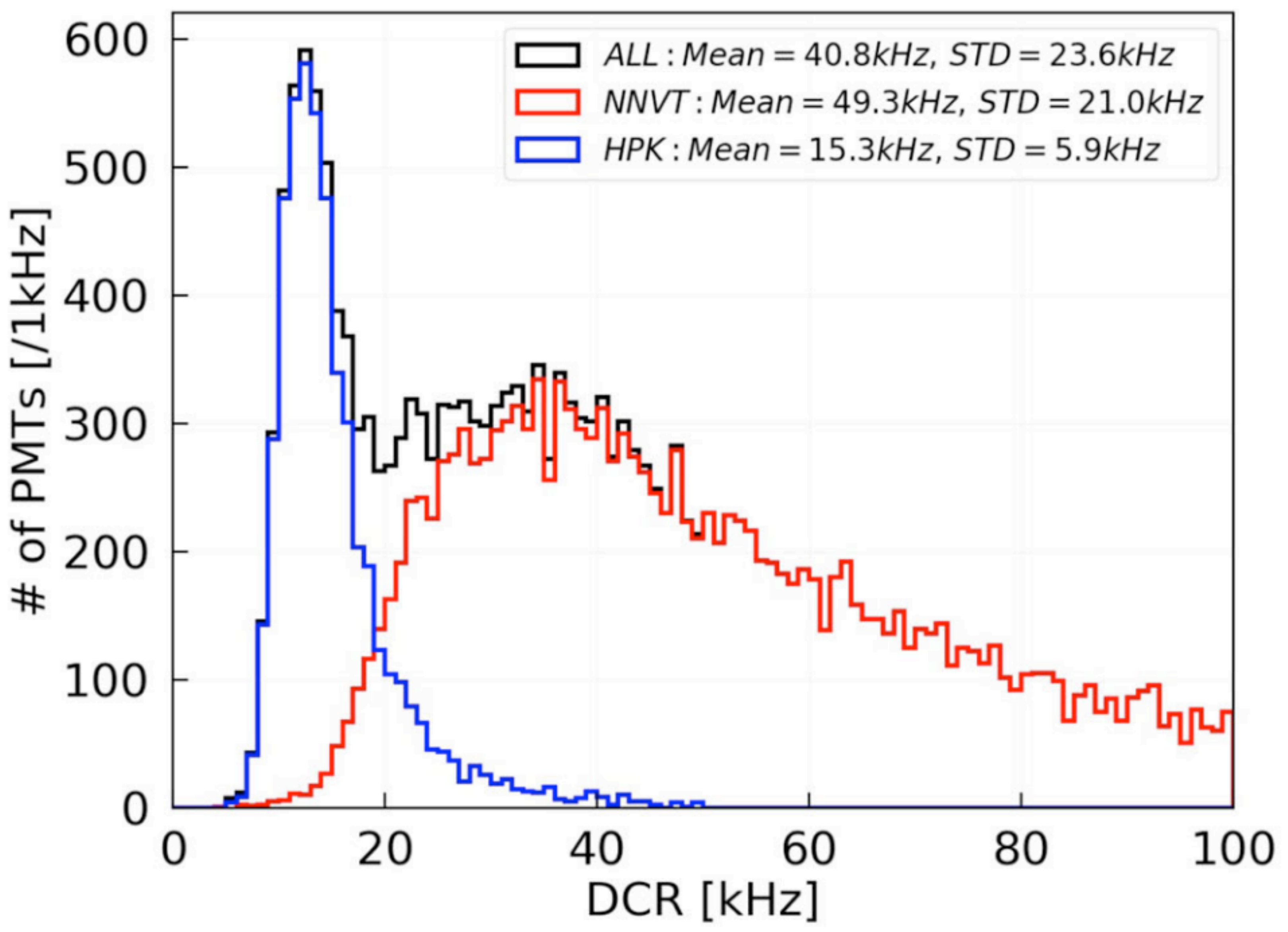
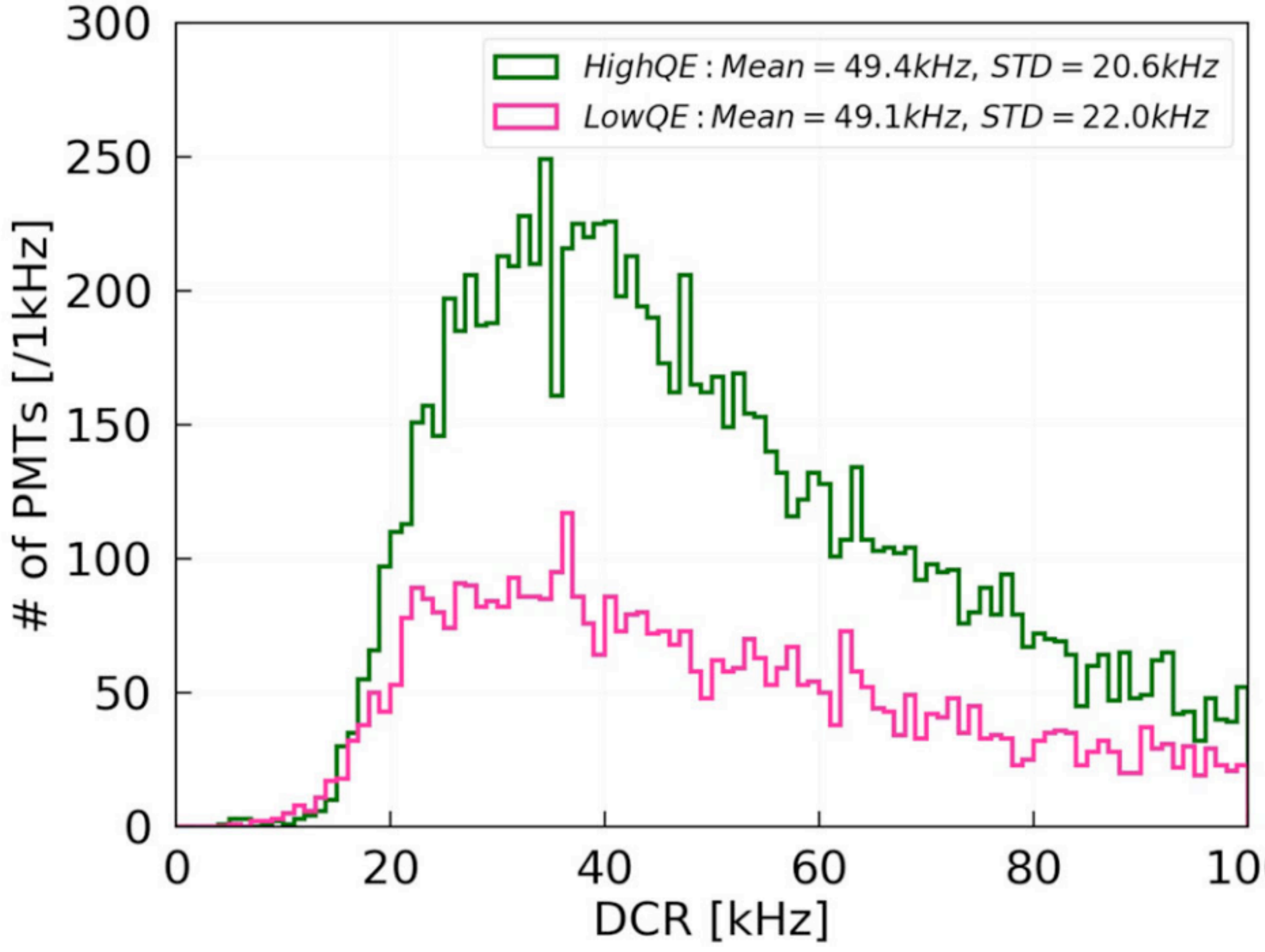
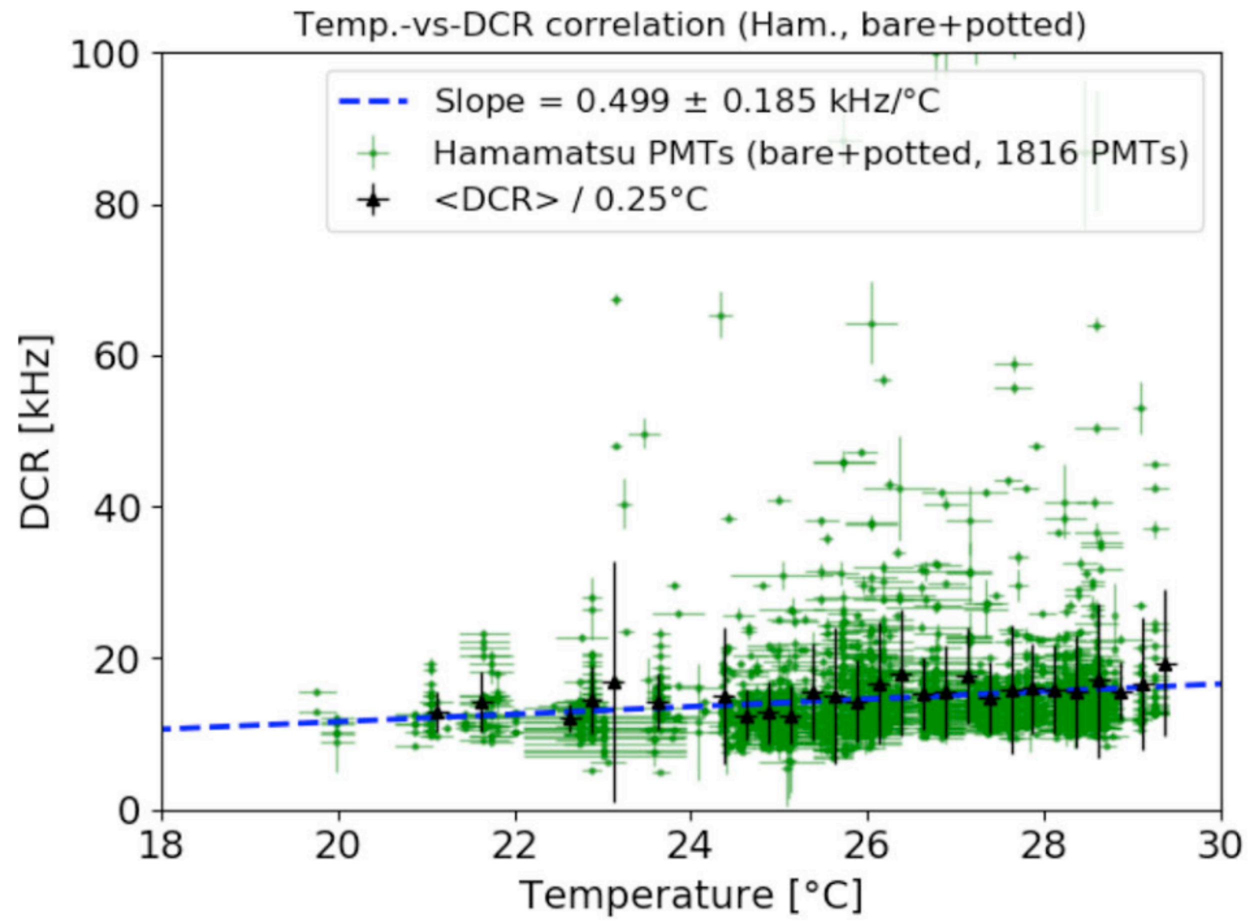
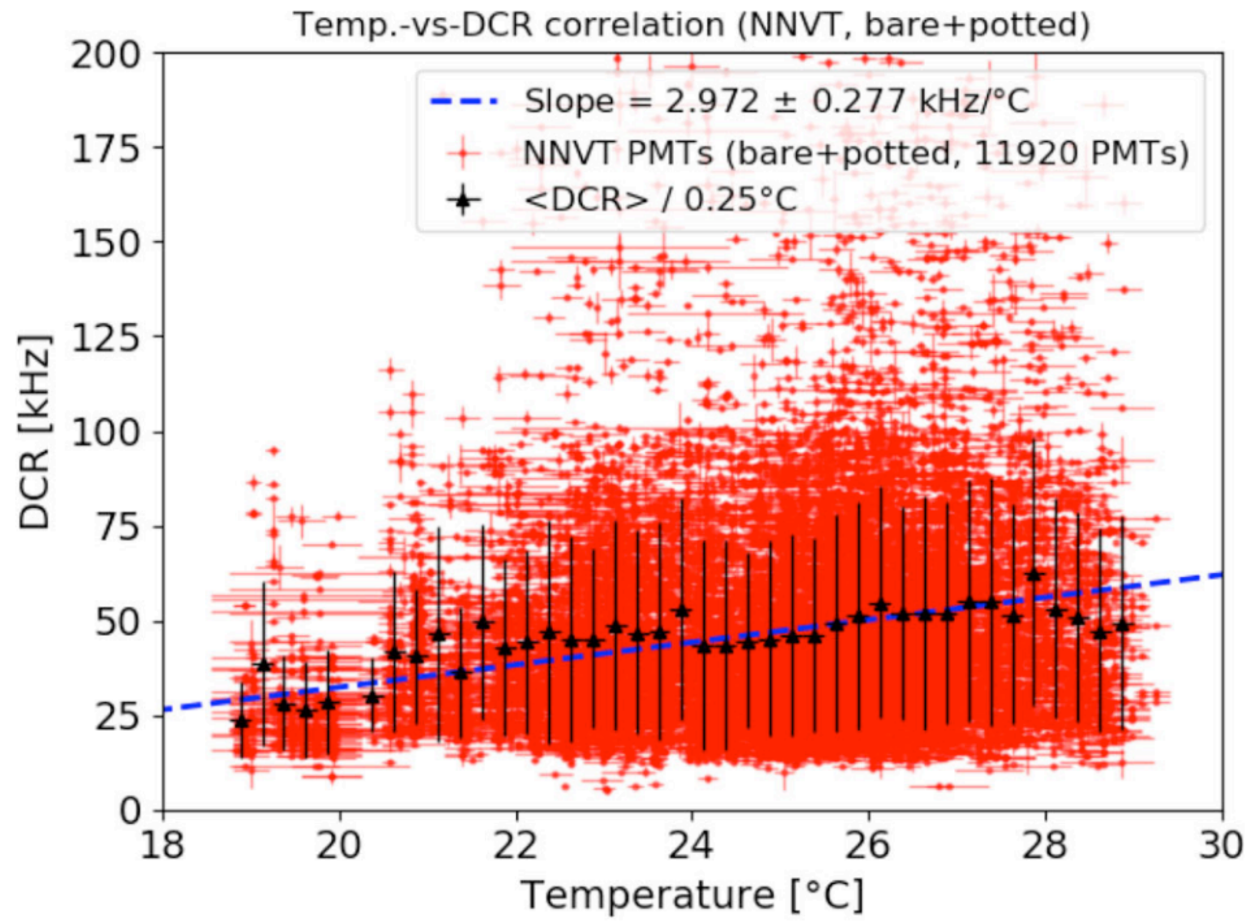
Selection criteria	DCR @ 0.25 pe cut, T = 22 °C
Dynode	**< 50 kHz**
MCP	
24% < PED < 27%	**< 50 kHz**
27% < PED < 28%	**< 60 kHz**
28% < PED < 29%	**< 80 kHz**
29% < PED	**< 100 kHz**

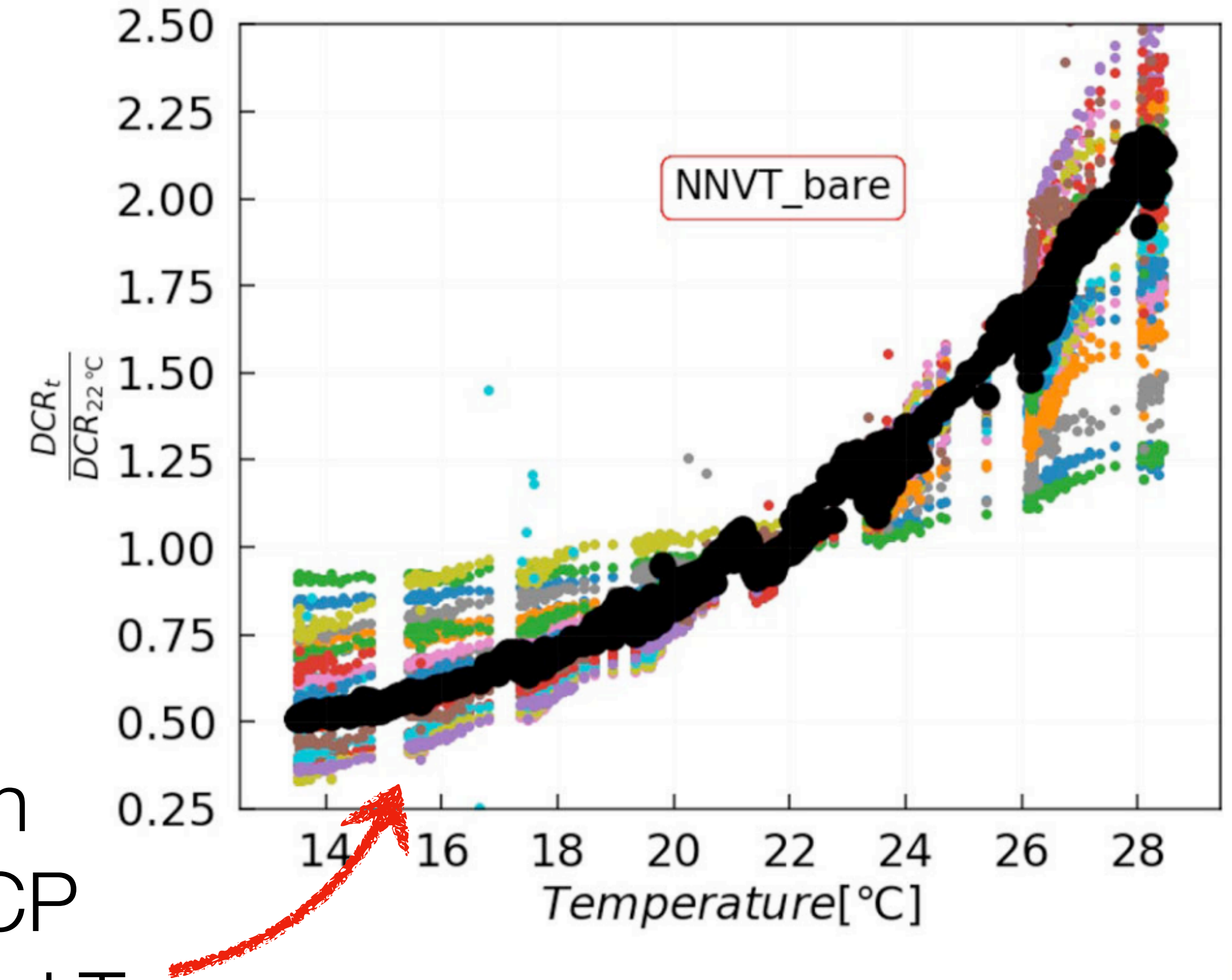








Expected JUNO temp: 21± 1 °C



Dedicated test on subsample of MCP PMTs @ controlled T

20” PMT Transit Time Spread

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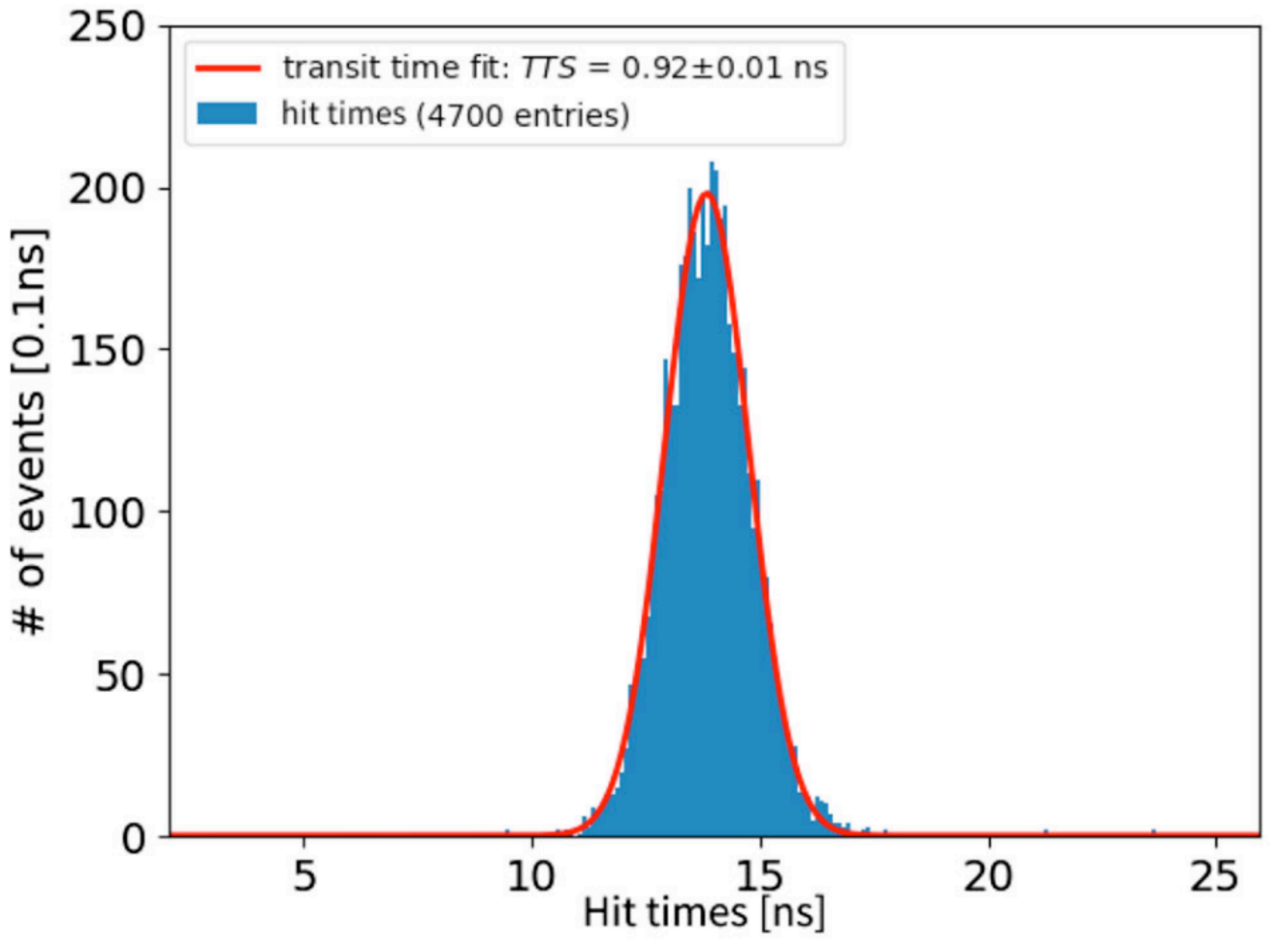
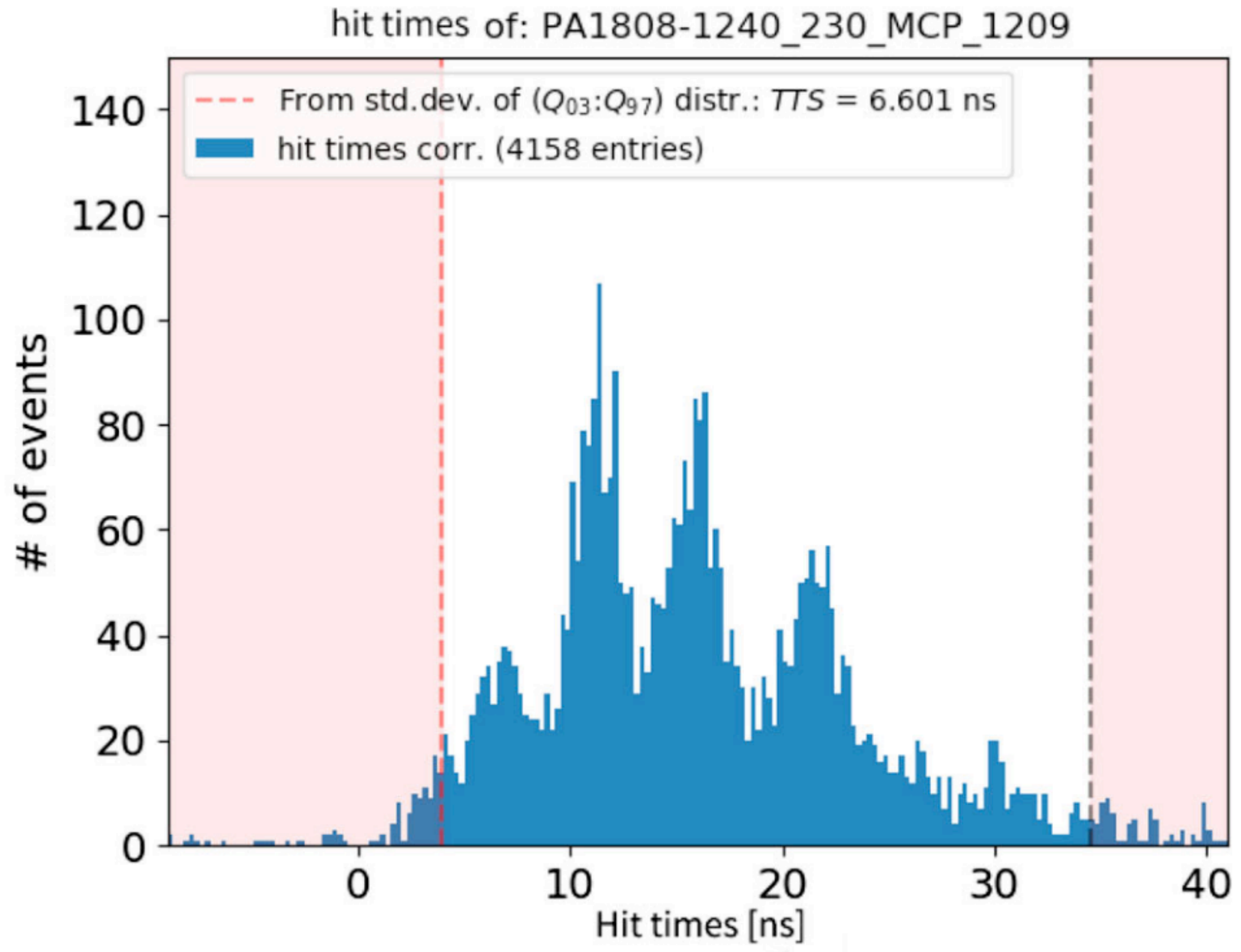
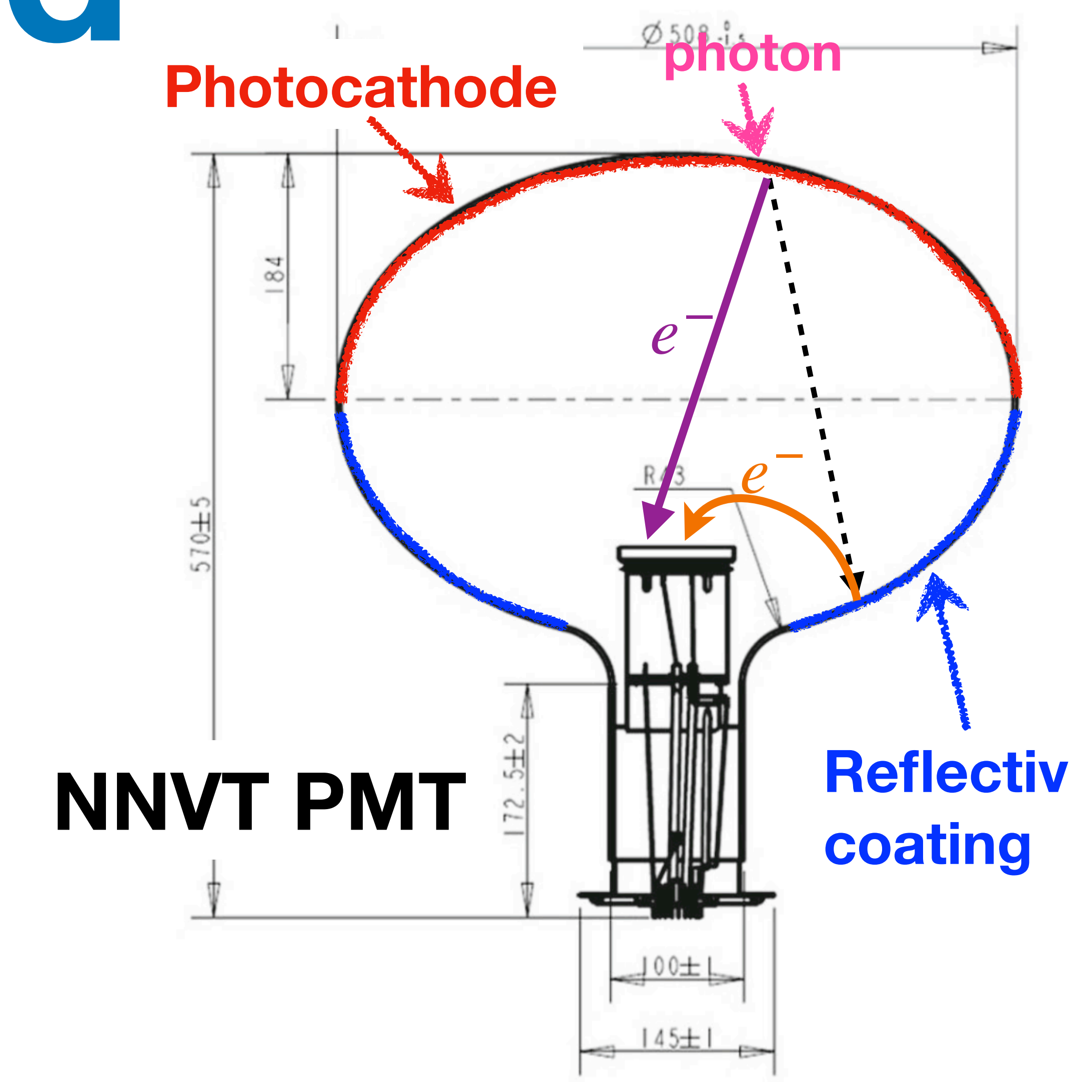
Pico-sec. laser fibre with 0.1-1 p.e. illumination

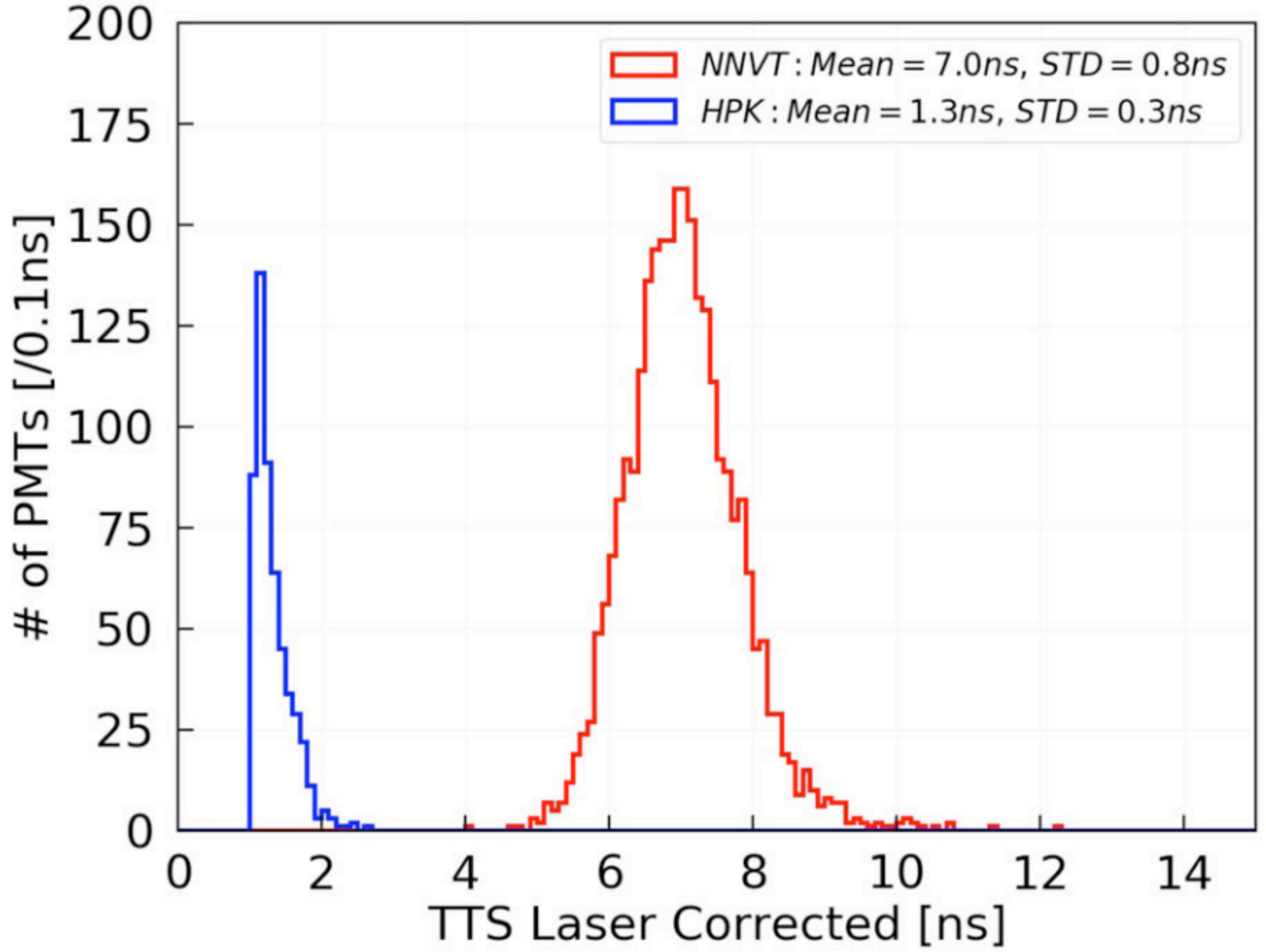




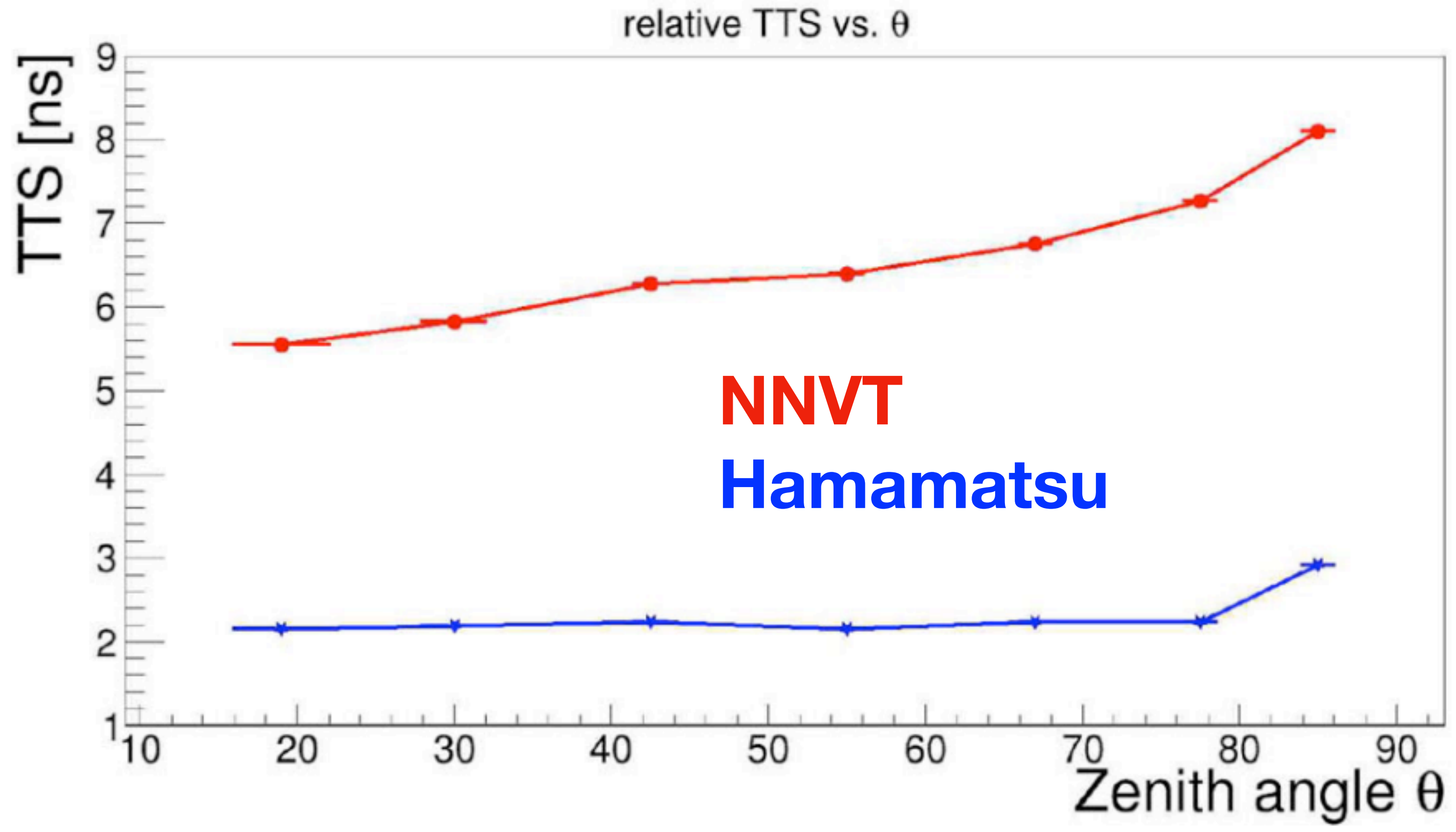
Std. between quantile Q_3 to Q_{97}

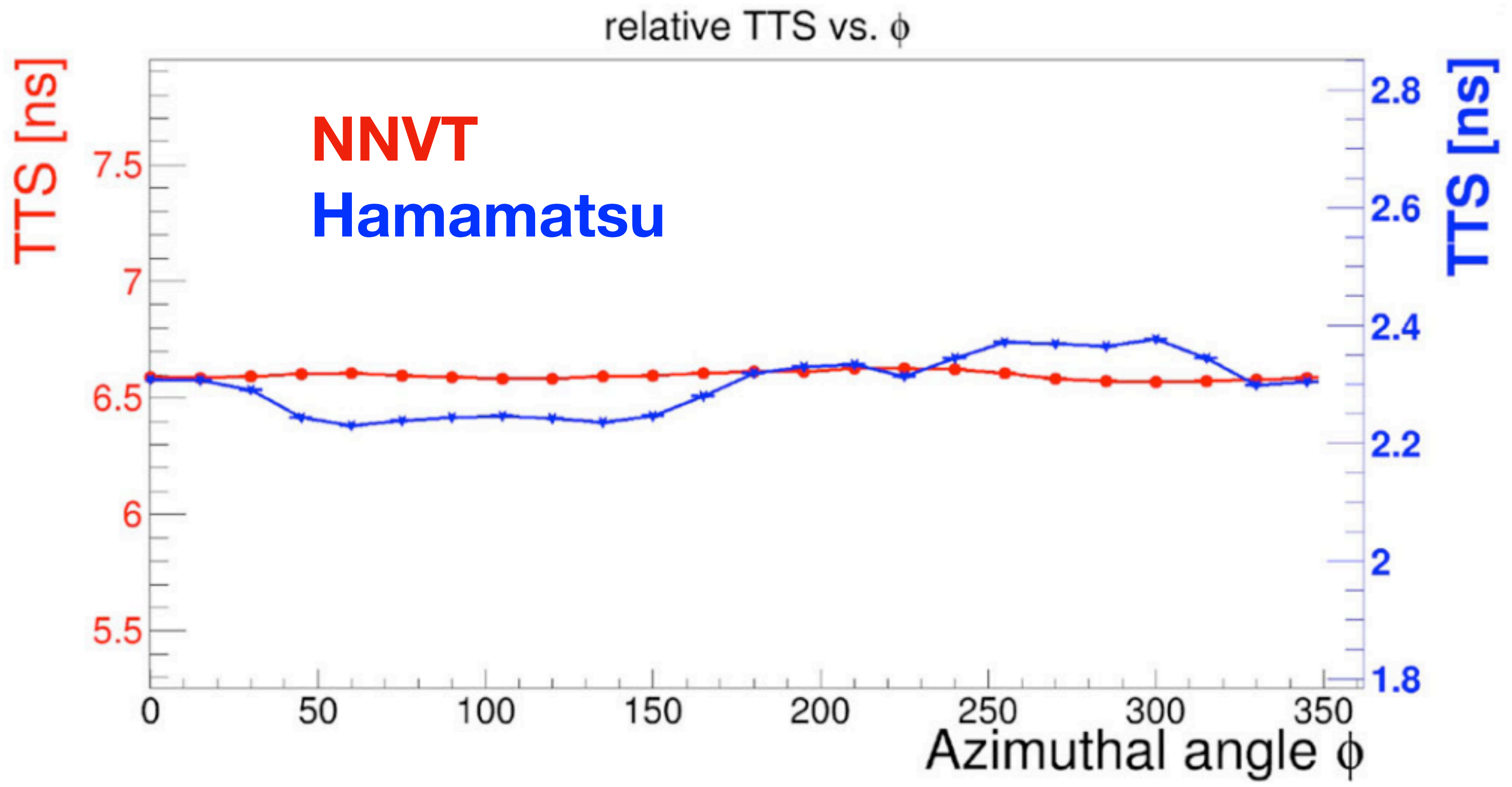
For NNVT PMTs the TTS depends on the path of the pe to the anode





Relative transit time using LEDs of the scanning station





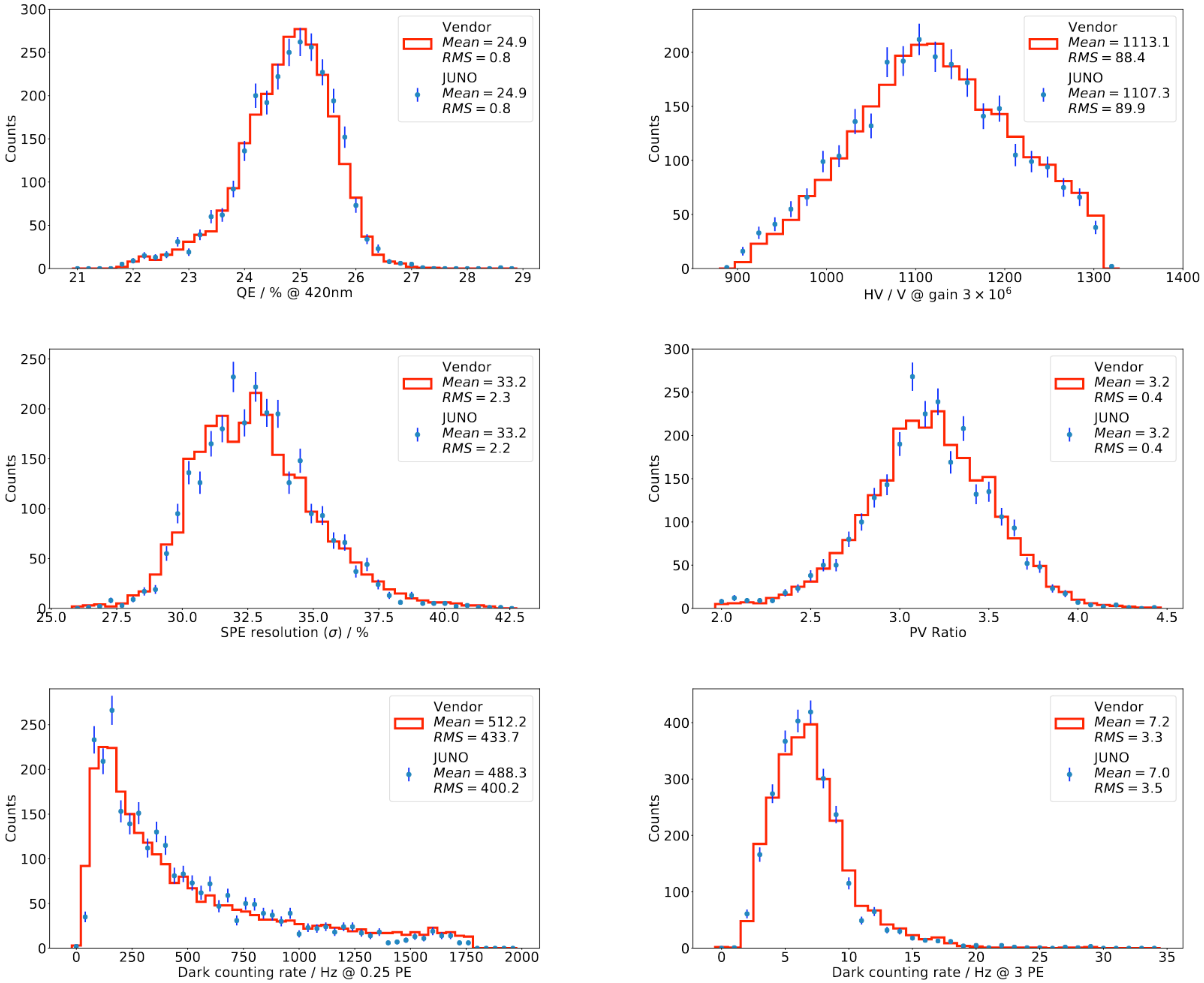
NIM-A (2021) 1005,165347

3” PMT production and test

- Assembly done by HZC.

- Acceptance test base on three class of parameters
  - (A) all PMTs by HZC, 10% by JUNO
  - (B) 3% of PMTs randomly selected by JUNO
  - (C) 1% of PMTs randomly selected by JUNO

Parameters	Class	Requirement		Test fraction		Tolerance	Results
		(limit)	(mean)	HZC	JUNO	of diff.	(mean)
Φ (glass bulb)	A	(78, 82) mm	-	100%	10%	-	OK
QE@420 nm	A	>22%	>24%	100%	10%	<5%	24.9%
High Voltage	A	(900,1300) V	-	100%	10%	<3%	1113 V
SPE resolution	A	<45%	<35%	100%	10%	<15%	33.2%
PV ratio	A	>2	>3	100%	10%	-	3.2
DCR@0.25 PE	A	<1.8 kHz	<1.0 kHz	100%	10%	-	512 Hz
DCR@3.0 PE	A	<30 Hz	-	100%	10%	-	7.2 Hz
TTS (σ)	B	<2.1 ns	-	-	3%	-	1.6 ns
Pre-pulse	B	<5%	<4.5%	-	3%	-	0.5%
After-pulse	B	<15%	<10%	-	3%	-	3.9%
QE non-uniformity	B	<11%	-	-	3%	-	5%
Φ (eff. cathode)	B	>74 mm	-	-	3%	-	77.2 mm
QE@320 nm	C	>5%	-	-	1%	-	10.2%
QE@550 nm	C	>5%	-	-	1%	-	8.6%
Aging	D	>200 nA·years	-	-	3 PMTs	-	OK



JUNO Expected performance

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.614\,\%}{\sqrt{E_{vis}}}\right)^2 + \left(0.64\,\%\right)^2 + \left(\frac{1.205\,\%}{E_{vis}}\right)^2}$$

Photon statistics

Quenching, non uniformity

Annihilation-induced γs
Dark noise

The expected **JUNO energy resolution** is **2.95% @ 1MeV** from a full simulation which include PMTs, LS and acrylic properties, calibration and reconstruction.

Main changes vs design *[JHEP03 (2021) 004]*

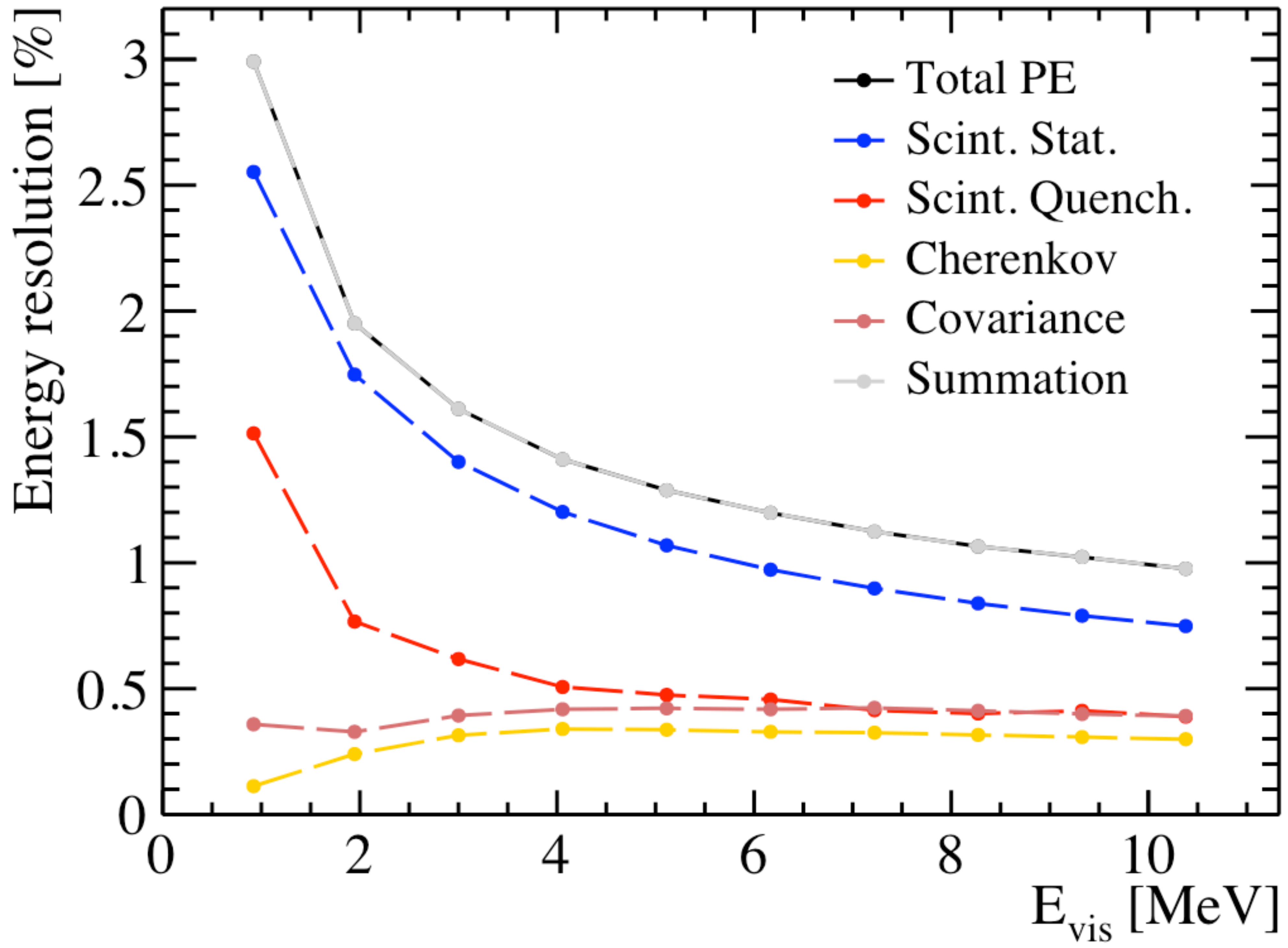
✓ Photon detection efficiency: 27% —> 30% *[EPJC (2022) 82, 1168]*

✓ New PMT optical model: +8% *[EPJC (2022) 82, 329]*

✓ New central detector geometry and LS: +3%

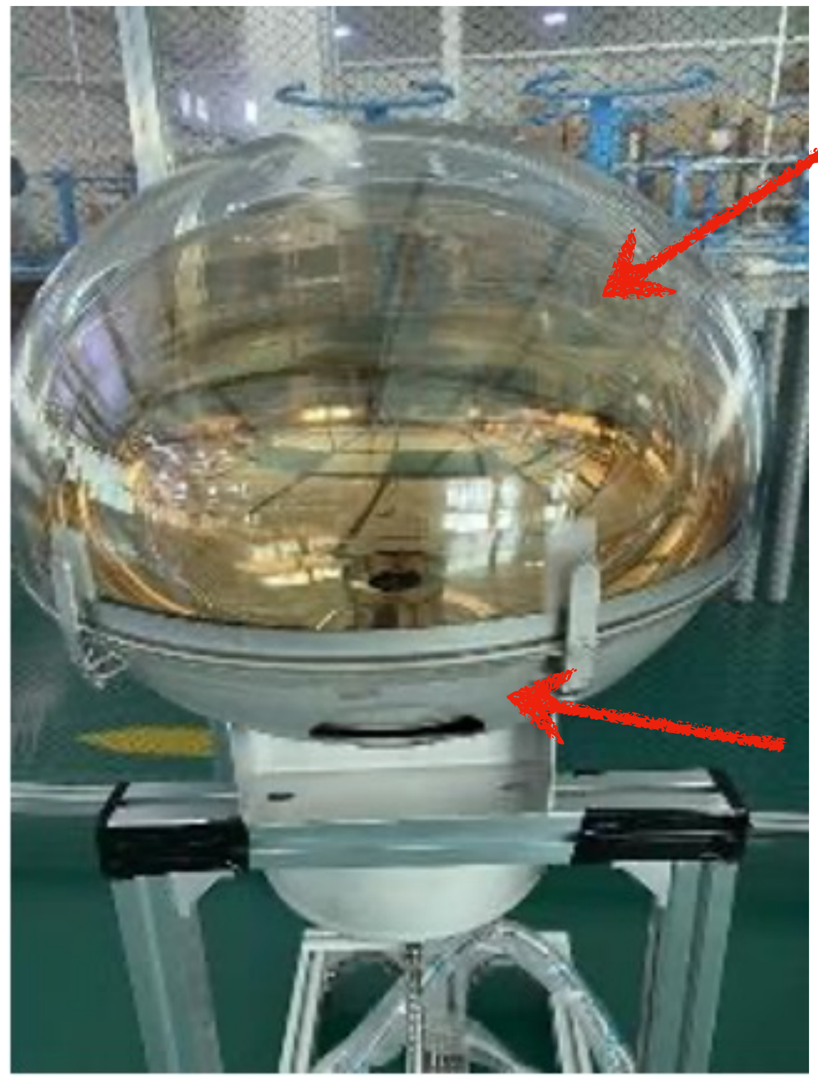
Total photon statistics **~ 1660 PE/MeV**

arXiv:2405.17860, accepted by Chin. Phys. C



PMT Installation

Implosion protection system
(JINST 18 (2023), P02013)



Acrylic cover

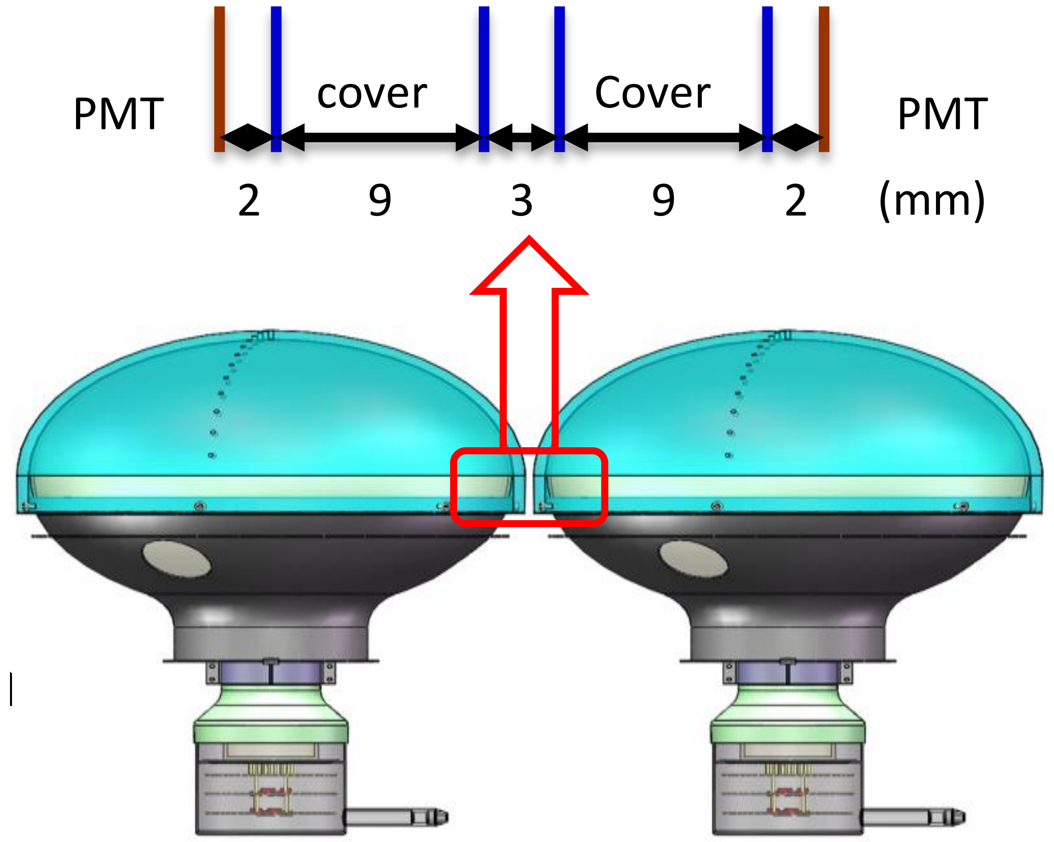
Stainless steel cover

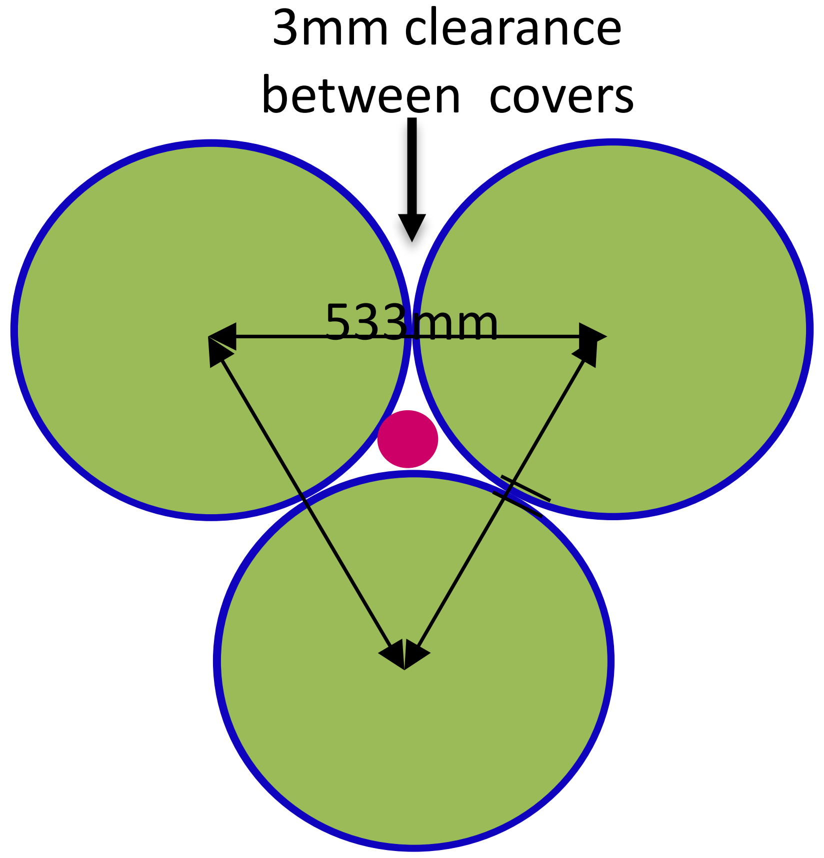
Final test: **no chain reaction**

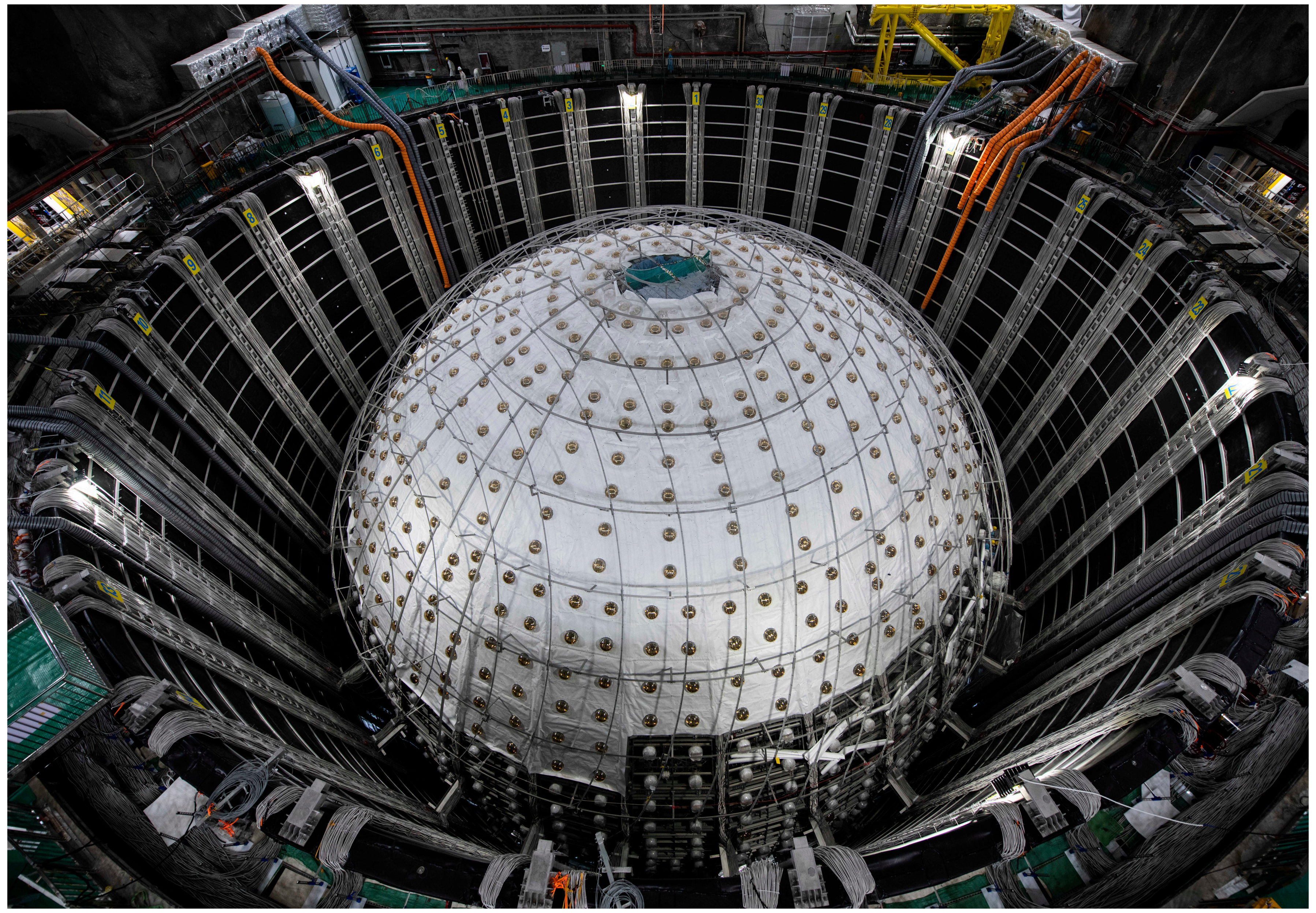
Cover minimum thickness 9 mm

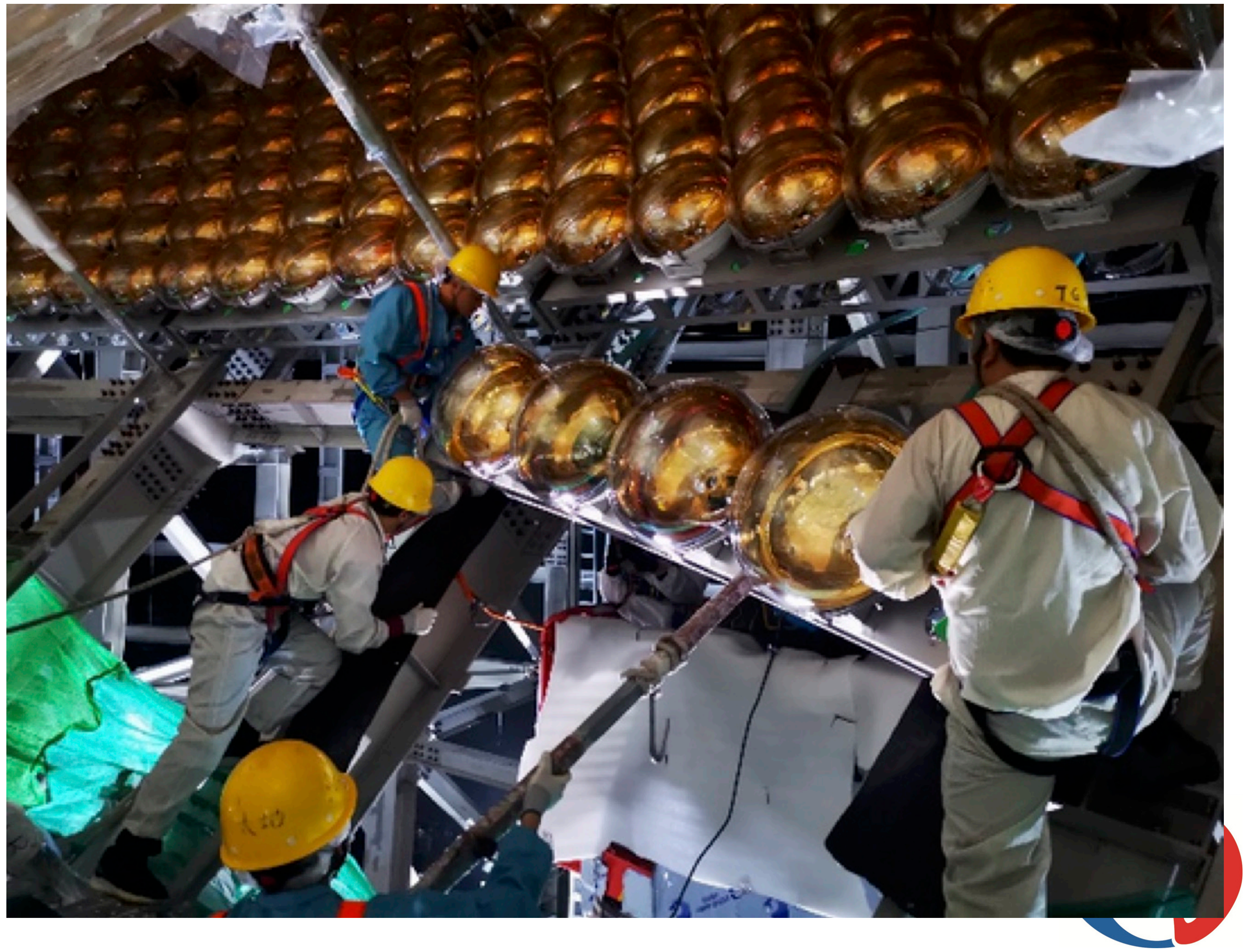
Gap between cover and PMT 2 mm

Distance between PMT cover 3 mm







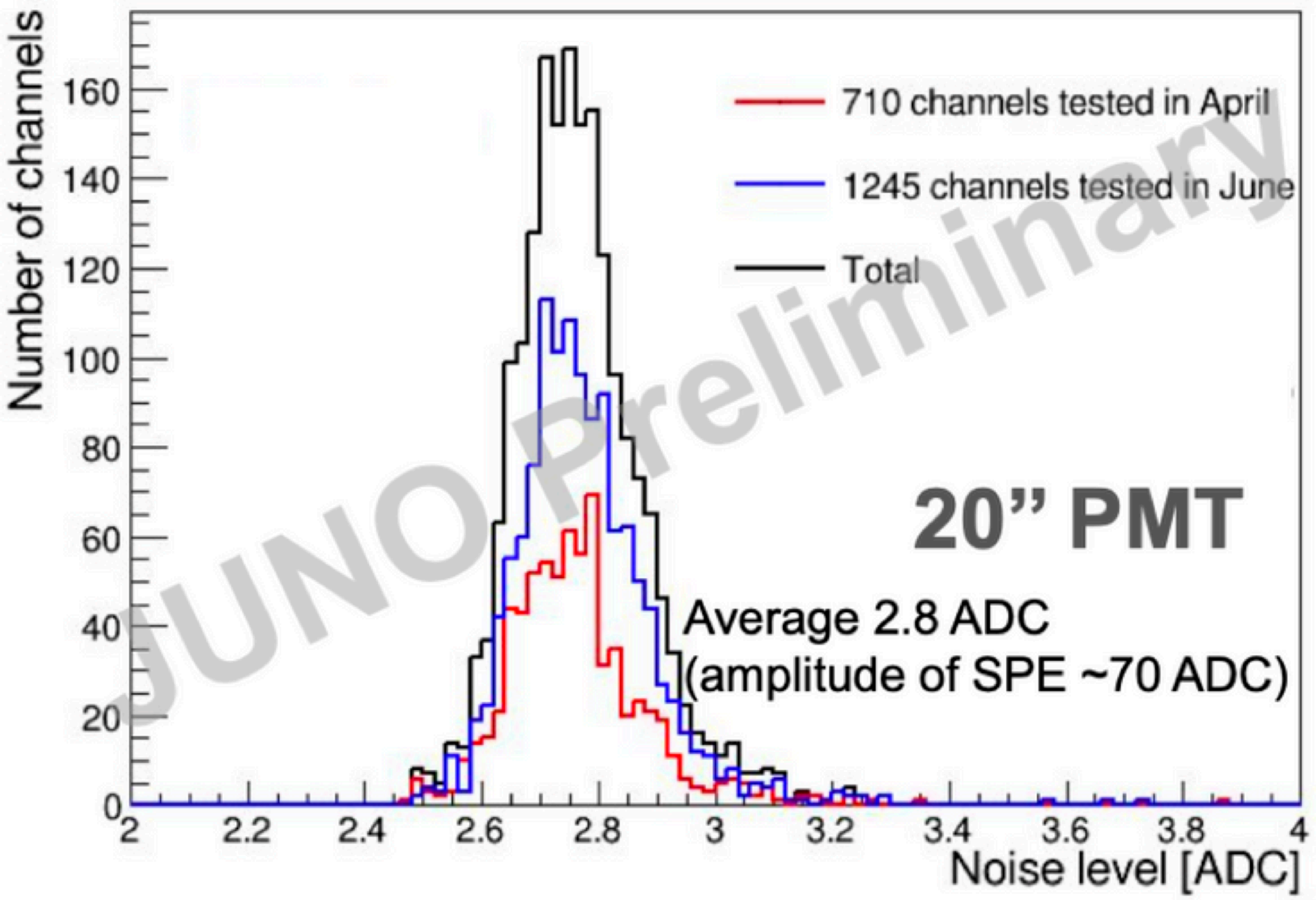


Installation status:

Almost completed: **> 99.5% of PMTs and UWB installed**

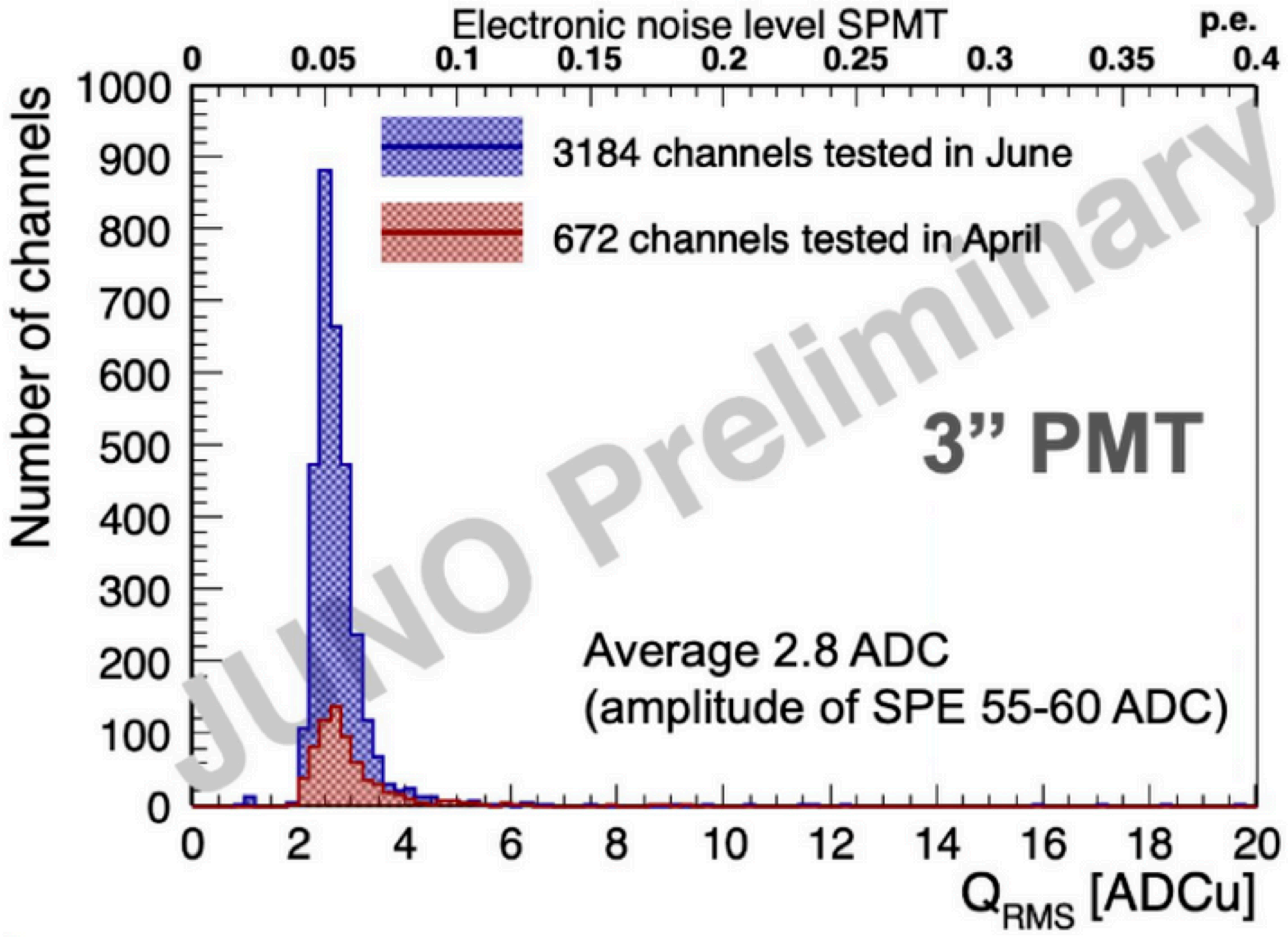
PMT system commissioning

- Regular light-off test during detector assembly:
  - ✓Light off tests: full data taking and processing chain with PMT HV on
  - ✓Light on tests: joint elec./trigger/DAQ/DCS test with PMT HV off
- Very good electronics, shielding and grounding
- Performances of tested PMTs are good



20" PMT

Average 2.8 ADC
(amplitude of SPE ~70 ADC)



3" PMT

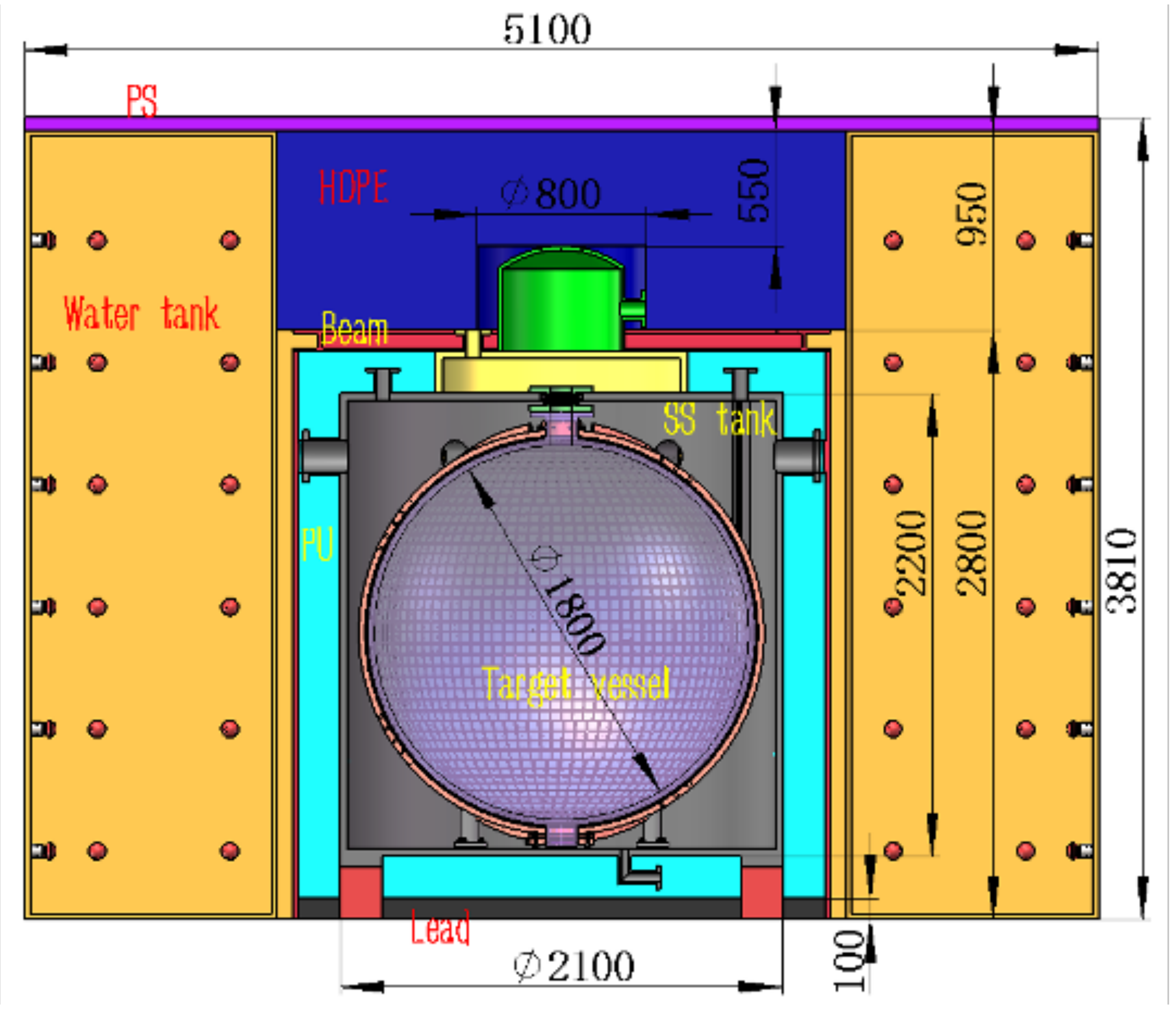
Average 2.8 ADC
(amplitude of SPE 55-60 ADC)

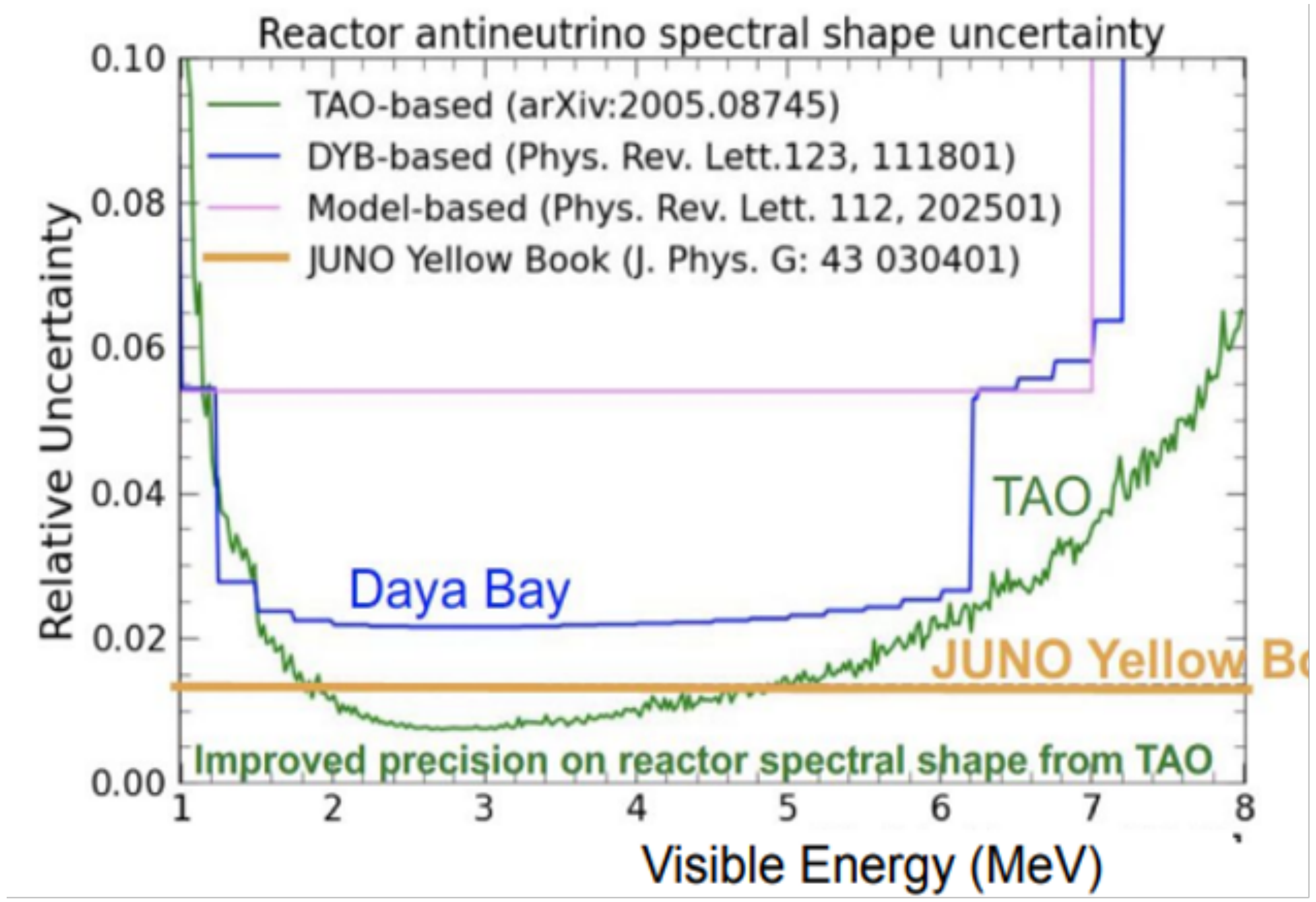
✓Electronic noise is 2.8 ADC counts, 4% of SPE
✓Much better than design of 10% of SPE

✓Electronic noise is 2.8 ADC counts, 5% of SPE
✓Much lower than trigger threshold of 1/3 pe

JUNO-TAO Taishan Antineutrino Observatory

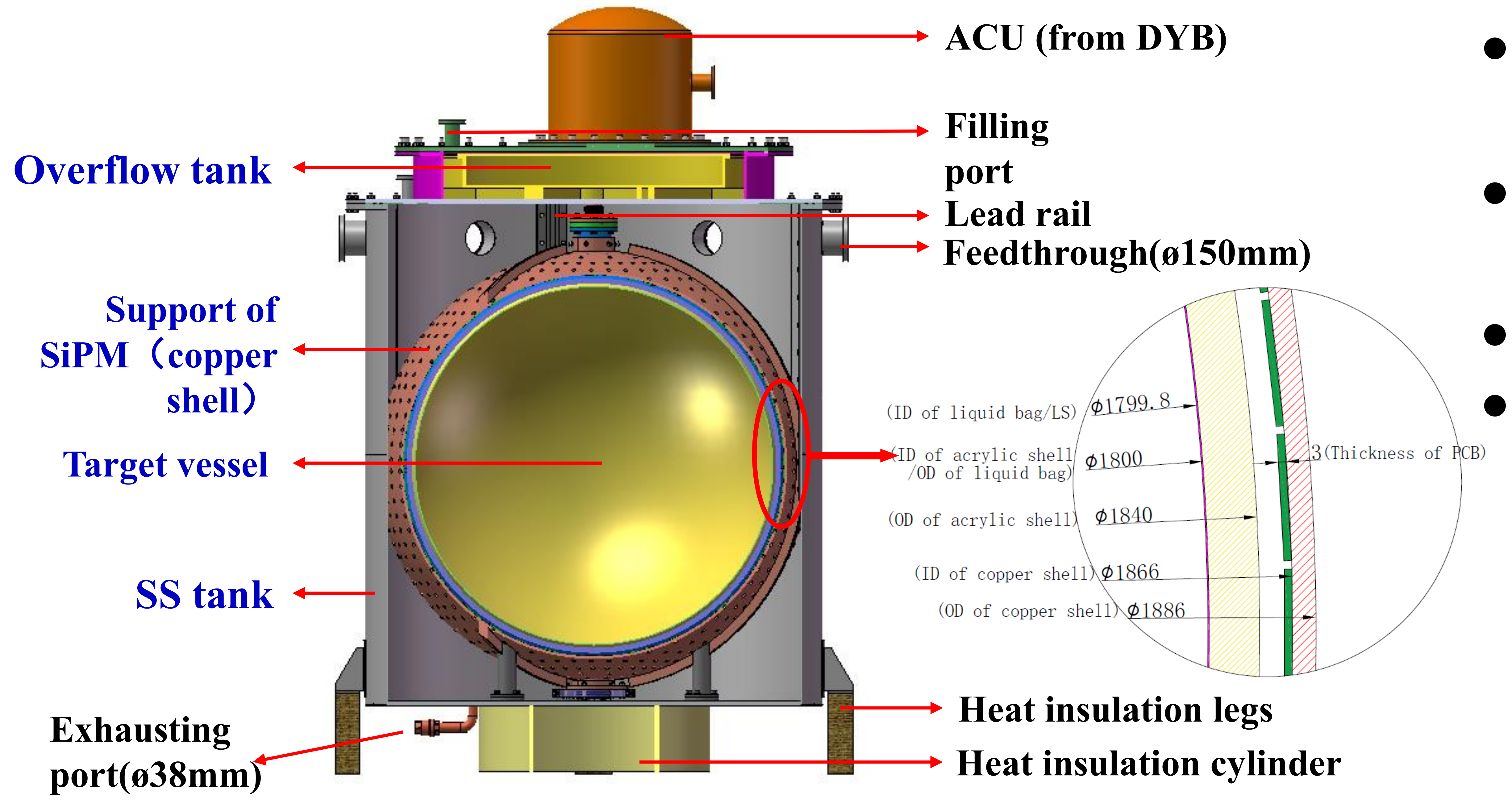
- Satellite experiment of JUNO to **measure reactor spectrum** with **sub-percent E resolution**
  - **—> reduce JUNO's** reactor spectrum **uncertainty**
- **44 meters from Taishan** NPP core (4.6 GW_{th}) —> 700 k-events/year
- Energy resolution: $\sim 1.5\,\%/\sqrt{E}$
- 10 m^2 SiPM, > 94% photo coverage)
- SiPM operated at -50^o C to reduce dark rate by factor 1000 to 100 Hz/mm^2
- 2.8 tons (1t fiducial) of Gd loaded liquid scintillator at -50^o C
  (LAB + 2 g/l PPO, 1 mg/l bis-MSB, 0.05% ethanol and 0.1% Gd by weight)



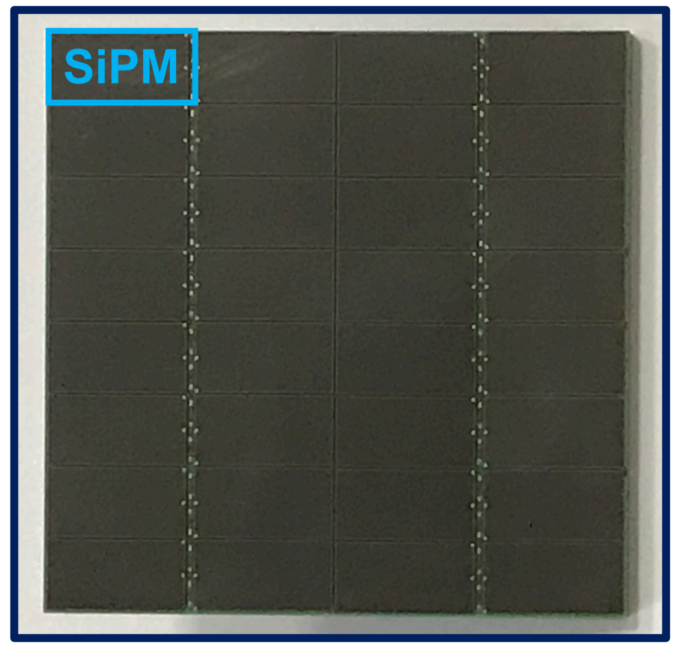


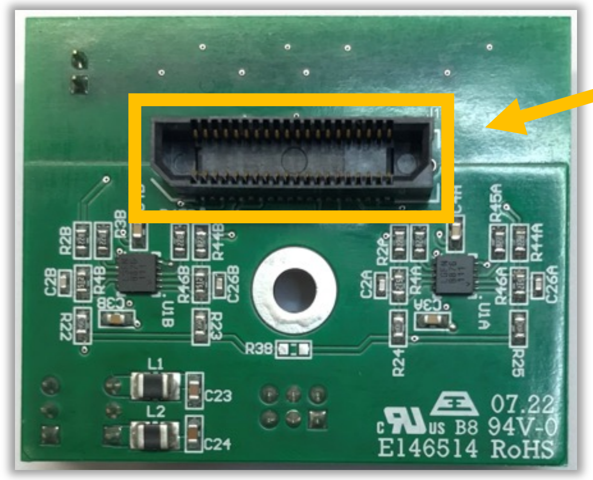
stefano.dusini@pd.infn.it

TAO Central detector instrumentation



- 4100 tiles 5x5 cm^2 for a total of ~ 10 m^2 of instrumented surface
- **SiPM operated at -50^o C** to reduce dark rate by factor 1000 **to 100 Hz/mm^2**
- each tile is composed 8x4 array of Hamamatsu (S16088) SiPM 12 x 6 mm^2
- Each SiPM tile is split in two channels
- Operating voltage 54 V.

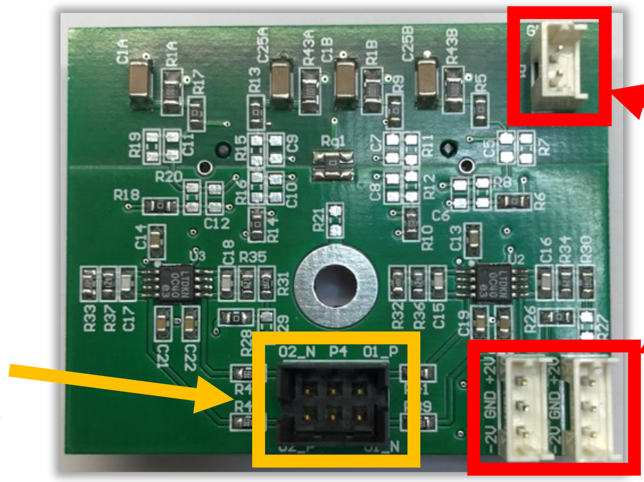




SiPM Tile
Board-to-board mating

Signal output
Differential pairs

FRONT: INPUT + 1st STAGE

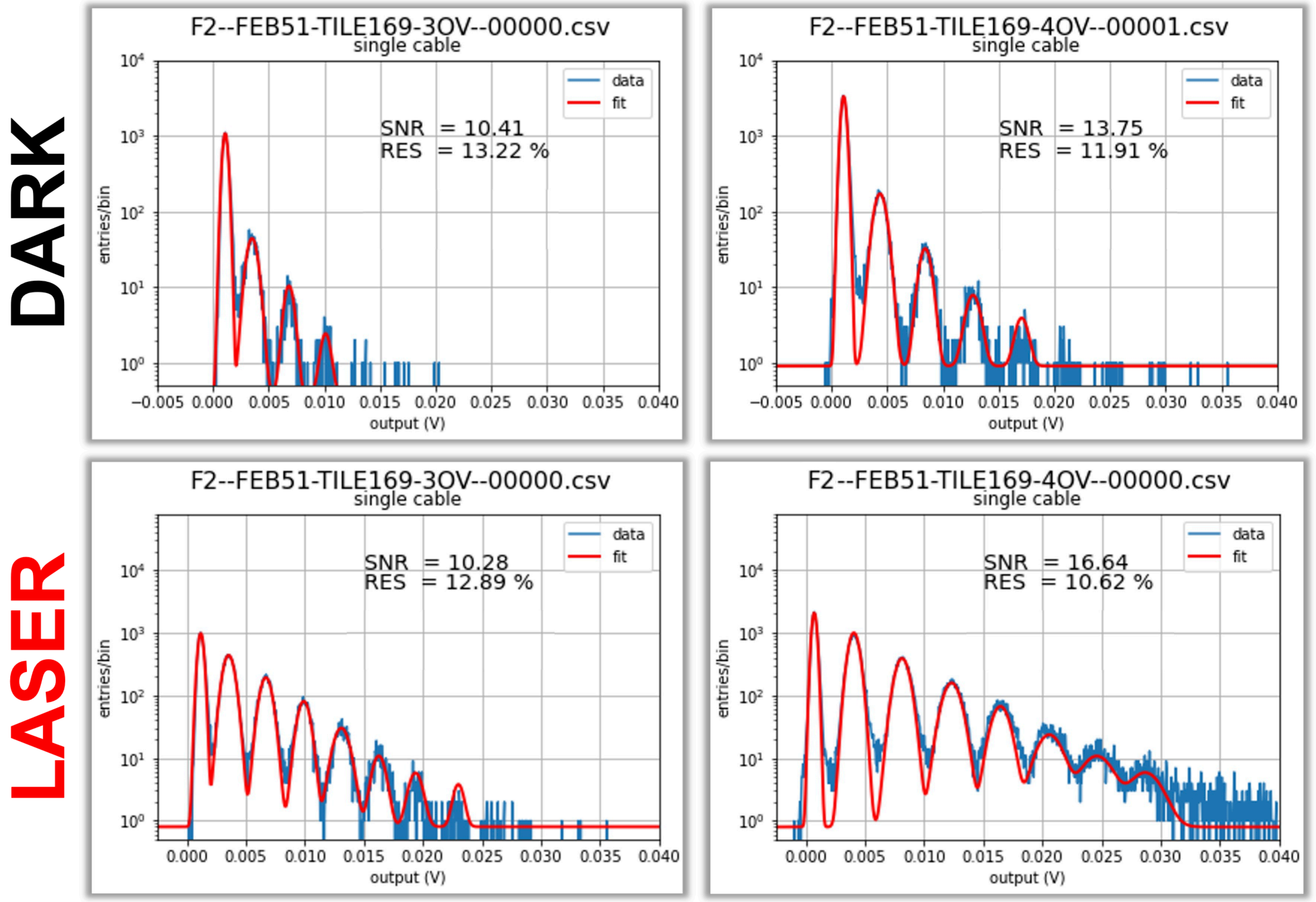


HV SiPM supply ≈2x50V

LV FEB supply ±2V

REAR: 2nd STAGE + OUTPUT

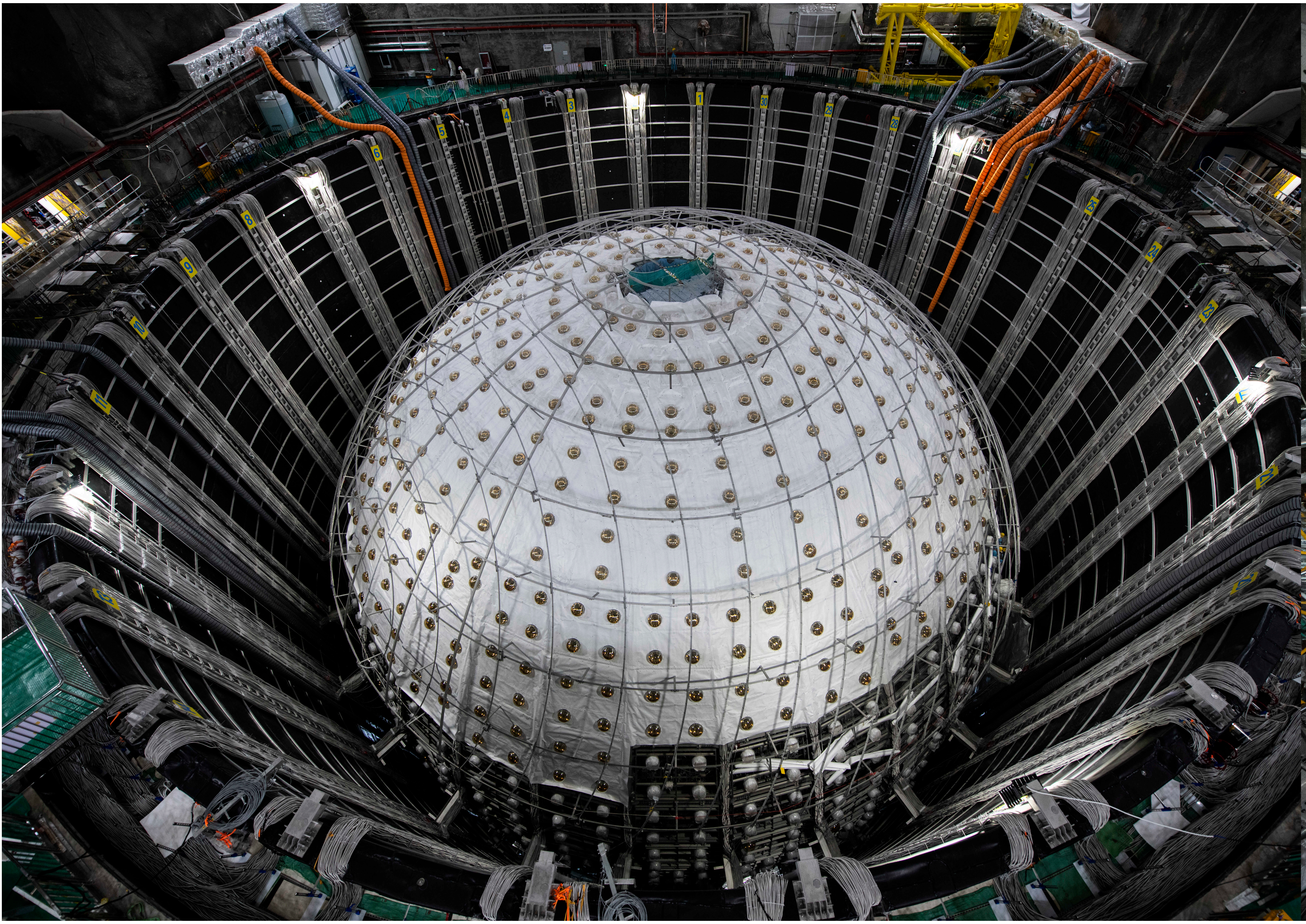
+ 3V OV (=V$_{OP}$) **+ 4V OV**

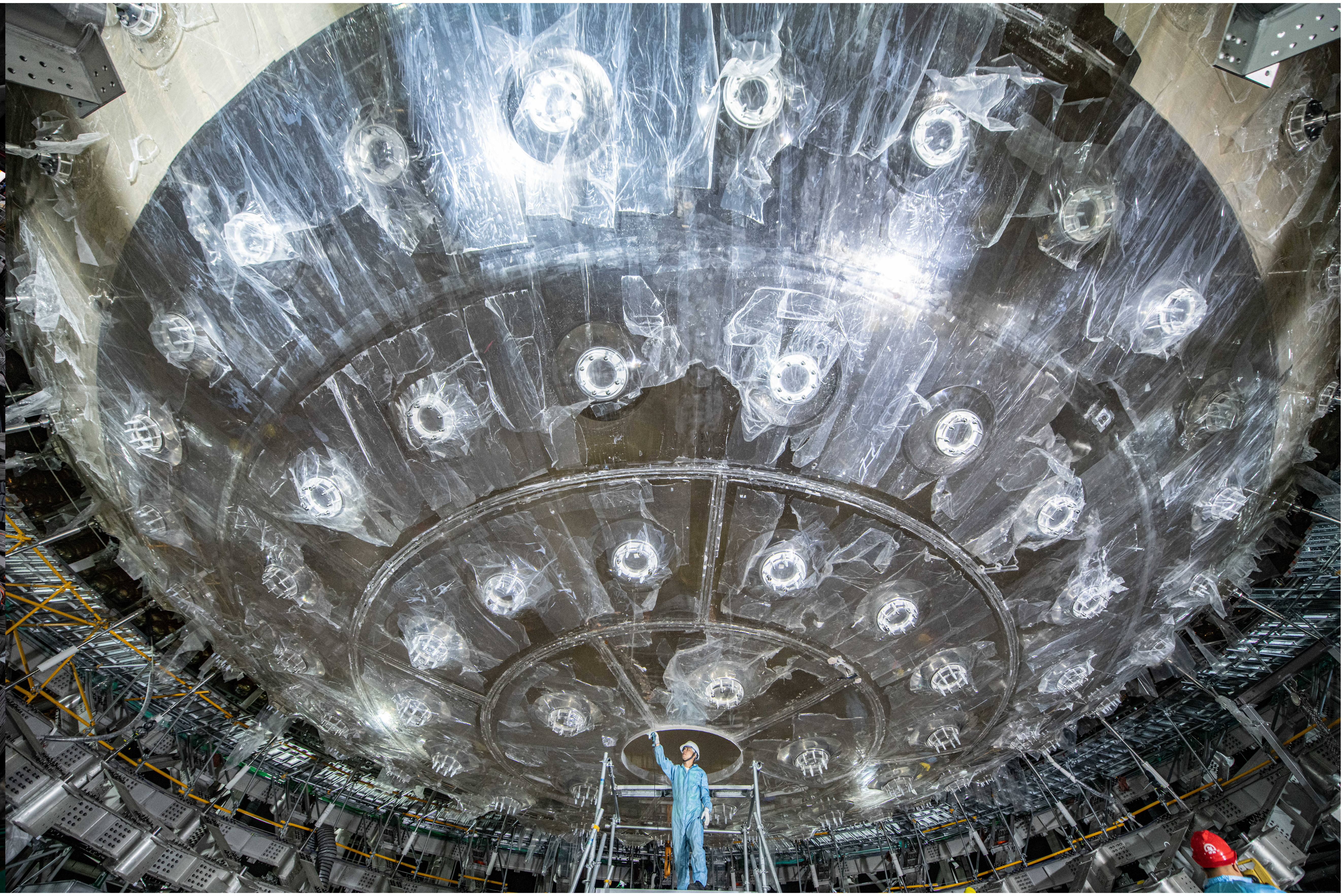


Status of detector construction

- Stainless steel structure completed
- **Installation of PMTs and electronics is almost completed > 99.5%**
- **expected to be completed by end of November 2024**
- **plan to begin filling before the end of the year**

- **Acrylic vessel completed** (13/10/2024)
- High transparency (> 96%) 12 cm acrylic panels
- Total mass ~ 600 ton
- Radio purity < 1ppt U/Th/K





Summary

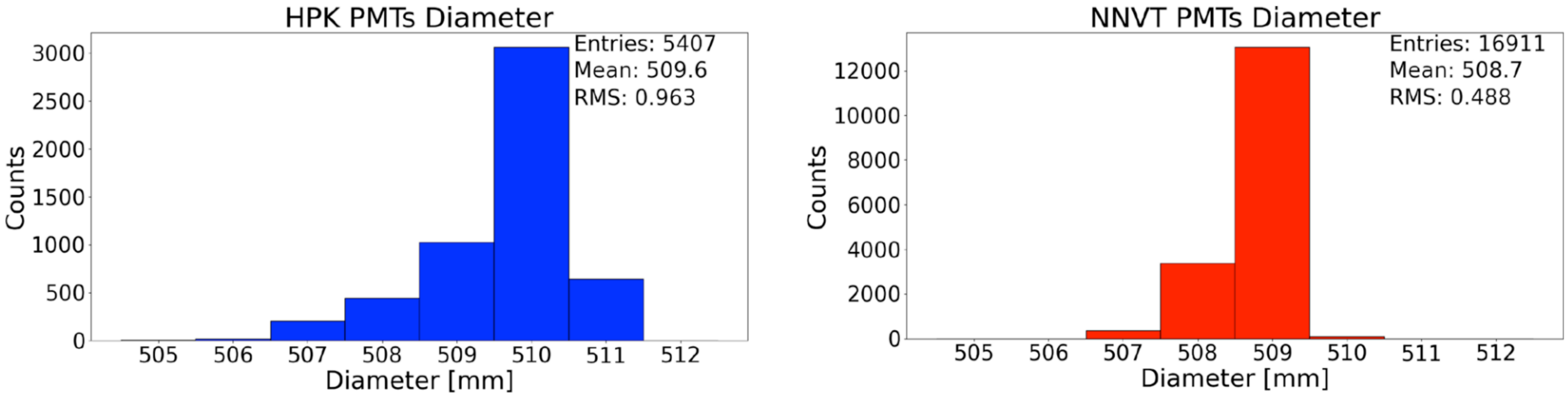
- **JUNO construction is nearly completed**
  - Start of **data-taking in 2025**
- JUNO is a major step in Liquid Scintillator detector design
  - 20 kton mass, 78% photocathode coverage
  - First dual readout LSD: 17k 20” PMT + 25k 3” PMT
  - Energy resolution 2.95% @ 1MeV
- Physics goals
  - **3σ NMO** median sensitivity in ~7 years with reactor only neutrinos via oscillation vacuum
  - **Sub-percent precision** $\Delta m^2_{21},\ \sin^2\theta_{12},\ \Delta m^2_{31}$
  - Synergy and complementarity with NMO measurers at LBL accelerator
  - + solar, + geo-neutrinos, +supernova, +DSNB, +p-decay….

Thank you

Since 2014, >700 collaborators from 74 institutions in 17 countries/regions

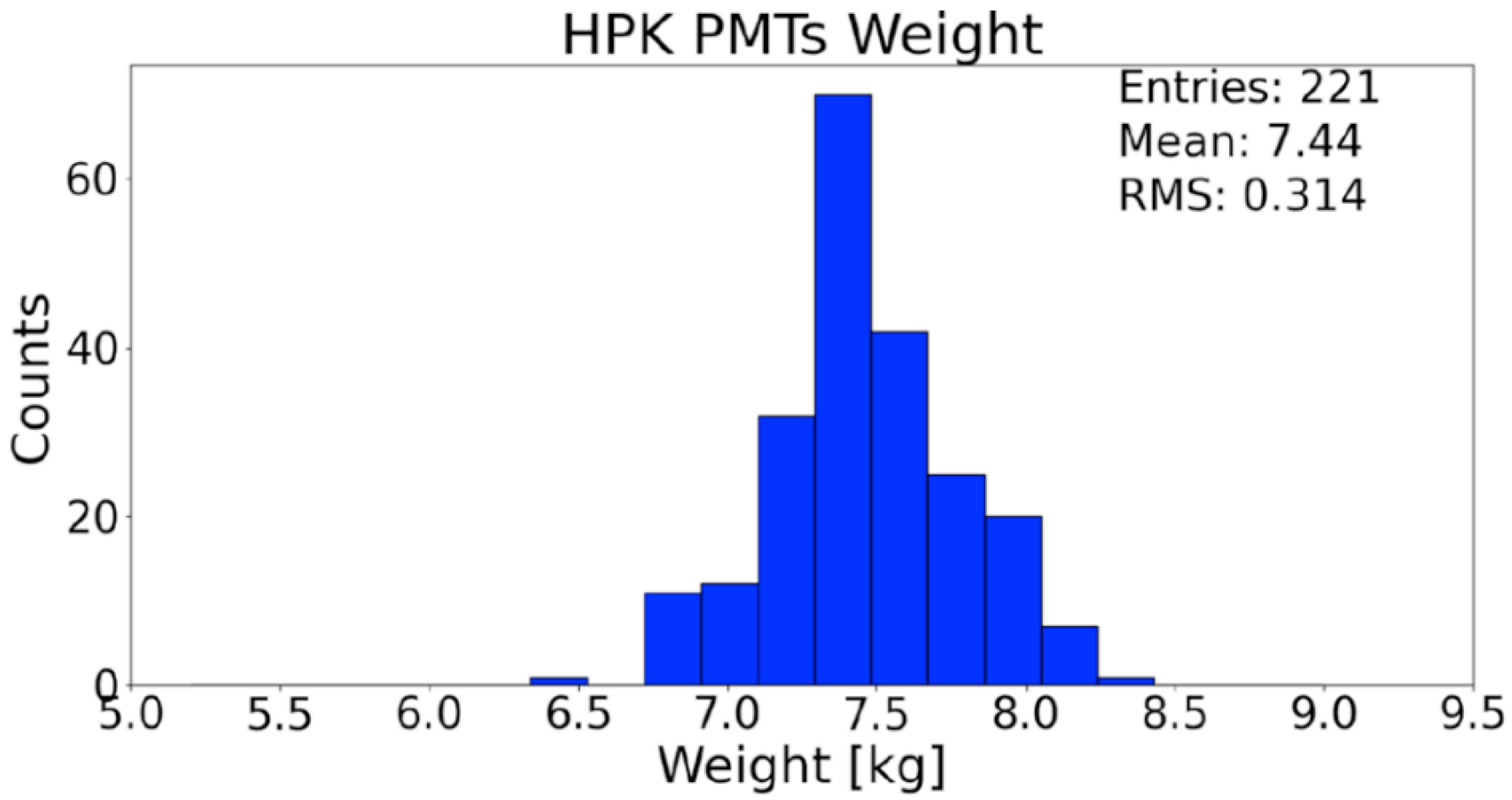
Backup

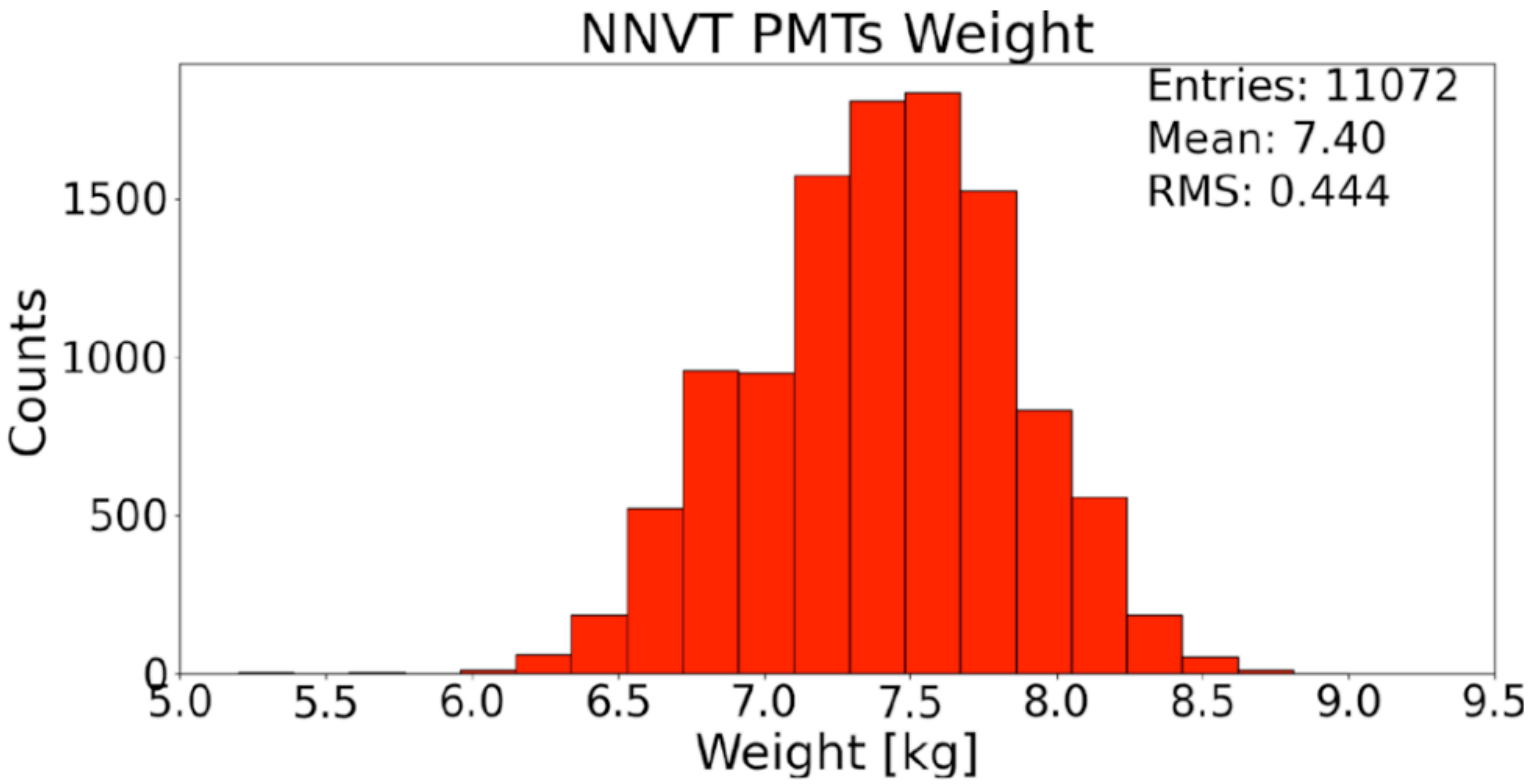
20” PMTs size and weight


HPK PMTs Diameter

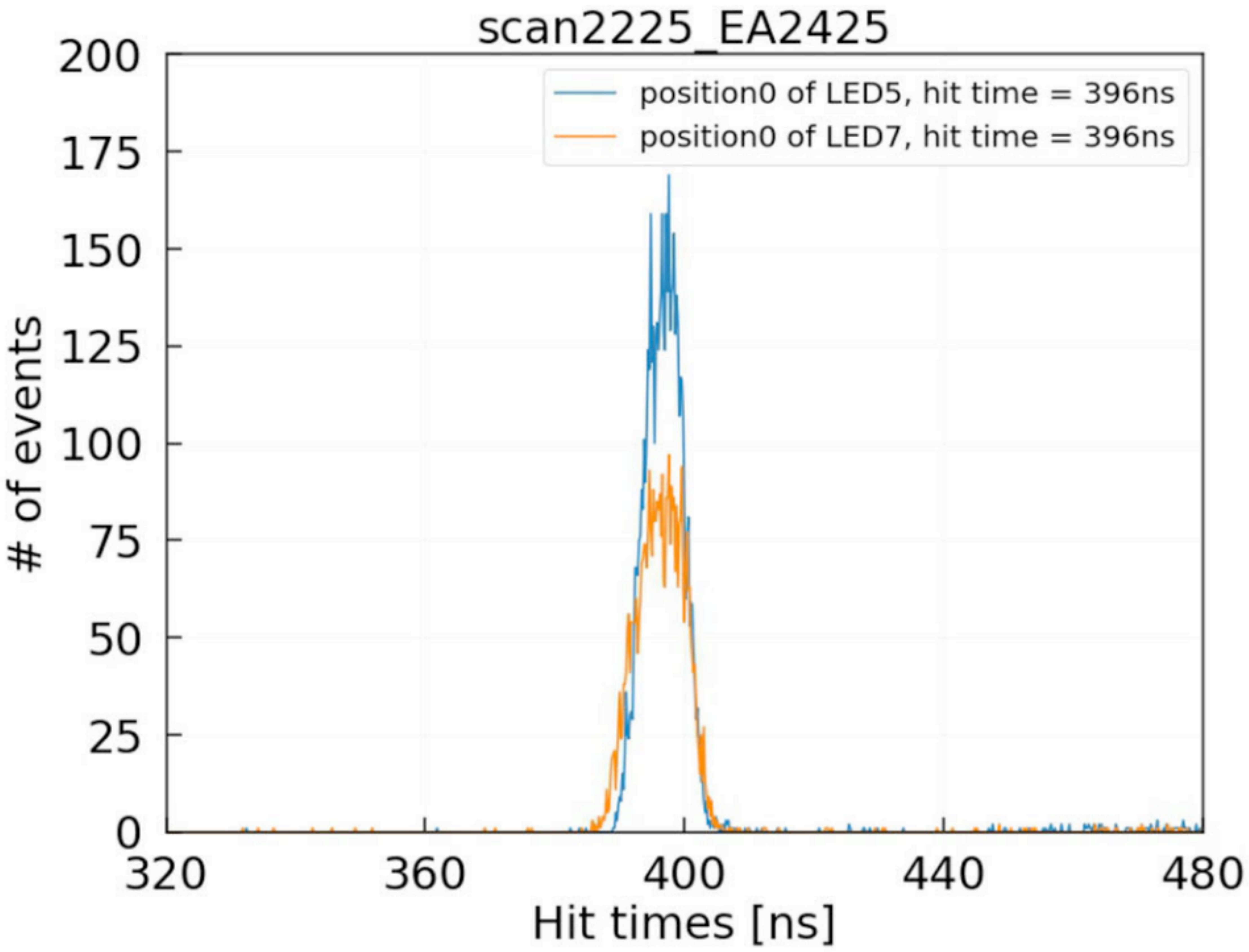
NNVT PMTs Diameter

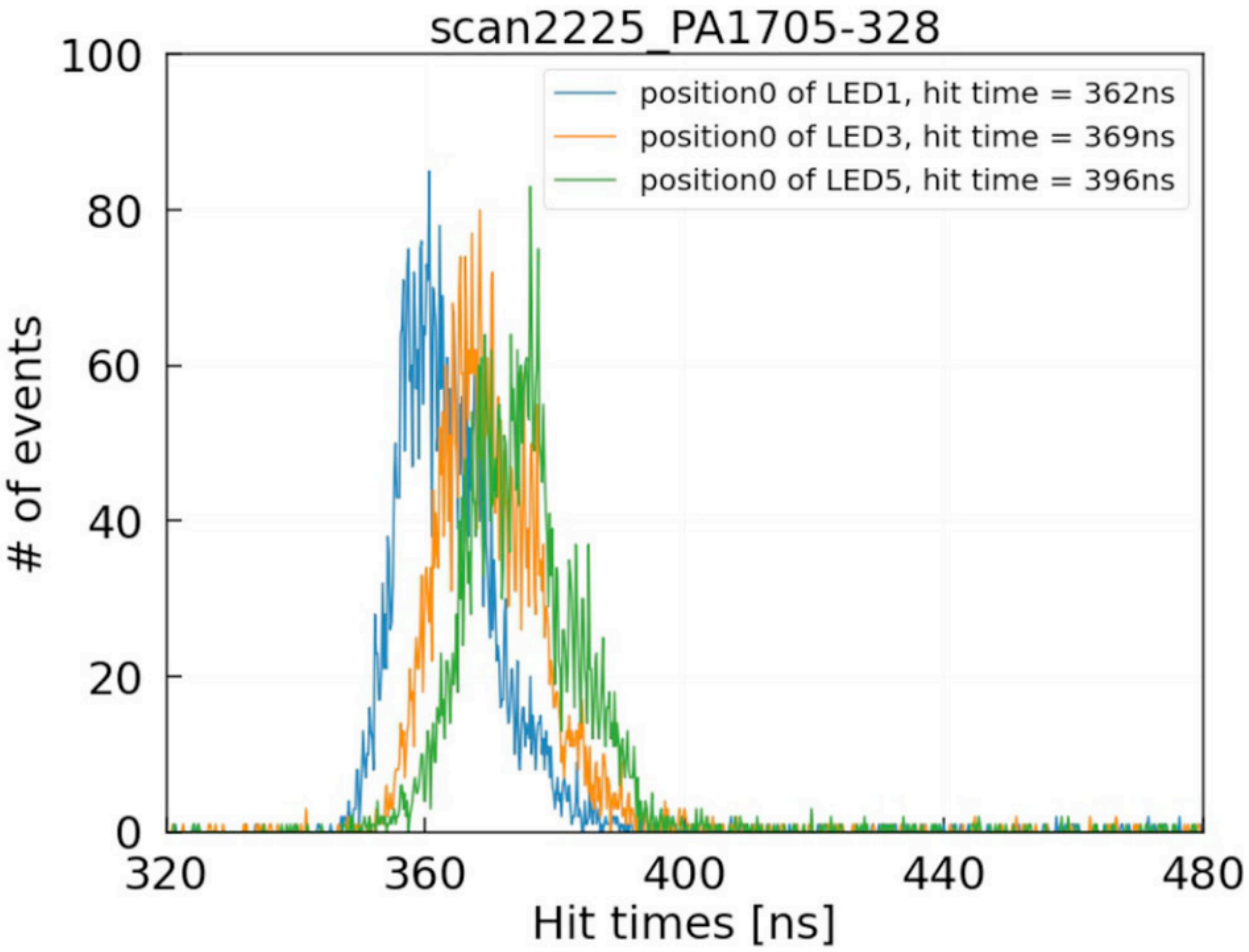
Fig. 8 Measured diameter in mm of all checked 20-inch PMTs. Some PMTs were rejected before the measurement after visual inspection, therefore the total number of tested PMTs is slightly reduced. Left: HPK; Right: NNVT


HPK PMTs Weight


NNVT PMTs Weight

Transit Time measured with the LED of the scanning station.





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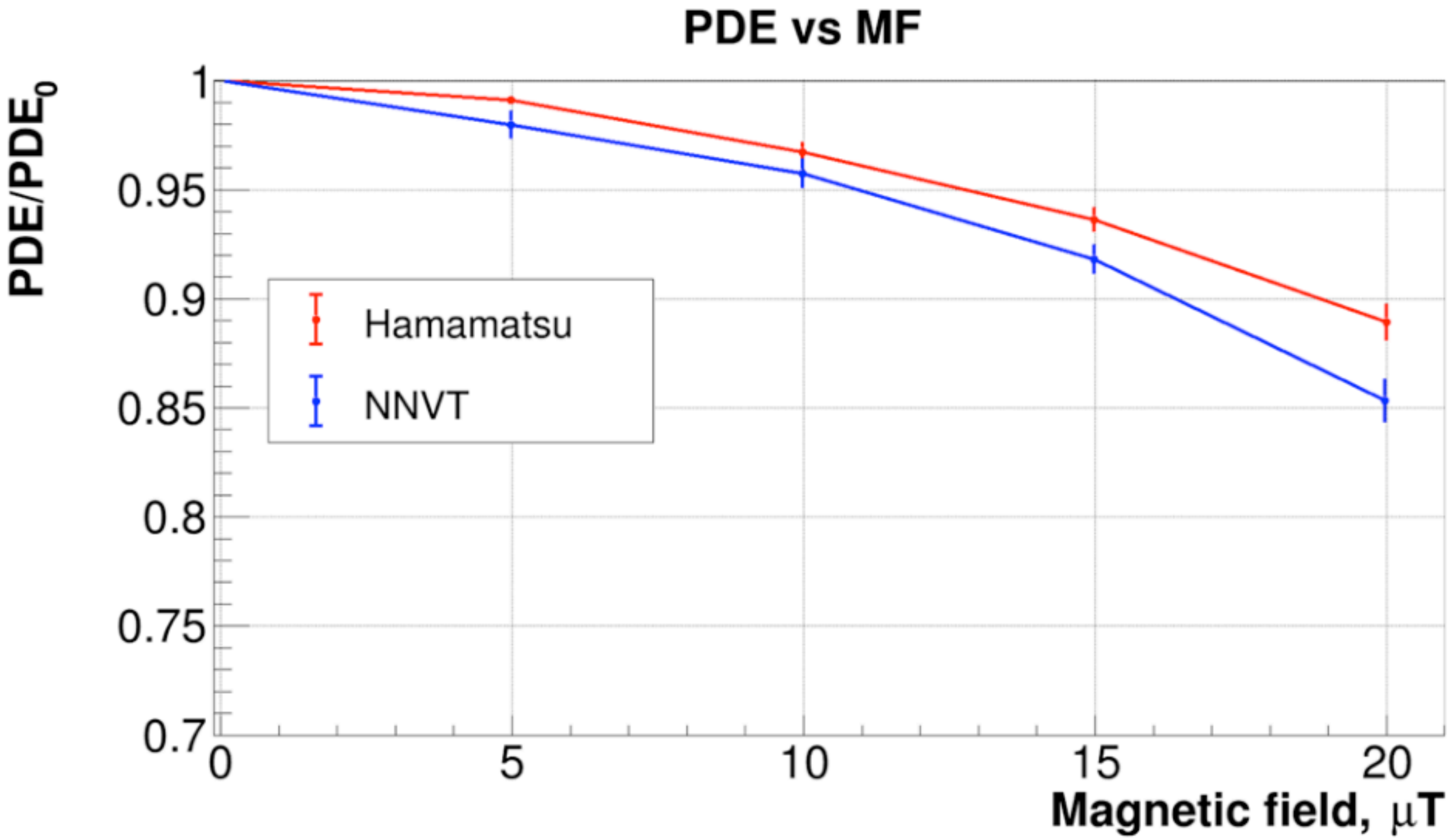
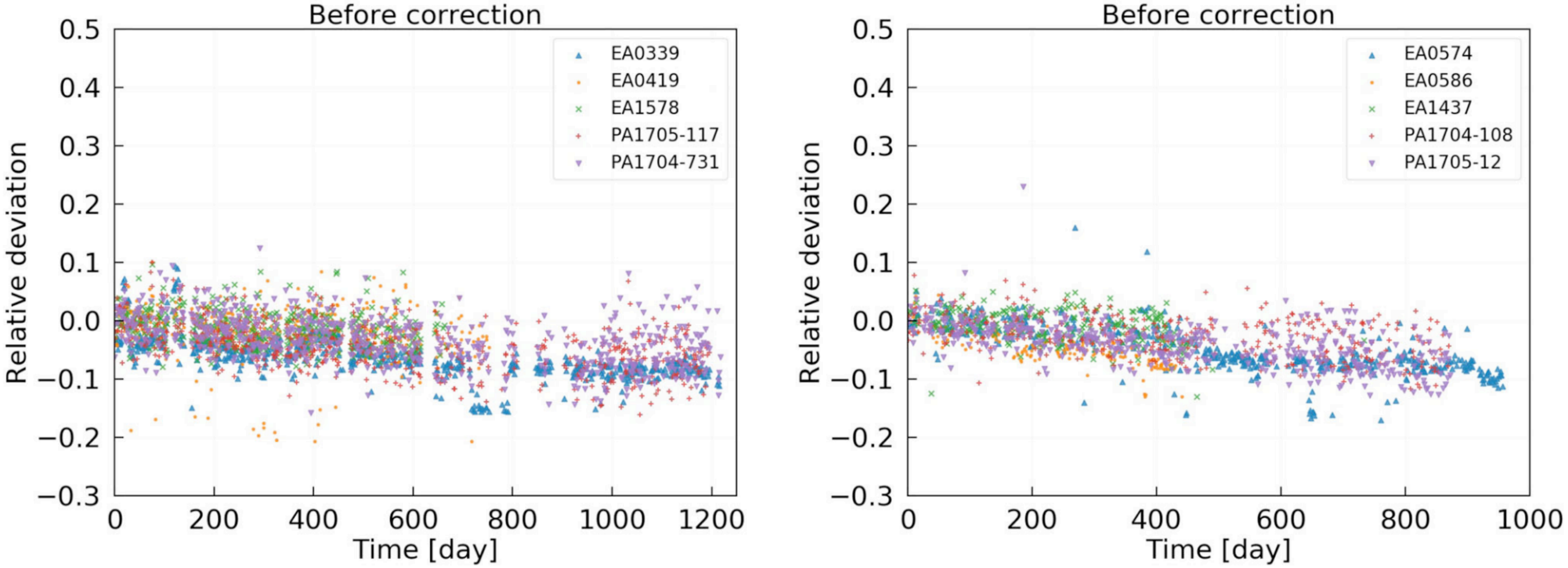
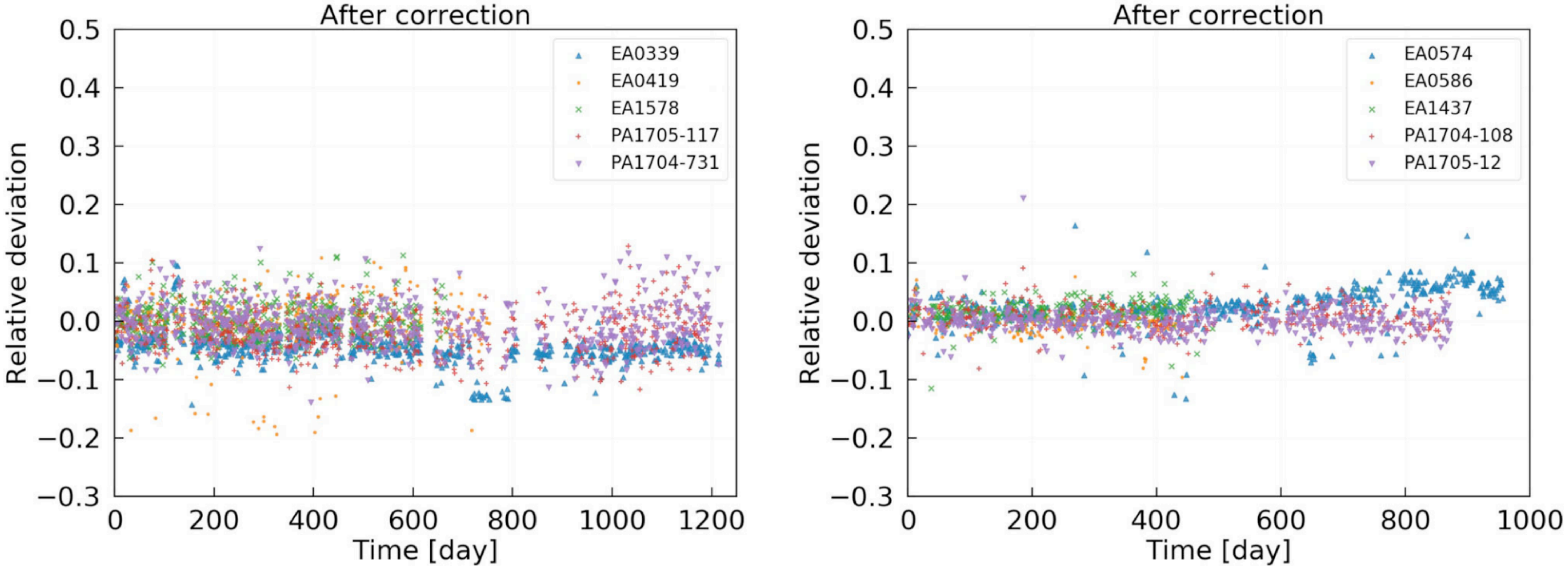


Fig. 32 Averaged PMT PDE versus remaining magnetic field (MF) strength tested with 9 HPK and 15 NNVT PMTs

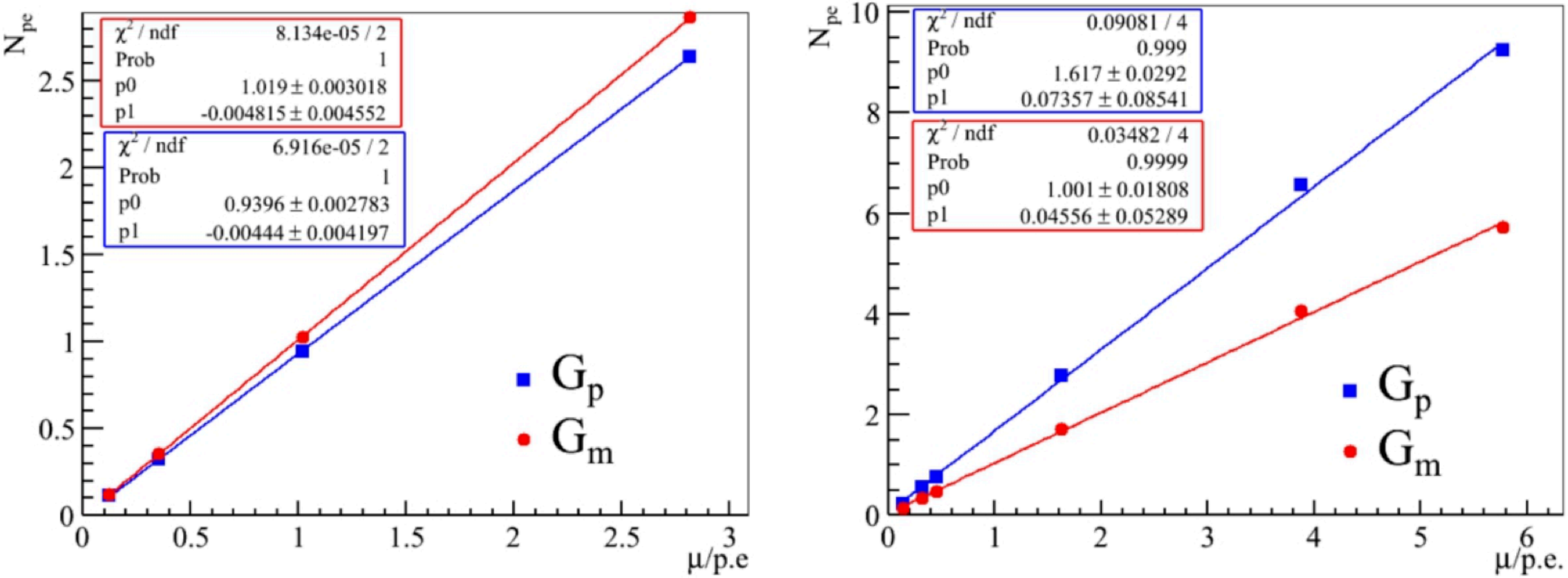
Relative variation of the measured PDE of the monitoring PMTs (HPK PMTs tagged by “EA”, NNVT PMTs tagged by “PA”) at the container system, before and after a correction based on a recalibration at the end of the regular testing period



(a) Container #A before correction **(b)** Container #B before correction



(c) Container #A after correction **(d)** Container #B after correction



N$_{pe}$
χ^2 / ndf 8.134e-05 / 2
Prob 1
p0 1.019 ± 0.003018
p1 -0.004815 ± 0.004552
χ^2 / ndf 6.916e-05 / 2
Prob 1
p0 0.9396 ± 0.002783
p1 -0.00444 ± 0.004197
0
0.5
1
1.5
2
2.5
3
μ/p.e
G$_p$
G$_m$
N$_{pe}$
10
8
6
4
2
0
χ^2 / ndf 0.09081 / 4
Prob 0.999
p0 1.617 ± 0.0292
p1 0.07357 ± 0.08541
χ^2 / ndf 0.03482 / 4
Prob 0.9999
p0 1.001 ± 0.01808
p1 0.04556 ± 0.05289
1
2
3
4
5
6
μ/p.e.
G$_p$
G$_m$

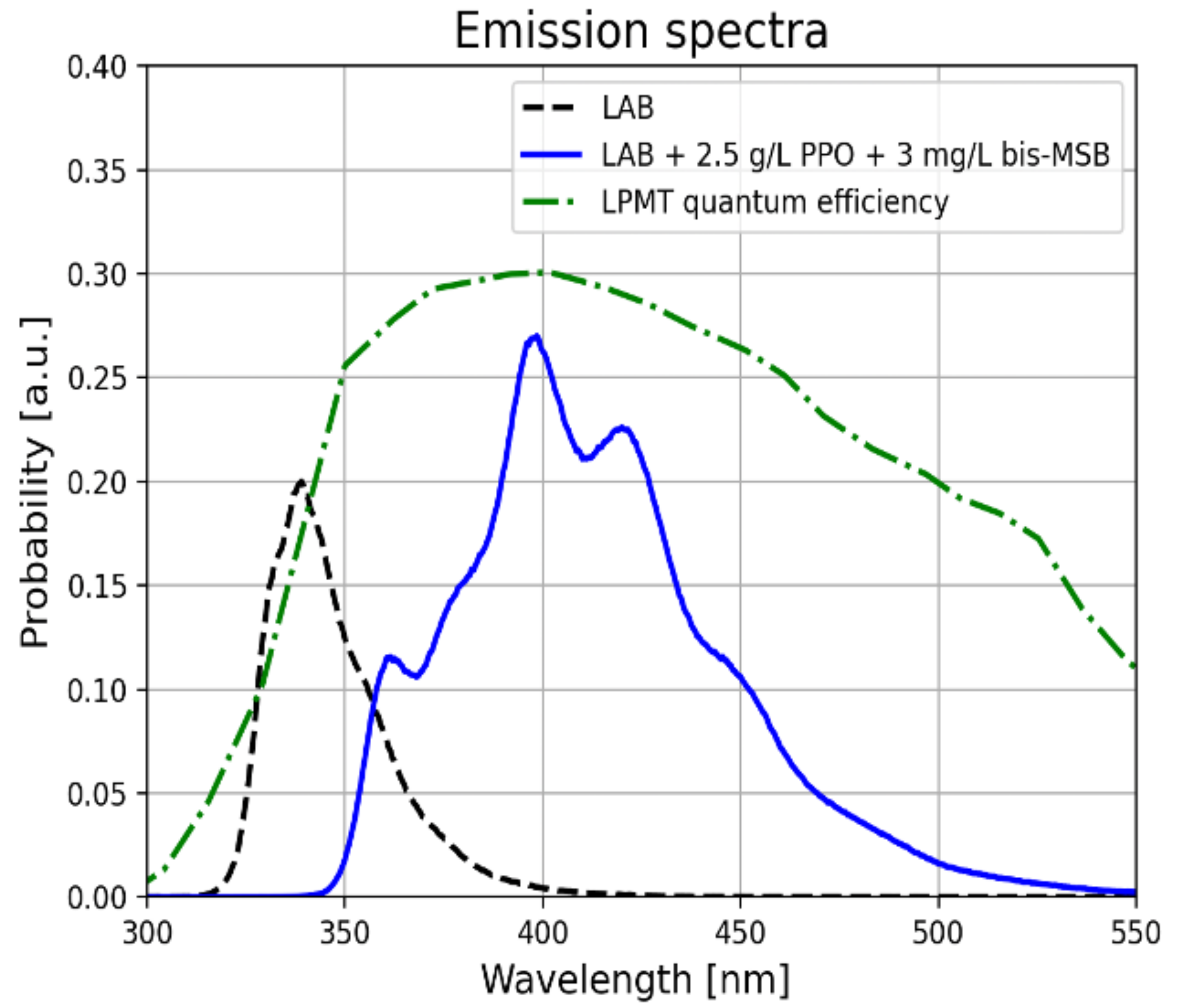
Liquid Scintillator

The energy resolution is related to the total number of photon detected

✓ high light yield

✓ light spectra matching PMT detection efficiency

✓ good liquid scintillator transparency



JUNO “recipe” :

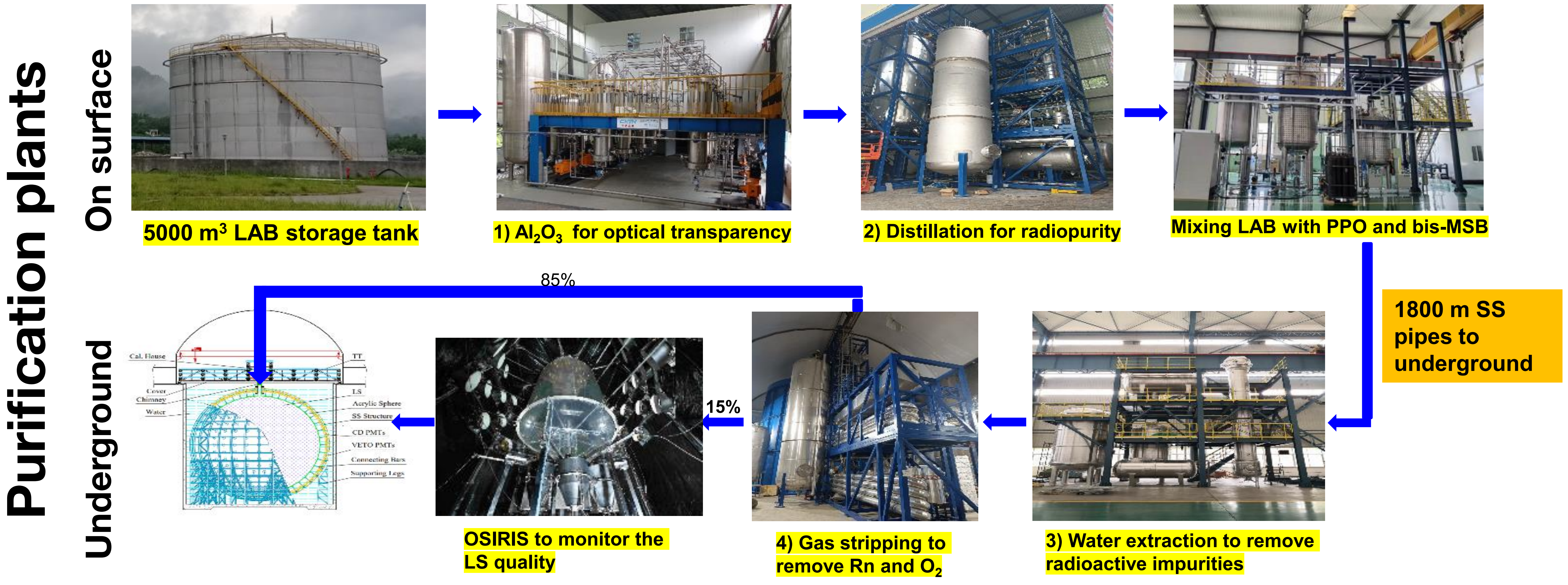
Solvent: **Linear Alkyl Benzene (LAB)**

Fluor: **2.5 g/l PPO**

Wavelength shifter: **3 mg/l bis-MSB**

- Optical impurities reduce transparency
- Radioactive contaminants yield background events

- Measured liquid scintillator attenuation length **> 20 m**
- **Contamination during the commissioning** of the purification plants
  - **U < 1.9 x 10^{-16} g/g** [solar physics < 10^{-17} g/g]
  - **Th < 1.5 x 10^{-16} g/g** [solar physics < 10^{-17} g/g]



Purification plants

On surface

5000 m^3 LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

Mixing LAB with PPO and bis-MSB

1800 m SS pipes to underground

Underground

3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

15%

85%

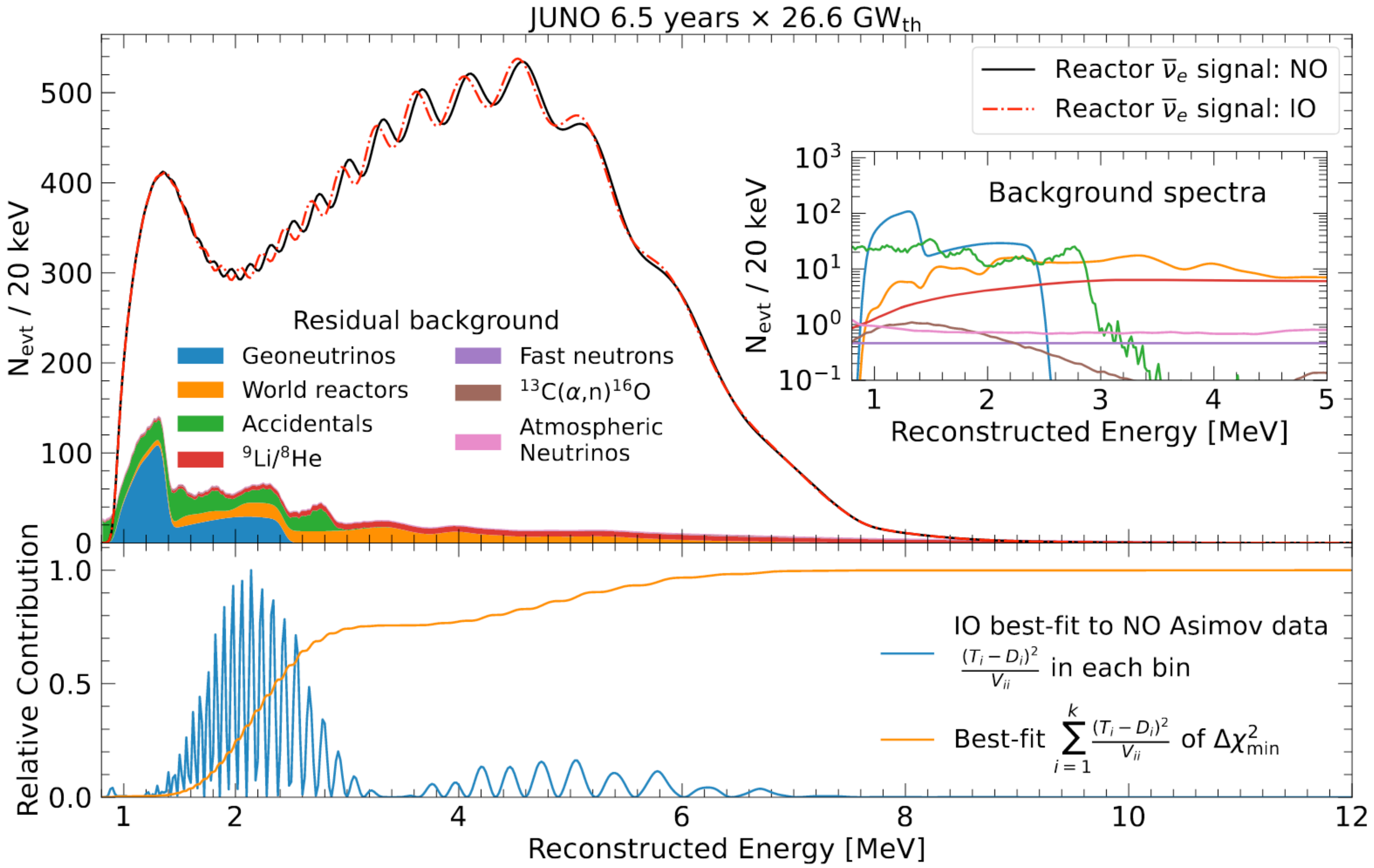
OSIRIS to monitor the LS quality

stefano.dusini@pd.infn.it

More details in Dmitrii Dolzhikov talk
JUNO's Physics with Reactor Antineutrinos
24 October 2024 08:40

JUNO Physics performances

arXiv:2405.18008

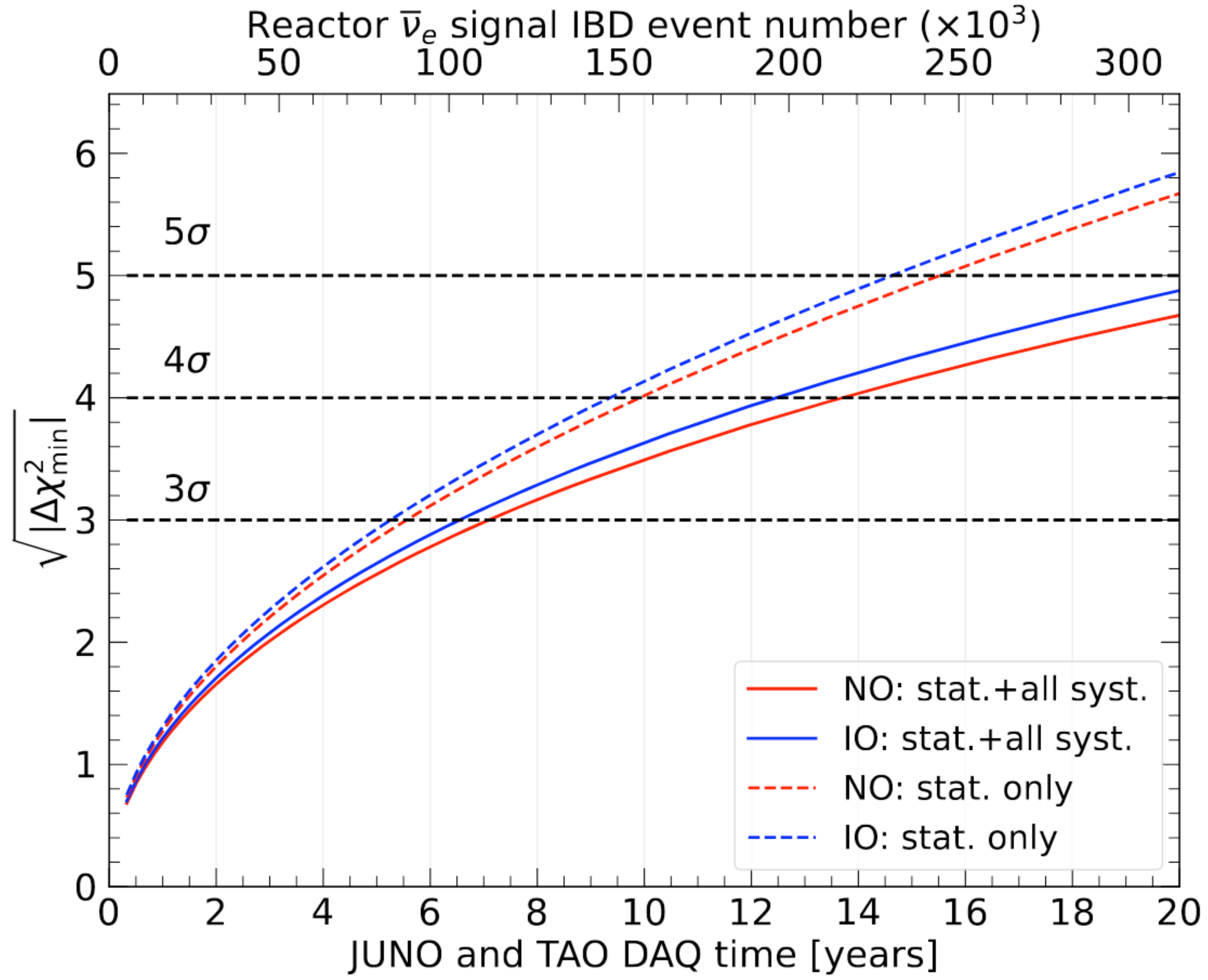


With 26.6 GW$_{th}$ (11/12 duty cycle)

- 47.1 IBD events per day in FV
- 4.1 backgrounds (B/S = 8.7%)

Sensitivity to Mass Ordering:

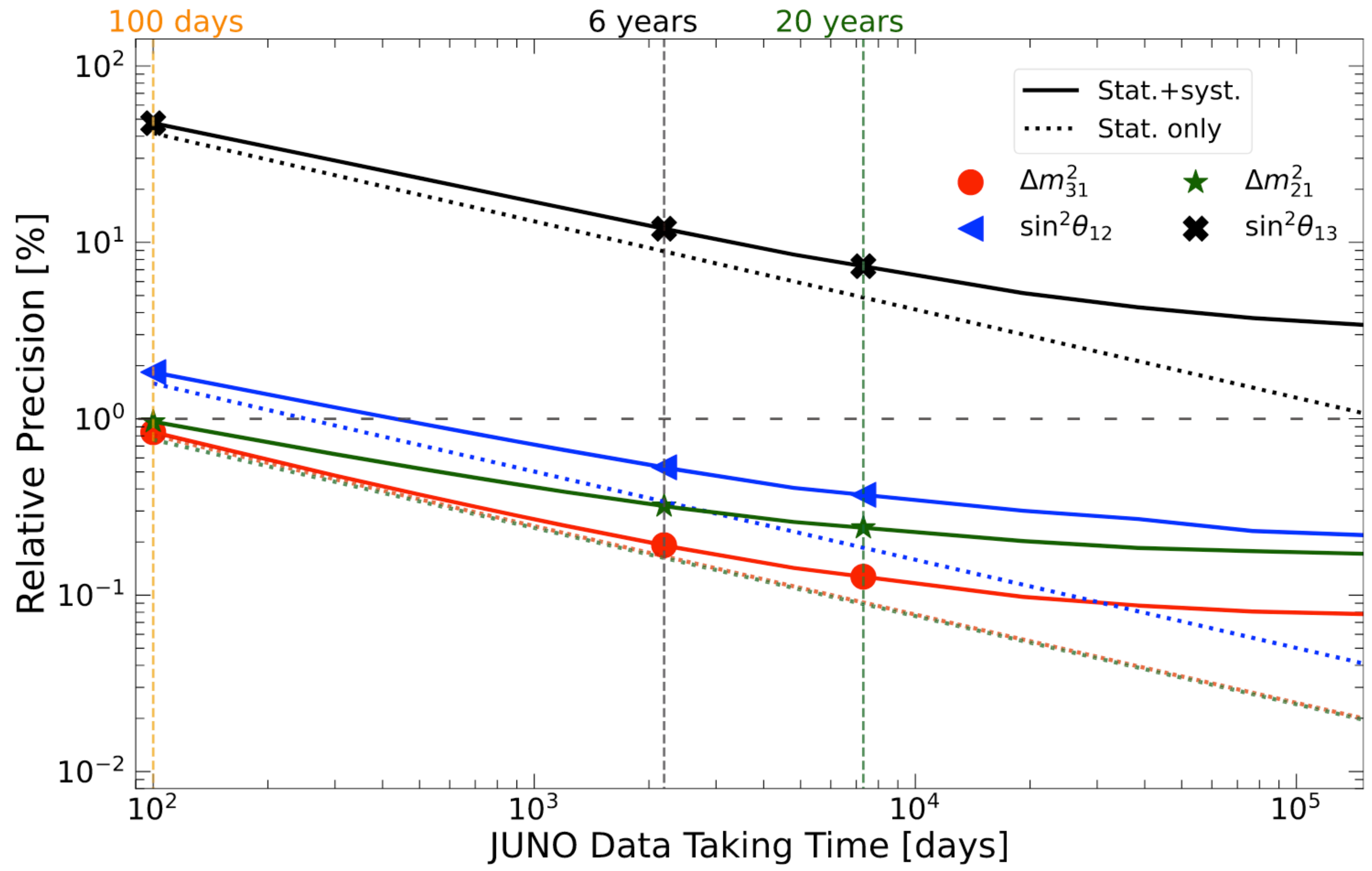
- Fitting data against NO and IO scenario
- Most sensitive region [1.5 - 3] MeV
- **3σ sensitivity** in 7.1 years



Sub-percent measurement of 3 (out of 5) oscillation parameters

$\Delta m^2_{31},\ \Delta m^2_{32},\ \sin^2\theta_{12}$

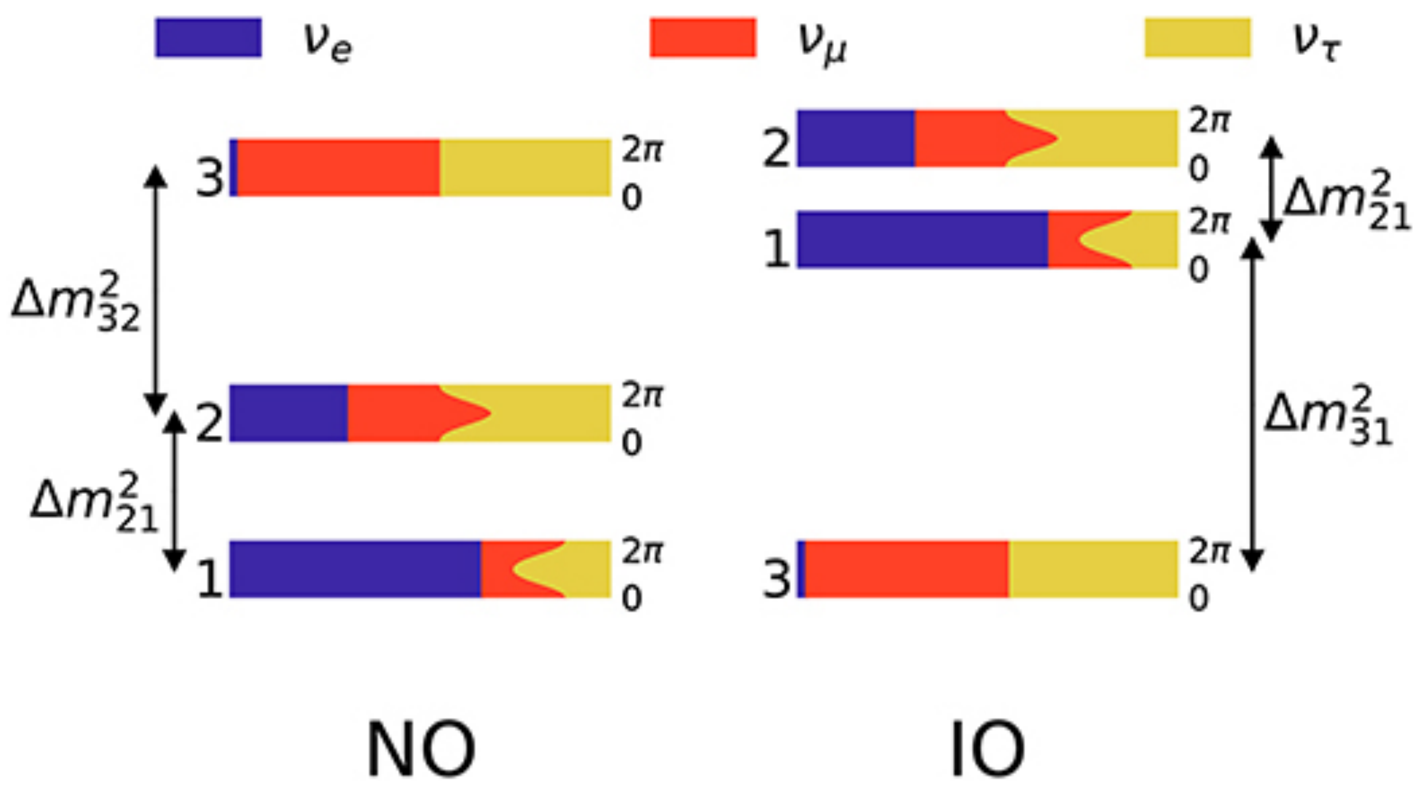
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)



JUNO experiments

Measure the reactor neutrino spectrum at the first solar minima to resolve the fast oscillation driven by the interference between Δm^2_{31}, Δm^2_{32} and extract NMO

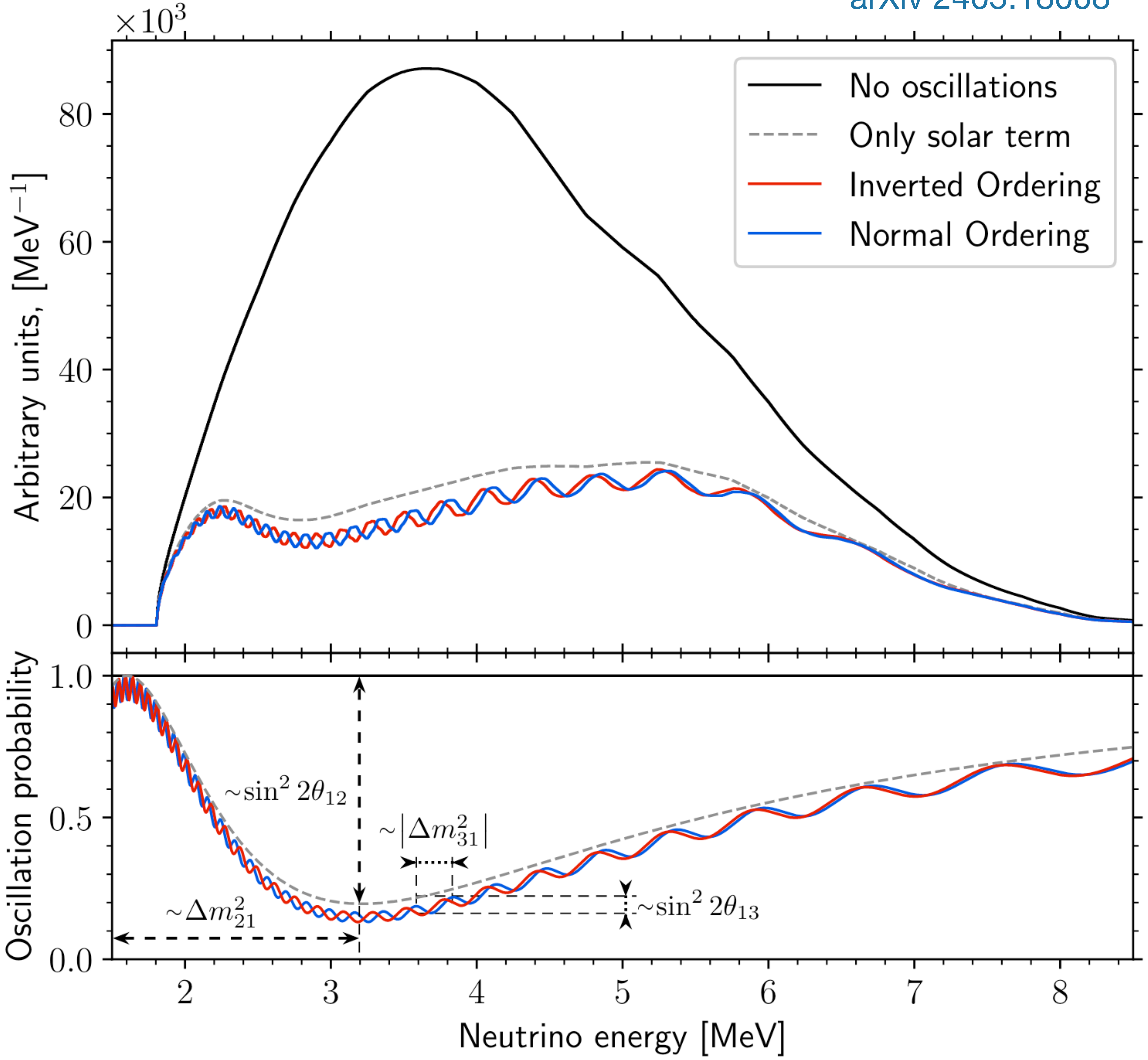
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \cos^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2 2\theta_{13} \sin^2 \theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



NO $\Delta m_{31} > \Delta m^2_{32} > 0$

IO $\Delta m_{32} < \Delta m^2_{31} < 0$

arXiv 2405.18008



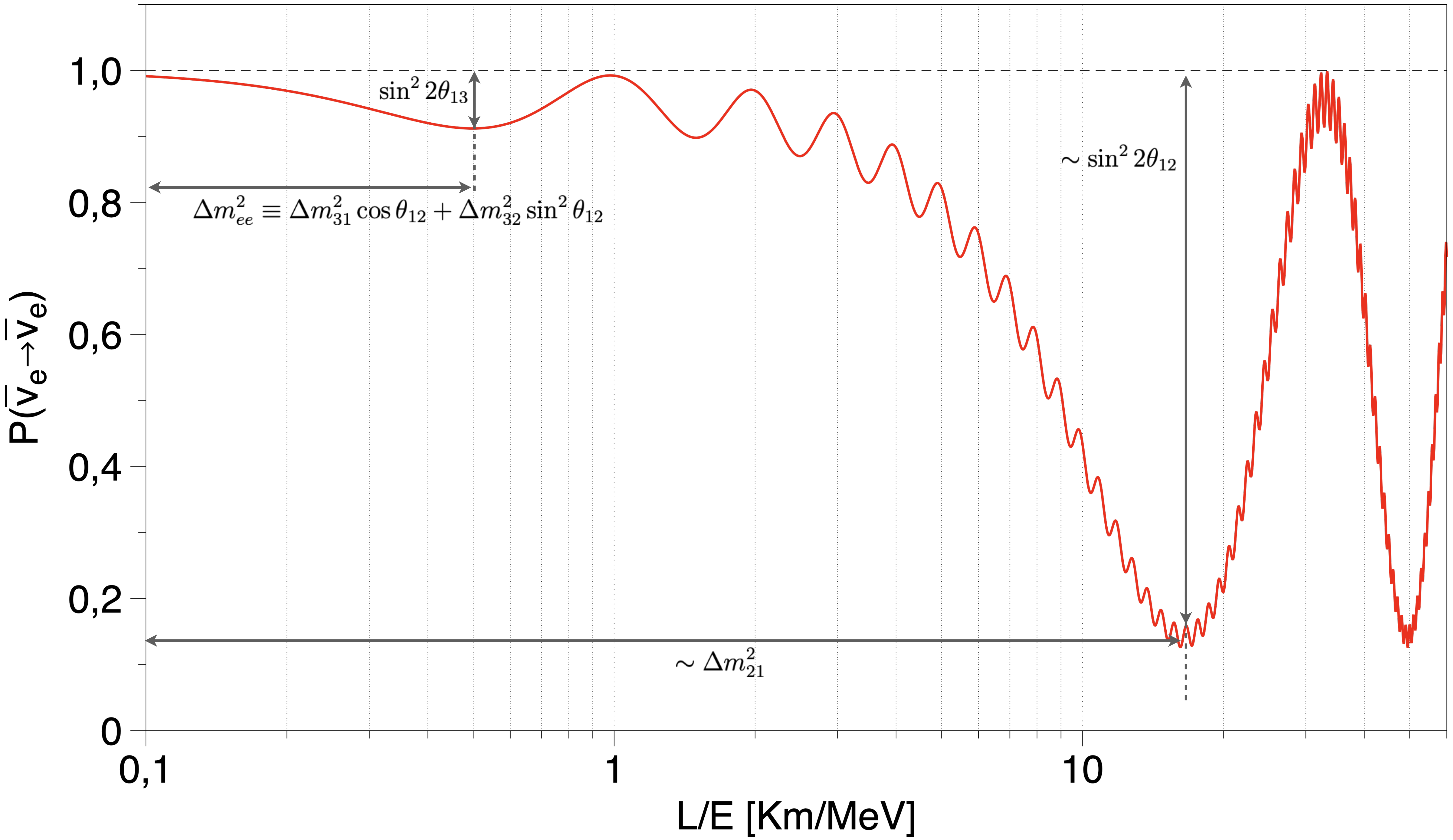
Key features of the experiment

- **Excellent energy resolution**
- **Large statistics**
- **Control of energy scale and systematics**

Reactor experiments

In reactor neutrino experiment we measure the $\bar{\nu}_e$ survival probability $P(\bar{\nu}_e \to \bar{\nu}_e)$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$
$$- \sin^2 2\theta_{13} \cos^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$
$$- \sin^2 2\theta_{13} \sin^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



The strong hierarchy between mass eigenstate

$$\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \sim \frac{1}{30}$$

allow to test the different component changing the baseline