JUNO Experiment

Current Status and Prospects

N. Anfimov on behalf of the JUNO Collaboration

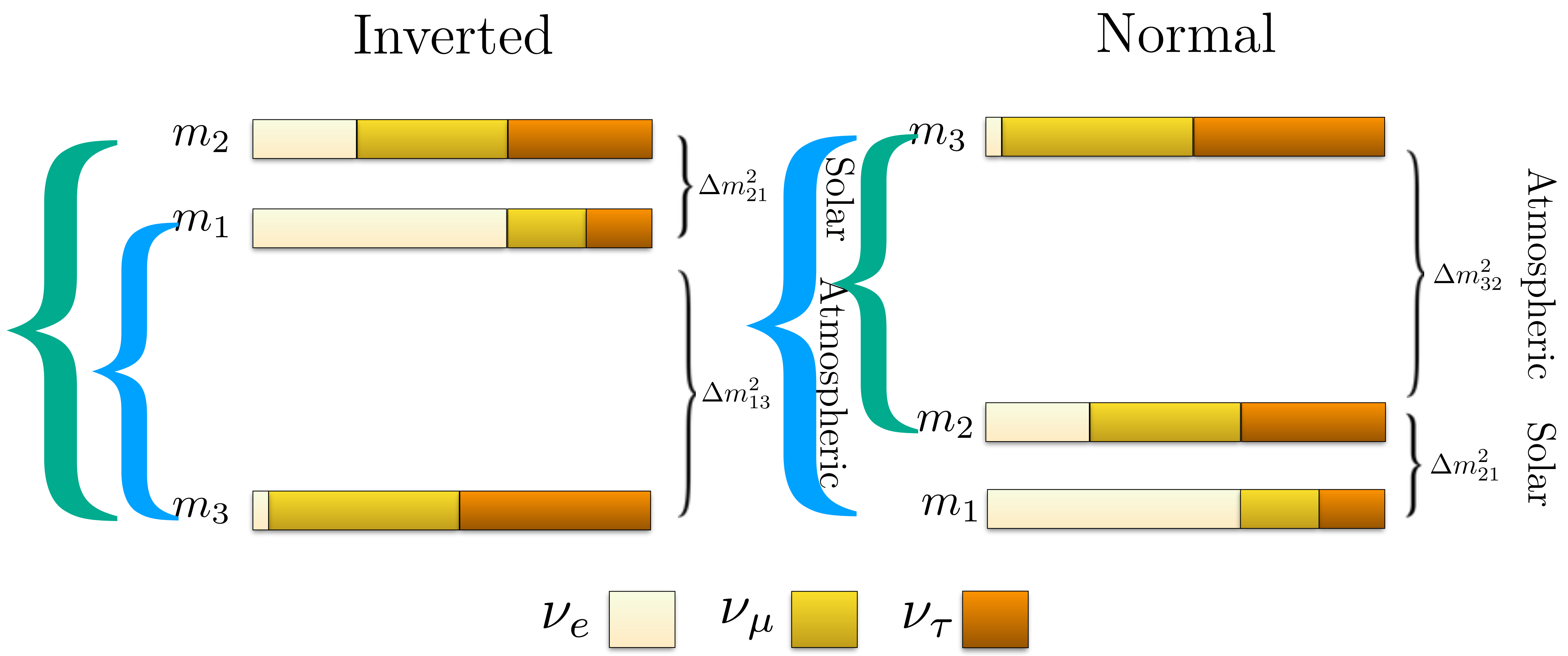
Nucleus-2024

Neutrino oscillation

What is missing?

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \overset{\substack{\text{ATMOSPHERIC}\\ \text{ACCELERATOR}}}{\begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}} \overset{\substack{\text{SHORT BASELINE REACTOR}\\ \text{ACCELERATOR}}}{\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}} \overset{\substack{\text{SOLAR}\\ \text{LONG BASELINE REACTOR}}}{\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}} \left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

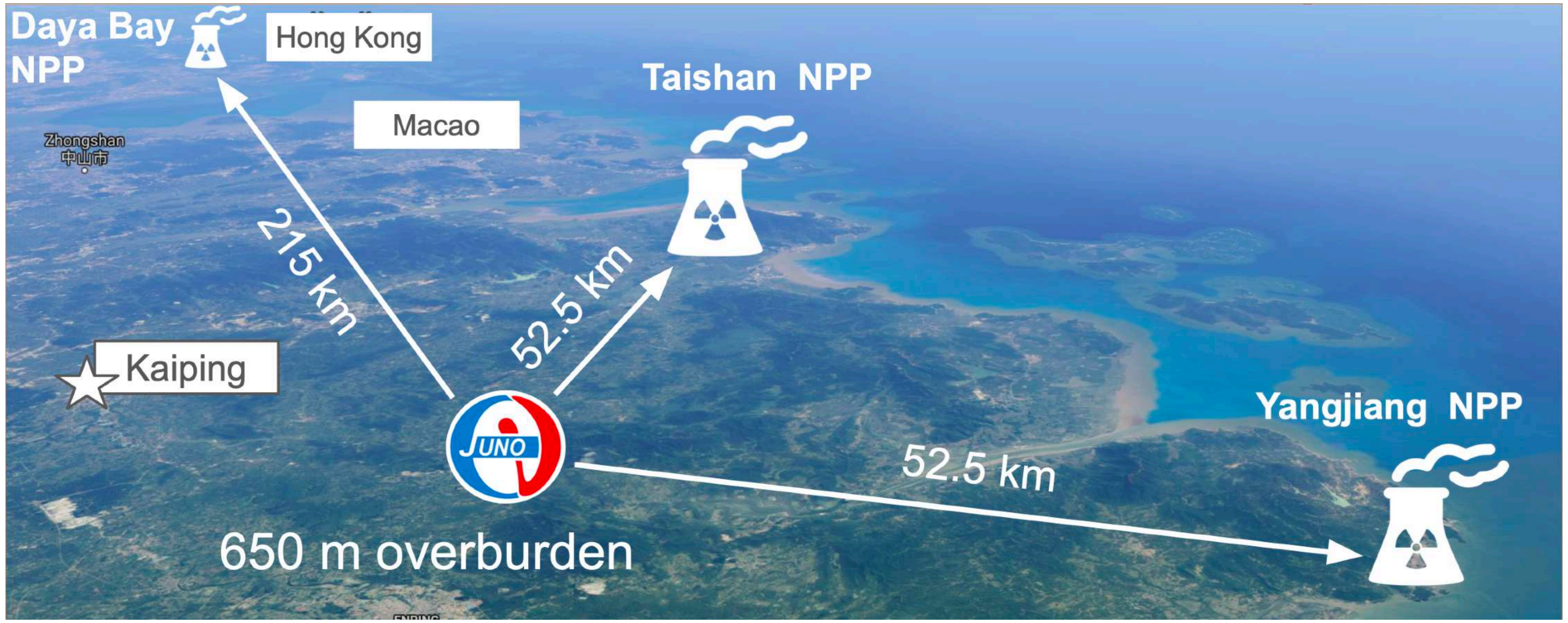
- Known parameters:
  $\theta_{23}, \theta_{12}, \theta_{13}, |\Delta m^2_{32}|, \Delta m^2_{21}$
- Unknown parameters:
  sign of Δm^2_{32} (mass ordering),
  CP phase δ

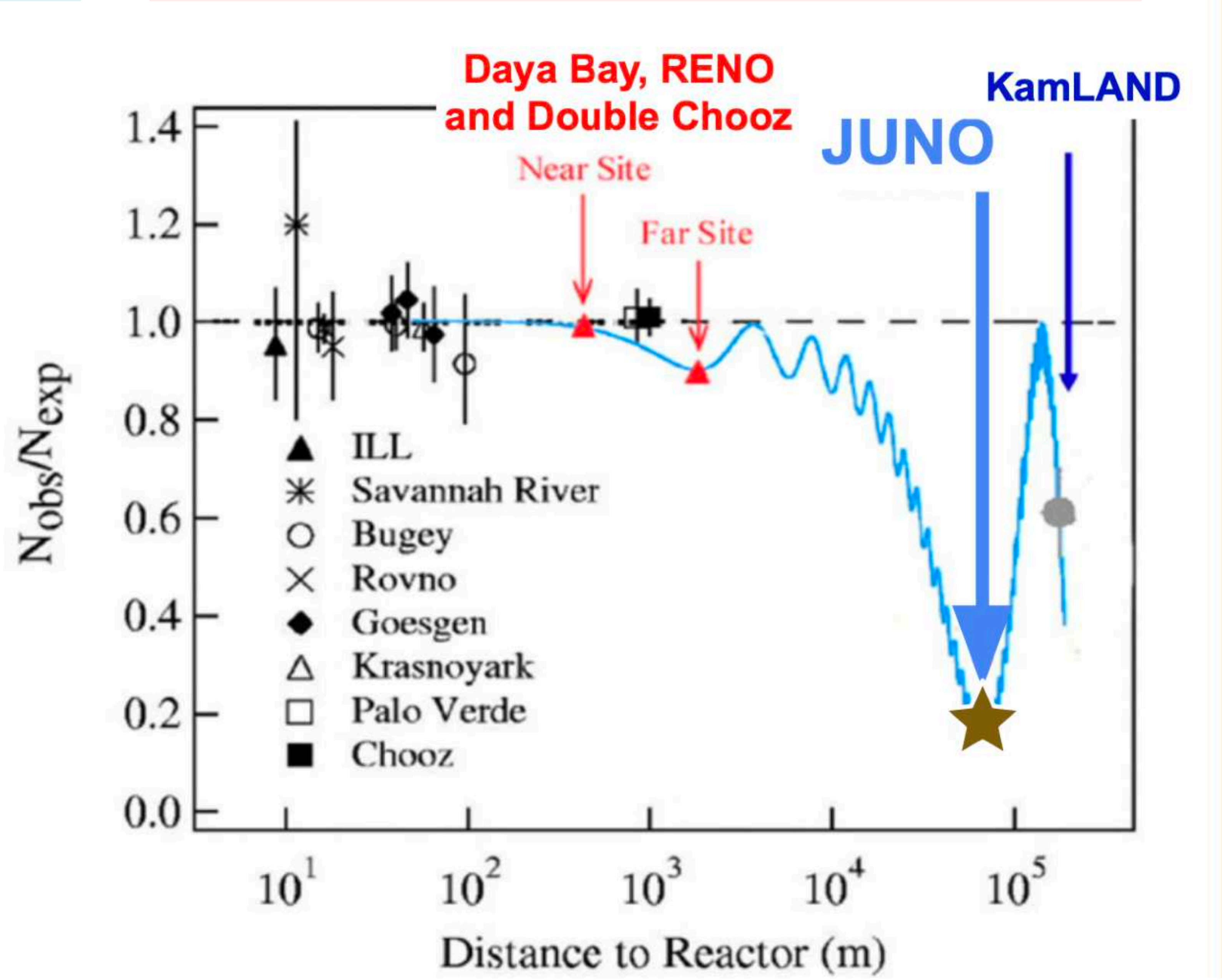


Jiangmen Underground Neutrino Observatory - JUNO

The concept

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

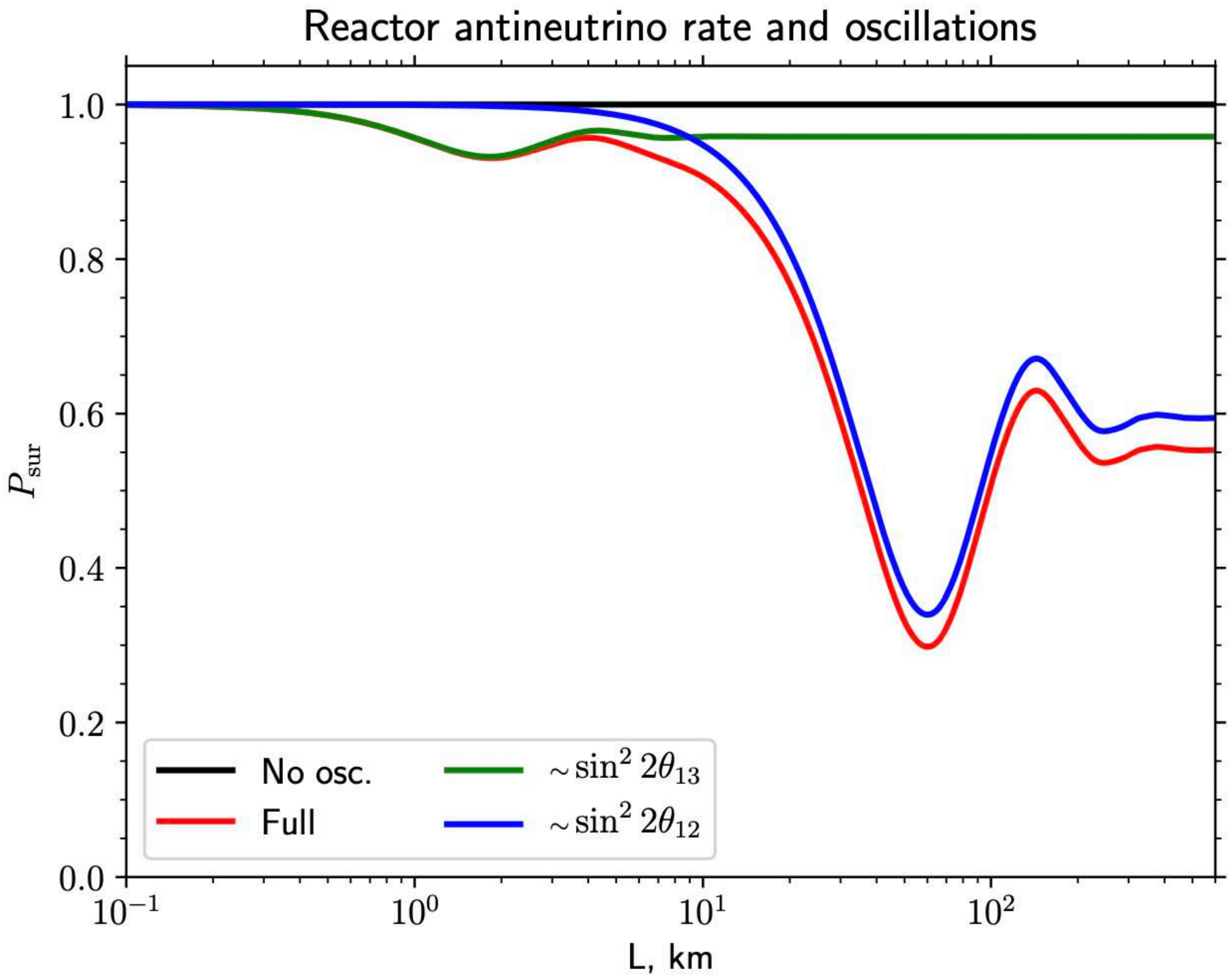


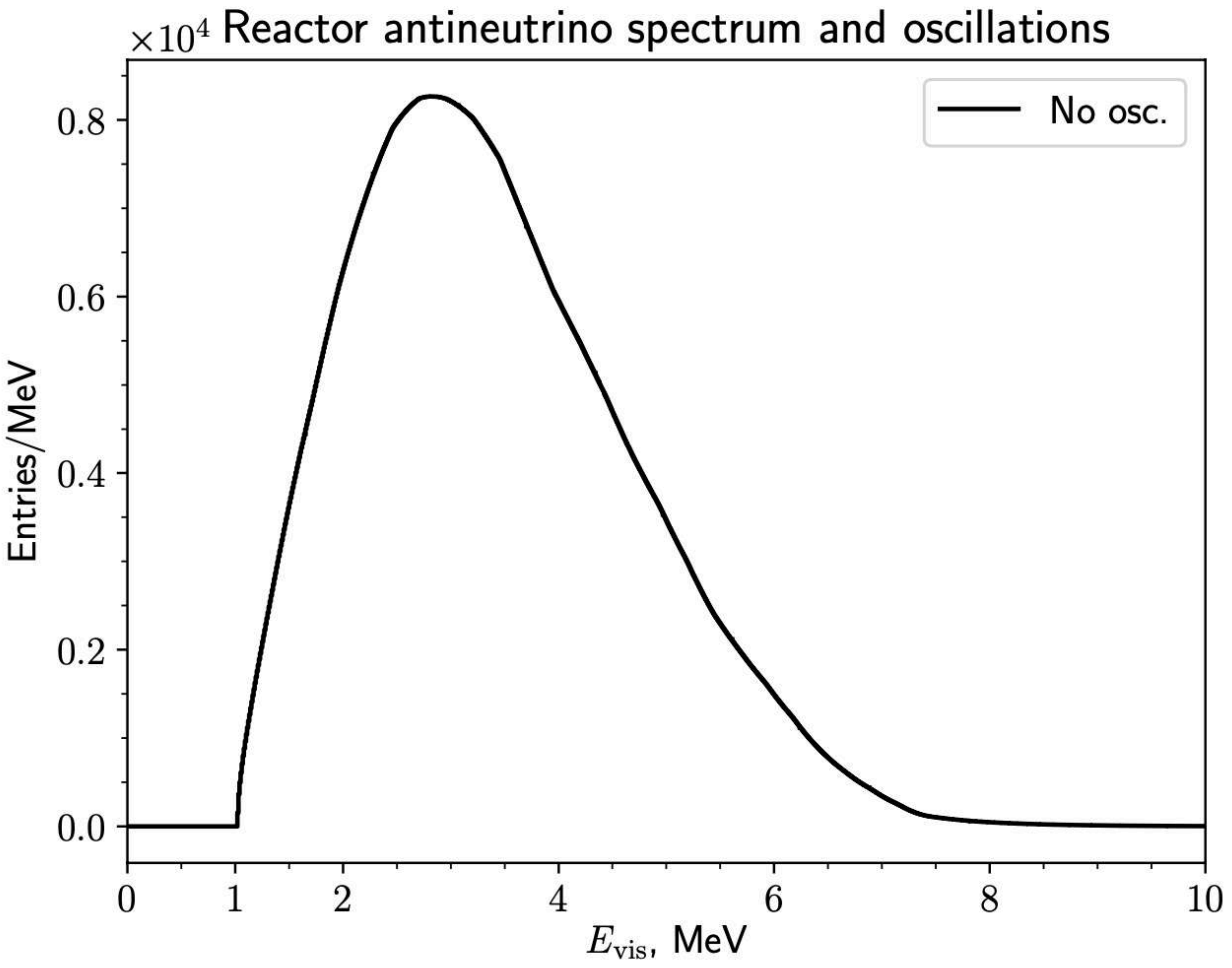


- Successor of the Daya Bay: continue using reactor neutrinos and liquid scintillator
- To determine the mass ordering (sign of Δm^2_{32}) independent of the CP phase δ
- Equal baseline to two reactor power plants: Yangjiang and Taishan

Oscillation of reactor antineutrino

Integrated with reactor $\overline{\nu}_e$ spectrum



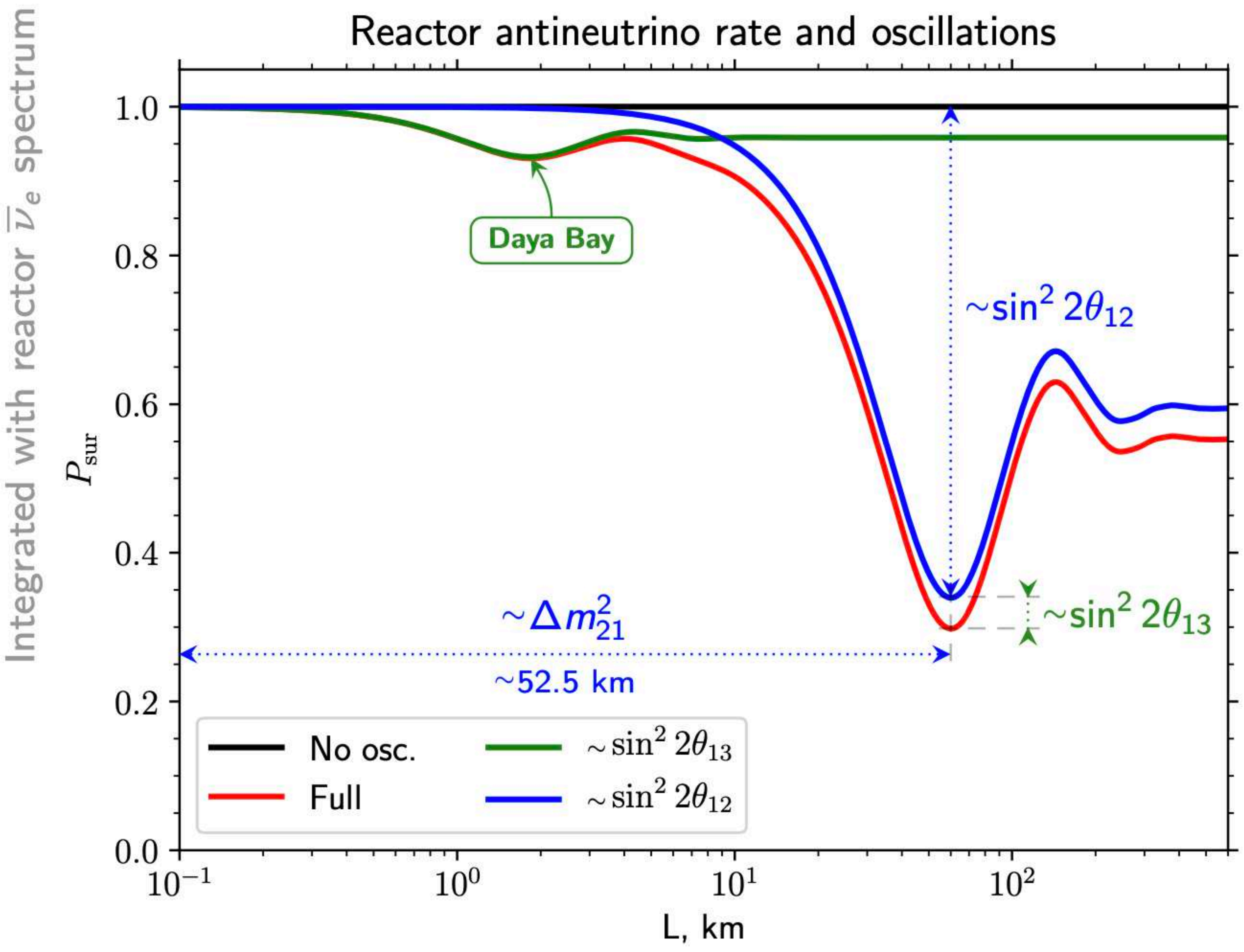


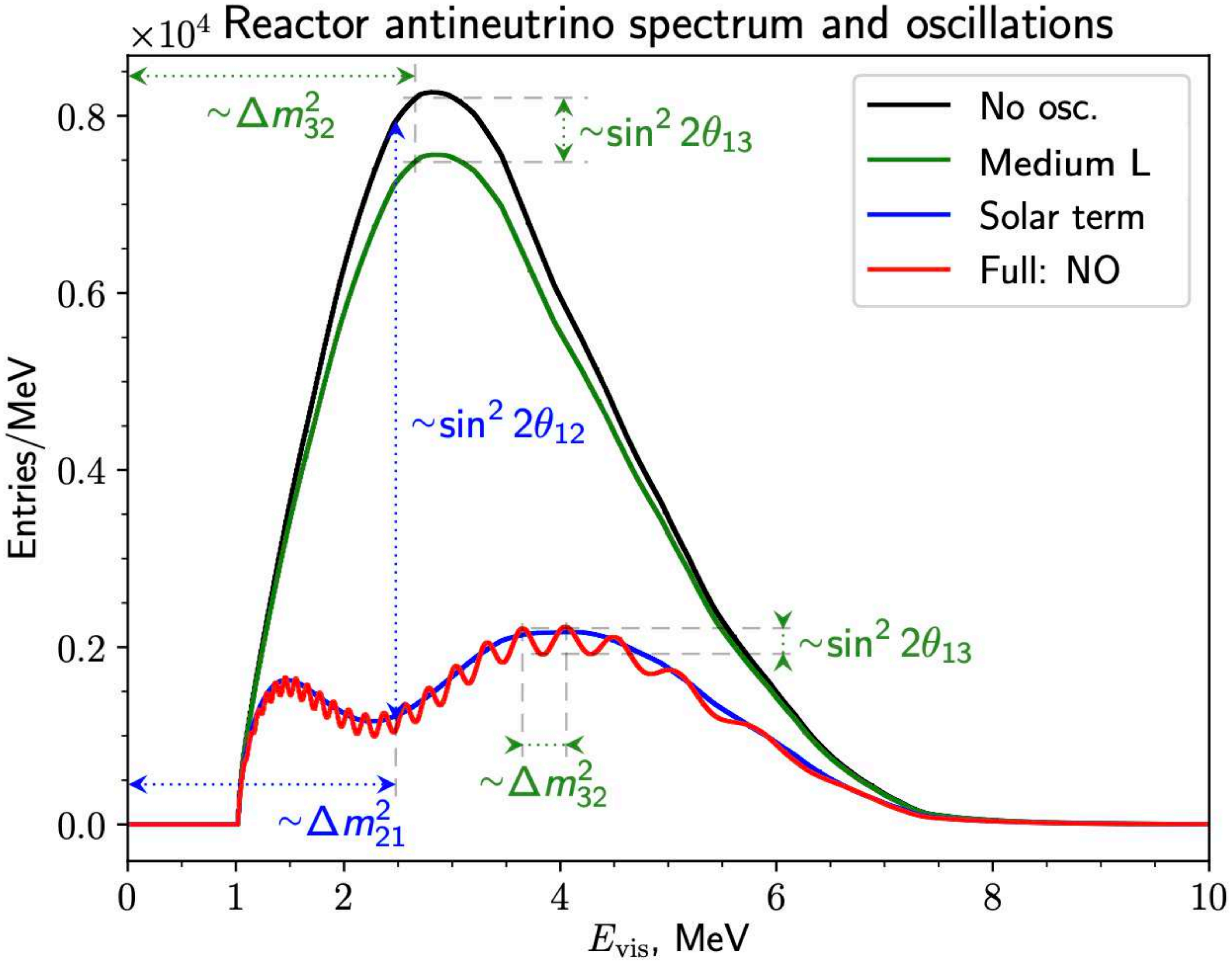
$$1 - P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13}\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

~~δ_{CP}, θ_{23}~~

$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$

Oscillation of reactor antineutrino





deficit value

minimum location

minimum location, solar

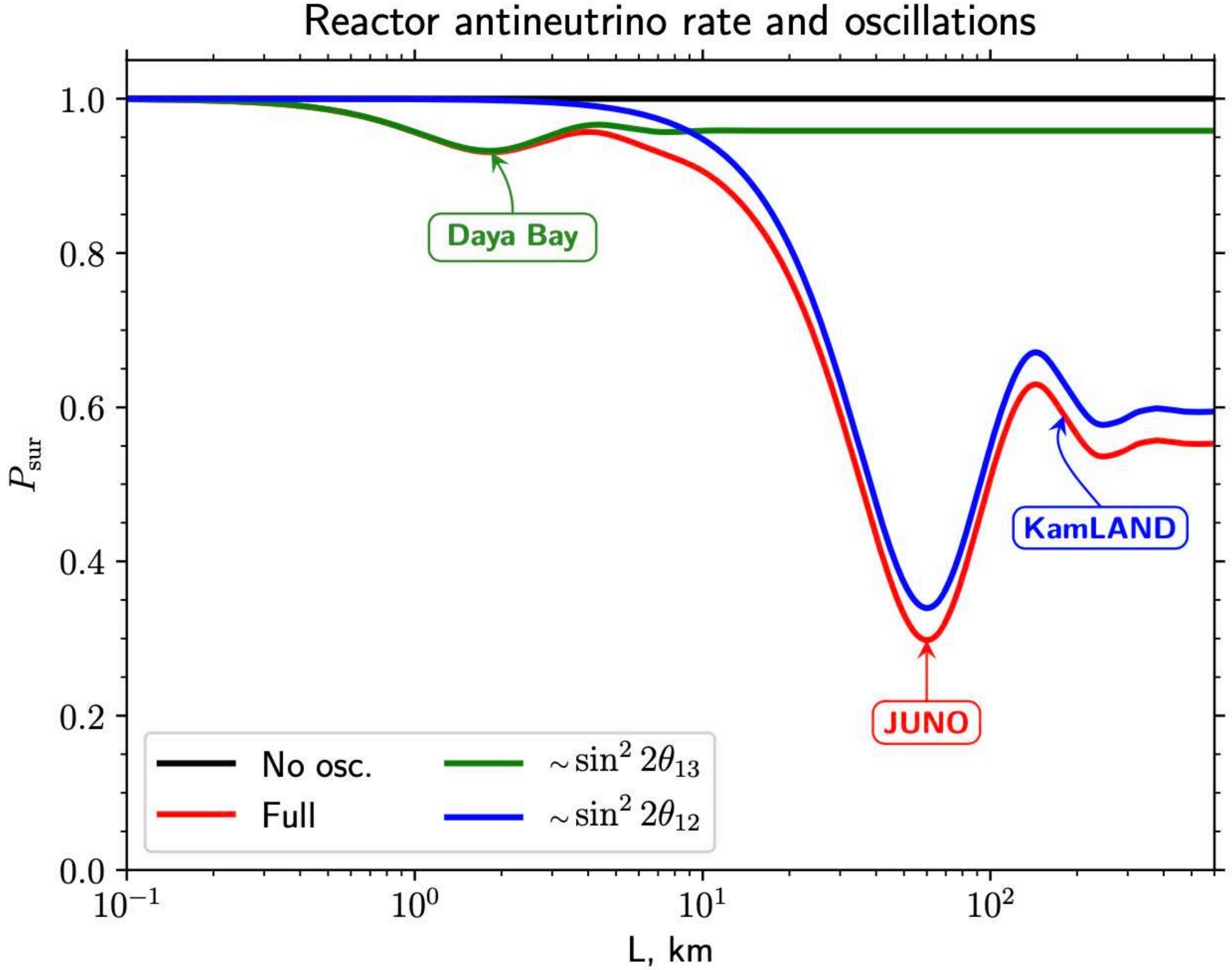
$$1 - P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13}\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

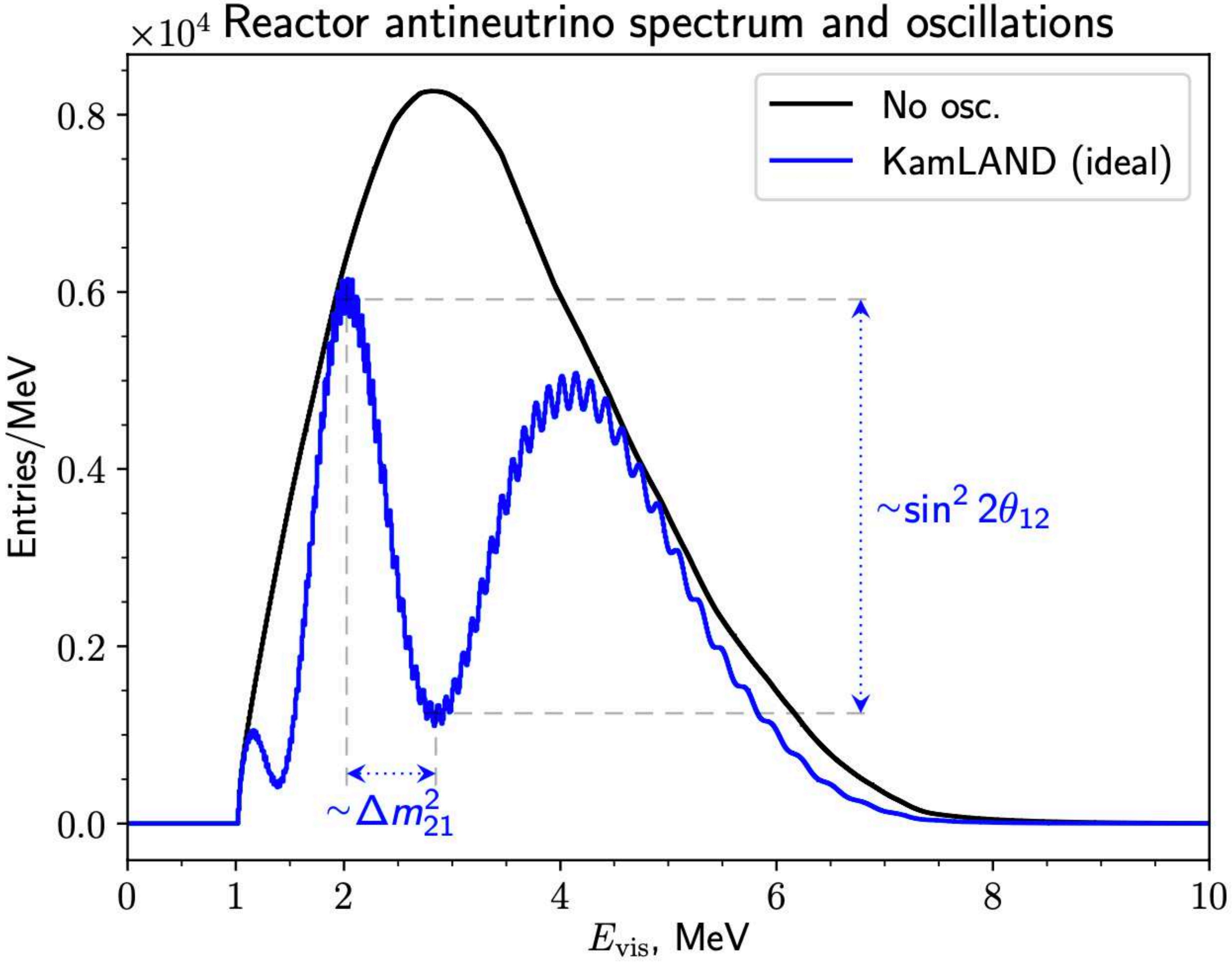
~~$\delta_{\rm CP}$, θ_{23}~~

$E_{\rm vis} \approx E_\nu - 0.78\,\mathrm{MeV}$

Oscillation of reactor antineutrino

Integrated with reactor $\overline{\nu}_e$ spectrum





deficit value

minimum location

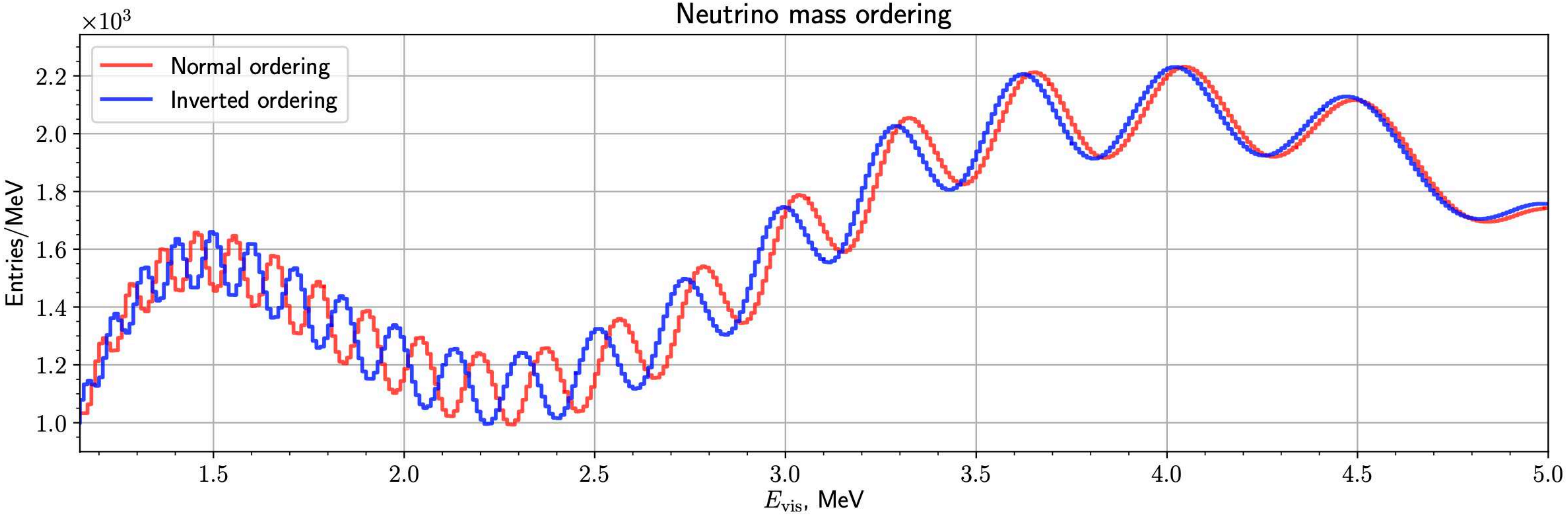
minimum location, solar

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

$E_{\rm vis} \approx E_\nu - 0.78\,\mathrm{MeV}$

Mass ordering determination

Shifted oscillation pictures

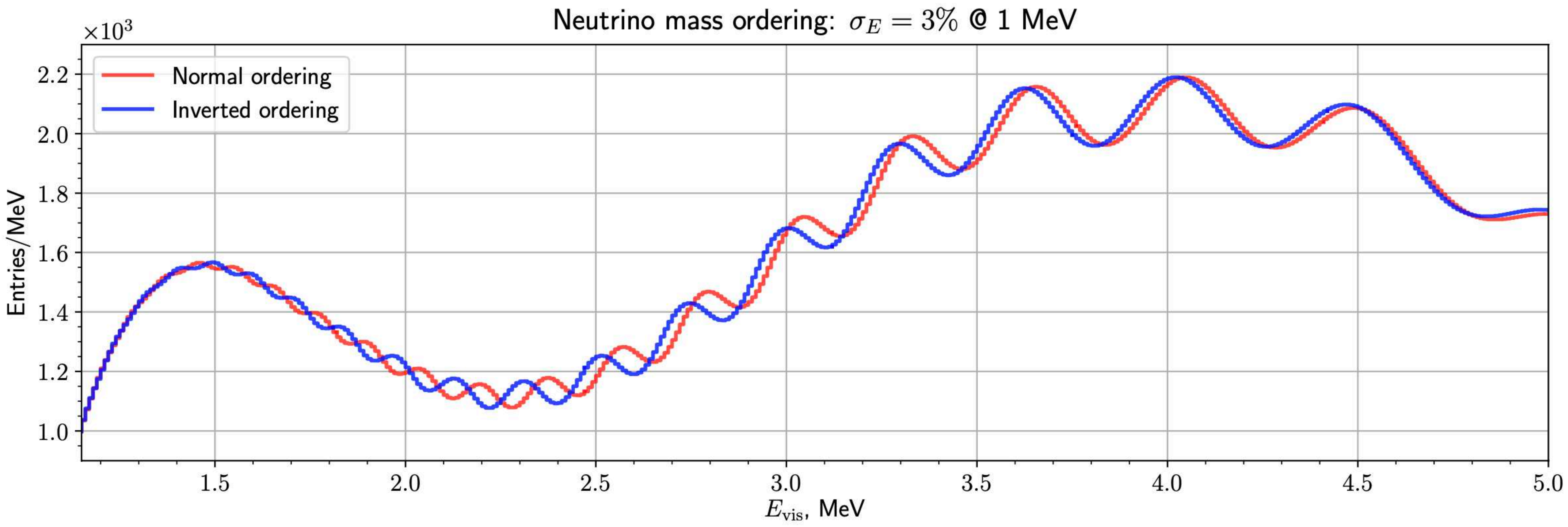


Energy resolution is important!

Knowledge of primary antineutrinos spectrum is needed!

Mass ordering determination

Shifted oscillation pictures

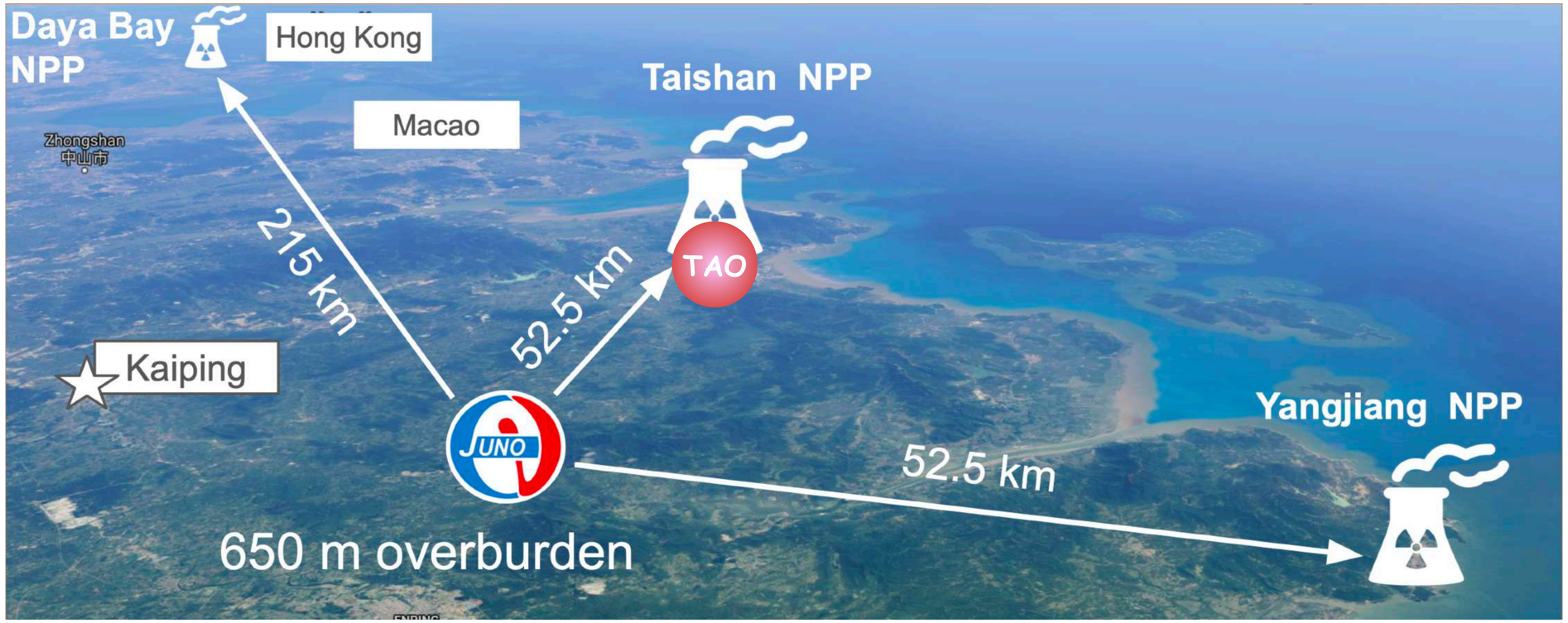


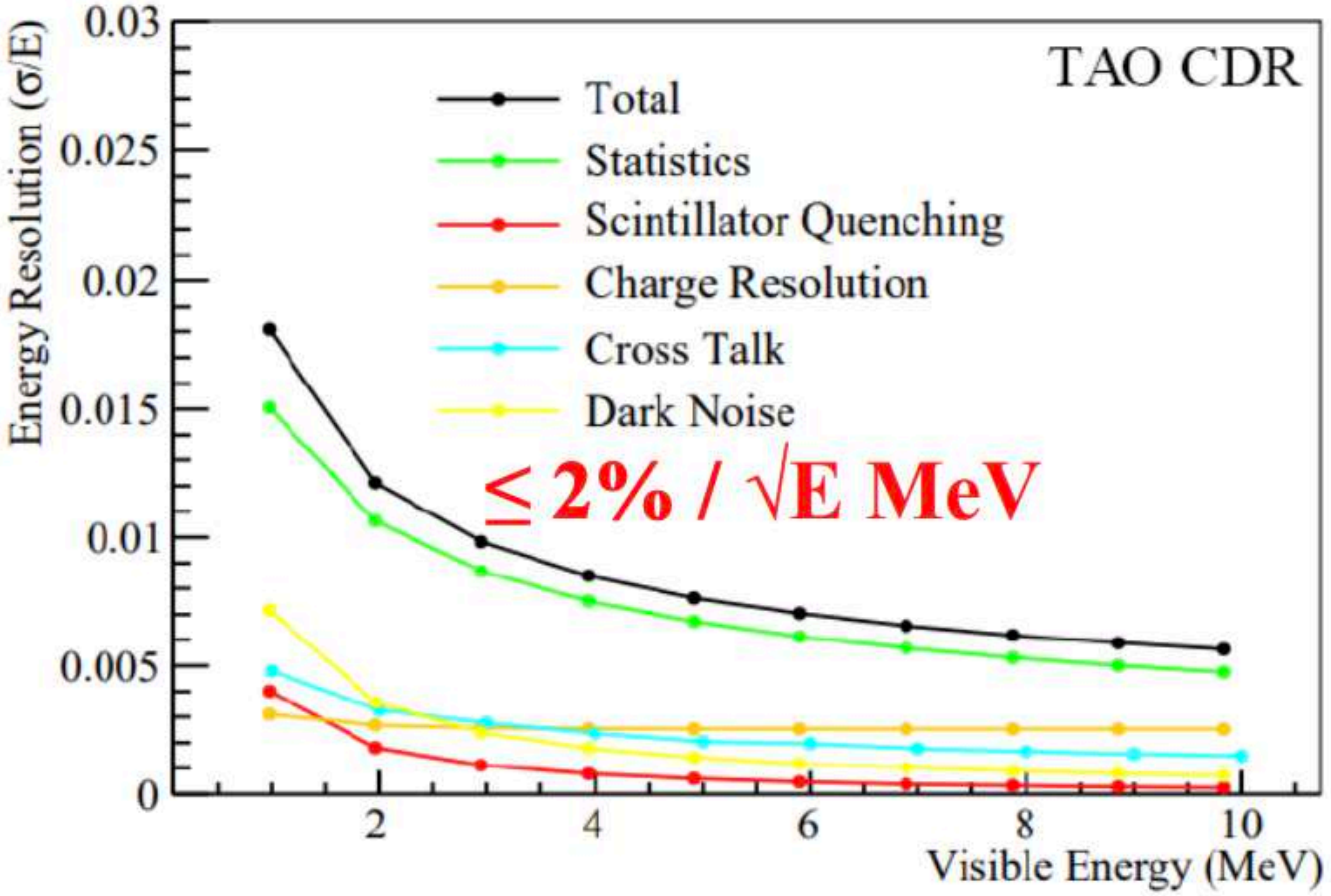
The energy resolution is 3% @ 1 MeV

Knowledge of the primary antineutrinos spectrum is needed

Taishan Antineutrino Observatory - TAO

JUNO’s satellite detector





TAO location is 44 m from a reactor core

Reactor antineutrino spectrum with Energy resolution $\lesssim 2\,\%$

JUNO site

Surface buildings/campus:

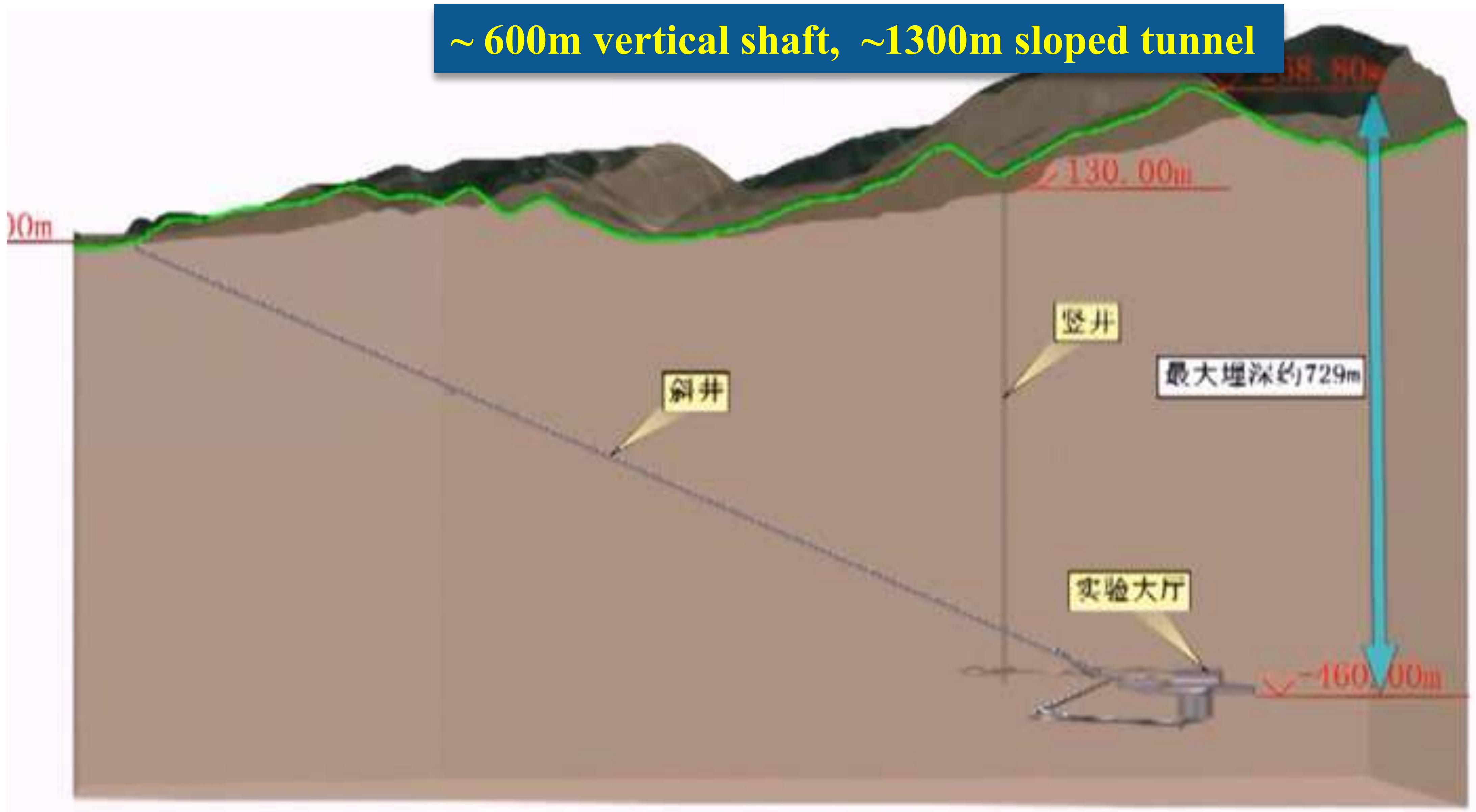
- Surface Assembly Building
- LAB storage (5k ton)
- Water purification/Nitrogen
- Computing
- Power station
- Cable train
- Office/Dorm

Vertical Shaft, 564 m
put into use in 2023

~ 650 m
R_μ ~ 0.004 Hz/m^2
$\langle E_\mu \rangle$ ~ 207 GeV

Slope tunnel, 1266 m

Civil Construction



~ 600m vertical shaft, ~1300m sloped tunnel

More water than expected:

- —Max water inflow ~ 600 m^3/h
- —Survey shows rock resistivity is low
- —Bore holes found no water
- —Water is mostly from cracks and faults

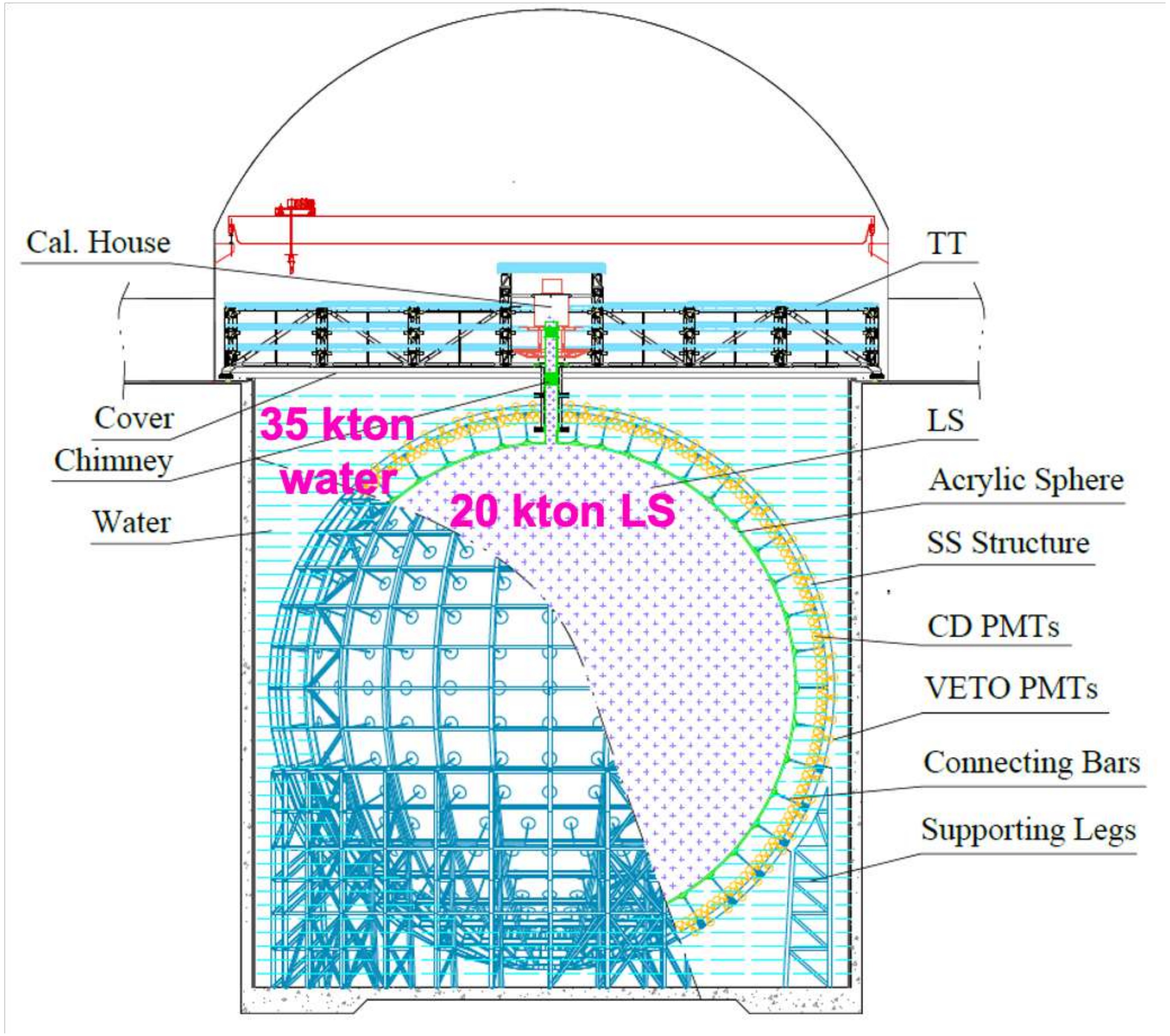
Mitigations:

- — Drill holes to inject cement to seal water
- — Elevate the hall by 35 m
- — Add a tunnel at the top of the hall to release the water pressure

Delayed by ~ 4 years

2015.11.06 16:52

JUNO central detector



Acrylic Sphere:

Inner ø=35.4m

Thickness:12cm

Steel Structure:

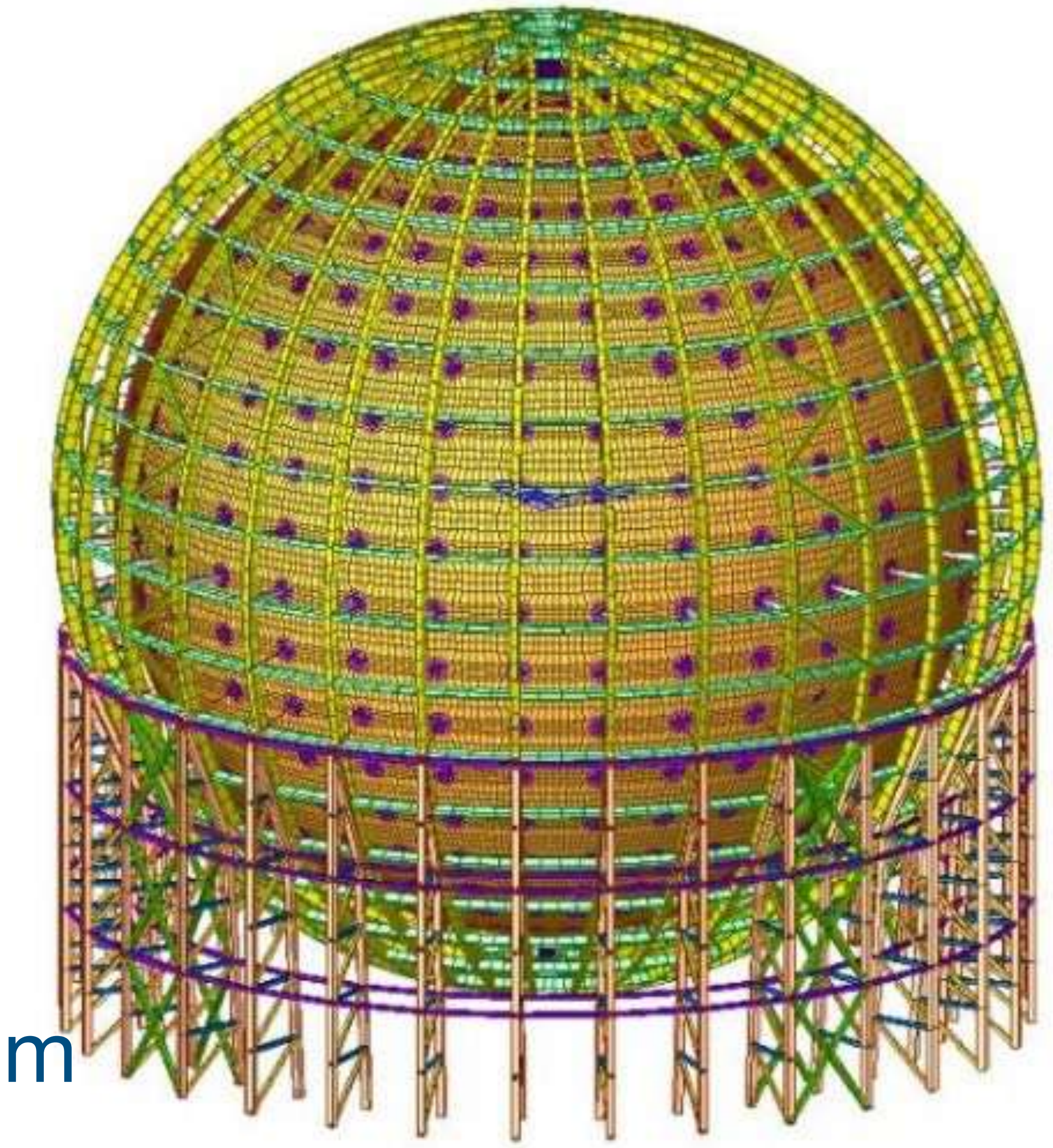
Inner ø=40.1m,
Outer ø= 41.1m

17716 20-inch PMTs,
25600 3-inch PMTs

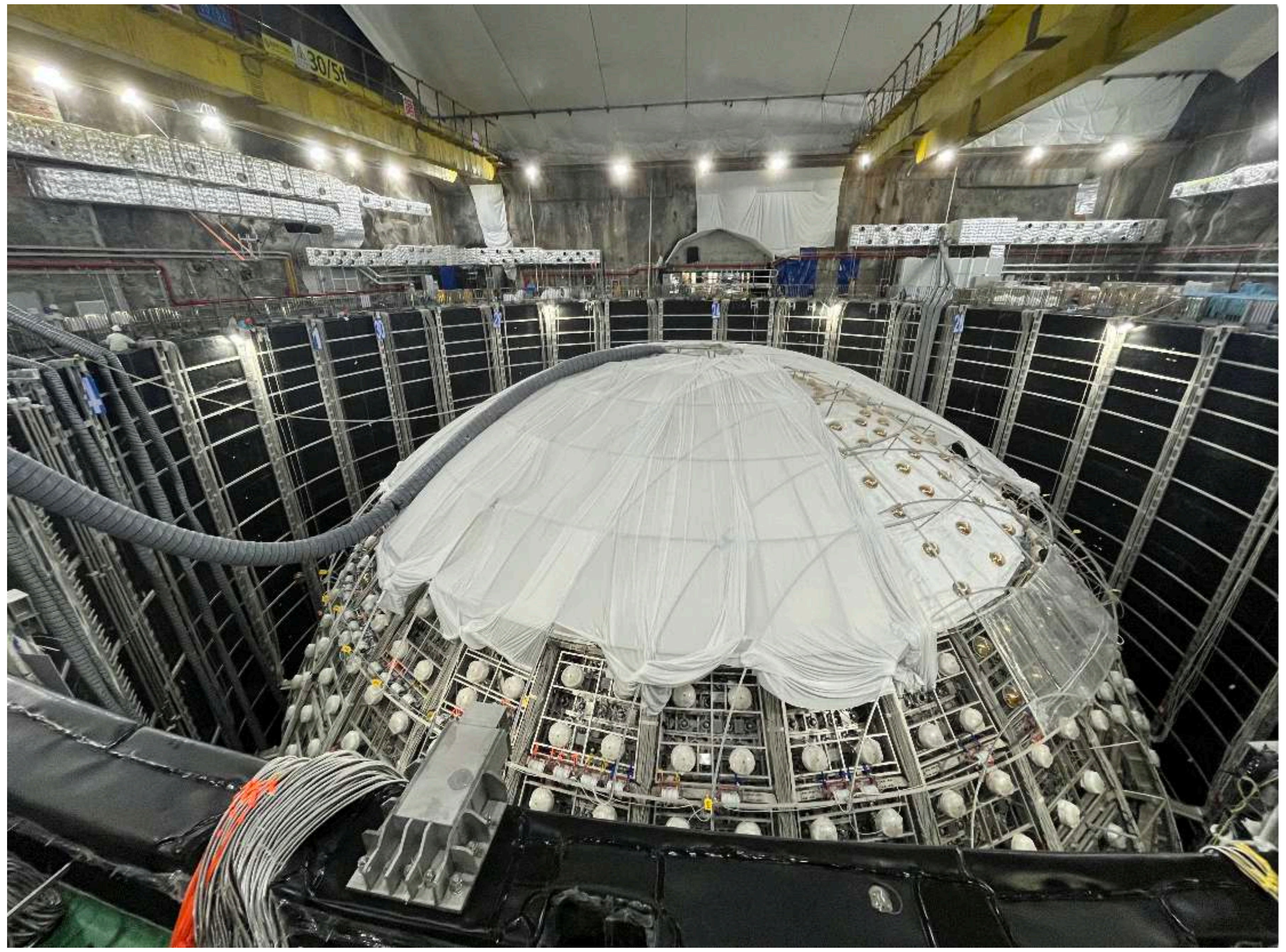
Water pool:

Inner ø=43.5m,
Height: 44m, Depth: 43.5m

2400 20-inch PMTs



JUNO central detector



35.4 m spherical acrylic vessel supported by **41.1 m** Stainless Steel structure via **590** supporting bars.

Steel structure completed **except bottom 4 layers**

Acrylic panel production completed

A special production line for low backgrounds (**< 1 ppt U/Th/K**)

Shaping, sanding/polishing, cleaning, machining and protection of panels by PE film, while maintaining **high transparency (>96%)** and low surface background **(<5 ppt U/Th in 50 mm thickness)**

Acrylic vessel construction on-going

Acrylic built from the top, **17/23 layers finished**, defects repaired

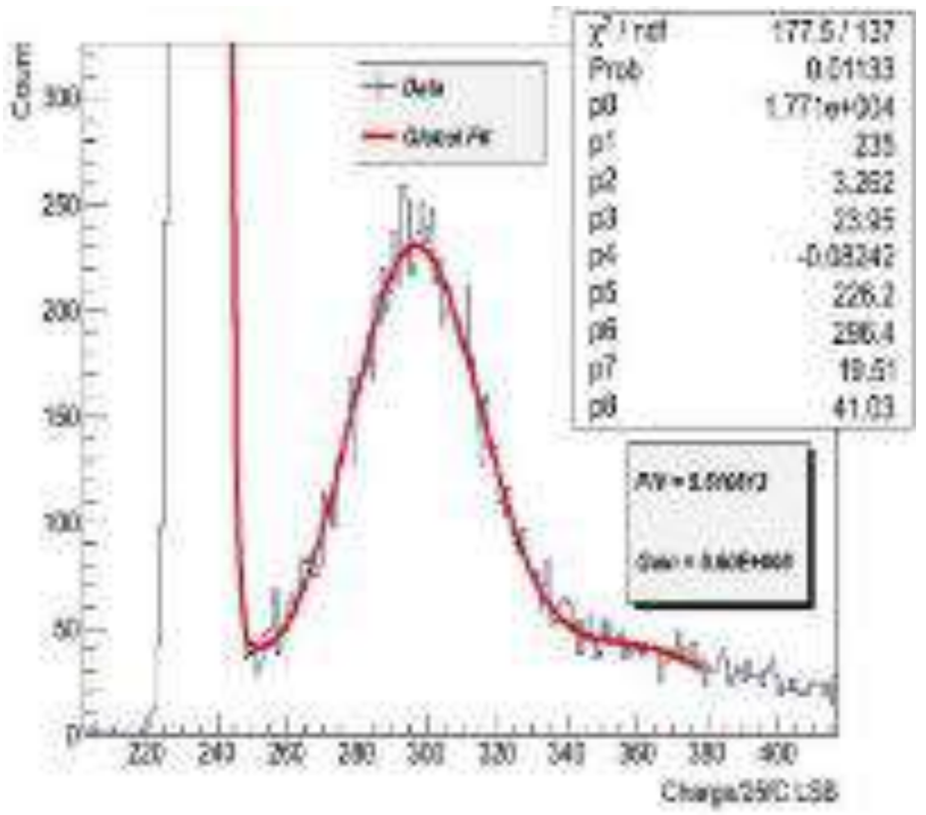
20 inches PMT

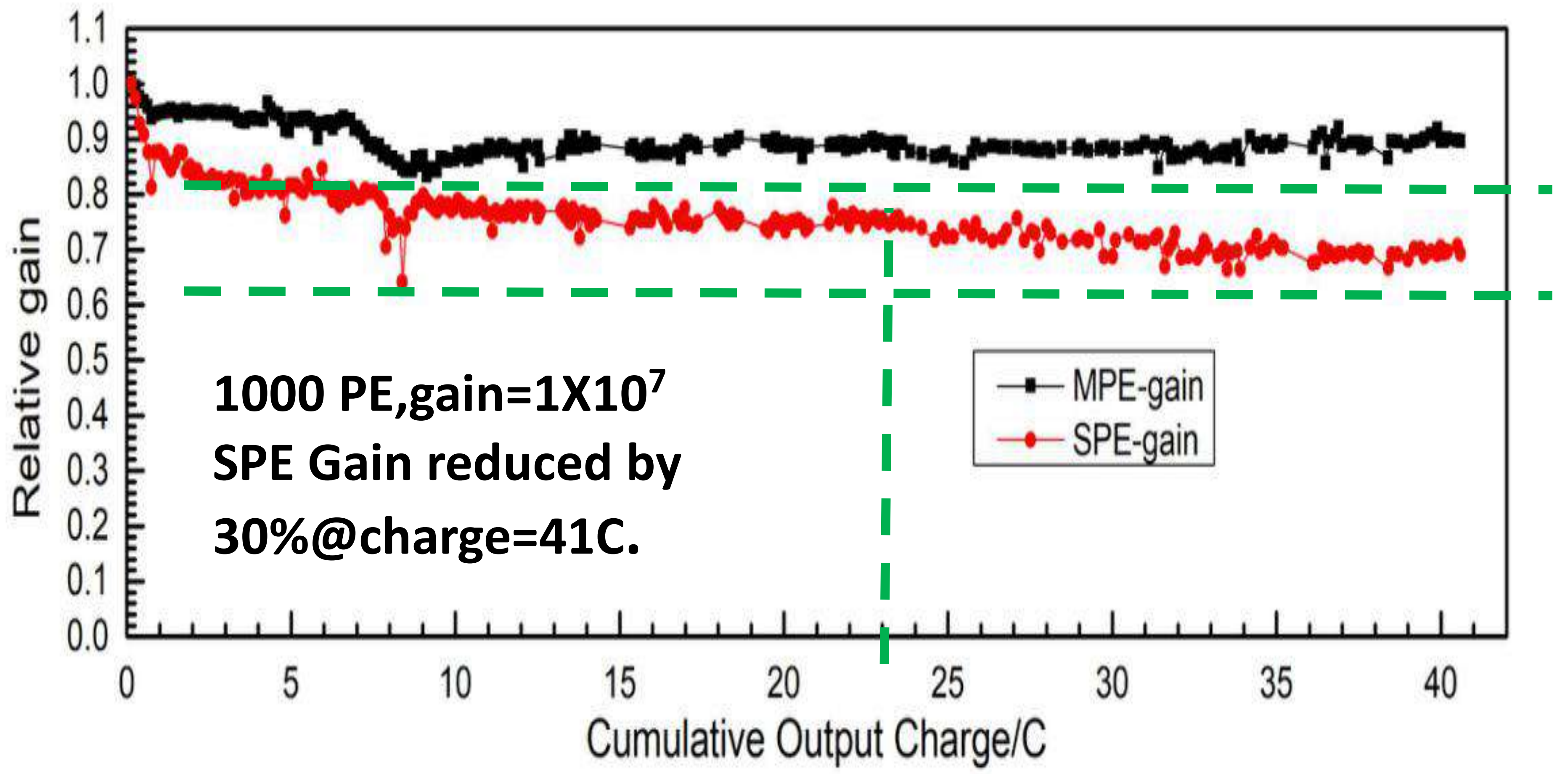
Micro-Channel Plates (MCPs) instead of dynode:

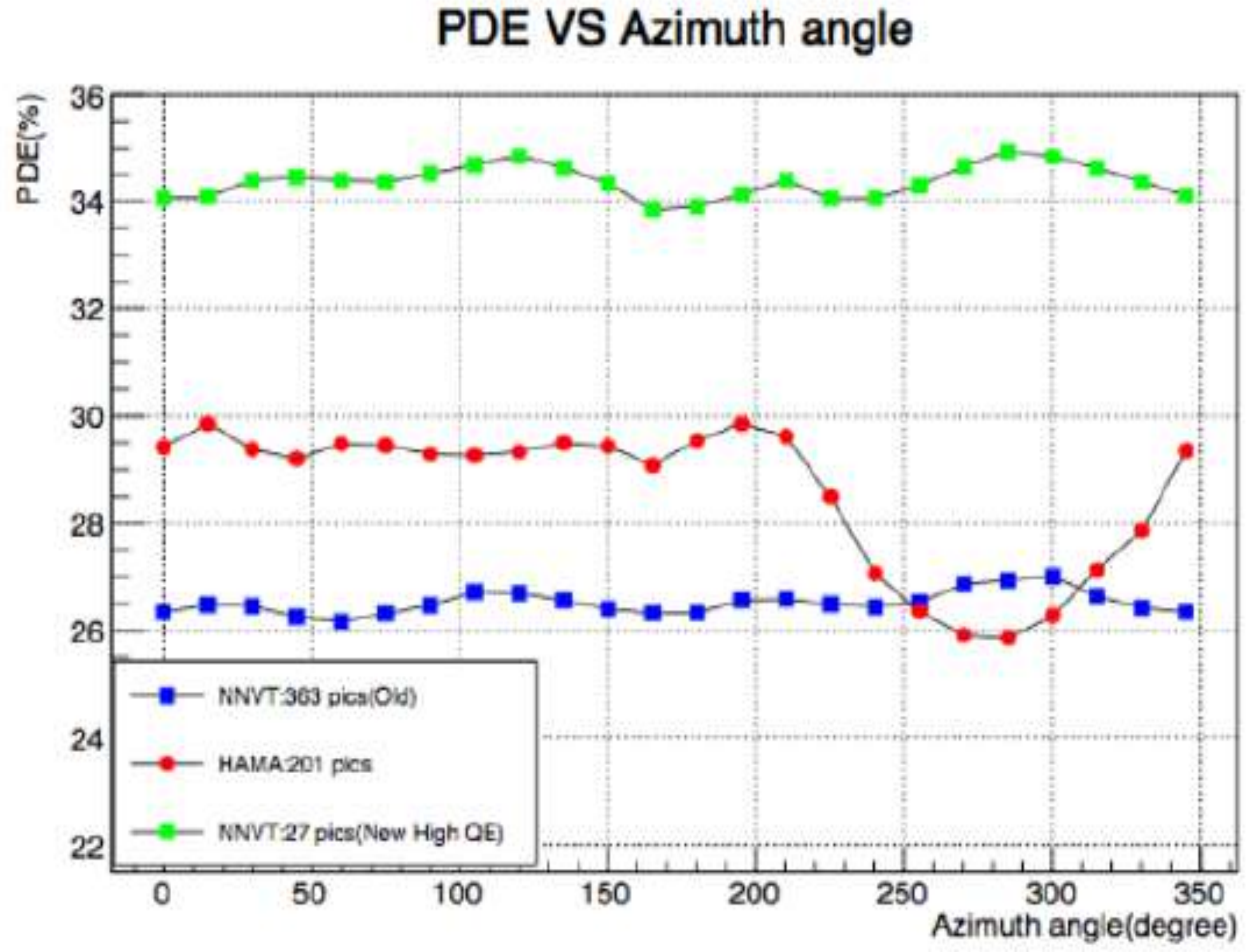
- IHEP & NNVT jointly developed technologies & prototypes
- Higher collection efficiency
- High **Photon Detection Efficiency ~30%**, low backgrounds glass, …
- High production yield, automatic mass production
- Hamamatsu developed 20” Super Bialkali PMTs
- Purchase optimized considering performance, cost, risk, etc.

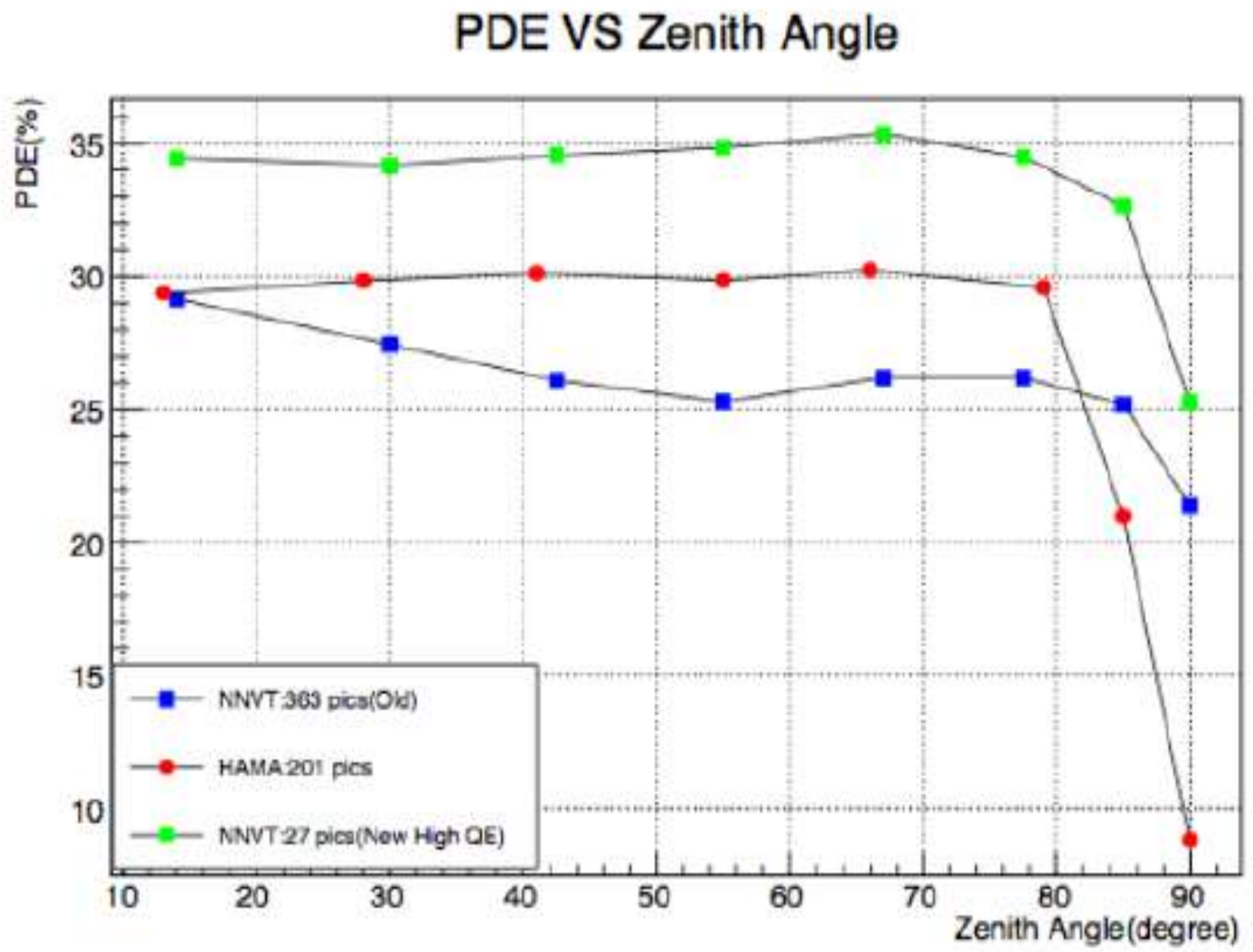
MCP-PMT: 15012

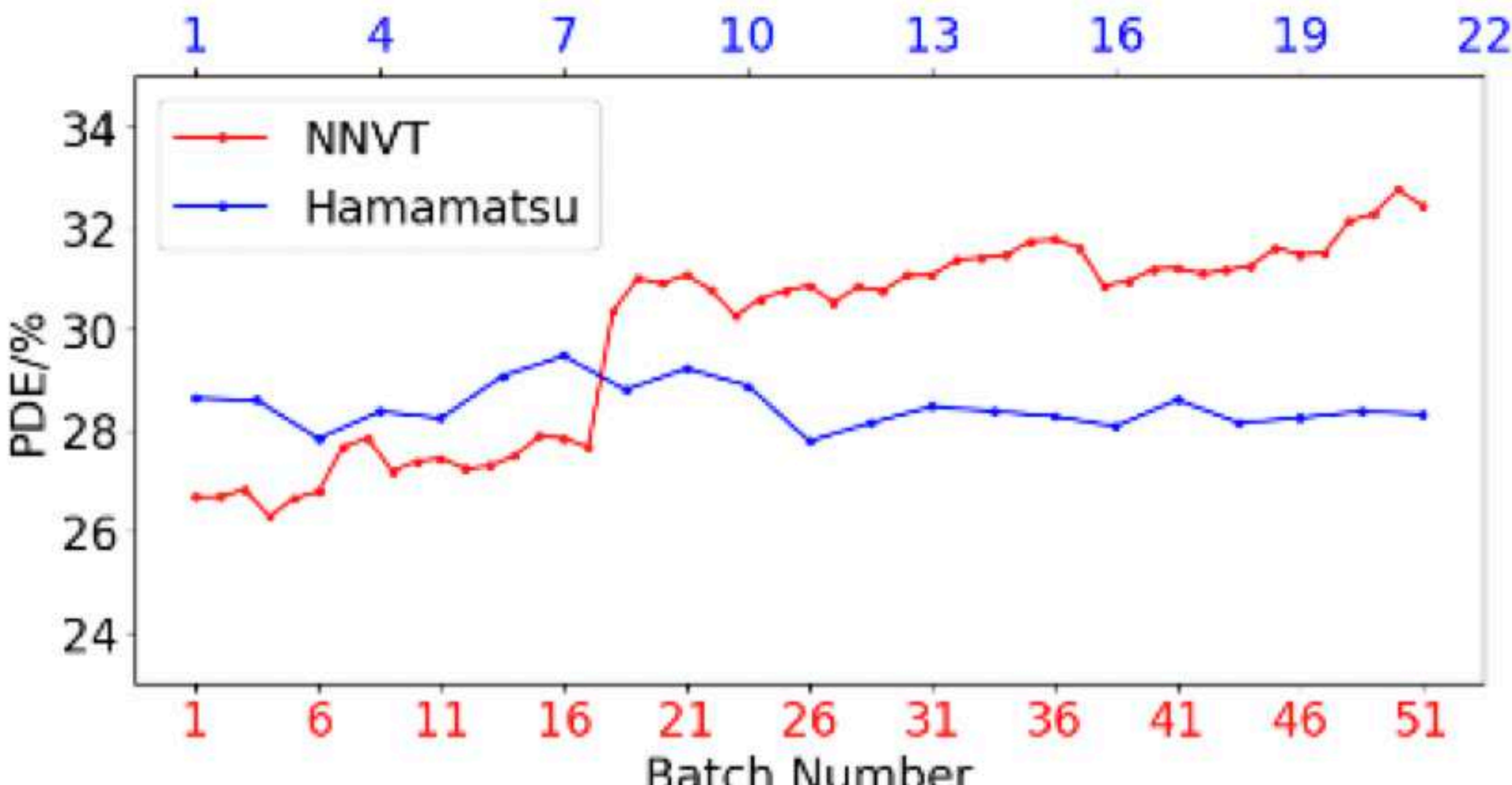
Dynode PMT(Hamamatsu): 5000




1000 PE,gain=1X10^7
SPE Gain reduced by
30%@charge=41C.







Large PMT Instrumentation

All PMTs tested in the Container (integral measurements)

Around **2500 tested by scanning station (zone characteristics)**

All PMTs delivered and their performance tested - OK

Water proof potting:

– Required failure rate<0.5%/6 years

– Technology invented, aging and pressurized tests are satisfactory

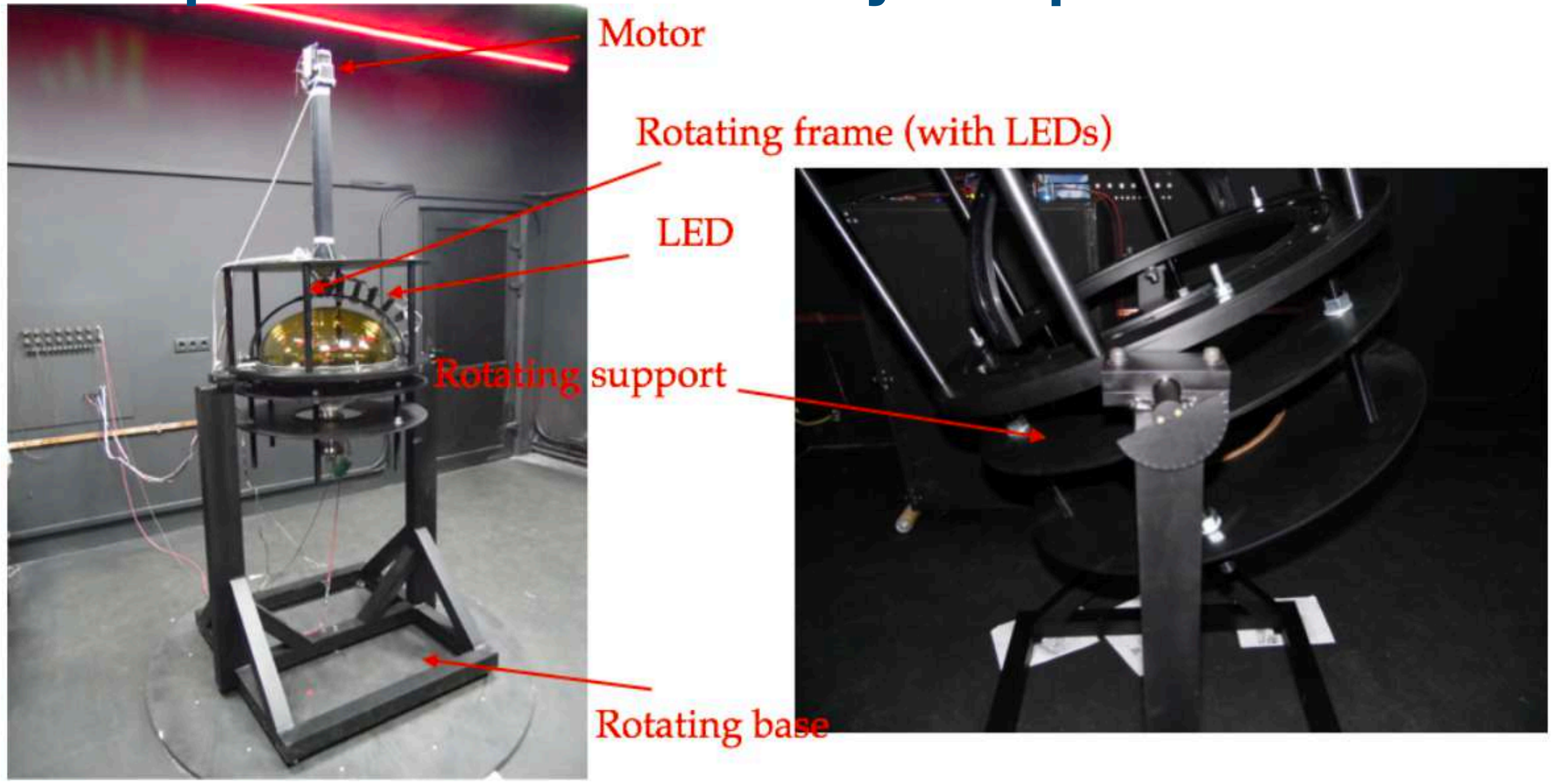
Implosion protection:

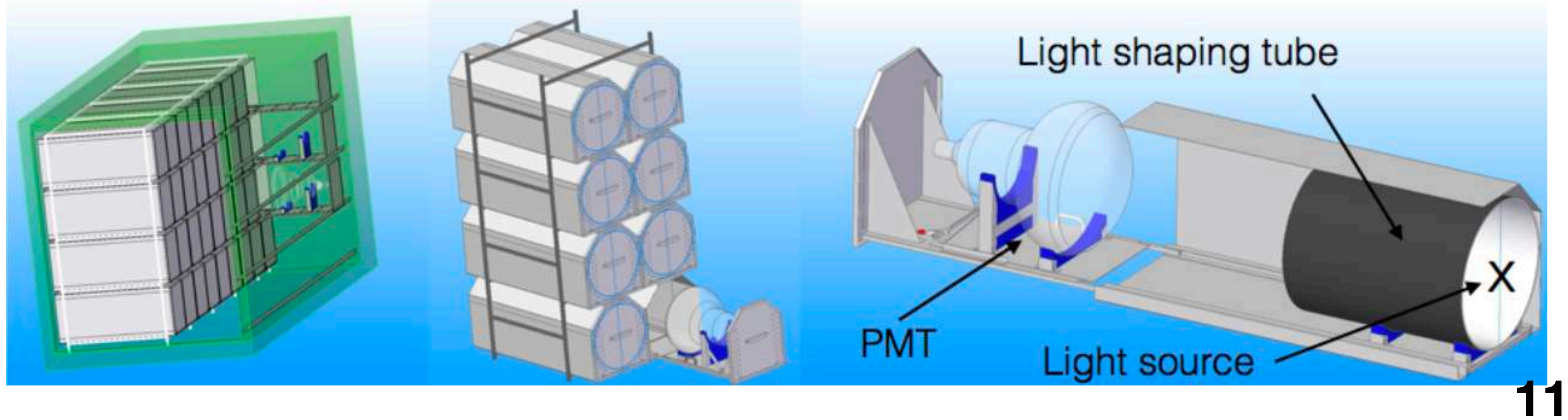
– Acrylic top & SS bottom

– Final test: no chain reactions

Mass production successfully completed

Implosion test of PMTs on the module structure



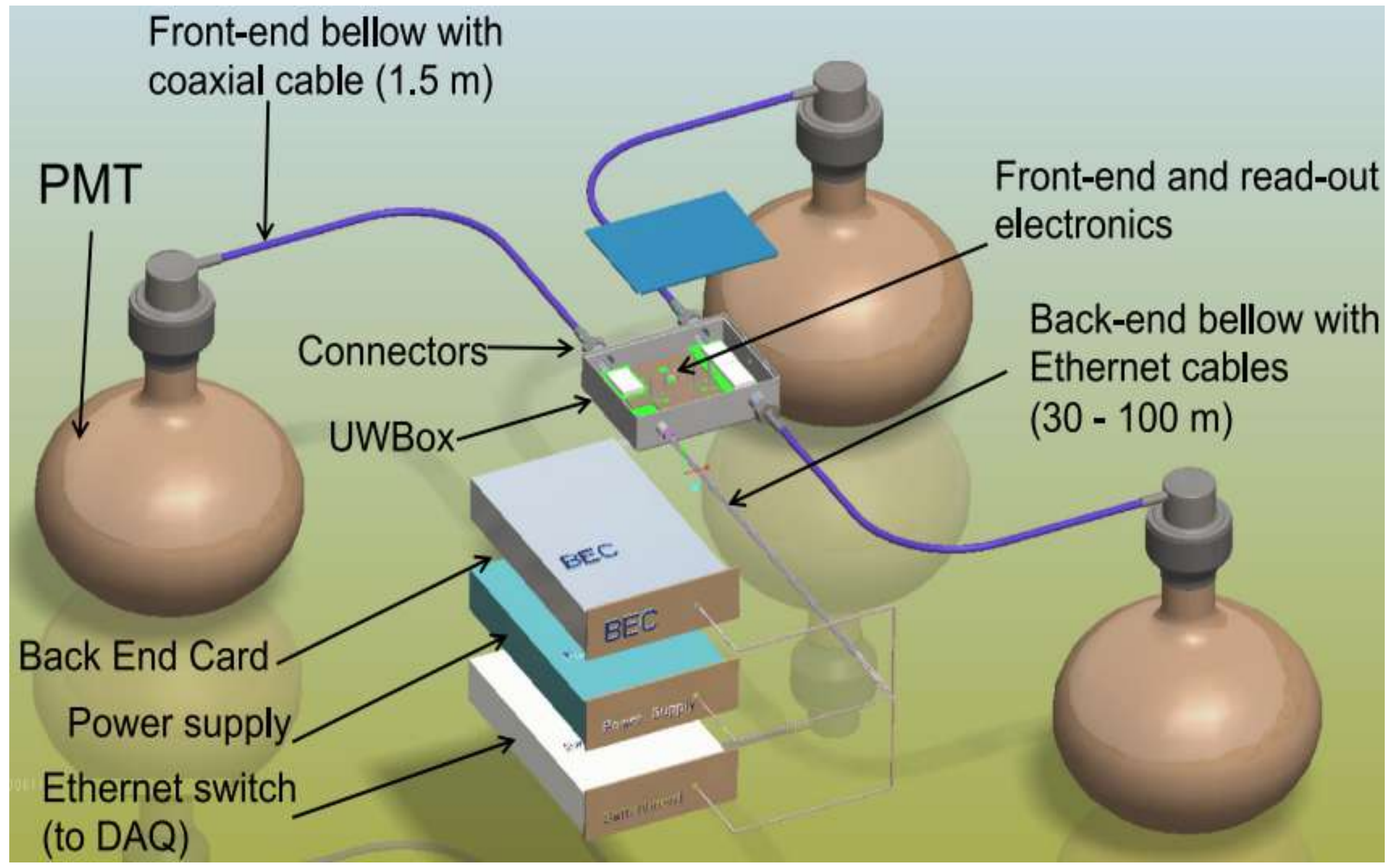


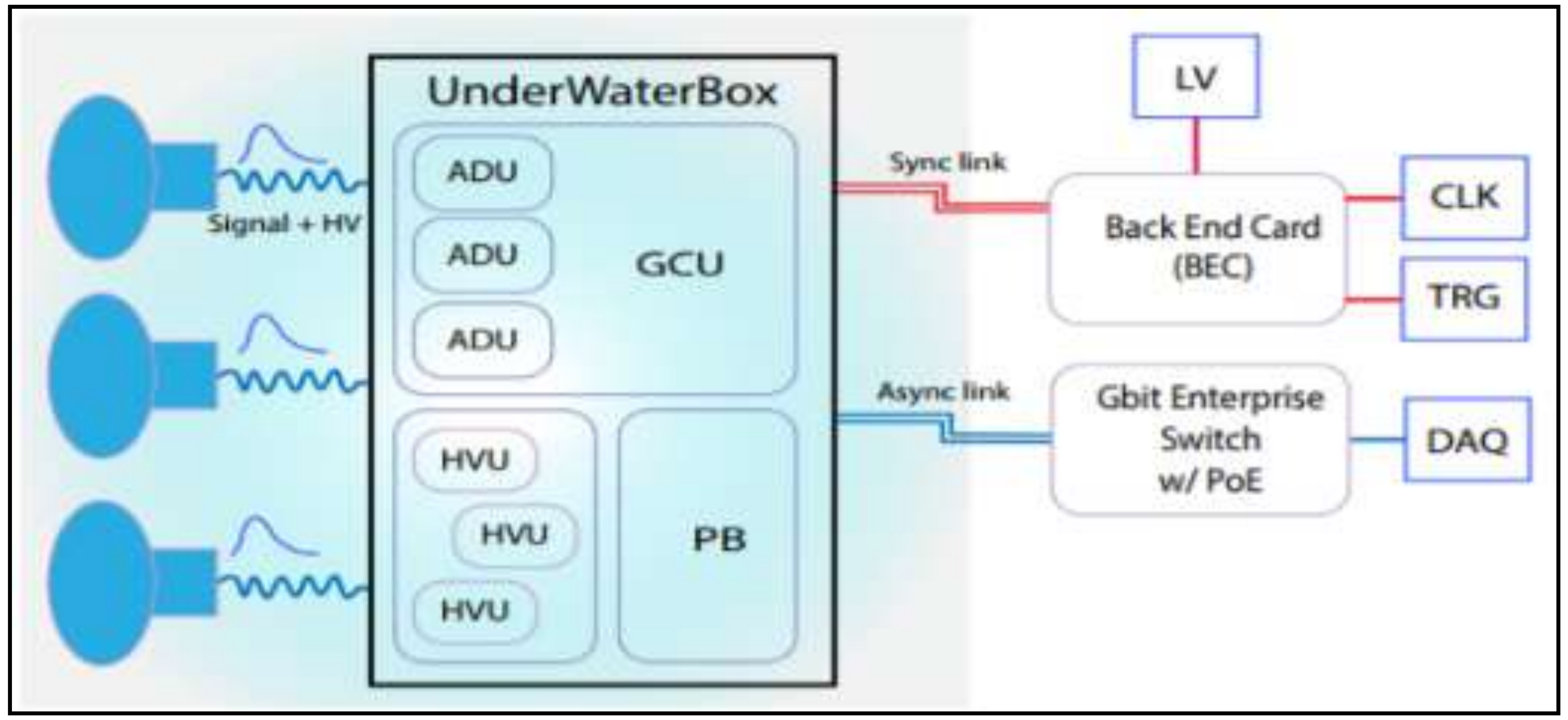
Large PMT Electronics

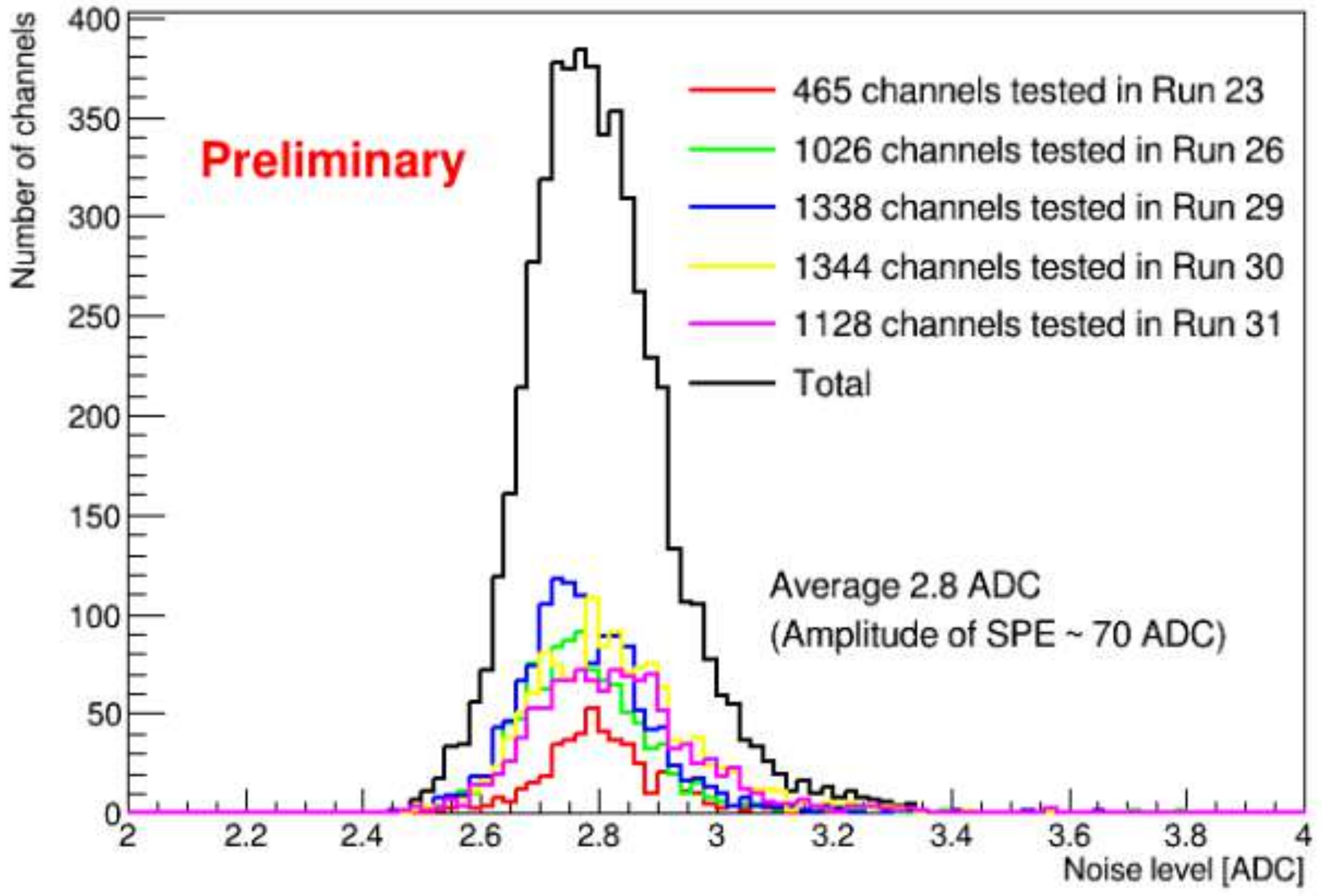
- **~20000 ch., each with 100 m long cable**
- **Dynamic range: 1- 4000 PE**
- **Noise threshold: < 10% of 1 PE**
- **Resolution: < 10% @ 1 PE, <1%@100 PE**
- **Failure rate: < 0.5%/6 years**

Design

- **1 GHz FADC** in an underwater box (**3 ch./box**), connected to PMTs by **water proof** connectors and < **2 m long cables**
- All cables in corrugated steel pipes for **water proof**
- **3 HV units** (controlled by GCU)







Joint **PMT-electronics-DAQ-software test shows** that all installed PMTs and related **systems work well**

Noise level is ~ 0.05 PE: good grounding and shielding

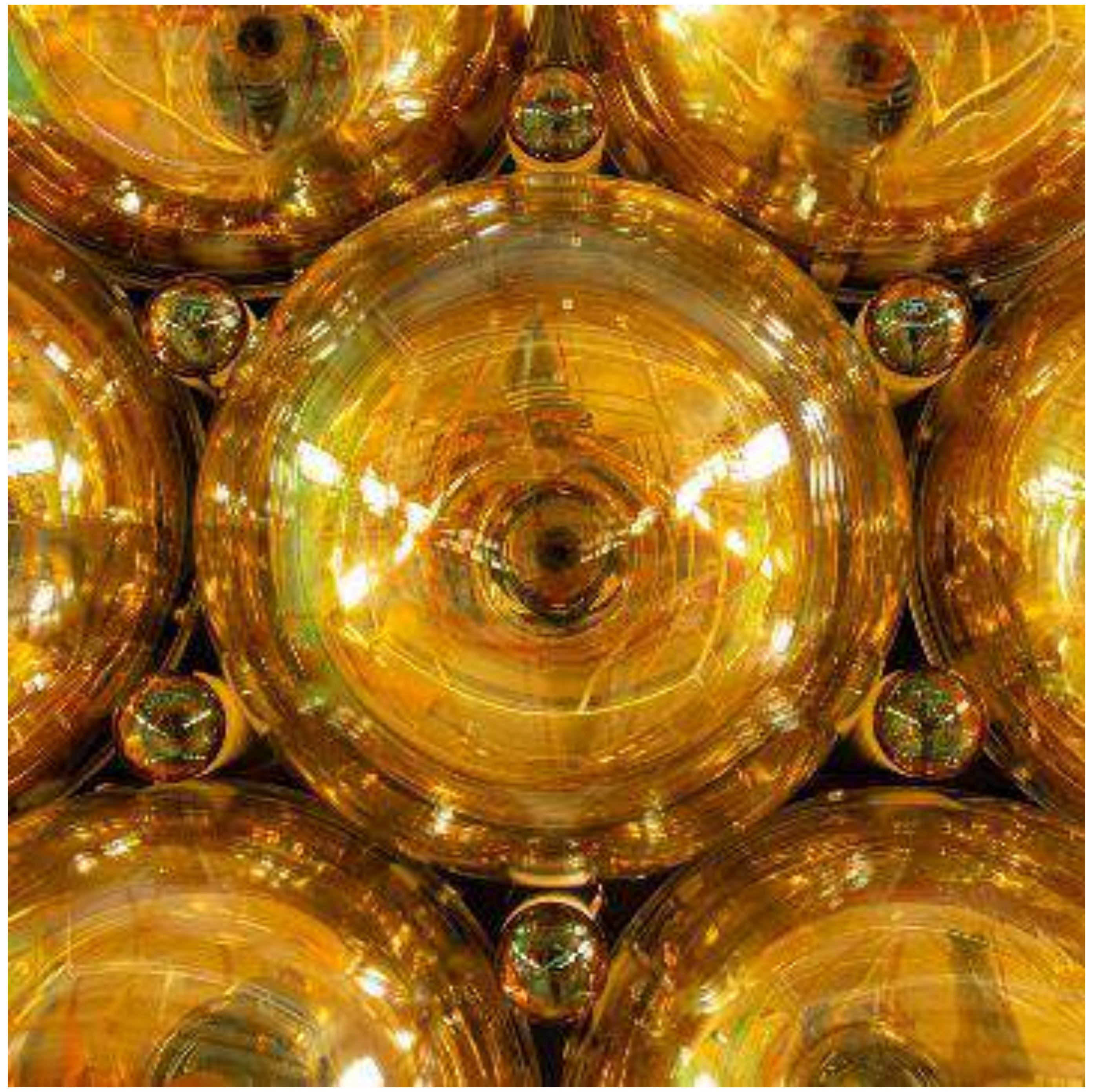
Small 3-inches PMT

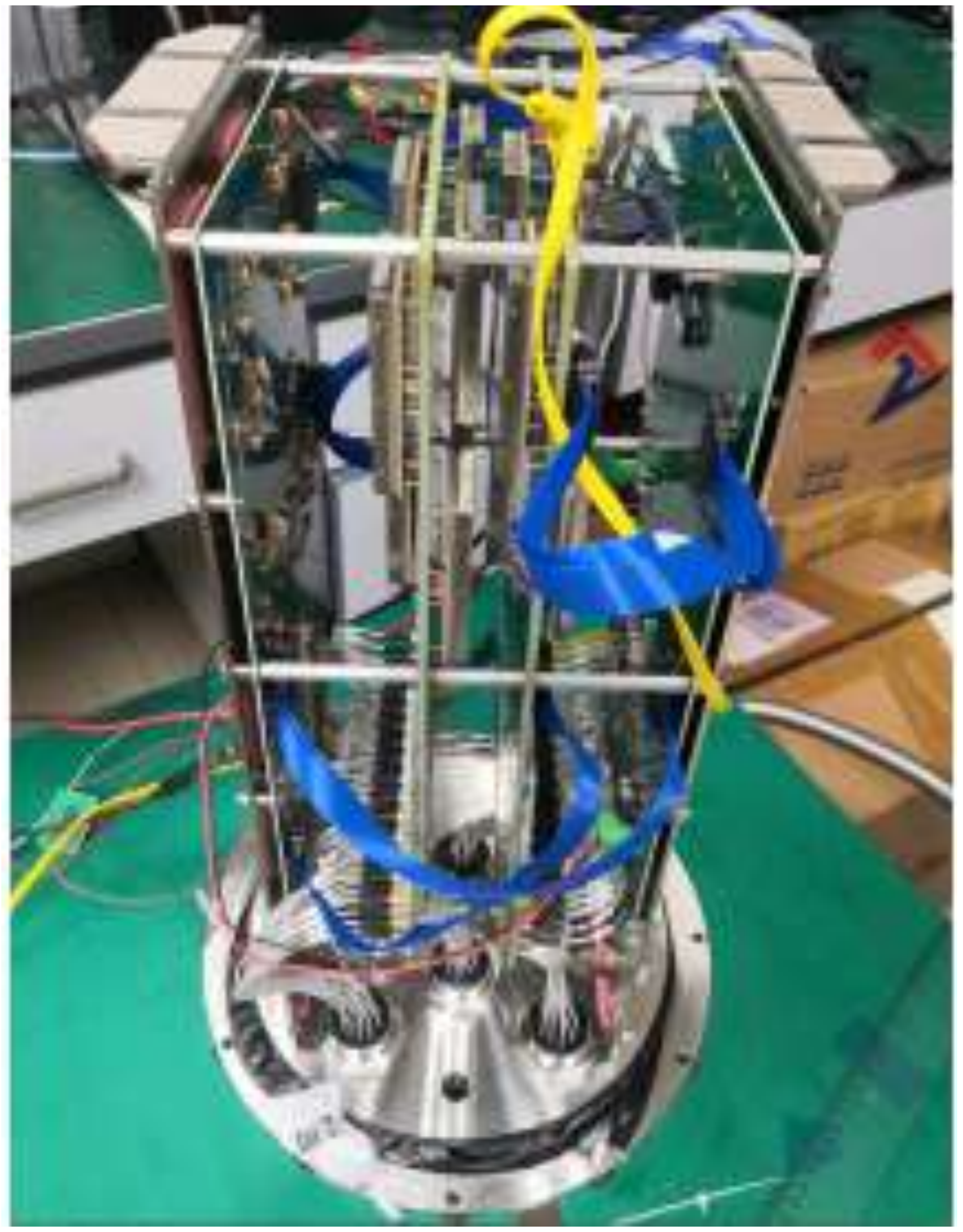
Goal: 3% more light, higher dynamic range for muons, uniformity and linearity calibration for large PMTs, …

Mass production and waterproofing of **26,000 3.1” PMTs (XP72B22) from HZC** Photonics completed, and tested OK

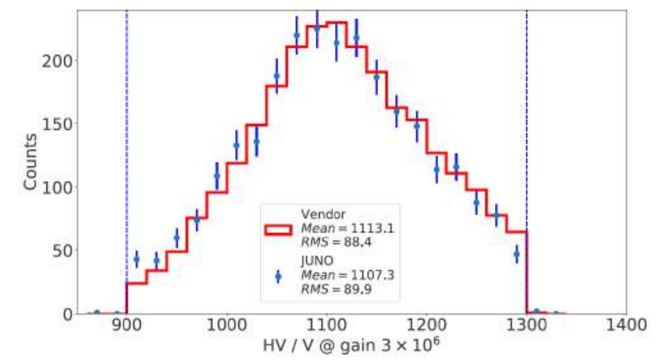
Electronics: 200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips

Installation and commissioning under way

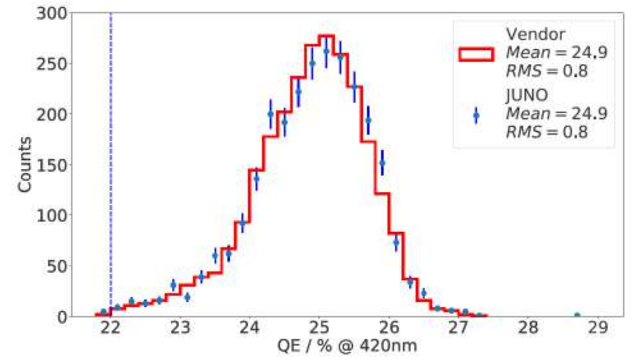




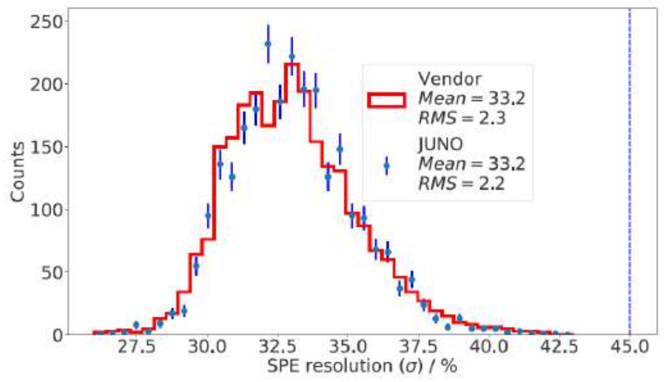
Performances highlight of all 26,000 PMTs



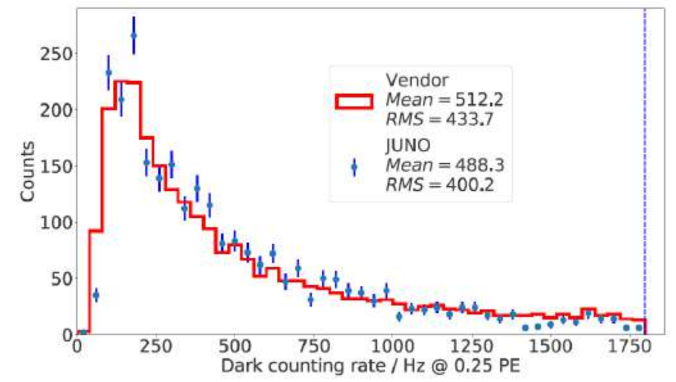
HV: 900-1325V



$\overline{\mathrm{QE}} = 24.9\%$

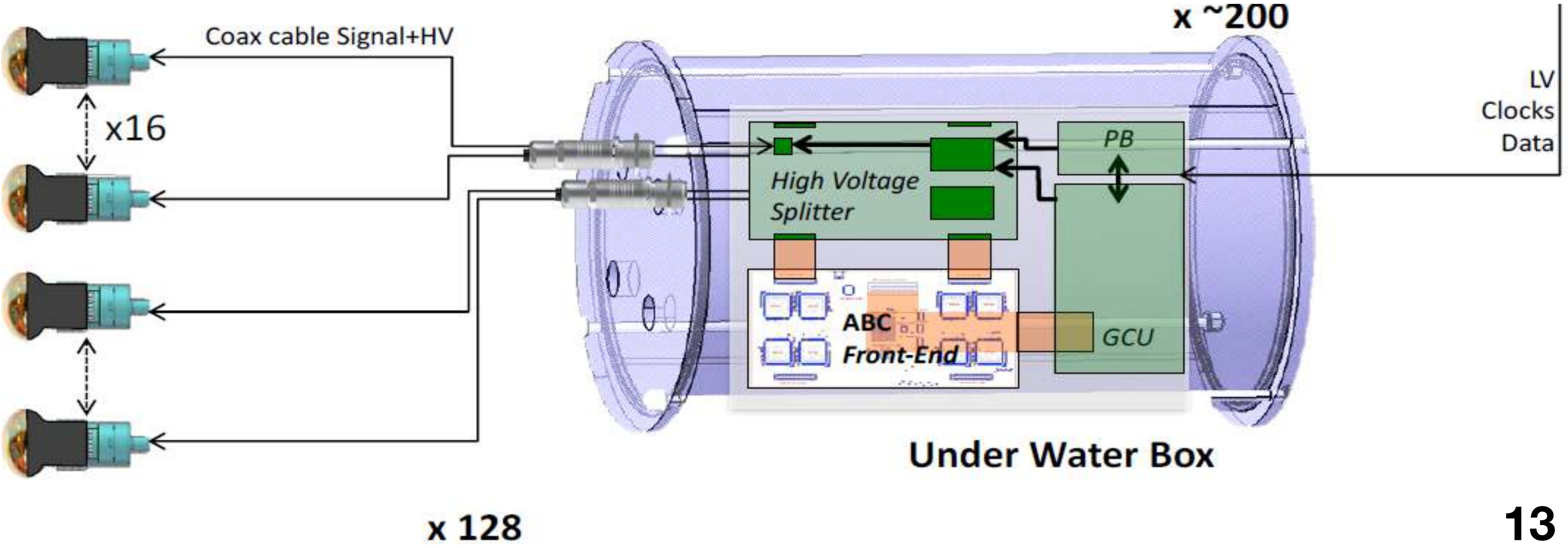


$\overline{\sigma_{\mathrm{SPE}}} = 33.2\%$

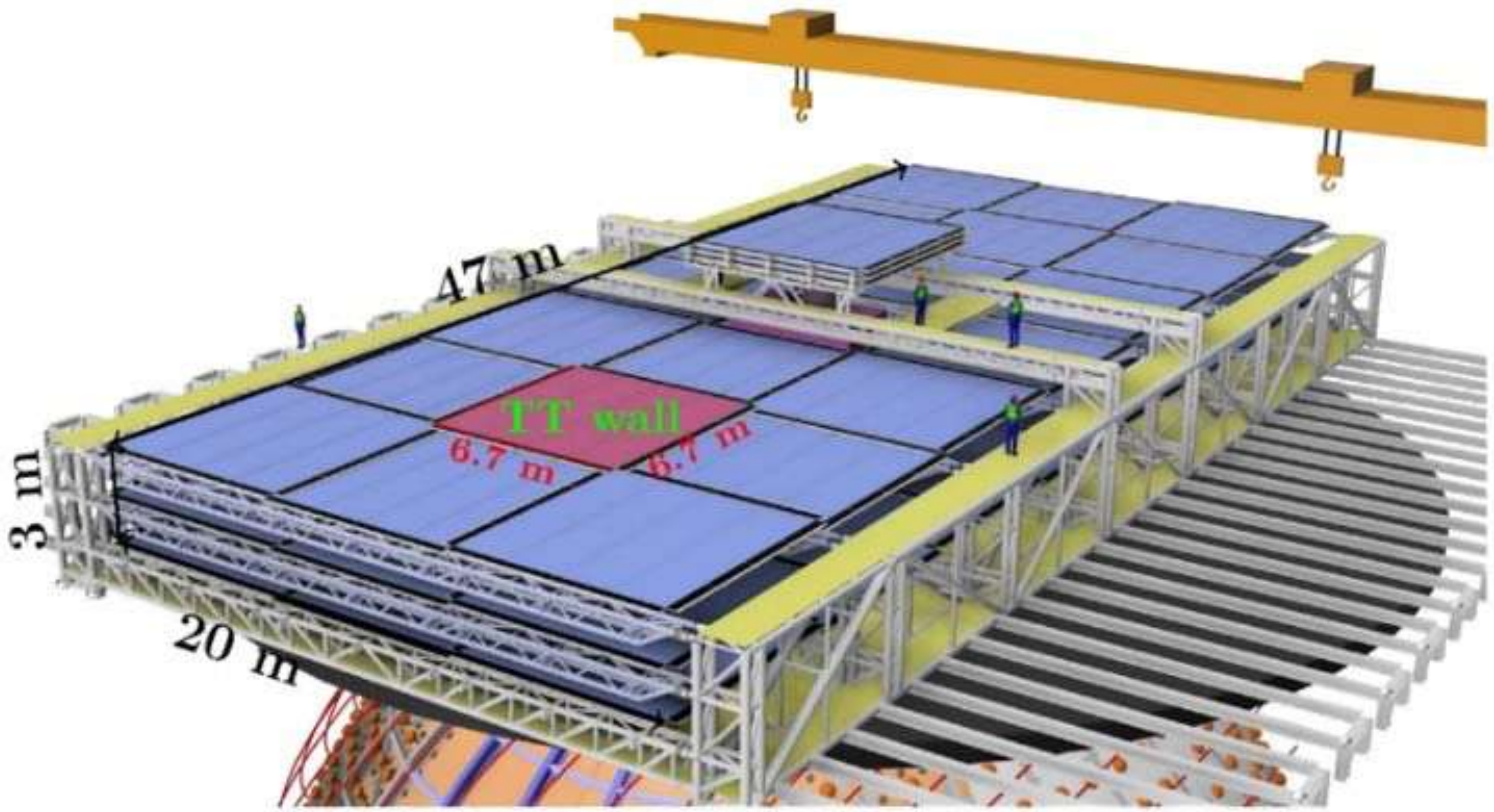


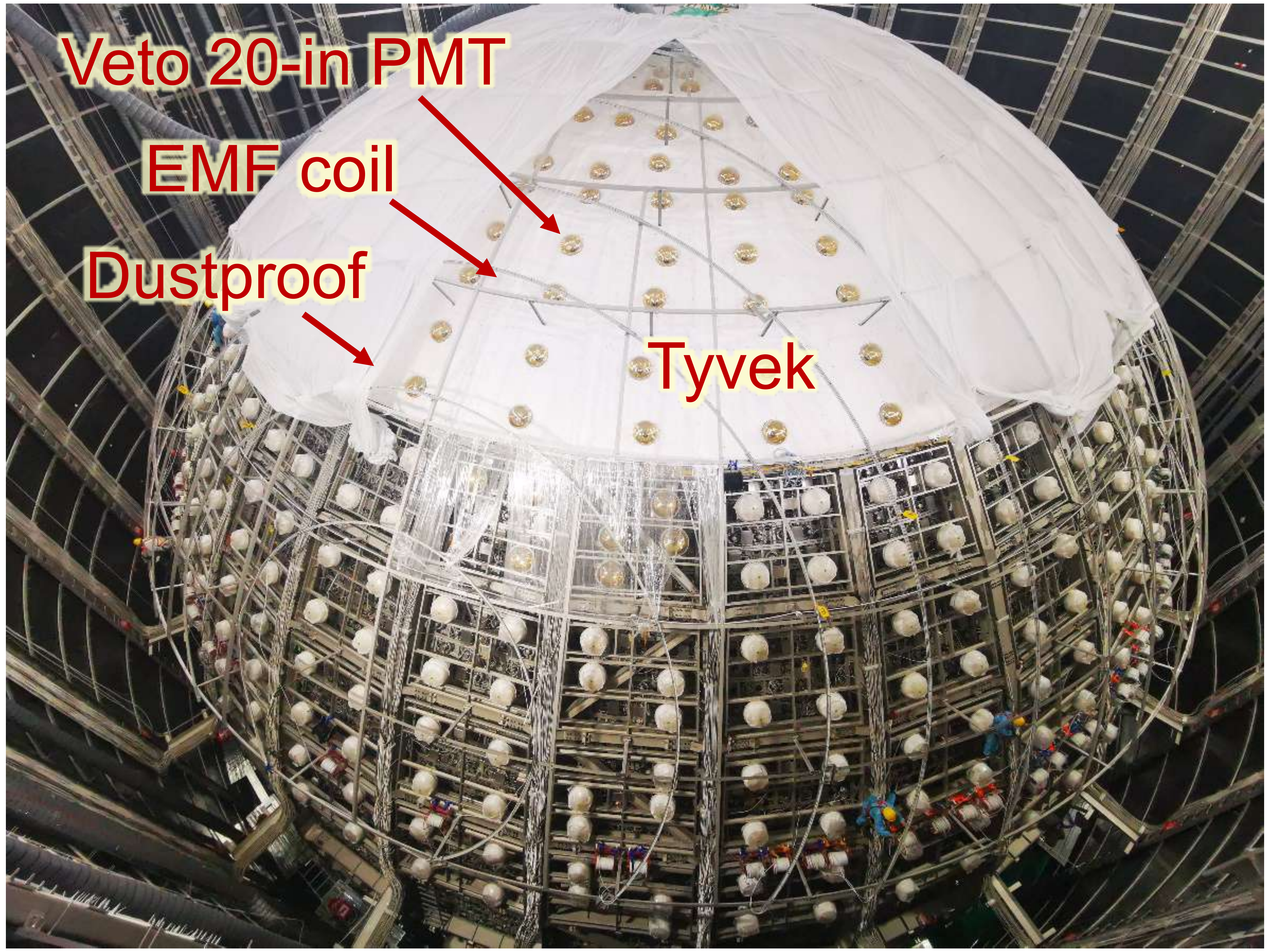
$\overline{\mathrm{DCR}} \approx 500$ Hz

System overview: 200 boxes × 128 PMTs



JUNO Veto





Top tracker (to be installed)

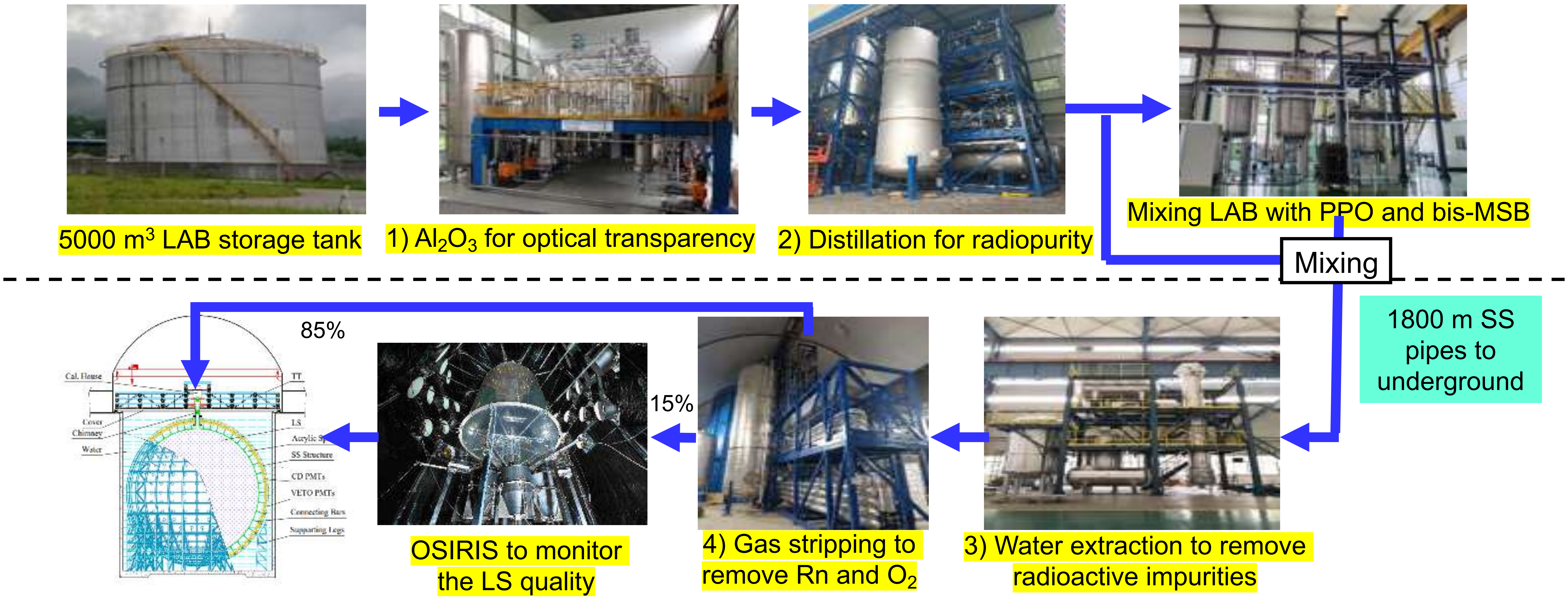
- Refurbished OPERA scintillators
- **3 layers, ~50%** coverage on the top
- $\Delta\theta \sim 0.2^\circ, \Delta D \sim 20\ cm$

Earth Magnetic Field compensation coil

Water Cherenkov detector

- **35 kton** water to shield backgrounds from the rock
- Instrumented with **2400 20"-PMTs**
- Water pool lining: **5mm HDPE (black)** to keep the clean water and to stop Rn from the rock, will cover with tyvek
- **100 tons/hour** water purification system installed. Requirements: **U/Th/K<10^{-14} g/g, Rn<10 mBq/m^3**, **attenuation length> 40 m**, temperature **21±1°C**

Liquid Scintillator Production and Purification



5000 m^3 LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

Mixing LAB with PPO and bis-MSB

Mixing

1800 m SS pipes to underground

3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

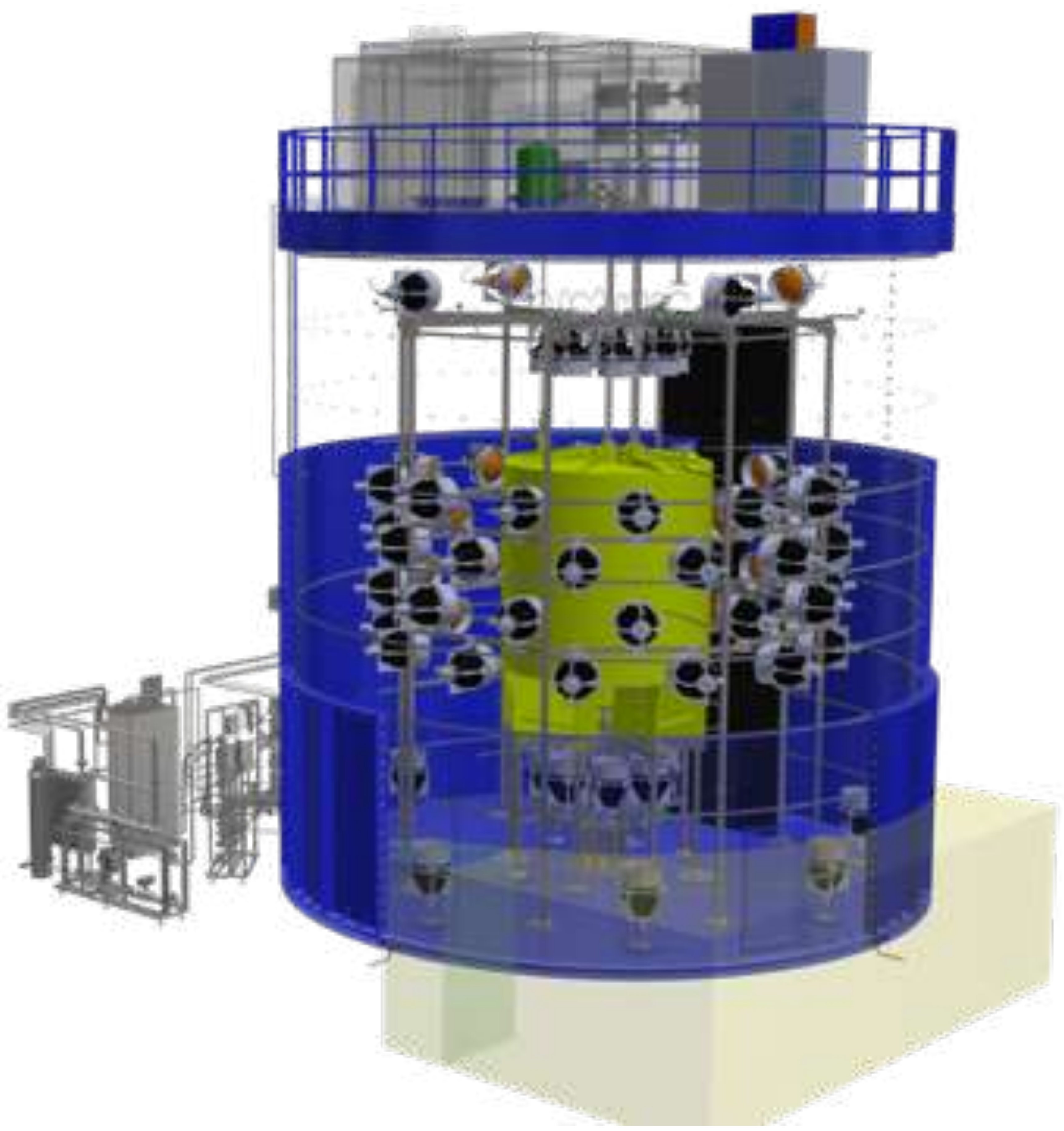
15%

85%

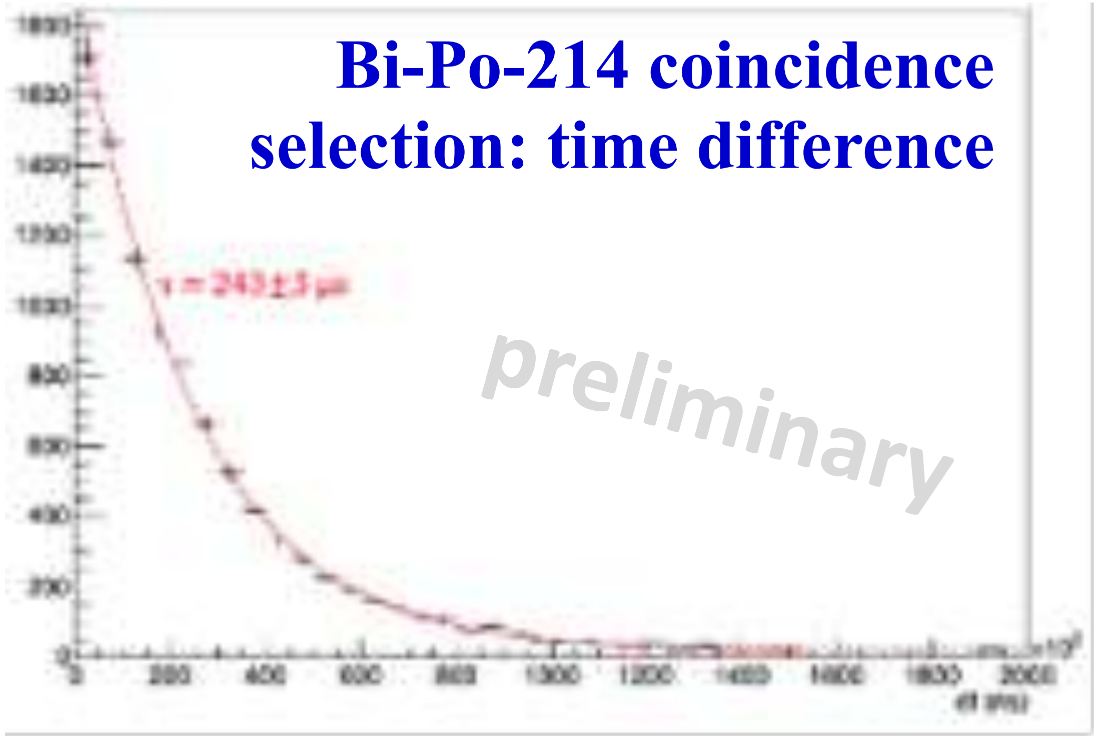
OSIRIS to monitor the LS quality

- **LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
- Attenuation length: **LAB > 24 m, LS > 20 m.**
- Minimum **U/Th** requirement (for NMO) < **10^{-15} g/g**, aiming at **10^{-17} g/g** for solar and future 0nββ
- All **60 ton PPO** delivered, **U/Th < 0.1 ppt**
- **Bis-MSB** complete production soon (**< 5 ppt**)
- Plants commissioned individually and jointly
- **20 kt LAB to be delivered, U/Th ~ 1 ppq**

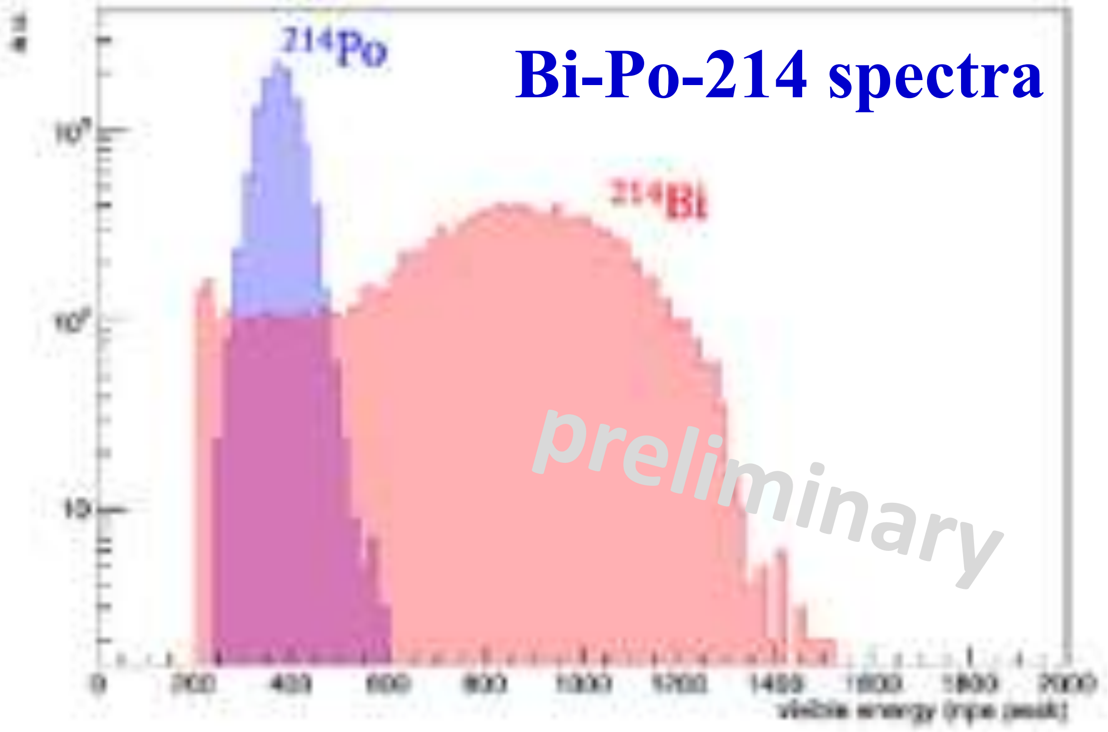
OSIRIS: LS Radiopurity Verification before Filling



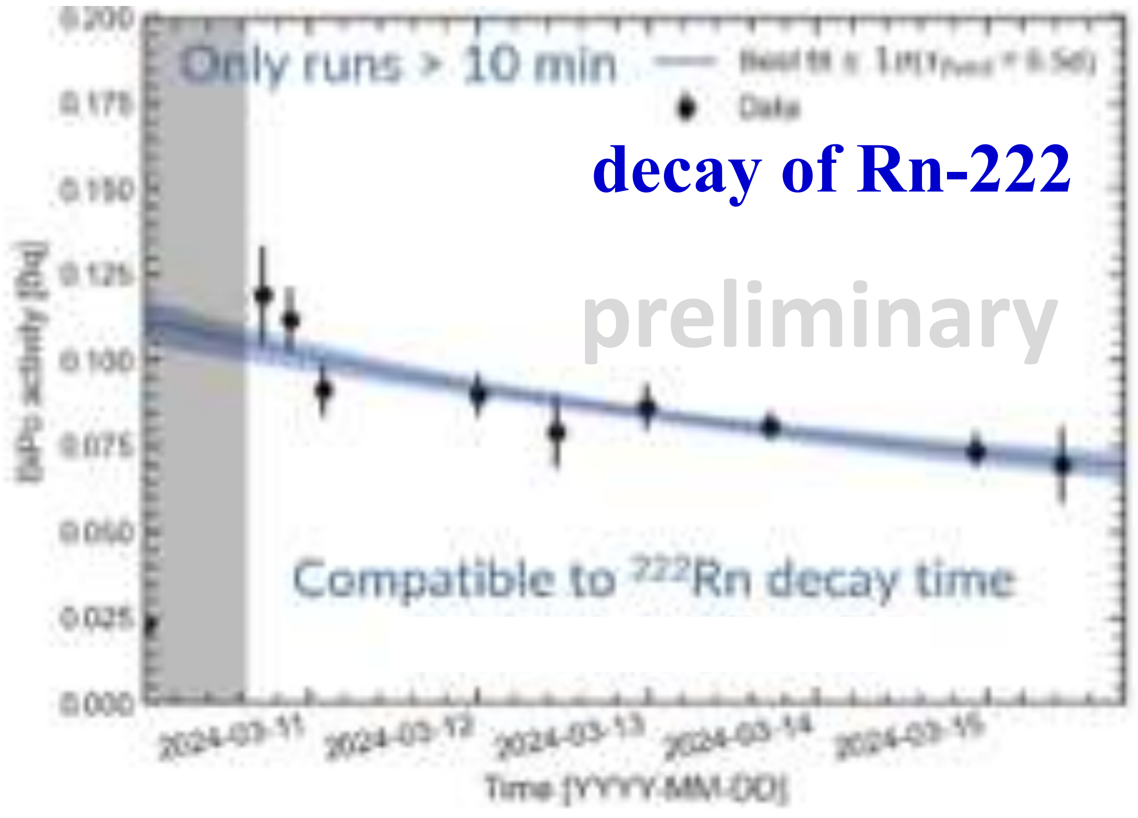
- A dedicated pre-detector to **verify the radioactivity levels of LS**
- 20 tons of LS in **3m x 3m** acrylic vessel, **76 MCP-PMTs**, 3m of water shielding → **first test run successful**
- First batch of JUNO LS filled into the detector on March 11
- **U/Th tagging by** Bi-Po-214 coincidence, which is now still dominated by ^{222}Rn → have to wait several ^{222}Rn lifetimes (τ=5.5 days) to reach U/Th <10^{-15} g/g
- Analysis for **^{14}C, ^{210}Po**, … in progress



Bi-Po-214 coincidence selection: time difference

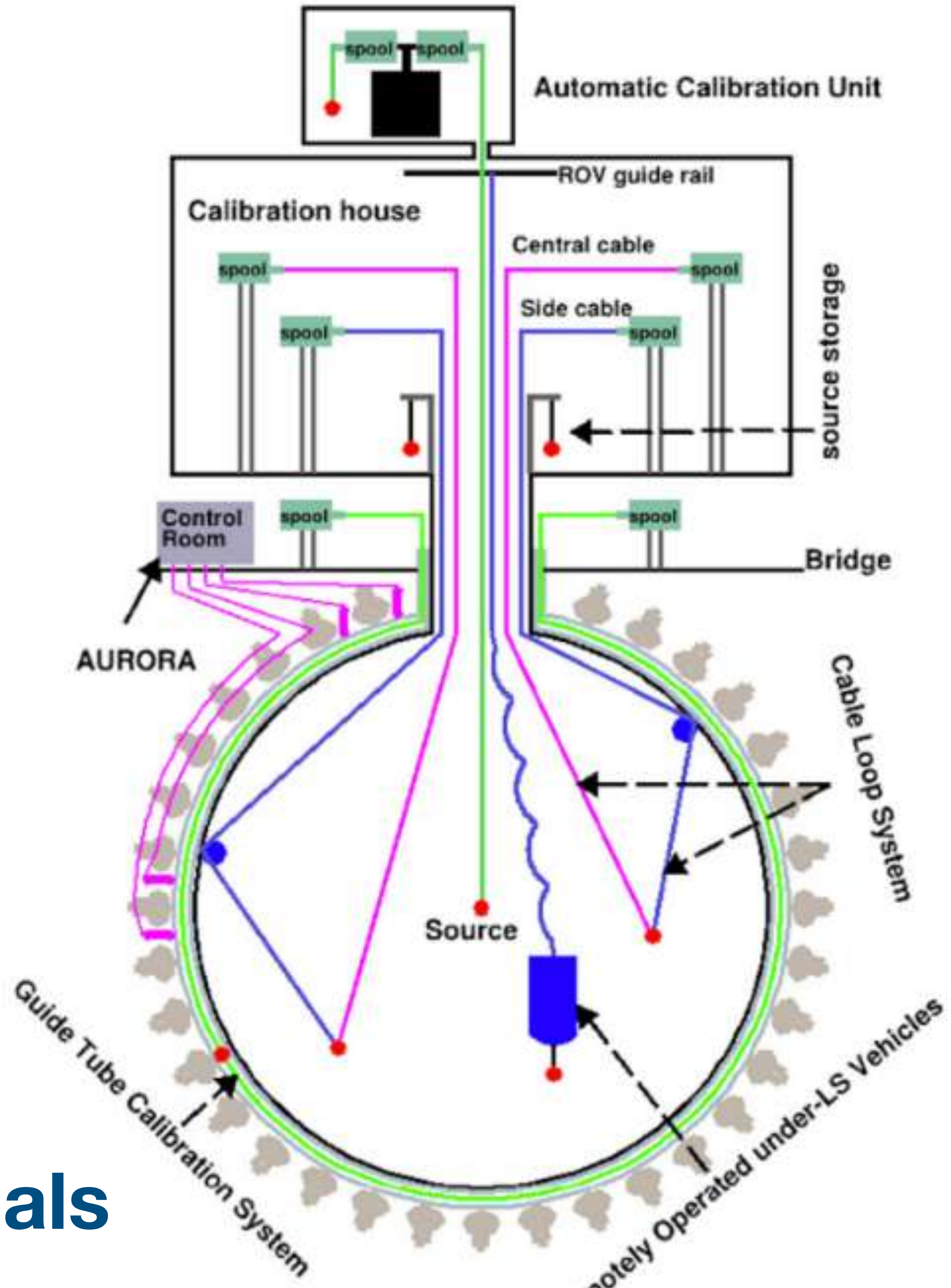


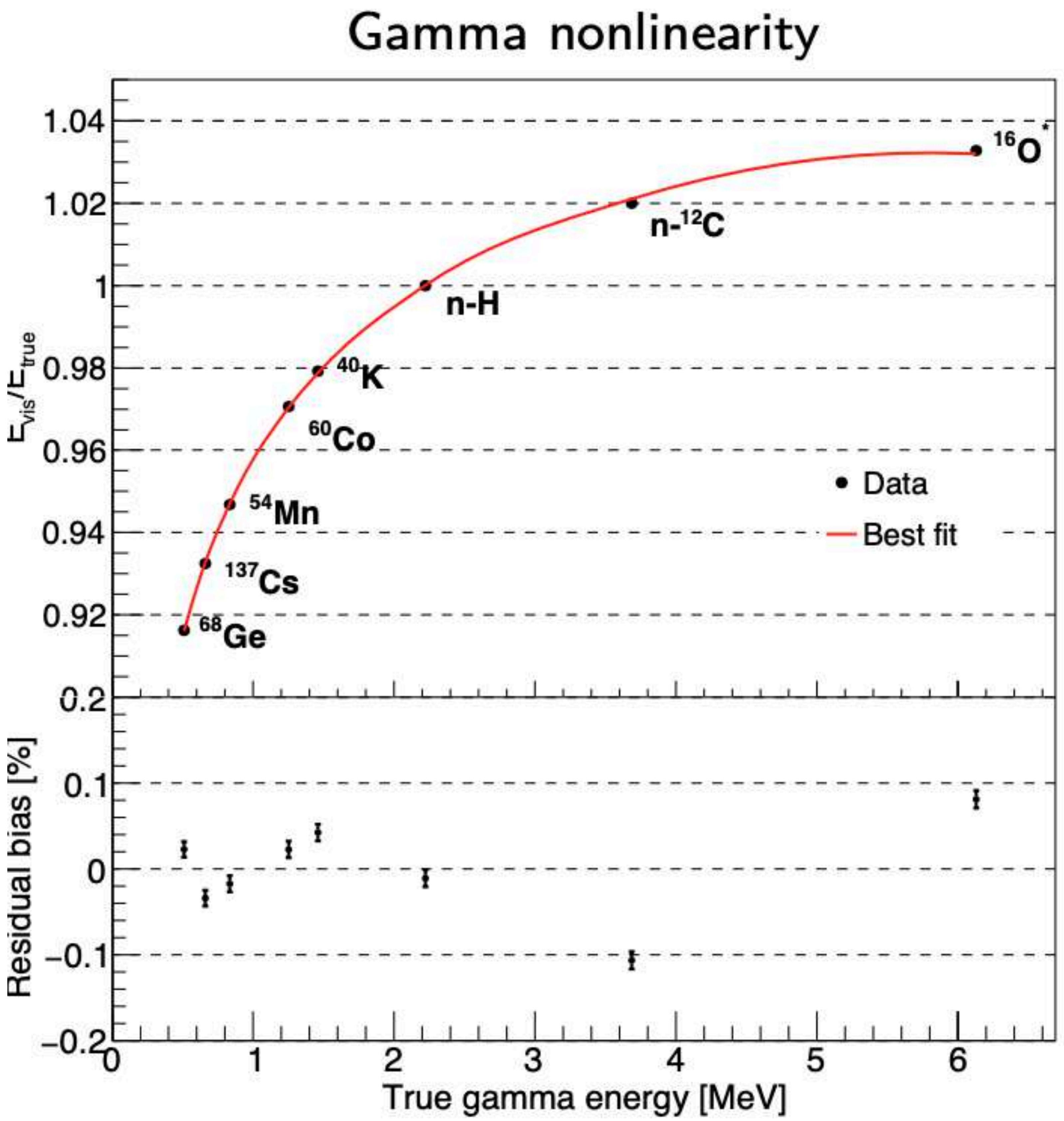
Bi-Po-214 spectra



decay of Rn-222

Calibration and Energy resolution





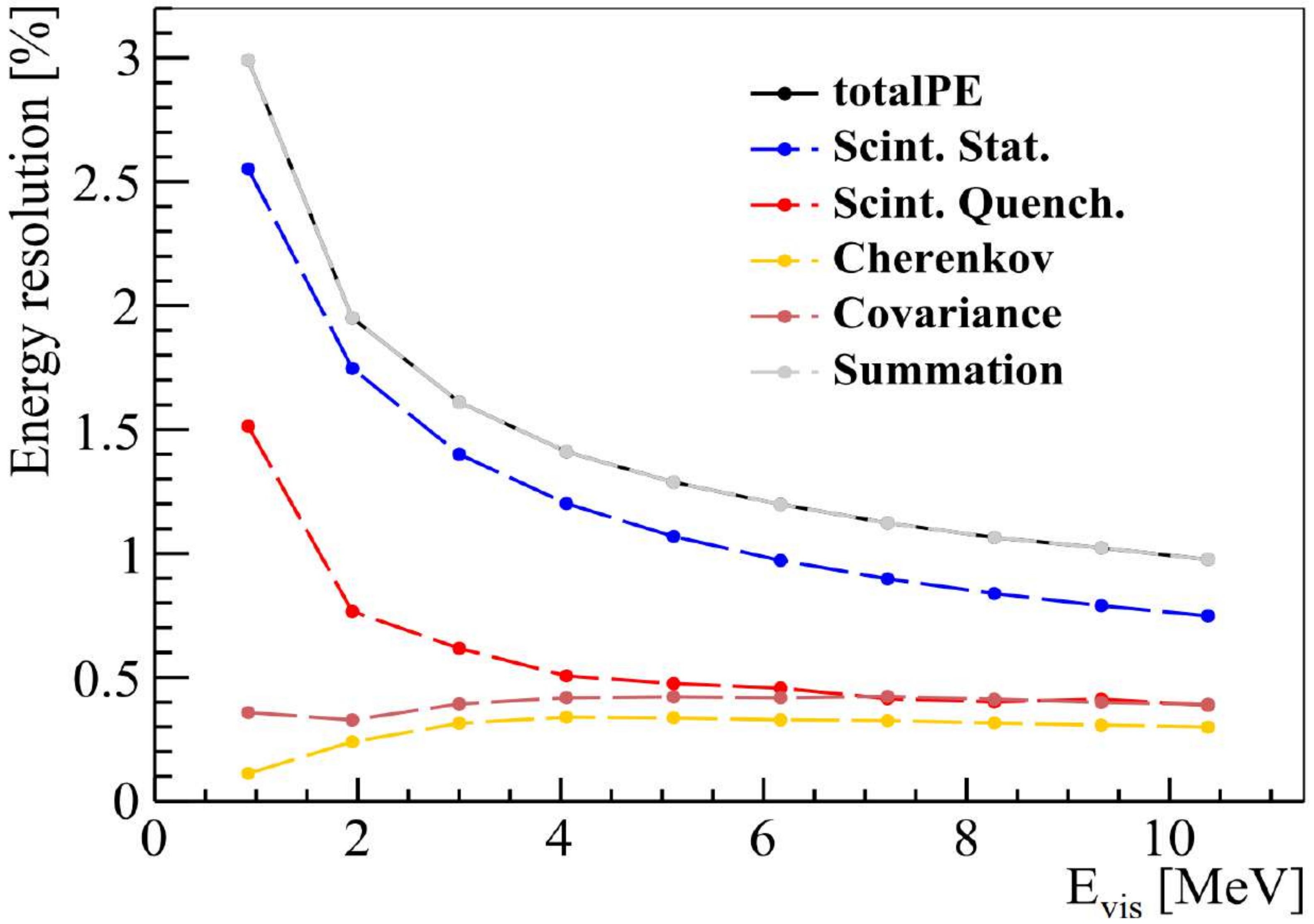
$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.614\%}{\sqrt{E_{vis}}}\right)^2 + 0.64\%^2 + \left(\frac{1.205\%}{E_{vis}}\right)^2}$$

Photon statistics

Constant term

Annihilation -induced γs

Dark noise



Energy resolution: **2.95% @1MeV**

Goals

- **Energy scale uncertainty <1%**
- **Reaching desired σE < 3% at 1 MeV**

arXiv:2405.17860

Methods

Four systems for 1D, 2D, 3D scan with multiple sources

Calibrate energy scale and non-linearity to better than 1% using γ-peaks and cosmogenic ^{12}B beta spectrum

TAO Detector

Mail goal: Measure the reactor neutrino spectrum (as a reference to JUNO)

- ➩ better resolution to reduce fine structure effects and spectrum uncertainties
- ➩ Improve nuclear database

10 m² SiPM + 2.8 ton Gd-loaded LS @-50°C

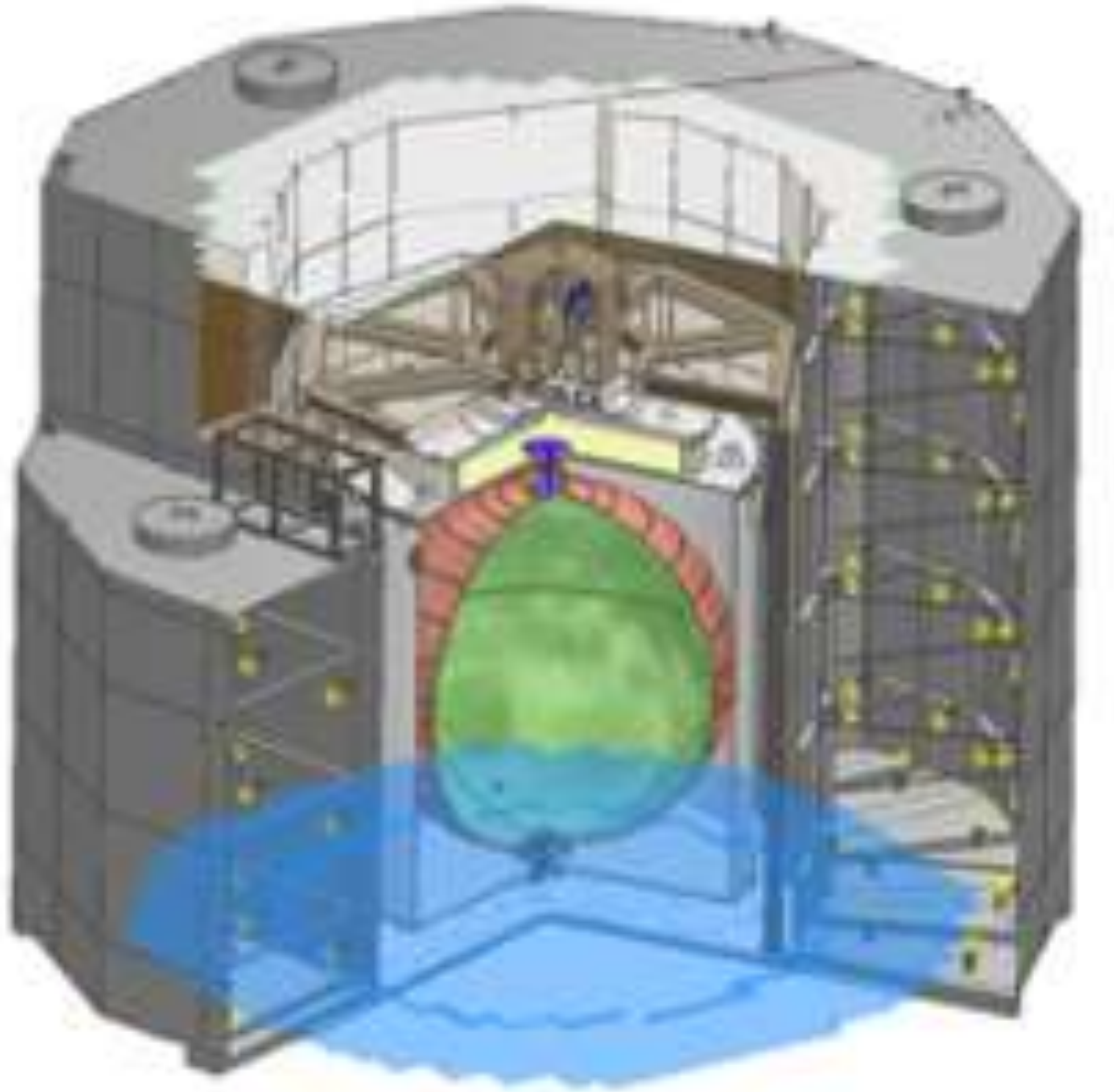
- ➩ 700k/year@44m from the core (4.6 GW), ~10% bkg
- ➩ Energy resolution: $< 2\,\%/\sqrt{E}$, 4500 p.e./MeV
- ➩ SiPM (> 94% coverage) w/ PDE > 50%
- ➩ Operating at -50°C, dark rate 100k→100 Hz/mm²
- ➩ 2.8 ton (1-ton FV) new type of Gd-LS for -50°C

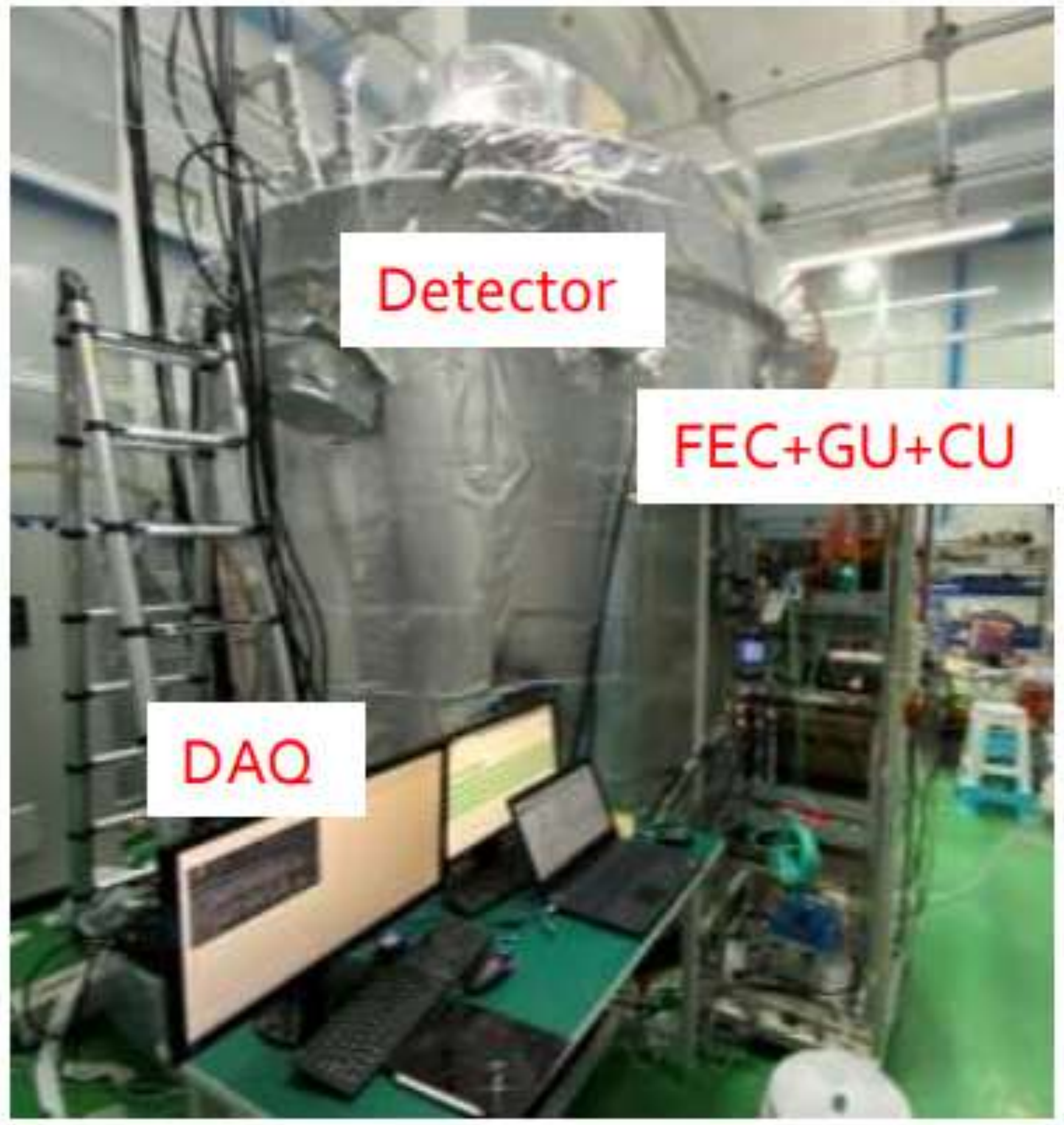
Detector tested (w/ ~100 SiPM tiles/readout out of 4100 in total) at IHEP

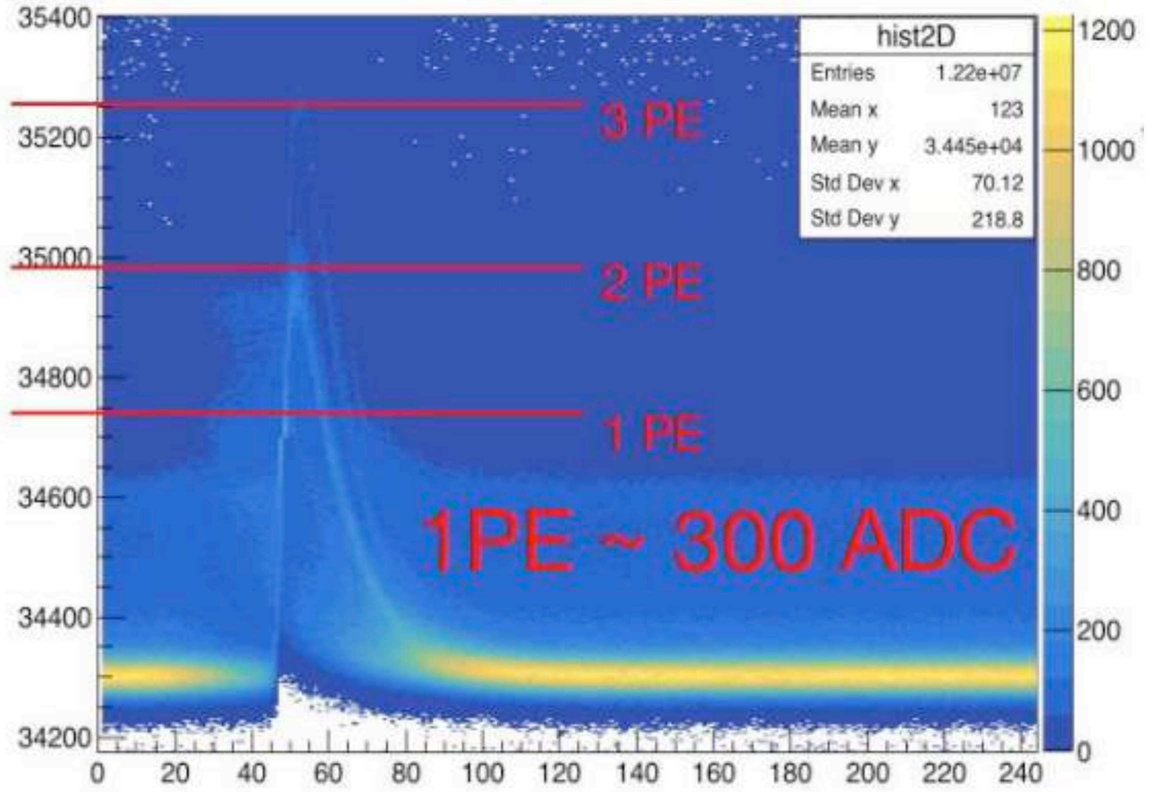
- ➩ Temperature uniformity and stability OK!
- ➩ Single PE Threshold

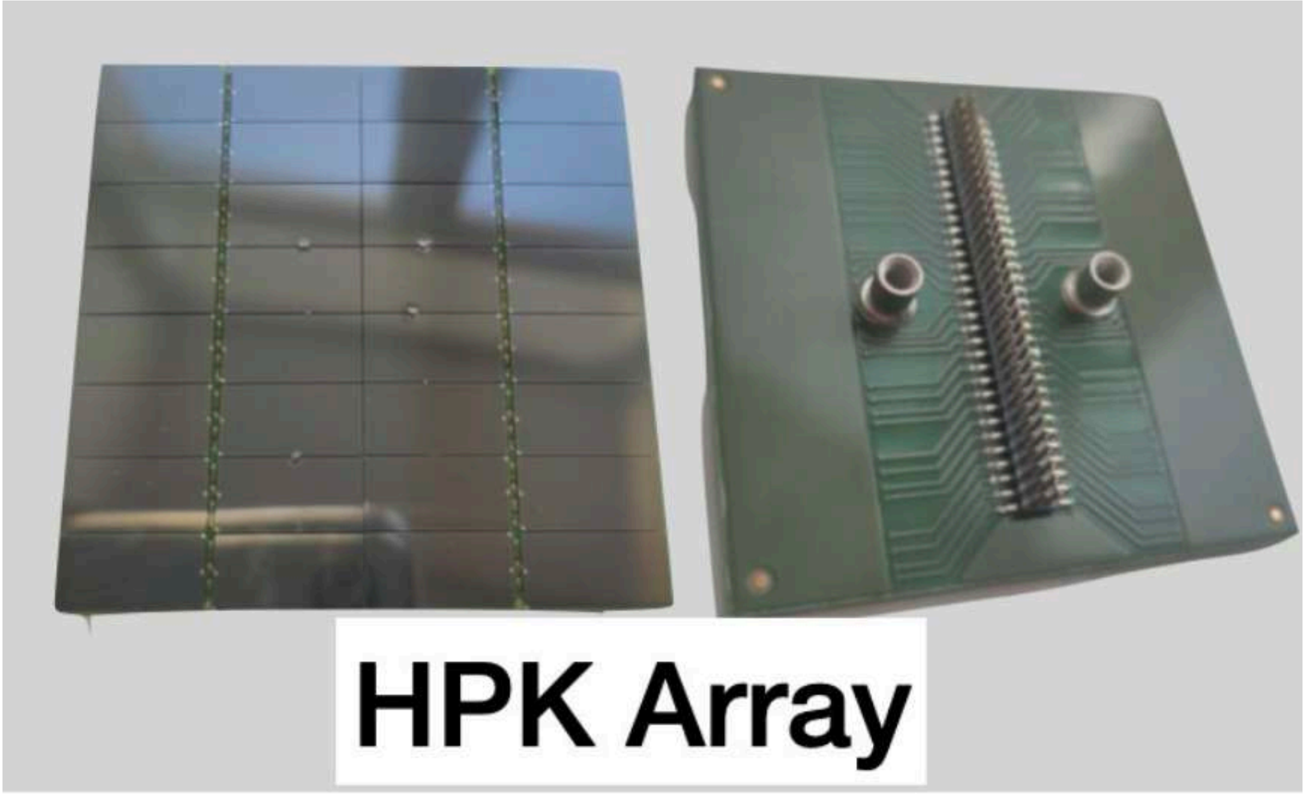
Disassembling, to be re-installed in the Taishan Nuclear Power Plant in 2024

arXiv:2005.08745









Physics in JUNO

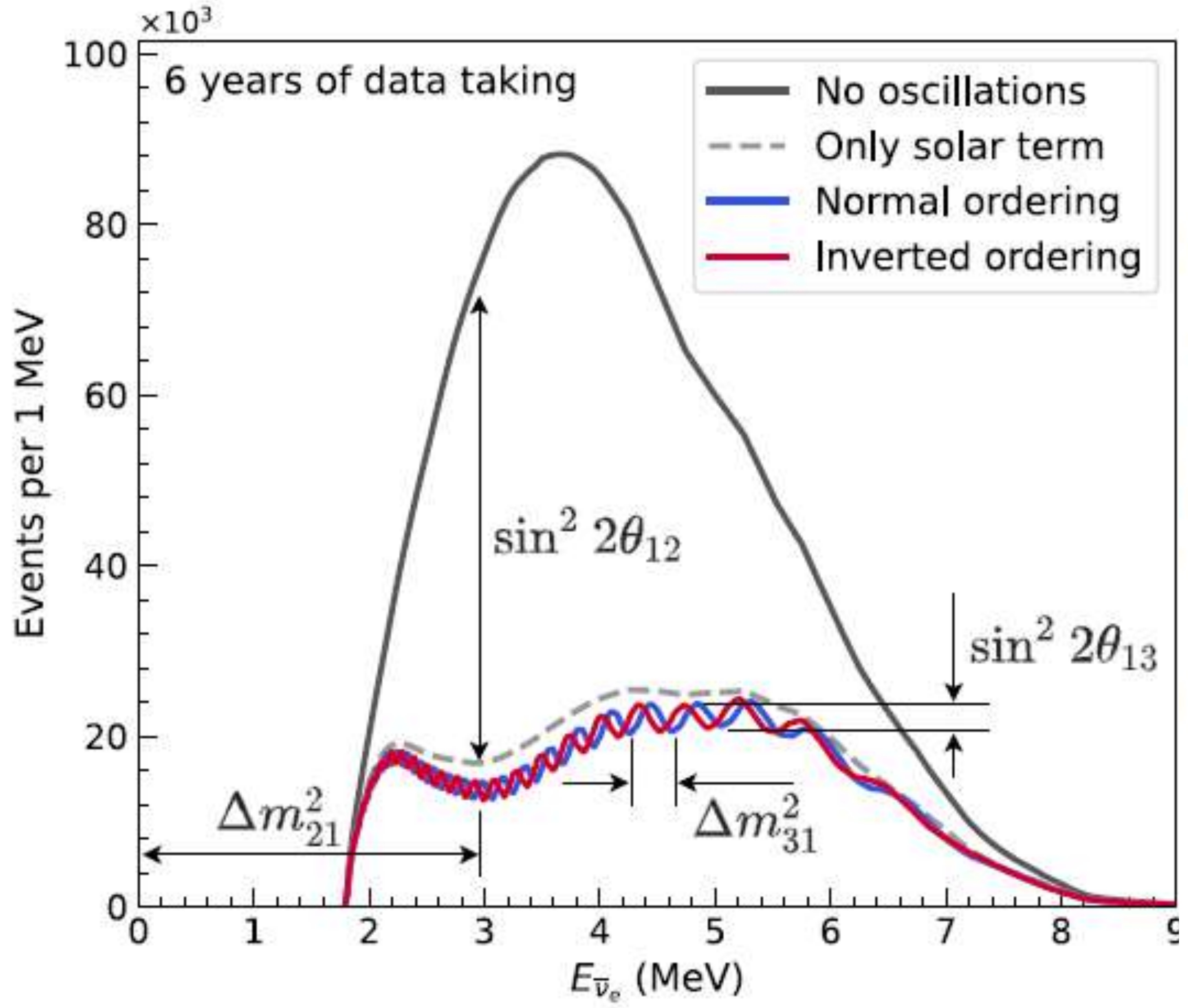
Rich physics programme

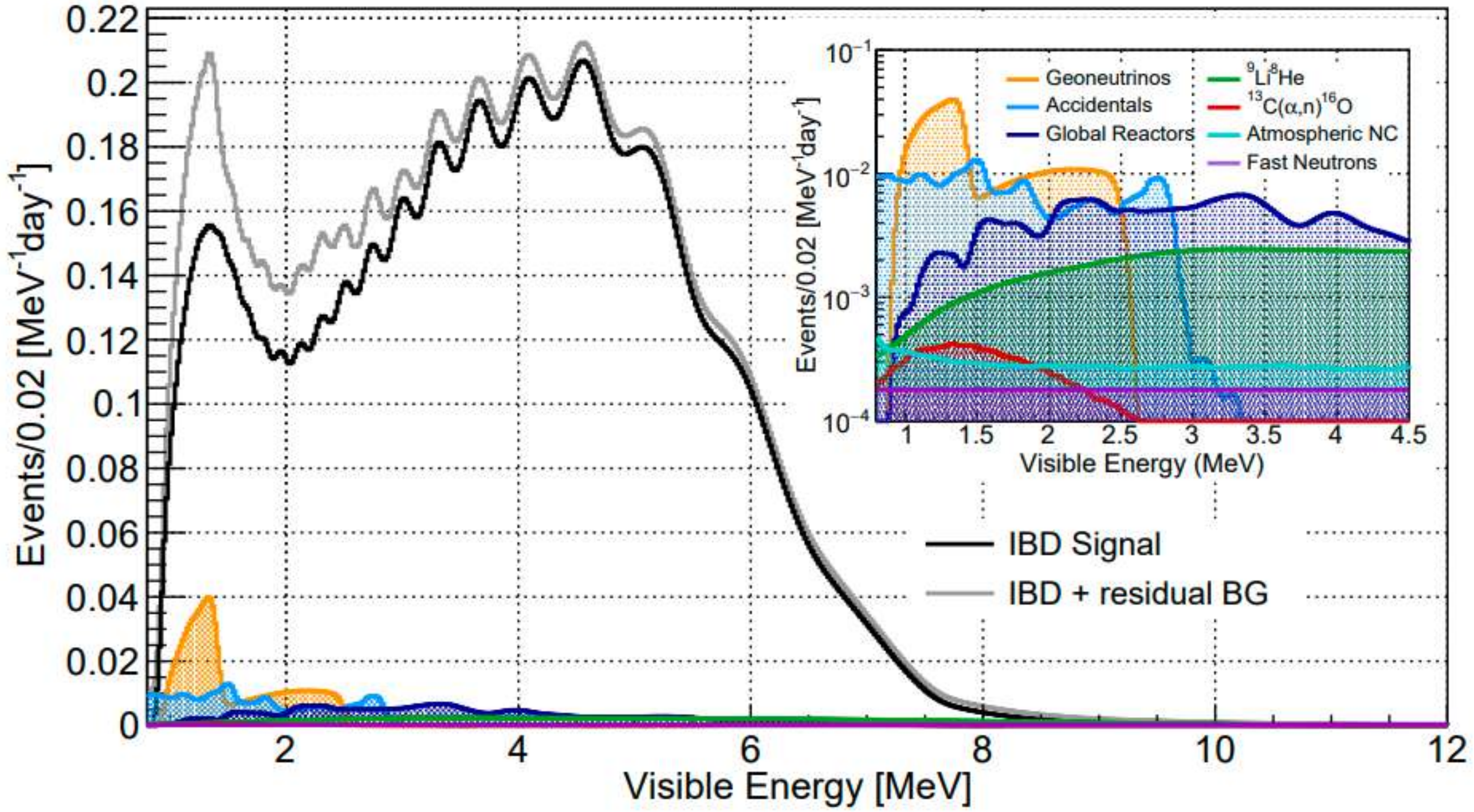
- Reactor ν_e at short (TAO) and large baseline:oscillation parameters, mass ordering, reactor ν_e spectrum, sterile neutrinos.
- Solar neutrinos from ^{7}Be, pep, CNO and ^{8}B. Possibly, *pp*.
- Atmospheric $\nu_\mu/\overline{\nu}_\mu$ and $\nu_e/\overline{\nu}_e$: mass ordering, θ_{23}.
- SuperNova neutrinos and Diffuse SuperNova Neutrino Background.
- Geo-neutrinos.
- Proton decay.

- Other topics:
- Search for dark matter.
- Study PMNS matrix unitarity.
- Probe Lorentz invariance.
- Search for physics beyond standard model and exotic particles.
- And more...

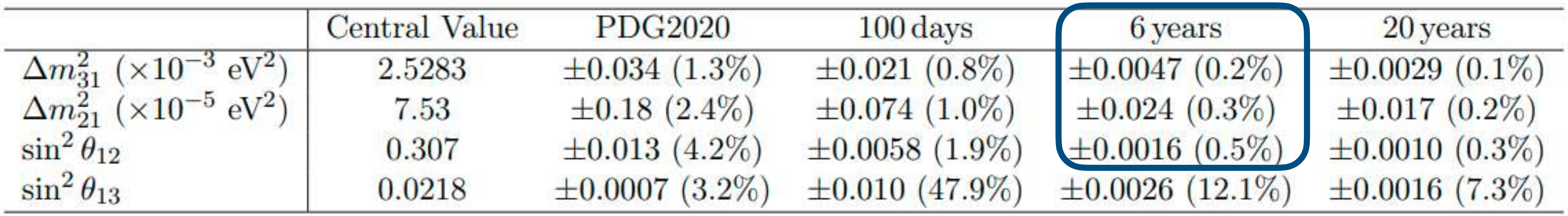
Precision Oscillation Measurement

Chin. Phys. C46 (2022) 12, 123001





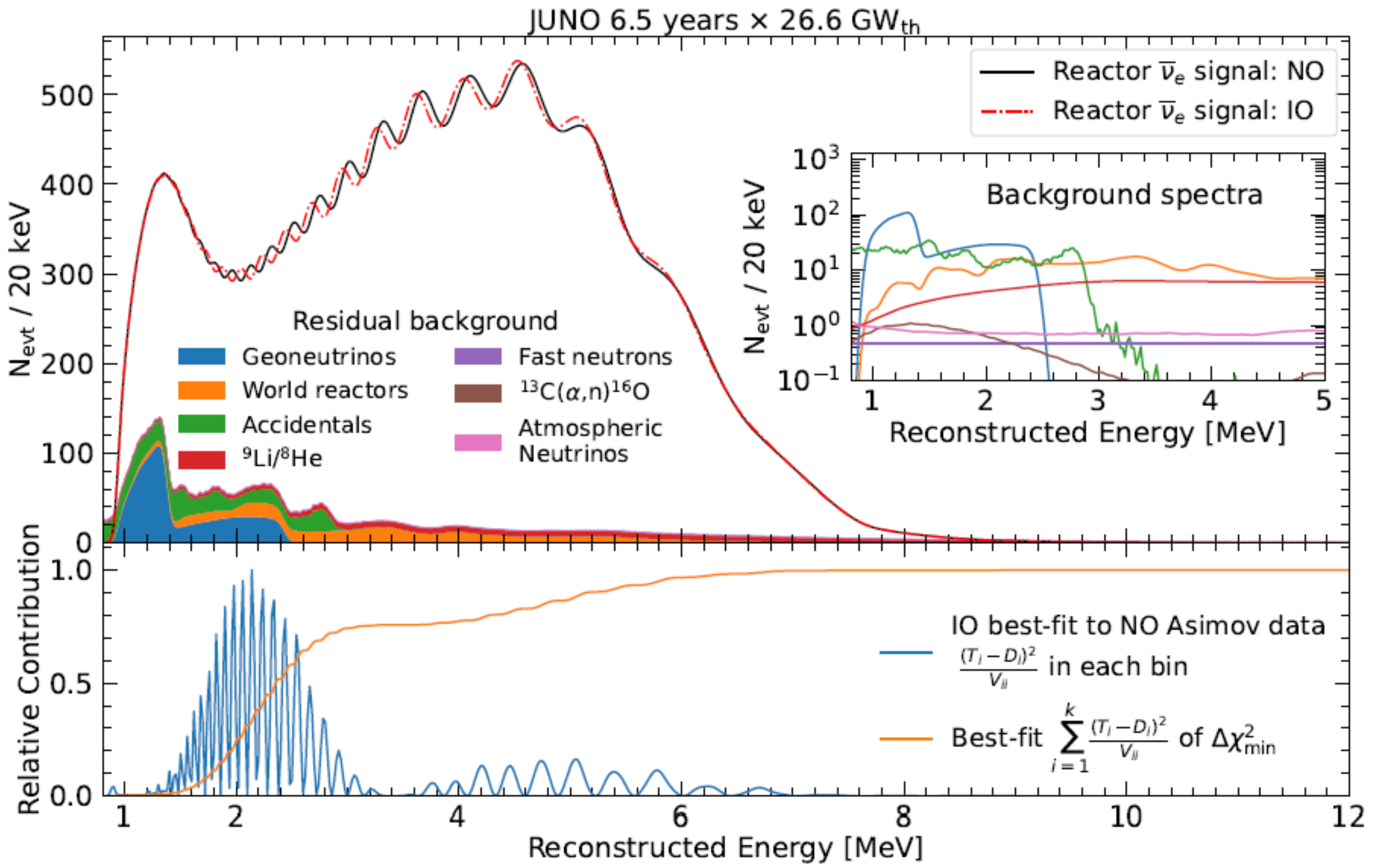
Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 ➔ 47	-	-
Geo-ν′s	1.1 ➔ 1.2	30 %	5 %
Accidental signals	0.9 ➔ 0.8	1 %	negligible
Fast-n	0.1	100 %	20 %
^{9}Li/ ^{8}He	1.6 ➔ 0.8	20 %	10 %
^{13}C (α ,n) ^{16}O	0.05	50 %	50 %
Global reactors	0 ➔ 1.0	2 %	5 %
Atmospheric ν^′ s	0 ➔ 0.16	50 %	50 %

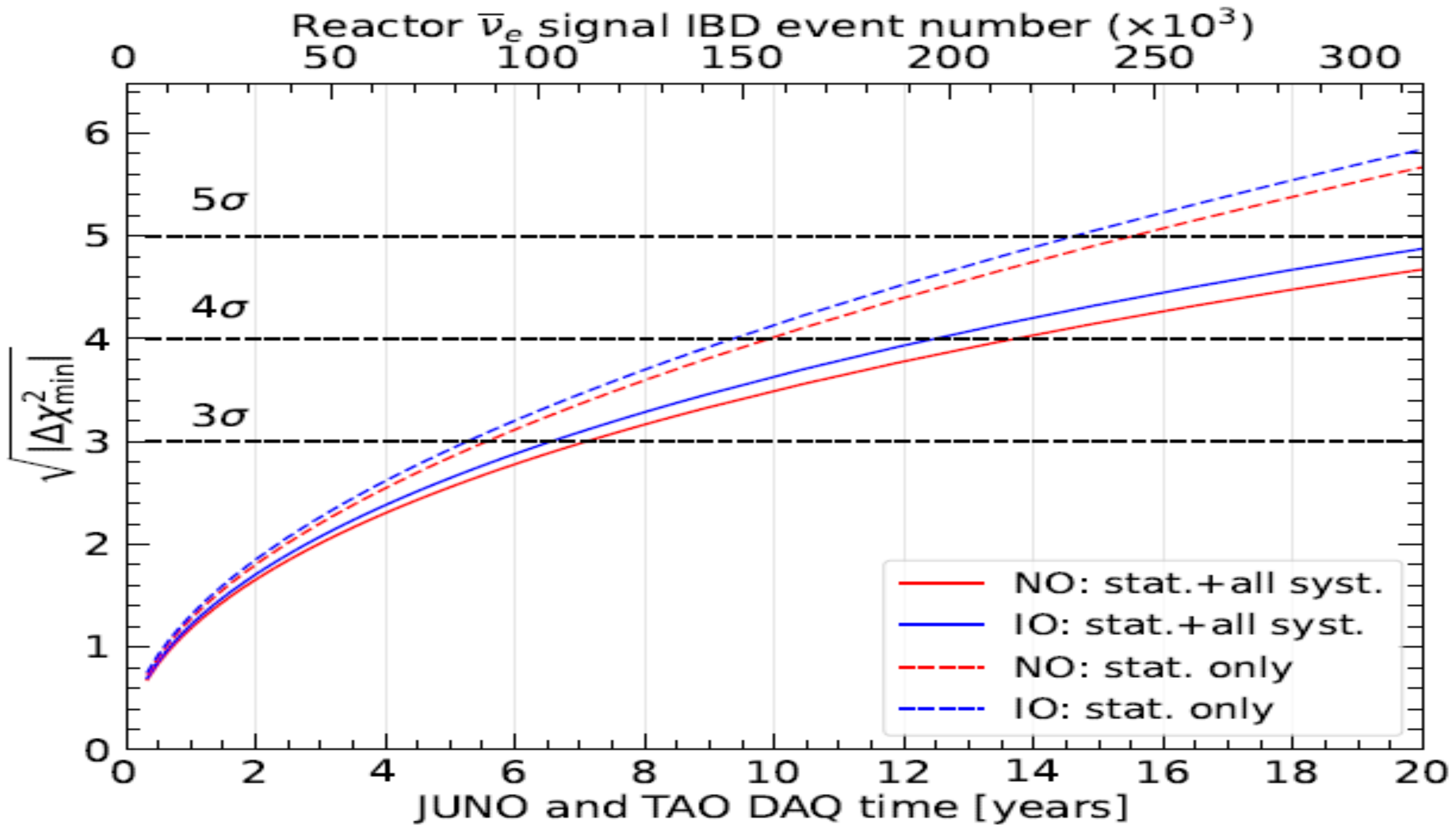


	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (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%)

$sin^2 2\theta_{12}, \Delta m^2_{21}, |\Delta m^2_{32}|$ **best measurements in 100 days; precision < 0.5% in 6 years**

Neutrino Mass Ordering

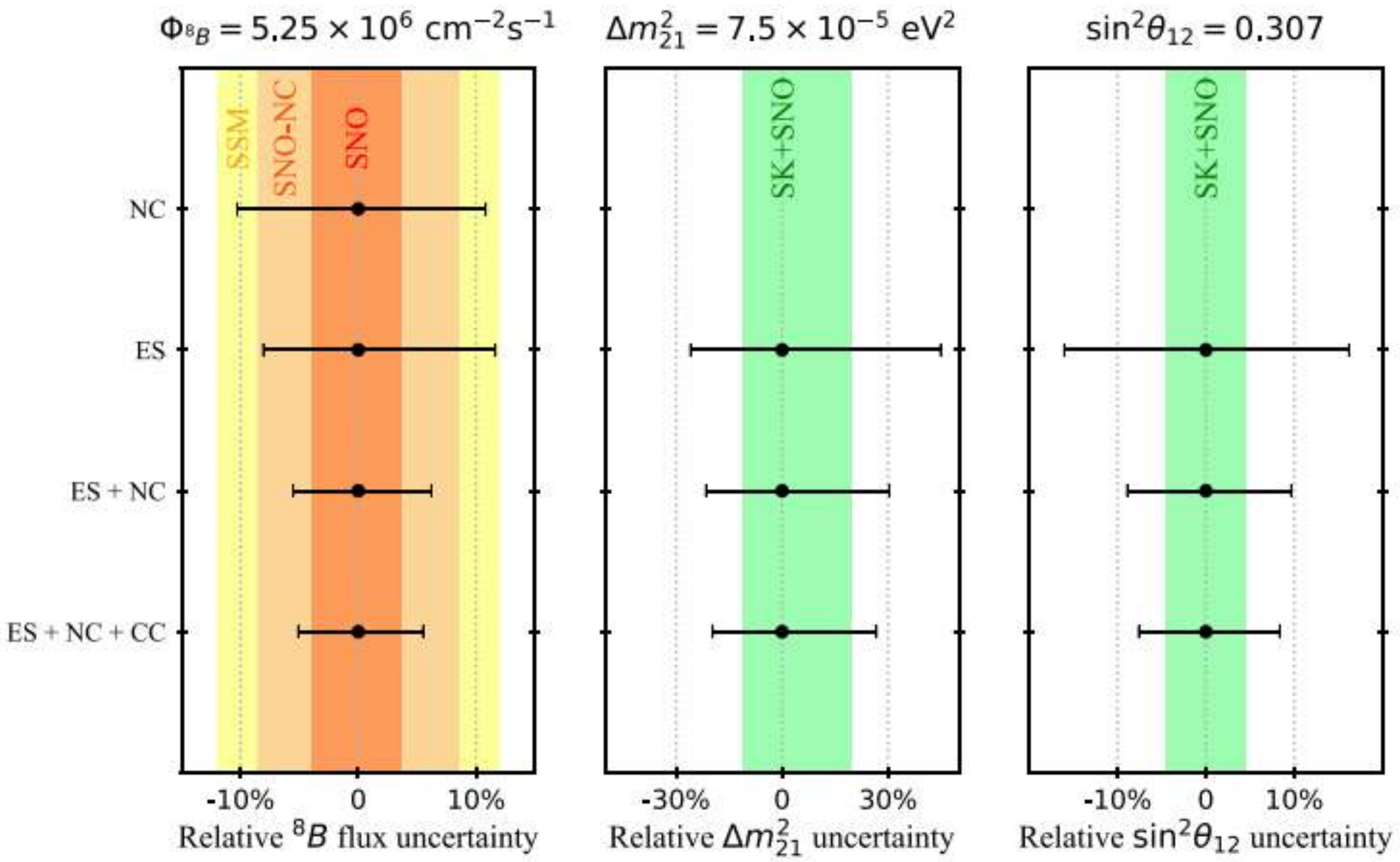




	Design *	**Now**
Thermal Power	36 GW$_{th}$	26.6 GW$_{th}$ (**26%↓**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (**33%↑**)
Muon veto efficiency	83 %	91.6% (**11%↑**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (**2%↑**)
Shape uncertainty	1 %	**JUNO+TAO**
3σ NMO sens. Exposure	**<6 yrs × 35.8 GW$_{th}$**	**~6 yrs × 26.6 GW$_{th}$**

- **JUNO NMO median sensitivity: 3σ (reactors only) @ ~6 yrs * 26.6 GWth exposure**
- **Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity**

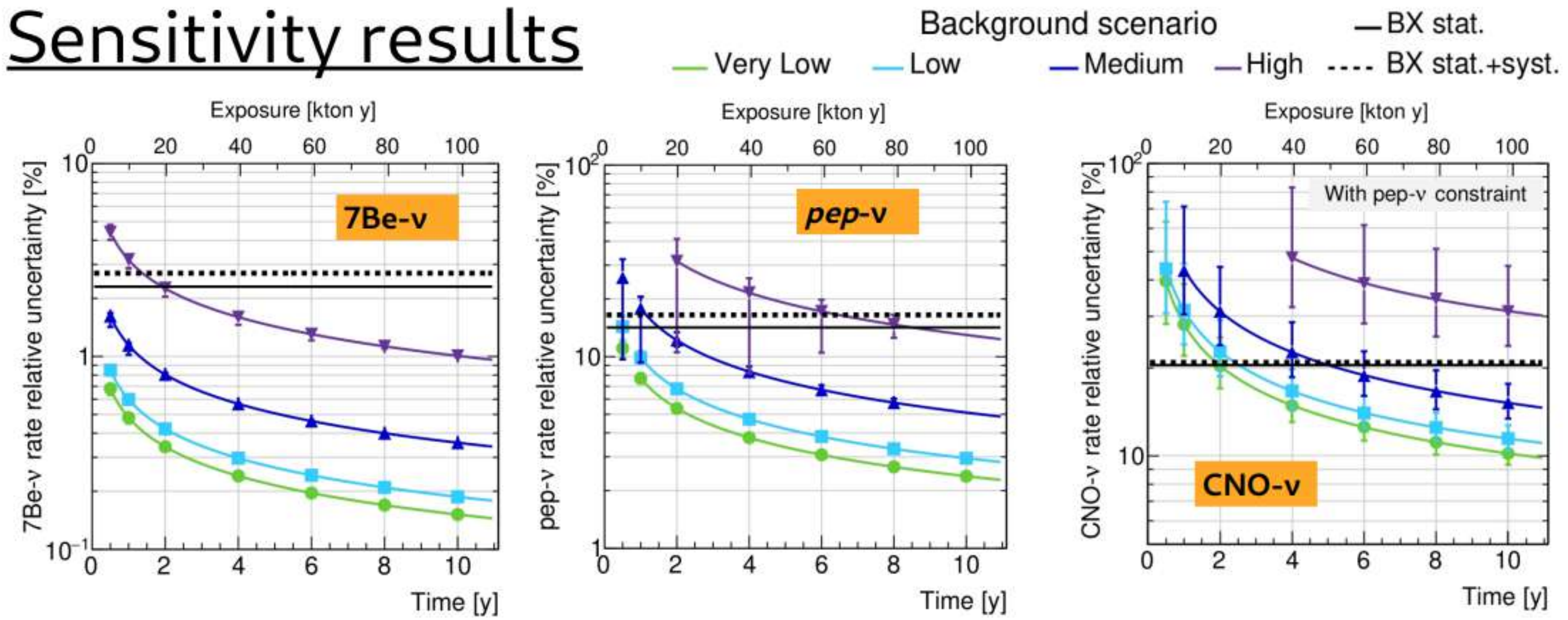
Solar and Geo-Neutrinos

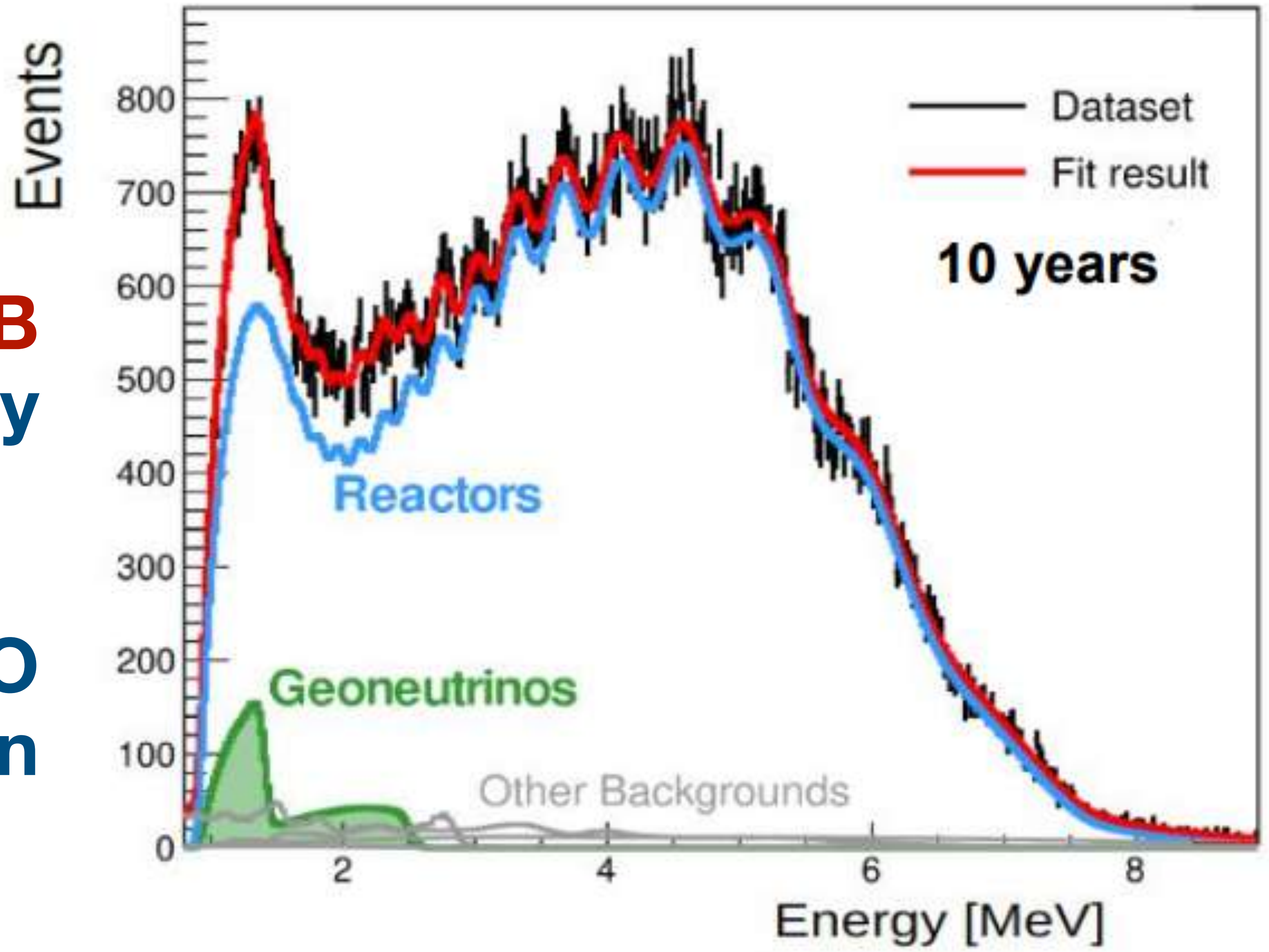


60,000 ES and 600 NC/CC on ^{13}C

The largest ES + NC+CC(^{13}C) sample, ^{8}B flux can be model-independently measured to 5% in 10 years (SNO 3%)

For most background scenarios, JUNO will reduce the Borexino uncertainty on ^{7}Be, pep, CNO flux measurement

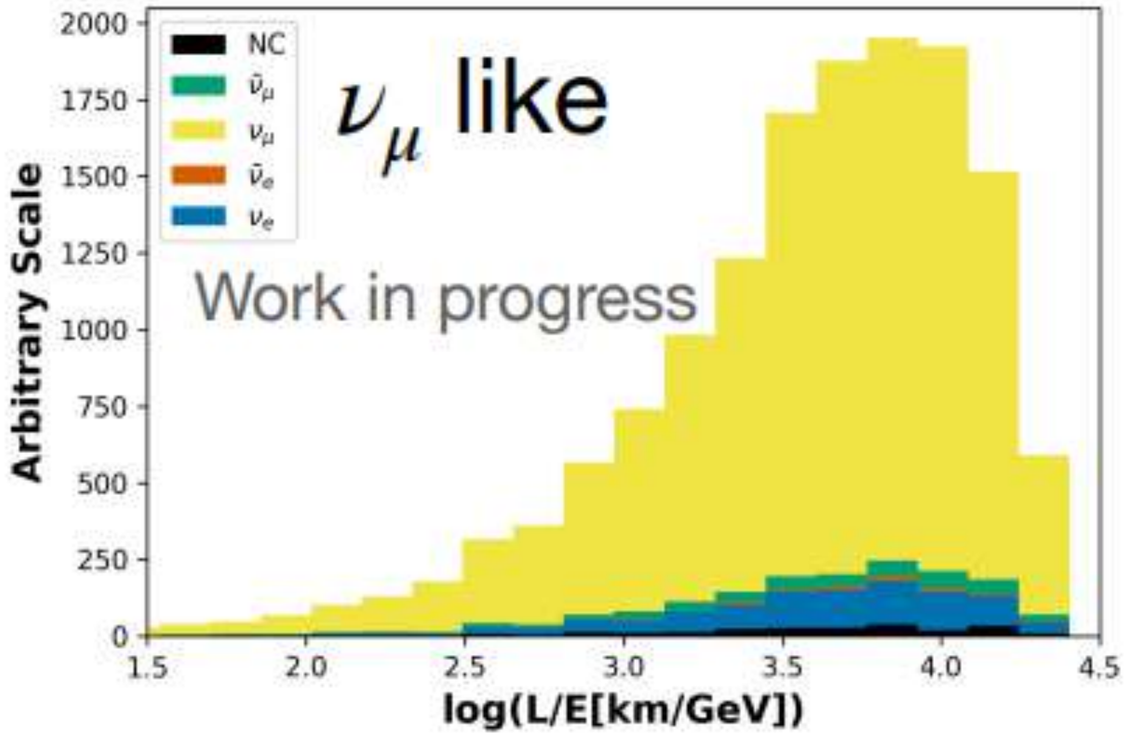


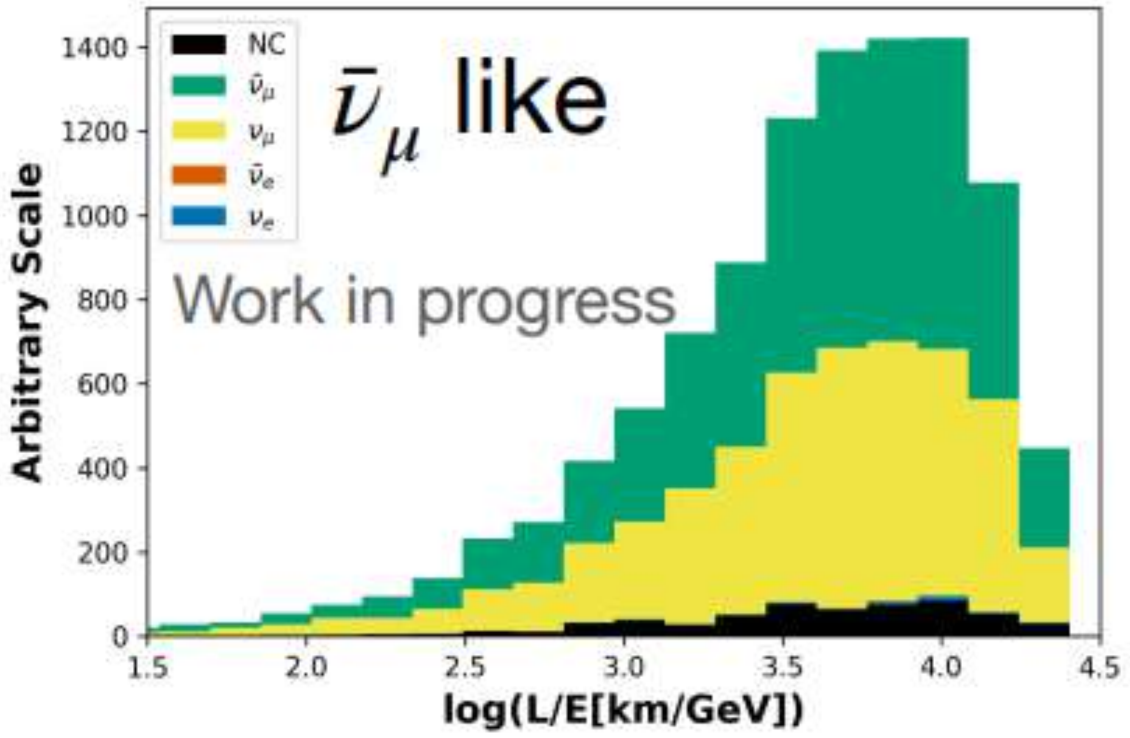


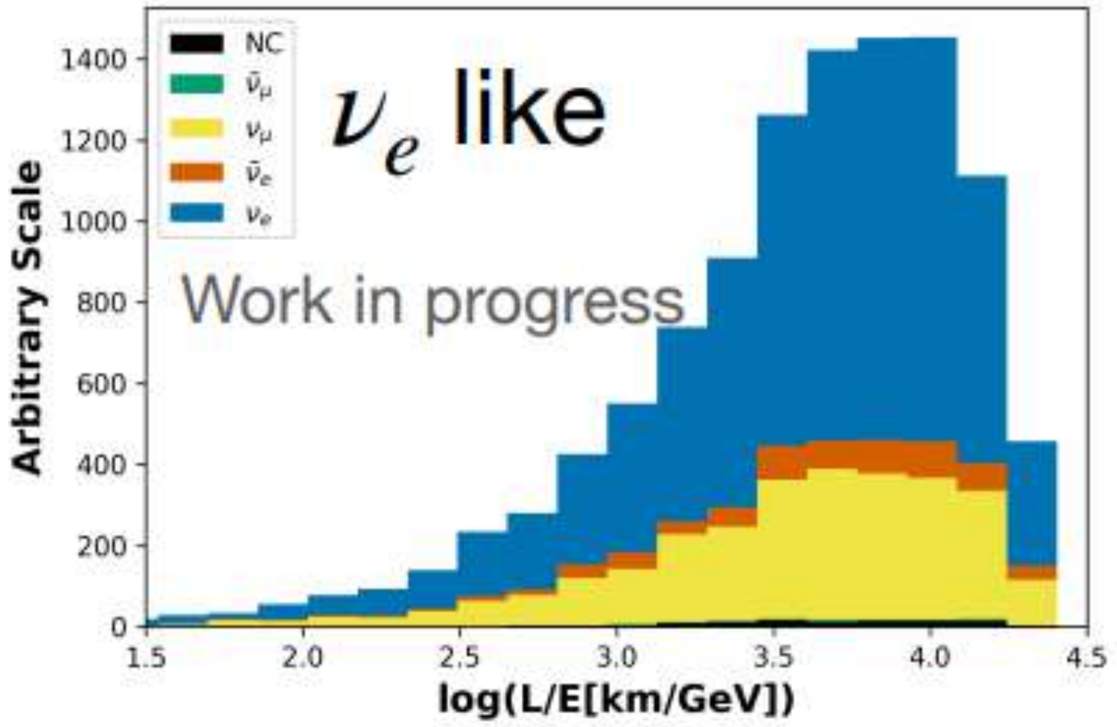
JUNO will collect the largest dataset of geoneutrinos and measure the flux with a precision ~ 8% in 10 years, assuming the fixed Th/U ratio.

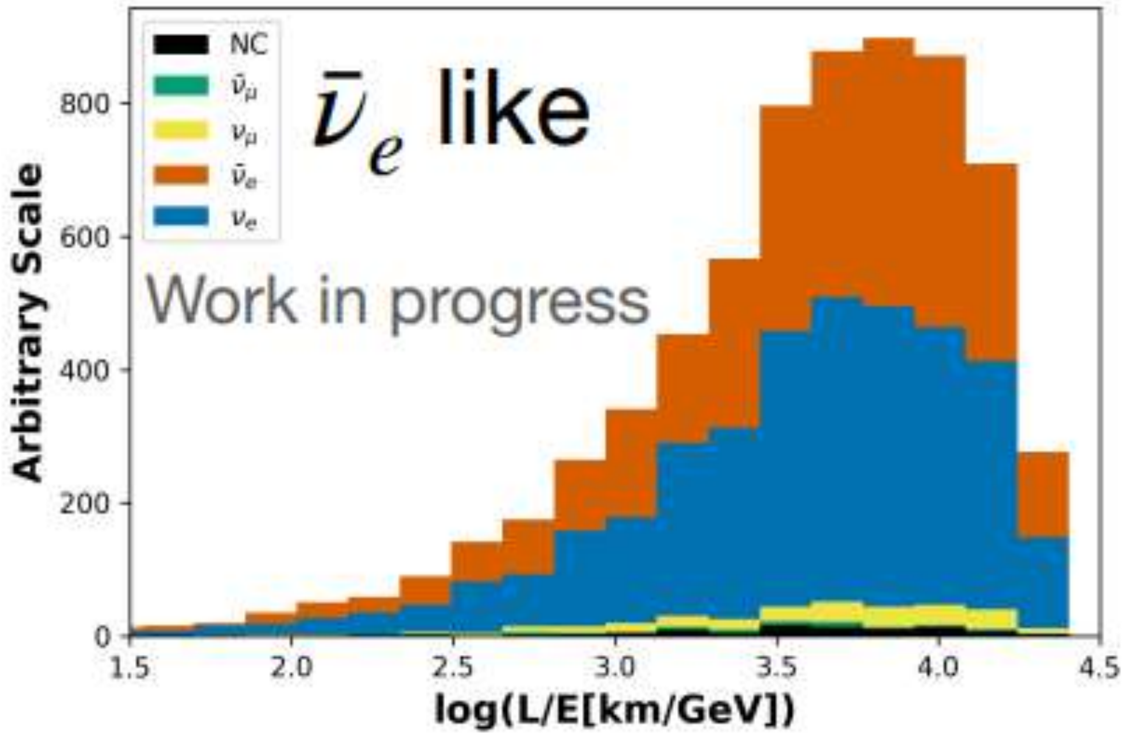
In comparison, KamLAND ~15%, Borexino ~17%

Atmospheric Neutrinos



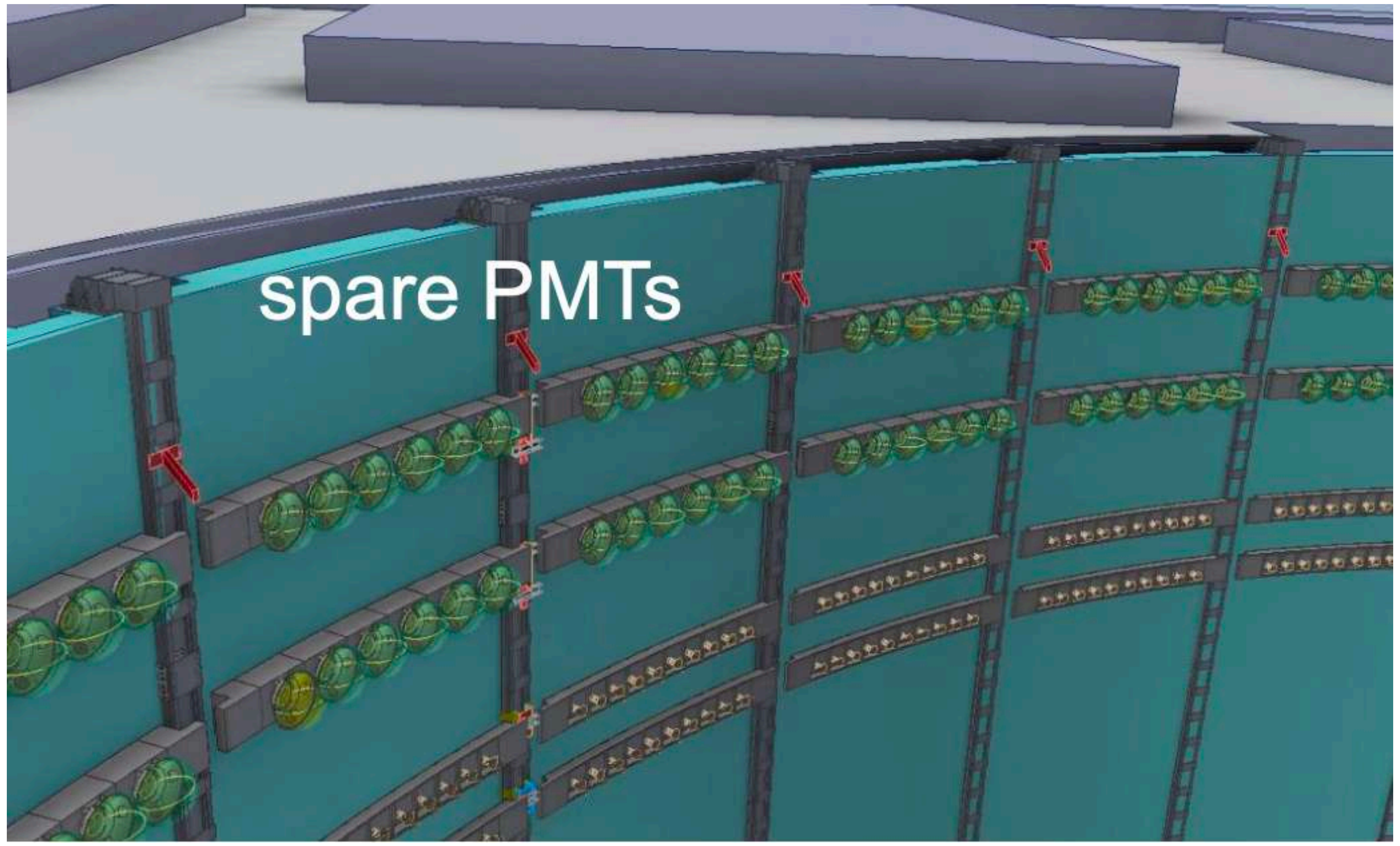




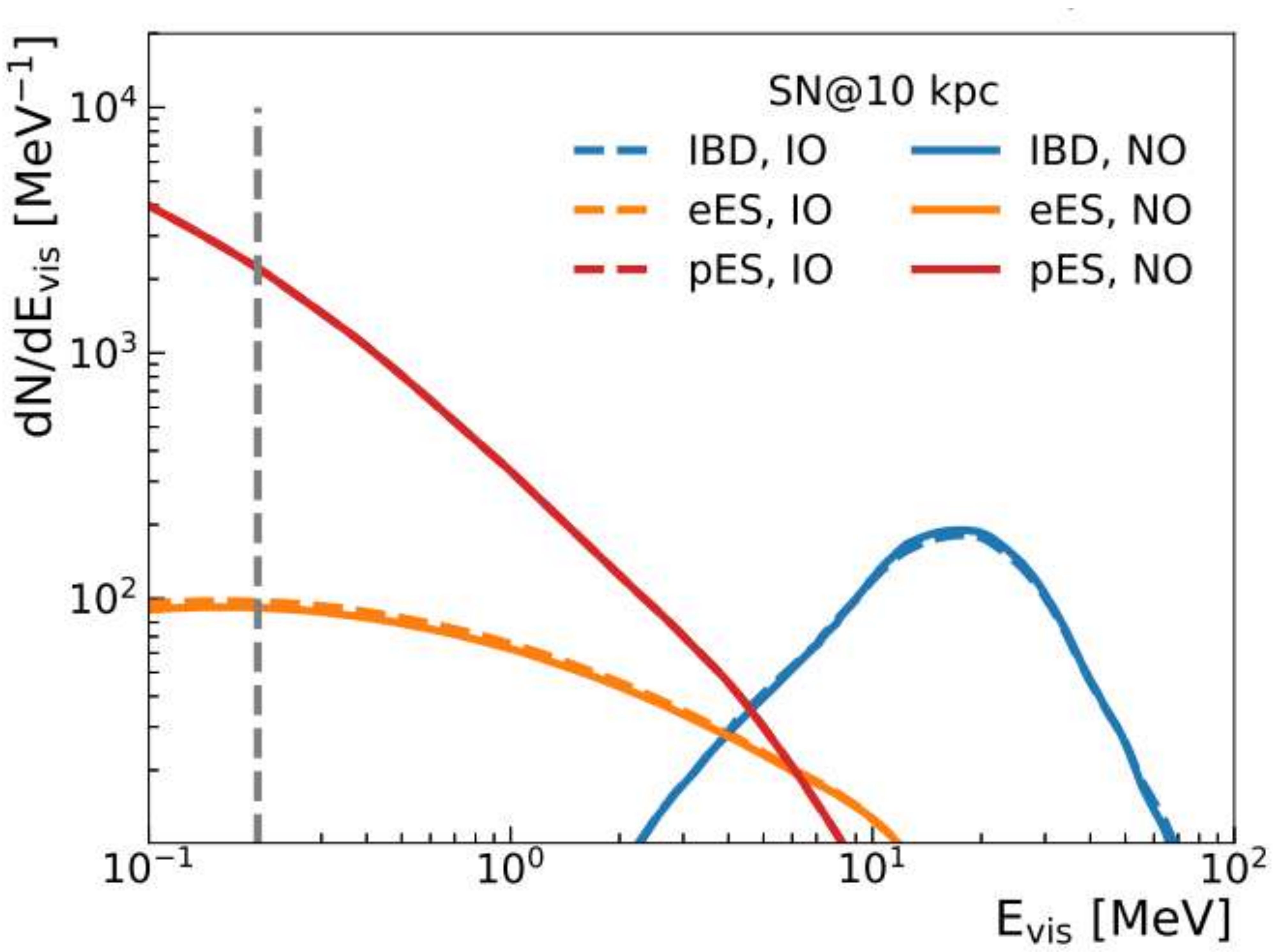


JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator: **e/μ separation**, **$\nu/\bar{\nu}$ separation**, **ν energy (instead of lepton energy)**, **track direction in LS**

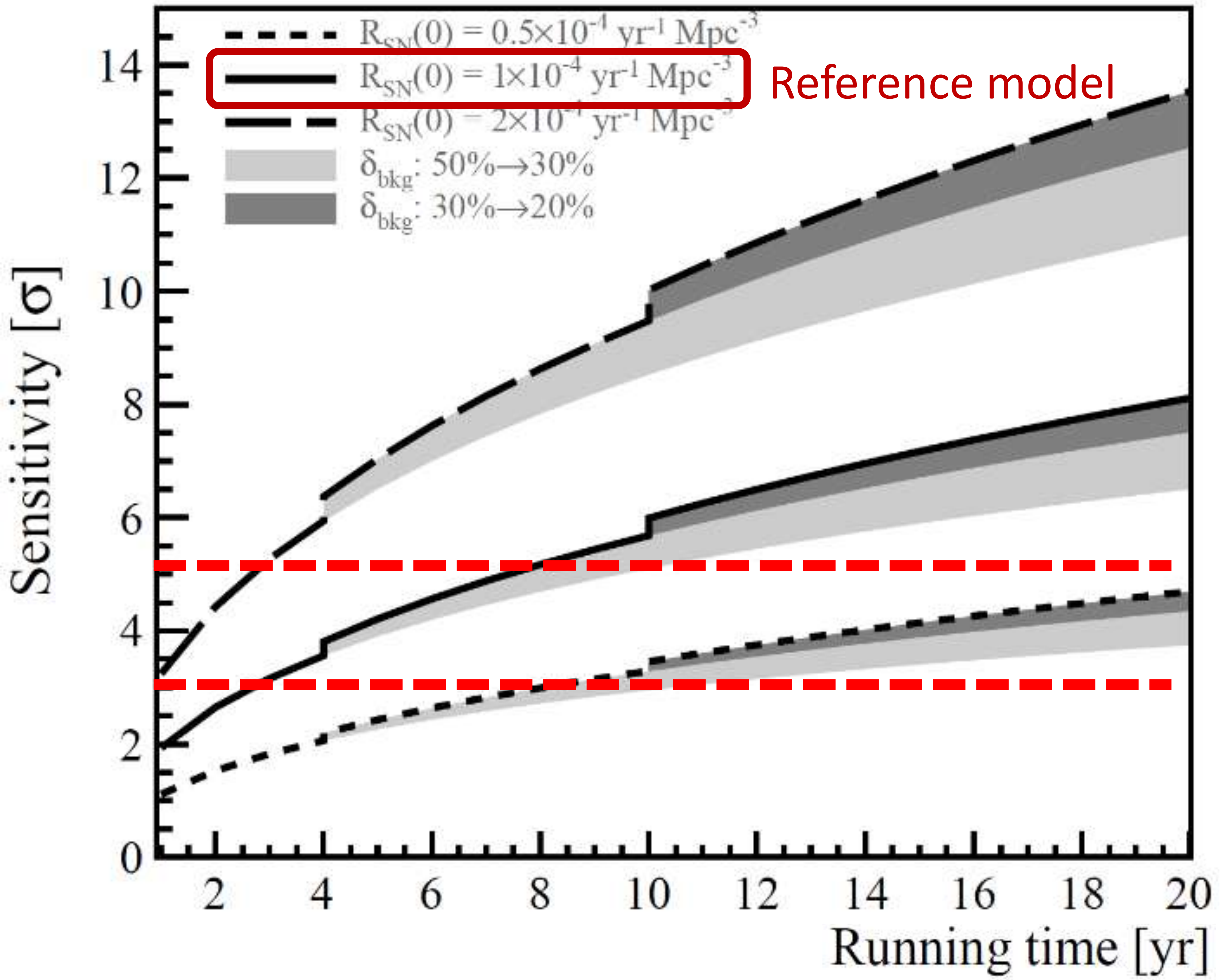
- **Sensitivity mostly from upward going, *e*-like sample**
- **Improving reconstruction and sensitivity**
- **Plan to install spare PMTs on top wall of the water pool to improve PID and direction reconstruction**



Supernovae Neutrinos



- 3 detection channels sensitive to all flavors
- Excellent capability for early warning
- 220 ~ 400 kpc with 50% probability
- pre-SN 1.6 (0.9) kpc
- Alert in 10 ~ 30 ms for typical 10 kpc


Reference model

Diffuse Supernova Neutrino Background:

- S/B ratio improved from 2 to 3.5 with PSD
- Using the reference model:
  3σ in 3 years and > 5σ in 10 years

Summary

- JUNO construction near completion, overcoming challenges
- Component quality exceeding the design value, performance may surpass expectations
- Neutrino mass ordering may be known within this decade
- Anticipate groundbreaking results in particle and astro-particle physics from JUNO