# The Magnificent JUNO


**王为 (Wei Wang, on behalf of the JUNO Collaboration)**

*School of Physics & Sino-French Institute of Nuclear Engineering & Technology*

*中山大学 (Sun Yat-sen University)*

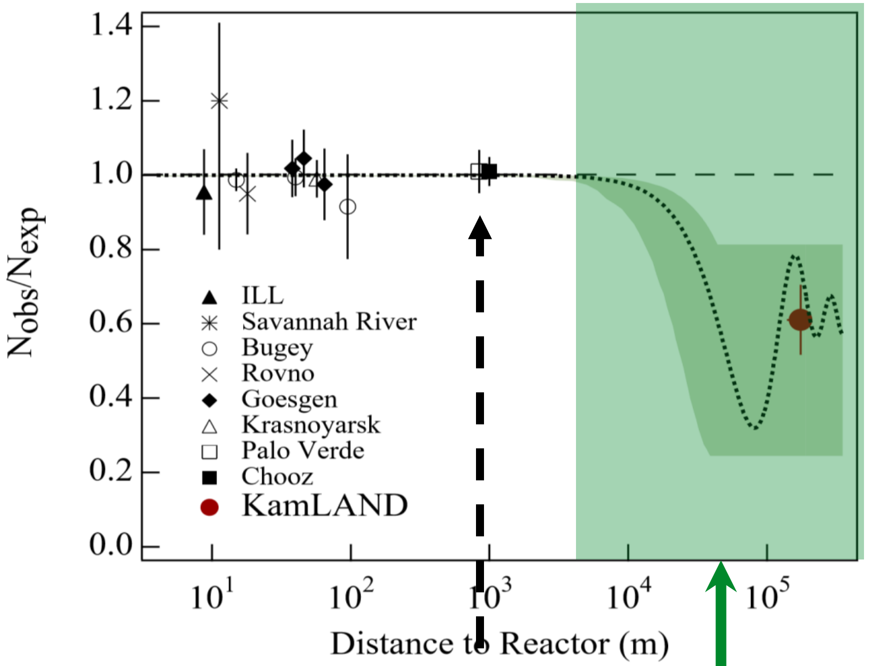

**Workshop on Ghost Particle Hunting: Neutrino Physics and its Applications for World Peace**

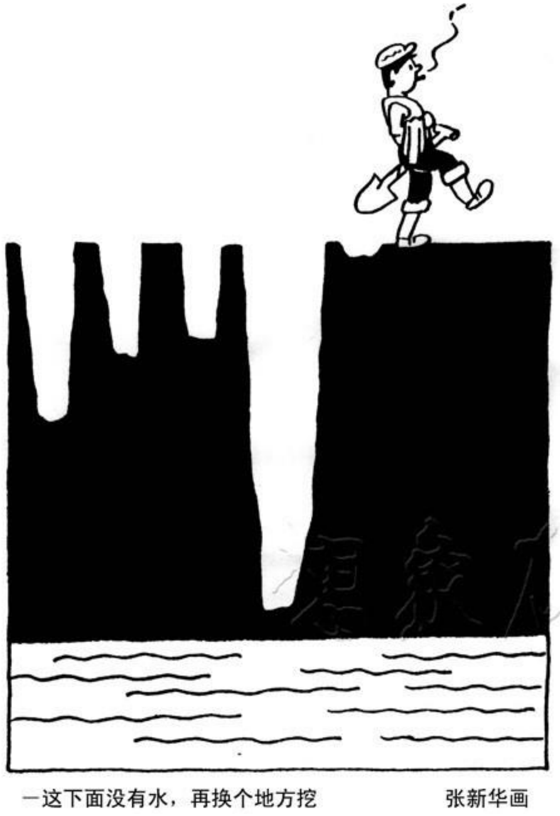
## SYSU has 5 Campuses in 3 Major Cities
## School of Physics is on the South Campus in Guangzhou
## IFCEN is on the Zhuhai Campus

# Outline

- ❖ Introduction of Neutrino Mass Hierarchy
- ❖ Searching for a Solution at Reactors
- ❖ The JUNO Approach and Design
- ❖ Summary and Future Perspectives

# One Page History of Discovering Reactor Neutrino Oscillations

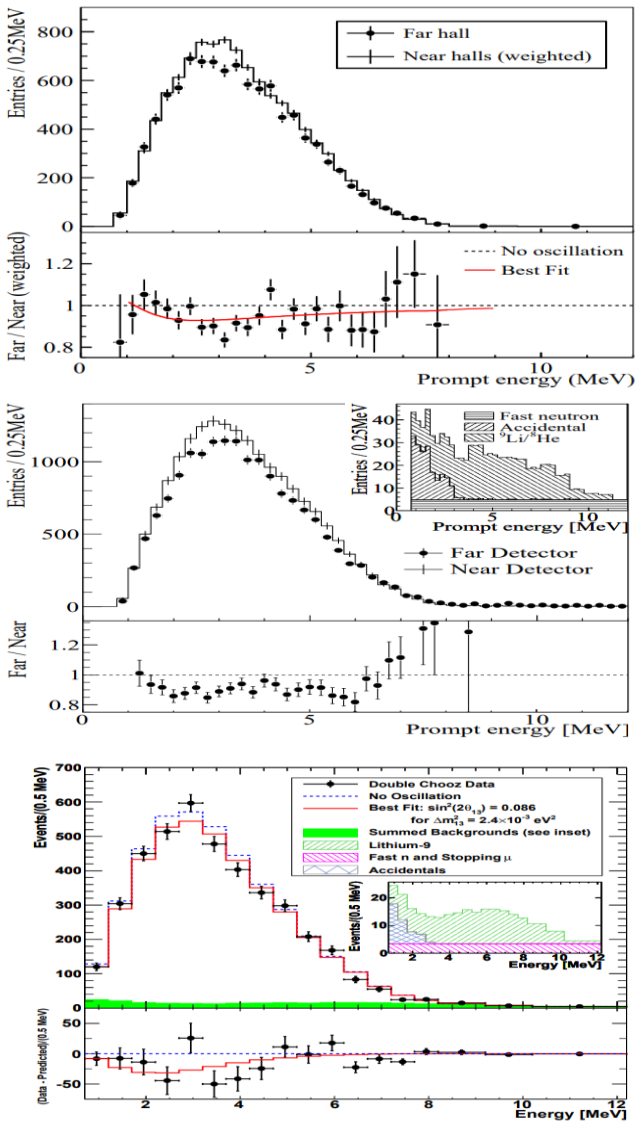



$\theta_{12}$ ***Driven***

**“No water here, try another place”**

**2012: Double Chooz, RENO, Daya Bay**



# Which Mixings Drive Which Reactor Neutrino Oscillations?

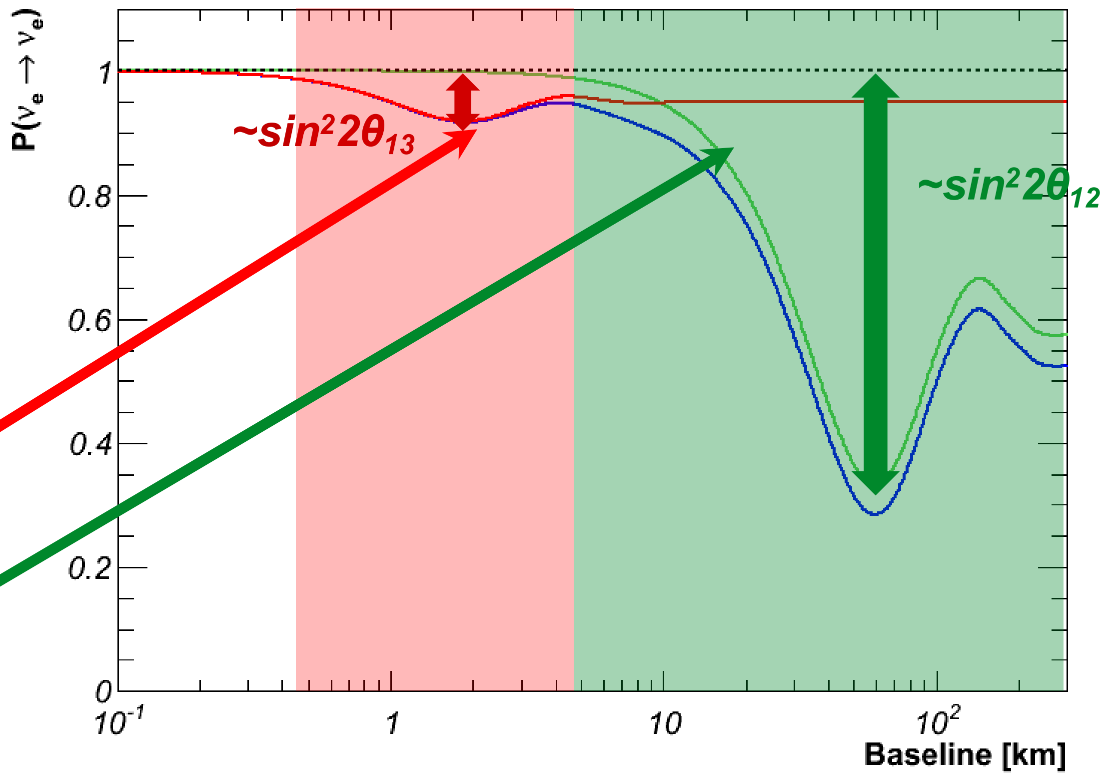
$$P\left(\bar{\nu}_e \to \bar{\nu}_e\right) \approx 1 - \boxed{\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)} - \boxed{\cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)}$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

- At different distances, the survival rate is dominated by different mixing angles
- To measure $\theta_{13}$, a baseline of ~2 km is optimal
- To measure $\theta_{12}$, a baseline of ~50-60 km is optimal

**$\theta_{13}$ Driven**

**$\theta_{12}$ Driven**



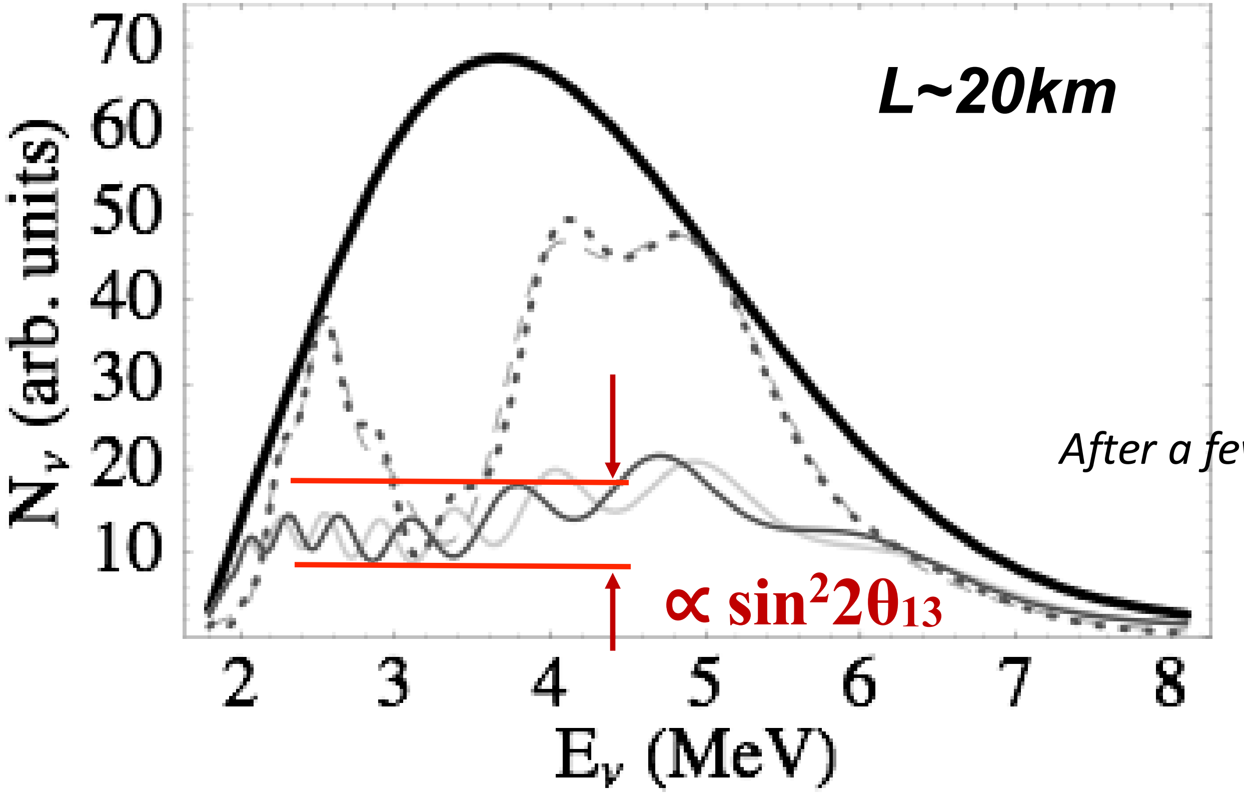
# Known θ13 Enables Neutrino Mass Hierarchy at Reactors

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$
$$- \boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

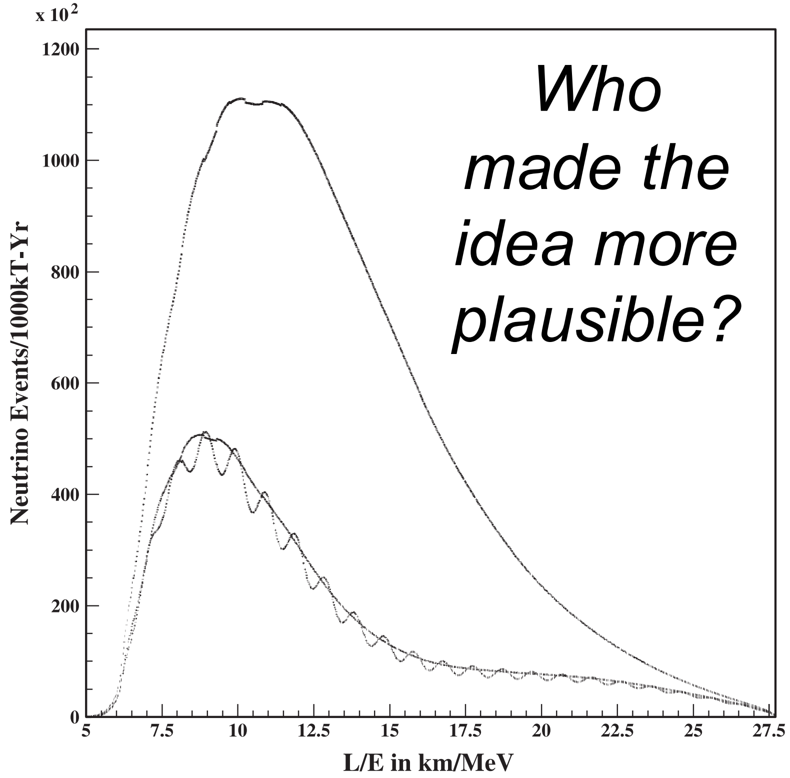
√**Mass hierarchy reflected in the spectrum**

√**Independent of the unknown CP phase**

***Petcov&Piai, Phys. Lett. B533 (2002) 94-106***




*After a few years……*



# Plausible Extracting the Mass Ordering Information? Yes!

***J. G. Learned, S. T. Dye, S. Pakavasa, R. C. Sovobota, PHYSICAL REVIEW D 78, 071302(R) (2008)***

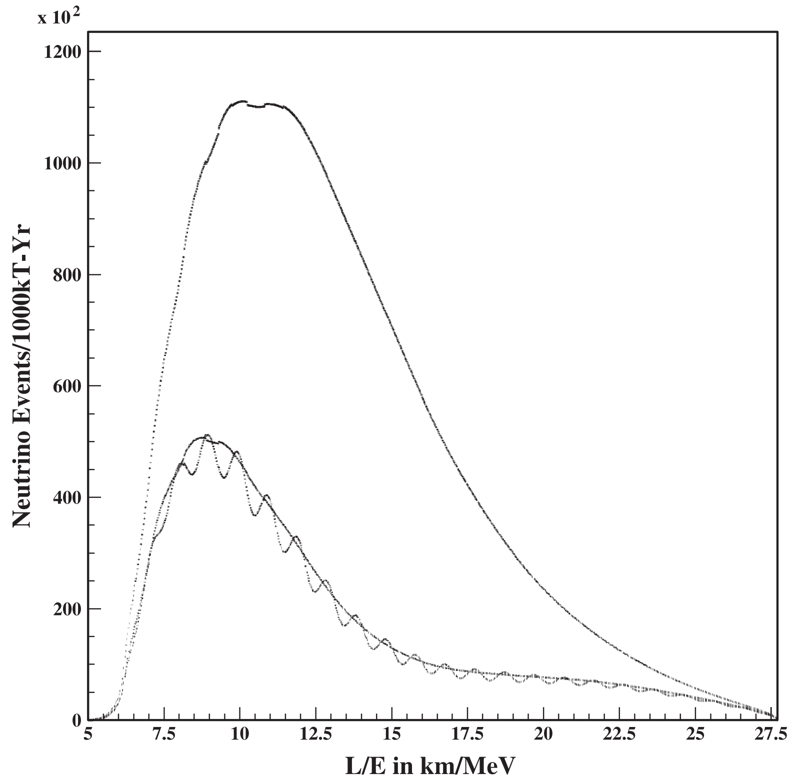



FIG. 1. Event rate versus $L/E$ in units of km/MeV for: no oscillations (top curve), oscillations with $\theta_{13} = 0$ (lower smooth curve), and oscillations with $\sin^2(2\theta_{13}) = 0.1$.

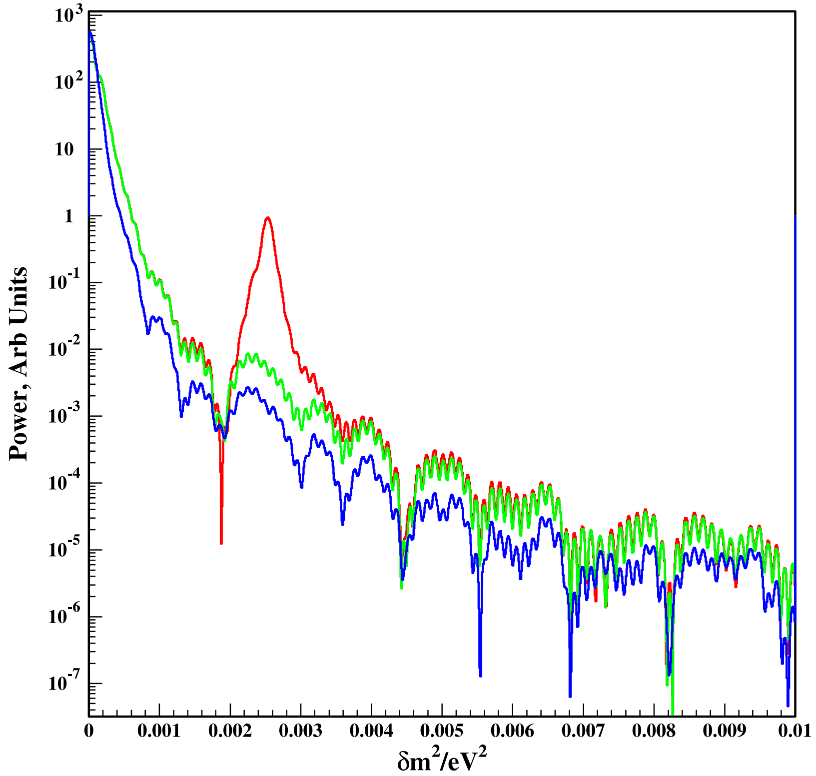



FIG. 2 (color online). Fourier power spectrum with modulation in units of $eV^2$ and power in arbitrary units on the logarithmic scale. The peak due to $\Delta_{31}$ with $\sin^2(2\theta_{13}) = 0.1$ is prominent.

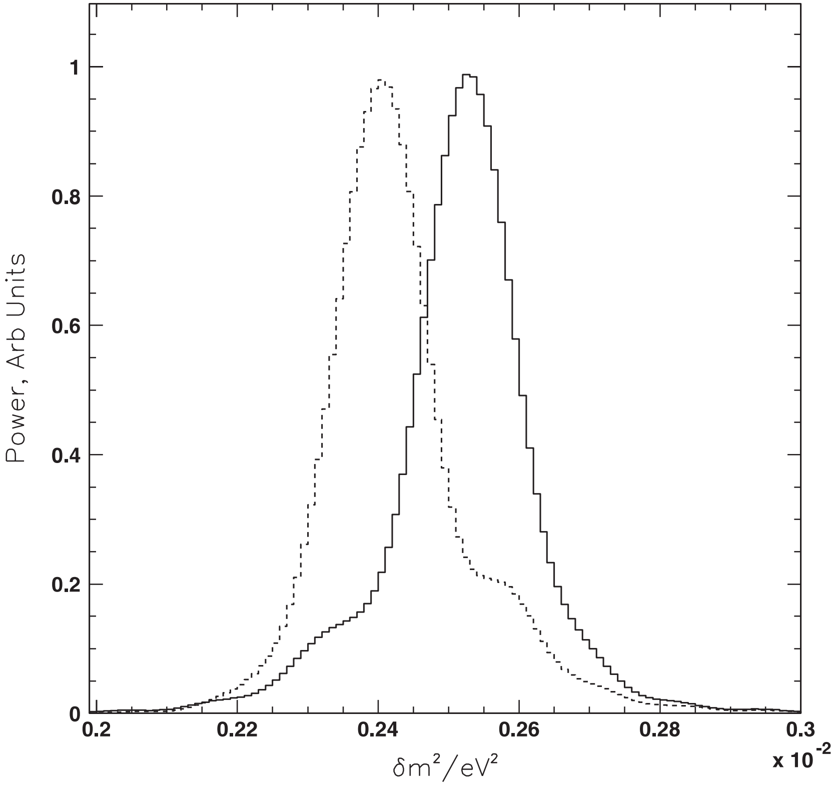
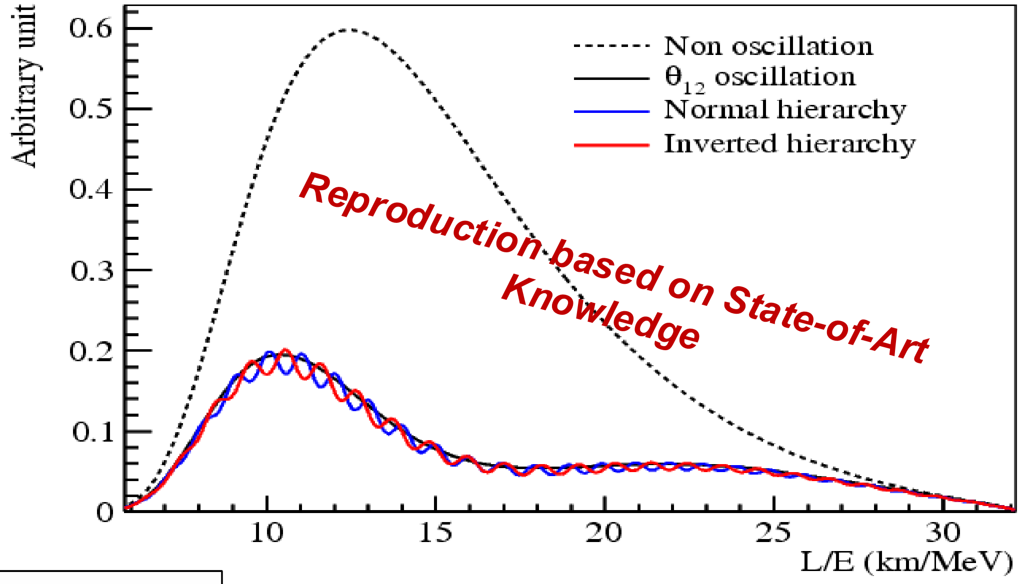
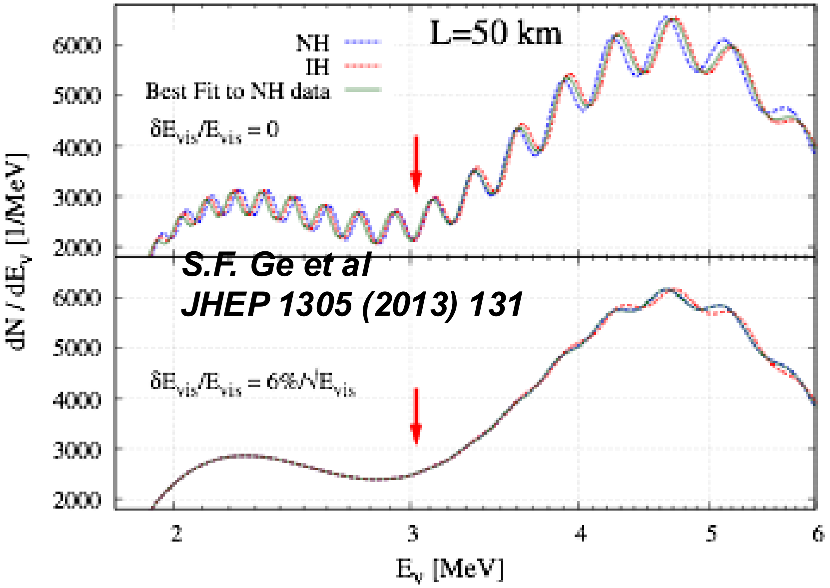


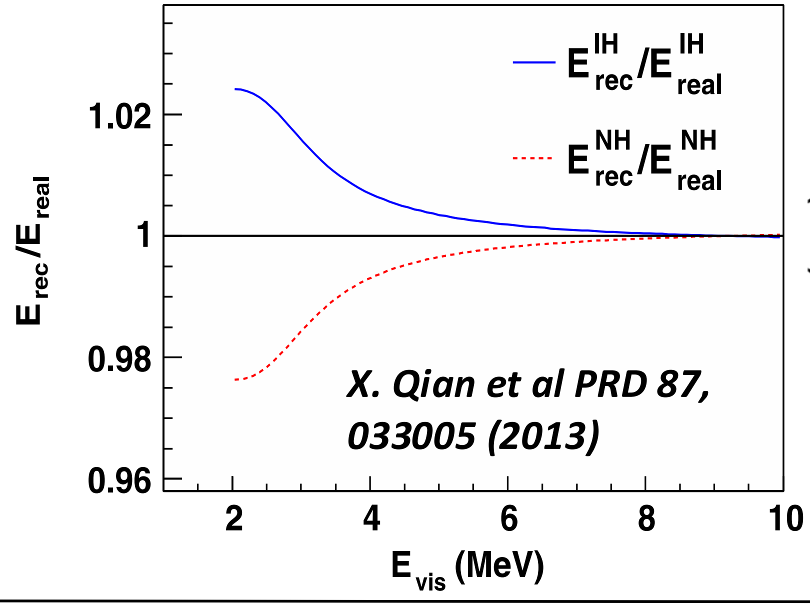

FIG. 3. Neutrino mass hierarchy (normal = solid; inverted = dashed) is determined by the position of the small shoulder on the main peak.

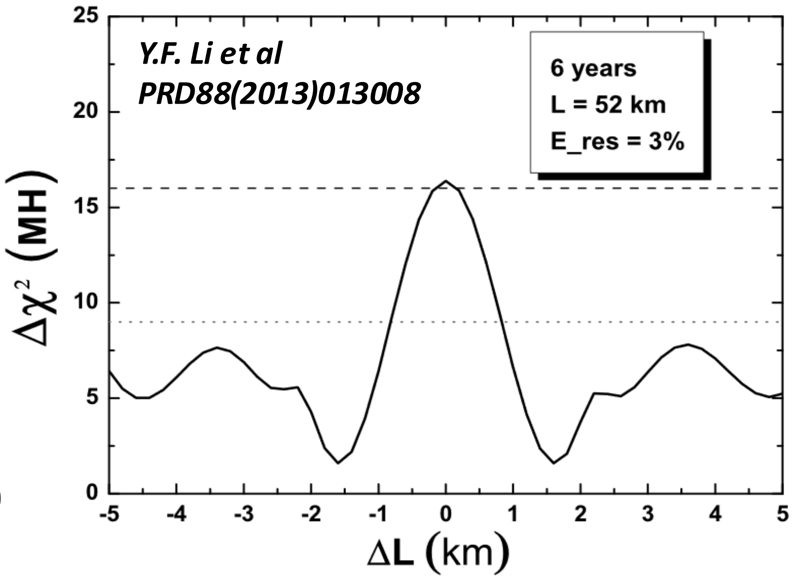
# Challenges in Resolving MH using Reactors

- Energy resolution: ~3%/sqrt(E)
- Energy scale uncertainty: <1%
- Statistics (the more the better)
- Reactor distribution: <~0.5km

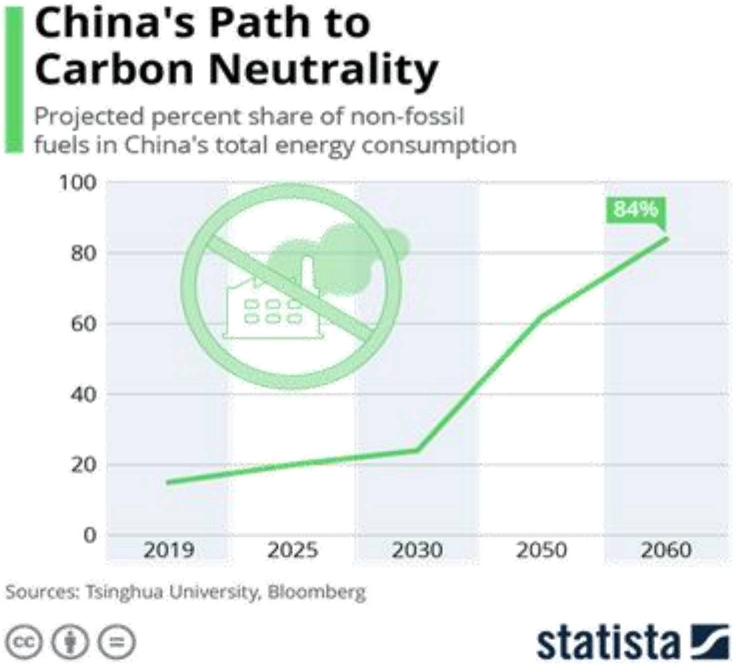


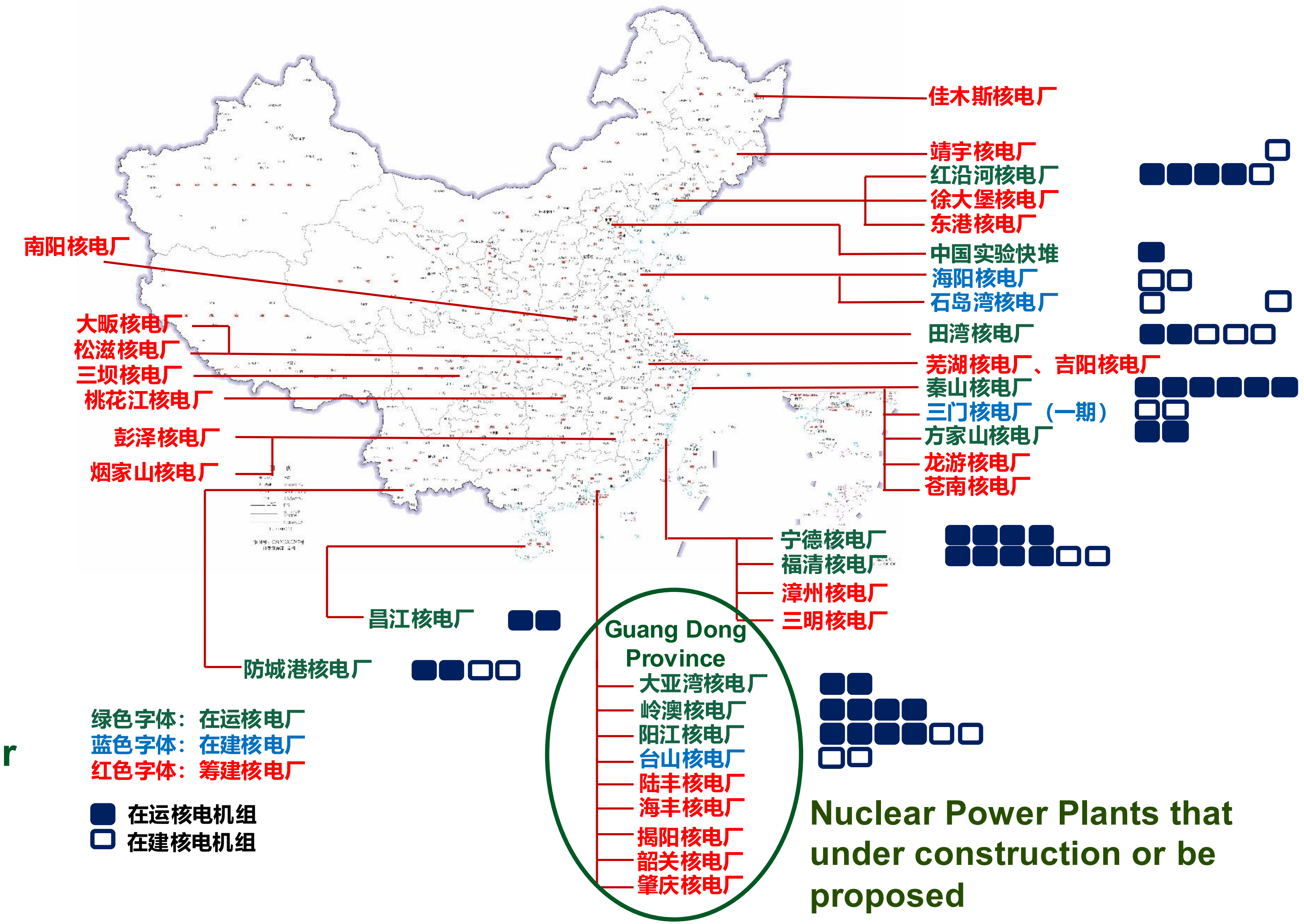



# Suitable Nuclear Power Plants (very easy now) in China



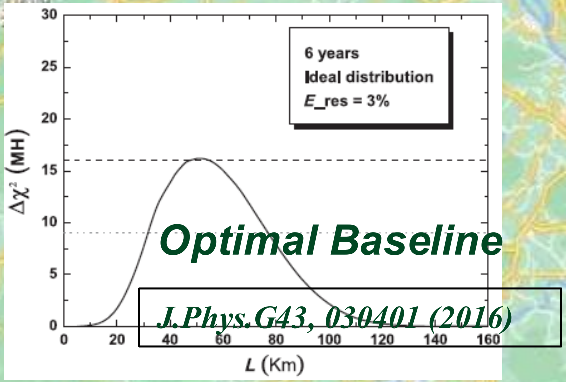




- China builds 6-8 new reactors a year
- Each reactor needs an average of 800 professional workers

Nuclear Power Plants that under construction or be proposed

# Jiangmen Underground Neutrino Observatory (JUNO)

- Proposed as a reactor neutrino experiment for mass ordering in 2008 (PRD78:111103,2008; PRD79:073007,2009)
  - **driving the design specifications: location, 20 kton LS, 3% energy resolution, 700 m underground**
- Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches
- Approved in 2013. Construction in 2015-2024

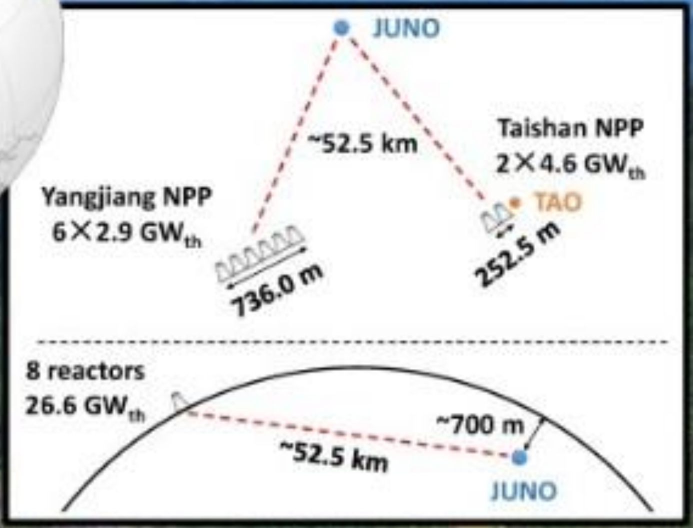




**70+ institutions, ~750 collaborators**

Asia: China (34), Taiwan,China (3) Thailand (3), Pakistan, Armenia
Europe: Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Latvia, Slovakia, UK
America: Brazil (2), Chile (2), USA (2)

# Jiangmen Underground Neutrino Observatory




Vertical tunnel: 563 m

Overburden: ~650 m (1800 m.w.e)

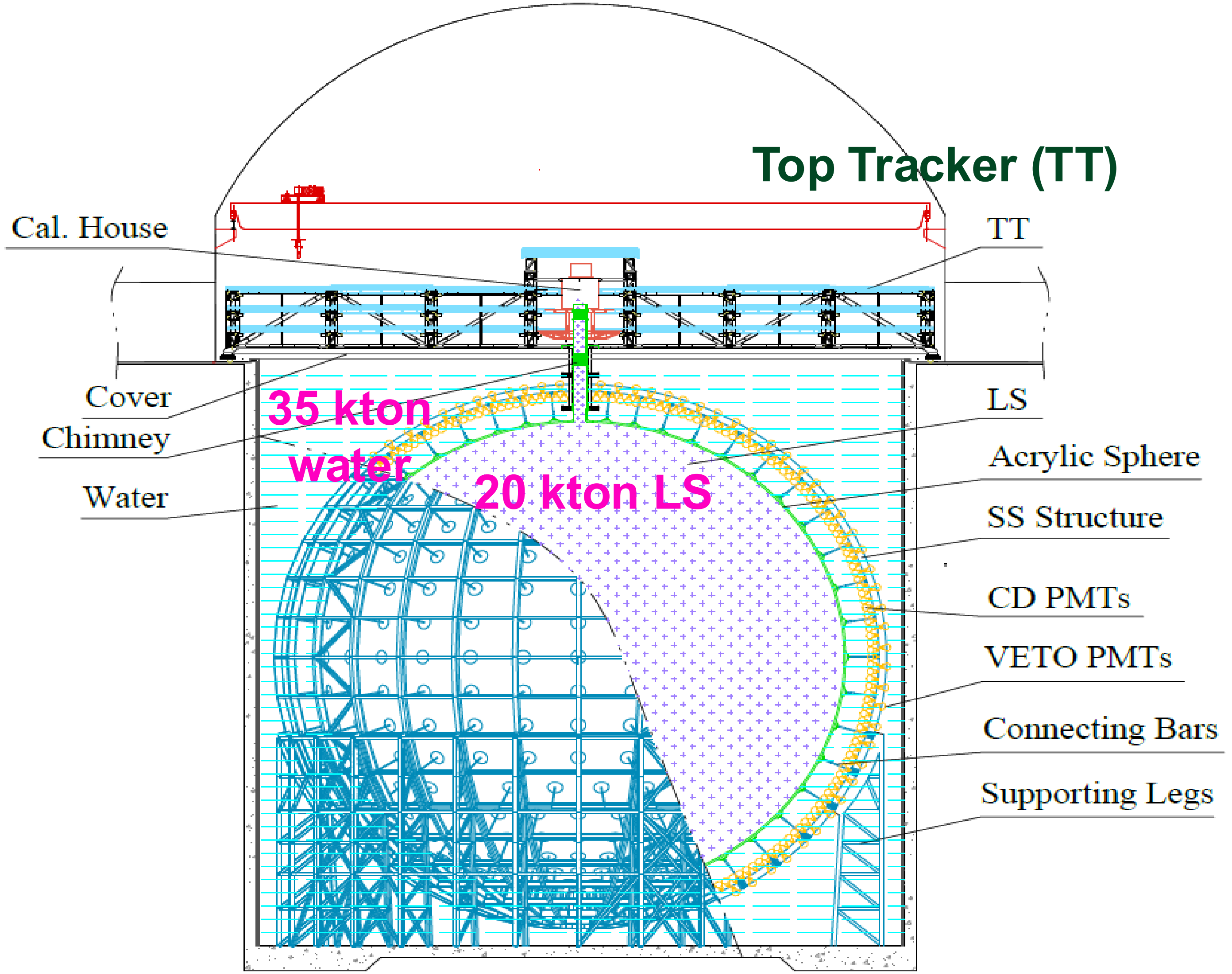
**Surface Buildings**

- Office/Dorm/Computation
- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Power station
- Cable train

Slope tunnel: 1265 m @ slope of 42%

Civil construction finished in Dec, 2021

# The JUNO Central Detector




**Acrylic Sphere:**

Inner Diameter (ID): 35.4 m

Thickness:12 cm

**Stainless Steel (SS) Structure:**

ID: 40.1 m, Outer Diameter (OD): 41.1 m

**17612** 20-inch PMTs, **25600** 3-inch PMTs

**Water pool:**

ID: 43.5 m, Height: 44 m, Depth: 43.5 m

**2400** 20-inch PMTs

$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage & non-uniformity

Photon statistics

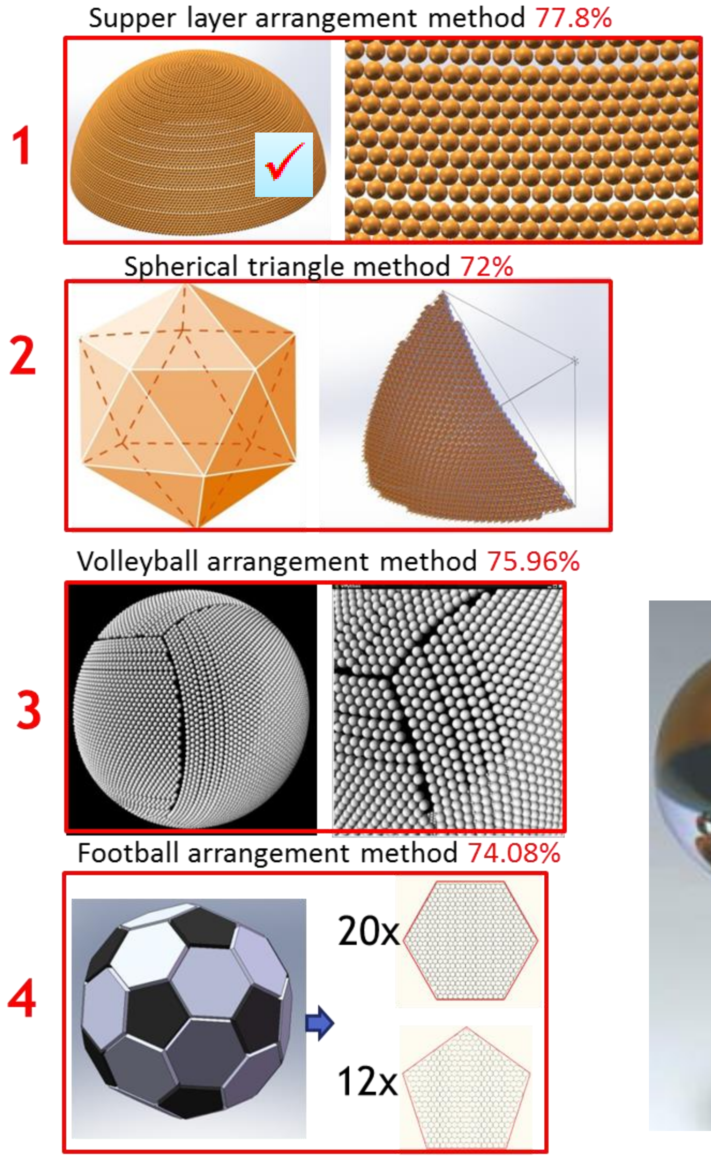
Noise (~background)

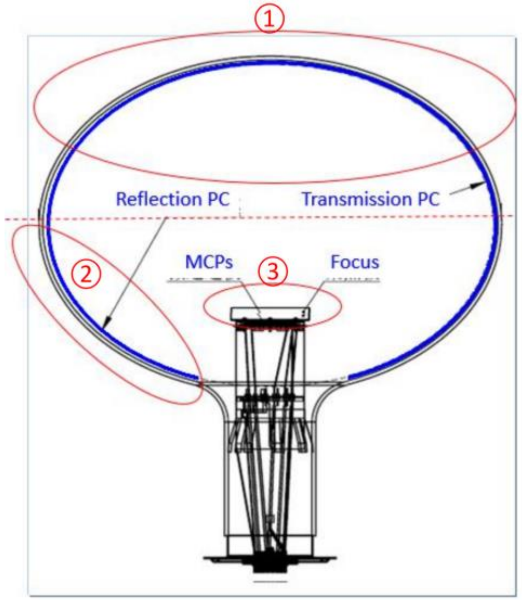
# The Detector Performance Goals

| | KamLAND | Daya Bay | PROSPECT | JUNO Concept (Design&Simulation) |
|---|---|---|---|---|
| Target Mass | **~1kt** | 20t | ~4t | **~20kt** |
| Photocathode Coverage | ~34% | ~12% (Effective) | ESR + PMTs | **~80% (75%+3%)** |
| PE Collection | ~250 PE/MeV | ~160 PE/MeV | **~850 PE/MeV** | **~1200 PE/MeV (1665)** |
| Energy Resolution | ~6%/√E | ~7.5%/√E | **~4.5%/√E** | **3%/√E** |
| Energy Calibration | ~2% | **1.5%→ 0.5%** | ~1% | **<1%** |

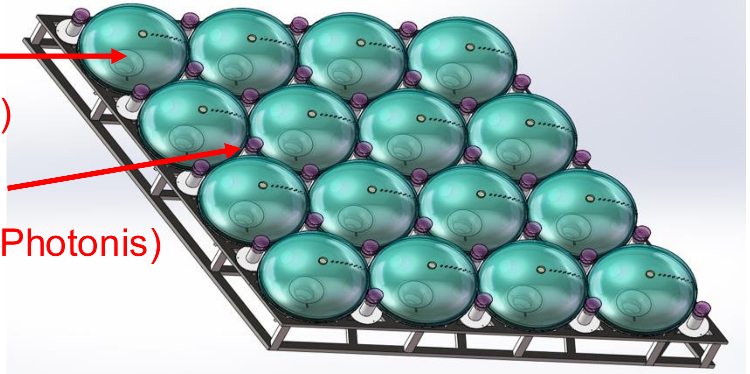
***An extremely demanding detector and a challenging job***

# Packing PMTs as Tight as Possible and Keep Them Safe

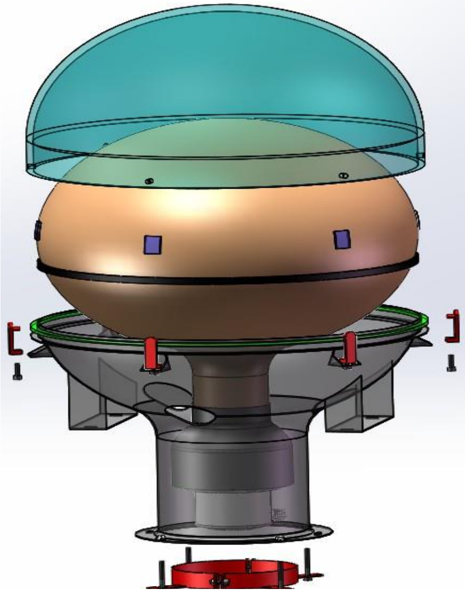



**20" PMT (~18K)**
MCP-PMT (~13K)
Hamamatsu HQE (5K)



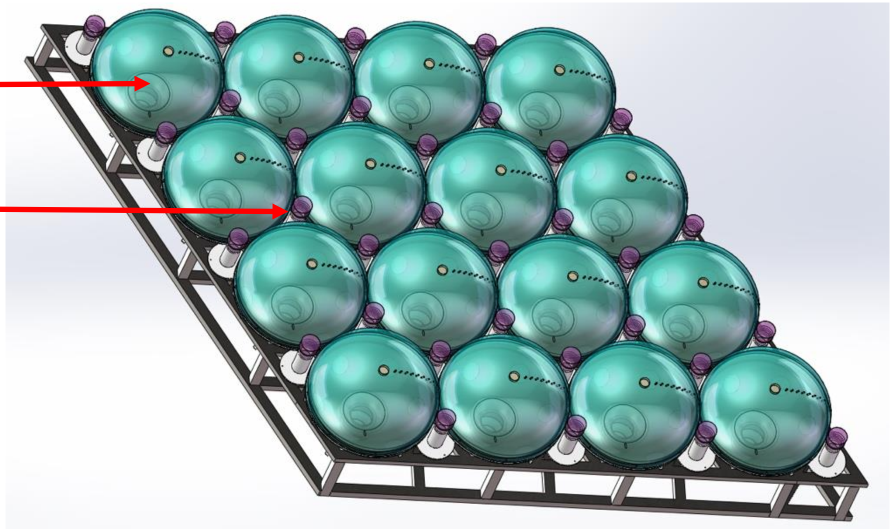
**3"sPMT(~25K)**
HZC XP72B22 (Photonis)

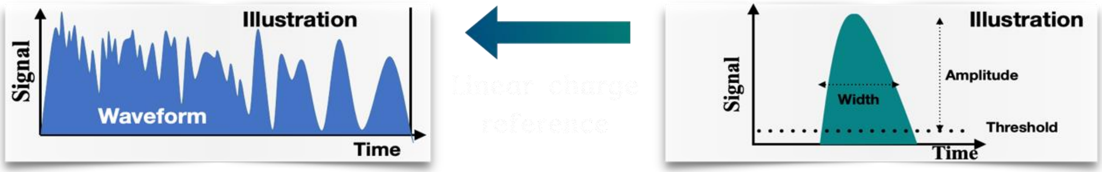


# Double Calorimetry: Large PMTs and Small PMTs

**20” LPMT (~18K)**
MCP-PMT (~13K) + Hamamatsu HQE (5K)

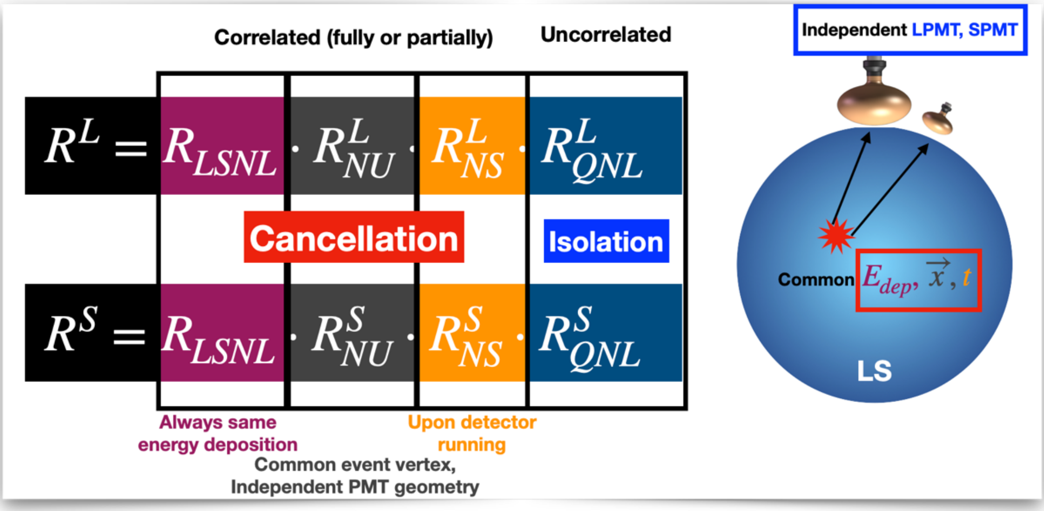
**3”sPMT(~25K)**
HZC XP72B22 (HZC Photonics)



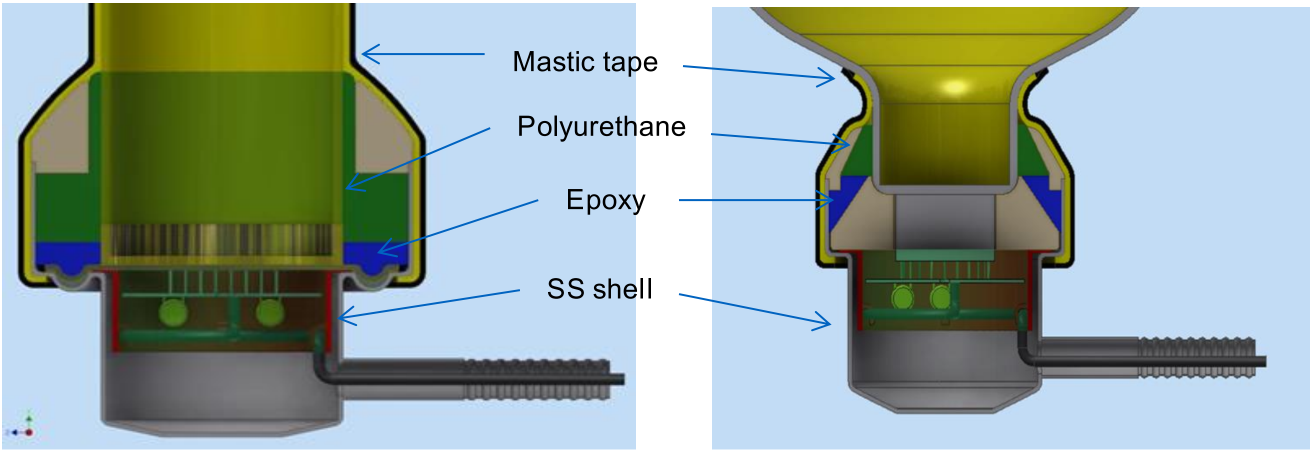




- **3”-PMT photocathode coverage: ~2.7% (~75.2% for LPMTs)**
- **More importantly, double calorimetry for energy non-linearity**

➢ ***For details, see arXiv: 2104.02565***



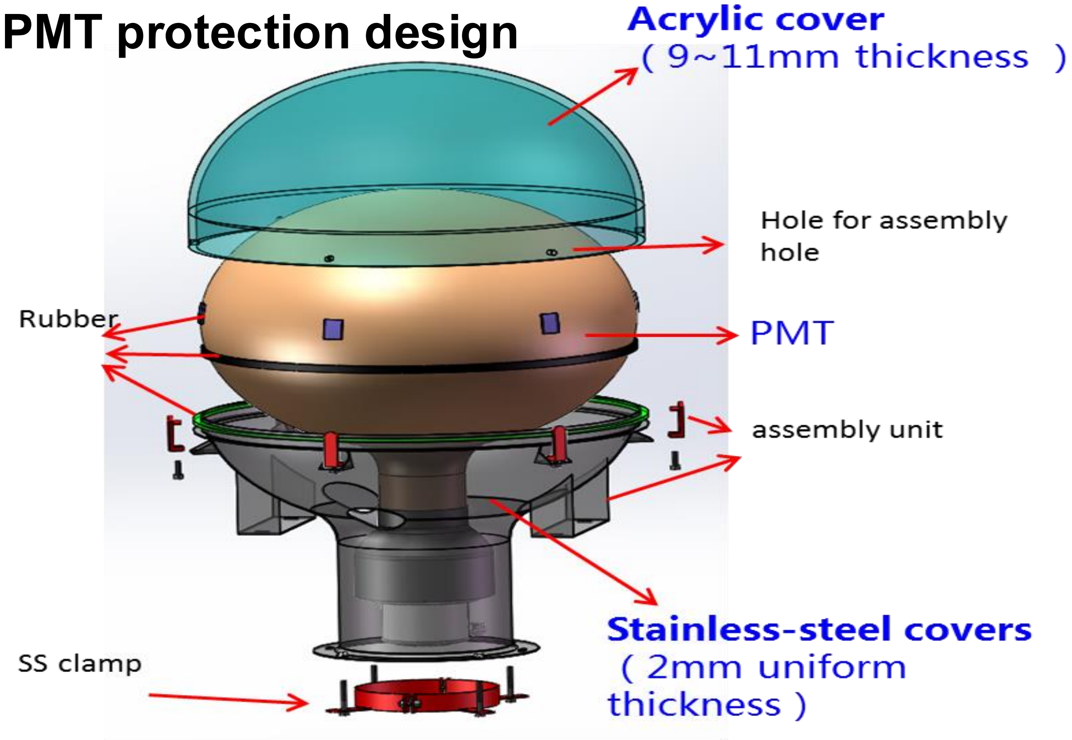
# 20” PMT Water-Proof Potting




**A Potting Lab of 650m$^2$ in the PMT workshop**

- Potting technique developed and matured in 2019; Assemble line built and potting started in Jul 2019, with a capacity of 40–50 PMTs/day;
- **The technique has been very successful: No leaks found after leakage tests (sampled) using pressurized water (@ 5 bar) and $SF_6$ gas sniffing**

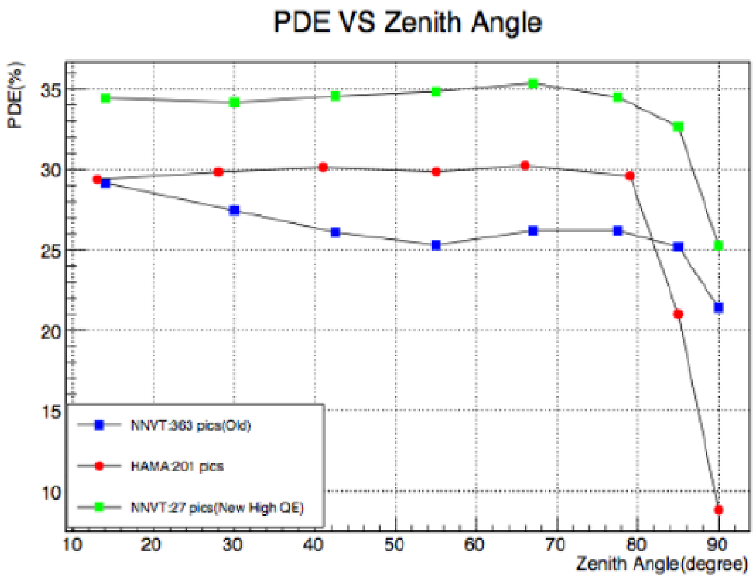
# 20” PMT Implosion Prevention System

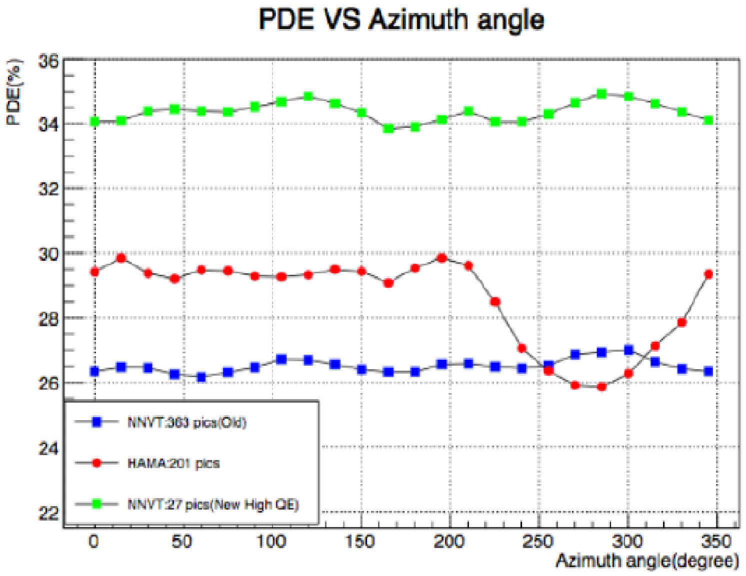


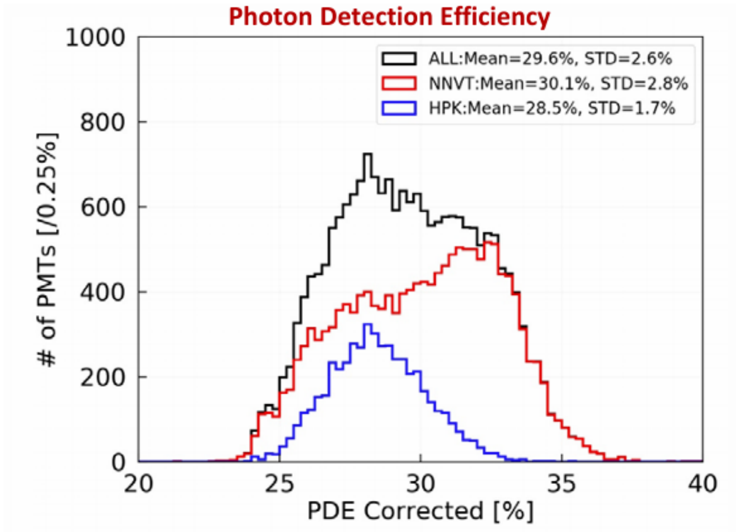

- Top cover: acrylic, 9~11mm, mass production started and 6,000 have been delivered
- Bottom cover: stainless-steel, 2mm; stainless-steel covers production started
- Multiple implosion tests have been carried out → **SAFE!**

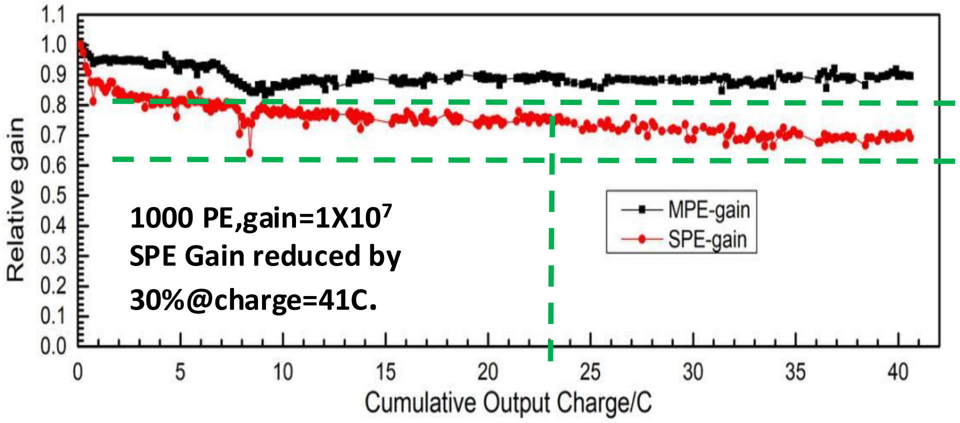
# A PMT Characterization, Potting and Assembly Station in a Warehouse

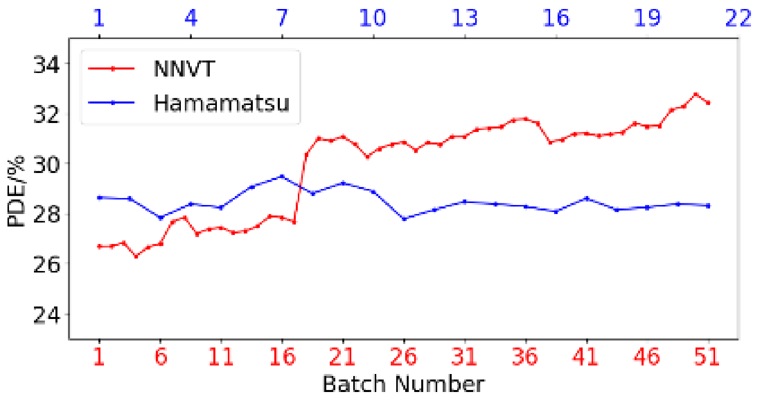
# Characterizing/Testing Every Single PMT with Great Care

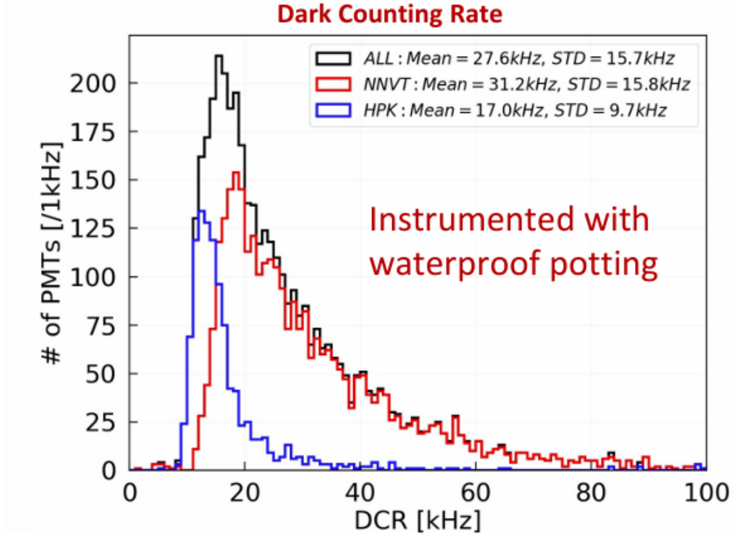


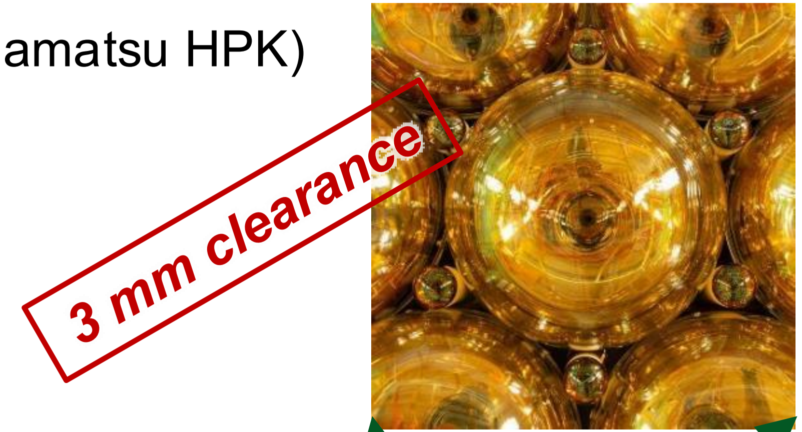



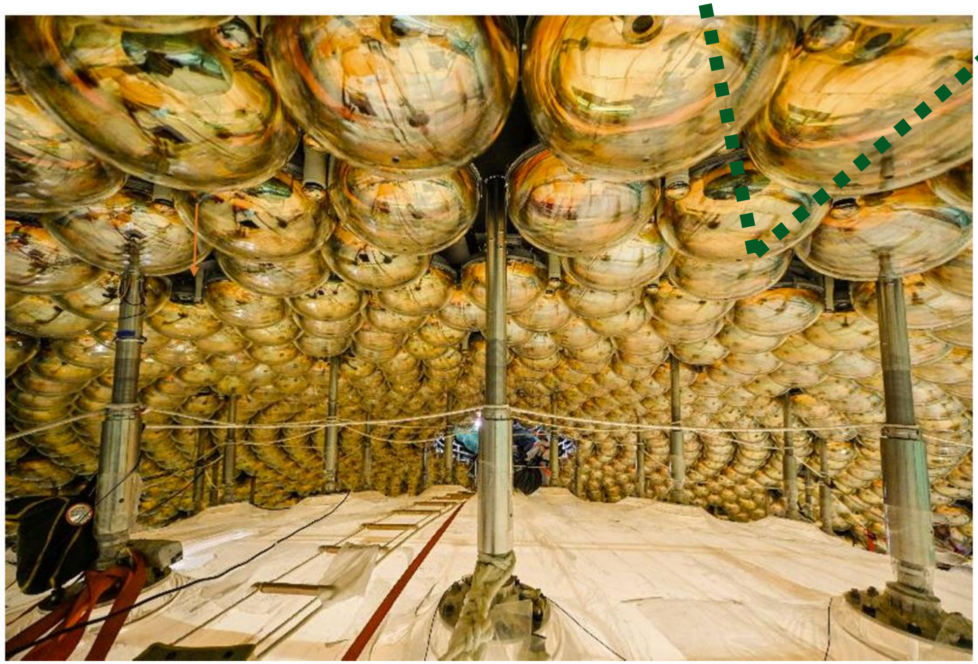



# PMT System Summary

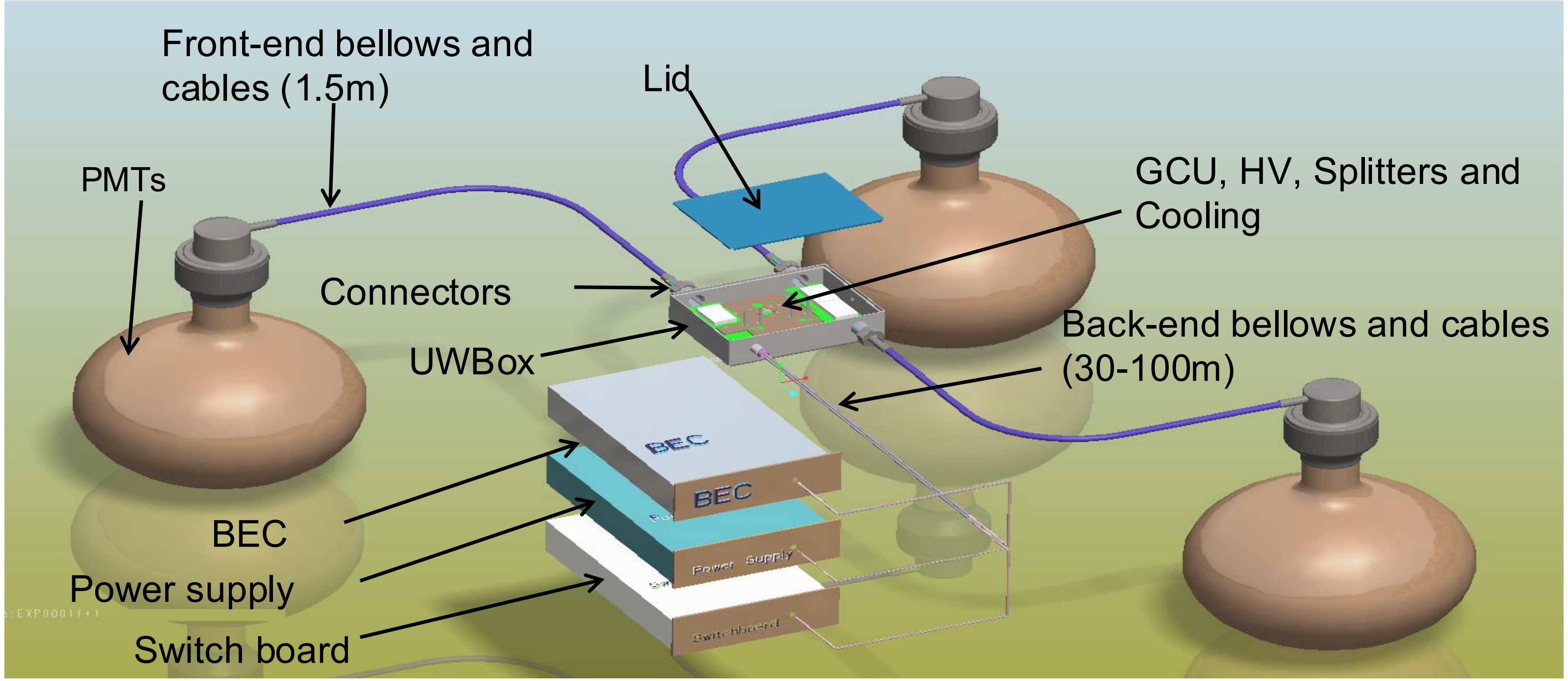
- 20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu HPK)
  3.1-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
  - All PMTs delivered and their performance tested OK
- Water proof potting done: failure rate < 0.5%/6 years
- Implosion protection: acrylic top & SS bottom (JINST 18 (2023), P02013)
  - Mass production completed

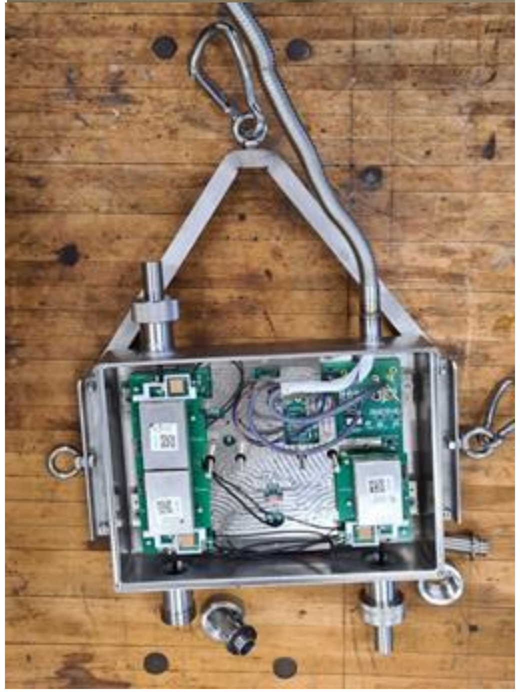



| | LPMT (20-in) | | SPMT (3-in) |
|---|---|---|---|
| | **Hamamatsu** | **NNVT** | **HZC** |
| **Quantity** | 5,000 | 15,012 | 25,600 |
| **Charge Collection** | Dynode | MCP | Dynode |
| **Photon Det. Eff.** | 28.5% | 30.1% | 25% |
| **Dynamic range for [0-10] MeV** | [0, 100] PEs | | [0, 2] PEs |
| **Coverage** | 75% | | 3% |
| **Reference** | Eur.Phys.J.C 82 (2022) 12, 1168 | | NIM.A 1005 (2021) 165347 |



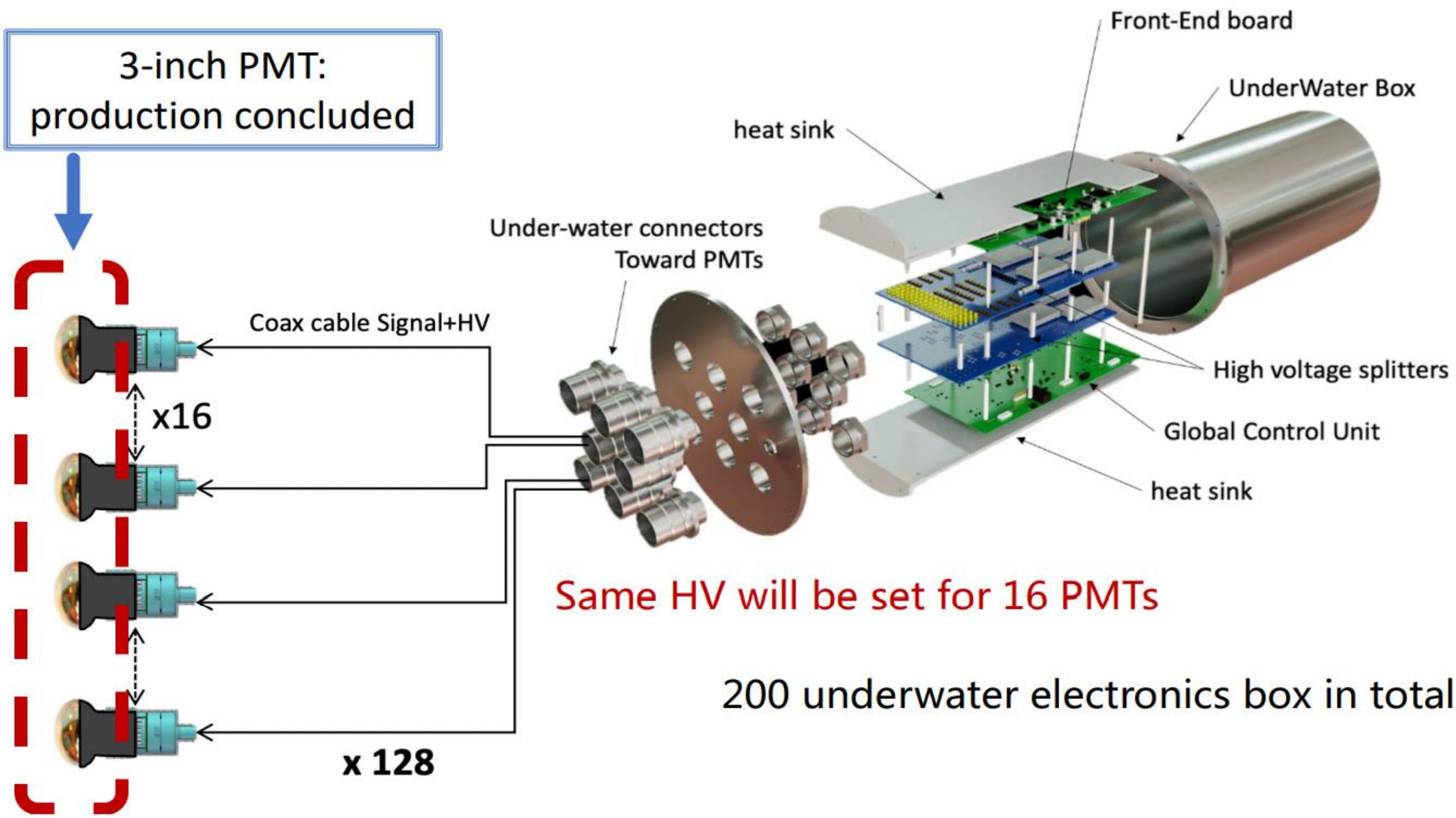
# The 20" PMT Electronics System Scheme



- The 1F3 system cases Splitter, HV FEC, ADC, GCU&FPGA in the underwater boxes
- Two cables, one CAT5 and one CAT6, supply low voltage DC power, timing signal and data transfer

# The 3” PMT Electronics System Scheme



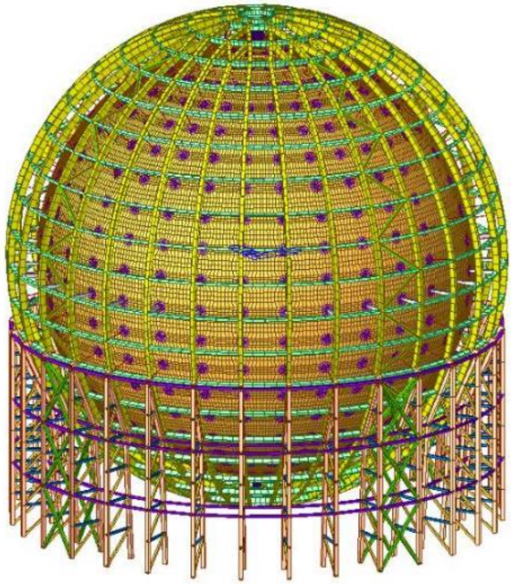

Same HV will be set for 16 PMTs

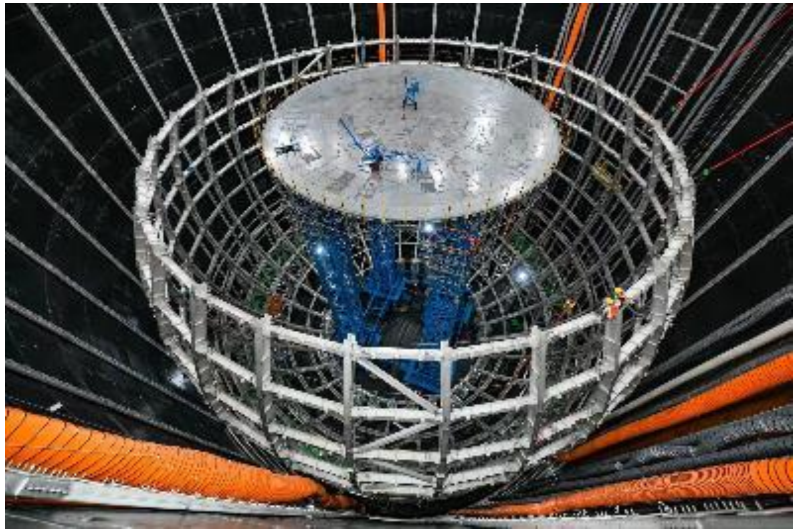
200 underwater electronics box in total

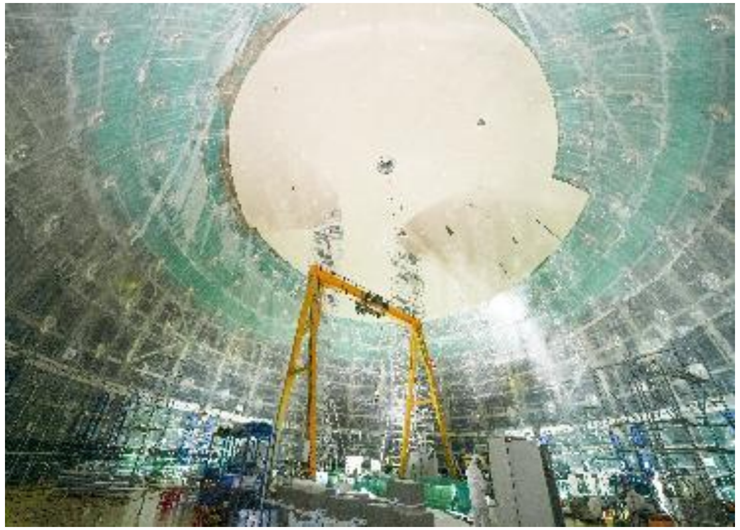
# The Construction of the Central Detector

arXiv: 2311.17314 (2023)

- **A 35.4m spherical acrylic vessel containing 20kton LS**
- **Supported by the 41.1 m Stainless Steel structure via 590 supporting bars**



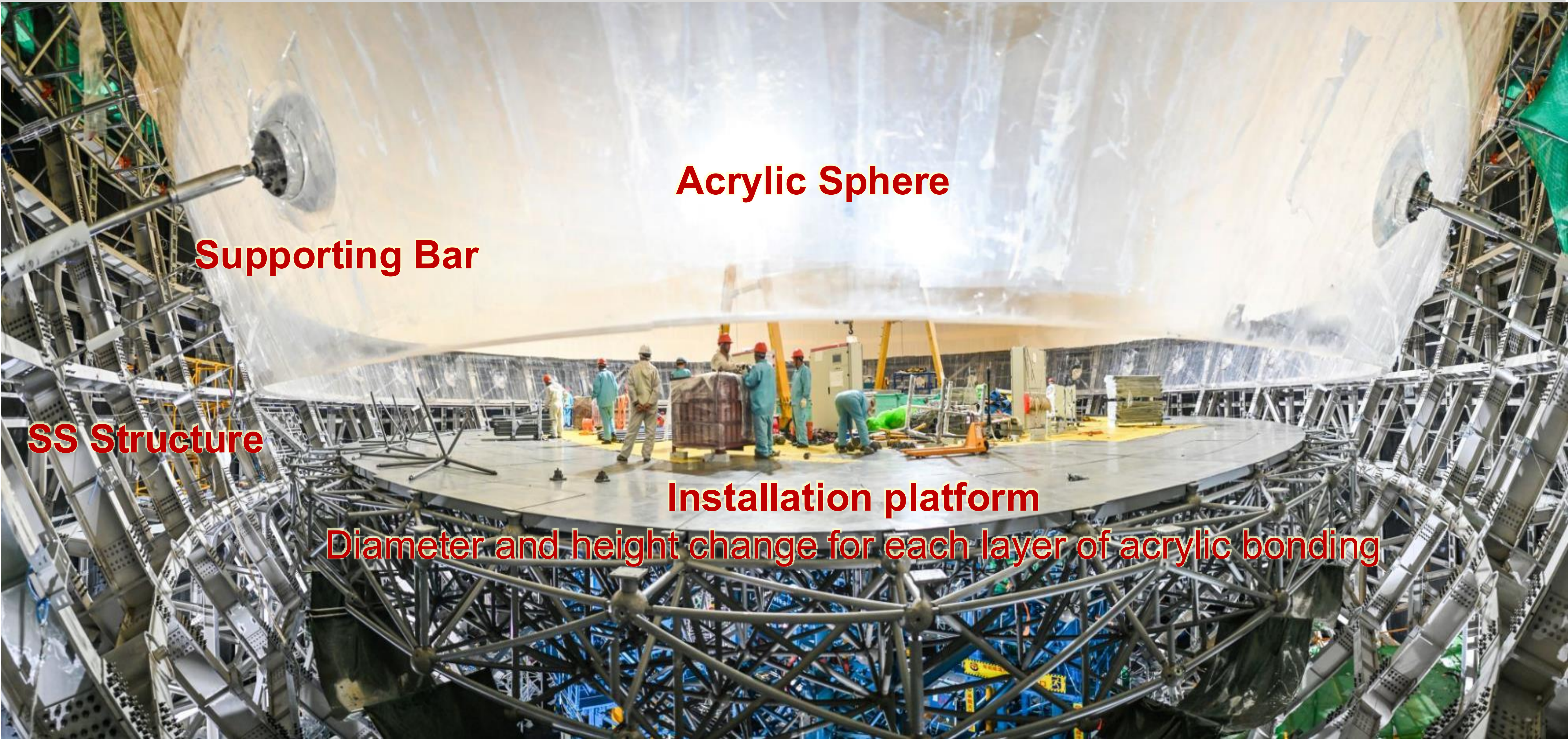




# JUNO Detector and Tightly Packed PMTs

*arXiv: 2311.17314 (2023)*

# The Last Steps of Completing the Central Detector



# Calibration and Expected Energy Resolution

- Four systems for 1D, 2D, 3D scan with multiple sources
- Energy scale and non-linearity will be calibrated to <1% using $\gamma$ peaks and cosmogenic $^{12}$B beta spectrum

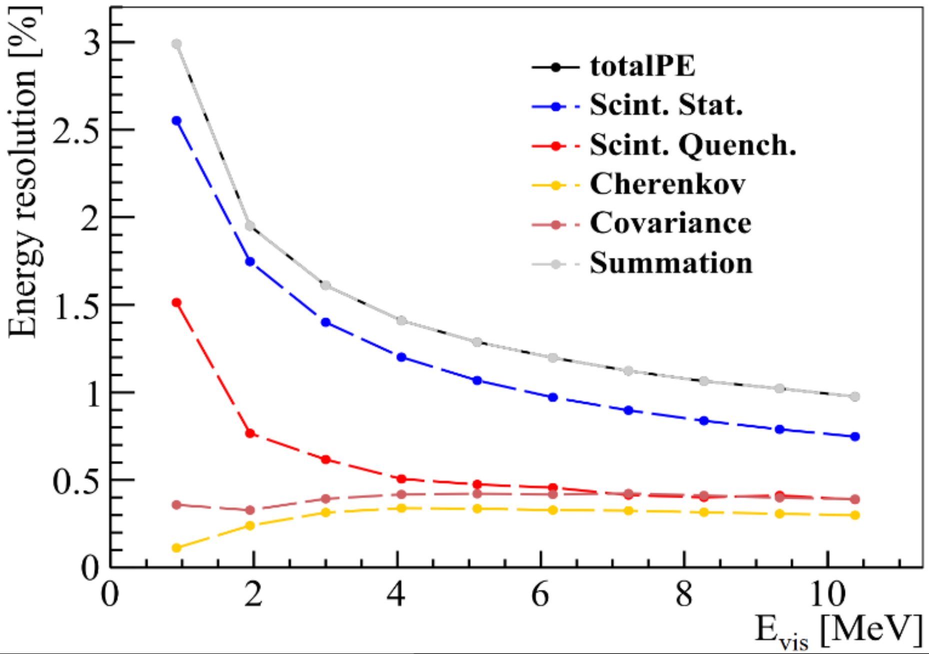

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

Photon statistics

Constant term

Dark noise, Annihilation -induced $\gamma$s

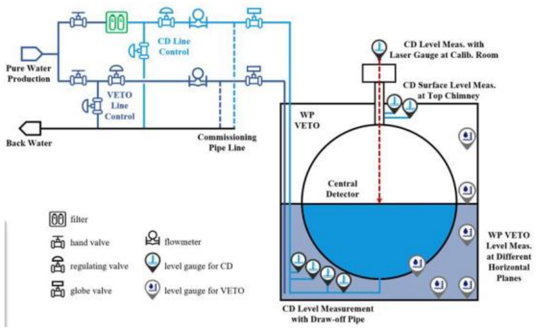
Expected energy resolution: **2.95% @1MeV**

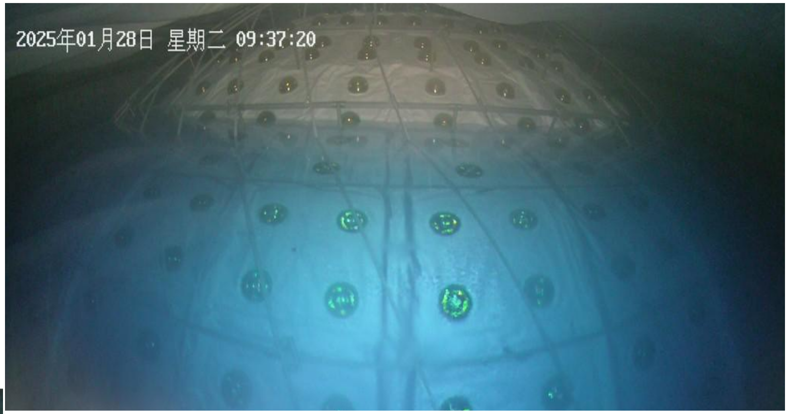



| | |
|---|---|
| *JHEP 03 (2021) 004* | *arXiv:2405.17860 (2024)* |

# Current Status of JUNO: Water Filling

- Dec 1, 2024, Installation finished
- Dec 18, 2024, water filling started
- Feb 2, 2025, water filling completed



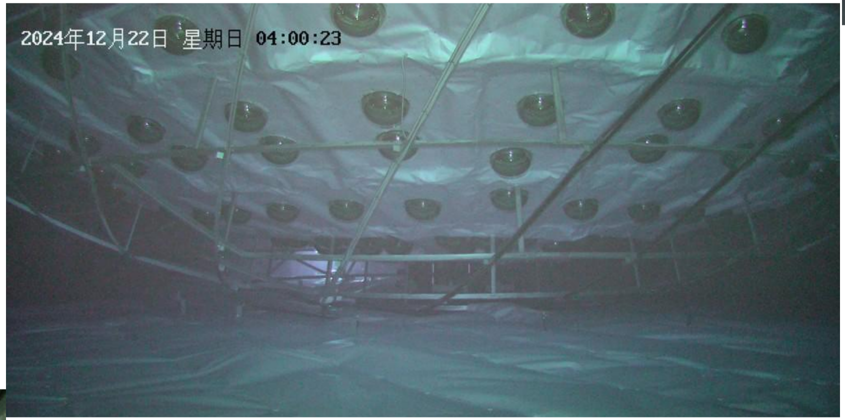

**out pure water filling**

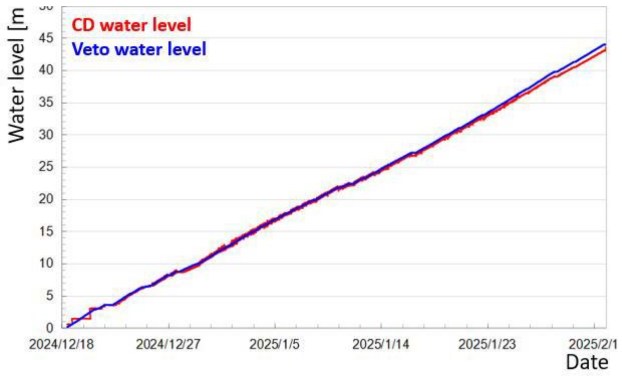
ynchronize pure water filling of CD and WP.

'ure water production for FOC ~90 m³/h.

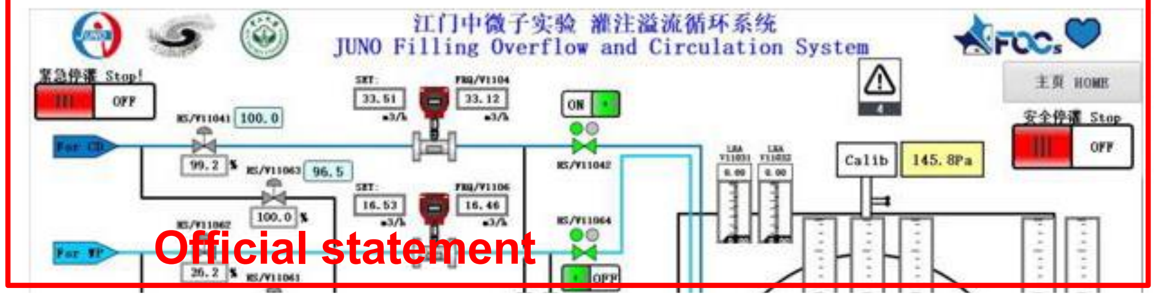
urther purification of CD line.

Jse regulating valves to regulate flow
ntering CD or WP for liquid level balance.



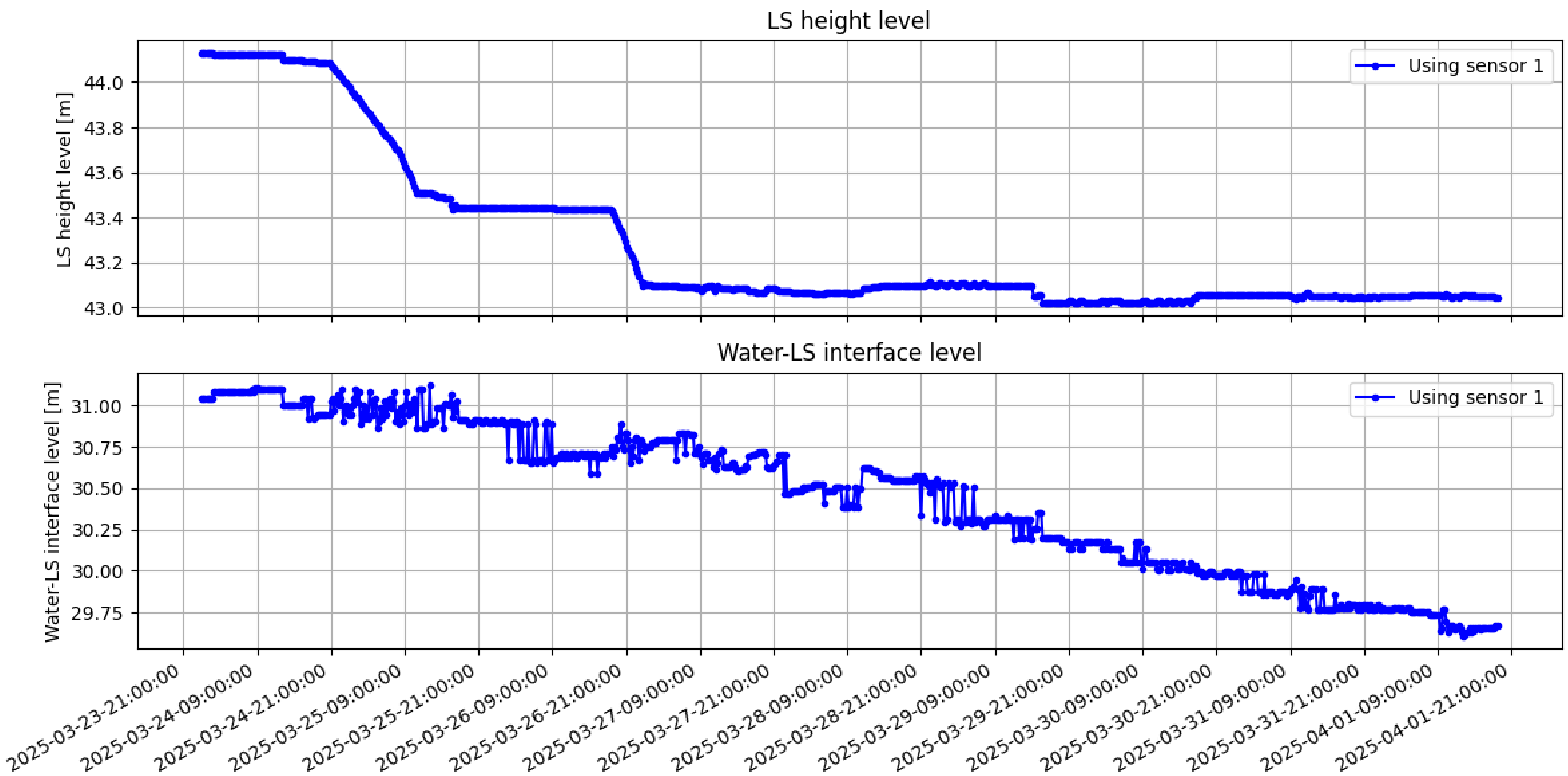


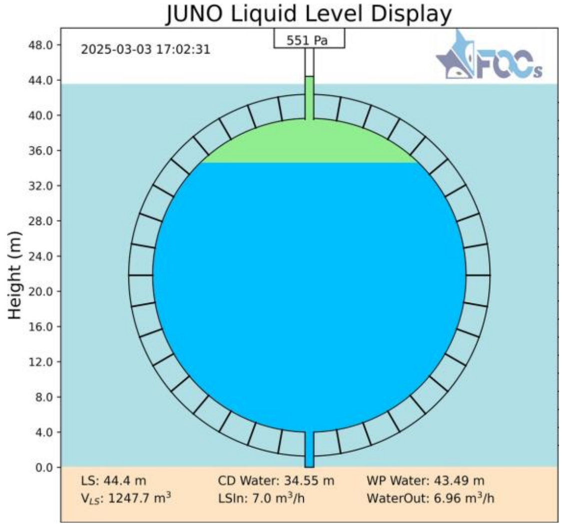



Official statement

# Current Status of JUNO: Water Filling

- ➢ Feb 8, 2024, LS replacing/filling started

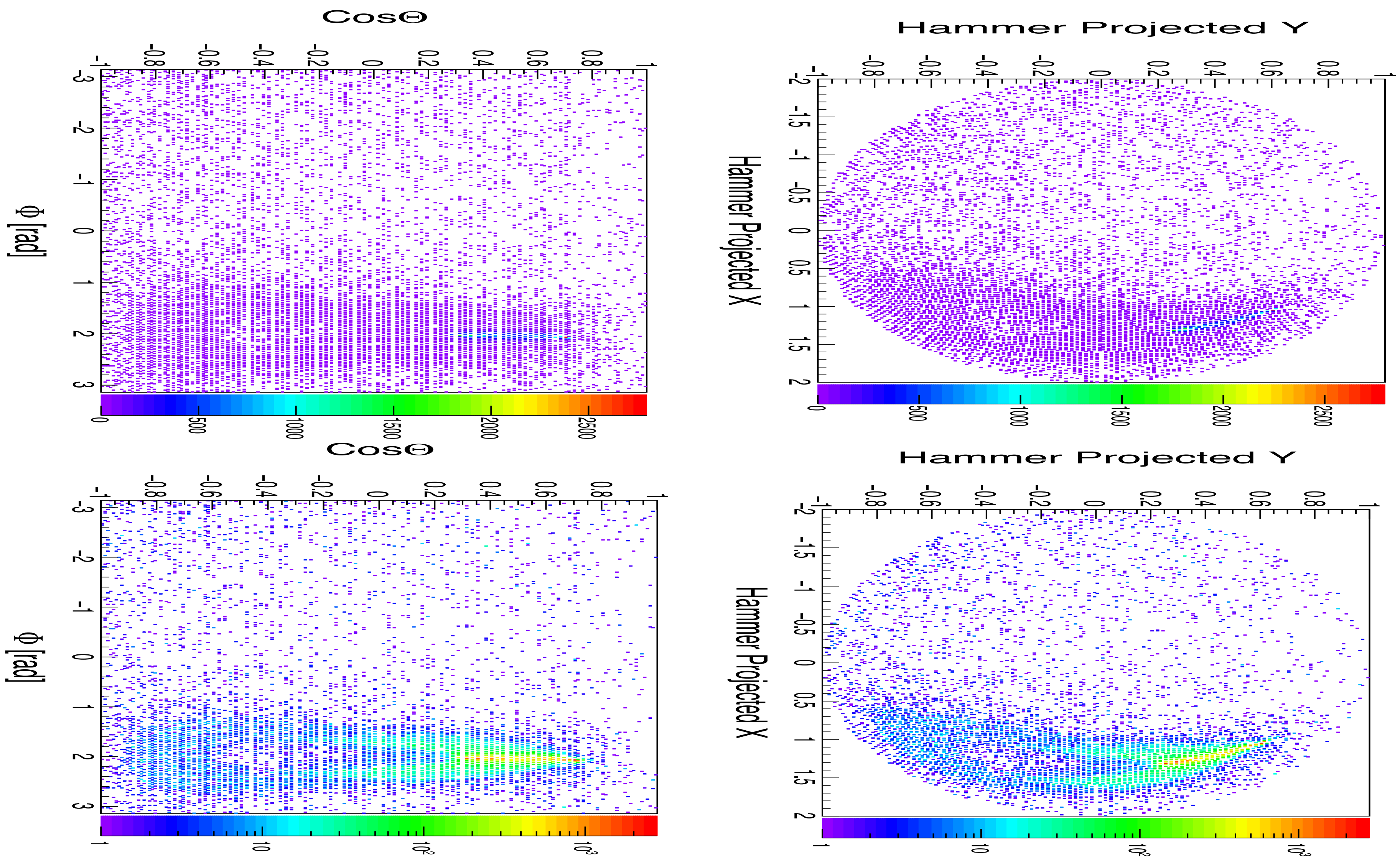



LS radiopurity better than $10^{-15}$ mBq/m$^3$ (ICP-MS)

- ➢ Apr 1, 2025, total LS in: ~4,248 m$^3$

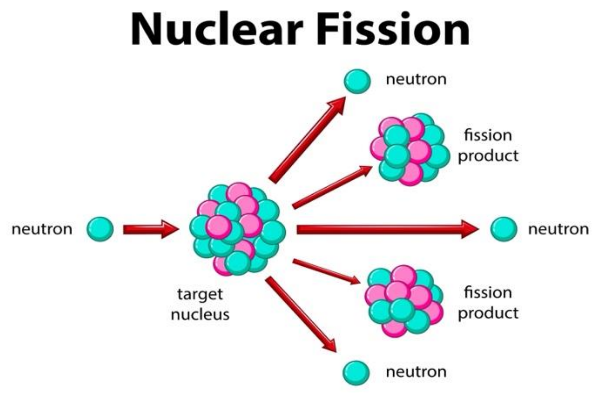
# Let's See Some Event/Photons!



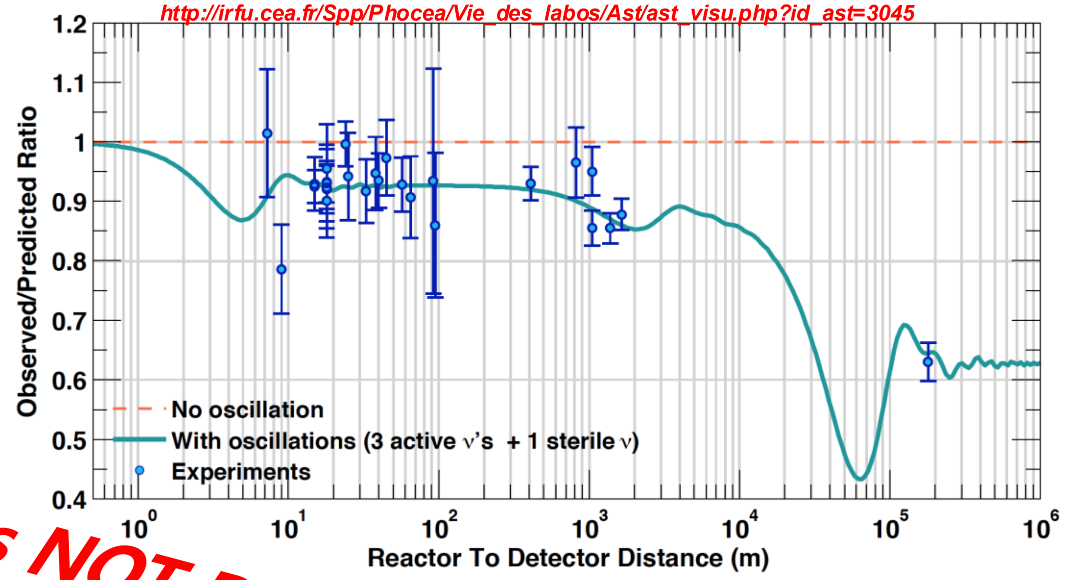

**Achievements**:

- Calibration of the large PMTs using laser data
- Small failure channels : ~7/17k (~0.04% loss at installation)
- Calibration sources working as expected (Am-Be and Am-C)
- We have seen some muon candidates

# Reactor Antineutrino Anomaly (RAA)

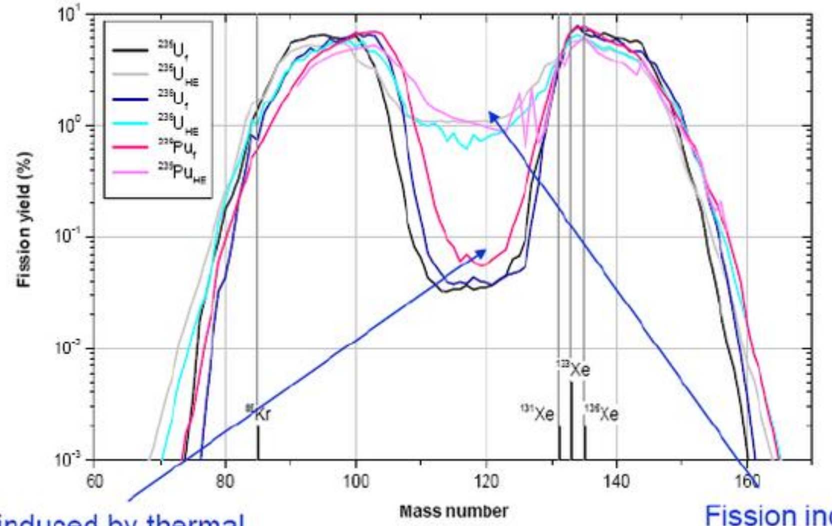


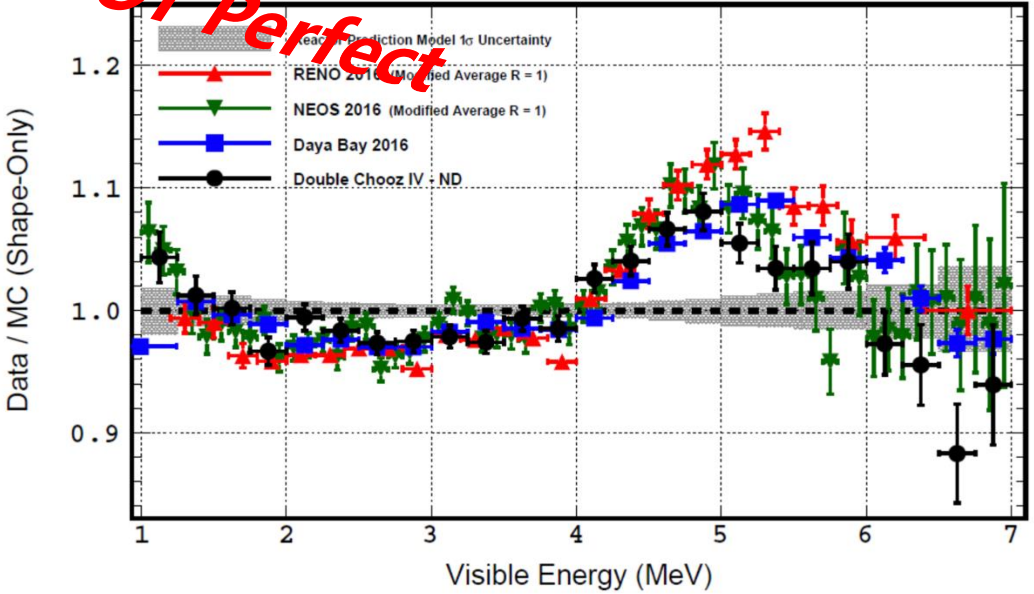

- *T. A. Mueller et al., PRC83, 054615 (2011)*
- *P. Huber, Phys. Rev.C84, 024617 (2011)*
- *Daya Bay, PRL116(2016), PRL123(2019)*
- *RENO, PRL121(2018)*
- *NEOS, PRL118(2017)*
- *Double Chooz, Nature Physics 16(2020)*




**Reactor Neutrinos NOT Perfect**

(Fission yield is a function of the fissioning nuclide and the incident neutron energy)



# The Tao Site

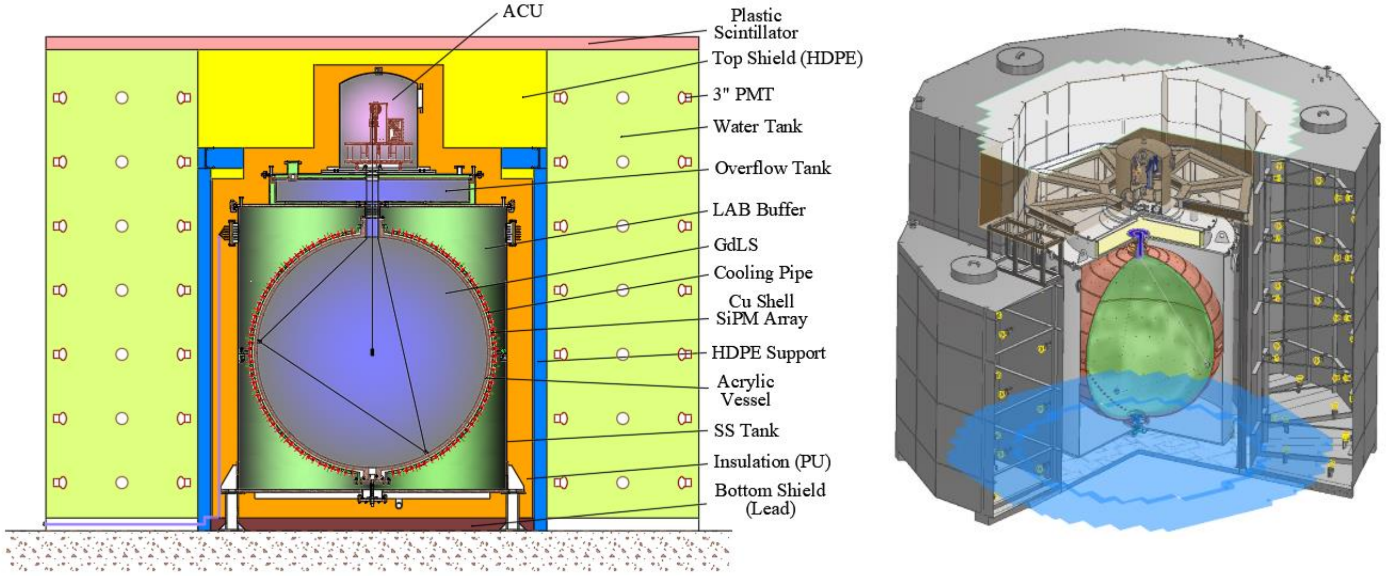
- Taishan Nuclear Power Plant has two cores currently in operation (other two cores might be built later)
- Both reactors are European Pressurized Reactor (EPR) with 4.6 GWth thermal power
- Taishan-1 reached first criticality and was connected to the grid in June 2018
  - the first running EPR in the world!

- The TAO detector will be installed in a basement at 9.6 m underground, outside of the concrete containment shell of the reactor core
  - >99.99% signal from Taishan-1+Taishan-2
  - 4% signal from Taishan-2
- Muon rate and cosmogenic neutron rate are measured to be 1/3 of those on the ground

# JUNO-TAO: another unprecedented reactor detector

*arXiv: 2005.08745*

| 2.8 ton GdLS detector | |
|---|---|
| Baseline | ~30 m |
| Reactor Thermal Power | 4.6 GW |
| Light Collection | SiPM |
| Photon Detection Efficiency | >50% |
| Working Temperature | -50 ℃ |
| Dark Count Rate [Hz/mm$^2$] | ~100 |
| Coverage | ~94% |
| Detected Light Level [PE/MeV] | 4500 |
| Energy resolution | < 2% @ 1 MeV |

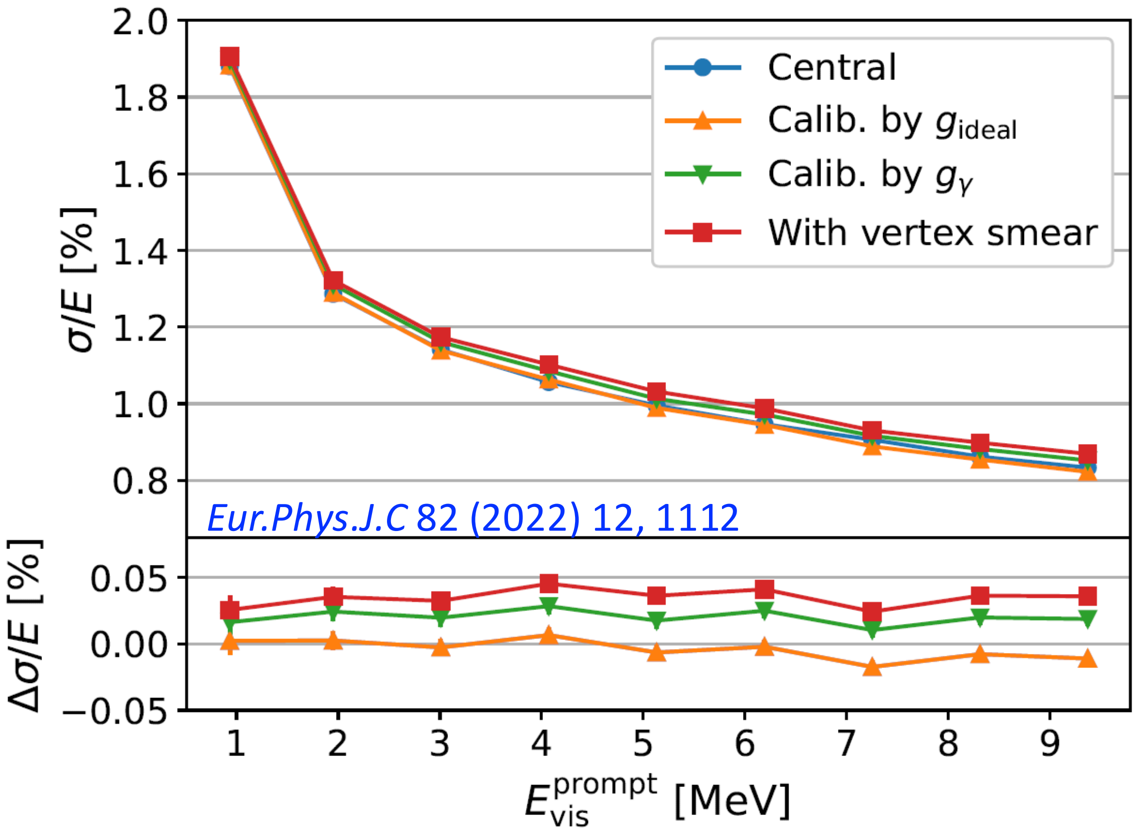



- ✓ SiPMs to achieve high light yield with ~94% coverage
  - ➢ 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

Start construction in Taishan Laboratory since Nov. 2024 and expected to be completed in Summer 2025.

# TAO Energy Resolution

| | JUNO | TAO |
|---|---|---|
| Coverage | $\sim 75\%$ | $\sim 94\%$ |
| Photon detection efficiency | $\sim 30\%$ | $> 50\%$ |
| Attenuation length | $> 20\text{ m}\ \ (R = 17.2\text{ m})$ | $> 20\text{ m}\ \ (R = 0.9\text{ m})$ |
| Photoelectron yield | $\sim 1665\text{ PE/MeV}$ | $\sim 4500\text{ PE/MeV}$ |
| Energy resolution | $2.95\%\ @\ 1\text{ MeV}$ | $\sim 2\%\ @\ 1\text{ MeV}$ |




Non-stochastic effects affecting energy resolution in TAO:

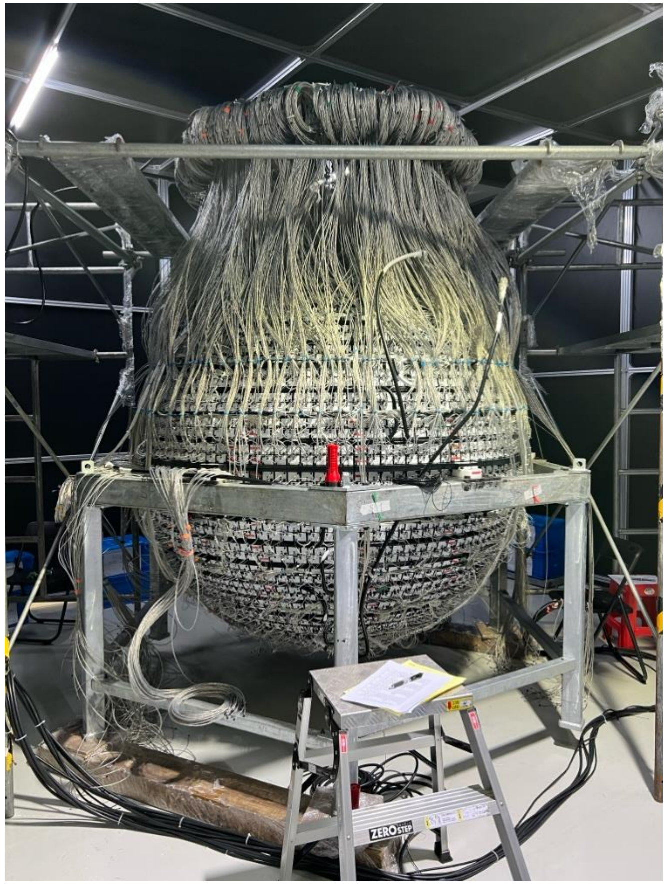
- at low energies, the contribution from the LS quenching effect might be quite large;
- at high energies, the smearing from neutron recoil of IBD becomes dominant.

In most of the energy region of interest, the energy resolution of TAO will be sub-percent!

1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, $\boldsymbol{L_{absorption}}$ very small
3. Gd-LS works at -50℃, increase the photon yield

# The TAO Detector Installation



# JUNO Milestones

***Project Approved and Funded!***

2013

**Civil Started**

2015

**NNVT PMTs Delivered**

2017

**Civil completed**

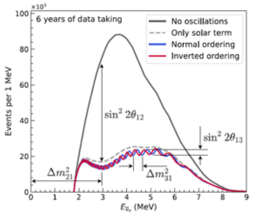
2021

**Detector Const. Started**

2022

2023-2024-2025

**Detector completing, Filling starting**




***Summer 2025: Data Taking!***

# Conclusions and Future Perspectives


❖***Absolutely*** possible using reactors for NMO

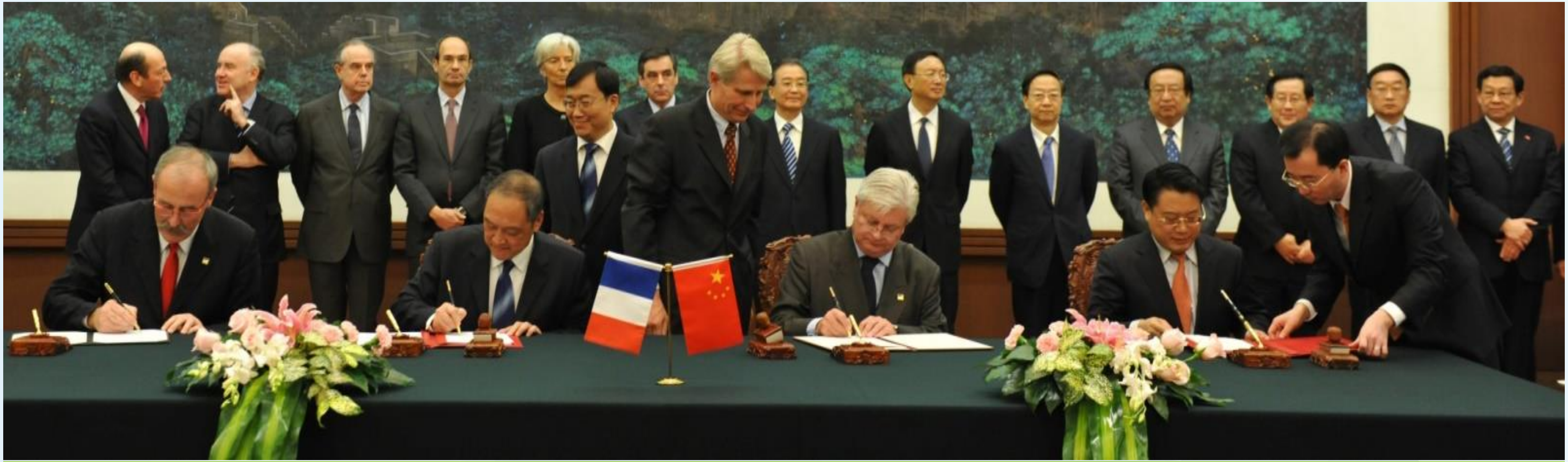
❖JUNO detector better than 3% (at 1MeV) in energy resolution and 1% in energy scale → NMO 3-4σ in 6 years (reactor neutrino alone); <1% precision oscillation parameters

❖JUNO construction completed → **Detector filling & Commissioning in parallel: water and LS quality good**

❖Reactor Neutrinos are useful also (**Creation of the AAP series by John and friends**) → **JUNO-TAO has great potential in reactor physics and nuclear data**

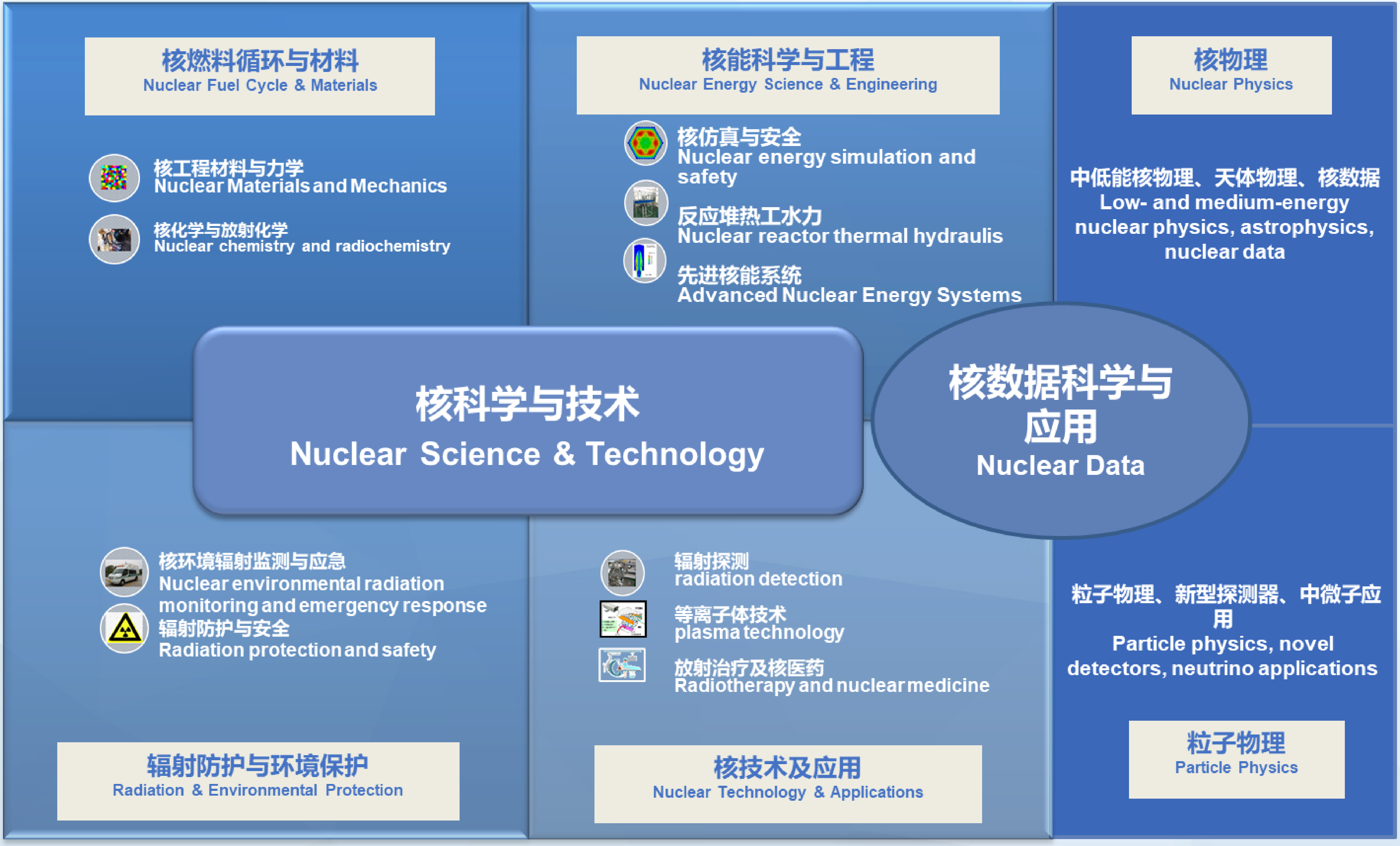
➢***Stay tuned for our data taking in July 2025!***

**2009:** IFCEN was jointly built by SYSU and FINUCI, an alliance formed by 5 French partners



**SYSU and FINUCI signed the first phase of cooperation (witnessed by the then prime ministers of the two countries at the Great Hall of the People)**

SUN YAT-SEN UNIVERSITY | GRENOBLE INP UGA | cea instn | Chimie Paris ParisTech | IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom | enscm CHIMIE Montpellier

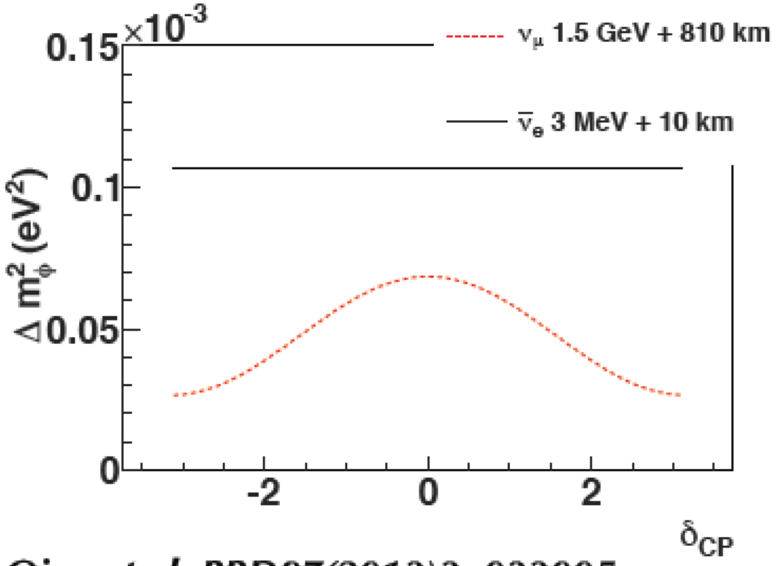

核燃料循环与材料
Nuclear Fuel Cycle & Materials
核工程材料与力学
Nuclear Materials and Mechanics
核化学与放射化学
Nuclear chemistry and radiochemistry
核能科学与工程
Nuclear Energy Science & Engineering
核仿真与安全
Nuclear energy simulation and safety
反应堆热工水力
Nuclear reactor thermal hydraulis
先进核能系统
Advanced Nuclear Energy Systems
核物理
Nuclear Physics
中低能核物理、天体物理、核数据
Low- and medium-energy nuclear physics, astrophysics, nuclear data
核科学与技术
Nuclear Science & Technology
核数据科学与应用
Nuclear Data
核环境辐射监测与应急
Nuclear environmental radiation monitoring and emergency response
辐射防护与安全
Radiation protection and safety
辐射防护与环境保护
Radiation & Environmental Protection
辐射探测
radiation detection
等离子体技术
plasma technology
放射治疗及核医药
Radiotherapy and nuclear medicine
核技术及应用
Nuclear Technology & Applications
粒子物理、新型探测器、中微子应用
Particle physics, novel detectors, neutrino applications
粒子物理
Particle Physics

# e- / μ-Flavor Feels Mass Ordering Differently

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1 - 4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

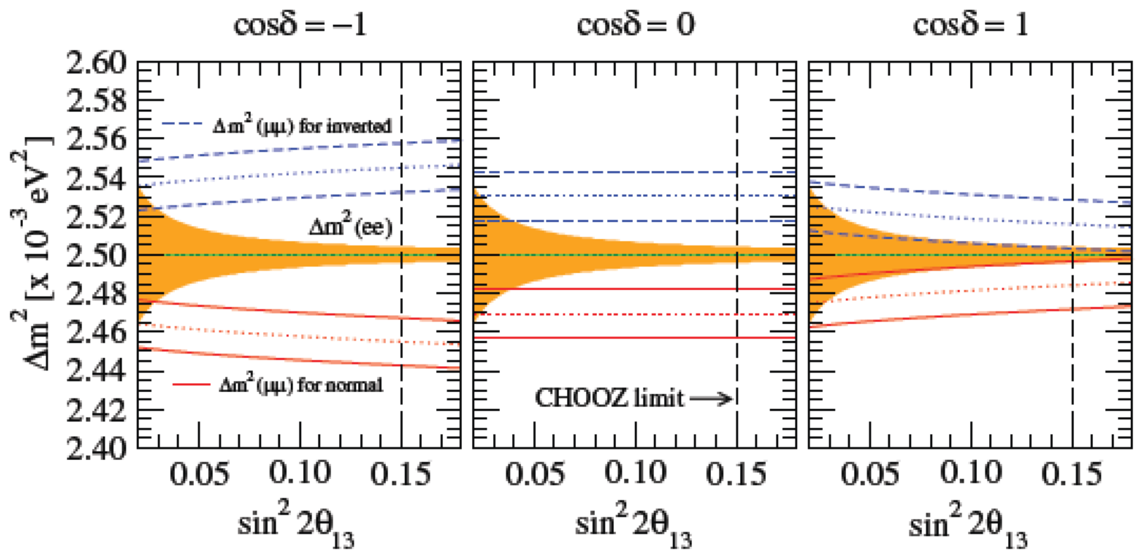
$$P_{\nu_\mu\to\nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$

- *Both reactor and long-baseline experiment measure mass-squared splitting*
- *A natural question to ask: Is this meaningful?*




***Qian et al, PRD87(2013)3, 033005***

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of $\delta_{CP}$ for $\bar{\nu}_e$ and $\nu_\mu$ disappearance measurements, respectively.




***Minakata et al PRD74(2006), 053008***

***Also See: Zhang&Ma, arXiv:1310.4443/ Mod. Phys. Lett. A29 (2014) 1450096***

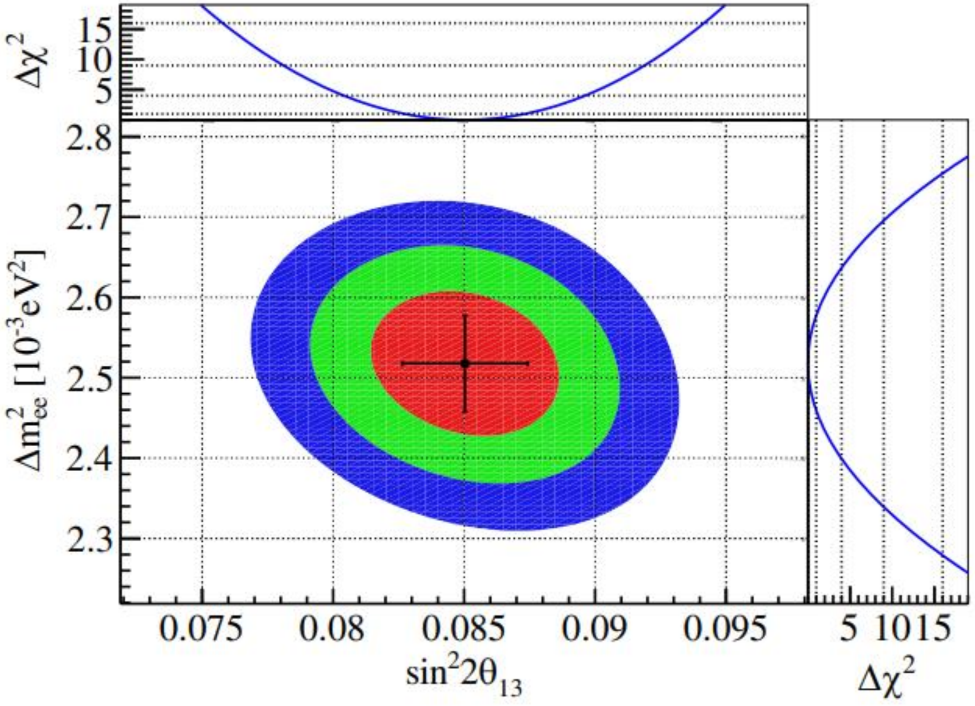
# Daya Bay Full Data Set (Neutrino 2024)

**Daya Bay reported the precision measurement with 3158-days full dataset in 2022**

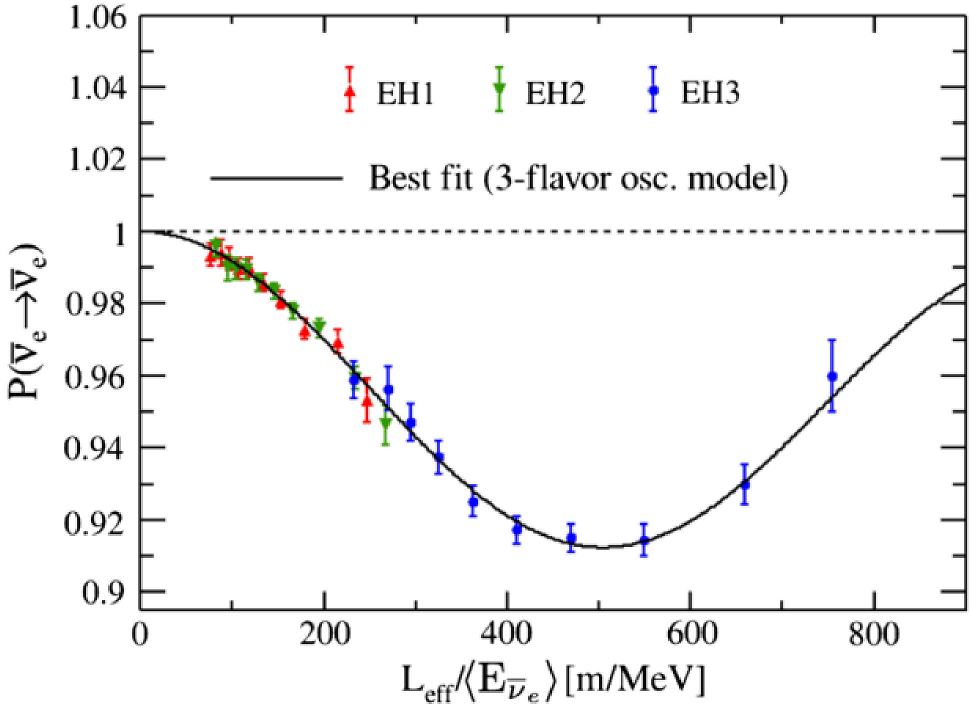
**$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$** **precision 2.8% → *the Best in the world***

**$\Delta m^2_{32} = 2.466 \pm 0.060\ (-2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2$** **precision 2.4% → *one of the Best in the world***

**Systematics, mainly detector differences, contributed about 50% in the total error**




PhysRevLett. 130 161802



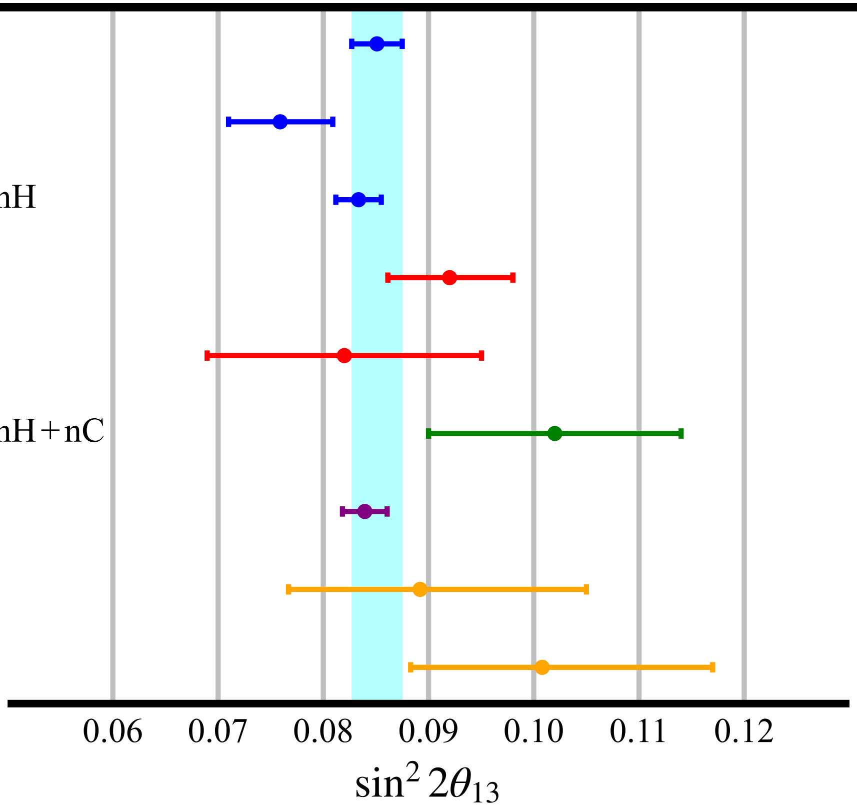
# Global comparison $\theta_{13}$

**Daya Bay leads the precision measurement, nGd+nH gives 2.6% precision**

**By combining all reactor results, ultimate precision of $\sin^2 2\theta_{13}$: 2.5%**

**Consistent results from reactor and accelerator experiments**

| Experiment | | Value | |
|---|---|---|---|
| **Daya Bay** | **nGd** | **0.0851 ± 0.0024** | **2.8%** |
| | nH | $0.0759^{+0.0050}_{-0.0049}$ | 6.5% |
| | nGd+nH | 0.0833 ± 0.0022 | 2.6% |
| RENO | nGd | $0.0920^{+0.0060}_{-0.0059}$ | 6.5% |
| | nH | 0.082 ± 0.013 | 15.9% |
| Double Chooz | nGd+nH+nC | 0.102 ± 0.012 | 11.8% |
| Reactor Average | | 0.0839 ± 0.0021 | 2.5% |
| T2K + NO$\nu$A | NO | $0.0892^{+0.0158}_{-0.0125}$ | 15.9% |
| | IO | $0.1008^{+0.0162}_{-0.0125}$ | 14.2% |



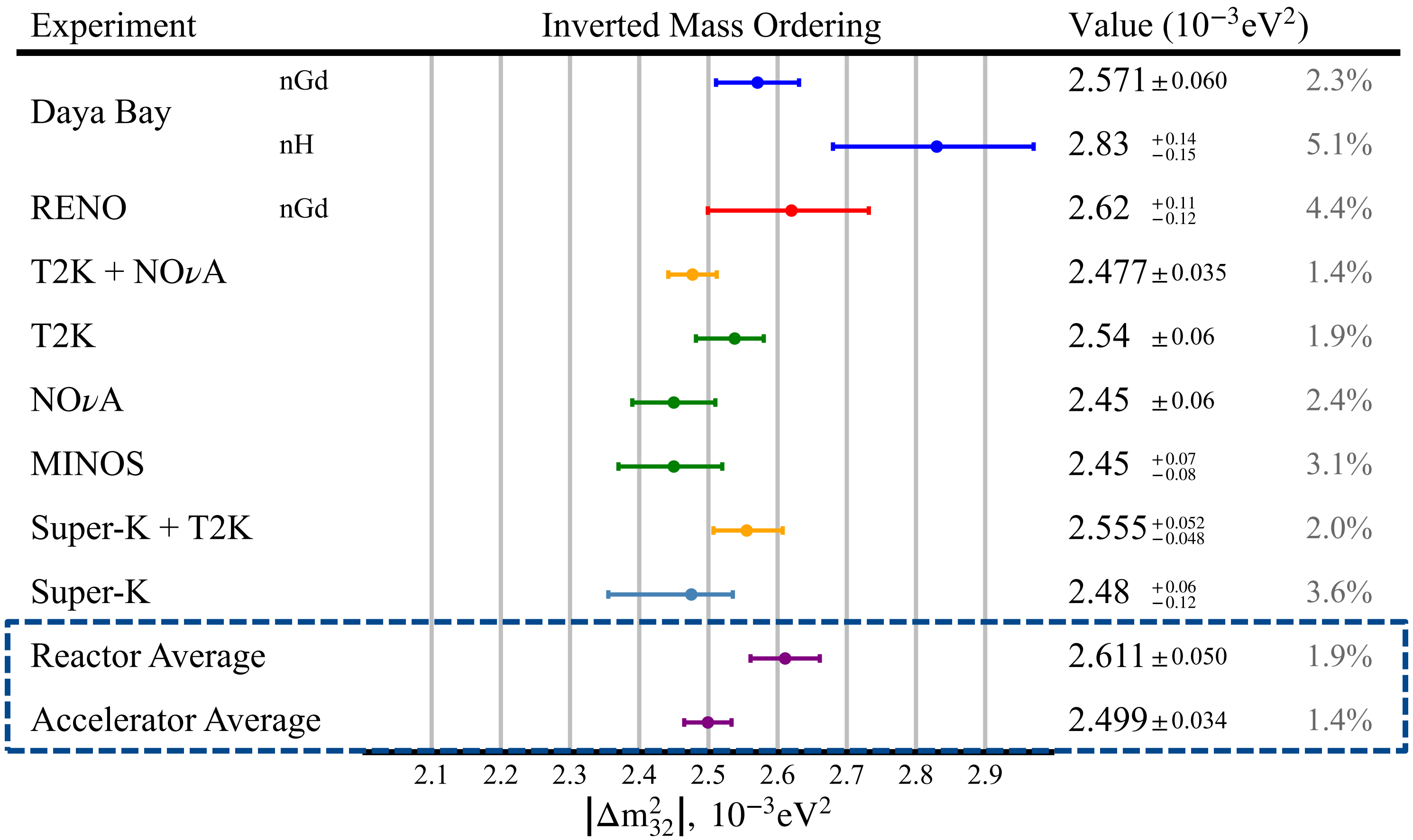

Note: average is error weighted average assuming no correlation

Figure by Hongzhao Yu

**Consistent results from reactor and accelerator experiments**

**Normal Ordering slightly preferred (<2σ) from reactor/accelerator averages**

Note: average is error weighted average assuming no correlation




**Reactor weighted average 2%**
dominated by Daya Bay

**Accelerator weighted average 1.5%**
(SK+T2K) + NOvA + MINOS + IceCube

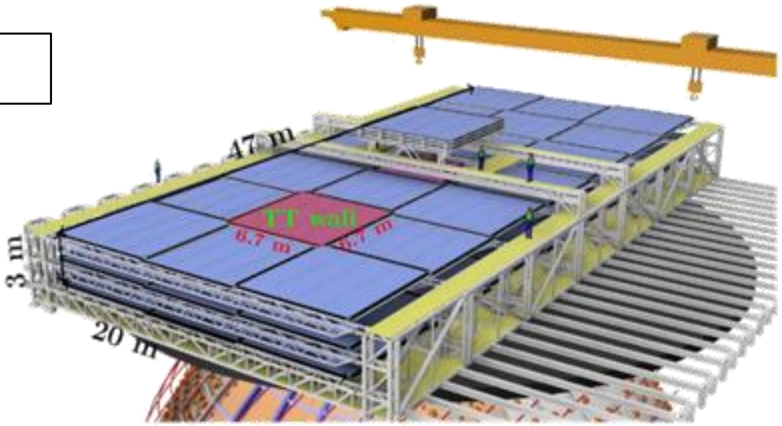
# Global Efforts Resolving ν Mass Hierarchy

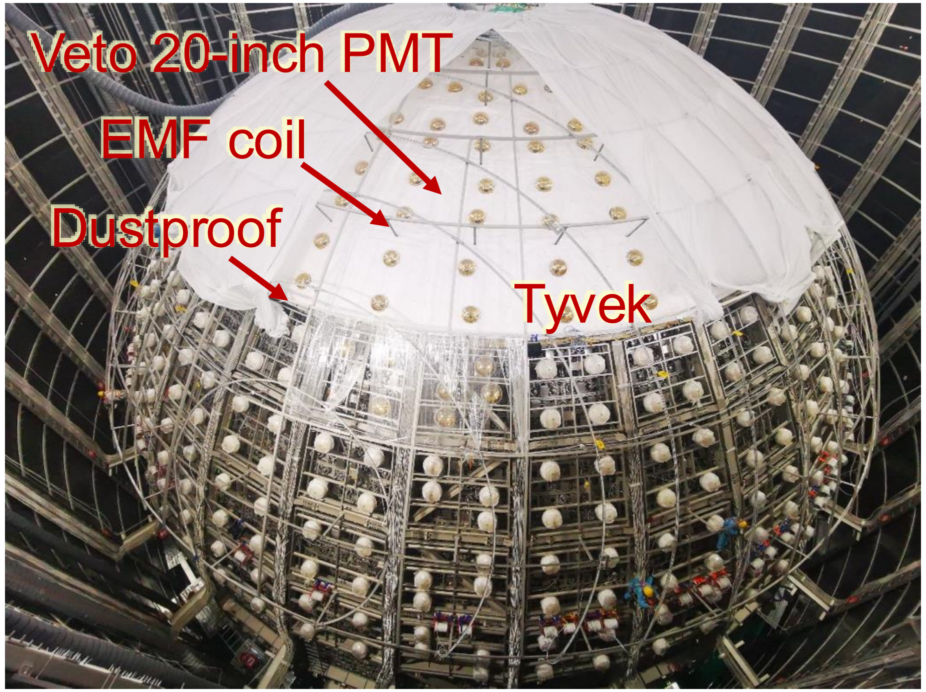
| Source / Principle | Matter Effect | Interference of Solar&Atm Osc. Terms | Collective Oscillation | Constraining Total Mass or Effective Mass |
|---|---|---|---|---|
| Atmospheric ν | Super-K, Hyper-K, IceCube PINGU, ICAL/INO, ORCA, DUNE | Atm $\nu_\mu$ + JUNO | | |
| Beam $\nu_\mu$ | T2K, NOνA, T2HKK, DUNE | Beam $\nu_\mu$ + JUNO | | |
| Reactor $\nu_e$ | | JUNO, JUNO + Atm/Beam $\nu_\mu$ | | |
| Supernova Burst ν | | | Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO | |
| Interplay of Measurements | | | | Cosmo. Data, KATRIN, Proj-8, 0νββ |

# Veto Detectors

- Water Cherenkov + Top tracker
- Water Cherenkov detector
  - 35 kton water to shield backgrounds from the rock
  - Instrumented w/ 2400 20-inch PMTs on SS structure
  - Water pool lining: 5mm HDPE (black) to keep the clean water and to stop Rn from the rock, covered w/ tyvek
  - 100 ton/h pure water system
    Requirement: U/Th/K<$10^{-14}$ g/g and Rn<10 $mBq/m^3$, attenuation length>40 m, temperature controlled to (21±1) °C
- Top tracker
  - Refurbished OPERA scintillators
  - 3 layers, ~60% coverage on the top
  - $\Delta\theta \sim 0.2°$, $\Delta D \sim 20$ cm
- Earth Magnetic Field compensation coil

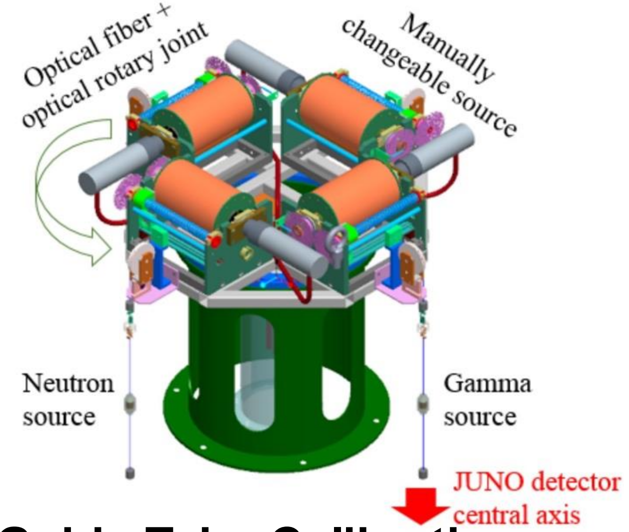
*NIMA 1057 (2023) 168680*

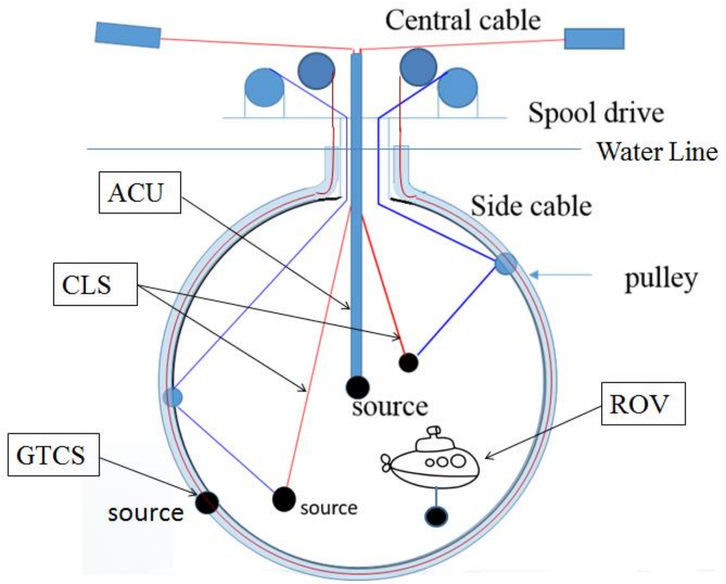


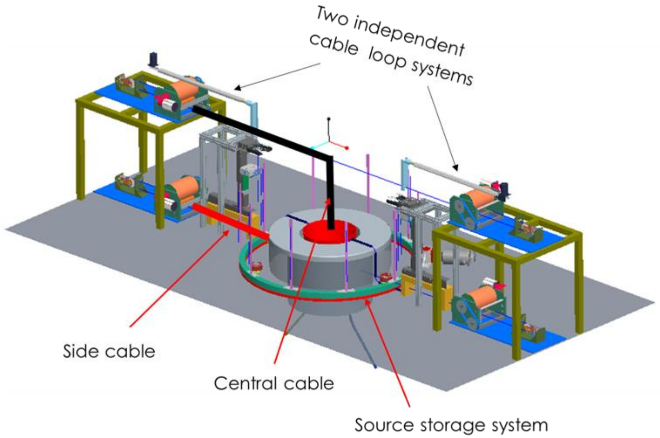
# A Comprehensive Calibration System

**Automatic Calibration Unit (ACU)**

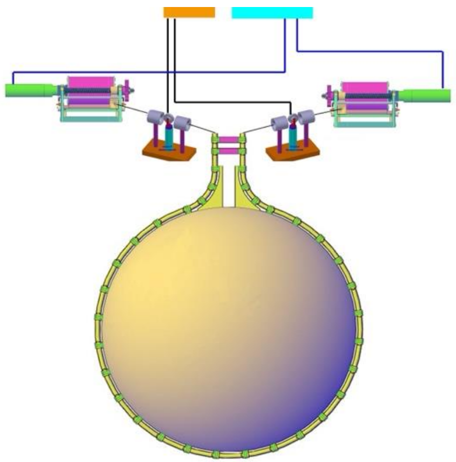



**Cable Loop System (CLS)**

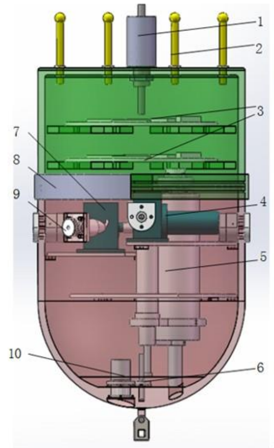



**Guide Tube Calibration System(GTCS)**



- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

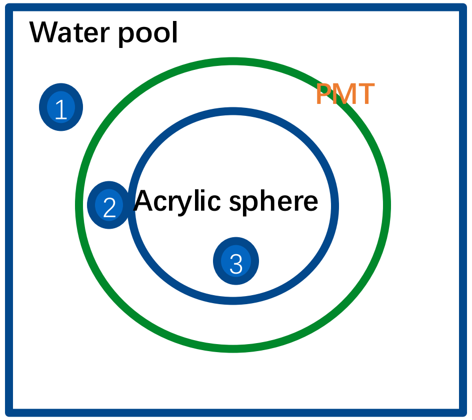
**Remotely Operated under-liquid-scintillator Vehicles (ROV)**



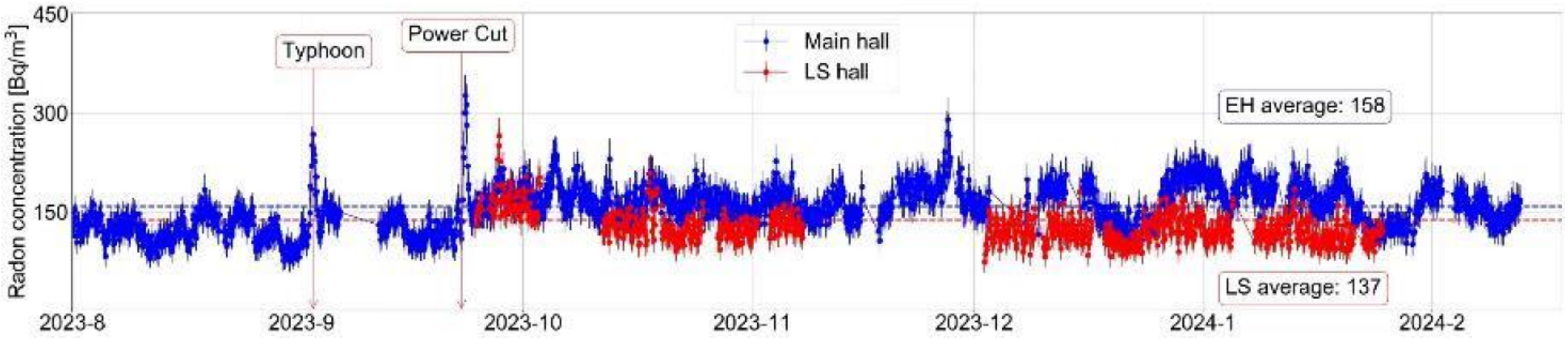
# A Controlled Installation Environment for Cleanness

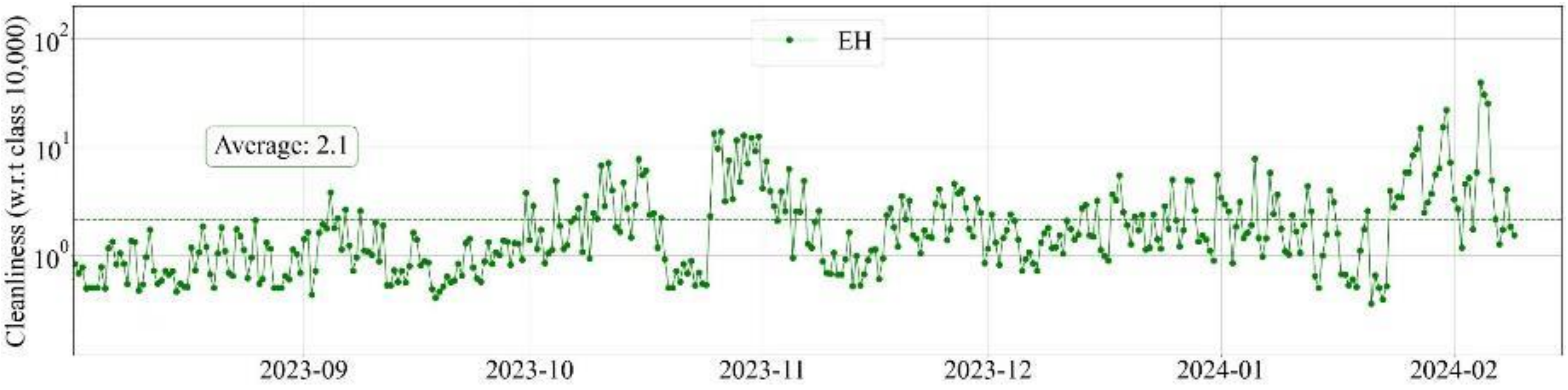
- Average radon and cleanliness:
  - Radon concentration: ~160 Bq/m$^3$ in the EH, ~140 Bq/m$^3$ in the LS hall
  - Cleanliness: class 20,000

| Region | Level |
|---|---|
| 1 | Class 100,000 |
| 2 | Class 10,000 |
| 3 | Class 1000 |




Radon concentration in air: < 200 Bq/m$^3$

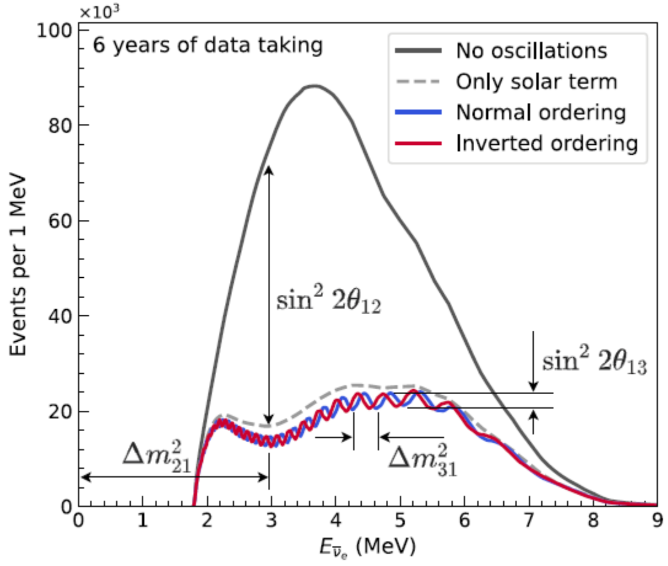


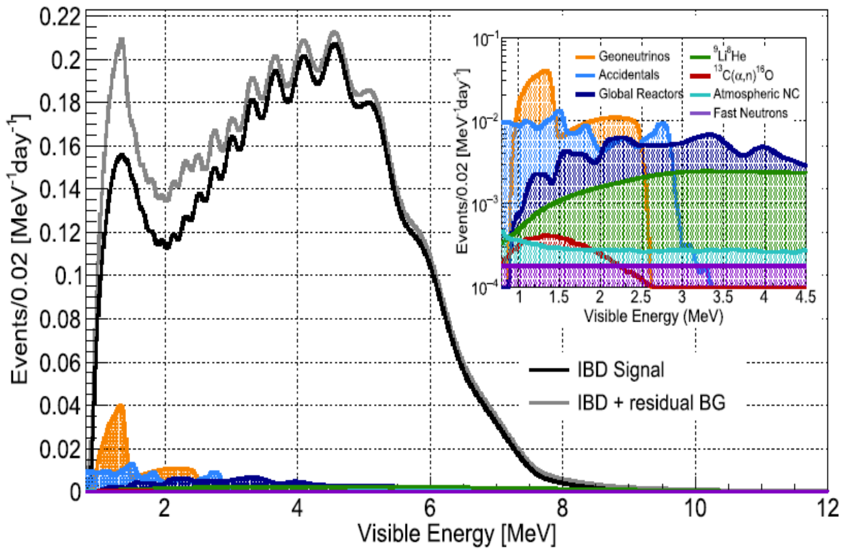



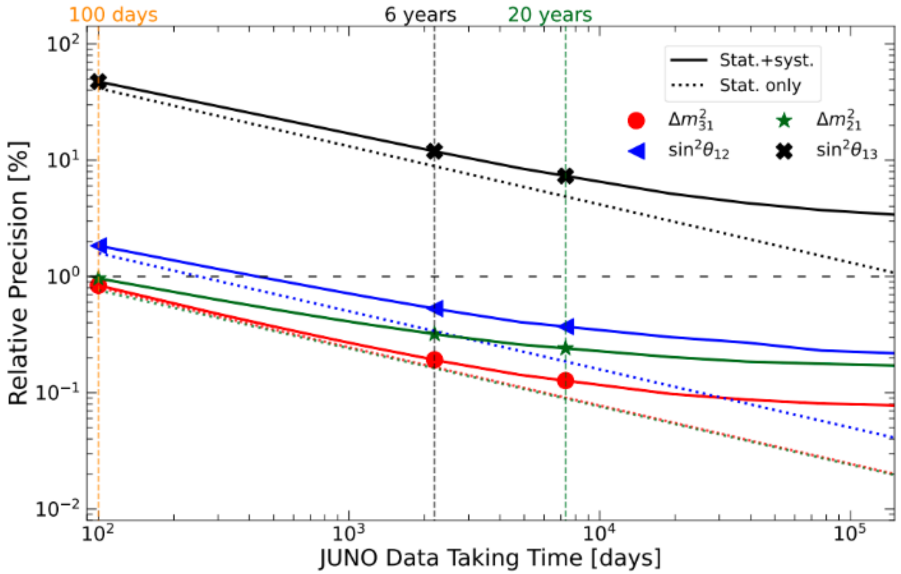
# Precision Measurement of oscillation parameters

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

Chin. Phys. C46 (2022) 12, 123001

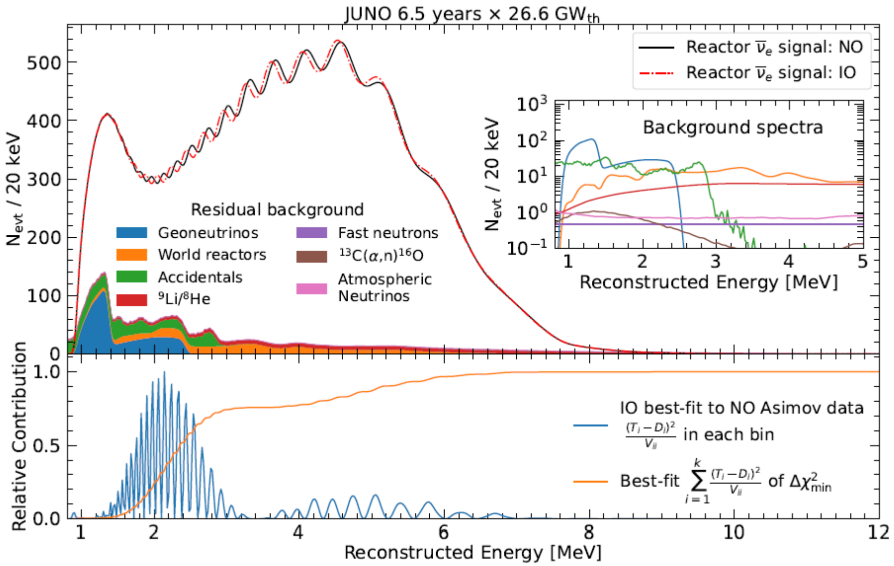


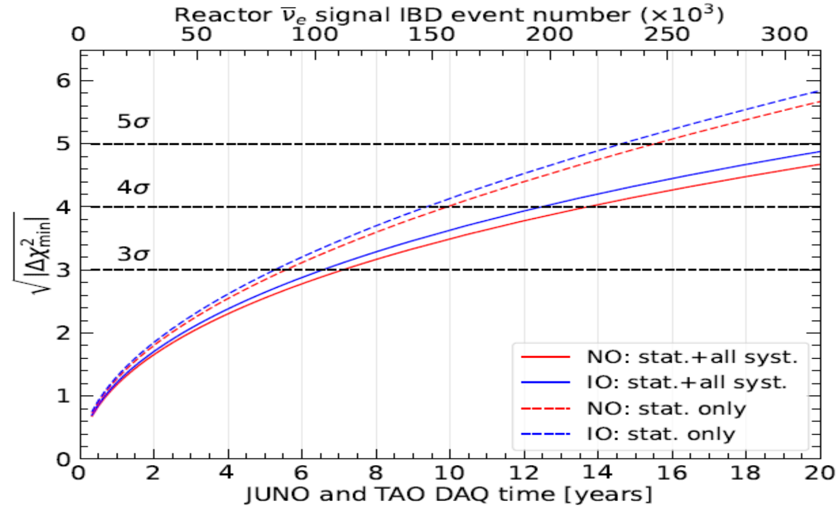




| | Central Value | PDG2020 | 100 days | 6 years | 20 years |
|---|---|---|---|---|---|
| $\Delta m^2_{31}$ ($\times10^{-3}$ eV$^2$) | 2.5283 | ±0.034 (1.3%) | ±0.021 (0.8%) | ±0.0047 (0.2%) | ±0.0029 (0.1%) |
| $\Delta m^2_{21}$ ($\times10^{-5}$ eV$^2$) | 7.53 | ±0.18 (2.4%) | ±0.074 (1.0%) | ±0.024 (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%) |

# Neutrino Mass Ordering




## Sensitivity mostly from 1.5-3 MeV



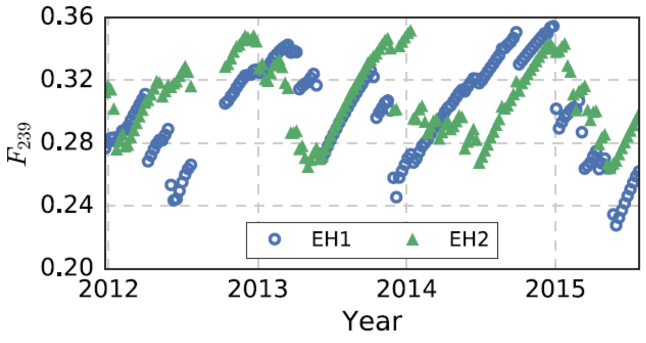

| | Design | Now |
|---|---|---|
| Thermal Power | 36 GW$_{th}$ | 26.6 GW$_{th}$ (**26%↓**) |
| Signal rate | 60 /day | 47.1 /day (**22%↓**) |
| Overburden | ~700 m | ~ 650 m |
| Muon flux in LS | 3 Hz | 4 Hz (**33%↑**) |
| Muon veto efficiency | 83% | 91.6% (**11%↑**) |
| Backgrounds | 3.75 /day | 4.11 /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$_{th}$** |

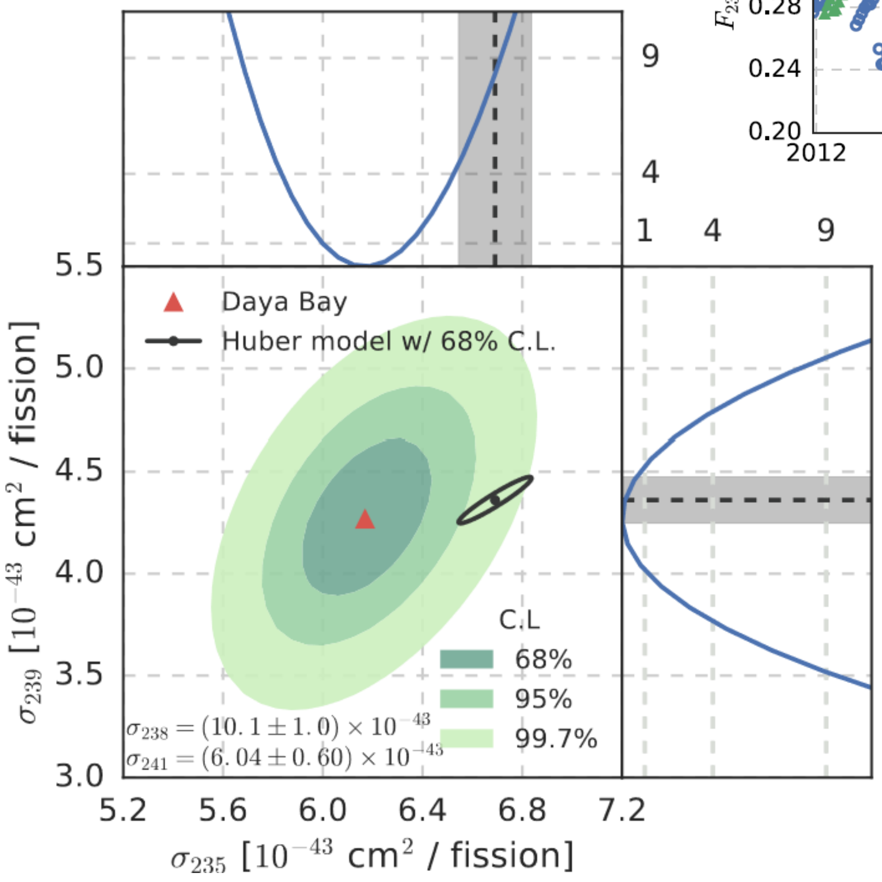
- JUNO NMO median sensitivity:
  3σ (reactors only) @ ~6 yrs * 26.6 GW$_{th}$ exposure
- Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity

***arXiv:2405.18008 (2024)***

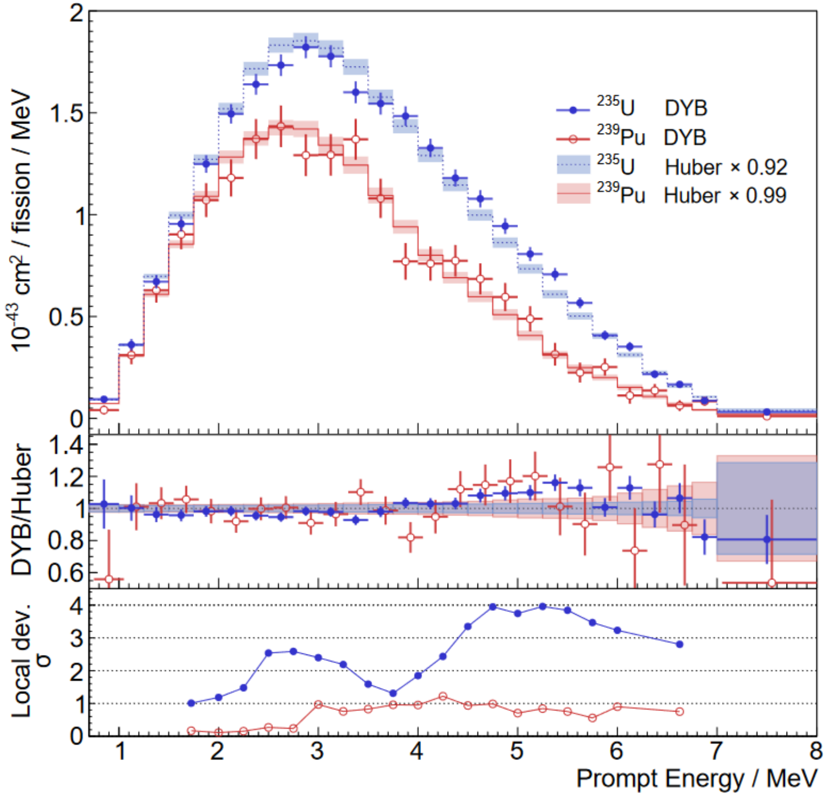
# Understanding Reactor Antineutrinos: Fuel Evolution

- ***Fuel evolution: Phys.Rev.Lett. 118 (2017) no.25, 251801***




- **Isotope decomposition**, *PRL 123 (2019) no.11, 111801*




***$^{235}$U: 4-sigma effect***

***$^{235}$Pu: 1.2-sigma effect***

# Understanding Reactor Antineutrinos: Improved Systematics

- ***Improved Fuel evolution: Phys.Rev.Lett. 130 (2023) no.21, 211801***