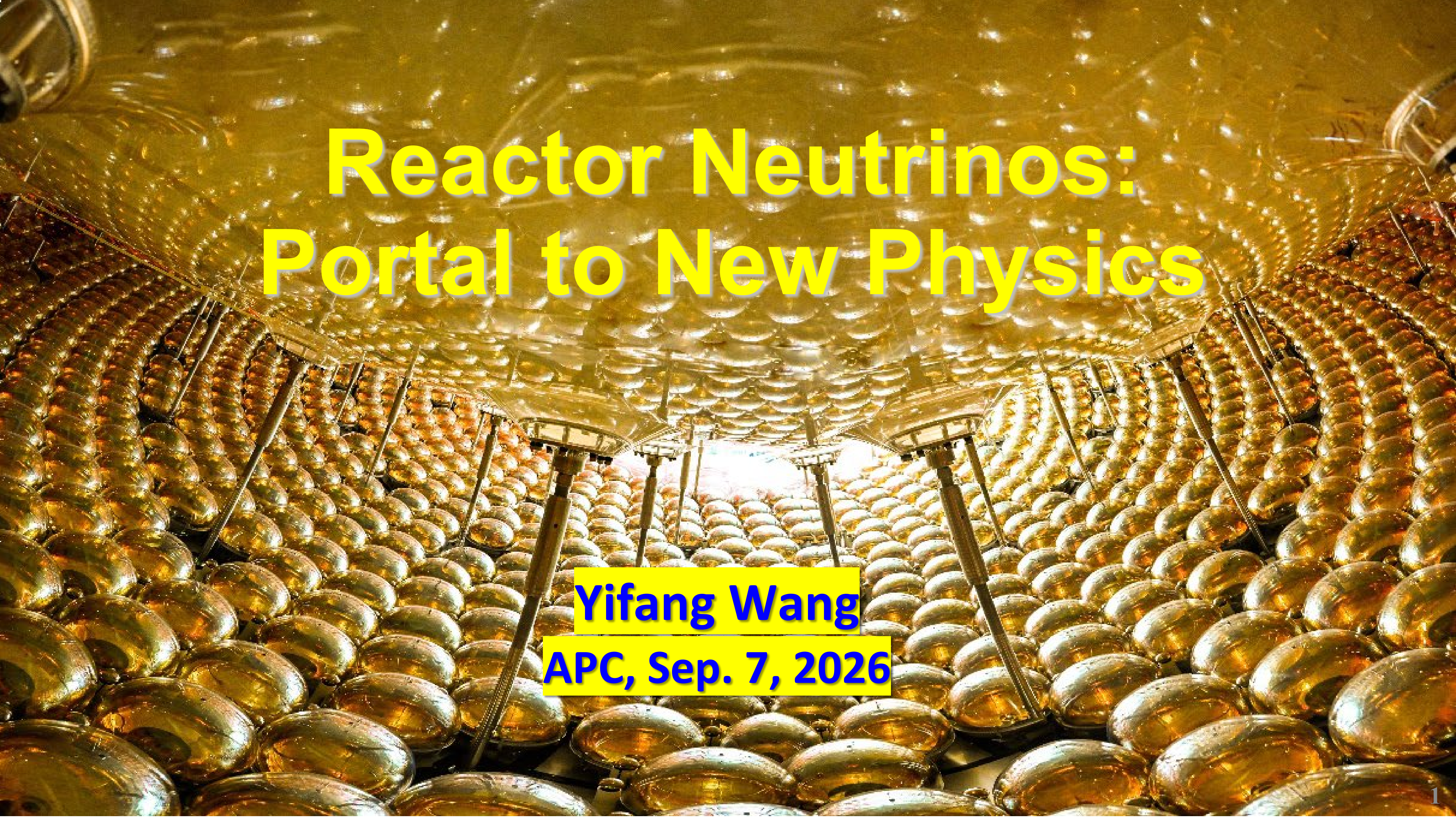


# Reactor Neutrinos: Portal to New Physics

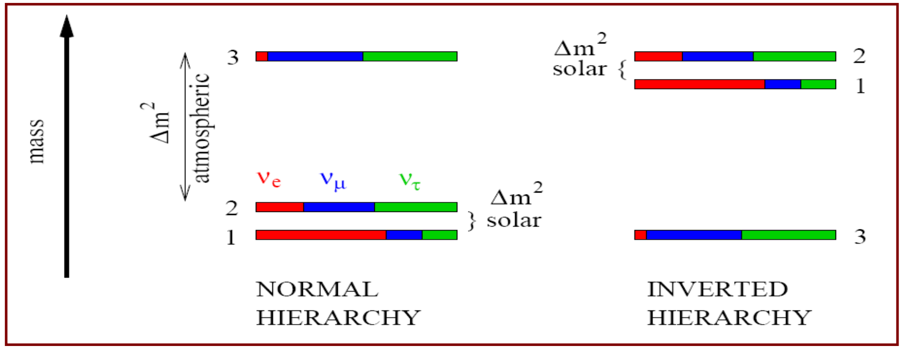
**Yifang Wang**

**APC, Sep. 7, 2026**

# Neutrino Oscillation

**Oscillation matrix for 3 generations：**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$




**Atmospheric** | **Reactor** | **Solar** | **Majorana phase**

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

**Atmospheric accelerator** | **reactor accelerator** | **solar reactor** | **Double beta decays**

## Neutrinos do oscillate

- Known parameters： $\theta_{23}$, $\theta_{12}$, $\theta_{13}$, $|\Delta M^2_{23}|$, $\Delta M^2_{12}$
- Unknown parameters: mass hierarchy($\Delta M^2_{23}$), CP phase $\delta$

1998 Atm. ν osc. $\theta_{23}$
2002 Solar ν osc. $\theta_{12}$
2002 reactor ν osc. $\theta_{13}$

# Neutrino-related Questions

| Experimental questions | Physics implications |
| --- | --- |
| Mass ordering ($m_3 > m_2$ ?) | Model building, fundamental properties |
| CP phase ➔ Leptogenesis | matter-antimatter asymmetry in the Universe |
| Only three generations ? Sterile neutrinos ? Right-handed neutrinos ? | Extension of Standard Model, parity restoration ? |
| Neutrinoless double beta decays ? Neutrinos are Dirac or Majorara ? | How to modify SM ? New physics beyond SM ($0\nu\beta\beta$ not exclusively from Majorara neutrinos) ? |
| Absolute mass ? | fundamental properties, Cosmology |
| Relic neutrinos, … ? | Cosmology |

Reactor $\nu$ is a great tool:

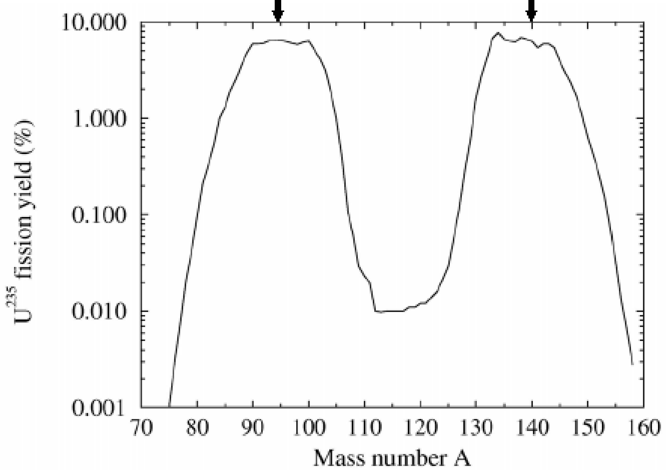
- In the past, used for $\nu$ discovery, and first measurement of $\theta_{12}$, $\theta_{13}$
- In the future for mass ordering, unitarity, sterile neutrinos, and $0\nu\beta\beta$/absolute mass

# Reactor Neutrinos: Production and Detection

**Neutrinos dominantly from $^{235}$U and $^{239}$Pu**
**For example:**

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$




**Signal: Inverse beta-decay (IBD) events**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\tau \approx 200\mu s$

**n + p → d + γ (2.2 MeV)**

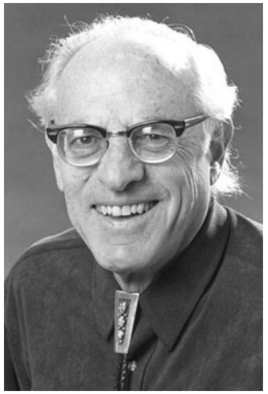
Prompt ($e^+$) and delayed(nH) coincidence in time, space with distinctive energy features

Proton source: Liquid Scintillator (LS, $C_nH_{2n+2}$) :

- Proton rich material (highest per volume)
- Target and detector are the same
- High light yield, fast, “well” understood
- Easy handling for very large volume
- Cheap, only second to water

Each fission generates ~6 neutrinos → 6 ×$10^{20}$ /s/reactor with 3 $GW_{th}$ power

# Beginning of Reactor Neutrino Oscillation exp.



F. Reines: Noble prize laureate 1995

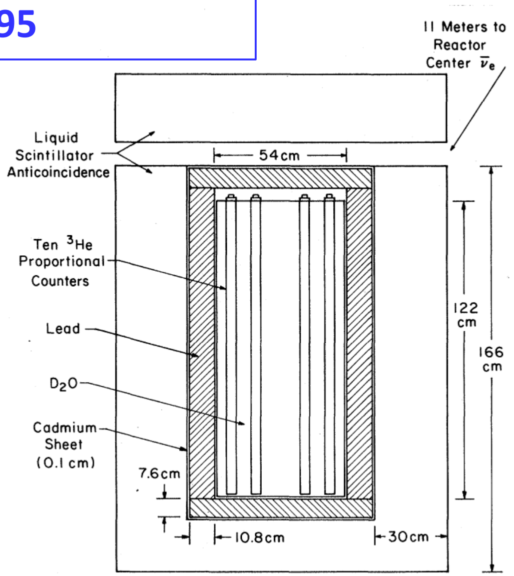
## Savannah River experiment:

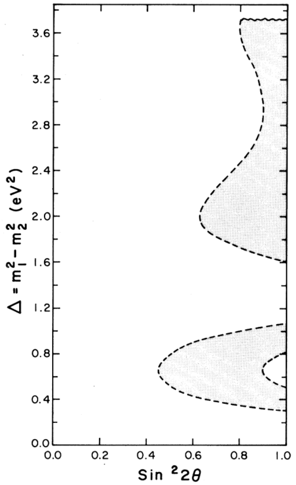
**“Observation of neutrino oscillation”**

$$\bar{\nu}_e + d \begin{cases} n + n + e^+ & (\mathrm{ccd}) \\ n + p + \bar{\nu}_e & (\mathrm{ncd}) \end{cases}$$

$$R \equiv r^{exp}_{ccd/ncd} / \, r^{theo}_{ccd/ncd}$$

$$= 0.40 \pm 0.22$$



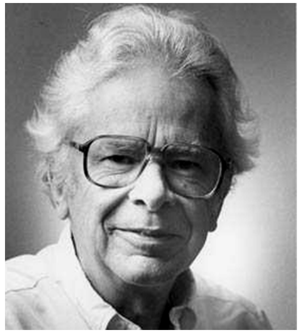




F. Reines et al., PRL 45(1980) 1307

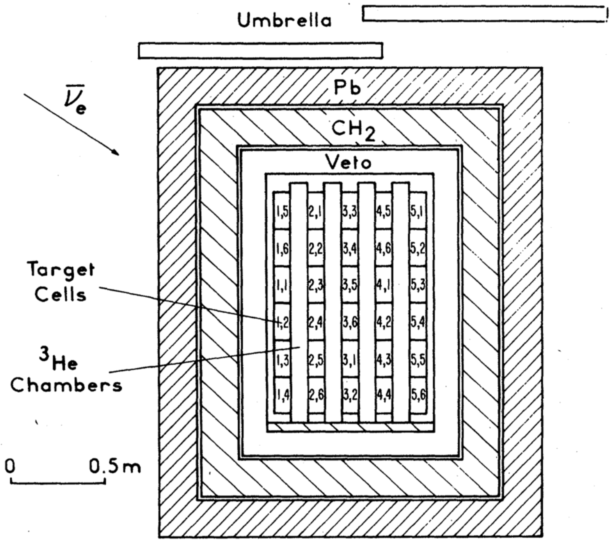
## ILL experiment in Grenoble

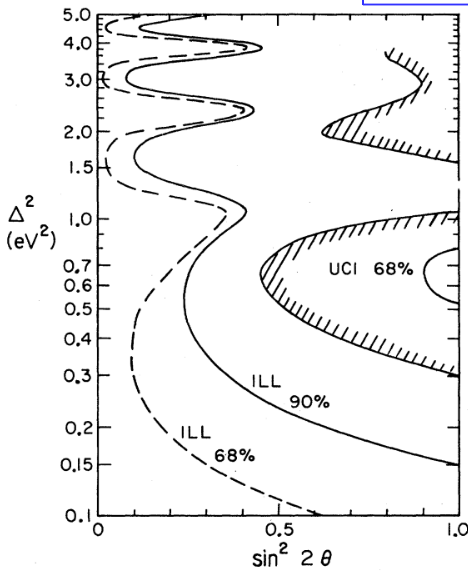
- Techniques used up to now
- Results: no oscillation
  - $N_{exp}/N_{theo.} = 0.89 \pm 0.04(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})$
- First reactor spectrum calculation:

P. Vogel, PRC 19(1979)2259



F. Boehm: disproved false oscillation claims twice
Last exp.: Palo Verde

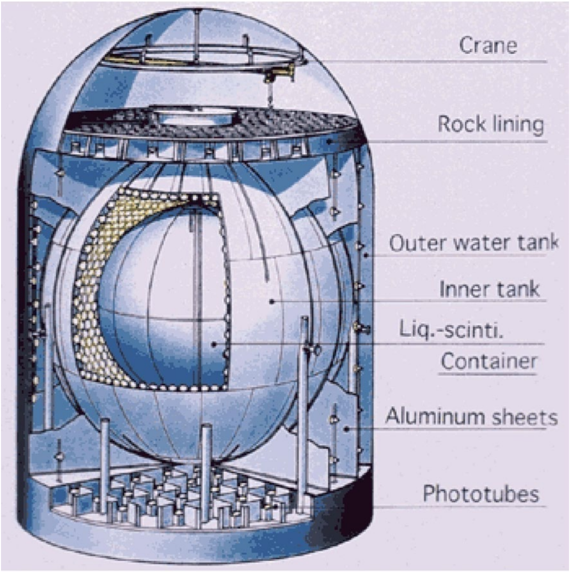


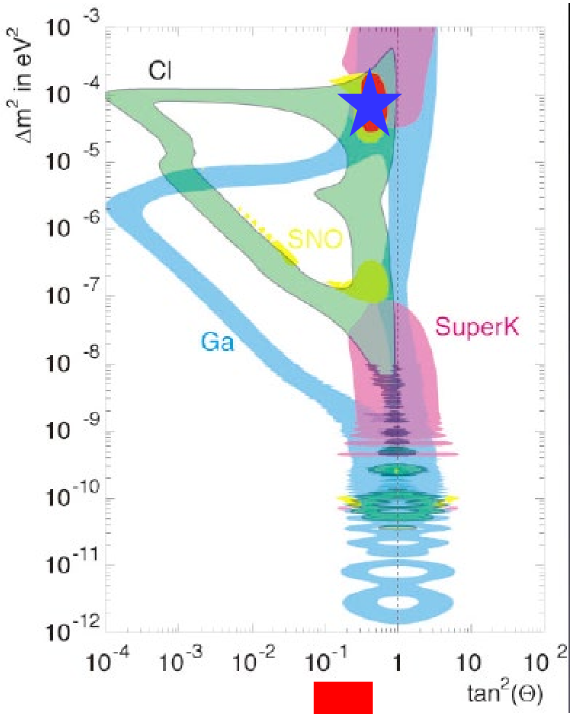



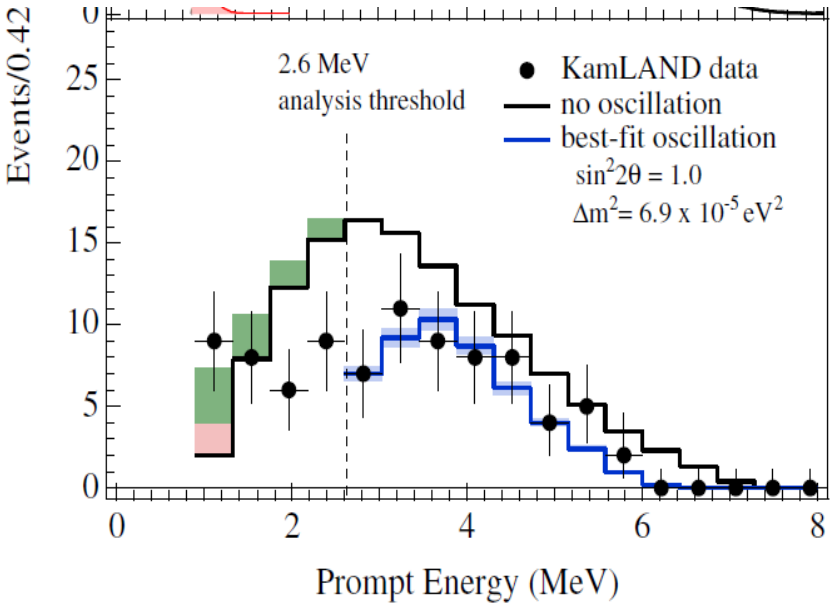

F. Boehm et al., PLB97(1980)310
H.Kwon et al., PRD24(1981)1097

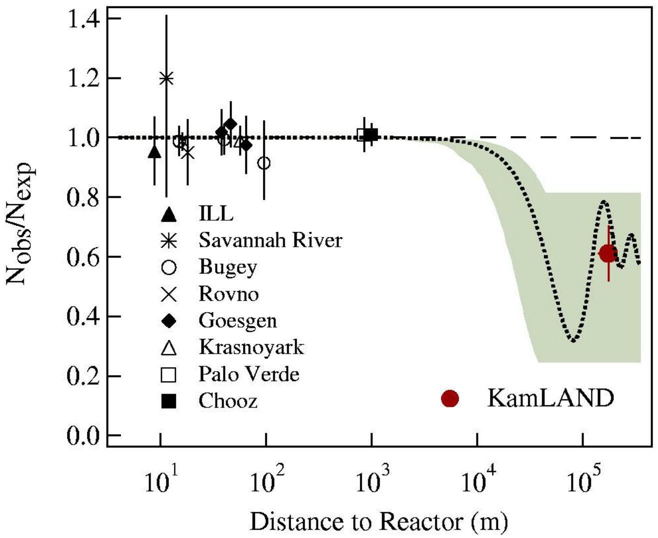
# A Great Success: KamLAND

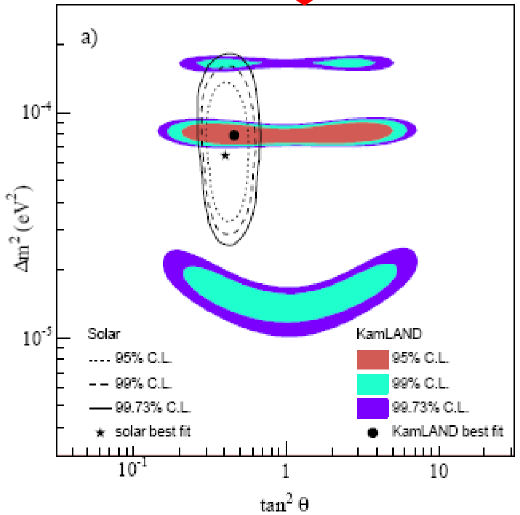
- KamLAND (1kt) was considered the ultimate reactor neutrino experiment
- It measures all reactor neutrinos in Japan with an average baseline of 180km
- It observed neutrino oscillation and determined $\theta_{12}$ for the first time, luckily and surprisingly



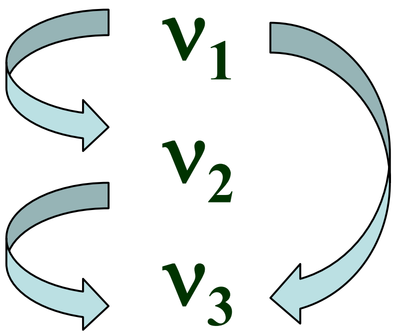
# After KamLAND: $\theta_{13}$

**Solar ν Oscillation**

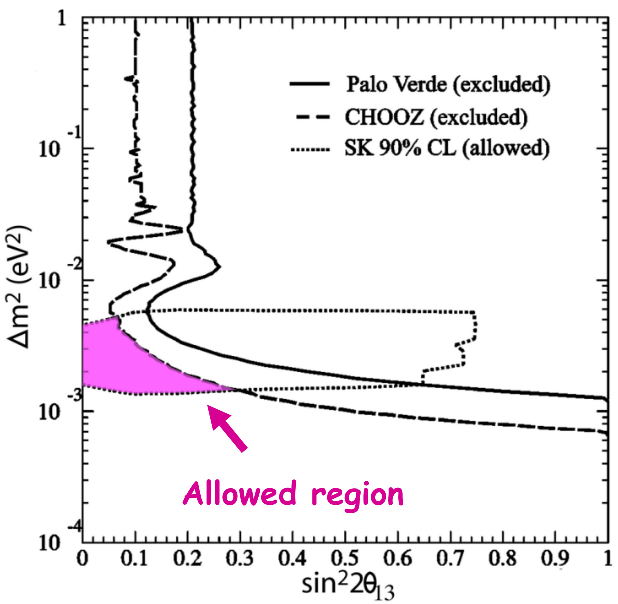
$\sin^2 2\theta_{12} \sim 0.9$

**Atm. ν Oscillation**

$\sin^2 2\theta_{23} \sim 1$

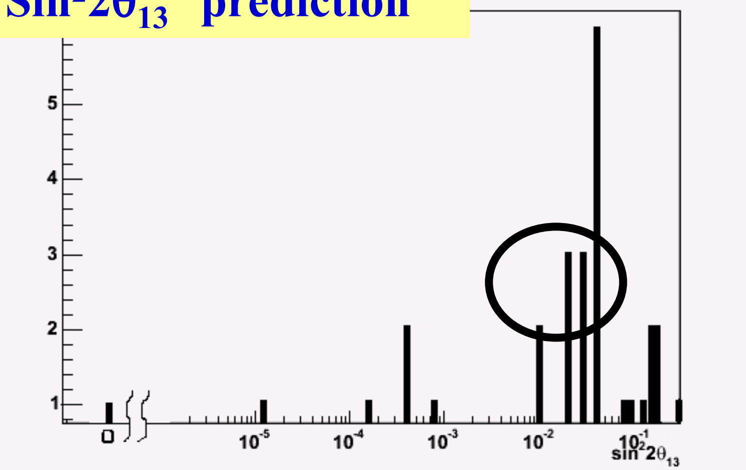



$\theta_{13}$ ?




- A fundamental parameter of the SM
- Direction of future neutrino physics:
  - Key for the CPV determination

**$\mathrm{Sin}^2 2\theta_{13}$ prediction**




3 exp.s: Daya Bay, RENO, Double Chooz

# Measuring $\theta_{13}$ at Reactors

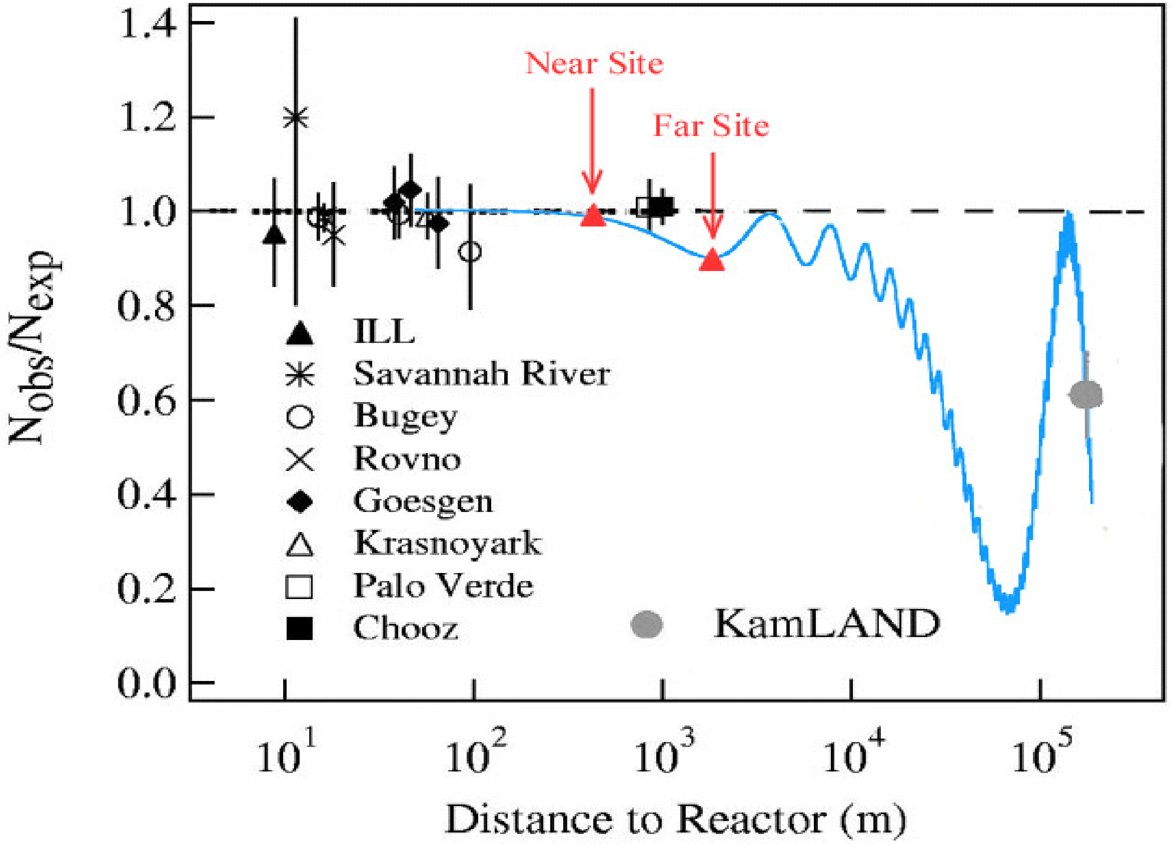
At reactors $P_{e \to e} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$

At accelerators $P_{\mu \to e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{23} L/E) + \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$
$- A(\rho) \bullet \cos^2\theta_{13} \sin\theta_{13} \bullet \sin(\delta)$

- Independent from CP d and matter effect
- Relatively cheap and quick

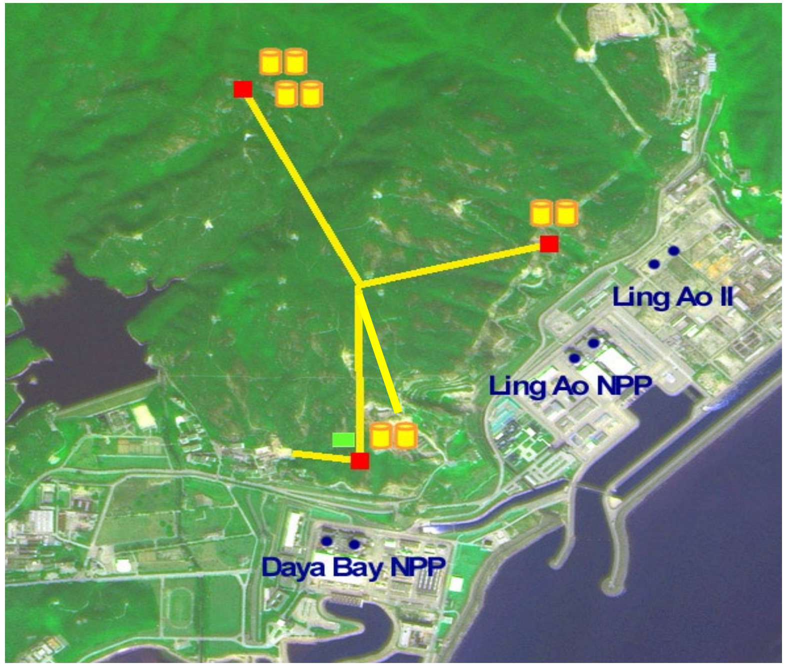
**Precision of past experiments (3-6%):**

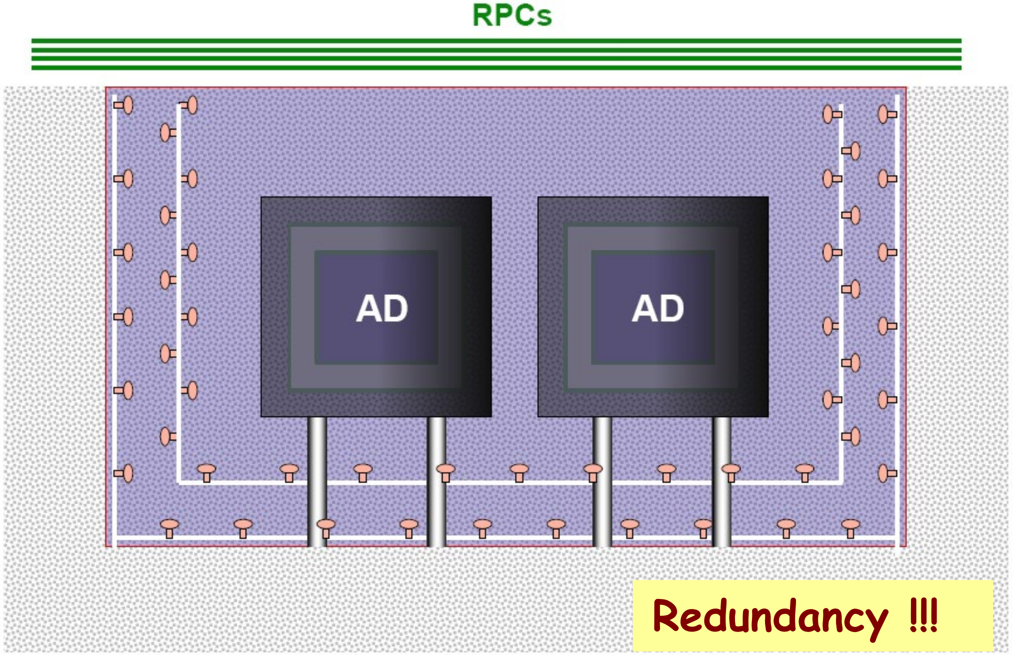
- Reactor power: ~ 1%
- Spectrum: ~ 0.3%
- Fission rate: 2%
- Backgrounds: ~1-3%
- Target mass: ~1-2%
- Efficiency: ~ 2-3%

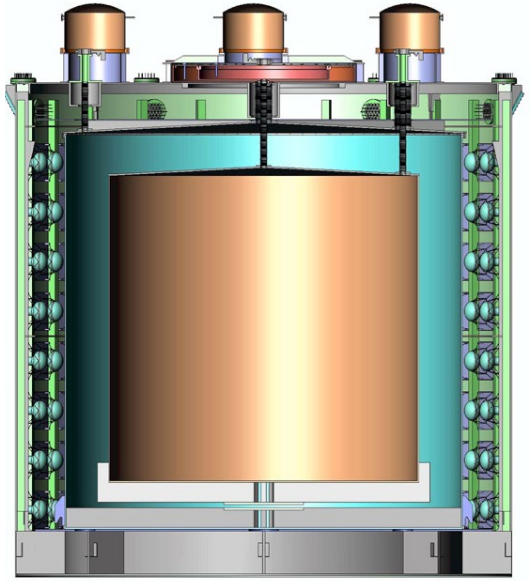



**Our design goal: $\Delta(N_{obs}/N_{exp}) \sim 0.4\%$ ➔ ÷10 improvement !**

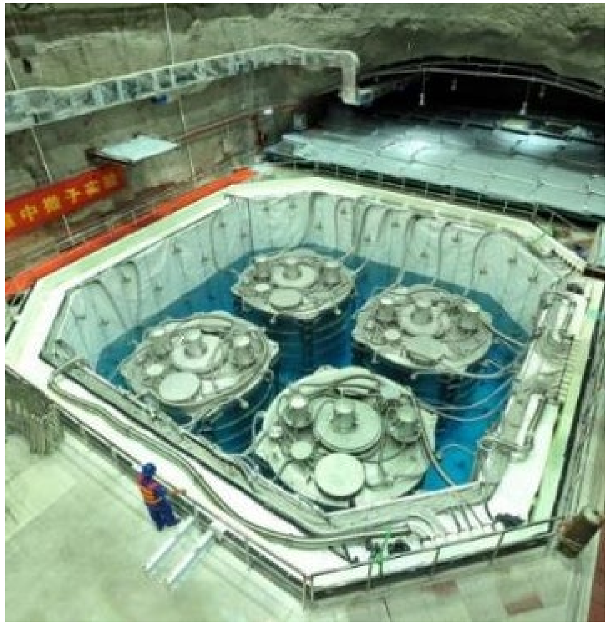
# Daya Bay Experiment: Concept



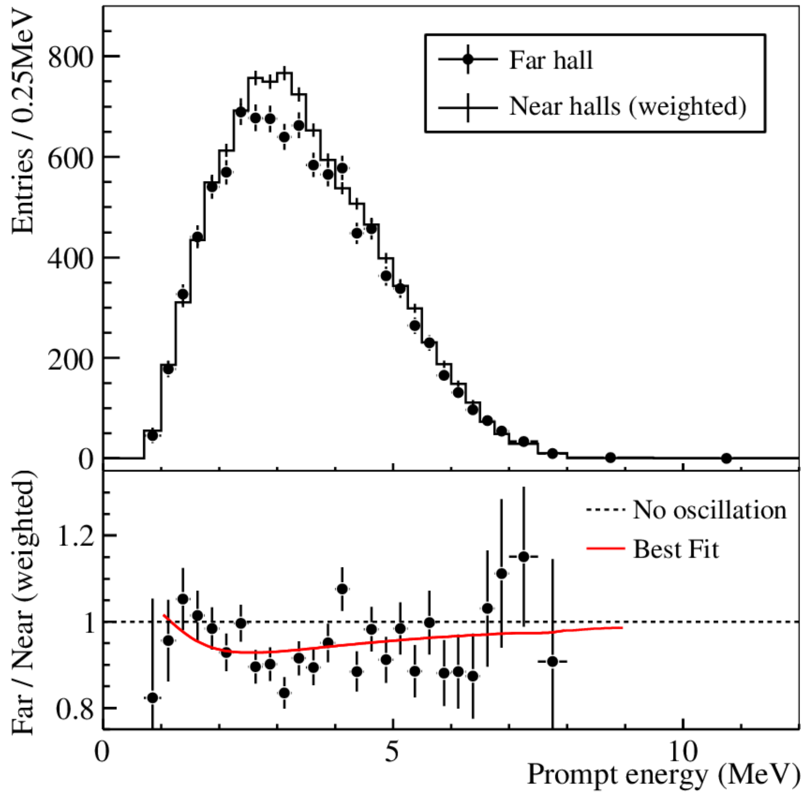
- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err. by $1/\sqrt{N}$
  - ⇨ Far: 4 modules， near: 2 modules
- Multiple muon detectors to reduce veto ineff. ➔ goal 0.5%
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the top + telescopes



# A New Type of Neutrino Oscillation

## On Mar. 8, 2012, Electron anti-neutrino disappearance announced:

**R = 0.940 ±0.011 (stat) ±0.004 (syst)**

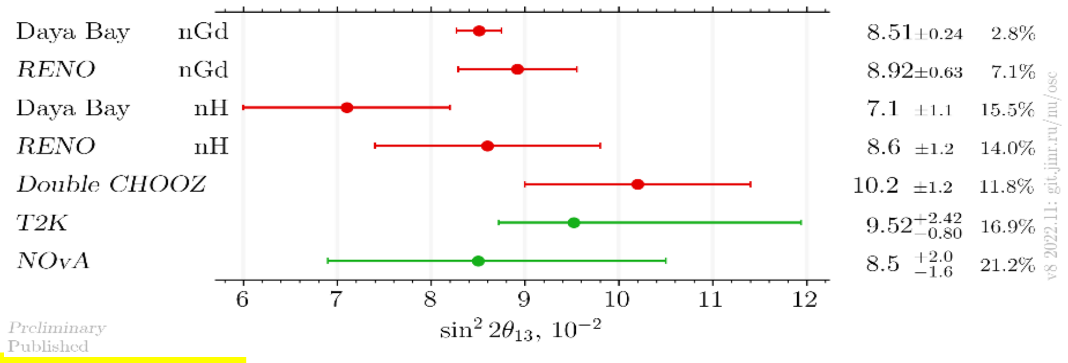



**$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$**

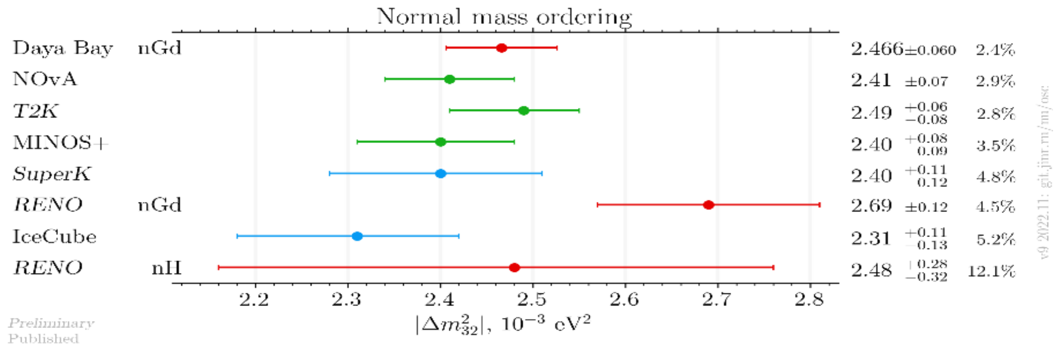
**$\chi^2/\text{NDF} = 4.26/4$, 5.2 σ for non-zero $\theta_{13}$**

F.P. An et al., Phys. Rev. Lett. 108, (2012) 171803

$\sin^2 2\theta_{13}$




$\Delta m^2_{32}$ (NO)

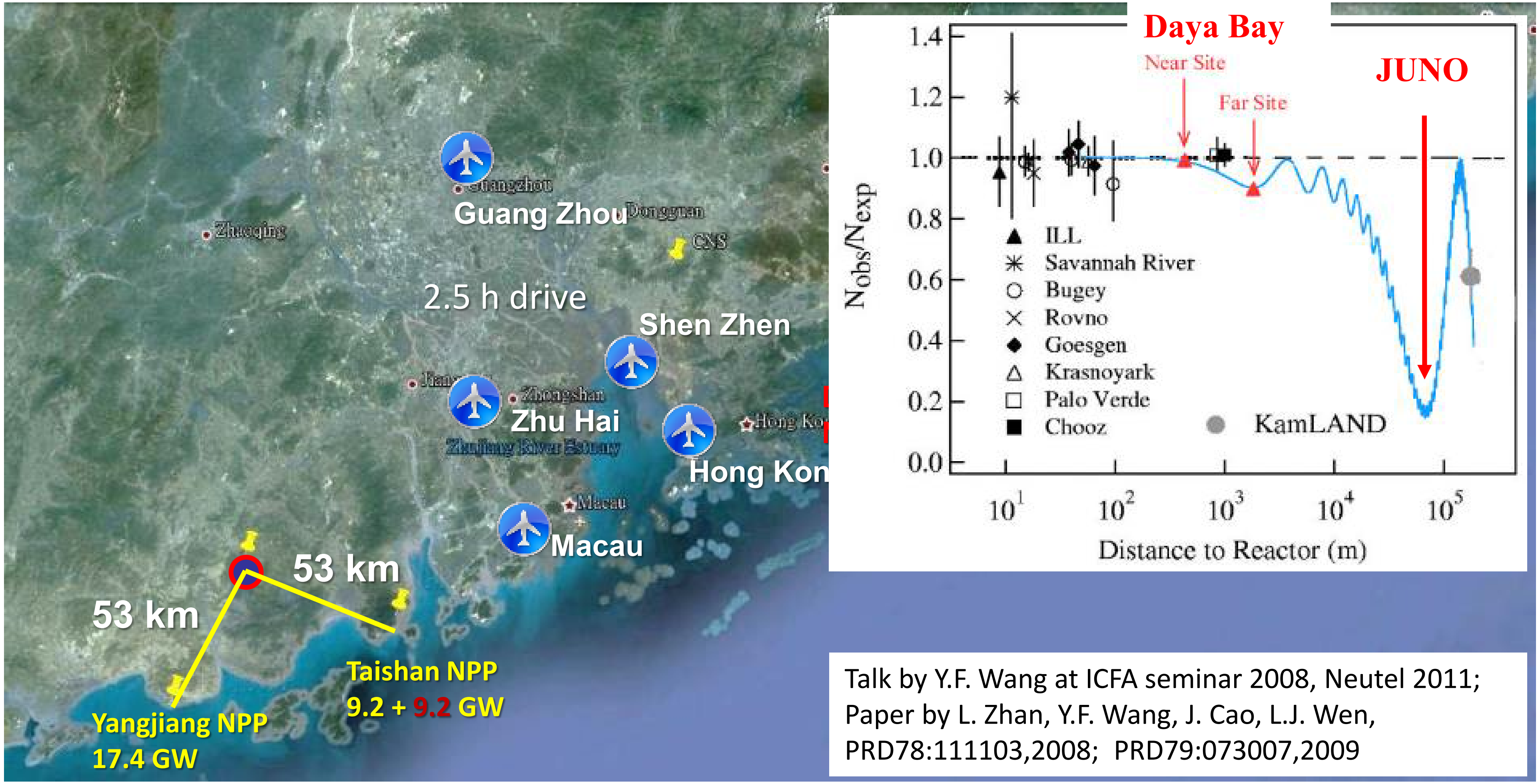



Compiled by Maxim Gonchar at git.jinr.ru/nu/osc

- All three experiments ceased operation
- Final result from Daya Bay may reach 2.5%

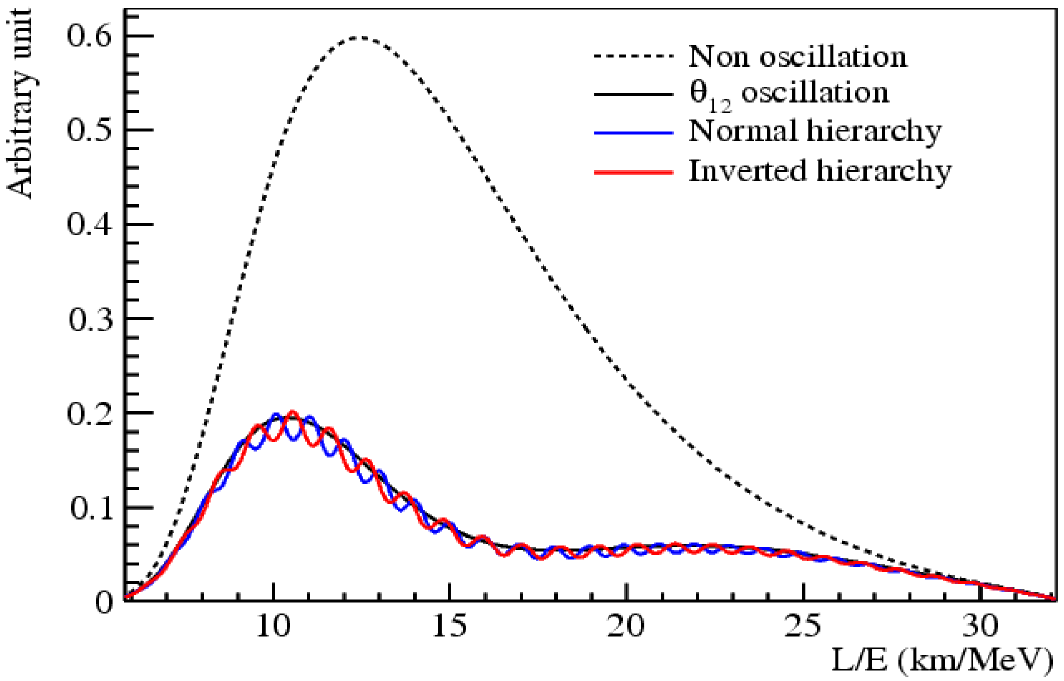
# Next Step: JUNO Experiment

- Continue to use reactor neutrinos and liquid scintillator
- To determine the mass ordering (sign of $\Delta m^2_{32}$) independent of the CP phase $\delta$
- Equal baseline to two reactor power plants: doubling the neutrino flux




Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

# Mass Ordering by Reactor Neutrinos




$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

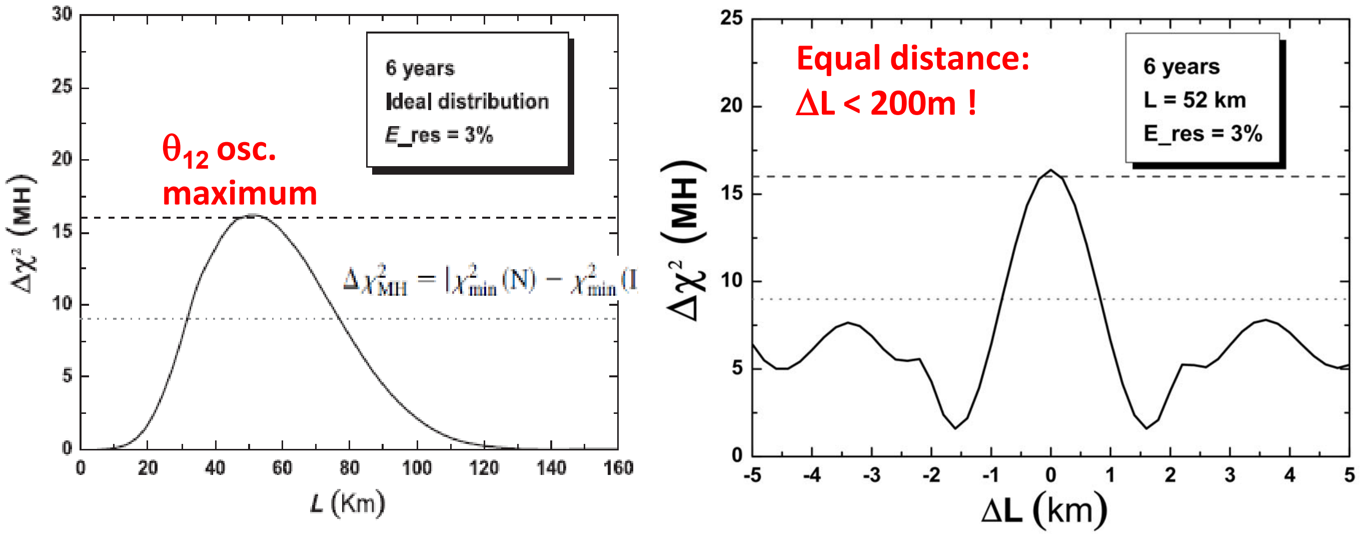
S. Petcov and Piai, Phys. Lett. B 553, 94-106(2002)
J. Learned et al., PRD 78(2008)071302
L. Zhan et al., PRD 78(2008)111103

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \text{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

$$\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \sim 3\%$$

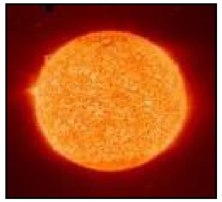
- **Key parameters:**
  - Detector size: 20 kt
  - Energy resolution: 3%/√E
  - Thermal power: 36 GW
  - Baseline: ~58 km

L. Zhan et.al, PRD79:073007, 2009




Y.F Li *et al*, PRD 88, 013008 (2013)

# Physics at JUNO



## Solar Neutrinos

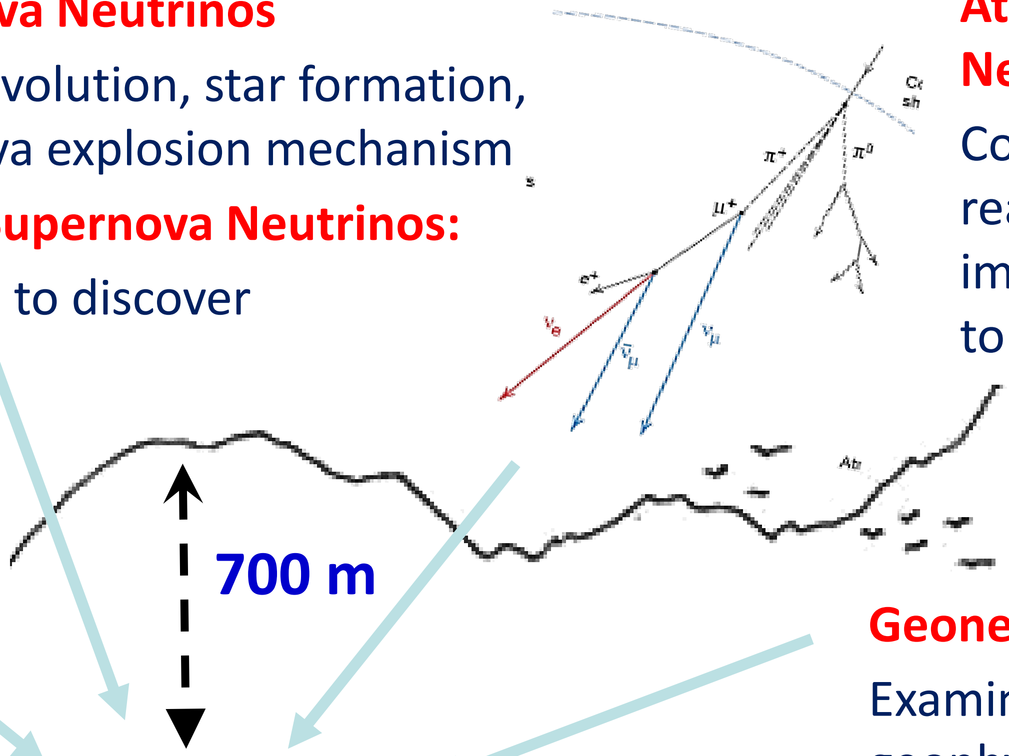
Examine the dynamics of stellar evolution

## Supernova Neutrinos

Cosmic evolution, star formation, supernova explosion mechanism

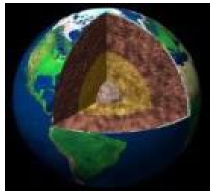
## Diffuse Supernova Neutrinos:

Potential to discover




## Atmospheric Neutrinos

Complementary to reactor neutrinos to improv the sensitivity to mass ordering

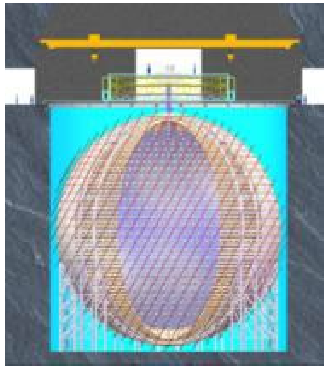


## Reactor Neutrinos

Determine neutrino mass ordering

Measure oscillation parameters

| | Current (PDG2020) | JUNO (100 days) | JUNO (6 years) |
|---|---|---|---|
| $\Delta m^2_{31}$ ($\Delta m^2_{32}$) | 1.3% | 0.8% | 0.2% |
| $\Delta m^2_{21}$ | 2.4% | 1.0% | 0.3% |
| $\sin^2\theta_{12}$ | 4.2% | 1.9% | 0.5% |
| $\sin^2\theta_{13}$ | 3.2% | 47.9% | 12.1% |



## Geoneutrinos

Examine the Earth's geophysical model

## New physics searches

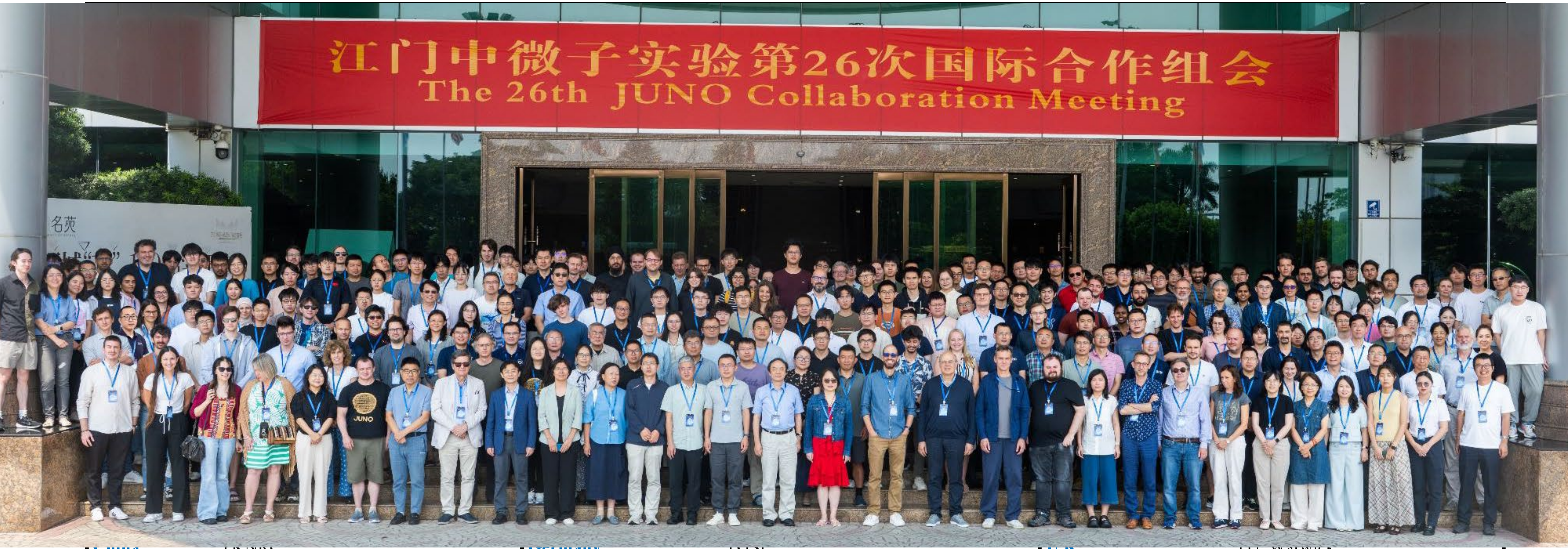
e.g., proton decay and sterile neutrinos

J. Phys. G 43 (2016) 030401

Prog. Part. Nucl. Phys. 123(2022), 103927

# JUNO Project and the collaboration

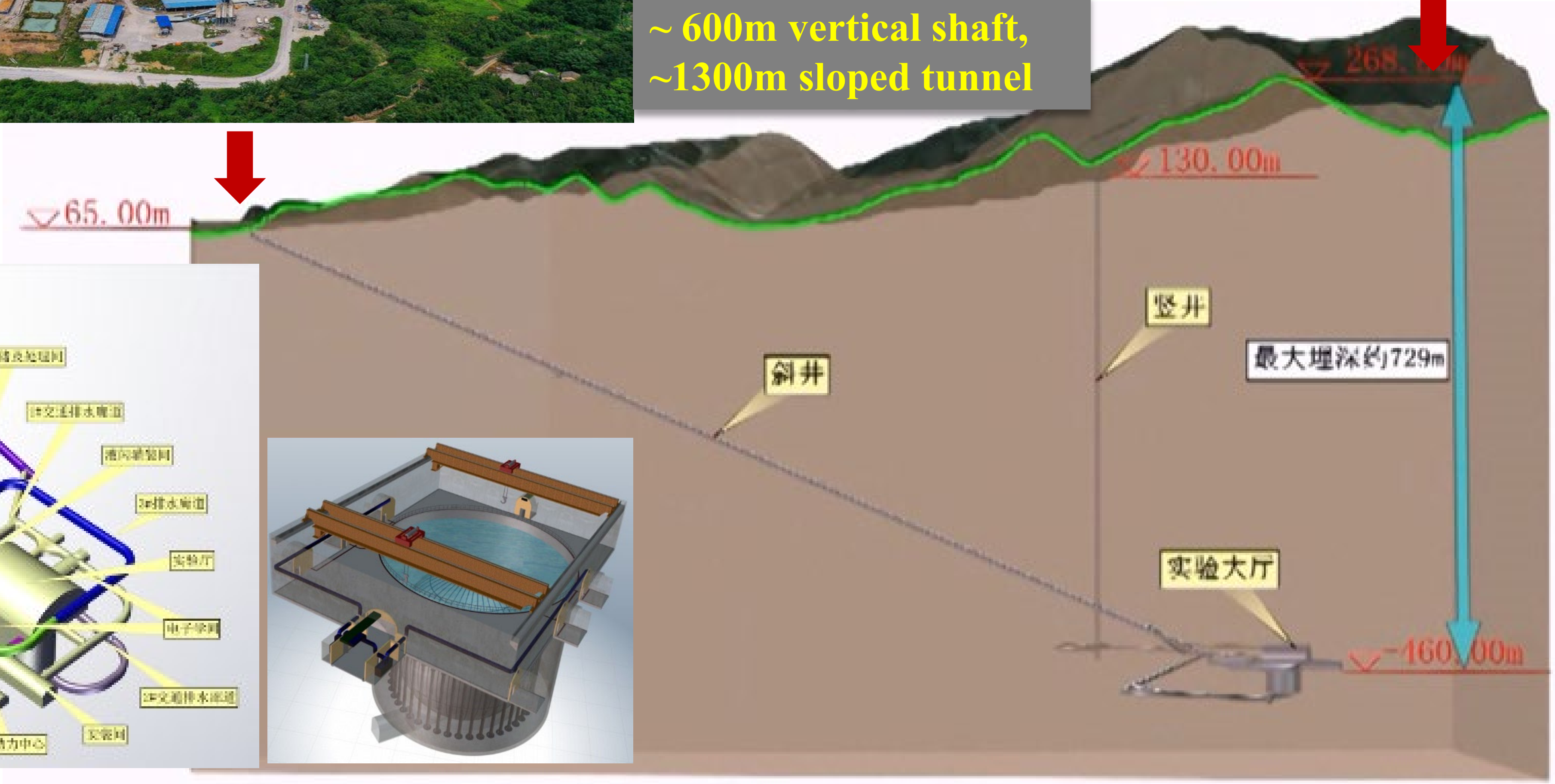
- Project firstly approved in China in 2013 and later in other countries. Civil construction started in 2015
- Collaboration established in 2014, now >700 collaborators from 70 institutions in 16 countries/regions

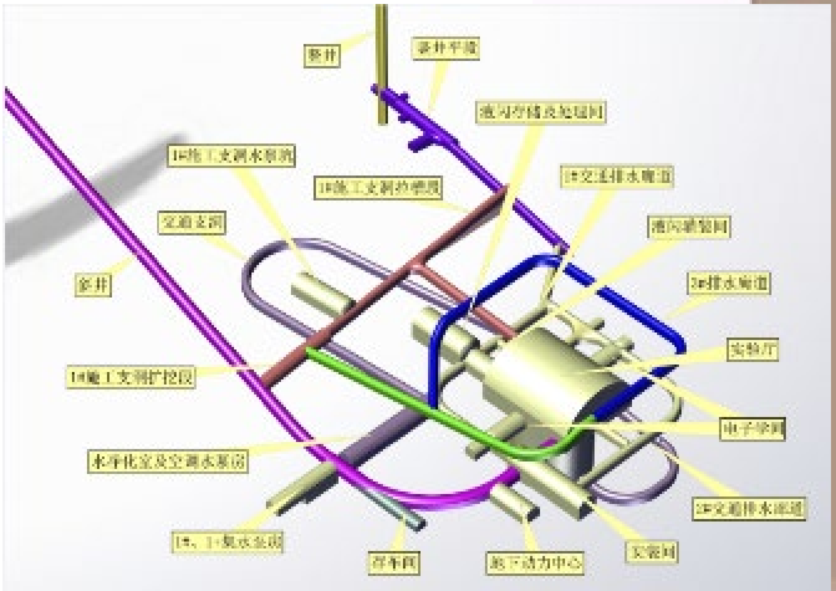



| | | | | | |
|---|---|---|---|---|---|
| China | KNRC | Germany | GSI | U.K. | U. Warwick |
| China | Nankai U. | Germany | U. Hamburg | USA | UC-Irvine |
| China | NCEPU | Germany | JGUMainz | USA | UMD-G |
| China | NJU | Germany | RWTH-AC | | |
| China | RNCG | Germany | TUM | | |

+**Observers:** **USTC, Peking Uni., Jilin Uni., Beijing Normal Uni., CIAE (China), PUC, UEL (Brazil)**


**~ 600m vertical shaft,**
**~1300m sloped tunnel**



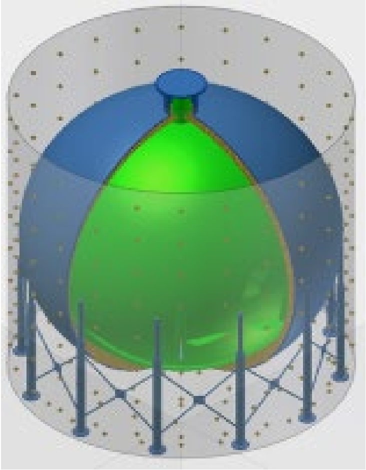



# Detector Concept

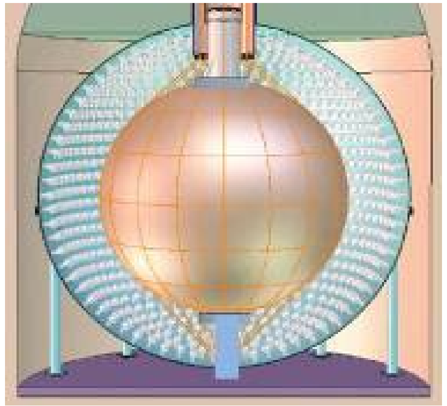
- Target mass of 20 kt liquid scintillator ➔ × 20 KamLAND, × 40 Borexino
- Energy resolution < 3%@ 1MeV ➔ >1200 PE/MeV

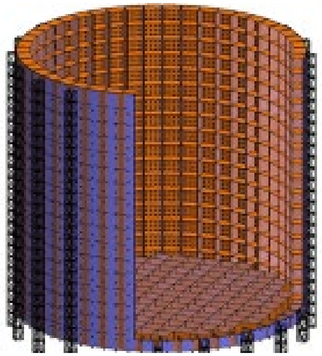
| | KamLAND | JUNO | PE Ratio |
|---|---|---|---|
| Photon Statistics | 250 p.e./MeV | 1200 p.e./MeV | 5 |
| PMT coverage | 34% | 75% | 2.2 |
| LS transparency | ~12 m | > 20 m | ~0.9 |
| Light yield(anthracene) | 30% | 45% | ~1.5 |
| Detection Eff.(QE×CE) | ~15% | 30% | ~ 2 |


Steel frame+ Acrylic tank


Steel tank+ Acrylic tank

- Key technologies needed:
  - Transparent & high light yield liquid scintillator
  - High detection efficiency 20” PMTs
  - Radiopurity U/Th/K < $10^{-17}$ g/g for 20 kt LS
- Detector Design(more than 10 options):
  - Central target container: acrylic or balloon ?
  - Mechanical structure: steel frame or steel tank ?
  - Buffer layer: Water or Mineral oil ?

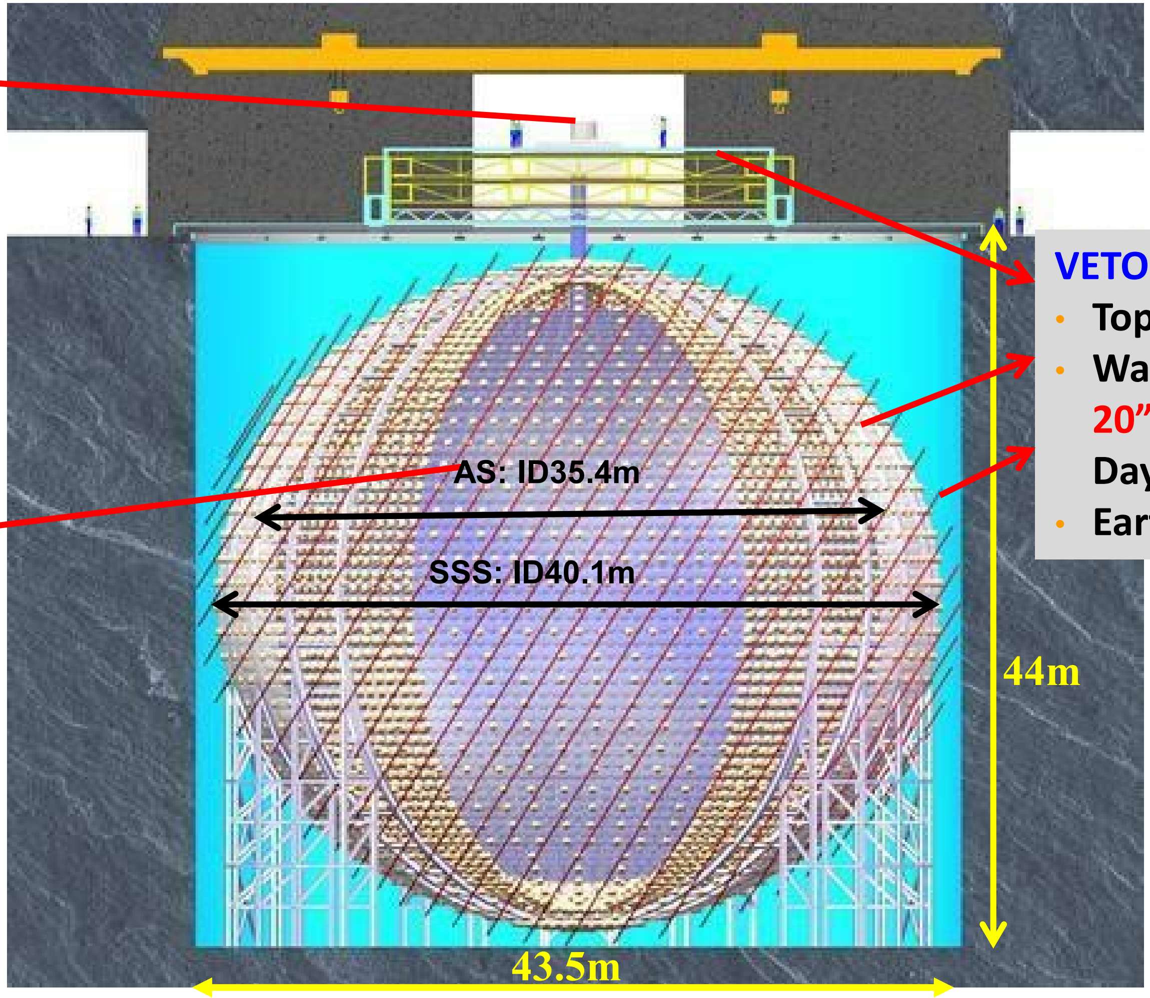

Steel Tank + Balloon


Steel Tank + Acrylic blocks

# Concept of JUNO for Mass Ordering

- Two-layer structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer ➔ radiopurity control of water

**Calibration house**




**Central detector**
- Steel structure (SSS)
- Acrylic sphere(AS) + 20kt Liquid scintillator
- 17612 20" PMT
- 25600 3" PMT

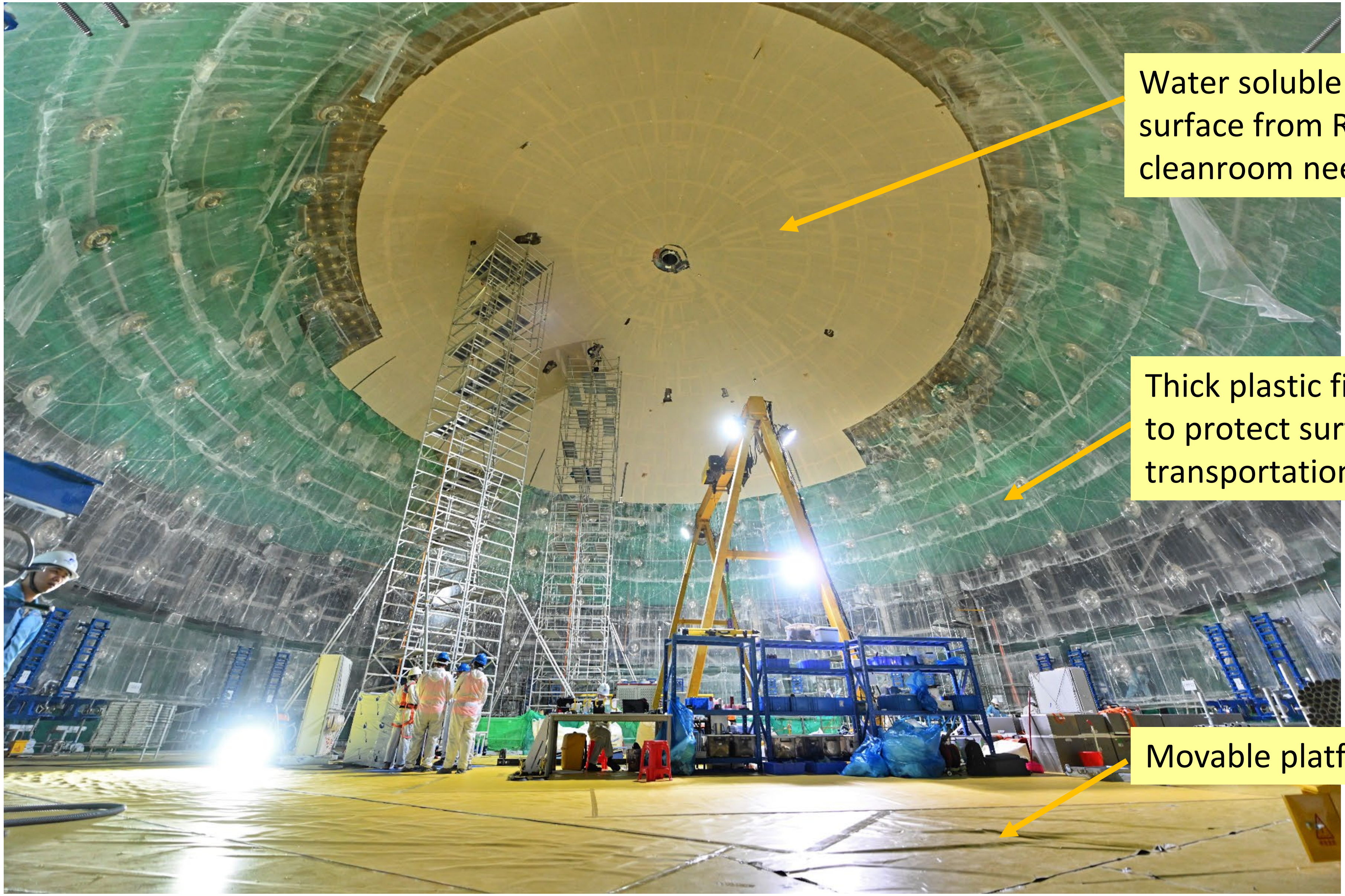
**VETO system**
- Top Tracker
- Water VETO with 2400 20" PMT + 348 20" spare PMTs + 600 8" PMTs from Daya Bay
- Earth Magnetic Field shielding coils

# Central Detector

- SS structure to hold the acrylic tank and PMTs, through steel bars with springs and rotating heads
- Stress sensors on steel bars
- Clearance between PMTs is ~3 mm, to maximize coverage
- 263 Acrylic panels thermally pressed and machined to the spherical shape, bonded together in-situ through PMMA polymerization
  - Stress on acrylic < 3.5 MPa
  - Difference of thermal expansion requires ±5 $^{o}C$ since construction

*Eur.Phys.J.Plus* 139 (2024) 12, 1128, arXiv: 2311.17314

# Acrylic Tank Construction



Water soluble paper put onsite to protect surface from Rn daughters: no class 1000 cleanroom needed during construction

Thick plastic film from the manufacturer to protect surface from damage of transportation and dust

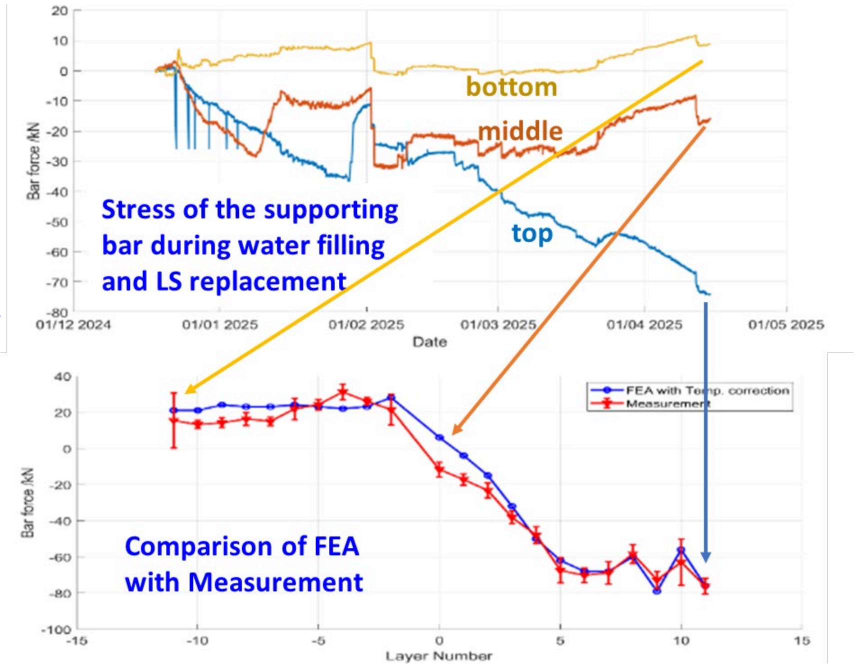
Movable platform for acrylic construction

# Check the Surface Quality of the Acrylic

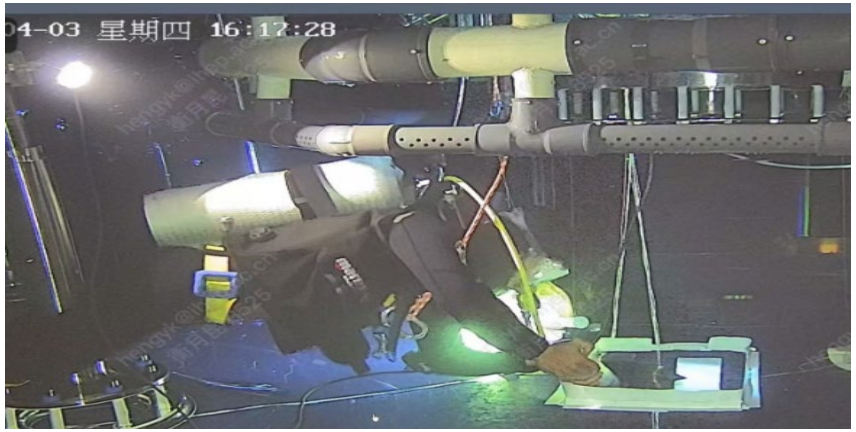
Minor defects may be developed to craze or even cracks
Sand them out to have smooth and clean surface

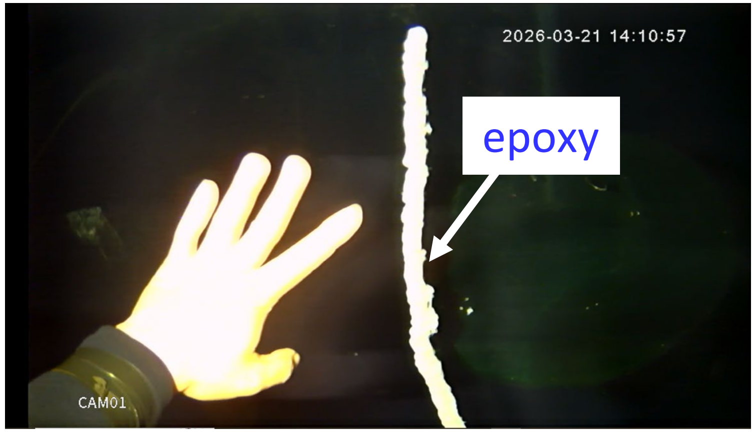
# But Cracks Happenned Anyway

- Main structure is safe, stress within expectations
- However, a LS leak to water happened on March 21, 2025:
  - ⇨ Abnormal trigger rate observed and confirmed by under water robot
  - ⇨ Leak was stopped within 1 week using epoxy and tape by divers
  - ⇨ Further repair by epoxy and acrylic plate to reduce the stress (pulling open the crack) by 50%
- Another leak of water to LS happened on March 19, 2026:
  - ⇨ Experienced divers were called to stop the leak within 2 days
  - ⇨ Further repair in the following two days
  - ⇨ A total of ~1Bq $^{222}$Rn went into LS, 13 days of data excluded
  - ⇨ No other increase of radioactive backgrounds in LS



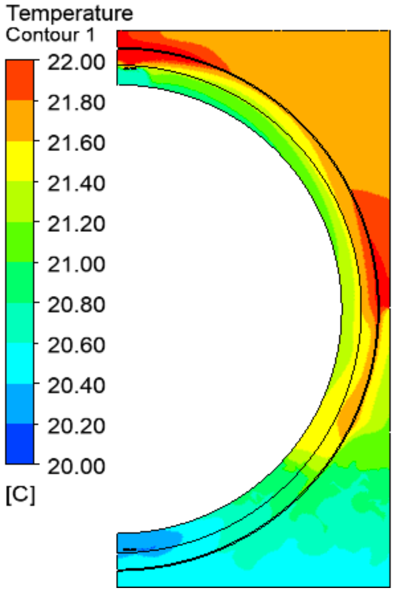


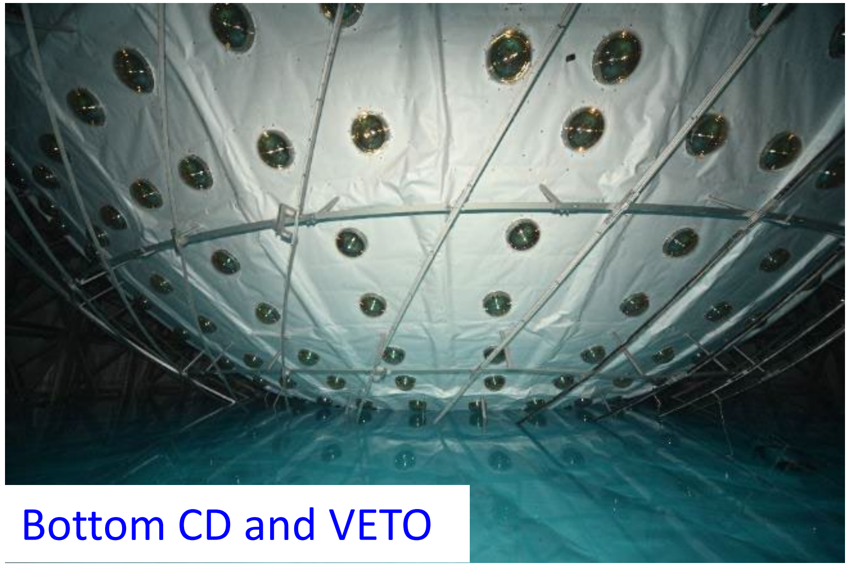


# VETO

- Water VETO:
  - 40 kt pure water for backgrounds shielding & tagging
  - PMTs on the SS trust and on the pool wall
  - 5mm HDPE+Tyvek as Pool lining for cleanness & reflection
  - 100t/h pure water production plant with Rn & Ra removal system
- Top tracker: refurbished OPERA plastic scintillators
- Earth magnetic field compensation: 10% residual



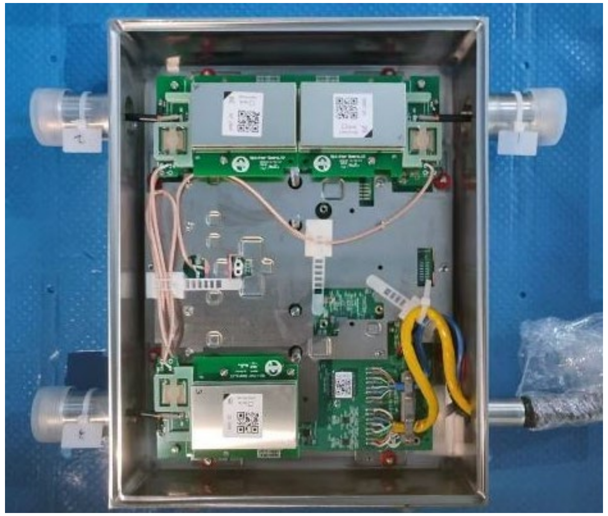
Bottom CD and VETO

Top tracker

# PMTs and Electronics

| | LPMT (20-inch) | | SPMT (3-inch) |
|---|---|---|---|
| | Hamamatsu | NNVT | HZC |
| Quantity | 5000 | 15012 | 25600 |
| Charge Collection | Dynode | MCP | Dynode |
| Photon Efficiency | 28.5% | 30.1% | 25% |
| Dynamic range | [0, 100] PEs | | [0, 2] PEs |
| Coverage | 75% | | 3% |
| Reference | Eur.Phys.J.C 82 (2022) 12, 1168 | | NIM.A 1005 (2021) 165347 |

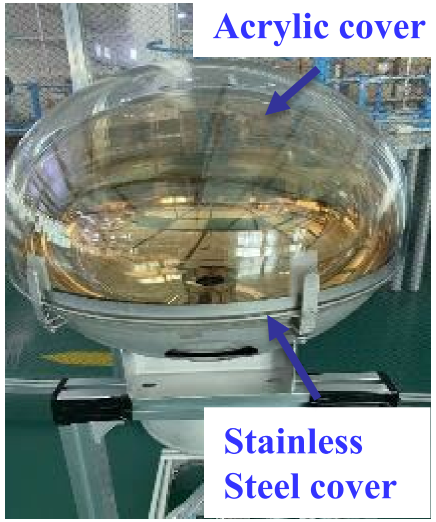
LPMT & sPMT



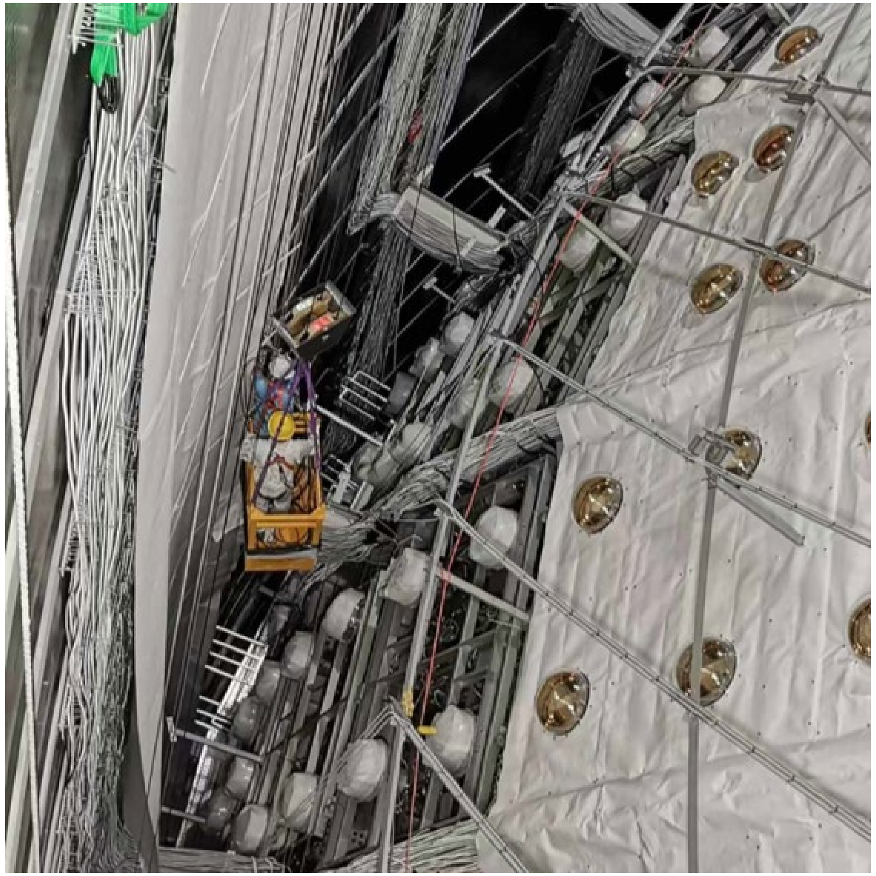
LPMT Underwater box

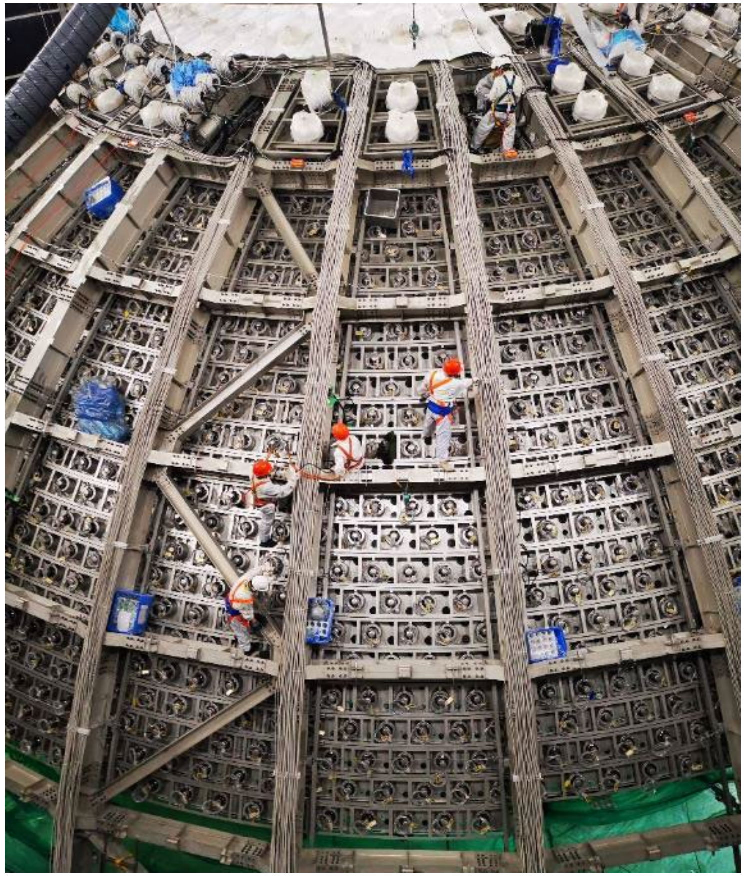
sPMT Underwater box

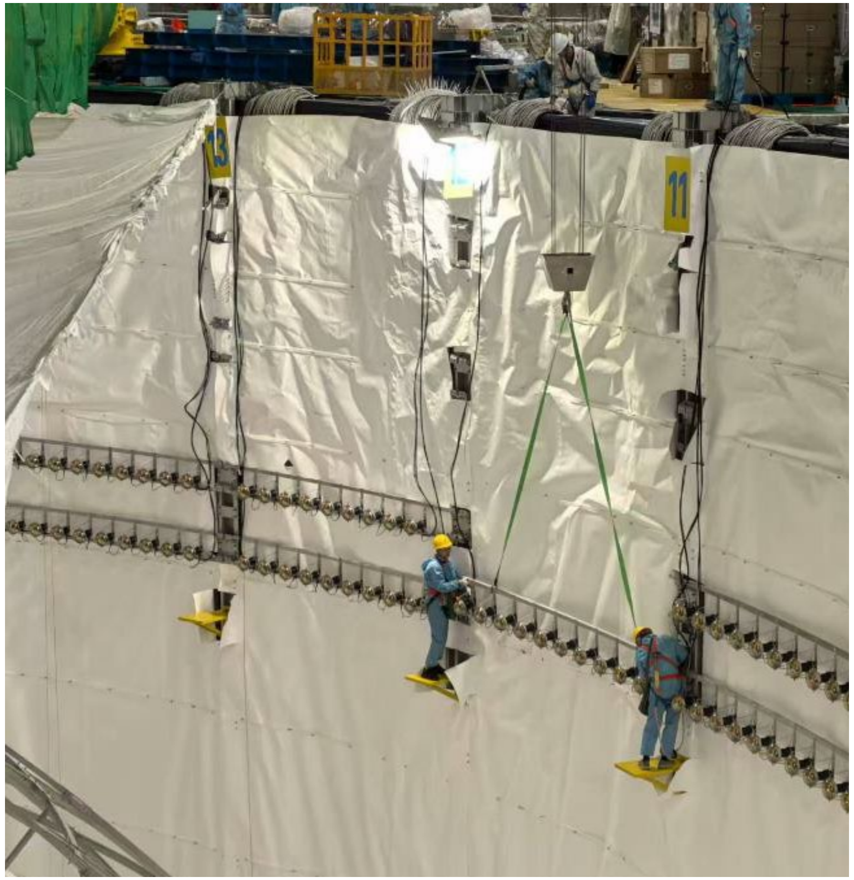
Potted PMT



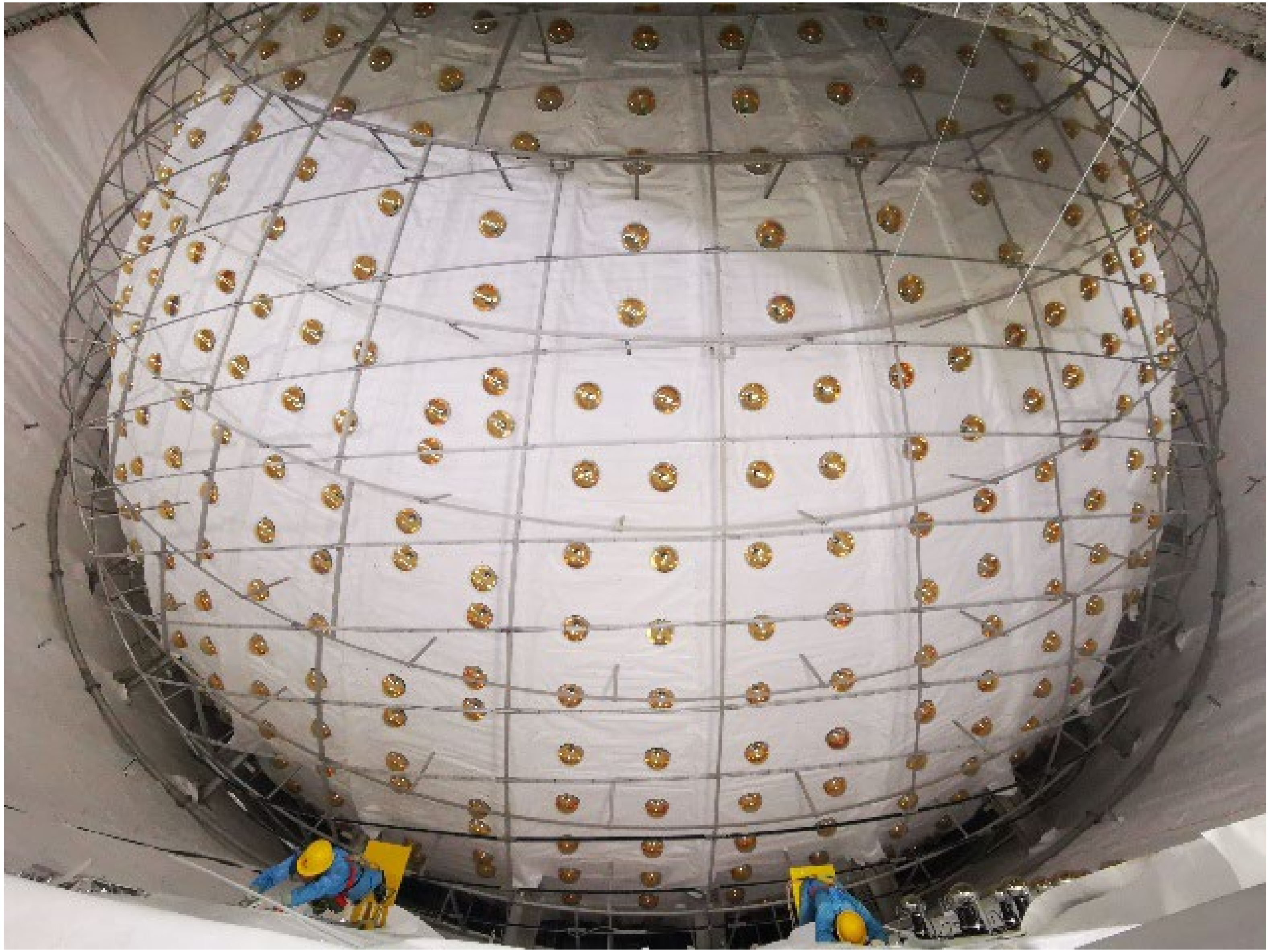
# PMT Installation





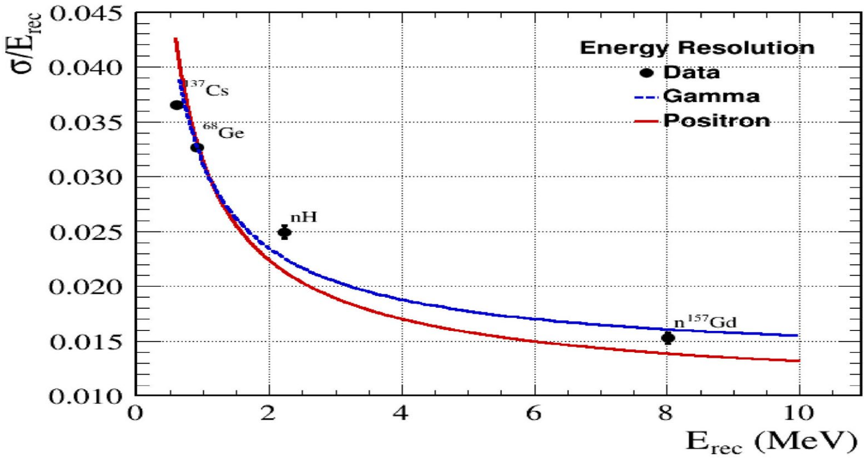


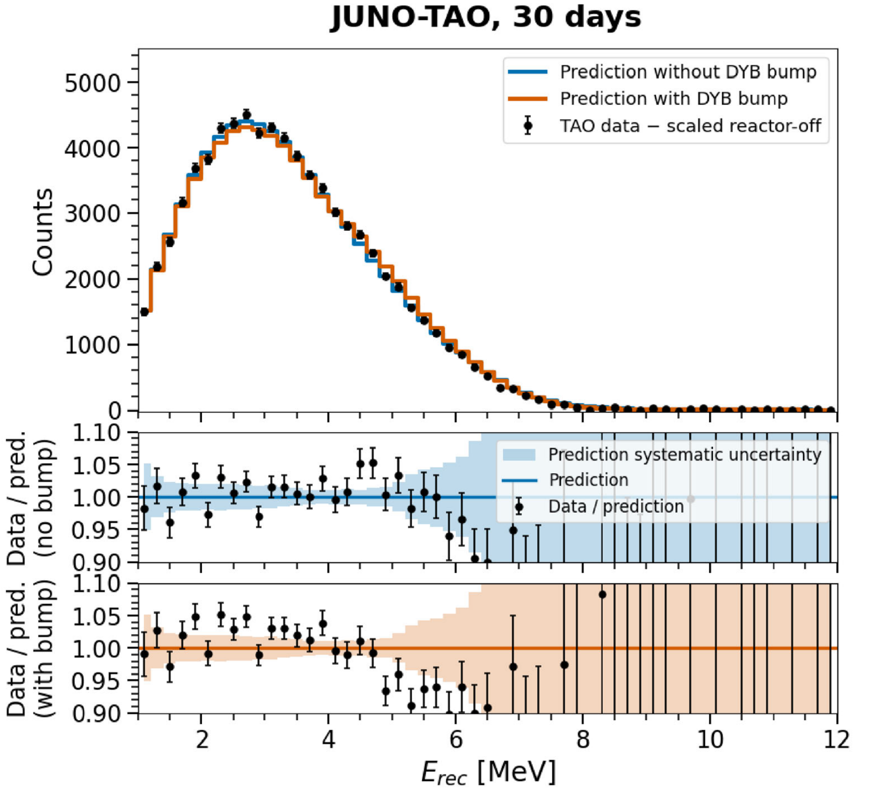
# Installation Completed

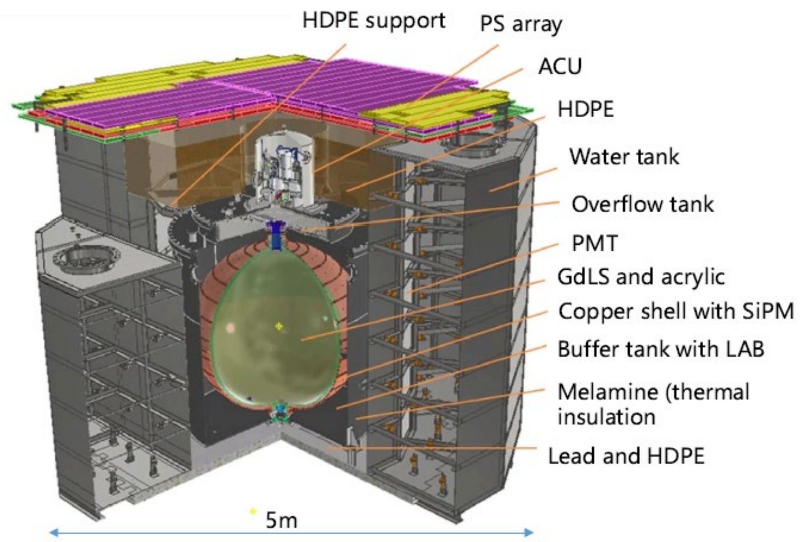


# JUNO-Tao

- **To measure the reactor neutrino spectrum as a reference**
  - ⇨ Mitigate possible fine structure and spectrum uncertainty issues
  - ⇨ Improve nuclear database, search for sterile neutrinos
- **Idea: Gd-loaded LS @-50°C + SiPM**
  - ⇨ 700k/year@44m from the core(4.6 GW ), with ~10% bkg.
  - ⇨ Energy resolution: 4500 p.e./MeV ➔ ~2%@1 MeV
  - ⇨ 10 $m^2$ SiPM (>94% coverage) w/ PDE > 50%
  - ⇨ Operating at -50 °C to reduce the SiPM dark rate by $10^3$ to 50 Hz/mm
  - ⇨ 2.8 ton(1t fiducial volume) new type of Gd-LS for -50 °C




# Liquid Scintillator

- For optimal transparency and light yield:
  - ⇨ Recipe: LAB + 2.5g/L PPO + 3 mg/L bis-MSB + 50mg/kg BHT
  - ⇨ Goal: LAB attenuation length > 24m, LS attenuation length > 20m, U/Th ~ $10^{-17}$ g/g
  - ⇨ Production: Four purification plants + LS Mixing + QA/QC + high purity $N_2$ and water

5000 $m^3$ LAB storage tank

1) $Al_2O_3$ for optical transparency

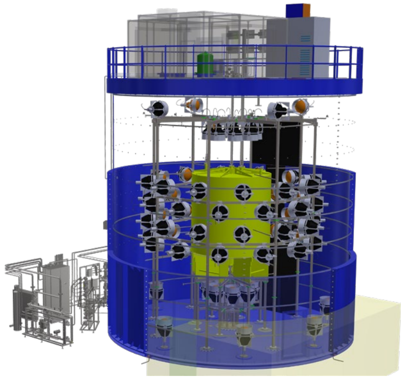
2) Distillation for radiopurity

Mixing LAB with PPO and bis-MSB

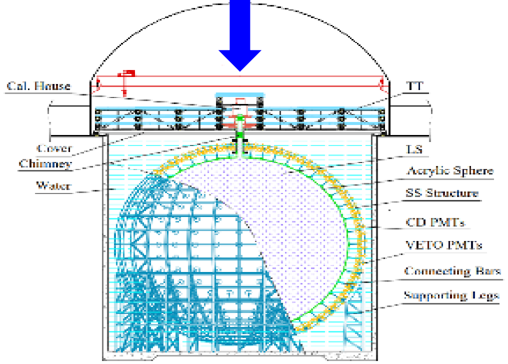
**1800 m SS pipes to underground**

3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and $O_2$

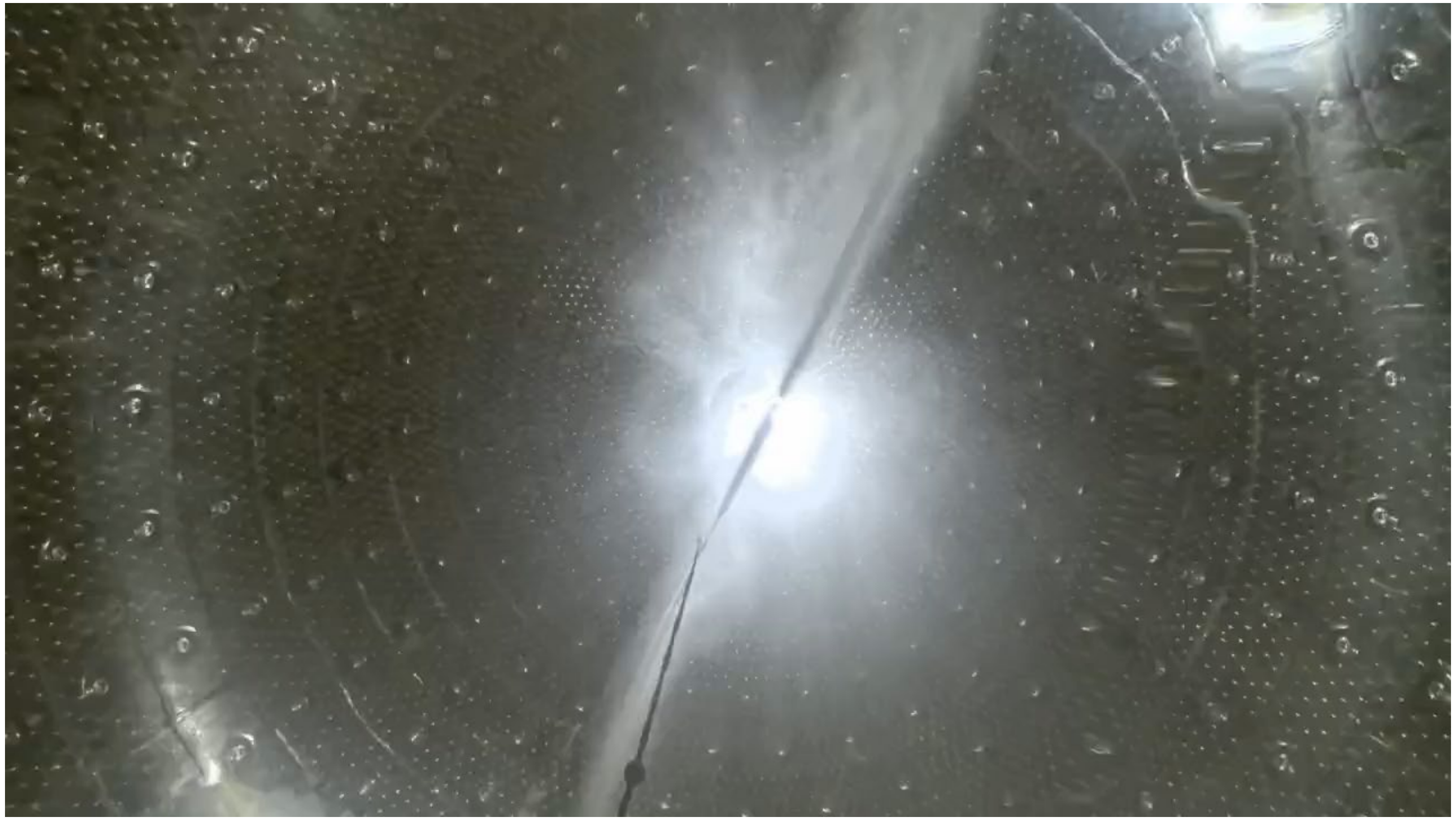


OSIRIS to monitor Rn and other backgrounds



# Background Control before the Liquid Filling

- U/Th/$^{40}$K in raw materials:
  - Steel <1 ppb, raw LAB <1 ppq, PPO <0.1 ppt, Bis-MSB <3 ppt, BHT <0.2 ppt, acrylic <1ppt, water <0.1-1.0 ppq
- Water:
  - Resistivity~18 MΩ*cm, U/Th < $10^{-15}$ g/g, Rn < 10mBq/m$^3$



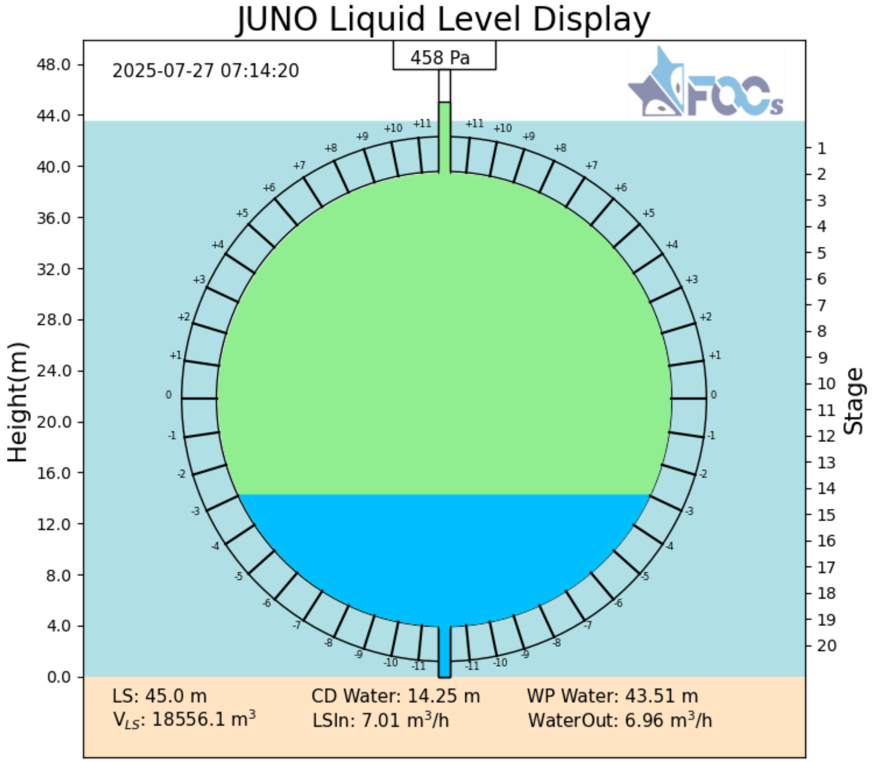
Water soluble paper film on acrylic to stop Rn decay daughters

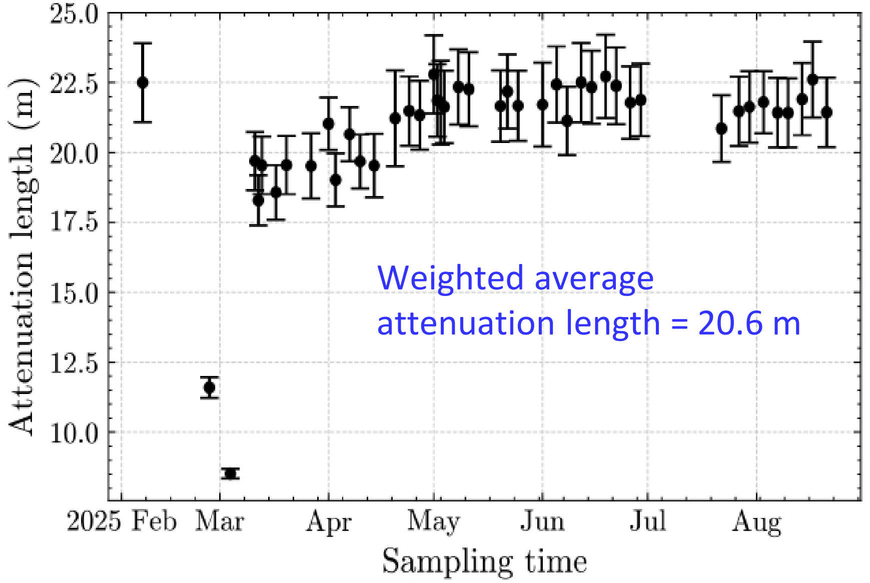
- Surface protection and cleaning, clean room and air dust removal, …
- Air tight by leak check:
  - < 1 mBq/m$^3$ $^{222}$Rn in fresh LS
- Surface cleanness:
  - Pure water wash to remove dust and paper film
  - Water filling before LS

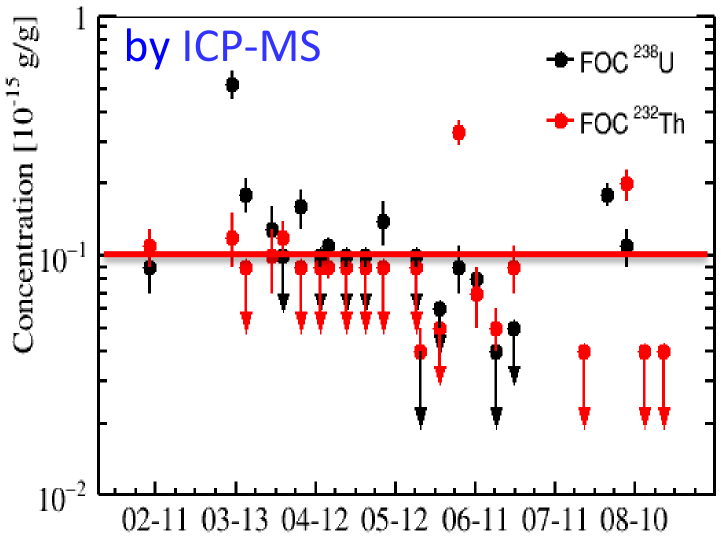
# Water and LS Filling

Posters 17, 324

- Water filling for cleaning the CD, testing the mechanical structure, as well as the detector commissioning
- Replace water by LS at a rate of 7 t/h, 6 months/volume
- Optical transparency and radioactive background control:
  - ✓ Weighted average LS attenuation length > 20m
  - ✓ Weekly LAB/LS sampling: U/Th < $1\times10^{-16}$ g/g by ICP-MS
  - ✓ $^{222}$Rn in fresh LS by OSIRIS+CD: < 1 mBq/m$^3$
  - ✓ $^{14}$C ~(4-5)$\times10^{-17}$ g/g measured by several methods



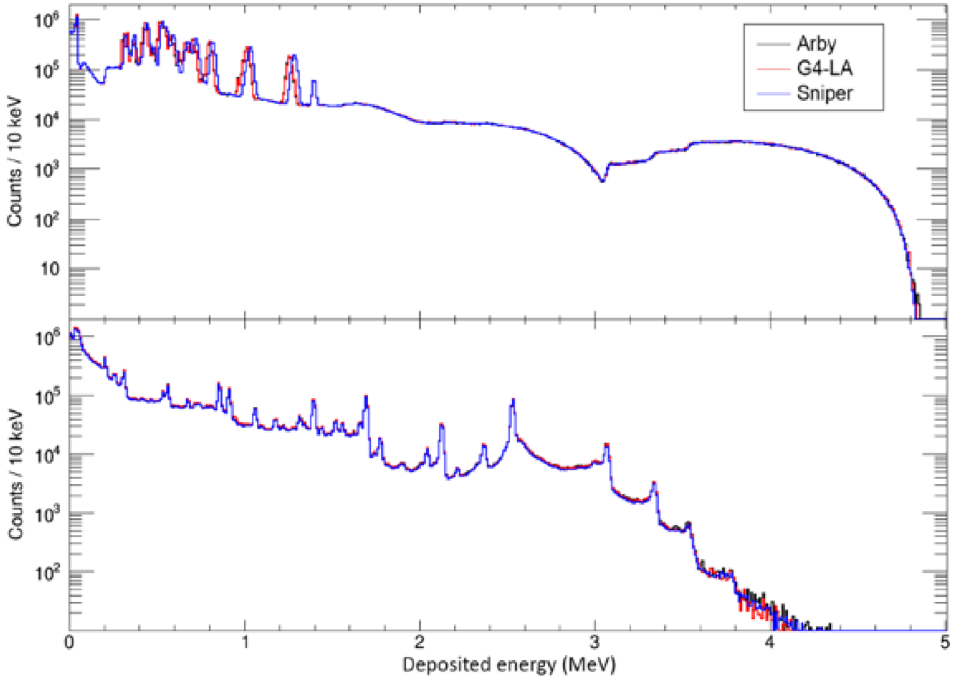

- ➢ LS Filling completed on 8/22/2025
- ➢ LS in the CD: 23231.6 m$^3$
- ➢ Water in the pool: 41225.1 m$^3$

# Important Contributions from In2P3

- Cooperation started in 2014
- Major contributions on top tracker, 3” PMTs & electronics, background study, software and analysis


Top Tracker: IPHC

3-inch PMT and electronics: LP2i, SUBATECH, IJCLab

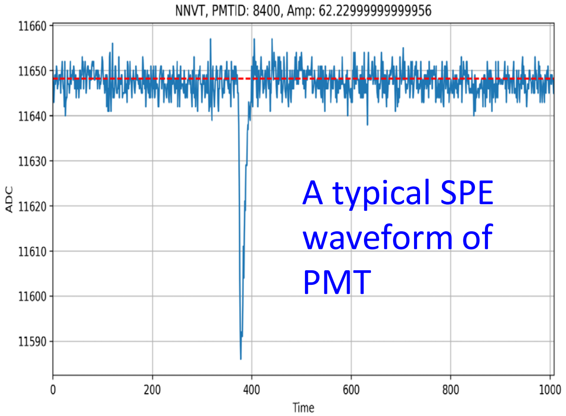


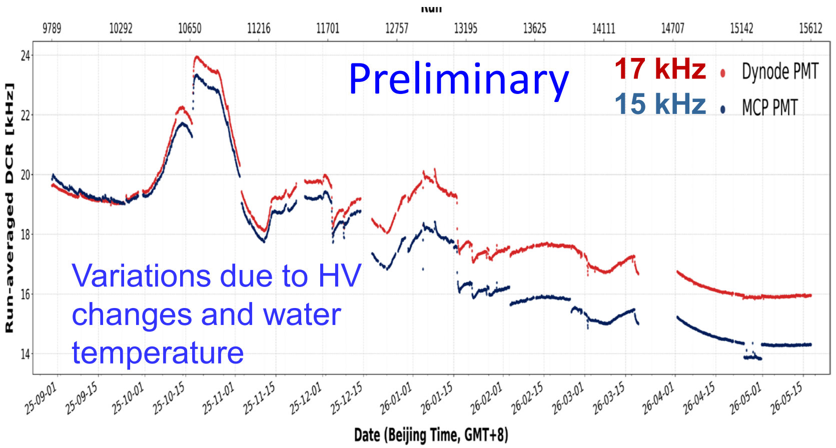

Radioactivity background: LP2i, CPPM

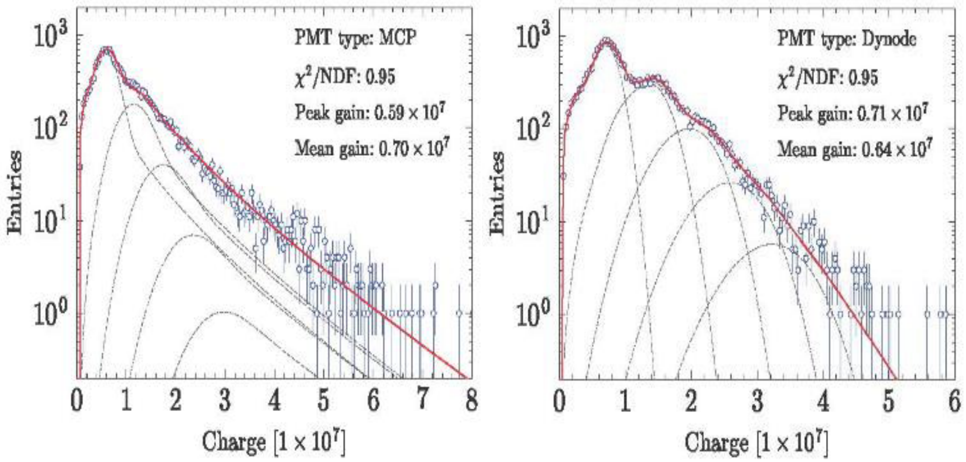
# Performance of the Detector

# PMTs, Electronics and Trigger

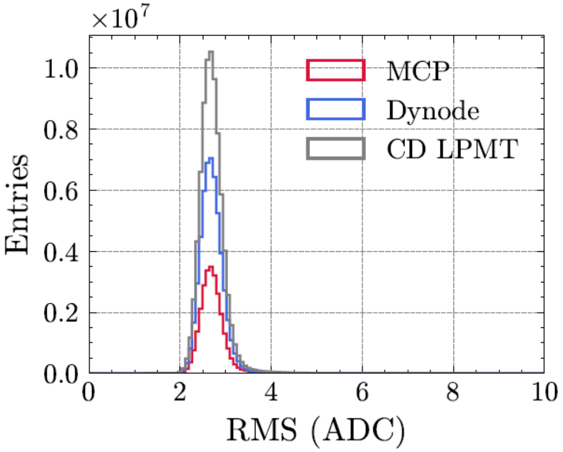
- Large PMTs
  - 17612-16 LPMTs installed for CD, 2400-1 LPMTs installed for VETO
  - ~26 dead PMTs + electronics, ~1.2/month
  - ~600 flashing PMTs (turned off)
  - Gains of MCP (Dynode) PMTs are reduced from $7.4\times10^6$ to $4.0\times10^6$ ($6.5\times10^6$ to $5.5\times10^6$), efficiencies not affected
- Noise of electronics for LPMTs:
  - Stable pedestals
  - RMS ~2.8 ADC ch. ➔ ~0.055 PE
  - PMT threshold: 0.2-0.3 PE
- Dark rate continuously decreasing
- sPMTs have similar performance
- Trigger threshold: ~200 keV




SPE pulse shape and calibration



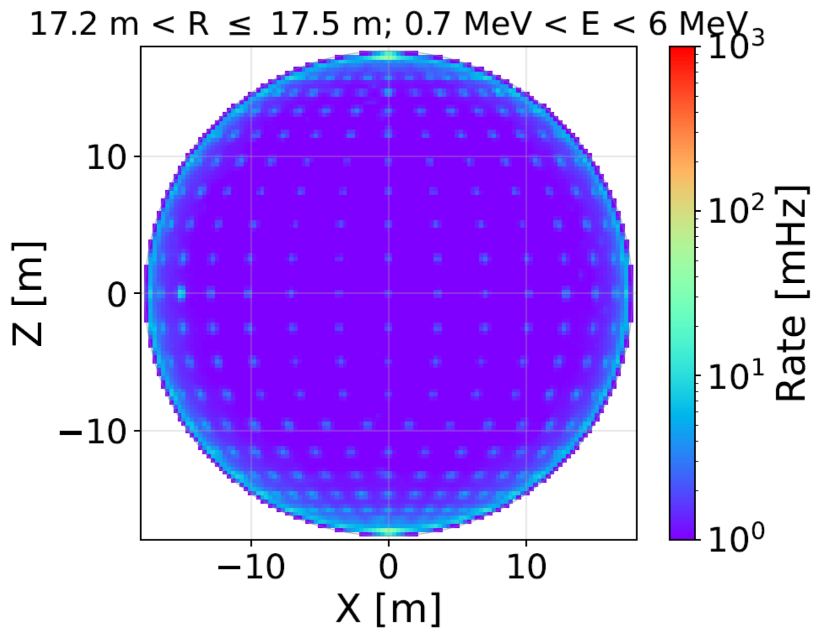

Noise of Electronics noise

# Backgrounds of the Detector

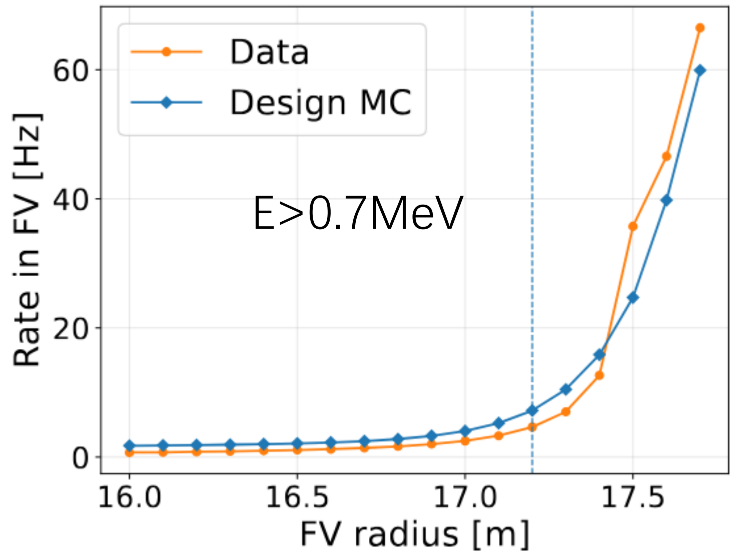
- For reactor neutrinos: (r < 17.2m & E > 0.7MeV)
  - ⇨ Clearly see the steel structure: acrylic surface background from dust is limited ➔ washing is effective
  - ⇨ Single event rate: < 6 Hz (design 7.2 Hz)
  - ⇨ Background simulation includes LS, PMTs, steel structure, acrylic and water (including Rn) ➔ Good agreement with data
- Current radioactivity levels in LS (new, preliminary):

| Fiducial volume | $^{238}U$ [$10^{-17}$ g/g] | $^{232}Th$ [$10^{-17}$ g/g] | $^{210}Po$ [$10^4$ cpd/kt] Present (Aug.30) |
|---|---|---|---|
| r < 16.5 m (hot spot at top chimney removed) | 3.63±0.07 | 2.2±0.2 | 1.96±0.14 |

Backgrounds at the top & bottom chimney are mainly from Rn
Errors are statistical and systematic combined

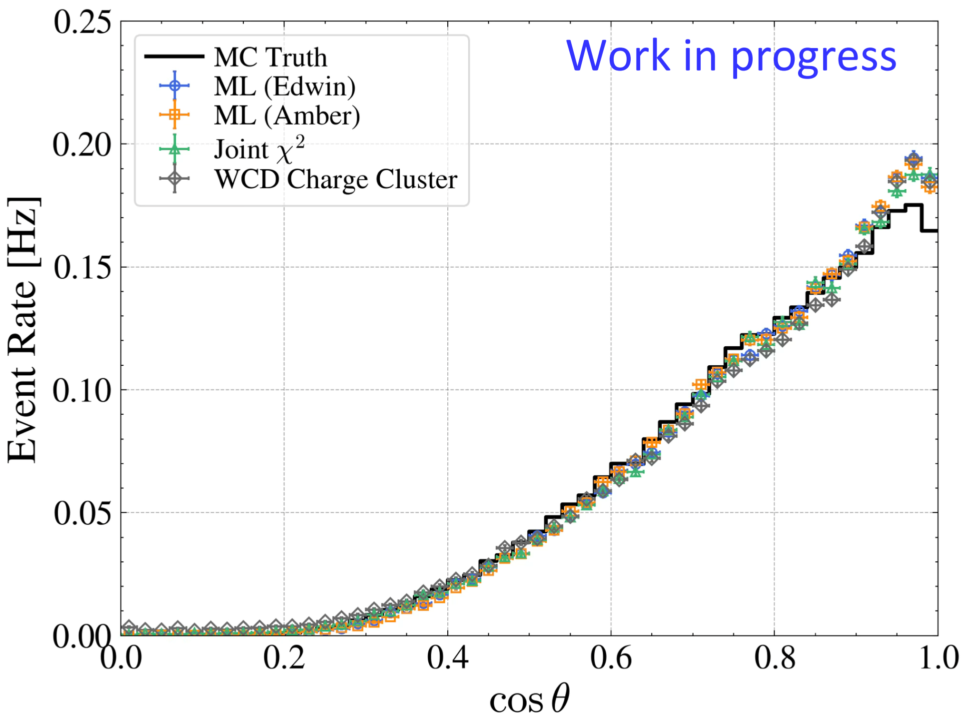


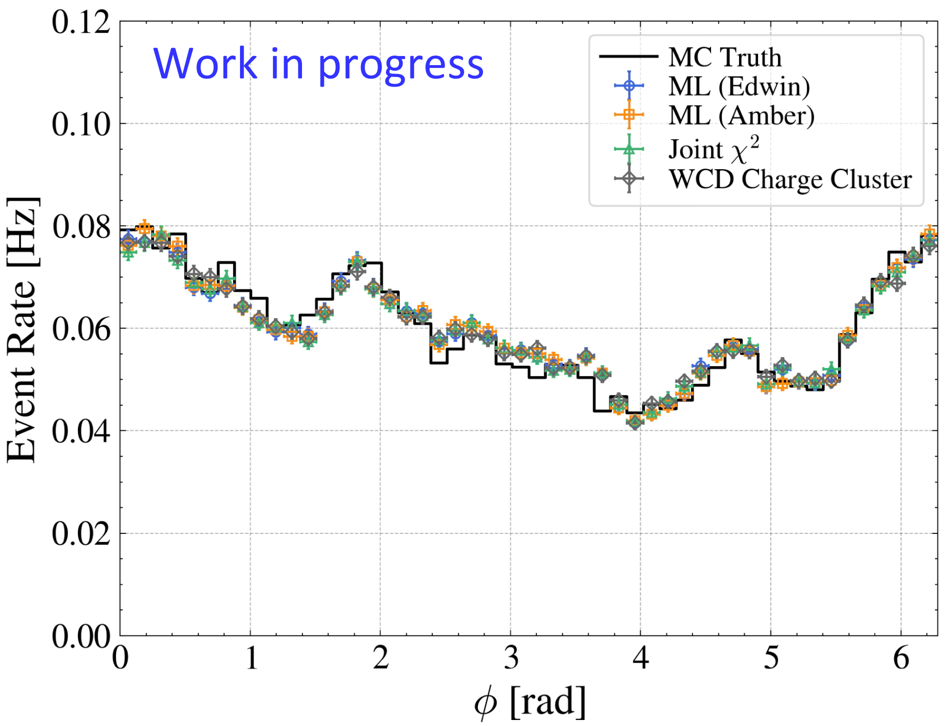

Preliminary



# Muon Events and Track Reconstruction

- Muon trigger rate in CD ~5 Hz, in Water Pool ~4 Hz
- Muon detection efficiency of CD through-going muons > 99.5%
- Two types of track reconstruction methods: traditional and data-driven ML
- Reconstructed angular distributions in good agreement with Monte Carlo simulation:
  - ⇨ Extremely important to veto muon tracks to reject cosmogenic $^{8}He/^{9}Li$ background

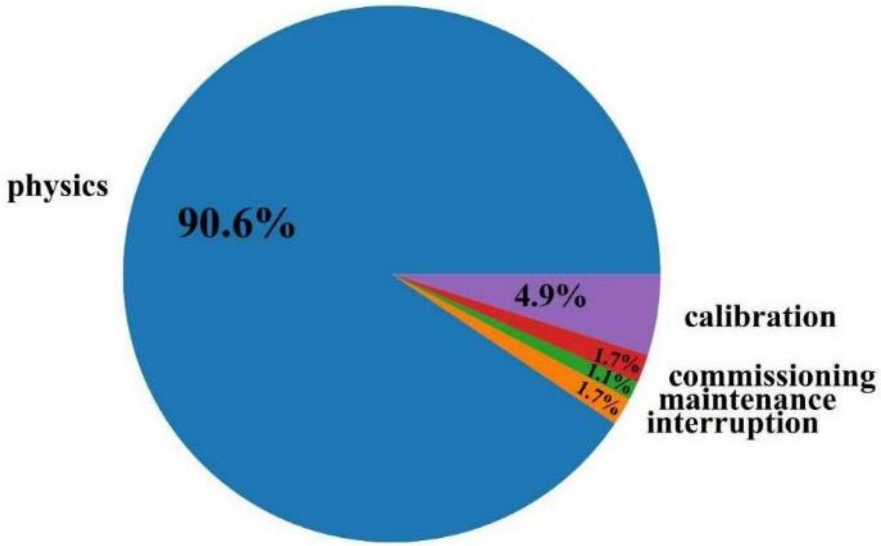


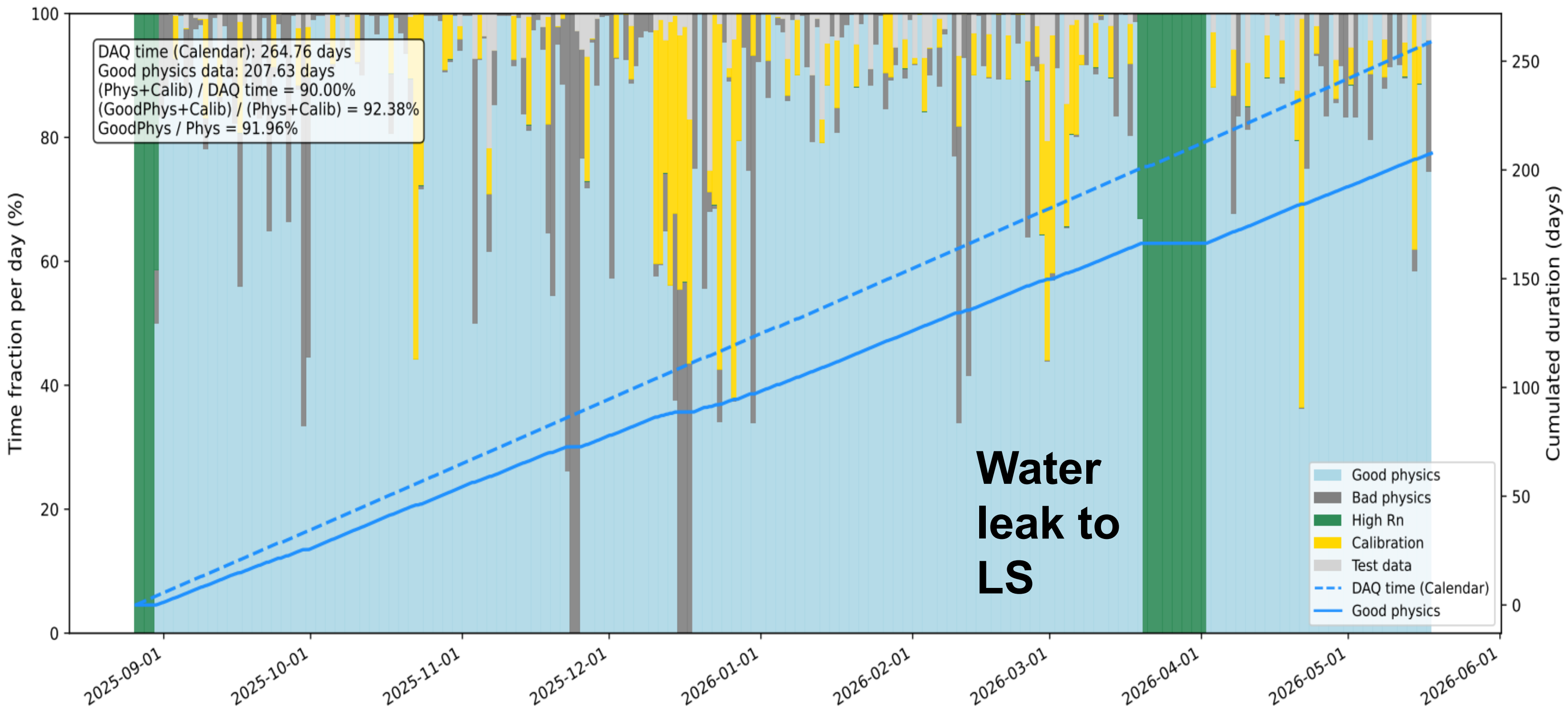




Muon's flux and energy spectrum, mountain's profile and density are well understood.

# Data Taking

- Data taking period for this analysis: 2025.08.30-2026.05.18
- Golden data are selected for physics analysis

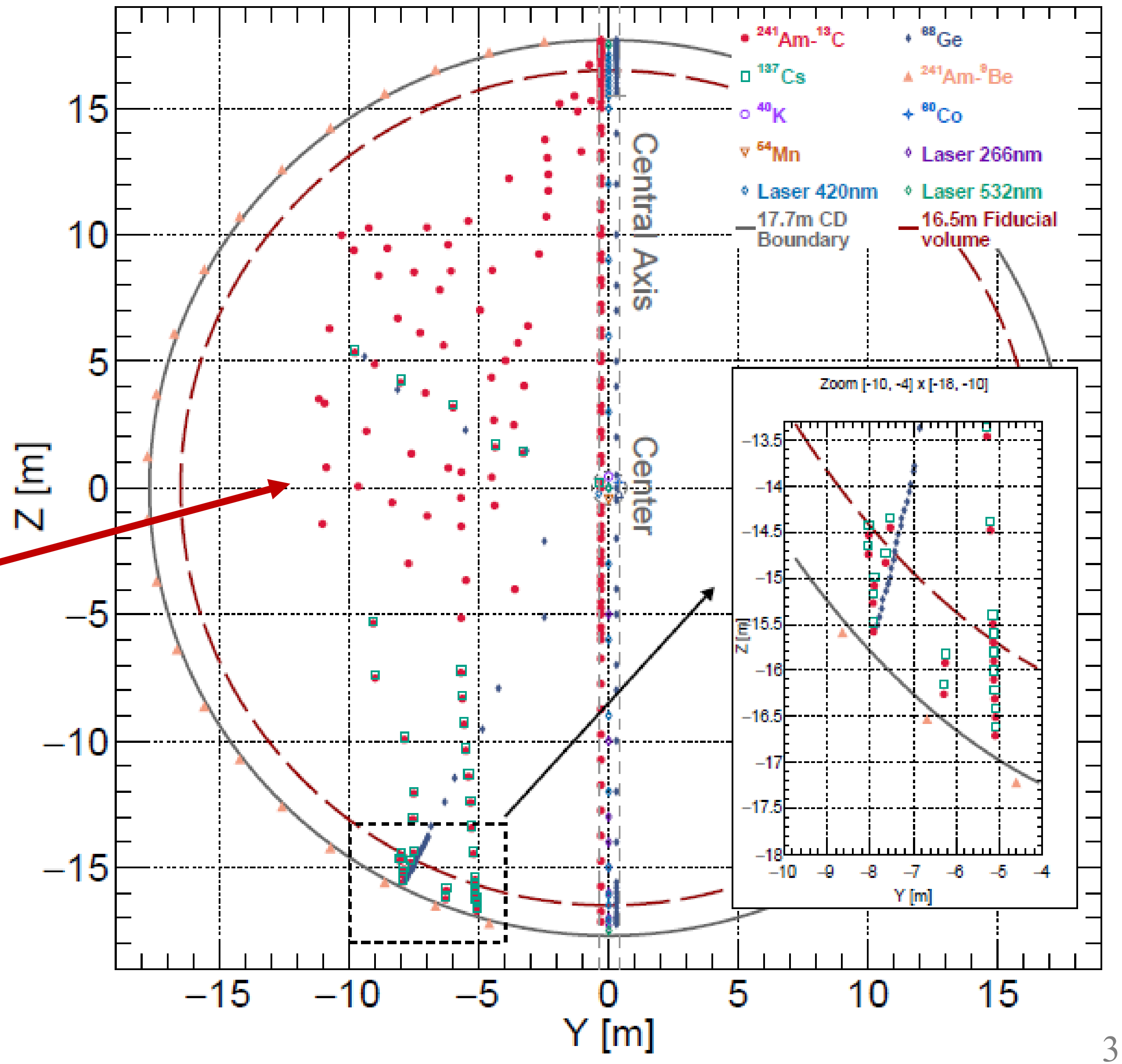



➢ Power outage due to weather is one of the main causes of interruptions

# Calibration

- 1D (central axis): $^{137}Cs$, $^{54}Mn$, $^{40}K$, $^{68}Ge$, $^{60}Co$, Am-C, Am-Be, sensors, laser
- 2D (cable loop): Am-C, $^{68}Ge$, $^{137}Cs$
- 3D using cosmogenic backgrounds:
  - ⇨ Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

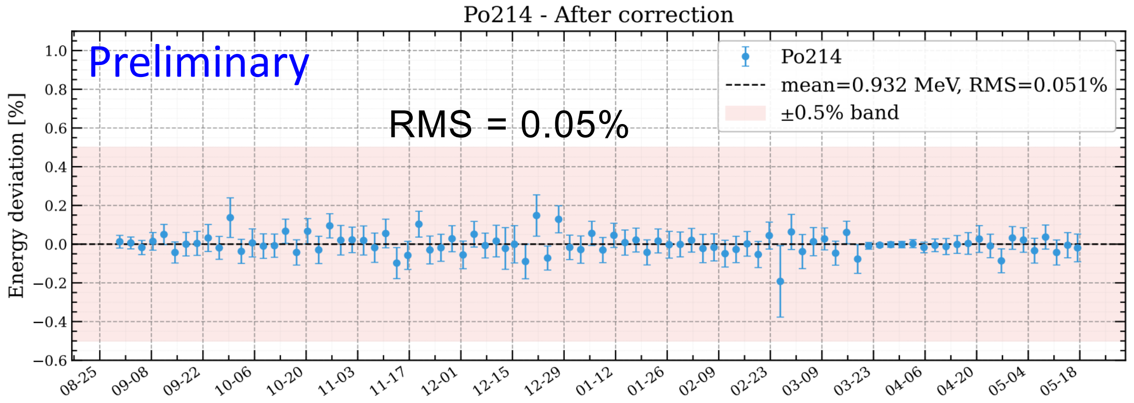


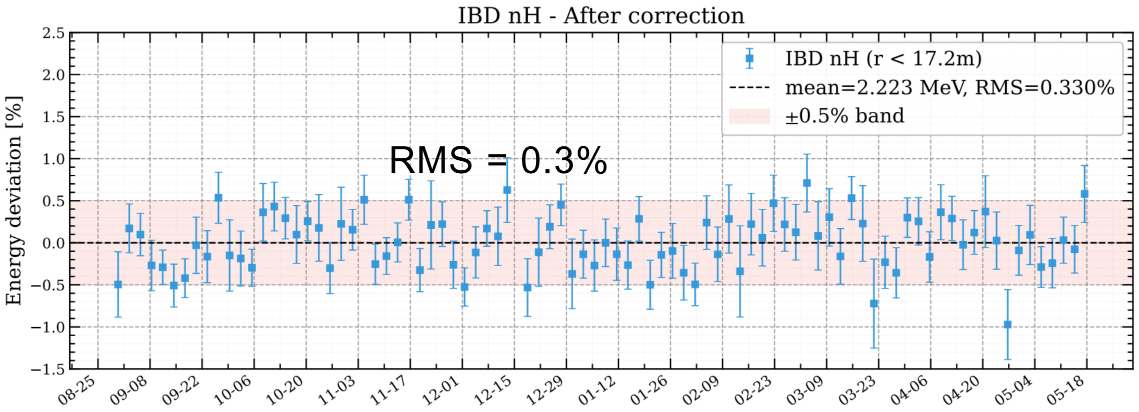

- Positions at which source calibration performed
- No $^{222}Rn$ leakage or other contaminations introduced during calibration

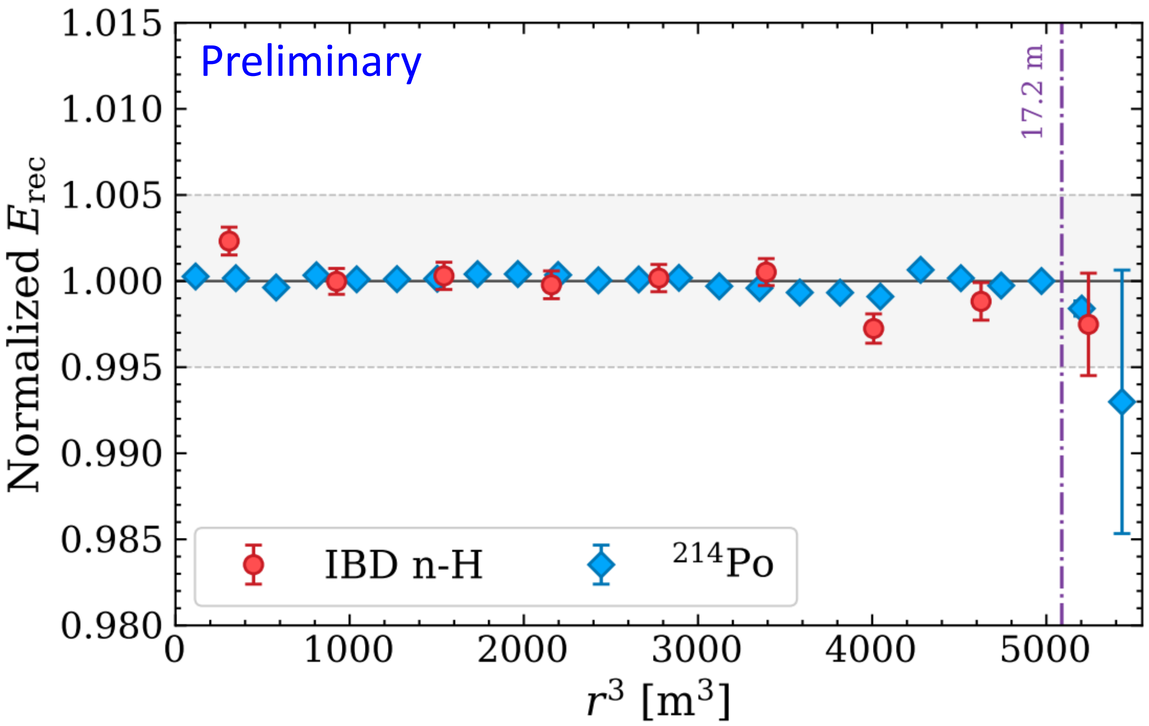
# Reconstruction and Energy Correction

- Vertex and energy are determined by maximum likelihood taking into account PMT response, geometry, optical properties, verified by calib. sources
- Other reconstruction methods give similar results
- Time dependent variations corrected by Po214 in the whole volume, check by n-H from IBD

- Residual r-θ-t dependence (~1%) further corrected by $^{214}$Po in the whole volume
- Energy scale anchored at nH from $^{9}$Li+IBD
- Final performance checked by IBD nH in r < 17.2m
  - Residual spatial non-uniformity RMS ~0.2%
  - Residual time dependent variation RMS ~0.3%



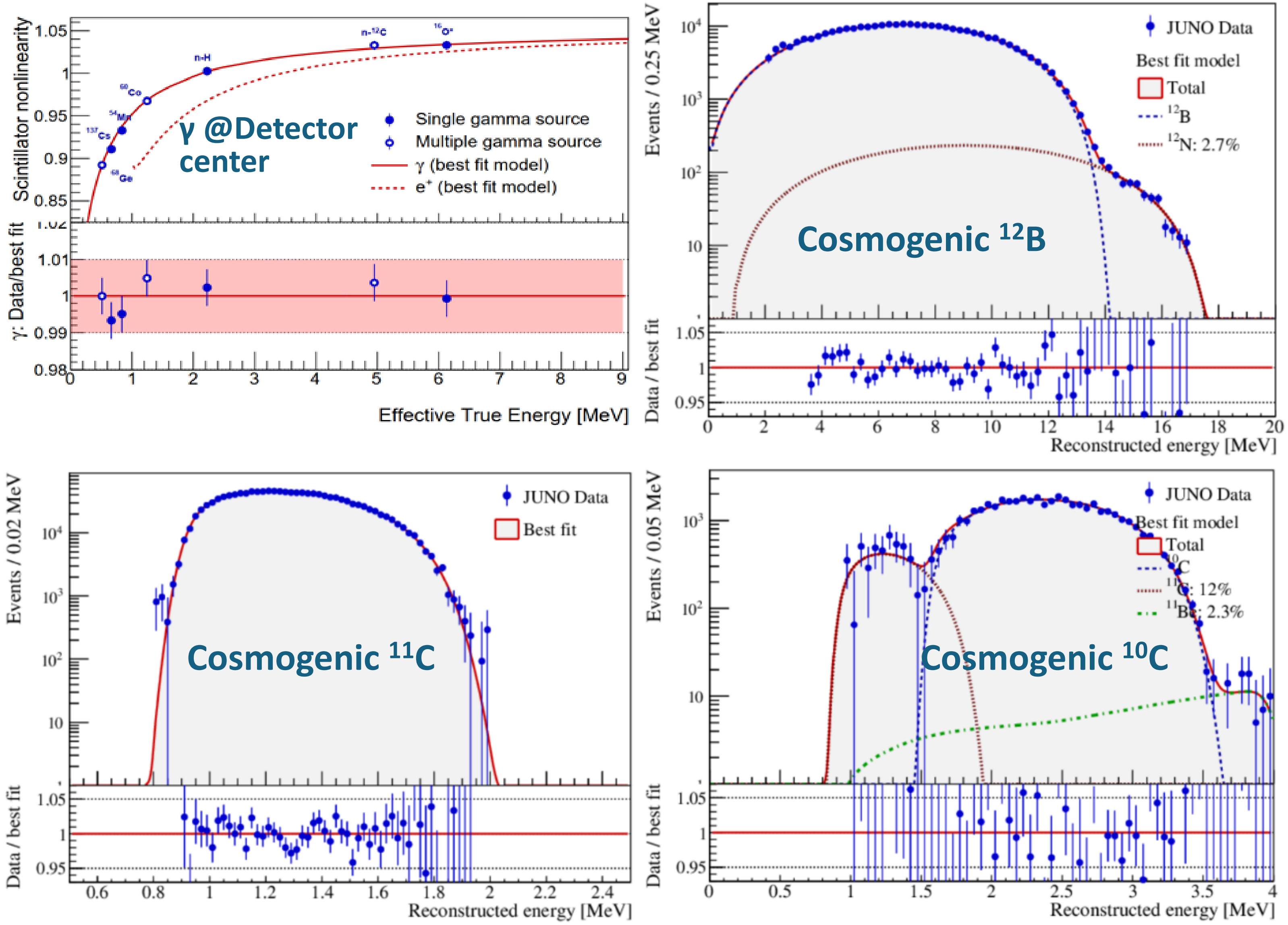



# Energy Non-linearity

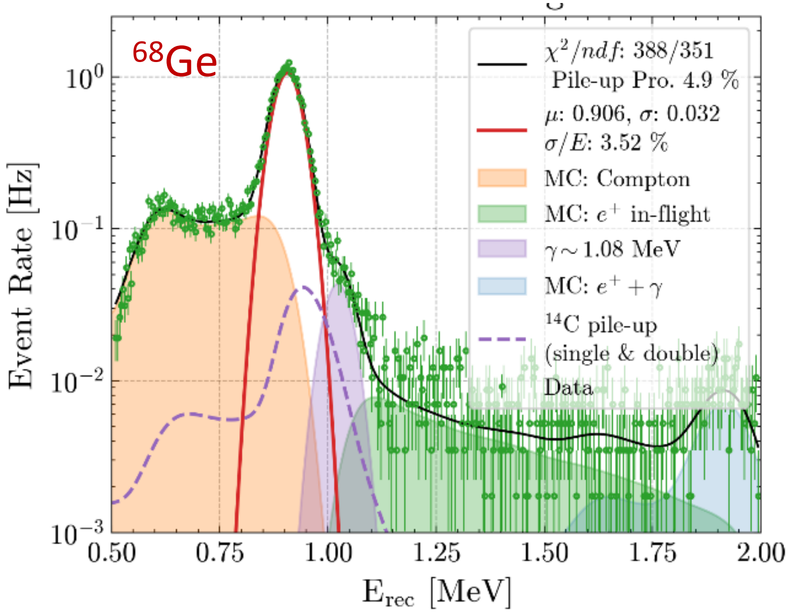
- Non-linearities of LS and electronics are determined by calibration sources at the center: $^{68}$Ge, $^{137}$Cs, $^{54}$Mn, $^{40}$K, $^{60}$Co, Am-C, and Am-Be
- The non-linearity model for $e^+$ is based on Geant4 and $\gamma$-sources
- The model is constrained by cosmogenic isotopes, $^{11}C(e^+)$, $^{10}C(e^+)$, $^{12}B(e^-)$, $^{8}Li\ (e^-)$, $^{8}B(e^+)$, $^{6}He(e^-)$, etc. in the whole volume
- Using sPMTs to correct and constrain LPMT instrumental non-linearity
- RMS ~ 0.5%, Uncertainty < 1%

Preliminary

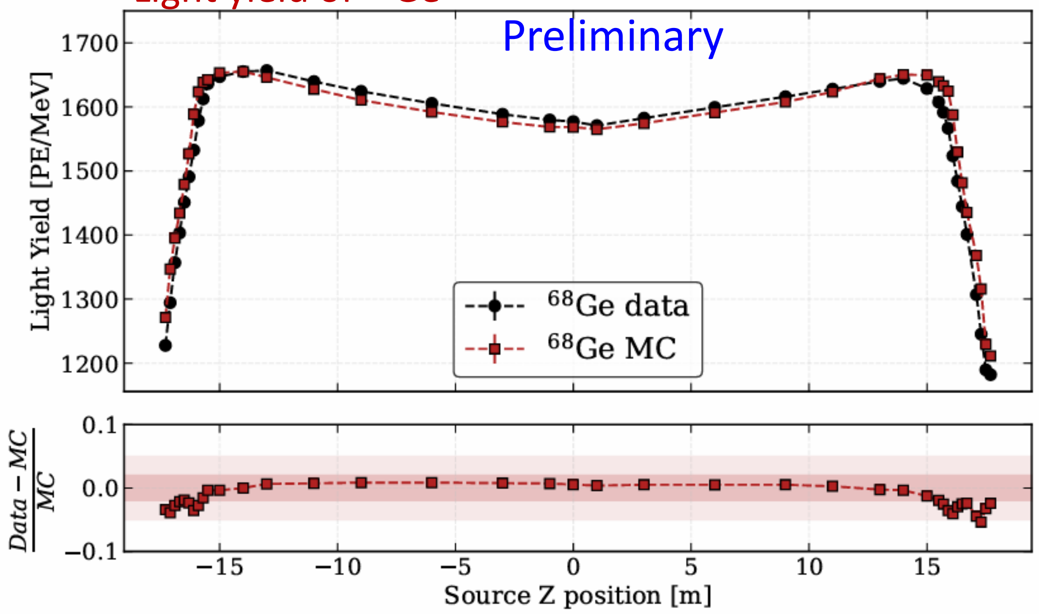


# Light Yield and Energy Resolution

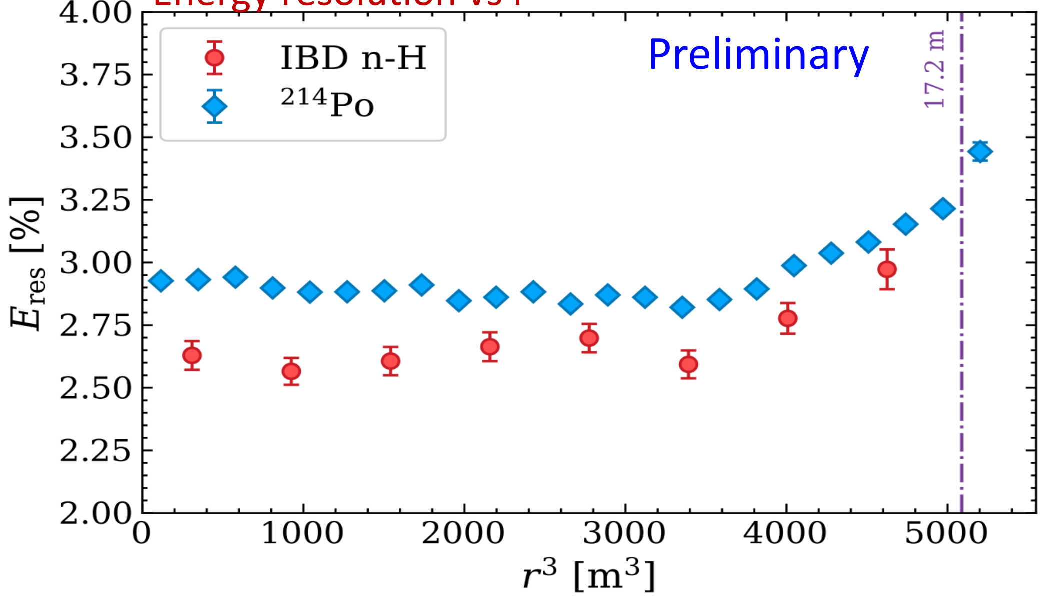
- Light yield at the detector center is ~1600 PE/MeV for $^{68}$Ge and ~1785 PE/MeV for neutrons, in good agreement with MC
- Energy resolution for $^{68}$Ge is ~3.5% @ 2× 0.511 MeV at the center, slightly worse than the expected 3.1%
  - ⇨ Better MC for Č process, optical boundaries, δ electrons, …
  - ⇨ Possible improvements: ML to remove $^{14}$C, more calibration, better reconstruction and fitting methods, …
- Energy resolution for alpha from $^{214}$Po is ~2.9% @0.93MeV




Light yield of $^{68}$Ge

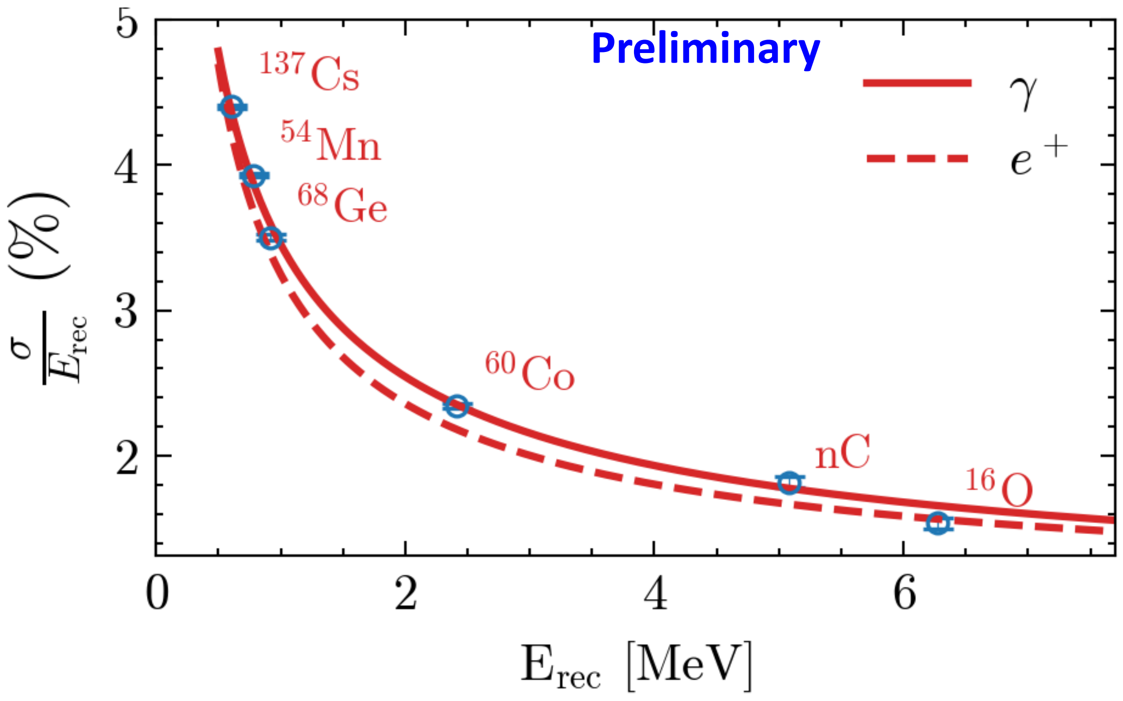


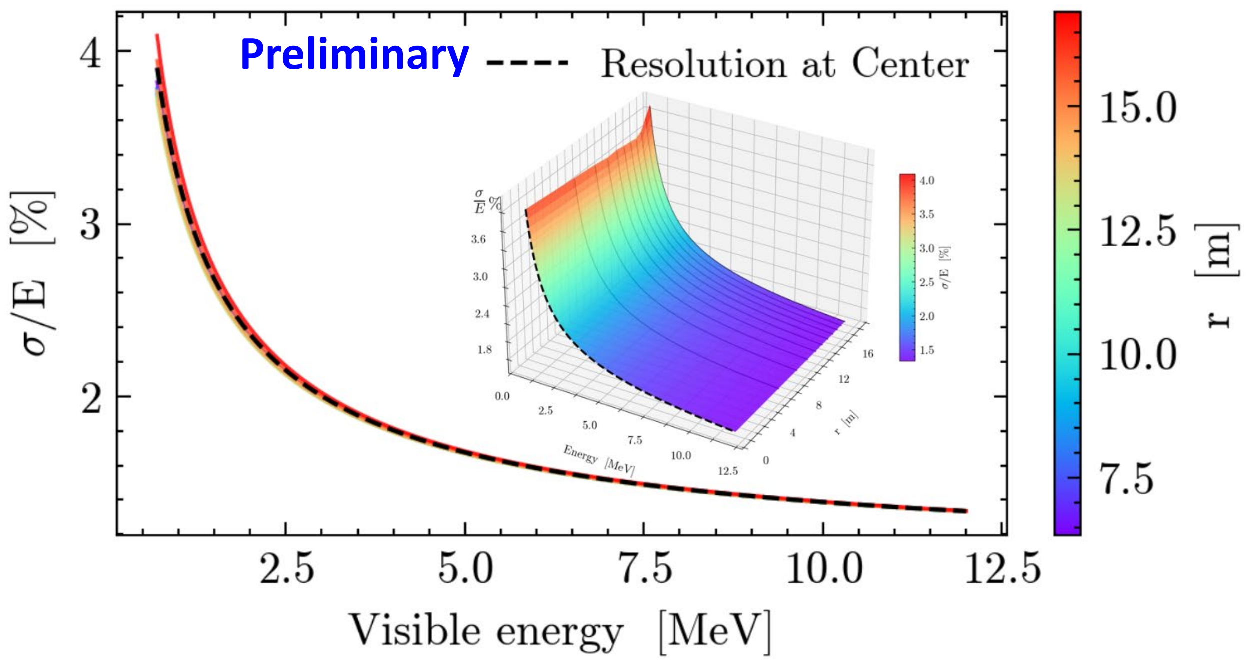

Energy resolution vs $r^3$



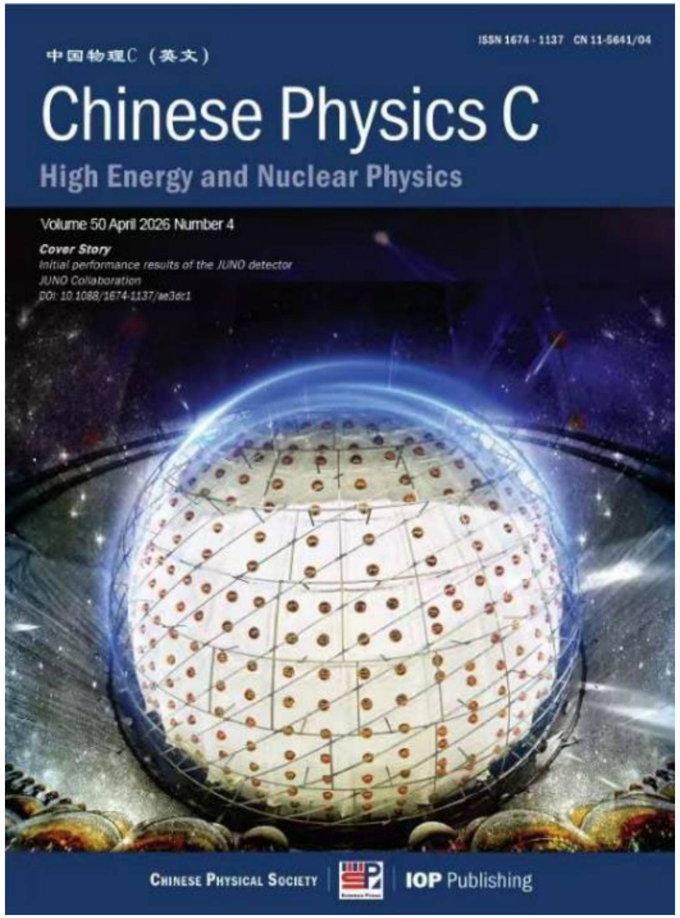
# Energy Resolution Model

- Energy resolution is particle type, energy and space dependent
- An analytical R-dependent resolution model for $e^+$ was built using Geant4 simulation and data from calibration sources ($\alpha$, $\gamma$)
- An energy response matrix was then used for $e^+$ spectrum fitting after adding $^{14}C$ pile-up to 5% events



First results using 59 days of data recently published


**New Results using 207 days of data**

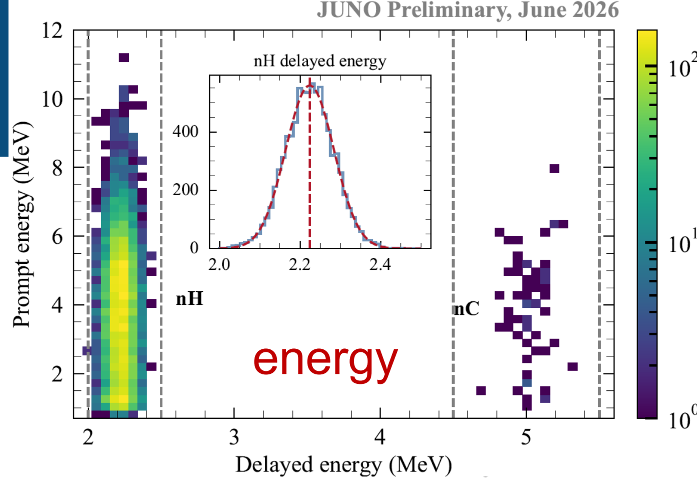
# Reactor Neutrino Selection

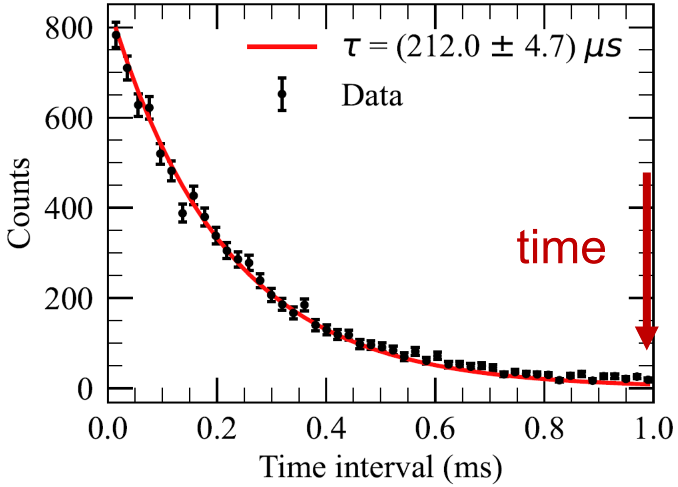
- Prompt and delayed coincidence in time, space with energy features

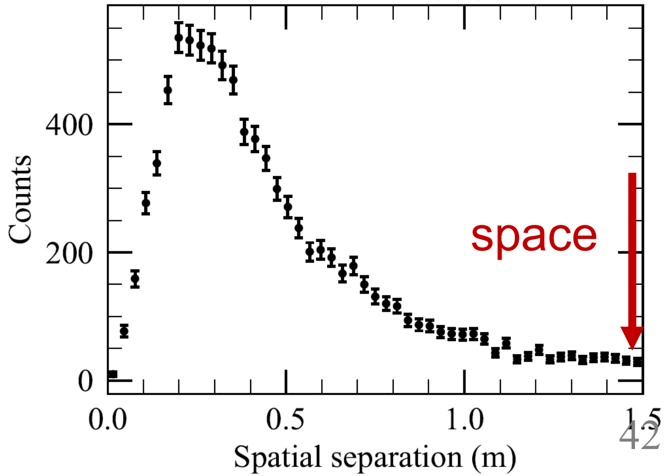
| Criterion | Selection |
|---|---|
| PMT flasher | Applied |
| Fiducial volume | $r_p < 17.2$ m, $\|z_p\|$<15.5m |
| Prompt energy | (0.7, 12) MeV |
| Delayed energy | (2.0, 2.5) ∪ (4.5, 5.5) MeV |
| Coincidence time | (5, 1000) $\mu$s |
| Relative distance | < 1.5 m |
| Multiplicity cut | No other events > 0.7 MeV in the FV or (2.0, 6.0) MeV outside the FV within 2 ms before and 1 ms after the delayed event |
| Water pool muon veto | Veto if the delayed is within (0, 2) ms after NPE > 700 in WP |
| CD muon veto | Veto if the delayed is within (0, 5) ms after NPE > $3 \times 10^4$ in CD |
| Spallation neutron veto | Veto if the delayed satisfies $\Delta r$ < 4 m and $\Delta t$ < 1.2 s after spallation neutrons with $NPE_{spn} \in$ (3000, 30000) and $T_{spn2\mu} \in$ (20, 2000) $\mu$s |
| Muon track veto | Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5\text{m}} + \frac{\Delta t_{\mu d}}{0.5\text{s}} < 1$ |
| Correlated discriminator | log(L.R.) > -1.26 |

Similar to our "Nature" paper

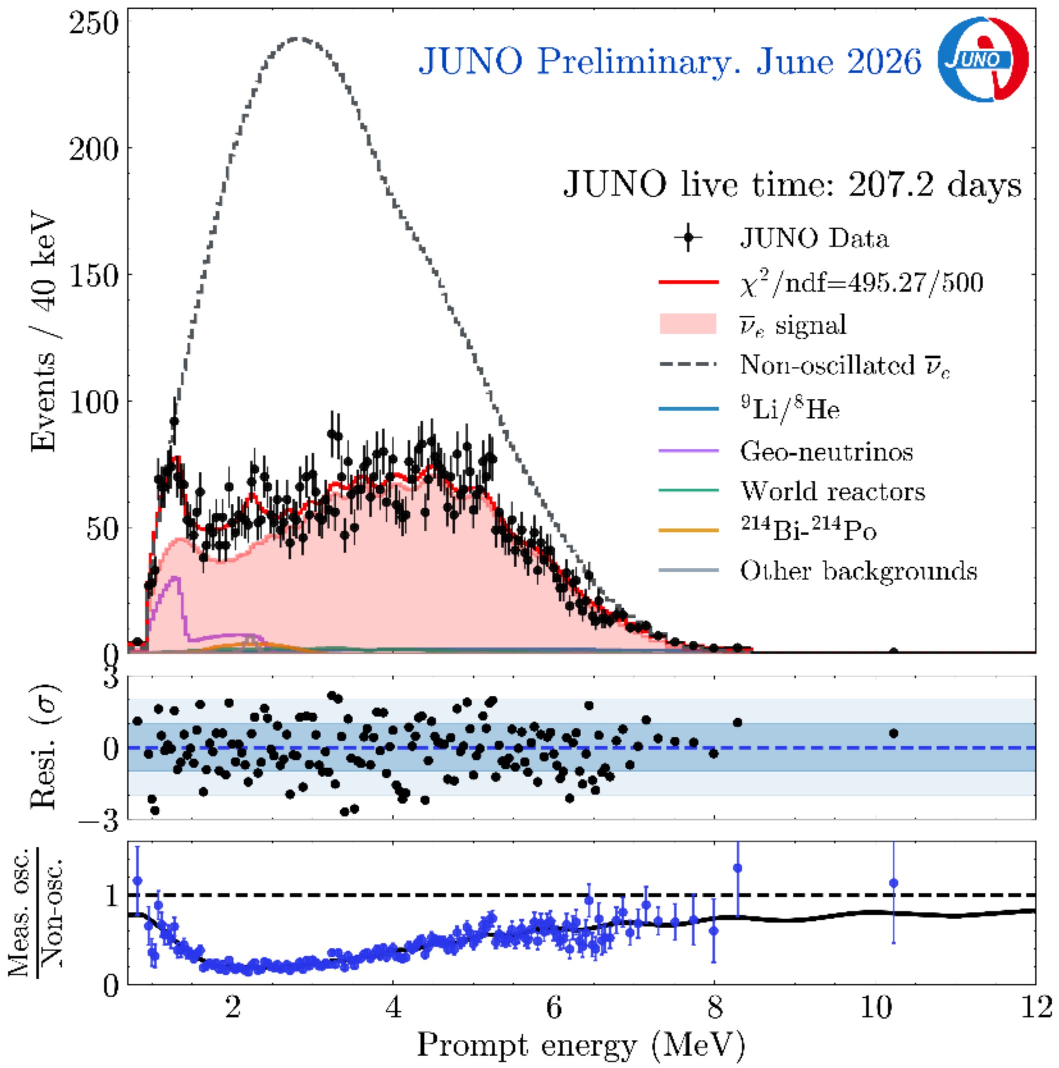
- What is new in this analysis:
  - ~10% more fiducial volume (R=16.5m➔17.2m)
  - a factor of 50 reduction of accidental bkg. using likelihood cut
  - ~60% reduction of $^{9}$Li bkg.
  - model independent estimate of the $^{214}$Bi bkg.



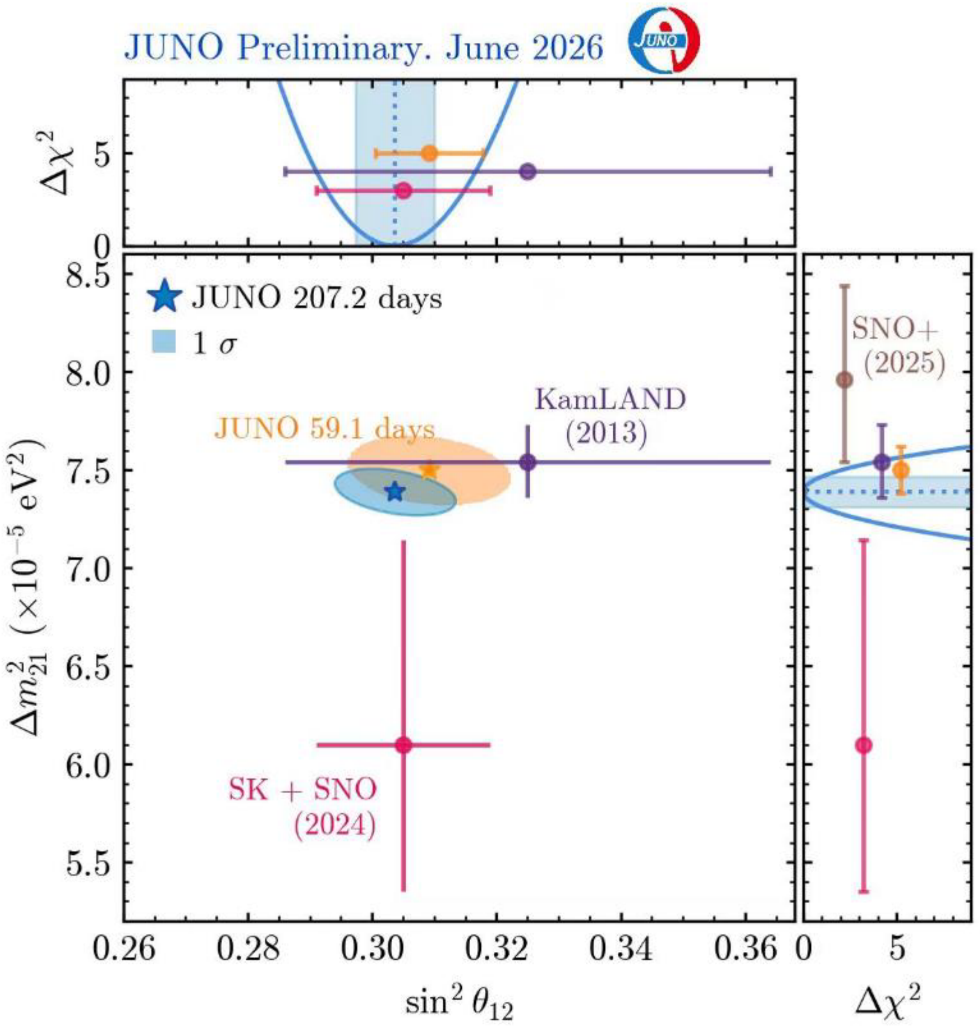



# Energy Spectrum and Solar Parameters




**Fitting constrained by the near detector spectra from TAO and Daya Bay** (PRL 130 16, 161802)

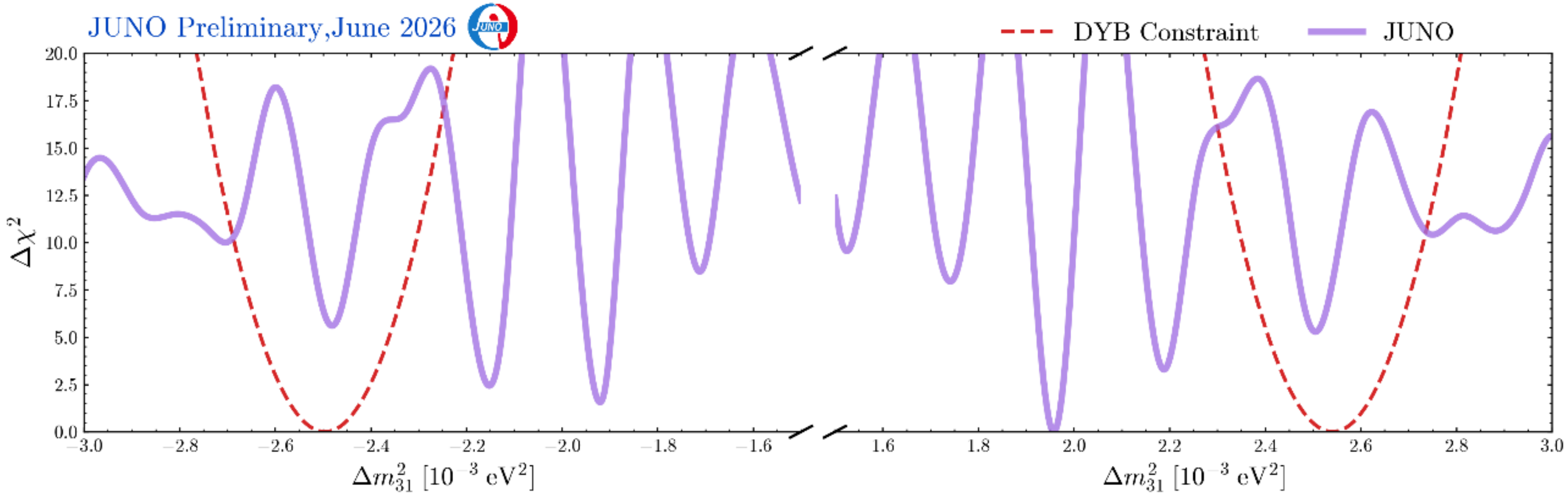



| | |
|---|---|
| $\Delta m^2_{21}$ | 7.388±0.078 (1.60% → 1.06%) |
| $\sin^2\theta_{12}$ | 0.3036±0.0064 (2.8%→2.1%) |

**Consistent results from three independent analyses**

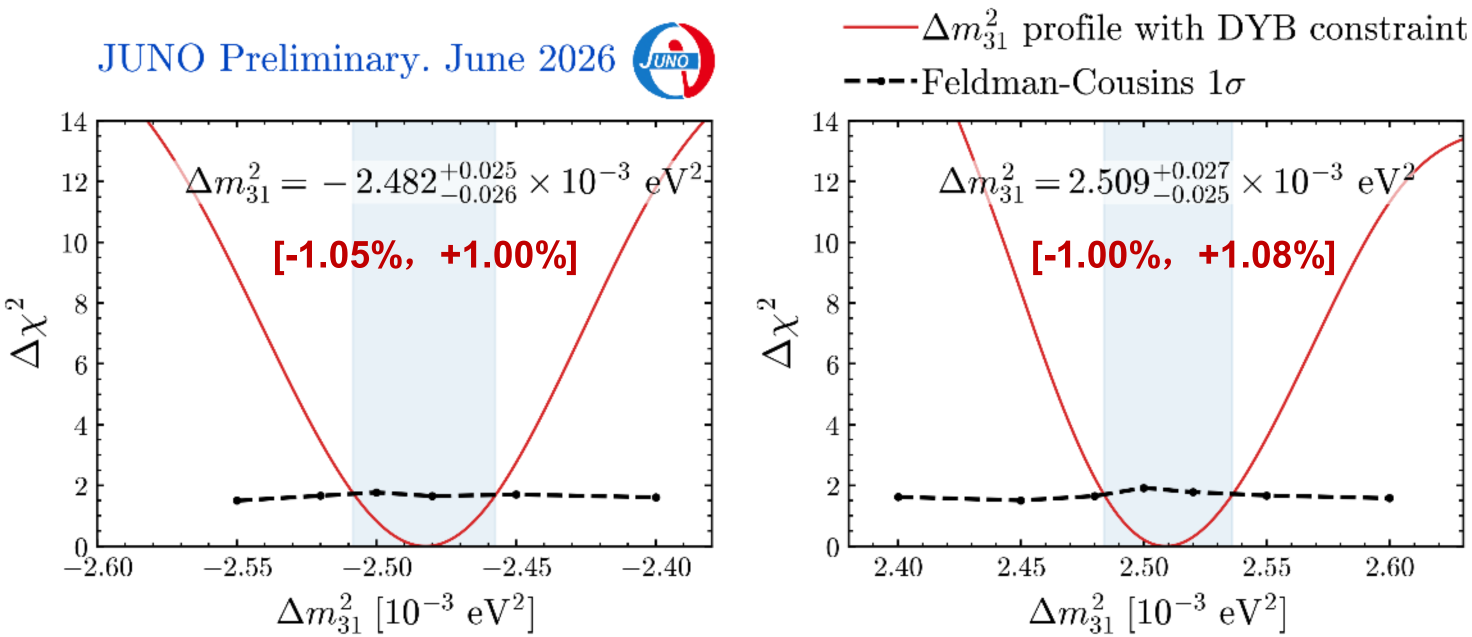
# First Result of $\Delta m^2_{31}$

- Due to statistical fluctuations, JUNO only profiles of $\Delta m^2_{31}$ have multiple minima



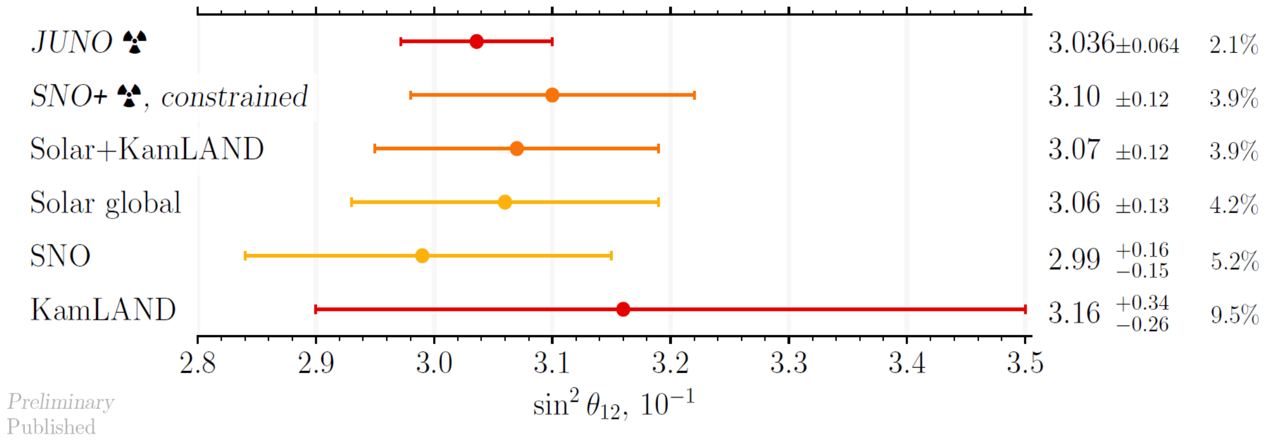

The final minimum for each mass ordering is obtained by using the $\Delta m^2_{31}$ constraint from the Daya Bay result (PRL 130 16, 161802)

Feldman-Cousins (FC) method is used to determine the 1σ range of $\Delta m^2_{31}$: ~1% precision achieved

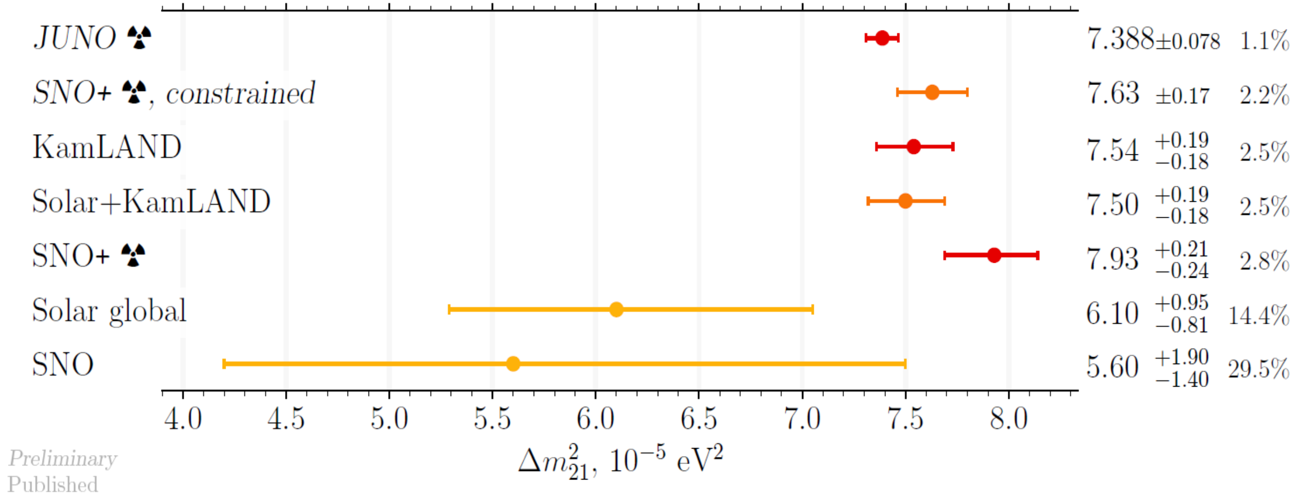


# Comparison of Results on Oscillation Parameters

## $\sin^2 2\theta_{12}$

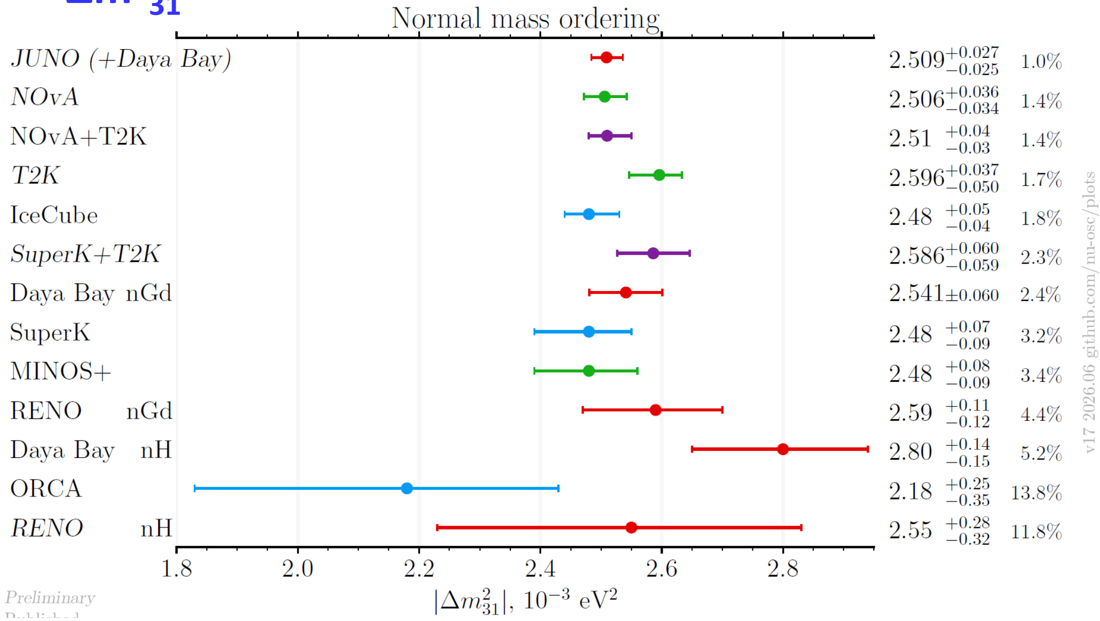


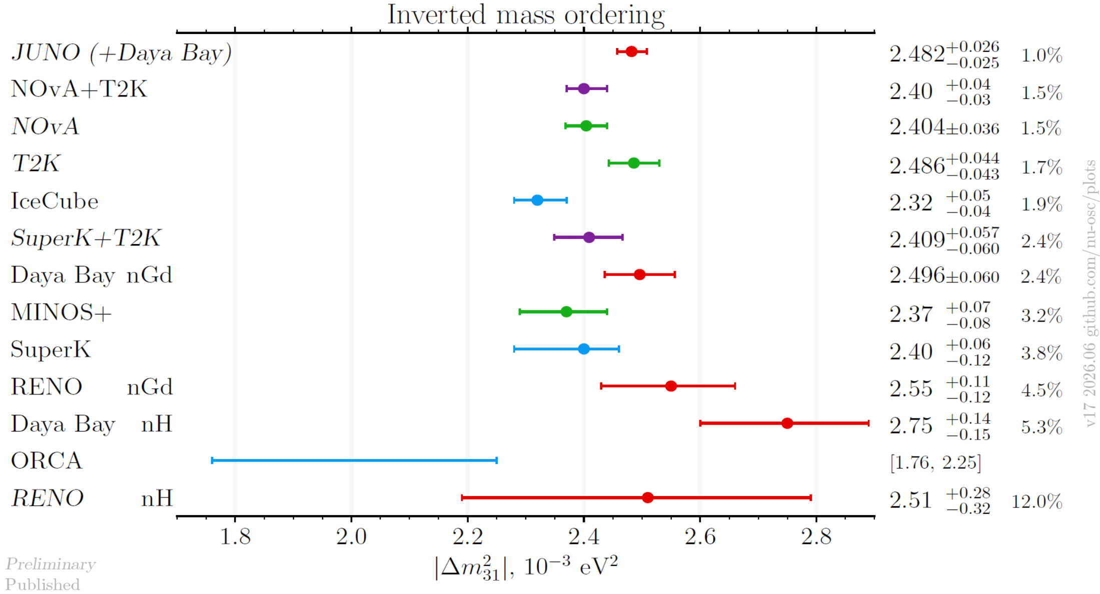

## $\Delta m^2_{21}$




**Results from JUNO have smallest uncertainties**

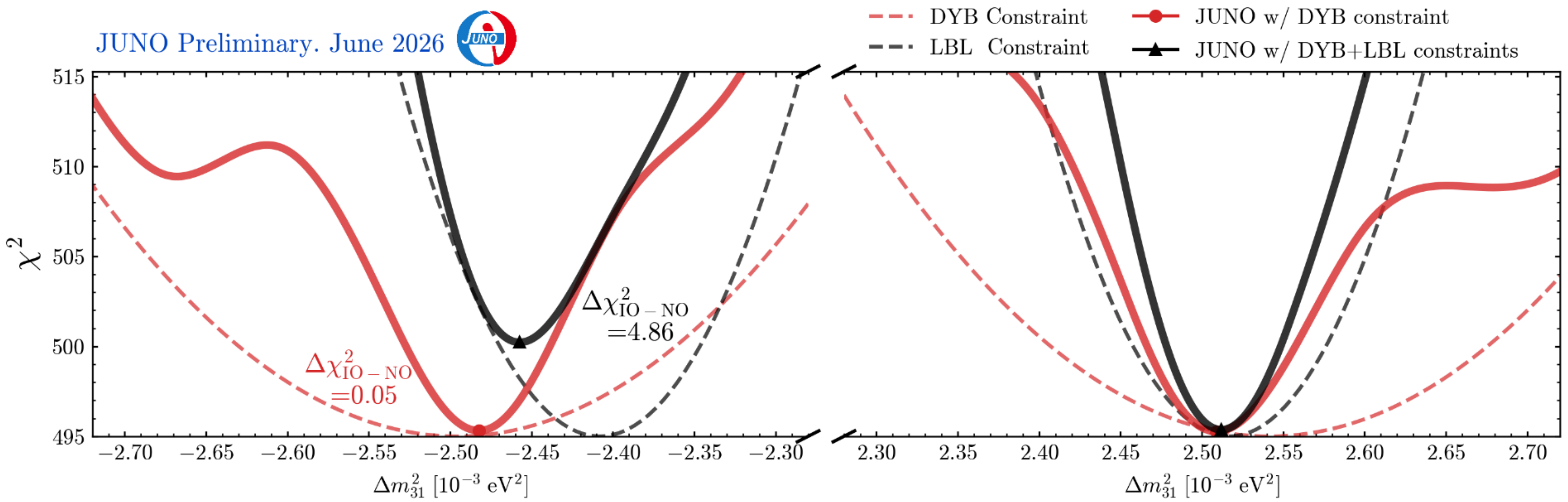
## $\Delta m^2_{31}$



# Adding Constraint from NuFit-LBL

- $\Delta m^2_{31}$ from reactor and accelerator neutrinos should align at the right mass ordering[1]
- Adopt the NuFit-LBL results from [2]: normal mass ordering is favored at $\Delta\chi^2 = 4.86$

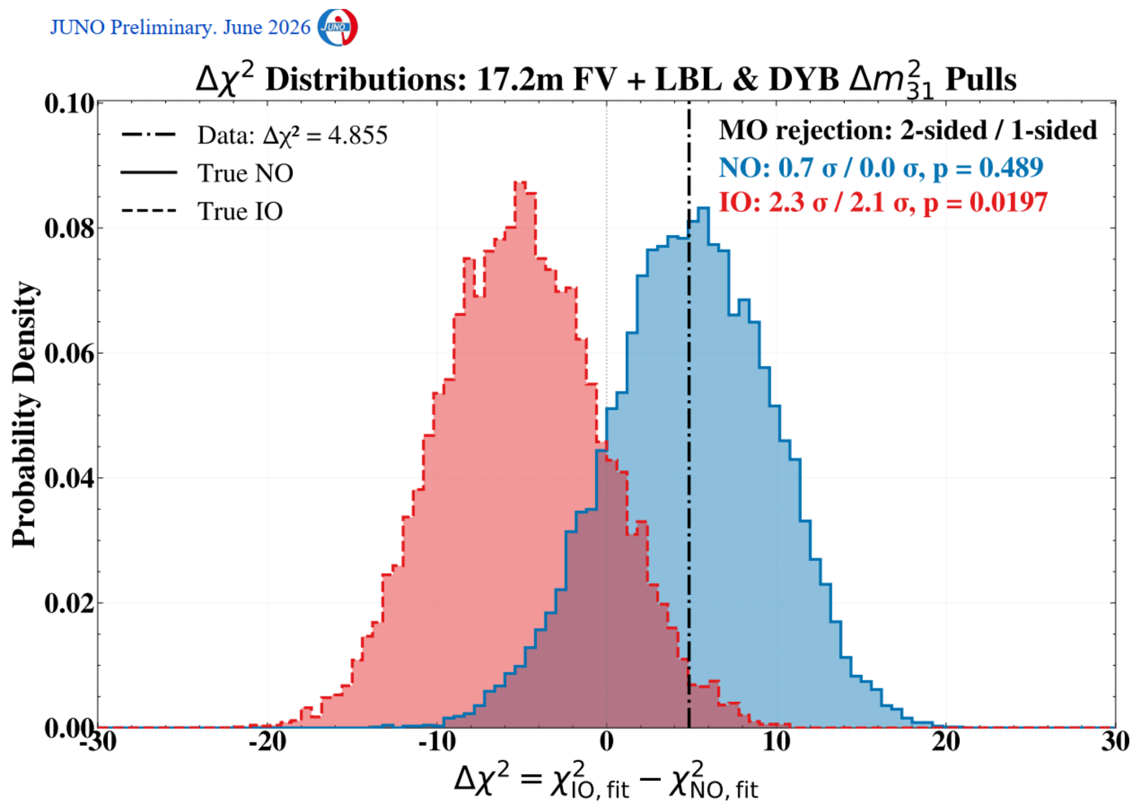




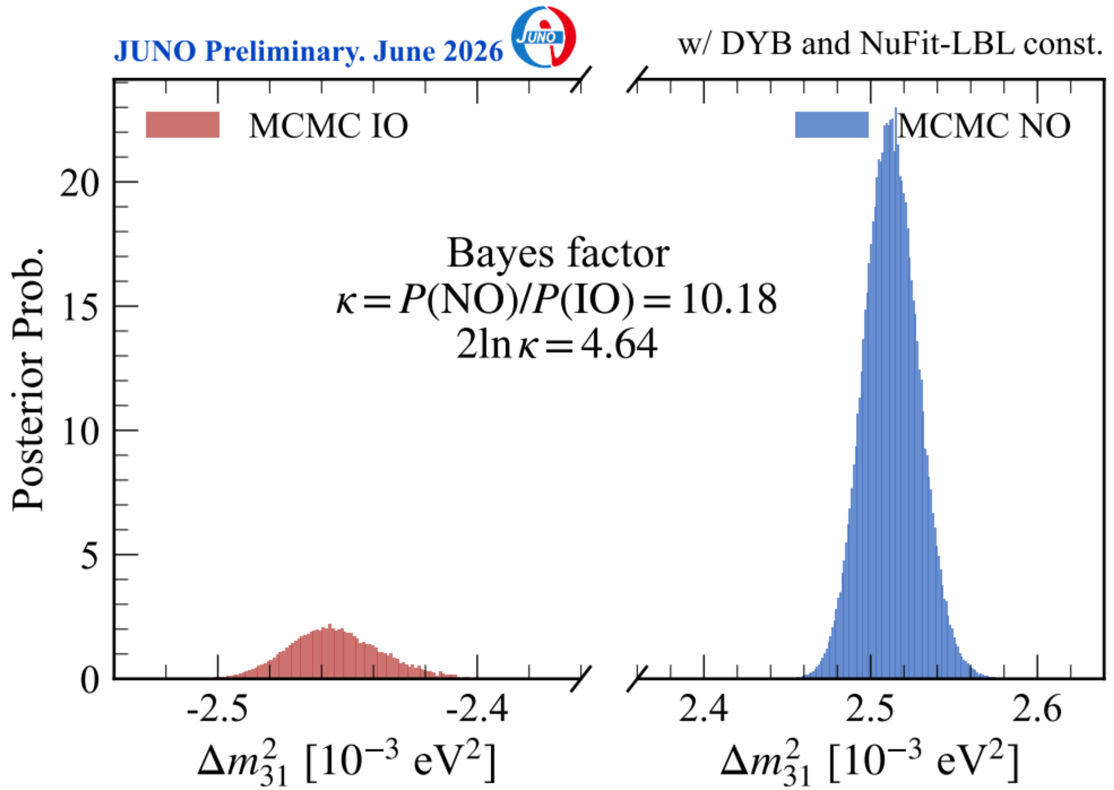
[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

# Neutrino Mass Ordering Significance

- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
- Influence of $\delta_{CP}$ considered (scanned)
- Normal Ordering is favored at **2.3σ**

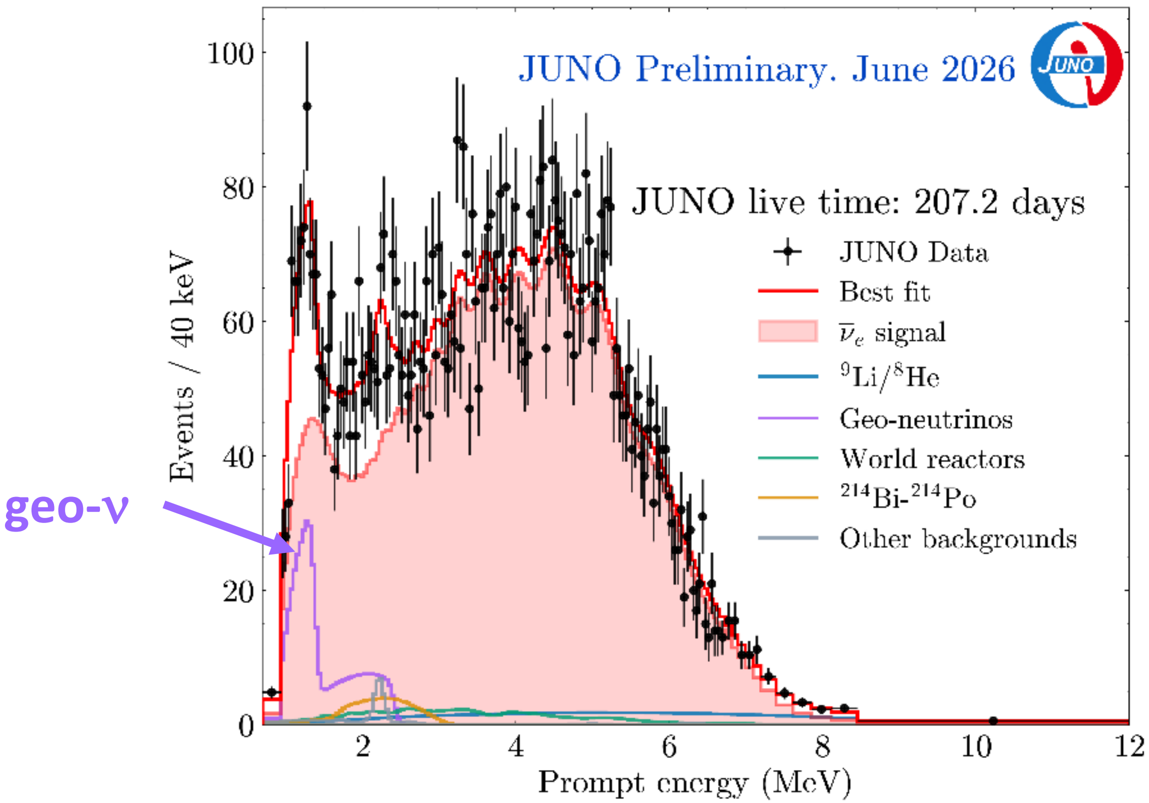


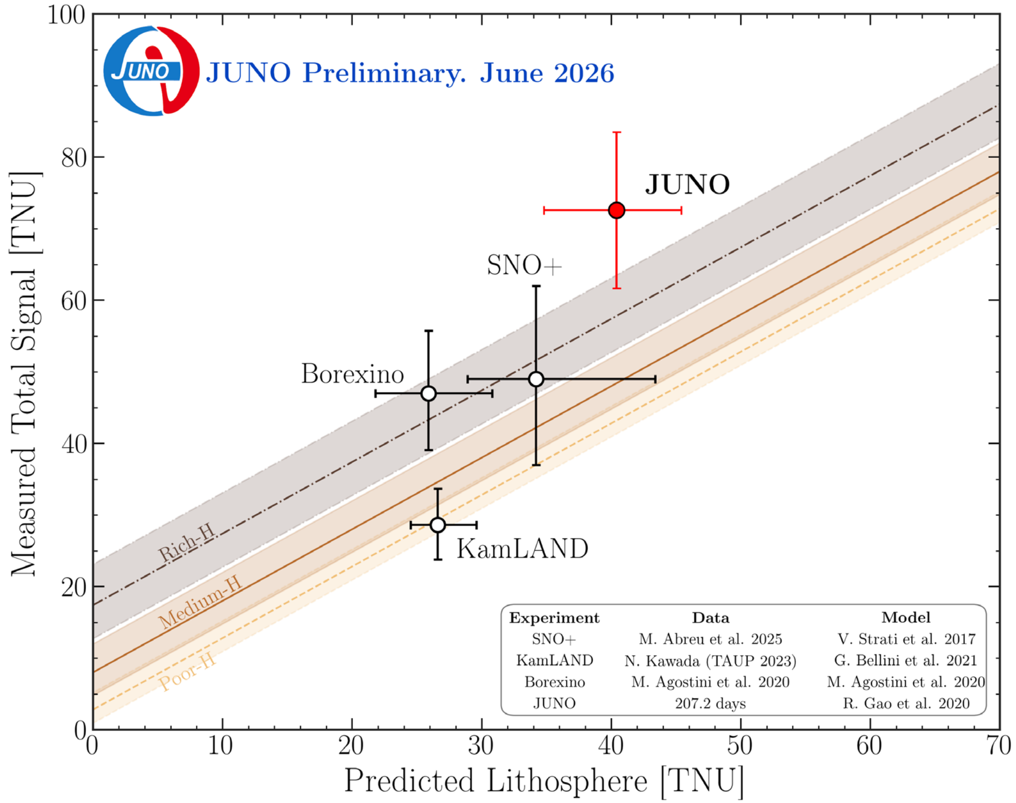

- Bayesian approach using Markov Chain Monte Carlo(MCMC) method
- Normal Ordering is favored with a Bayes factor of **10.18** ➔ 2ln κ= 4.64
  - ⇨ Consistent with the frequentist $\Delta\chi^2$



# New Results on Geo-neutrinos

- Fits are performed without constraint on geo-neutrino flux, but with 3.4±10% U/Th ratio
  - ⇨ Constraining the geo-nu flux doesn't change oscillation results
- Clear geo-nu signals at 1-3 MeV, giving a flux of 73 ± 11 TNU
  - ⇨ Largest geo-neutrino samples so far, and most precise measurement
- JUNO result is higher than expectation from existing models, but not statistically significant
- Need more JUNO data and more refined geological model predictions

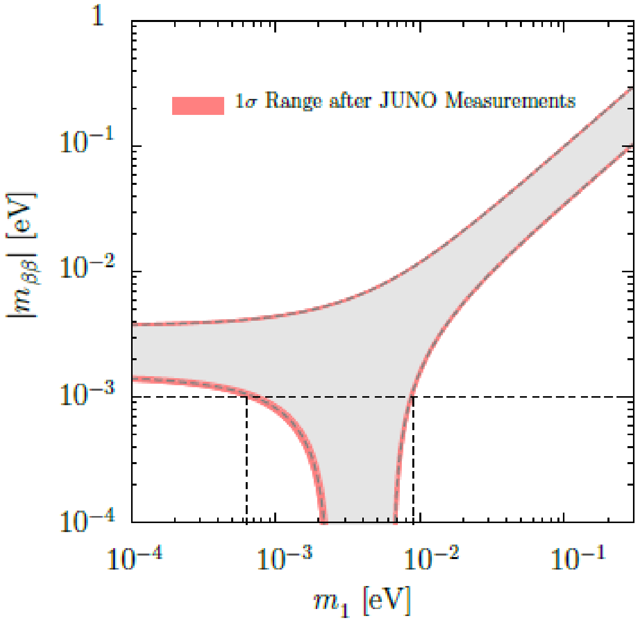



| Experiment | Data | Model |
|---|---|---|
| SNO+ | M. Abreu et al. 2025 | V. Strati et al. 2017 |
| KamLAND | N. Kawada (TAUP 2023) | G. Bellini et al. 2021 |
| Borexino | M. Agostini et al. 2020 | M. Agostini et al. 2020 |
| JUNO | 207.2 days | R. Gao et al. 2020 |

# Future of Neutrino Physics

- In 5 years from now, Nova+T2K/SuperK +ORCA/Icecube +JUNO will determine the mass hierarchy
- In 10 years from now, DUNE+HyperK will determine the CP phase
- 0νββ decay will be the next breakthrough



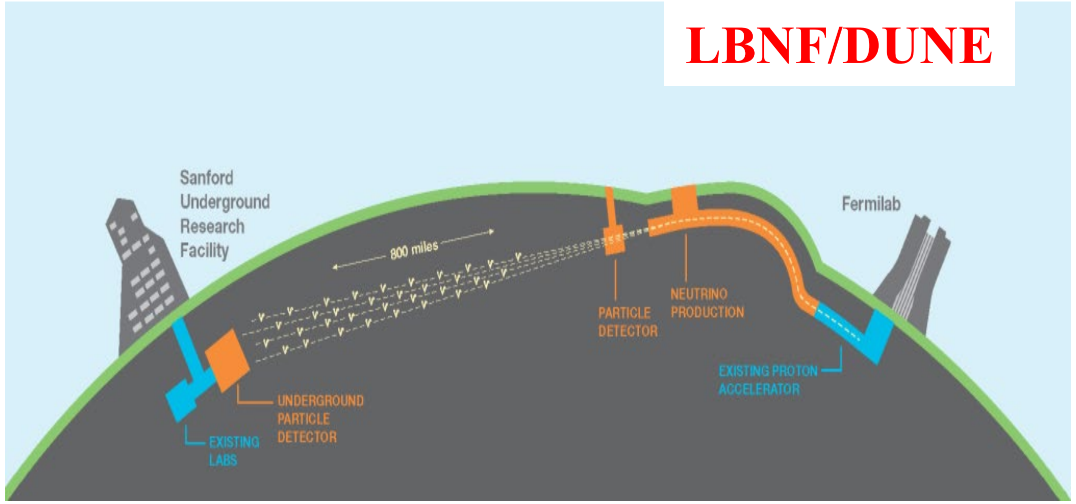

J. Cao et al., arXiv:1908.08355

- Hints from cosmology: < ~1 eV
- Guess from Oscillation: ~1 meV
- Katrin will probe to ~ 0.2 eV

$$(m_{\nu_e})^{eff} = [\Sigma_i \, |U_{ei}|^2 \, m^2_{\nu_i}]^{1/2}$$

- 0ν ββ decay should target for ~ 1meV

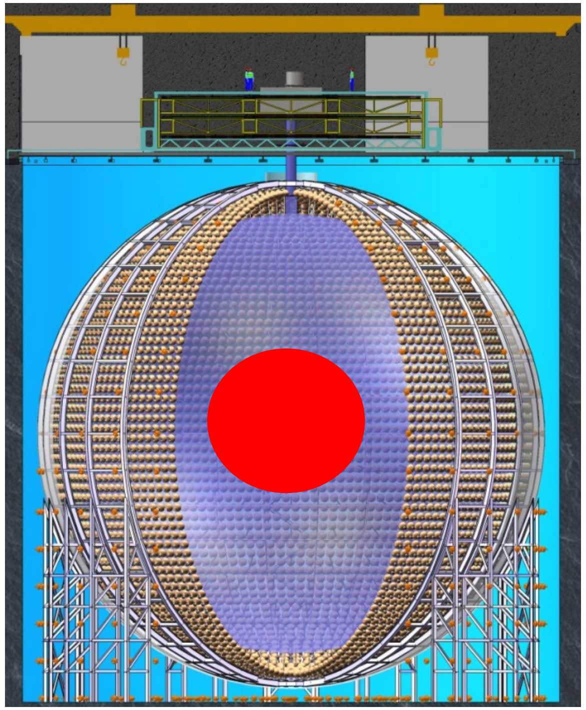
$$|M_{\beta\beta}| = |\Sigma_i \, (U_{ei})^2 \, m_{\nu_i}|$$



# JUNO-ββ

- Once mass ordering is determined (~2030), JUNO will be upgraded for ββ-decays, in addition to existing capabilities
- Cosmogenic backgrounds can be removed by a cut of LS volume along the muon track for seconds

| | Isotope | Mass(t) | $<m_{\beta\beta}>$,meV |
|---|---|---|---|
| SNO+ | $^{130}$Te | 8 | 19-46 |
| KamLAND2-Zen | $^{136}$Xe | 1 | ~20 |
| NEXT-HD | $^{136}$Xe | 1 | 14-40 |
| nEXO | $^{136}$Xe | 5 | 7-22 |
| Darwin/Panda-nT | $^{136}$Xe | 3-5 | 7-22 |
| LEGEND-1000/CDEX-1t | $^{76}$Ge | 1 | 10-40 |
| AMoRE-II | $^{100}$Mo | 0.1 | 12-22 |
| CUPID | $^{100}$Mo | 0.24 | 12-20 |
| CUPID-1T | $^{100}$Mo | 1 | 4-7 |
| JUNO-ββ | $^{136}$Xe | 50 | 4-10 |
| | $^{130}$Te | 100 | 3-14 |



**Insert a balloon filled with $^{136}$Xe-loaded LS(or $^{130}$Te) into the JUNO detector**

Zhao et al., arXiv: 1610.07143, CPC 41（2017）5

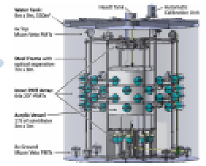
# Latest R&D for LS

- Xe Loading (~ 3%) seems easy, but expensive and balloon seems needed
- Te loading seems cheap but difficult, R&D status at IHEP:
  - ⇨ Backgrounds, in particular cosmogenic ones are still a challenge

| | |
| --- | --- |
| Te-doping concentration: 3~5% Te | Achieved |
| Minimum impact on LS transparency | 1%Te-LAB: A.L.= **20.1** ±1.1 m |
| Minimum impact on LS light yield | **80%** for 0.5%Te-LS, **66%** for 1%Te-LS |
| Ultra-low radio background, $10^{-16}$ - $10^{-17}$ | Highly challenging, continued research |
| High-quality retention >10 years | Spectral stability > 3 years (0.6% Te) to dates |

*NIM A 1049 (2023) 168111*
*NIM A 1088 (2026) 171531*

**Lab-scale preparation** → **100-kg production** → We're here. → **Near Future** **OSIRIS-20t**



# Summary

- Neutrinos are mysterious, interesting and full of treasure
- Daya Bay is a good start for IHEP/China
- JUNO will bring us more: mass ordering, diffused supernova neutrinos, unitarity of mixing matrix, and if we are lucky, a supernova explosion
- JUNO-$\beta\beta$ is very promising for the future: $0\nu\beta\beta$, neutrino absolute mass
- International collaboration is greatly helpful !