

Neutrino Experiments:

A journey from discovery to precision

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The 19th PPC @ UNSW, Sydney, Australia, Aug 31-Sep 4, 2026



- 1 Open questions
- 2 The experimental landscape
- 3 Focus: the neutrino mass ordering (NMO)
- 4 Pursue of NMO by JUNO (DYB is the precursor)
- 5 Summary and outlook

NOT duplicated here

Hyper-Kamiokande — dedicated talk at 10:00
(T. Tashiro)

KM3NeT — dedicated talk at 12:00 (F. Filippini)

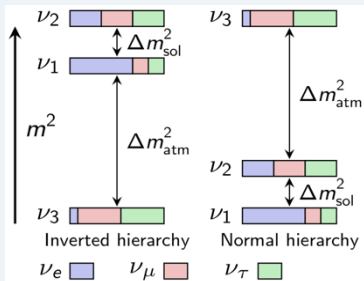
New-physics reach of JUNO / HK / DUNE —
11:00 (M. Dolan)

Astrophysical neutrinos — 11:30 (A. Suliga)

What we still do NOT know

Neutrino mass remains the only laboratory evidence for physics beyond the Standard Model

● Mass Ordering



● Leptonic CP Violation

Is $\delta_{CP} \neq 0, \pi$?
A new *CP* source beyond the CKM phase.

● θ_{23} Octant & Precision

Above or below 45° ?
Sub-percent tests of the 3ν paradigm.

● Absolute Mass Scale

Hierarchical or quasi-degenerate?
Oscillations only give Δm^2 .

● Dirac or Majorana

Is lepton number violated?
 $0\nu\beta\beta$ can answer this.

● Sterile States, Unitarity, etc

Are the short-baseline anomalies new states — or experimental issues?



The Experimental Landscape

~45 experiments appeared across Neutrino 2026 and ICHEP 2026 (Disclaimer: I might be still missing some)

Physics objective	Experiments presented in 2026
Mass ordering & 3v precision	JUNO · T2K · NOvA · MINOS+ · Super-K · KM3NeT/ORCA · IceCube/DeepCore · DUNE · Hyper-K
Leptonic CP violation	T2K · NOvA · DUNE · Hyper-K (+ ESSnuSB and beyond-DUNE/HK concepts)
Sterile ν & SBL anomalies	MicroBooNE · SBND · ICARUS · JSNS ² · DANSS · KATRIN (eV & keV scale)
Absolute mass scale	KATRIN · Project 8 · PTOLEMY · cosmology (DESI, CMB)
Majorana nature — $0\nu\beta\beta$	LEGEND-200/1000 · KamLAND-Zen · CUORE → CUPID · NEXT-100 · SNO+ · (PandaX · CDEX)
ν -nucleus cross sections	MicroBooNE · ND280/ND280++ · SBND · ANNIE · DUNE ND (ND-LAr, SAND) · nuSCOPE · FASER ν · SND@LHC · DsTau
CEvNS & ν electromagnetics	COHERENT · LZ · PandaX · XENONnT · CONNIE · NEON · SATURNE
Astrophysical & supernova ν	IceCube · KM3NeT/ARCA · Pierre Auger · radio arrays · Super-K · JUNO · SNO+

The objective, especially the mass ordering, of the first row is where the rest of this talk lives.

Why the Ordering is the Linchpin

→ *It is not just an isolated sign — it is the door/bottleneck to other programs*

A

Untangles the oscillation fit

The ordering, δ_{CP} and the θ_{23} octant are correlated in the global fit. Fixing the sign sharpens the other two immediately.

B

Sets the $0\nu\beta\beta$ target

Inverted ordering has a floor in $\langle m_{\beta\beta} \rangle$ that next generation multiton-scale detectors could potentially cover. Normal ordering has no such floor — the experimental strategy would differ.

C

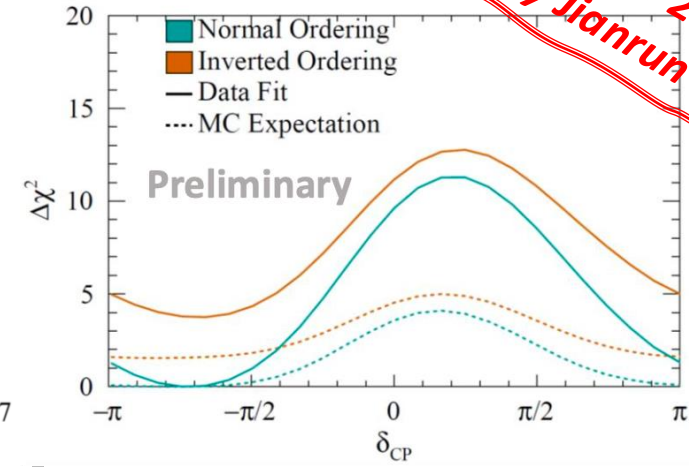
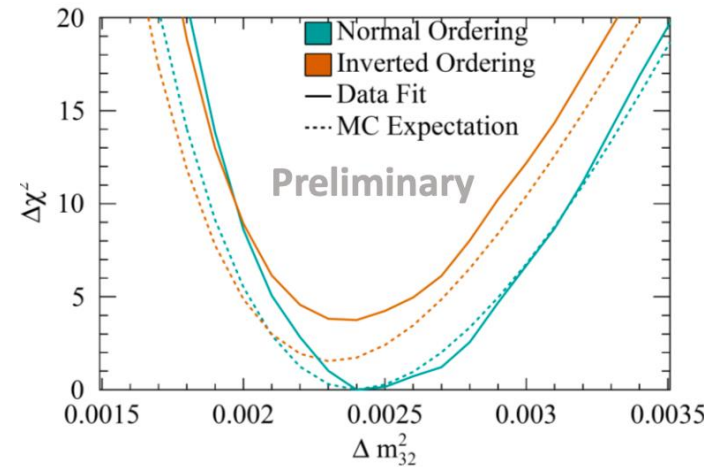
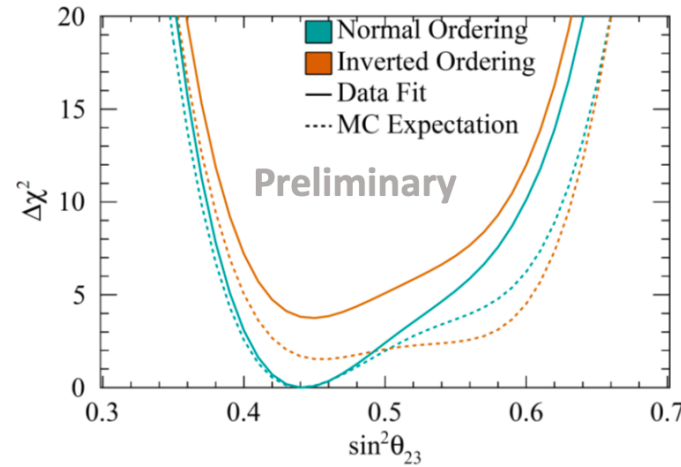
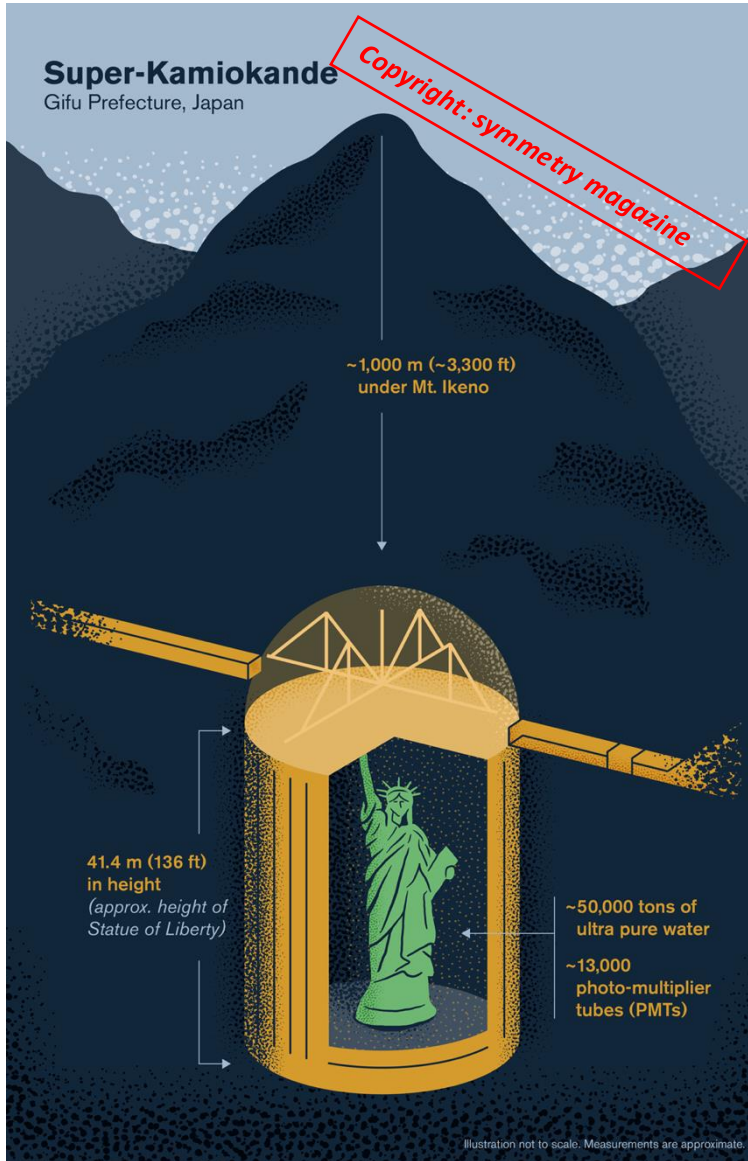
Anchors cosmology & model building

$\Sigma m_\nu \gtrsim 0.059\text{eV}$ (NO) vs $\gtrsim 0.10\text{eV}$ (IO). Cosmological surveys are now sensitive to exactly this difference; leptogenesis models care too.

Efforts Resolving the ν Mass Ordering

Source / Principle	Matter Effect	Interference of Solar&Atm Osc.	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Super-K, Hyper-K , IceCube/DeepCore, KM3NeT/ORCA			
Beam ν_μ	T2K, NOvA, Hyper-K , DUNE			
Reactor ν_e		JUNO		
Supernova Burst ν			Massive Detectors with Good E Resolution	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, $0\nu\beta\beta$

Atmospheric Neutrinos by Super-Kamiokande



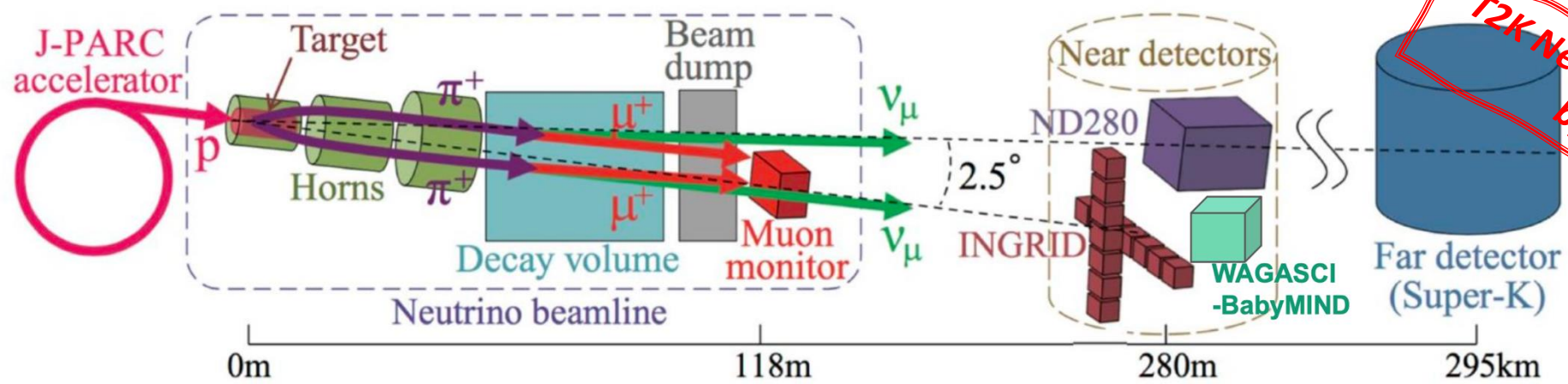
	Previous study (SK I-V)	This study (SK I-VI)
$\sin^2\theta_{23}$	0.45	0.44
$\Delta m^2_{32} [10^{-3} \text{ eV}^2]$	2.40	2.40
δ_{CP}	$-\pi/2$	$-3\pi/4$
$\Delta\chi^2_{IO-NO}$	5.69	3.69

* $\sin^2\theta_{13}$ prior: 0.0220 ± 0.0007

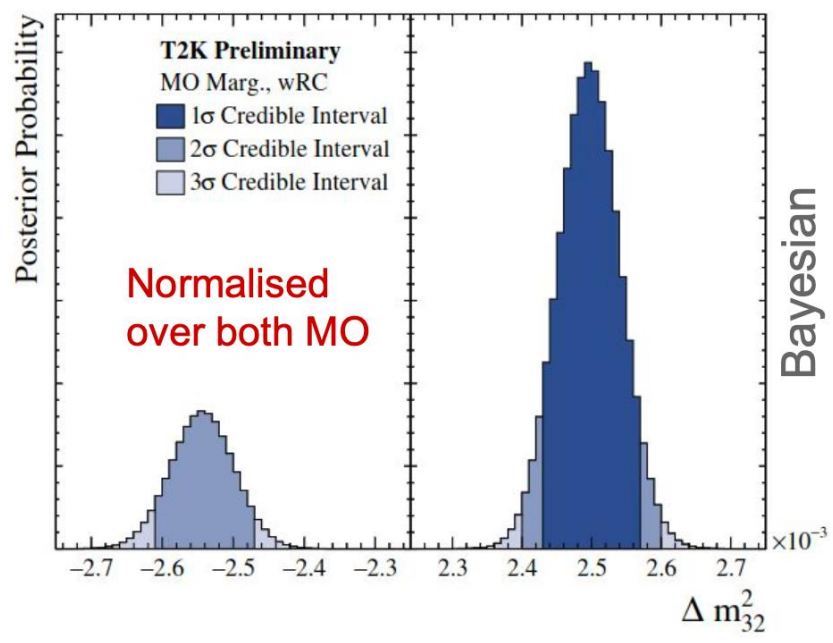
**Results of MO and δ_{CP} exceed sensitivity

Super-K Neutrino'26 Presentation
by Jianrun Hu

T2K = Tokai to Kamioka



*T2K Neutrino'26 Presentation
by Sophie King*

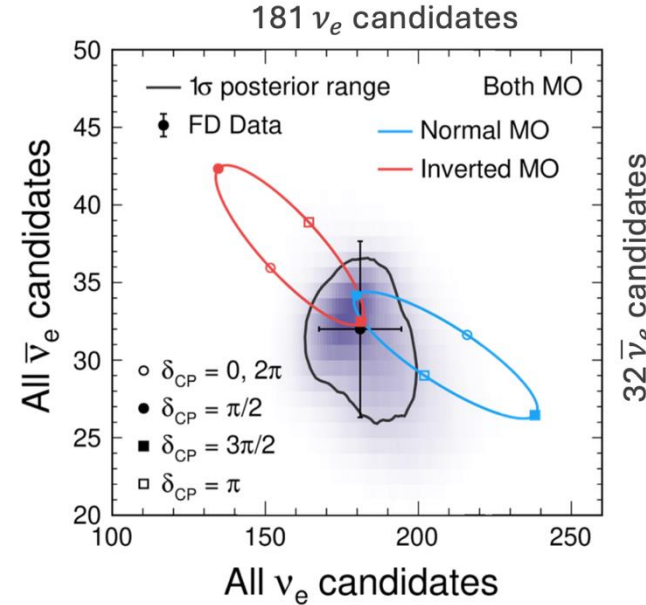
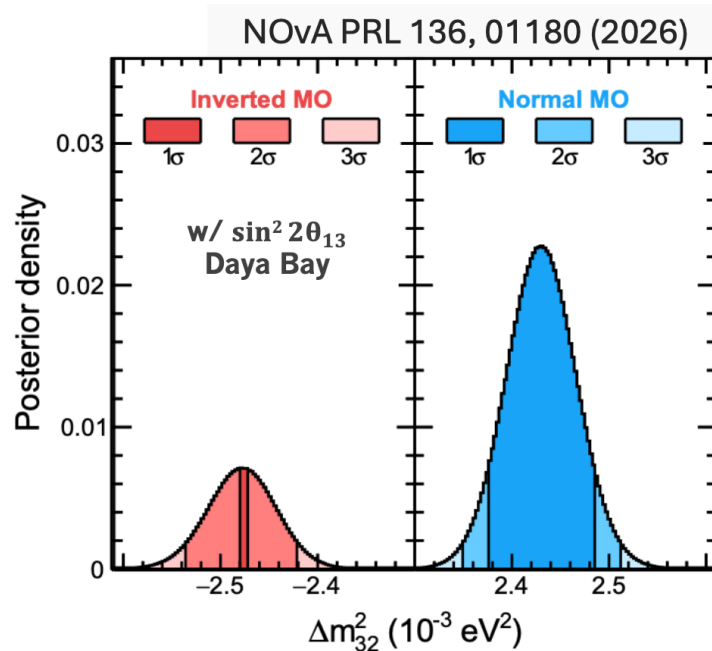
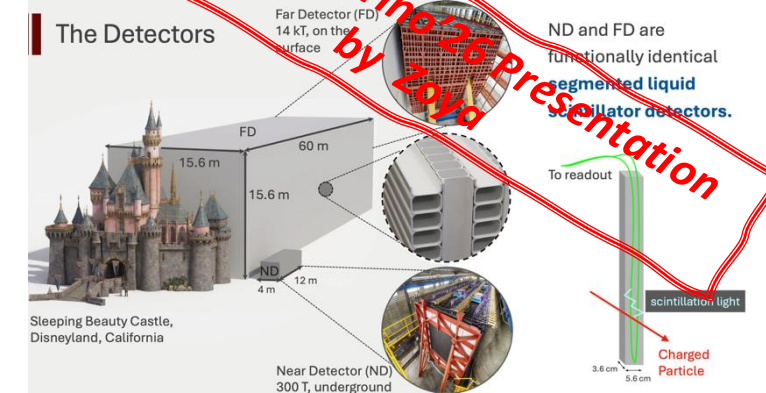
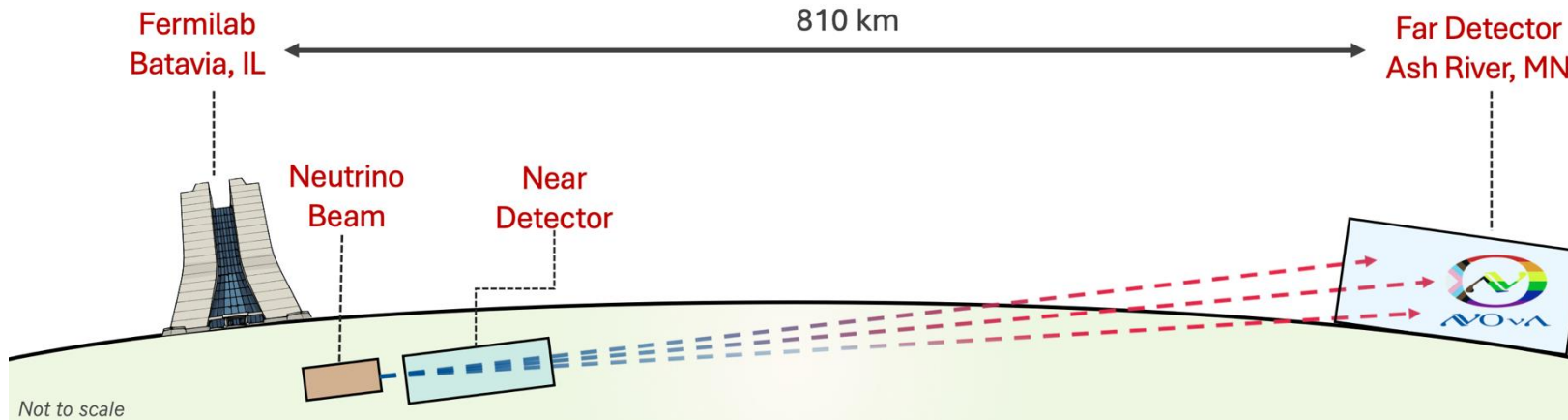


	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.271	0.509	0.780
IO ($\Delta m^2_{32} < 0$)	0.061	0.159	0.220
Sum	0.332	0.668	1.000

Weak preference for **NO** at **78%** posterior probability
 → Increases to **81%** when including Δm^2_{32} data in the reactor constraint

→ Bayes factor: 3.5/4.3 w/ and w/o Daya Bay input

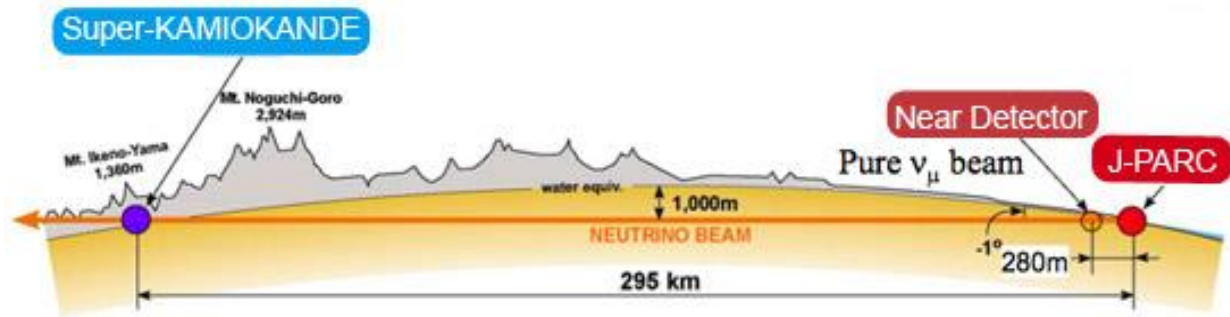
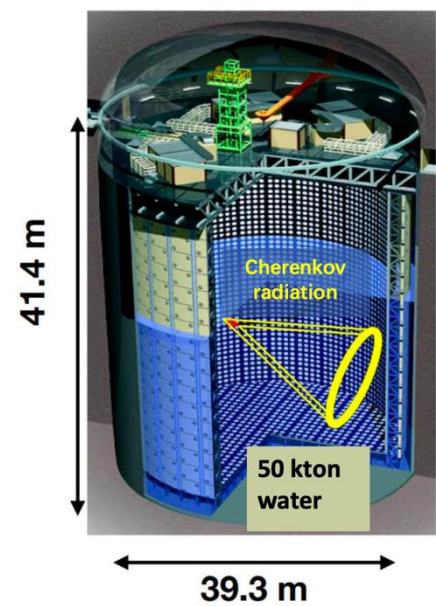
NOvA: FermiLab to Ash River in Minnesota



➤ NOvA data show a preference for NO (77% posterior) with a Bayes factor of 3.3

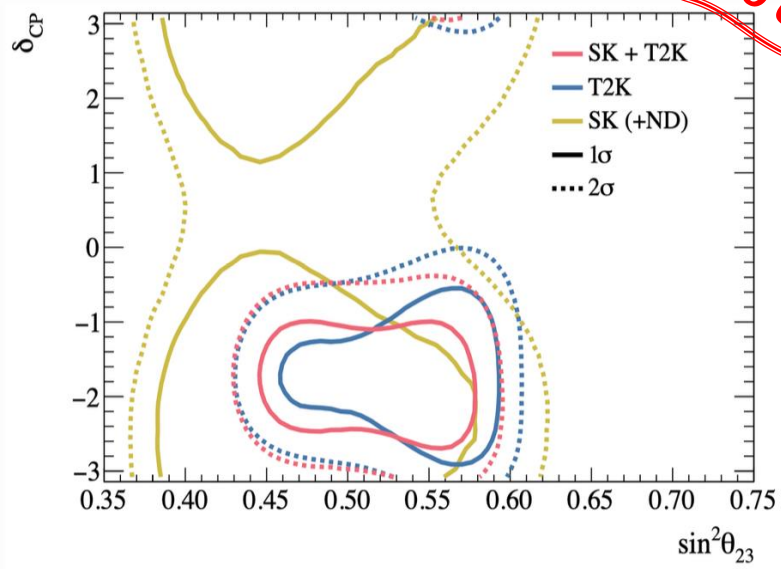
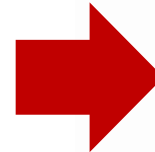
Combining Super-K with T2K (by T2K)

- Super-K: wide energy, matter density and baseline coverage
- T2K: narrow band beam, pure particle/antiparticle → reflecting NMO directly



T2K Super-K (atmospheric) joint analysis Phys. Rev. Lett. 134, 011801 (2023)

T2K ICHEP Presentation by
Lorenzo Restrepo Orrantia



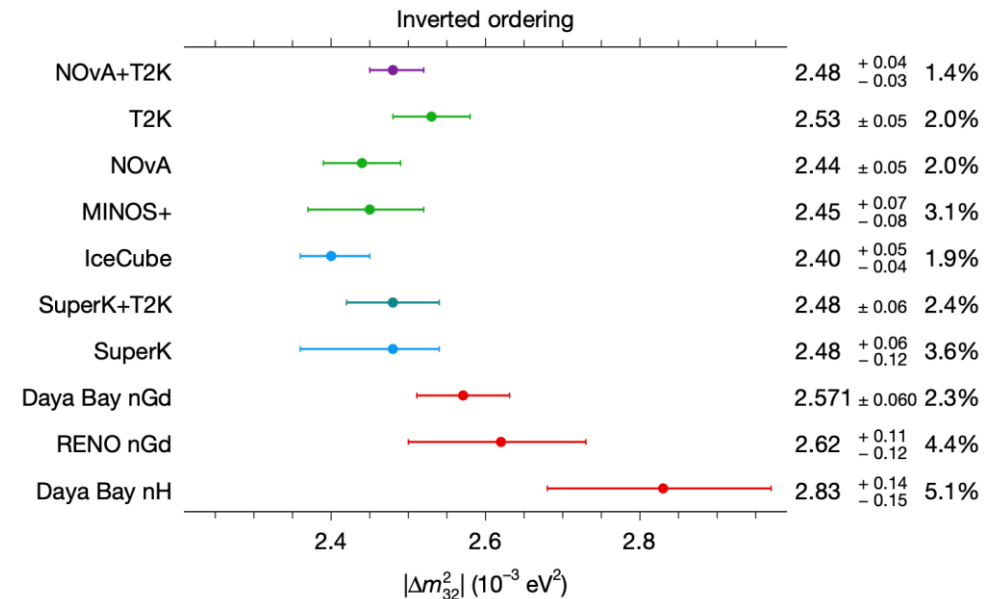
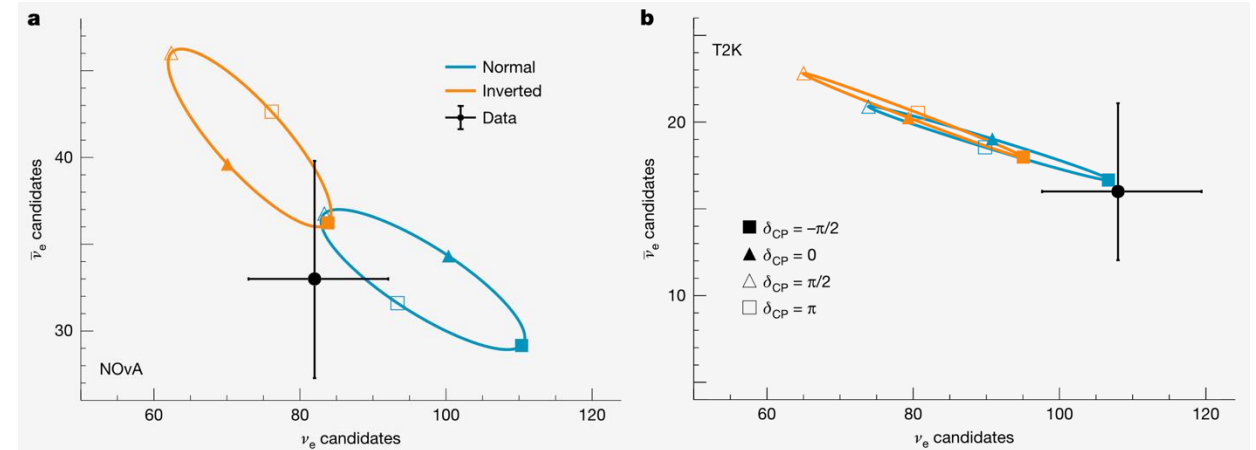
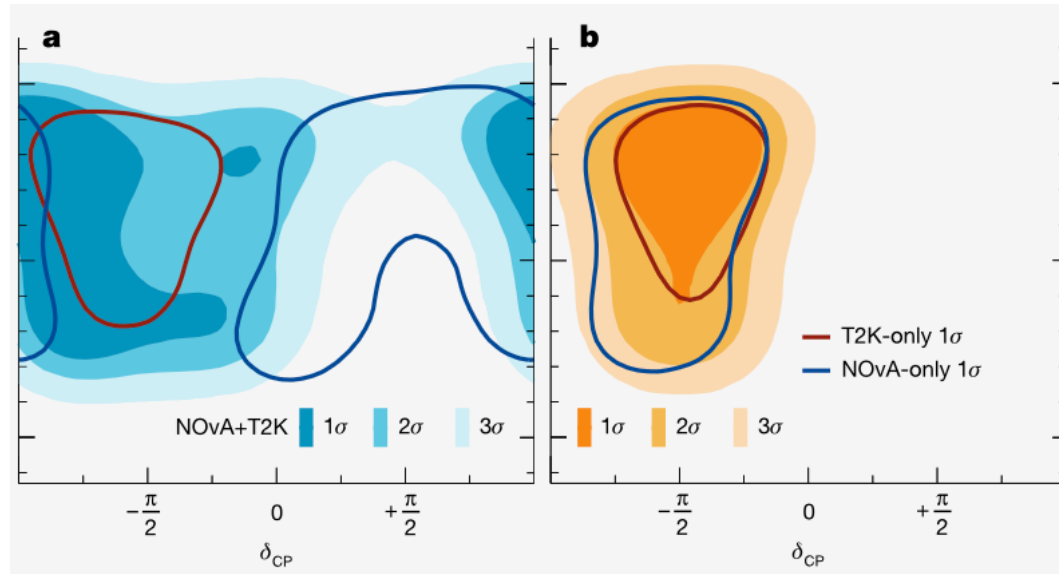
- **CP conservation** is disfavoured with a lower *p*-value of 3.7%
- 1.2 σ exclusion of the **IO**
- No $\sin^2(\theta_{23})$ octant preference

The Synergy between T2K and NOvA

For details, see *Nature* 646, 818-824 (2025)

	T2K	NOvA
Location	Tokai→Kamioka	Illinois→Minnesota
Baseline	295 km	810 km
Flux peak	0.6 GeV	1.8 GeV
CD	Water Cherenkov	Tracking calorimeter
ND	Magnetised tracker	Tracking calorimeter

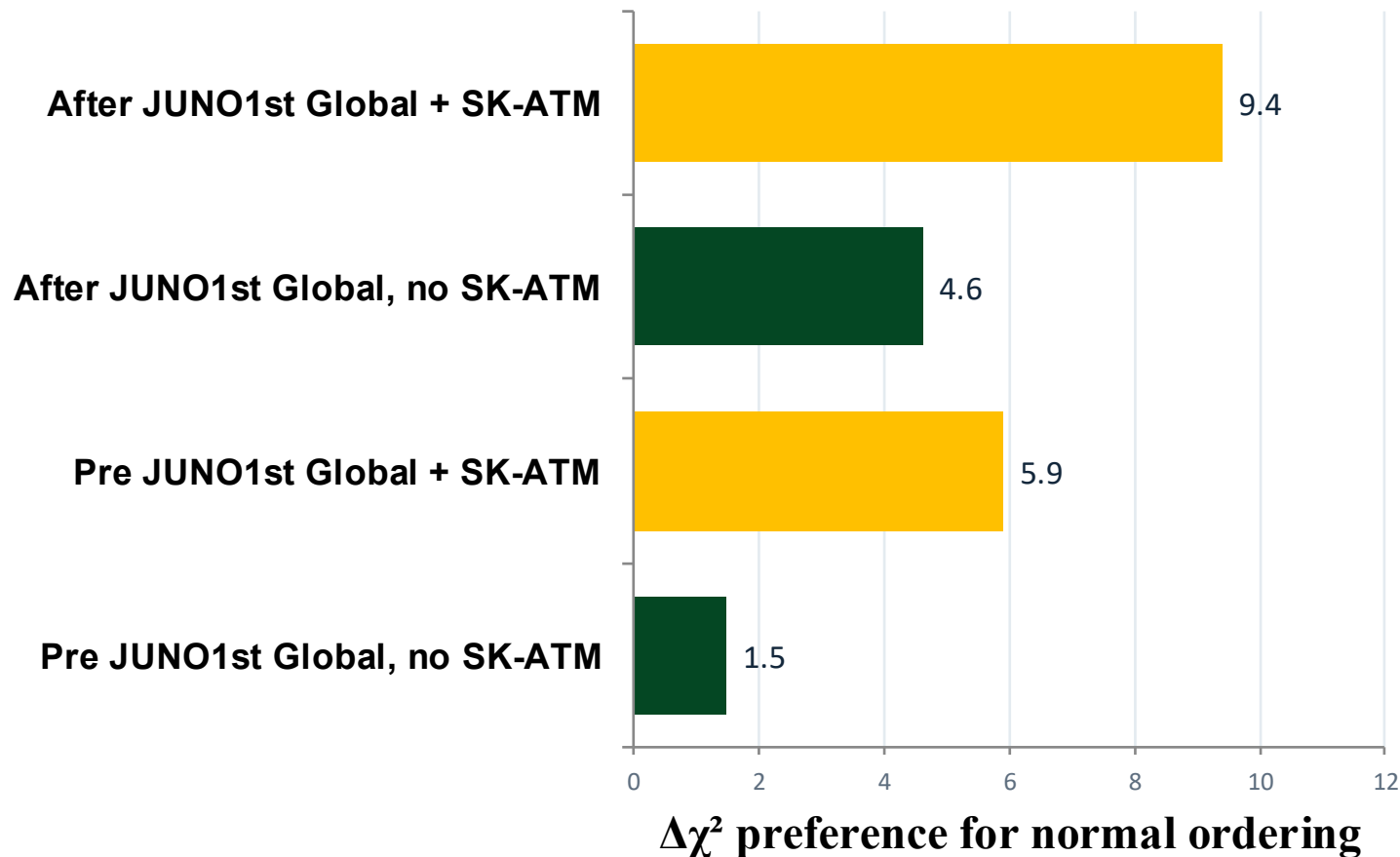
T2K Neutrino 2026
Poster by Hank Hua



→ A slight preference to inverted ordering

What if we combine all the data? *(from NuFIT group and their Neutrino 2026 talk)*

Preference for normal ordering depends strongly on which data are included; Note that, JUNO, even just the first 59 days, played an important role.



- ❖ SK-ATM means Super-K data plus the IC24 data
- ❖ JUNO's first release moves the combination to $\Delta\chi^2 \approx 9.4$, roughly 3σ
- ❖ $\Delta\chi^2 = 1.5 \approx 1.2\sigma$, $4.6 \approx 2.1\sigma$, $5.9 \approx 2.4\sigma$, $9.4 \approx 3.1\sigma$. None of this is a measurement yet.

References: NuFIT 6.0, arXiv:2410.05380 · Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Pinheiro, Schwetz, "Lessons from the first JUNO results", JHEP 04 (2026) 089 [arXiv:2601.09791]

Different Data Pull Different Ways

● T2K + Super-K

**Subtle preference
for
NORMAL ordering**

CP-conserving Jarlskog
excluded at $1.9\text{--}2.0\sigma$

● T2K + NOvA

**Subtle preference
for
INVERTED ordering**

First joint fit, Nature 646
(2025); 1.4% on $|\Delta m^2_{32}|$

● Global $\Delta m^2_{3\ell}$ disappearance

**Prefers
NORMAL ordering**

Complementary splittings;
JUNO now world-leading

● DESI DR2 + CMB

**Disfavours
INVERTED ordering**

$\Sigma m_\nu < 0.064$ eV (95%),
against a 0.10 eV IO floor

❖ *And the θ_{23} octant ambiguity managed to survive in every one of these analyses!*

➤ *The hints are not yet mutually consistent — which is why more channels matter, and cleaner measurements naturally have advantages at this stage.*

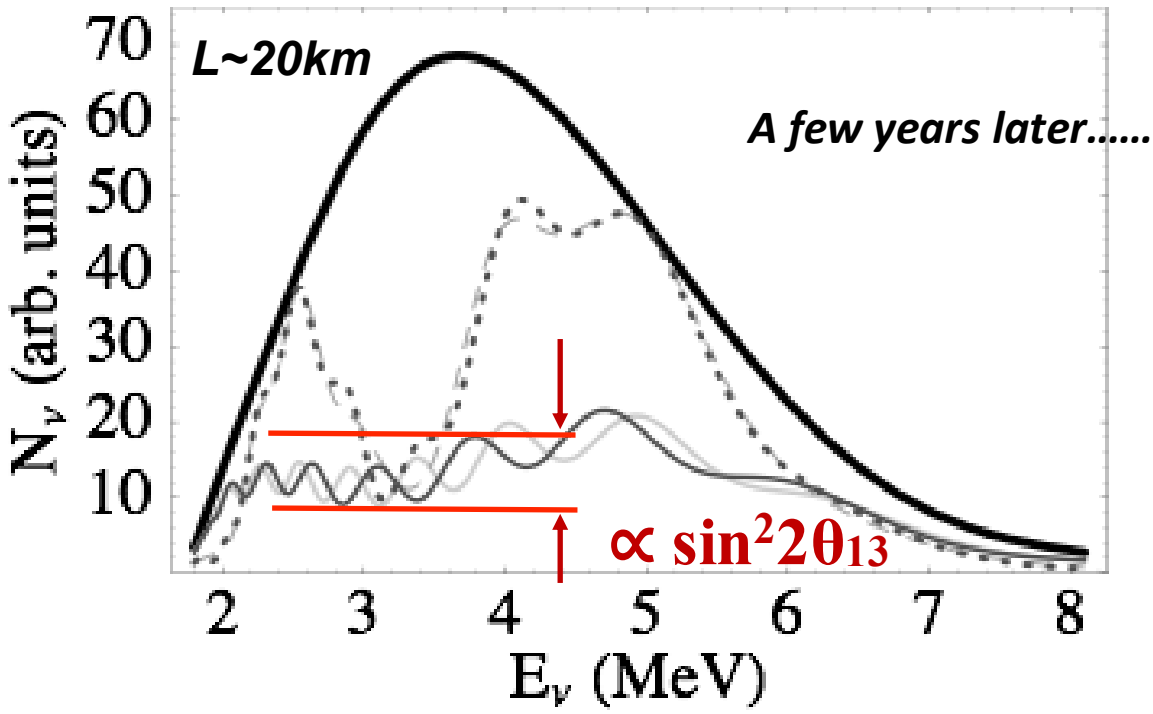
For Detailed References: NOvA & T2K Collaborations, Nature 646, 818 (2025) · DESI DR2 BAO + CMB, arXiv:2503.14744 · NuFIT 6.0

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors

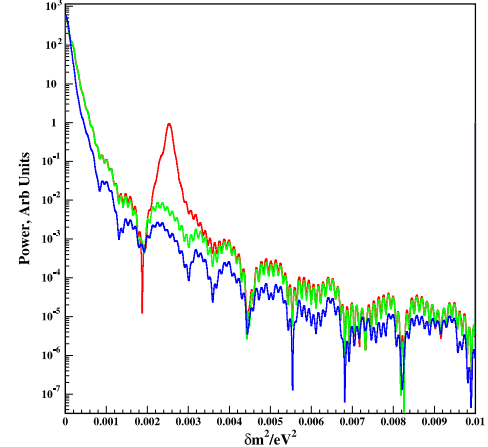
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \boxed{\cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}} - \boxed{\sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})}$$

- ✓ Mass ordering reflected in the survival spec.
- ✓ Independent of CP phase, the octant ambiguity

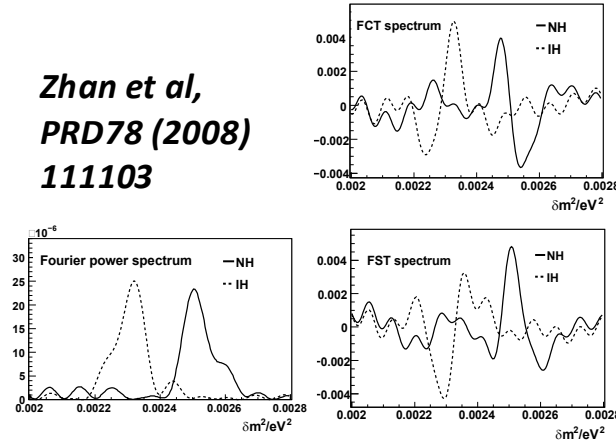
Petcov&Piai, Phys. Lett. B533 (2002) 94-106



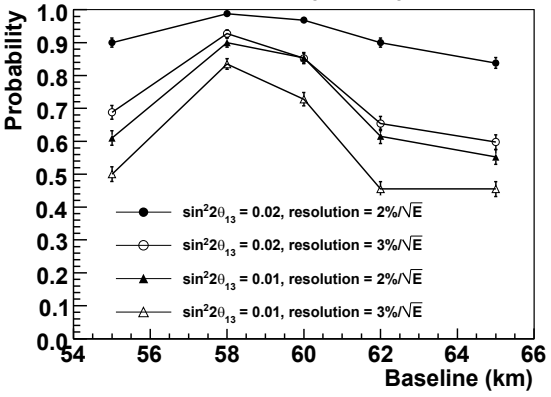
Learned et al, PRD78(2008)071302(R)



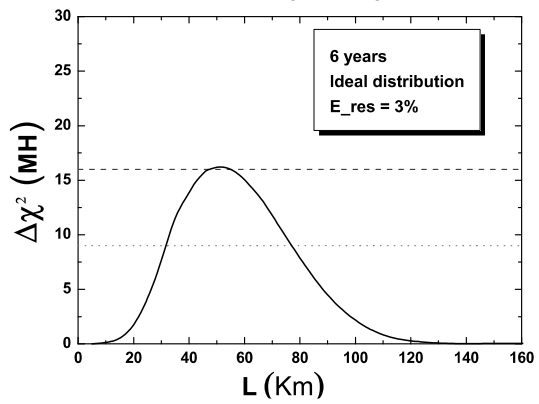
Zhan et al, PRD78 (2008) 111103



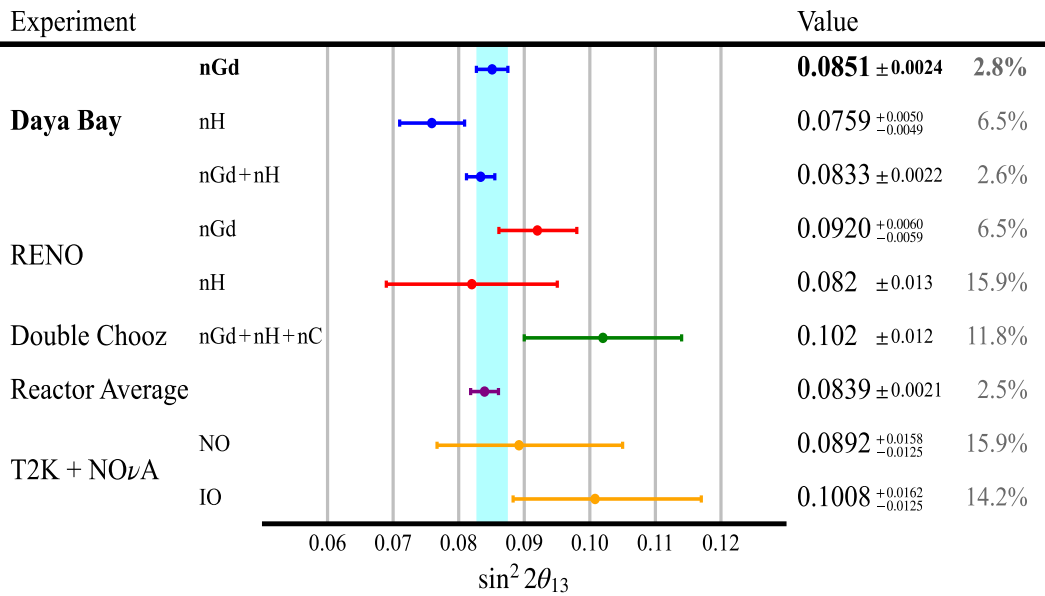
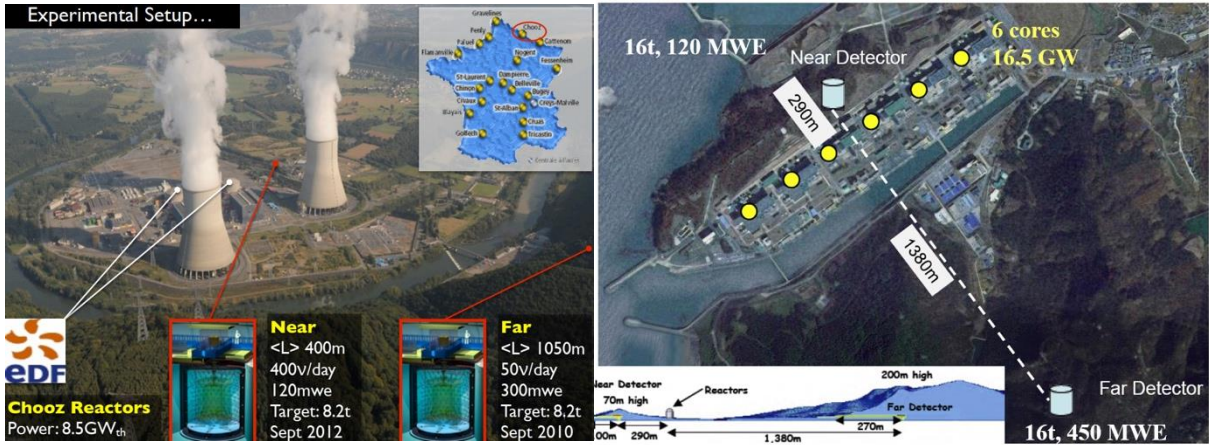
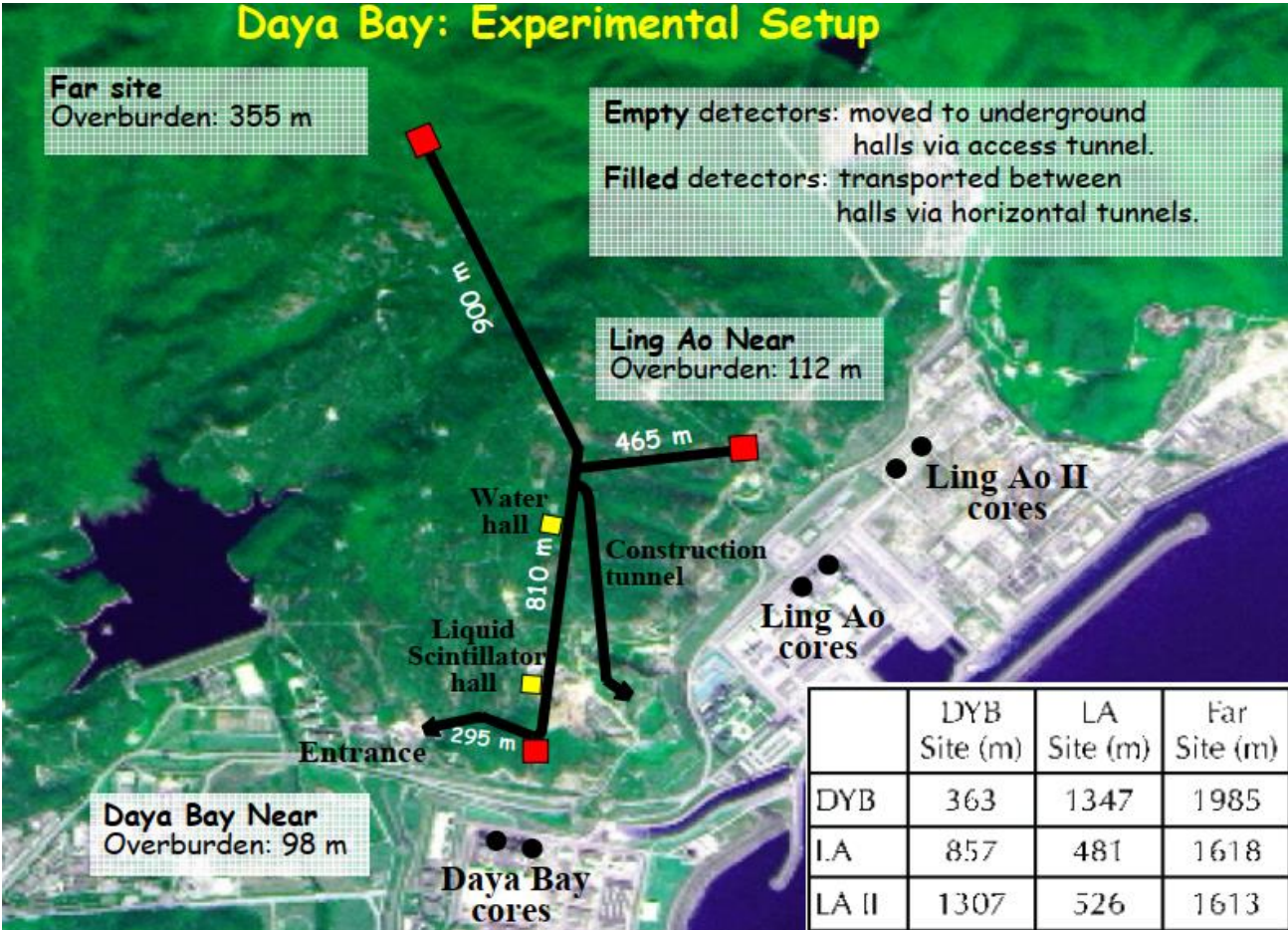
Zhan et al, PRD79 (2009) 073007



Li et al, PRD 88 (2013) 013008

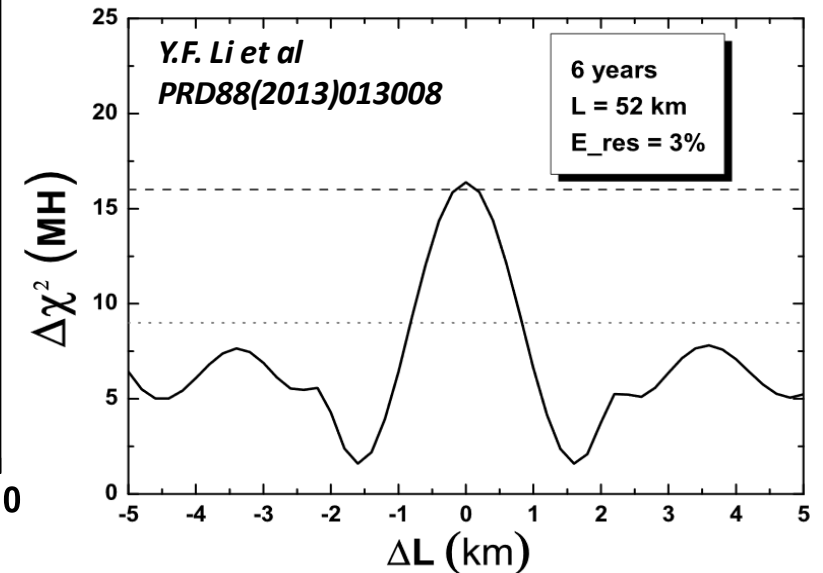
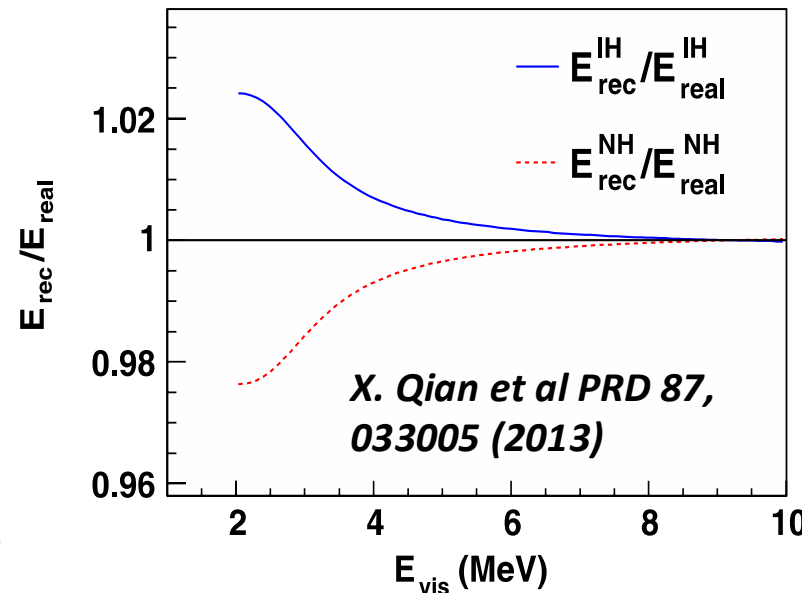
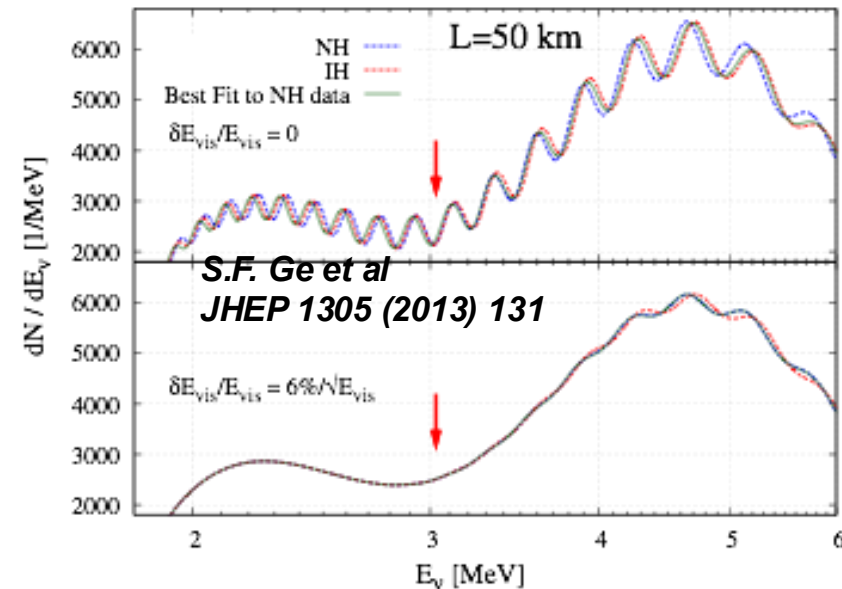
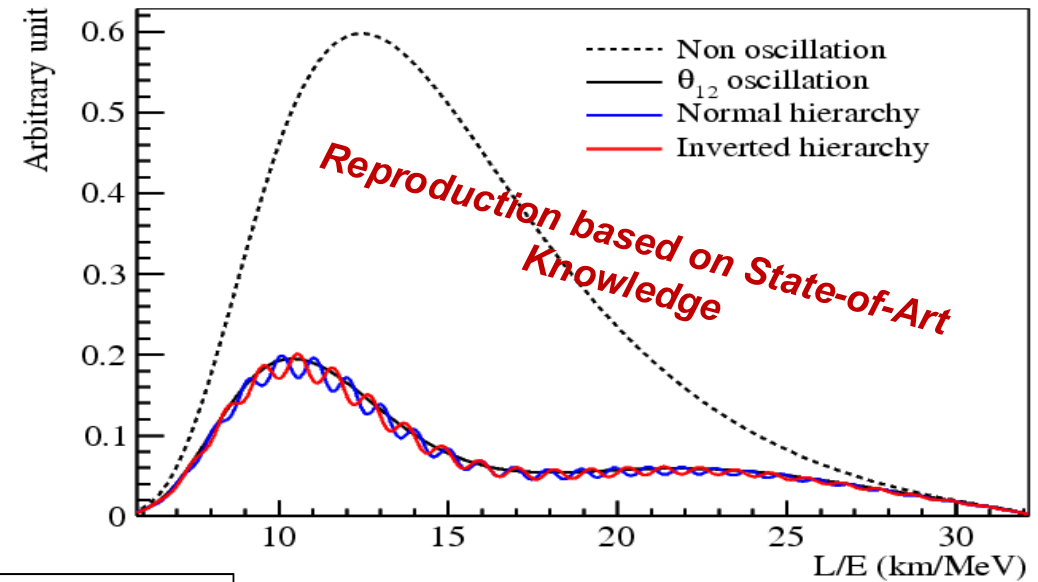


Daya Bay Discovered a Big θ_{13} , DC and RENO Confirmed

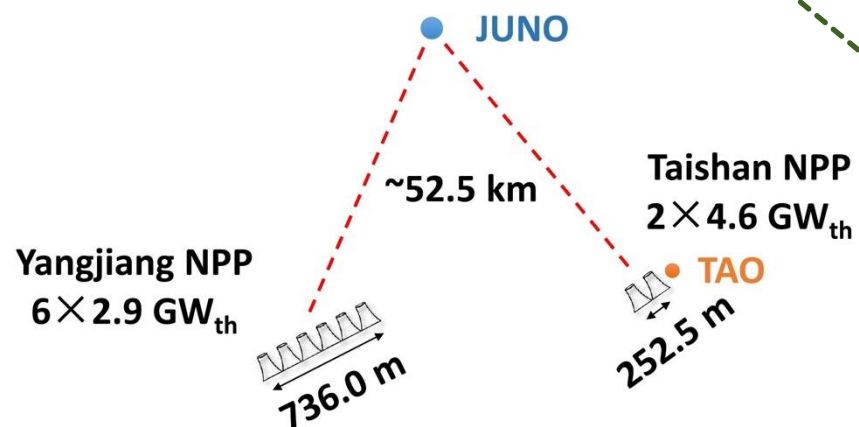


4 More Challenges in Resolving NMO using Reactors

- Energy resolution: $\sim 3\%/\sqrt{E}$
- Energy scale uncertainty: $< 1\%$
- Statistics (the more the better)
- Reactor distribution: $< \sim 0.5\text{km}$



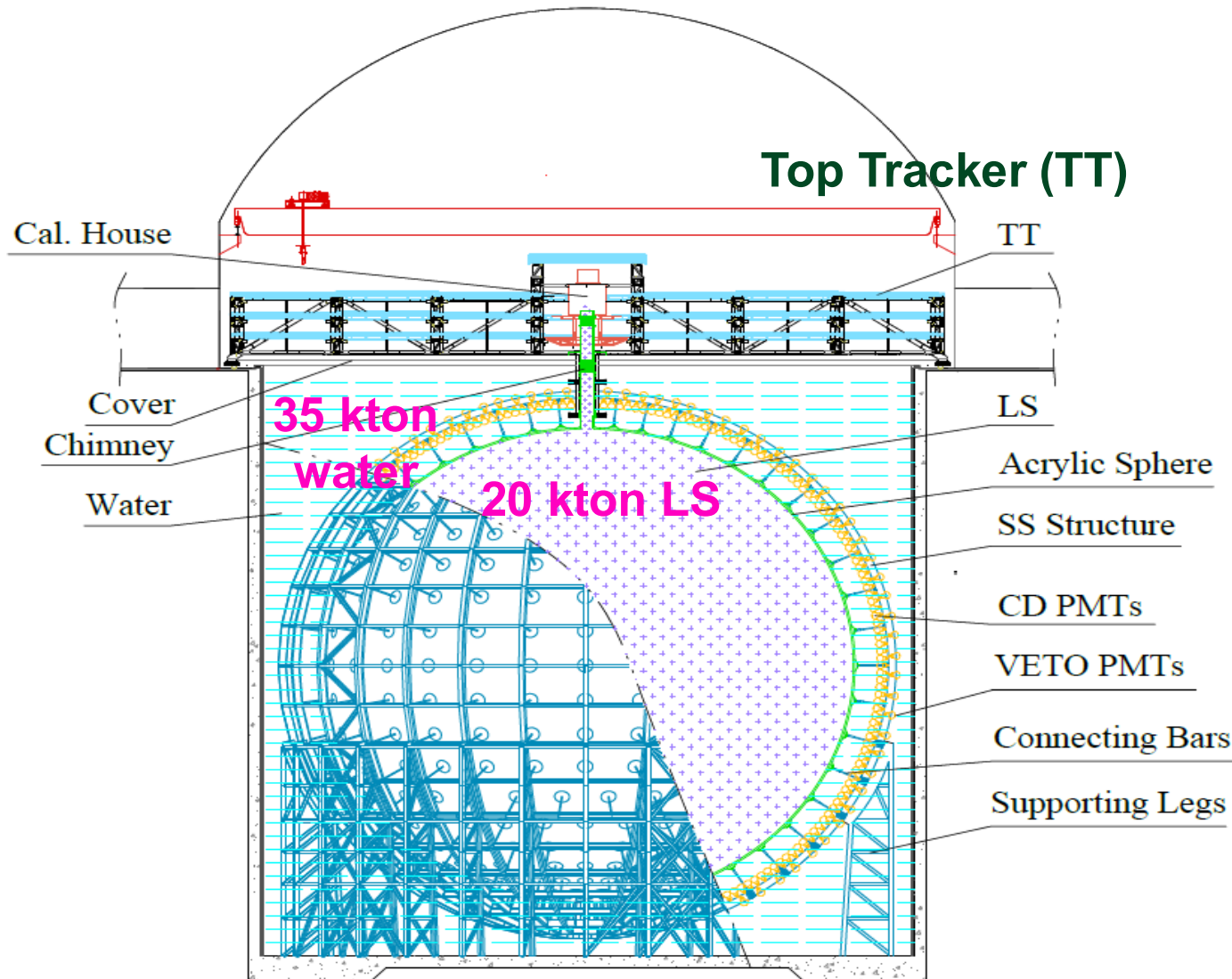
Jiangmen Underground Neutrino Observatory (JUNO)



- ❖ A medium-baseline detector JUNO, ~52.5km
- ❖ A very short-baseline detector TAO, ~43m
- **Primary Physics: Neutrino Mass Ordering**



The Conceptual Design of the JUNO 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

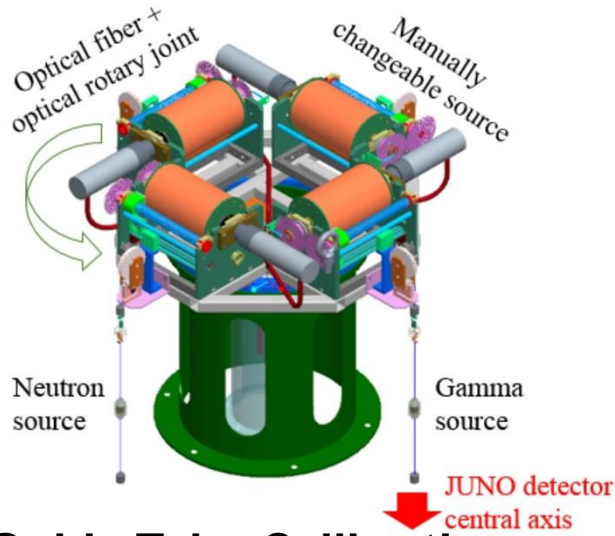
Photon
statistics

Noise
(~background)

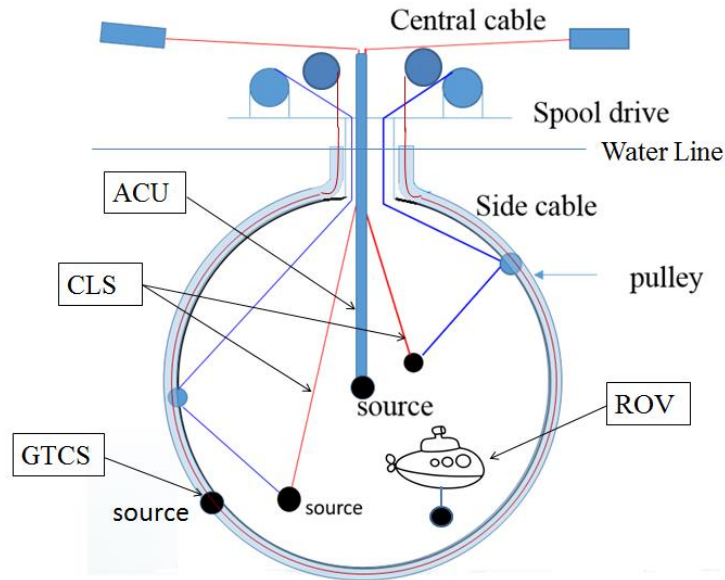
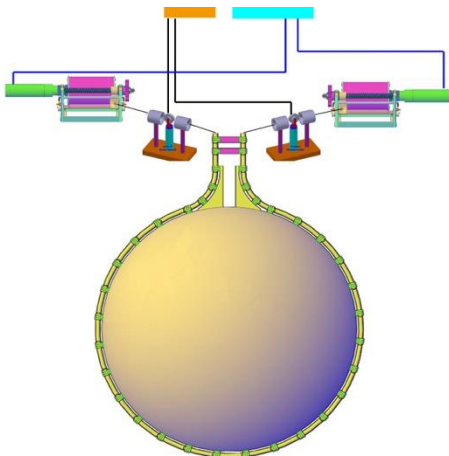
A Comprehensive Calibration System



Automatic Calibration Unit (ACU)

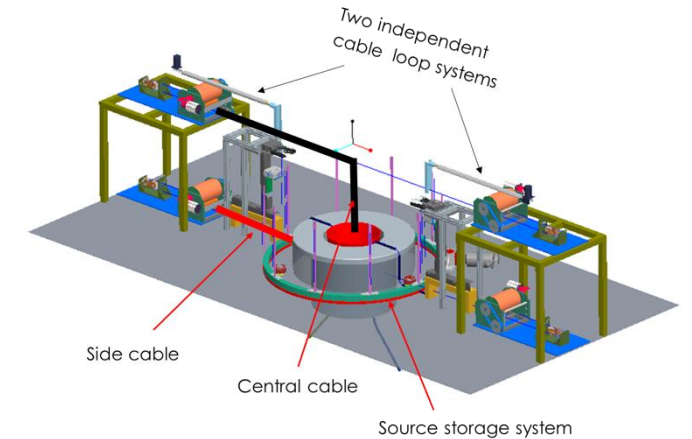


Guide Tube Calibration System (GTCS)

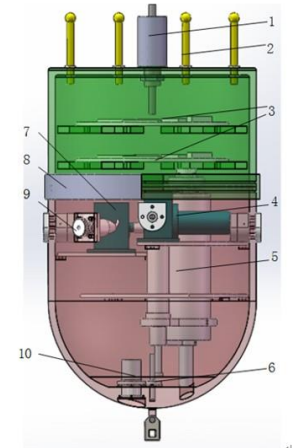


□ Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

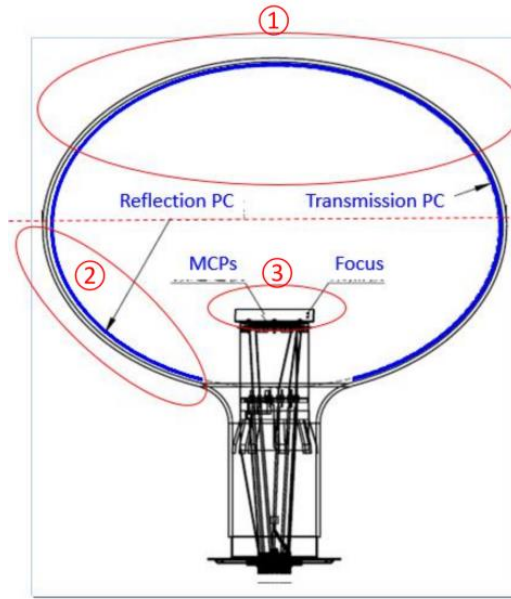
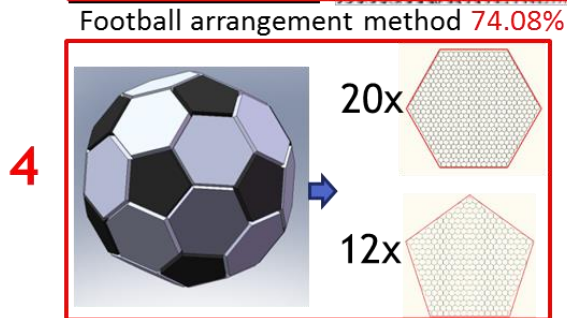
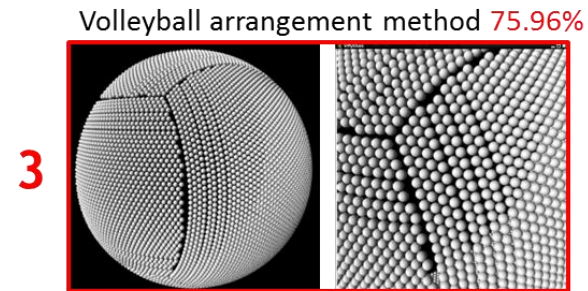
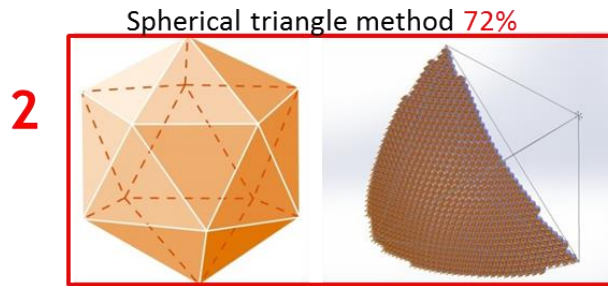
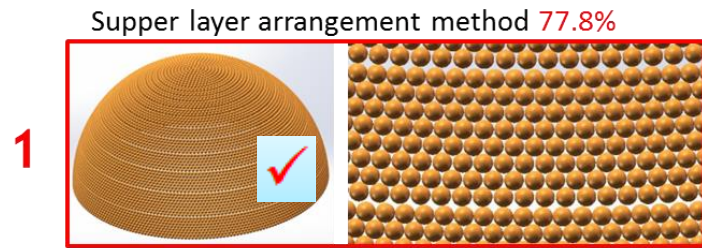
Cable Loop System (CLS)



Remotely Operated under-liquid-scintillator Vehicles (ROV)

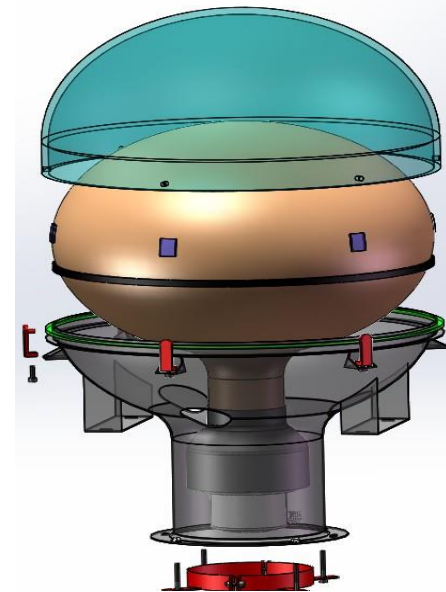
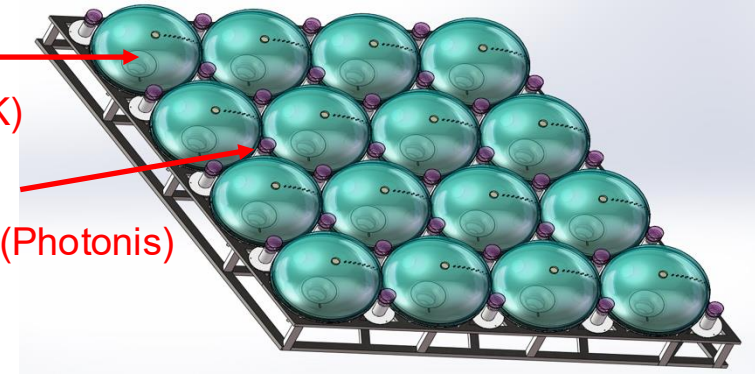


Packing PMTs as Tight as Possible and Keep Them Safe



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

3"sPMT(~25K)
HZE XP72B22 (Photonis)



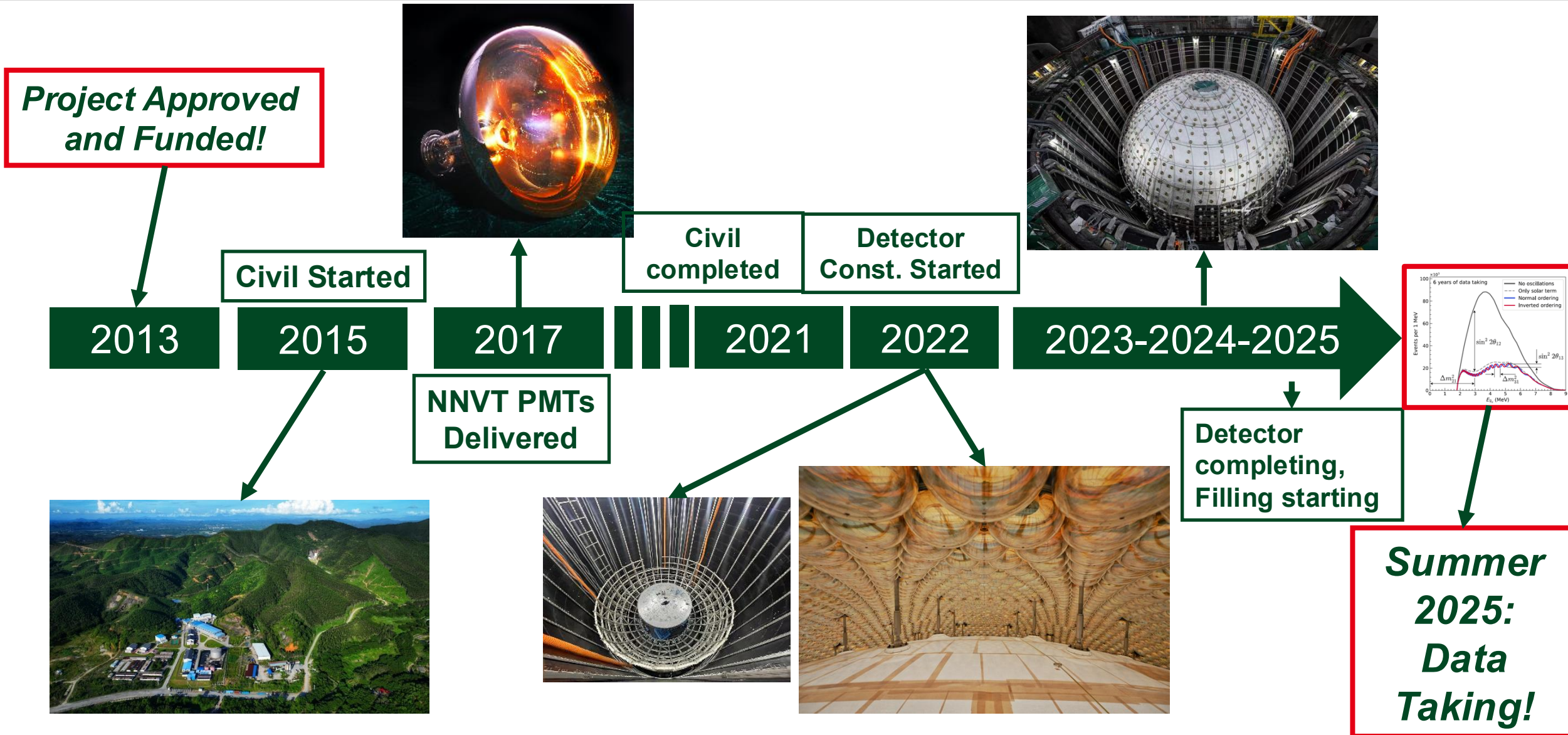
Views from Inside the Central Detector



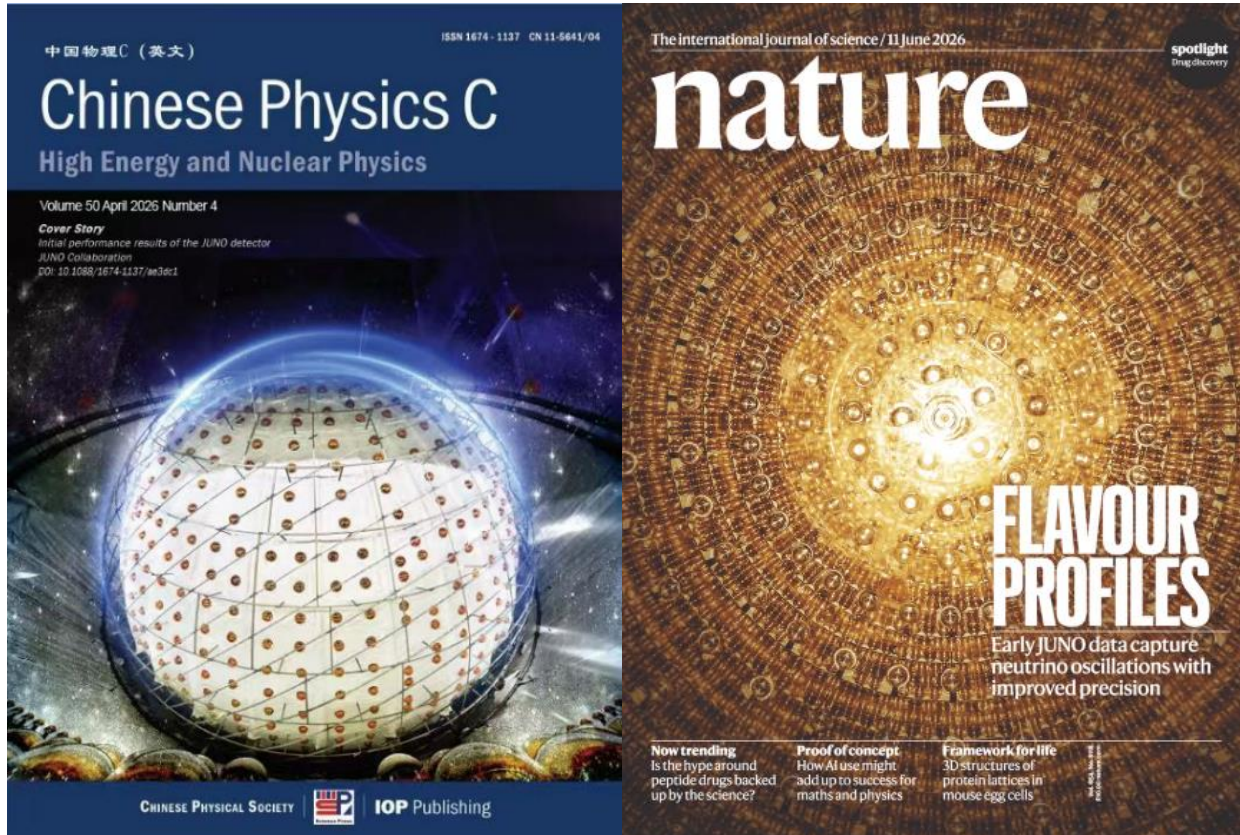
	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Coverage	75%		3%
Reference	Eur.Phys.J.C 82(2022) 12, 1168		NIM.A 1005 (2021) 165347



Major Milestones of the JUNO Experiment



The First Results from JUNO (Nov 2025 & Jun 2026)

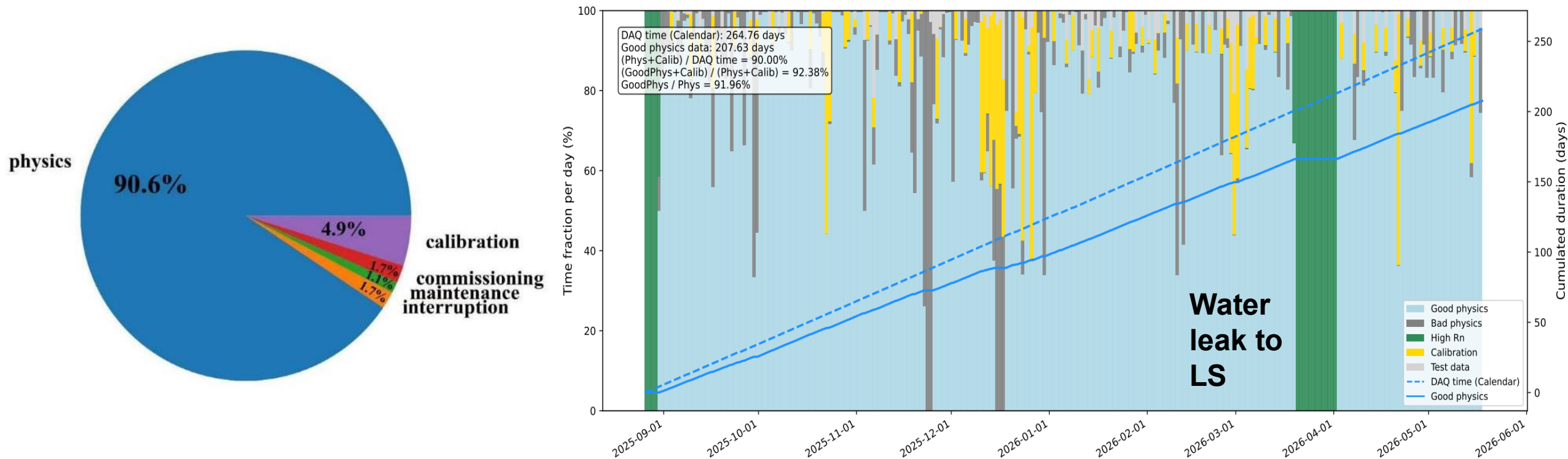


First results using 59 days of data already published, Nov 2025 – Jun 2026



**First Neutrino Mass Ordering
207 days of data @ v'26**

- 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

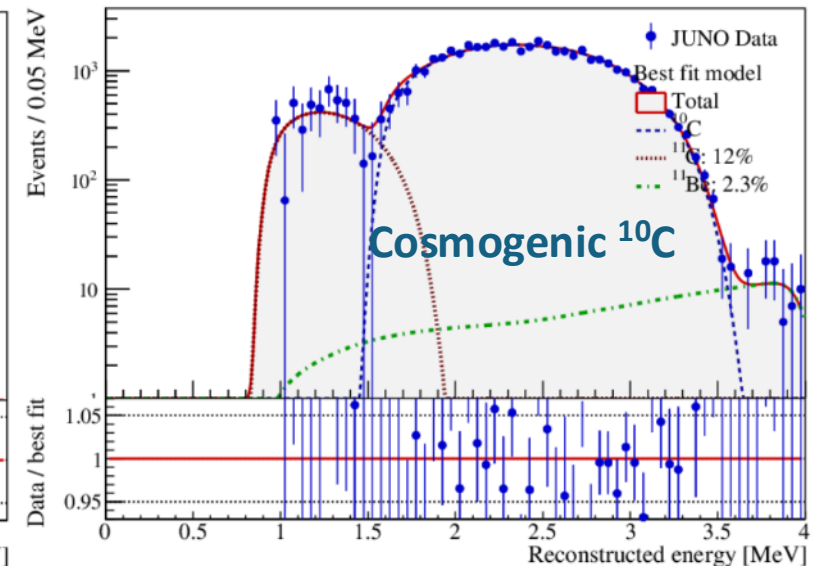
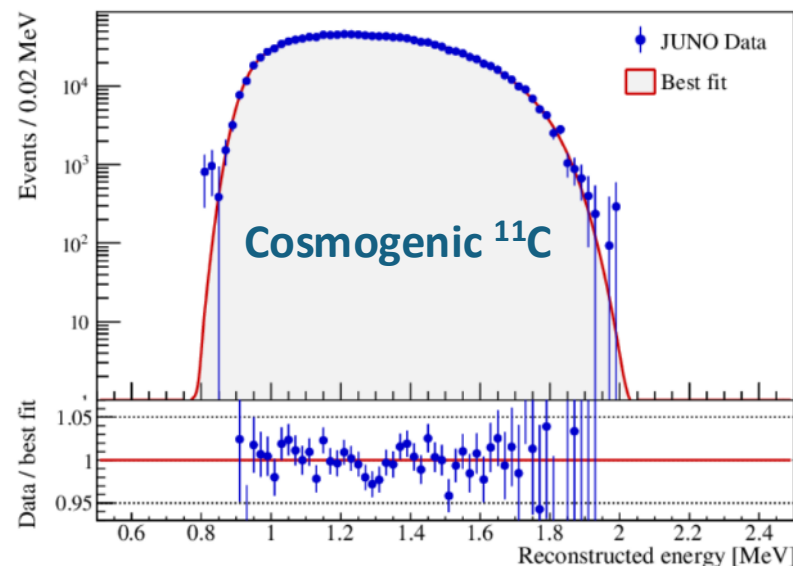
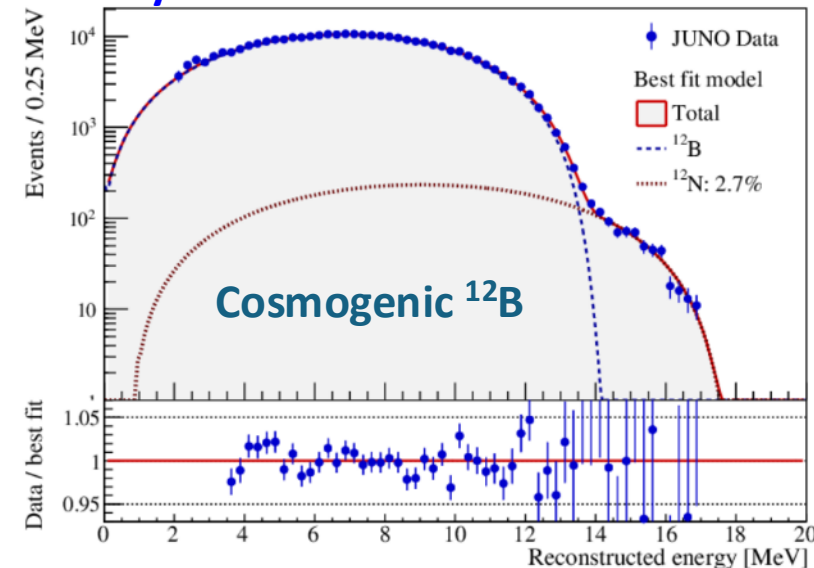
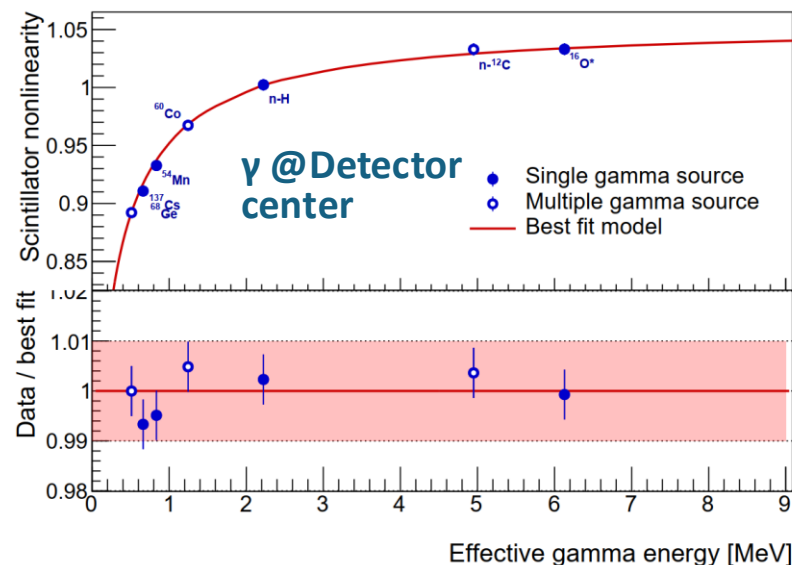
Energy Non-linearity

Yifang's Slide @ v26



- 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 γ -sources
- The model is constrained by cosmogenic isotopes, $^{11}\text{C}(e^+)$, $^{10}\text{C}(e^+)$, $^{12}\text{B}(e^-)$, $^8\text{Li}(e^-)$, $^8\text{B}(e^+)$, $^6\text{He}(e^-)$, etc. in the whole volume
- Using sPMTs to correct and constrain LPMT instrumental non-linearity
- Uncertainty < 1%

Preliminary

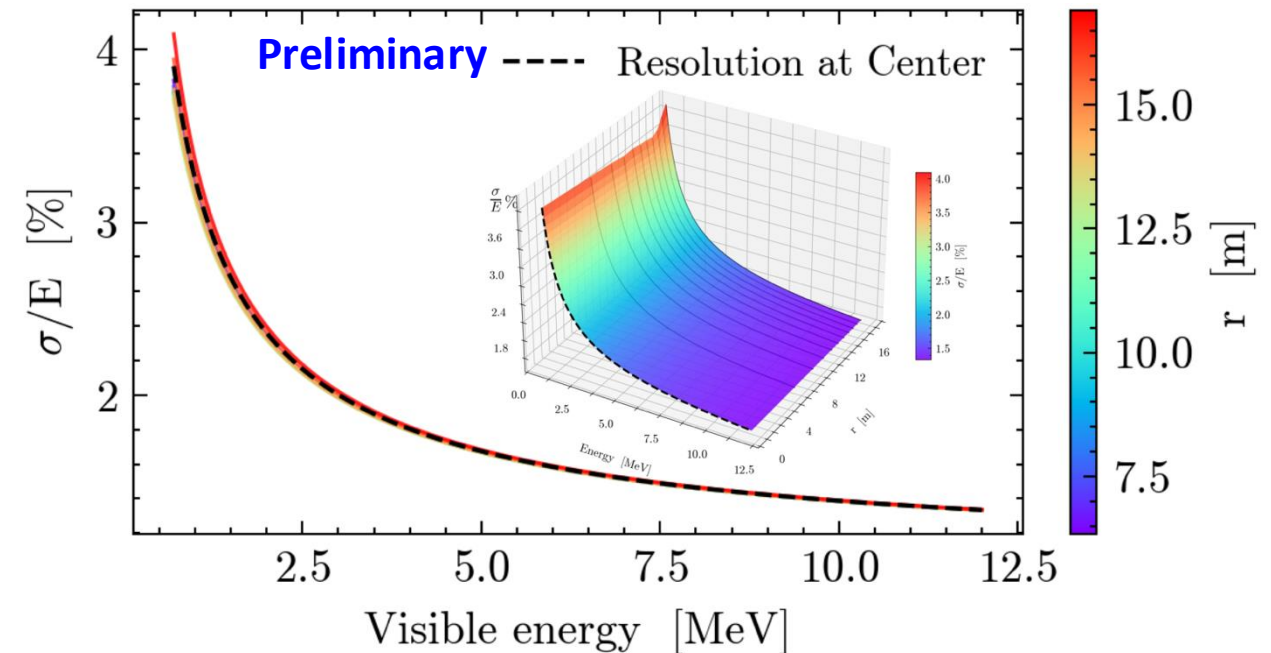
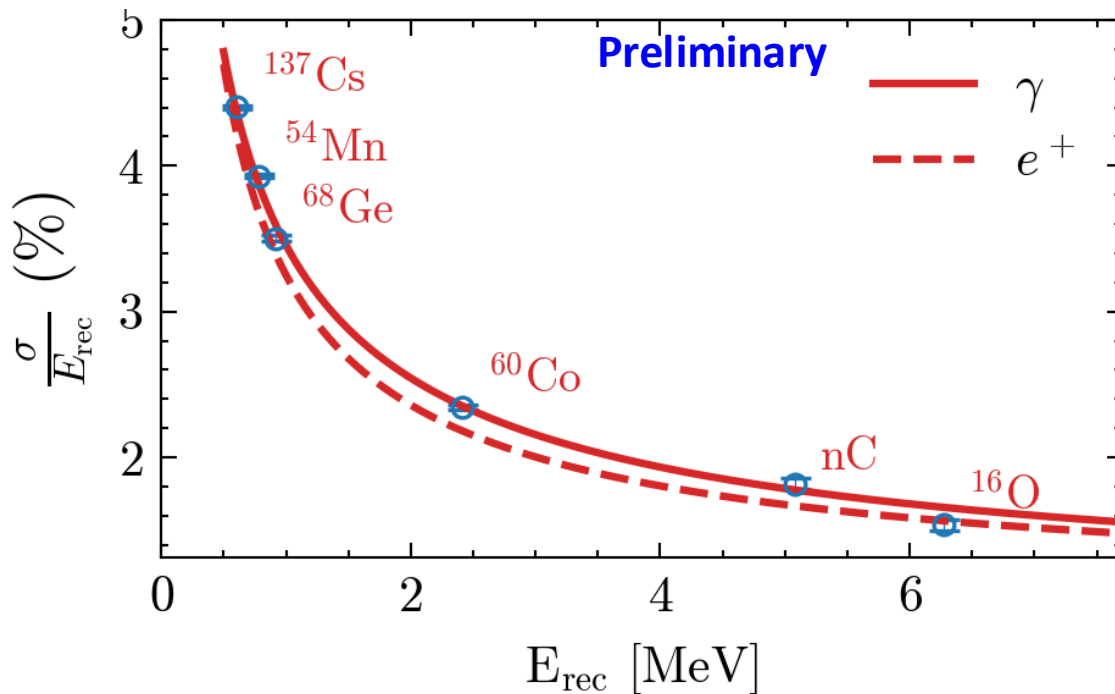


Energy Resolution Model

Yifang's Slide @ v26



- 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 (α , γ)
- An energy response matrix was then used for e^+ spectrum fitting after adding ^{14}C pile-up to 5% events



Reactor Neutrino Selection

Yifang's Slide @ v'26

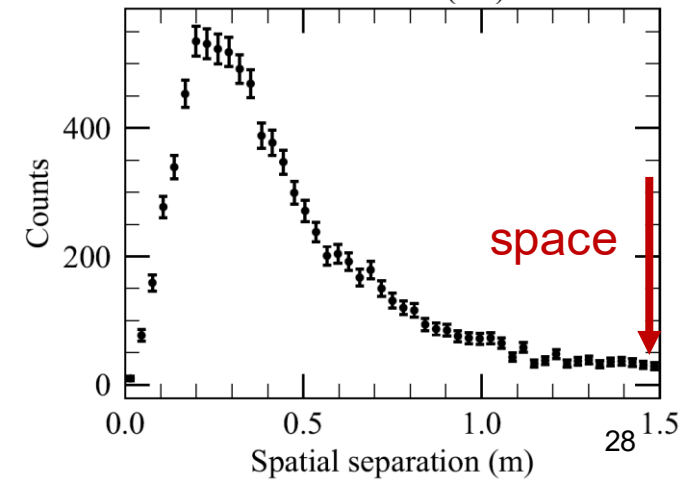
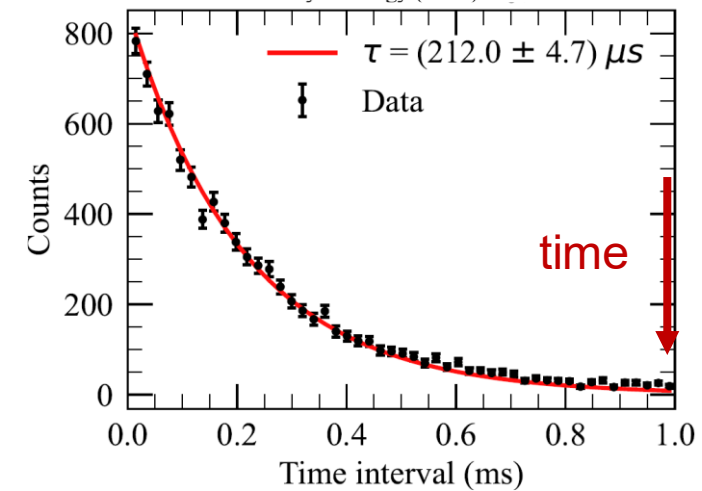
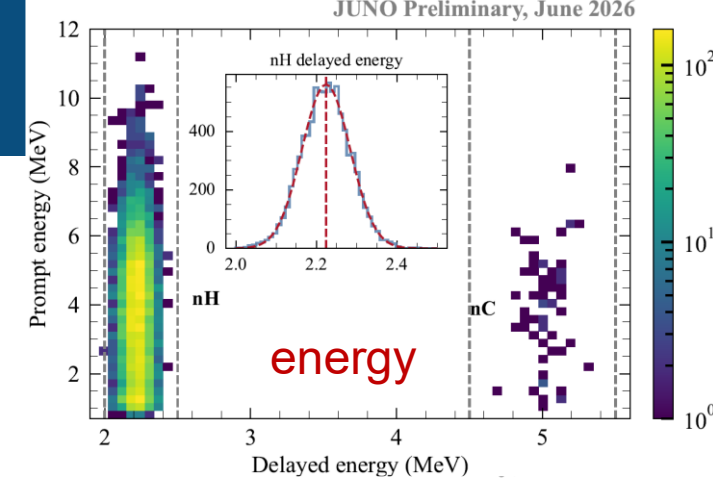
- Prompt and delayed coincidence in **time**, **space** with **energy** features

Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2$ m, $ z_p < 15.5$ m
Prompt energy	(0.7, 12) MeV
Delayed energy	(2.0, 2.5) $\cup$ (4.5, 5.5) MeV
Coincidence time	(5, 1000) μ 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 $NPE_{\text{spn}} \in (3000, 30000)$ and $T_{\text{spn}2\mu} \in (20, 2000)$ μ 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	$\log(\text{L.R.}) > -1.26$

Similar to the JUNO
“Nature” paper

- What is new in this analysis:

- $\sim 10\%$ more fiducial volume (R=16.5m $\rightarrow$ 17.2m)
- $\sim 60\%$ reduction of ^9Li bkg.
- a factor of 50 reduction of accidental bkg. using likelihood cut
- model independent estimate of the ^{214}Bi bkg.

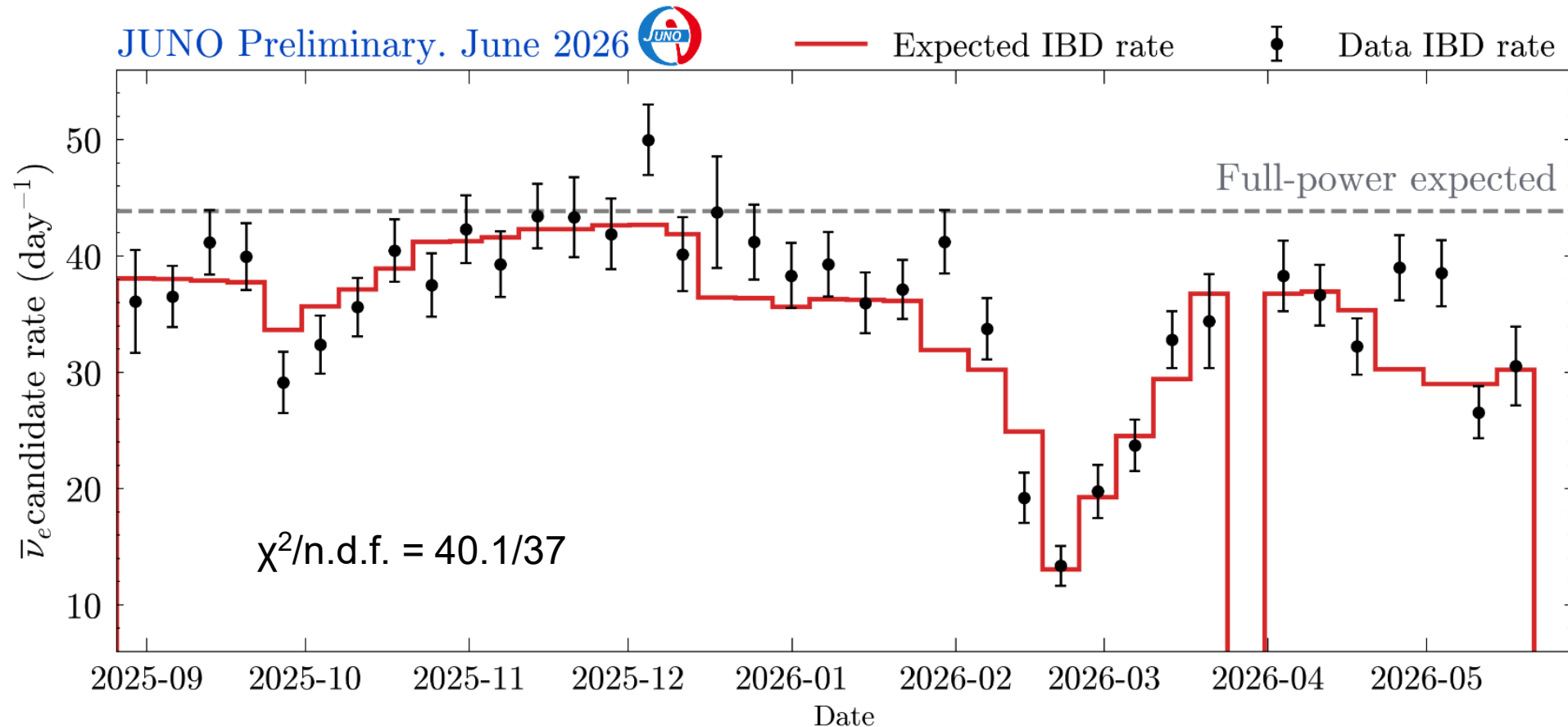


Reactor Neutrino Event Rate versus Time

Yifang's Slide @ ν 26



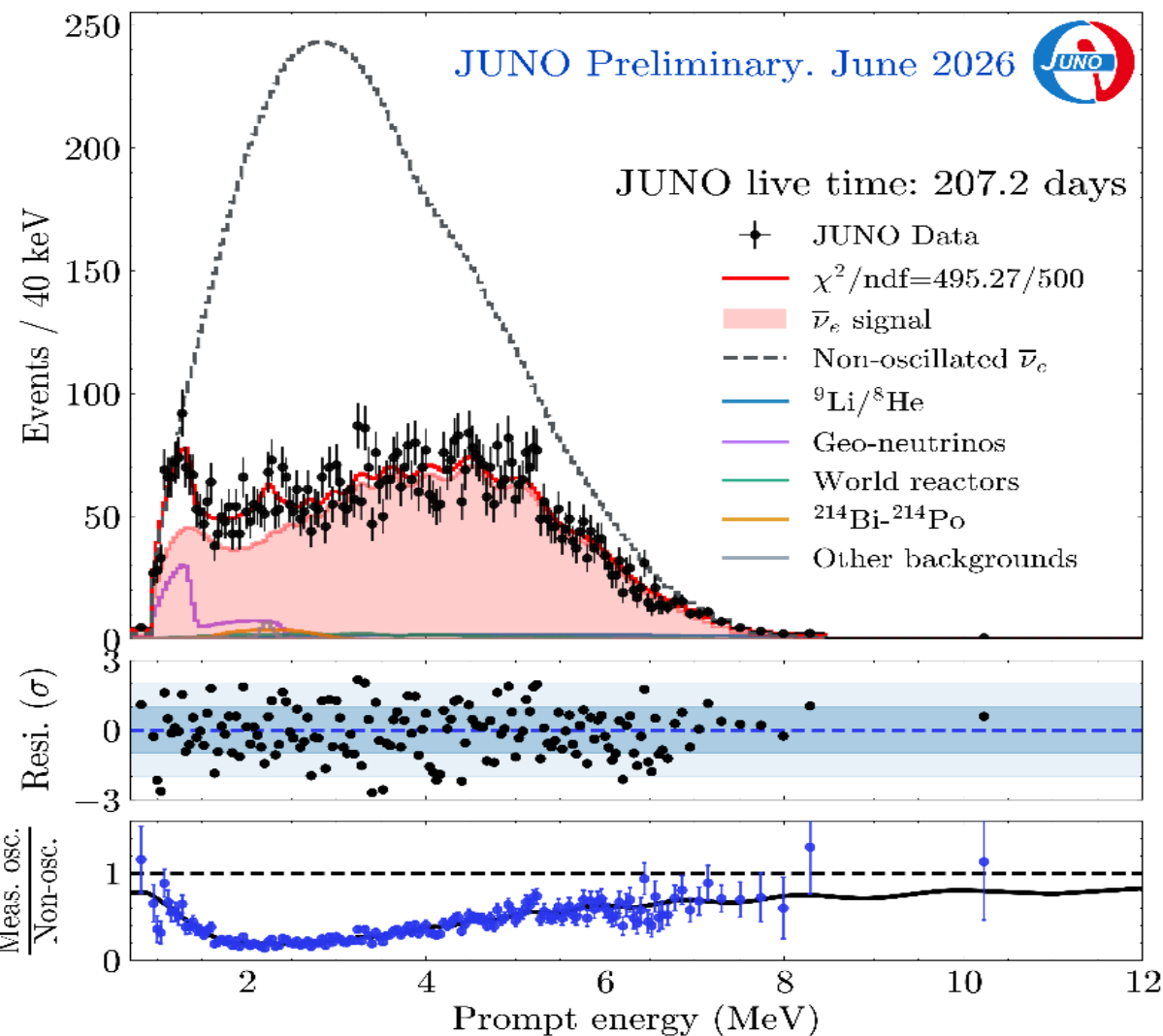
- Measured reactor neutrino event rate consistent with expectation
- Total live time is 207.2 days



Measured Reactor Neutrino Spectrum



Yifang's Slide @ $\nu 26$



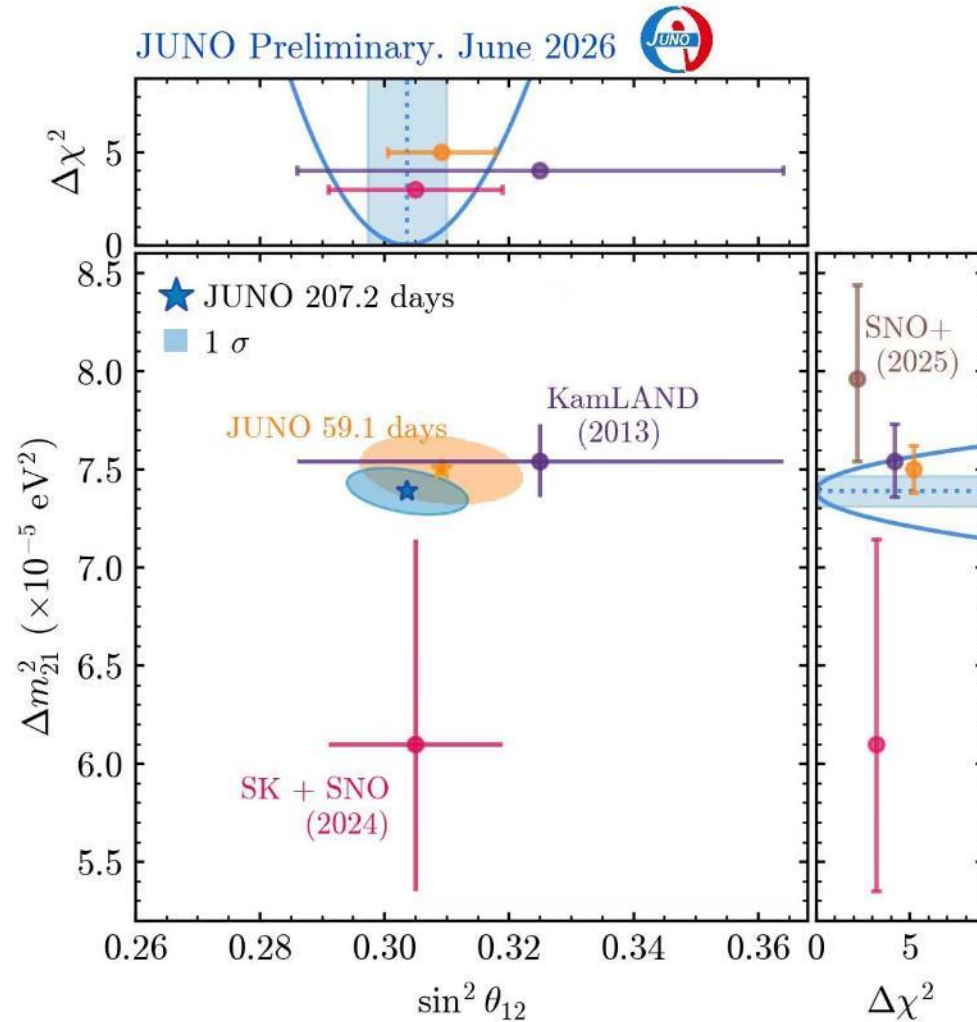
Fitting constrained
by the near detector
spectra from JUNO-
TAO and Daya Bay
(PRL 130 16, 161802)

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ϵ	σ_{rel}
Fiducial volume	87.12%	0.96%
PMT flasher rejection	> 99.9%	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency (ϵ_{tot})	74.01%	1.02%
$\bar{\nu}_e$ signal (cpd)		
w/o ϵ_{tot} corrected	36.02 ± 0.62	
w/ ϵ_{tot} corrected	48.67 ± 1.08	
Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 ± 0.09	0.92 ± 0.09
^{214}Bi - ^{214}Po	0.42 ± 0.31	0.57 ± 0.34
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01

Consistent results from three independent analyses

New Results of Solar Oscillation Parameters

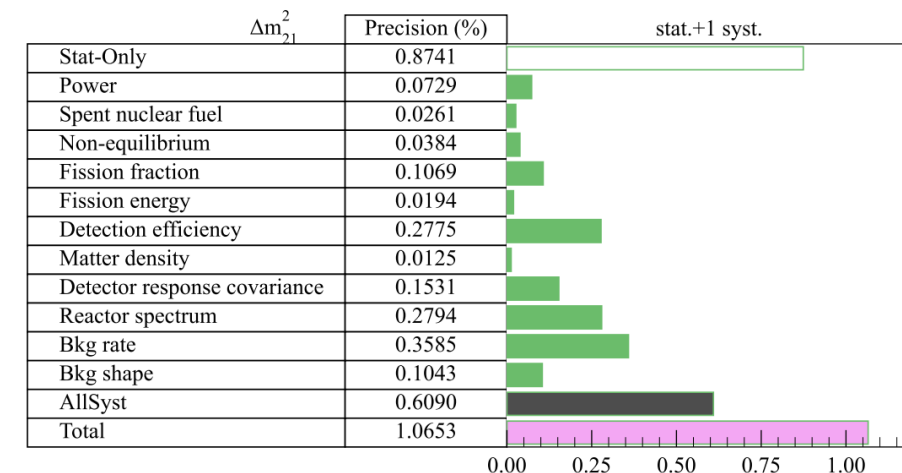
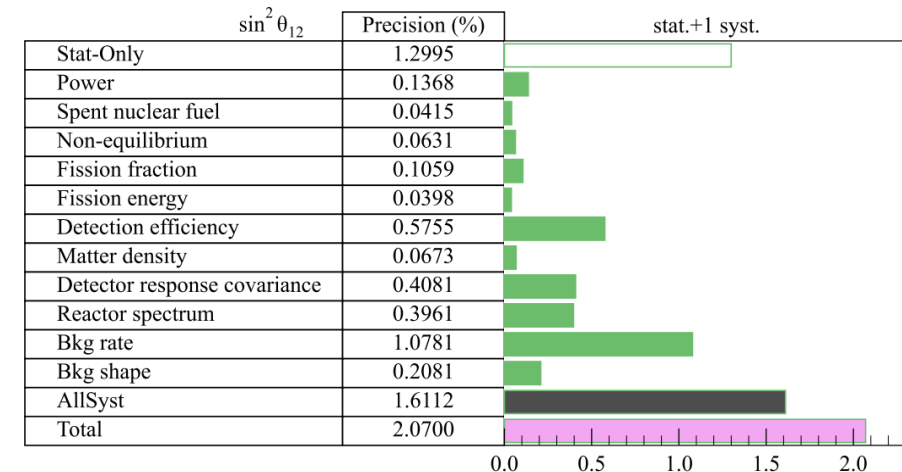
Yifang's Slide @ V26



Δm_{21}^2	7.388 ± 0.078 (1.60% $\rightarrow$ 1.06%)
$\sin^2 \theta_{12}$	0.3036 ± 0.0064 (2.8% $\rightarrow$ 2.1%)

- Even though the statistical uncertainty is dominant, systematic errors become important:

$\Rightarrow$ ^{214}Bi bkg. and detection eff. can be improved

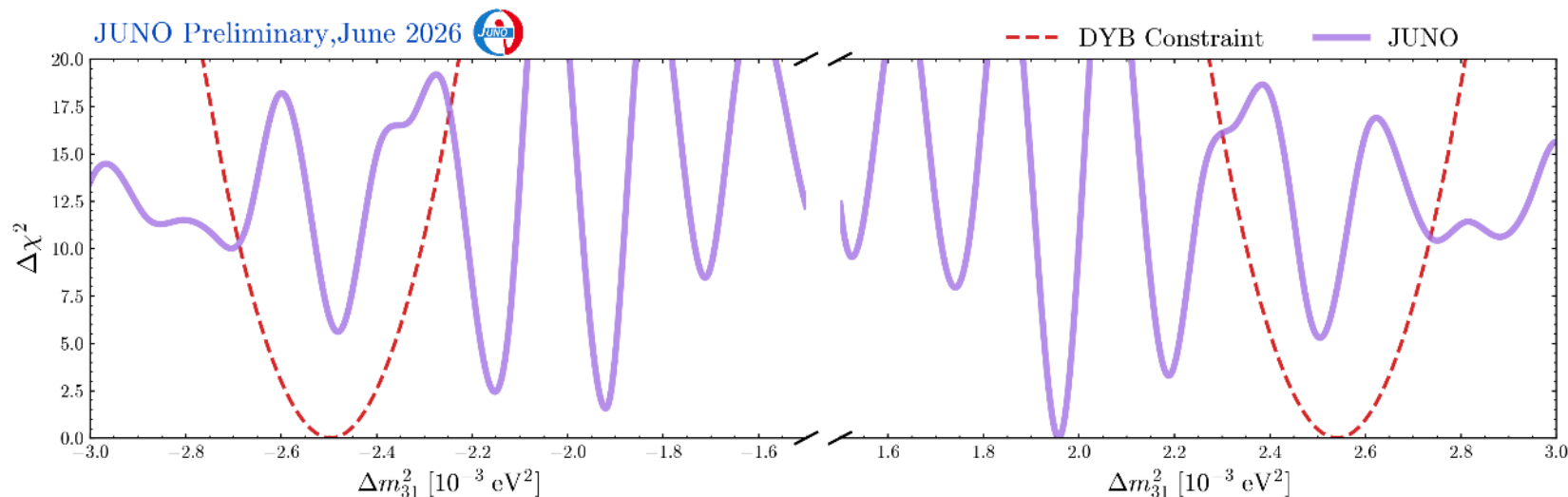


First Result of Δm_{31}^2

Yifang's Slide @ $\nu 26$

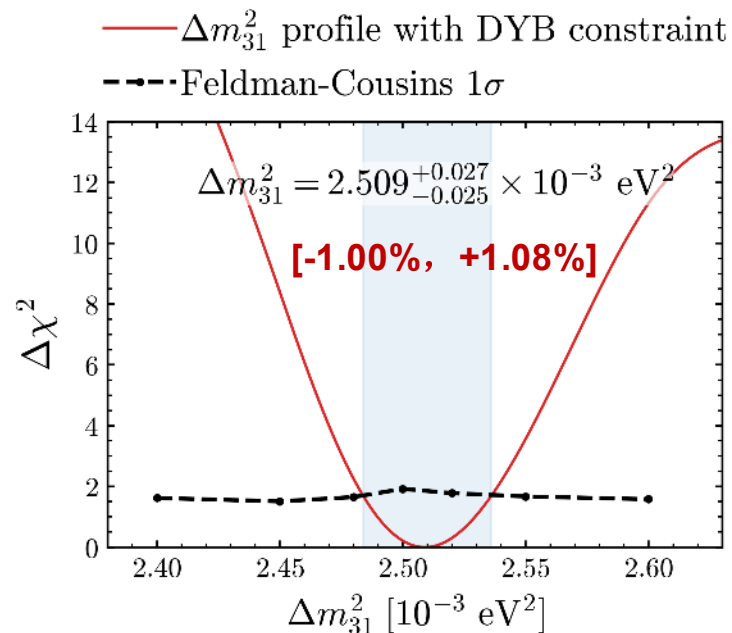
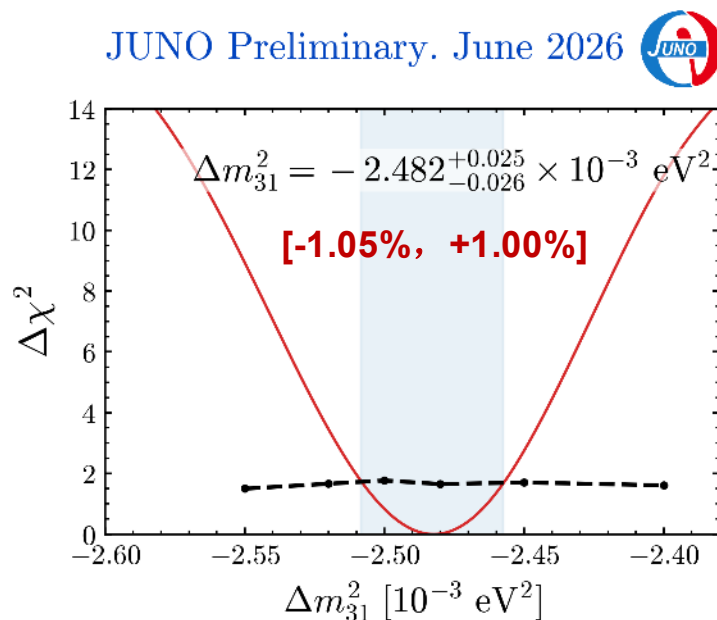


- Due to statistical fluctuations, JUNO only profiles of Δm_{31}^2 have multiple minima

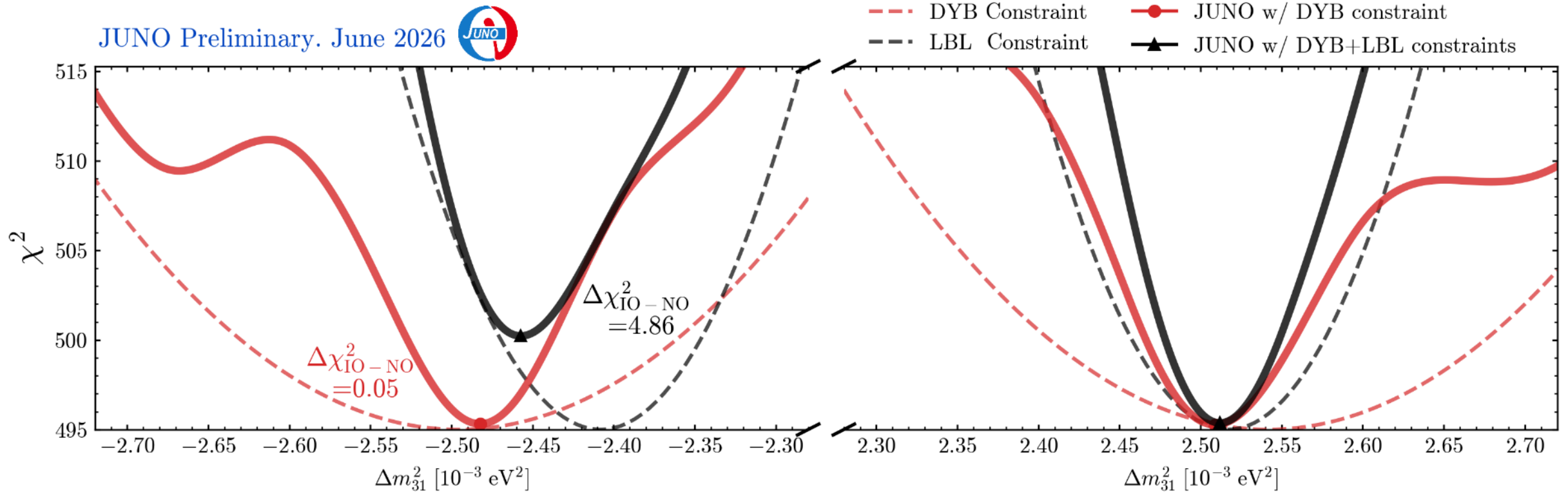


The final minimum for each mass ordering is obtained by using the Δm_{31}^2 constraint from the Daya Bay result (PRL 130 16, 161802)

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



- ◆ Δm_{31}^2 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)

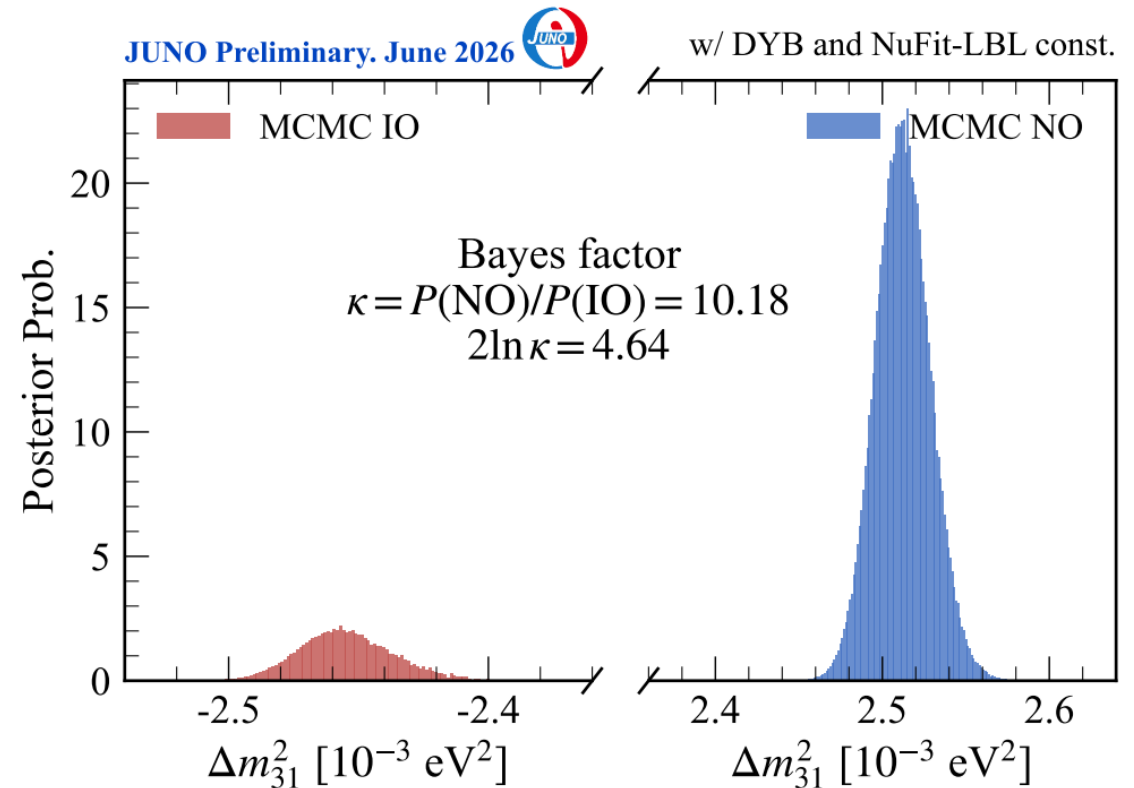
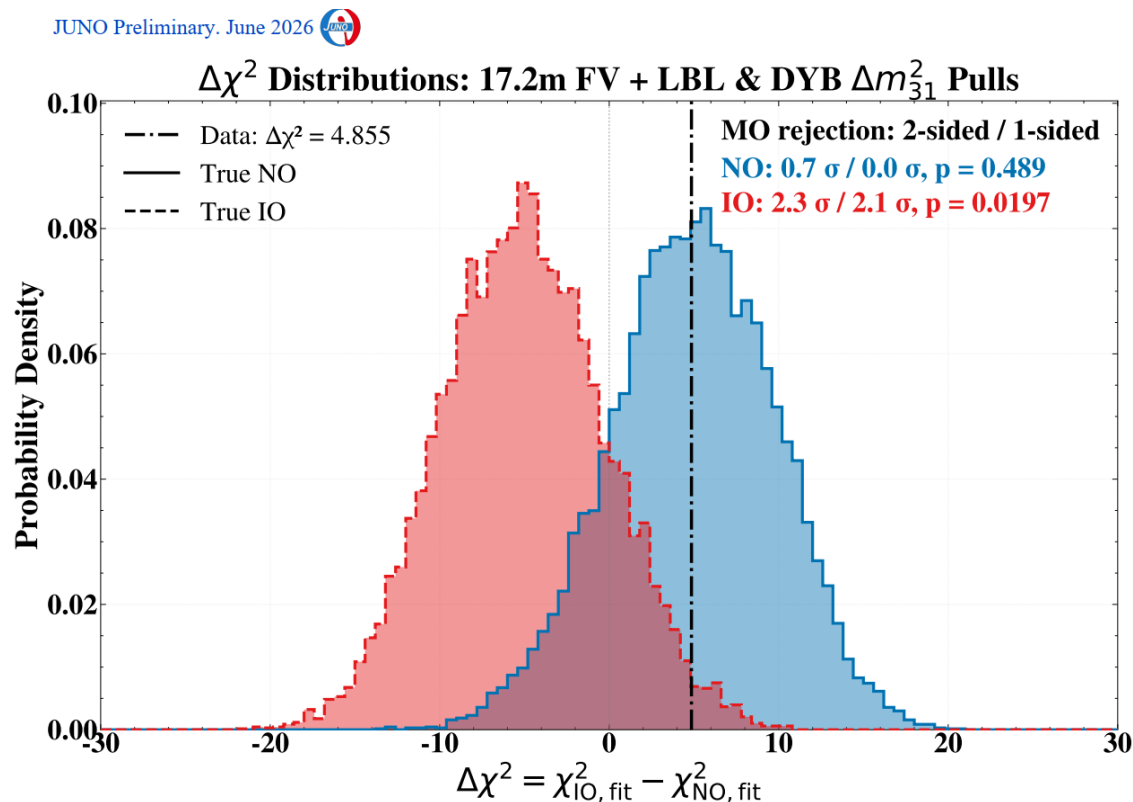
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Neutrino Mass Ordering Significance

Yifang's Slide @ $\nu 26$

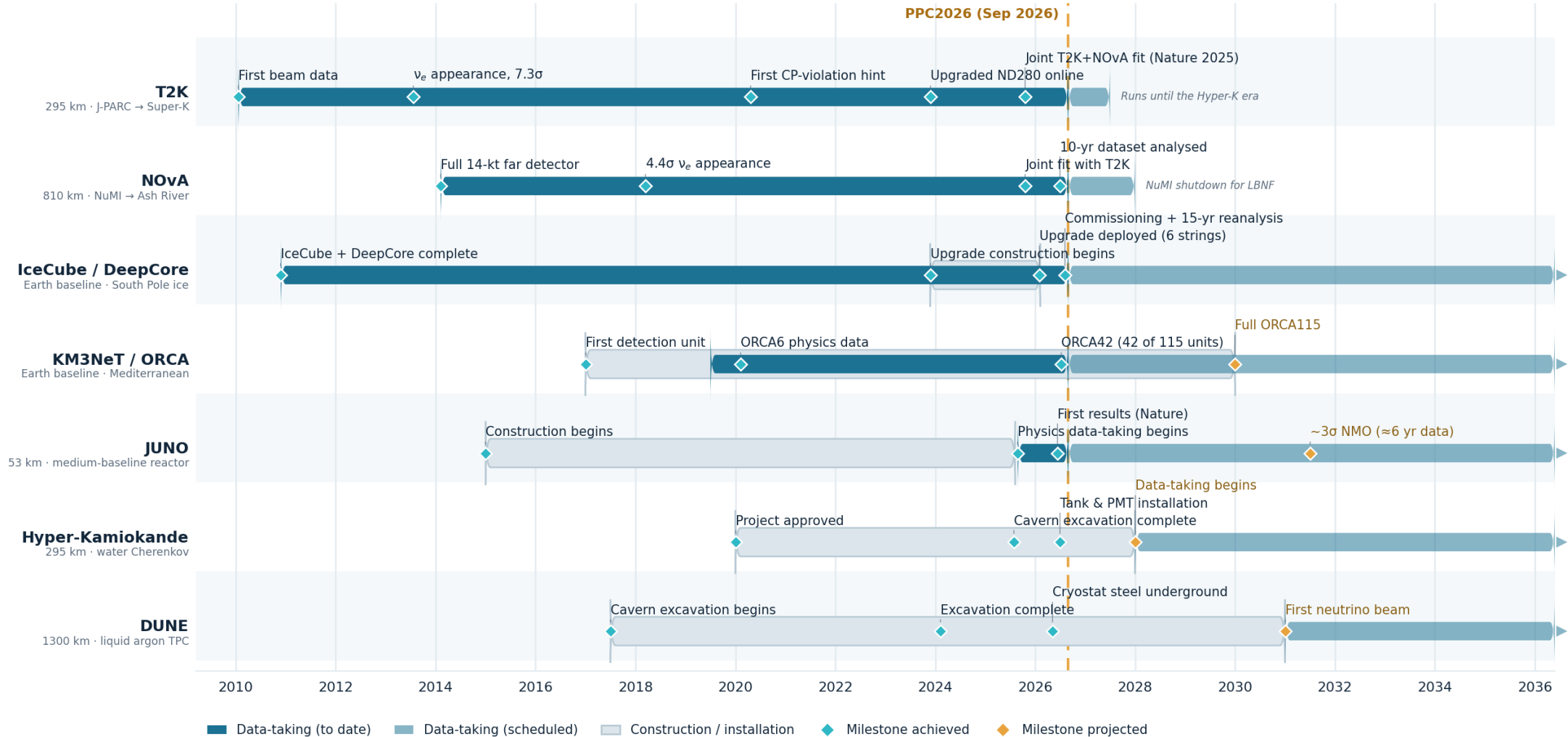


- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
 - Influence of δ_{CP} considered (scanned)
 - Normal Ordering is favored at **2.3 σ**
- Bayesian approach using Markov Chain Monte Carlo(MCMC) method
 - Normal Ordering is favored with a Bayes factor of **10.18** $\rightarrow 2\ln \kappa = 4.64$
- $\Rightarrow$ Consistent with the frequentist $\Delta\chi^2$



Looking Forward: No single experiment gets there alone

On a realistic timescale, the ordering could be and should be settled by a combination.



Sources: JUNO Collab., Nature (2026) and arXiv:2511.14593 · NOvA & T2K Collabs., Nature 646, 818 (2025) · IceCube Collab. press release, Feb 2026 (six of seven planned Upgrade strings deployed) · KM3NeT Collab., ORCA-42 announcement, 8 Jul 2026 · Hyper-K: arXiv:2605.11580 and ICHEP 2026 · LBNF/DUNE project milestones (fnal.gov) and Fermilab news release, 7 May 2026

Summary and Looking Forward

❖ **The neutrino mass ordering is not yet measured**

Global fits sit between roughly 2σ and 3σ for normal ordering, and the number depends on which atmospheric sample is included. Some analyses don't agree.

❖ **Four independent technologies are converging**

Medium-baseline reactor, accelerator long-baseline, atmospheric, and indirect probes.

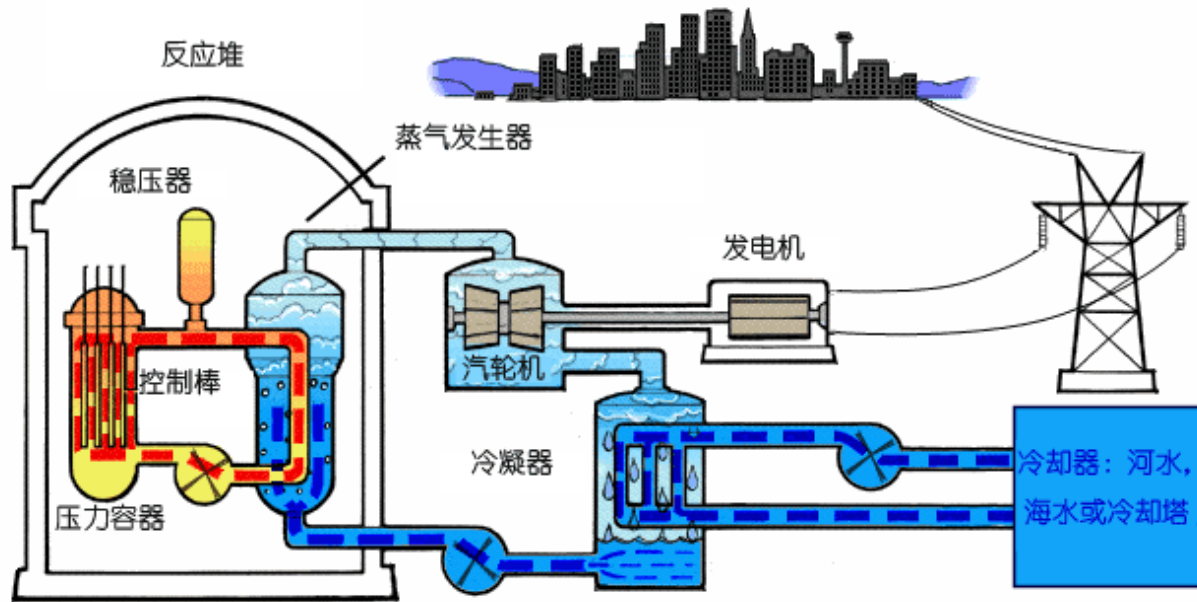
❖ **JUNO detector is a big success and has delivered first results**

World-leading θ_{12} and Δm^2_{21} from 59 days of data already; 207 days of data further improve precision; an **indication of normal mass ordering**.

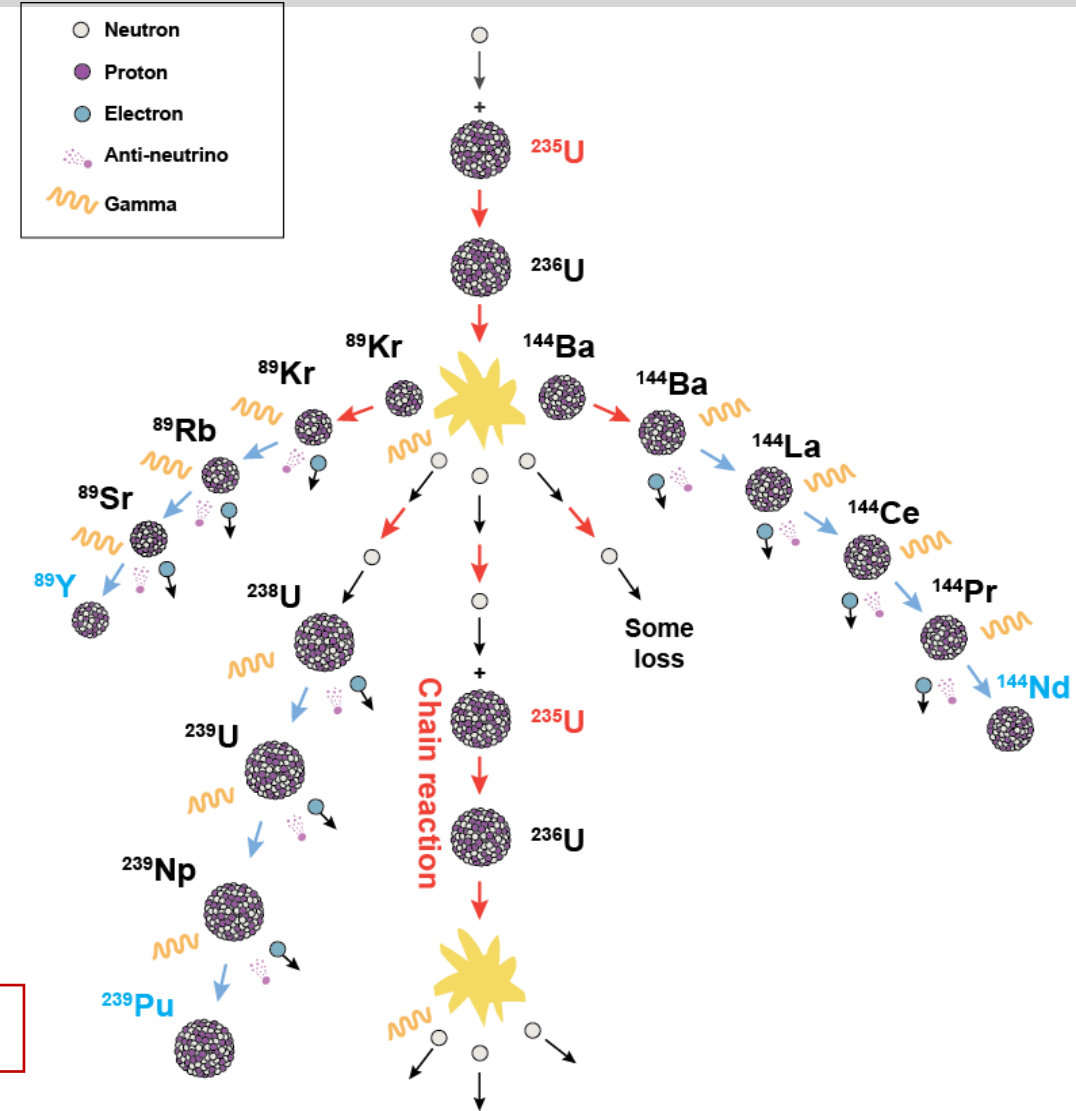
❖ **The first answer will come from a combination**

A structural change for neutrino physics: the field is moving from single-experiment discovery to global, multi-technology precision measurements.

Nuclear Power Plants and Reactor Neutrinos

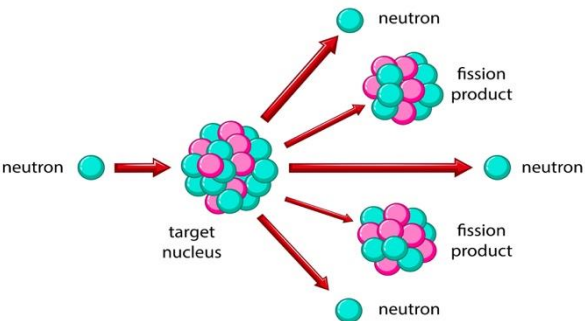


Reactor neutrinos take away ~5% fission energy.



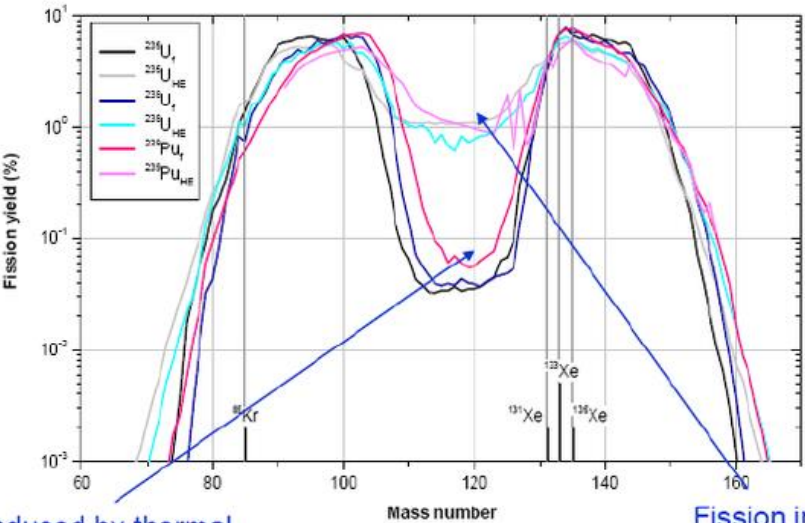
Reactor Antineutrino Anomaly (RAA)

Nuclear Fission



- *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)*

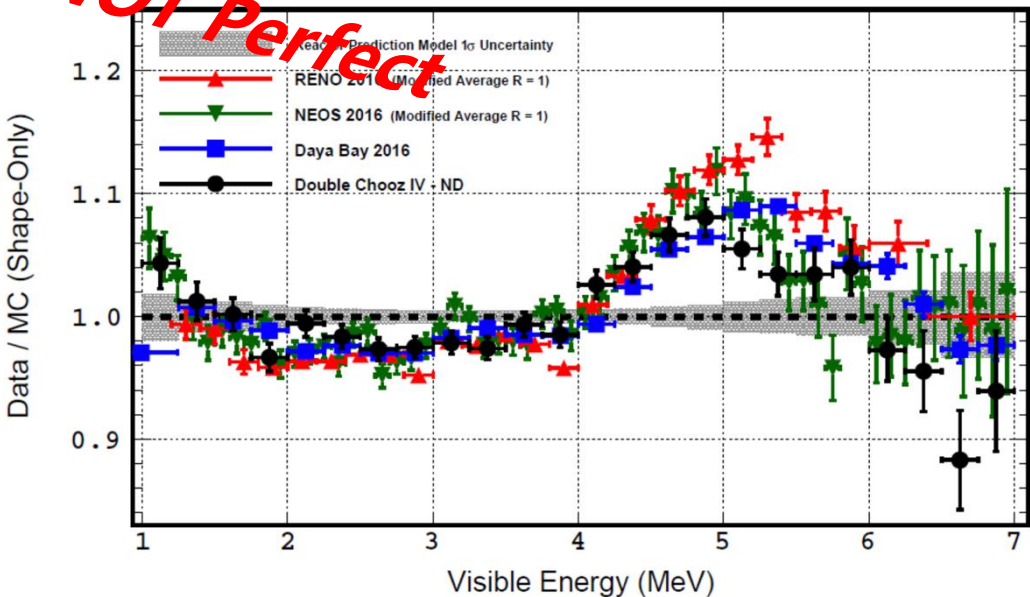
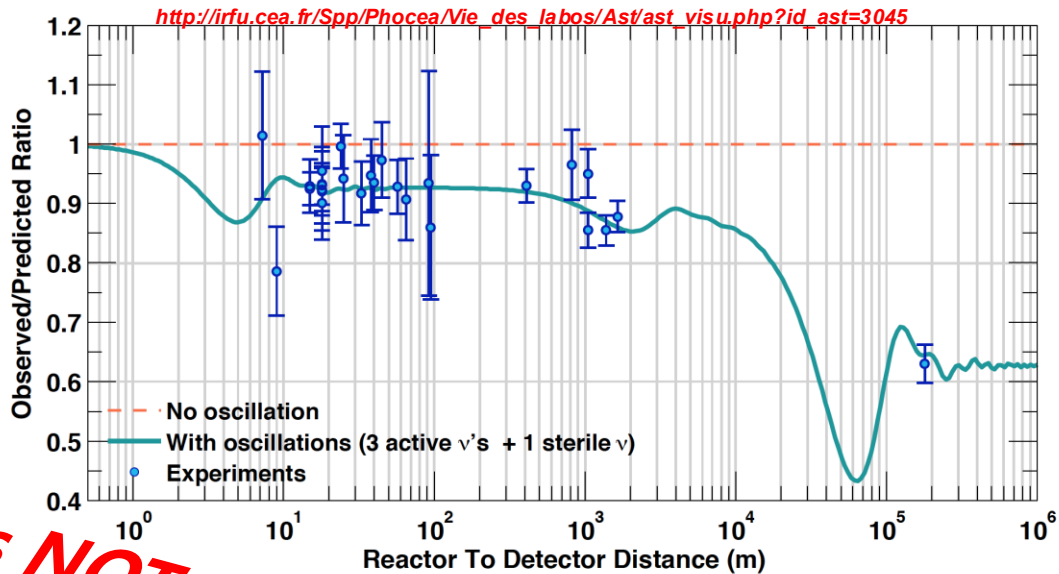
(Fission yield is a function of the fissioning nuclide and the incident neutron energy)



Fission induced by thermal (fission spectrum) neutrons

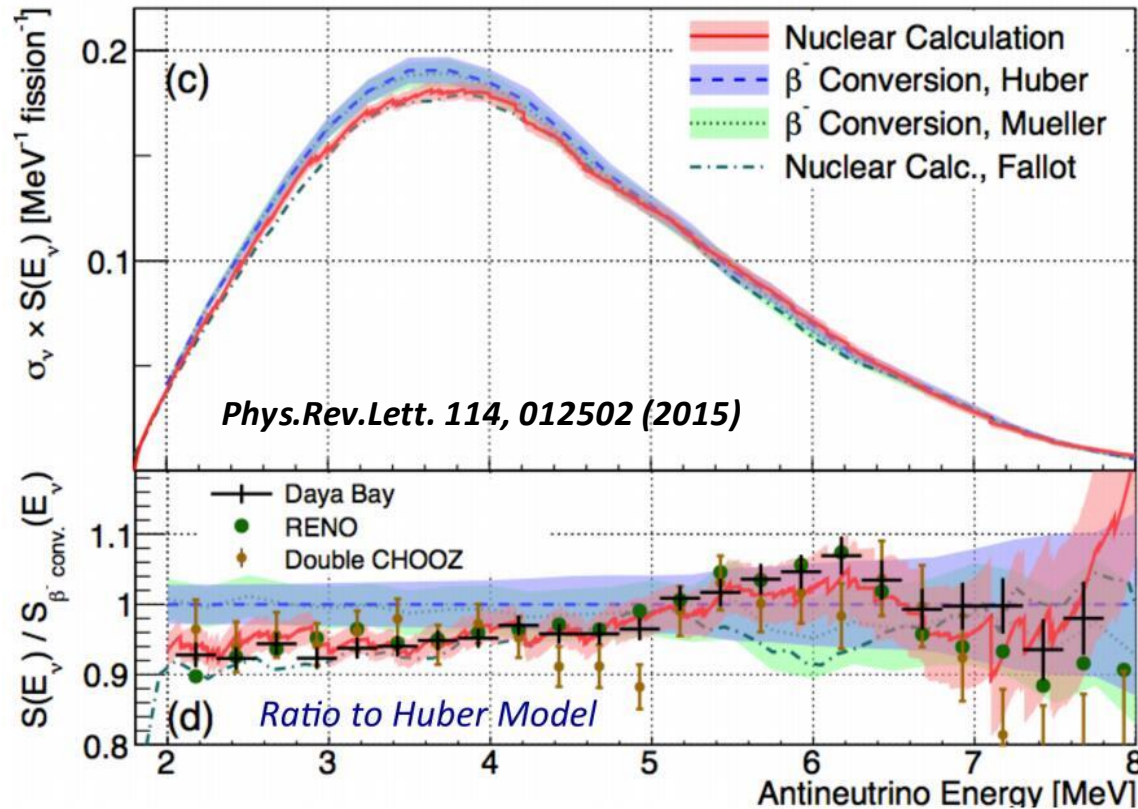
Fission induced by high energy neutrons (14.7 MeV)

Reactor Neutrinos NOT Perfect



The “*ab initio*” (summation) Method

$$S(E_{\bar{\nu}}) = \sum_{i=0}^n R_i \sum_{j=0}^m f_{ij} S_{ij}(E_{\bar{\nu}}) \quad f_{ij} \text{ — the branching fraction from isotope } i \text{ decaying to the energy level } j \text{ of daughter isotope}$$



R_i — the equilibrium decay rate of isotope i

$$R_i \cong \sum_{p=0}^P R_p^f Y_{pi}^c$$

✓ R_p^f — the fission rate of the parent *isotope* p

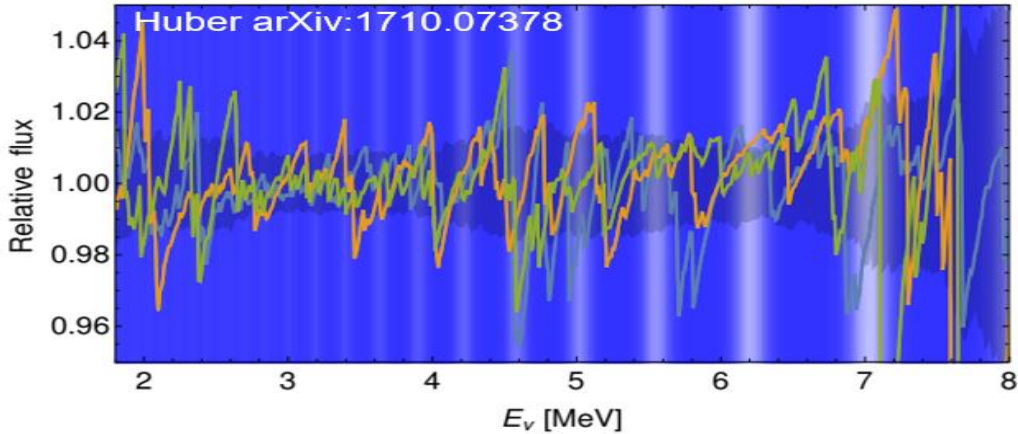
✓ Y_{pi}^c — the cumulative yield of isotope i

The 5 MeV bump was predicted with a **large uncertainty** from summation calculation.

Additionally, the **saw-tooth structures** were also predicted in the summation spectrum.

Why JUNO-TAO?

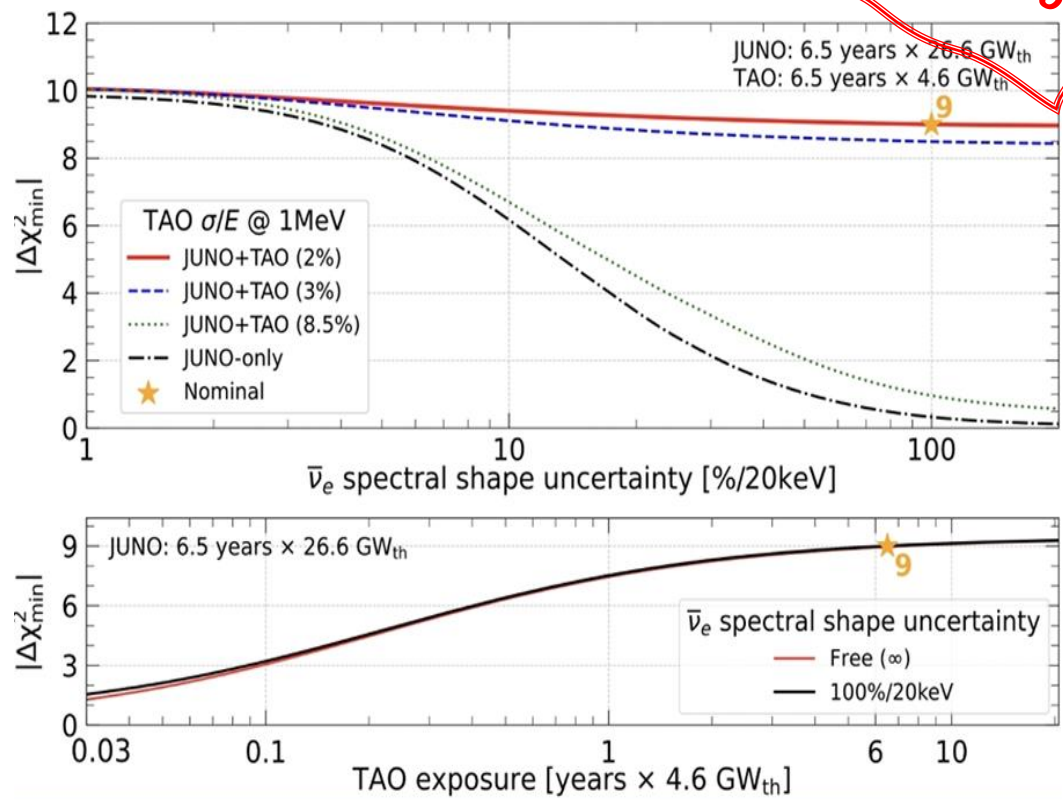
- Unknown intrinsic fine structures could bias JUNO's neutrino mass ordering (NMO) measurement



- No reliable theory/measurement to constrain
→ a **NEW DETECTOR**, with better energy resolution than JUNO (3% @1MeV)
- Taishan Nuclear Power Plant: 4.6 GW, a basement lab (500m², baseline 43.2 m, -9.6 m)
→ **Taishan Antineutrino Observatory, TAO**
(CDR arXiv 2005.08745)

JUNO NMO sensitivity dependency on TAO's energy resolution

JUNO-TAO@Neutrino'26
by Yichen Li

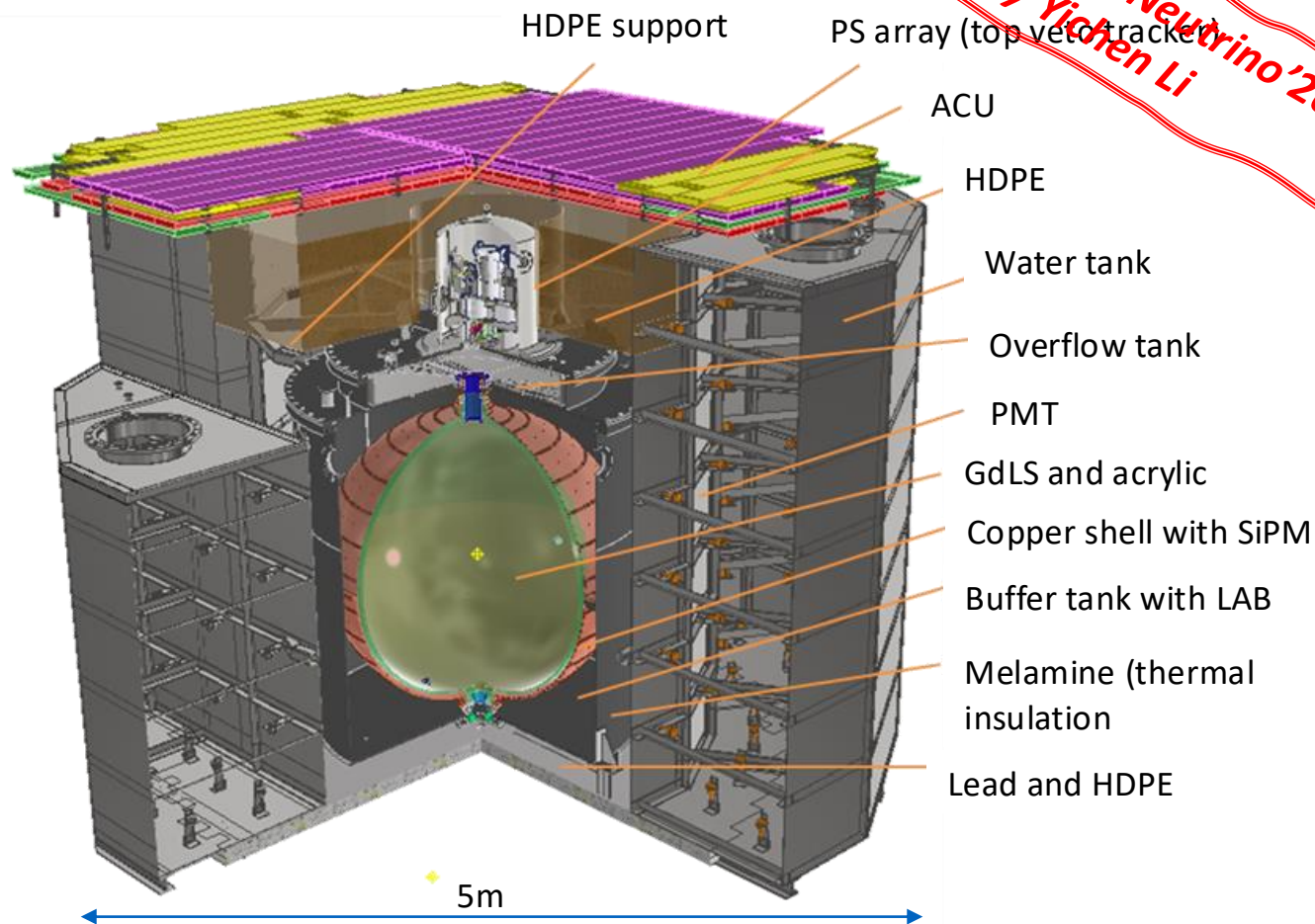


Chinese Physics C, 2025, 49(3)

JUNO-TAO Detector Design



- Central detector (CD)
 - 2.8 t GdLS in an acrylic vessel ($\phi = 1.8\text{m}$)
 - 10 m^2 SiPM on a copper shell
 - Tank filled with buffer LAB
 - Automated Calibration Unit (ACU) (from Daya Bay) and Cable Loop System (CLS)
- 2 veto detectors
 - 3 water Cerenkov detectors
 - 4 layers of plastic scintillator (PS) bars

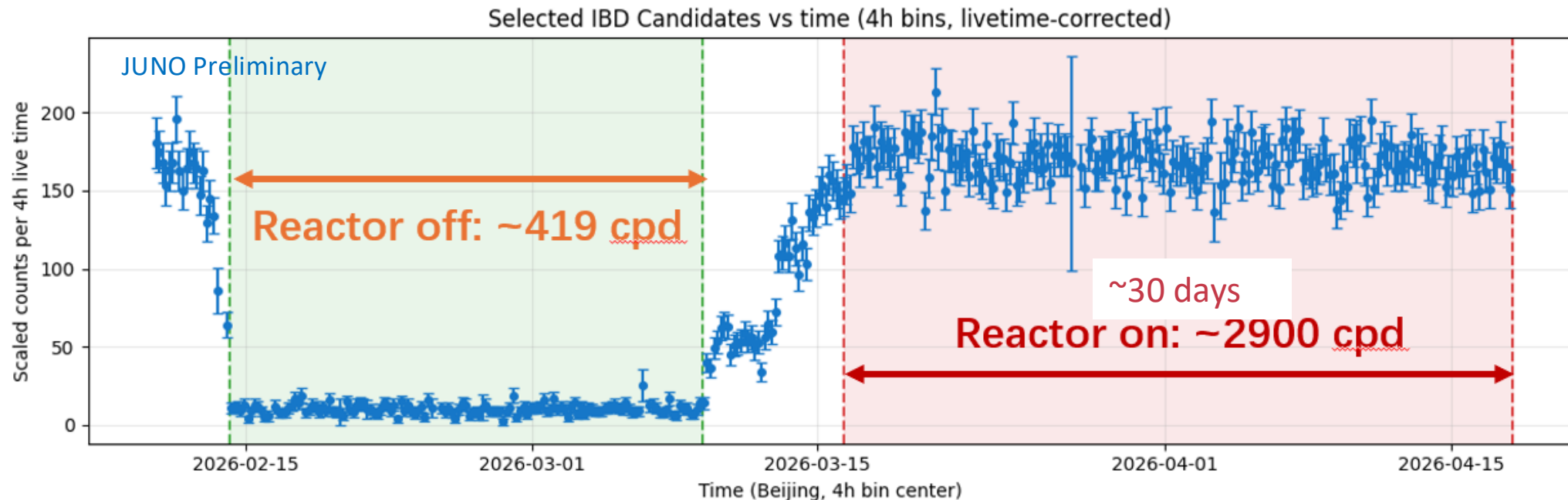


JUNO-TAO @ Neutrino'26
by Yichen Li

IBD Analysis: Observed IBD Signal Rate

- **Observed IBD signal rate:** $\sim 2500/\text{day}$, from reactor-on data minus (scaled) reactor-off data.
- **S:B = 6:1 w/o PSD (pulse shape discrimination),**
 - Really good for shallow overburden experiment
 - could be improved in future

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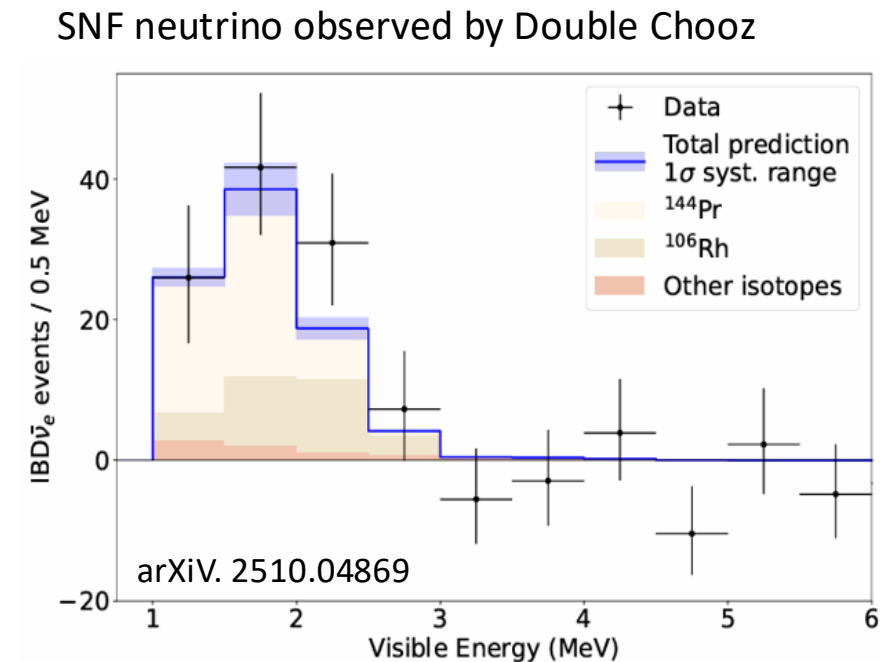
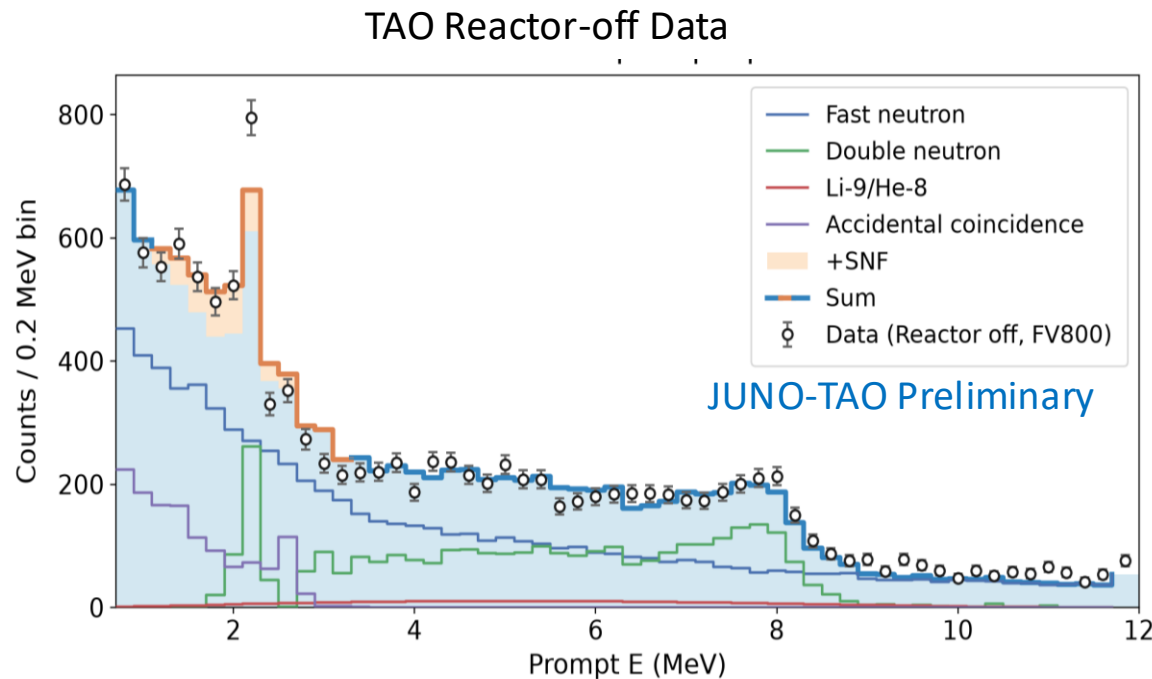


IBD Analysis: Reactor-off & SNF Neutrino



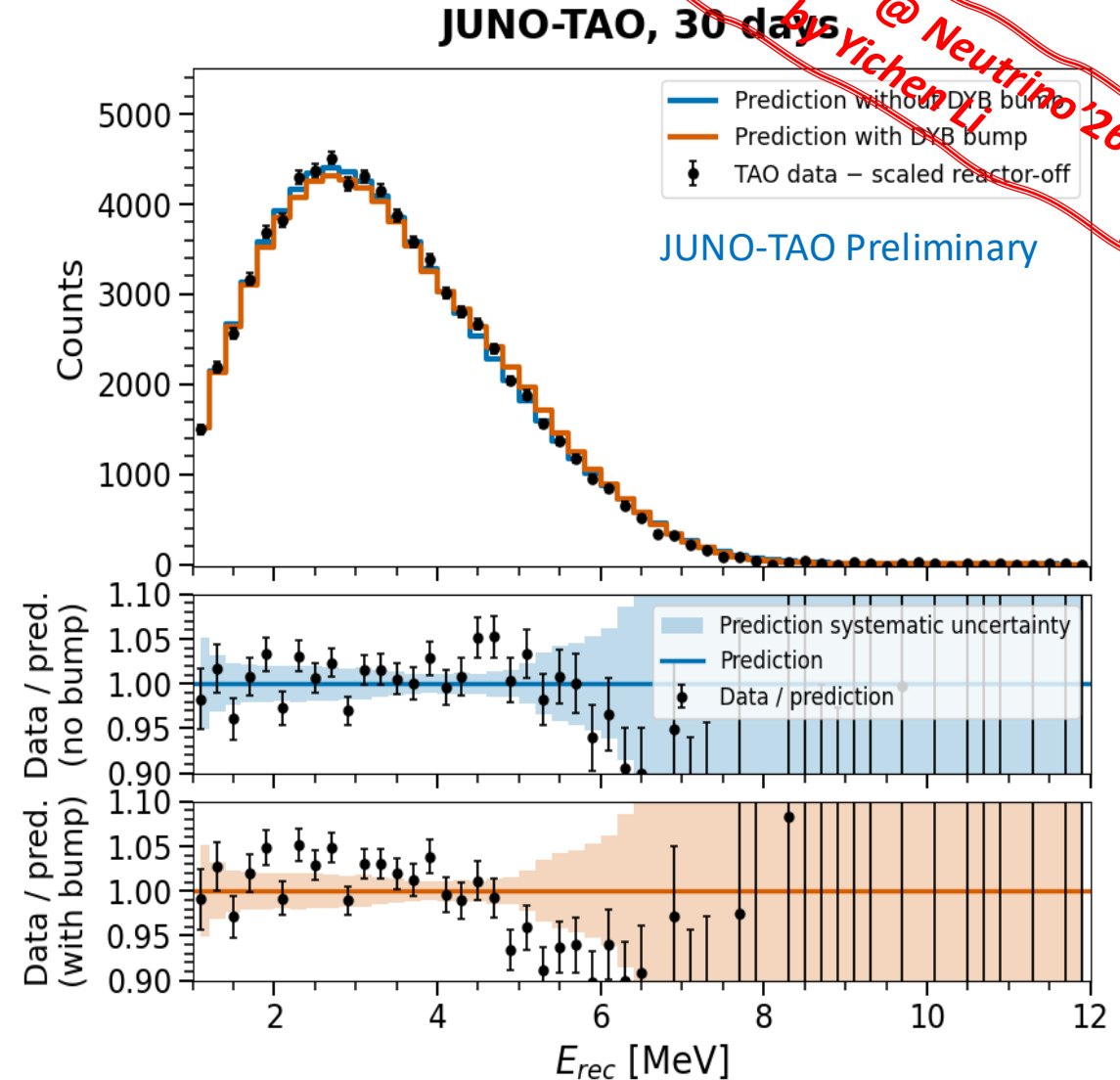
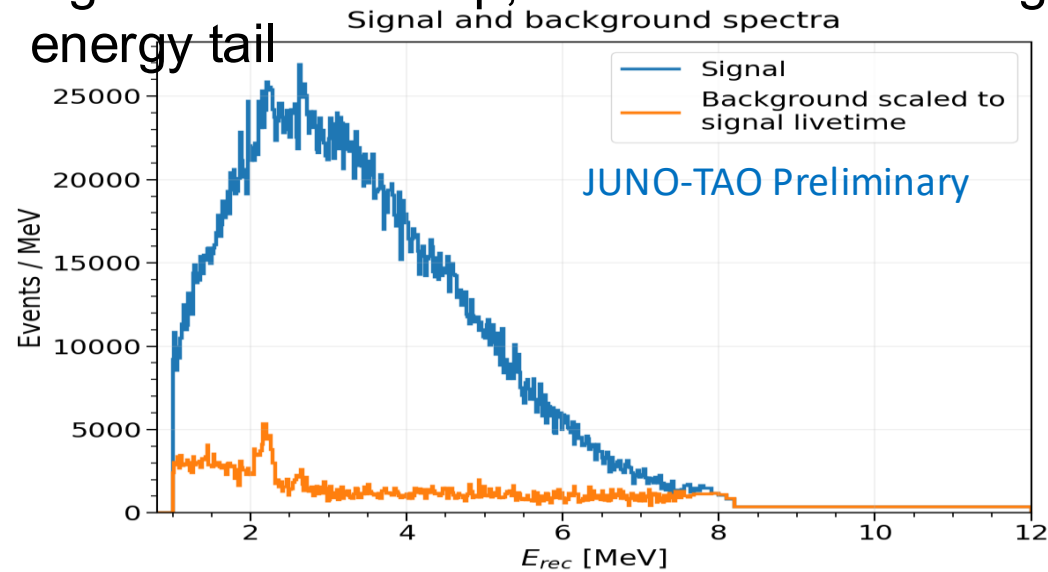
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- Direct measurement of background
- Direct measurement of spent nuclear fuel (SNF) neutrino
 - Background: date-driven estimation except for Li-9/He-8, can be further suppressed
 - Remote reactor OFF makes SNF neutrino signal clearer



IBD Analysis: Prompt Event Energy Spectrum

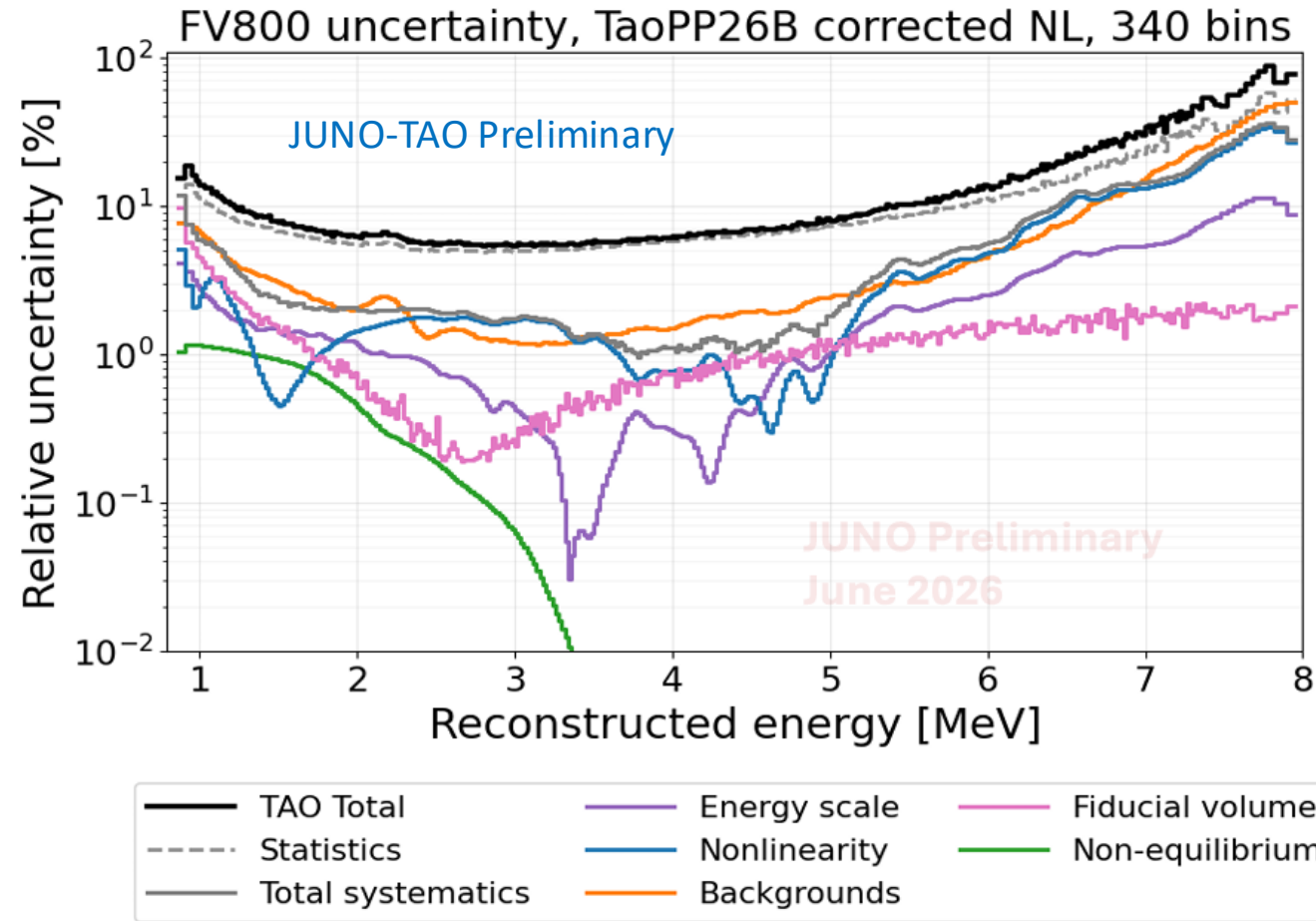
- **Prediction:** Huber-Mueller model (PRC, 83:054615, 2011, PRC, 84:024617, 2011) + Daya Bay correction (PRL 123(11):111801, 2019) + non-equilibrium correction, convoluted with TAO detector response
- **Results:** good data/prediction agreement, sign of 5 MeV bump, small difference in high energy tail



IBD Analysis : Shape Uncertainty

- **Statistical uncertainty dominates**, with 1 month data and 20 keV bin
- **Systematics**: energy non-linearity and background (neutron) subtraction (neutron)

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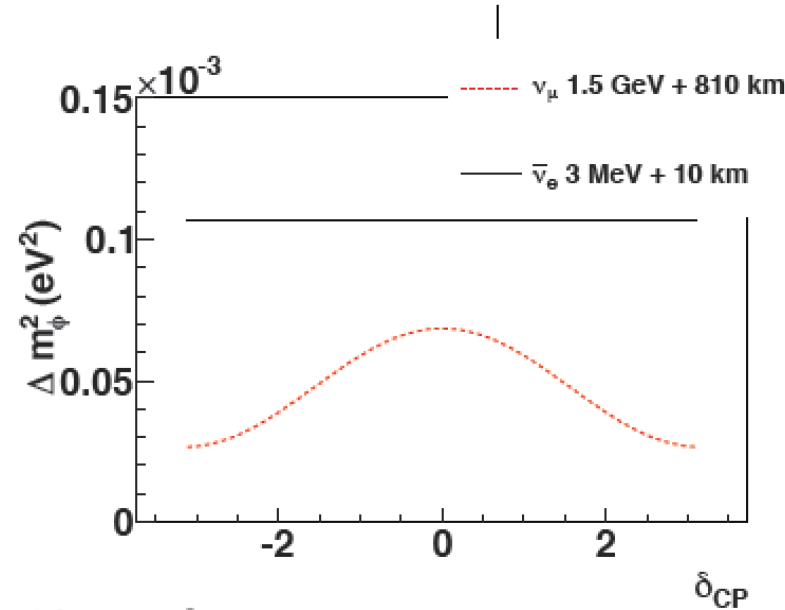
e- / μ -Flavor “Feels” Mass Ordering Differently

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

$$= 1 - 2s_{13}^2 c_{13}^2 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \Delta_{21} + 2s_{13}^2 c_{13}^2 \sqrt{1 - 4s_{12}^2 c_{12}^2 \sin^2 \Delta_{21}} \cos(2\Delta_{32} \pm \phi)$$

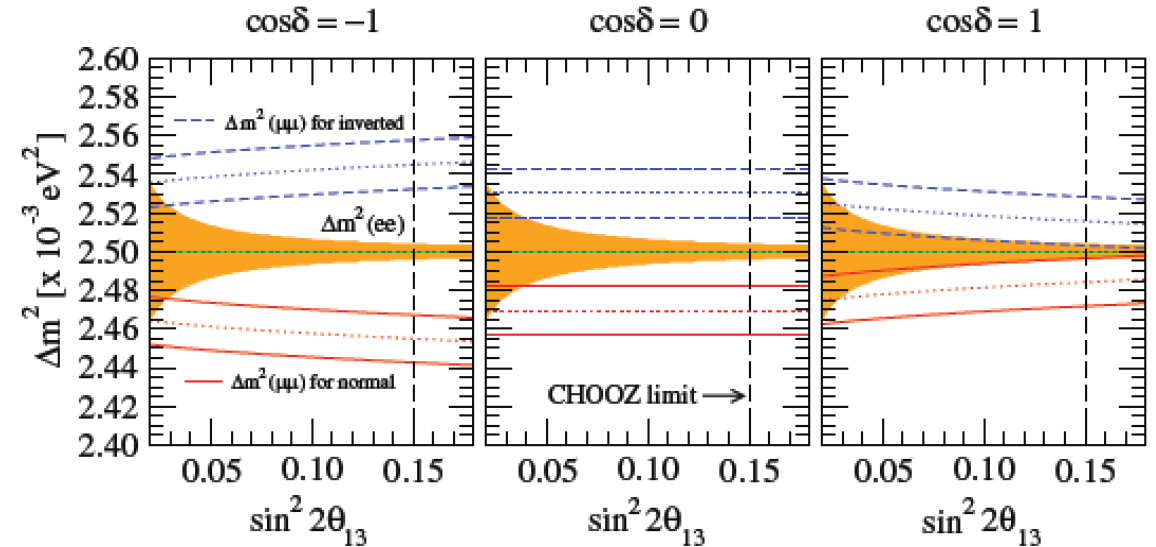
- Both reactor and long-baseline experiment measure mass-squared splitting
- A natural question to ask: Is this meaningful?

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



Qian et al, PRD87(2013)3, 033005

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



Minakata et al PRD74(2006), 053008

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

The Evolution of Large Volume LS Detectors: 1956-2025



From 200+ kg to 20kt over 70 years



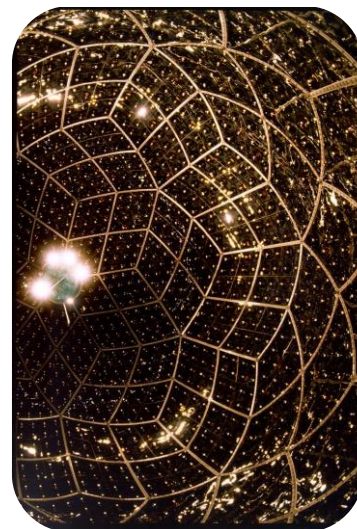
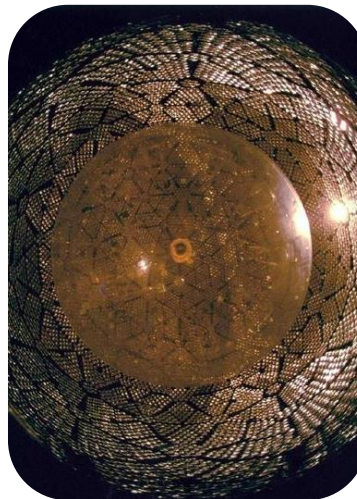
300 L



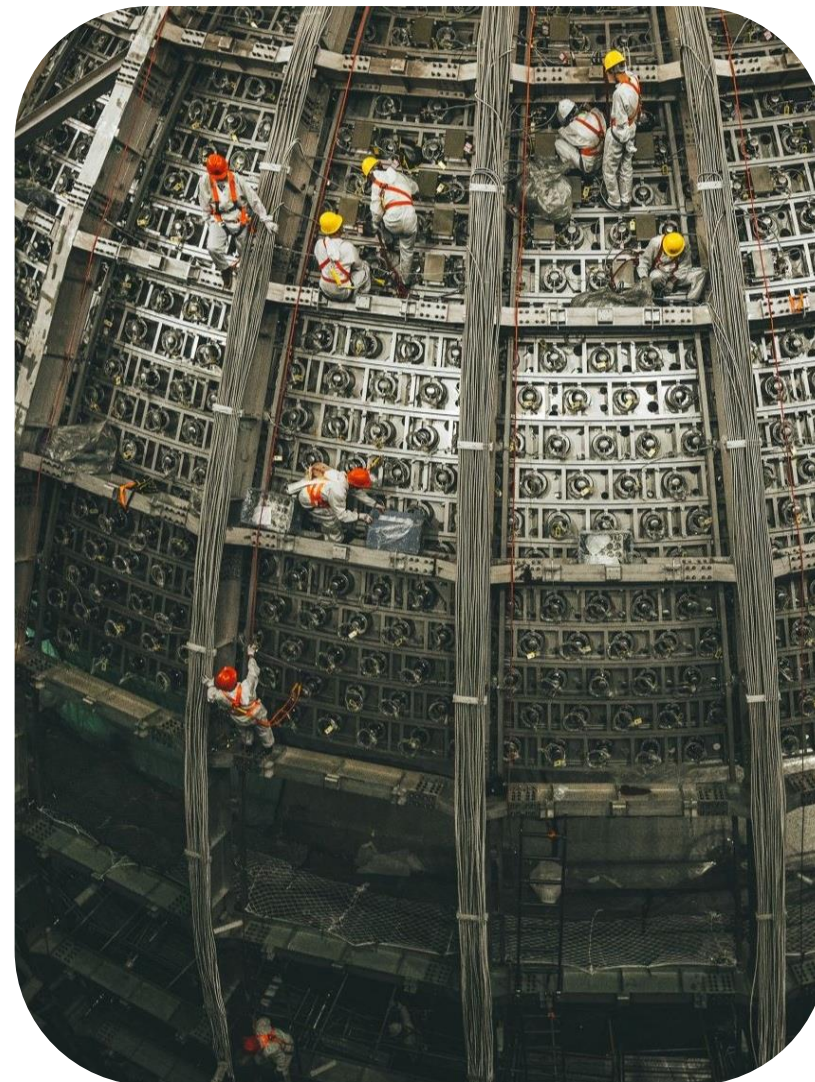
8 x 20 tons



300 t



1000 t



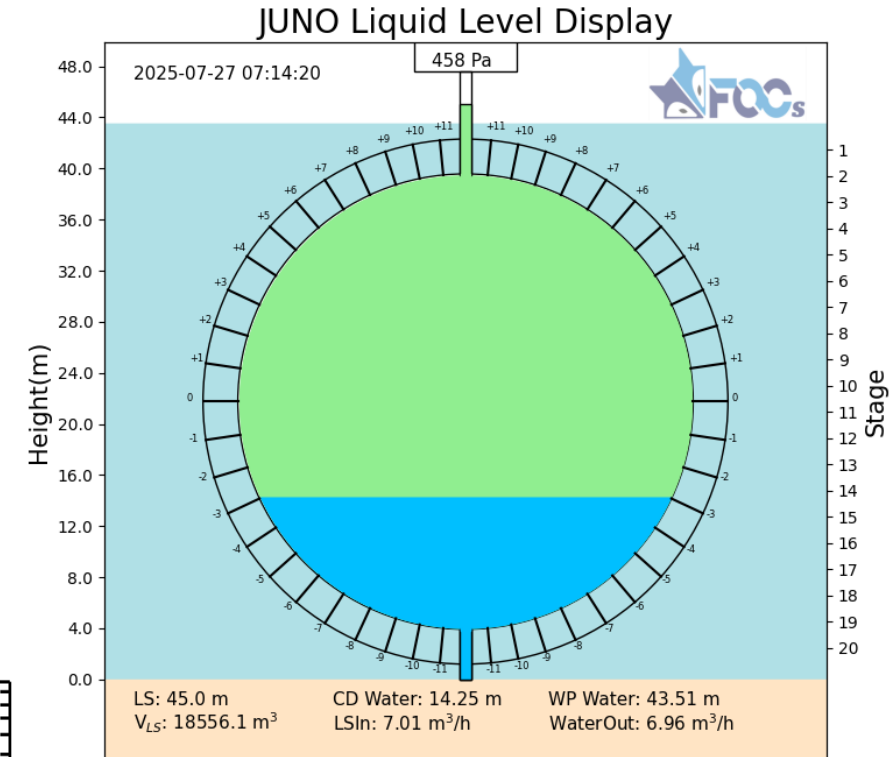
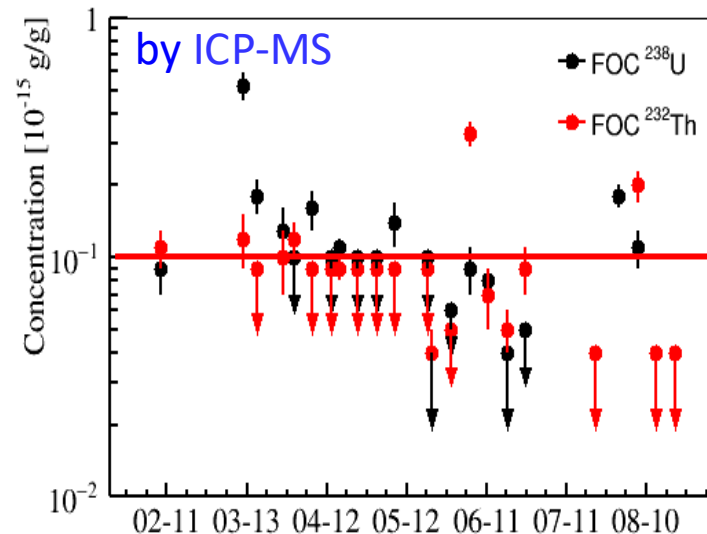
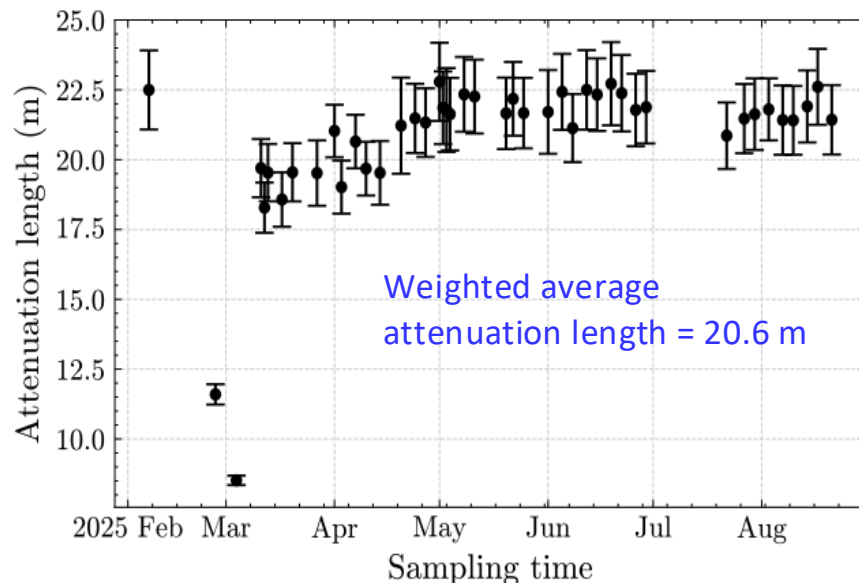
20,000 t

Water and LS Filling

Yifang's Slide @ v26

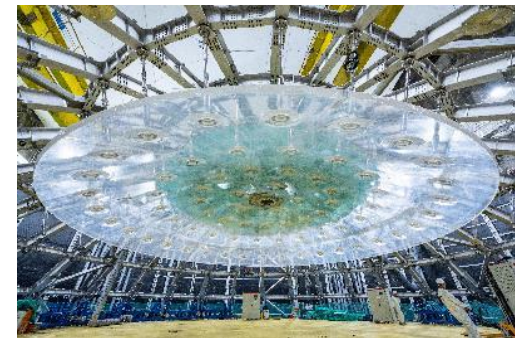
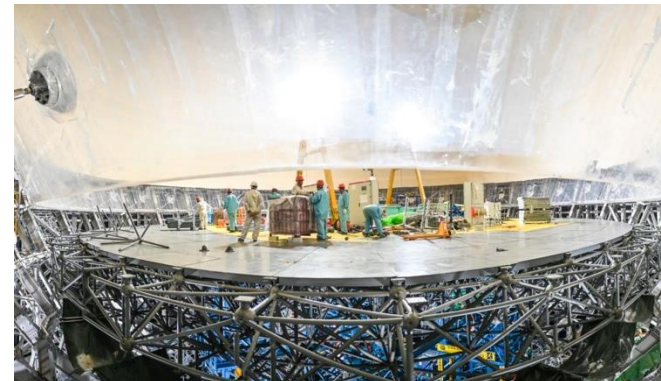
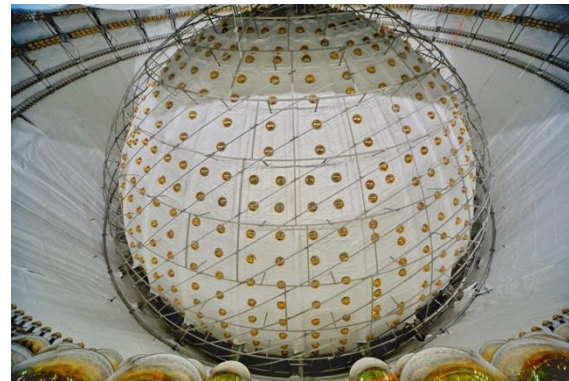
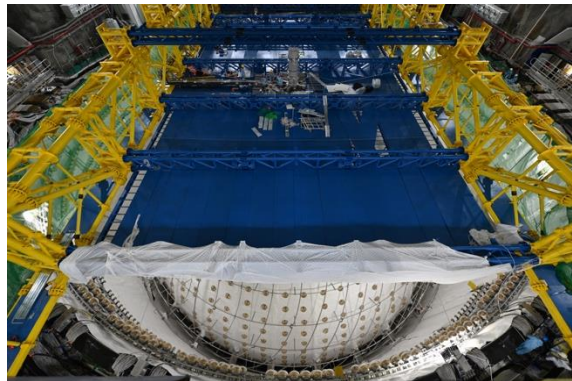
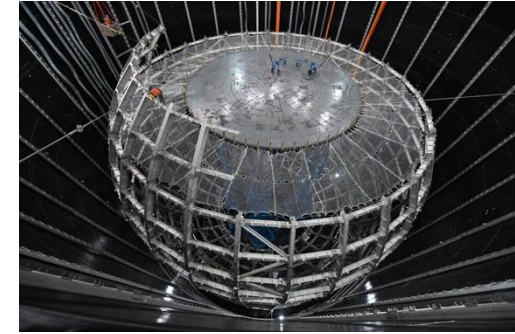


- Water filling for cleaning the CD, testing the mechanical structure, as well as the detector commissioning
- Replace water by LS at a rate of 7 t/h, 6 months/volume
- Optical transparency and radioactive background control:
 - ✓ Weighted average LS attenuation length > 20m
 - ✓ Weekly LAB/LS sampling: U/Th < 1×10^{-16} g/g by ICP-MS
 - ✓ ^{222}Rn in fresh LS by OSIRIS+CD: < 1 mBq/m³
 - ✓ ^{14}C $\sim (4-5) \times 10^{-17}$ g/g measured by several methods



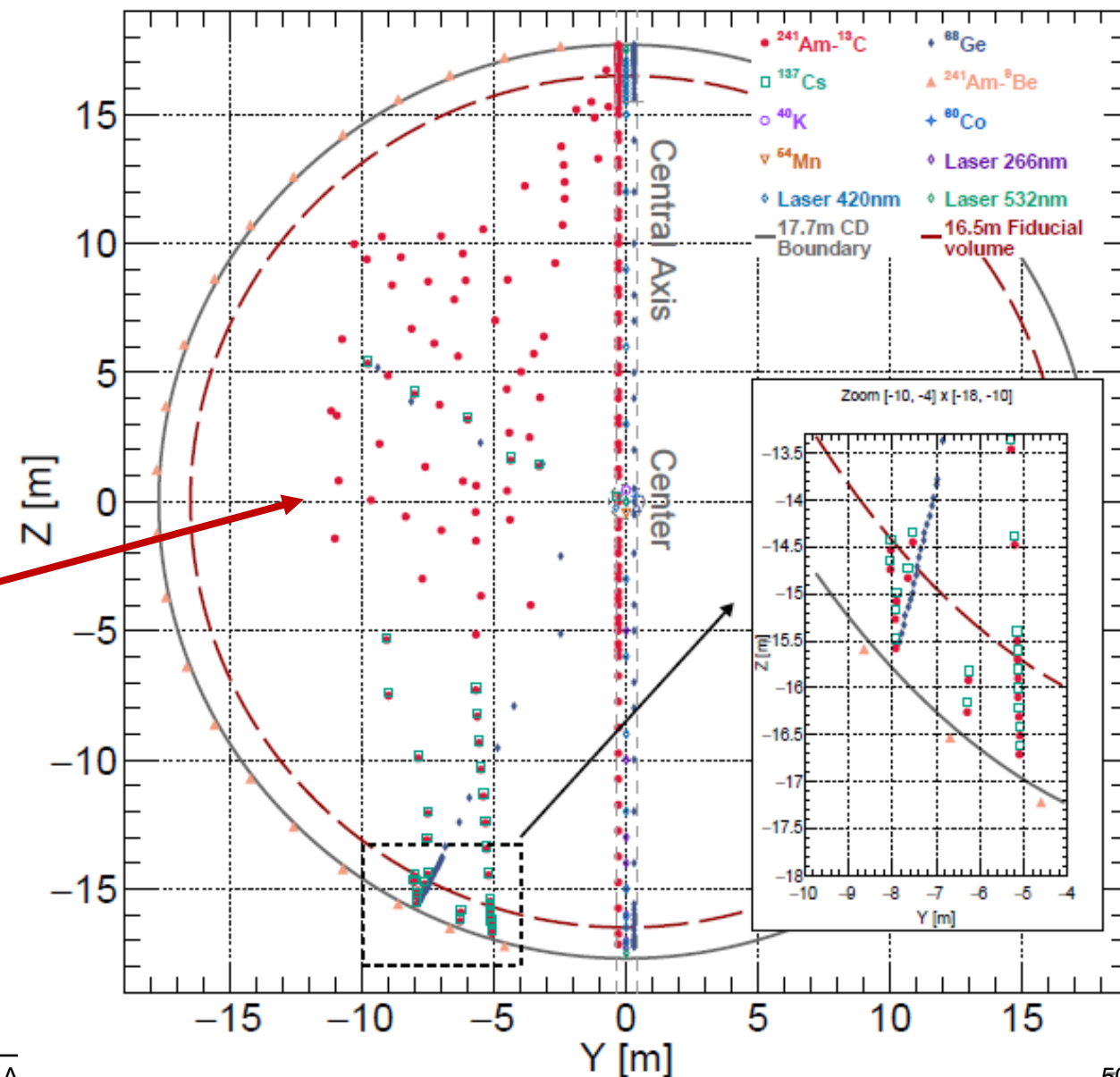
- LS Filling completed on 8/22/2025
- LS in the CD: 23231.6 m³
- Water in the pool: 41225.1 m³

The Construction of the Central Detector of JUNO



- 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

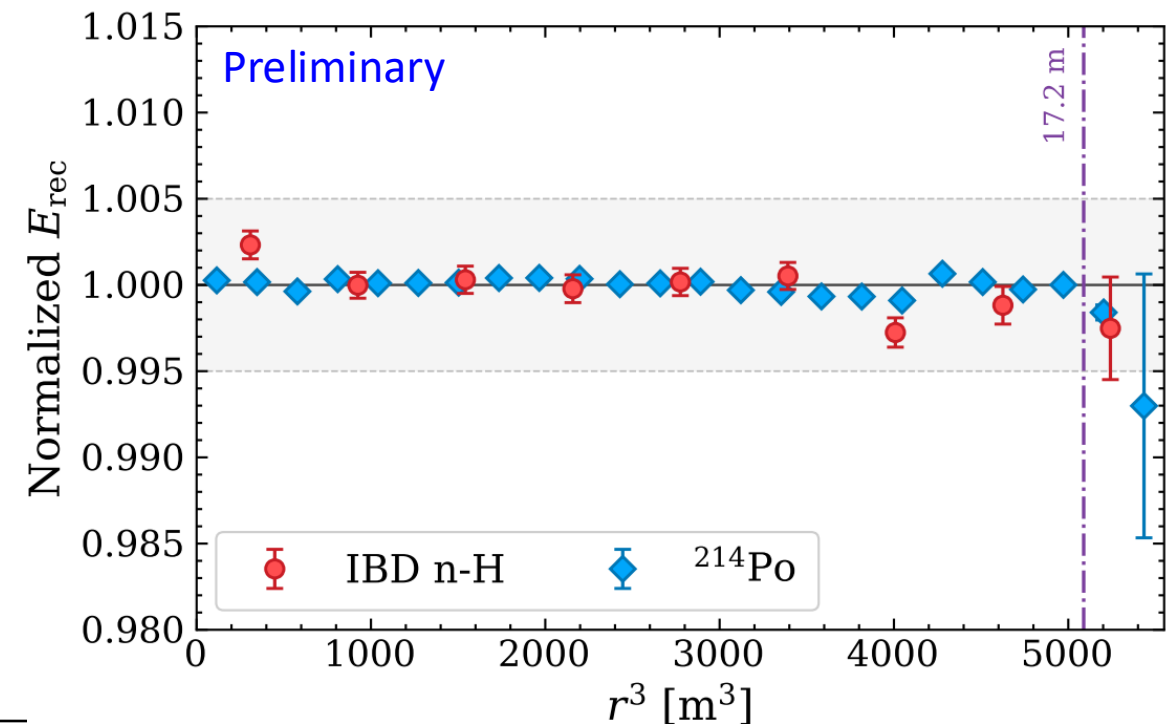
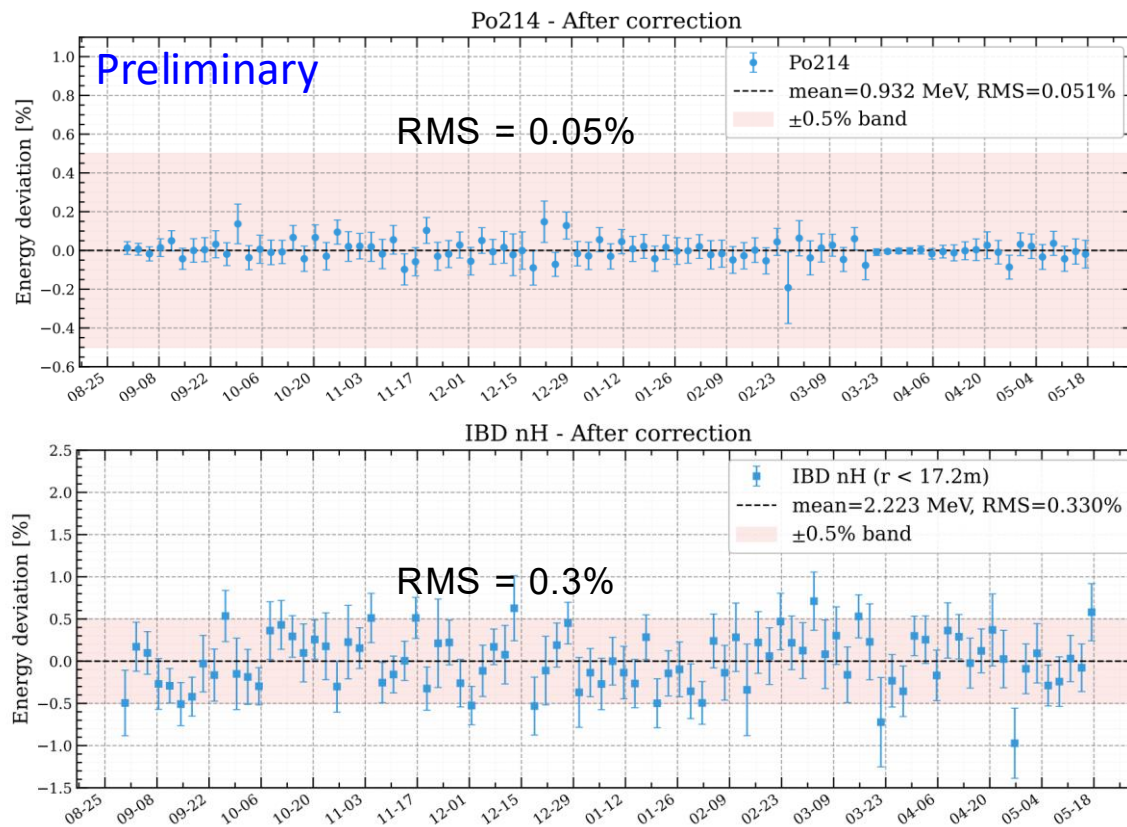


Reconstruction and Energy Correction

Yifang's Slide @ v26



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

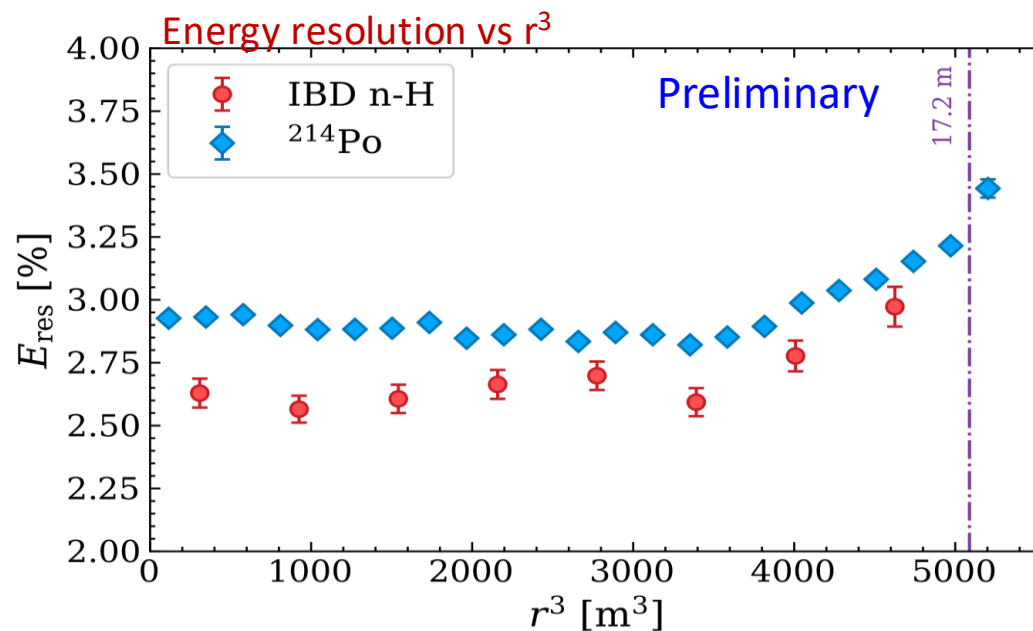
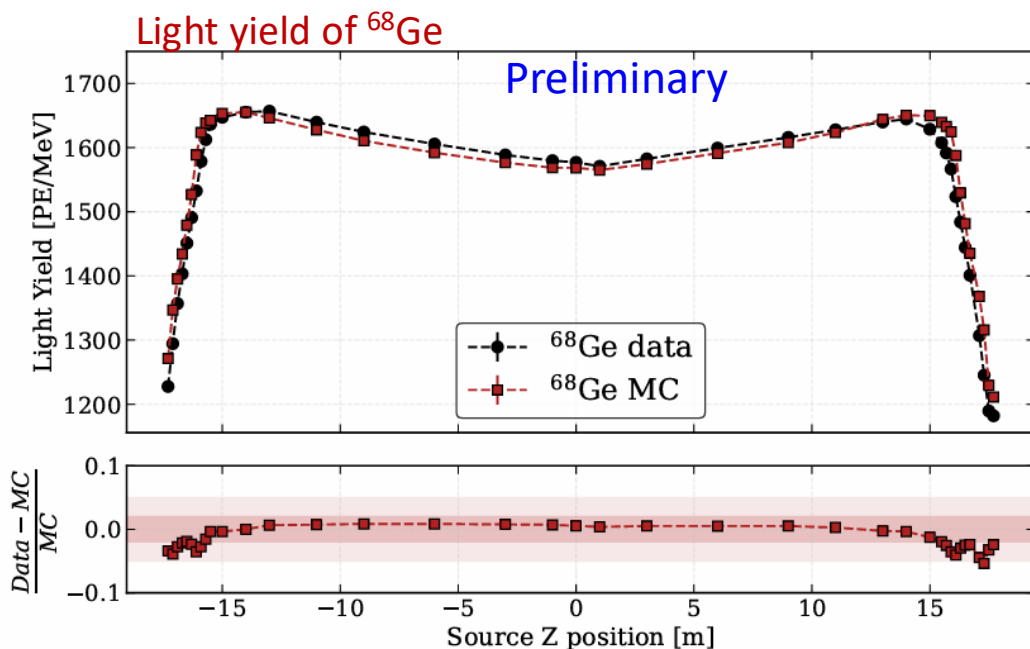
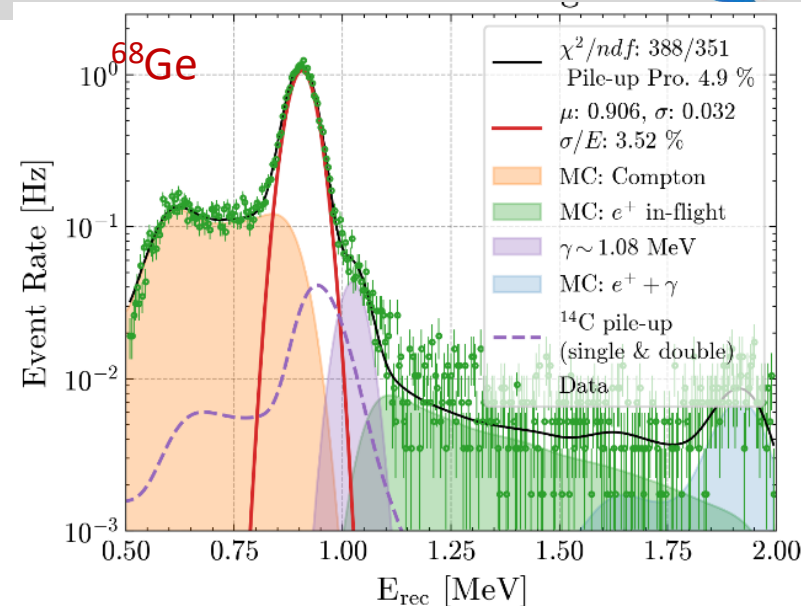


Light Yield and Energy Resolution

Yifang's Slide @ ν 26



- 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 $\sim 3.5\%$ @ 2×0.511 MeV at the center, slightly worse than the expected 3.1%
 - ⇒ Better MC for $\check{C}$ 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 $\sim 2.9\%$ @ 0.93MeV



Medium-baseline reactor: the idea in words

The measurement

- The baseline is chosen so that both Δm^2_{21} and Δm^2_{31} imprint on the same reactor neutrino survival spectrum.
- The ordering appears as a subtle beat pattern between the two frequencies.
- No matter effect. No δ_{CP} dependence. No θ_{23} octant dependence.
- Challenges: this is an energy-resolution and energy-scale problem, at the $\sim 3\%/\sqrt{E}$ / $\sim 1\%$ level.

20kt

liquid scintillator
target

$\sim 53\text{km}$

baseline to both
reactor complexes

$\sim 78\%$

photocathode
coverage

700m

rock
overburden