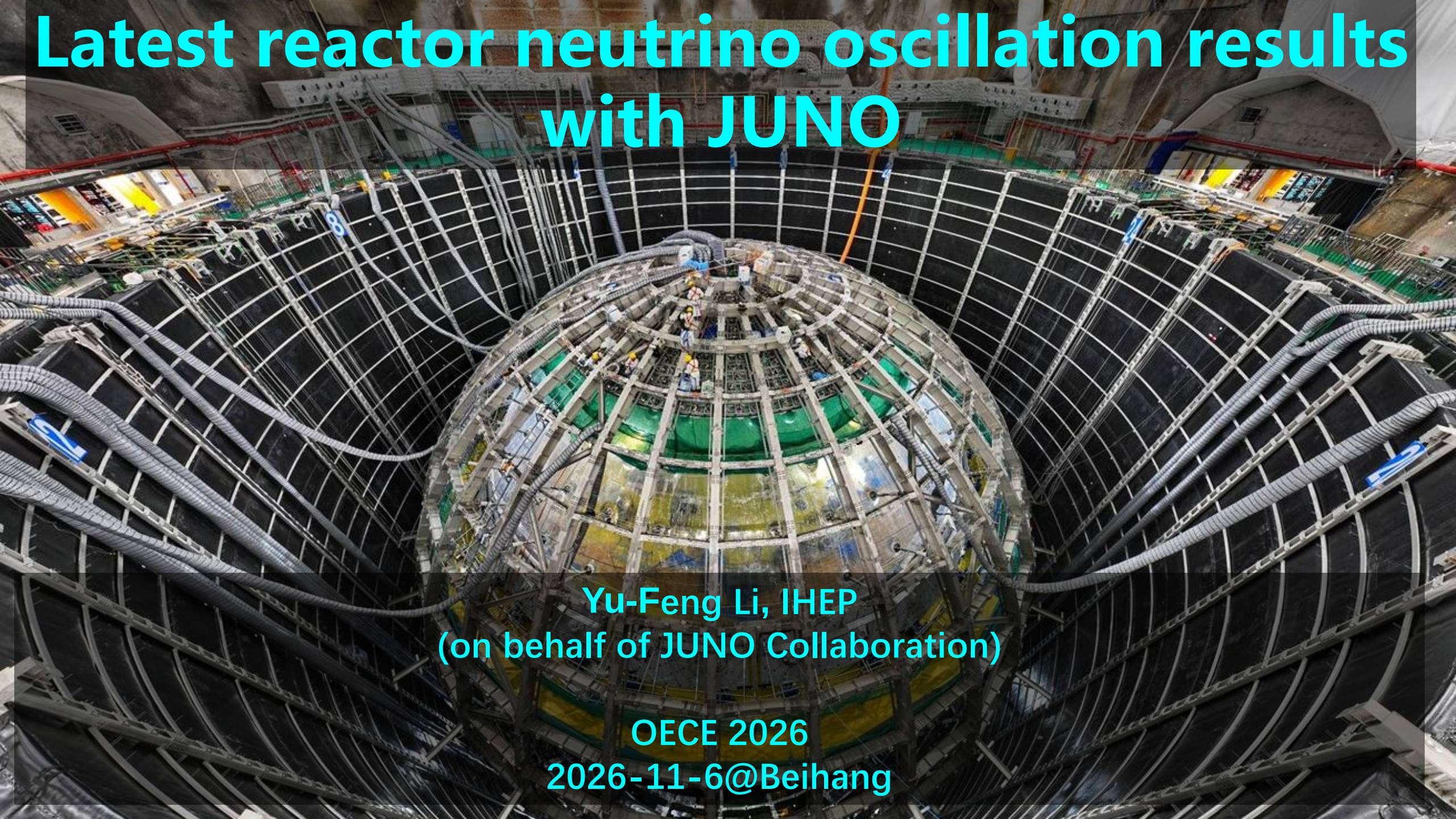
Latest reactor neutrino oscillation results with JUNO



Yu-Feng Li, IHEP
(on behalf of JUNO Collaboration)

OECE 2026
2026-11-6@Beihang

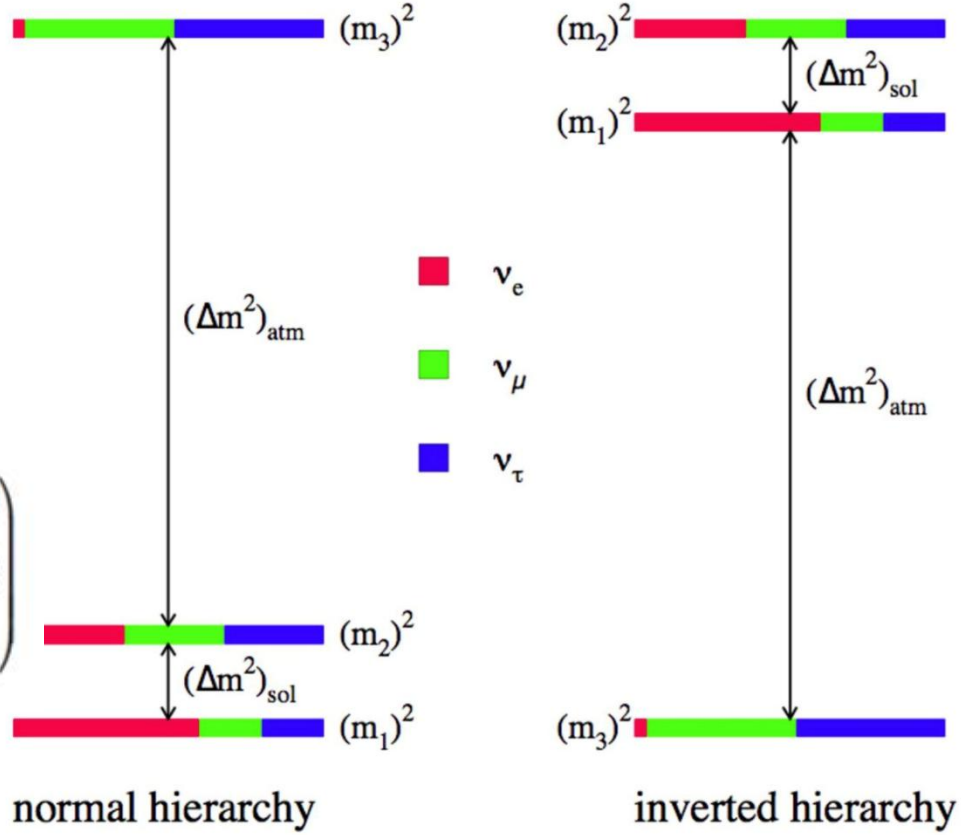
Parameters in the 3-flavor Neutrino Paradigm

◆ Neutrino oscillation indicates non-zero neutrino mass

Neutrino flavor states and mass states are connected by a unitary matrix *U:*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Known: θ_{23}, θ_{12}, θ_{13}, $|\Delta m^2_{32}|$, Δm^2_{21}
- Unknown: sign of Δm^2_{32}, δ_{CP}, octant of θ_{23}

- Normal ordering (NO): $m_1 < m_2 < m_3$
- Inverted ordering (IO): $m_3 < m_1 < m_2$

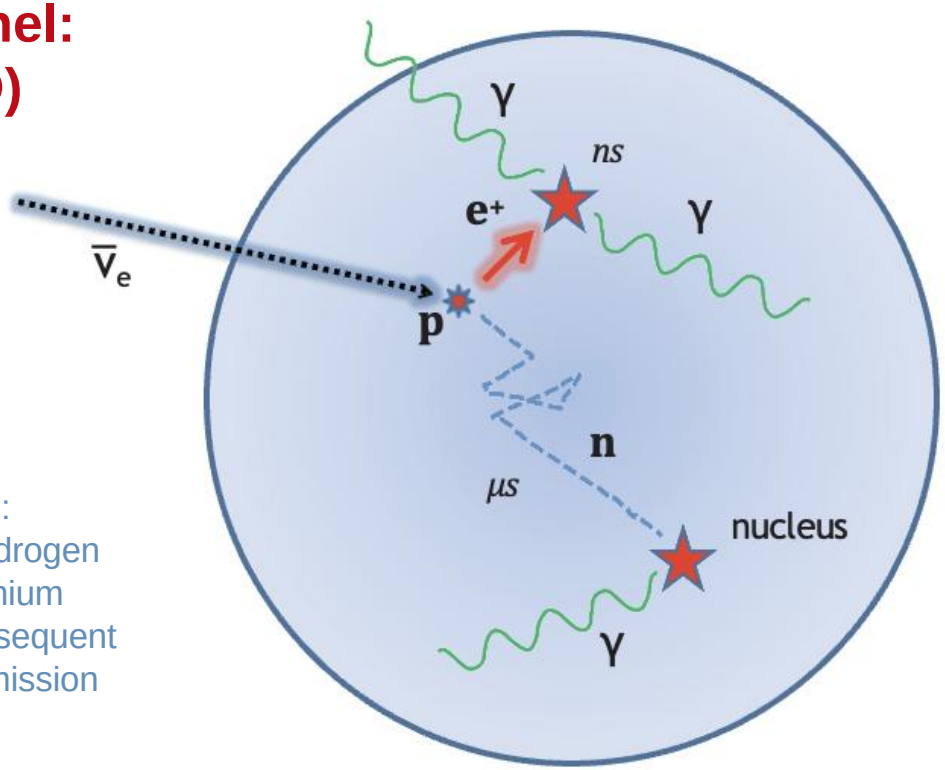
Reactor Antineutrino Detection

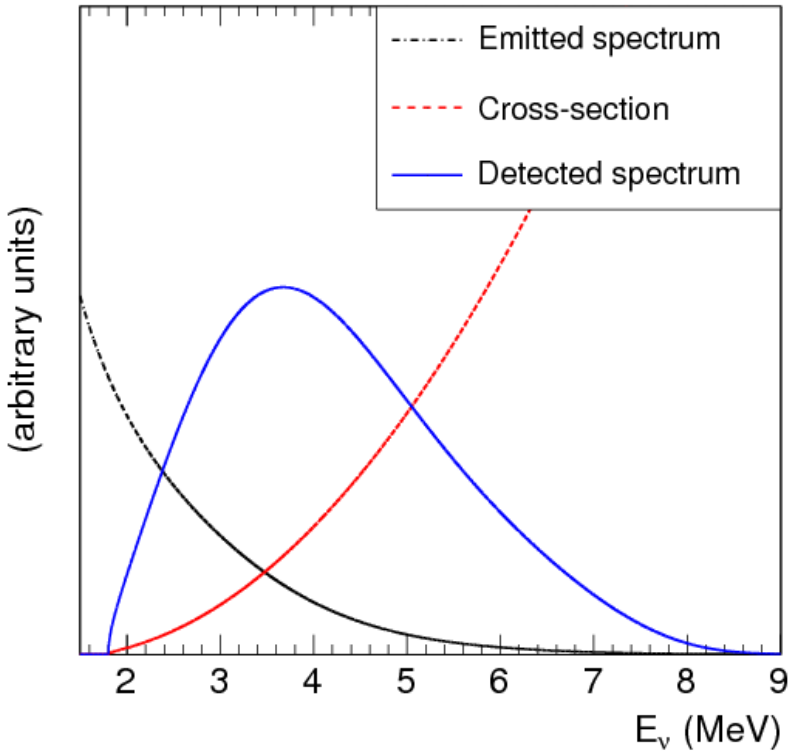
Primary detection channel:
Inverse Beta Decay (IBD)

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

Prompt signal: e^+ kinetic energy loss + annihilation

Delayed signal: capture on Hydrogen (nH) or Gadolinium (nGd) and subsequent gamma-ray emission

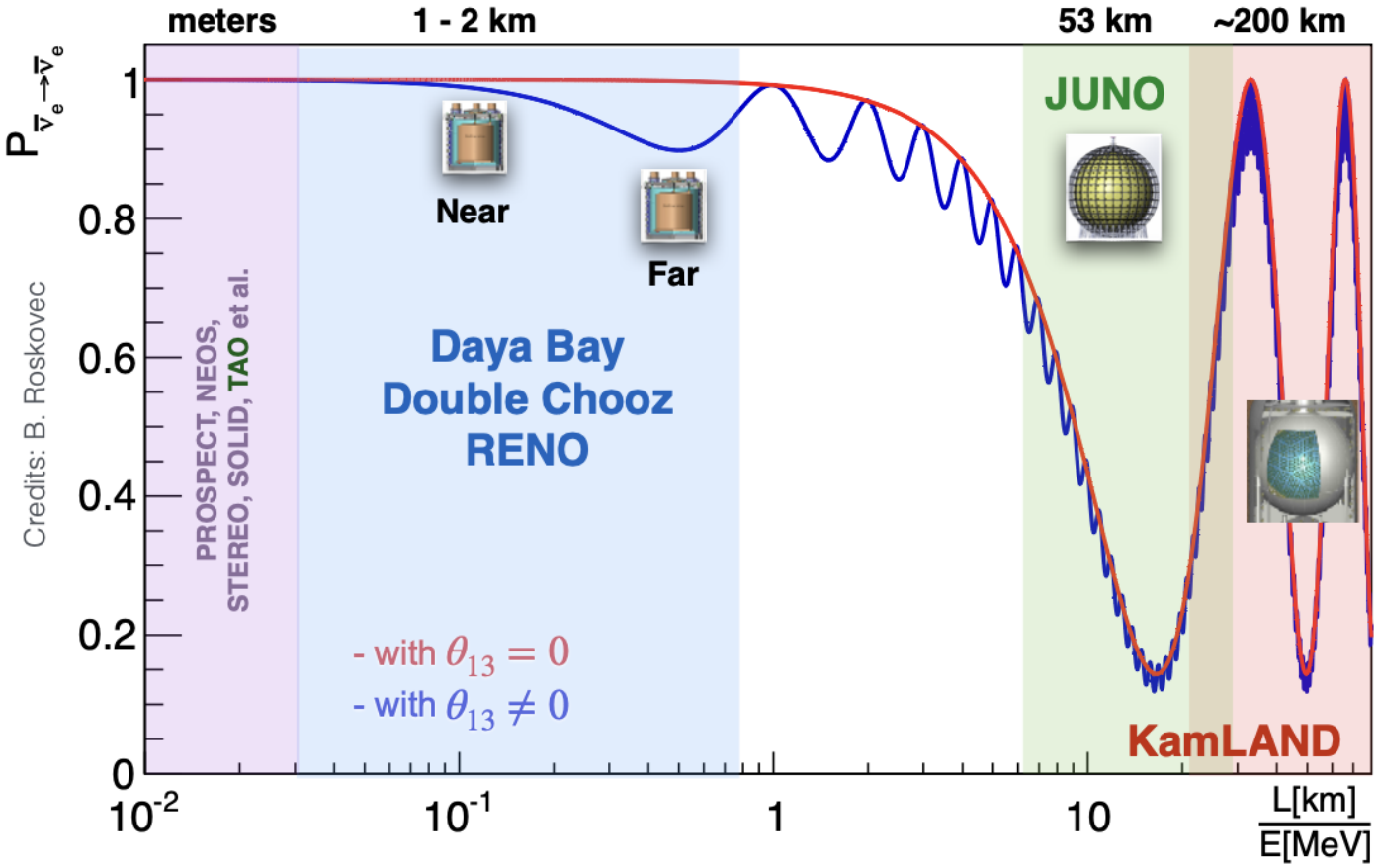




- **Coincidence between prompt positron and delayed neutron signals allows for powerful background rejection.**
- **Energy of positron preserves information about energy of incoming $\bar{\nu}_e$: $E_{\bar{\nu}_e} \approx E_{e^+} + 0.78$ MeV**

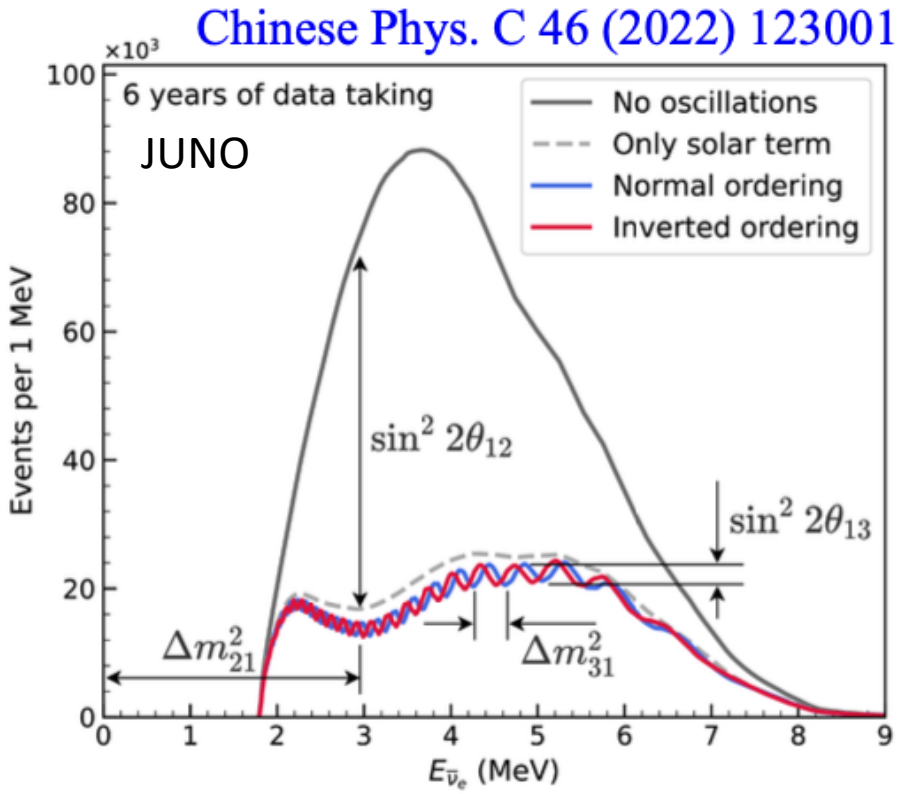
Reactor Antineutrino Oscillations

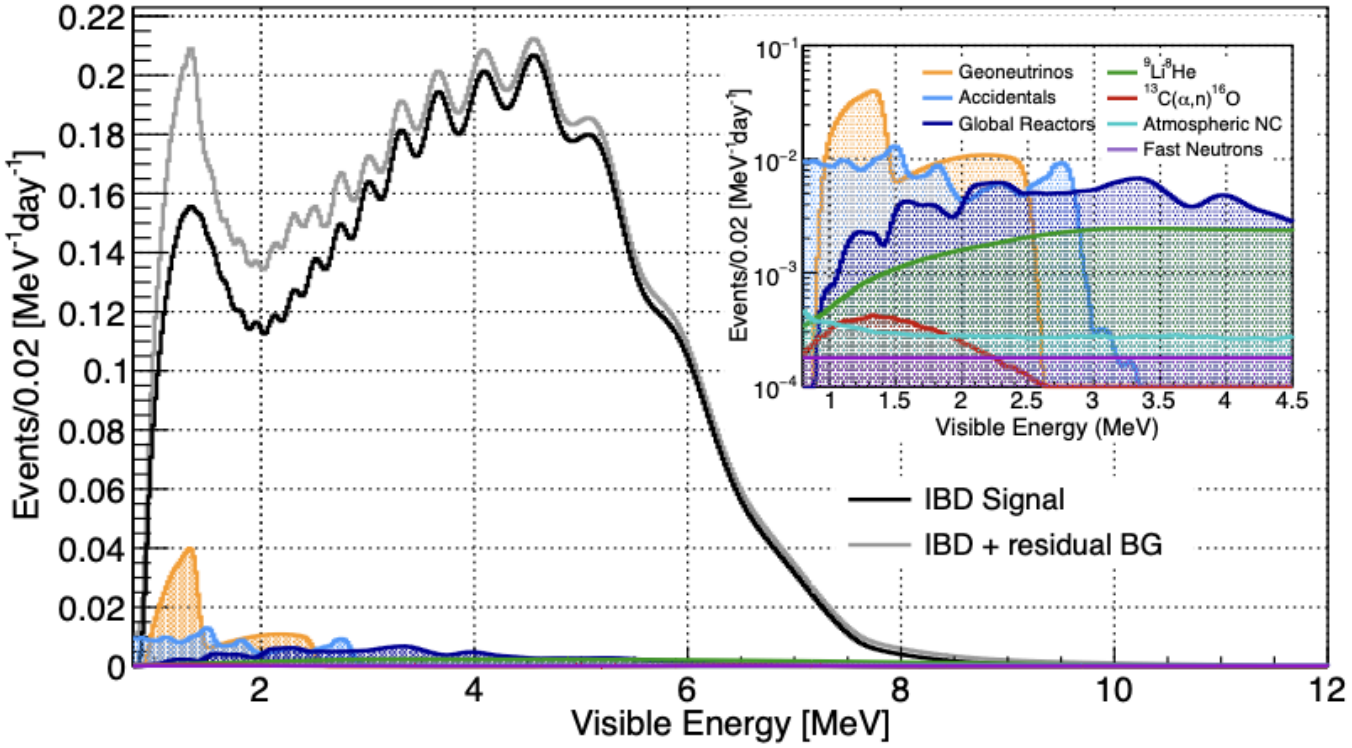
- Reactor neutrinos provide a clean tool to make precision measurements of neutrino oscillations



- Measure how $\bar{\nu}_e$ oscillate into other flavors
- Access to θ_{12} , θ_{13}, Δm^2_{21}, Δm^2_{31} and the mass ordering
- No dependence on θ_{23} and δ_{CP}
- Baseline is set by physics goals

Mass Ordering by Reactor Neutrinos





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

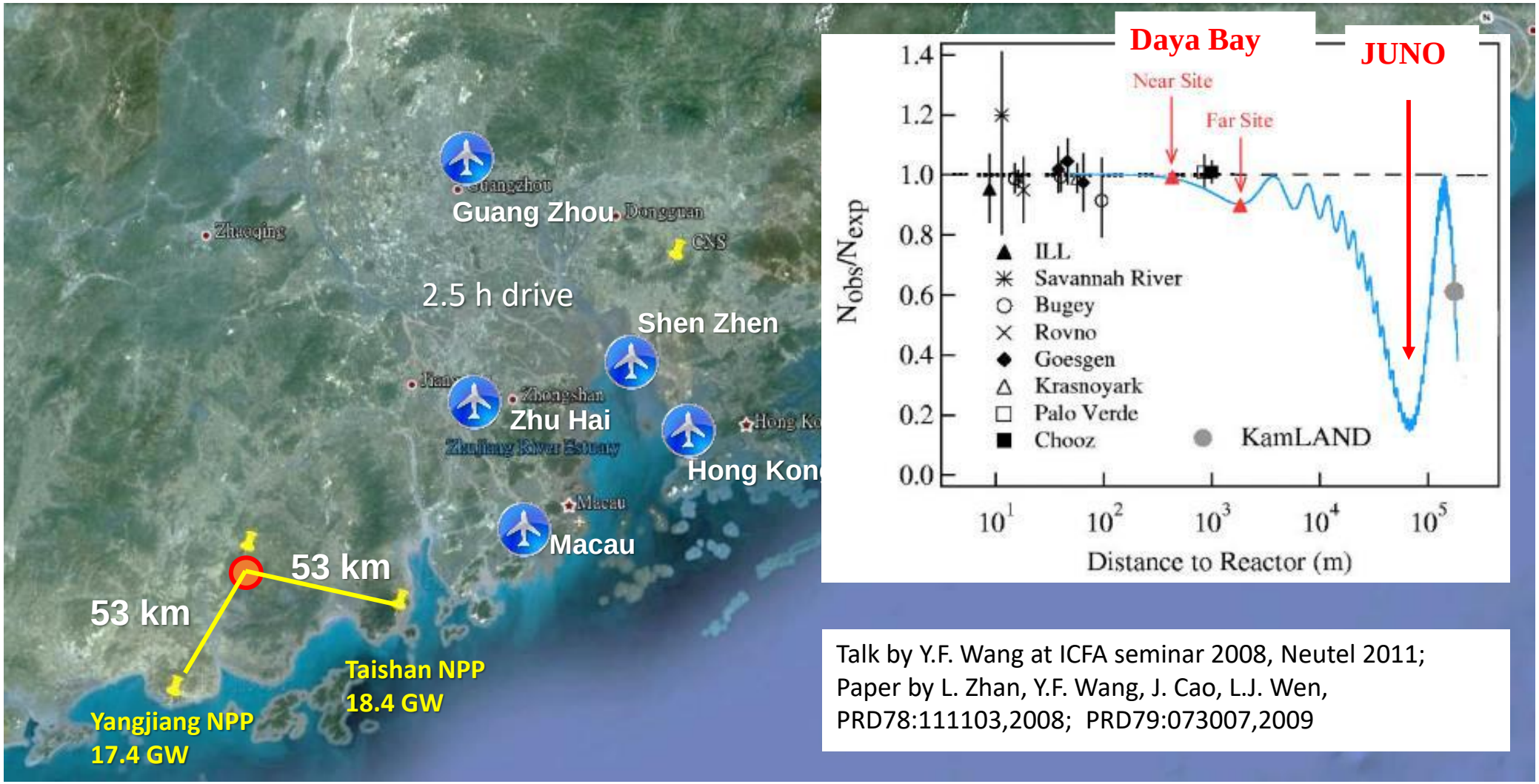
$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\text{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\text{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

$$\frac{\Delta m^2_{21}}{|\Delta m^2_{32}|} \sim 3\%$$

Require high statistics, excellent energy resolution and low backgrounds.

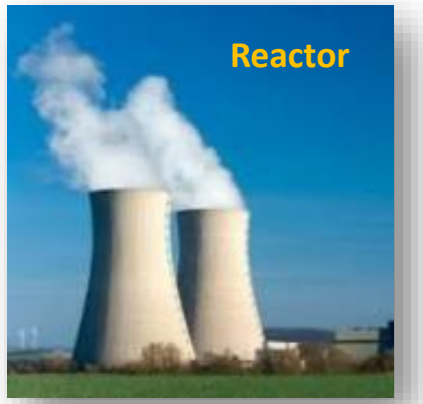
Jiangmen Underground Neutrino Observatory

- Use reactor neutrinos to determine the mass ordering
- Equal distance to two reactor power plants for doubling the neutrino flux

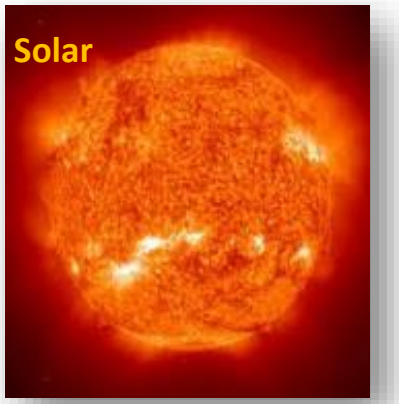


Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen,
PRD78:111103,2008; PRD79:073007,2009

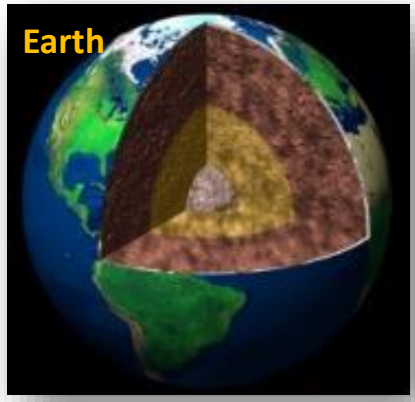
A multi-purpose observatory











\+ New physics

~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for CCSN @10 kpc

Several IBDs per day

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

Supernova neutrino topics will be covered by Dr. Yi Jia in the afternoon

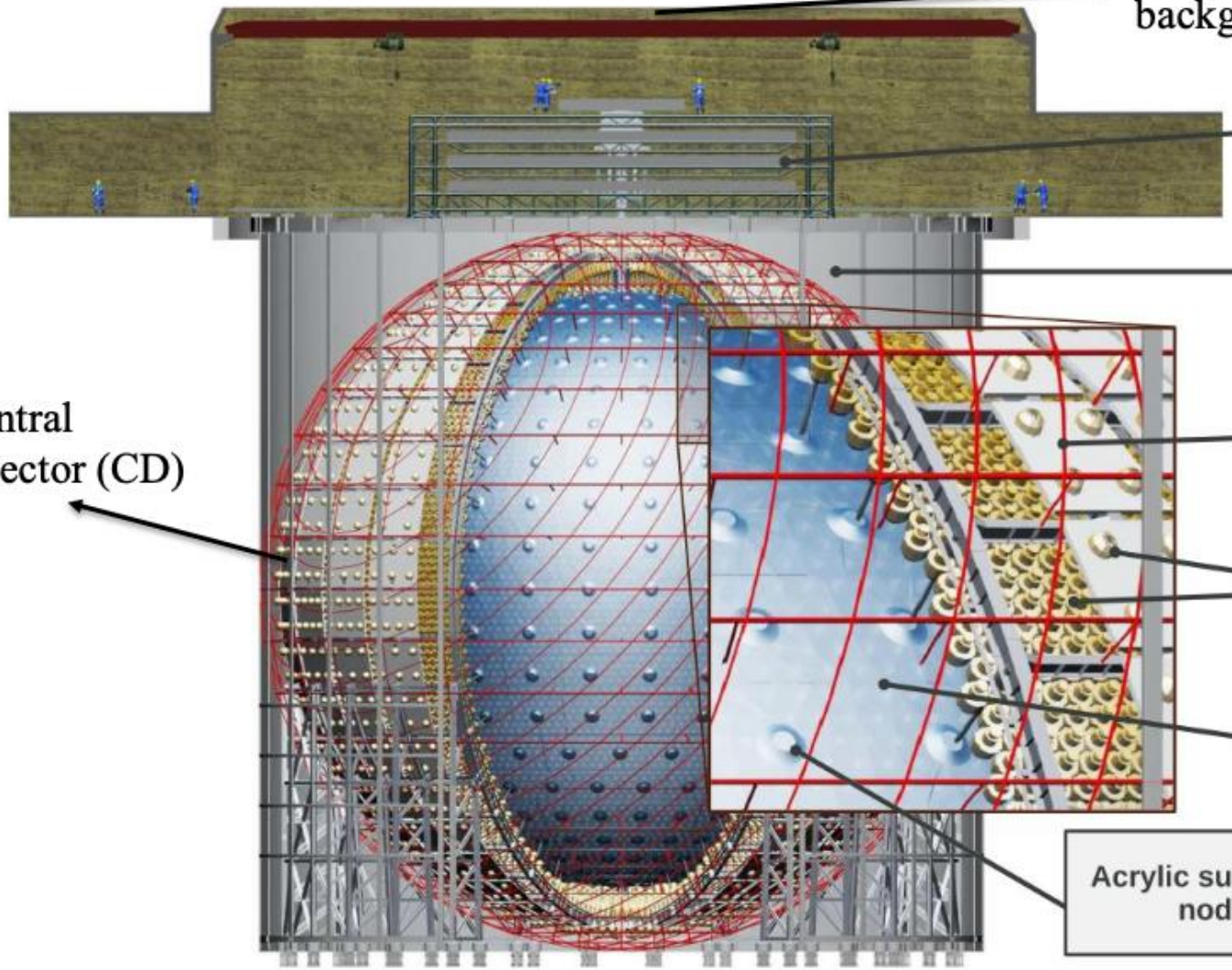
JUNO Project and the Collaboration

- 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

Country	Institute	Country	Institute	Country	Institute
Armenia	YerPhI	China	SDU	Italy	INFN-CT
Belgium	ULB	China	SJTU	Italy	INFN-FE
Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile	UNAB	China	SYSU	Italy	INFN-MI
China	BISEE	China	THU	Italy	INFN-MIB
China	CDUT	China	UCAS	Italy	INFN-PD
China	CNPRI	China	WHU	Italy	INFN-PG
China	CUGB	China	WuYiU	Italy	INFN-Roma3
China	DGUT	China	XJTU	Pakistan	PINSTECH (PAEC)
China	ECUT	China	XMU	Russia	JINR
China	GXU	China	ZZU	Slovakia	FMFI-UK
China	HIT	Czech	Charles U.	Taiwan-China	NCTU
China	HunanU	Finland	JyU	Taiwan-China	NKNU
China	IGGCAS	France	CPPM	Taiwan-China	NTU
China	IHEG-CAGS	France	IJCLab	Taiwan-China	NTUT
China	IHEP	France	IPHC	Thailand	CHULA
China	IMP	France	LP2iB	Thailand	NARIT
China	JNU	France	Subatech	Thailand	SUT
China	JXNU	Germany	EKUT	U.K.	U. Liverpool
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)

JUNO Detector



~700 m overburden for cosmic background suppression

Central detector (CD)

Top Tracker and calibration house

Top tracker for cosmic muon veto

Water pool

Water Cherenkov detector for external background suppression and muon veto

Earth magnetic field compensation coils

Photomultiplier tubes

17612 20-inch CD PMTs
~ 75% coverage

25600 3-inch CD PMTs
~ 3% coverage

Acrylic spherical vessel filled with liquid scintillator

20 kton liquid scintillator (LS)
LAB + 2.5 g/L PPO + 3 mg/L bis-MSB

Acrylic supporting nodes

Steel Structure and the Installation Platform



Working for Acrylic on the Platform



Water filling began on December 18, 2024.



Liquid-scintillator filling began on February 8, 2025

Base solvent Fluors

NIM.A 908 (2021) 164823

to guarantee radio-purity and transparency Recipe: LAB + 2.5g/L PPO + 3 mg/L bis-MSB





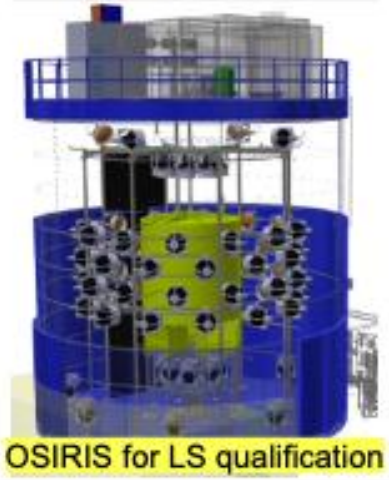


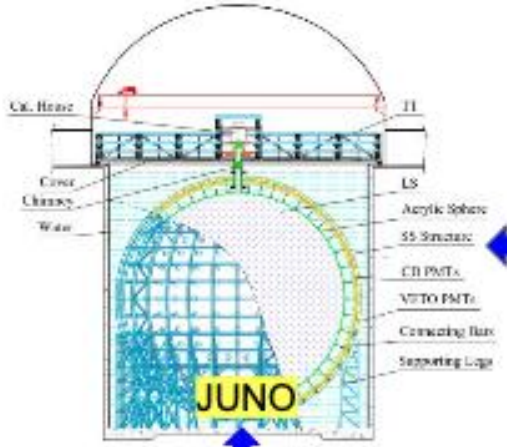


SS pipes to underground



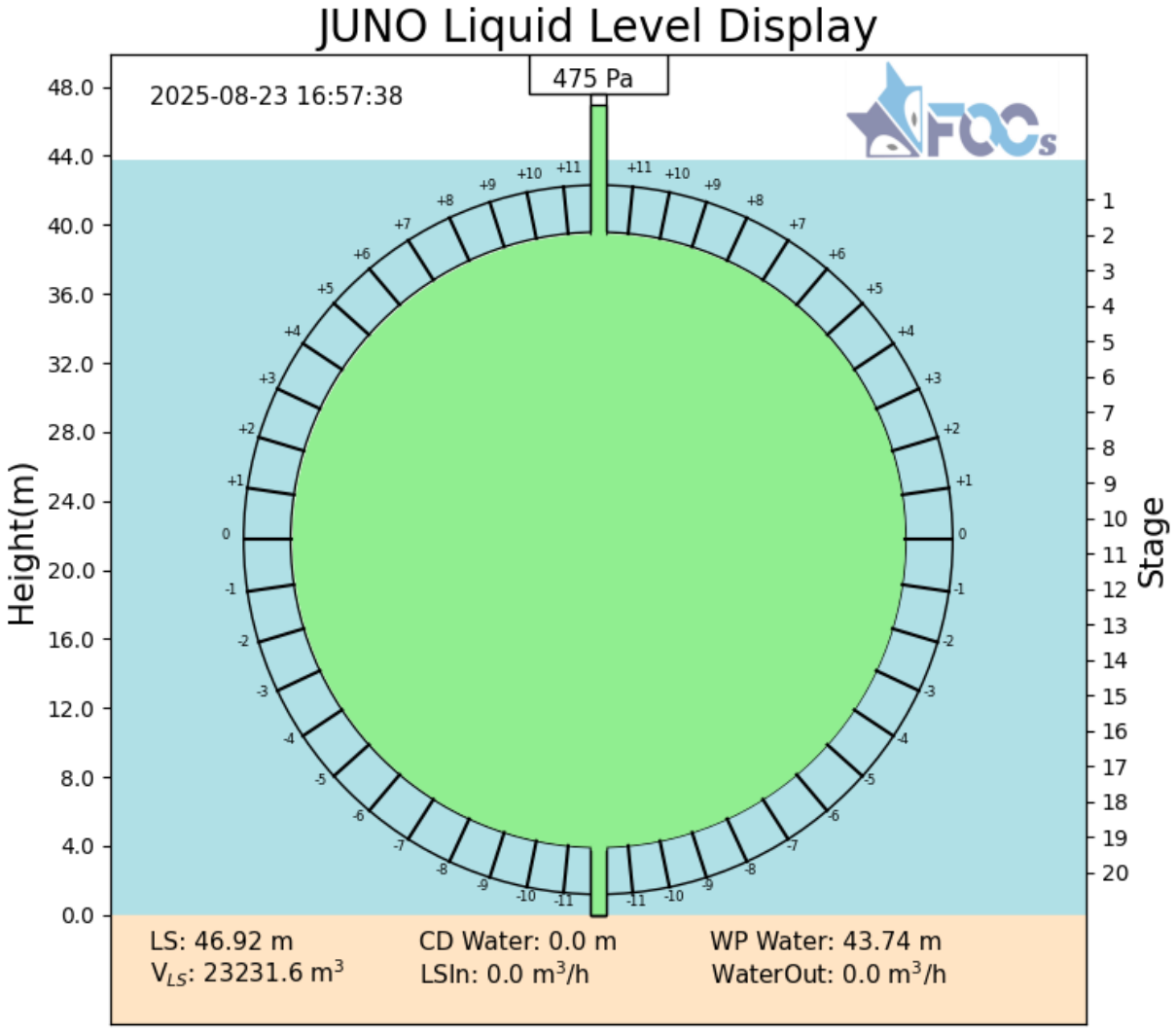






Samples tested by ICP-MS every week for radiopurity, verified by NAA and other methods

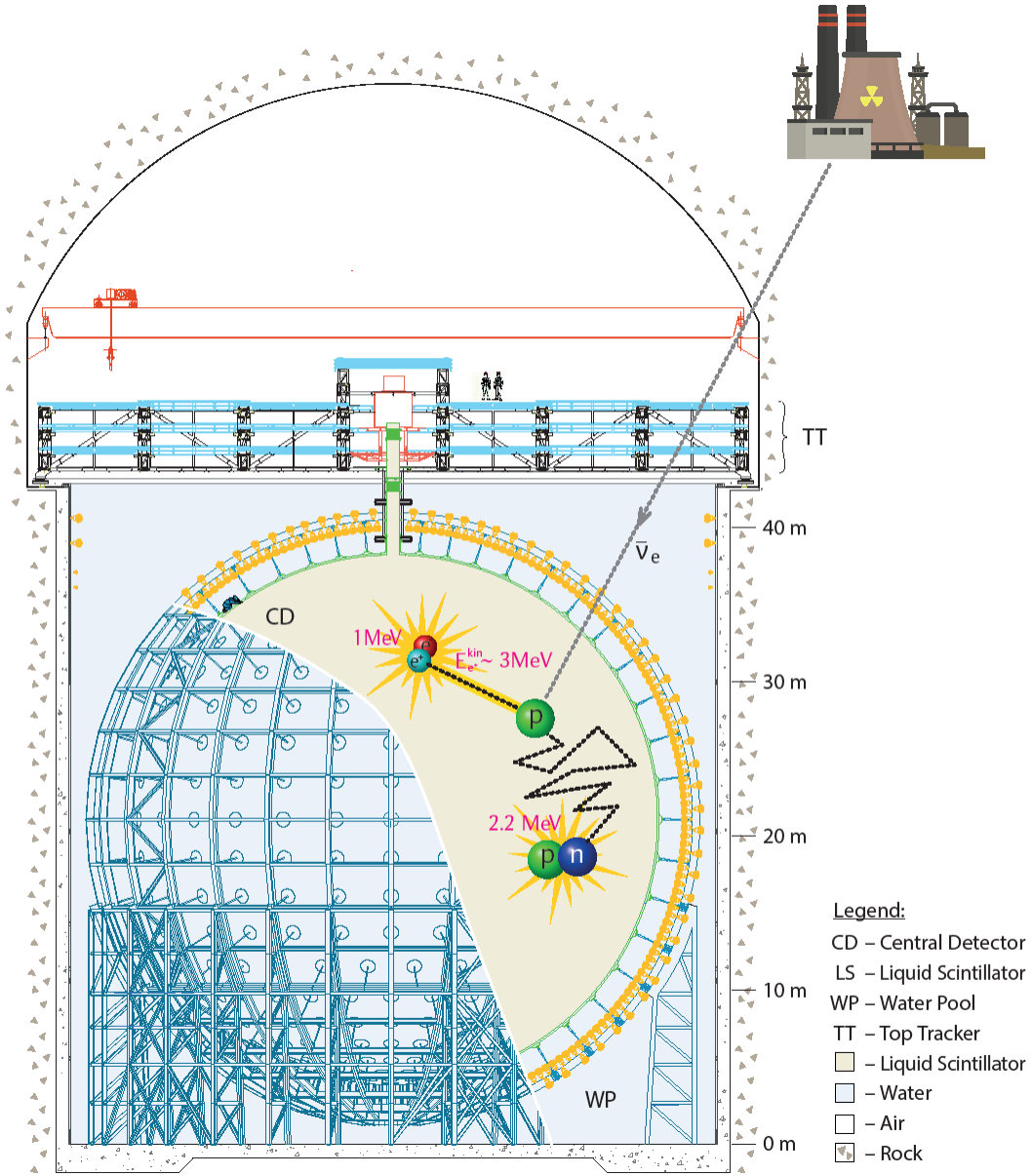
Physics data taking began on August 26, 2025



- On August 22,2025 at ~22:12, water in Acrylic tank was fully replaced by Liquid Scintillator
- Calibration started at 14:00 of Aug. 23
- Data taking for physics started on Aug. 26 at 5:30 am (Beijing time)

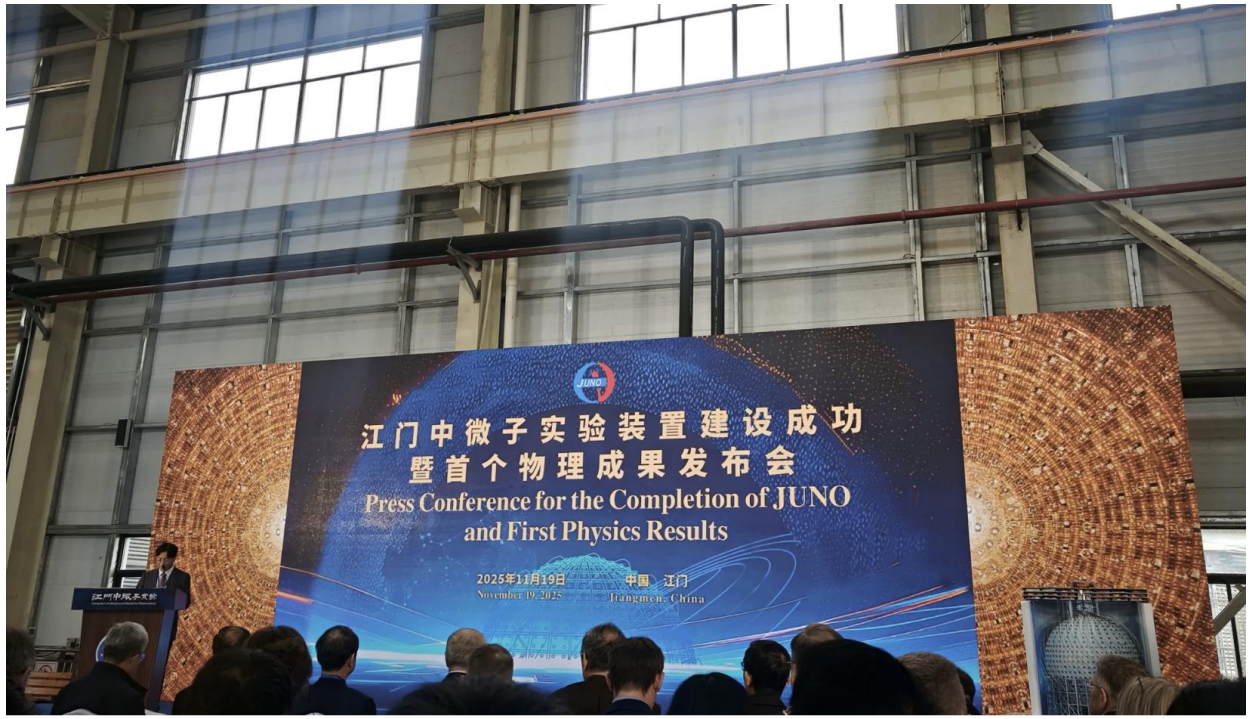
- Total LS in CD: 23231.6 m^3
- Total water in pool: 41225.1 m^3

First Results from JUNO



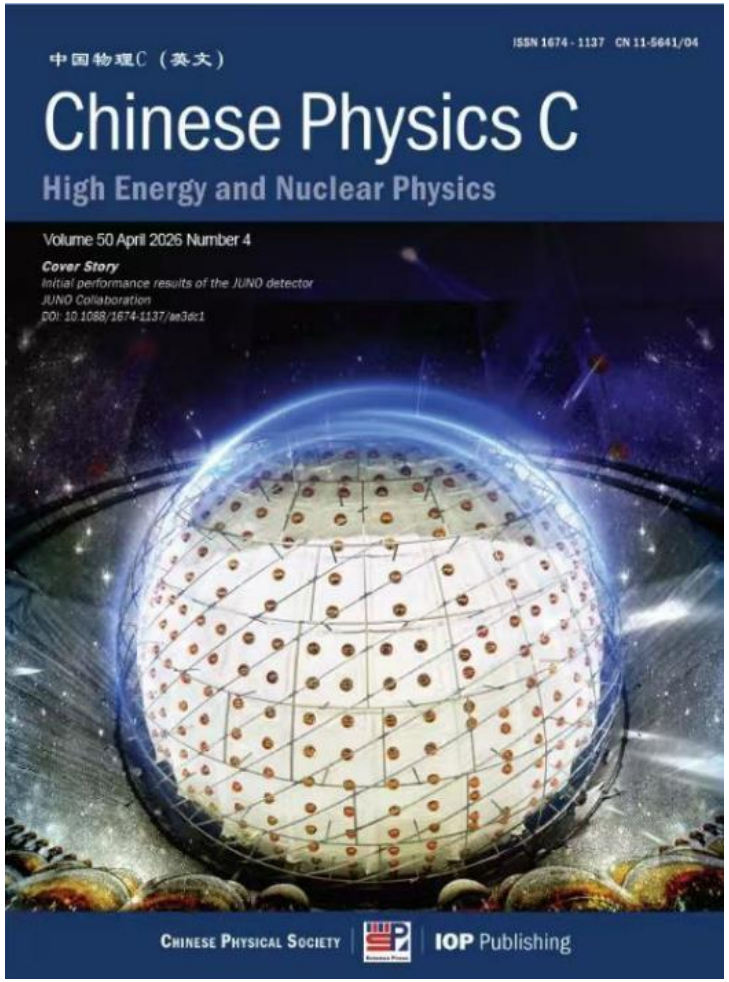
- **Released on Nov. 19, 2025. "First measurement of reactor neutrino oscillations at JUNO", arXiv:2511.14593**

Press Conference in Jiangmen



First Results from JUNO

“Initial Performance of the Detector” Chinese Phys. C 50, 043001 (2026)



First results using 59 days of data recently published

Article | Published: 10 June 2026

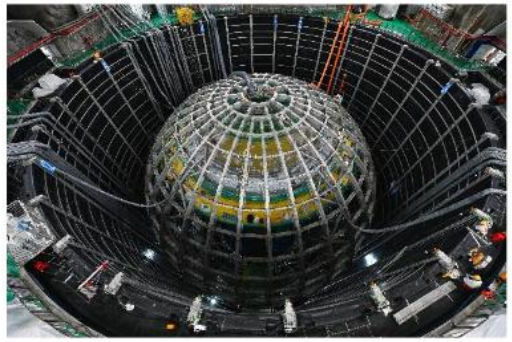
Measurement of reactor neutrino oscillation with the first JUNO data

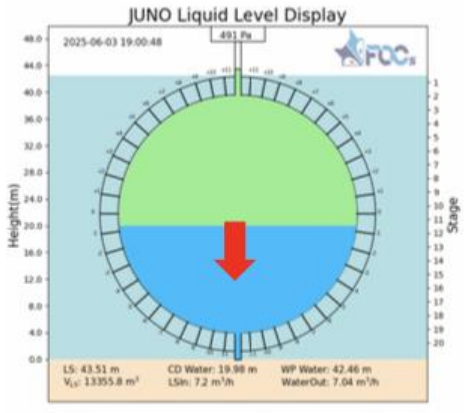
The JUNO Collaboration

Nature **654**, 343–348 (2026) | Cite this article



JUNO Timeline





Collaboration formed — 2014

2015 — Civil construction



2022 — Start of detector installation

2024.12 — Start of water filling



2025.2 — Start of LS filling

2025.8.26 — Physics data-taking start

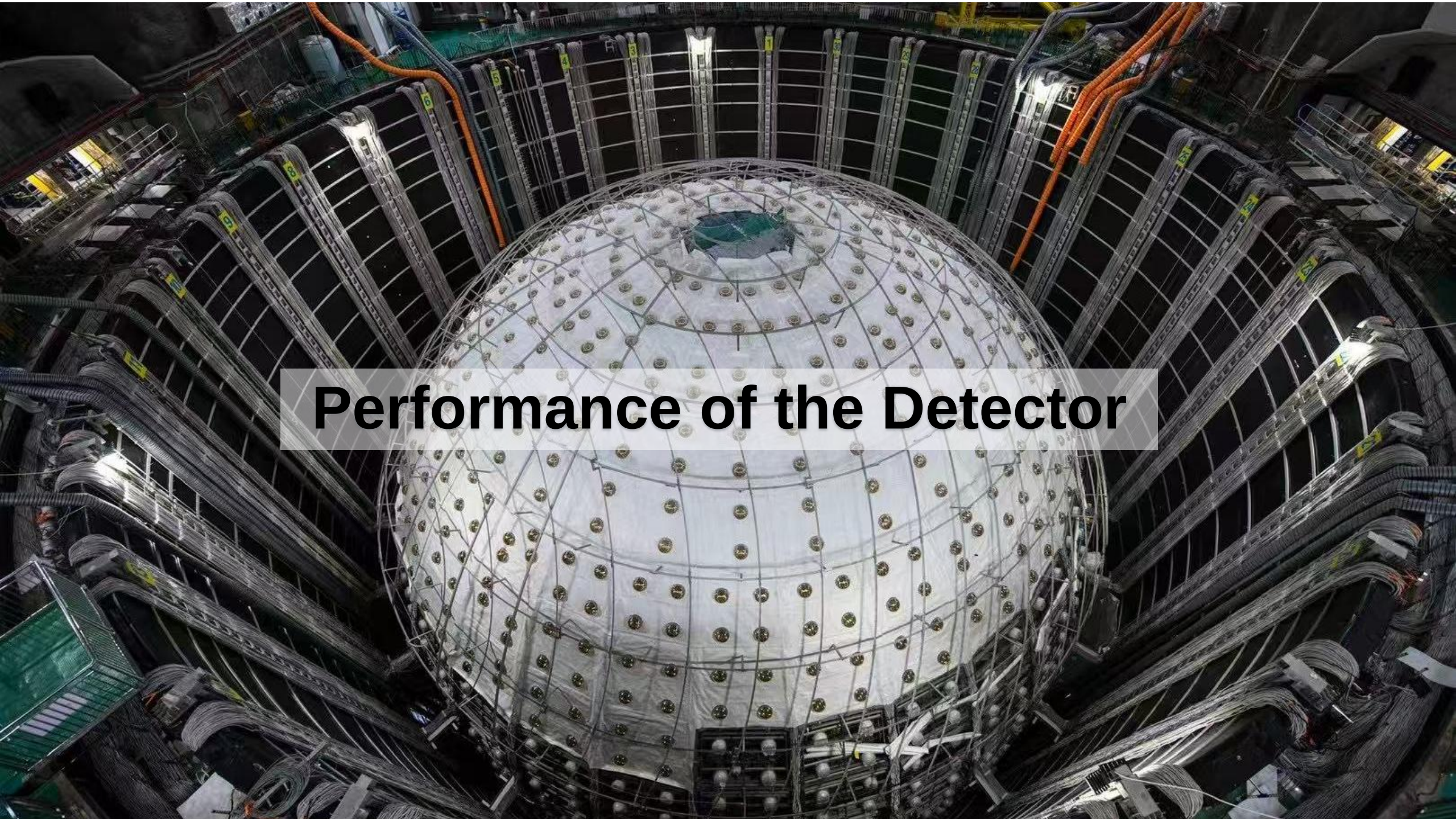


2025.11 — First Results announced

2026.6 — First Results published in Nature

New Results released in Neutrino 2026!





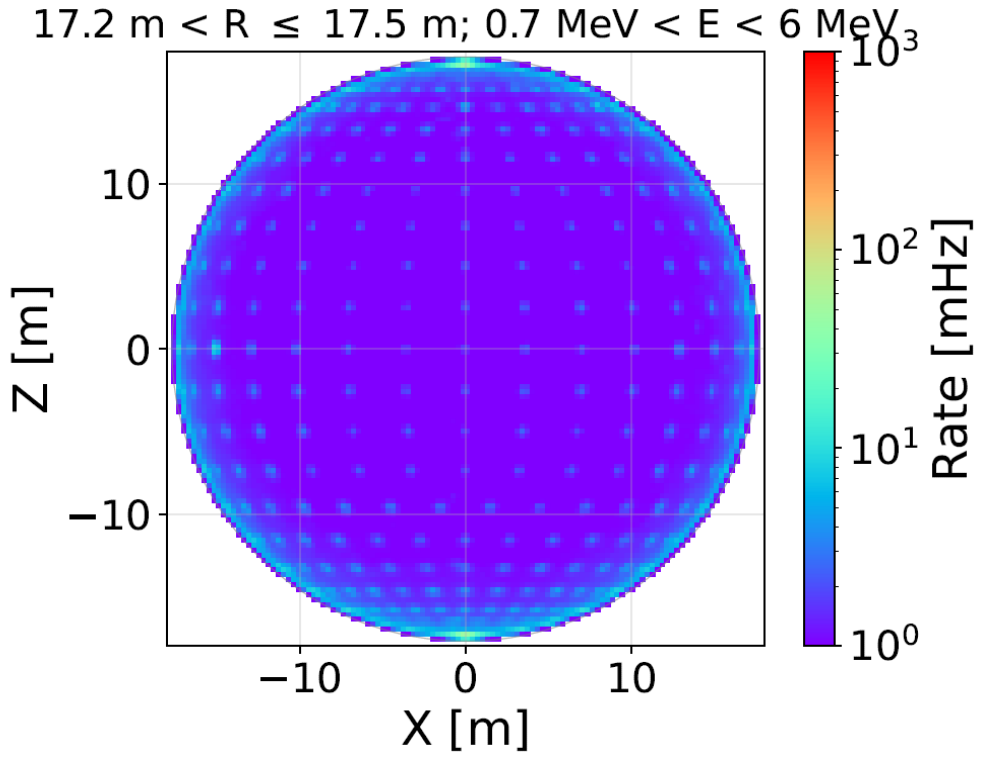
Performance of the Detector

Clean Detector

- **Ultra-low natural radioactivity, fulfill reactor neutrino oscillation measurement**

Central Detector	Specification	Measure
Singles Rate (Hz)	< 7.2 Hz	< 7 Hz
$^{238}U/^{232}Th$ ($\times 10^{-15}$ g/g)	< 1	< 0.1
^{210}Po ($\times 10^{4}$ cpd/kt)	< 8	< 5

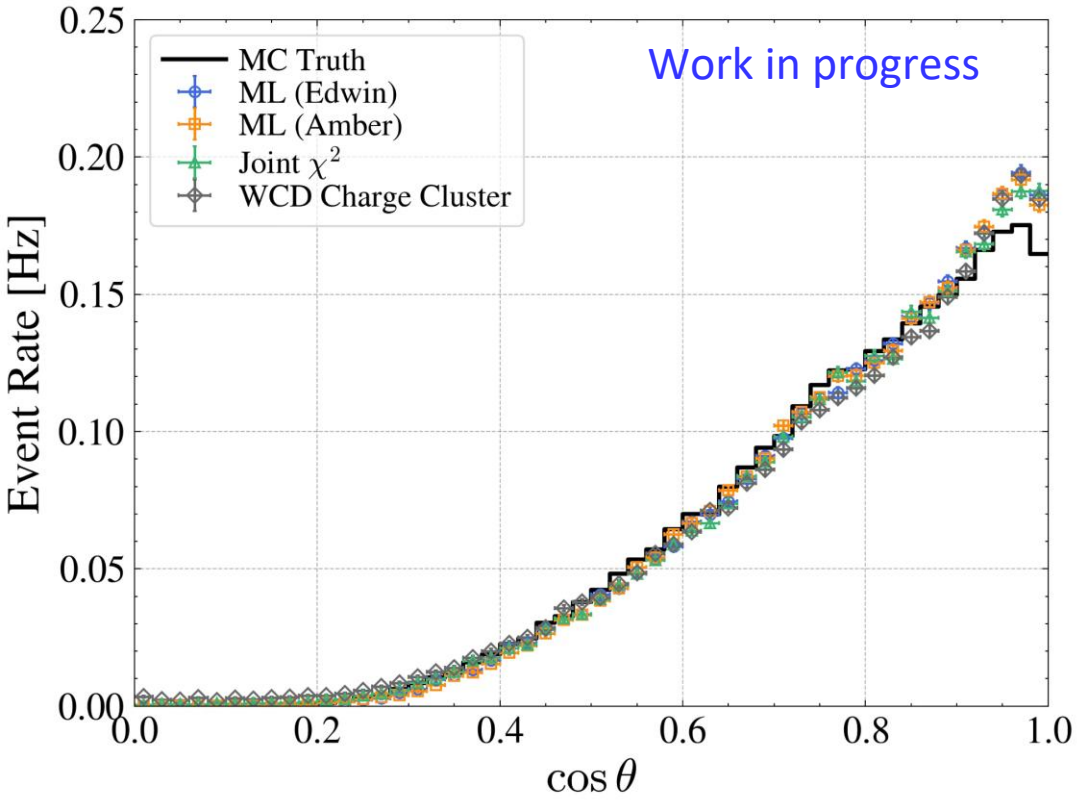
Muon Veto Detector	Specification	Measure
^{222}Rn (mBq/m^3)	< 10	<10
^{226}Ra (mBq/m^3)	< 1	< 0.01
U/Th ($\times 10^{-15}$ g/g)	<10	<0.4

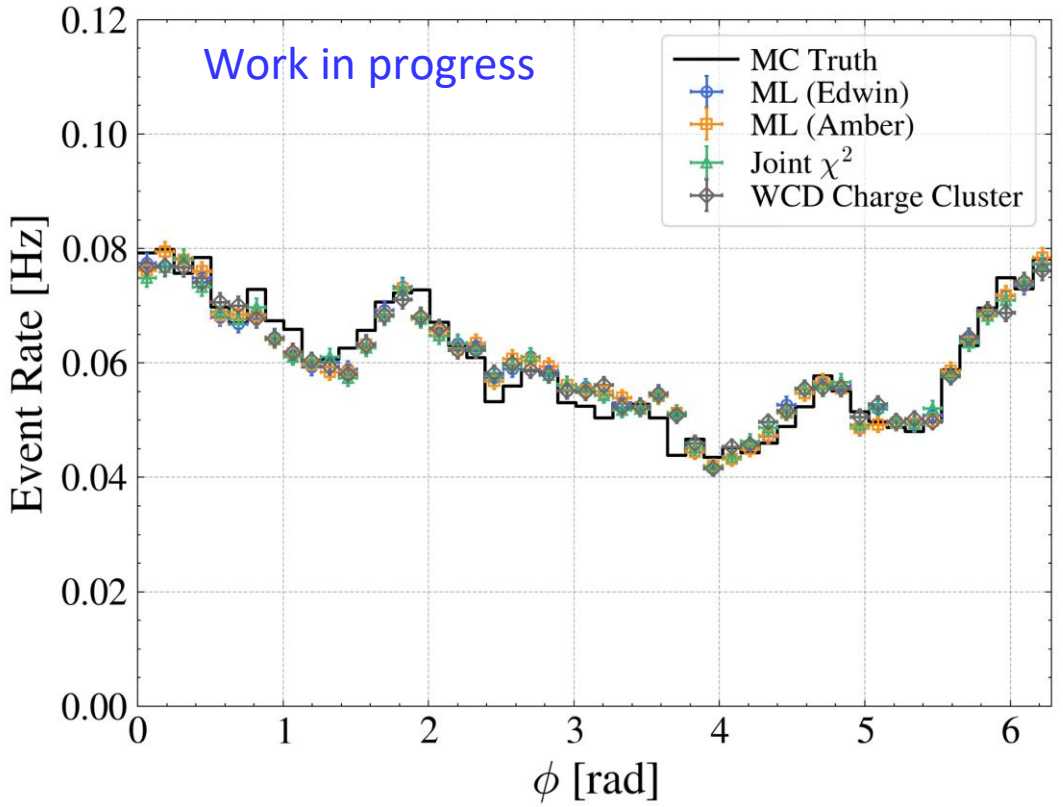


20,000 tons of liquid scintillator with dust levels on the order of 10 milligrams.

Measurement of Cosmic Muons

- Muon trigger rate in CD ~5 Hz, in Water Pool ~4 Hz
- Muon detection efficiency of CD through-going muons > 99.5%
- Reconstructed angular distributions in good agreement with Monte Carlo simulation

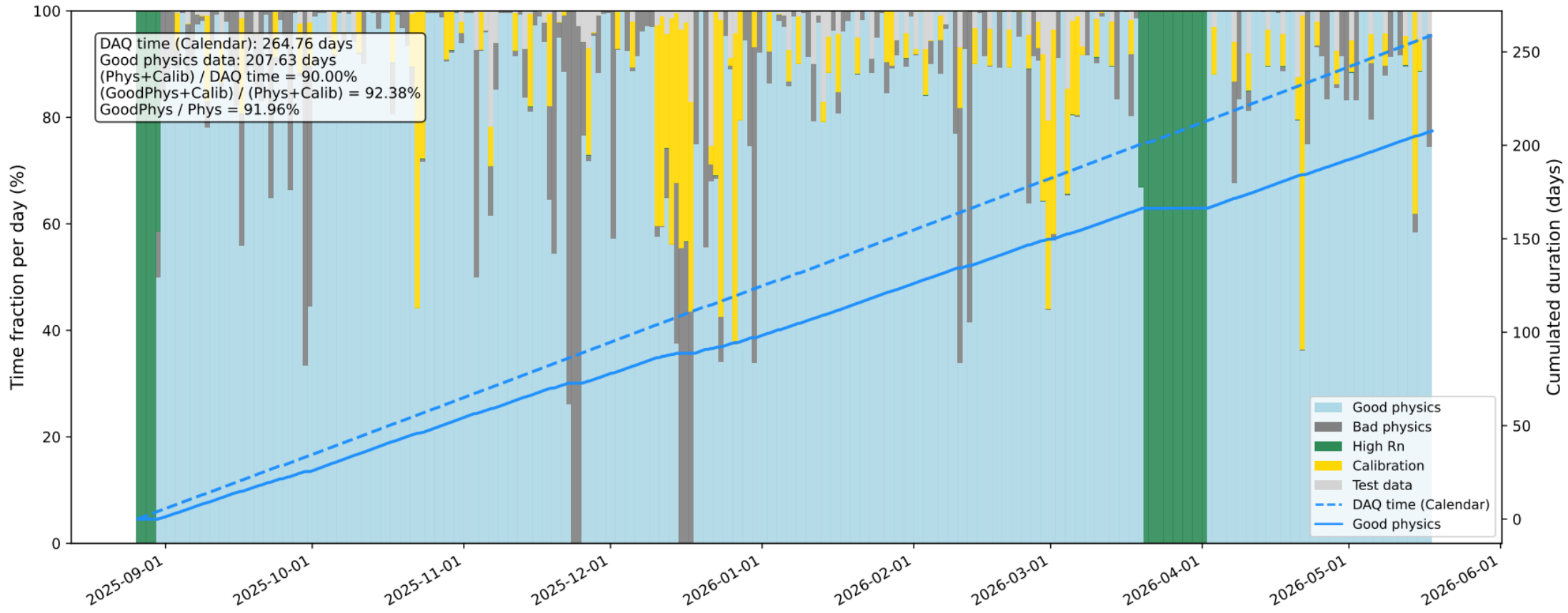




Muon's flux and energy spectrum, mountain's profile and density are well understood.

Data Taking

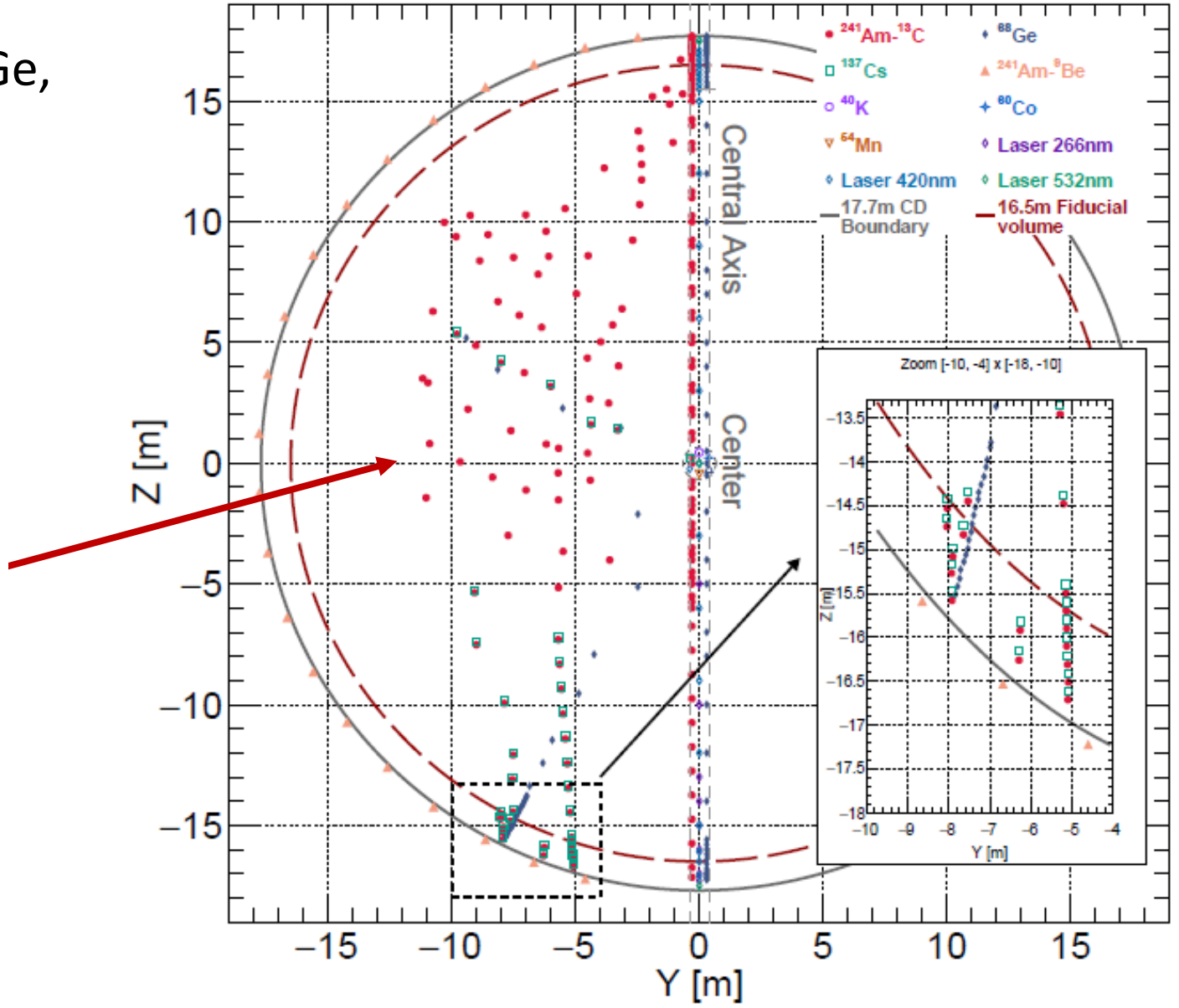
- Smooth data-taking, gaps mainly due to weather-related power outage



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

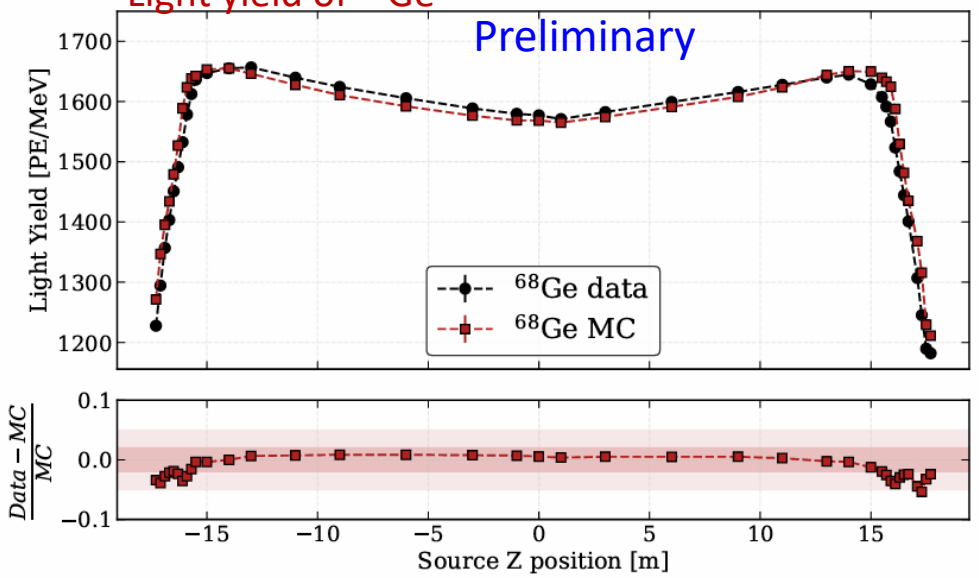
- Positions at which source calibration performed
- No ^{222}Rn leakage or other contaminations introduced during calibration



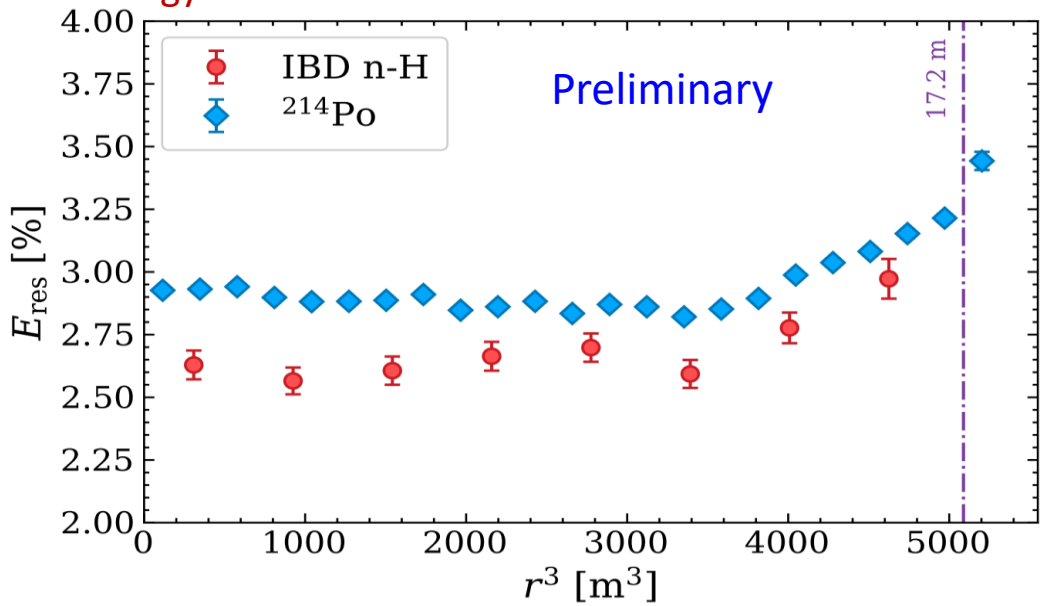
Reconstruction and Energy Correction

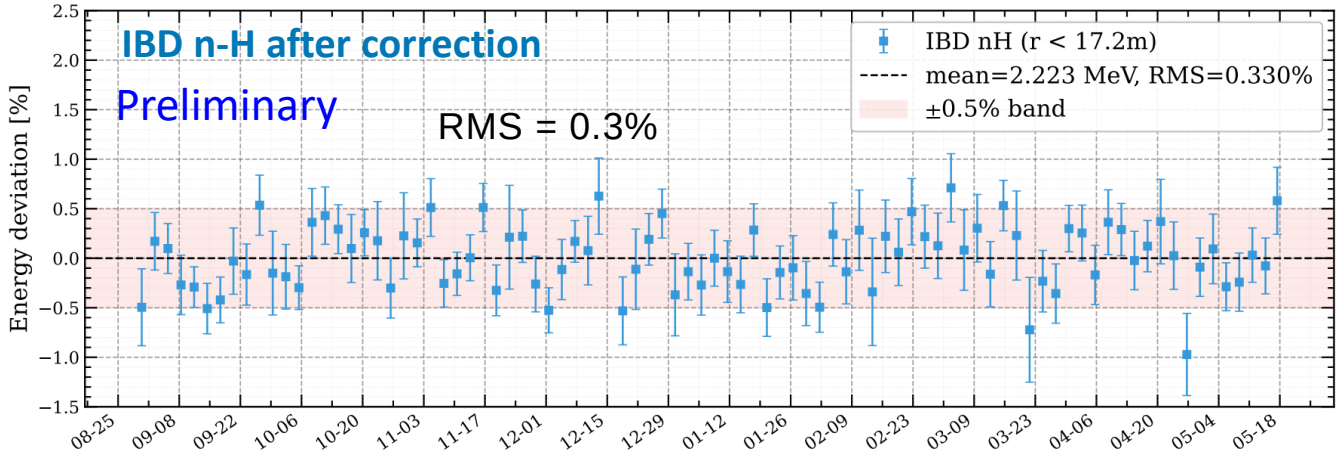
- Light yield at the detector center is ~1600 PE/MeV for ^{68}Ge and ~1785 PE/MeV for neutrons, in good agreement with MC
- Energy resolution for ^{68}Ge is ~3.5% @ 2× 0.511 MeV at the center
- Energy resolution for alpha from ^{214}Po is ~2.9% @0.93MeV
- Energy scale anchored at neutron capture on hydrogen (**n-H**) from ^{9}Li+IBD
- Time dependent variations corrected by **^{214}Po** in the whole volume, check by n-H from IBD

Light yield of ^{68}Ge



Energy resolution vs r^3

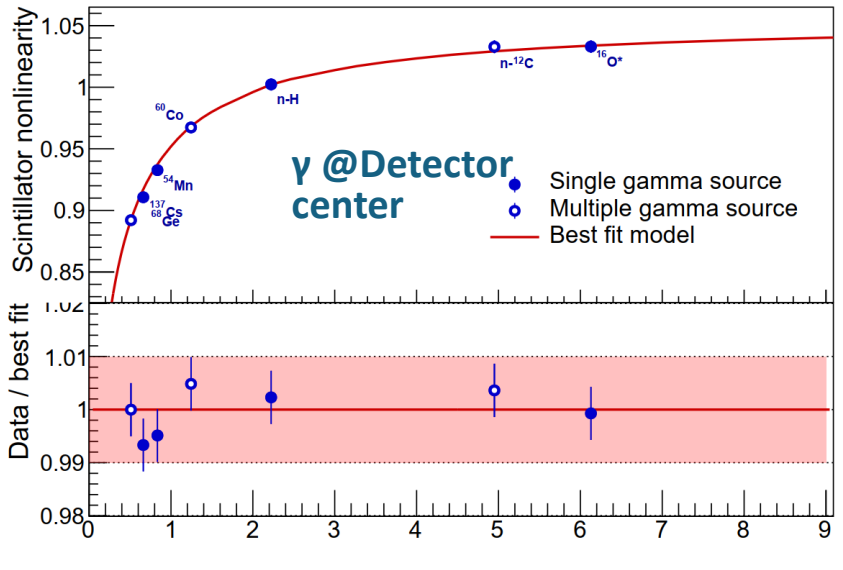


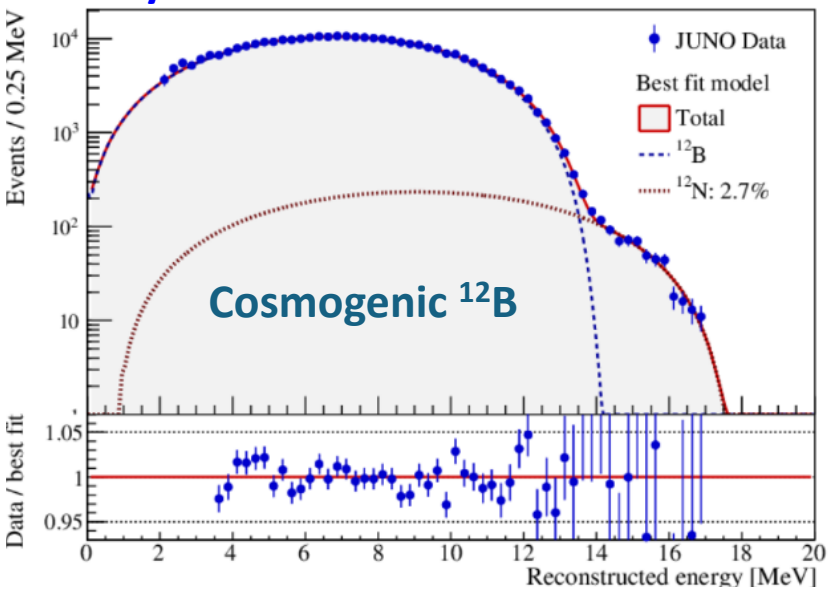


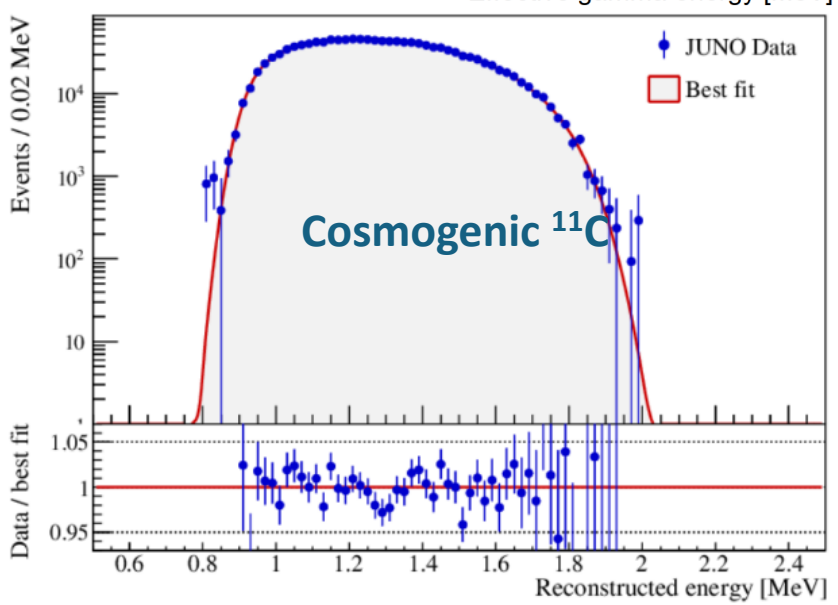
Energy Non-linearity

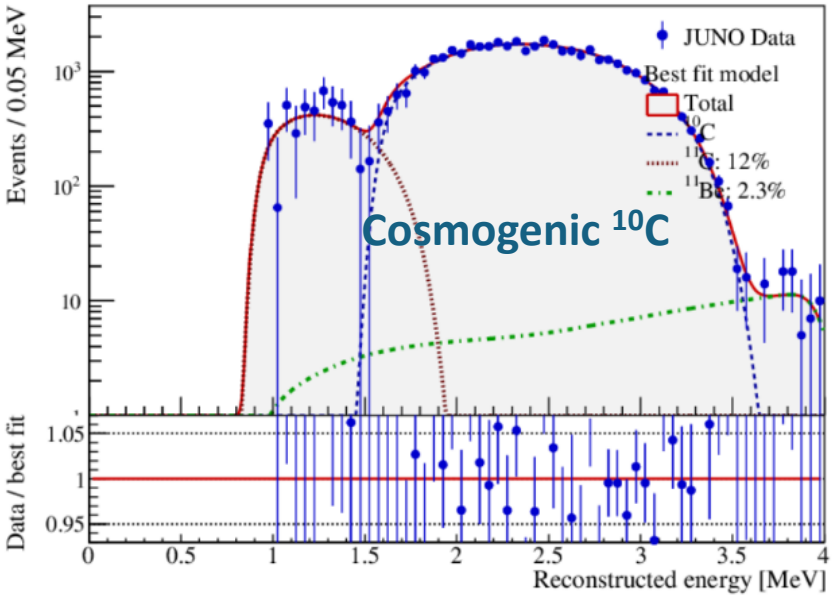
- Non-linearities of LS and electronics are determined by calibration sources at the center: ^{68}Ge, ^{137}Cs, ^{54}Mn, ^{40}K, ^{60}Co, Am-C, and Am-Be
- The non-linearity model for e^+ is based on Geant4 and γ-sources
- The model is constrained by cosmogenic isotopes, ^{11}C(e^+), ^{10}C(e^+), ^{12}B(e^-),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

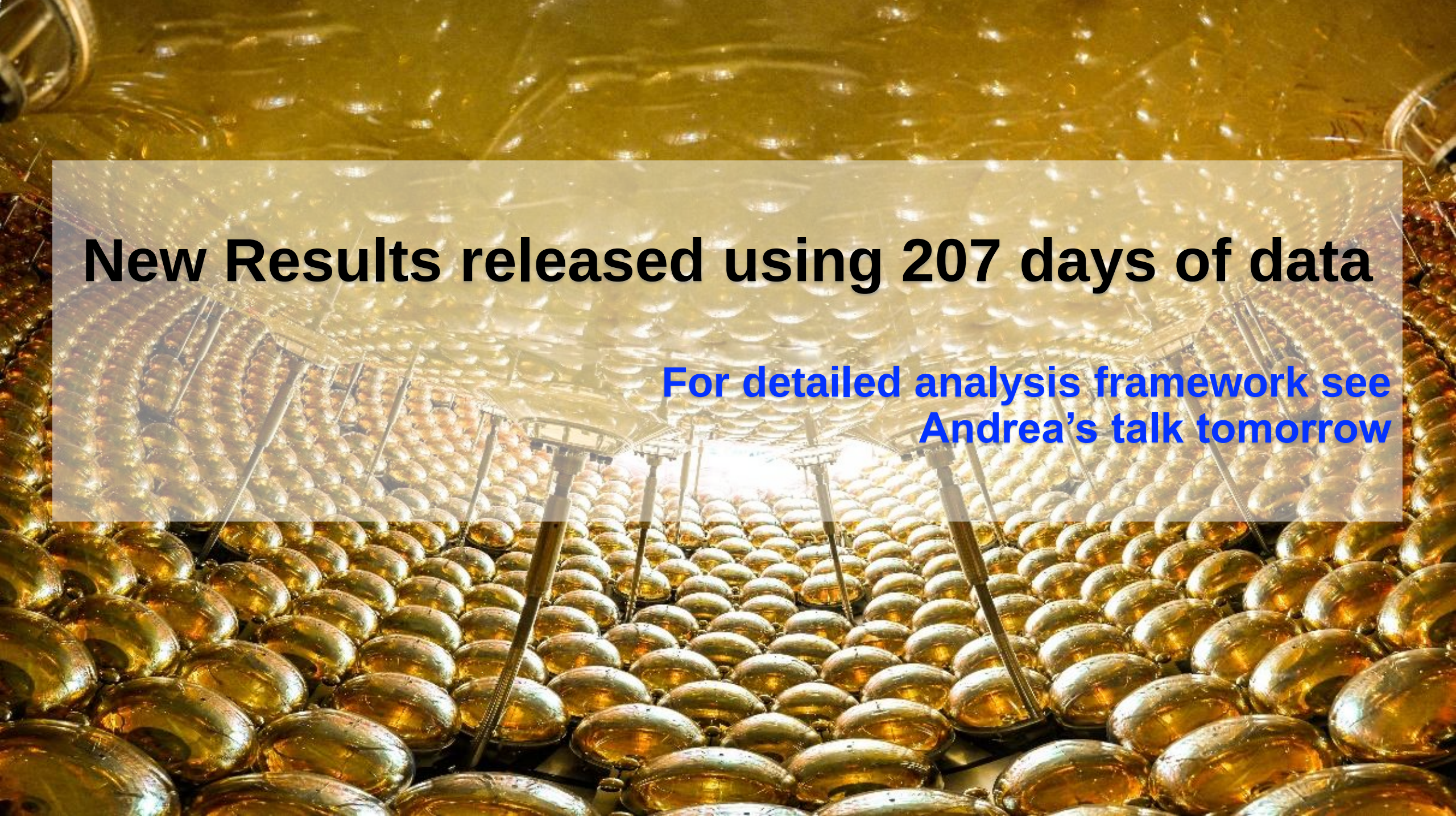
Preliminary











New Results released using 207 days of data

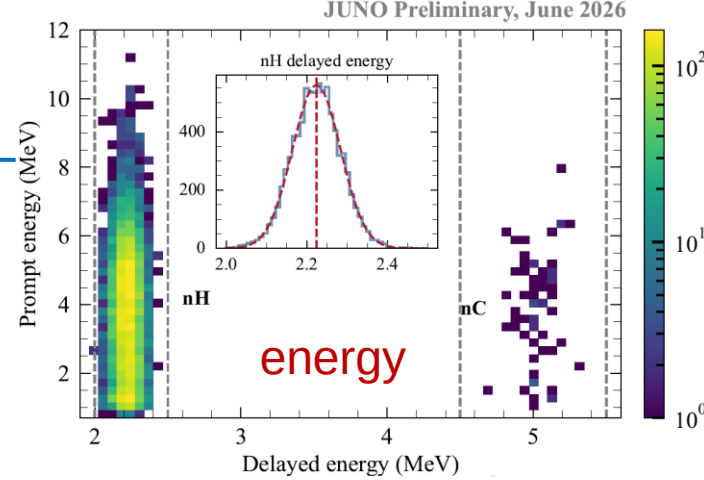
For detailed analysis framework see
Andrea's talk tomorrow

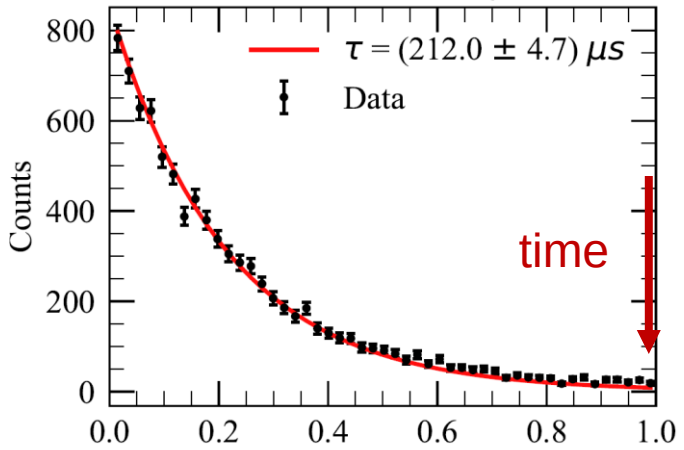
Reactor Neutrino Selection

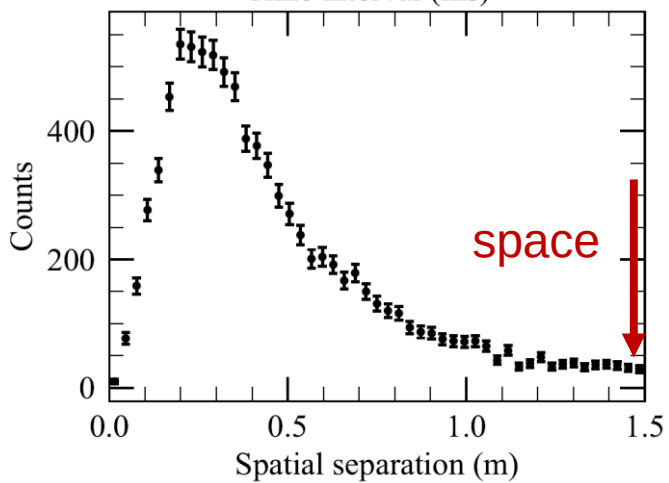
- Prompt and delayed coincidence in time, space with energy features

Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2$ m, $\|z_p\|<15.5$m
Prompt energy	(0.7, 12) MeV
Delayed energy	(2.0, 2.5) ∪ (4.5, 5.5) MeV
Coincidence time	(5, 1000) μs
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 > 3×10^4 in CD
Spallation neutron veto	Veto if the delayed satisfies $\Delta r < 4$ m and $\Delta t < 1.2$ s after spallation neutrons with $\mathrm{NPE_{spn}} \in$ (3000, 30000) and $T_{\mathrm{spn2}\mu} \in$ (20, 2000) μs
Muon track veto	Veto if the delayed event: $\frac{\Delta r_{\mu d}}{2.5\mathrm{m}} + \frac{\Delta t_{\mu d}}{0.5\mathrm{s}} < 1$
Correlated discriminator	log(L.R.) > -1.26

Similar to our "Nature" paper



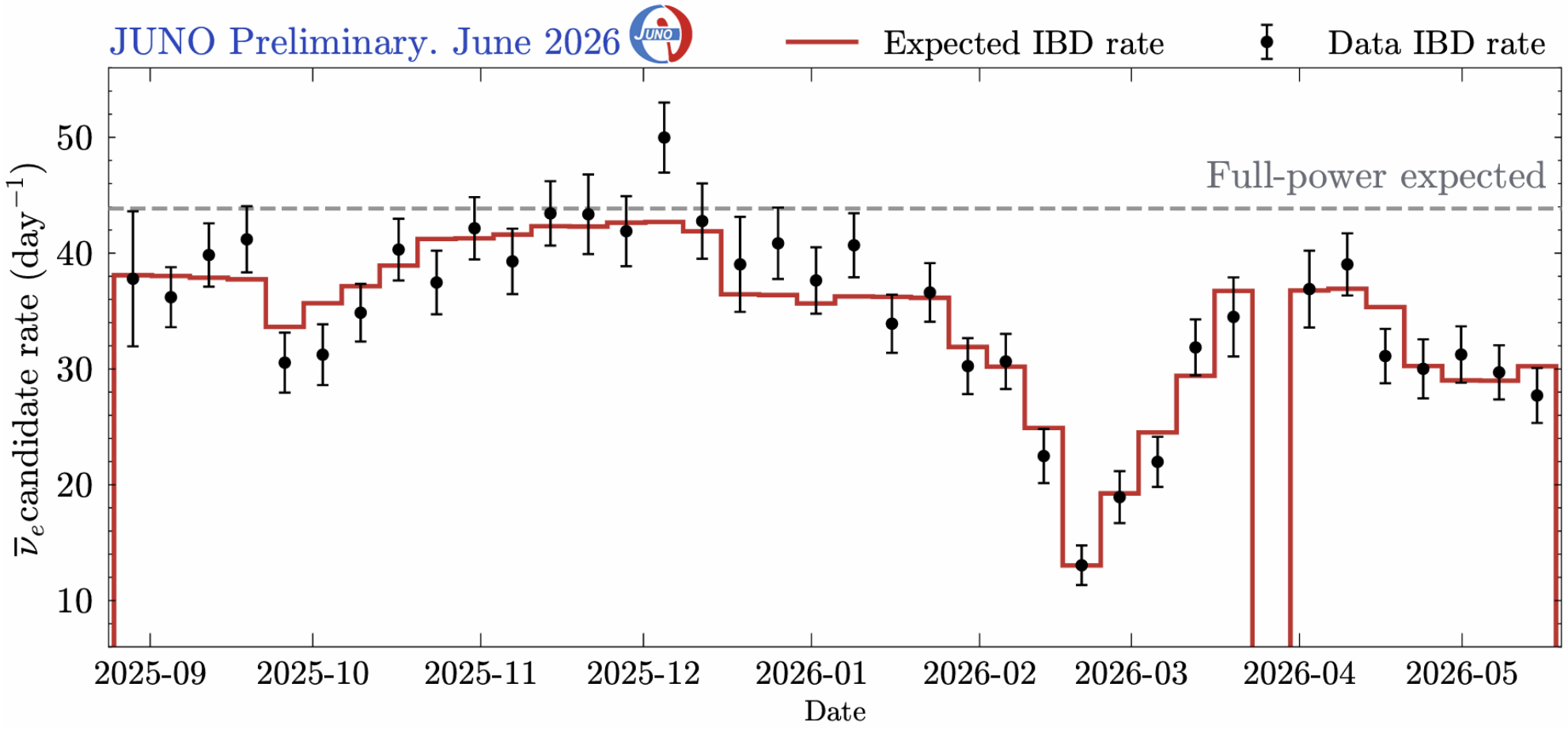




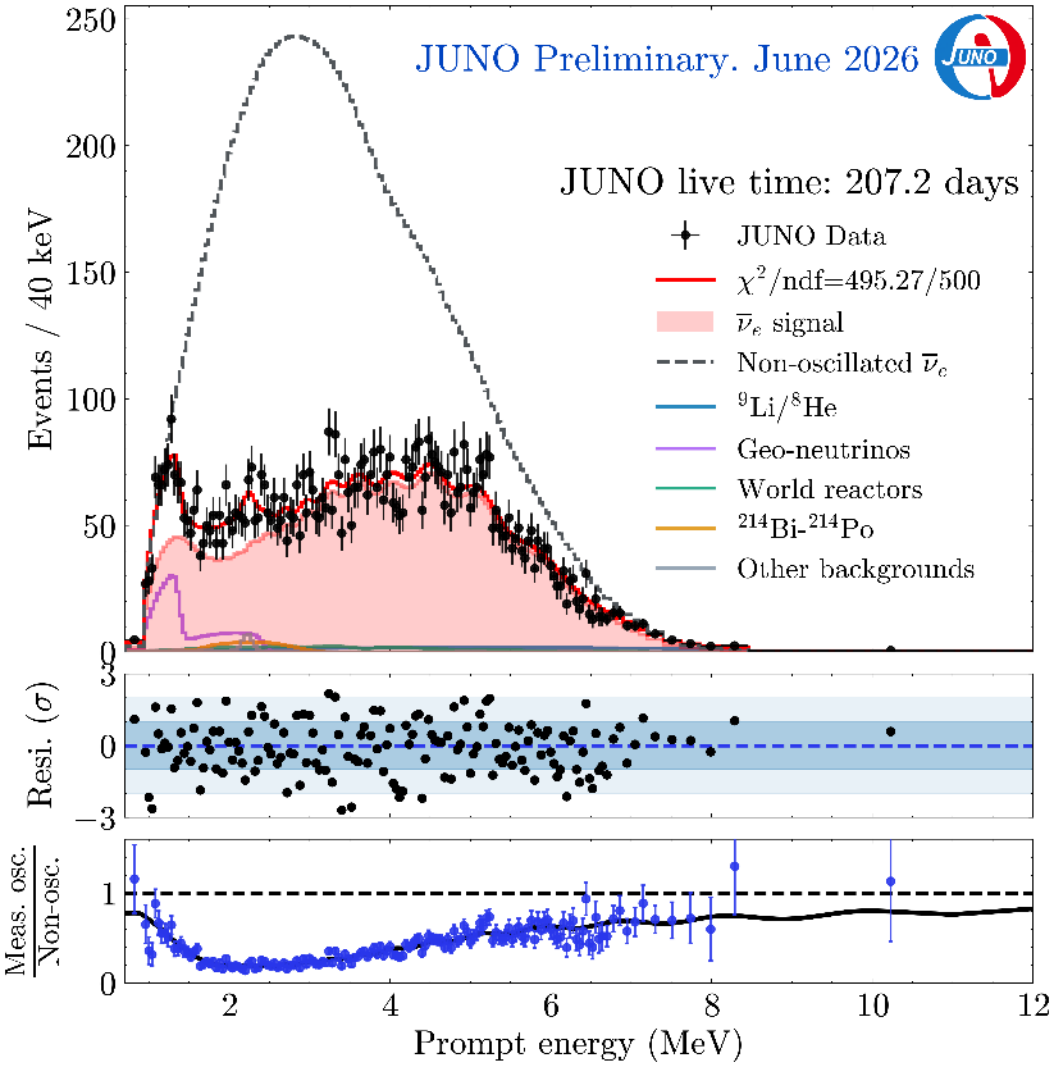
- What is new in this analysis:
  - ~10% more fiducial volume (R=16.5m➔17.2m)
  - ~60% reduction of ^{9}Li bkg.
  - a factor of 50 reduction of accidental bkg. using likelihood cut
  - model independent estimate of the ^{214}Bi bkg.

Reactor Neutrino Event Rate versus Time

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



Measured Reactor Neutrino Spectrum

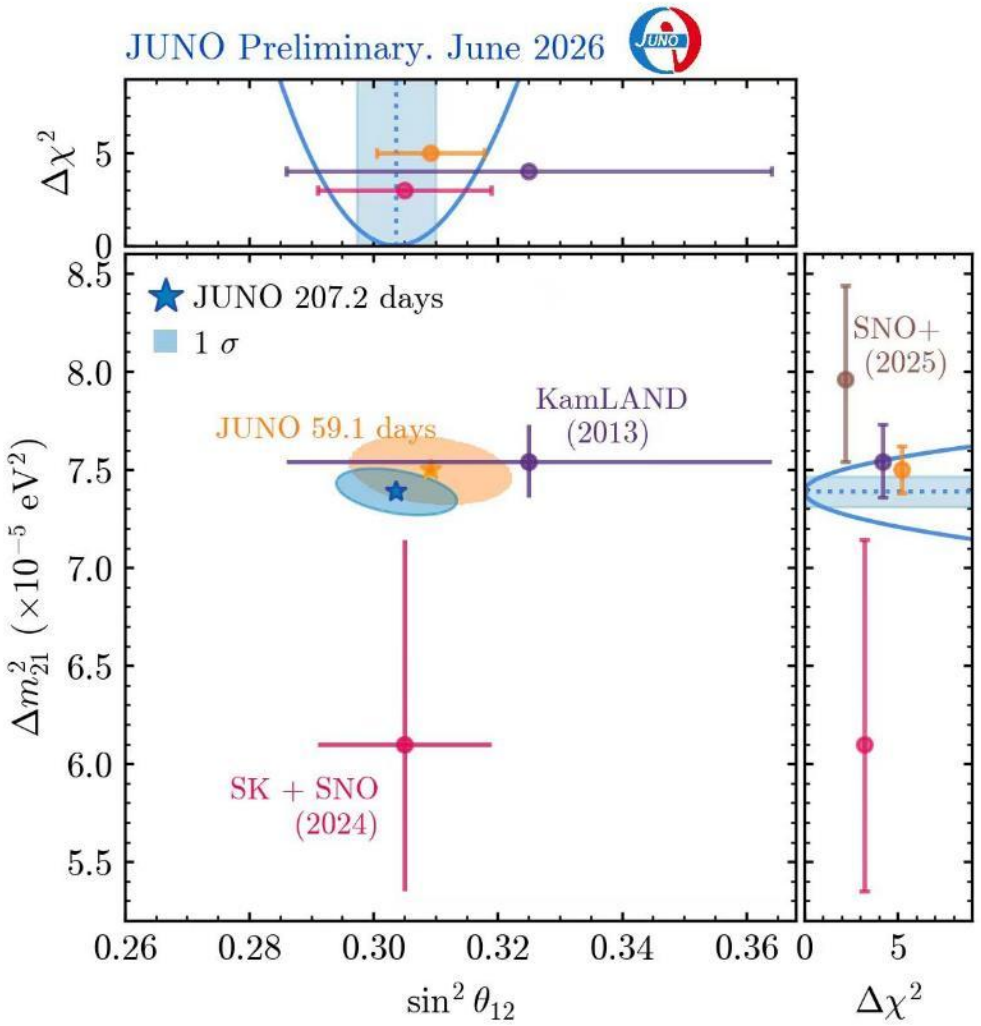


Fitting constrained by the near detector spectra from TAO and Daya Bay

Consistent results from three independent analyses

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ε	$\sigma_{\rm rel}$
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 ($\varepsilon_{\rm tot}$)	74.01%	1.02%
$\bar{\nu}_e$ signal (cpd)		
w/o $\varepsilon_{\rm tot}$ corrected	36.02 $\pm$ 0.62	
w/ $\varepsilon_{\rm tot}$ corrected	48.67 $\pm$ 1.08	
Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}He	1.05 $\pm$ 0.27	1.41 $\pm$ 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 $\pm$ 0.09	0.92 $\pm$ 0.09
^{214}Bi-^{214}Po	0.42 $\pm$ 0.31	0.57 $\pm$ 0.34
^{13}C(α, n)^{16}O	0.05 $\pm$ 0.02	0.05 $\pm$ 0.02
Fast neutrons	0.02 $\pm$ 0.02	0.02 $\pm$ 0.02
Double neutrons	0.10 $\pm$ 0.10	0.13 $\pm$ 0.10
Atmospheric neutrinos	0.09 $\pm$ 0.04	0.11 $\pm$ 0.05
Accidentals	0.07 $\pm$ 0.01	0.07 $\pm$ 0.01

New Results of Solar Oscillation Parameters

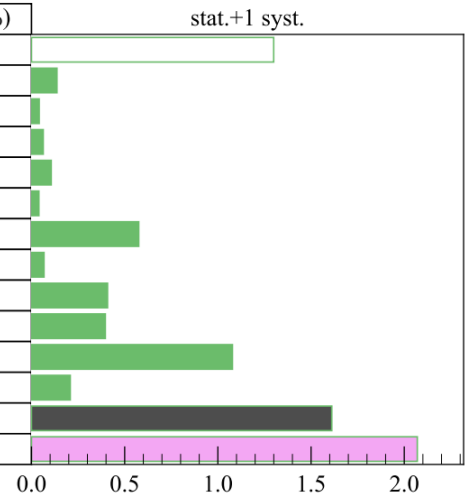


Δm^2_{21}	7.388±0.078 (1.60% →1.06%)
$\sin^2\theta_{12}$	0.3036±0.0064 (2.8%→2.1%)

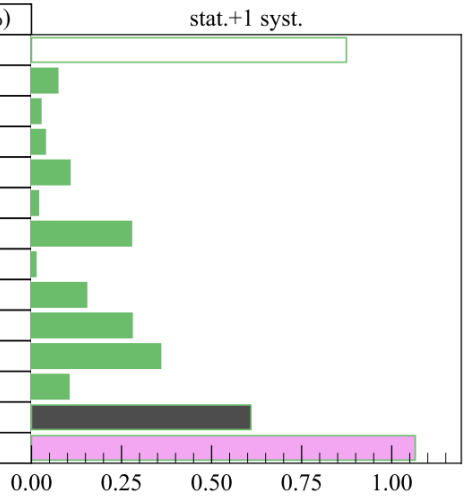
- Even though the statistical uncertainty is dominant, systematic errors become important:

⇨ ^{214}Bi bkg. and detection eff. can be improved

$\sin^2\theta_{12}$	Precision (%)
Stat-Only	1.2995
Power	0.1368
Spent nuclear fuel	0.0415
Non-equilibrium	0.0631
Fission fraction	0.1059
Fission energy	0.0398
Detection efficiency	0.5755
Matter density	0.0673
Detector response covariance	0.4081
Reactor spectrum	0.3961
Bkg rate	1.0781
Bkg shape	0.2081
AllSyst	1.6112
Total	2.0700

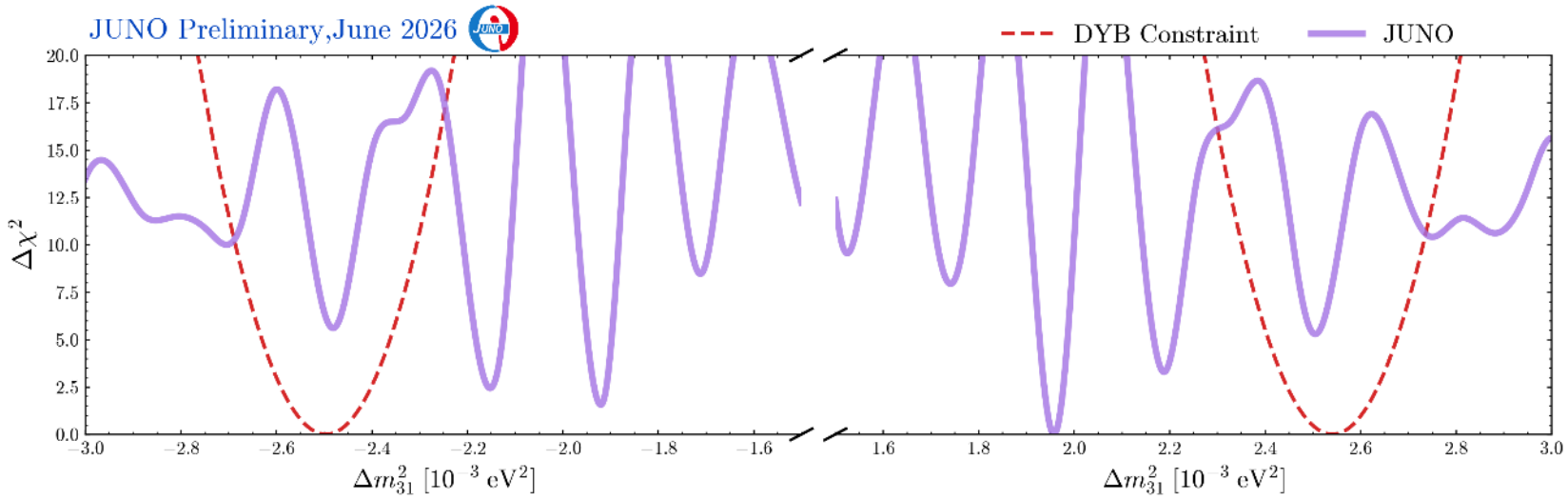


Δm^2_{21}	Precision (%)
Stat-Only	0.8741
Power	0.0729
Spent nuclear fuel	0.0261
Non-equilibrium	0.0384
Fission fraction	0.1069
Fission energy	0.0194
Detection efficiency	0.2775
Matter density	0.0125
Detector response covariance	0.1531
Reactor spectrum	0.2794
Bkg rate	0.3585
Bkg shape	0.1043
AllSyst	0.6090
Total	1.0653



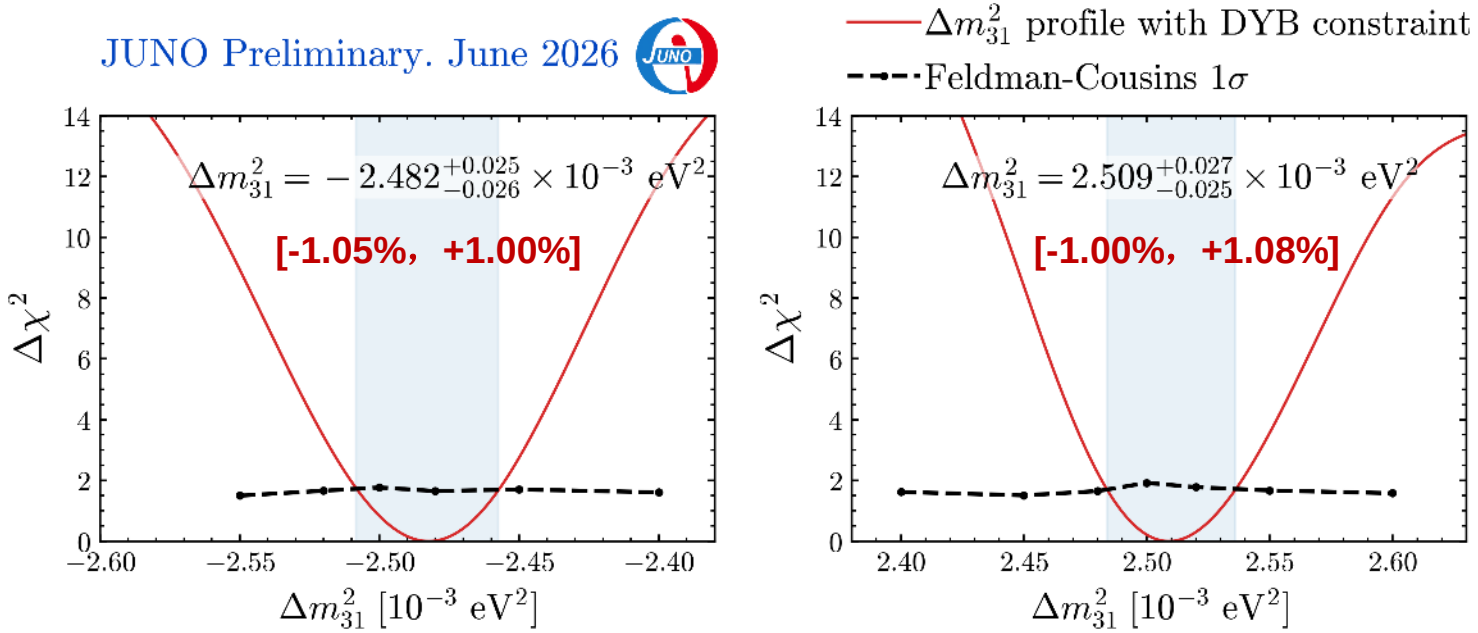
First Result of Δm^2_{31}

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



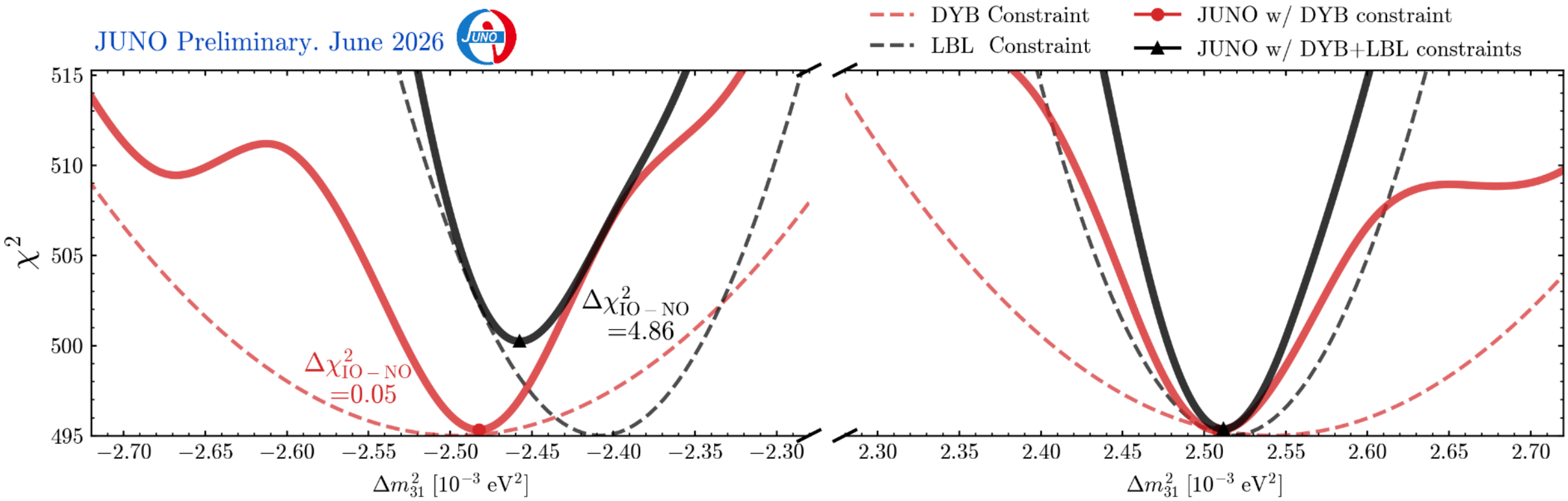
The final minimum for each mass ordering is obtained by using the Δm^2_{31} constraint from the Daya Bay result (PRL 130 16, 161802)

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



Adding Constraint from NuFit-LBL

- Δm^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 $\Delta\chi^2 = 4.86$

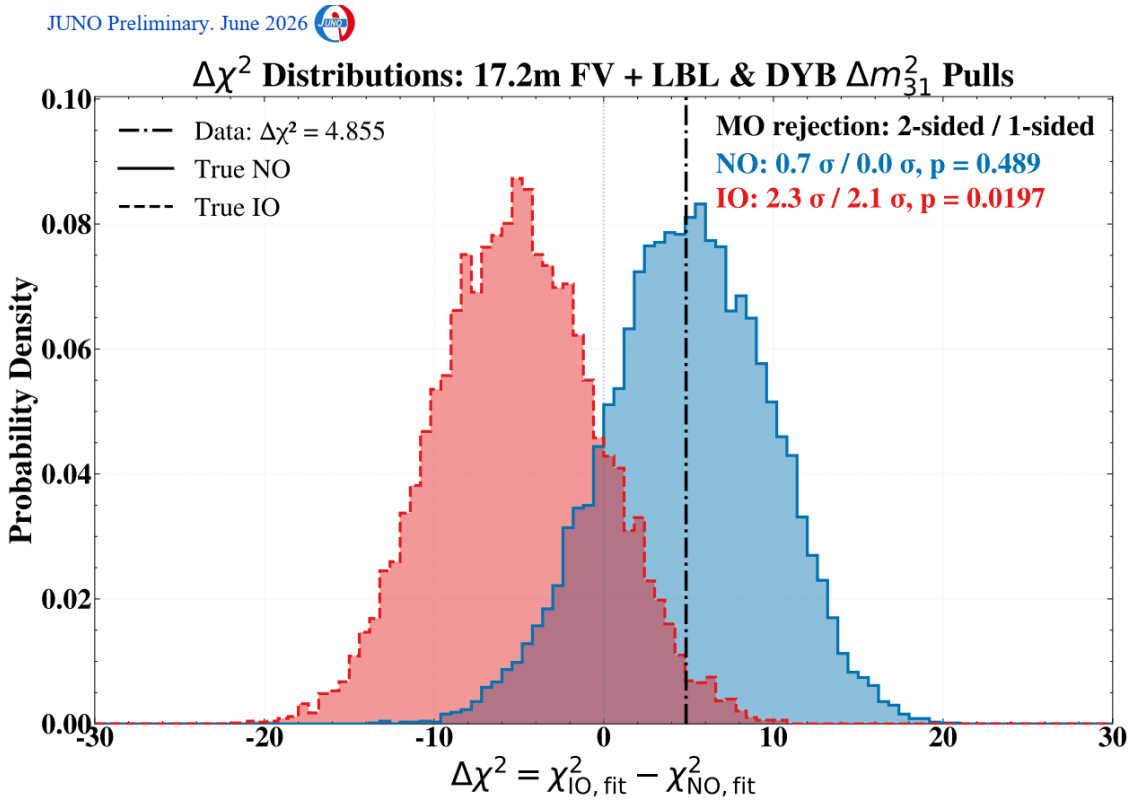


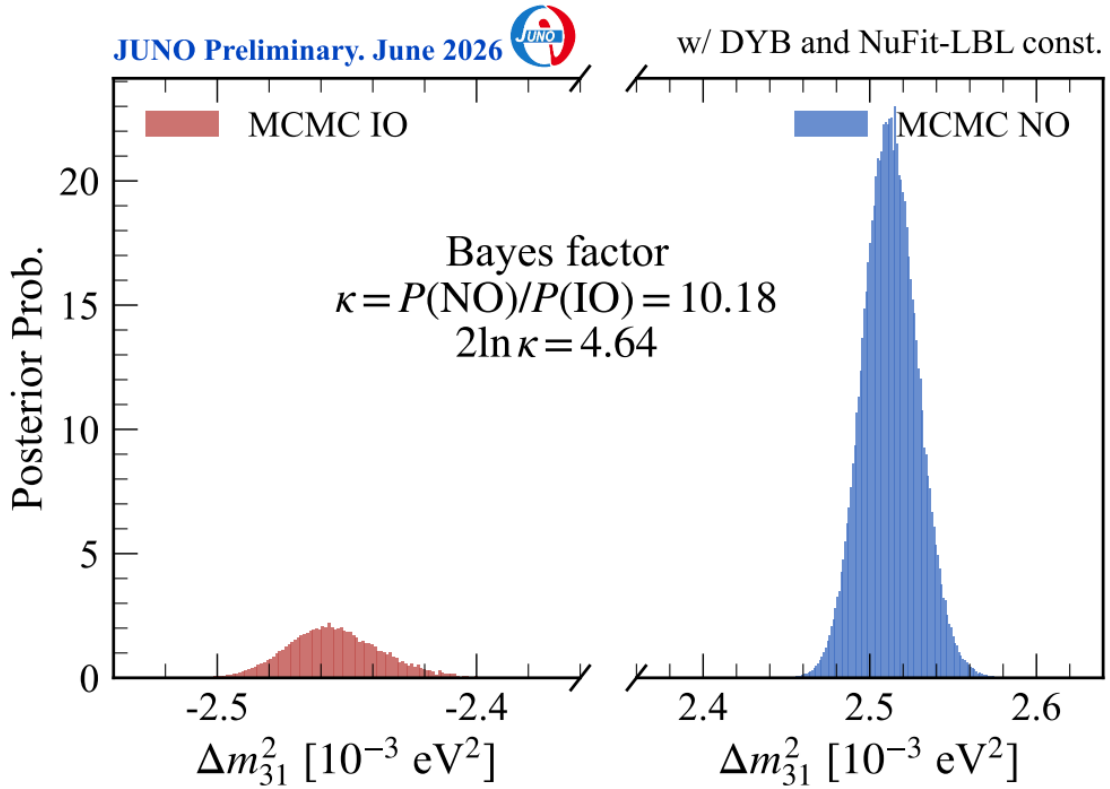
[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Neutrino Mass Ordering Significance

- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
- Influence of δ_{CP} considered (scanned)
- Normal Ordering is favored at **2.3σ (2.1σ)**

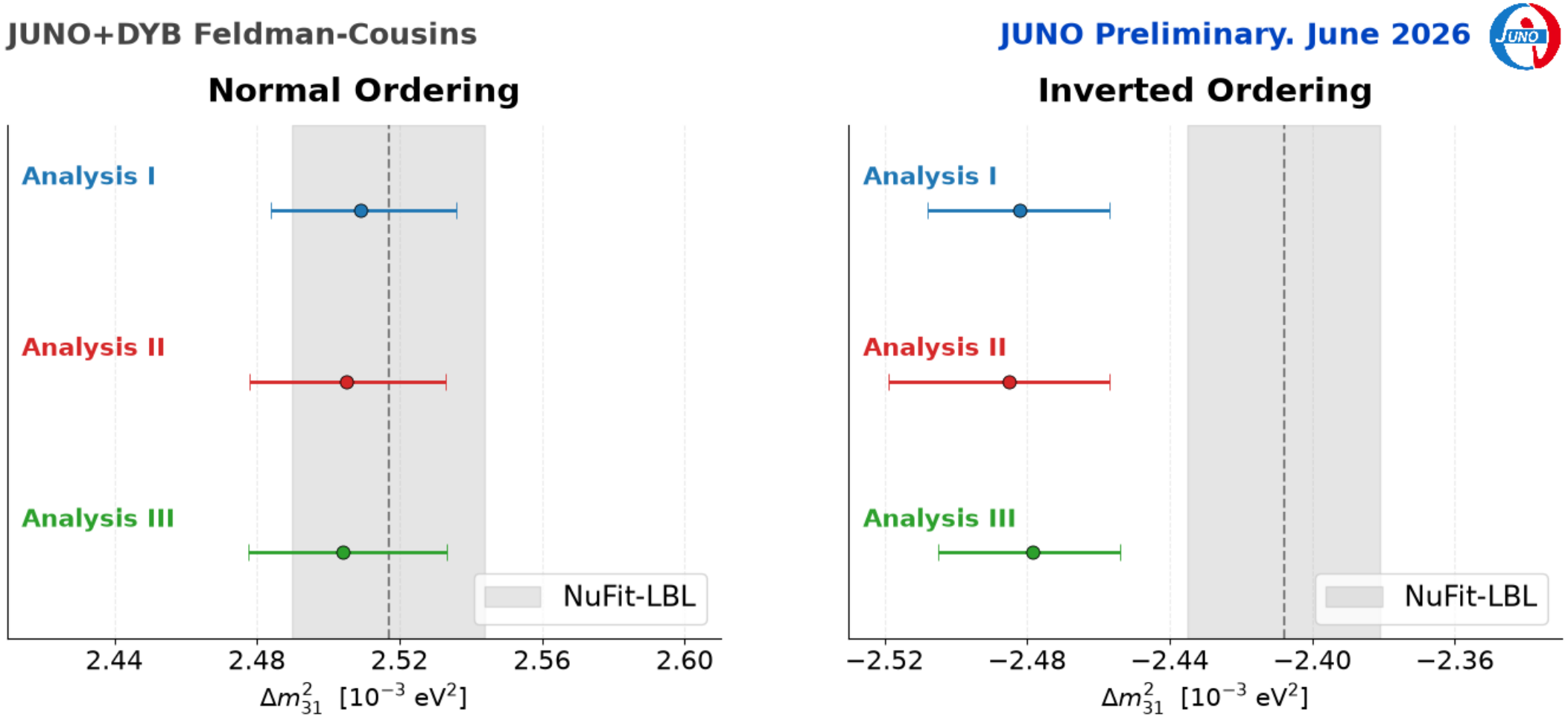
- Bayesian approach using Markov Chain Monte Carlo(MCMC) method
- Normal Ordering is favored with a Bayes factor of **10.18** ➔ $2\ln\kappa = 4.64$





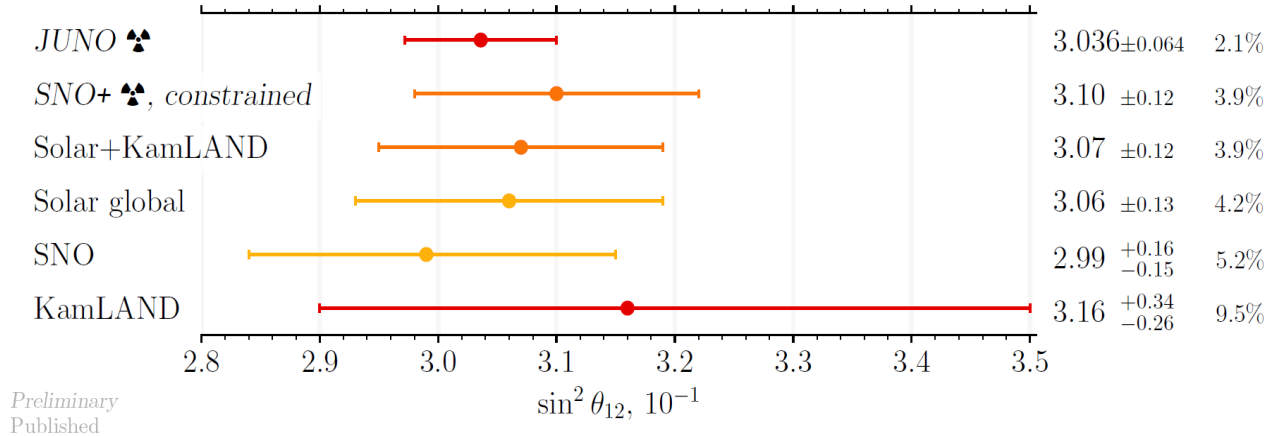
Consistent Results from Independent Analyses

- **Our 3 independent analyses got consistent results (0.2σ)**
  - ⇨ different event reconstruction code, fiducial volume, selection cuts, efficiency, background estimation, energy response models and oscillation fitters

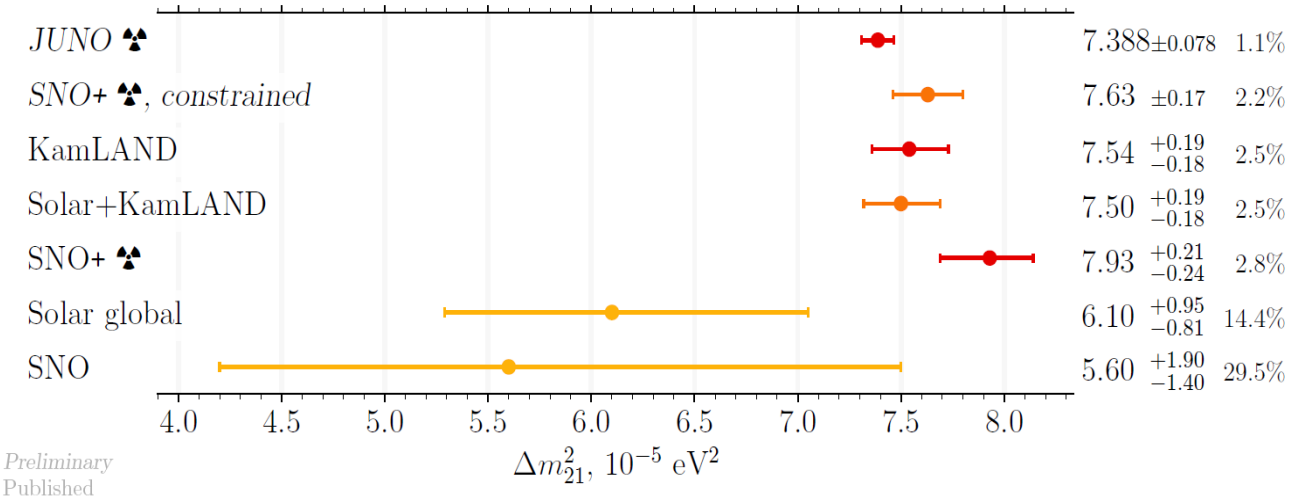


Comparison of Results on Oscillation Parameters

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

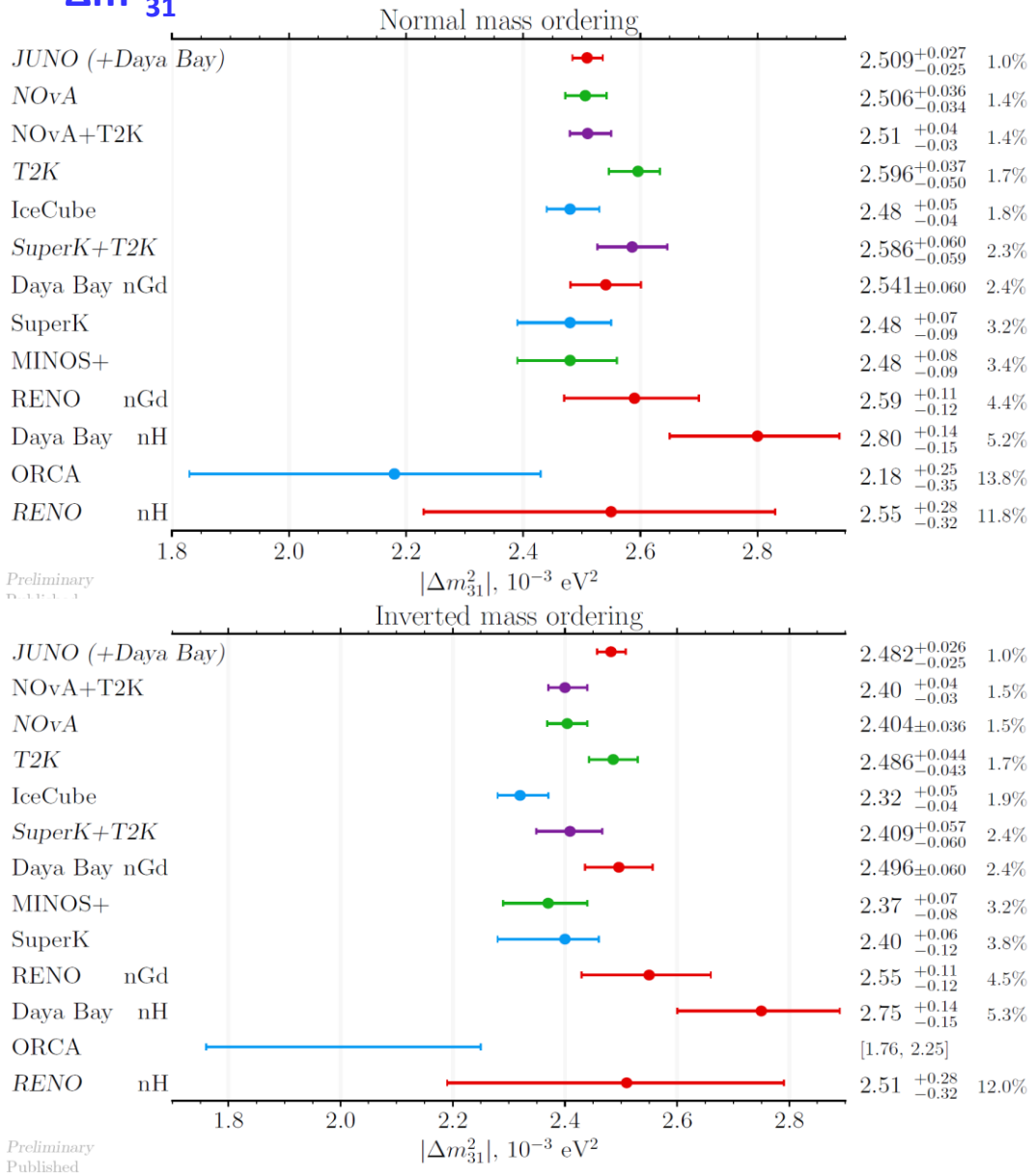


Δm^2_{21}



Results from JUNO have smallest uncertainties

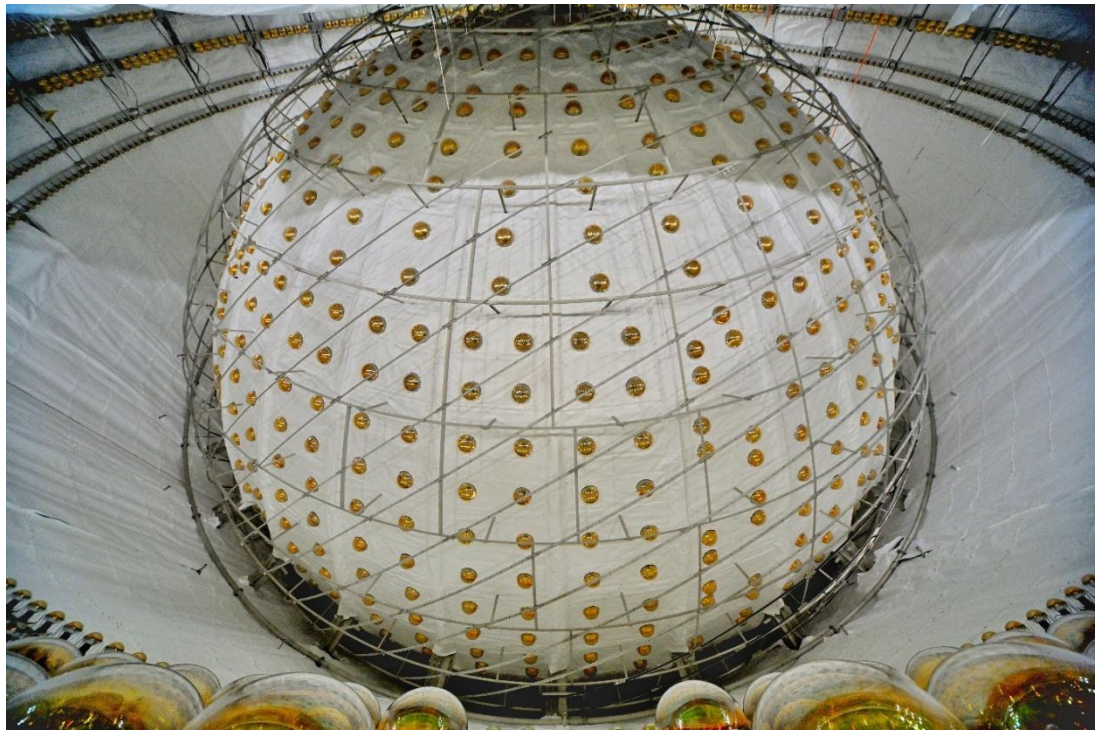
Δm^2_{31}



Summary

- JUNO has begun stable physics data-taking. Study shows that the detector works well as designed.
- With 59 days of data, world-leading precision was achieved in the measurements of $\sin^2\theta_{12}$ and Δm^2_{21}. The 207-day dataset has further improved the measurement precision by a factor of 1.3–1.5.

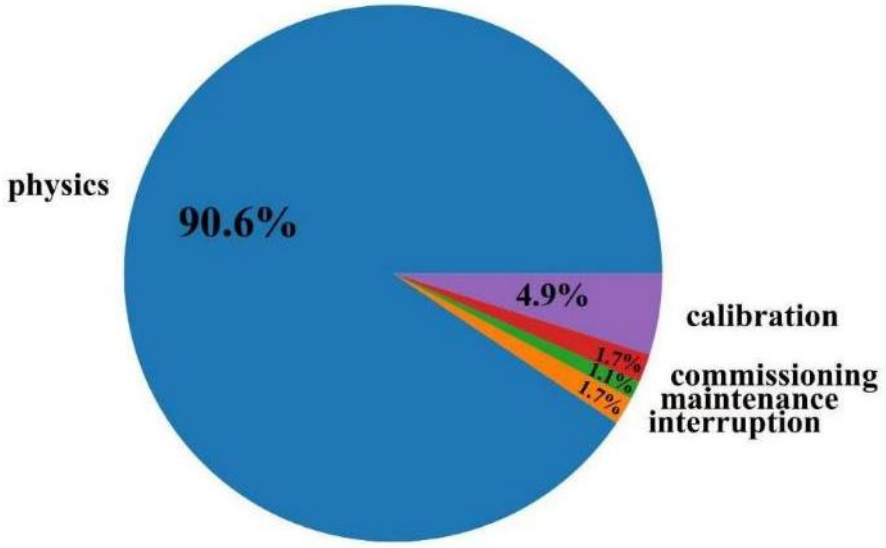
- First measurement on Δm^2_{31} achieved a precision of ~1%
- With external constraint, Normal Mass Ordering is favored at ~2.1σ (1-sided)
- First geo-neutrino results yield a flux of 73 ± 11 TNU
- Stay tuned for what will come next!

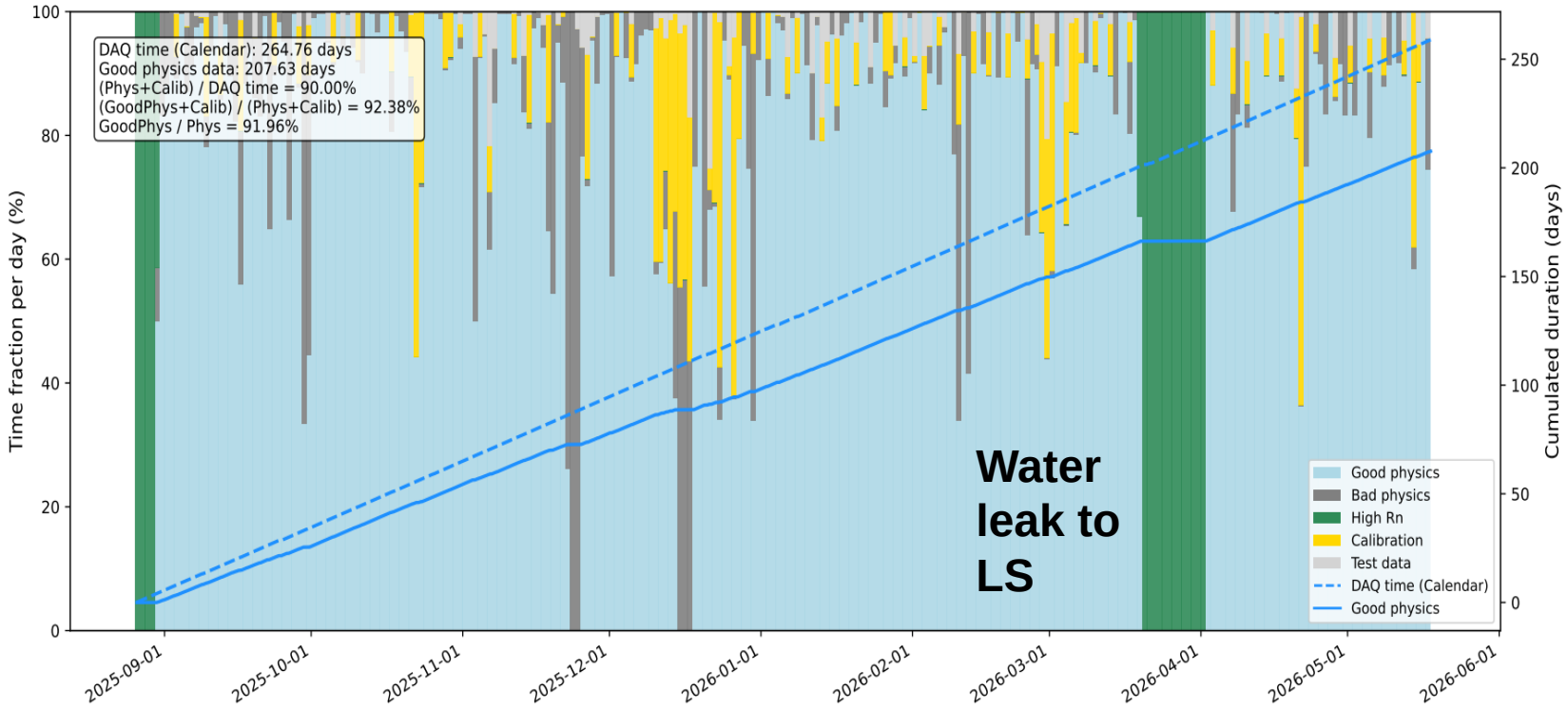


Back up

Data Taking

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



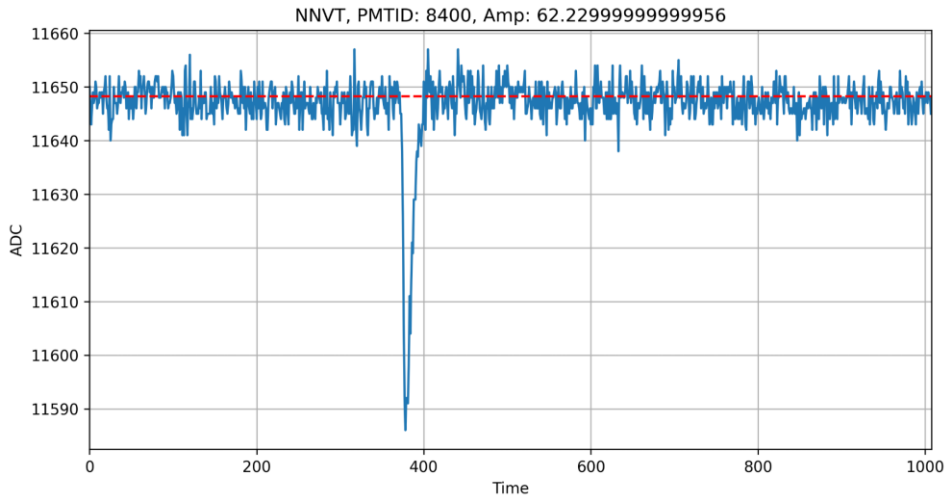


➢ Power outage due to weather is one of the main causes of interruptions

Low-Level Detector Performance

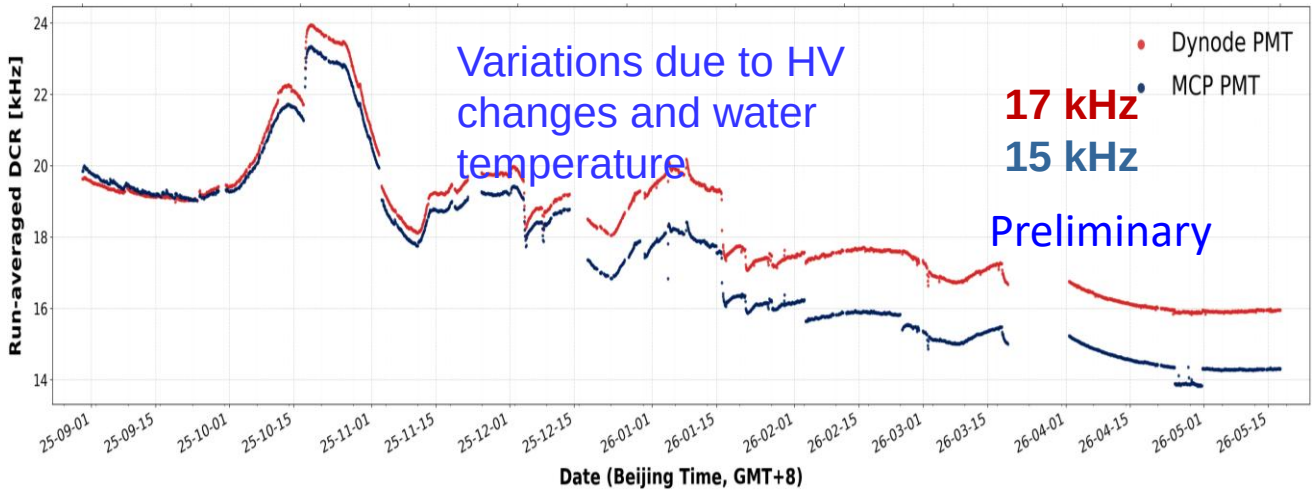
- Large PMTs work fine
  - 17612-16 LPMTs installed for CD, 2400-1 LPMTs installed for VETO
  - ~26 dead PMTs, ~600 flashing PMTs
  - Gains of MCP (Dynode) PMTs are reduced from 7.4×10^6 to 4.0×10^6 (6.5×10^6 to 5.5×10^6), efficiencies not affected

Waveform of a typical PMT



- Great performance of electronics:
  - Good grounding and low noise:
    - RMS ~2.8 ADC ch. ➔ ~0.055 PE
  - PMT threshold: 0.2-0.3 PE/ch.

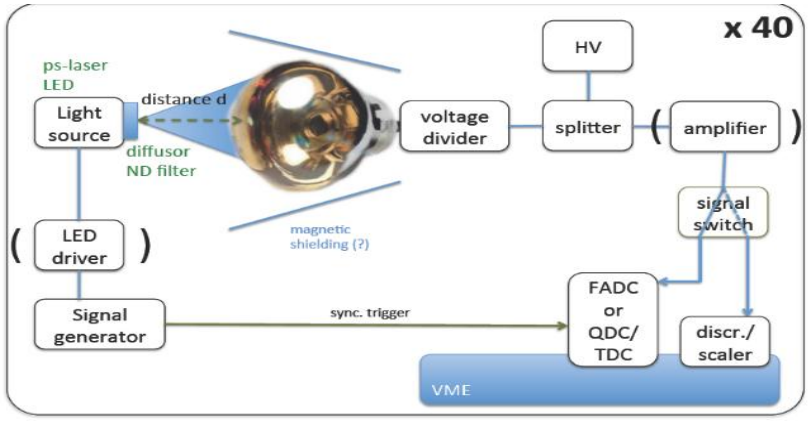
Dark Count Rate continuously decreasing



- Trigger and DAQ work fine
  - Trigger threshold: ~200 keV

PMT Testing and Installation

Container test stations



Scanning station



Cables in corrugated pipes

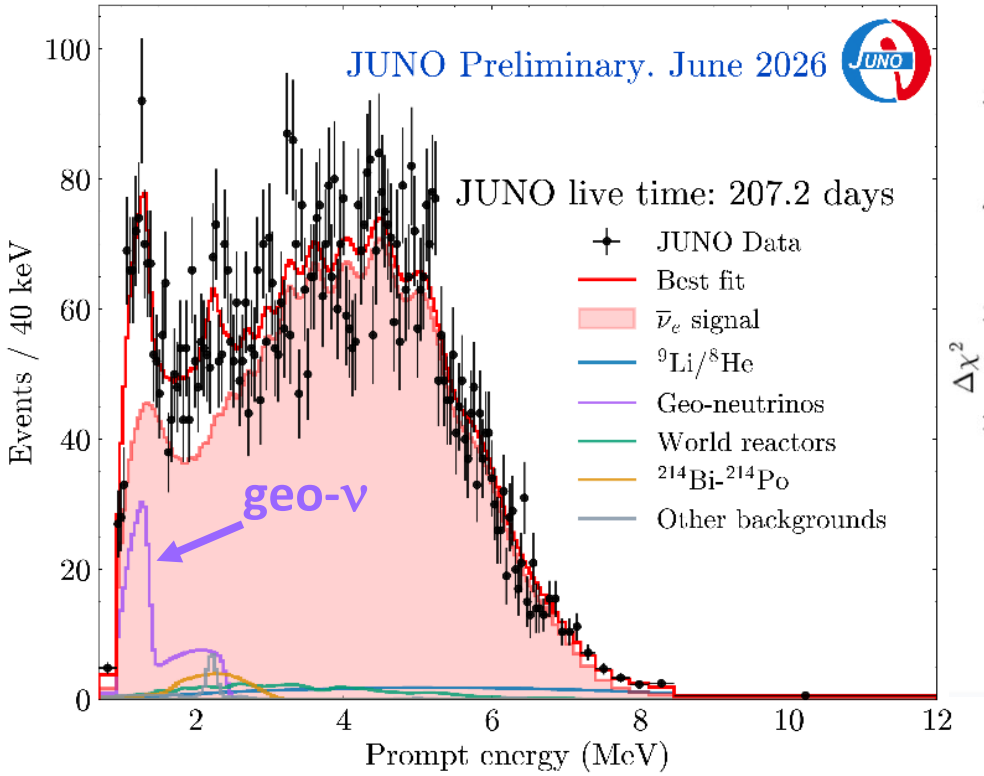


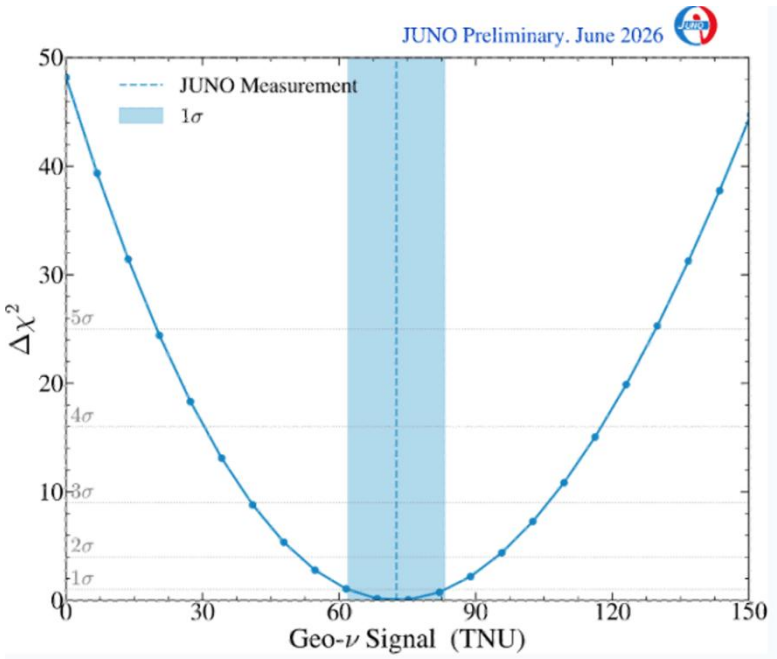
	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Charge Collection	Dynode	MCP	Dynode
Photon Detection Efficiency	28.5%	30.1%	25%
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

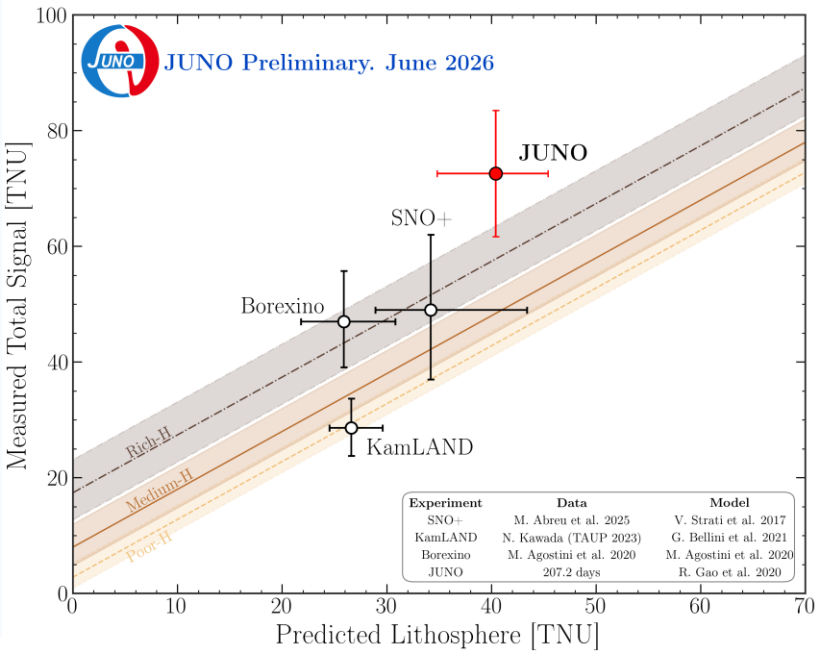


New Results on Geo-neutrinos

- 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







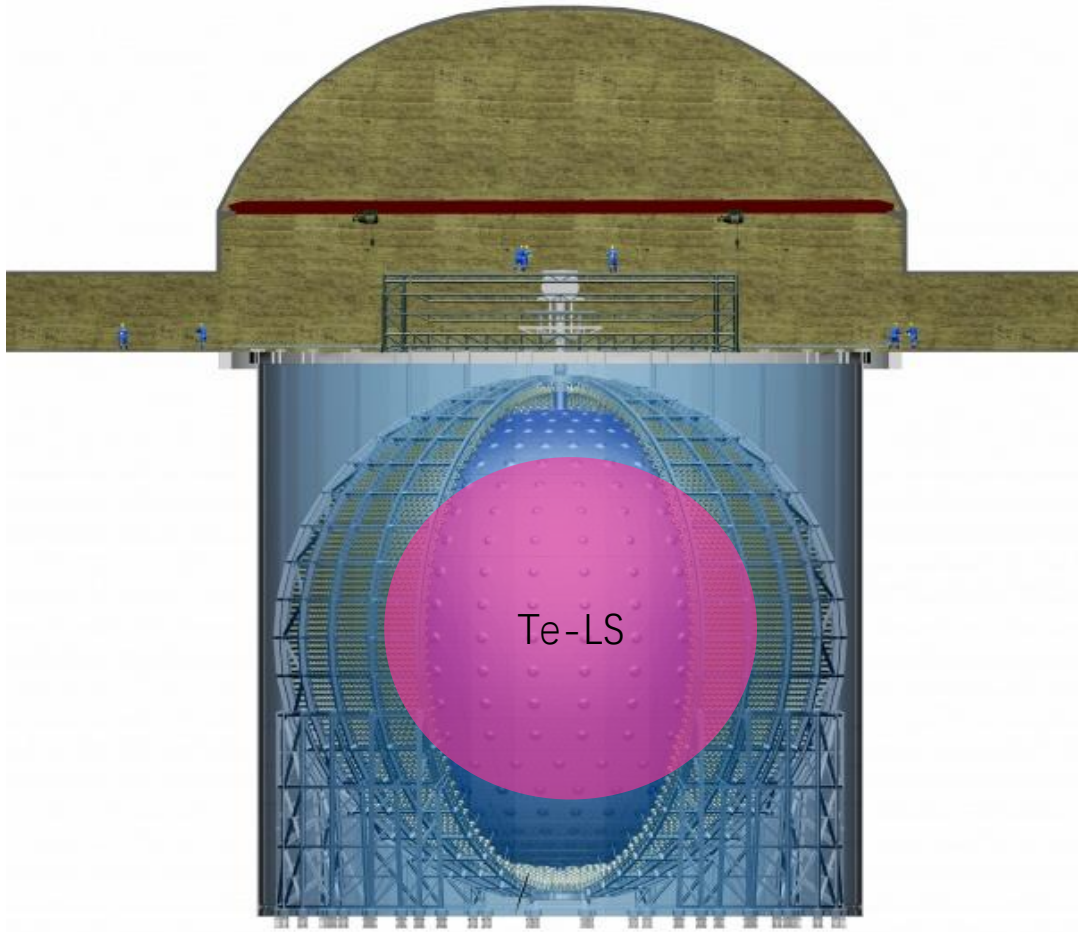
JUNO-0$\nu\beta\beta$ Upgrade

JUNO offers a unique opportunity to search for 0νββ

- **20 kton LS → 100-ton scale isotope loading (e.g., Tellurium)**
- **Low background**
- **Energy resolution < 3% @ 1 MeV**

Critical R&D

- **Isotope loading technology**
- **Background control**



Concept of the experiment