Reactor oscillation analysis using 207 days of JUNO data

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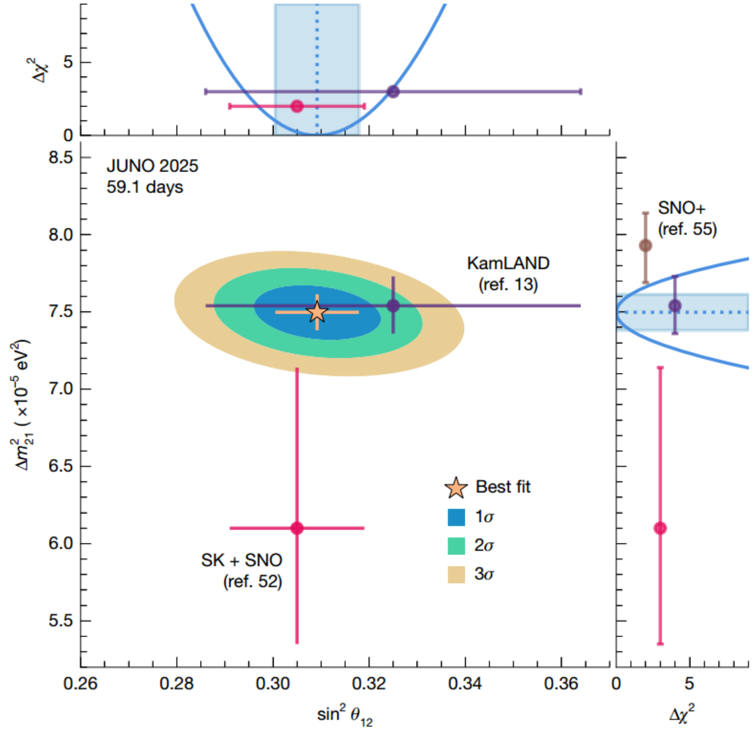
Introduction

- JUNO’s first results with 59 days of data released in Nov. 2025 [Nature 654, 343 (2026)]

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087, \quad (2.8\%)$$

$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \mathrm{eV}^2. \quad (1.6\%)$$

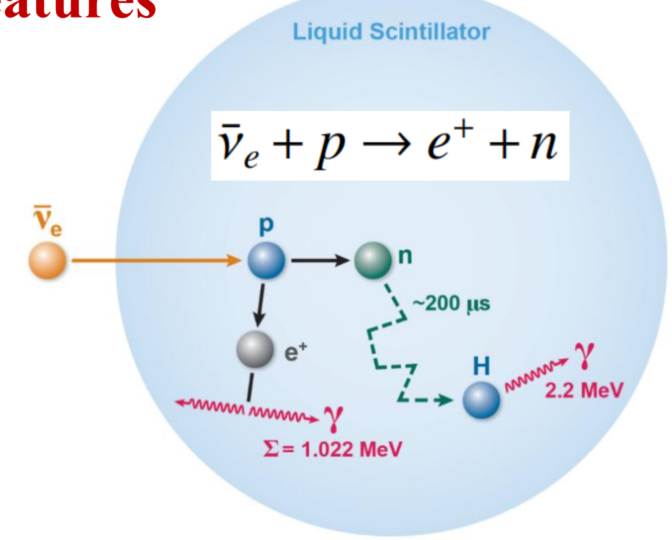


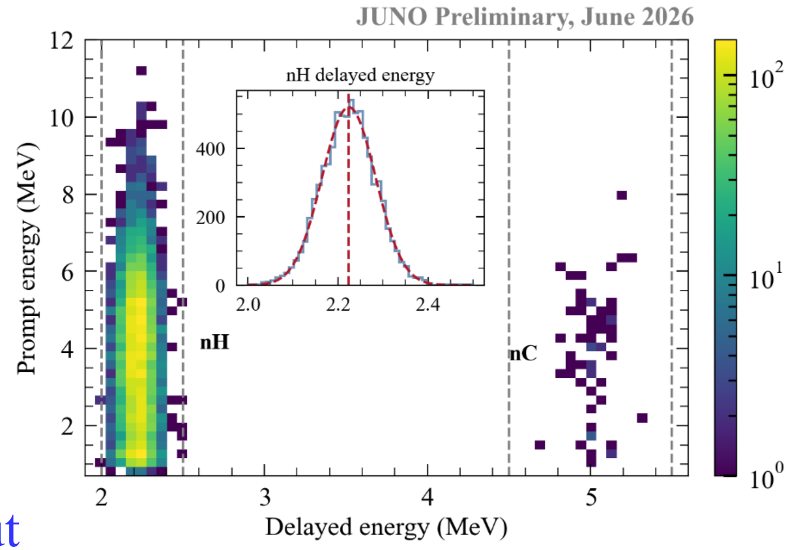
- This analysis focus on new results with 207 days of data
  - Data taking period: 2025.08.30-2026.05.18
  - Golden data is selected for physics analysis
- New things: first measurement of Δm^2_{31} and neutrino mass ordering (NMO) at JUNO

Reactor antineutrino candidate 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	$(2.0, 2.5) \cup (4.5, 5.5)$ 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: $\frac{\Delta r_{d2\mu}}{2.5\mathrm{m}} + \frac{\Delta t_{d2\mu}}{0.5\mathrm{s}} < 1$
Correlated discriminator	log(L.R.) > -1.26





- Optimized selection criteria:
  - ~10% more fiducial volume (R = 16.5m → 17.2m)
  - ~60% reduction of ^{9}Li bkg. with muon track veto
  - a factor of 50 reduction of accidental bkg. using likelihood ratio cut

Efficiency and background analysis

Main updates in this analysis:

- More precise estimation of fiducial volume cut ($\sigma_{FV} \sim 1.6\% \rightarrow \sim 1.0\%$)
- Combine time and spatial distributions since adjacent muons to estimate $^{9}Li/^{8}He$ bkg.
- Model independent estimate of the ^{214}Bi bkg. (spectrum shape model → enriched samples)
- Free geo-nu rate for their measurement (see Qishan's talk)

Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\overline{\nu}_e$ 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%
$\overline{\nu}_e$ **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
$^{9}Li/^{8}He$	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
$^{13}C(\alpha, n)^{16}O$	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

Fitting strategy

- Reactor antineutrino oscillation probability

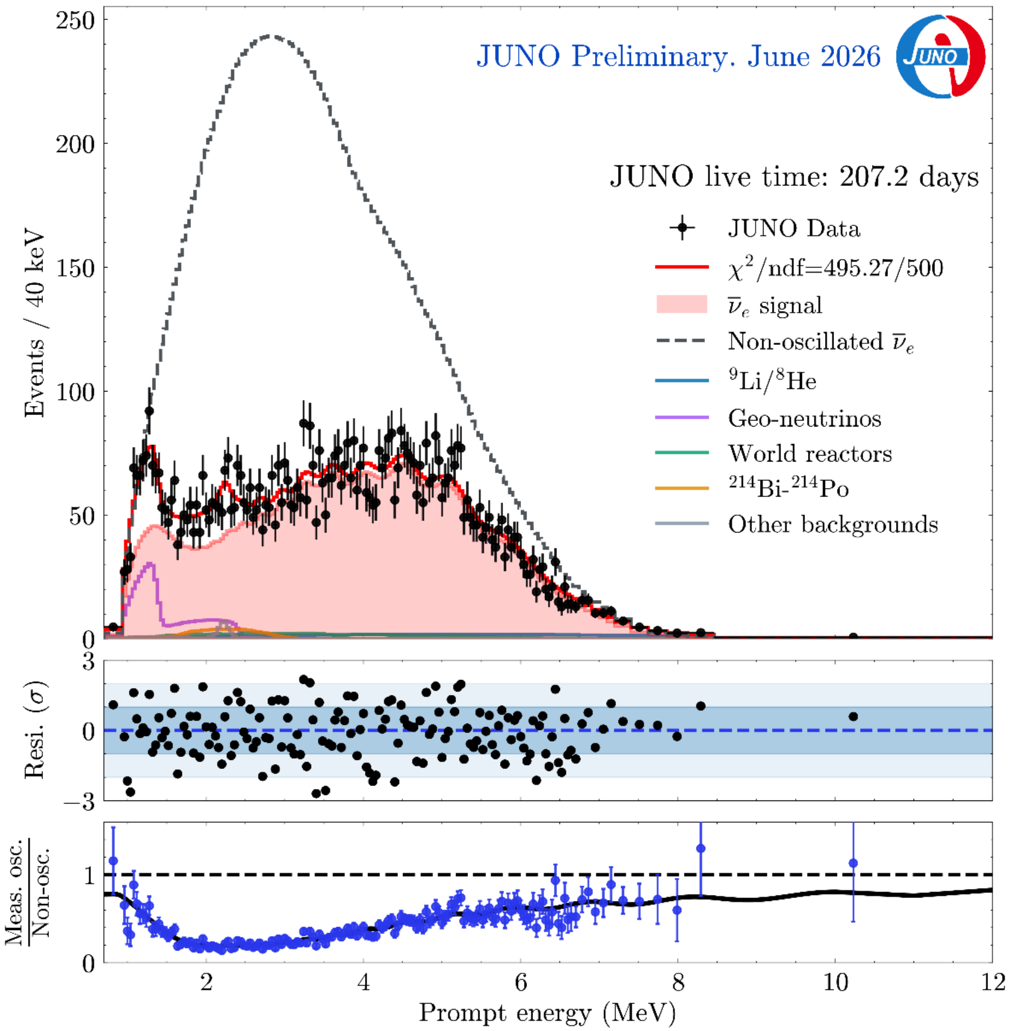
$$\mathcal{P}_{ee} = 1 - \sin^2 2\tilde{\theta}_{12}\, \tilde{c}_{13}^{4} \sin^2 \tilde{\Delta}_{21} - \sin^2 2\tilde{\theta}_{13} (\tilde{c}_{12}^{2} \sin^2 \tilde{\Delta}_{31} + \tilde{s}_{12}^{2} \sin^2 \tilde{\Delta}_{32})$$

- χ^2 combined with DYB and TAO

$$\chi^2(\vec{p}, \vec{\eta}, \vec{\alpha}) = \sum_X (\mu^X - D^X)^T V_X^{-1} (\mu^X - D^X) + \lambda^2_{\mathrm{nuis}}(\vec{\eta}) + \lambda^2_{\mathrm{flux}}(\vec{\alpha}) + \chi^2_{\mathrm{osc}}(\sin^2\theta_{13}, \Delta m^2_{31}). \quad (1)$$

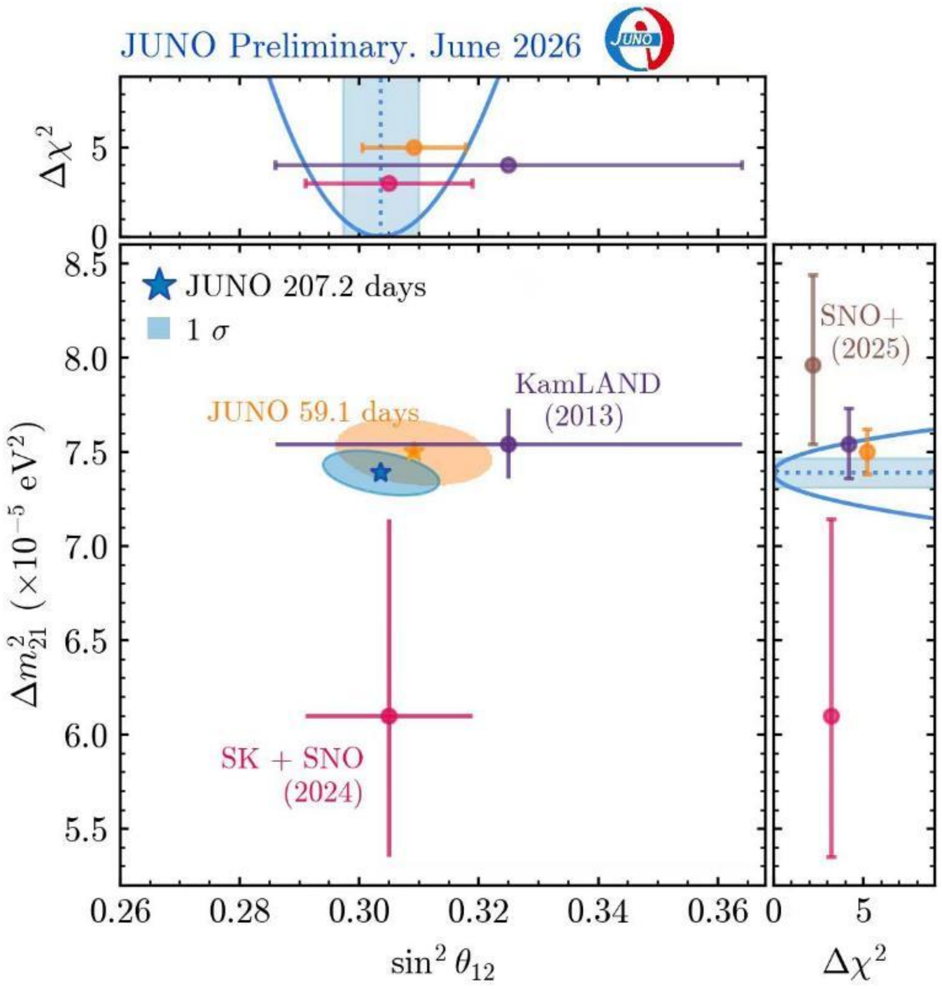
(X = JUNO, DYB, TAO)

- External θ_{13} constraint from DYB [1]
- Δm^2_{31} measurement: DYB Δm^2_{31} constraint [1]
- NMO: using Δm^2_{31} constraints from DYB and NuFit-LBL [2]



[1] DYB collaboration, PRL 130, 161802 (2023)
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380])

Updated measurement on solar parameters



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

$\sin^2\theta_{12}$	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

^{214}Bi dominate

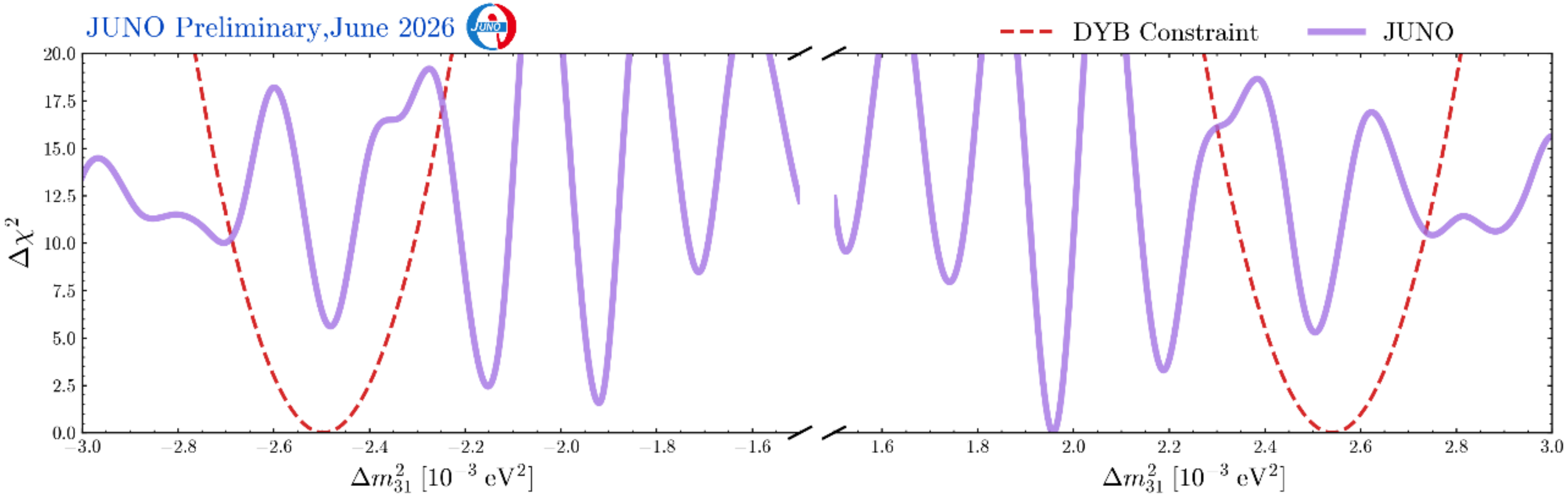
Syst. dominate

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

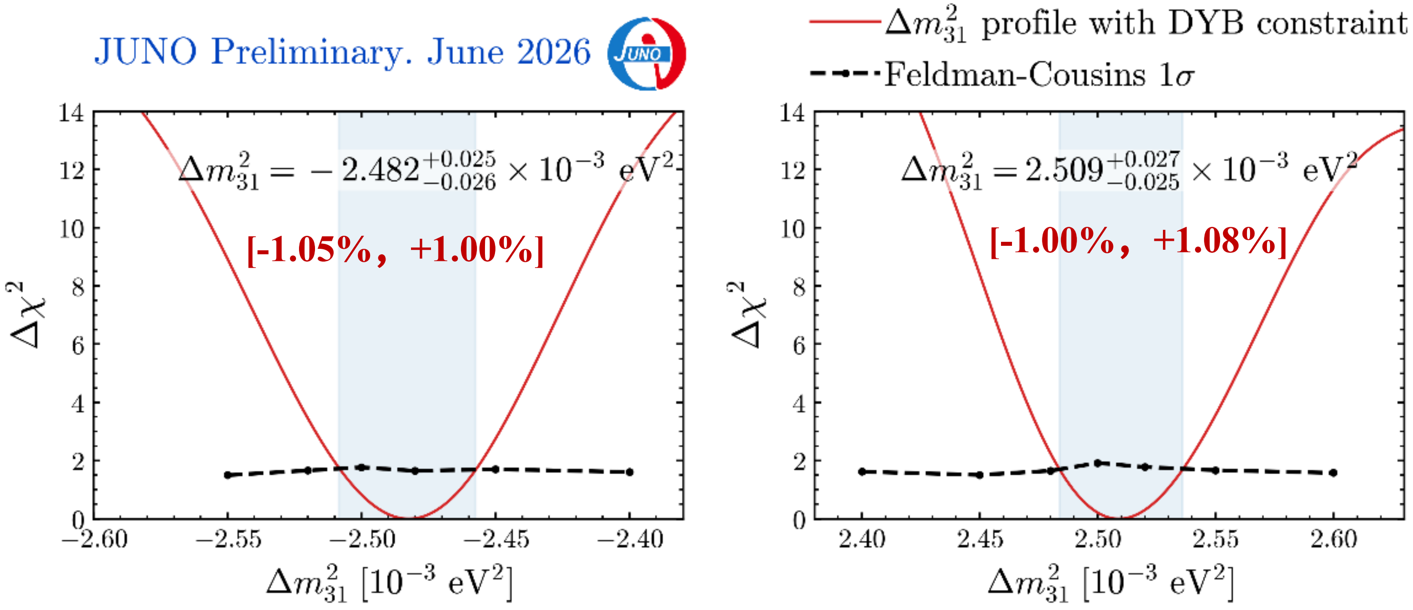
- ^{214}Bi bkg. and detection eff. can be improved

First result of Δm^2_{31}

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

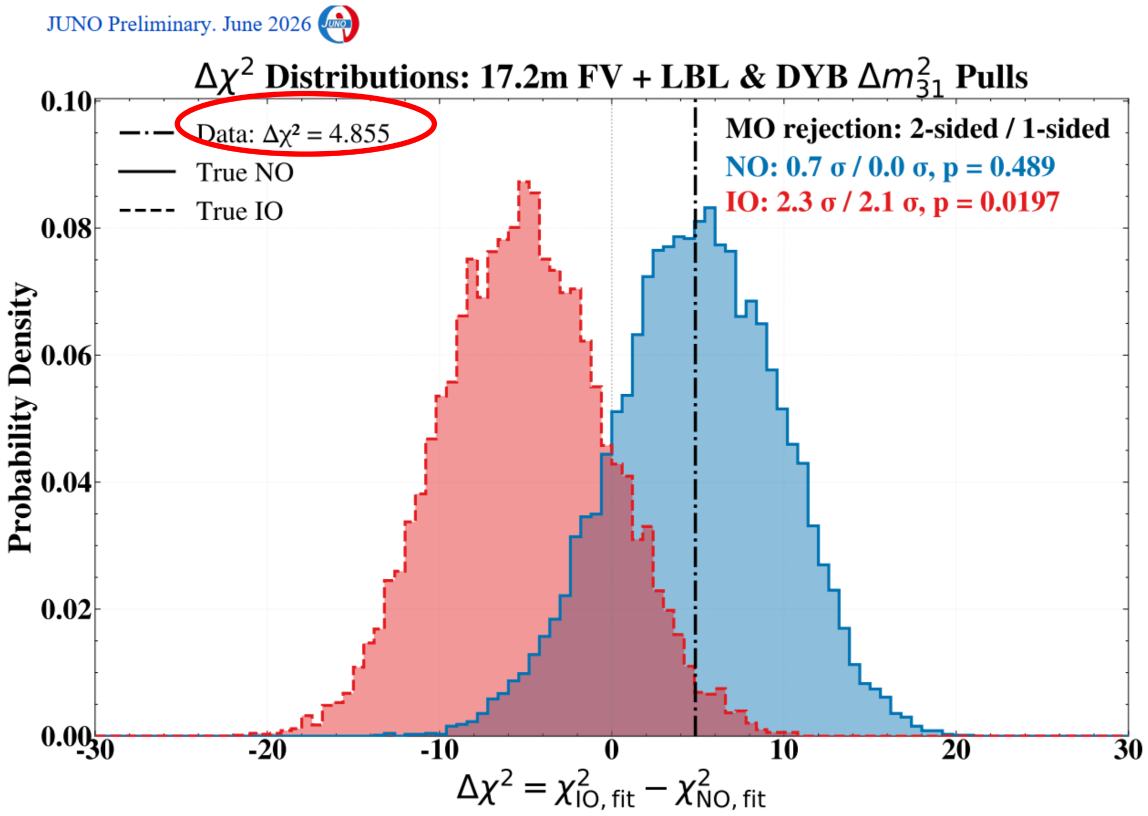


- Using the Δm^2_{31} constraint from DYB to obtain final minimum for each mass ordering.
- Feldman-Cousins (FC) method is used to determine the 1σ range of Δm^2_{31}： ~1% precision achieved

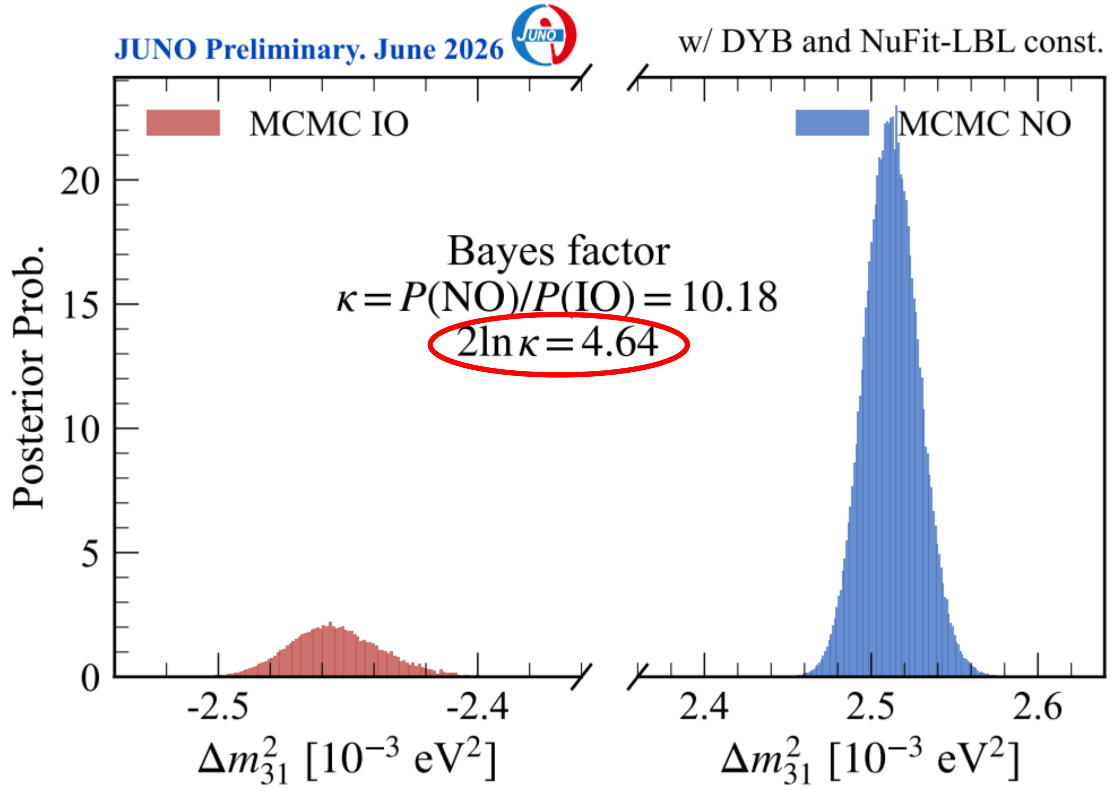


Significance of neutrino mass ordering

- 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**



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



Summary

- 207 days of golden data was used in this analysis
- Precision of solar oscillation parameters further improved by a factor of 1.3-1.5

$$\sin^2\theta_{12} = 0.3036 \pm 0.0064\,, \qquad (2.1\%)$$
$$\Delta m^2_{21} = (7.388 \pm 0.078) \times 10^{-5}\ \mathrm{eV}^2\,, \qquad (1.1\%)$$

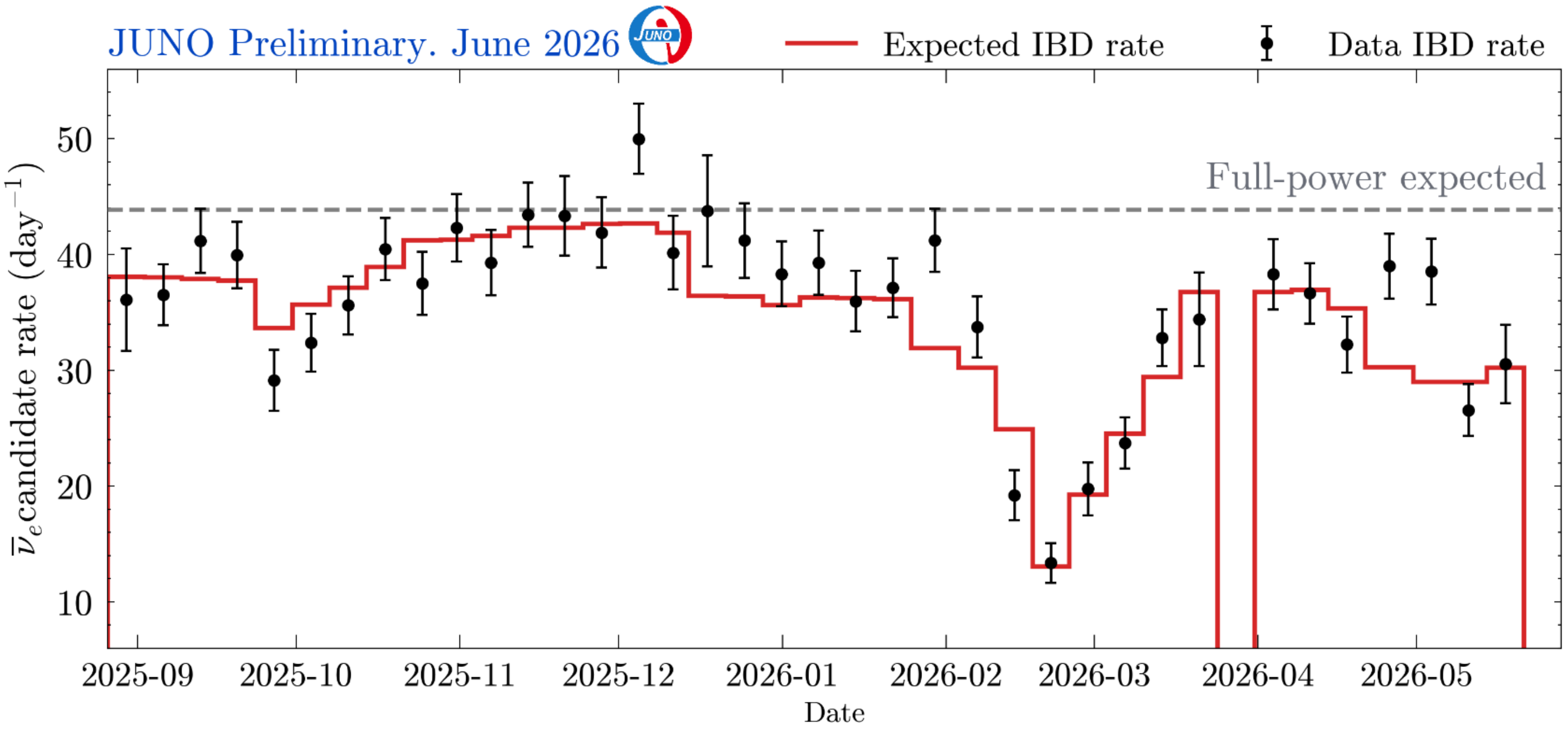
- First measurement on Δm^2_{31} achieved a precision of ~1%

$$\Delta m^2_{31} = -2.482^{+0.025}_{-0.026} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})\,,$$
$$\Delta m^2_{31} = +2.509^{+0.027}_{-0.025} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})\,,$$

- With external constraints from DYB and NuFit-LBL, Normal Mass Ordering is favored at ~2.3σ

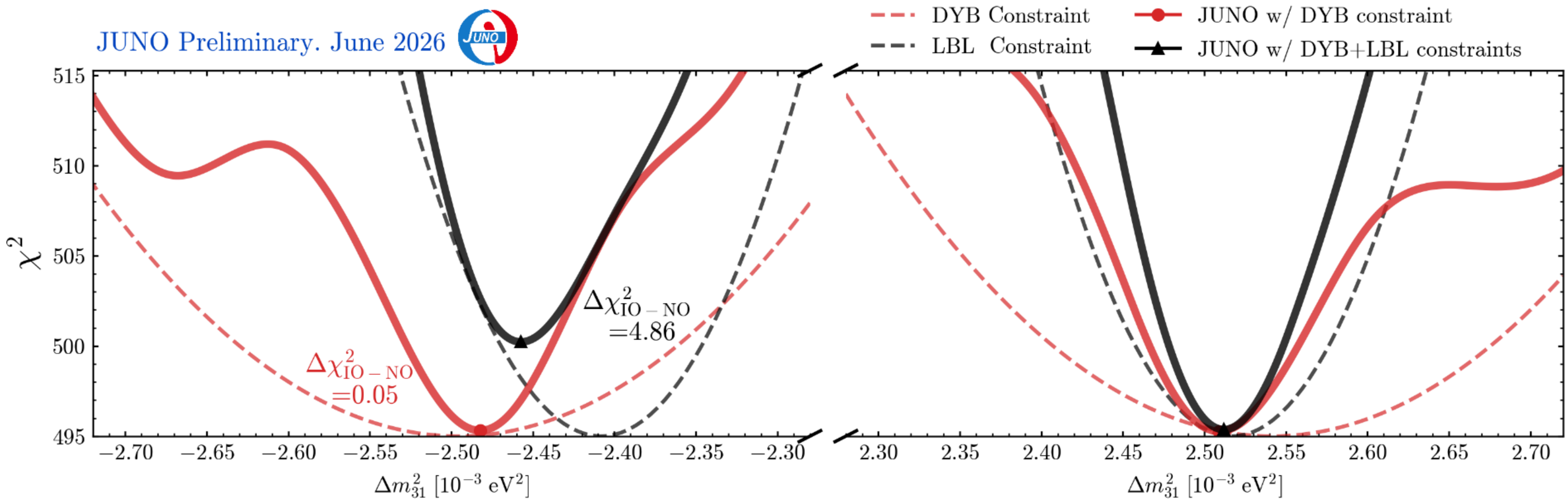
Backup

Reactor Neutrino Event Rate versus Time



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