Fitting Framework for JUNO's Reactor Antineutrino Oscillation Analysis

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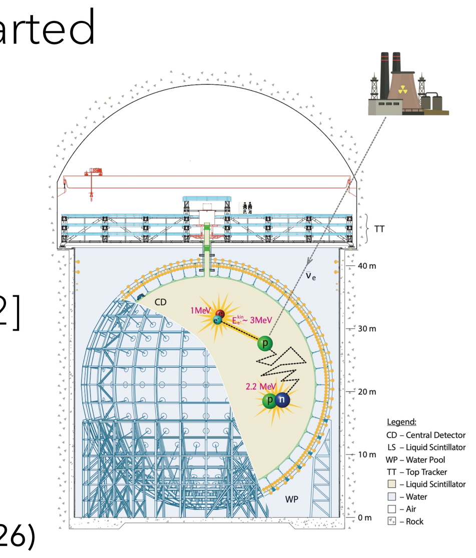
THE JUNO EXPERIMENT

The Jiangmen Underground Neutrino Observatory (**JUNO**) [1] is a multi-purpose neutrino experiment in South China, started data taking in August 2025



- Largest Liquid Scintillator (LS) -based neutrino detector → 20 kton target
- Energy resolution ~3.5% for ^{68}Ge @ 2× 0.511 MeV [2]
- **First measurement of Δm^2_{21}, $\sin^2\theta_{12}$ with 59 days of data → Improved by a factor 1.6 all previous constraints**

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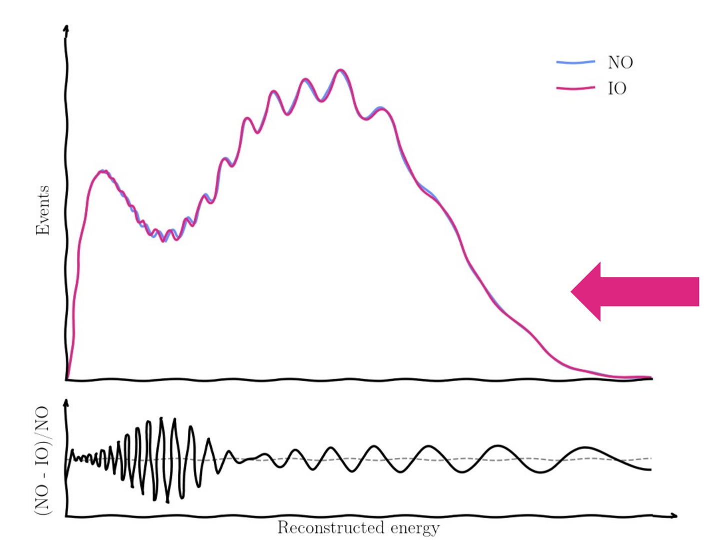
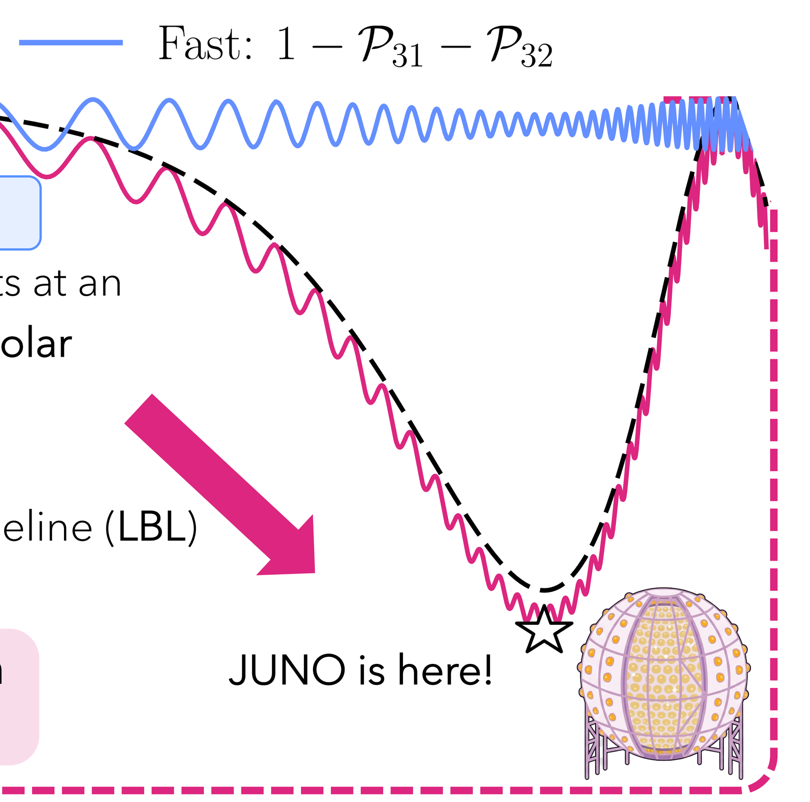
REACTOR ANTINEUTRINO OSCILLATIONS IN JUNO





$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $\Delta_{ij} = \Delta m^2_{ij} L/4E$

- JUNO [1] detects $\bar{\nu}_e$'s emitted by the nearby Taishan and Yangjiang Nuclear Power Plants at an average distance of **52.5 km** from the experimental site → **strategic baseline at the first solar oscillation maximum, to optimize NMO sensitivity**
- Independent determination of oscillation parameters: Δm^2_{21}, $\sin^2\theta_{12}$, Δm^2_{31} [3]
- Determination of the Neutrino Mass Ordering (NMO) [4] → complementary to long baseline (LBL) beam experiments and atmospheric experiments, independent of δ_{CP} and θ_{23}

First experiment to **simultaneously** probe the effects of oscillations on both solar (Δm^2_{21}) and atmospheric (Δm^2_{31}) scales

JUNO is here!

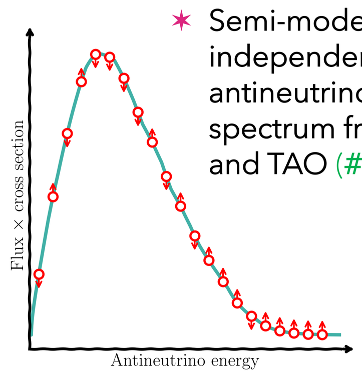
SIGNAL AND BACKGROUNDS

Antineutrino detection and model

- Reactor antineutrinos detected in JUNO through the **Inverse Beta Decay** (IBD) reaction.

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

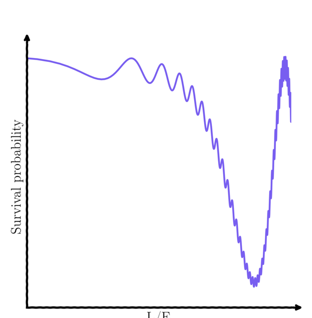
- The predicted spectrum incorporates the key detector response effects [2], **energy non-linearity (NL), resolution, and ^{14}C pile-up**, characterized with several gamma sources at different positions and uniformly distributed events, e.g., cosmogenic isotopes (#334, #406)



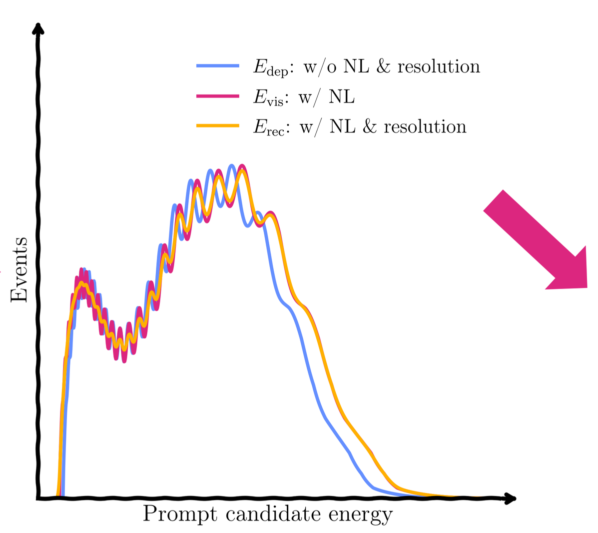
- Semi-model independent antineutrino spectrum from DYB and TAO (#205)

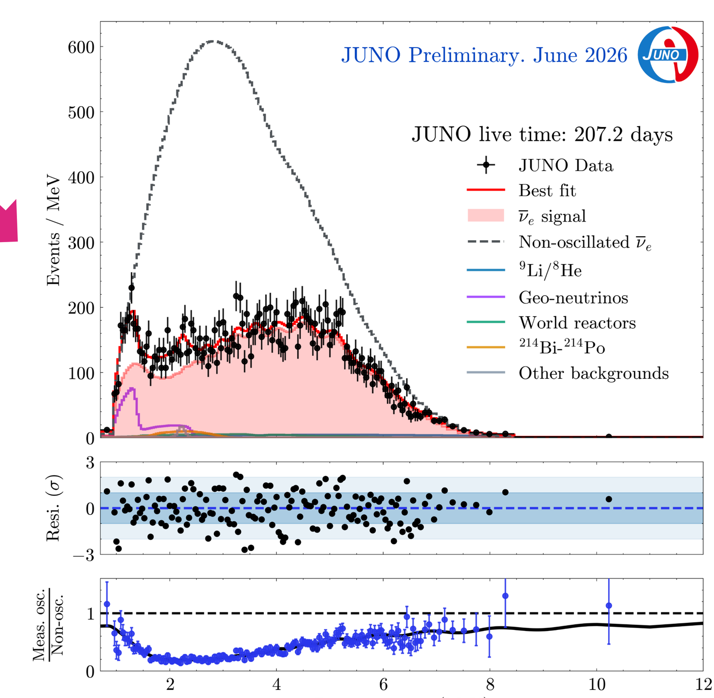
E_ν → (Interaction) $E_{\rm dep}$ → (Light emission) $E_{\rm vis}$ → (Light detection) $E_{\rm rec}$

Antineutrino energy | Deposited energy | Visible energy | Reconstructed energy

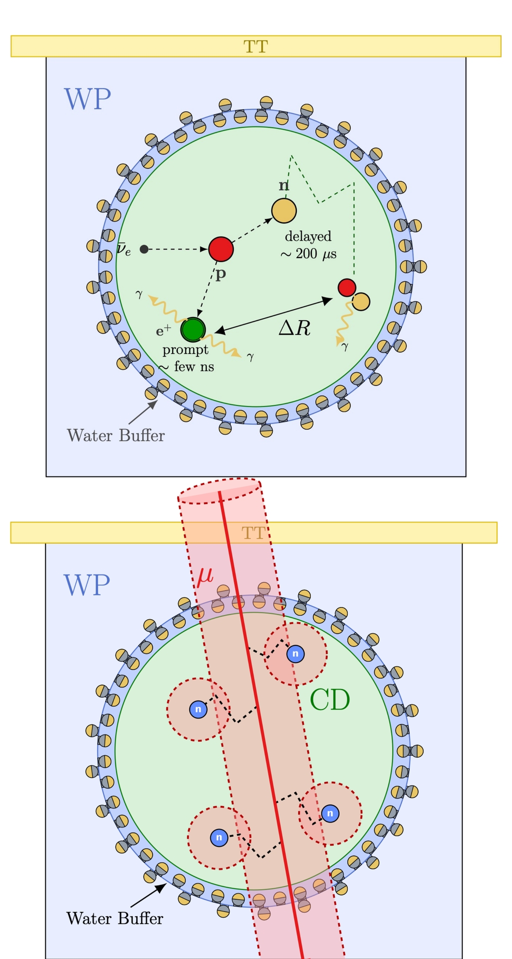


Detector response





IBD selection and backgrounds (#346)



- IBD selection cuts mostly based on prompt-delayed typical signature
- Fiducial volume (FV) cut at 17.2 m to suppress accidental coincidences
- Spherical veto around cosmogenic neutrons and cylindrical veto around tracks to suppress ^{9}Li-^{8}He events
- IBD efficiency (74.01 ± 0.75) %
- Best fit reactor IBD rate (36.02 ± 0.62) cpd, total best fit background rate: 5.40 cpd → S/B ratio ≈ 6.7

STATISTICAL ANALYSIS AND OSCILLATION RESULTS

Dataset and cost function

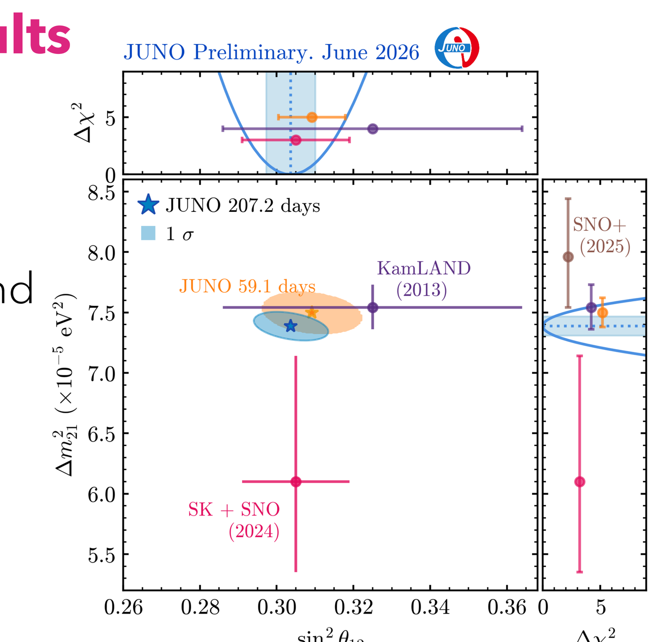
- Combined fit with 207.2 days JUNO dataset , 31.3 days TAO dataset, and Daya Bay (DYB) near detector data [5]
- Analysis crosschecked by three groups with independent reconstruction, selection (e.g., different FV cuts), detector response model, and fit machinery.
- Combined Neyman-Pearson χ^2 cost function, $\boldsymbol{\theta}$: oscillation parameters, $\boldsymbol{\eta}$: nuisance parameters for detector response, backgrounds, and overall reactor flux normalization, $\boldsymbol{\alpha}$: free params in antineutrino spectrum constrained by Daya Bay and TAO, $\sin^2\theta_{13}$ and Δm^2_{31} constrained with DYB measurement [6]

$$\chi^2(\boldsymbol{\theta},\boldsymbol{\eta},\boldsymbol{\alpha}) = \chi^{2,\rm J}(\boldsymbol{\theta},\boldsymbol{\eta},\boldsymbol{\alpha}) + \chi^{2,\rm T}(\boldsymbol{\theta},\boldsymbol{\eta},\boldsymbol{\alpha}) + \chi^{2,\rm D}(\boldsymbol{\alpha}) + \lambda^2_{\rm nuis}(\boldsymbol{\eta}) + \lambda^2_{\rm shape}(\boldsymbol{\alpha}) + \chi^2_{\rm osc}(\sin^2\theta_{13}, \Delta m^2_{31}), \qquad \chi^{2,\rm X} = (\boldsymbol{\mu}^{\rm X} - \boldsymbol{D}^{\rm X})^T V_{\rm X}^{-1} (\boldsymbol{\mu}^{\rm X} - \boldsymbol{D}^{\rm X})$$

X = D (DYB), T (TAO), J (JUNO)

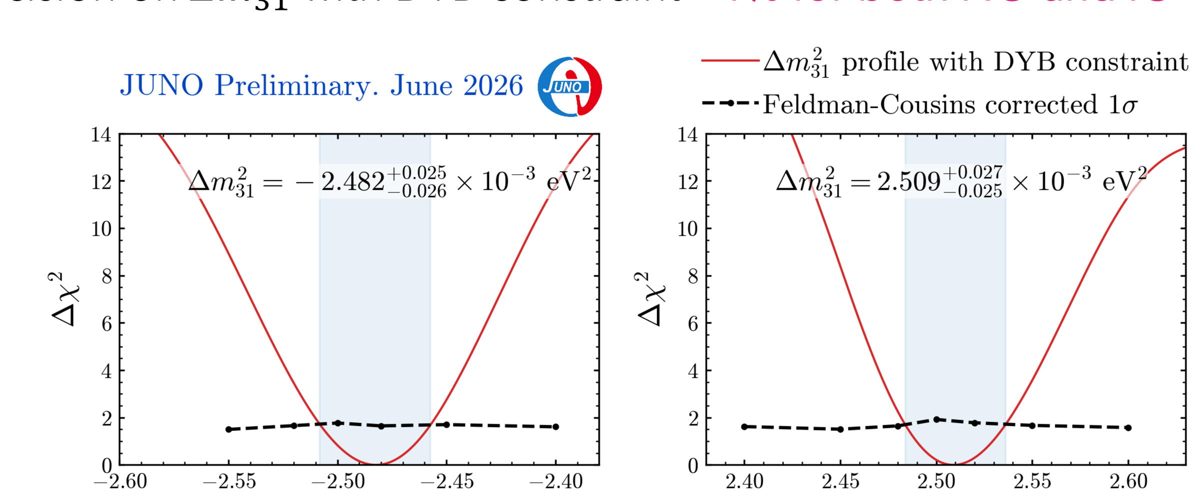
Latest oscillation parameters results

- Critical χ^2 for Δm^2_{21} and $\sin^2\theta_{12}$ consistent with Wilks' theorem
- World-leading **1.06%** precision for Δm^2_{21} and **2.10%** for $\sin^2\theta_{12}$, factor ≈ 2 improvement with respect to global constraints
- Consistent results under NO and IO, no impact due to Δm^2_{31} constraint



Δm^2_{21} [× 10^{-5}eV^2]	$\sin^2\theta_{12}$
7.388 ± 0.078	0.3036 ± 0.0064

- Wilks' theorem not valid for Δm^2_{31} at low statistics
- Degeneracy in Δm^2_{31} profiles mitigated by DYB Δm^2_{31} external constraint
- **Profiled Feldman-Cousins** procedure using DYB [6] Δm^2_{31} as external constraint → critical values for 68.27% confidence interval at ≈ 1.6 (critical value for Wilks' theorem = 1)
- Precision on Δm^2_{31} with DYB constraint ≈1% for both NO and IO

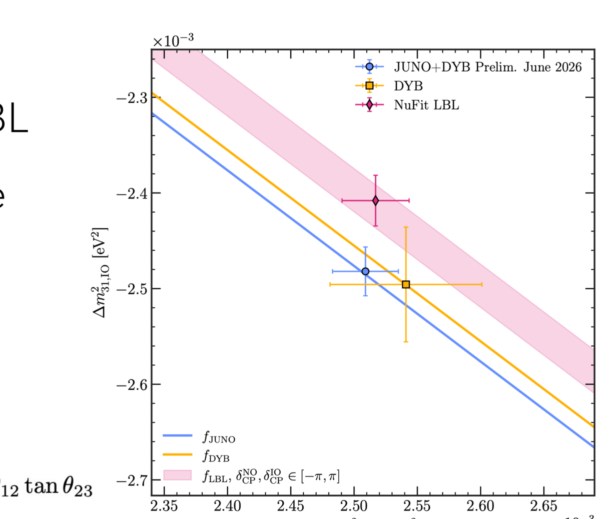


NMO significance

- NMO significance incorporating DYB and LBL Δm^2_{31} from NuFit as external constraints → **Boost thanks to synergy between reactor and LBL experiments** [7,8]
- The *"wrong ordering"* measurements of Δm^2_{31} obtained by JUNO and atmospheric/LBL experiments will likely disagree, breaking the degeneracy between NO and IO [7,8,9,10]

$$f_{\rm DYB}(\Delta m^2_{31}) = -\Delta m^2_{31} + 2\sin^2\theta_{12}\Delta m^2_{21}$$
$$f_{\rm JUNO}(\Delta m^2_{31}) = -\Delta m^2_{31} + 2\sin^2\theta_{12}\Delta m^2_{21} - \Delta m^2_{\phi,ee}$$
$$f_{\rm LBL}(\Delta m^2_{31}) = -\Delta m^2_{31} - \Delta m^2_{21}\left(\mathcal{A}^{\rm NO}_{\rm CP} + \mathcal{A}^{\rm IO}_{\rm CP} - 2\cos^2\theta_{12}\right)$$

$\mathcal{A}_{\rm CP} \equiv \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}$

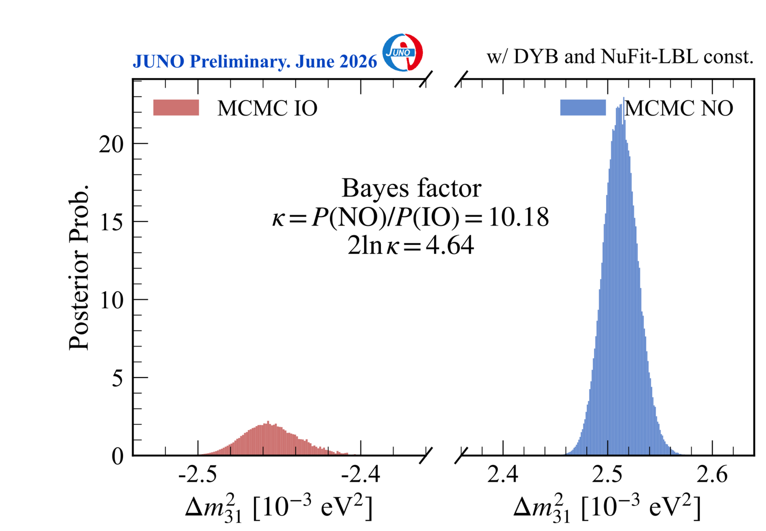


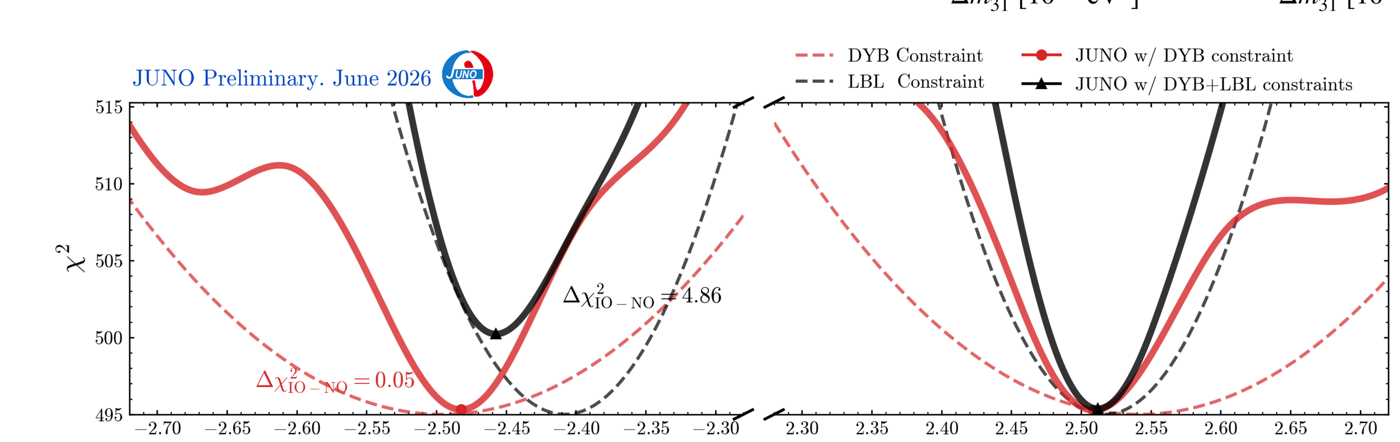
NMO Bayesian results

- Markov chain Monte Carlo to sample Δm^2_{31} posterior distributions
- Bayes factor k = 10.18 → mild preference for Normal Ordering

Comparison with frequentist results:

$\Delta\chi^2$ = 4.86, 2.3σ IO rejection (#205)





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[3] JUNO collaboration. "Sub-percent precision measurement of neutrino oscillation parameters with JUNO." CPC 46 123001.
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[5] Daya Bay collaboration. "Comprehensive Measurement of the Reactor Antineutrino Spectrum and Flux at Daya Bay", PRL134, 201802
[6] Daya Bay collaboration. " Precision Measurement of Reactor Antineutrino Oscillation at Kilometer-Scale Baselines by Daya Bay, PRL 130, 161802"
[7] Nunokawa, Parke, and Funchal. "Another possible way to determine the neutrino mass hierarchy." PRD 72.1 (2005): 013009.
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[9] Aiello, S., et al., "Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering.", JHEP03(2022)055
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