First results of the JUNO experiment

LAPP seminar, Annecy

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2026/10/02











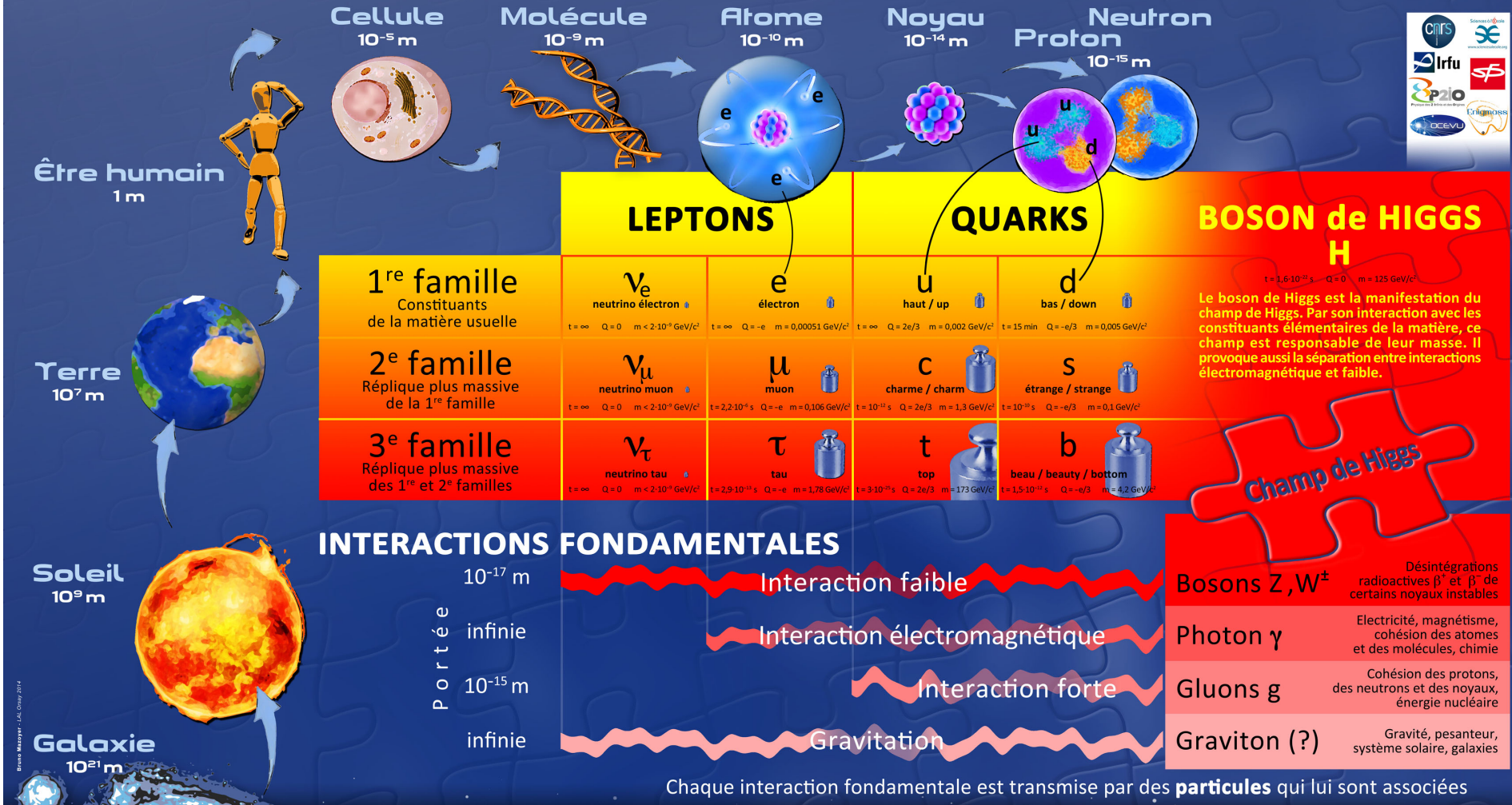
Outline

1. Introduction
2. The expected sensitivity of JUNO
3. The JUNO detector and performances
4. First JUNO results on the solar parameters
5. First JUNO results on the neutrino mass ordering
6. Combination of JUNO results
7. Conclusion

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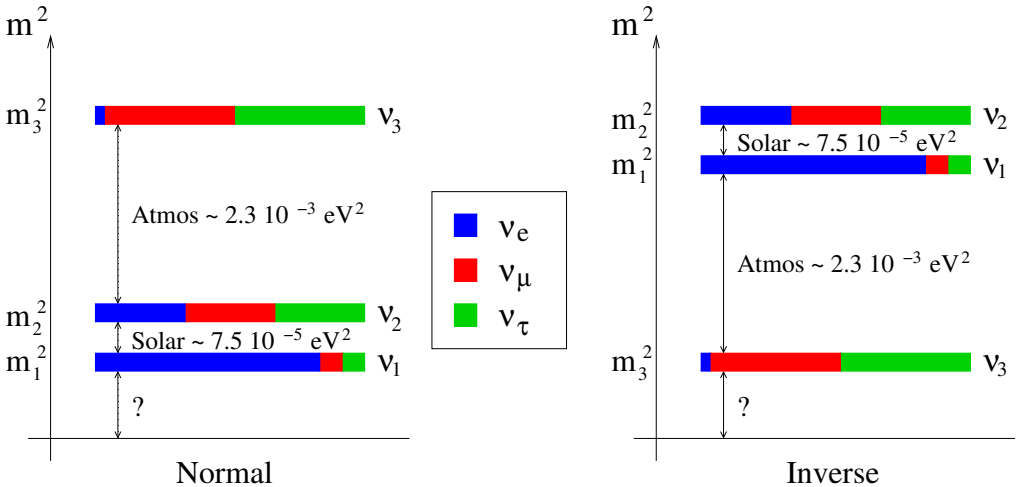
Composants élémentaires de la matière

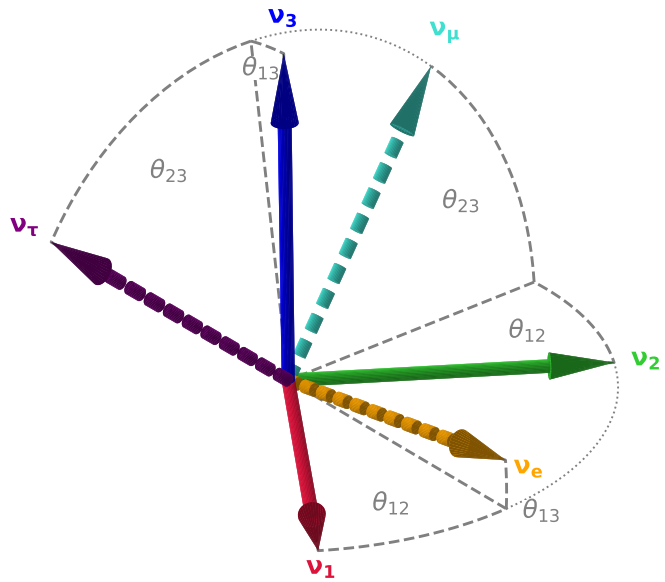


Neutrino mixing

Neutrino flavours states $\alpha \in \{e, \mu, \tau\}$ differ from the mass eigenstates $i \in \{1, 2, 3\}$:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} \, |\nu_i\rangle$$





Böser et al. - 2020

Parametrised by the Pontecorvo, Maki, Nakagawa and Sakata matrix

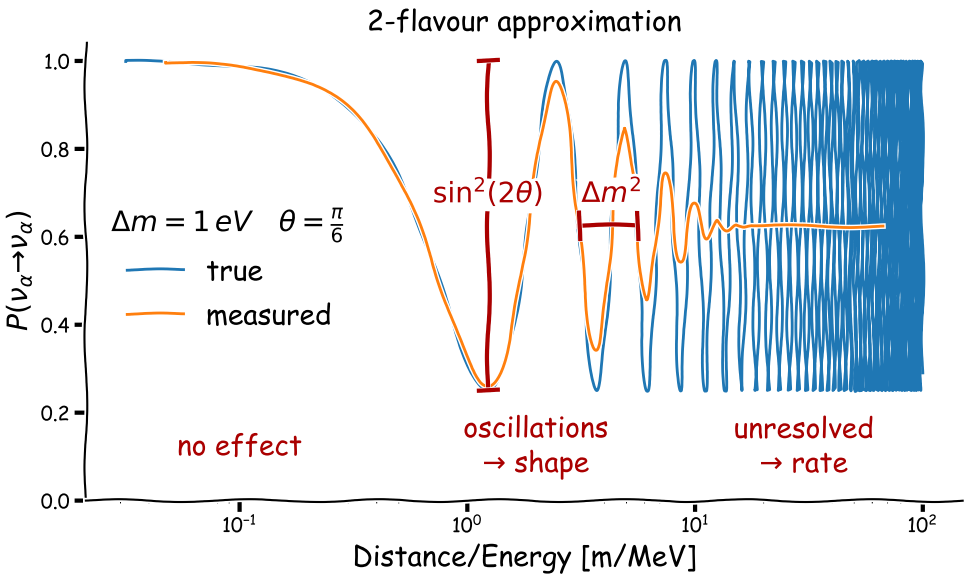
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

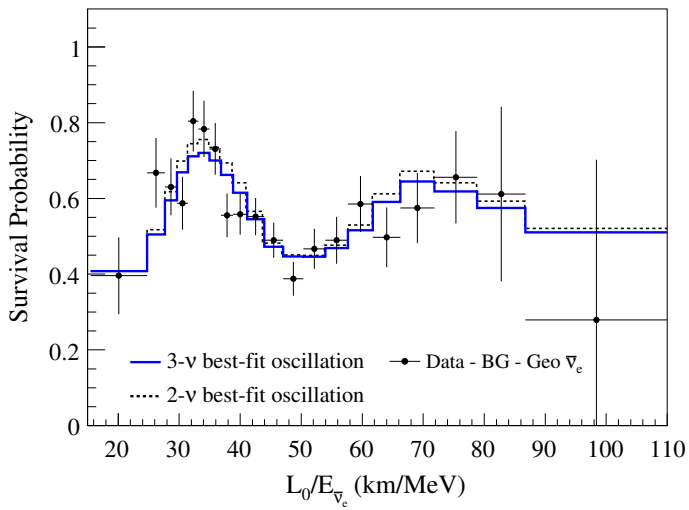
Neutrino oscillations

Quantum mechanics allows to compute the neutrino oscillation probabilities *(e.g. with 2-flavour)*:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - \sin^2 2\boldsymbol{\theta_{ij}} \ \sin^2\left(1.267 \ \frac{\boldsymbol{\Delta m^2_{ji}}\ [eV^2]\ L\ [m]}{E\ [MeV]}\right)$$



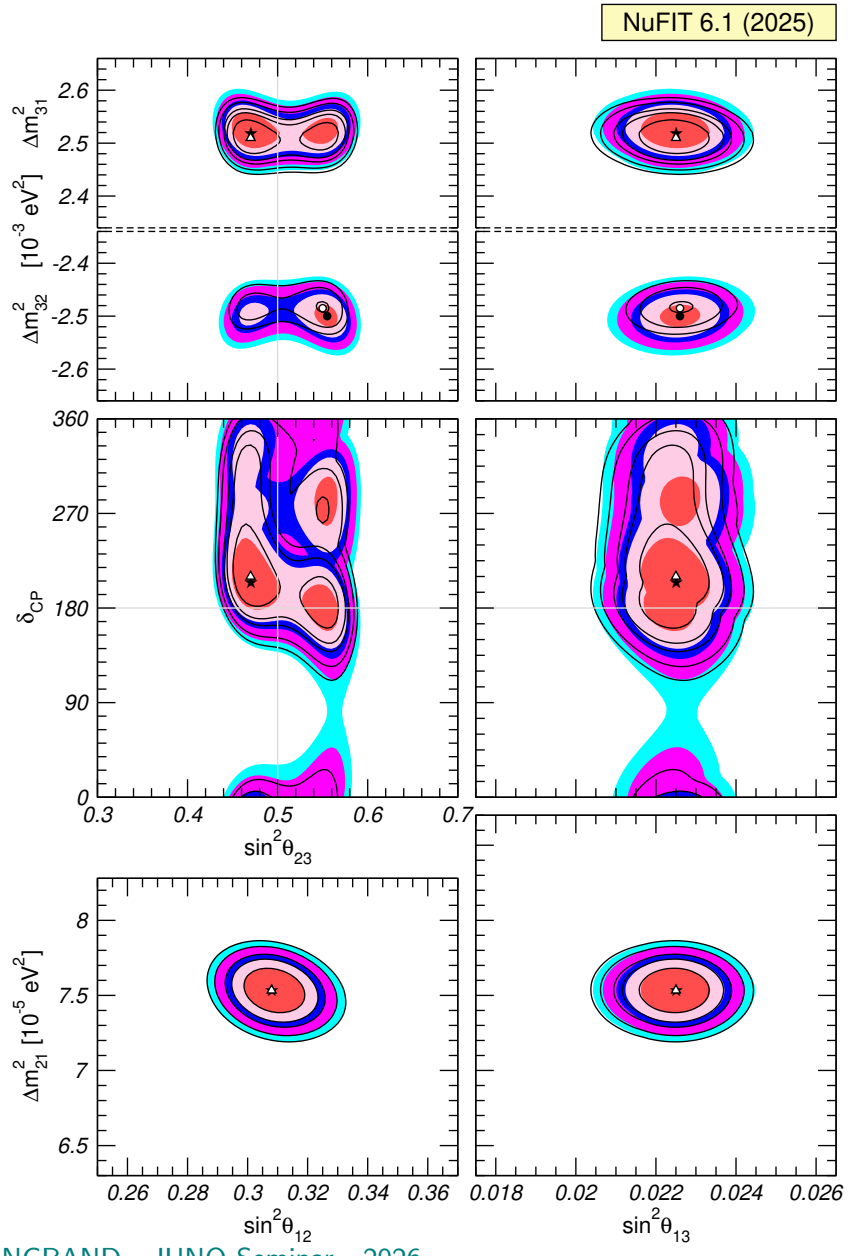
[Böser et al., 2020]

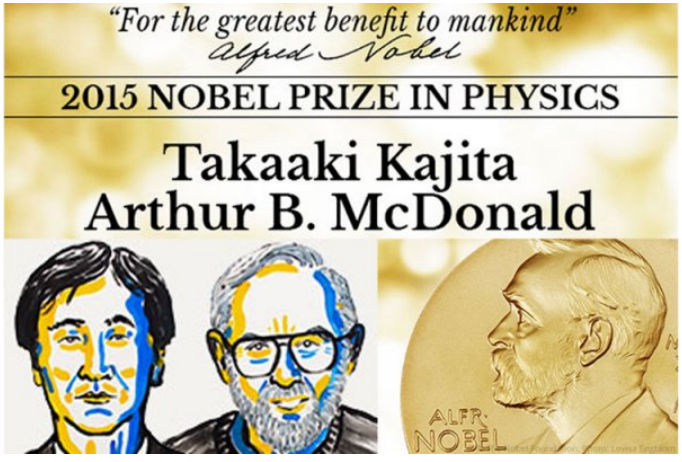


[Gando et al., 2011]

Measuring the oscillation probabilities allows to determine θ_{ij} and $|\Delta m^2_{ji}|$ but not the absolute neutrino mass scale.

Current oscillation results





Still to be determined:

- octant of θ_{23}
- δ_{CP} violating phase
- anomalies @ short baselines
- neutrino mass ordering (NMO)
  $\Delta m^2_{31} > 0$ or $\Delta m^2_{32} < 0$
  $\hookrightarrow$ goal of JUNO

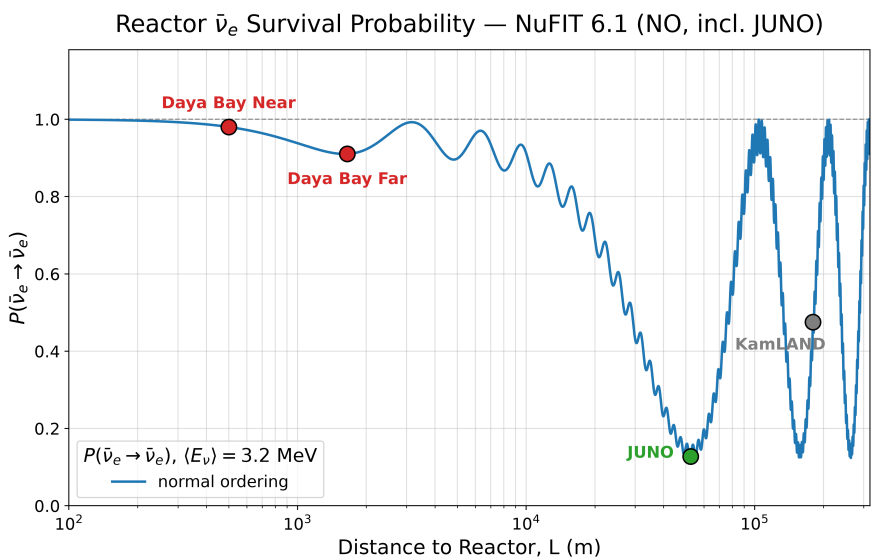
JUNO principle to measure NMO

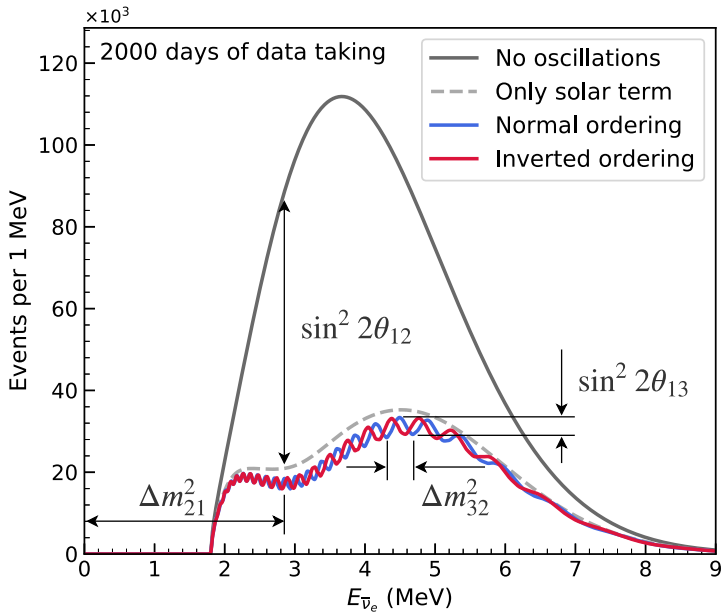
With a 52.5 km baseline, JUNO can measure two oscillations at once:

- slow oscillation: to measure the solar parameters θ_{12} and Δm^2_{21}
- fast oscillation: driven by θ_{13} and $\Delta m^2_{31/32}$ to measure the NMO

NMO through $(\Delta_{31} - \Delta_{21})$ inteference in the quasi-vacuum oscillations:

$$\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12}\, c_{13}^4\, \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32} \right)$$





JUNO experimental site

The JUNO experiment is located in Jinji town (43 km to the southwest of Kaiping city) in Guangdong province, China. Around 200 km away from several megacities: Guangzhou, Shenzhen, and Hong Kong.



JUNO site is at equal 52.5 km from the Yangjiang (6×2.9 GW_{th}) and the Taishan (2×4.6 GW_{th}) NPPs, for the best sensitivity in the NMO.

JUNO collaboration

JUNO firstly approved in China in 2013, collaboration established in 2014.

At present, more than 700 collaborators from 70 institutions, in 16 countries/regions.



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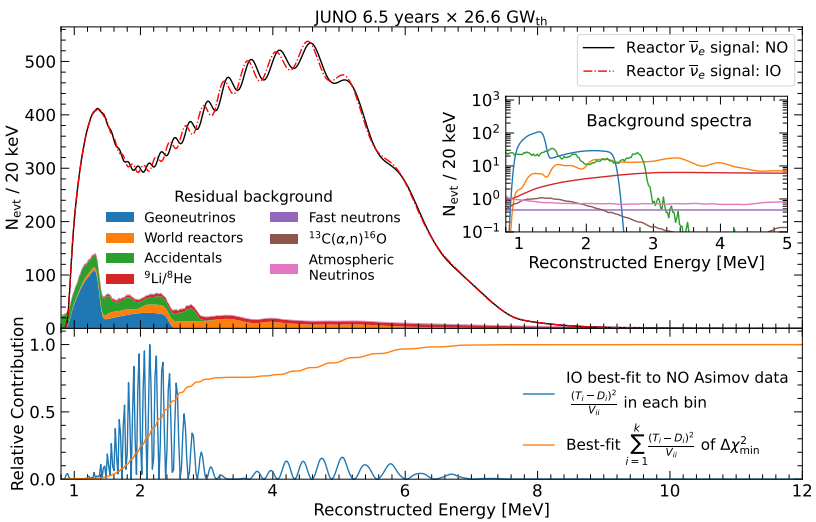
6 Combination of JUNO results

7 Conclusion

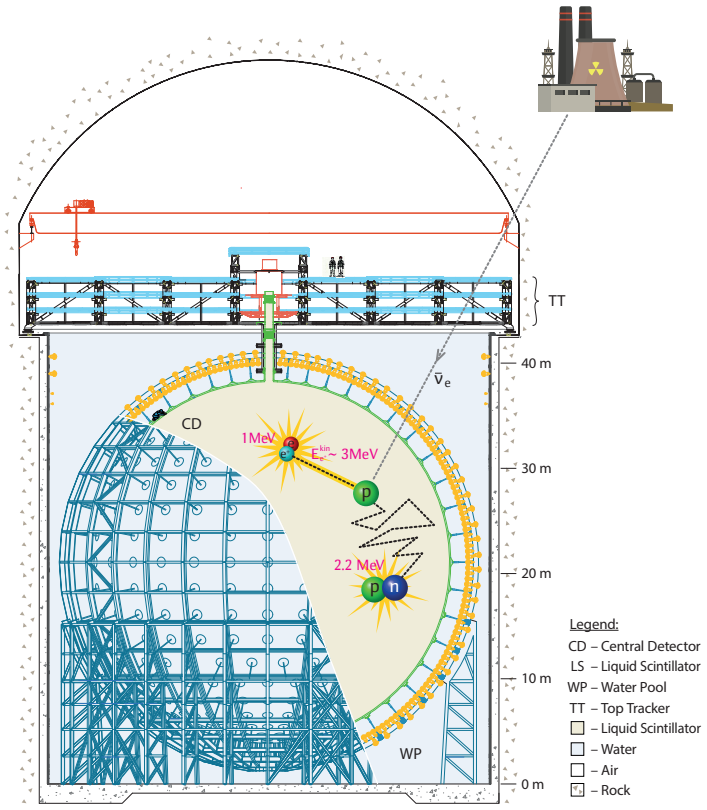
Signal and backgrounds in JUNO

Signal:

- Anti-neutrino detection throught inverse beta decay (IBD): $\overline{\nu}_e p \rightarrow e^+ n$
- Energy threshold of 1.8 MeV
- Neutrino energy from E_{e^+}
- Efficient prompt-delayed coincidence to reject backgrounds

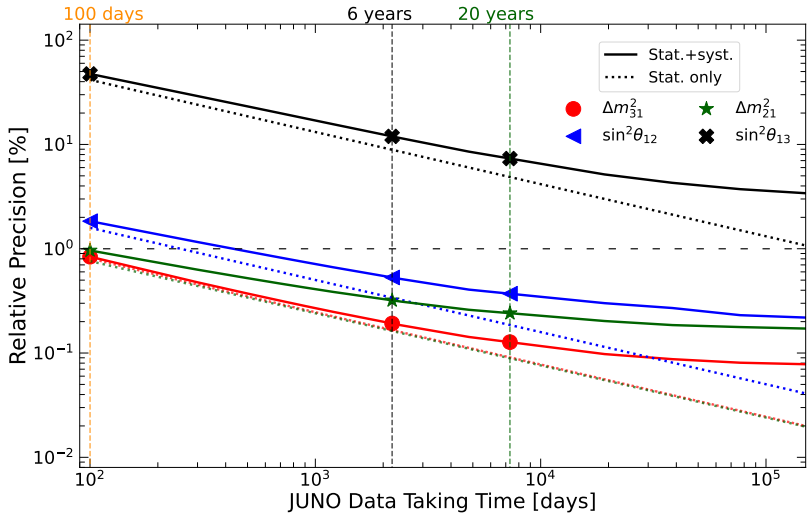


[Abusleme et al., 2025b]

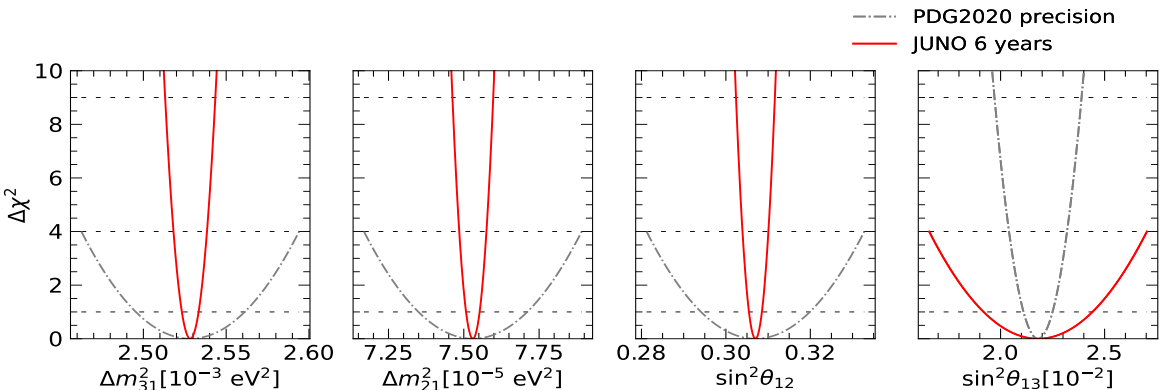


Sub-percent precision to the oscillation parameters

JUNO will improve significantly the precision on the solar parameters θ_{12} and Δm^2_{21}, as well as on the atmospheric mass splitting $|\Delta m^2_{31}|$.

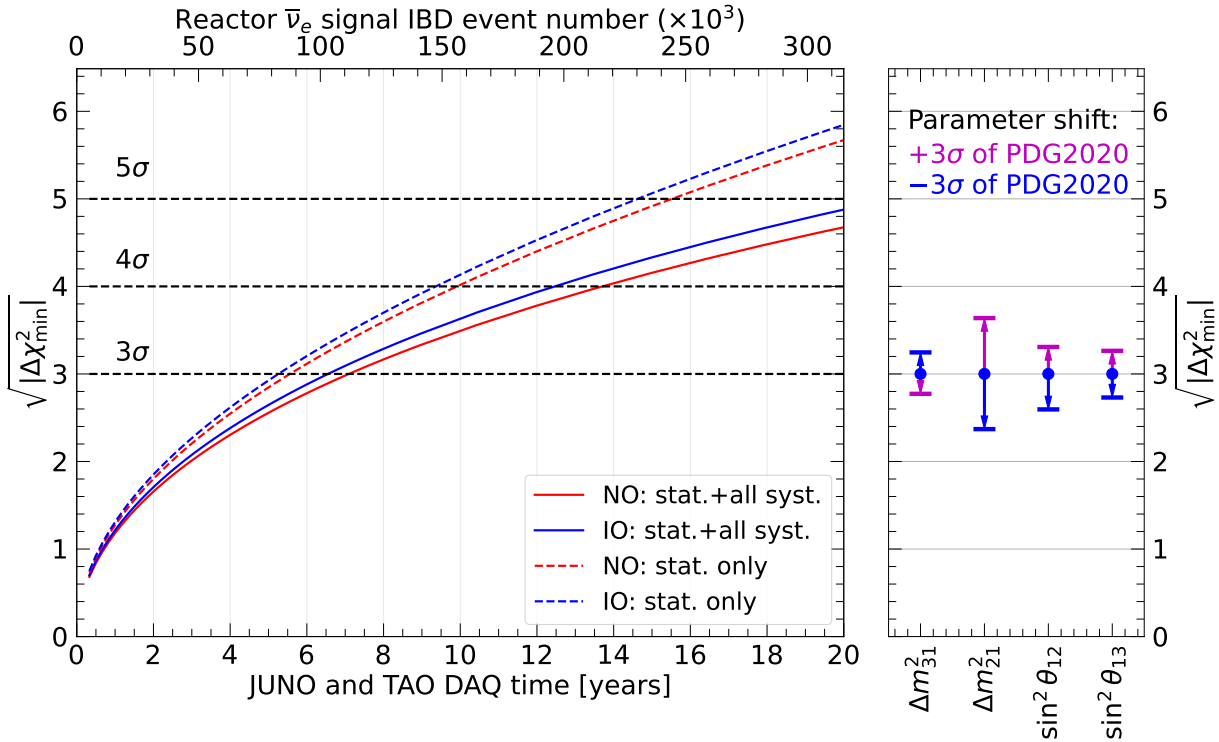


As published in [Abusleme et al., 2022], after 6 years the precision on these parameters should be <0.5% (Asimov study).



JUNO sensitivity to the NMO (1/2)

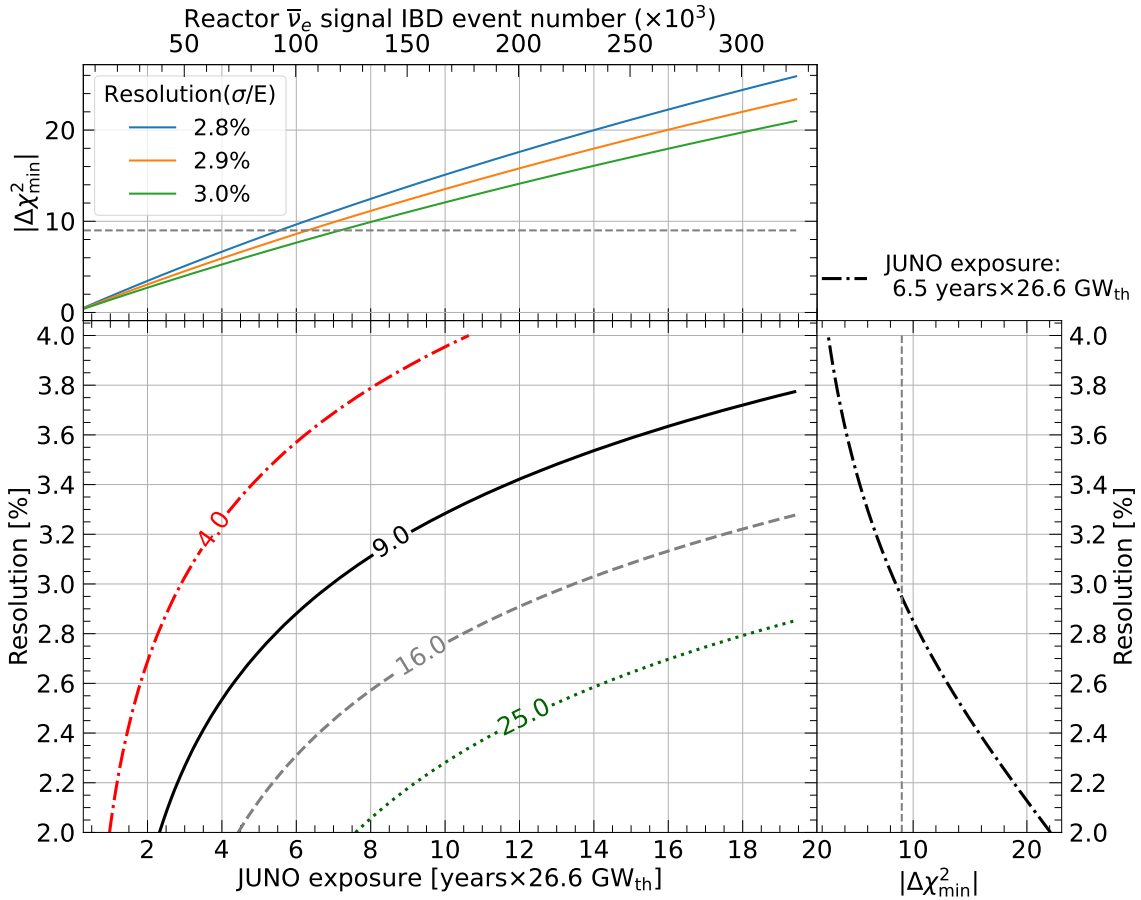
The mediane sensitivity of JUNO to the NMO takes into account the best knowledge of the JUNO and TAO detectors with their signals and backgrounds [Abusleme et al., 2025b], including all the systematics (Asimov study using PDG 2020)



After 7.1 years of data taking, JUNO could determine the neutrino mass ordering with 3σ significance when NO is true or 3.1σ if IO is true.

JUNO sensitivity to the NMO (2/2)

The energy resolution and exposure are crucial factors for determining the NMO with JUNO. It was also investigated in [Abusleme et al., 2025b] and provides important insights on where JUNO might be.



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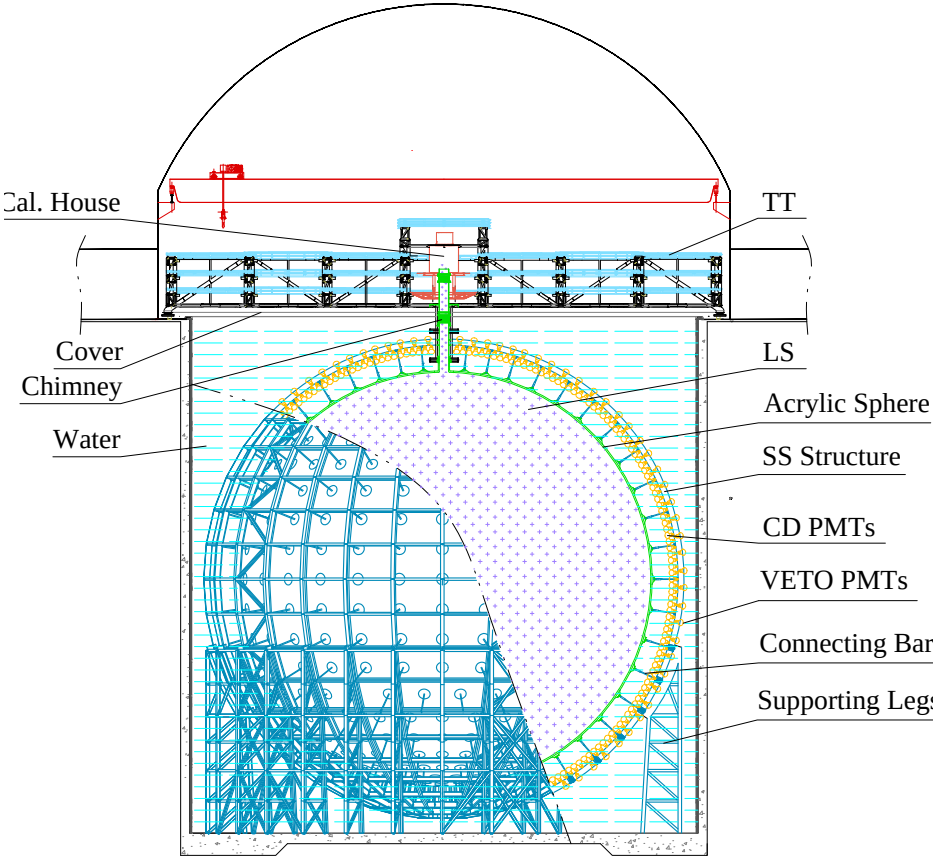
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JUNO detector design

The Jiangmen Underground Neutrino Observatory (JUNO) is the biggest liquid scintillator neutrino detector in the world, with a 20 kton target.



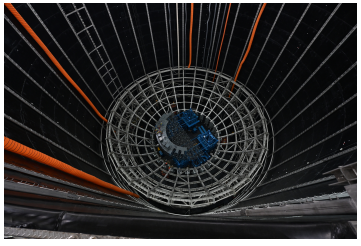
- 20 kton LS central detector in an acrylic sphere (ϕ 35.4 m)
- 35 kton water Cherenkov
- 17,612 20-inch PMTs
- 25,600 3-inch PMTs
- target 3% energy resolution at 1 MeV
- 1000 m^2 top tracker
- ~650 m underground (1800 m.w.e.)
- ~10% background for reactor anti-neutrinos

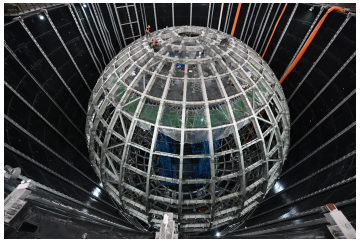
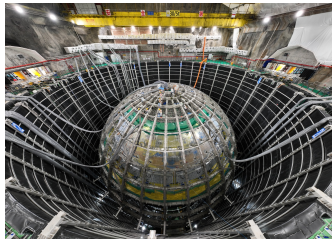
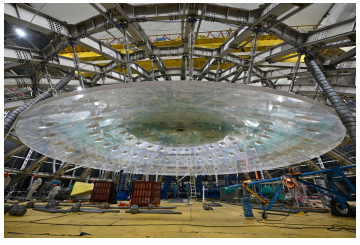
JUNO is a multi-sources observatory: reactor $\overline{\nu}_e$, solar ν, supernova ν burst and diffuse, geoneutrinos, atmospherics ν...

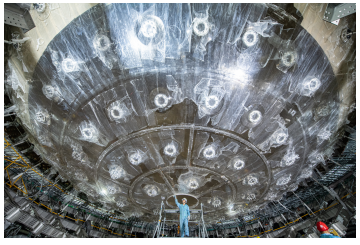
JUNO detector construction (2015-2025)

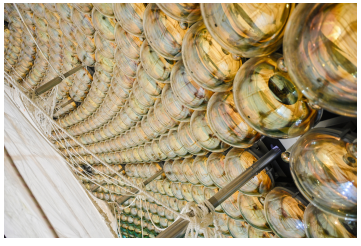


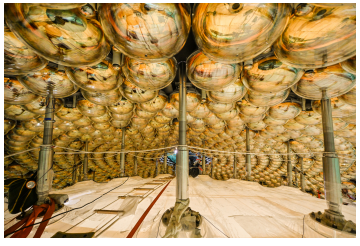
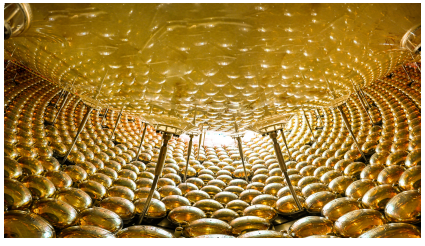


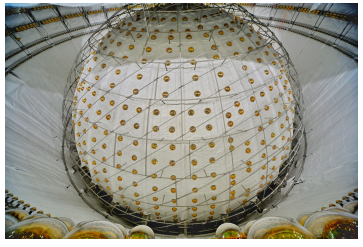
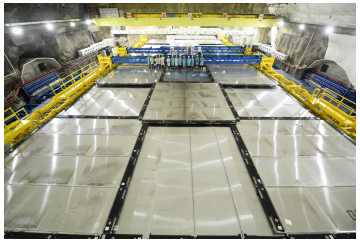




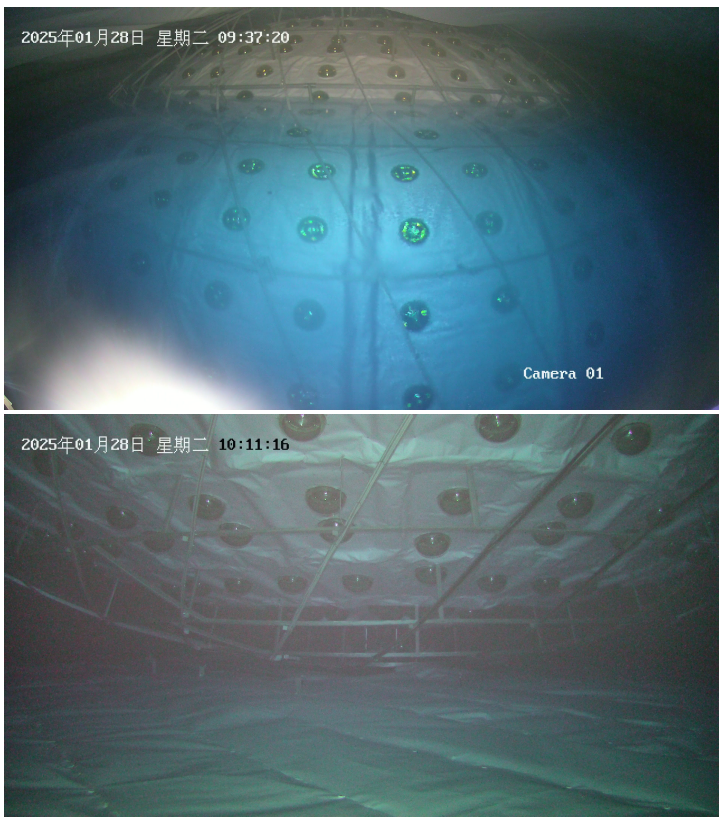


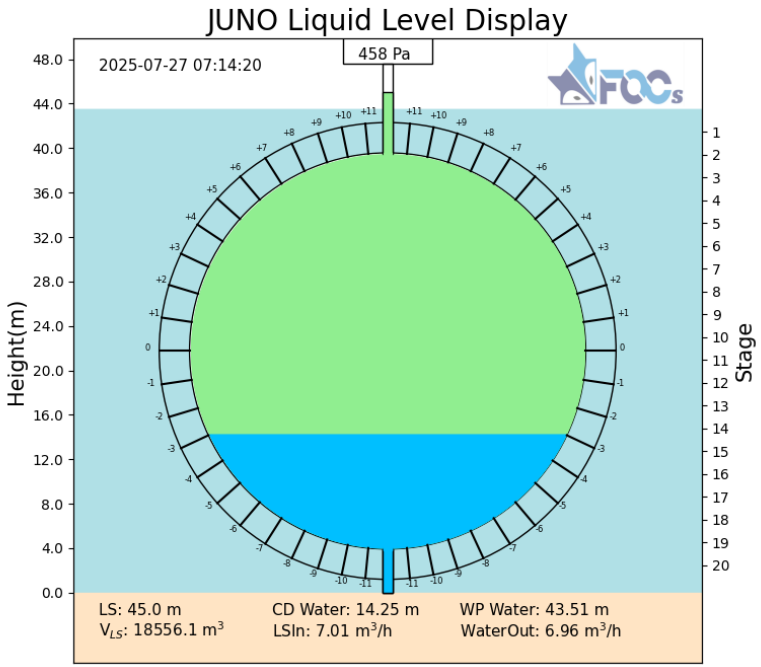




JUNO first data taking

After detector construction ended, water filling started directly on December 18th, 2024
(CD cleaning, mechanical structure test and commissioning)



In February 2025, LS filling started by replacing water at a rate of 7 t/h.

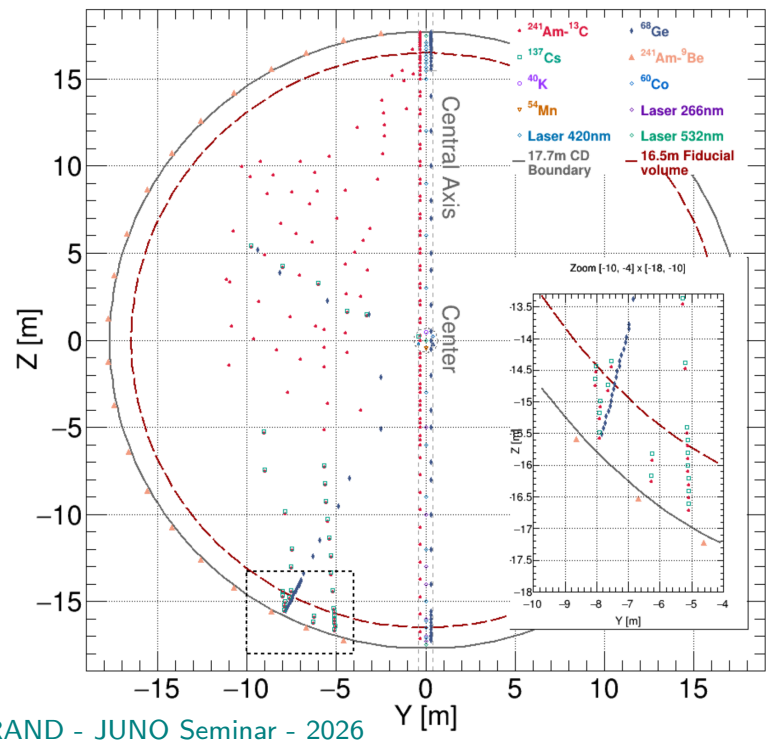


The filling was completed on August 22nd, 2025.

Energy calibration of JUNO

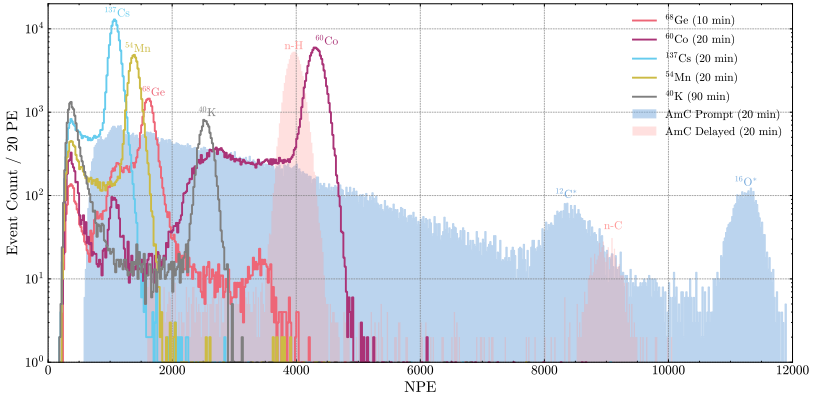
Three systems used to calibrate:

- vertical calibration with ACU: precision < 7 mm
- YZ plane calibration with CLS: precision < 3 cm
- loop around the acrylic vessel with GT: accuracy $<0.1°$



Several energies for non-linearity

Source	Energy	System	Activity
	Gamma Sources		
^{68}Ge	0.511 × 2 MeV	ACU	595 Bq[a]
^{137}Cs	0.662 MeV	ACU	140 Bq[b]
^{54}Mn	0.835 MeV	ACU	521 Bq[a]
^{40}K	1.460 MeV	ACU	13 Bq
^{60}Co	1.173+1.333 MeV	ACU	165 Bq [b]
	Neutron Sources		
^{241}Am–^{13}C	neutron + 6.13 MeV (^{16}O*) (n,γ)p 2.223 MeV (n,γ)^{12}C 4.94 MeV (n,γ)^{56}Fe 7.63 MeV, etc.	ACU CLS	130 Bq 100 Bq
^{241}Am–^{9}Be	neutron + 4.43 MeV (^{12}C*) (n,γ)p 2.22 MeV	GT	30 Bq
	Optical Calibration		
Laser	Optical pulses (420 nm and 266 nm)	ACU	50 Hz

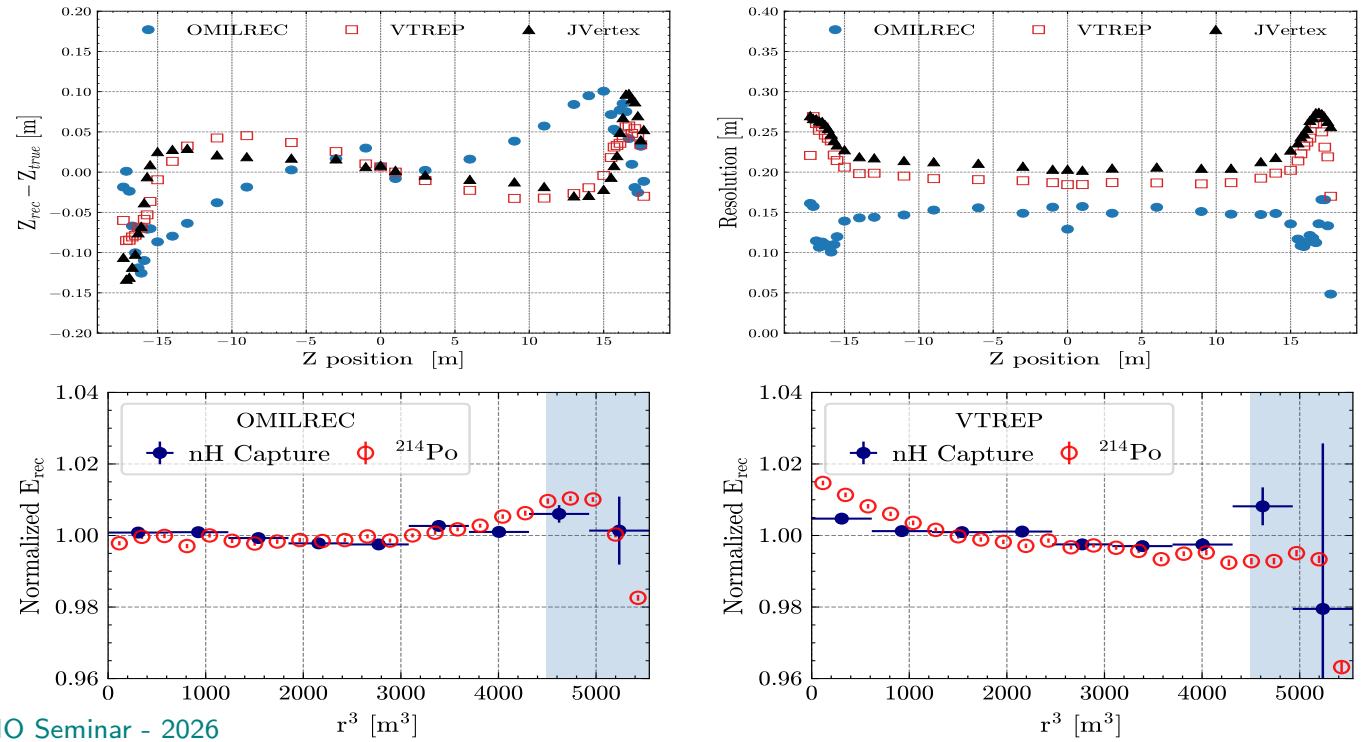


At detector center, the light-yield is 1785 PE/MeV for the 2.223 MeV nH capture [Abusleme et al., 2026]

Vertex and energy reconstruction

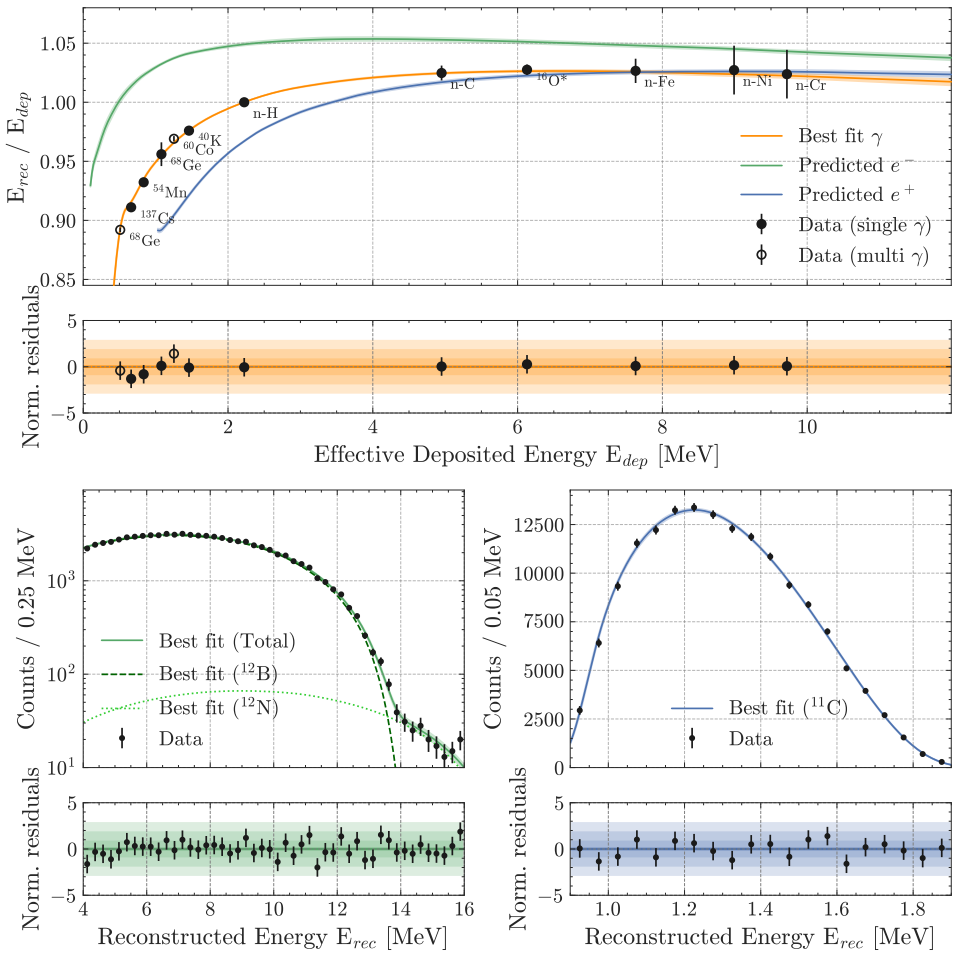
Vertex rely on PMT timing while energy depends on PMT charge

- JVertex: maximum-likelihood estimation method constructed from first hit times after time-of-flight subtraction
- OMILREC: combined time and charge likelihood method to reconstruct vertex and energy simultaneously
- VTREP: time-of-flight corrections for sharpest PMT hit-time and maximum likelihood using probabilities of fired and unfired PMTs



Continuous energy spectra

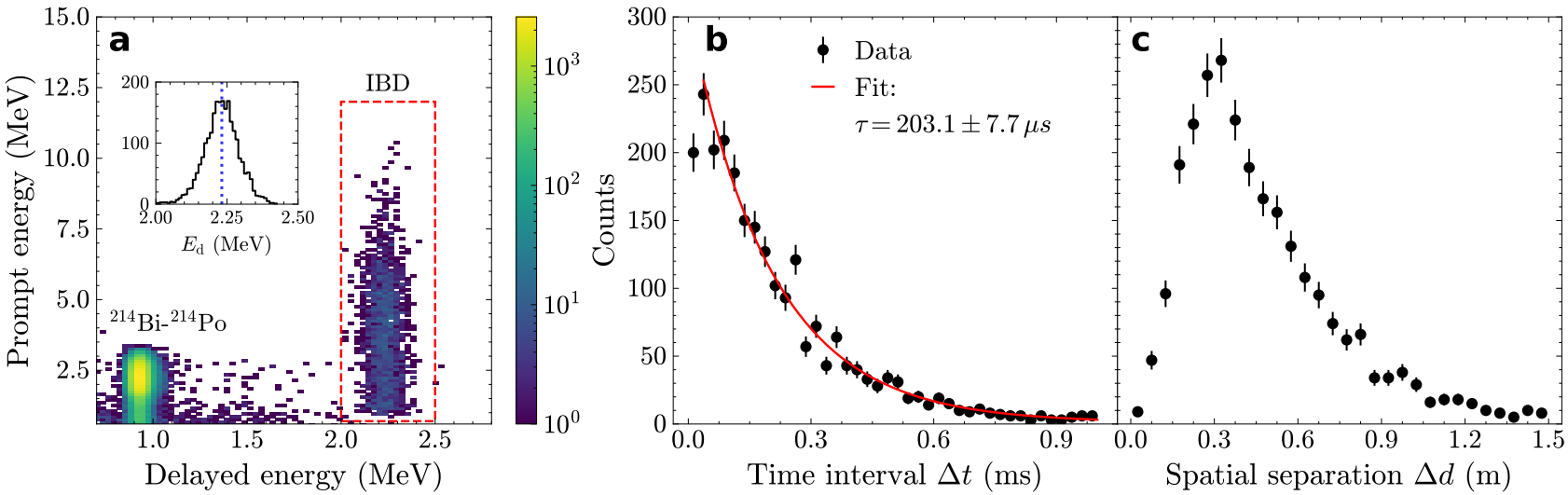
Good control of a continous energy spectra can be perfomed with several cosmogenic isotopes decays (^{12}B β^- and ^{11}C β^+) in the whole detector volume



IBD selection

Anti-neutrinos are detected through IBD interaction

- apply muon and spallation neutron vetoes
- search for a delayed candidate (neutron in capture energy range) in the fiducial volume (FV)
- search back for a prompt signal in FV, correlated in time and space
- reject multiplicity events around these two signals



Calibration runs with AmC source are precious to test the event selection

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First physics results of JUNO in 2025

- Physics data taking started on the 26th of August
- First dataset stopped the 2nd of November
- 59.1 days of data collected
- Publication of these results on November 19th

  [Abusleme et al., 2025a]

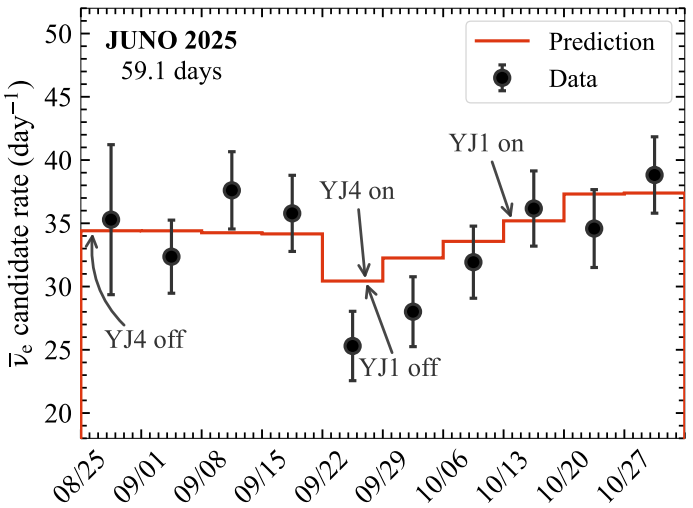


IBD candidates selection

Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\overline{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	$\sigma_{\rm rel}$
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency ($\varepsilon_{\rm tot}$)	69.9	1.6
$\overline{\nu}_e$ signal (cpd^1)		
w/o $\varepsilon_{\rm tot}$ corrected	33.5 ± 1.7	
w/ $\varepsilon_{\rm tot}$ corrected	47.9 ± 2.6	
Non-oscillated $\overline{\nu}_e$	150.9 ± 2.7	

- fiducial volume:
  $|Z| < 15.5$ m & $R < 16.5$ m
- μ-veto:
  - $>$ 5 ms full detector
  - $>$ 4 m + $>$1.2 s spallation neutron
  - cylinder around μ-track
- multiplicity: [-2ms,1ms]
- prompt-delayed coinc:
  $\Delta t \in$ [5µs,1ms] & $\Delta d < 1.5$ m

Weekly rate of IBD candidates



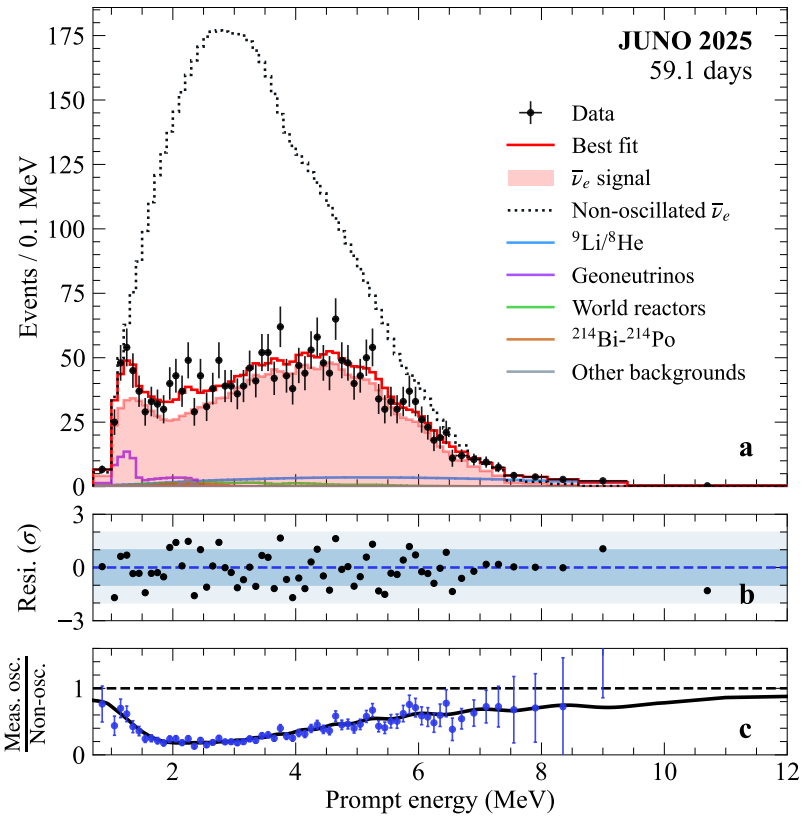
- Operations on Yangjiang cores
- Super Typhoon Ragasa hit Yangjiang on September 24$^{\rm th}$

Backgrounds and energy spectrum

The backgrounds have been evaluated from dedicated analyses and fitted on the IBD candidates energy spectrum

$\overline{\nu}_e$ signal (cpd^1)	
w/o ε_{tot} corrected	33.5 ± 1.7
w/ ε_{tot} corrected	47.9 ± 2.6
Non-oscillated $\overline{\nu}_e$	150.9 ± 2.7

Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}He	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
^{214}Bi-^{214}Po	0.18 ± 0.10	0.20 ± 0.10
^{13}C(α, n)^{16}O	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3



Best fit results:

- background 6.63 $\pm$ 0.74 cpd
- background $\approx$ 0.20 $\times$ signal
- signal / background = 5.05

Solar parameters

After 59.1 days, JUNO provided the first simultaneous high-precision determination of the two solar oscillation parameters, using Combined Neyman-Pearson χ^2 [Ji et al., 2020]:

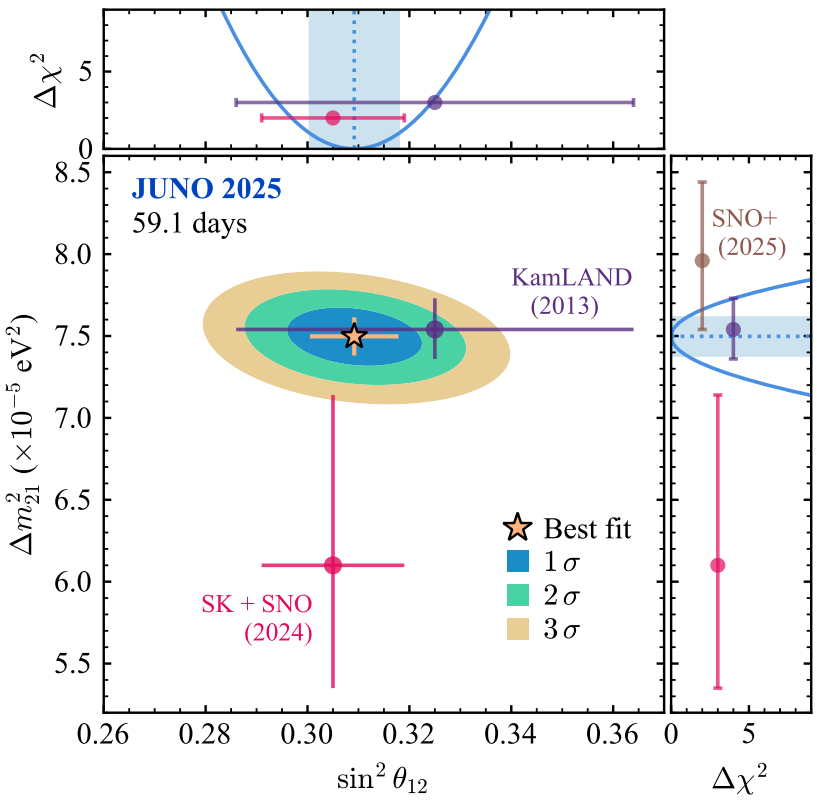
$$\chi^2(\vec{p}, \eta, \alpha) = (\mu - D)^T V^{-1} (\mu - D) + \lambda^2_{\text{nuis}}(\eta) + \lambda^2_{\text{shape}}(\alpha) + \chi^2_{\text{osc}}(\sin^2\theta_{13}, \Delta m^2_{31})$$

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087$$

$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\text{eV}^2$$

The precisions become:

- 2.8% for $\sin^2\theta_{12}$ (4.6%)
- 1.6% for Δm^2_{21} (2.5%)



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Search for the neutrino mass ordering

At Neutrino 2026, JUNO released its first search for NMO, as well as an improved measurement of $|\Delta m^2_{31}|$, Δm^2_{21} and $\sin^2\theta_{12}$ [Adam et al., 2026]

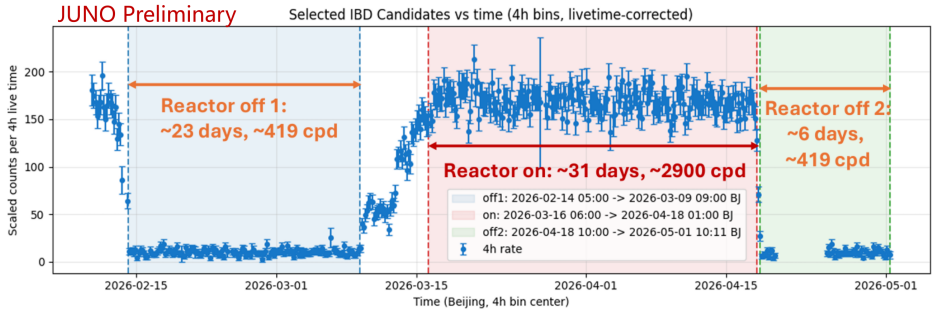


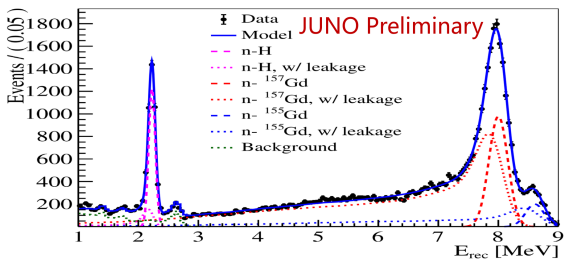
As well as the first results of the Taishan Antineutrino Observatory (TAO)

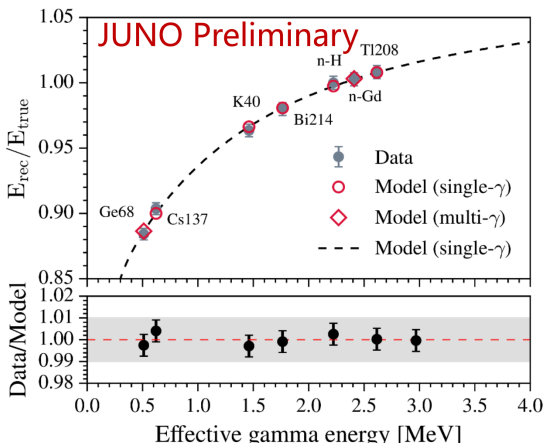
TAO in a nutshell

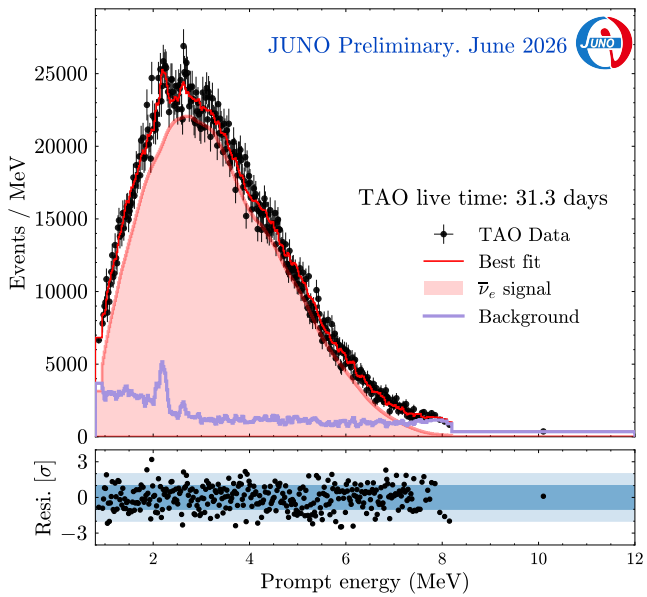
TAO is a satellite experiment of JUNO to measure the energy spectrum with high precision

- 43.2 m from reactor core
- 2.8-ton Gd liquid-scintillator
- operated at -50°C
- 4024 sipm tiles
- 4518 PE/MeV at center
- 2.8% energy resolution





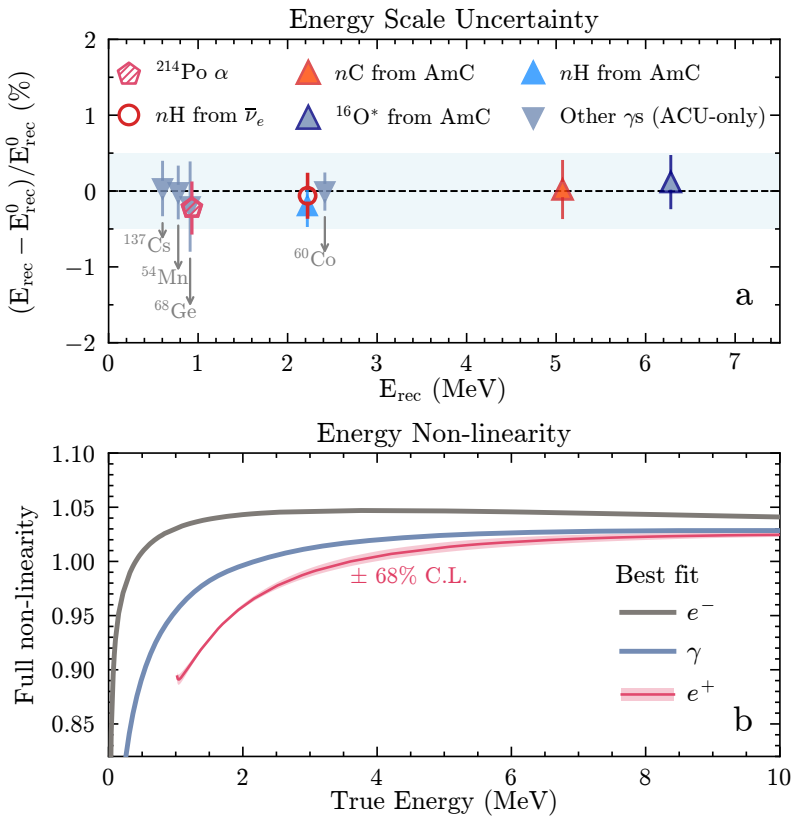




JUNO's energy scale

JUNO's energy scale has been carefully studied over position and time

- 1785 PE/MeV for the 2.223 MeV neutron-capture γ on H
- $\sim$3% time variation correction using the α peak from ^{214}Po
- $\sim$1% spatial (r, θ) correction (time sliced)
- energy scale anchored to the nH peak (<17.2 m)
- residual spatial non-uniformity <0.2% and time variation <0.3%

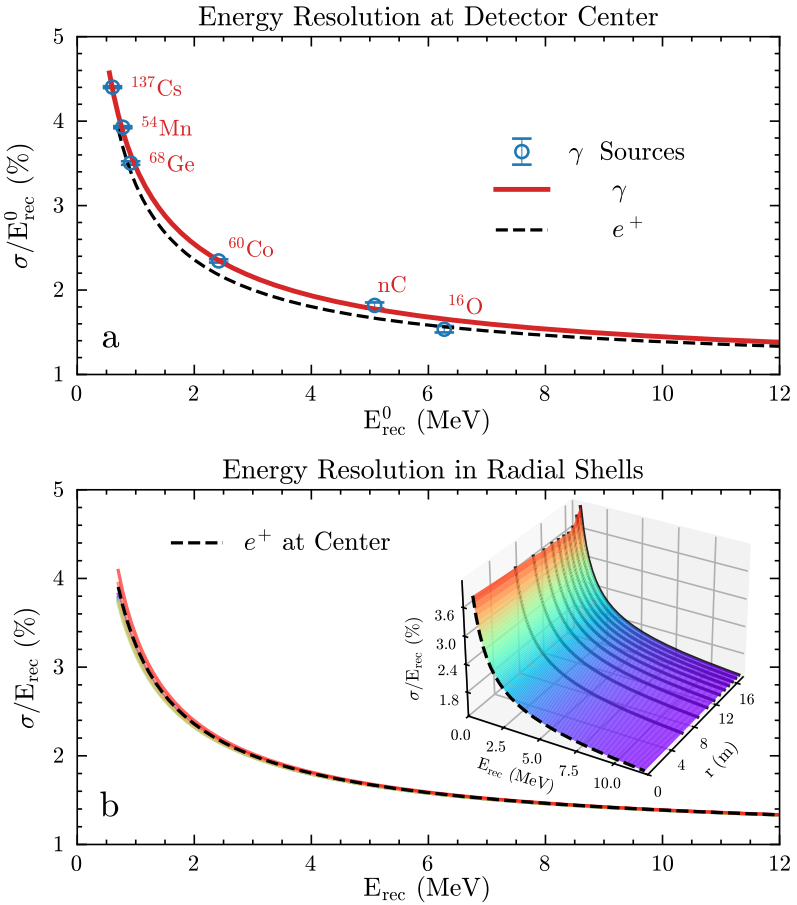


Non-linearity constrained by γ sources and continuous β spectra of cosmogenic isotopes (^{12}B for β^- and $^{11/10}$C for β^+)
$\rightarrow$ 0.6% precision across the energy range

JUNO's energy resolution

The energy resolution characterisation has been improved compared to the first publication

- The energy resolution is 3.5% for ^{68}Ge γ's at the detector center
- e^+ energy resolution model was applied (Geant4 γ-to-e^+ correction)
- $<$5% radial dependence measured with α's from ^{214}Po



$\Rightarrow$ detector response matrix built to incorporate all these effects in the oscillation fit + toy MC energy covariance matrix for uncertainties

IBD candidates selection in JUNO

The IBD analysis has also been improved compared to the first release

- extending the fiducial volume to 17.2 m (+9% IBDs)
- adding neutron capture on carbon (+0.7% IBDs)
- extending the energy range of the multiplicity cut
- using muon track informations to improve the veto
- improving accidental background rejection with a log-likelihood ratio (LLR) analysis

Muon (μ) and spallation neutron (spn) identification	
μ	$Q > 3 \times 10^4$ pe (CD), or $Q > 700$ pe (WP)
spn	$Q \in (3, 30) \times 10^3$ pe, $\Delta T_{spn-\mu} \in (0.02,\ 2)$ ms
IBD selection criteria	
PMT flasher removal	Using hit multiplicity and timing info
Prompt E	$0.7 < E_p < 12.0$ MeV
Delayed E	$2.0 < E_d < 2.5$ MeV (n capture on H) $4.5 < E_d < 5.5$ MeV (n capture on ^{12}C) †
Coincidence	$5 < \Delta T_{p-d} < 1000$ μs, $\Delta R_{p-d} < 1.5$ m
Fiducial volume	$r_p < 17.2$ m †, $\lvert z_p \rvert < 15.5$ m
Muon veto	$\Delta T_{d-\mu} > 5$ ms (CD), $\Delta T_{d-\mu} > 2$ ms (WP) $\Delta R_{d-spn} > 4$ m or $\Delta T_{d-spn} > 1.2$ s $\frac{\Delta R_{d-\mu}}{2.5\text{ m}} + \frac{\Delta T_{d-\mu}}{0.5\text{ s}} > 1$ †
Multiplicity	No additional event with $E > 0.7$ MeV (inside the FV) nor $2.0 < E < 6.0$ MeV (outside the FV) † occurred within $(t_d - 2,\ t_d + 1)$ ms
L.L.R.	Likelihood-ratio selection †

† Improved selections with respect to Ref. [19].

⇒ The IBD selection efficiency ends up at 74.01 ± 0.77 %

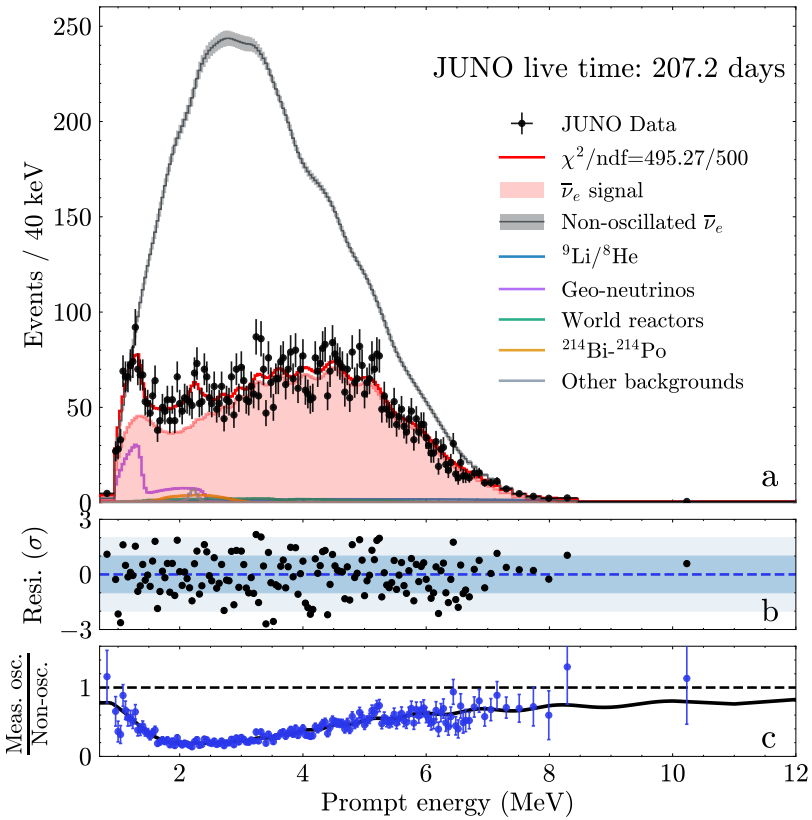
Backgrounds and energy spectrum

Thanks to the analysis improvements, the background has been further reduced to 5.40 ± 0.47 cpd while IBDs increased to 34.62 ± 0.64 cpd

DAQ live time (days)	207.2	
IBD candidates	8294	
Signal rates (cpd)	Pre-fit	Post-fit
Reactor $\overline{\nu}_e$	36.02 ± 0.81	34.62 ± 0.64
Backgrounds (cpd)		
^{9}Li/^{8}He	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	1.30 ± 0.52 [a]	2.12 ± 0.32
World reactors	0.92 ± 0.09	0.92 ± 0.09
^{214}Bi-^{214}Po	0.42 ± 0.31	0.57 ± 0.34
^{13}C(α, 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
Total backgrounds	4.01 ± 0.68	5.40 ± 0.47

signal / background = 6.41

background = 0.16 × signal



Fitting method

Neutrino oscillation parameters are extracted via a joint frequentist binned-χ^2 fit of JUNO data, with TAO and Daya Bay near detectors

$$\chi^2\ (\vec{p},\vec{\eta}) = \sum_{X=JUNO,TAO,DYB} (\mu^X(\vec{p},\vec{\eta}) - D^X)^T\ V_X^{-1}\ (\mu^X(\vec{p},\vec{\eta}) - D^X) + \lambda^2_{\text{nuis}}\ (\vec{\eta}) + \chi^2_{\text{pull}}\ (\sin^2\theta_{13})$$

- V_X: covariance matrices including statistical, shape and systematics uncertainties of each experiment
- $\vec{p}$: contains the oscillation parameters ($\sin^2\theta_{12}, \Delta m^2_{21}, \sin^2\theta_{13}$ and Δm^2_{31}) and the geo-neutrinos rate
- $\vec{\eta}$: nuisance parameters for detector response, backgrounds and reactor flux normalisation and unoscillated spectrum shape

Solar parameters further improved

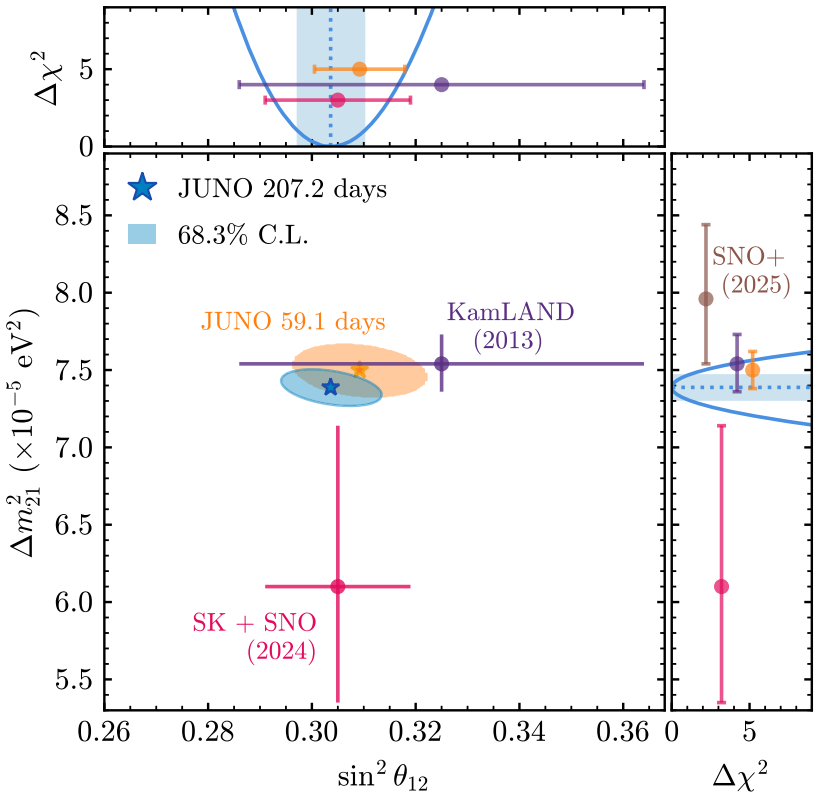
The solar parameters are not sensitive to an external constraint on Δm^2_{31} (shift $< 0.05\sigma$)

$$\sin^2\theta_{12} = 0.3036 \pm 0.0064$$

$$\Delta m^2_{21} = (7.388 \pm 0.078) \times 10^{-5}\text{eV}^2$$

The precisions become:

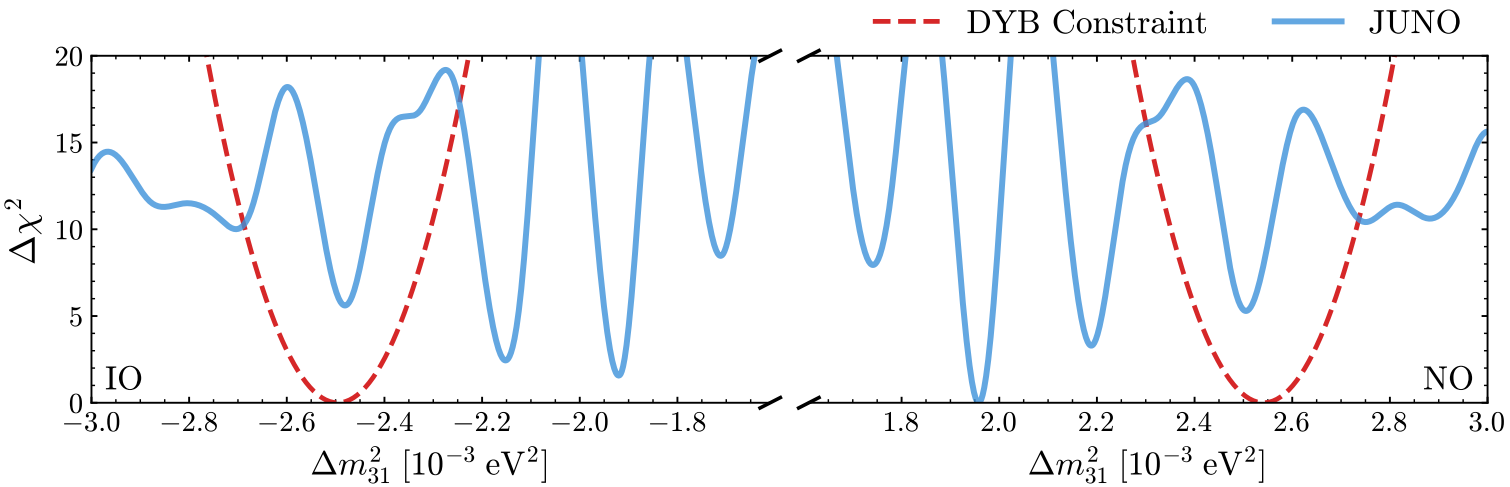
- 2.10% for $\sin^2\theta_{12}$
- 1.06% for Δm^2_{21}



Search for the NMO

Without external constraint on Δm^2_{31}, the joint fit exhibit multiple local minima in the $\Delta\chi^2$ profile.

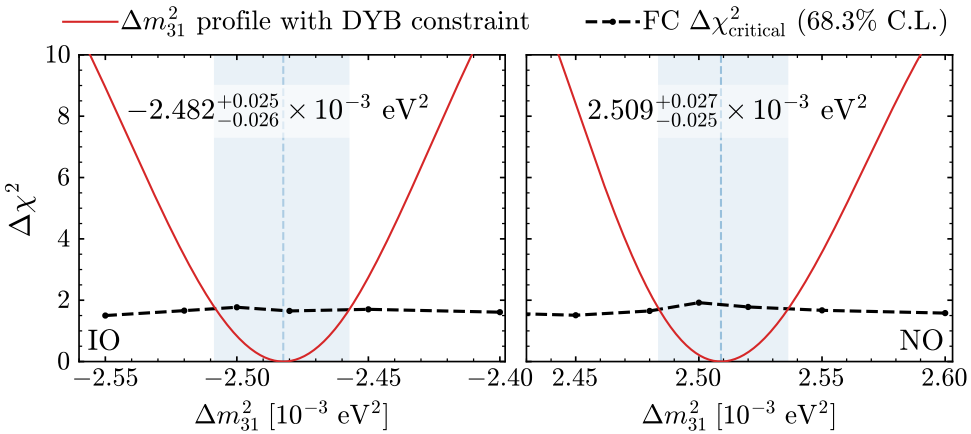
$\Rightarrow$ use the Δm^2_{31} constraint from Daya Bay additional pull term (2.4%)



The 1σ confidence interval coverage is determined by the Feldman-Cousins method

[Feldman and Cousins, 1998]

$\sim$1% precision achieved



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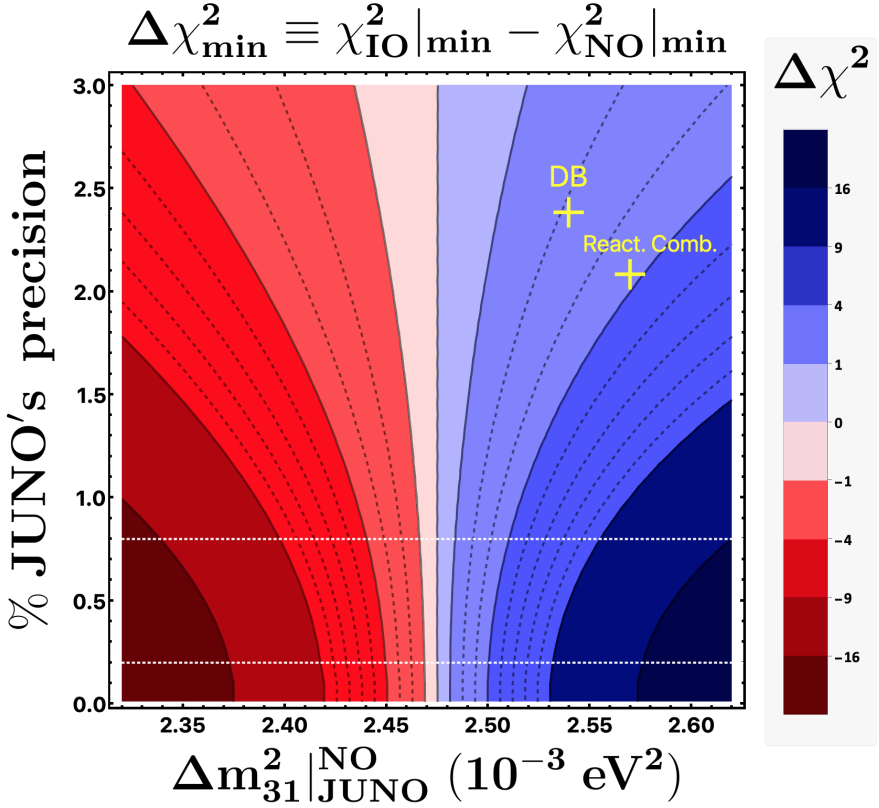
7 Conclusion

Boosting JUNO's sensitivity

High precision measurements of $|\Delta m^2_{31}|$ in reactor ($\overline{\nu}_e \to \overline{\nu}_e$) and long baseline ($\nu_\mu \to \nu_\mu$) combination can boost the determination of the mass ordering independently of matter effects [Nunokawa et al., 2005]

This idea has been updated in 2025, by [Parke and Funchal, 2025]:

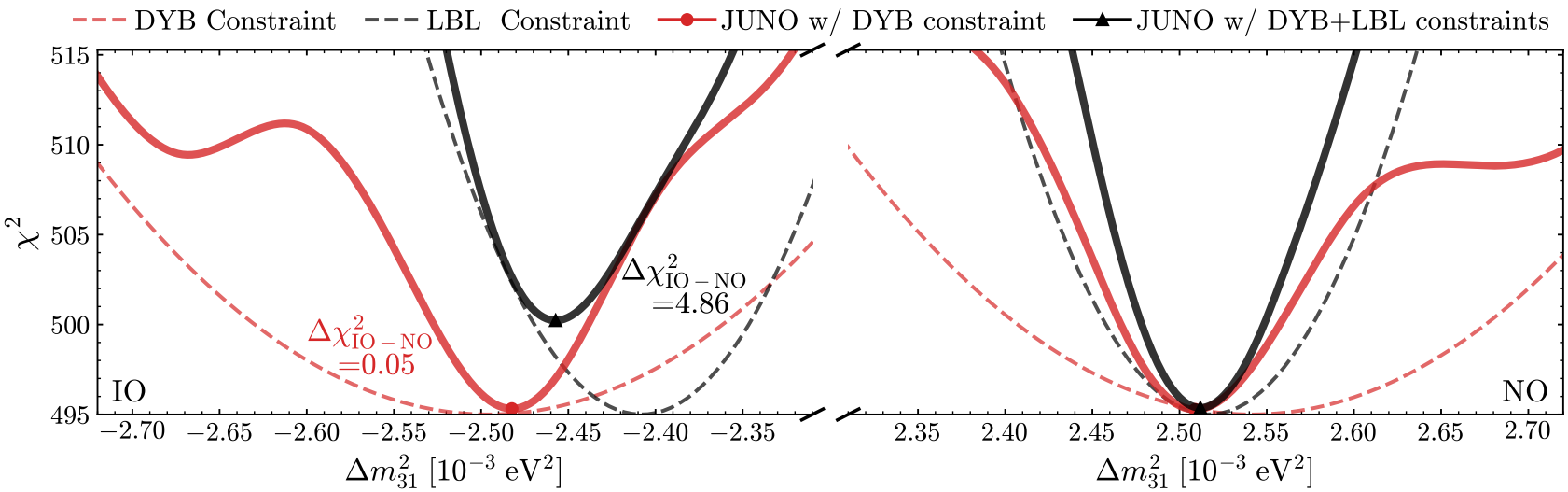
- Combine T2K and NOνA $|\Delta m^2_{32}|$ from NuFit 5.2 (2022)
- Build IO and NO LBL χ^2's
- JUNO's $|\Delta m^2_{31}|$ precision increases rapidly but not $\Delta\chi^2_{IO-NO}$
- Incorporate LBL in JUNO χ^2's via "boost" term
- Enhances the combined $\Delta\chi^2_{IO-NO}$ which depends on $(\Delta m^2_{31}, \sigma_{JUNO})$



JUNO (207 days) and LBL boost χ^2 profiles

The 207 days JUNO's Δm^2_{31} χ^2 profiles constrained by Daya Bay have been released for *JUNO-only* and with the *boost* from LBL NuFit 6.0

[Adam et al., 2026]

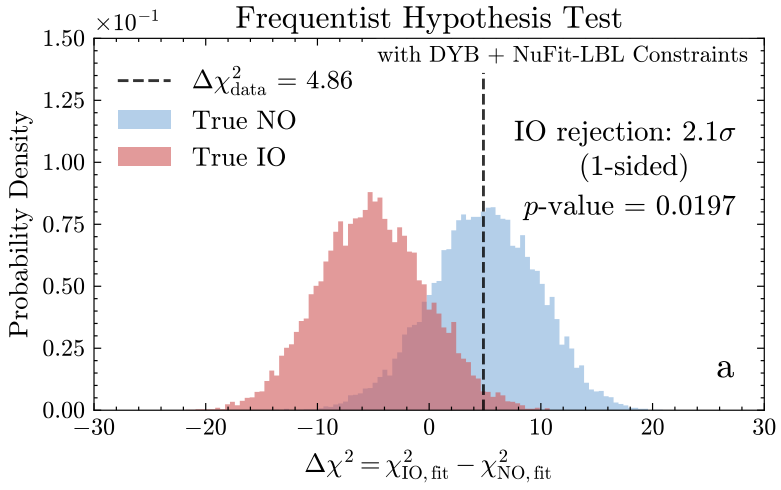


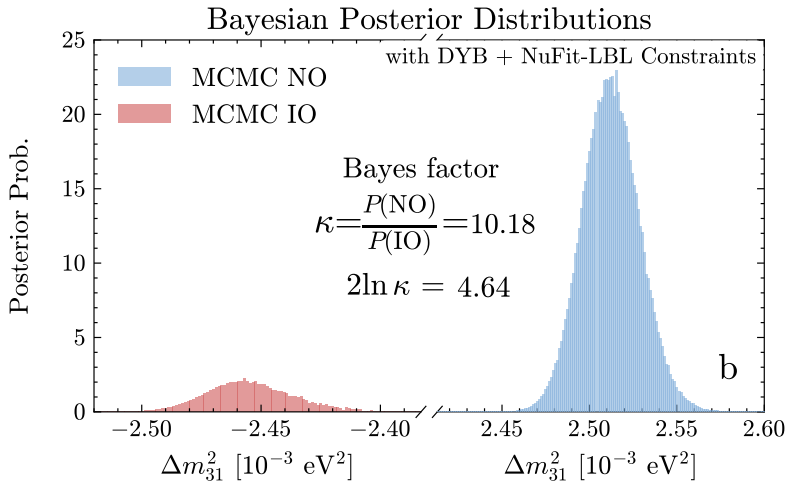
JUNO's fit with LBL boost favors NO over IO with $\Delta\chi^2 = 4.86$

JUNO (207 days) and LBL boost significance

The significance of this result is derived from frequentist approach of [Blennow et al., 2014] and confirmed by the Bayesian study

- expected $\Delta\chi^2$ from pseudo-experiments
- sampling Δm^2_{31} DYB and LBL pulls
- scan the full δ_{CP} range and its NO-IO correspondence
- **one-sided IO rejection of 2.1σ**
- confirmed in Bayesian MCMC **BF = 10.18**





Summary and conclusion

- The JUNO experiment has been designed to measure the neutrino mass ordering via the interference of $(\Delta_{31} - \Delta_{21})$ oscillations
- 10 years of construction of a 20 kt liquid scintillator detector, readout by ∼43200 PMTs, 650 m underground
- TAO satellite detector started to provide valuable inputs on the un-oscillated reactor $\overline{\nu}_e$ energy spectrum
- The detector performances are very good, but more work is needed on the energy resolution
- The precision on the solar parameters has been improved after only two months of data
- After 207 days of data, JUNO was able to reach ∼1% precision on $|\Delta m^2_{31}|$ and to provide a first indication of the NMO, boosted by long-baseline constraint
- JUNO only 3σ determination might take 7 years, but the LBL "boost" will speed-up this result

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