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JUNO: Neutrino Oscillations, Mass Ordering, and First Results

From Wiggles to a Glimpse of the Ordering

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Roadmap

Based on: JUNO Collab., PPNP **123** (2022) 103927 [2104.02565] • Nufiters, 2601.09791 • Nunokawa, Parke & Funchal, PRD **72** (2005) 013009 [hep-ph/0503283] • Forero, Parke, Ternes & Funchal, PRD **104** (2021) 113004 [2107.12410]

Section 1

Neutrino Oscillations: A Brief Reminder

Neutrino Mixing in One Slide

Flavor states are superpositions of mass eigenstates:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}^{*} \, \nu_i$$

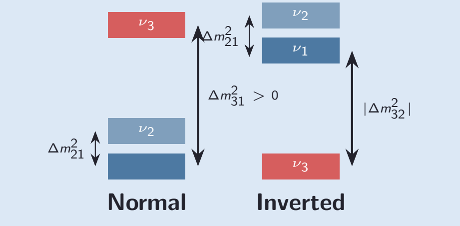
PMNS matrix U has 4 physical parameters:

- 3 mixing angles: θ_{12}, θ_{13}, θ_{23}
- 1 CP phase: δ_{CP}

2 independent mass-squared splittings:

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \approx 7.5 \times 10^{-5}\,\mathrm{eV}^2$$
$$\Delta m_{31}^2 \equiv m_3^2 - m_1^2 \approx \pm 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

Mass orderings



The open question

Is ν_3 the **heaviest** or the **lightest**?

Reactor $\bar{\nu}_e$ Survival Probability

At baseline L in vacuum:

$$\begin{aligned} P_{ee} = 1 - \cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\frac{\Delta m^2_{21}L}{4E} \\ -\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\,\sin^2\frac{\Delta m^2_{31}L}{4E}\right. \\ \left. +\sin^2\theta_{12}\,\sin^2\frac{\Delta m^2_{32}L}{4E}\right) \end{aligned}$$

Two oscillation scales:

- **Slow oscillation** $\leftarrow \Delta m^2_{21}$, amplitude $\sin^2 2\theta_{12} \approx 0.84$
- **Fast oscillation** $\leftarrow \Delta m^2_{31,32}$, amplitude $\sin^2 2\theta_{13} \approx 0.084$

Wiggles

The **sign** of $\Delta m^2_{3\ell}$ enters via the *interference* between the Δm^2_{31} and Δm^2_{32} terms:

$$\Delta m^2_{31} \neq \Delta m^2_{32} \Longleftrightarrow \begin{cases} \Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32} & \text{NO} \\ \Delta m^2_{32} = \Delta m^2_{21} + \Delta m^2_{31} & \text{IO} \end{cases}$$

The **fine structure** (wiggles) of the reactor spectrum encodes the mass ordering.

Why Does the Mass Ordering Matter?

Resolving the ordering has cascading consequences:

- $0\nu\beta\beta$ **decay:** effective Majorana mass $m_{\beta\beta}$ differs by $\sim 2\times$ between orderings
- δ_{CP} **extraction:** MO–δ degeneracy contaminates long-baseline fits
- **Cosmology:** $\sum m_i \geq 58\,\mathrm{meV}$ (NO) vs. $\geq 100\,\mathrm{meV}$ (IO) — within reach of CMB-S4 + DESI

Where we stand (NuFIT 6.1)

- w/o SK-ATM: $\Delta\chi^2_{\mathrm{IO-NO}} \approx 1.5$
- w/ SK-ATM: $\Delta\chi^2_{\mathrm{IO-NO}} \approx 6$
- **No definitive answer yet**

⇒ JUNO was designed to resolve this.

Section 2

JUNO: The Experiment

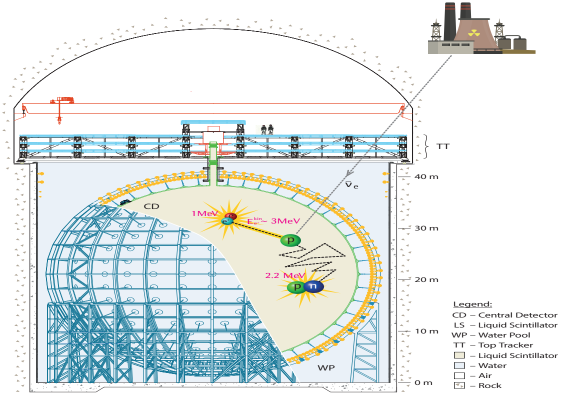
JUNO at a Glance

- Jiangmen, Guangdong, China — ∼700 m underground
- Equidistant from two nuclear power plants:
  - Yangjiang: 6 cores × 2.9 $\mathrm{GW_{th}}$
  - Taishan: 2 cores × 4.6 $\mathrm{GW_{th}}$
- Baseline: **∼53 km** | Total power: ∼ 26.6 $\mathrm{GW_{th}}$
- Expected rate: ∼ 60 IBD events/day

Why 53 km?

Optimal baseline for observing **both** the slow (Δm^2_{21}) and fast (Δm^2_{31}) oscillation in the same spectrum.

The Detector



Central Detector

- **20 kton** liquid scintillator (LAB-based)
- Spherical acrylic vessel, $\oslash = 35.4\,\text{m}$
- 17,612 large PMTs (20") + 25,600 small PMTs (3")
- Photocathode coverage: ~75%

Veto systems

- Water Cherenkov detector ($\oslash = 43.5\,\text{m}$)
- Top Tracker (recycled OPERA strips)

The JUNO resolution

$$\sim 1345\ \text{p.e./MeV} \ \Rightarrow\ \sigma_E/E \approx 3\%/\sqrt{E}\,(\textbf{MeV})$$

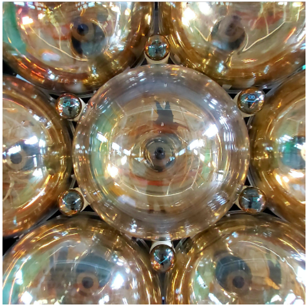
What Makes JUNO's Resolution Unprecedented?

Energy resolution has three contributions:

$$\left(\frac{\sigma_E}{E}\right)^2 = \underbrace{\frac{a^2}{E}}_{\text{statistics}} + \underbrace{b^2}_{\text{systematics}} + \underbrace{\frac{c^2}{E^2}}_{\text{noise}}$$

JUNO attacks the dominant (statistical) term:

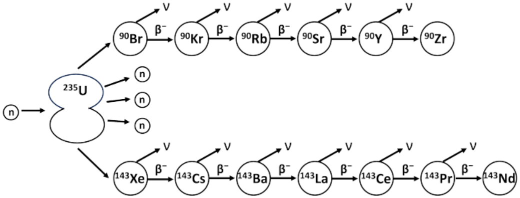
- High light yield: LAB+PPO scintillator
- High-QE PMTs: avg. 29.1% PDE
- 75% photocathode coverage
- Ultra-pure LS: 10^{-17} g/g U/Th



Comparison

Experiment	Resolution	Mass
KamLAND	$6.4\%/\sqrt{E}$	1 kt
Daya Bay	$8\%/\sqrt{E}$	0.2 kt
JUNO	**$3\%/\sqrt{E}$**	**20 kt**

Where Do Reactor $\bar{\nu}_e$ Come From?



Nuclear fission of heavy isotopes (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) produces neutron-rich fragments far from the valley of stability.

These fragments undergo chains of β^- decays:

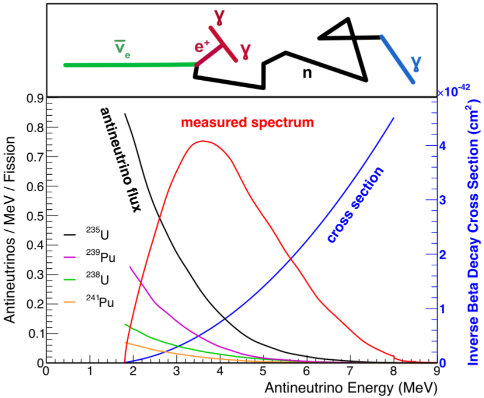
$$n \to p + e^- + \bar{\nu}_e$$

until they reach stable nuclei.

Electron antineutrino flux

- On average **$\sim$6 $\bar{\nu}_e$** emitted per fission
- $\bar{\nu}_e$ spectrum extends up to $\sim$8 MeV
- Spectrum shape depends on the fissioning isotope mix ⇒ evolves as fuel burns

Inverse Beta Decay: From Flux to Detected Spectrum



Detection reaction:

$$\bar{\nu}_e + p \longrightarrow e^+ + n \qquad (E_{\text{thr}} = 1.8\ \text{MeV})$$

The detected spectrum is the product of three factors:

1. **Reactor $\bar{\nu}_e$ flux** — sum over ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu weighted by their fission fractions (bottom, colored curves)
2. **IBD cross section** $\sigma_{\text{IBD}} \propto E_e\, p_e$ — rises steeply with energy (blue curve)
3. Their product gives the **detected event spectrum** (red curve), peaking around 3–4 MeV

The 1.8 MeV threshold cuts the abundant low-energy $\bar{\nu}_e$s, while the falling flux suppresses high energies.

IBD Event Signature and Backgrounds

The coincidence signature:

- **Prompt:** e^+ kinetic energy + $2\times0.511\,\mathrm{MeV}$ annihilation
- **Delayed:** n capture on H after $\sim200\,\mu$s → $2.2\,\mathrm{MeV}\ \gamma$
- **Observable:** $E_{\mathrm{prompt}} \simeq E_\nu - 0.78\,\mathrm{MeV}$

This space–time coincidence gives powerful background rejection.

Main backgrounds: ^{9}Li/^{8}He (cosmogenic), accidentals, fast neutrons, geoneutrinos.

Expected rates (after cuts)

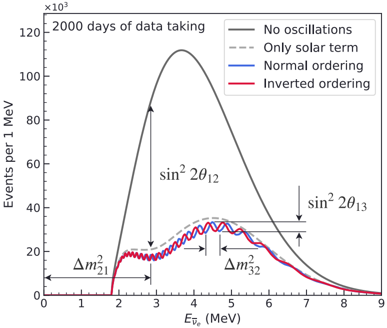
Component	day^{-1}
Reactor $\bar{\nu}_e$ (IBD)	60
Geoneutrinos	1.1
Accidentals	0.9
^{9}Li/^{8}He	1.6
Total bkg.	≈ 3.8

Signal/Background ≈ 16 : 1

Section 3

Mass Ordering from the Wiggles

The Oscillated Spectrum at 53 km



- **Slow envelope:** Δm^2_{21}, θ_{12} — large amplitude, few MeV period
- **Fast wiggles:** Δm^2_{31}, θ_{13} — small amplitude, $\sim$0.2 MeV period
- The **phase shift between NO and IO wiggles** is measurable **only** with $\sigma_E/E \lesssim 3\%/\sqrt{E}$

How the Wiggles Encode the Ordering

The fast-oscillation part of P_{ee} can be written *exactly* as (Forero et al. 2021):

$$\frac{1}{2}\sin^2 2\theta_{13}\left[1 - A(E)\,\cos\!\big(2|\Delta_{ee}| \pm \Phi_\odot\big)\right]$$

where $A(E) = \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}$, $\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$, and the **solar phase**:

$$\Phi_\odot = \arctan\!\big(\cos 2\theta_{12}\tan\Delta_{21}\big) - \Delta_{21}\cos 2\theta_{12}$$

- $+$ (NO): **phase advance** — wiggles complete a half-cycle *sooner* in energy
- $-$ (IO): **phase retardation** — wiggles lag behind the $|\Delta m^2_{ee}|$-only prediction
- Both orderings give the *same* $|\Delta m^2_{ee}|$, yet the retardation makes $|\Delta m^2_{ee}|_{\rm IO}$ look $\sim$0.7% **larger** than $|\Delta m^2_{ee}|_{\rm NO}$

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\,\Delta m^2_{31} + \sin^2\theta_{12}\,\Delta m^2_{32}$$

What makes JUNO's approach unique

- Based on **vacuum oscillations**
- No $\delta_{\rm CP}$ or θ_{23} dependence
- No matter effects at this L/E
- Systematics independent from LBL/atmospheric

Requirement

$\sigma_E/E < 3\%/\sqrt{E}$ **and** large statistics ($\sim$60 IBD/day $\times$ 6 yr)

Forero, Parke, Ternes & Funchal,
PRD **104** (2021) 113004 [arXiv:2107.12410]

Why Not Just Accelerators or Atmospherics?

Approach	**Mechanism**	**Main limitations**
Long-baseline (T2K, NOvA, DUNE)	MSW matter effects in the Earth	Depends on θ_{23} octant and δ_{CP}
Atmospheric (SK, ORCA, PINGU)	Matter effects + large statistics	Complex reconstruction; energy/direction smearing
JUNO (medium-baseline reactor)	**Vacuum oscillations** (interference pattern)	Extreme energy resolution required

JUNO provides a **complementary, clean** measurement: no matter effects, no δ_{CP} ambiguity.

But there is a **second method** that combines JUNO with LBL. . .

JUNO's unique contribution

Measures $|\Delta m^2_{ee}|$ to **0.6%** — enabling the Nunokawa–Parke–Funchal method.

Section 4

Combining Reactors and Long-Baseline: The NPF Method

The Main Idea: Flavor-Dependent Effective Δm^2

Each flavor α measures a *different* effective atmospheric splitting:

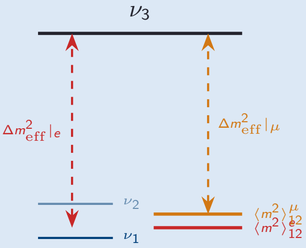
$$\boxed{\Delta m^2_{\text{eff}}\big|_\alpha = \frac{|U_{\alpha 1}|^2\,\Delta m^2_{31} + |U_{\alpha 2}|^2\,\Delta m^2_{32}}{|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2}}$$

This is m_3^2 minus the α-**flavor weighted average** of m_1^2 and m_2^2.

Since $|U_{e1}|^2/|U_{e2}|^2 \neq |U_{\mu 1}|^2/|U_{\mu 2}|^2$, the effective splittings differ:

$$\Delta m^2_{\text{eff}}\big|_e \neq \Delta m^2_{\text{eff}}\big|_\mu$$

Physical picture



Same ν_3, different weighted average
$\Rightarrow$ different gap!

The Two Effective Splittings

Substituting PMNS elements:

$$\Delta m^2_{ee} \equiv \Delta m^2_{\text{eff}}\Big|_e = \cos^2\theta_{12}\,\Delta m^2_{31} + \sin^2\theta_{12}\,\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} \equiv \Delta m^2_{\text{eff}}\Big|_\mu = \sin^2\theta_{12}\,\Delta m^2_{31} + \cos^2\theta_{12}\,\Delta m^2_{32} + \mathcal{O}(\cos\delta\,\sin\theta_{13})\,\Delta m^2_{21}$$

- $|\Delta m^2_{ee}| \leftarrow$ **reactor $\bar{\nu}_e$** (JUNO, Daya Bay)
- $|\Delta m^2_{\mu\mu}| \leftarrow$ **LBL ν_μ** (T2K, NOvA, DUNE)

The NPF identity (2005)

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\,\Delta m^2_{21}(\cos 2\theta_{12} + \ldots)$$

$+ \Rightarrow$ **Normal Ordering**
$- \Rightarrow$ **Inverted Ordering**

The difference is ∼1–2% of $|\Delta m^2_{3\ell}|$, set by $\Delta m^2_{21}/\Delta m^2_{3\ell} \approx 1/30$ and $\cos 2\theta_{12} \approx 0.38$.

Two numbers, two experiments, one sign.

Why This Works: The Intuition

Recall: $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$

Normal Ordering ($m_3 > m_2 > m_1$)

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$

ν_e weighs $|31|$ more (via $\cos^2\theta_{12}$)

ν_μ weighs $|32|$ more (via $\cos^2\theta_{12}$)

Since $\cos^2\theta_{12} > \sin^2\theta_{12}$:

$$\Rightarrow \; \Delta m^2_{ee} > \Delta m^2_{\mu\mu}$$

Inverted Ordering ($m_3 < m_1 < m_2$)

Roles reversed: $|\Delta m^2_{32}| > |\Delta m^2_{31}|$

$$\Rightarrow \; \Delta m^2_{ee} < \Delta m^2_{\mu\mu}$$

Matter-effect-free MO

This method works in **vacuum**:

- No Earth matter effects needed
- Different $\cos\delta$ dependence vs. LBL appearance
- Complementary to MSW-based methods

Main uncertainty: the $\cos\delta$ correction is sub-leading ($\lesssim 0.3\%$ of $\Delta m^2_{\rm eff}$).

This is precisely the mechanism JUNO exploits!

Section 5

Precision Oscillation Measurements

Precision Measurements: θ_{12}, Δm^2_{21}, $|\Delta m^2_{31}|$

After 6 years, JUNO will achieve:

Parameter	Current	JUNO goal
$\sin^2 2\theta_{12}$	$\sim 2.3\%$	$< 0.6\%$
Δm^2_{21}	$\sim 2.3\%$	$< 0.6\%$
$\|\Delta m^2_{ee}\|$	$\sim 1.6\%$	$< 0.6\%$
$\sin^2 2\theta_{13}$	$\sim 1.5\%$	$\sim 1.5\%$ (✗)

- First experiment to simultaneously observe solar *and* atmospheric oscillations in one detector
- $|\Delta m^2_{ee}|$ at 0.6% feeds directly into the NPF combination

Why θ_{13} won't improve

θ_{13} amplitude modulates the fast wiggles. Daya Bay/RENO at ∼1–2 km have direct access with high statistics; JUNO at 53 km is not competitive.

MO determination

Sub-percent $|\Delta m^2_{ee}|$ (JUNO) $+$ independent $|\Delta m^2_{\mu\mu}|$ (LBL) $\Rightarrow$ sign of Δm^2_{31} without matter effects.

JUNO Physics Programme: Overview

Physics	**Source**	**Main measurement**
Mass ordering (wiggles)	Reactor $\bar{\nu}_e$	Fine structure at 53 km
Mass ordering (NPF)	Reactor + LBL	$\lvert\Delta m^2_{ee}\rvert$ vs. $\lvert\Delta m^2_{\mu\mu}\rvert$
Oscillation params	Reactor $\bar{\nu}_e$	$< 0.6\%$ on 3 parameters
Supernova burst ν	Galactic SN	Flavor & time profile
DSNB	Relic SN	First detection
Geoneutrinos	Earth mantle	U/Th composition
Atmospheric ν	Cosmic rays	MO synergy
Proton decay	BSM	$p \to \bar{\nu} K^+$

JUNO is a multi-purpose neutrino observatory. Primary goal: mass ordering via two independent vacuum methods.

Section 6

First Results: 59.1 Days of Data

JUNO Turns On (2025)

Milestone

First JUNO results published in 2025:
59.1 days, 2379 IBD events

- **World-leading precision** on Δm^2_{21} and $\sin^2\theta_{12}$ from the very first data release
- Dominant (solar) oscillation mode measured with unprecedented reactor statistics
- Official analysis limited to “12” sector — no published $|\Delta m^2_{31}|$ or MO yet

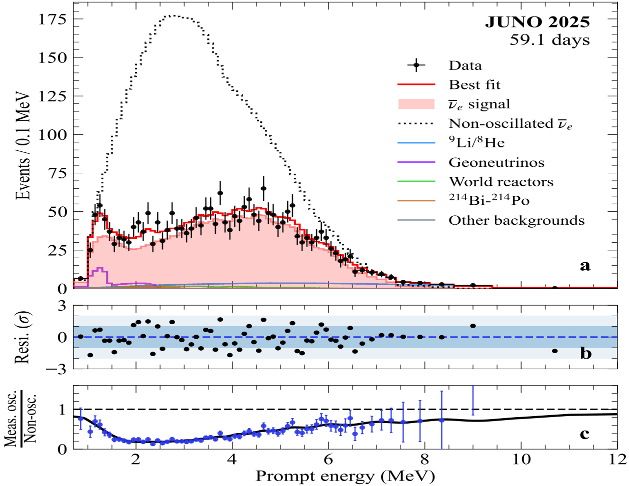
Nufiters (2601.09791)

Independent exploratory analysis:

- Reproduce official spectrum & contours
- Extend to fast oscillations ($\Delta m^2_{3\ell}$)
- Combine with NuFIT-6.1 global data
- MC study of MO significance

The following slides are based on this analysis.

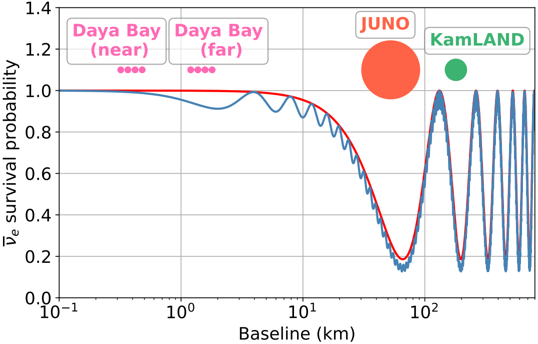
The Observed Spectrum



- **2379 IBD candidates** in 59.1 days of data
- Data (black) vs. best-fit oscillated spectrum (red)
- Clear deficit vs. unoscillated expectation (dashed)
- Dominant backgrounds constrained: ^{9}Li/^{8}He, geoneutrinos, accidentals
- Overall energy scale uncertainty: **0.5%**

JUNO Collab., *Nature* (2025)
arXiv:2511.14593

Oscillation Probability: Direct Observation



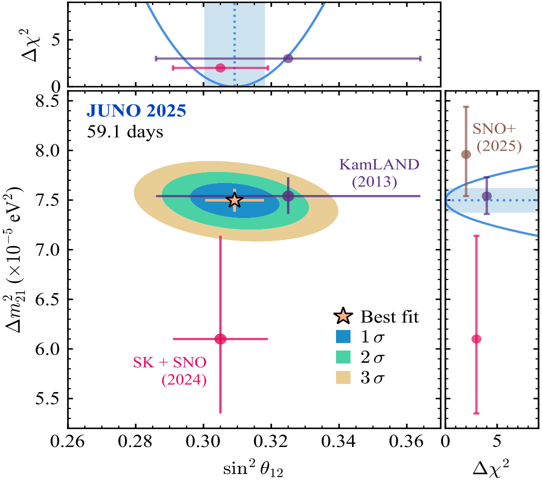
- Data divided by no-oscillation expectation reveals the oscillatory structure directly
- Solar oscillation maximum clearly resolved at $L/E \sim 50\,\text{km}/\text{MeV}$
- Fast θ_{13}-driven wiggles hinted at 2σ–3σ

Both slow (solar, Δm^2_{21}) and fast (atmospheric, $|\Delta m^2_{3\ell}|$) oscillation frequencies are encoded in the reactor antineutrino spectrum.

Section 7

Solar Parameters from First Data

Measuring Δm^2_{21} and $\sin^2\theta_{12}$



Official JUNO results (arXiv:2511.14593):

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

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

- **Factor of 1.6** improvement over previous world-best
- Relative uncertainties: 2.8% ($\sin^2\theta_{12}$), 1.6% (Δm^2_{21})
- Mild KamLAND–solar tension in Δm^2_{21} resolved in favor of KamLAND

In just 59.1 days!

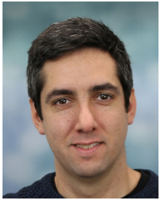
Already the world reference for solar oscillation parameters.

The Nufiters: Lessons from the first JUNO results (arXiv:2601.09791)

Ivan Esteban

M.C. González-García

Michele Maltoni

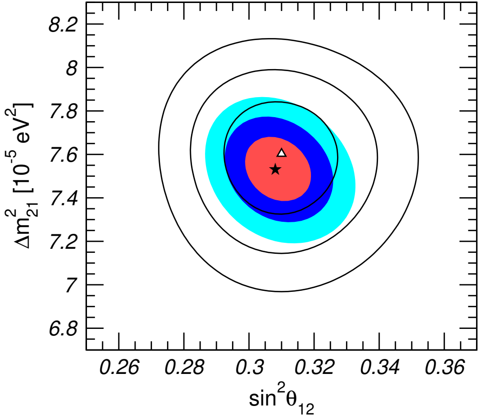


Ivan Martínez-Soler

J.P. Pinheiro

Thomas Schwetz

Impact on the Global θ_{12}–Δm^2_{21} Fit



- **Black:** global fit *without* JUNO
- **Colored:** global fit *with* JUNO
- JUNO shrinks the allowed region dramatically
- Mild KamLAND–solar tension in Δm^2_{21} resolved in favor of KamLAND

Implication

JUNO is already the reference experiment for θ_{12} and Δm^2_{21} — at day 59.

Section 8

Sensitivity to Atmospheric mass splitting and the Mass Ordering

Seeing Fast Oscillations in First Data

Can the fast wiggles already be seen?

The θ_{13}-driven term has amplitude $\sin^2 2\theta_{13} \approx 0.084$ — small but non-zero.

- Nufiters profile χ^2 over $\Delta m^2_{3\ell}$ after marginalizing solar parameters
- Several minima found with $\Delta\chi^2 \lesssim 8$
- $\Rightarrow$ Fast oscillatory feature present at 2σ–3σ

JUNO alone cannot distinguish the ordering yet ($|\Delta\chi^2_{\mathrm{IO-NO}}| < 10^{-3}$).

NPF mechanism in action

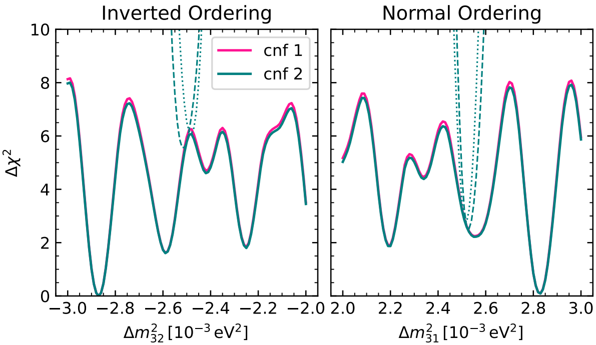
JUNO alone: measures $|\Delta m^2_{ee}|$ but sees degenerate minima.

LBL global data: measures $|\Delta m^2_{\mu\mu}|$ independently.

Combination:
$|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}| \Rightarrow$ NO
$|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}| \Rightarrow$ IO

Even 59 days suffices to test this!

χ^2 Profile in $\Delta m^2_{3\ell}$ and MO Combination



- **Solid:** JUNO only (multiple degenerate minima)
- **Dashed:** + NuFIT-6.1 (w/o SK-ATM)
- **Dotted:** + NuFIT-6.1 (w/ SK-ATM)
- NO gives **better agreement**

$\Delta\chi^2_{\mathrm{IO-NO}} \approx$ 3.1 (w/o SK) or 3.3 (w/ SK)

Physical intuition

If NO is true, JUNO's best-fit Δm^2_{31} should agree with LBL data — and it does, slightly better than IO.

Robustness of the MO Result

Six analysis configurations tested:

Config.	Modification	$\Delta\chi^2_{\mathrm{IO-NO}}$
cnf 1	Baseline (CNP)	3.18
cnf 2	$+15\%$ bkg (Poisson)	3.05
cnf 3	Energy scale $+2.4\%$	**0.30**
cnf 4	$\sigma_{\mathrm{bias}} = 5\%$	2.89
cnf 5	Resolution $\times 1.3$	2.08
cnf 6	$\sigma_{\mathrm{res}} = 40\%$	2.06

- Only a large ($> 2\sigma$) energy **scale shift** strongly alters the result (cnf 3)
- But: JUNO's own Δm^2_{21} measurement would flag such a shift
- Resolution uncertainty has modest impact

Why energy scale matters

An energy-scale shift moves both Δm^2_{21} and $\Delta m^2_{3\ell}$ in the same direction. If JUNO's Δm^2_{21} is self-consistent, the systematic is essentially self-constrained.

Caveat

This analysis goes **beyond** the official JUNO publication. It is exploratory and needs full systematics + more statistics.

Section 9

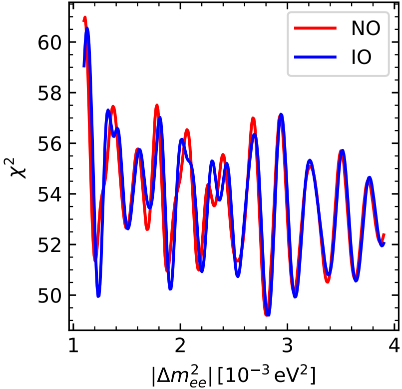
Global Picture and Outlook

Full Global Analysis Including JUNO

Adding both the “12” and exploratory “3ℓ” information:

Dataset	$\Delta\chi^2_{\mathrm{IO-NO}}$
NuFIT-6.1 (w/o SK-ATM)	1.49
NuFIT-6.1 (w/ SK-ATM)	5.91
+ JUNO (w/o SK-ATM)	**4.62**
+ JUNO (w/ SK-ATM)	**9.41**

- Without SK-ATM: growth driven by JUNO’s “12” dominance
- With SK-ATM: approaching 3σ
- Full dataset (6 yr) targets $> 3\sigma$ standalone



χ^2_{JUNO} vs. Δm^2_{ee}: multiple minima per ordering, with NO minima in better agreement with global data.

The Road Ahead

What 59.1 days achieved:

- ✓ World-best Δm^2_{21} and θ_{12}
- ✓ Fast oscillations hinted at 2σ
- ✓ $\sim 2.2\sigma$ preference for NO (NPF, exploratory)

What is coming:

- Official $|\Delta m^2_{ee}|$ and MO analysis
- TAO commissioning: removes flux shape uncertainty
- 6-year goal: $> 3\sigma$ MO (wiggles alone)
- JUNO + DUNE/HK: definitive MO + δ_{CP}
- NPF combination strengthens as LBL $|\Delta m^2_{\mu\mu}|$ precision improves

Timeline

2022	Detector commissioning
2023–24	First fills / calibrations
2025	**First physics results**
2026+	Official $\lvert\Delta m^2_{ee}\rvert$ + MO
2030	Full 6-year dataset

Bottom line

JUNO has already changed the landscape of neutrino oscillation measurements. The MO story is just beginning.

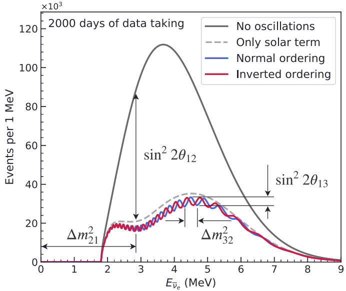
Summary

JUNO design principles

- 20 kton LS at 53 km from $\sim$26 GW reactors
- Unprecedented $3\%/\sqrt{E}$ resolution $\Rightarrow$ visible wiggles
- **Method 1 (Wiggles):** $\Delta m^2_{31}/\Delta m^2_{32}$ interference in vacuum
- **Method 2 (NPF):** $|\Delta m^2_{ee}|$ vs. $|\Delta m^2_{\mu\mu}| \Rightarrow$ sign without matter effects
- Sub-percent precision on θ_{12}, Δm^2_{21}, $|\Delta m^2_{ee}|$

First results (59.1 days)

- World-leading Δm^2_{21} and θ_{12}
- Fast oscillations visible at $\sim 2\sigma$
- Preference for NO: $\sim 2.2\sigma$ (NPF, exploratory)



The era of precision neutrino oscillation physics has begun.

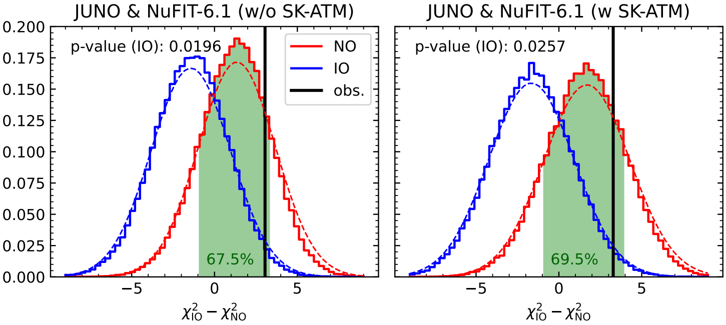
References

1. JUNO Collaboration, *Prog. Part. Nucl. Phys.* **123** (2022) 103927 [2104.02565]
2. H. Nunokawa, S. Parke & R. Zukanovich Funchal, *Phys. Rev. D* **72** (2005) 013009 [hep-ph/0503283]
3. D.V. Forero, S.J. Parke, C.A. Ternes & R.Z. Funchal, *Phys. Rev. D* **104** (2021) 113004 [arXiv:2107.12410] — phase advance/retardation and JUNO MO prospects
4. Nufiters, arXiv:2601.09791 (2026)
5. JUNO Collaboration, *First measurement of reactor neutrino oscillations at JUNO*, *Nature* (submitted, 2025) [arXiv:2511.14593]
6. Nufiters, NuFIT-6.1, www.nu-fit.org [2410.16291]
7. S.T. Petcov & M. Piai, *Phys. Lett. B* **533** (2002) 94 — first proposal of MO from reactor wiggles
8. M. Blennow & T. Schwetz, *JHEP* **09** (2013) 089 — combined MO sensitivity

Thank you!

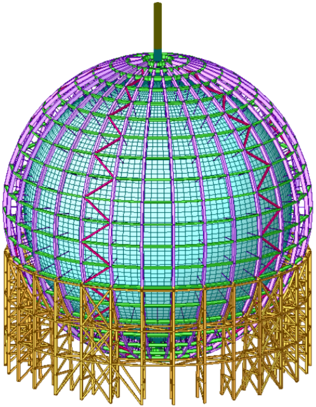
Questions ?

Statistical Significance: Monte Carlo Study



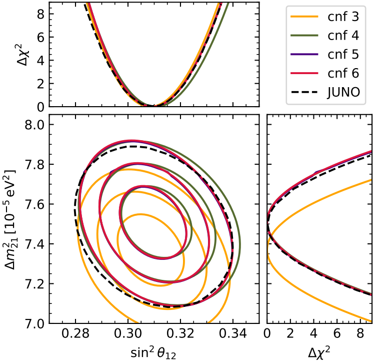
- 10^5 pseudo-experiments for NO (green) and IO (blue)
- **Vertical line:** observed $\Delta\chi^2_{\rm IO-NO}$ from real data
- *p*-value for IO: $\approx 2.0\%$ **(w/o SK-ATM)** $\Rightarrow$ $\sim 2.2\sigma$ preference for NO
- Observed value lies within the NO 68% band: consistent with expected fluctuation

Backup: CD Structure



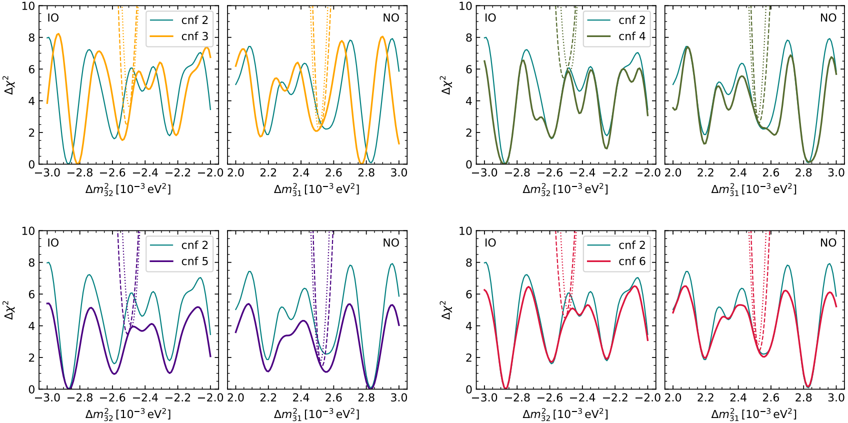
- Spherical acrylic vessel (35.4 m ⌀)
- 590 connecting bars to stainless steel truss
- 1.42 m water buffer between acrylic and PMTs
- Outer Cherenkov pool shields from rock radioactivity
- Top chimney for calibration access

Backup: Solar Parameter Configurations (cnf 3–6)

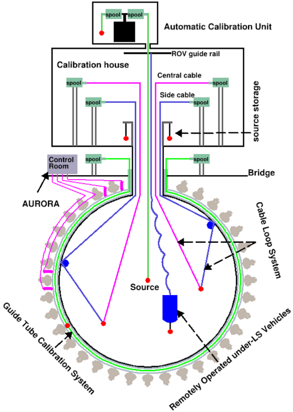


All configurations give consistent Δm^2_{21} and $\sin^2\theta_{12}$, confirming robustness of the solar parameter measurements.

Backup: $\Delta m^2_{3\ell}$ Profiles (cnf 3–6)

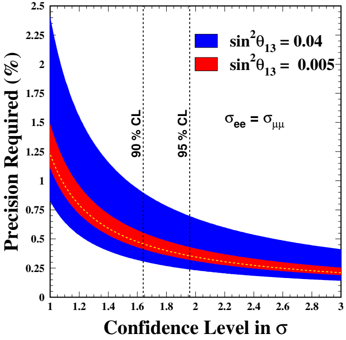


Backup: Calibration Strategy



- Multiple systems along detector axes
- Radioactive sources, LEDs, laser systems
- Controls energy non-linearity and spatial non-uniformity
- Target: energy scale uncertainty $< 0.5\%$

Required Precision for MO Determination



Assuming $\sigma_{ee} \simeq \sigma_{\mu\mu}$:

- 1σ: need ~1.5% precision
- 2σ: need ~0.75%
- 3σ: need ~0.5%

Current & projected precision

JUNO: $|\Delta m^2_{ee}|$ to **<0.6%**
LBL (T2K, NOvA, DUNE): $|\Delta m^2_{\mu\mu}|$ to ~1–2%

⇒ MO determination **possible even before** the wiggle method reaches 3σ!

From Nunokawa, Parke & Funchal (2005)