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Precision-era reactor neutrino oscillations

# Mass Ordering in JUNO with Renormalization Group Running

Quantum corrections to leptonic mixing and their spectral signatures

João Paulo Pinheiro
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2026

*Disentangle RG Running Parameters with Medium-Baseline Reactor Experiments* — Ge, Pinheiro, Qin • arXiv:2606.26720

# About me

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**NuFit-6.0: updated global analysis of three-flavor neutrino oscillations** #18

Ivan Esteban (Basque U., Bilbao), M.C. Gonzalez-Garcia (U. Barcelona (main) and ICREA, Barcelona and Stony Brook U.), Michele Maltoni (Madrid, Autonoma U.), Ivan Martinez-Soler (Durham U.), João Paulo Pinheiro (U. Barcelona (main)) et al. (Oct 7, 2024)

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**Solar model independent constraints on the sterile neutrino interpretation of the Gallium Anomaly** #17

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# Outline

**Central question**

The PMNS matrix runs with energy scale.

**What are the observable traces of this running
in neutrino oscillation experiments?**

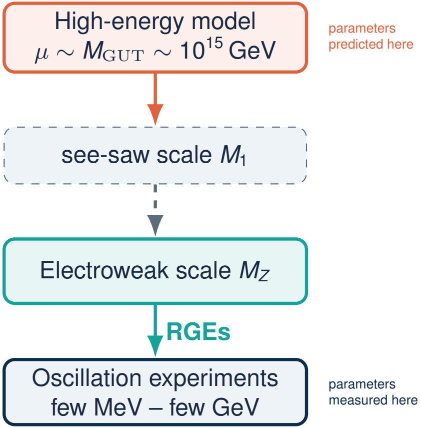
- **I** RG running of neutrino mixing parameters
- **II** From RGEs to oscillation corrections — amplitude and phase
- **III** Why reactors are the ideal probe
- **IV** JUNO: slow mode & first data
- **V** Fast mode: mass ordering at risk
- **VI** JUNO-TAO restores the sensitivity

Part I

# RG Running of Neutrino Mixing Parameters

# Coupling constants run — and the PMNS matrix is no exception

- In QFT, couplings depend on the renormalization scale $\mu$: $\alpha_s(M_Z) \simeq 0.12$ but $\alpha_s(M_{\mathrm{GUT}}) \simeq 0.04$. This has been **directly measured** at colliders.
- The PMNS matrix $U_{\mathrm{PMNS}}$ encodes leptonic couplings — it runs too (Lindner et al., hep-ph/0305273).
- In BSM scenarios, neutrino masses originate at a high scale $M_1$ (see-saw, GUT …). Parameters at $M_1$ are evolved **down to low energy** by RG equations (RGEs).
- Low-energy oscillation measurements constrain what we can infer about the high-scale model. RG corrections are unavoidable.



# The neutrino mass operator and its RGE

- Below the see-saw scale, light neutrino masses come from the **dimension-5 Weinberg operator** $\kappa$:

$$\mathcal{L}_\kappa = \frac{1}{4}\kappa_{gf}\overline{\ell_g^C}\,\varepsilon\phi\,\ell_f\varepsilon\phi + \text{h.c.}$$

- Its **one-loop RGE** (Antusch, Kersten, Lindner, Ratz, hep-ph/0305273):

$$16\pi^2\frac{d\kappa}{dt} = C(Y_e^\dagger Y_e)^T\kappa + C\kappa(Y_e^\dagger Y_e) + \alpha\kappa$$

with $t = \ln(\mu/\mu_0)$, $C = 1$ (MSSM), $C = -\frac{3}{2}$ (SM).


From $\kappa(\mu)$, extract: $m_i(\mu),\ \theta_{ij}(\mu),\ \delta_D(\mu),\ \varphi_{1,2}(\mu)$

- **Dominant driver**: $\tau$ Yukawa $y_\tau$ ($y_e$, $y_\mu$ negligible).
- MSSM: enhanced by $(1+\tan^2\beta)$.

# Analytical RGEs for mixing parameters

(Antusch, Kersten, Lindner, Ratz, hep-ph/0305273) — at leading order in $\theta_{13}$:

**Mixing angles:**

$$\dot{\theta}_{12} \approx -\frac{Cy_\tau^2}{32\pi^2} \sin 2\theta_{12}\, s_{23}^2\, \frac{|m_1 e^{i\varphi_1} + m_2 e^{i\varphi_2}|^2}{\Delta m^2_{\mathrm{sol}}}$$

$$\dot{\theta}_{23} \approx -\frac{Cy_\tau^2}{32\pi^2} \frac{\sin 2\theta_{23}}{\Delta m^2_{\mathrm{atm}}} \times \left[c_{12}^2 |m_2 e^{i\varphi_2} + m_3|^2 + \ldots\right]$$

**Dirac CP phase:**

$$\dot{\delta} \approx \frac{Cy_\tau^2}{32\pi^2} \frac{\delta^{(-1)}}{\theta_{13}} + \frac{Cy_\tau^2}{8\pi^2} \delta^{(0)}$$

($\delta^{(-1)}$ model-dependent; $1/\theta_{13} \sim 7$ enhancement!)

**Majorana phases $\varphi_{1,2}$:**

$$\dot{\varphi}_1 \approx \frac{Cy_\tau^2}{4\pi^2} \left\{ m_3 \cos 2\theta_{23} \frac{m_1 s_{12}^2 \sin\varphi_1 + m_2 c_{12}^2 \sin\varphi_2}{\Delta m^2_{\mathrm{atm}}} + \ldots \right\}$$

- All parameters run simultaneously.
- **Solar angle** $\theta_{12}$ is most sensitive (small $\Delta m^2_{\mathrm{sol}}$).
- Majorana phases **dampen or enhance** $\dot{\theta}_{12}$: $|\varphi_1 - \varphi_2| = \pi \Rightarrow$ maximal suppression.
- $\delta_D$ **can run fast** due to $1/\theta_{13}$.

Part II

# From RGEs to Oscillation Corrections

# The standard picture vs. the complete picture

## Standard treatment

$U_{\mathrm{PMNS}}$ is a *single constant* matrix. Production and detection use the *same* mixing matrix.

$$P_{\alpha\beta} = \left| \sum_i U_{\beta i}\, e^{-im_i^2 L/2E}\, U^*_{\alpha i} \right|^2$$

The PMNS phases always cancel in $P_{\bar{e}\bar{e}}$.

This is an approximation valid when $Q_p^2 \approx Q_d^2$.

## Complete treatment (Babu et al., arXiv:2108.11961)

Quantum corrections make $U$ *scale-dependent*: $U_{\alpha i} \to U_{\alpha i}(Q^2)$. Production and detection happen at different scales — they use *different* mixing matrices!

$$P_{\alpha\beta} = \left| \sum_i U_{\beta i}(Q_d^2)\, e^{-im_i^2 L/2E}\, U^*_{\alpha i}(Q_p^2) \right|^2$$

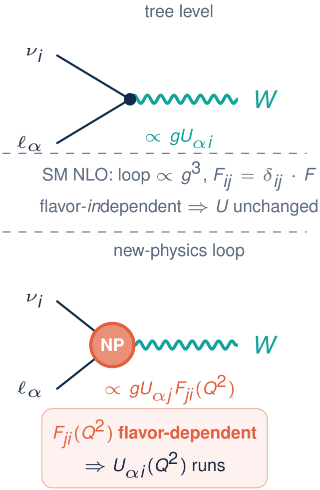
The flavor eigenstate produced is $\nu_\alpha(Q_p^2) = U_{\alpha i}(Q_p^2)\nu_i$; the one detected is $\nu_\alpha(Q_d^2) = U_{\alpha i}(Q_d^2)\nu_i$. **If $Q_p^2 \neq Q_d^2$, these are literally different particles.**

# Where does $Q^2$-dependence come from?

- CC coupling: $-\mathcal{L} \supset \frac{g}{\sqrt{2}} U_{\alpha i} \bar{\ell}_\alpha W^- P_L \nu_i + \text{h.c.}$
- SM at one loop: corrections $\propto g^3$, flavor-*in*dependent $\Rightarrow$ $U$ unchanged.
- **New physics** (light scalar $\Phi, \ldots$): loop factors become $F_{ij}(Q^2)$ flavor-dependent:

$$gU_{\alpha i} \to g\left[U_{\alpha i} + \textstyle\sum_j U_{\alpha j} F_{ji}(Q^2)\right] \equiv gU_{\alpha i}(Q^2)$$

- The mixing matrix **inherits a $Q^2$ dependence** — and so do all oscillation parameters.



# The two mixing matrices and the beta-function parametrization

- The difference between the two mixing matrices is parametrized by **beta functions** (Ge, Pinheiro, Qin, arXiv:2606.26720):

$$\Delta X_I = \beta_{X_I} \ln\left|\frac{Q_d^2}{Q_p^2}\right|, \quad \beta_{X_I} \equiv \frac{\partial X_I}{\partial \ln \mu^2}$$

  where $X_I \in \{\theta_s, \theta_r, \theta_a, \delta_D, \delta_{\mathrm{M1}}, \delta_{\mathrm{M3}}\}$.
- $\beta_{X_I}$ encodes the rate of RG running — a **model-independent** parametrization.
- When $Q_p^2 = Q_d^2$: $\Delta X_I = 0$, standard oscillations recovered.
- Note: $\beta_r/\beta_s \propto \Delta m_{21}^2/\Delta m_{31}^2 \approx 3\%$ — reactor angle running safely negligible.

**Six beta functions for the full PMNS matrix:**

- $\beta_s$ — solar angle (largest)
- $\beta_a$ — atmospheric angle
- $\beta_r \approx 0$ — reactor angle (negligible)
- $\beta_D$ — Dirac CP phase ($1/\theta_{13}$ enhanced!)
- $\beta_{\mathrm{M1}}$ — CP phase $\delta_{\mathrm{M1}}$ †
- $\beta_{\mathrm{M3}}$ — CP phase $\delta_{\mathrm{M3}}$ †

† For Majorana $\nu$: true Majorana phases. For **Dirac** $\nu$: $\delta_{M1,3}$ are physical CP phases from the RG mismatch — *no lepton-number violation* (Babu et al., arXiv:2108.11961).

# What gets corrected: amplitude and phase

The RG-corrected $\bar{\nu}_e$ survival probability (Ge, Pinheiro, Qin, arXiv:2606.26720):

$$P_{\bar{e}\bar{e}} \approx 1 - 4c_r^4 c_s^2 s_s^2 \,(1 + \underbrace{\Delta\Theta_{21}}_{\text{ampl.}})\, \sin^2(\Phi_{21} + \underbrace{\Delta\Phi_{21}}_{\text{phase}})$$
$$- 4c_r^2 s_r^2 \left[c_s^2(1 + \Delta\Theta_{31})\sin^2(\Phi_{31} + \Delta\Phi_{31}) + s_s^2(1 + \Delta\Theta_{32})\sin^2(\Phi_{32} + \Delta\Phi_{32})\right]$$

## Amplitude corrections $\Delta\Theta_{ij}$

From running of **mixing angles**:

$$\Delta\Theta_{21} \approx (\cot\theta_s - \tan\theta_s)\Delta\theta_s$$

$\beta_s$ **rescales the dip depth** of each oscillation term.
Driven by $\beta_s$ (dominant) — $\beta_r$ negligible.

## Phase corrections $\Delta\Phi_{ij}$

From **CP-phase running** ($\delta_D$, $\delta_{\rm M1}$, $\delta_{\rm M3}$):

$$\Delta\Phi_{21} = -\tfrac{1}{4}\Delta\delta_{\rm M1}$$
$$\Delta\Phi_{32} = -\tfrac{1}{2}\Delta\delta_D + \tfrac{1}{4}\Delta\delta_{\rm M3}$$
$$\Delta\Phi_{31} = -\tfrac{1}{2}\Delta\delta_D - \tfrac{1}{4}\Delta\delta_{\rm M1} + \tfrac{1}{4}\Delta\delta_{\rm M3}$$

Invisible in standard $P_{\bar{e}\bar{e}}$ — revealed only when $Q_p^2 \neq Q_d^2$.

# Physical signatures of RG running in oscillations

## 1. Zero-baseline flavor transitions

- Standard: $P_{\alpha\neq\beta}(L \to 0) = 0$.
- With $U(Q_d^2) \neq U(Q_p^2)$: $U(Q_d^2)U^\dagger(Q_p^2) \neq \mathbb{I}$
  $\Rightarrow$ non-zero at $L = 0$ at $\mathcal{O}(\epsilon^2)$.
- Near detectors are **direct probes**.

## 2. Apparent CPT violation

- $P_{\alpha\alpha} \neq P_{\bar{\alpha}\bar{\alpha}}$ at finite baseline.
- Could explain tensions like T2K vs NOvA! (Babu et al., arXiv:2108.11961)

## 3. Spectral distortions

- The oscillatory spectrum is **shifted in amplitude and phase** in an **energy-dependent** way.
- Different beta functions leave **distinct energy fingerprints** — separable with high-resolution experiments.

## 4. Inconsistent parameter measurements

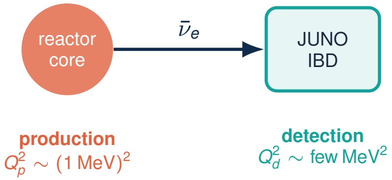
- $\theta_{12}$ from solar $\neq \theta_{12}$ from reactor (different $Q^2$).
- $\theta_{23}$ from disappearance $\neq$ from appearance.
- Provides a **natural explanation** for apparent inconsistencies between experiments.

Part III

# Why Reactor Experiments Are the Ideal Probe

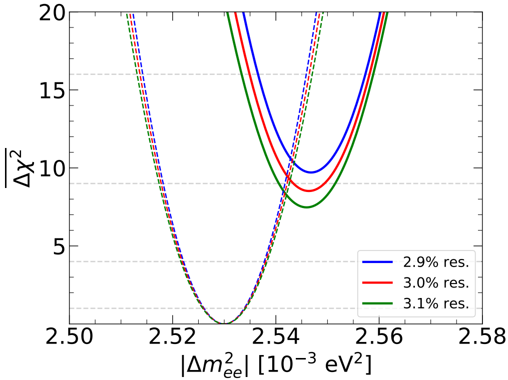
# The kinematic advantage: largest $Q^2$ mismatch

- The RG shift scales as $\ln|Q_d^2/Q_p^2|$: *the bigger the ratio, the stronger the effect.*
- For **reactor $\bar{\nu}_e$**:
  - **Production:** nuclear $\beta$ decay. Typical momentum transfer $Q_p^2 \sim (1\,\text{MeV})^2$.
  - **Detection:** IBD ($\bar{\nu}_e + p \to e^+ + n$). Transfer $Q_d^2 \sim$ few MeV$^2$.
  - Ratio: $Q_d^2/Q_p^2 \sim \mathcal{O}(4-5)$ (Ge, Kong, Pasquini, arXiv:2411.18251)
- Effect is larger for accelerator experiments ($\pi \to \mu\nu$ vs. CC DIS: ratio $\sim 10$).
- More logarithm $\Rightarrow$ **more RG running accumulated**.



# The experimental advantage: energy resolution

- RG corrections distort the spectrum in an **energy-dependent** way — fine resolution is essential.
- **JUNO**: $\sigma_E/E \approx 3\%/\sqrt{E/\mathrm{MeV}}$ — $2\times$ better than KamLAND, which could not probe these effects.
- JUNO can **resolve individual oscillation cycles** across 2–8 MeV with **66 energy bins**.
- RG fingerprints — $\beta_s$ in amplitude, $\beta_{\mathrm{M1}}$ in phase — peak at different energies: separable only with $\sigma_E \lesssim 3\%/\sqrt{E}$.




(Forero, Parke, Ternes, Funchal, PRD 104 (2021) 113004)

# Reading the spectral distortions

## $\beta_s \neq 0$ — amplitude shift

$\beta_s$ enters through $\Delta\Theta_{21}$ — it **rescales the dip depth** of the slow oscillation.

Largest effect at $\Phi_{21} = \pi/2$, i.e., $E_\nu \approx 3.2\,\mathbf{MeV}$ ($E_{\rm vis} \approx 2.4\,$MeV):

- Too few events at the solar dip $\rightarrow \beta_s > 0$
- Too many events $\rightarrow \beta_s < 0$

Similar in shape to a shift of $\theta_{12}$, but cannot be absorbed by it (different $Q^2$ dependence).

## $\beta_{\rm M1} \neq 0$ — phase shift

$\beta_{\rm M1}$ enters through $\Delta\Phi_{21} = -\frac{1}{4}\Delta\delta_{\rm M1}$ — it **shifts the phase** of the slow oscillation.

Largest effect at $\Phi_{21} = \pi/4$, i.e., $E_\nu \approx 6.5\,\mathbf{MeV}$ ($E_{\rm vis} \approx 5\,$MeV):

- Distortion near the zero-crossing of $\sin 2\Phi_{21}$
- **Orthogonal** to $\beta_s$ in energy space — the two are separable!

## $\beta_D - \beta_{\rm M3}/2 \neq 0$ — fast-mode shift

Shifts the apparent $|\Delta m^2_{ee}|$ in the fast wiggles — threatens mass ordering sensitivity (Part V).

Part IV

# JUNO — Slow and Fast Oscillation Modes

# JUNO: two oscillation scales at 52.5 km

At baseline $L$ in vacuum:

$$P_{\bar{e}\bar{e}} = 1 - \underbrace{c_r^4 \sin^2 2\theta_s \sin^2\Phi_{21}}_{\text{slow mode}} - \underbrace{\sin^2 2\theta_r \left[c_s^2 \sin^2\Phi_{31} + s_s^2 \sin^2\Phi_{32}\right]}_{\text{fast mode}}$$

$\Phi_{ij} \equiv \Delta m_{ij}^2 L/4E_\nu$.

- **Slow**: amplitude $\approx$0.84, period $\sim$few MeV ($\Phi_{21}=\pi/2$ at $E_\nu\approx$3.2 MeV)
- **Fast**: amplitude $\approx$0.084, period $\sim$0.2 MeV — needs $\sigma_E<3\%/\sqrt{E}$
- **Interference** of $\Phi_{31}$ and $\Phi_{32}$ encodes mass ordering

## JUNO parameters

- 20 kton LS, 8 cores, $\langle L\rangle = 52.5$ km
- $\sigma_E/E \approx 3\%/\sqrt{E/\mathrm{MeV}}$, 1345 p.e./MeV
- $\bar{\nu}_e + p \to e^+ + n$, $\sim$60 IBD/day
- Data taking since summer 2025

## Why 52.5 km?

Optimal baseline for observing **both** the slow ($\Delta m_{21}^2$) and fast ($|\Delta m_{ee}^2|$) oscillations in one detector.

# The fast mode encodes the mass ordering

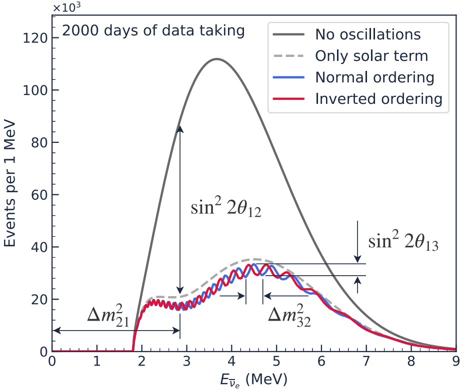
(Forero, Parke, Ternes, Funchal, PRD 104 (2021) 113004)

Fast part of $P_{\bar{e}\bar{e}}$ *exactly*:

$$P_{\bar{e}\bar{e}}^{\text{fast}} \propto 1 - A(E)\cos\big(2|\Phi_{ee}| \pm \Phi_{\odot}\big)$$

$|\Phi_{ee}| = |\Delta m^2_{ee}|L/4E$, $\Phi_{\odot}$ from $\Delta m^2_{21}$, $\theta_{12}$.

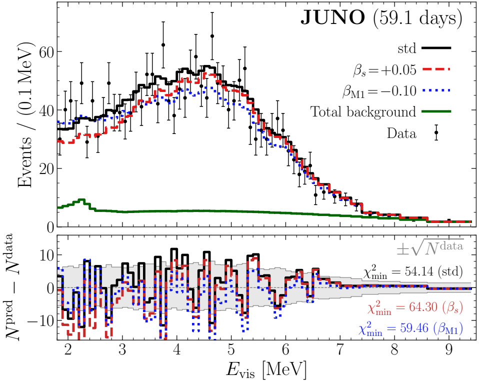
- $+\Phi_{\odot}$ for NO: wiggles advance in energy.
- $-\Phi_{\odot}$ for IO: wiggles retard — IO appears $\sim$0.7% **larger** in $|\Delta m^2_{ee}|$.
- No $\delta_{\text{CP}}$, no $\theta_{23}$, no matter effects.



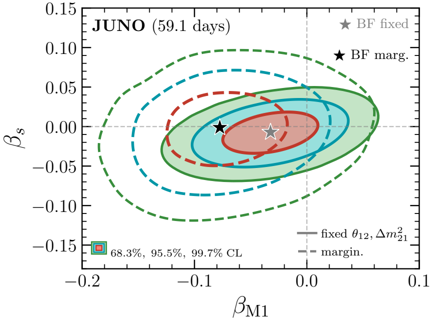
# The slow oscillation mode and its RG corrections

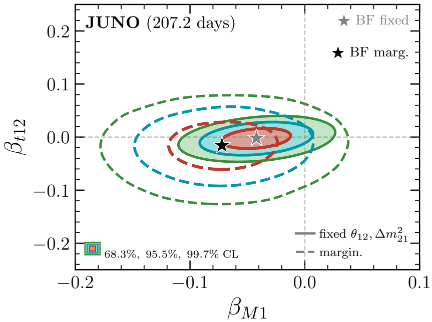
$$P^{\text{slow}}_{\bar{e}\bar{e}} \approx -4c_r^4 c_s^2 s_s^2\,(1+\Delta\Theta_{21})\,\sin^2\!\big(\Phi_{21}+\Delta\Phi_{21}\big),\ \Delta\Theta_{21} \approx (\cot\theta_s - \tan\theta_s)\Delta\theta_s,\ \Delta\Phi_{21} = -\tfrac{1}{4}\Delta\delta_{\rm M1}$$

- $\beta_s = \beta_s$ affects the **amplitude** — enters like a shift in $\sin^2\theta_{12}$.
- $\beta_{\rm M1}$ affects the **phase** — shifts where the dip sits in energy.
- Both effects are *energy-dependent* and **peak at different $E_\nu$**:
  - $\beta_s$: peaks at $\Phi_{21} = \pi/2$ ($E_{\rm vis} \approx 2.4\,$MeV)
  - $\beta_{\rm M1}$: peaks at $\Phi_{21} = \pi/4$ ($E_{\rm vis} \approx 5\,$MeV)
- The two parameters can be **simultaneously fit** to data — their energy fingerprints are orthogonal.



# Constraints in the $(\beta_s,\ \beta_{\mathrm{M1}})$ plane




**1st release (59.1 days)**: $\beta_s \in [-0.036, +0.020]$, $\beta_{\mathrm{M1}} \in [-0.078, +0.013]$ at 90% C.L.
Min. at $\beta_{\mathrm{M1}} = -0.078$: $\Delta\chi^2 = 3.8$ — preference for $\beta_{\mathrm{M1}} \neq 0$.

(Ge, Pinheiro, Qin, arXiv:2606.26720)

**2nd release (207 days)**: $\beta_{\mathrm{M1}} \in [-0.073, -0.010]$ at 90% C.L.; preference for $\beta_{\mathrm{M1}} \neq 0$ strengthens.

**Full 2400-day** projection: $|\beta_s| < 0.0066$, $|\beta_{\mathrm{M1}}| < 0.012$ — permille-to-percent level.

Part V

# Fast Mode — Mass Ordering Under Attack

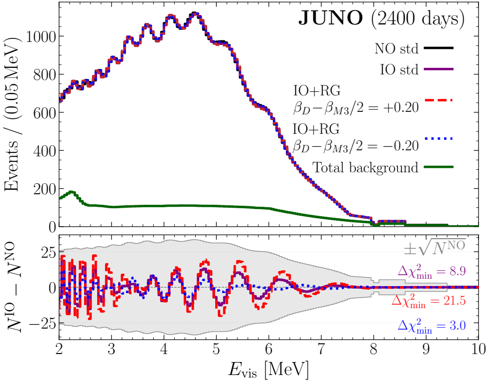
# The fast oscillation mode and the mass ordering

Fast mode: $P_{\bar{e}\bar{e}}^{\text{fast}} \propto \cos(2\Phi_{ee} \pm \Phi_{\odot})$, $\Phi_{ee} \equiv |\Delta m^2_{ee}| L/4E_\nu$, $\Delta m^2_{ee} \equiv c_s^2 \Delta m^2_{31} + s_s^2 \Delta m^2_{32}$

- $\Phi_{ee}$ **advances** $(+)$ for NO, **retards** $(-)$ for IO.
- With RG running (Ge, Pinheiro, Qin, arXiv:2606.26720):

$$\hat{\Phi}_{ee} = \Phi_{ee} - \underbrace{\tfrac{1}{2}\Delta\delta_D + \tfrac{1}{4}c_s^2\Delta\delta_{\mathrm{M1}} - \tfrac{1}{4}\Delta\delta_{\mathrm{M3}}}_{\Delta\Phi_{ee}}$$

- Negative $\Delta\Phi_{ee}$ mimics IO retardation for true NO — **masking MO sensitivity**.



# MO sensitivity degradation: how bad can it get?

- **Standard JUNO** (2400 days, $\beta_D = \beta_{\mathrm{M3}} = 0$):

$$\Delta\chi^2_{\min}(\mathrm{IO}) = 8.9 \quad (3.0\sigma)$$

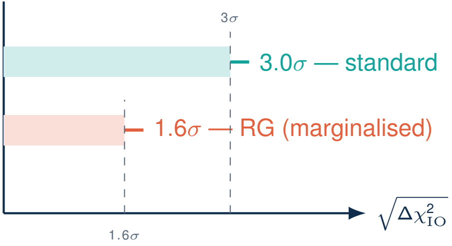
- With $\beta_D - \beta_{\mathrm{M3}}/2 = -0.2$ (IO-like shift):

$$\Delta\chi^2_{\min}(\mathrm{IO}) \to 3.0 \quad (1.7\sigma)$$

- With $\beta_D - \beta_{\mathrm{M3}}/2 = +0.2$ (NO-like advance):

$$\Delta\chi^2_{\min}(\mathrm{IO}) \to 21.5 \quad (4.6\sigma)$$

- Marginalizing over unknown $\beta_D, \beta_{\mathrm{M3}}$: $3.0\sigma \to 1.6\sigma$ — nearly **half** the ordering sensitivity lost.
- The slow mode *cannot* fix this: $\beta_D - \beta_{\mathrm{M3}}/2$ does not appear in the slow mode at leading order.




$\beta_D - \beta_{\mathrm{M3}}/2$ is baseline-independent while $\Phi_{ee}$ depends on $L/E$ — the two cannot be disentangled from a single far-detector measurement alone.

Part VI

# JUNO-TAO — Zero-Distance RG Running

# What happens at zero distance?

At $L \approx 44\,\text{m}$, all oscillation phases vanish ($\Phi_{21} \approx 1.7 \times 10^{-4}$ at $E_\nu = 5\,\text{MeV}$):

- Standard: $P_{ee} = [UU^\dagger]_{ee} = 1$ (unitarity).
- With RG running: $P_{ee} = [U(Q_d^2)U^\dagger(Q_p^2)]_{ee}^2 \neq 1$.

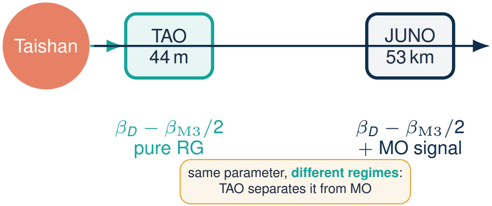
Leading-order result (Ge, Kong, Pasquini, arXiv:2411.18251):

$$\boxed{P_{ee}(L \to 0) = 1 - \sin^2\!\left(\frac{\Delta\delta_D - \Delta\delta_{\mathrm{M3}}/2}{2}\right) \sin^2 2\theta_r}$$

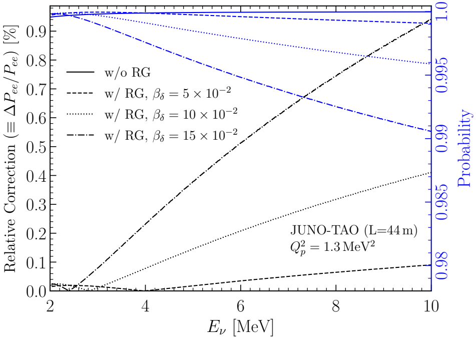
$$\Delta\delta_D - \Delta\delta_{\mathrm{M3}}/2 = (\beta_D - \beta_{\mathrm{M3}}/2) \ln |Q_d^2/Q_p^2|.$$

**Same combination** $\beta_D - \beta_{\mathrm{M3}}/2$ as the fast mode — but here: no oscillatory background, pure RG signal.

- TAO and JUNO probe **the same** $\beta_D - \beta_{\mathrm{M3}}/2$, in complementary regimes.
- At JUNO: $\beta_D - \beta_{\mathrm{M3}}/2$ shifts the fast-mode phase, **mimicking MO** — entangled with the ordering.
- At TAO: **no oscillation** $\Rightarrow P_{ee} \neq 1$ is pure RG. Same parameter, clean environment.



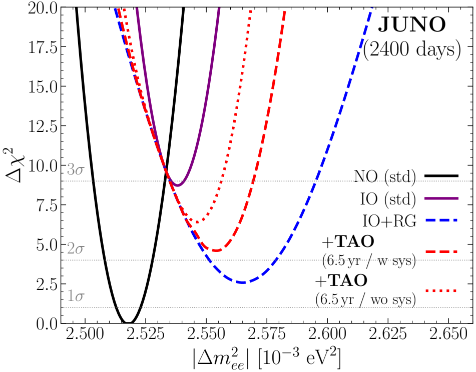
# TAO sensitivity: from spectral tilt to $\beta_D$ constraint




(Ge, Kong, Pasquini, arXiv:2411.18251)

- $\Delta P_{ee}/P_{ee}$ **rises with energy** (larger $Q_d^2$ at high $E_\nu$) — up to $\sim$1% for $\beta_D = 0.15$.
- Backgrounds concentrated at low $E$; high-$E$ region ($> 3.5\,\mathrm{MeV}$) is **clean** and most sensitive.
- TAO: $\sim$1000 IBD/day, $\sigma_E = 1.5\%/\sqrt{E}$, $2.4 \times 10^6$ events in 6.5 yr.
- **Projected bound**: $|\beta_D| \lesssim 10\%$ at 90% C.L.
- Main challenge: spectral tilt uncertainty ($\sim$1%) mimics the rising RG signal.

# JUNO-TAO restores mass ordering sensitivity




TAO probes $\beta_D$ in the pure RG regime (no oscillations) — JUNO probes $\beta_D - \beta_{\mathrm{M3}}/2$ in the fast mode.

| **Scenario** | $\sqrt{\Delta\chi^2_{\mathrm{IO}}}$ |
|---|---|
| JUNO alone (standard) | $3.0\sigma$ |
| JUNO alone (RG marg.) | $1.6\sigma$ |
| JUNO + TAO (real. norm.) | $2.2\sigma$ |
| JUNO + TAO (ideal norm.) | $2.6\sigma$ |

- Slow $\rightarrow \beta_s, \beta_{\mathrm{M1}}$; TAO fast $\rightarrow \beta_D, \beta_{\mathrm{M3}}$.
- JUNO-TAO is essential for MO sensitivity with unknown CP-phase RG running.

# Summary

# The big picture

## RG Running

- $Q_p^2 \neq Q_d^2 \Rightarrow$ two mixing matrices.
- Difference $\propto \beta_{X_l} \ln|Q_d^2/Q_p^2|$.
- Reactor: $Q_d^2/Q_p^2 \sim 10^2$ — **largest mismatch** in any experiment.

## JUNO+TAO results

**Slow mode:** $\beta_s \in [-0.036, +0.020]$, $\beta_{\mathrm{M1}} \in [-0.078, +0.013]$; hints at $\beta_{\mathrm{M1}} \neq 0$

**Fast mode (MO):** $\beta_D - \beta_{\mathrm{M3}}/2$ degrades $3.0\sigma \to 1.6\sigma$

**TAO (zero-dist.):** pure RG regime, constrains $\beta_D$; MO recovery $\to 2.2\sigma$

## Corrections to $P_{\bar{e}\bar{e}}$

- **Amplitude** ($\Delta\Theta_{ij}$): from $\beta_s$
- **Phase** ($\Delta\Phi_{ij}$): from $\beta_D$, $\beta_{\mathrm{M1}}$, $\beta_{\mathrm{M3}}$ — invisible in standard $P_{\bar{e}\bar{e}}$

JUNO can constrain beta functions of the PMNS matrix — including CP phases.

## Take-away messages

- Neutrino mixing parameters **run with energy scale** — a fundamental prediction of QFT.
- At reactor experiments, $Q_p^2 \neq Q_d^2$ means the oscillation amplitude carries **two different mixing matrices**. CP phases that normally cancel in $P_{\bar{e}\bar{e}}$ no longer do.
- JUNO's $3\%/\sqrt{E}$ resolution makes it uniquely sensitive to the **energy-dependent spectral distortions** from amplitude ($\beta_s$) and phase ($\beta_{\mathrm{M1}}$, $\beta_D$, $\beta_{\mathrm{M3}}$) running.
- First JUNO data already constrains $\beta_s$ and $\beta_{\mathrm{M1}}$; hints at $\beta_{\mathrm{M1}} \neq 0$.
- The fast mode is degraded from $3\sigma$ to $1.6\sigma$ by unknown $\beta_D - \beta_{\mathrm{M3}}/2$ — **JUNO-TAO restores** it via the zero-distance limit.

# Thank you!

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Backup

# Supplementary slides

# Backup — The full corrected $P_{\bar{e}\bar{e}}$: phase details

- The PMNS matrix $U = \mathcal{P} V \mathcal{Q}$ contains two rephasing matrices: $\mathcal{P}$ (unphysical) and $\mathcal{Q} = \mathrm{diag}\{e^{i\delta_{\mathrm{M1}}/2}, 1, e^{i\delta_{\mathrm{M3}}/2}\}$ (Majorana phases).
- In standard oscillations, $\mathcal{Q}(Q^2)\mathcal{Q}^\dagger(Q^2) = \not{\Bbbk}$ — Majorana phases always cancel in $P_{\bar{e}\bar{e}}$.
- With mismatched $Q^2$: $\mathcal{Q}(Q_d^2)\mathcal{Q}^\dagger(Q_p^2) \neq \not{\Bbbk}$ — they no longer cancel!
- The $\delta_D$ enters $U_{e3}$ as an overall phase; its mismatch $\Delta\delta_D$ also contributes to $\Delta\Phi_{31}$ and $\Delta\Phi_{32}$.
- Phase corrections explicitly: $\Delta\Phi_{21} = -\frac{1}{4}\Delta\delta_{\mathrm{M1}}$, $\Delta\Phi_{32} = -\frac{1}{2}\Delta\delta_D + \frac{1}{4}\Delta\delta_{\mathrm{M3}}$, $\Delta\Phi_{31} = -\frac{1}{2}\Delta\delta_D - \frac{1}{4}\Delta\delta_{\mathrm{M1}} + \frac{1}{4}\Delta\delta_{\mathrm{M3}}$
- The fast-mode combination: $\Delta\Phi_{ee} \equiv \frac{1}{2}\Delta\delta_D + \frac{1}{4}c_s^2\Delta\delta_{\mathrm{M1}} - \frac{1}{4}\Delta\delta_{\mathrm{M3}}$ $= (\beta_D - \frac{1}{2}\beta_{\mathrm{M3}}) \ln|Q_d^2/Q_p^2| + \dots$

# Backup — JUNO analysis pipeline

- Event rate in bin $k$: $N_k = C \sum_r \frac{\mathcal{P}_r}{4\pi L_r^2} \int dE_\nu \, \phi(E_\nu) \sigma_{\rm IBD}(E_\nu) \langle P_{\bar{e}\bar{e}} \rangle_k R_k(E_\nu)$
- 9 reactor cores (6 Yangjiang + 2 Taishan + Daya Bay); $\langle L \rangle \approx 52.5\,\mathrm{km}$.
- Flux: Huber-Mueller with Daya Bay burn-cycle fractions (Huber:2011wv, Mueller:2011nm, DayaBay:2025ngb).
- RG running averaged over $Q_d^2$ at each energy bin (Ge, Kong, Pasquini, arXiv:2411.18251).
- Energy resolution: $\sigma(E_{\rm pr}) = E_{\rm pr} \sqrt{(3.3\%)^2 / E_{\rm pr} + (1.0\%)^2}$.
- Test statistic: Combined Neyman-Pearson (CNP) (Ji, Xu, arXiv:1903.03572).
- Systematics: signal norm (1.8%), 5 backgrounds, energy scale (0.5%), 25 flux parameters, non-linearity.
- Projected (Asimov): Pearson $\chi^2$, NuFIT 6.1 NO best-fit, 2400 effective detector-days.

# Backup — Key references


- **Lindner et al.** — Antusch, Kersten, Lindner, Ratz, *Running neutrino masses, mixings and CP phases*, hep-ph/0305273 (2003). [Analytic one-loop RGEs for all PMNS parameters]
- **Babu et al.** — Babu, Brdar, de Gouvêa, Machado, *Energy-Dependent Neutrino Mixing Parameters at Oscillation Experiments*, arXiv:2108.11961 (2022). [Mismatched $Q^2$, phenomenology, benchmark models]
- **Ge et al. (2023)** — Ge, Pinheiro et al., *Neutrino CP Measurement in the Presence of RG Running*, arXiv:2310.04077. [Long-baseline signatures, CP phase running]
- **Ge, Kong, Pasquini (2024)** — *Testing the RG Running of the Leptonic Dirac CP Phase with TAO*, arXiv:2411.18251. [TAO near detector, $Q^2$ averaging]
- **Ge, Pinheiro, Qin (2025)** — *Disentangle RG Running Parameters with Medium-Baseline Reactor Experiments*, arXiv:2606.26720. [Full JUNO analysis — main paper of this talk]