JUNO's Physics with Reactor Antineutrinos

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on behalf of the JUNO collaboration

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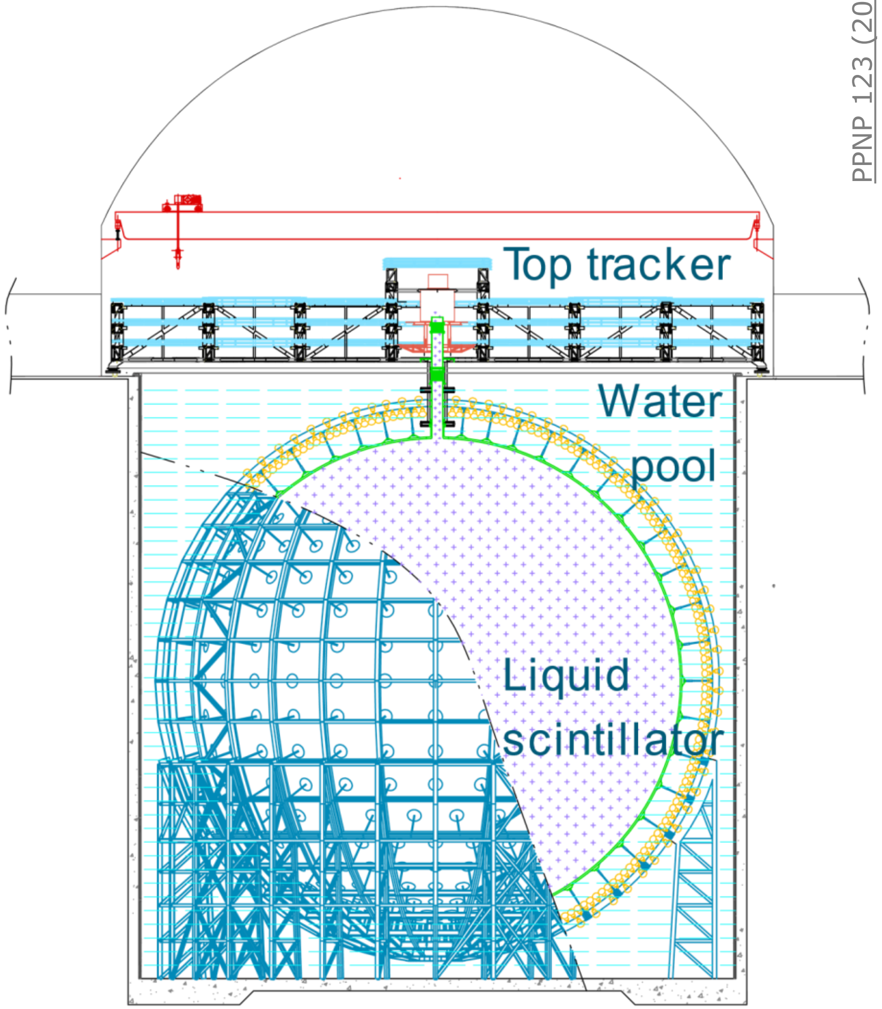
JUNO and ν oscillations

JUNO experiment

The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a multi-purpose neutrino experiment under construction in South of China

PPNP 123 (2022): 103927

- 20 kton of Liquid Scintillator (LS) inside a 35 m diameter acrylic sphere surrounded by a 35 kton water Cherenkov detector
- 52.5 km from 8 nuclear reactors (26.6 GW_{th})
- Energy resolution $\sigma < 3\%$ at 1 MeV
- Energy scale uncertainty $< 1\%$



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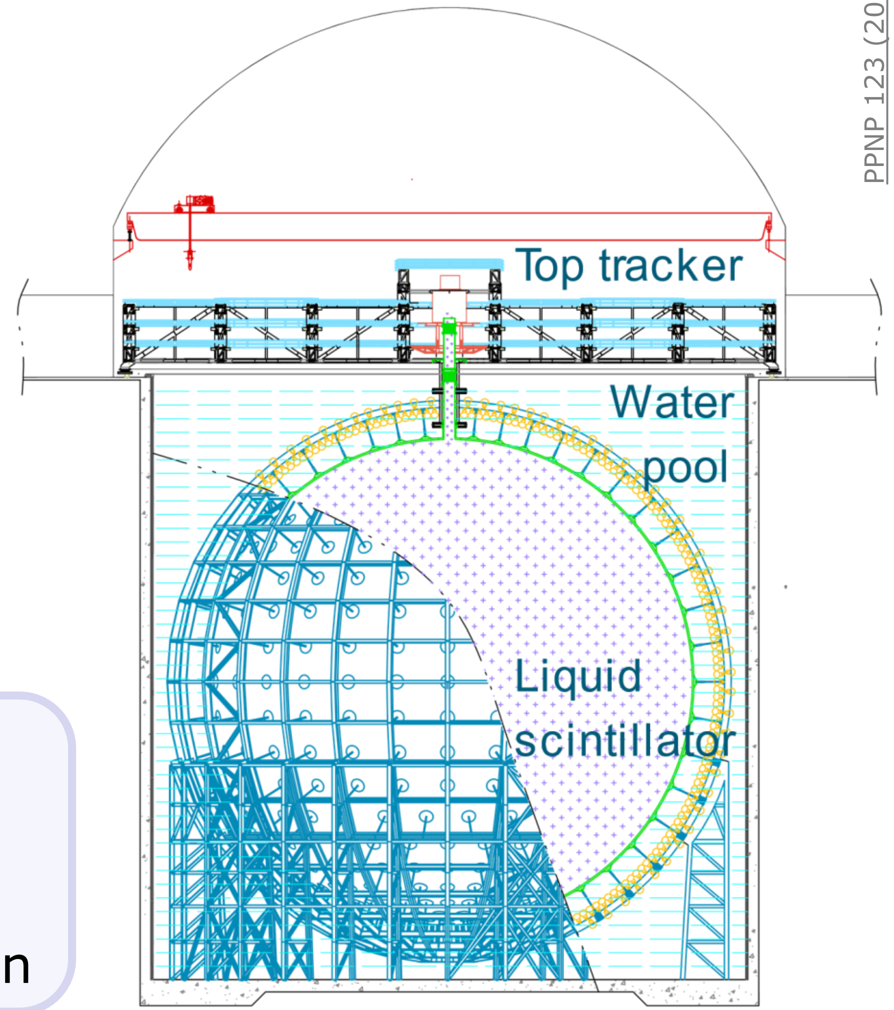

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Main physics goals with reactor antineutrinos:
- Determine Neutrino Mass Ordering (NMO)
- Measure oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and Δm^2_{31} with sub-percent precision

Neutrino mixing

Weak ($e,\ \mu,\ \tau$) and mass ($1, 2, 3$) eigenstates differ:

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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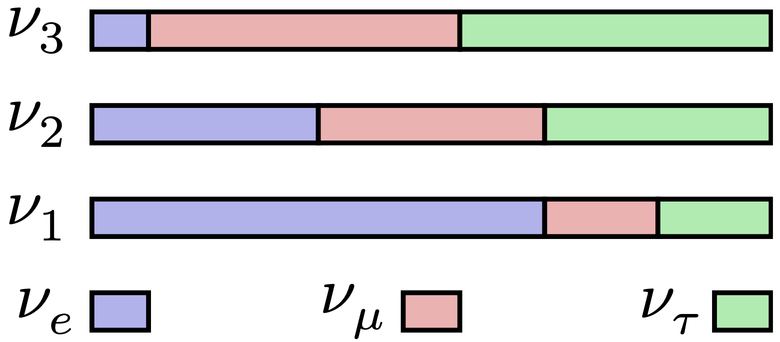
Mixing is parametrized by:

- Three mixing angles: $\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}}$
- CP-violating phase: $\boldsymbol{\delta_{\mathrm{CP}}}$



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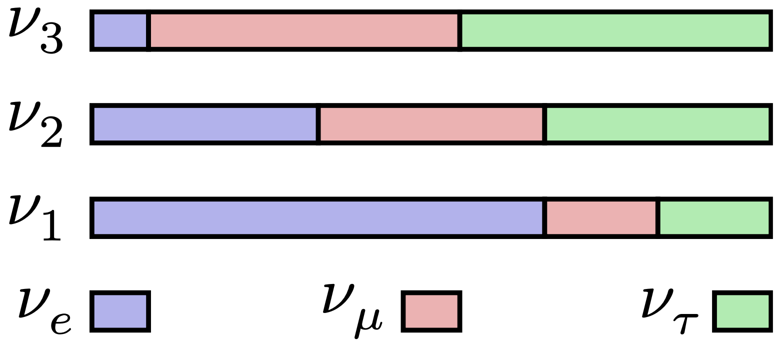

Three neutrino mass splittings ($\boldsymbol{\Delta m^2_{ij} = m^2_i - m^2_j}$):

- Involved in oscillation probability calculations
- Only two independent: $\Delta m^2_{21}, |\Delta m^2_{31}|$ (or equivalently $|\Delta m^2_{32}|$)

Status of neutrino oscillation physics

What we know (PDG 2024):

- ✓ $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2\ (\pm 2.4\%)$
- ✓ $\left|\Delta m^2_{31}\right| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2\ (\pm 1.1\%)$
- ✓ $\sin^2\theta_{12} \sim 0.3\ (\pm 4.2\%)$
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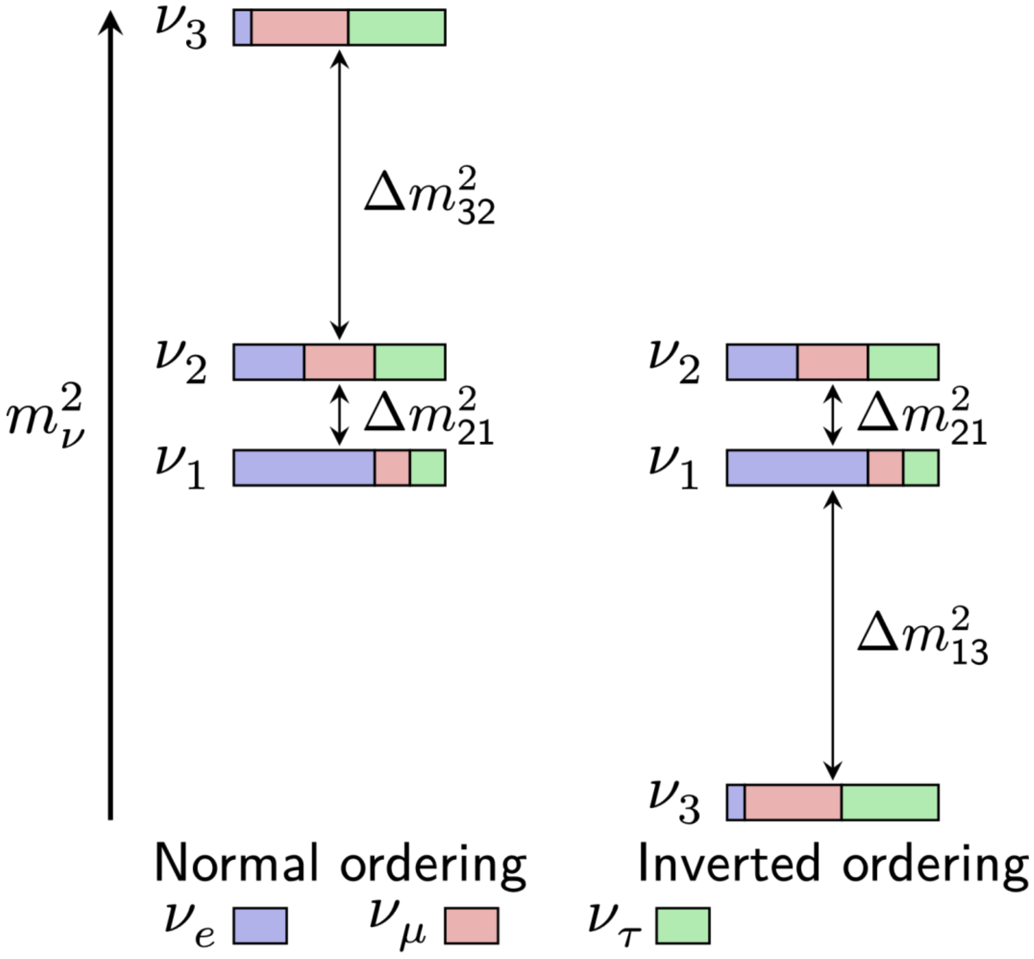
Open questions:

- ? Mass ordering: $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$

Two possibilities for Neutrino Mass Ordering



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- CP phase: δ_{CP} value? CP parity violated or not?

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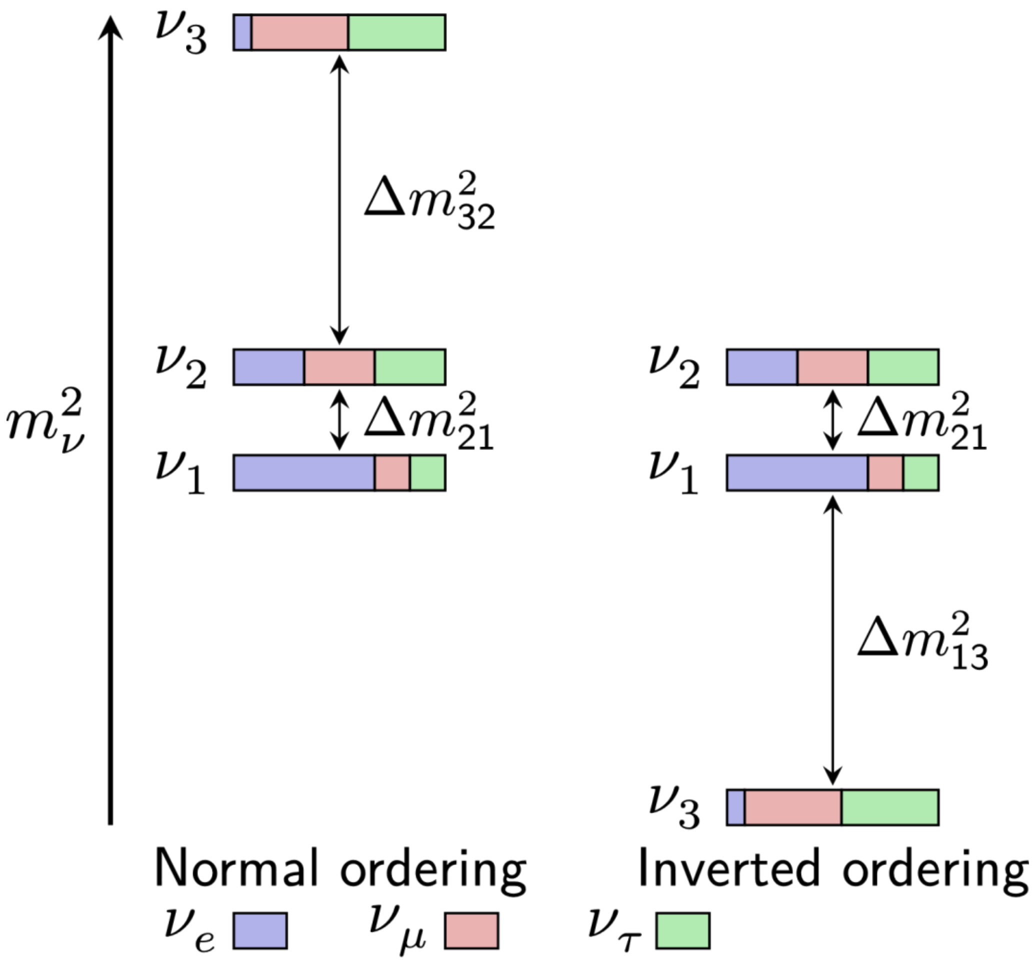

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JUNO will both contribute to precise measurements of oscillation parameters and answer the NMO question

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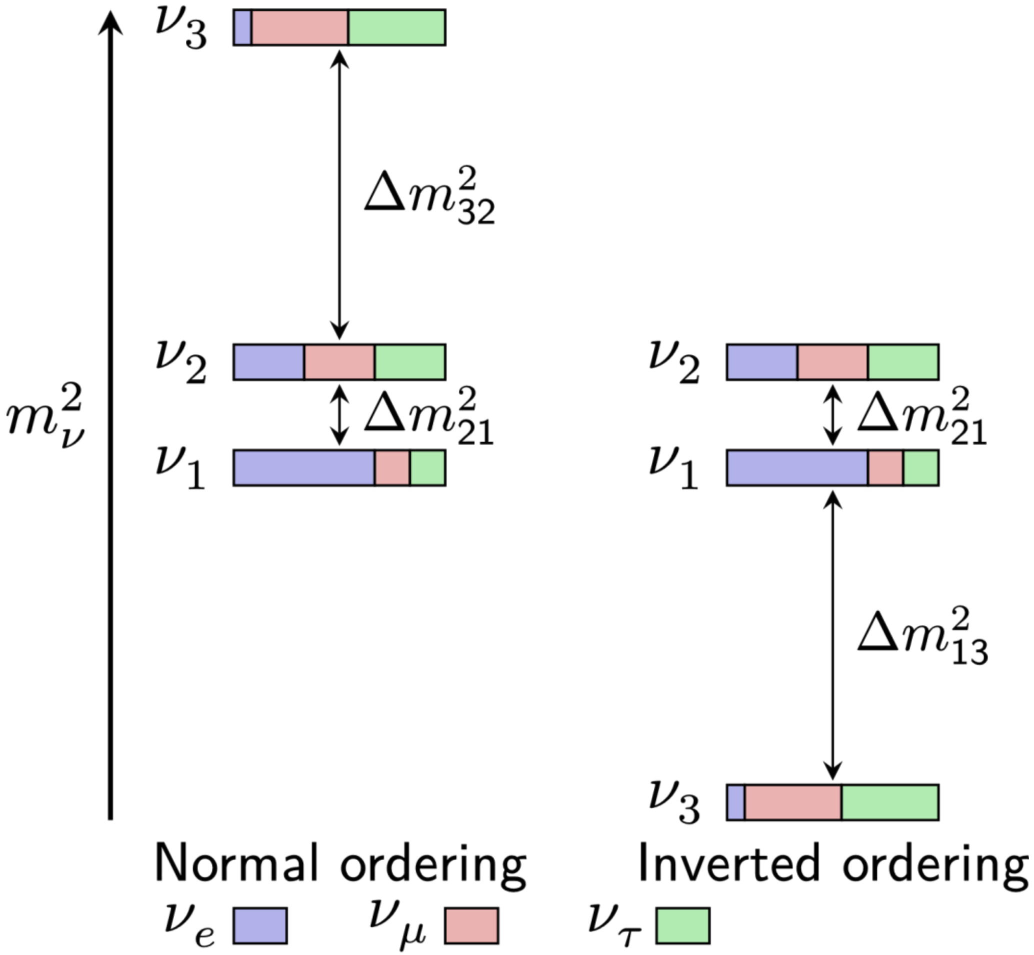

Reactor $\bar{\nu}_e$ oscillations

- JUNO will observe deficit of $\bar{\nu}_e$ due to oscillation

- $\bar{\nu}_e$ survival probability:

$$\begin{aligned}\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) \;=\; & 1 - \sin^2 2\theta_{12}\, c_{13}^4 \,\sin^2 \Delta_{21} \\ & - \sin^2 2\theta_{13}\, c_{12}^2 \sin^2 \Delta_{31} \\ & - \sin^2 2\theta_{13}\, s_{12}^2 \sin^2 \Delta_{32}\end{aligned}$$

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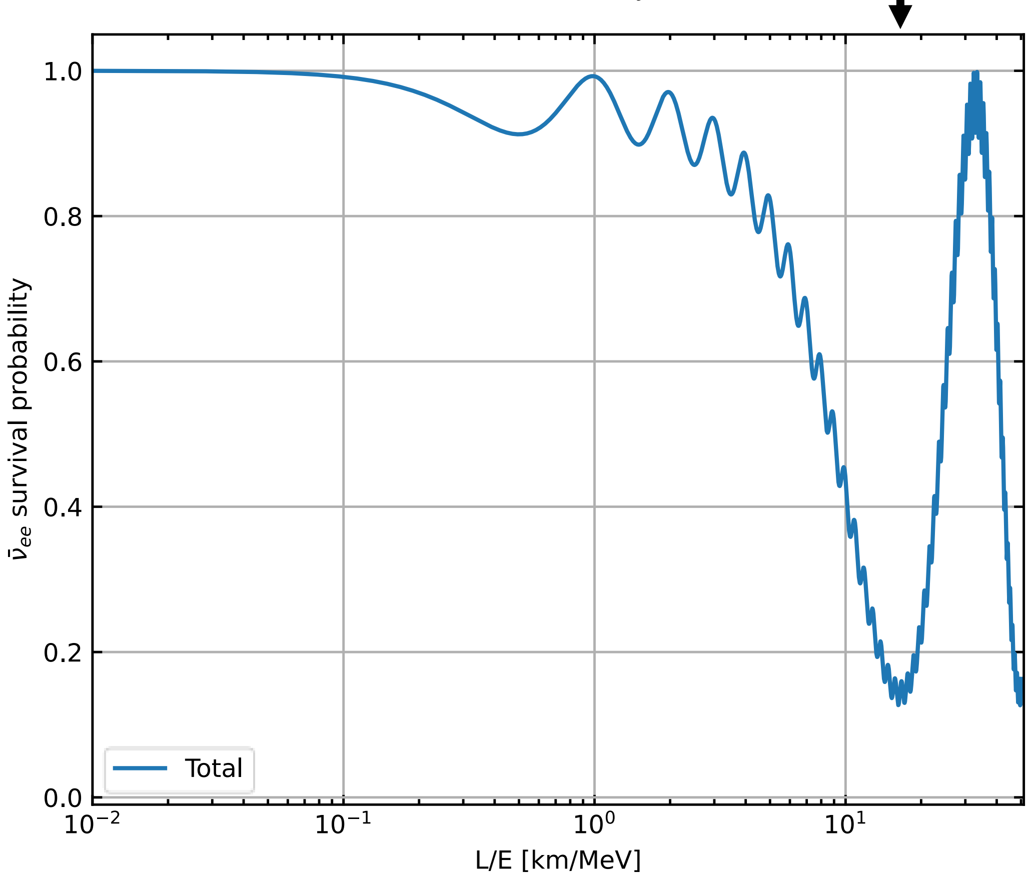

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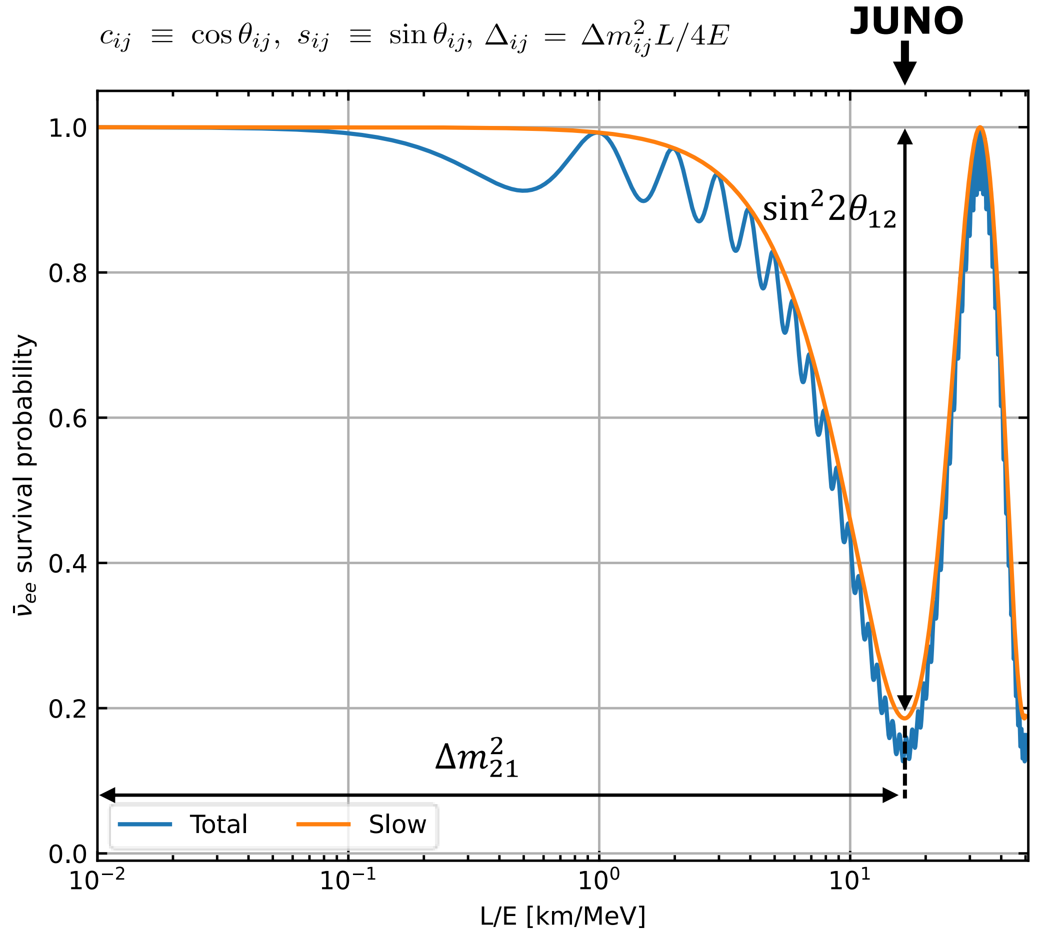

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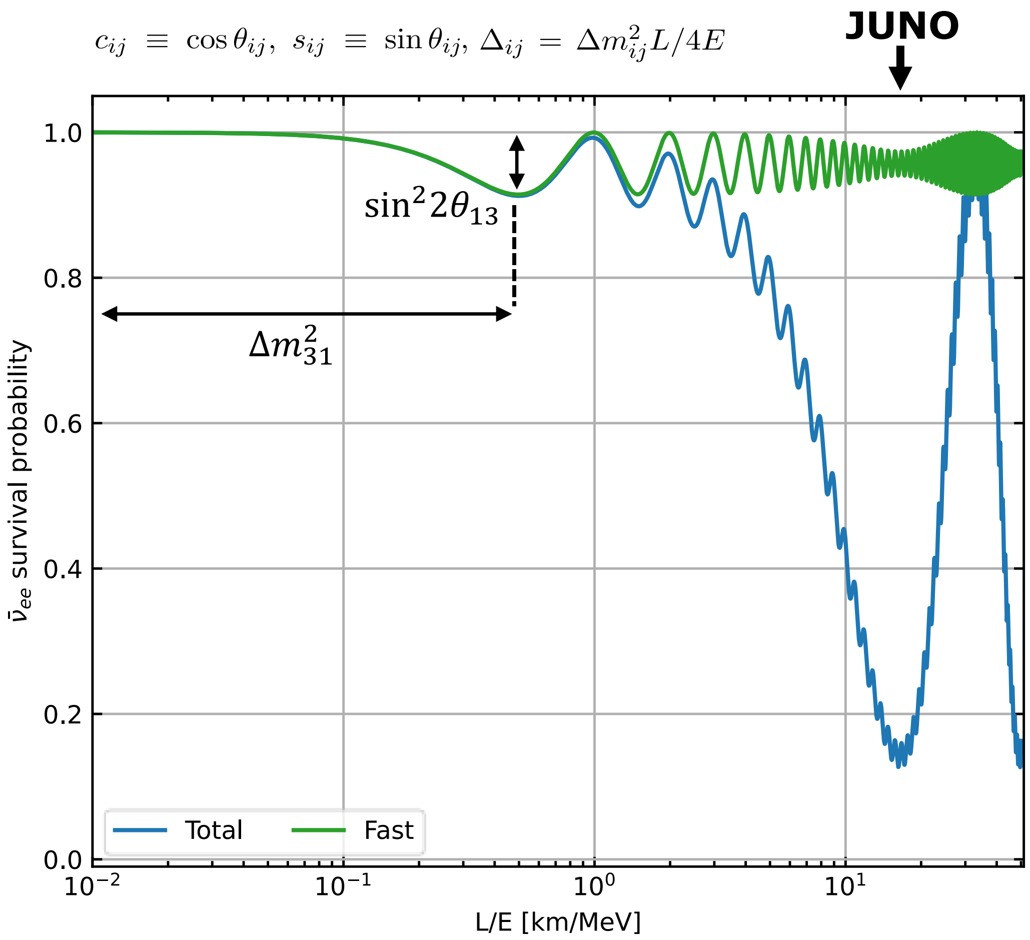

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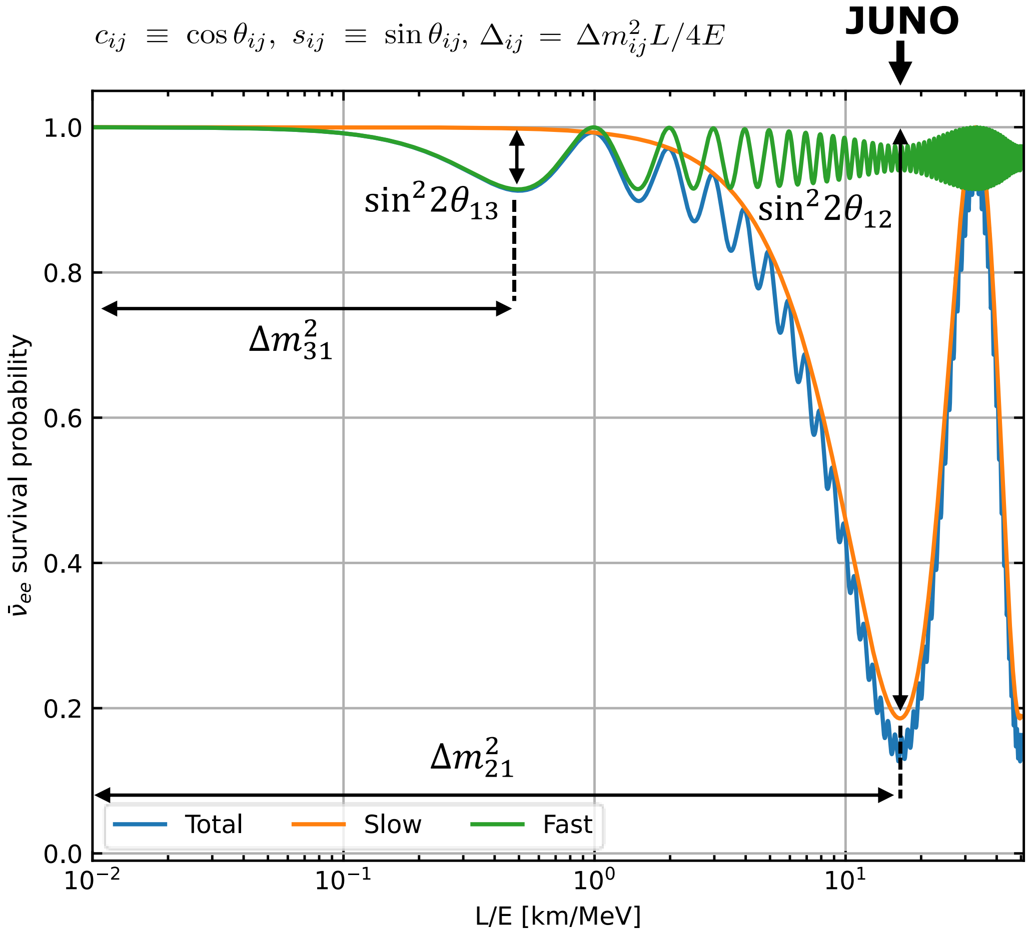

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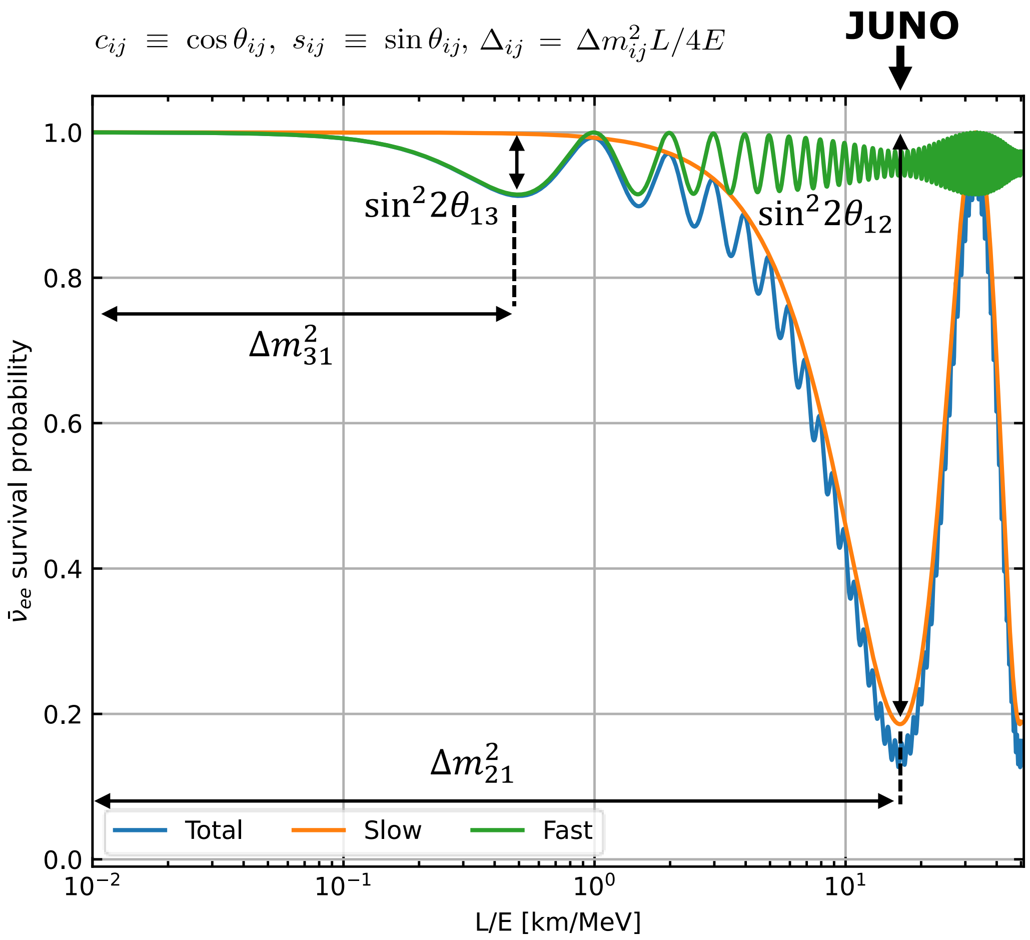


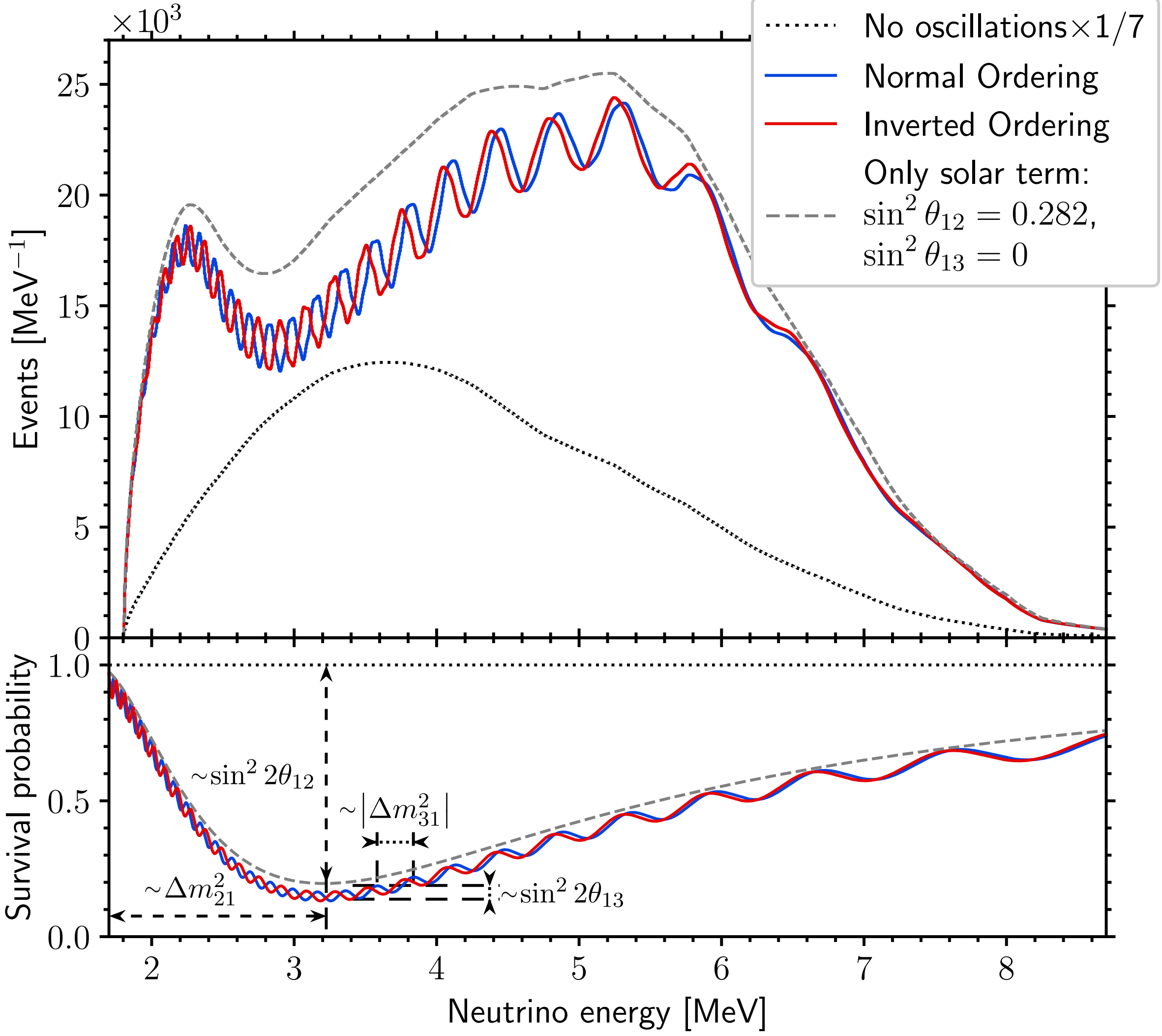
- JUNO sensitive to the Δm_{31}^2, Δm_{21}^2, $\sin^2\theta_{12}$, and $\sin^2\theta_{13}$

- Probability does not depend on δ_{CP} and θ_{23} → no degeneracies

$\bar{\nu}_e$ oscillations in JUNO

- JUNO studies fine interference pattern caused by quasi-vacuum oscillations in the oscillated antineutrino spectrum
- Interference pattern depends on NMO
- To resolve peaks → **need good energy resolution**
- To define peak positions → **need well defined energy scale**
- Complementary to other neutrino oscillation experiments (accelerator and atmospheric)

JUNO spectra,
perfect energy resolution, 6 years of data taking



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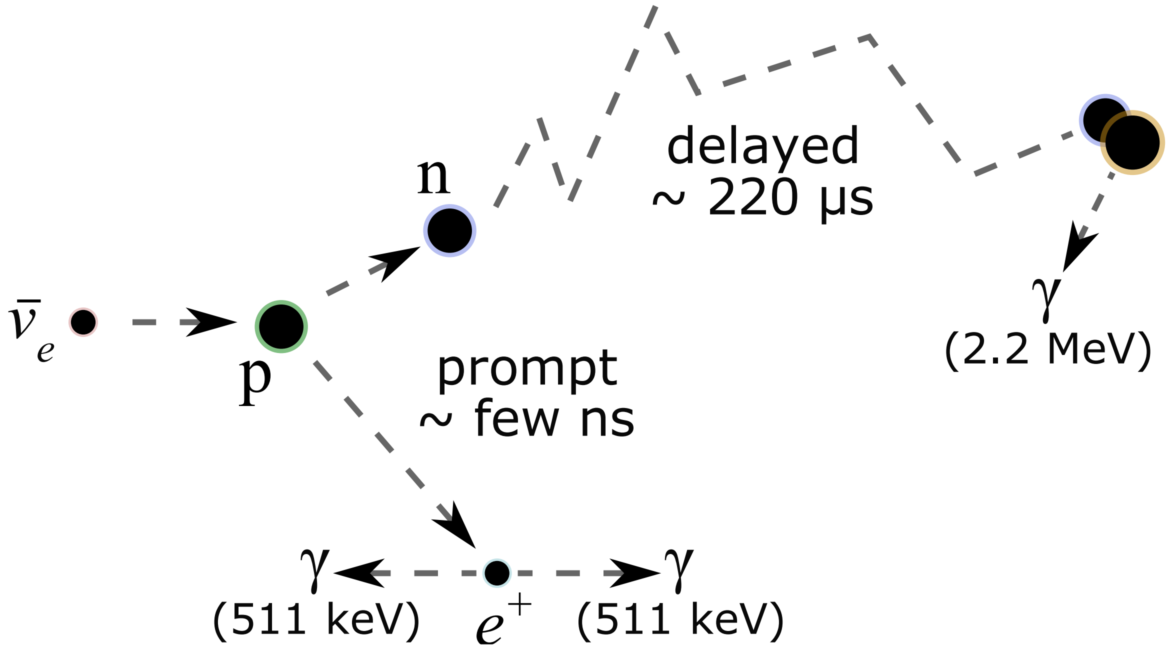
Antineutrino detection in JUNO

- Inverse Beta Decay (IBD) reaction is used for $\bar{\nu}_e$ detection:

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

- $\bar{\nu}_e$ transfers most of its energy to the positron



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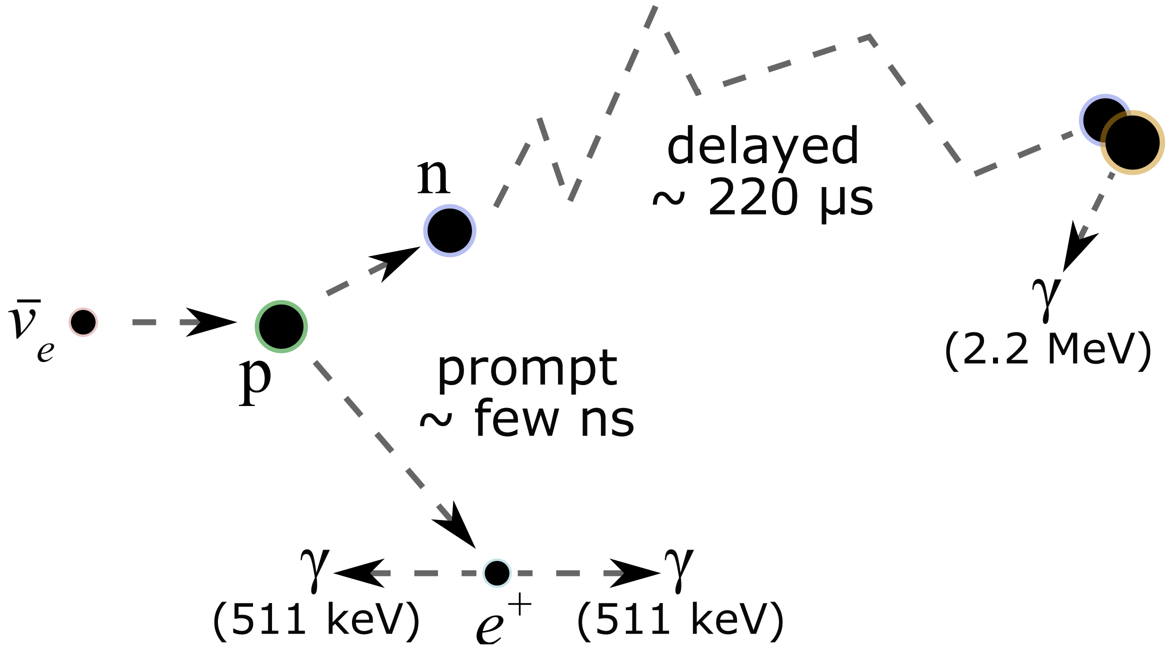
- **Prompt signal**: energy deposited by positron in the LS (kinetic + annihilation),
- **Delayed signal**: photon emission from neutron capture on hydrogen (~99%) or carbon (~1%)



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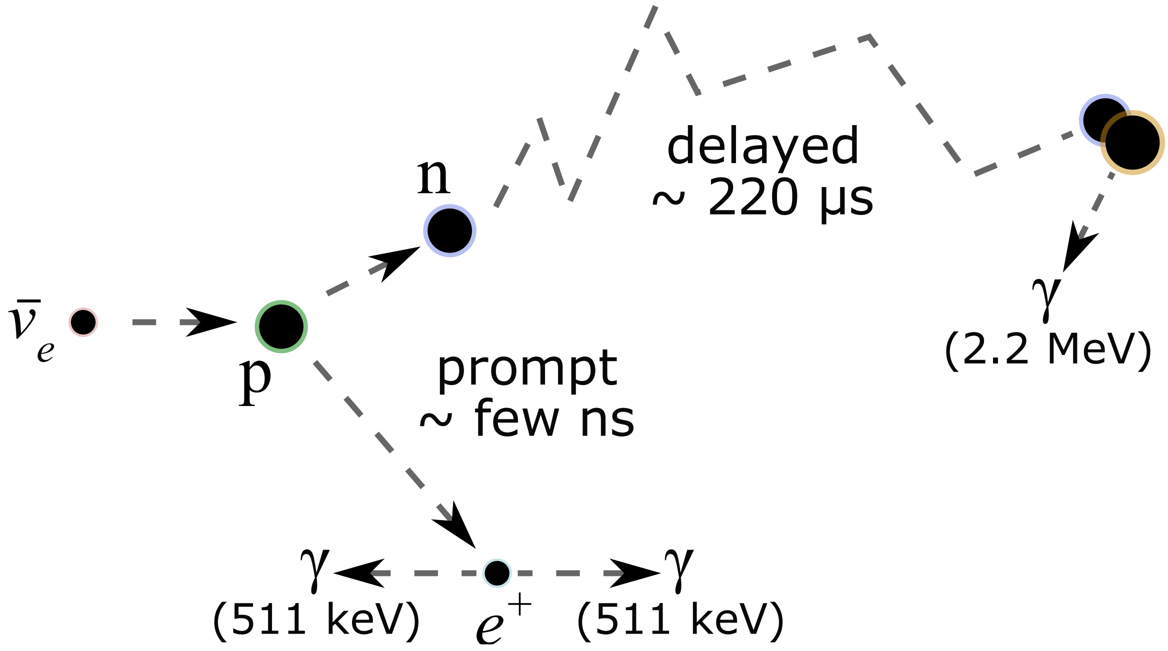


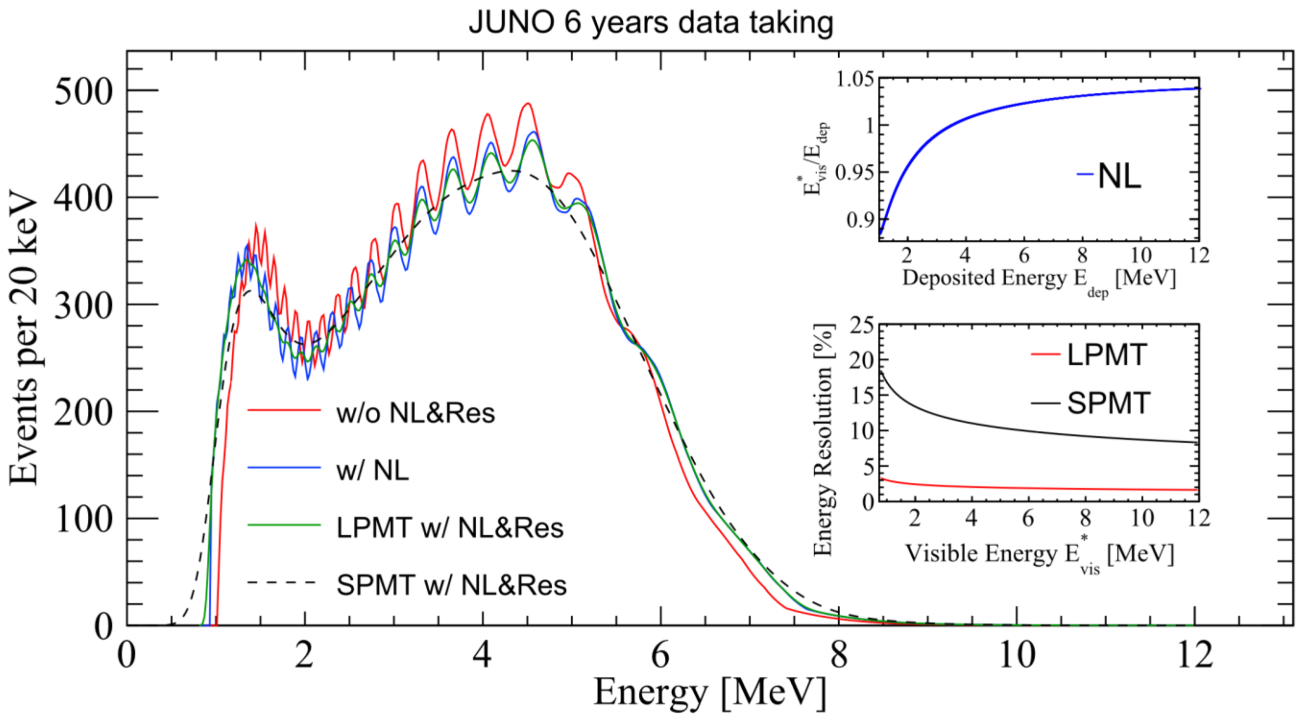
Energy signature, temporal and spatial correlation of prompt-delayed pairs allows effective separation of the signal from the background

JUNO's detector response

Approximate energy conversion model

$$E_\nu \rightarrow E_{\text{dep}} \rightarrow E_{\text{vis}} \rightarrow E_{\text{rec}}$$

Antineutrino energy | Deposited energy | Visible energy | Reconstructed energy



1. IBD reaction kinematics and annihilation → e^+ deposited energy

$$E_{\text{dep}} \simeq E_{\bar{\nu}_e} - 0.782\ \text{MeV}$$

2. Quenching → Liquid Scintillator Non-Linearity (NL):

$$E_{\text{vis}} = f_{\text{LSNL}}(E_{\text{dep}}) \cdot E_{\text{dep}}$$

3. Smearing due to Energy Resolution (Res):

$$\frac{\sigma_{E^{\text{rec}}}}{E^{\text{vis}}} = \sqrt{\frac{a}{\sqrt{E^{\text{vis}}}} + b^2 + \left(\frac{c}{E^{\text{vis}}}\right)}$$

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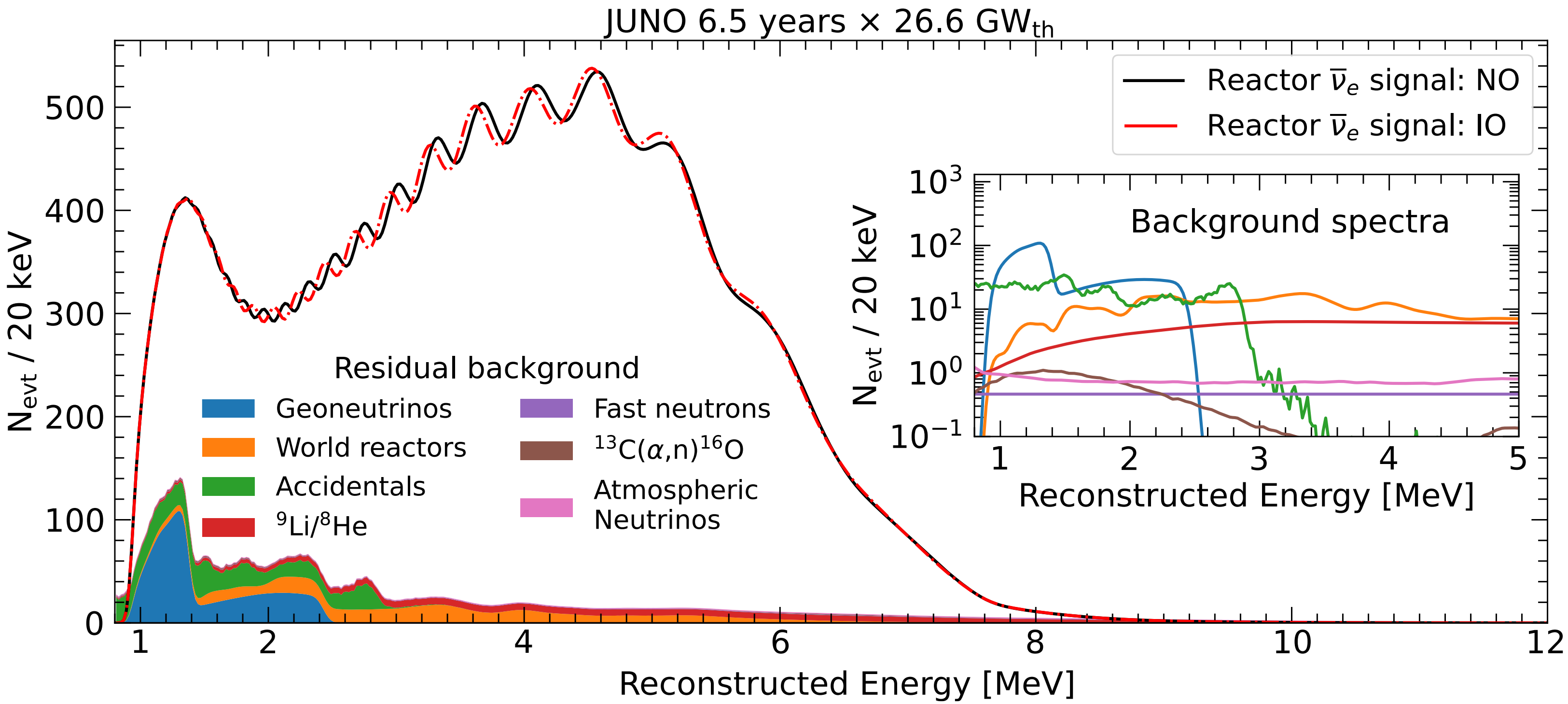
JUNO's expected signal and backgrounds

- IBD selection efficiency: 82.2%
  - Cuts: fiducial volume, energy, time, and relative distance
  - Cosmogenic background rejection: muon veto

- Expected IBD rate: 47.1/day
- Expected Background rate: 4.11/day
- High signal to background ratio



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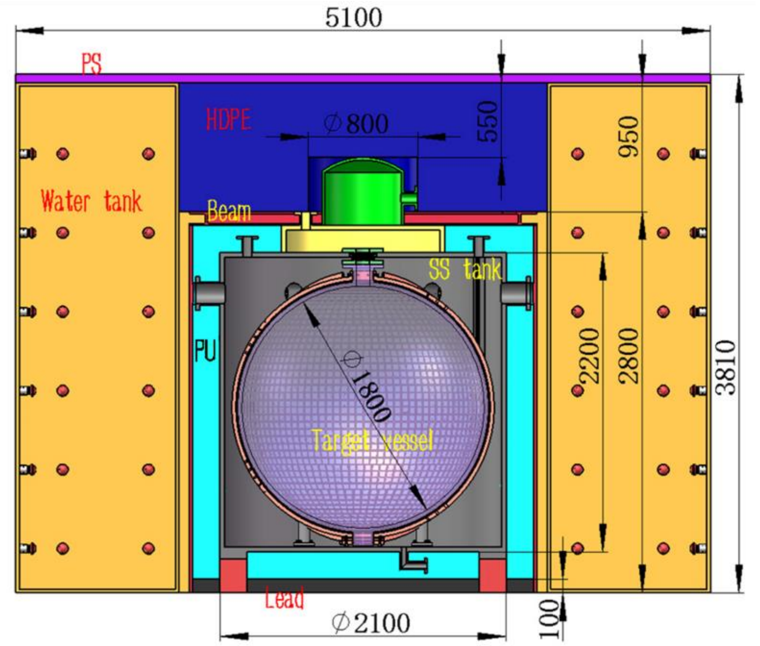
JUNO-TAO reference spectrum

Taishan **A**ntineutrino **O**bservatory (**TAO**) satellite detector:

- 44 m from one of the Taishan NPP cores (4.6 GW_{th})
- 2.8 ton of Gd-doped Liquid Scintillator
- SiPM and GD-LS at -50°C
- Energy resolution $\sigma < 2\%$ at 1 MeV



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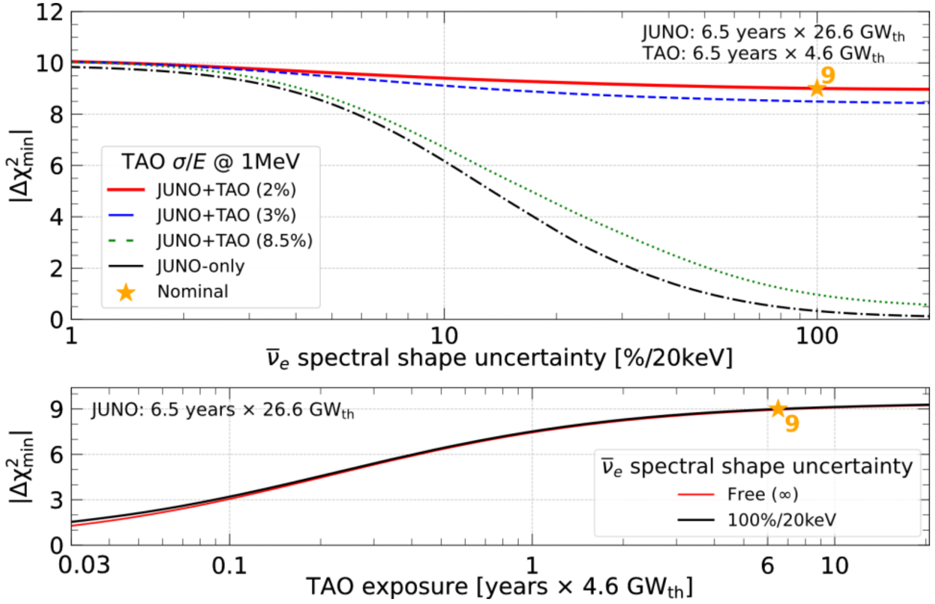

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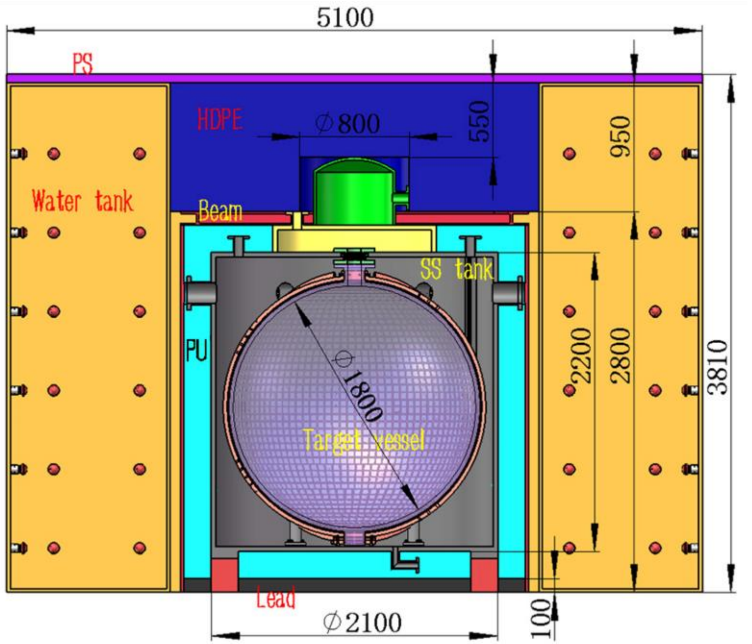

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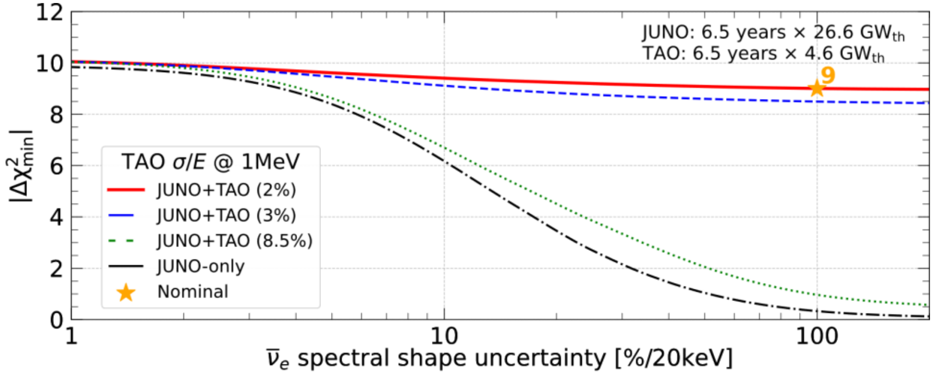
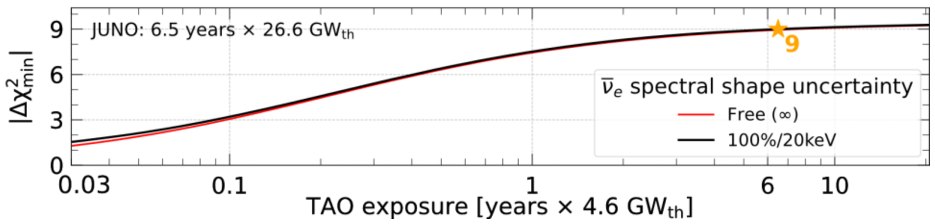
Main goals: provide reference antineutrino spectrum for JUNO

Why: to eliminate antineutrino model dependence in the determination of NMO

How: by simultaneously analyzing JUNO and TAO spectra





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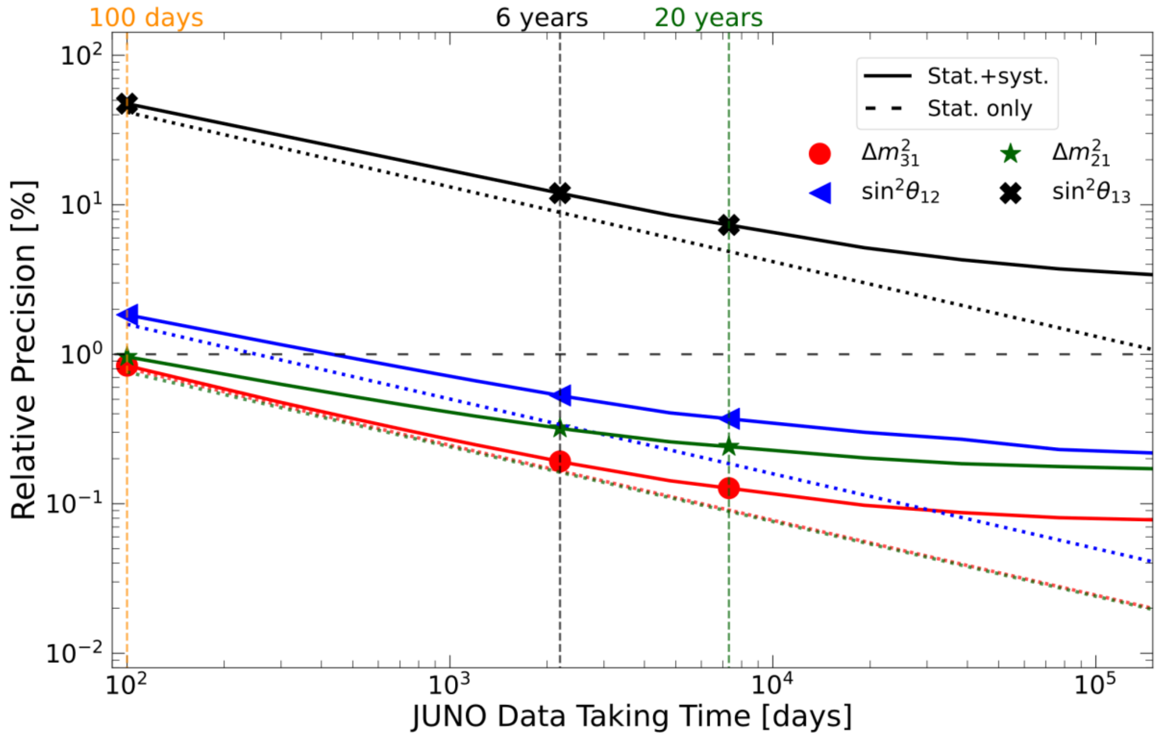
Sensitivity Studies

Oscillation Parameters and Neutrino Mass Ordering

Sensitivity to oscillation parameters

- JUNO will achieve **sub-percent precision** on Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ during first 2 years of data taking
- Sub-percent measurements can:
  - be used as inputs to other experiments
  - provide constraints for model building
  - enable more precise searches of physics beyond Standard Model



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	Central value	PDG2020	100 days	6 years
$\Delta m^2_{31} (\times 10^{-3}\ \mathrm{eV}^2)$	2.5253	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)
$\Delta m^2_{21} (\times 10^{-5}\ \mathrm{eV}^2)$	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)

Systematic uncertainties

Dominant systematic uncertainties sources:

- Δm^2_{31}: antineutrino spectrum shape uncertainty, detector non-linearity, backgrounds
- Δm^2_{21}: backgrounds, spent nuclear fuel, non-equilibrium (particularly in the low energy region)
- $\sin^2\theta_{12}, \sin^2\theta_{13}$: reactor flux normalization, detector efficiency

	Δm^2_{31} 1σ (%)	Δm^2_{21} 1σ (%)	$\sin^2\theta_{12}$ 1σ (%)	$\sin^2\theta_{13}$ 1σ (%)
Statistics	0.17	0.16	0.34	8.94
Reactor:				
- Uncorrelated	< 0.01	0.01	0.10	2.53
- Correlated	0.01	0.03	0.27	6.83
- Reference spectrum	0.05	0.07	0.09	3.48
- Spent Nuclear Fuel	< 0.01	0.07	0.05	1.55
- Non-equilibrium	< 0.01	0.14	0.10	2.65
Detection:				
- Efficiency	0.01	0.02	0.23	5.81
- Energy resolution	< 0.01	0.01	0.01	0.39
- Nonlinearity	0.04	0.05	0.09	2.09
- Backgrounds	0.04	0.18	0.20	4.89
Matter density	0.01	0.01	0.07	0.98
All systematics	0.08	0.27	0.40	8.16
Total	0.19	0.32	0.52	12.11

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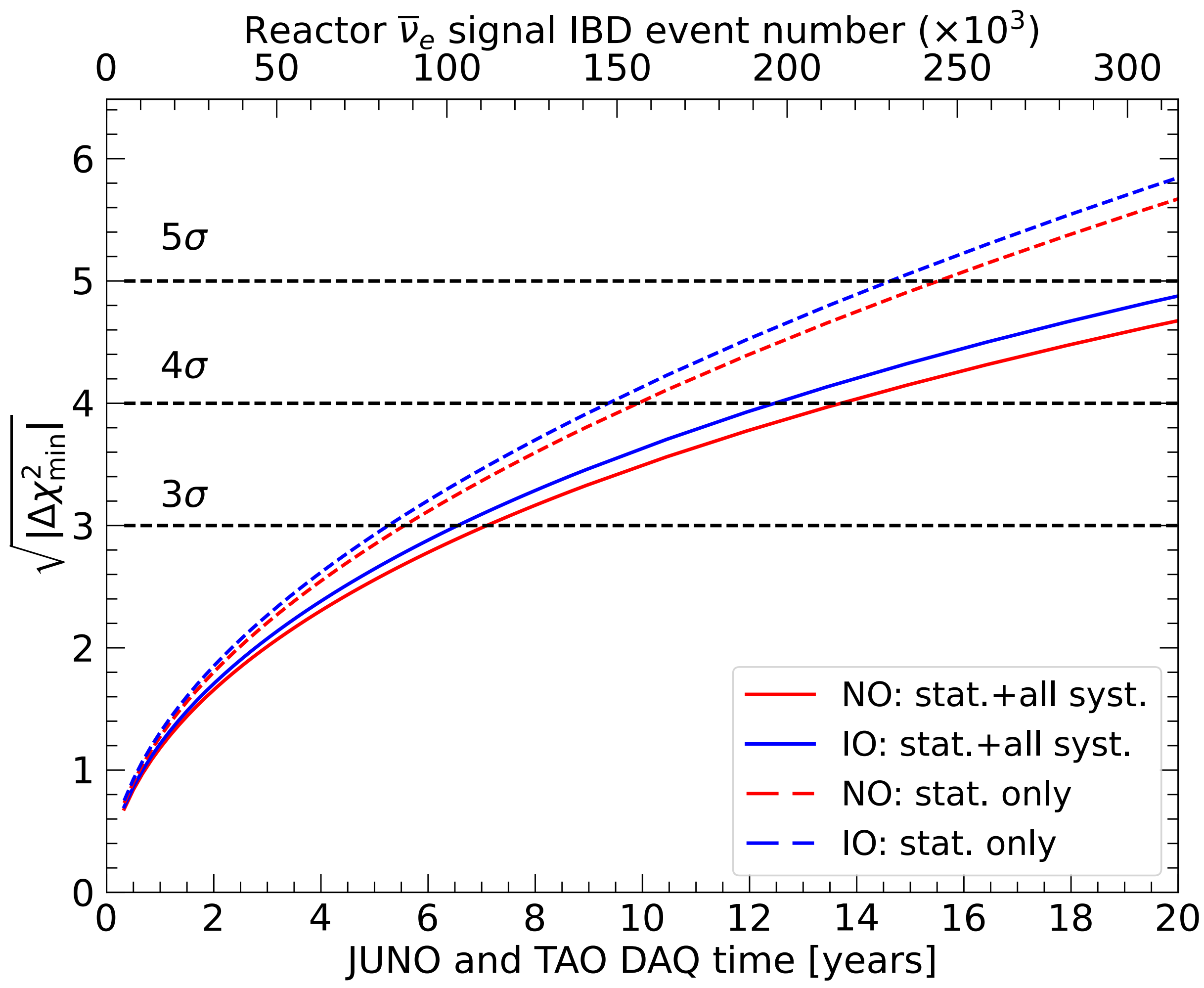
Sensitivity to Neutrino Mass Ordering

- Median sensitivity to NMO is based on Asimov dataset:

$$\Delta\chi^2_{\min} = \min\chi^2_{\text{IO}} - \min\chi^2_{\text{NO}}$$

- **3σ median sensitivity to NMO after 7.1 years of data taking**
  - using only reactor $\bar{\nu}_e$
  - assuming 11/12 duty cycle
  - 6.5 years × 26.6 GW_{th} exposure
- Dominant sources of uncertainty: backgrounds, reference spectrum, non-linearity



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Conclusion

- JUNO will both contribute to precise measurements of oscillation parameters and answer the NMO question

- Using only reactor $\bar{\nu}_e$ oscillations, JUNO:

  - Will achieve **sub-percent precision on Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$** during first two years of data taking

  - Will determine the **Neutrino Mass Ordering with a median sensitivity of 3σ** after about 7 years of data taking

- JUNO is expected to start filling in 2024

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