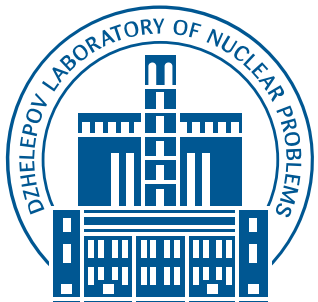


First JUNO results: Precision Measurements of θ_{12} and Δm_{21}^2

XXIII International Seminar on High-Energy Physics
QUARKS-2026

Dmitrii Dolzhikov
on behalf of JUNO collaboration

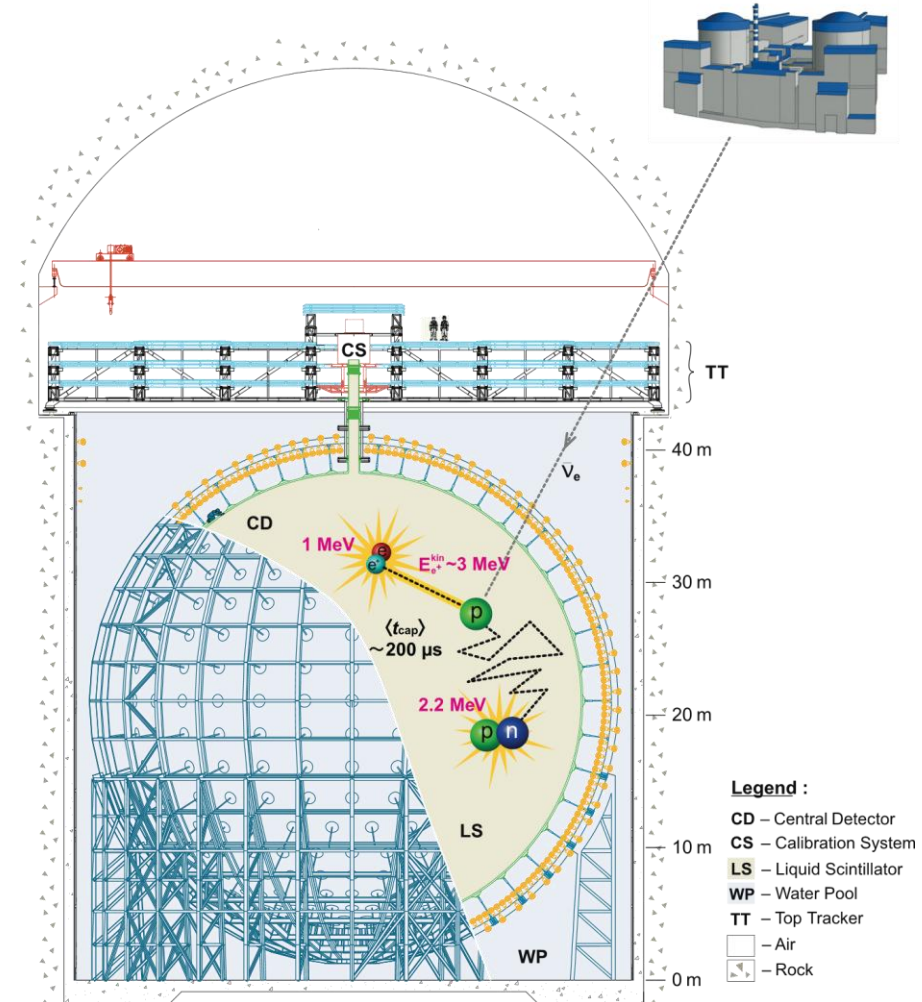


JUNO and ν oscillations

JUNO experiment

The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a multi-purpose neutrino experiment located 650 m underground in South of China

- ❖ 20 kton of Liquid Scintillator 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})
- ❖ Current energy resolution $\sigma \approx 3.4\%$ at 1 MeV
- ❖ Energy non-linearity control at $\sim 1\%$



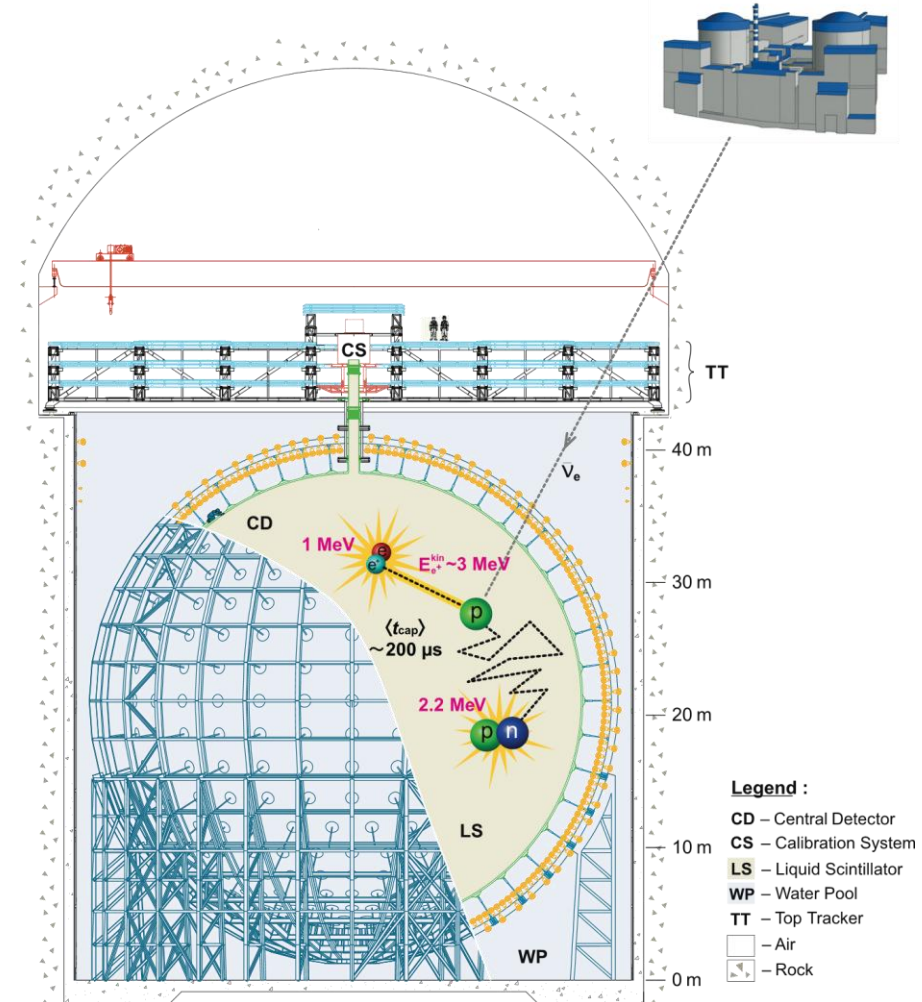
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Main physics goals with reactor antineutrinos:

- ❖ Determine Neutrino Mass Ordering (NMO)
- ❖ Measure oscillation parameters $\sin^2\theta_{12}$, Δm_{21}^2 , and Δm_{31}^2 with sub-percent precision



Status of neutrino oscillation physics

What we know ([PDG 2024](#)):

- ✓ $\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$ ($\pm 2.4\%$)
- ✓ $|\Delta m_{31}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$ ($\pm 1.1\%$)
- ✓ $\sin^2 \theta_{12} \sim 0.3$ ($\pm 4.2\%$)
- ✓ $\sin^2 \theta_{13} \sim 0.02$ ($\pm 3.2\%$)
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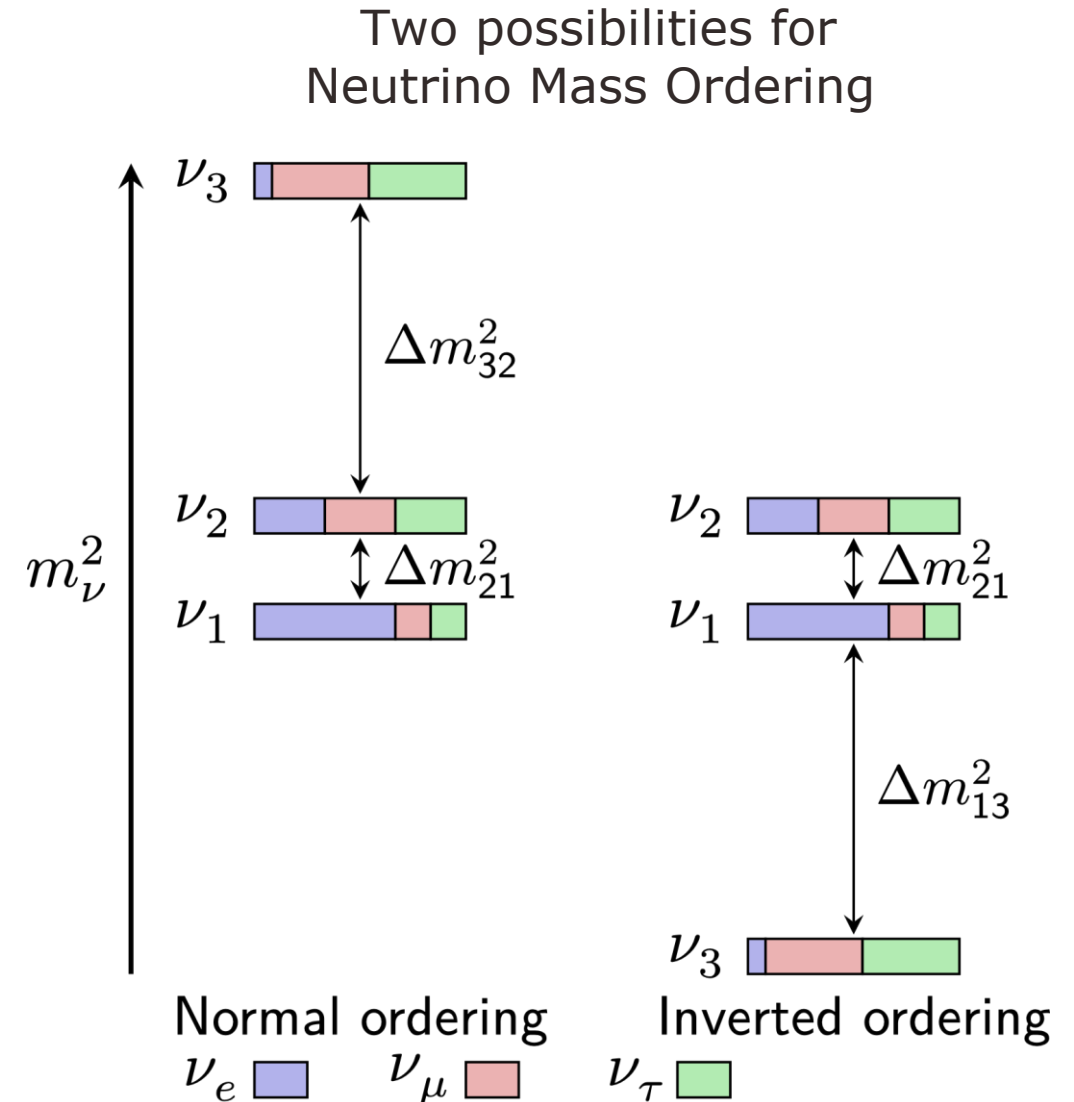
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Open questions:

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



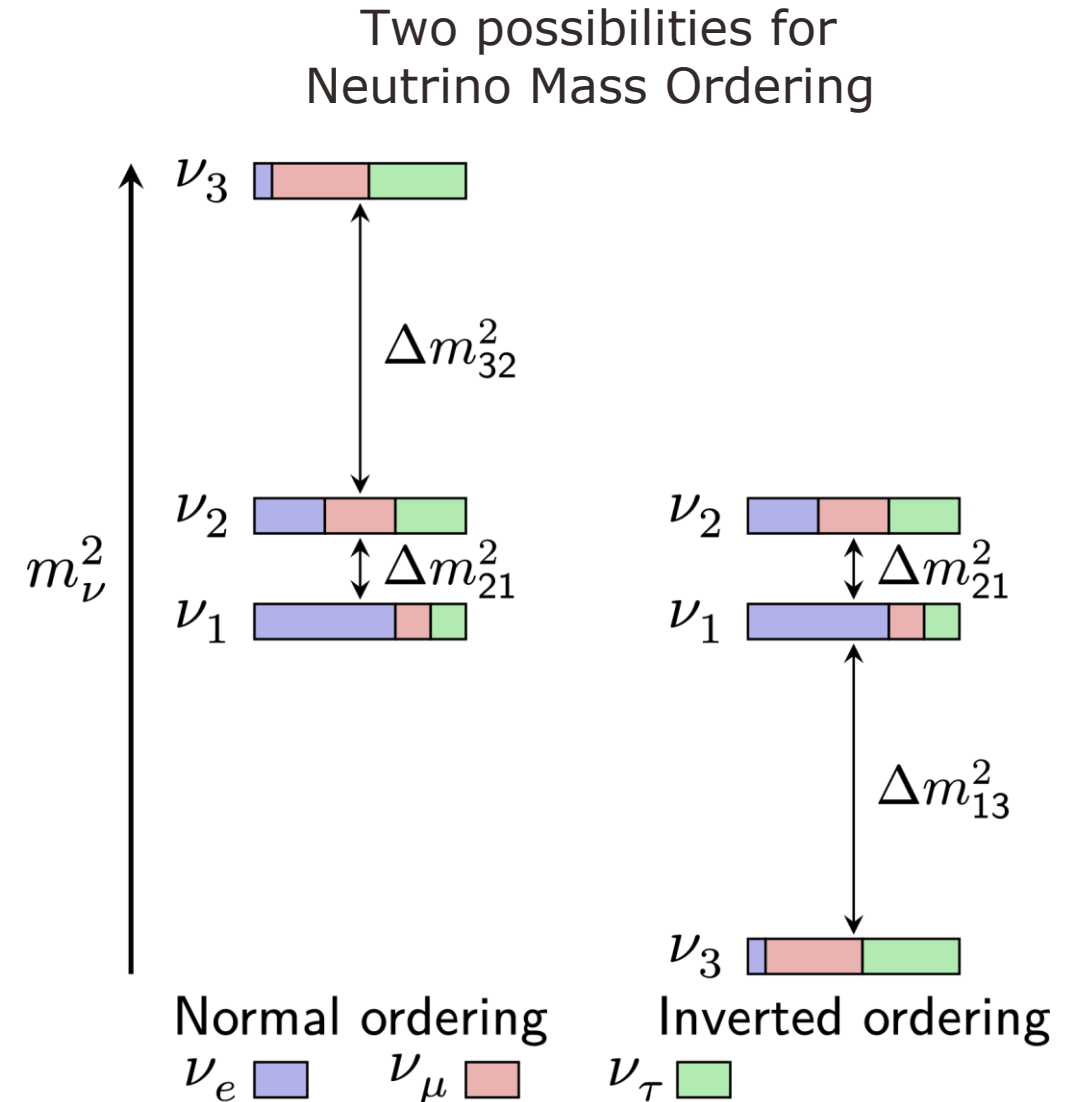
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Status of neutrino oscillation physics

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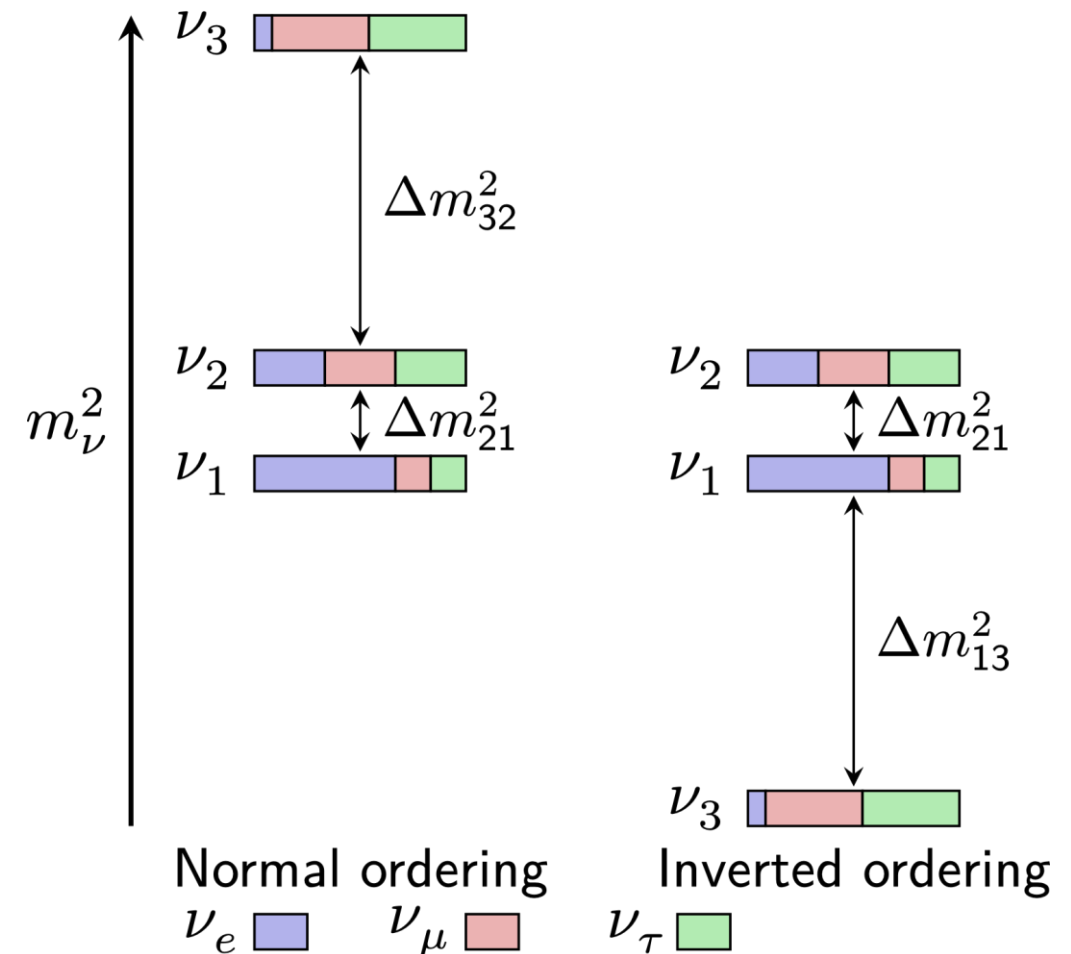
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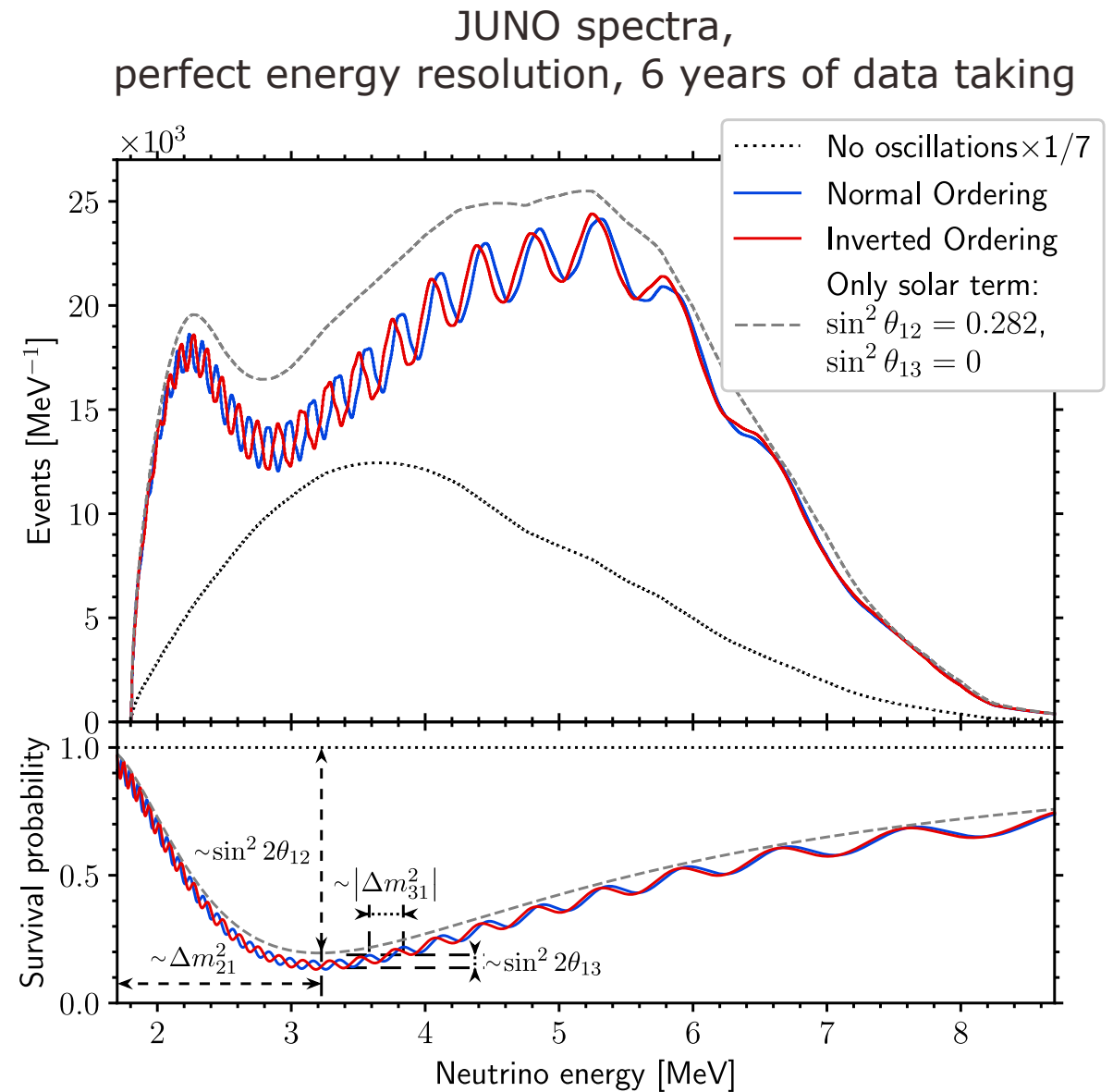
JUNO will contribute to precise measurements of oscillation parameters and answer the NMO question

Two possibilities for Neutrino Mass Ordering



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

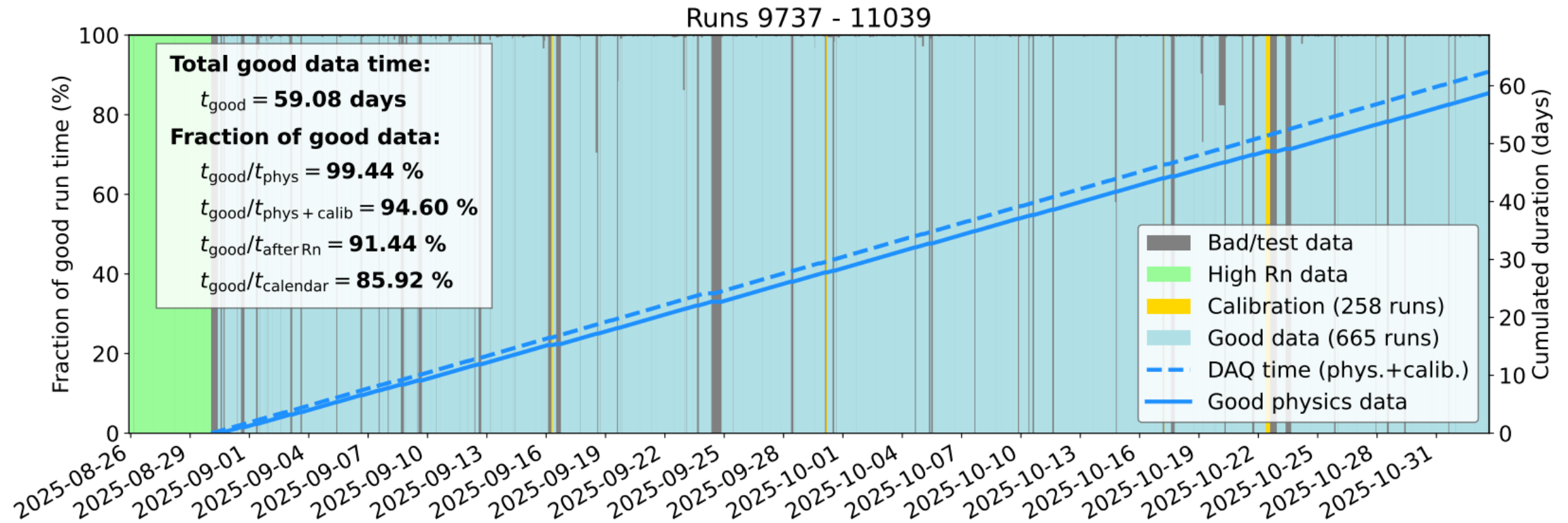
- ❖ JUNO studies fine interference pattern caused by quasi-vacuum oscillations in the oscillated antineutrino spectrum
- ❖ Interference pattern depends on NMO
- ❖ To resolve peaks → **need good energy resolution**
- ❖ To define peak positions → **need well defined energy scale**
- ❖ Complementary to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



JUNO performance and first results

Dataset

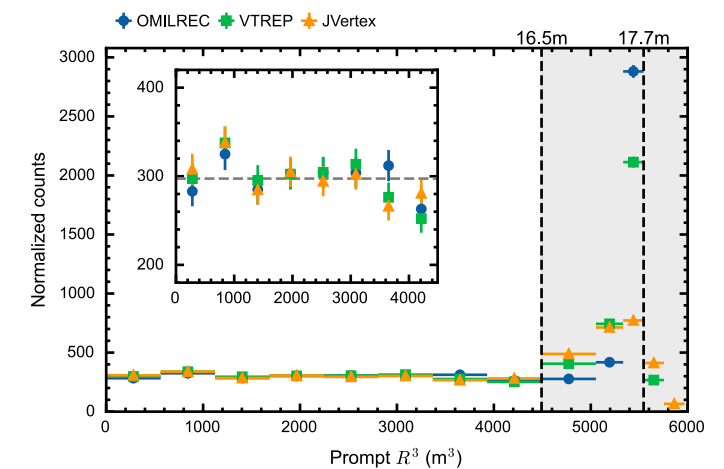
- ❖ 59.1 days of high-quality physics data were used for the analysis
- ❖ Detector was live 97.8% of the time from 30th August to 2nd November 2025



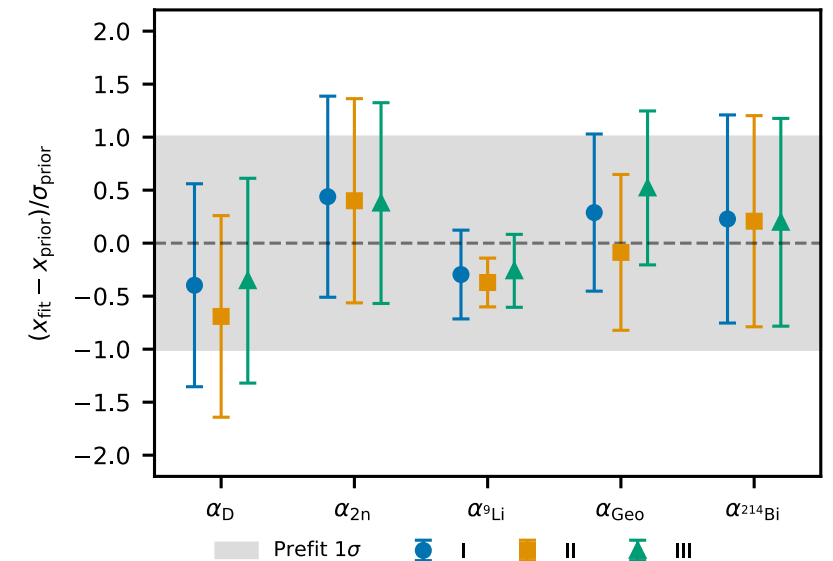
Organization of the analysis

- ❖ Three independent analysis groups
 - Essential to provide results robustness
- ❖ Each group has unique:
 - Reconstruction algorithms
 - Energy response model
 - Event selection strategy
 - Spectral fit frameworks
 - Statistical analysis approaches
- ❖ Great agreement found, up to fit quality and nuisance parameters
 - To avoid confusions, only one result will be shown

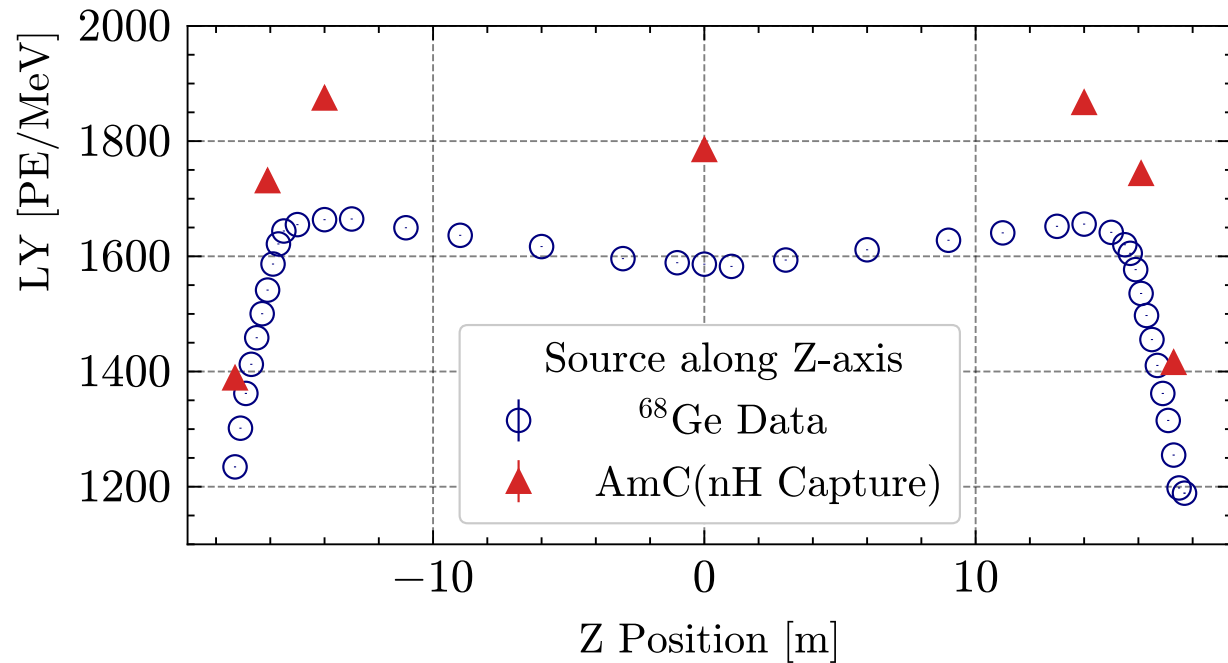
3 reconstructions



3 statistical analyses

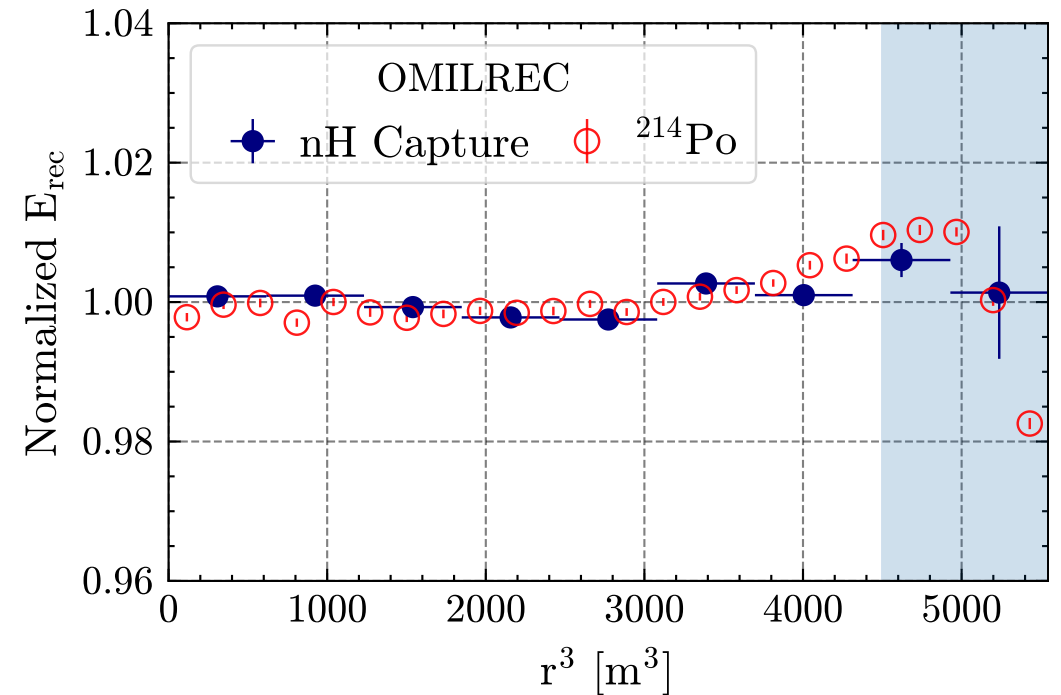


Detector light yield and uniformity



❖ Light yield:

- ~ 1600 PE/MeV for ^{68}Ge
- ~ 1800 PE/MeV for neutron capture
- Better than design values



❖ Energy reconstruction non-uniformity:

- Better than 1% for $R < 16.5$ m region

Energy response: scintillator non-linearity

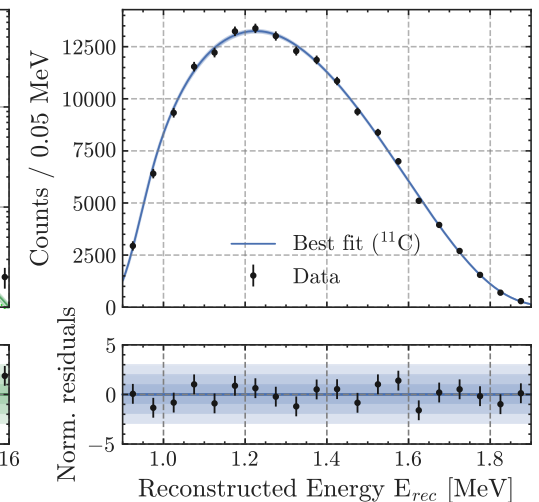
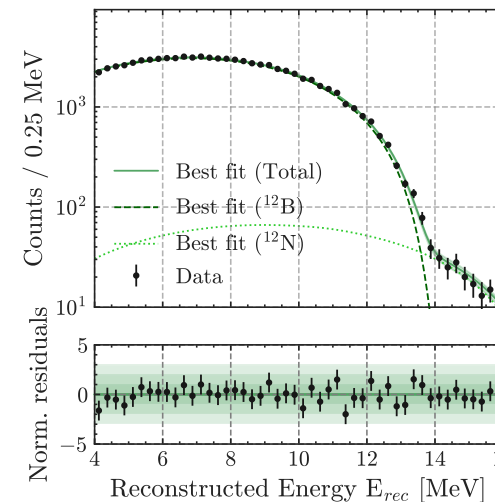
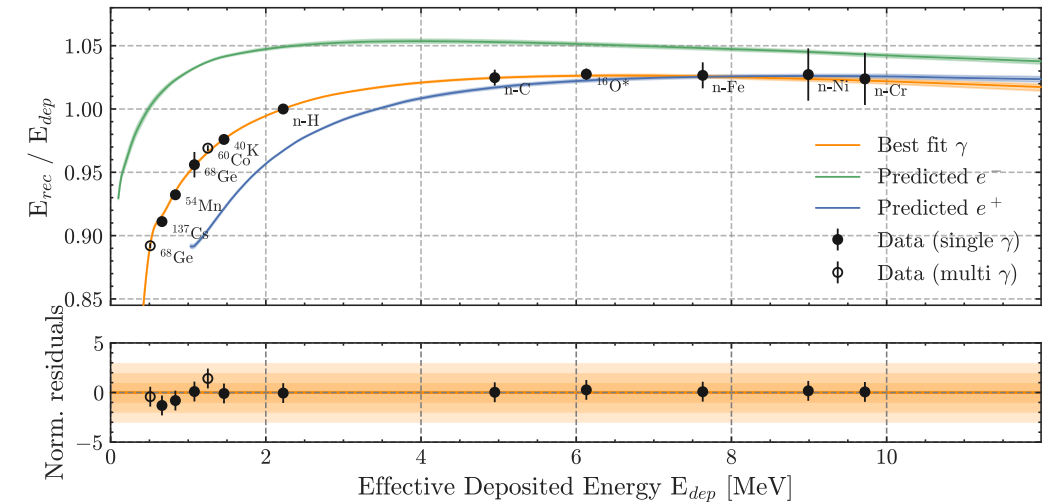
❖ Sources of non-linearity:

- Quenching effects
- Cherenkov radiation contribution

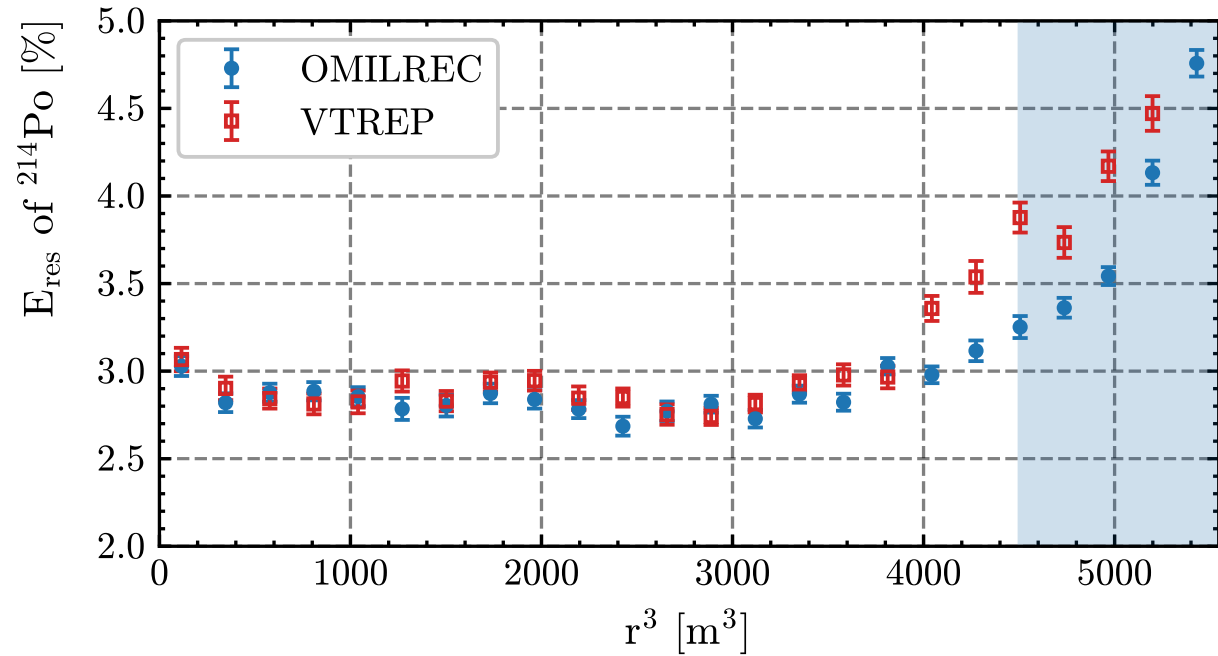
❖ Energy non-linearity control within $\sim 1\%$ level

- Model agrees well with calibration data and cosmogenic ^{12}B and ^{11}C

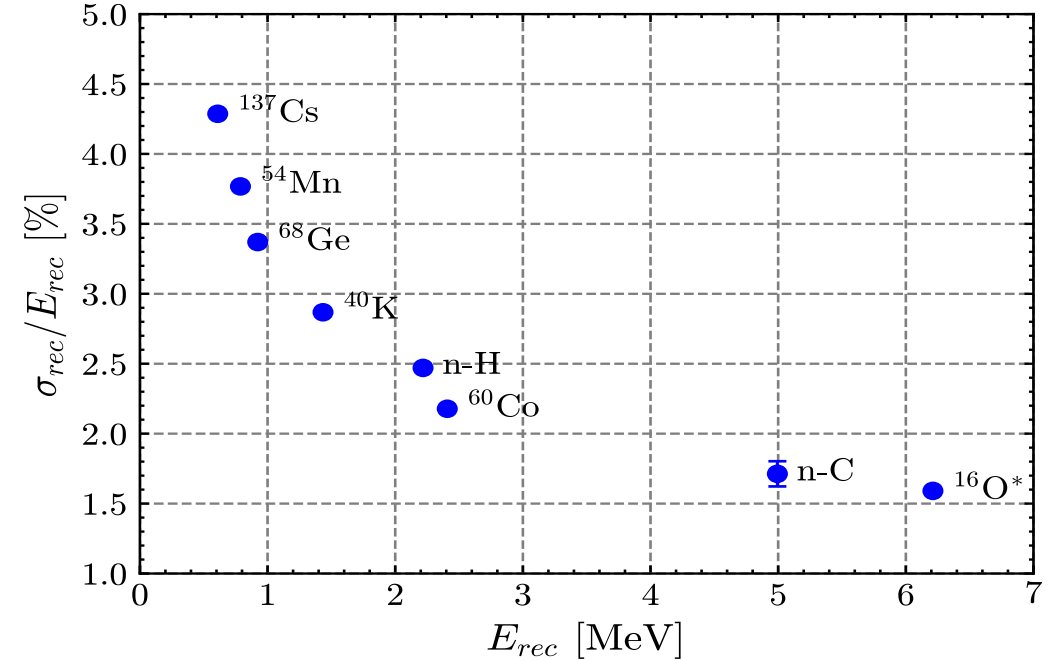
Energy non-linearity at detector center



Energy response: energy resolution



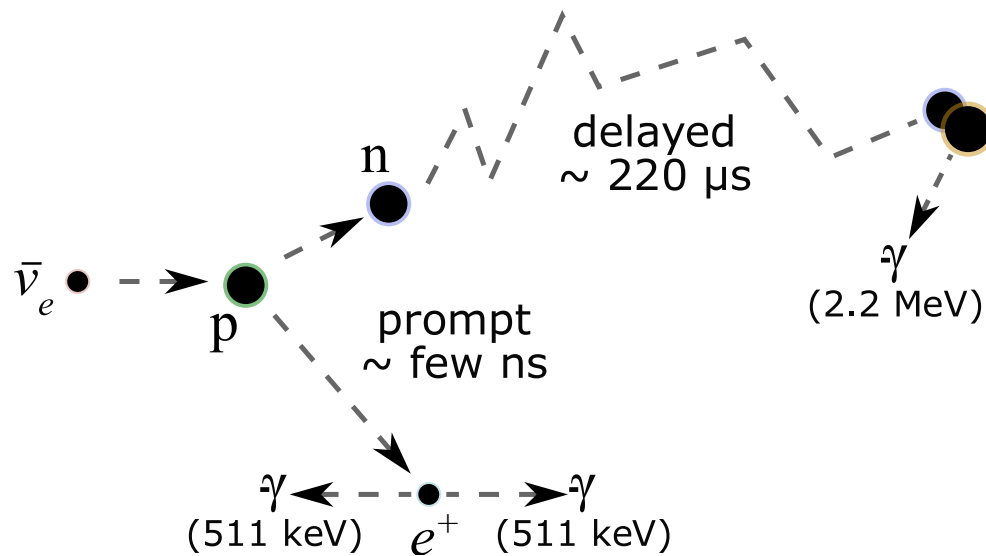
- ❖ Energy resolution for α from ^{214}Po is $< 3\%$ at 0.93 MeV for most of the $R < 16.5$ m region



- ❖ Energy resolution: 3.4% at 0.9 MeV (2 γ s from ^{68}Ge)

Event selection and backgrounds

- ❖ Inverse Beta Decay (IBD) as detection channel:

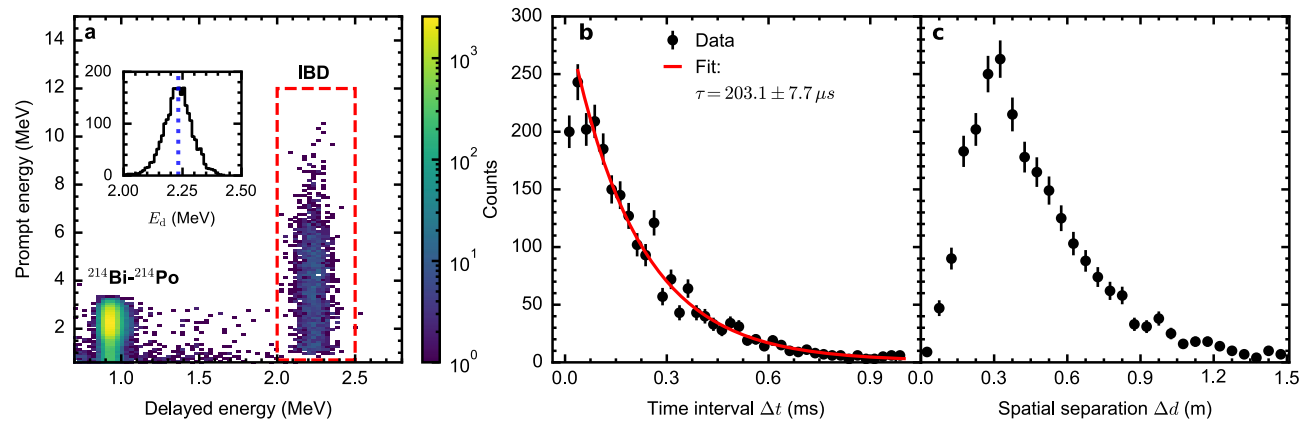


Event selection and backgrounds

- ❖ Inverse Beta Decay (IBD) as detection channel:



- ❖ Utilizes the energy, temporal, and spatial signatures of prompt-delayed pairs for signal isolation

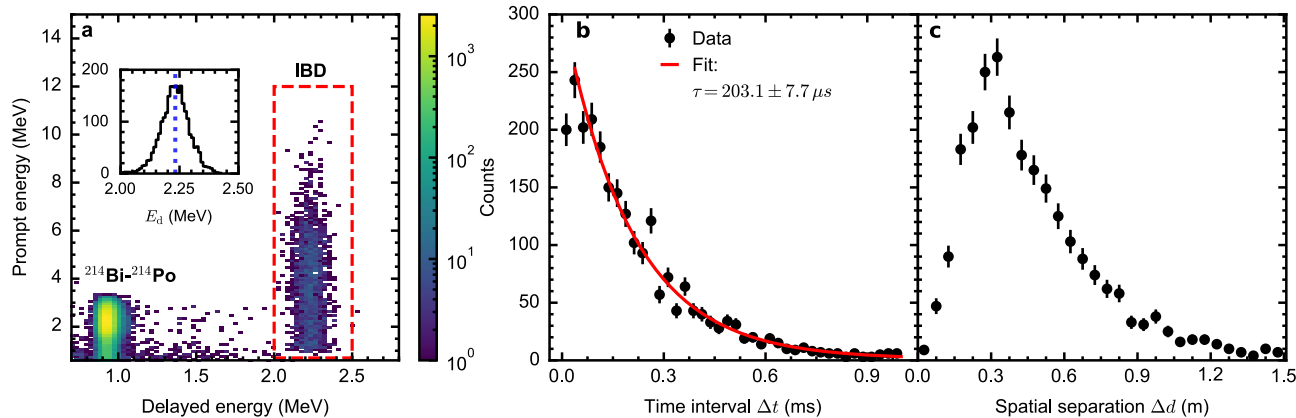


Event selection and backgrounds

- ❖ Inverse Beta Decay (IBD) as detection channel:



- ❖ Utilizes the energy, temporal, and spatial signatures of prompt-delayed pairs for signal isolation
- ❖ Backgrounds: $\sim 14\%$ of the total candidate sample



Antineutrinos ($\bar{\nu}_e$) Candidates Summary

DAQ live time (days)	59.1	
$\bar{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ϵ	σ_{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 (ϵ_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ϵ_{tot} corrected	33.5 ± 1.7	
w/ ϵ_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\bar{\nu}_e$	150.9 ± 2.7	

Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	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
$^{214}\text{Bi}-^{214}\text{Po}$	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	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
Total	6.80 ± 1.49	6.63 ± 0.74

¹cpd \equiv counts per day

Daya Bay as near detector

- ❖ Need a way to constrain initial $\bar{\nu}_e$ spectrum from reactors
 - Can't rely on $\bar{\nu}_e$ spectrum models due to large shape uncertainties
- ✓ **Solution:** use publicly available Daya Bay near detectors data (two options, consistent results):
 1. Comprehensive Measurement of the Reactor Antineutrino Spectrum and Flux at Daya Bay¹
 2. Full Data Release of the Daya Bay Reactor Neutrino Experiment²

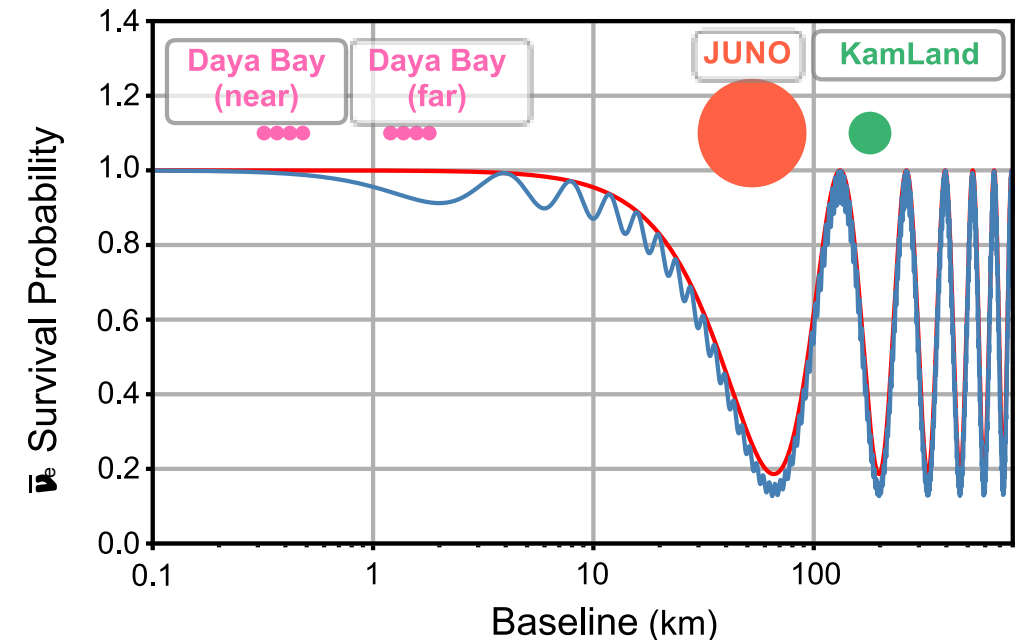
¹ doi.org/10.1103/PhysRevLett.134.201802

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- ❖ No $\bar{\nu}_e$ oscillation at near detectors → near detectors naturally constrain $\bar{\nu}_e$ spectrum shape in a **combined analysis**
- ❖ JUNO and Daya Bay share the same $\bar{\nu}_e$ spectrum model that can be floated during the fit



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Statistical analysis results

- ❖ Frequentists analysis with binned
Combined Neyman Pearson (CNP) χ^2 :

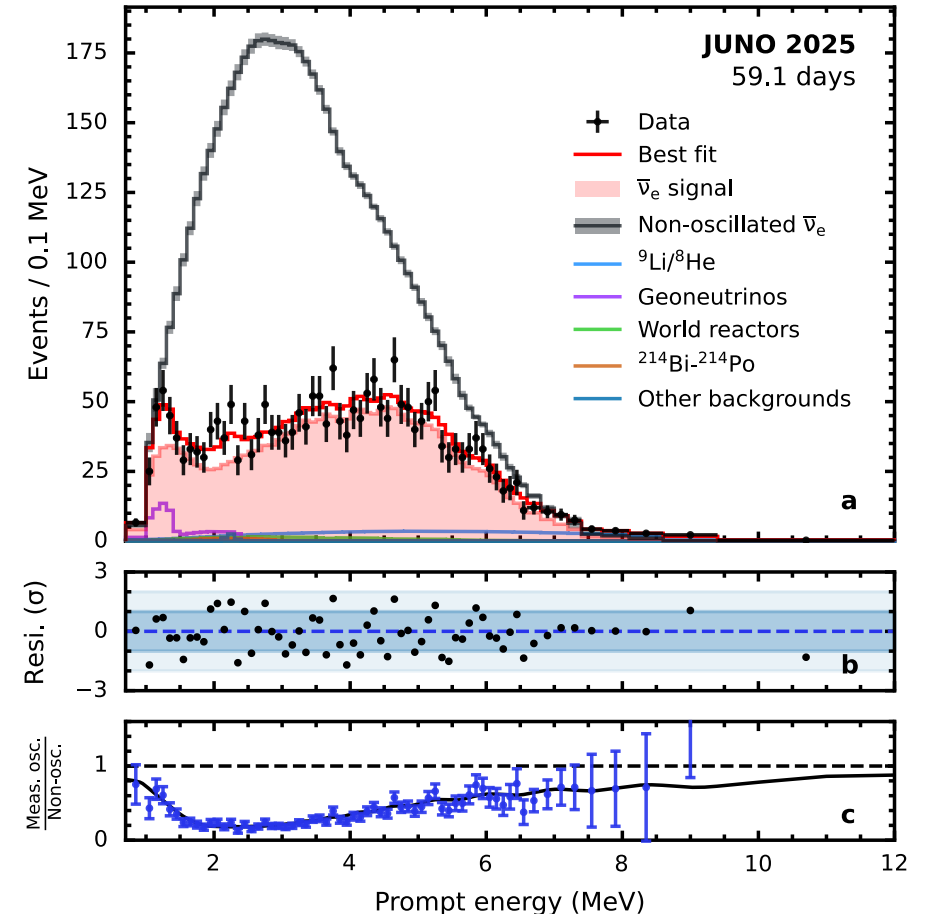
$$\chi_{\text{CNP}}^2 = [x - \mu(\theta, \eta)]^T \times (V_{\text{stat.}} + V_{\text{syst.}})^{-1} \times [x - \mu(\theta, \eta)]$$

$$(V_{\text{stat.}})_{ij} = \frac{3\delta_{ij}}{\frac{1}{x_i} + \frac{2}{\mu_i}}$$

- ❖ Full χ^2 function:

$$\chi_{\text{full}}^2 = \chi_{\text{CNP,JUNO}}^2 + \chi_{\text{CNP,DYB}}^2 + \chi_{\text{nuis.}}^2 + \chi_{\sin^2\theta_{13}}^2 + \chi_{\Delta m_{31}^2}^2$$

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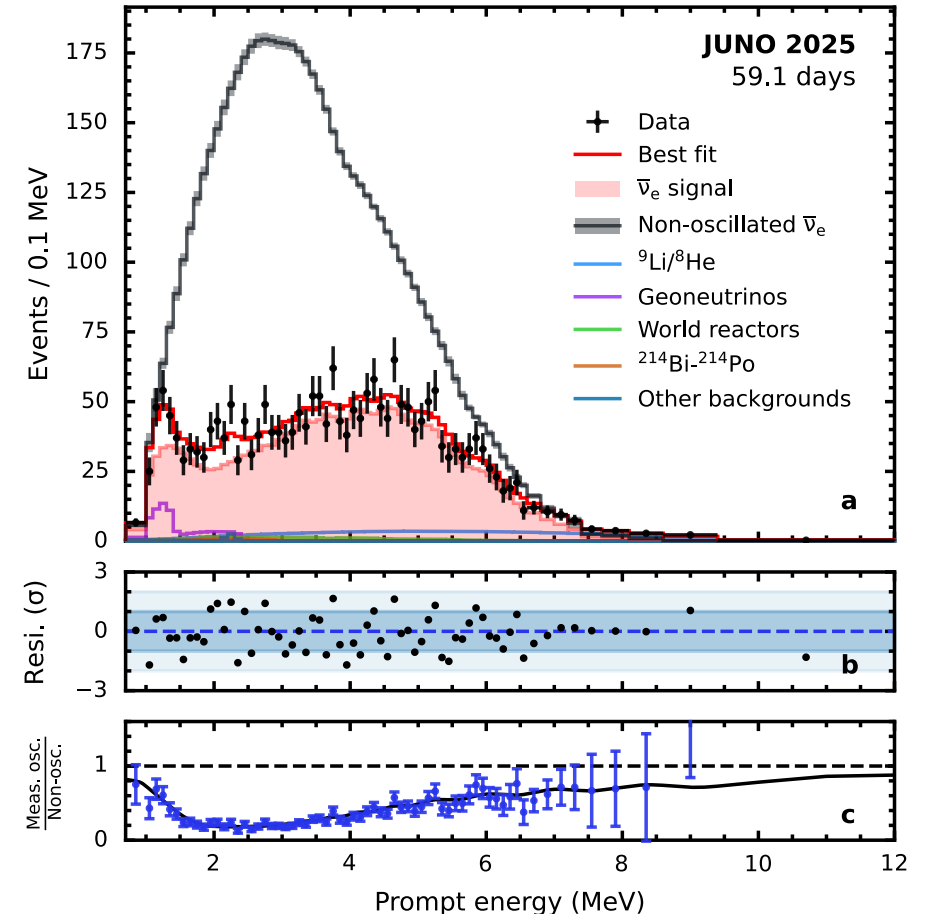
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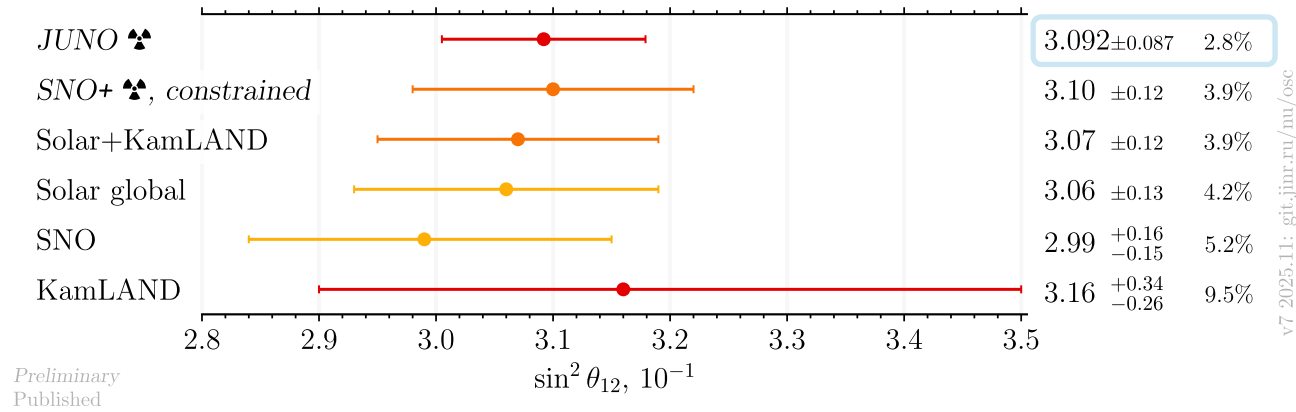
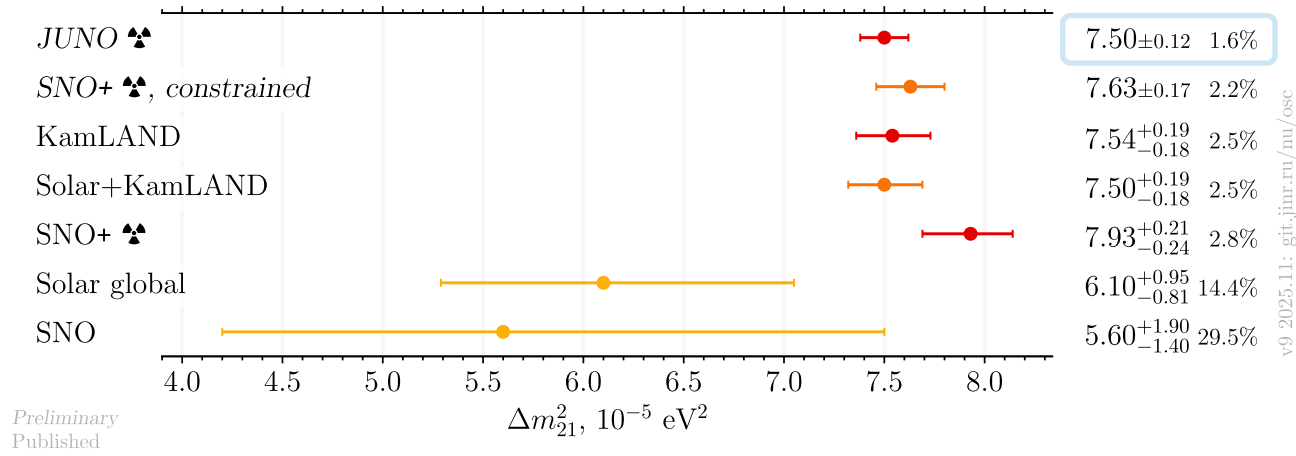
- ❖ Δm_{31}^2 is constrained by Daya Bay measurement via Gaussian pull term
- ❖ Best-fit values:

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087 \text{ (2.81\%)}$$

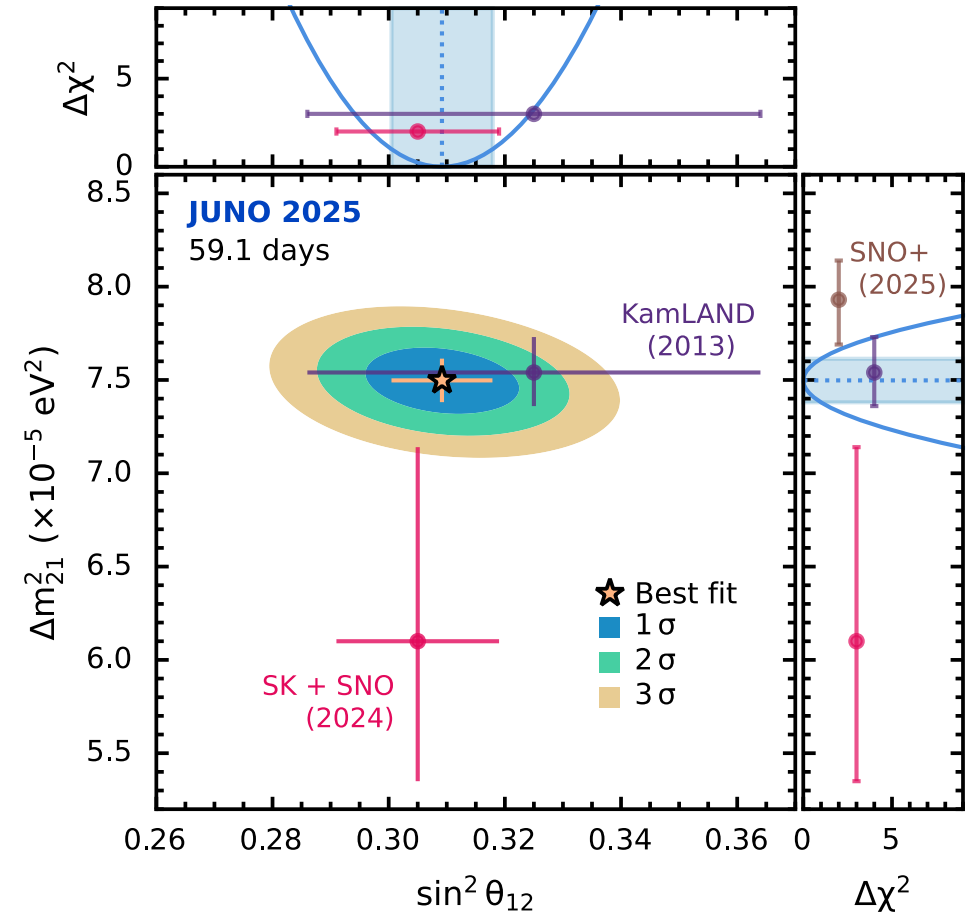
$$\Delta m_{21}^2 = (7.50 \pm 0.12) \times 10^{-5} \text{ eV}^2 \text{ (1.6\%)}$$



Statistical analysis results



v9 2025.11: git.jinr.ru/nu/osc
v7 2025.11: git.jinr.ru/nu/osc



❖ JUNO achieved world leading precision on Δm_{21}^2 and $\sin^2 \theta_{12}$ with only 59 days of data taking

Summary

- ❖ JUNO oscillation results have been released with the first 59 days of data
 - World leading precision on Δm_{21}^2 and $\sin^2\theta_{12}$
 - Factor of about 1.6 improvement over global constraints
 - Good detector performance

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 - World leading precision on Δm_{21}^2 and $\sin^2\theta_{12}$
 - Factor of about 1.6 improvement over global constraints
 - Good detector performance
- ❖ JUNO oscillation parameters precision measurement can help to
 - Verify the three-flavor neutrino oscillation paradigm and test unitarity of the lepton mixing matrix
 - Improve the determination of the θ_{23} mixing angle and searches for CP violation in leptonic sector in accelerator/atmospheric experiments
 - Reduce uncertainties in effective neutrino mass to better probe the Majorana nature of neutrinos

Backup

Neutrino mixing

Weak (e, μ, τ) and mass (1,2,3) eigenstates differ:

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

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

Neutrino mixing

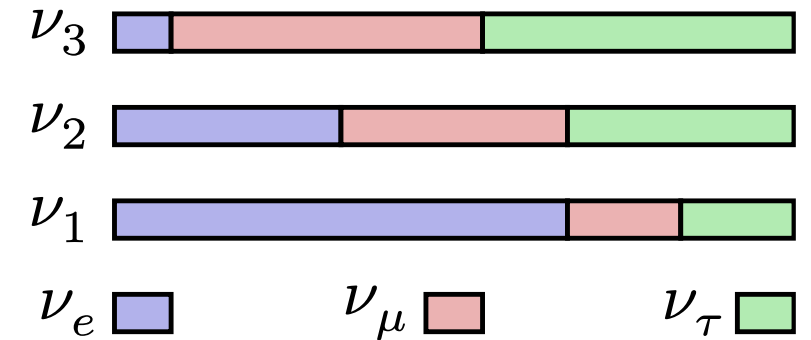
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Mixing is parametrized by:

- ❖ Three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- ❖ CP-violating phase: δ_{CP}



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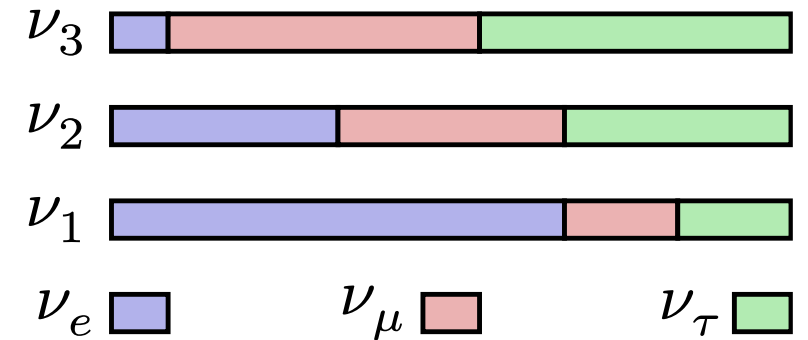
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- ❖ CP-violating phase: δ_{CP}

Three neutrino mass splittings ($\Delta m_{ij}^2 = m_i^2 - m_j^2$):

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

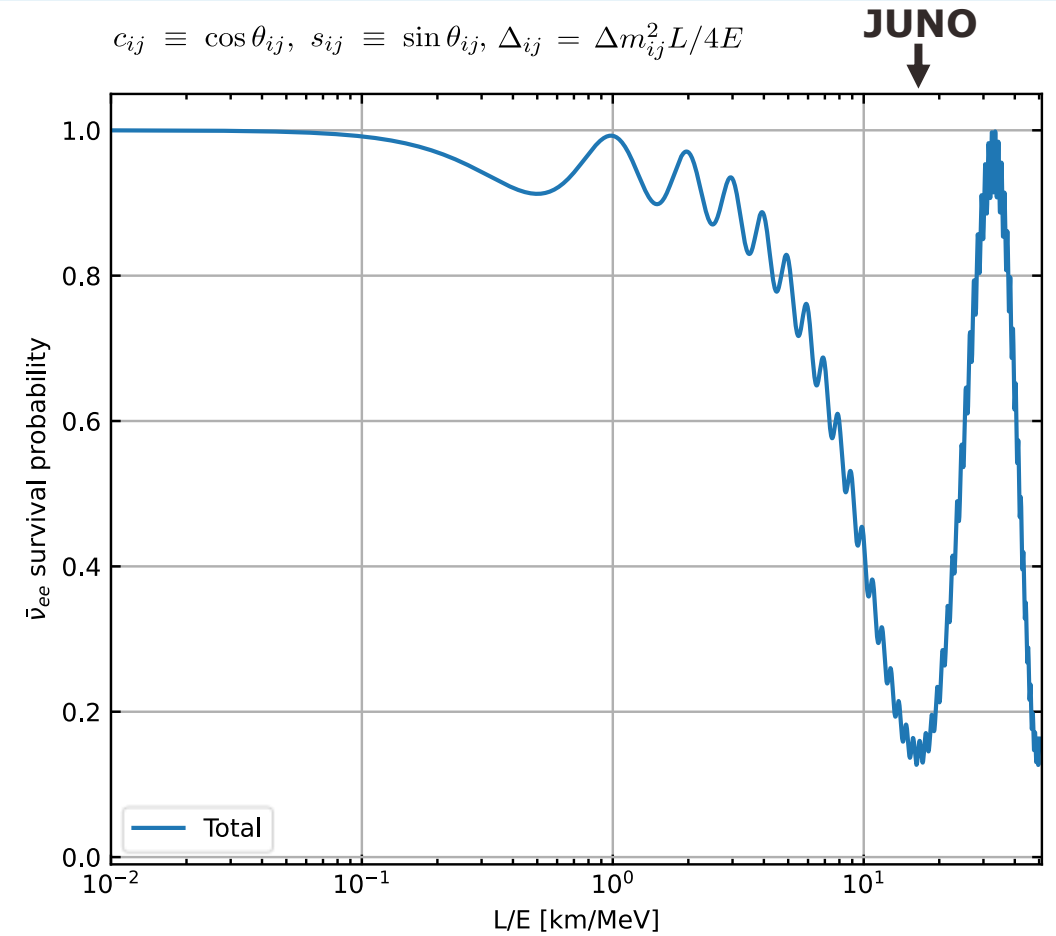


Reactor $\bar{\nu}_e$ oscillations

❖ JUNO observes deficit of $\bar{\nu}_e$ due to oscillation

❖ $\bar{\nu}_e$ survival probability:

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

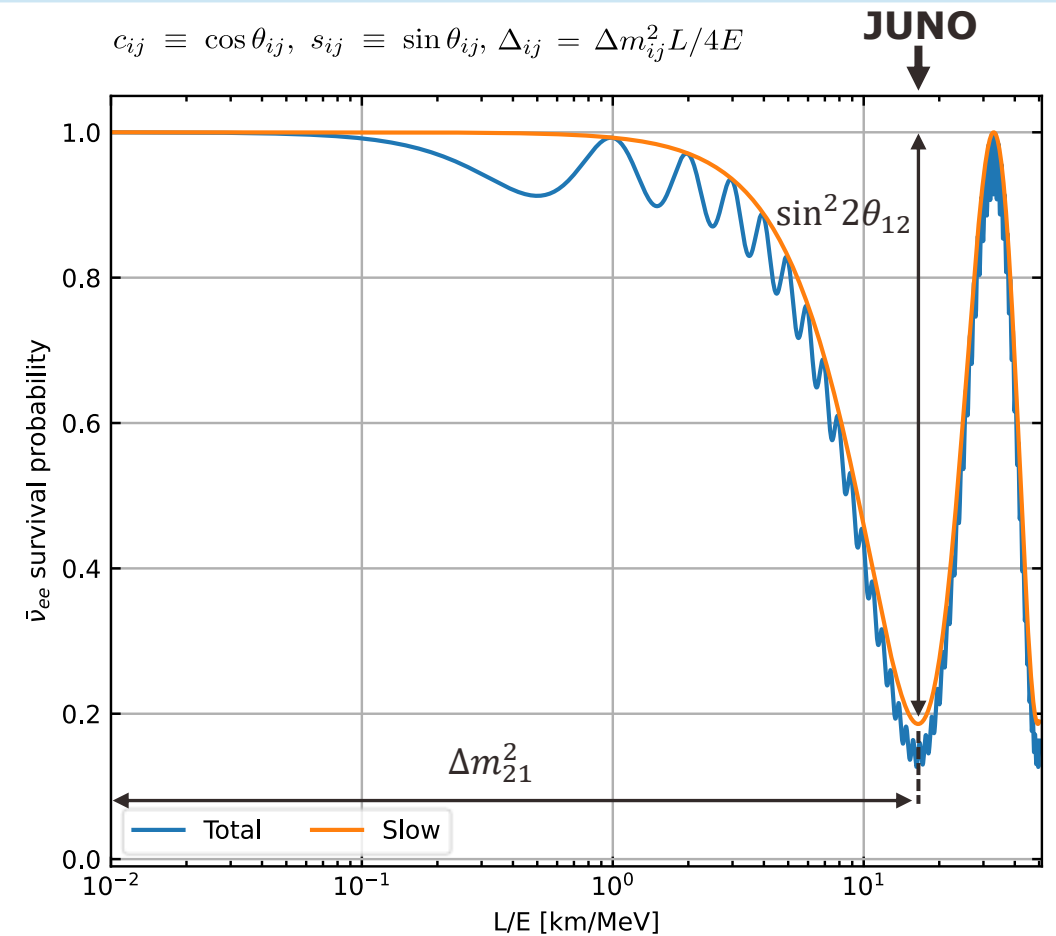


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$$- \sin^2 2\theta_{13} c_{12}^2 \sin^2 \Delta_{31}$$
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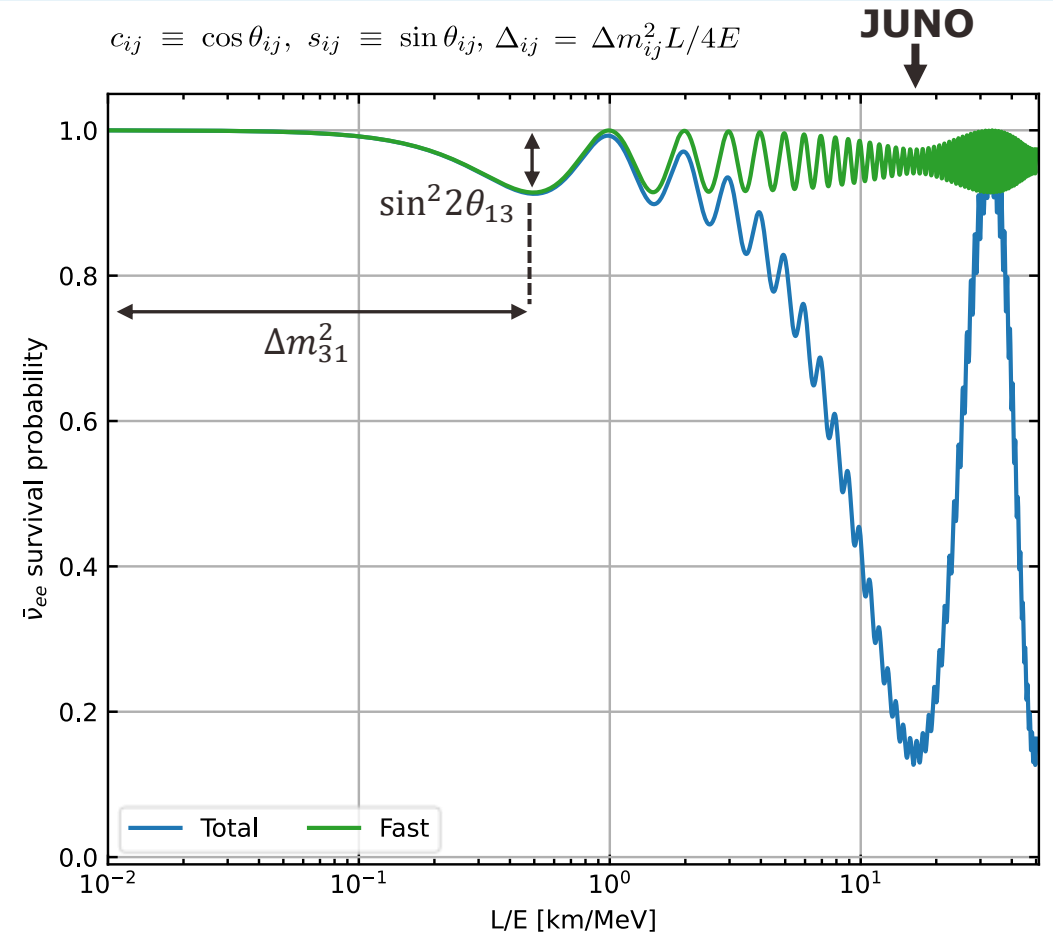
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FAST

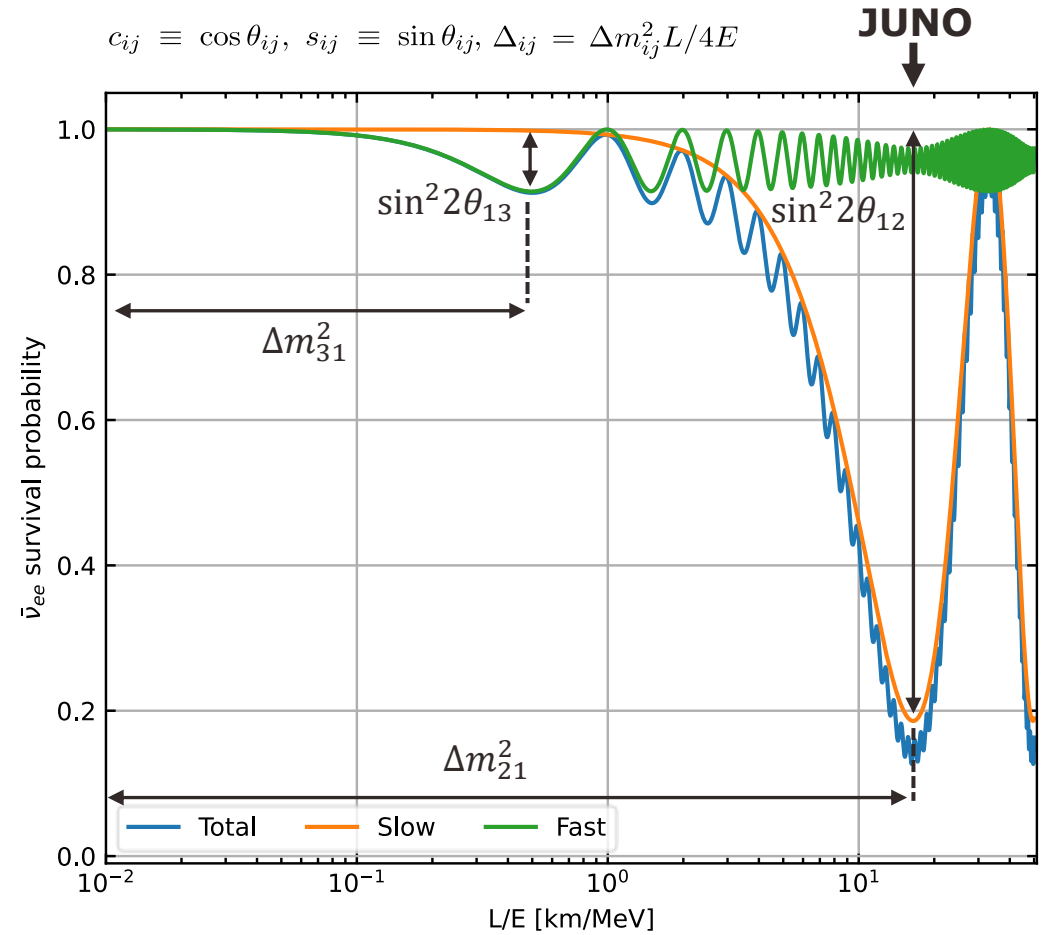


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❖ $\bar{\nu}_e$ survival probability:

$$\mathcal{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \underbrace{\sin^2 2\theta_{12} c_{13}^4 \sin^2 \Delta_{21}}_{\text{SLOW}} - \underbrace{\sin^2 2\theta_{13} c_{12}^2 \sin^2 \Delta_{31}}_{\text{FAST}} - \sin^2 2\theta_{13} s_{12}^2 \sin^2 \Delta_{32}$$



Reactor $\bar{\nu}_e$ oscillations

❖ JUNO observes deficit of $\bar{\nu}_e$ due to oscillation

❖ $\bar{\nu}_e$ survival probability:

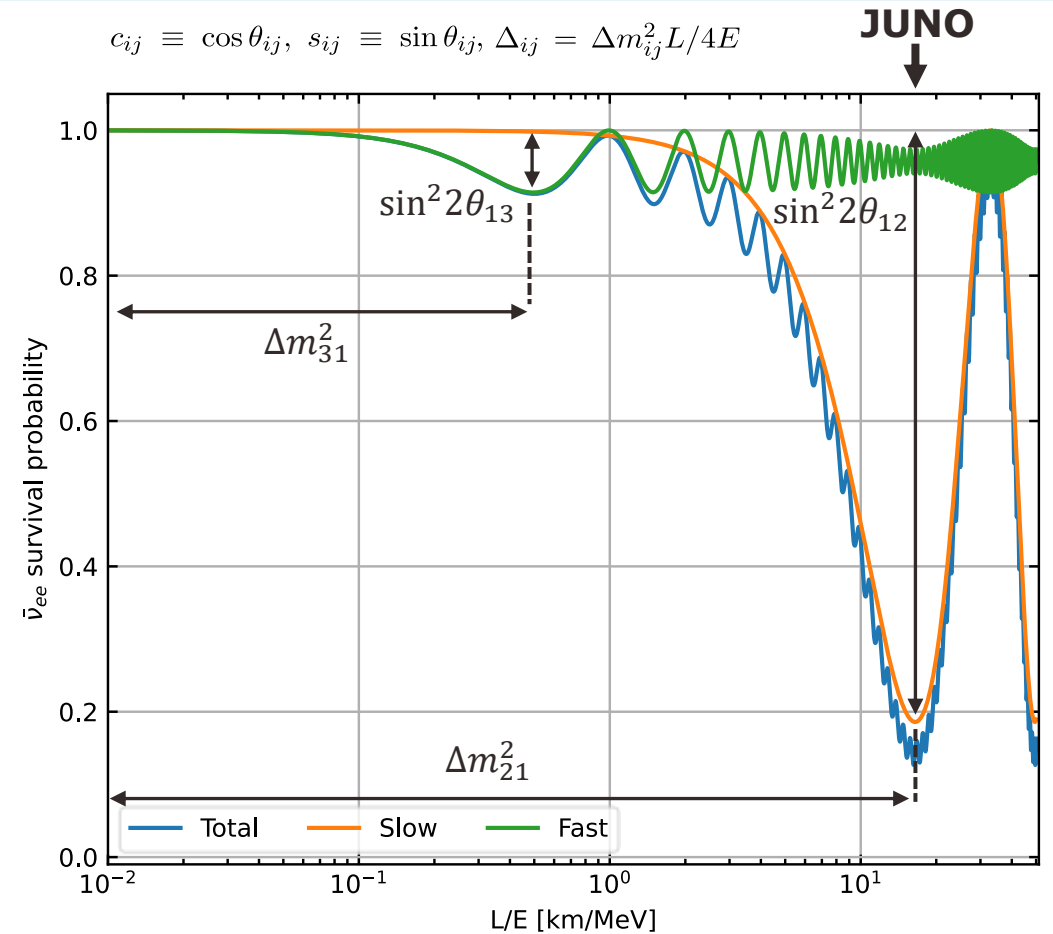
$$\mathcal{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \boxed{\sin^2 2\theta_{12} c_{13}^4 \sin^2 \Delta_{21}} \quad \text{SLOW}$$

$$- \boxed{\sin^2 2\theta_{13} c_{12}^2 \sin^2 \Delta_{31}} \quad \text{FAST}$$

$$- \boxed{\sin^2 2\theta_{13} s_{12}^2 \sin^2 \Delta_{32}}$$

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

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

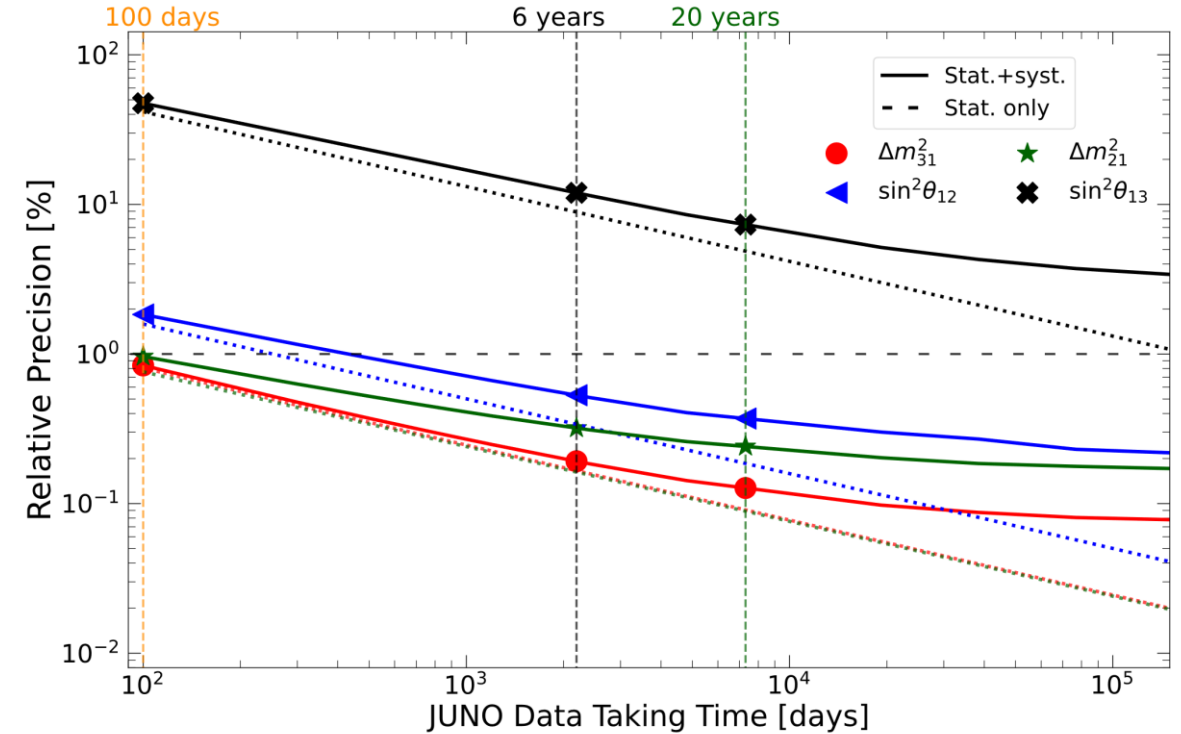


Sensitivity Studies

(based on design level performance)

Sensitivity to oscillation parameters

- ❖ JUNO will achieve **sub-percent precision** on Δm_{31}^2 , Δm_{21}^2 , 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

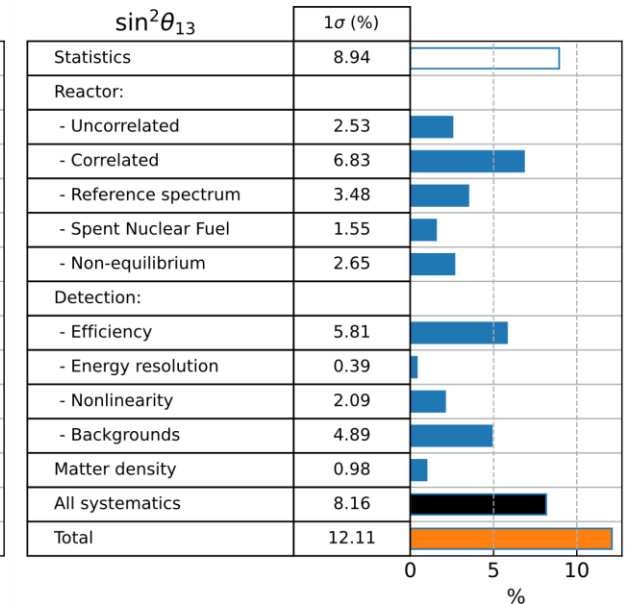
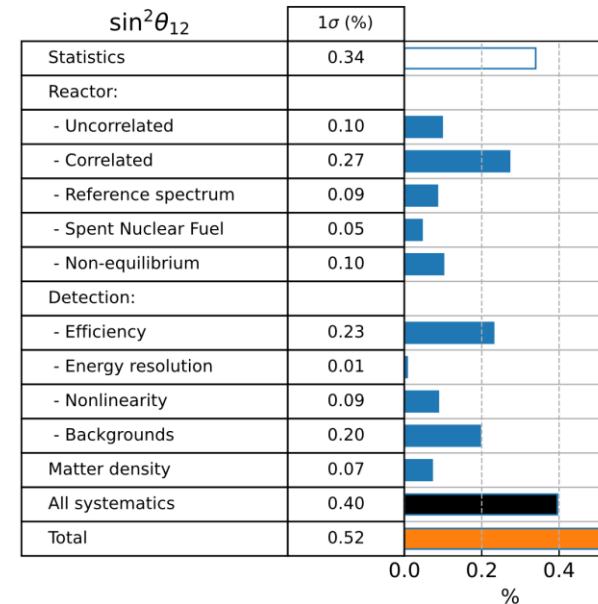
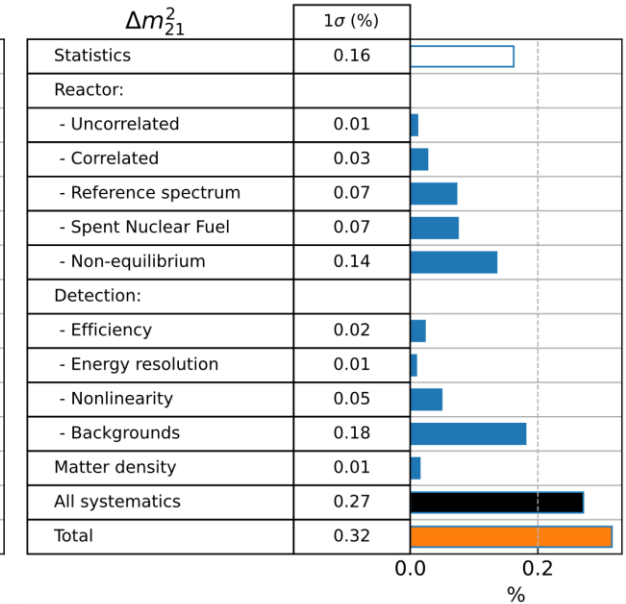
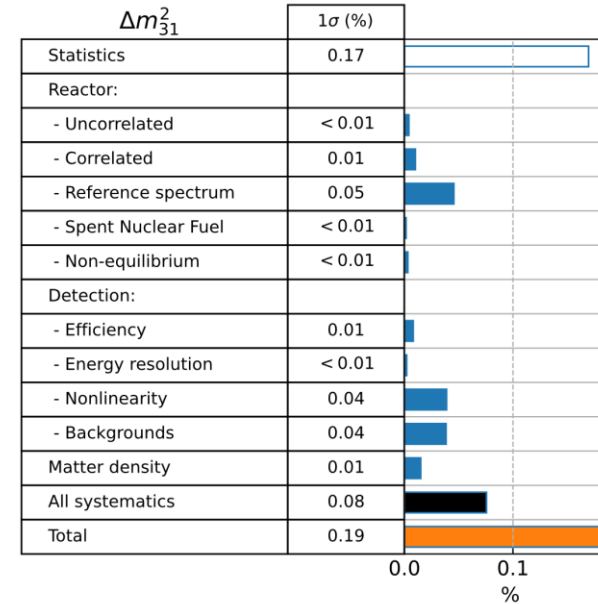


	Central value	PDG2020	100 days	6 years
$\Delta m_{31}^2 (\times 10^{-3} \text{ eV}^2)$	2.5253	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)
$\Delta m_{21}^2 (\times 10^{-5} \text{ eV}^2)$	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (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_{31}^2 : antineutrino spectrum shape uncertainty, detector non-linearity, backgrounds
- ❖ Δm_{21}^2 : 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



Sensitivity to Neutrino Mass Ordering

- ❖ Median sensitivity to NMO is based on Asimov dataset:

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

- ❖ **3 σ 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 \times 26.6 GW_{th} exposure

- ❖ Dominant sources of uncertainty: backgrounds, reference spectrum, non-linearity

