JUNO SENSITIVITY TO MASS ORDERING AND OSCILLATION PARAMETERS

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on behalf of the JUNO collaboration

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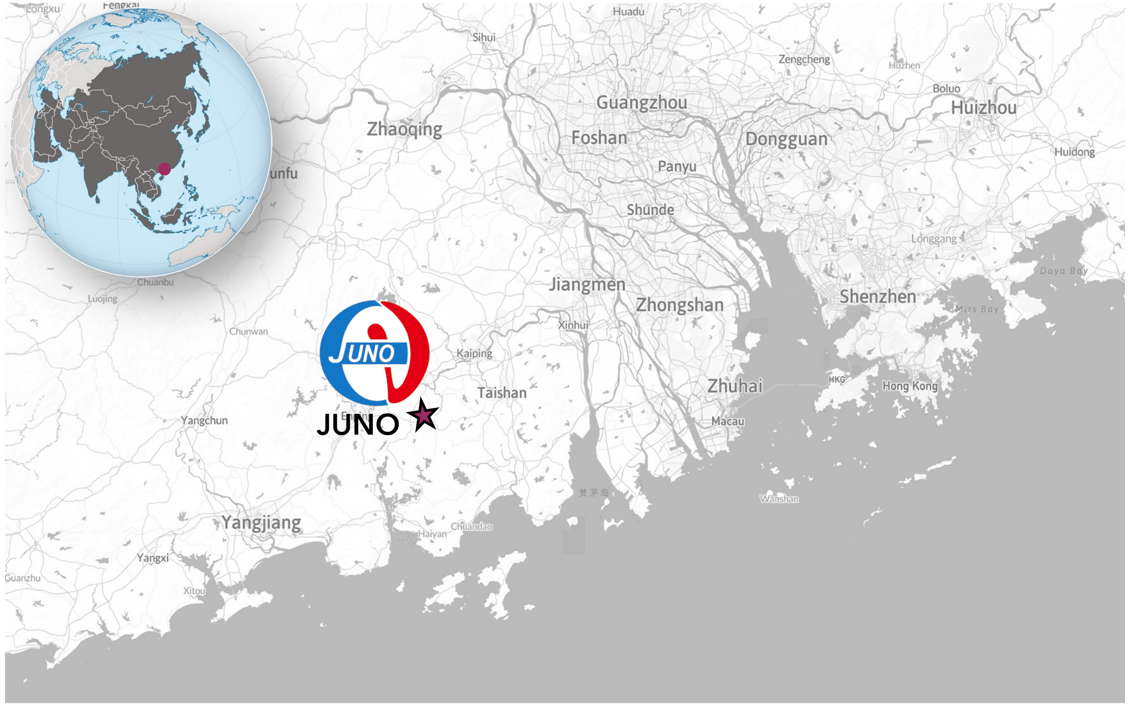
Neutrino Oscillation Workshop, Otranto, 2-9 September 2024

INFN Istituto Nazionale di Fisica Nucleare
JUNO
NOW 2024 Neutrino Oscillation Workshop
Università degli Studi di Padova

JUNO AT A GLANCE

PPNP 123 (2022): 103927

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



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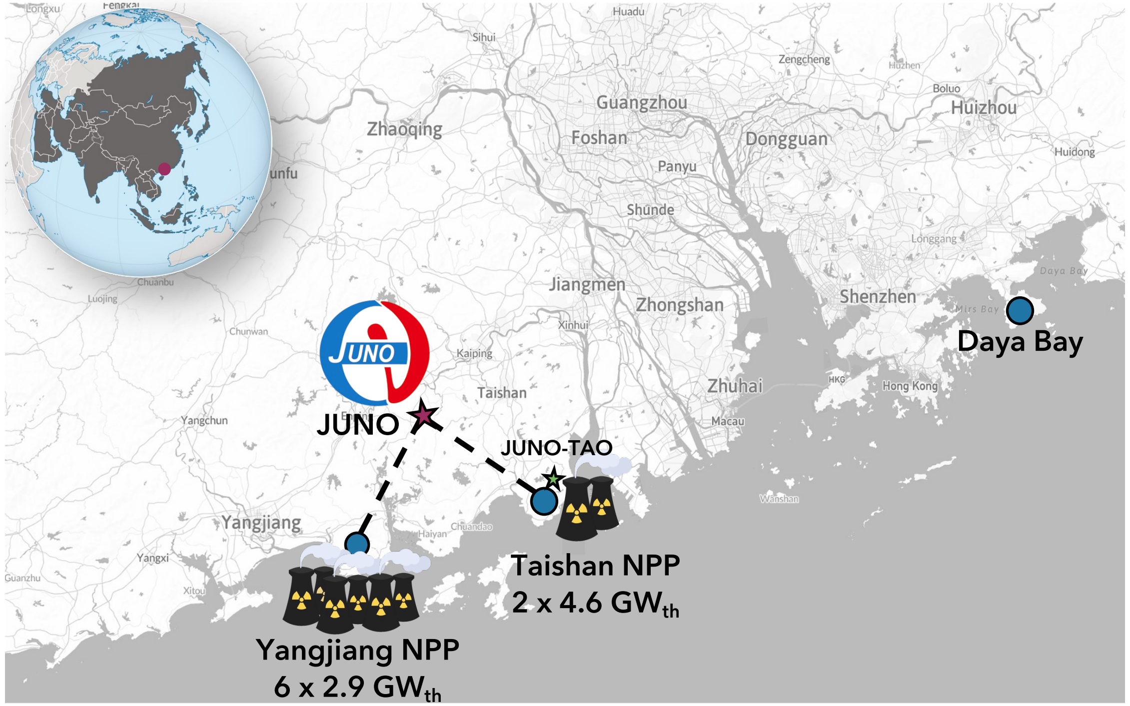
The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a multi-purpose neutrino experiment currently under construction in South China.

- ✶ 52.5 km from two major Nuclear Power Plants (NPPs) with eight nuclear reactors (26.6 GW_{th})
- ✶ 35 m-diameter sphere with **20 ktons of liquid scintillator** (LS) surrounded by a water Cherenkov detector
- ✶ Unprecedented energy resolution for a LS-based detector → 3% at 1 MeV arXiv 2405.17860



Main goals with reactor antineutrino oscillations
- ✶ Determination of the **Neutrino Mass Ordering** (NMO)
- ✶ Precision measurement of three oscillations parameters: Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}

STATUS OF ν OSCILLATION PHYSICS

5 knowns:

- ✓ $\Delta m^2_{21} \sim 7.5 \times 10^{-5} \mathrm{eV}^2$
- ✓ $|\Delta m^2_{31}| \sim 2.5 \times 10^{-3} \mathrm{eV}^2$
- ✓ $\sin^2 \theta_{12} \sim 0.3$
- ✓ $\sin^2 \theta_{23} \sim 0.5$
- ✓ $\sin^2 \theta_{13} \sim 0.02$

All known with better than 5% precision

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5 known unknowns:

- ? Mass ordering: $\Delta m^2_{21} > 0$ but $\Delta m^2_{31} \gtrless 0$?
- ? Octant of θ_{23}: $\theta_{23} \gtrless 45°$?
- ? CP phase δ: δ not 0 or π ? CP violation?
- ? Dirac or Majorana nature
- ? Absolute mass scale

Cannot be probed with ν oscillations

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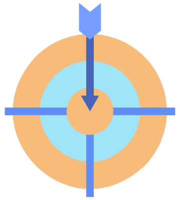
Cannot be probed with ν oscillations

JUNO will contribute to both the precision and discovery frontiers

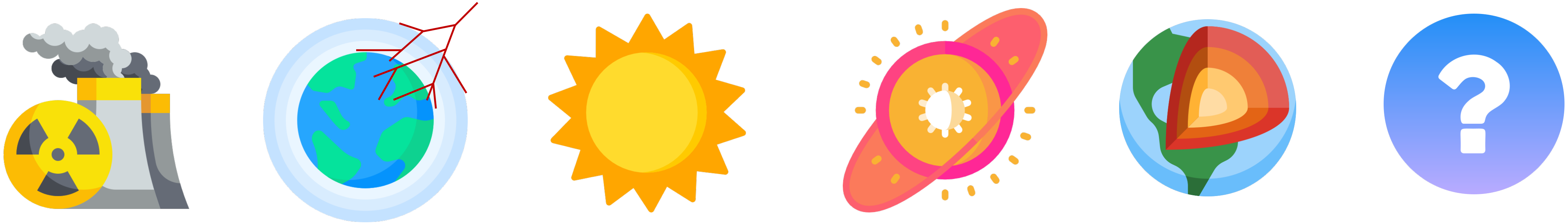


Precision measurement of three parameters: Δm^2_{21}, Δm^2_{31}, and $\sin^2 \theta_{12}$

Mass ordering determination

JUNO PHYSICS PROGRAM

JUNO has a **rich physics program** and will detect neutrinos from several sources.



Reactor $\bar{\nu}_e$ | Atmospheric $\nu/\bar{\nu}$ | Solar ν_e | Supernovae | Geo-neutrinos | BSM physics

Neutrino oscillations (Reactor $\bar{\nu}_e$, Atmospheric $\nu/\bar{\nu}$, Solar ν_e)

Neutrinos as a probe (Solar ν_e, Supernovae, Geo-neutrinos, BSM physics)

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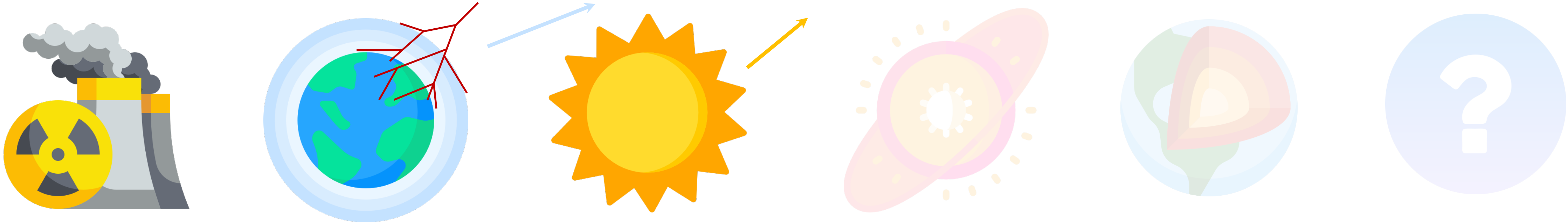
M. Malabarba's talk on Saturday



Reactor $\bar{\nu}_e$ Atmospheric $\nu/\bar{\nu}$ Solar ν_e Supernovae Geo-neutrinos BSM physics

Neutrino oscillations

Neutrinos as a probe

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Reactor $\bar{\nu}_e$ | Atmospheric $\nu/\bar{\nu}$ | Solar ν_e | Supernovae | Geo-neutrinos | BSM physics

Neutrino oscillations

Neutrinos as a probe

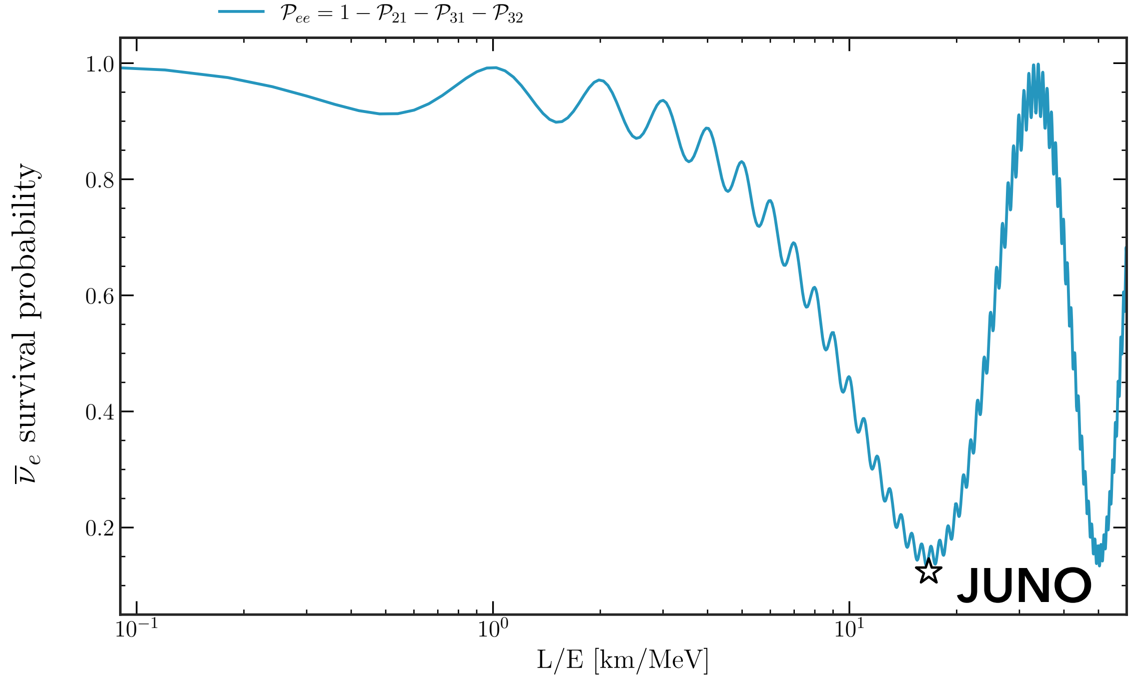
In this presentation focus mainly on reactor $\bar{\nu}_e$

REACTOR $\bar{\nu}_e$ OSCILLATIONS IN JUNO

$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij},\ \Delta_{ij} = \Delta m^2_{ij} L/4E$

- Experimental observable: deficit in number of $\bar{\nu}_e$ interactions → $\bar{\nu}_e$ **survival probability**

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



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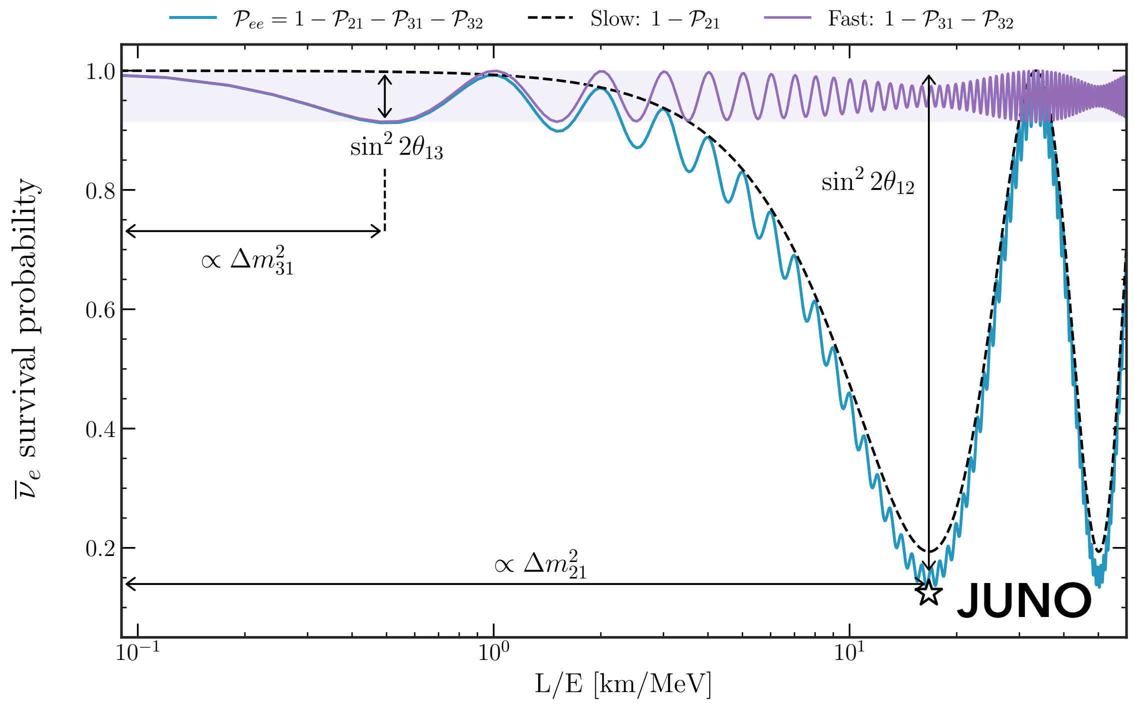
$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c^4_{13} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} c^2_{12} \sin^2 \Delta_{31} - \sin^2 2\theta_{13} s^2_{12} \sin^2 \Delta_{32}$$

- ✶ Measurement of four oscillation parameters, no dependence on $\boldsymbol{\delta_{\mathrm{CP}}}$ and $\boldsymbol{\theta_{23}}$

- ✶ Unique capability to simultaneously probe oscillations on both **slow** (Δm^2_{21}) and **fast** (Δm^2_{31}) scales



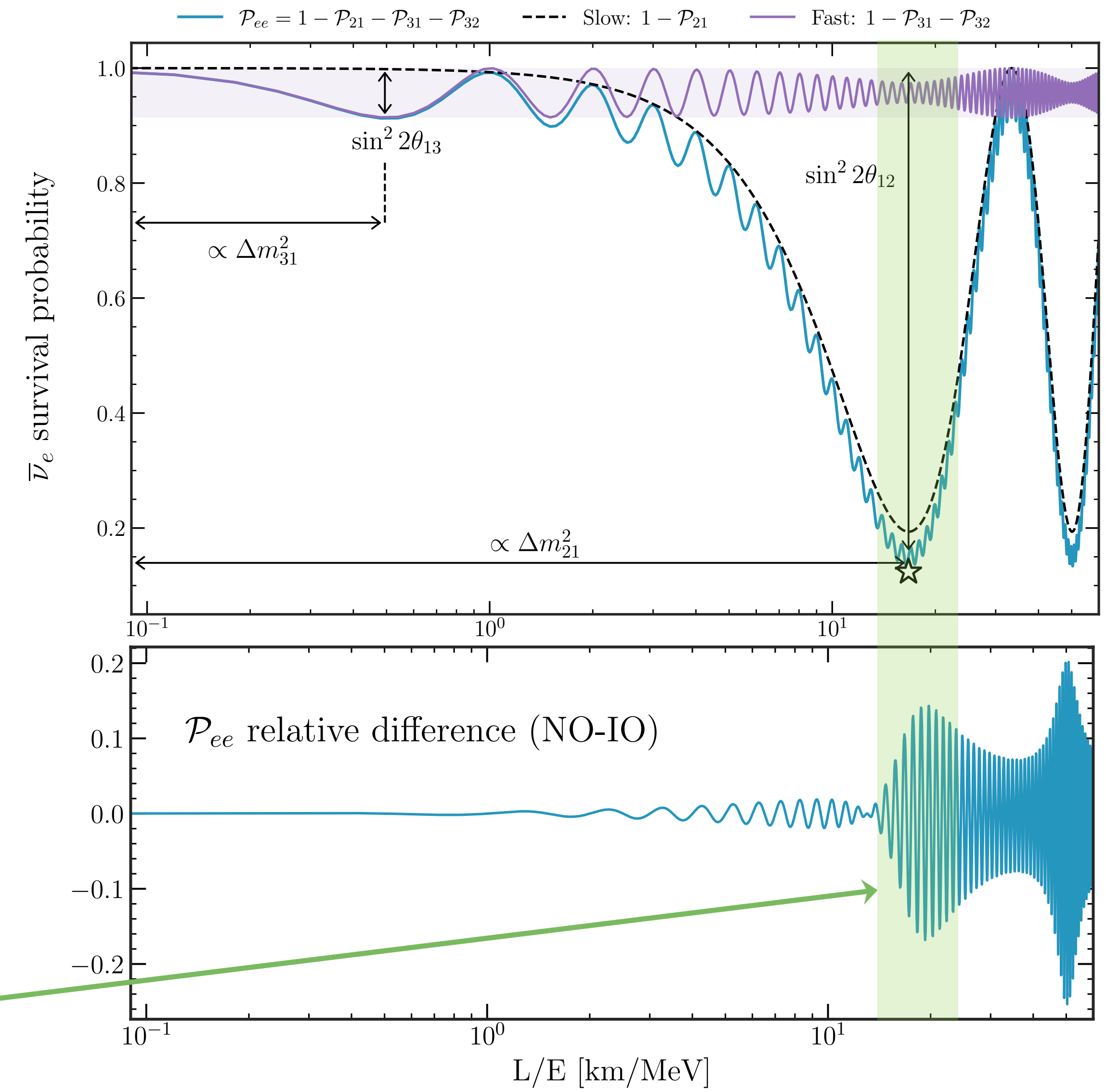
REACTOR $\bar{\nu}_e$ OSCILLATIONS IN JUNO

- Experimental observable: deficit in number of $\bar{\boldsymbol{\nu}}_e$ interactions → $\bar{\nu}_e$ **survival probability**

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

- Measurement of four oscillation parameters, no dependence on $\boldsymbol{\delta_{CP}}$ and $\boldsymbol{\theta_{23}}$
- Unique capability to simultaneously probe oscillations on both **slow** (Δm^2_{21}) and **fast** (Δm^2_{31}) scales
- **Optimized baseline** @ first solar oscillation **maximum** for NMO determination

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $\Delta_{ij} = \Delta m^2_{ij} L/4E$



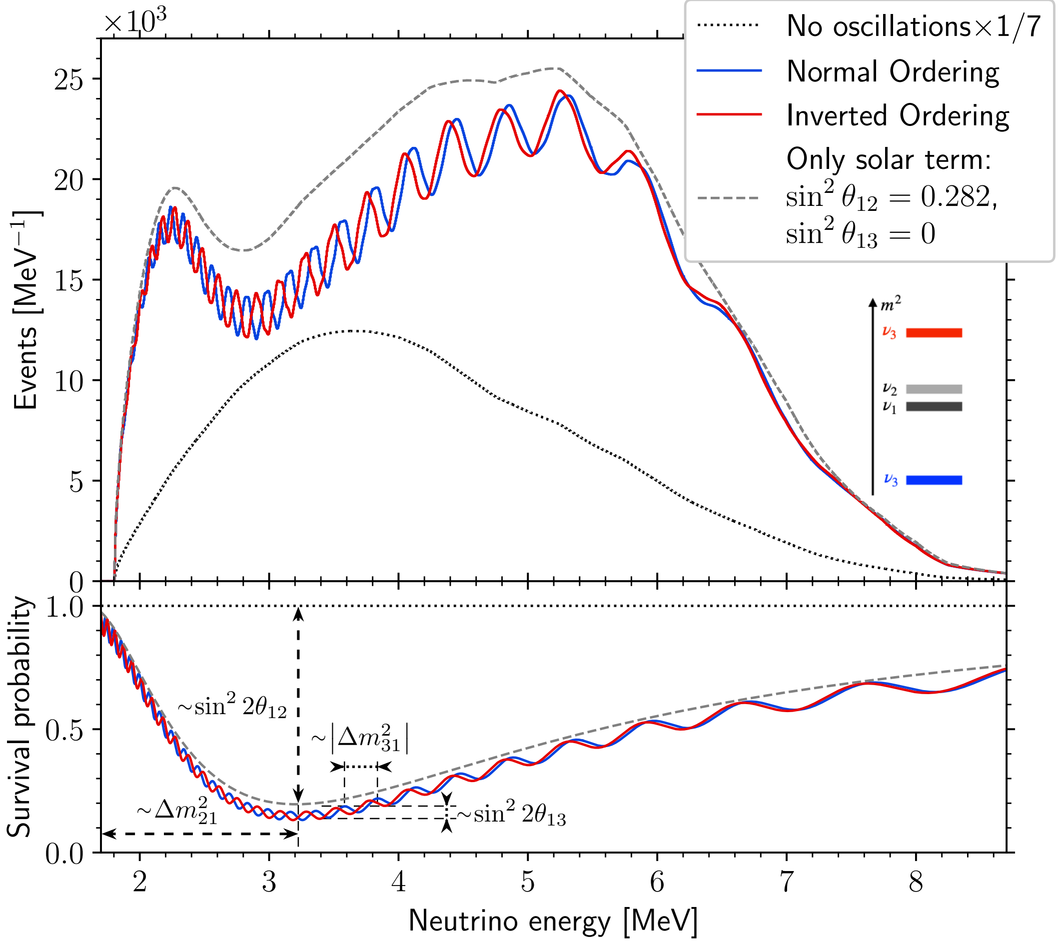
NEUTRINO MASS ORDERING IN JUNO

arXiv 2405.18008

NMO sensitivity through **interference** effects of oscillations driven by small and large mass splittings, Δm^2_{21} and Δm^2_{31} → Energy-dependent phase shift in the antineutrino spectrum

- ✶ First experiment to exploit vacuum-dominated oscillations for NMO determination
- ✶ Complementary to accelerator and atmospheric experiments
- ✶ Need to precisely and accurately resolve the fast *wiggles* in the energy spectrum → **high energy resolution** and good **control of the energy scale** are needed

Antineutrino spectrum at JUNO, 6 years of data taking, perfect energy resolution



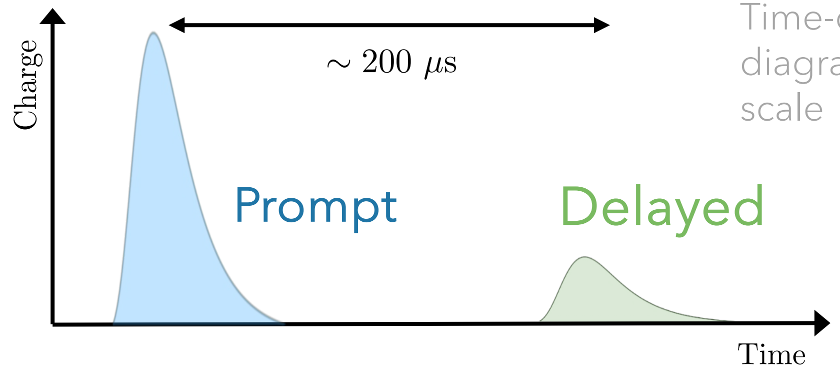
ANTINEUTRINO DETECTION IN JUNO

- ✶ The detection of reactor antineutrinos is done via the Inverse Beta Decay (IBD) reaction:

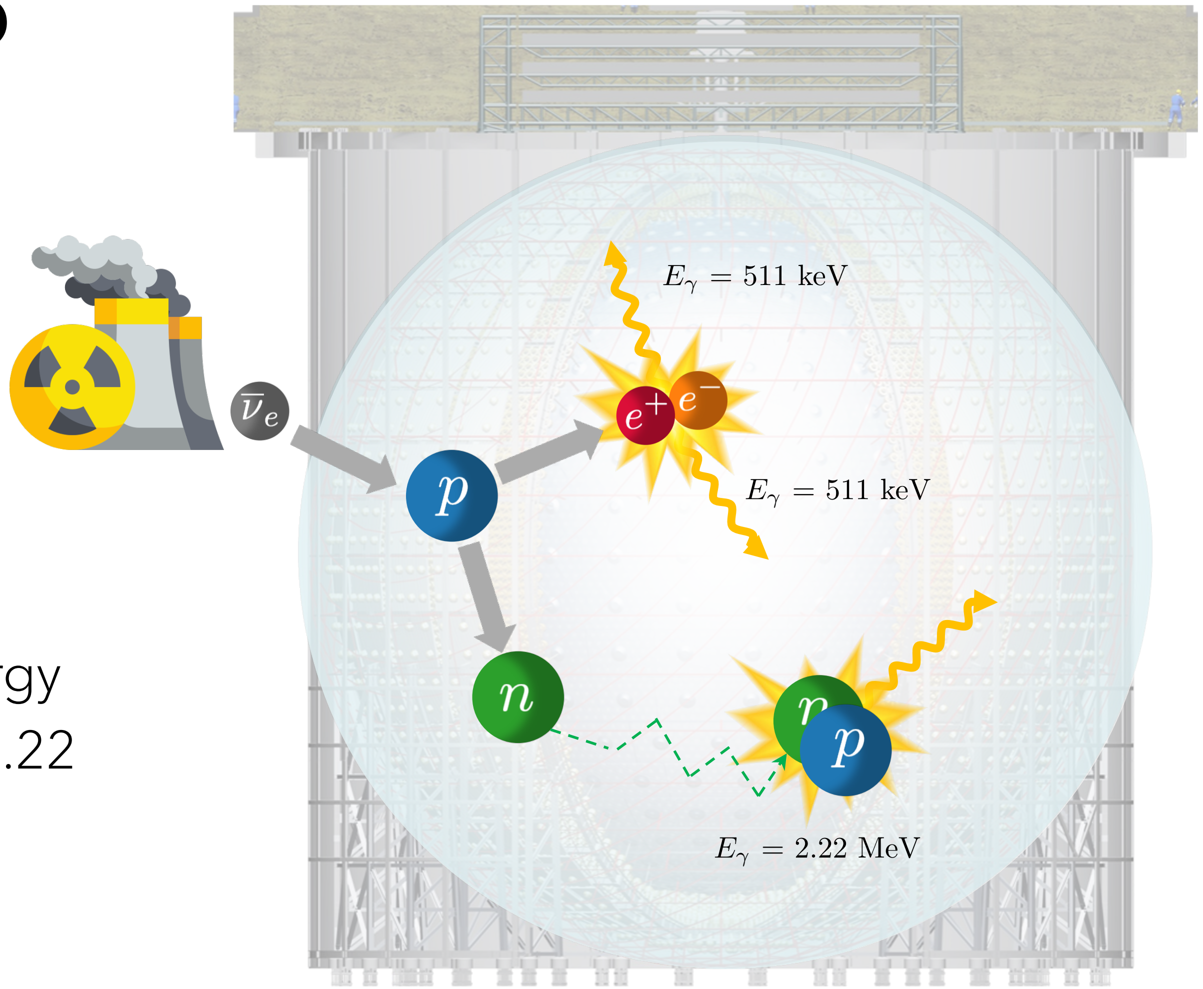
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Prompt signal: energy deposited by positron in liquid scintillator (LS), including annihilation energy

Delayed signal: neutron capture on H (or ^{12}C): 2.22 MeV (4.95 MeV) gamma emission, $\tau \approx 200\ \mu s$



Time-charge diagram not to scale



Close time and space correlation of prompt-delayed pairs
→ **efficient background suppression** and **event tagging**.

DETECTOR RESPONSE: WHAT JUNO MEASURES

Chinese Phys. C 46 123001

$$E_\nu \xrightarrow{\text{Interaction}} E_{\mathrm{dep}} \xrightarrow{\text{Light emission}} E_{\mathrm{vis}} \xrightarrow{\text{Light detection}} E_{\mathrm{rec}}$$

E_ν	E_{dep}	E_{vis}	E_{rec}
Antineutrino energy	Deposited energy	Visible energy	Reconstructed energy

DETECTOR RESPONSE: WHAT JUNO MEASURES

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E_ν → *Interaction* → $E_{\rm dep}$ → *Light emission* → $E_{\rm vis}$ → *Light detection* → $E_{\rm rec}$

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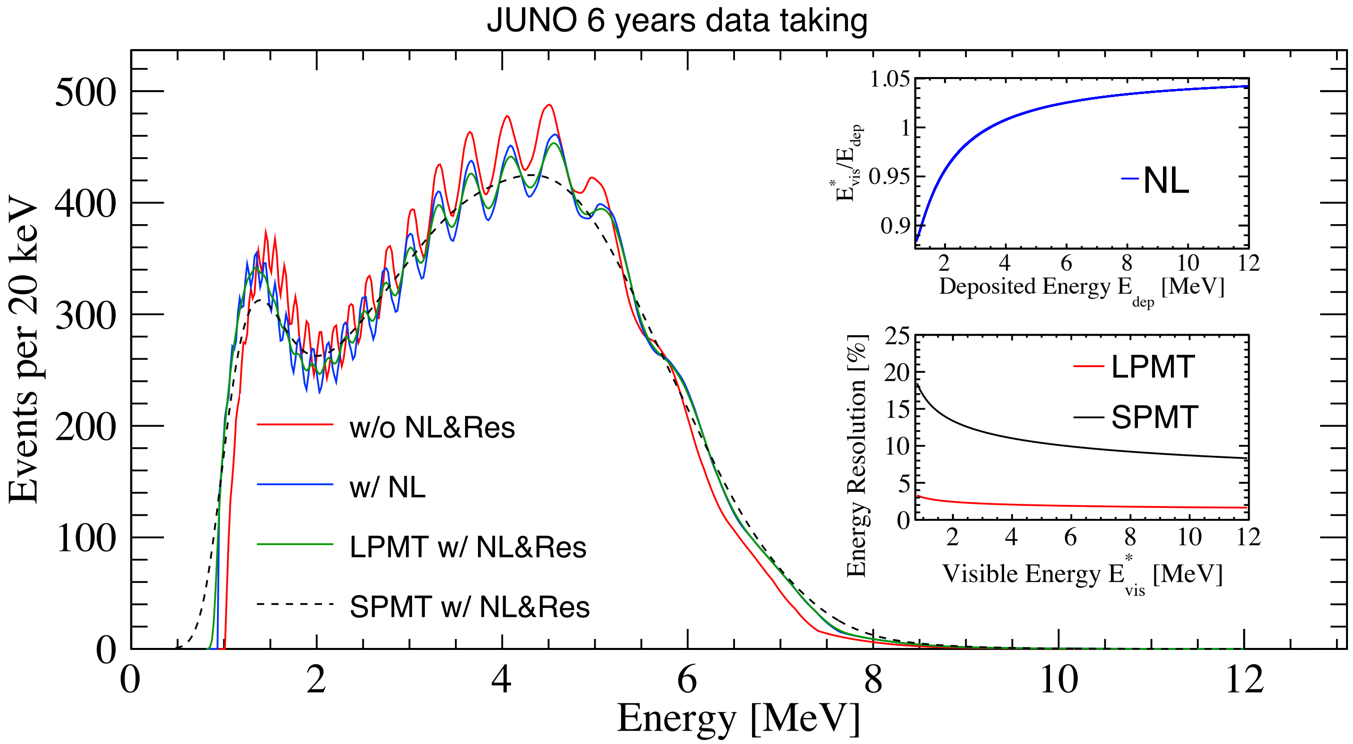


1. IBD reaction and cross section, e^+ deposited energy

$$E_{\rm dep} \simeq E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$$

2. Liquid scintillator non-linearity (NL), visible energy ∝ detected photoelectrons

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

3. Energy resolution (Res)

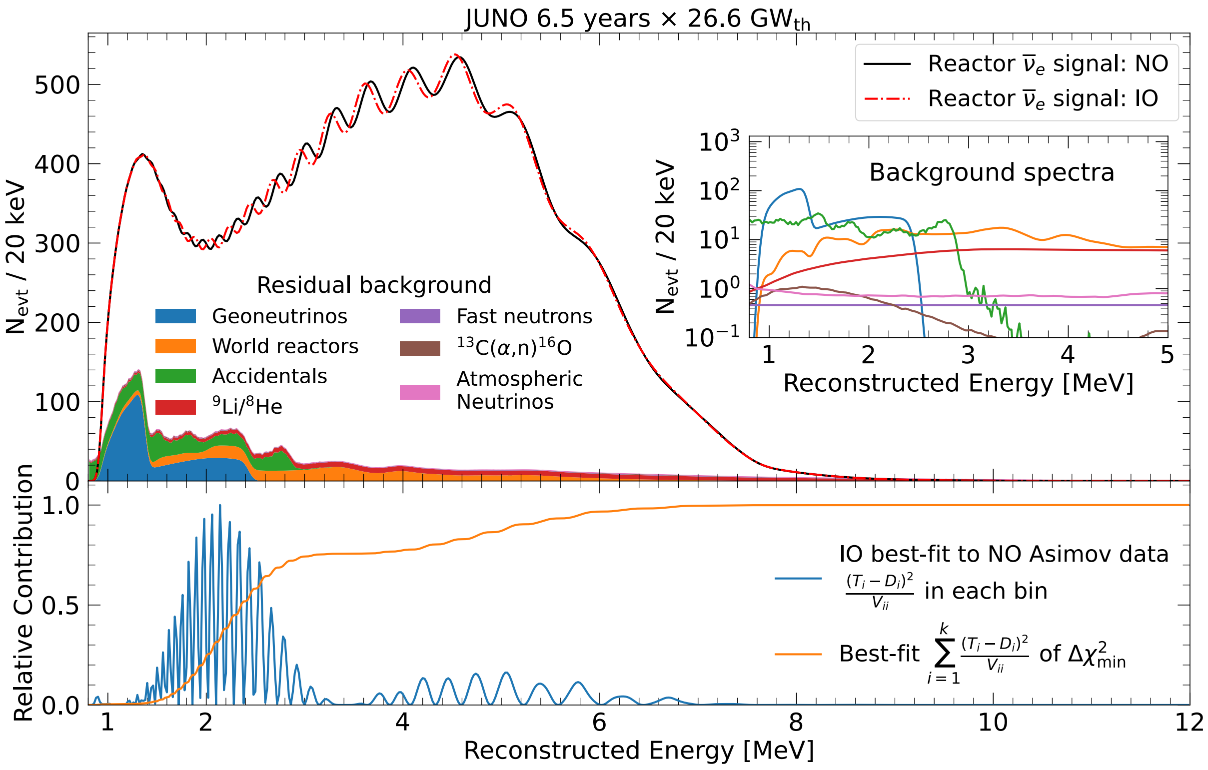
$$\frac{\sigma_{E_{\rm rec}}}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

EXPECTED SIGNAL AND BACKGROUNDS

arXiv 2405.18008

- Selection cuts are designed for the **IBD typical prompt-delayed signature**

Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1



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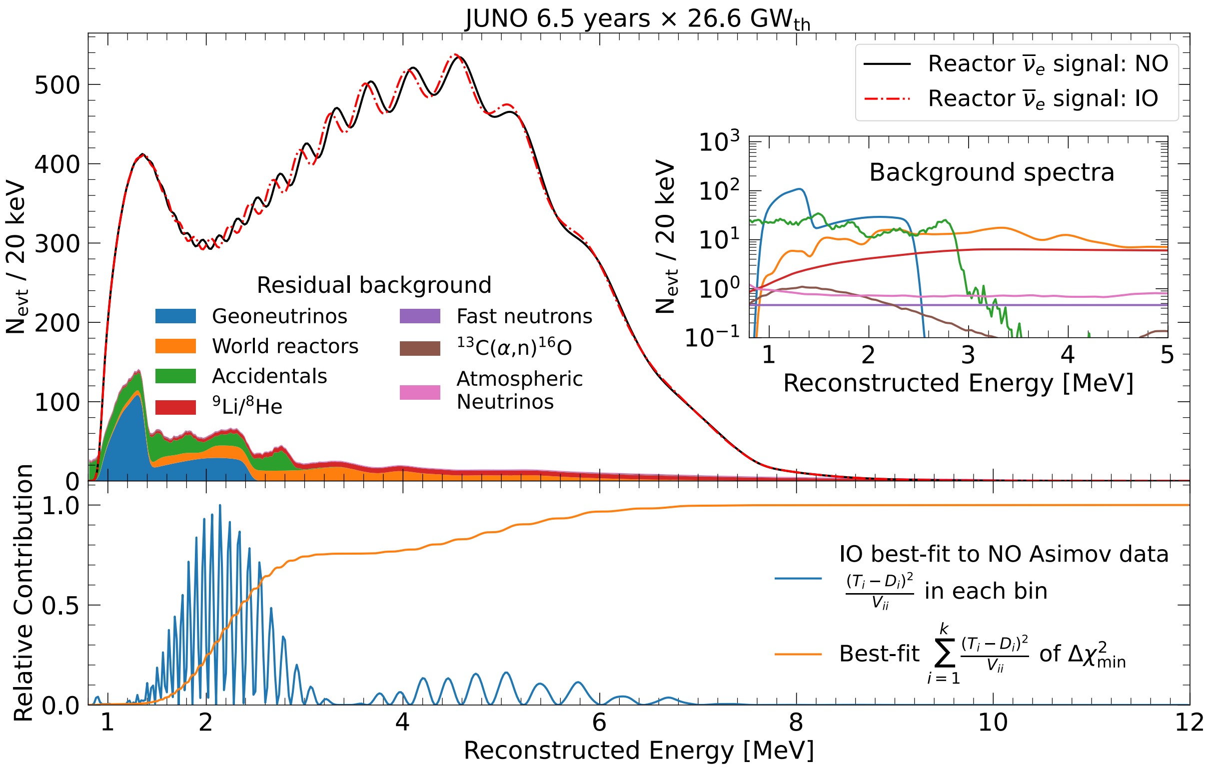


- ✶ Main backgrounds:
  - Accidental coincidences from natural radioactivity → Fiducial volume cut
  - Muon-induced isotopes → Muon veto
  - Irreducible backgrounds

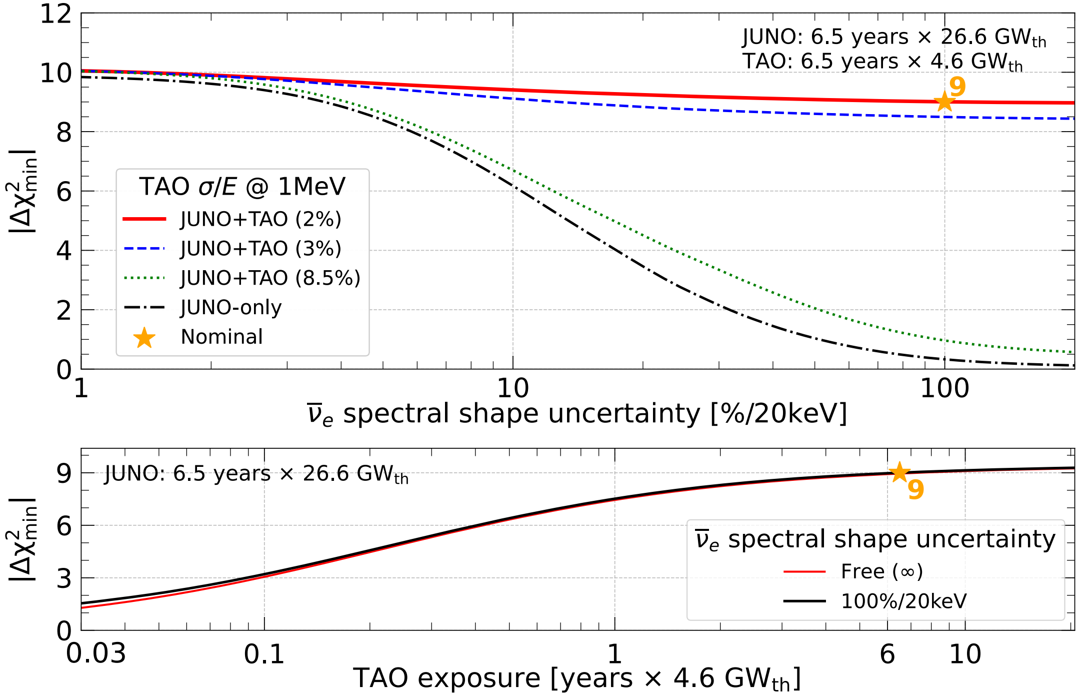
Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

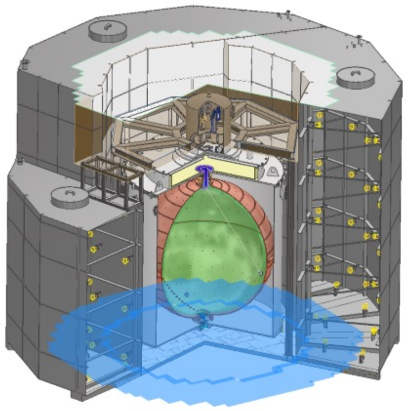
47.1/day reactor IBD candidates and ≈ 4/day residual background events → High s/b ratio

REFERENCE SPECTRUM WITH TAO

arXiv 2405.18008

- ✶ **T**aishan **A**ntineutrino **O**bservatory (TAO): satellite detector @ 44 m from one of the Taishan cores
- ✶ **Good knowledge of the reactor spectrum** is needed for JUNO oscillation physics goals
  - ✗ Theoretical models affected by large uncertainties
  - ✗ Discrepancy between models and data
  - ✓ **TAO will provide reference spectrum for JUNO at sub-percent precision**
- ✶ 2.8 ton Gd-loaded LS @ -50 °C
- ✶ Energy resolution: < 2 % at 1 MeV





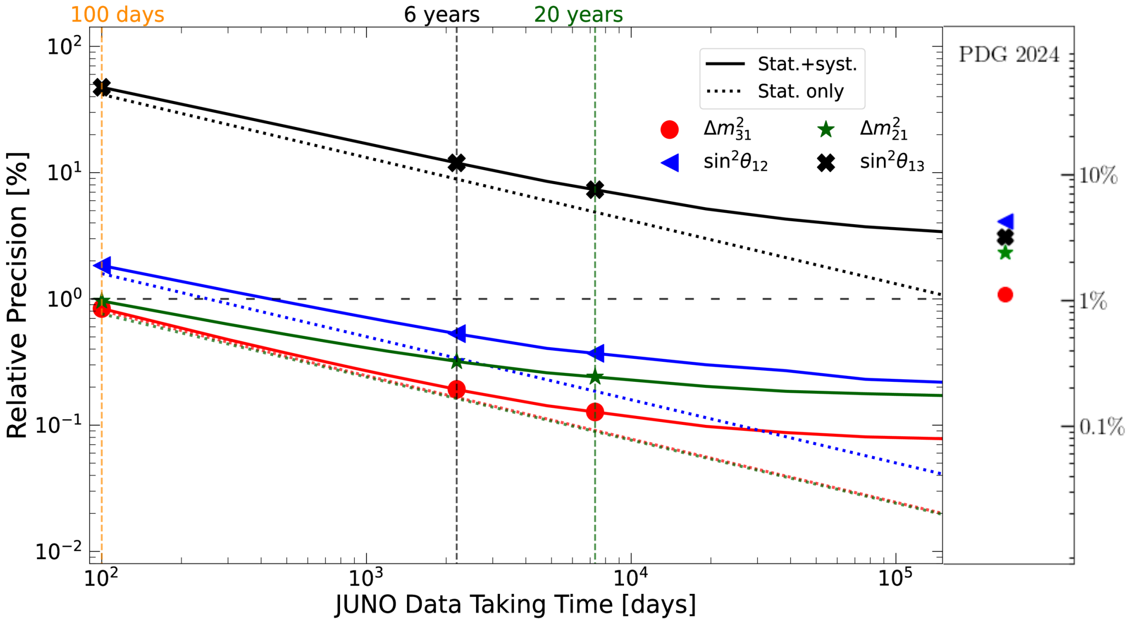
Model-independent measurement of reactor spectrum → **JUNO+TAO joint fit** introduced in NMO sensitivity study

SENSITIVITY STUDIES

PRECISION MEASUREMENT OF OSCILLATION PARAMETERS

- ✶ **Sub-percent precision** on Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31} → exceed global precision within the first year of data-taking

- ✶ **One order of magnitude improvement** in 6 years for Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}



	PDG 2024	JUNO 100 days	JUNO 6 years
Δm^2_{31}	1.1%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5%
$\sin^2\theta_{13}$	3.2%	47.9%	12%

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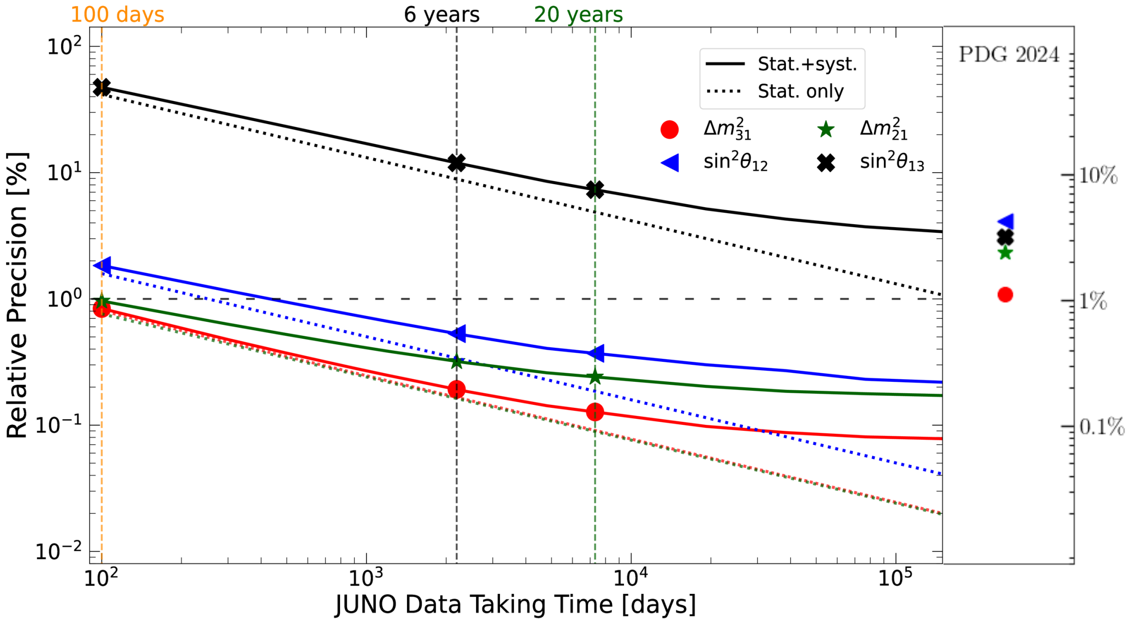

Impact of sub-percent precision

- ✶ Reduce parameter space for leptonic CP violation
- ✶ Precision enables to identify anomalies → new physics?
- ✶ Discriminator of neutrino masses and mixing models

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SYSTEMATIC UNCERTAINTIES

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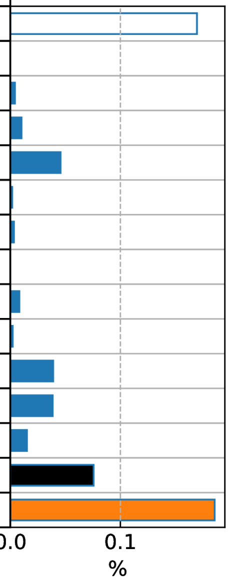
Dominant systematic uncertainties:

- ✶ Δm^2_{31}: Reactor spectral shape → importance of TAO for NMO
- ✶ Δm^2_{21}: backgrounds (in low energy region, i.e., geo-neutrinos)
- ✶ $\sin^2\theta_{12}$, $\sin^2\theta_{13}$: normalization factors (flux, detector efficiency)
- ✶ Matter effects are small but *matter*!

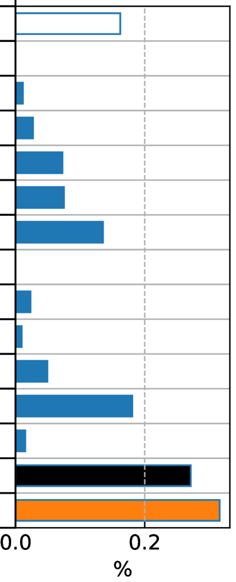
CPC 40 091001, PLB 803 (2020) 135354

Note: spectrum rich in information, provides good constraint on rate normalization

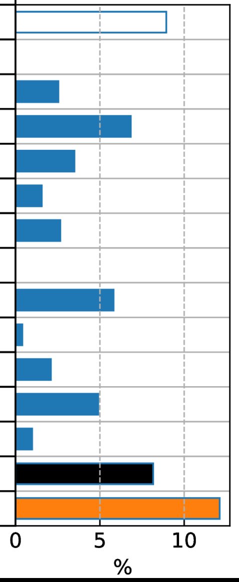
Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19



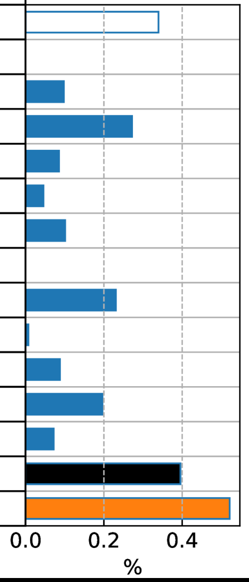
Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32



$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11



$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52



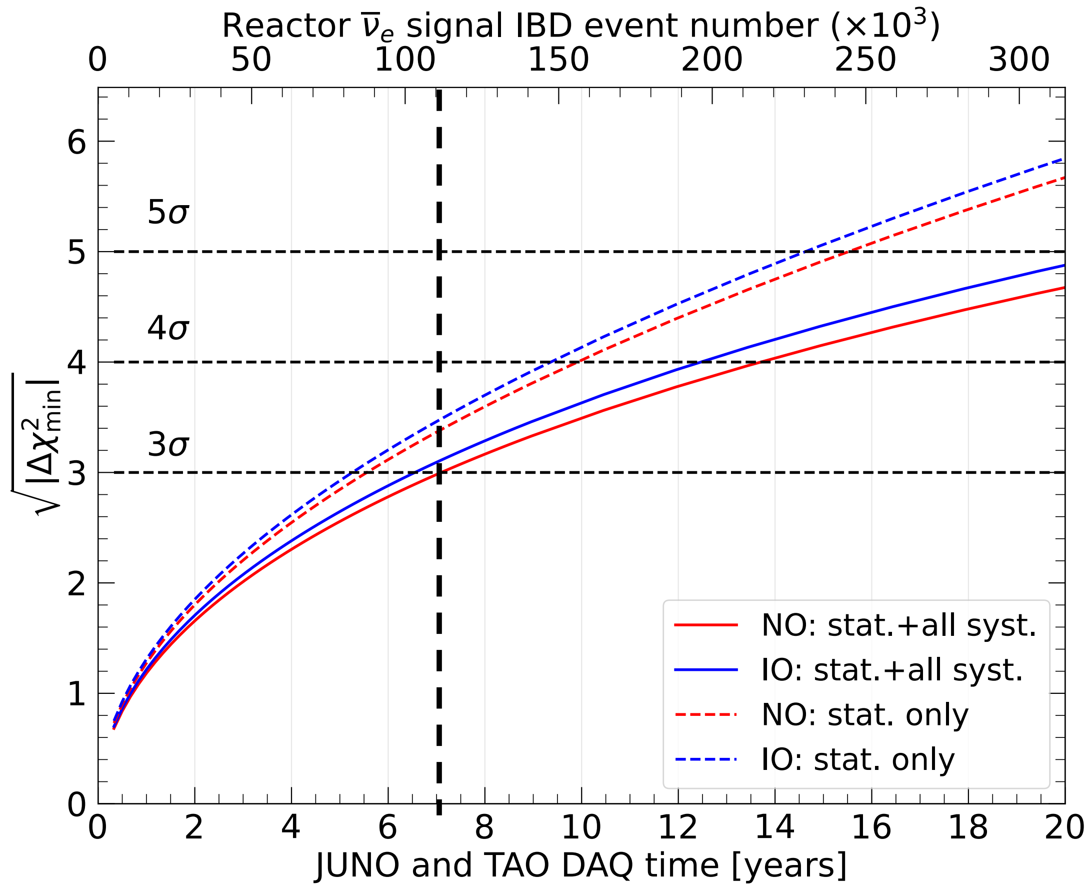
DETERMINATION OF NEUTRINO MASS ORDERING

arXiv 2405.18008

- ✶ Fit data against both NO and IO scenarios
  → Median sensitivity discriminator:

$$\Delta\chi^2_{\mathrm{MO}} = |\chi^2_{\mathrm{min}}(\mathrm{NO}) - \chi^2_{\mathrm{min}}(\mathrm{IO})|$$

- ✶ 3σ median sensitivity in **~7.1 years of data taking** via **only reactor $\bar{\nu}_e$**, with 11/12 duty cycle (6.5 years × 26.6 GW_{th})



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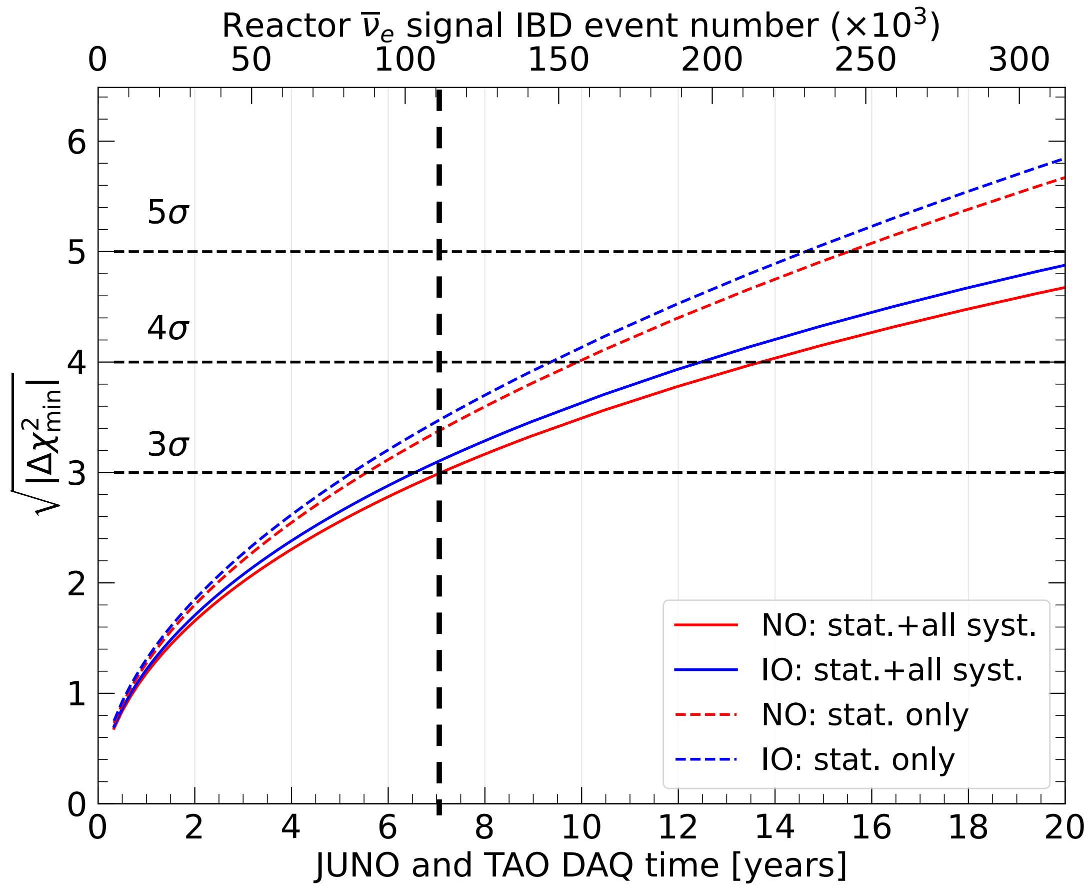
- ✶ Dominant systematics: reference spectrum uncertainty, nonlinearity, and backgrounds



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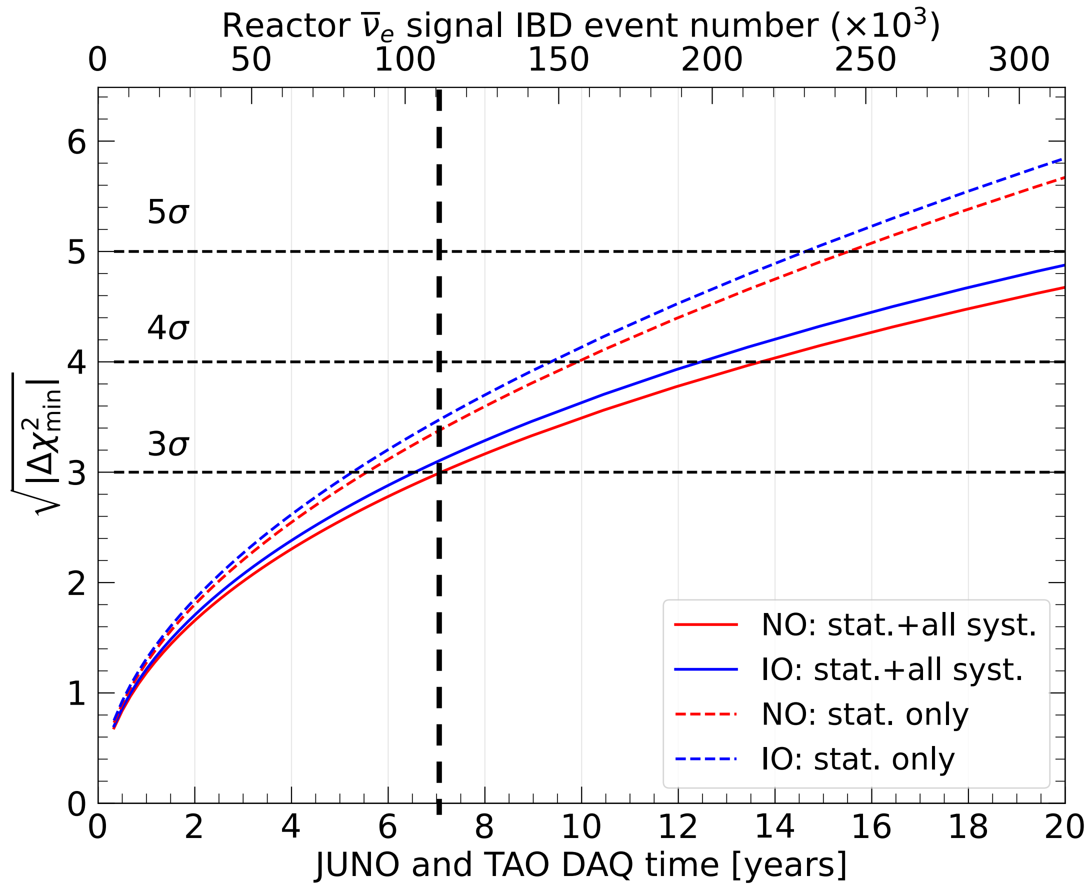


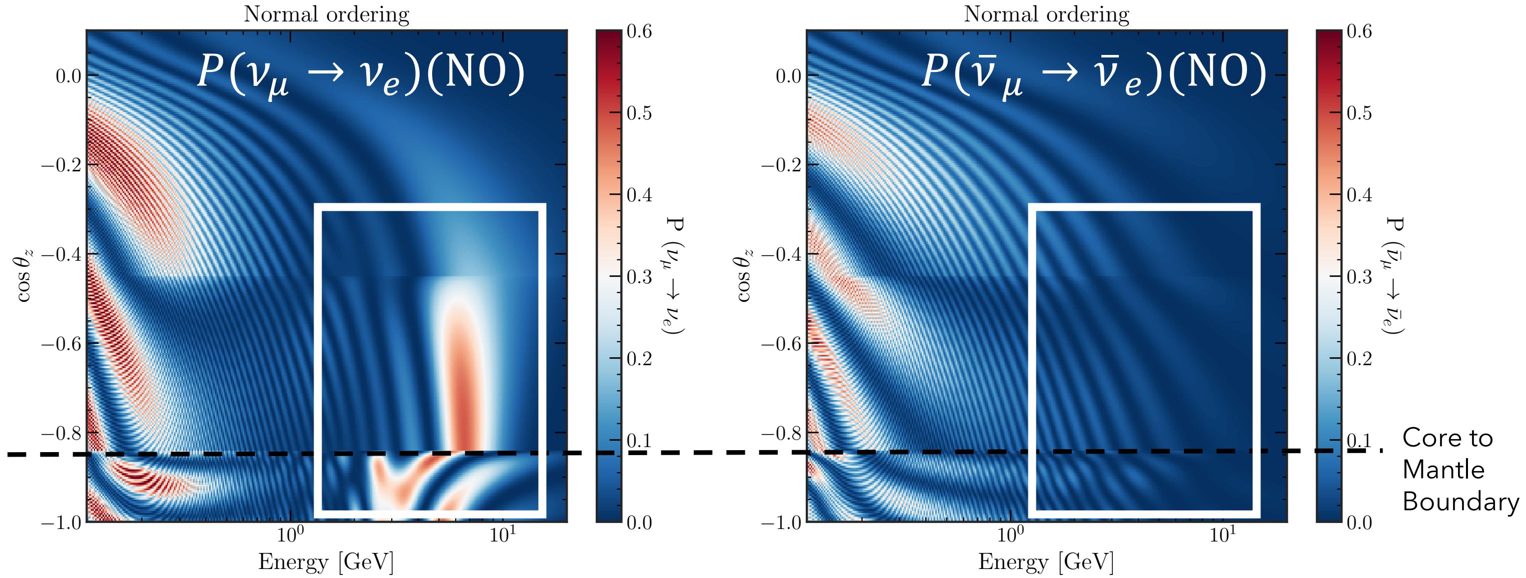
- ✶ Sensitivity boost via atmospheric $\nu_\mu/\bar{\nu}_\mu$ in JUNO → Analysis ongoing

- ✶ Vacuum-dominated oscillations, no dependence on $\boldsymbol{\delta_{CP}}$ and $\boldsymbol{\theta_{23}}$ → Complementarity/synergy with LBL and atmospheric experiments Phys. Rev. D 72, 013009 , Phys. Rev. D.88.013008, SciRep12,5393(2022) , Phys. Rev. D 101, 032006, JHEP 03 (2022) 055

BOOSTING NMO SENSITIVITY WITH ATMOSPHERIC ν

- ✶ First measurement of atmospheric neutrinos with a LS detector → sub-GeV to multi-GeV energy range
- ✶ NMO through **matter effects**, complementary to reactor antineutrinos

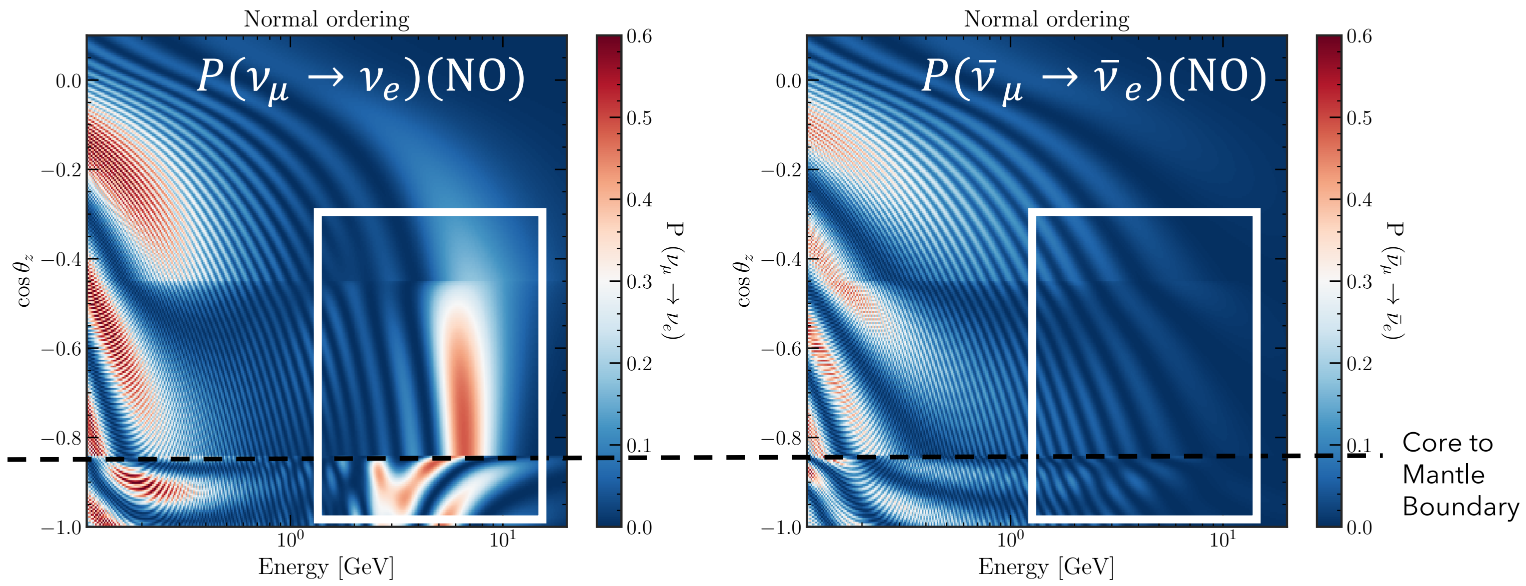
Flavor transition enhanced for **neutrinos** (antineutrinos) if **NO** (IO)



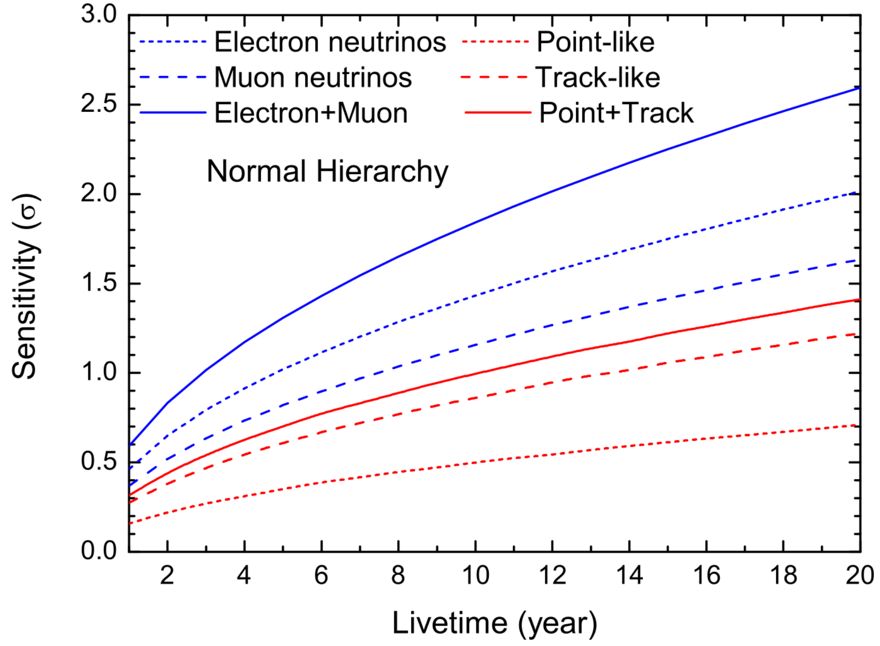
BOOSTING NMO SENSITIVITY WITH ATMOSPHERIC ν

- ✶ First measurement of atmospheric neutrinos with a LS detector → sub-GeV to multi-GeV energy range
- ✶ NMO through **matter effects**, complementary to reactor antineutrinos

Flavor transition enhanced for **neutrinos** (antineutrinos) if **NO** (IO)



J. Phys. G. 43 030401



- ✶ Expected > 3σ in 6 years in combination with reactor antineutrinos
- ✶ Re-evaluation of sensitivity in progress

CONCLUSIONS

- ✶ JUNO has a rich **oscillation** physics program → reactor $\bar{\nu}_e$, atmospheric $\nu/\bar{\nu}$, solar ν_e, sterile ν with TAO

- ✶ First experiment to simultaneously probe **two oscillation frequencies**

- ✶ Stringent experimental requirements needed for ambitious goals:

  - ✶ **Sub-percent precision** on Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}

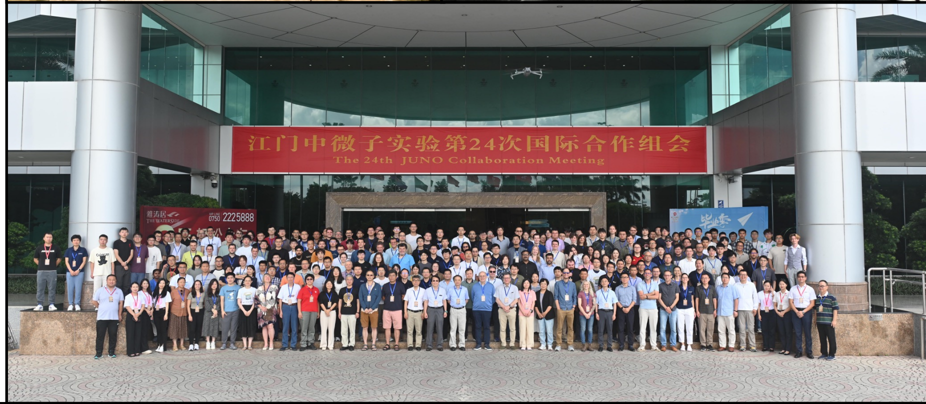
  - ✶ **3σ NMO median sensitivity** in ~ 7.1 years of data taking via only reactor $\bar{\nu}_e$

  - ✶ NMO through interference and vacuum-dominated oscillations → complementarity with experiments exploiting matter effects

- ✶ Expect to start filling soon… Stay tuned for exciting results!







BACKUP

SENSITIVITY STUDIES: WHAT'S NEW

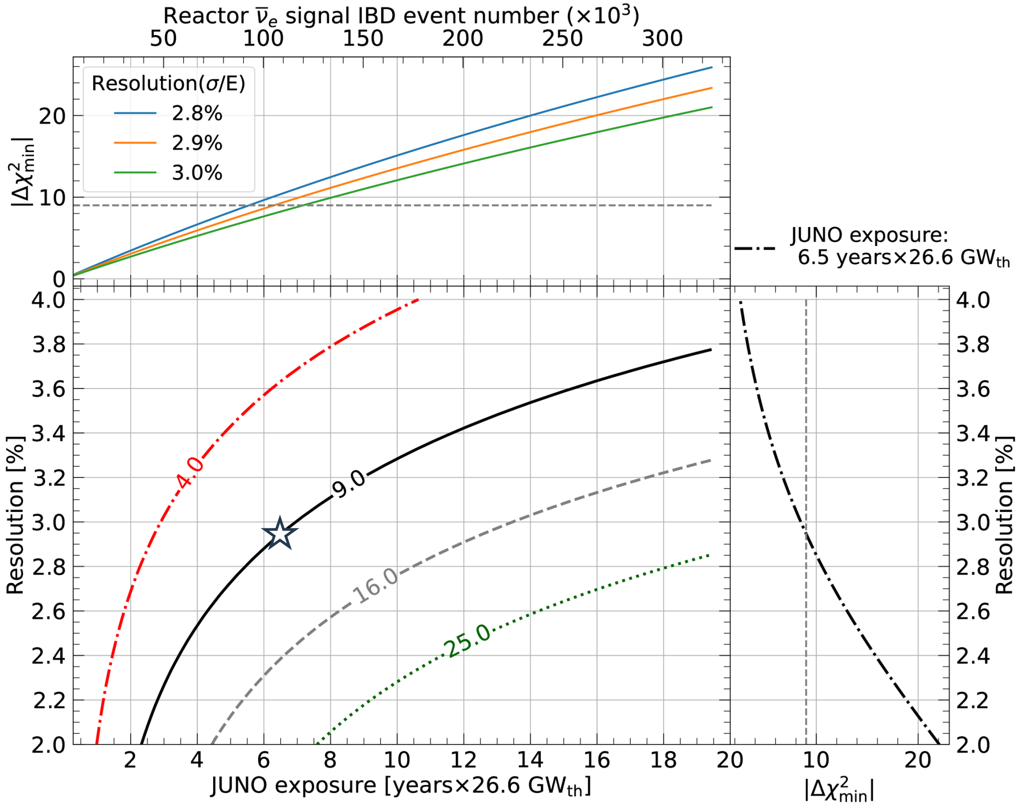
- ✶ 2022-2024: Oscillation parameters and NMO sensitivity studies update
- ✶ **Better knowledge of JUNO detector:** realistic MC simulations and commissioning data → updated detector response, more detailed evaluation of backgrounds

Some changes:

- ✓ More realistic PMT and LS optical models + larger *measured* PMT photon detection efficiency → Energy resolution improvement 3% → 2.95%
- ✓ Optimized event selection and muon veto strategy → IBD selection efficiency 73% → 82%
- ✗ Two Taishan reactors not built → ~ 25% flux decrease
- ✗ Lower overburden due to shift in experimental hall → ~30% muon flux increase

SENSITIVITY STUDIES: WHAT'S NEW

- ✶ NMO sensitivity studies update, changes with respect to arXiv 1507.05613



Changes	Design	Now
Thermal power	36 GW_{th}	26.6 GW_{th} (26% ↓)
Signal rate	60 / day	47.1 / day (22% ↓)
Overburden / Muon flux in LS	~700 m / 3 Hz	~650 m / 4Hz (33% ↑)
Muon veto efficiency	83%	91.6% (11%↑)
Backgrounds	3.75 / day	4.11 / day (10%↑)
Energy resolution	3.0 % @ 1 MeV	2.95 % @ 1 MeV (2%↑)
Oscillation parameters	arXiv 1312.2878	PDG 2020
Shape uncertainty	1% / 36 keV	JUNO + TAO
DAQ time to get 3σ significance	< 6 years	~ 7.1 years

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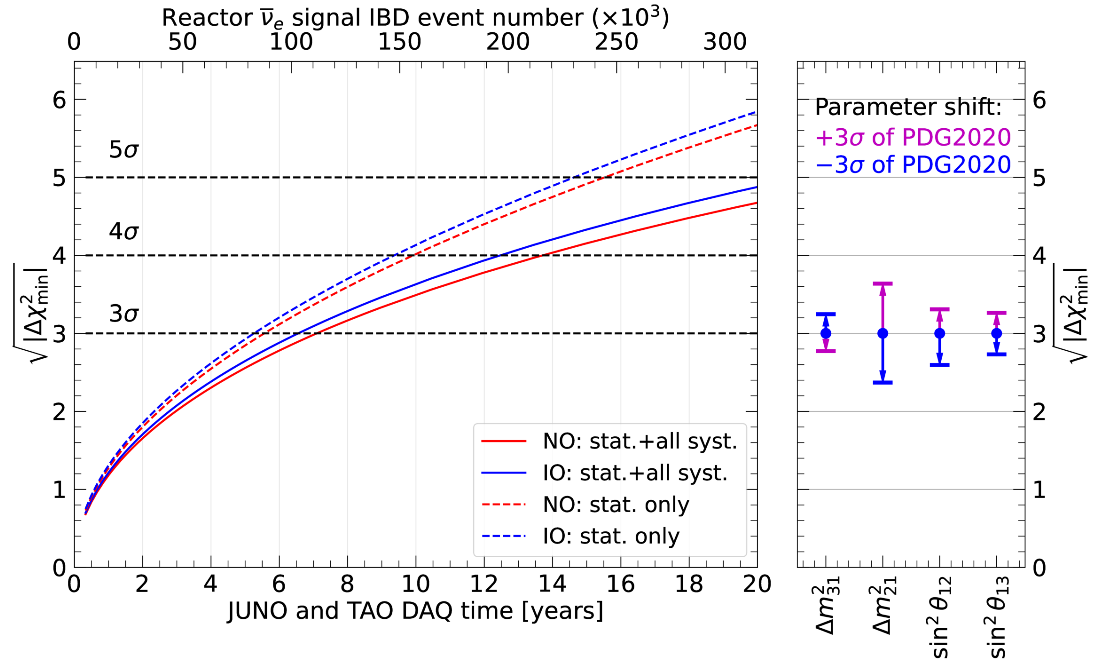

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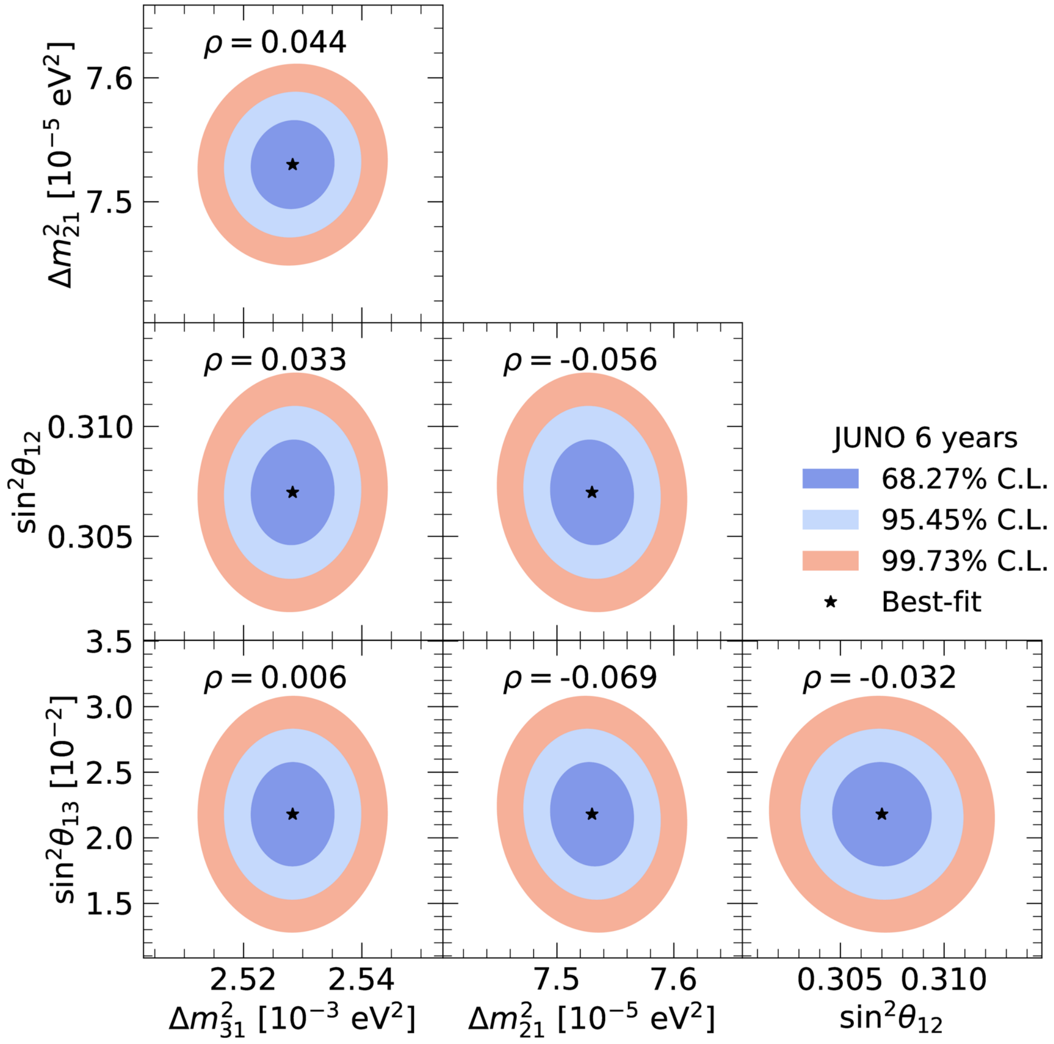
PRECISION MEASUREMENT OF OSCILLATION PARAMETERS

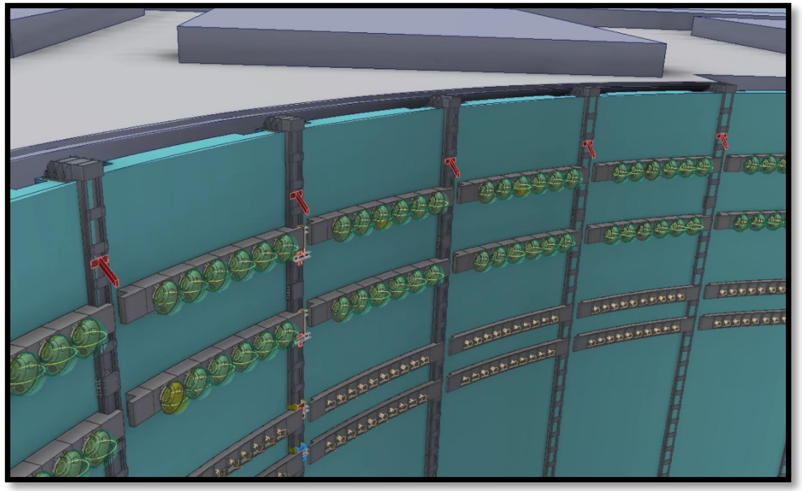
- ✶ Almost no correlation between parameters → solid measurement
- ✶ Constraint on $\sin^2\theta_{13}$ has a minor impact, < 0.3%
- ✶ Negligible impact of NMO choice

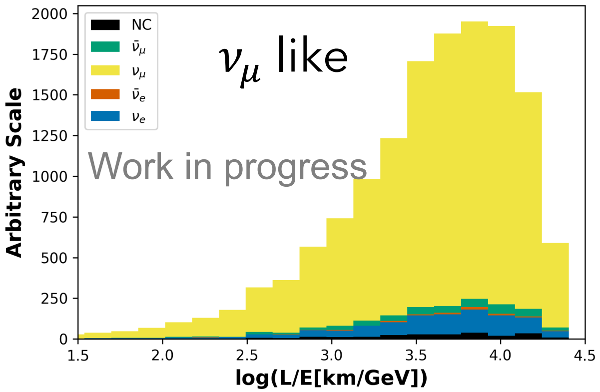


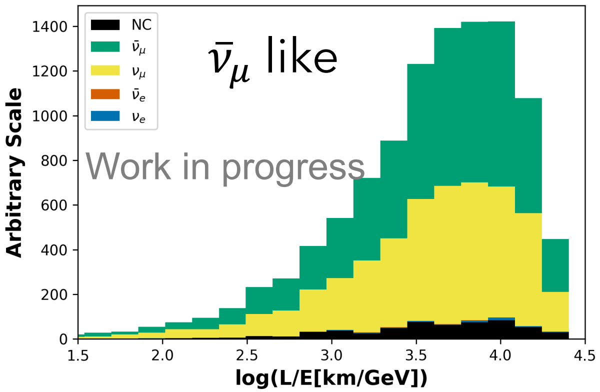
BOOSTING NMO SENSITIVITY WITH ATMOSPHERIC ν

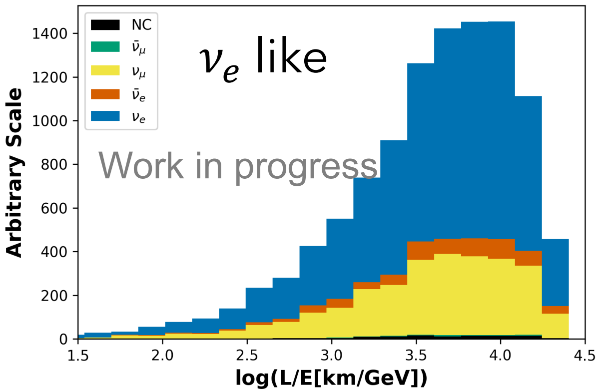
- ✶ Estimation of joint reactor-atmospheric sensitivity in progress
- ✶ Good direction reconstruction and flavor identification are needed
- ✶ Novel machine learning and conventional techniques for e/μ, $\nu/\bar{\nu}$ separation under development

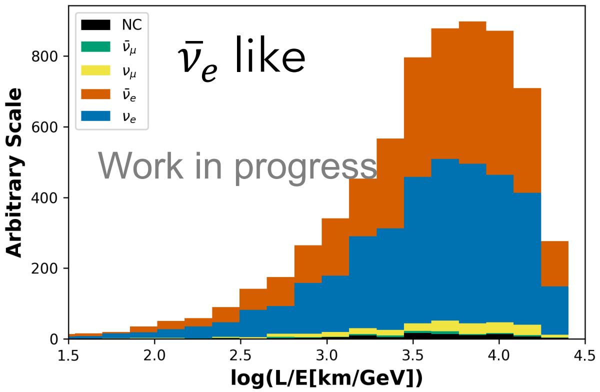
Plan to install additional PMTs on top wall of the water pool to improve PID and direction reconstruction





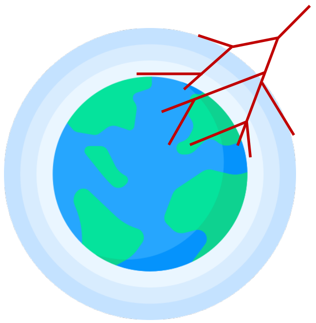






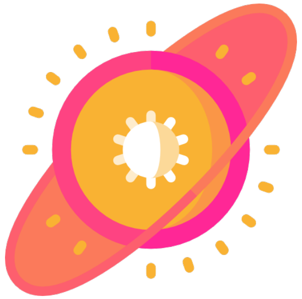
NEUTRINO SOURCES IN JUNO

Reactor $\bar{\nu}_e$

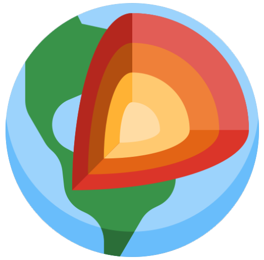


Atmospheric $\nu/\bar{\nu}$

Solar ν_e



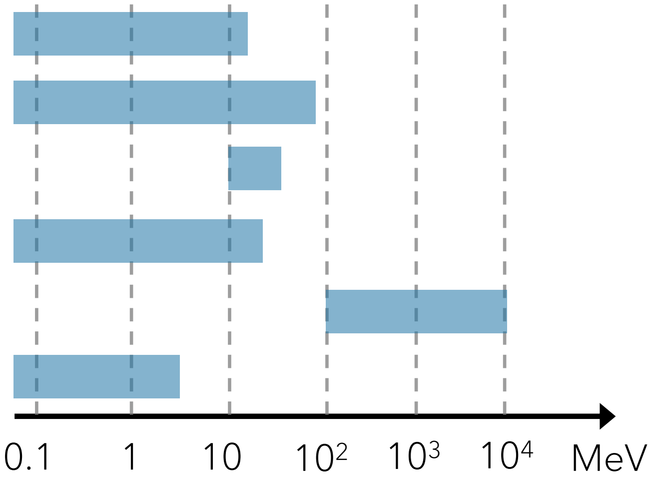
Supernovae



Geo-neutrinos

Source	Expected rate
Reactor	~ 60 / day
SN burst	~ 7300 @ 10 kpc in few s
DSNB	~ 2-4 / year
Solar (^8B)	O(100) / day
Atmospheric	~ O(100) /year
Geo-neutrinos	~ 400 / year

Energy range

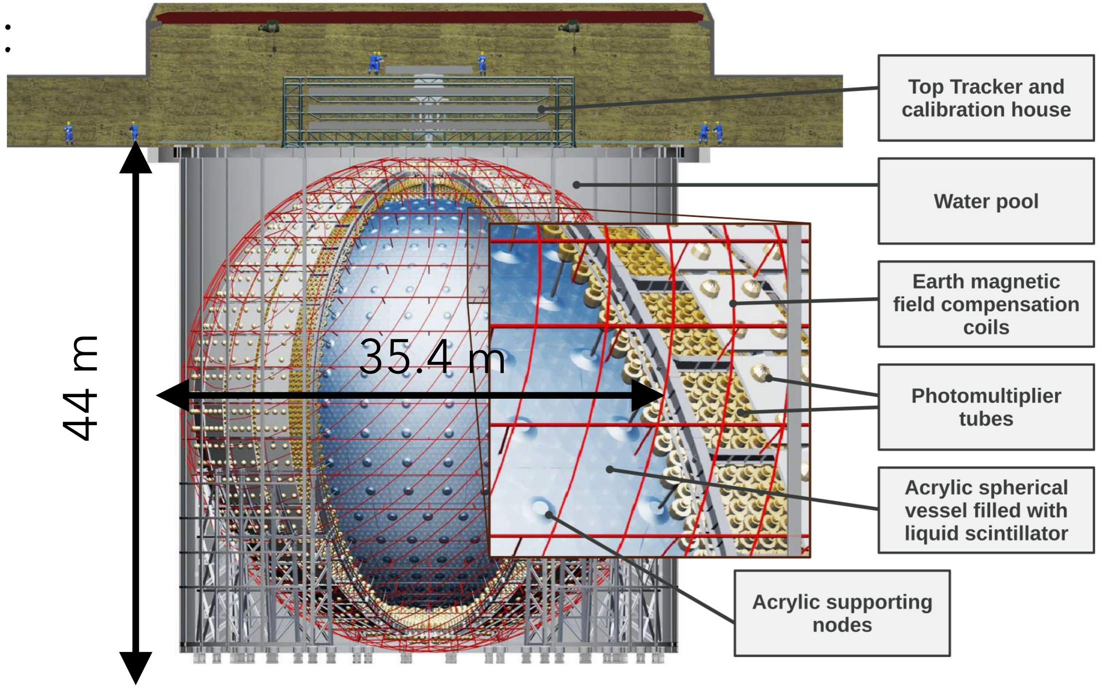


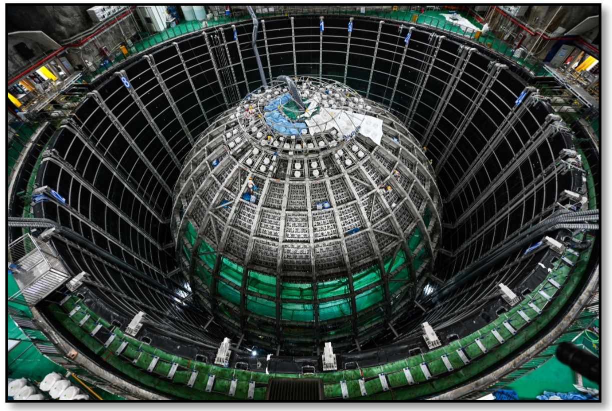
JUNO KEY EXPERIMENTAL FEATURES

[PPNP 123 (2022): 103927](#)

Detector design is driven by ambitious physics goals:

- ✶ Large statistics
  - ✓ Huge LS target mass
  - ✓ Powerful nuclear reactors





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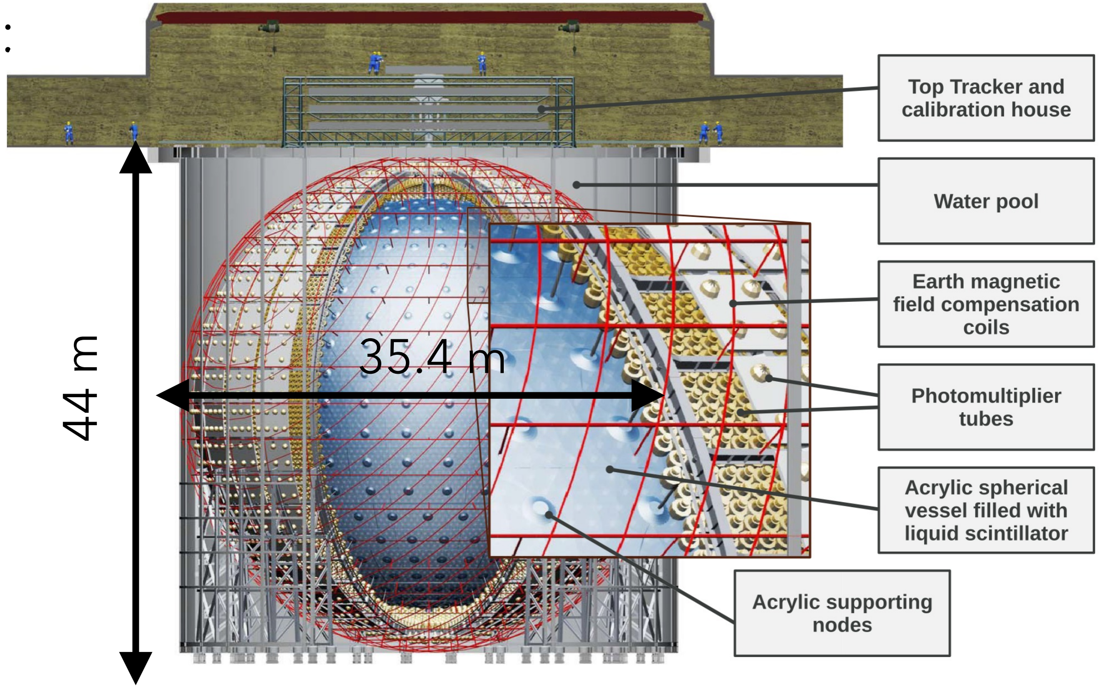
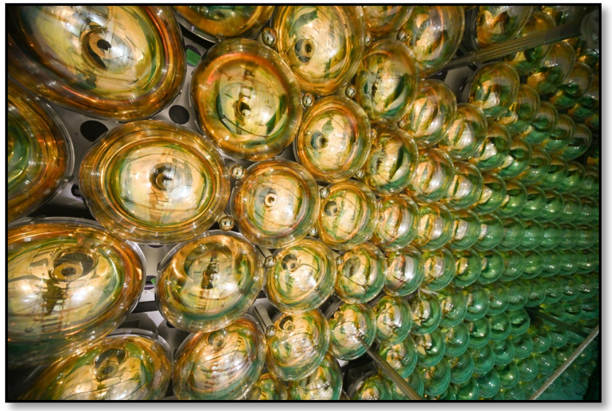
  - ✓ Total photo-coverage ≈ 78%
- ✶ Control of non-linear energy scale within 1%
  - ✓ Comprehensive calibration program
- ✶ Low background
  - ✓ 650 m underground
  - ✓ LS purification system and material screening
  - ✓ Efficient veto systems





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- ✶ Low background
  - ✓ 650 m underground
  - ✓ LS purification system and material screening
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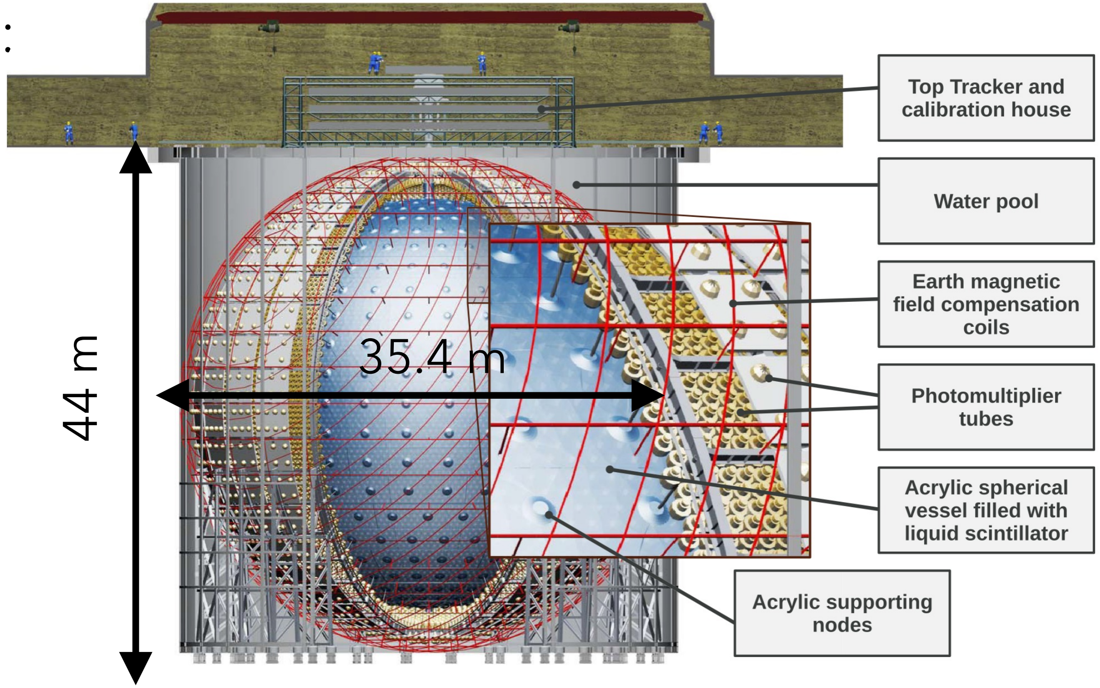
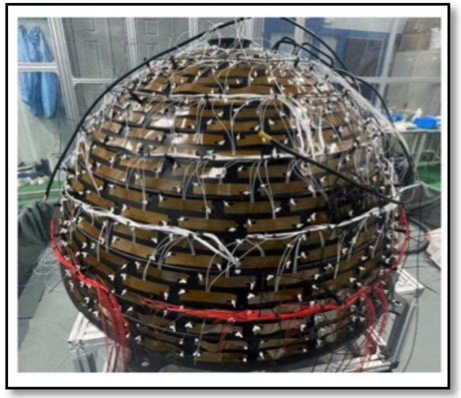
- ✶ Accurate knowledge of reactor spectra
  - ✓ Satellite near detector: **Taishan Antineutrino Observatory (TAO)** at 44 m from Taishan reactor





STERILE NEUTRINO SEARCHES WITH JUNO-TAO

- ✶ JUNO will also deploy a satellite detector TAO (Taishan Antineutrino Observatory) at 44 m from the Taishan NPP
- ✶ Short baseline → great potential for sterile neutrino searches
- ✶ Sensitivity needs to be re-assessed with new TAO baseline of 44 m

arXiv:2005.08745