JUNO Neutrino Mass Ordering Sensitivity

Jinnan Zhang [1,2] **(张金楠)**

On behalf of the JUNO collaboration

August 11, 2022

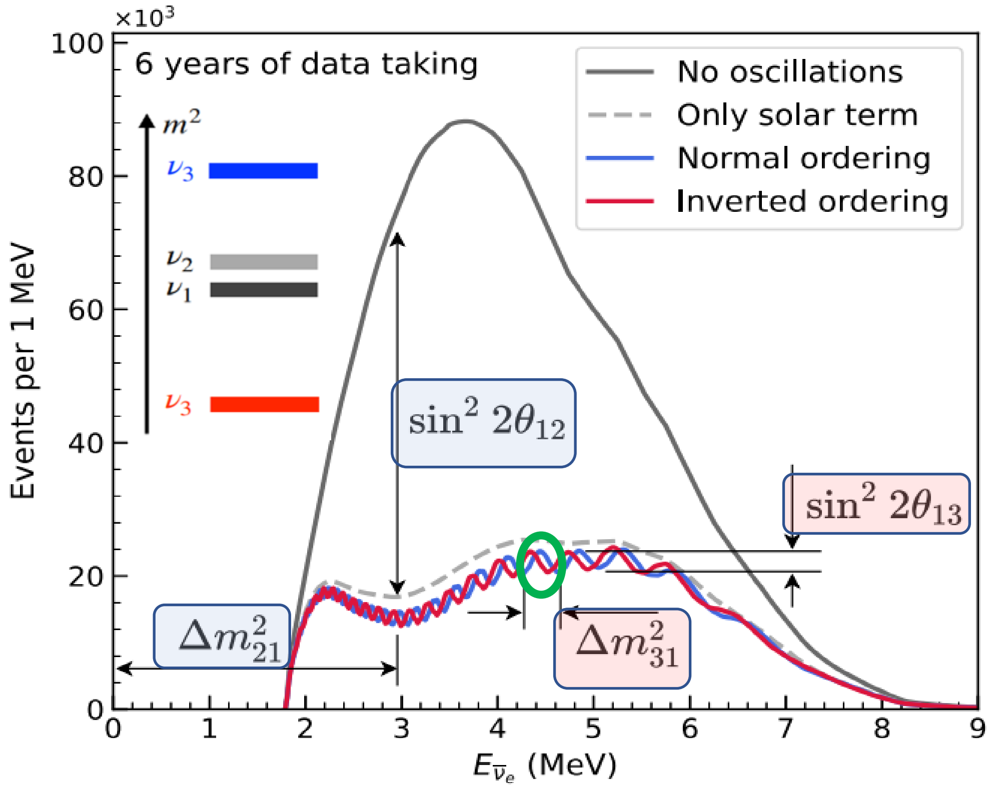
中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

E-mail: zhangjinnan@ihep.ac.cn

[1] 中国科学院高能物理研究所
[2] 中国科学院大学

Outline

- Introduction
- Reactor neutrino analysis of JUNO
  - Reactor $\overline{\nu}_e$ flux and detection
  - Detector response
  - NMO sensitivity
- Atmospheric neutrinos of JUNO
  - Complementary measurement
- Summary



Neutrino Mixing Open Question

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

Flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

parametrization

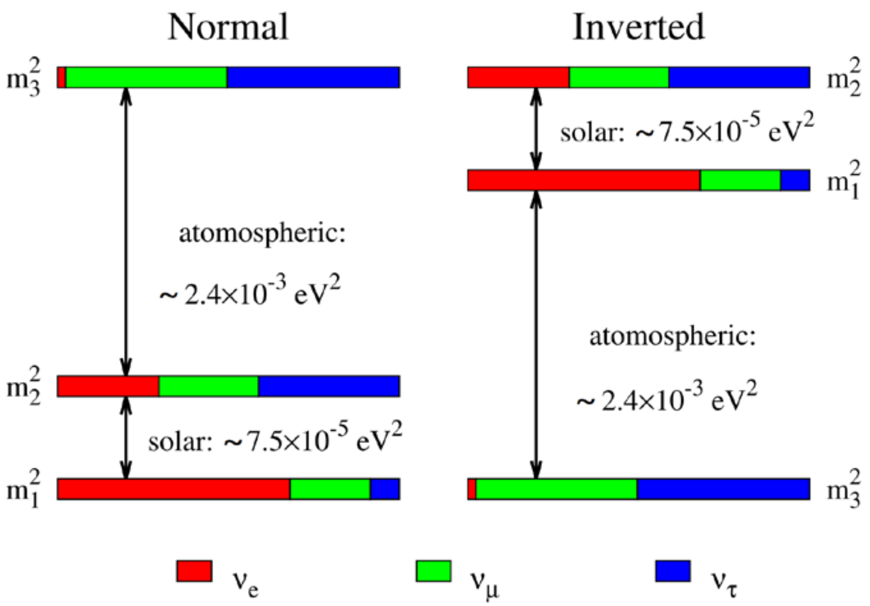
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 49°$	$\theta_{13} \sim 9°$	$\theta_{12} \sim 34°$	
Atmospheric Accelerator	Reactor Accelerator	Solar Reactor	$0\nu\beta\beta$

JHEP09(2020)178

Neutrino oscillation:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_{i=1}^{3} \sum_{j=1}^{3} U_{\alpha i}^* U_{\beta j} \langle \nu_j | \nu_i(t) \rangle \right|^2$$



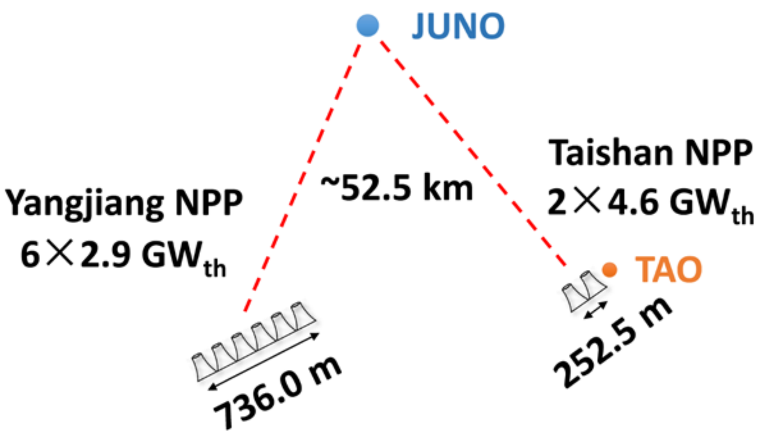
- ν_1 has the largest component of the ν_e.
- ν_3 has the smallest component of the ν_e.

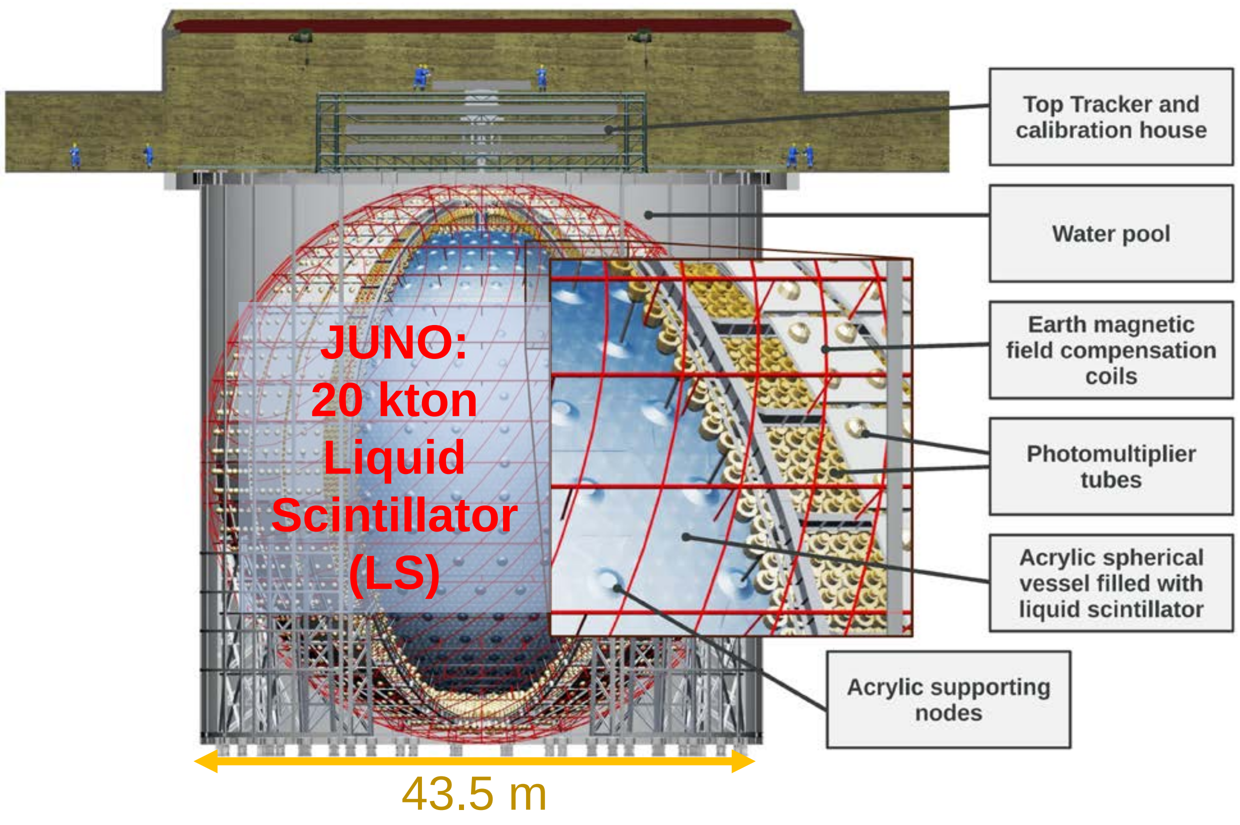
- **Neutrino mass ordering:**

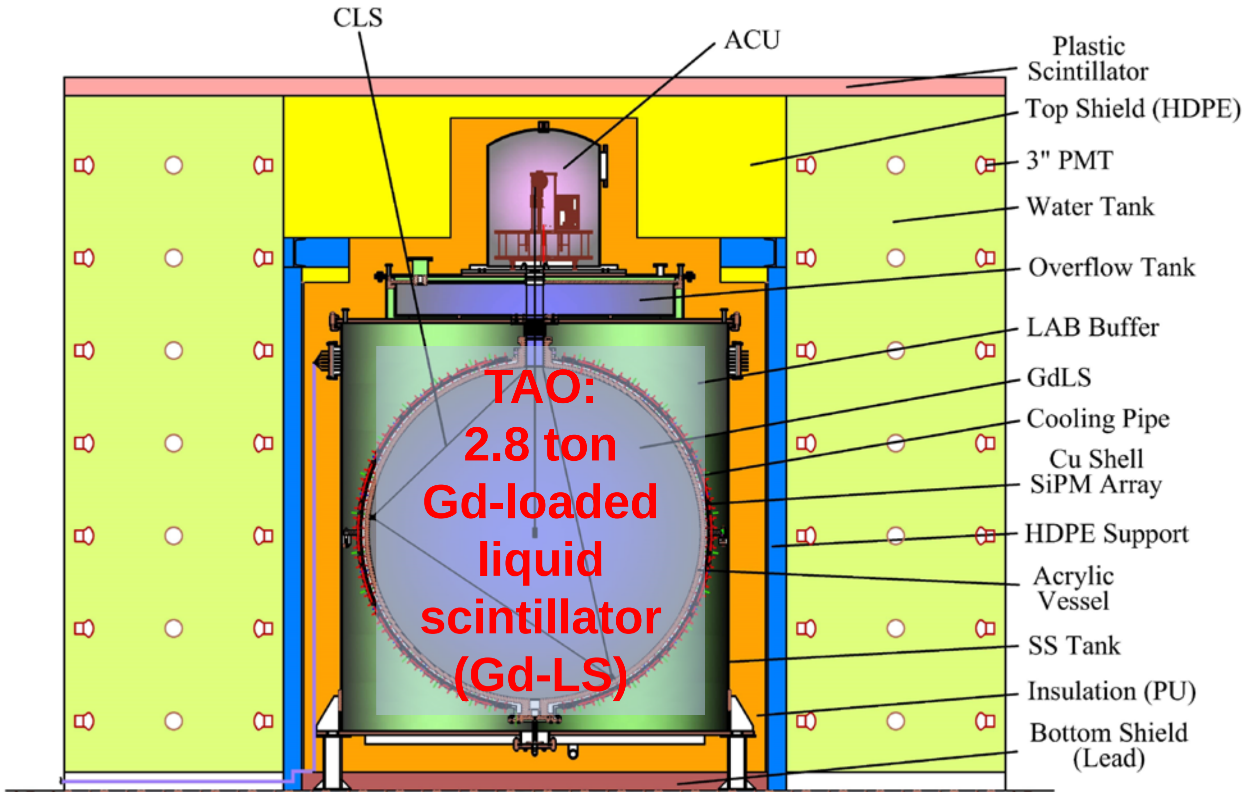
Whether ν_3 mass eigenstate is heavier or lighter than the ν_1 and ν_2?

The JUNO detectors

- A 20 kton multipurpose liquid scintillator (LS) detector
  - < 3% resolution @1 MeV
  - Optimized of neutrino mass ordering (NMO) determination
- A 2.8 ton Gd-loaded LS satellite detector
  - < 2% resolution @1 MeV







Reactor neutrino analysis

Reactor $\bar{\nu}$ flux: $\phi(E_{\bar{\nu}})$

Yangjiang NPP $6 \times 2.9\ GW_{th}$ 736.0 m

Taishan NPP $2 \times 4.6\ GW_{th}$ 252.5 m

Oscillation: $P_{\bar{\nu}_e \to \bar{\nu}_e}(E_{\bar{\nu}}|NMO)$

oscillation ~52.5 km

oscillation ~30 m

Detector response

IBD cross-section

Detector response : Liquid scintillator nonlinearity (LSNL)

Energy leakage: TAO

Energy resolution: JUNO

Energy resolution: TAO

Visible energy spectrum: $S_{JUNO}(E_{vis}|NMO)$

Visible energy spectrum: $S_{TAO}(E_{vis}|NMO)$

Oscillation χ^2 analysis

JUNO Background

TAO Background

Reactor $\overline{\nu}_e$ flux and detection

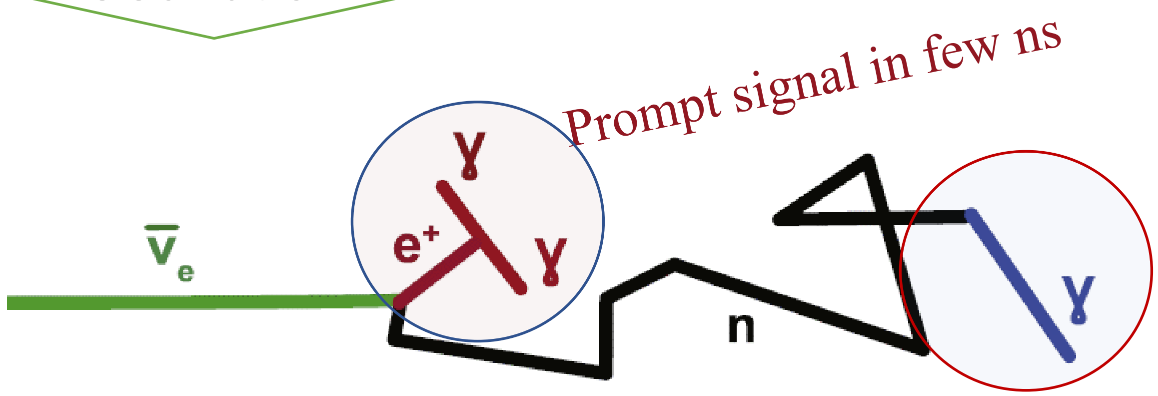
- **Signal source**: $\bar{\nu}_e$ from fission of $^{235}\mathrm{U}$, $^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, and $^{241}\mathrm{Pu}$
- Major: 6 Yangjiang (YJ) cores, 4→2 Taishan (TS) cores:
- $\mathbf{35.8 \rightarrow 26.6\ GW_{th}}$

J. Phys. G43:030401 (2016) → arXiv:2104.02565

- Detection channel: $\bar{\nu}_e + \boldsymbol{p} \rightarrow \boldsymbol{e}^{+} + \boldsymbol{n}$
  - e^+ gives **prompt signal**
  - $E_p \in [0.7,12]$ MeV, in a few ns
  - $\boldsymbol{n}$ on H or C gives **delayed signal**
  - $E_d \in [1.9,2.5] \cup [4.4,5.5]$ MeV
  - After ~200 μs
- Prompt-delayed vertex distance
  - Tens of centimeters

Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

Oscillation

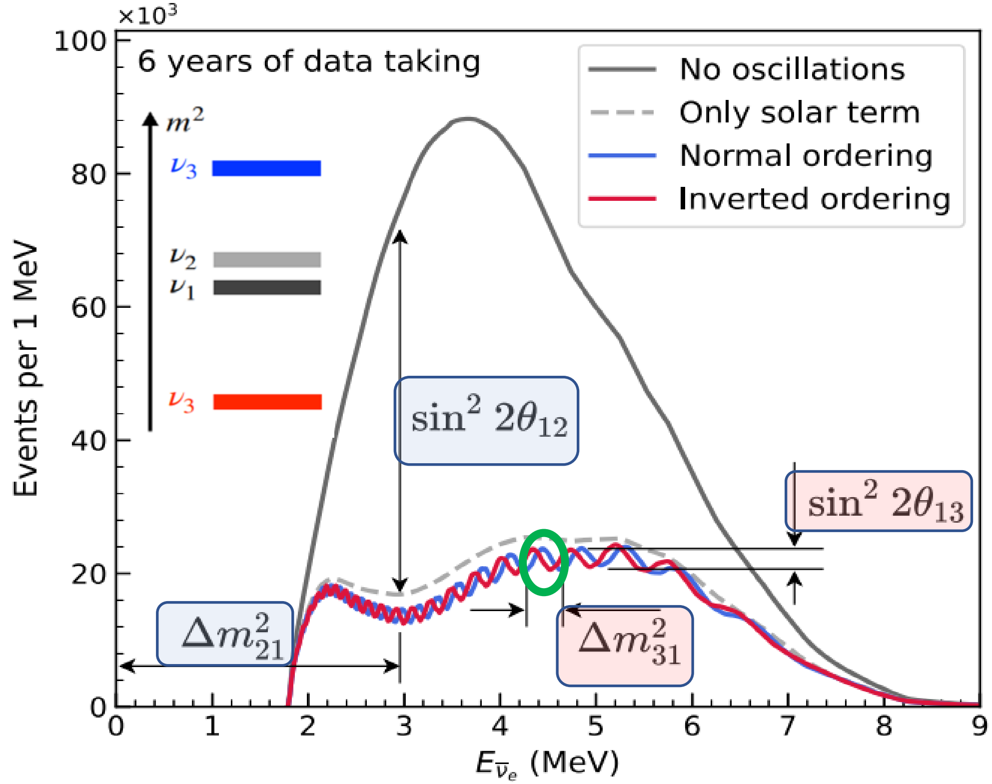


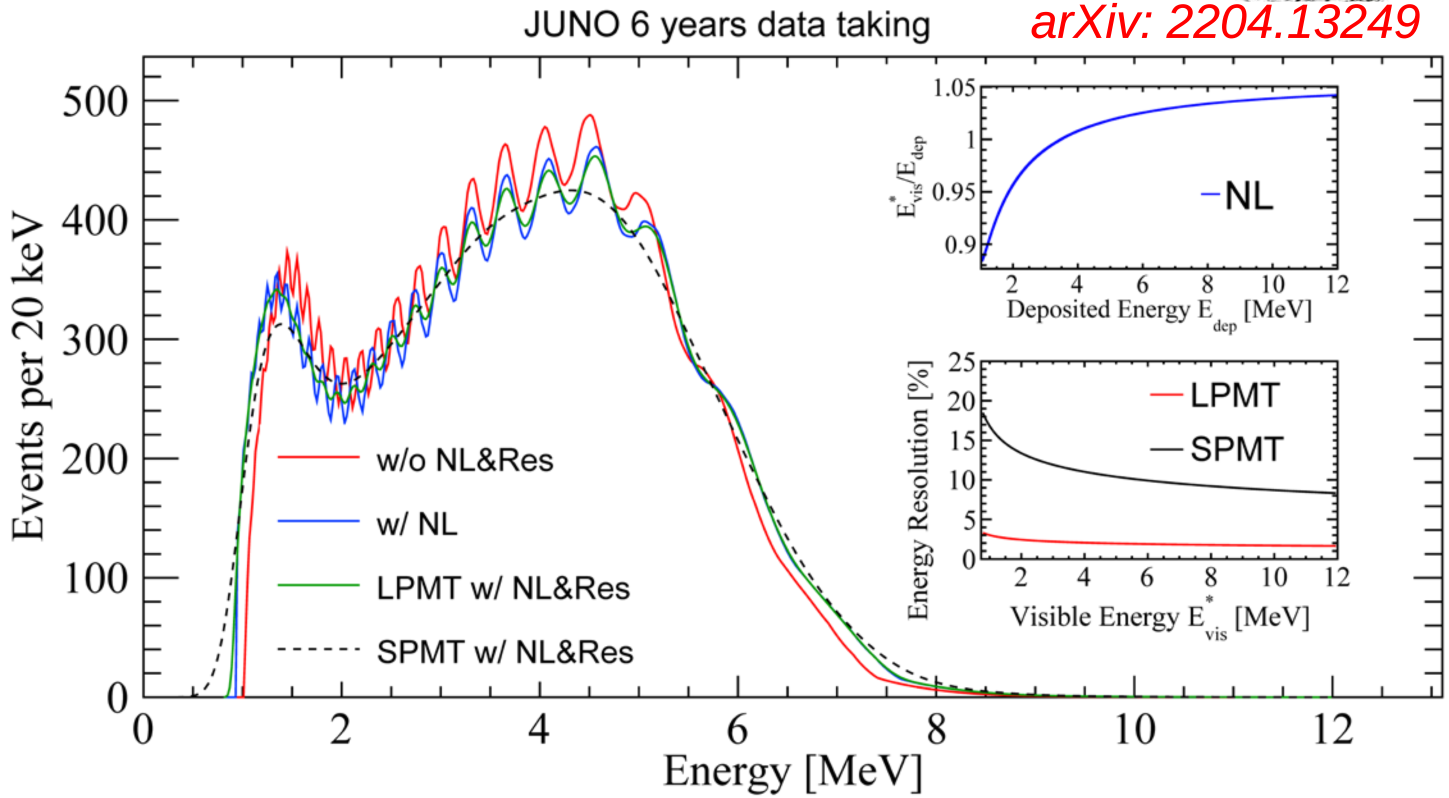
Inverse Beta Decay

Delayed signal
~200 μs as tag

Reactor neutrinos at JUNO

arXiv: 2204.13249





- **Oscillation** [1]:

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right).$$

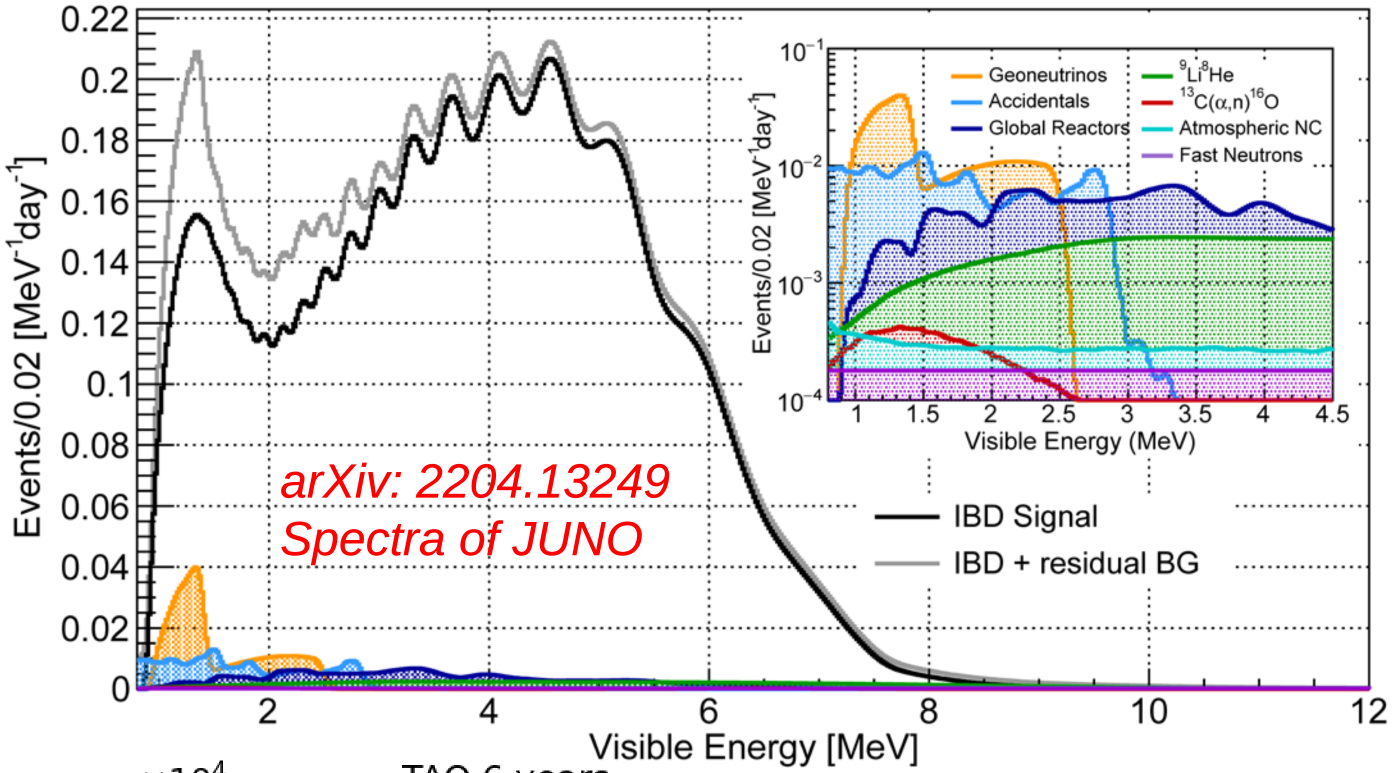
- In inverse beta decay (IBD) $\boldsymbol{\overline{\nu}_e + p \to e^+ + n}$
  - Prompt signal by e^+, brings most of the neutrino energy, consider energy nonlinearity (NL) and resolution (Res) effects

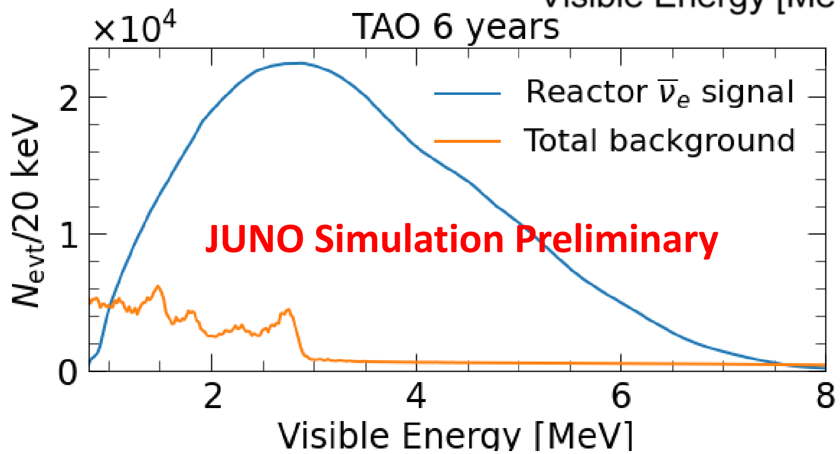
[1] Matter effect contributes maximal ~4% correction at ~3 MeV: Chin.Phys.C 40 (2016) 9, 091001, Phys.Lett.B 803 (2020) 135354

Reactor neutrinos at JUNO

- Time-energy-space coincidence to suppress background [1, 2]
  - ➢ JUNO delayed signal: n-H (~2.2 MeV)
  - ➢ TAO delayed signal: n-Gd (~8 MeV)

Rate [/day]	JUNO	TAO
Reactor IBD signal	**47**	**2000**
Geo-ν's	**1.2**	**-**
Accidental signals	**0.8**	**155**
Fast-n	**0.1**	**92**
^{9}Li/ ^{8}He	**0.8**	**54**
$^{13}C(\alpha, n)^{16}O$	**0.05**	**-**
Global reactors	**1.0**	**-**
Atmospheric ν's	**0.16**	**-**

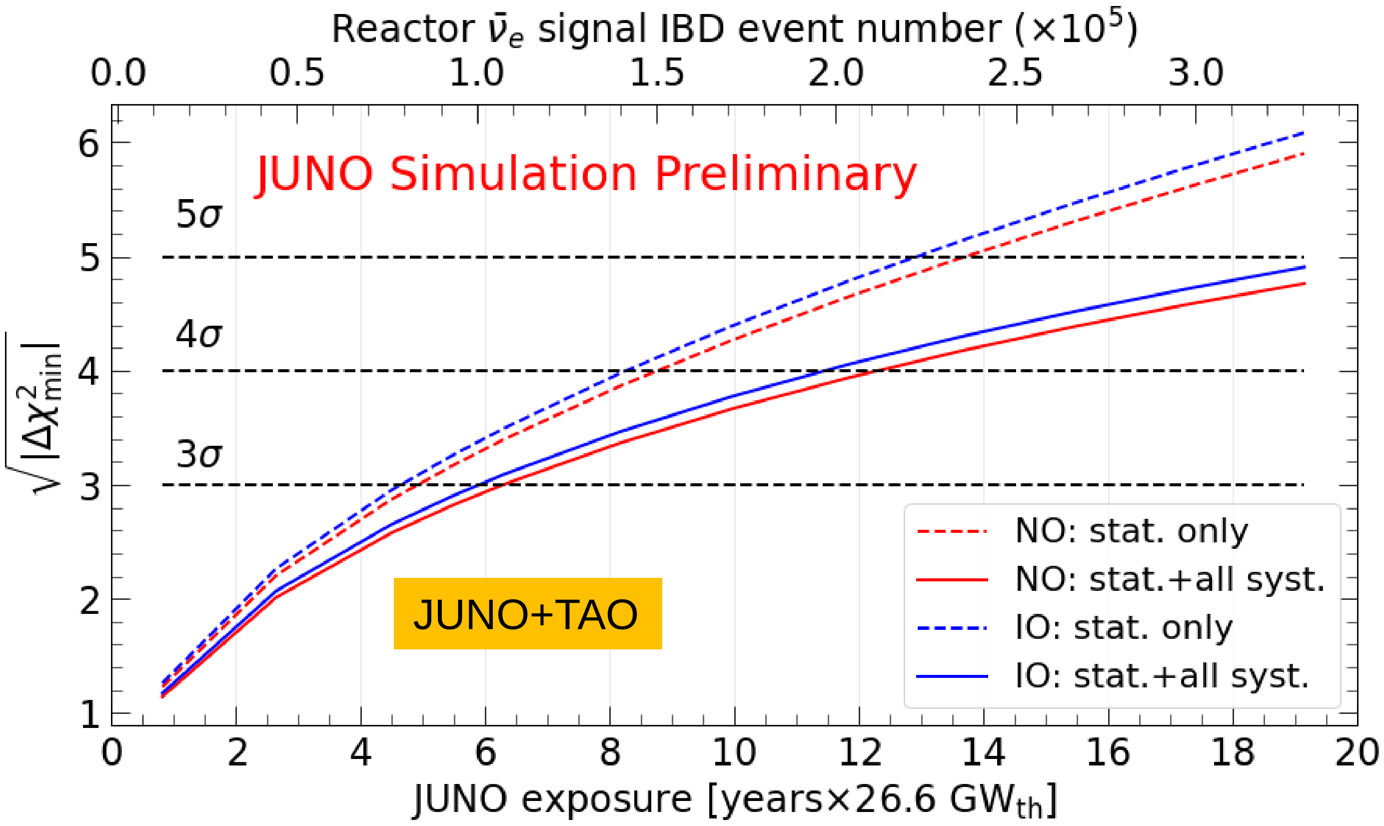




TAO: ~30 m from the reactor, provides high precision measurement of reactor $\overline{\nu}_e$ spectrum [3].

[1] arXiv: 2204.13249. [2] arXiv: 2005.08745. [3] DOI: 10.5281/zenodo.6775075.

Reactor neutrinos at JUNO



	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

JUNO Simulation Preliminary

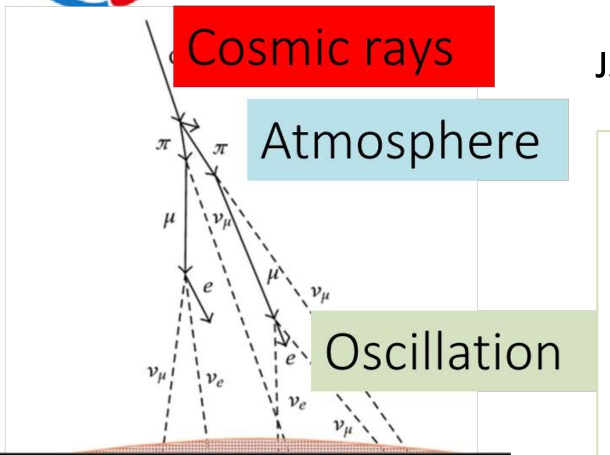
- JUNO NMO median sensitivity $|\Delta\chi^2_{\text{min}}| \equiv |\chi^2_{\text{min}}(\text{NO}) - \chi^2_{\text{min}}(\text{IO})|$ [1]:

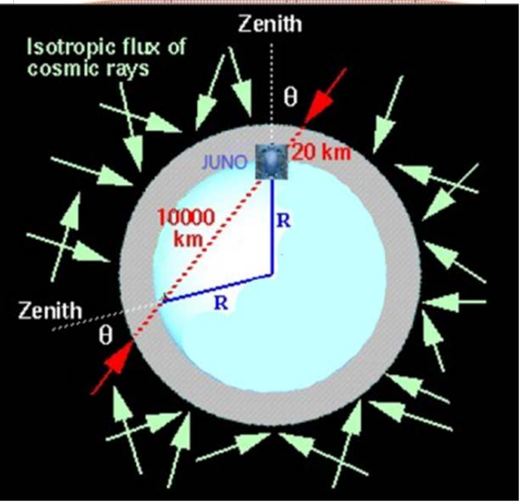
  3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure

- Paper under preparation.

[1] DOI: 10.5281/zenodo.6775075.

Atmospheric neutrinos at JUNO





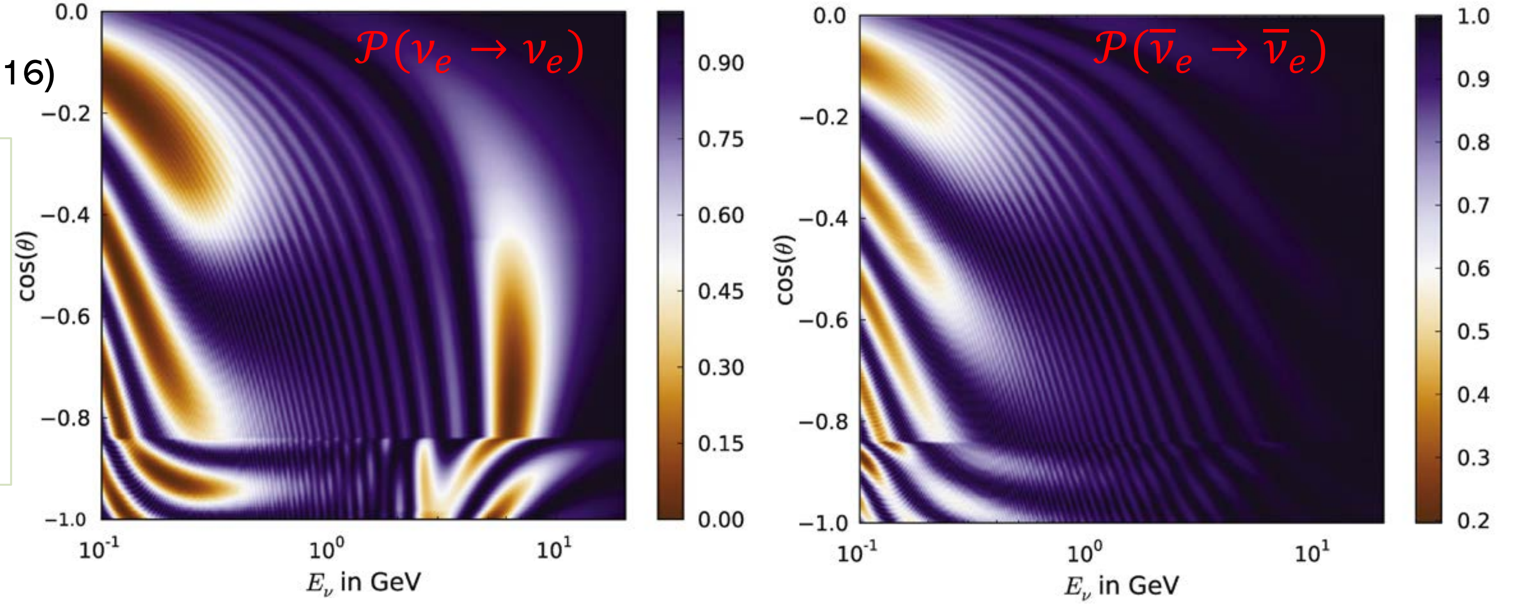
Major flavors: $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

J. Phys. G 43, 030401 (2016)

For different mass orderings:

$$\mathcal{P}_{\mathrm{NO}}(\nu_\alpha \to \nu_\beta) = \mathcal{P}_{\mathrm{IO}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta).$$

Matter effect with PREM density profile.



- Signal **detection** channels: **Charged Current (CC)** interactions
- Major backgrounds: Neutral Current (NC) interactions and cosmic muons.
- ~78% optical coverage of JUNO offers
  - Great potential in PID, direction and energy reconstruction of atmospheric ν's.

N/10 yrs	ν	$\bar{\nu}$	Total
$\nu_e/\bar{\nu}_e$ CC	6637	2221	8858
$\nu_\mu/\bar{\nu}_\mu$ CC	8662	3136	11798
$\nu_\tau/\bar{\nu}_\tau$ CC	90	44	133
NC	8558	3697	12255

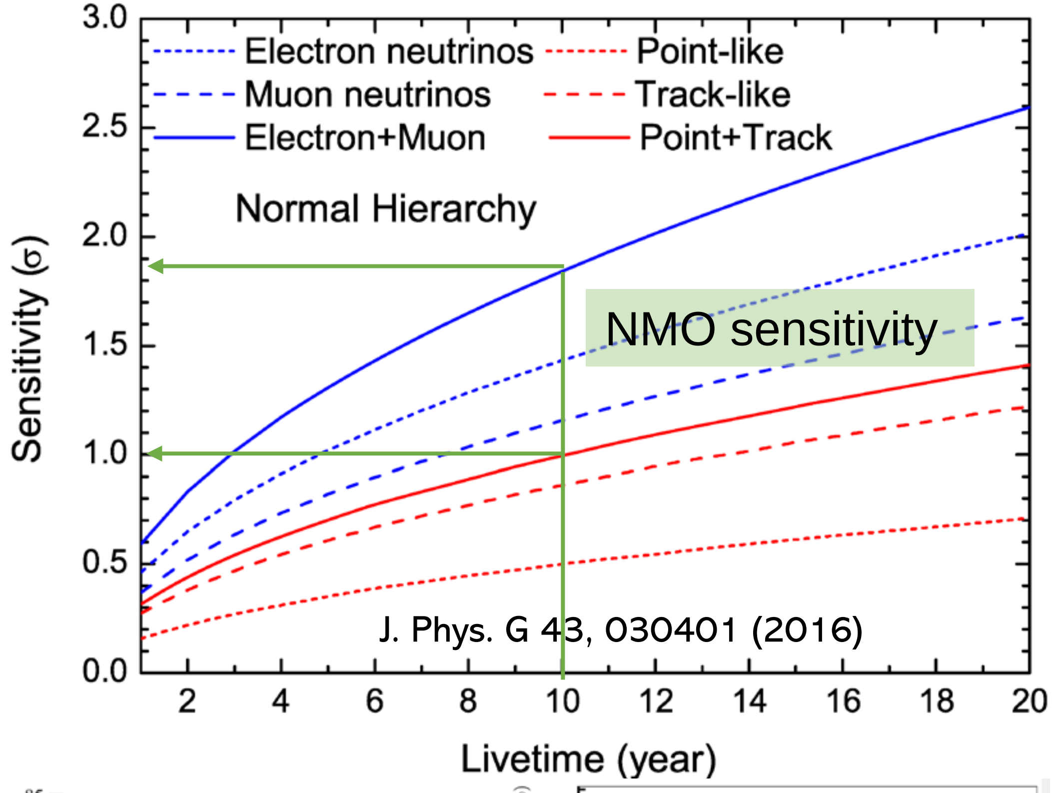
Number of atmospheric ν interactions in JUNO

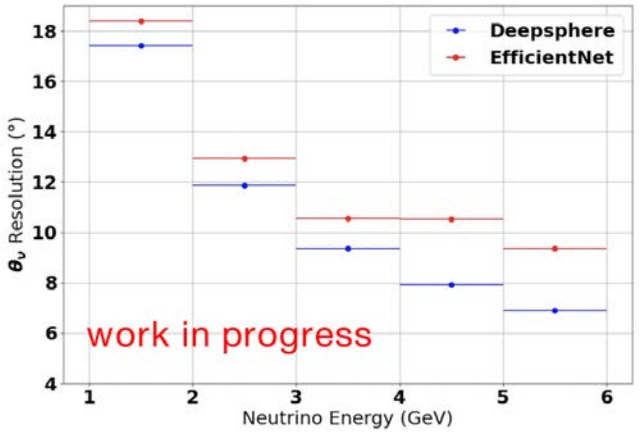
Atmospheric neutrinos at JUNO

- Conservative 10 yrs sensitivity:

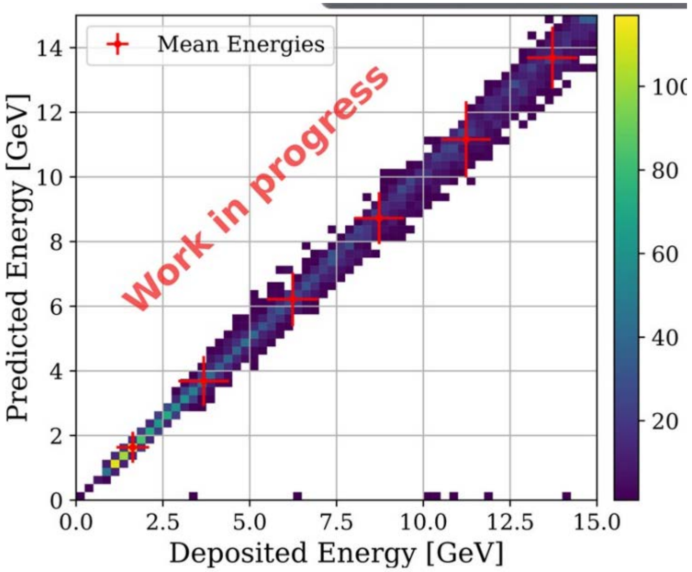
➢ NMO: $1\sim1.8\sigma$.

➢ More realistic sensitivity study with reconstruction performance [1, 2, 3, 4] and combined with **reactor $\bar{\nu}_e$** are **in progress**.

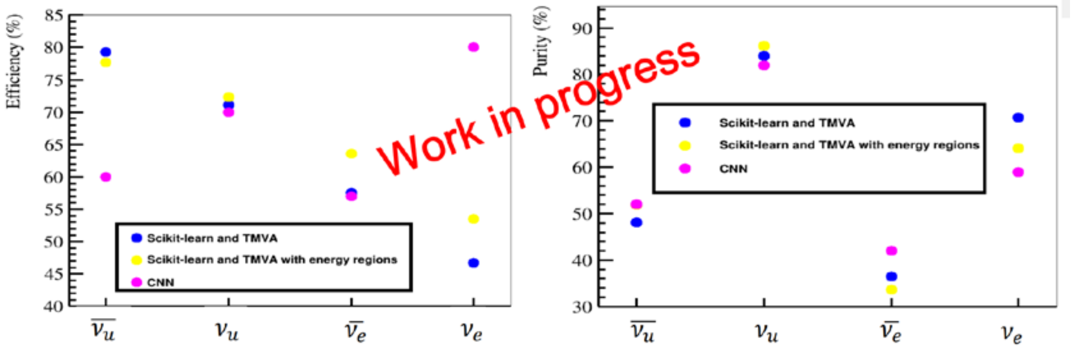




Neutrino reconstruction angular resolution progresses, by T. Li, H. Duyang, Z. Liu [1].



Energy reconstruction performance by M. Rifai, M. M. Colomer, R. Wirth [3].



Particle identification (PID) progress by Y. Zhang [2]

[1] DOI: 10.5281/zenodo.6769313. [2] DOI: 10.5281/zenodo.6782362. [3] DOI: 10.5281/zenodo.6785153. [4] DOI: 10.5281/zenodo.6804861.

Summary

- JUNO NMO sensitivity with reactor $\bar{\nu}_e$: 3σ with ~ 6 years $\times$ $26.6\ \mathrm{GW_{th}}$
- With nominal exposure, statistical-only $\Delta\chi^2_{\mathrm{min}}$: 11.3
- Crucial systematics and $\Delta\chi^2_{\mathrm{min}}$ decrease:
  - Backgrounds: -1.4
  - Flux shape: -0.6
  - LS nonlinearity: -0.4

- Atmospheric neutrinos of JUNO provide different channels for NMO
  - Conservative sensitivity: $1\sim 1.8\sigma$ for 10 years
- Combination analysis of reactor and atmospheric neutrinos is **in progress** that would increase the JUNO NMO sensitivity.
- Detector completion in 2023!

谢谢大家！

张金楠

Backup

Reactor antineutrino analysis updates

	Design (J. Phys. G 43:030401 (2016))	Now (2022)
Thermal Power	36 GW_{th}	**26.6 GW_{th} (26%↓)**
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	**4 Hz (33%↑)**
Muon veto efficiency	83%	**91.6% (10%↑)**
Signal rate	60 /day	**47.1 /day (22%↓)**
Backgrounds	3.75 /day	**4.11 /day (10%↑)**
Energy resolution	3% @ 1 MeV	**2.9% @ 1 MeV (3%↑)**
Shape uncertainty	1% for 36 keV	**JUNO+TAO**
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → **47**	-	-
Geo-ν's	1.1 → **1.2**	30%	5%
Accidental signals	0.9 → **0.8**	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 → **0.8**	20%	10%
$^{13}C(\alpha, n)^{16}O$	0.05	50%	50%
Global reactors	0 → **1.0**	**2%**	**5%**
Atmospheric ν's	0 → **0.16**	**50%**	**50%**

Design in Physics book → **this update [1]**

J. Phys. G 43:030401 (2016)

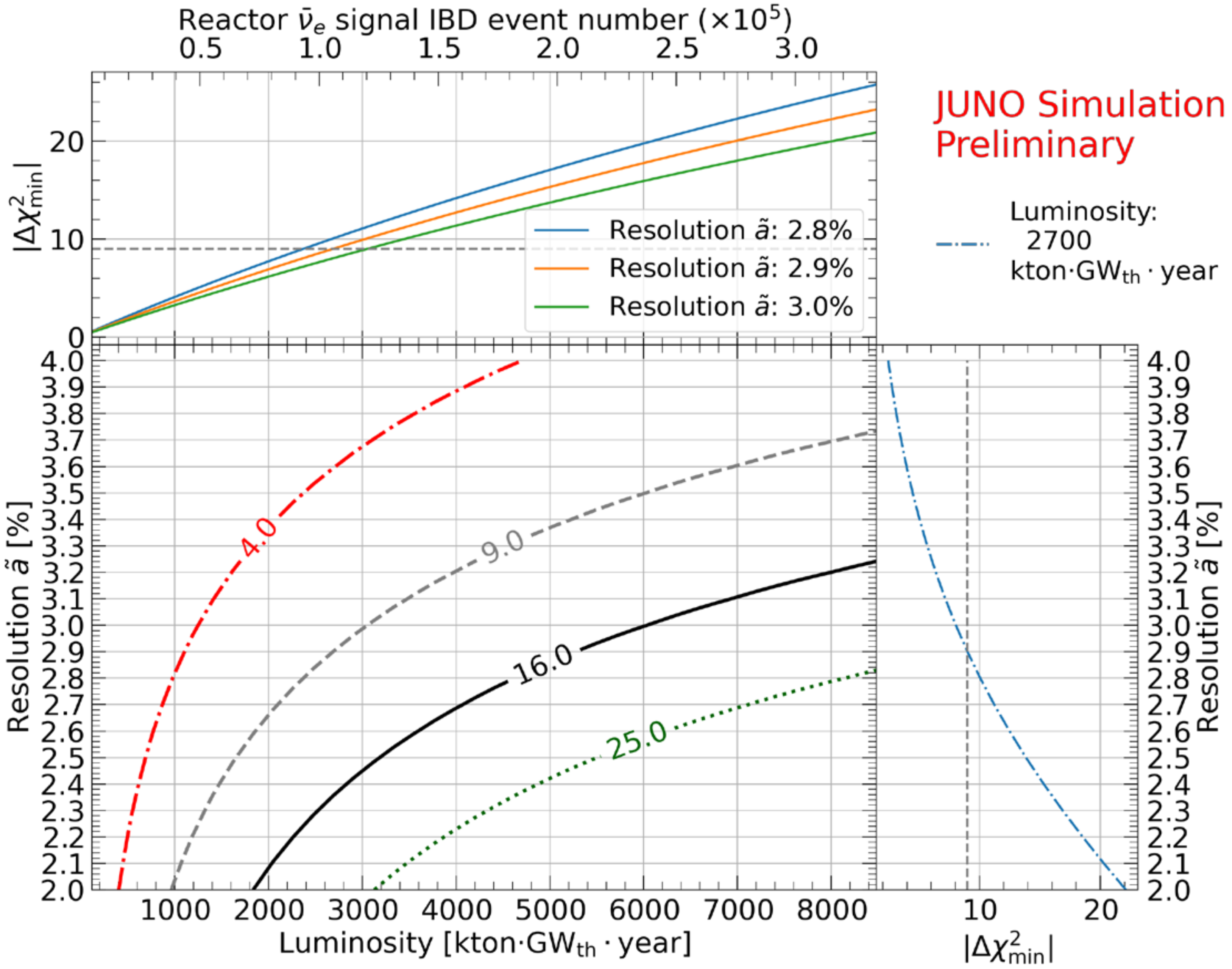
Major input updates:

Less statistics, better energy resolution

[1] DOI: 10.5281/zenodo.6775075.

JUNO NMO sensitivity

- The statistics and energy resolution are two key factors for NMO determination with reactor $\overline{\nu}_e$



$\Delta\chi^2_{\mathrm{min}}$ contour for statistics and energy resolution

Reactor antineutrino analysis updates

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Design in Physics book → **this update**

J. Phys. G 43:030401 (2016)

Update of energy resolution

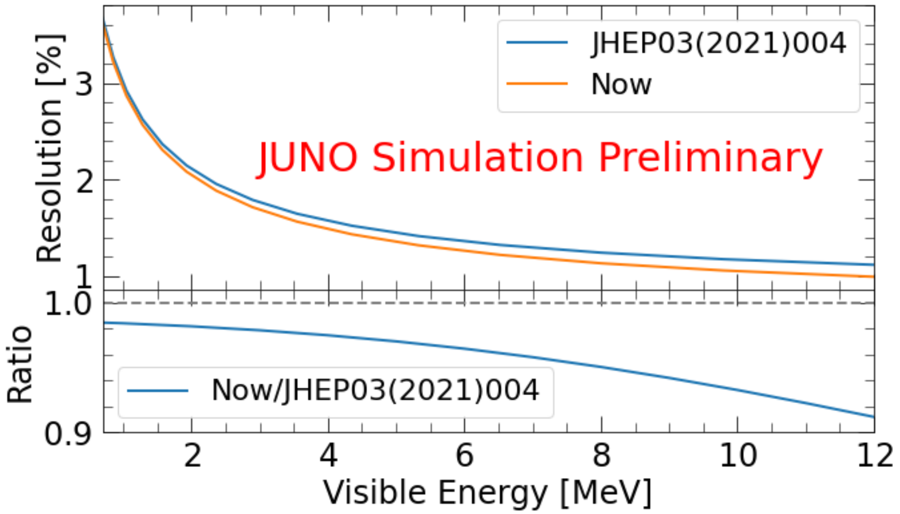
Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	*JHEP03(2021)004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV**	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		
New PMT Optical Model	+8%↑		*EPJC 82 329 (2022)*

Positron energy resolution is understood:

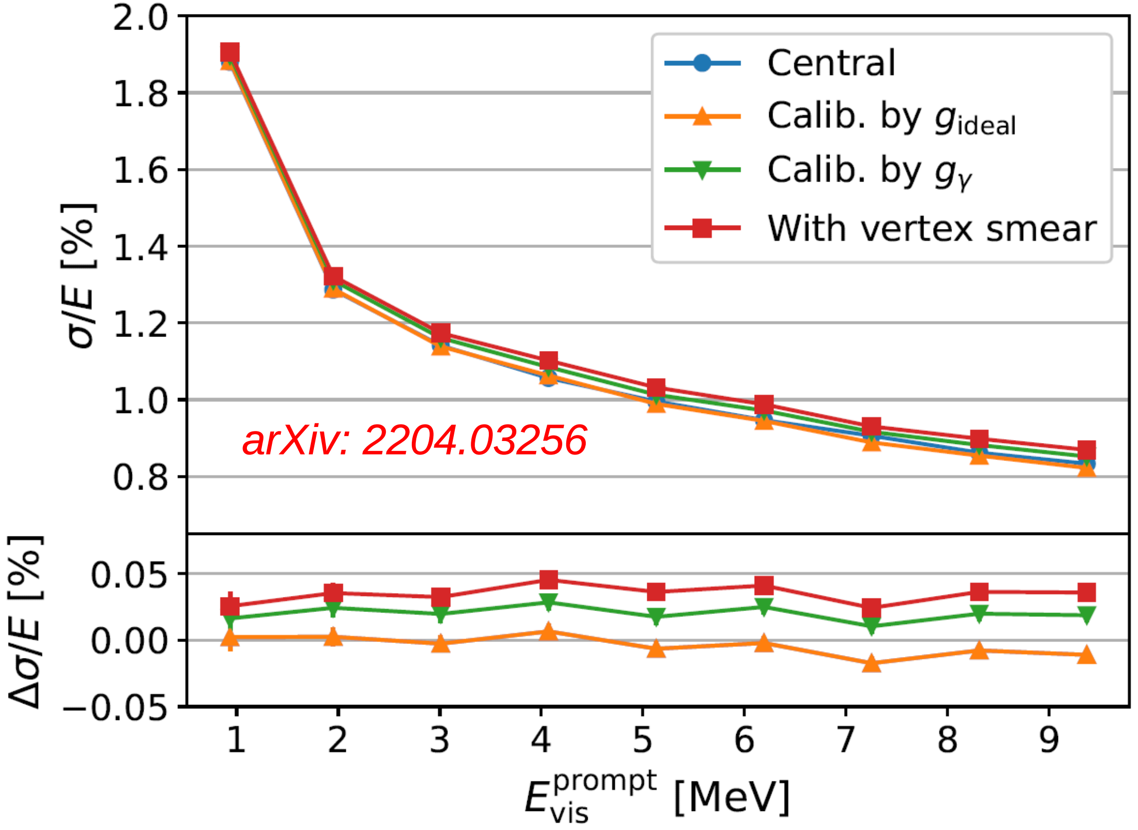
$$\frac{\sigma}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}$$

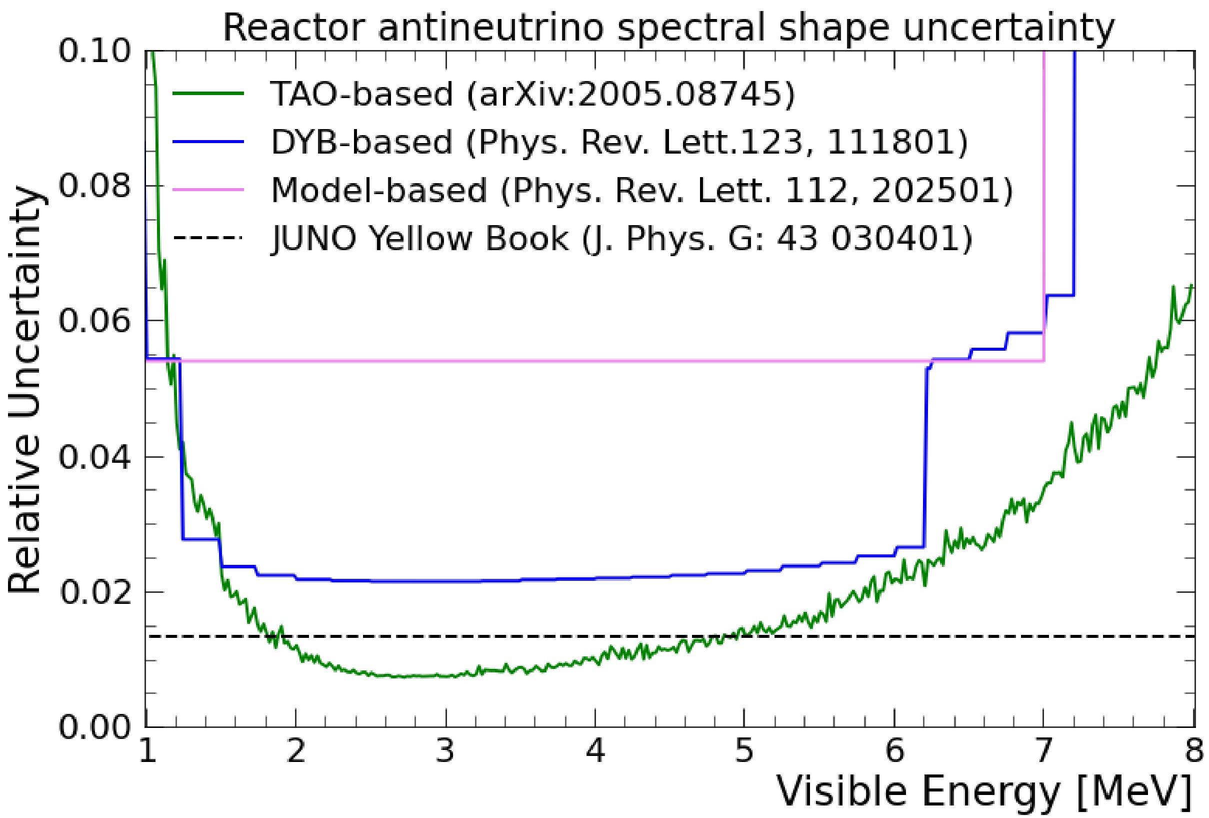
- **Photon statistics**
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**

- **Annihilation-induced γs**
- **Dark noise**



Reactor Antineutrino Spectrum from TAO

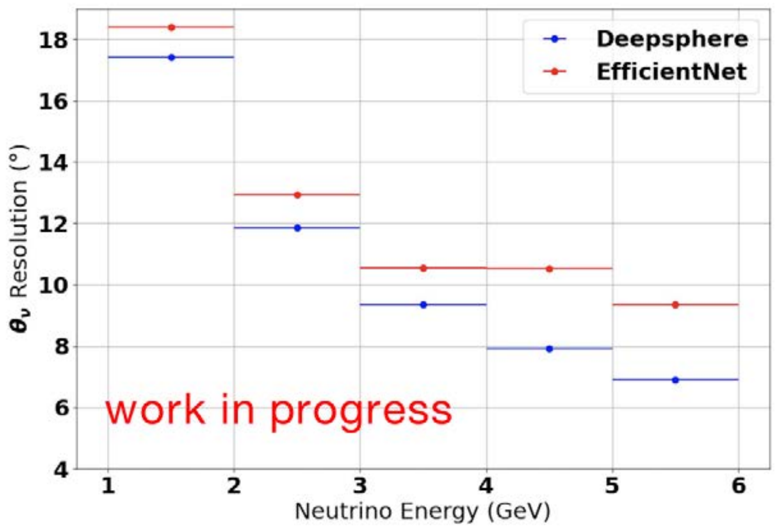




1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, absorption of scintillation very small
3. Gd-LS works at -50℃, increase the photon yield

- ✓ Unprecedented energy resolution < 2% @ 1 MeV
- ✓ Shape uncertainty close to the assumption in the JUNO Physics Book (*J. Phys. G43:030401 (2016)*)

Atmospheric ν's reconstruction progresses



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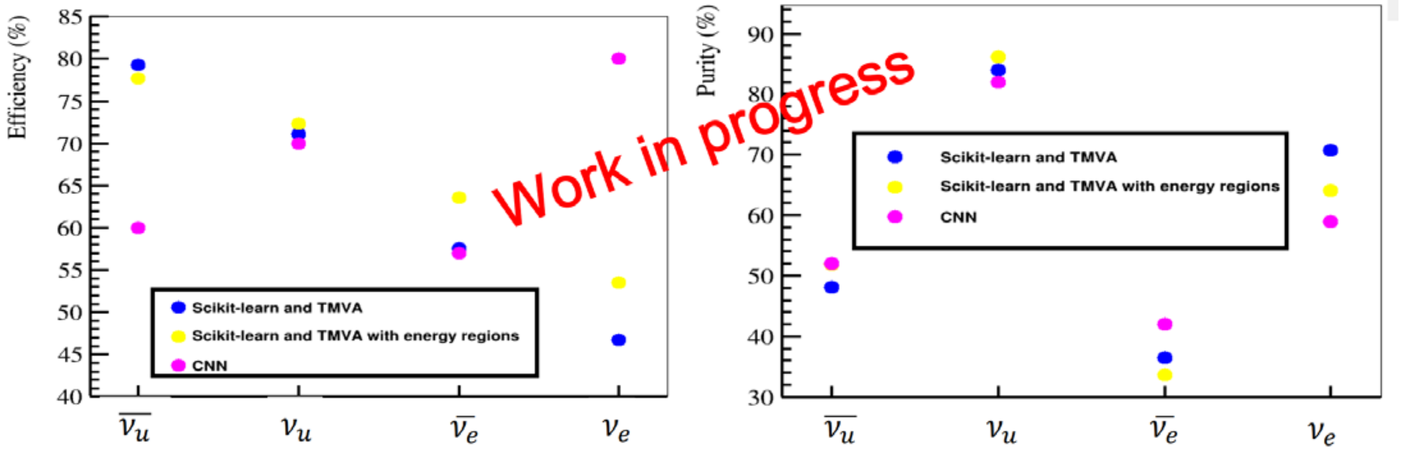

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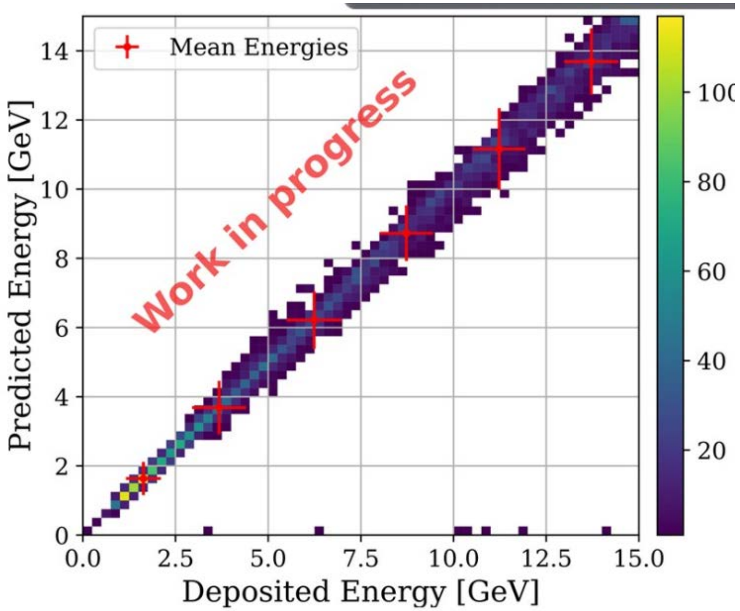

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