Oscillation Physics Potential of JUNO

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On behalf of the JUNO collaboration

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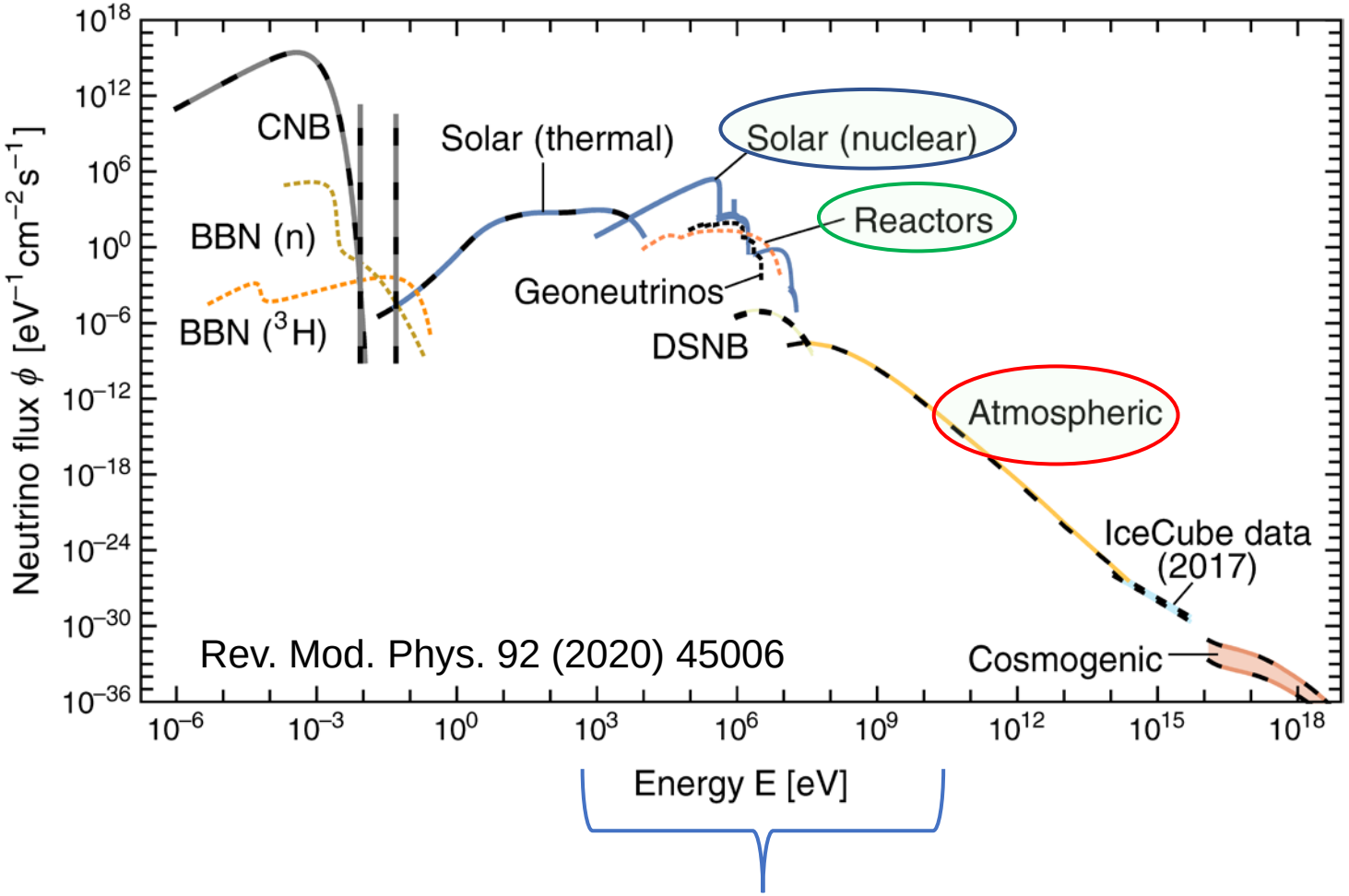
Outline

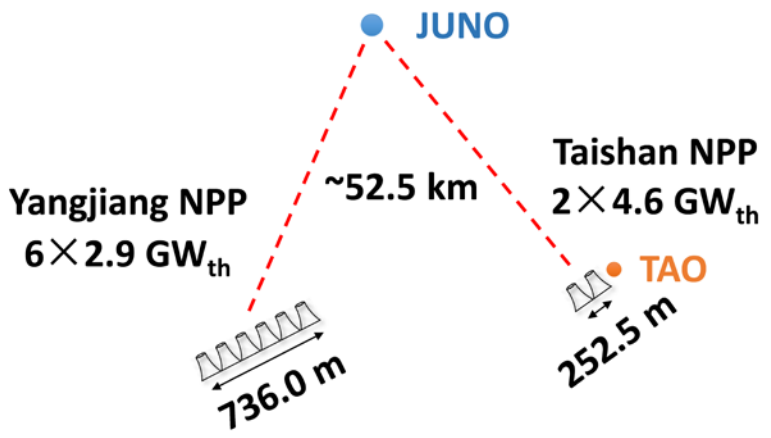
- The **J**iangmen **U**nderground **N**eutrino **O**bservatory detectors
  - JUNO and TAO
- Reactor neutrinos
  - Neutrino Mass Ordering (NMO)
  - $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31}, $\sin^2\theta_{13}$
- Atmospheric neutrinos
  - NMO, θ_{23}, and δ_{CP}
- Solar neutrinos
  - $\sin^2\theta_{12}$ and Δm^2_{21}
- Summary

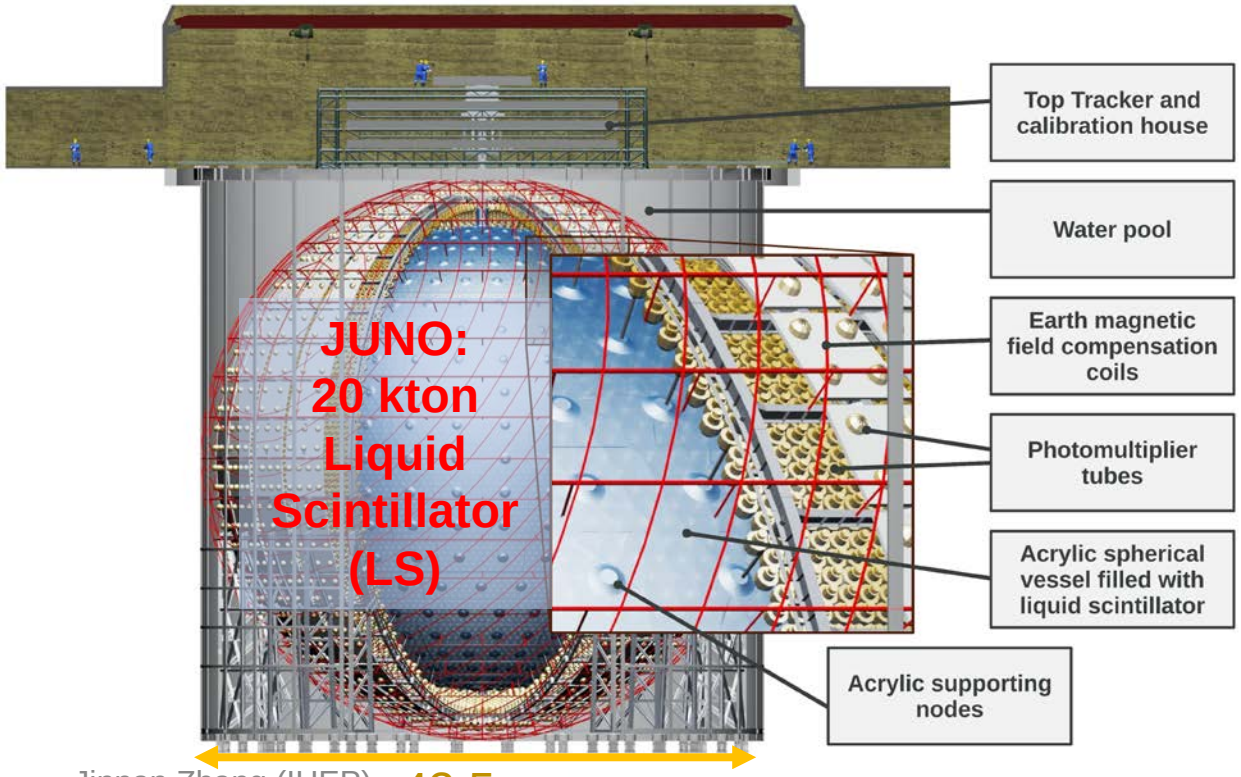


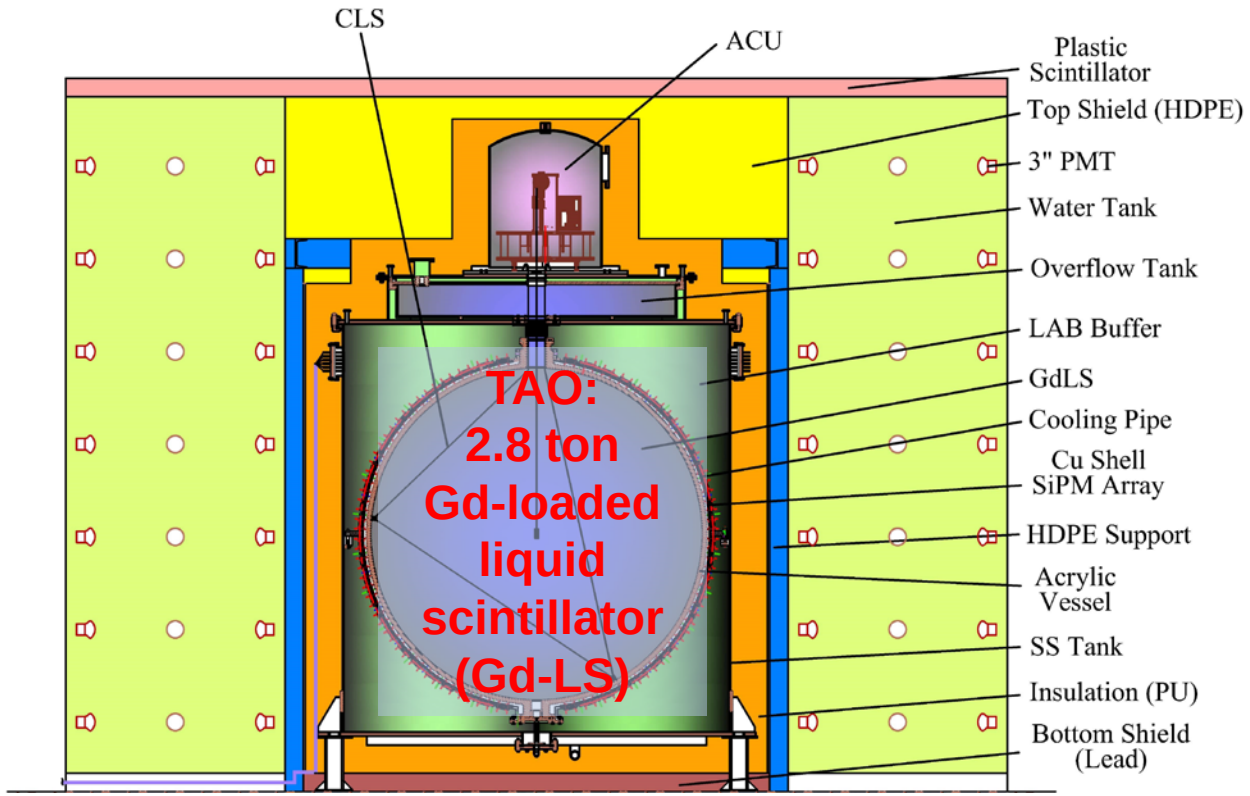
JUNO: from ~MeV to tens of GeV

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



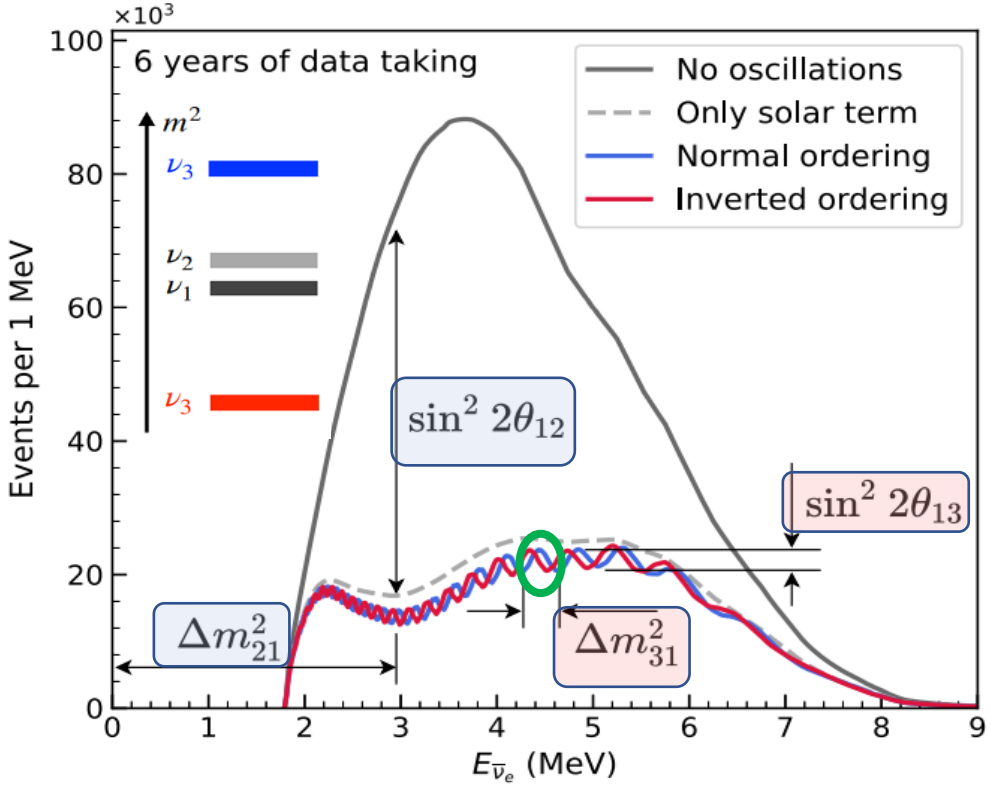


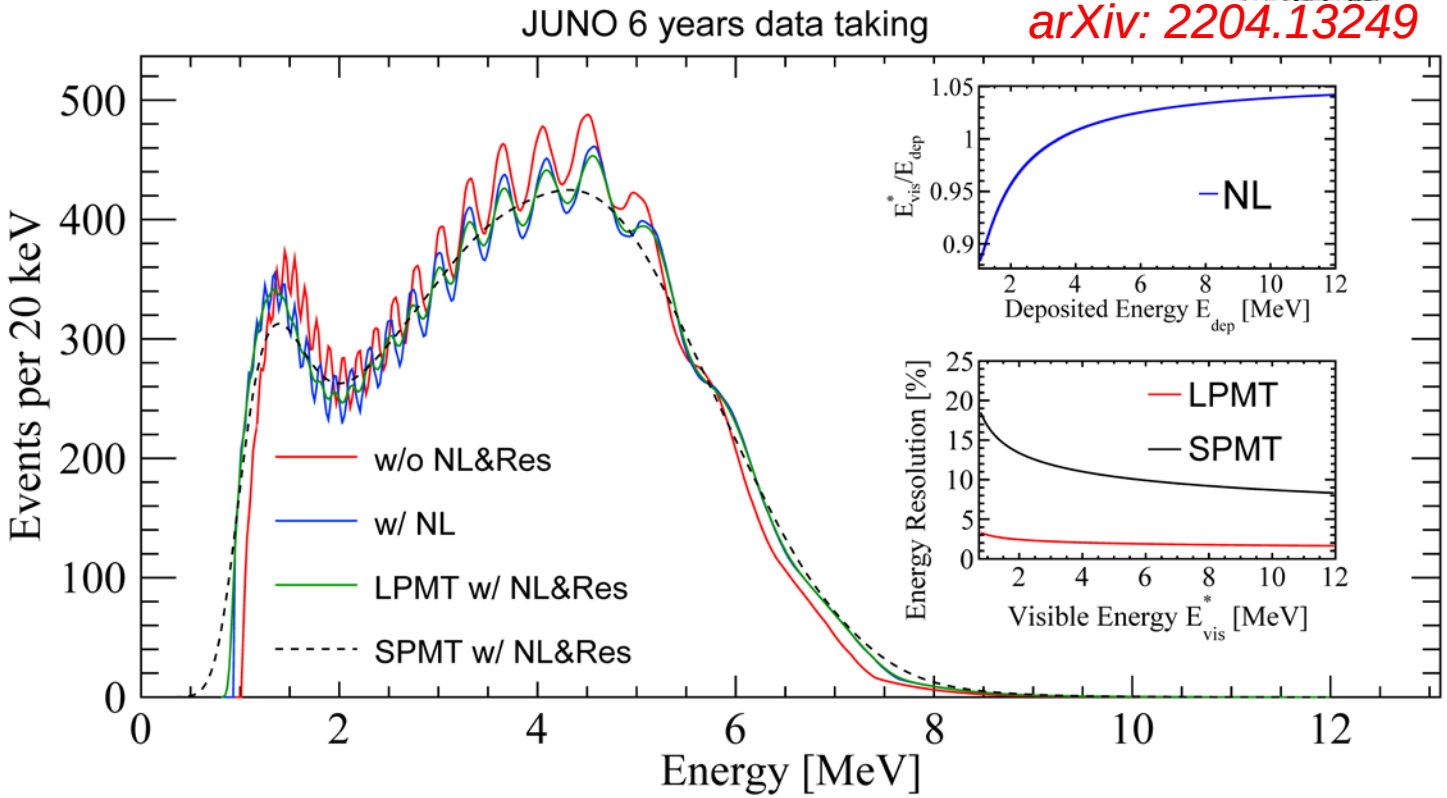


For detector status and challenges of JUNO, see plenary talks by Livia Ludhova and Michele Montuschi.

Reactor neutrinos at JUNO

arXiv: 2204.13249





- Signal **source**: 26.6 $\mathrm{GW_{th}}$ reactor complexes (6 cores of Yangjiang, 2 cores of Taishan).
- **Oscillation** [1]:

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

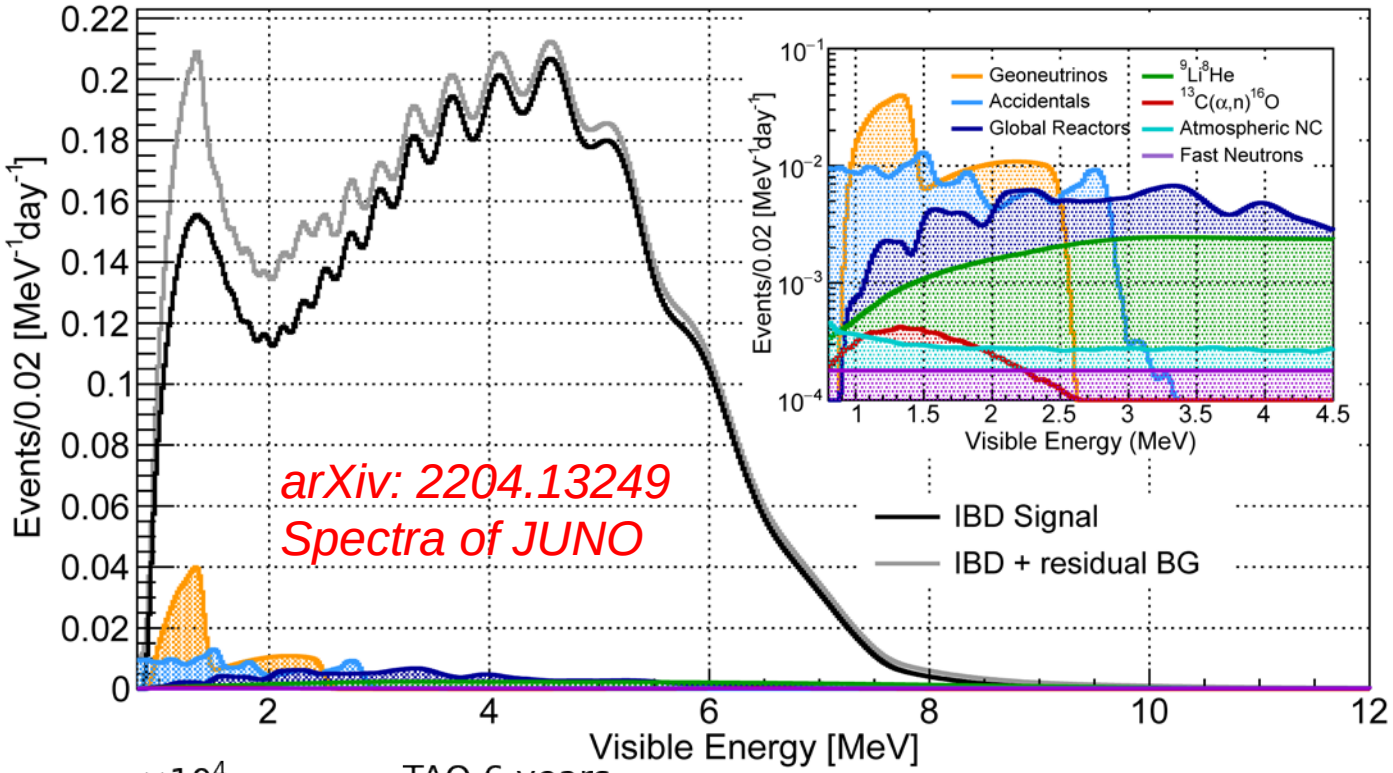
- **Detection** channel: inverse beta decay (IBD) $\bar{\nu}_e + p \to e^+ + n$
  - Prompt signal by e^+, consider energy nonlinearity (NL) and resolution (Res) effects

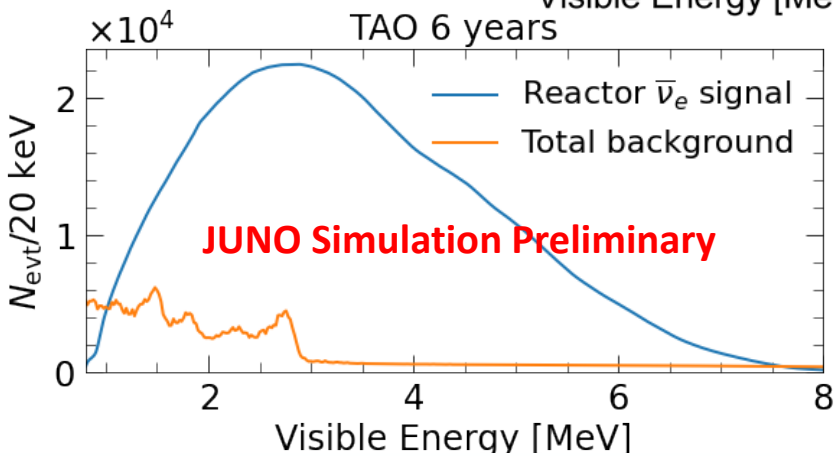
[1] Matter effect contributes maximal ~4% correction at ~3 MeV: Chin.Phys.C 40 (2016) 9, 091001, Phys.Lett.B 803 (2020) 135354

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(α , n) ^{16}O	**0.05**	**-**
Global reactors	**1.0**	**-**
Atmospheric ν's	**0.16**	**-**

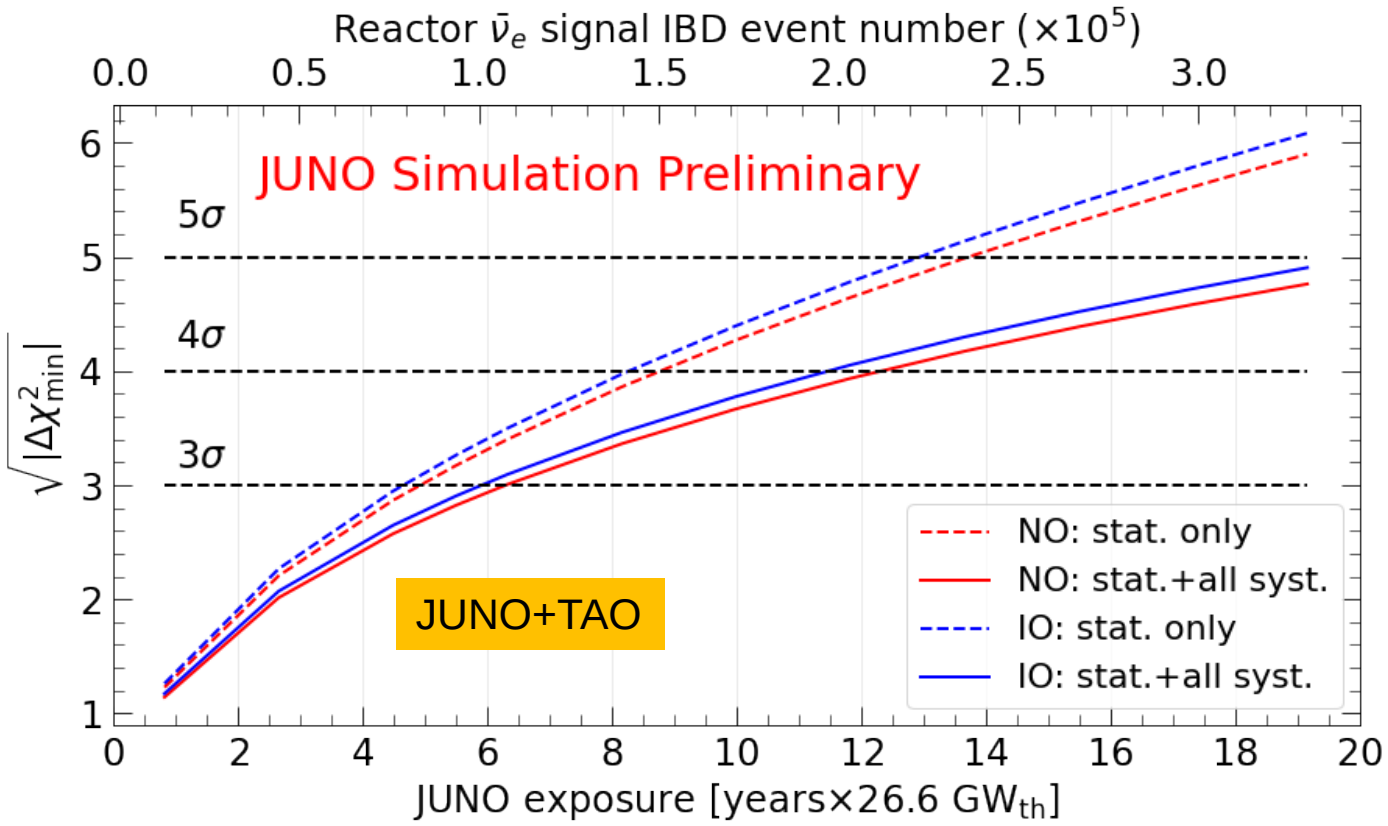


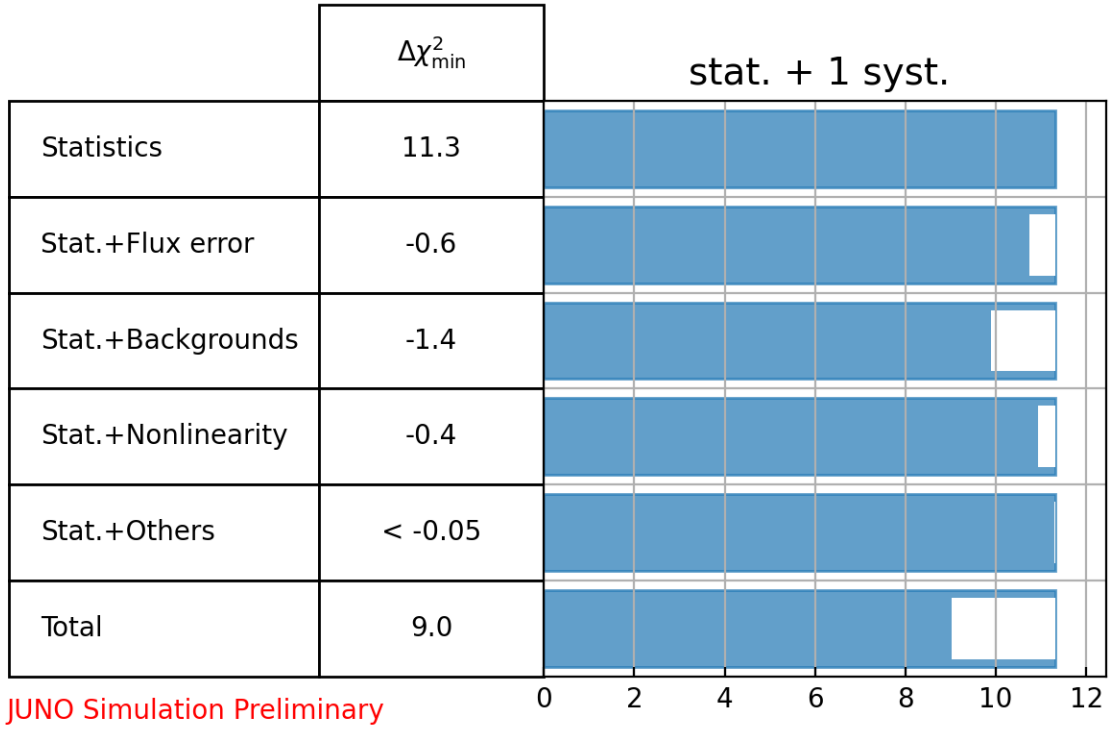


TAO: ~30 m from the reactor, provides high precision measurement of reactor $\bar{\nu}_e$ spectrum [3].

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

Reactor neutrinos at JUNO





For calibration and uncertainty control, see talk by Davide Basilico at WG6.

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

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

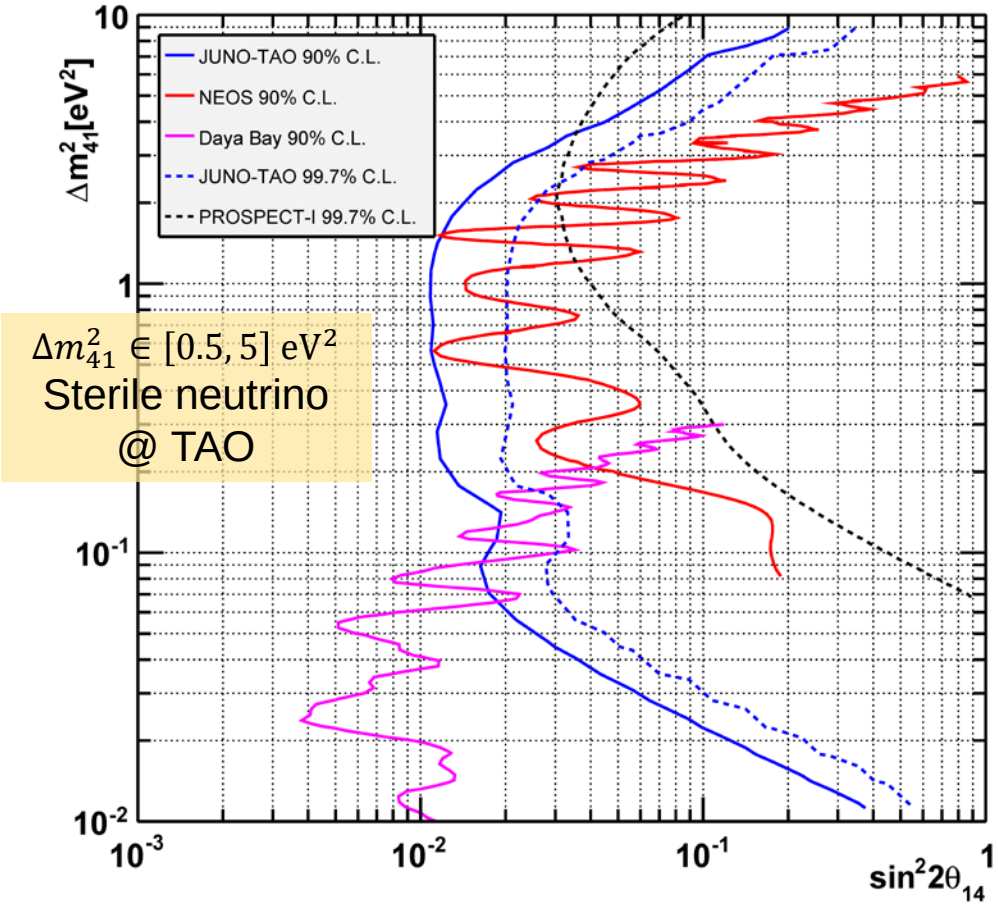
- Paper under preparation.

[1] DOI: 10.5281/zenodo.6775075.

Reactor neutrinos at JUNO

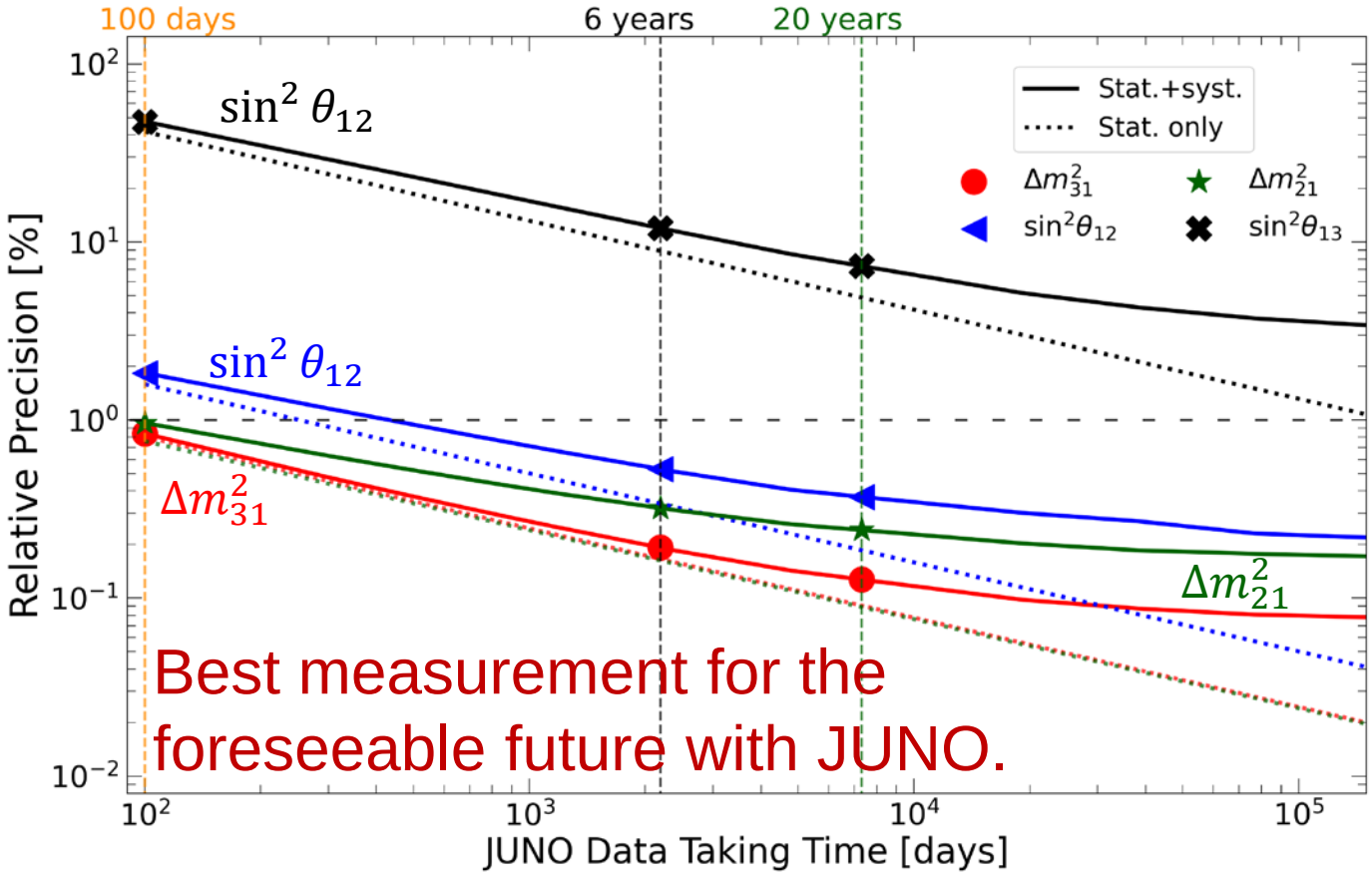
arXiv: 2204.13249

- Precision measurement of the oscillation parameters



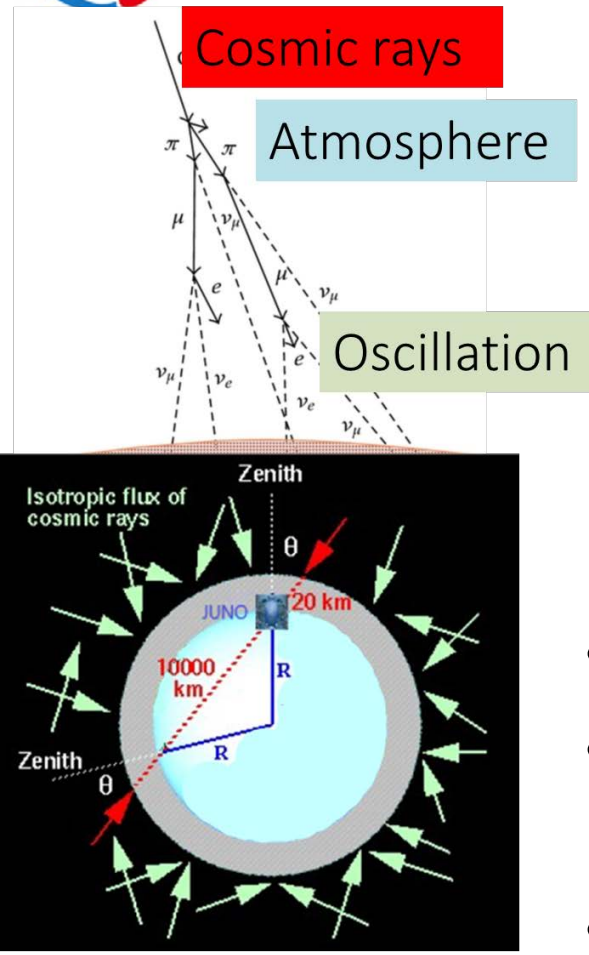
Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|/|\Delta m^2_{32}| < 0.5\%$ in 6 yrs

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)



Best measurement for the foreseeable future with JUNO.

Atmospheric neutrinos at JUNO



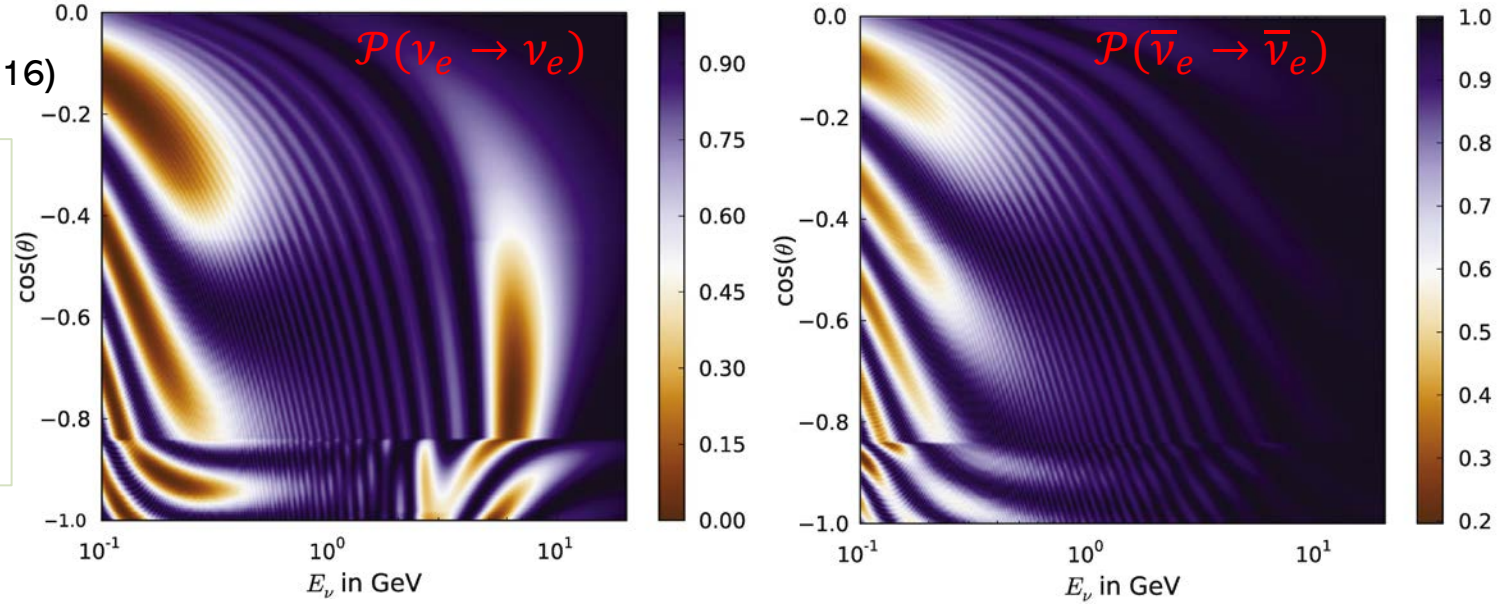
Major flavors: $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

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.

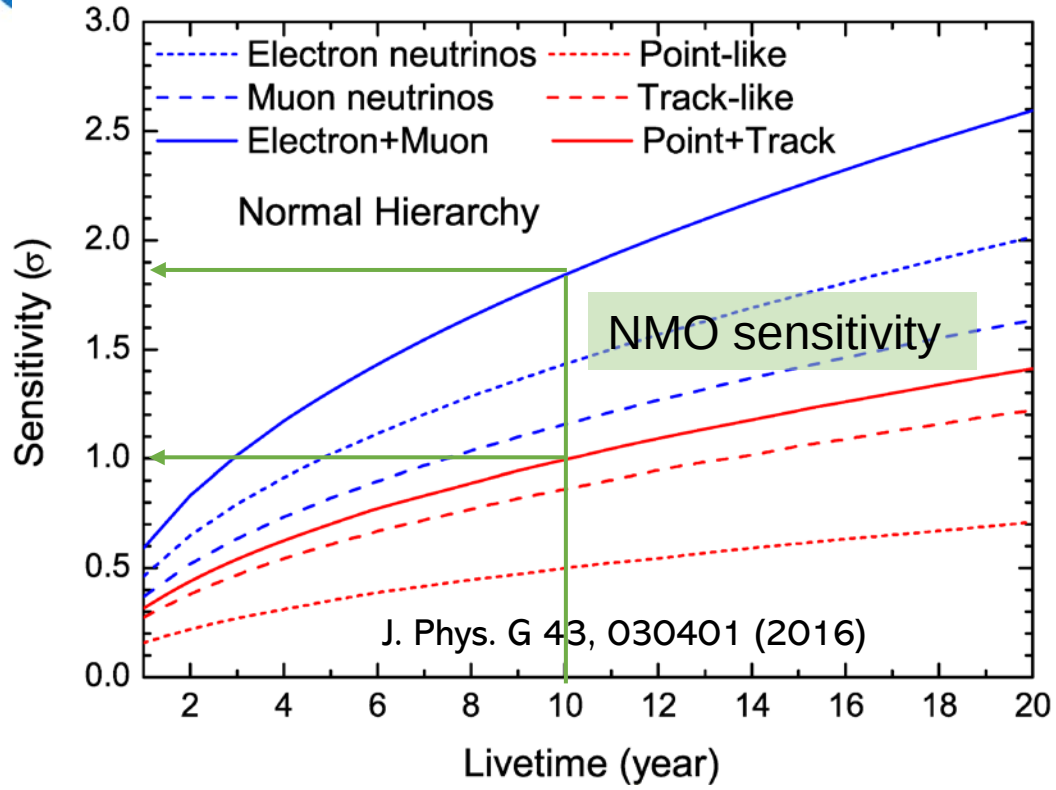


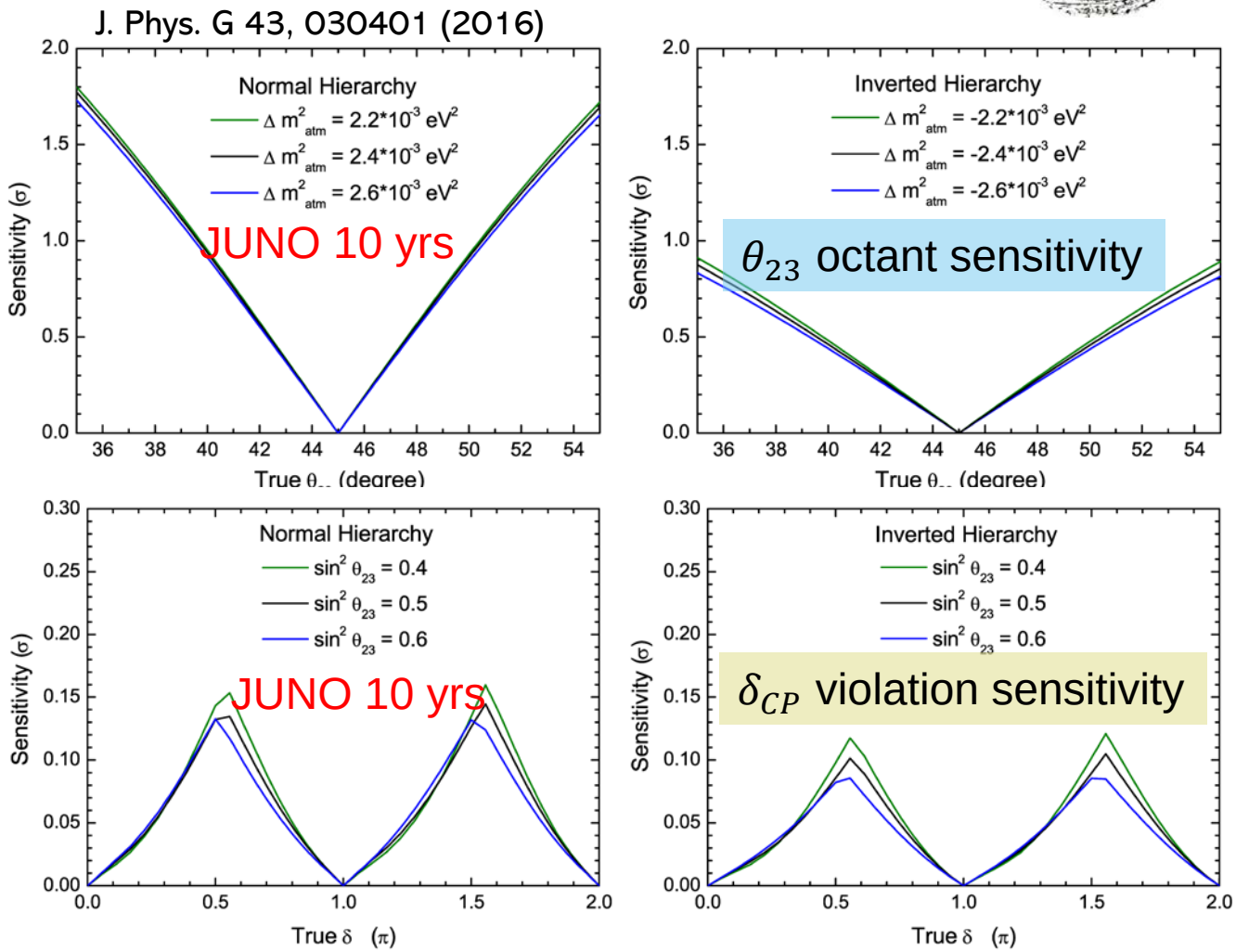
- Signal **detection** channels: **Charged Current (CC)** interactions
- Major backgrounds: Neutral Current (NC) interactions and cosmic muons.
- ~78% optical coverage of JUNO offers
  - ➢ Great potential in PID, direction and energy reconstruction of atmospheric ν's.

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: $1\sim1.8\sigma$.
  - ➢ θ_{23} octant: 1.8σ (0.9σ) for $35°$, NO (IO).
  - ➢ CP violation: complementary measurement

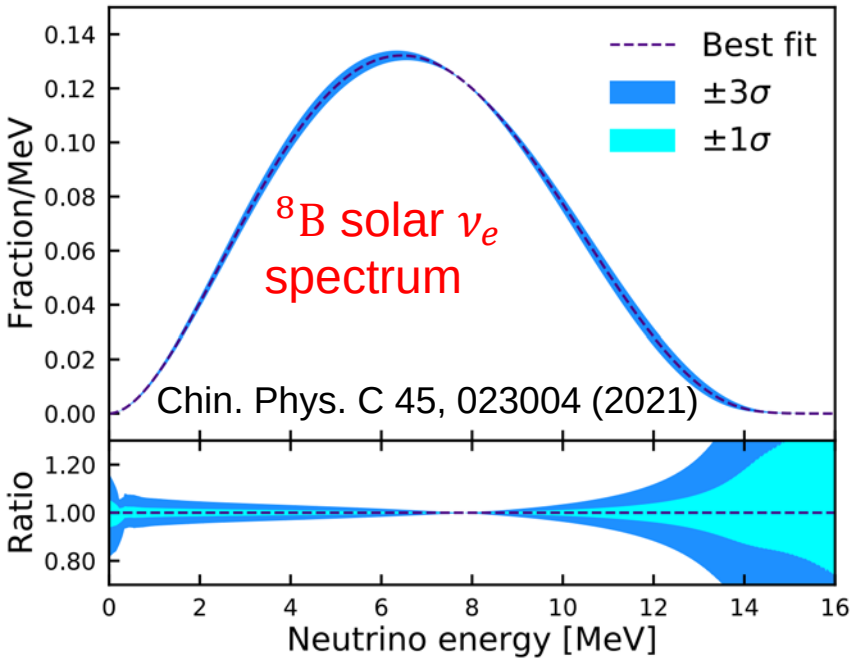
More realistic sensitivity study with reconstruction performance [1, 2, 3, 4] and combined with **reactor $\bar{\nu}_e$** are **in progress**.

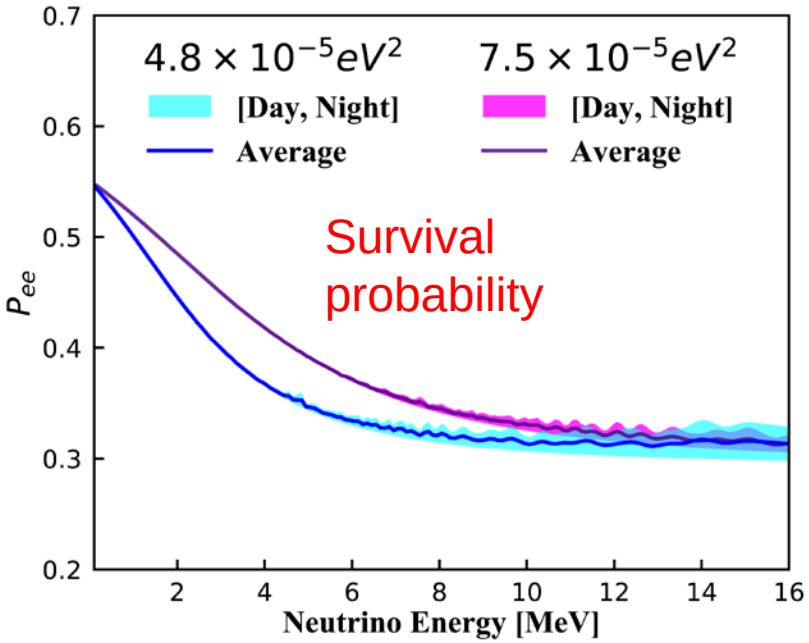
[1] DOI: 10.5281/zenodo.6769313. [2] DOI: 10.5281/zenodo.6782362. [3] DOI: 10.5281/zenodo.6785153. [4] DOI: 10.5281/zenodo.6804861.

Solar neutrinos at JUNO

- **Source**:
  - ^{8}B solar ν_e, $5.25 \times 10^6/\mathrm{cm}^2/\mathrm{s}$
- **Oscillation** [1, 2]:
  - MSW resonance in the Sun
  - Earth matter effect: regeneration of ν_e
- **Detection**:
  - CC (correlated) and NC (singles) on ~200 ton ^{13}C in JUNO LS
  - Elastic scattering (ES) on e^- (singles)

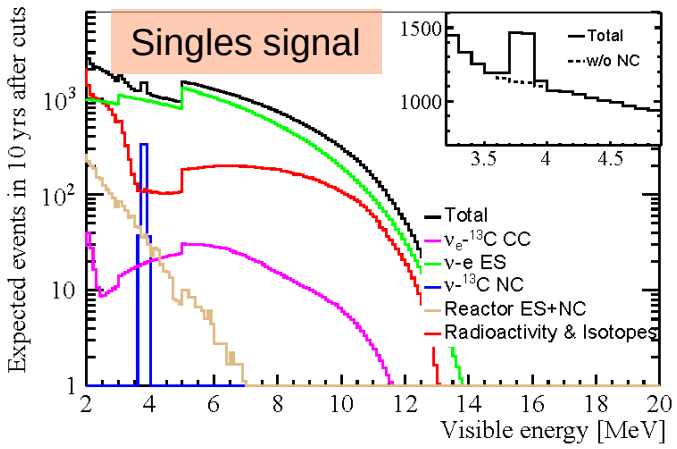
Channels		Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + {}^{13}$N decay	3929	647
NC	$\nu_x + {}^{13}\mathrm{C} \to \nu_x + {}^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \to \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

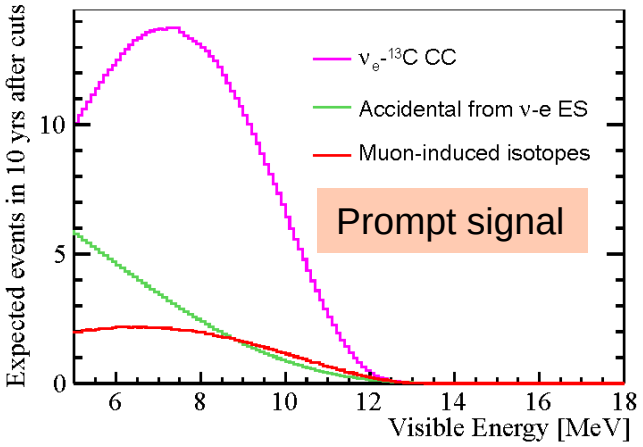


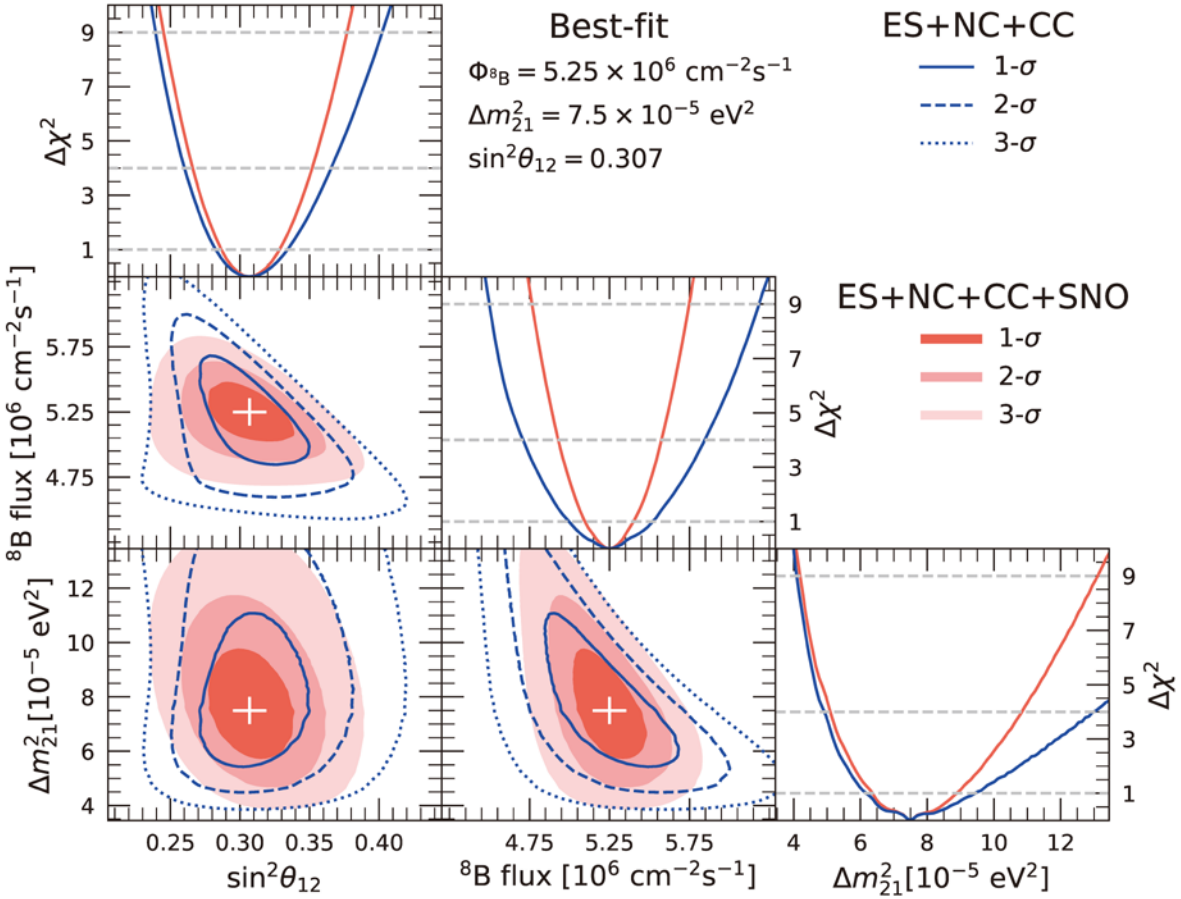


[1] Chin.Phys.C 45 (2021) 2, 023004. [2] DOI: 10.5281/zenodo.6785200.

Solar neutrinos at JUNO







- Independent measurement sensitivity in 10 years [1]:
  - ➢ ^{8}B flux: 5% JUNO-only, 3% JUNO+SNO
  - ➢ $\sin^2\theta_{12}$:+9%/−8%
  - ➢ Δm^2_{21}: +27%/−17%

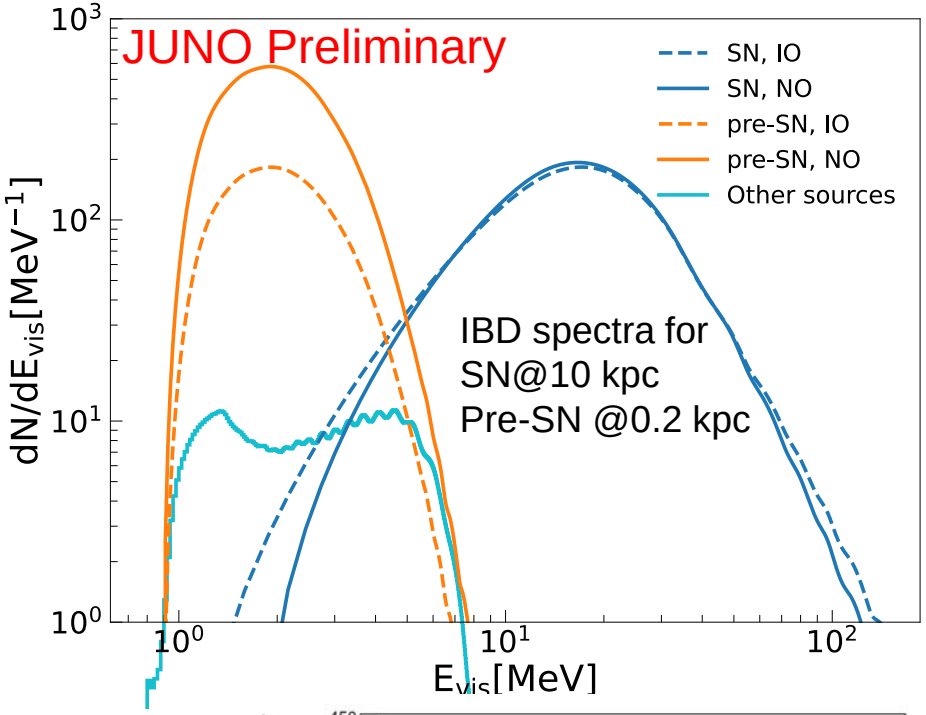
ES: Chin.Phys.C 45 (2021) 2, 023004
ES+NC+CC combined: paper under preparation

[1] DOI: 10.5281/zenodo.6785200.

Oscillation physic for other neutrinos at JUNO

- Core-collapse supernova (CCSN) neutrino [1]:
  - ➢Visible oscillation effect on energy spectra.

Detection channel	IBD	pEs	eEs	C12, NC	C12, CC
Statistics for SN@10 kpc [2]	5000	2000	300	300	200

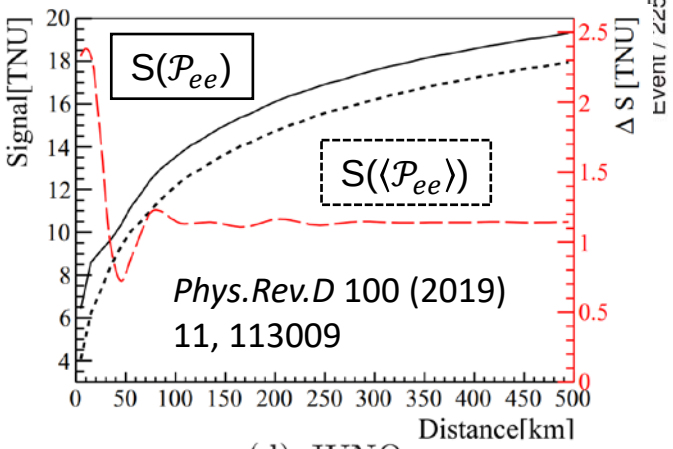


- Geo-neutrino (decay of U and Th, ~400 IBDs/year):
  - ➢In [2], with averaged survival probability $\mathcal{P}_{ee}$ [3]
  - ➢1-2 TNU larger with exact probability $\langle\mathcal{P}_{ee}\rangle$ [4]

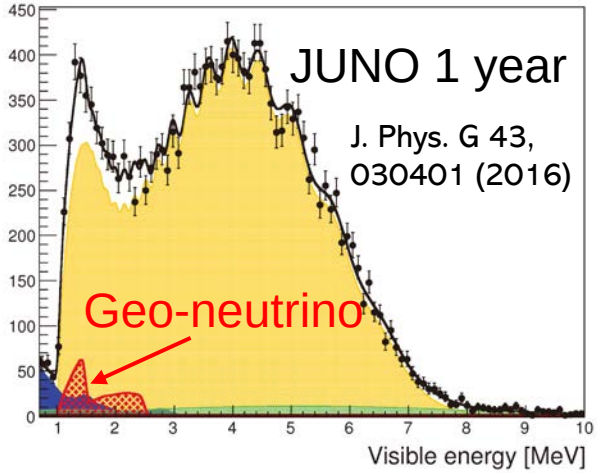
rock density — abundance

$$\frac{d\Phi(i)}{dE} = \int dV \frac{\rho(\vec{r})}{4\pi L^2} \frac{A(i,\vec{r})}{\tau_i m_i} P(E,L)$$

lifetime — atomic mass



(d) JUNO



[1] DOI: 10.5281/zenodo.6785184. [2] *Prog.Part.Nucl.Phys.* 123 (2022) 103927. [3] DOI: 10.1016/j.pepi.2019.106409. [4] *Phys.Rev.D* 100 (2019) 11, 113009

Summary

- JUNO is a multipurpose large liquid scintillator detector
- Great potential in oscillation physics,

Neutrino source	Oscillation physics prospects
Reactor $\overline{\nu}_e$	3σ NMO significance with 6 yrs× $26.6\ \mathrm{GW_{th}}$
	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{31}\rvert/\lvert\Delta m^2_{32}\rvert$ better than 0.5% (1%) in 6 yrs (1 yrs)
Atmospheric ν's	Conservative 10 yrs sensitivity for NMO: 1~1.8σ
	Complementary θ_{23} and δ_{CP} measurement
Solar $^8\mathrm{B}\ \nu_e$	Independent measurement of oscillation parameters: 10 yrs, $\sin^2\theta_{12}$:$+9\%/-8\%$, Δm^2_{21}: $+27\%/-17\%$
Others	Visible oscillation effect in CCSN and Geo $\overline{\nu}_e$

- Detector completion in 2023!

Thank you for your attention!

Looking forward to results with data!

Jinnan Zhang (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 $\nu's$	0 → **0.16**	**50%**	**50%**

Design in Physics book → **this update**

J. Phys. G 43:030401 (2016)

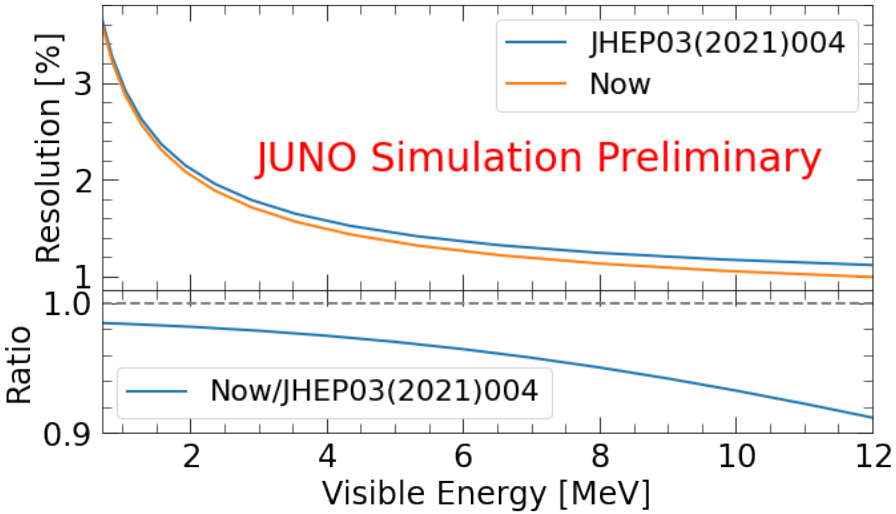
Update of energy resolution

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)*

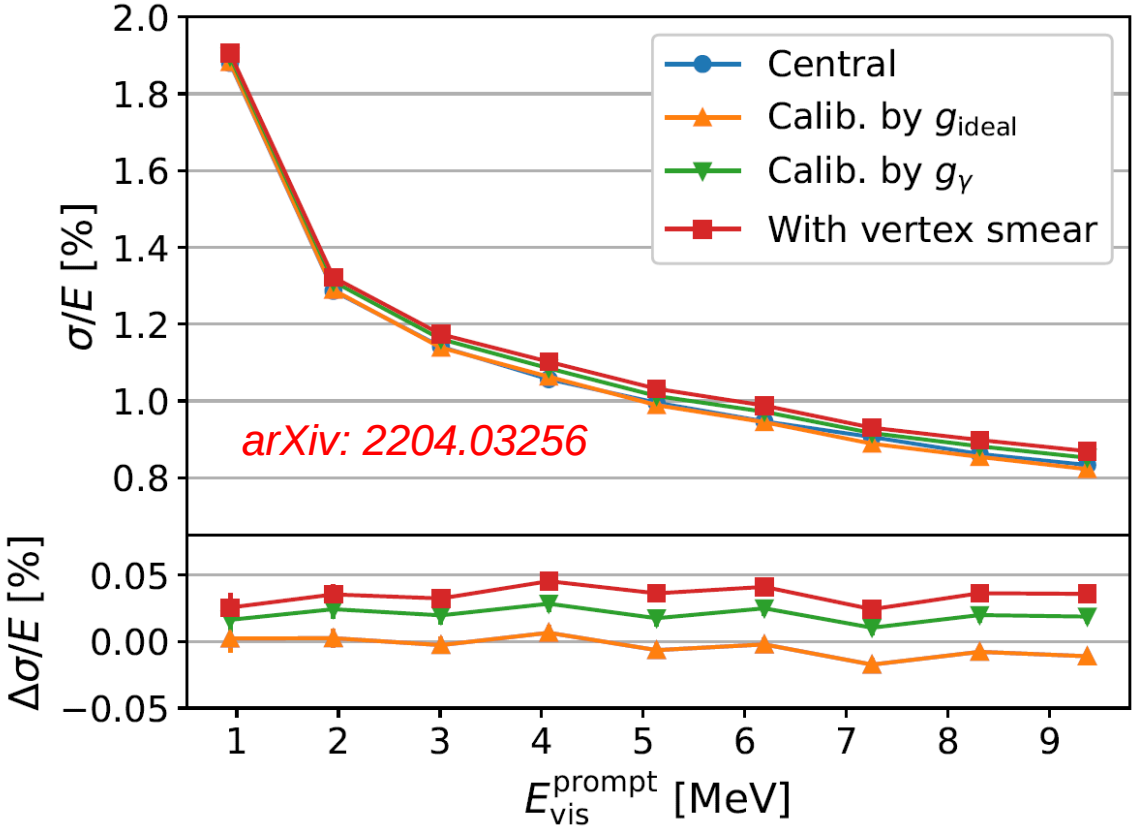
Positron energy resolution is understood:

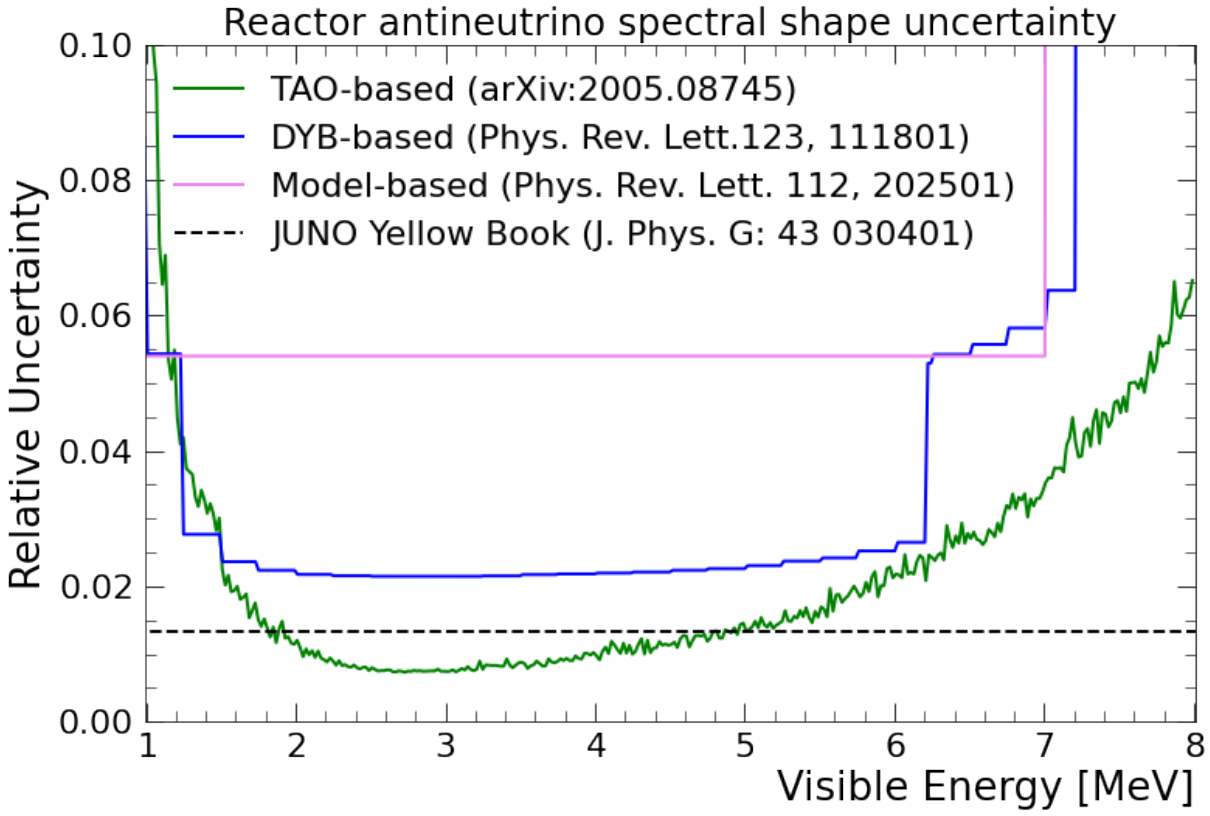
$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}$$

- **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



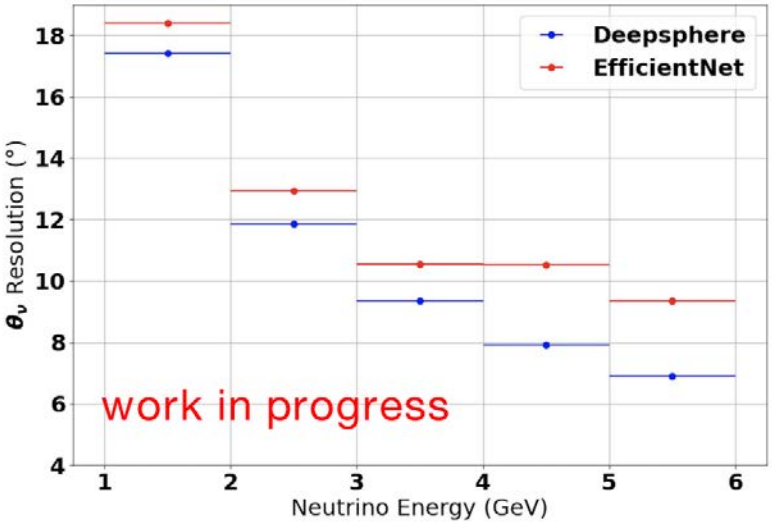


1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, absorption of scintillation very small
3. Gd-LS works at -50℃, increase the photon yield

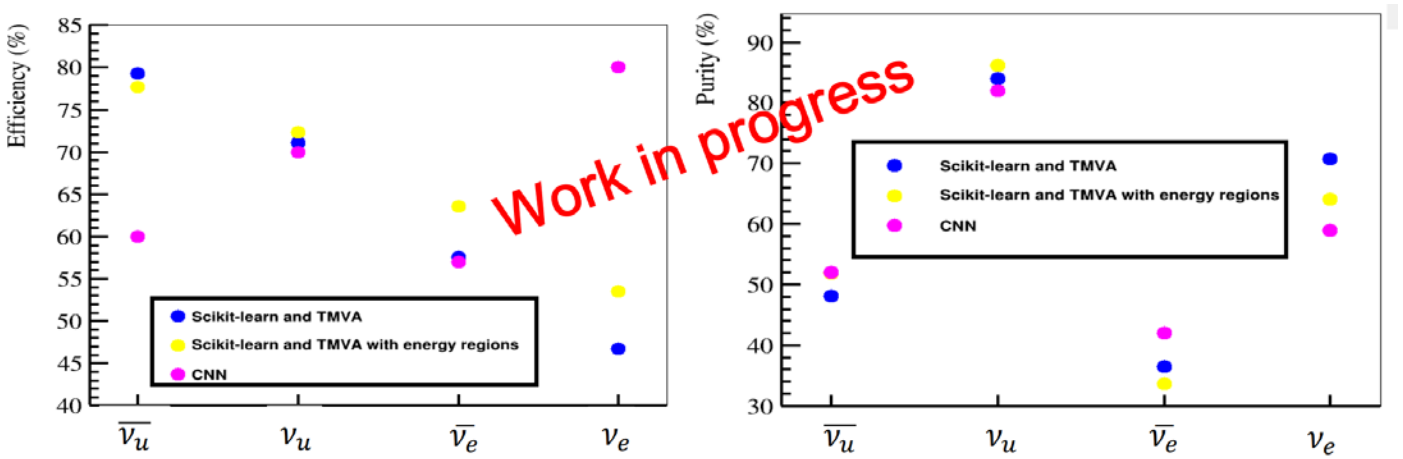
✓ Unprecedented energy resolution < 2% @ 1 MeV

✓ Shape uncertainty close to the assumption in the JUNO Physics Book (*J. Phys. G43:030401 (2016)*)

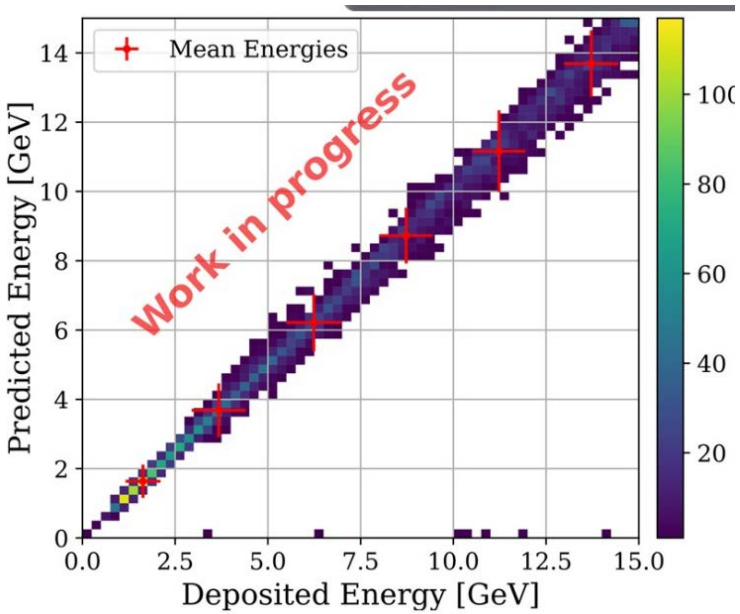
Atmospheric ν's reconstruction progresses



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



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



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

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