Oscillation physics with reactor neutrinos in JUNO

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On behalf of the JUNO collaboration

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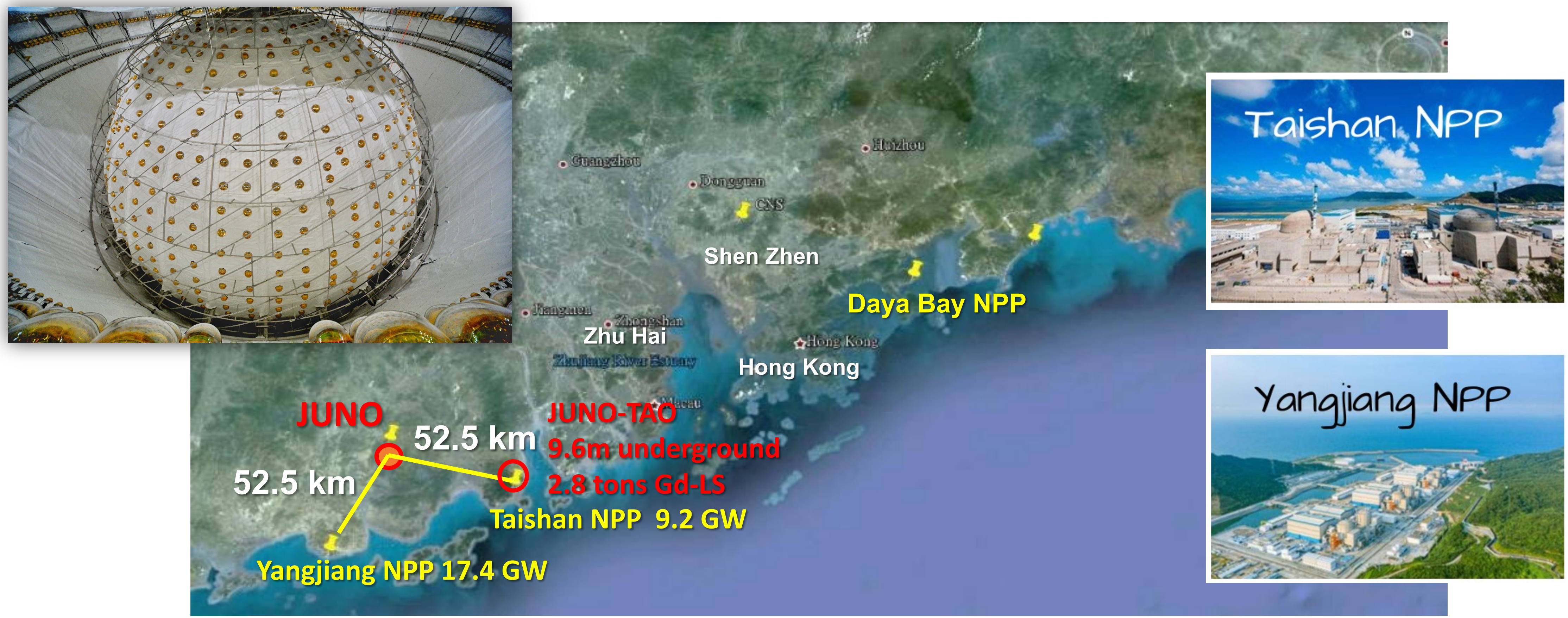
JUNO is a large multi-purpose liquid-scintillator neutrino experiment in Southern China

- Located at a baseline of ~52.5 km from 8 reactors in Yangjiang and Taishan NPPs
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by water Cherenkov detector

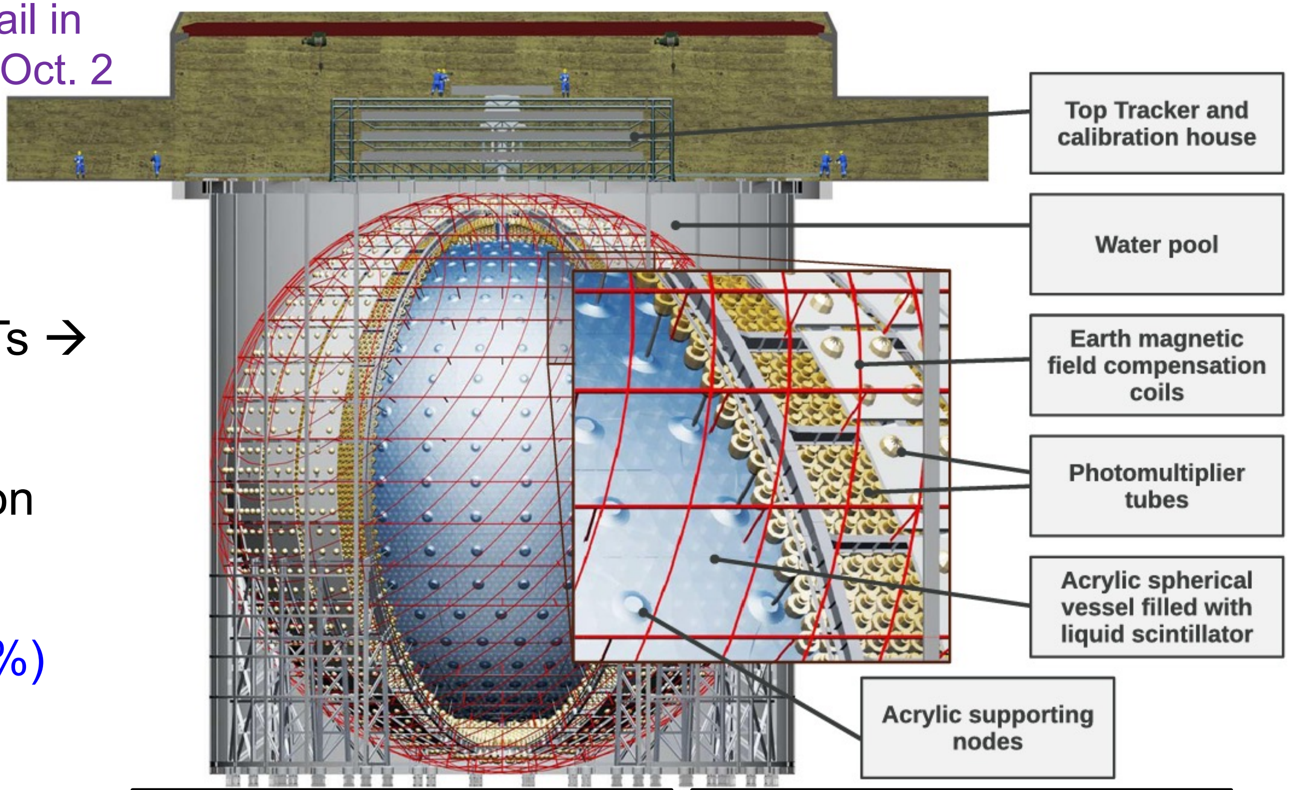


JUNO detector

Key parameters:

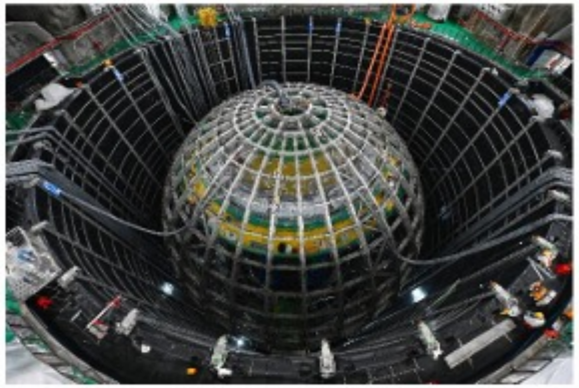
See detector detail in Monica's talk on Oct. 2

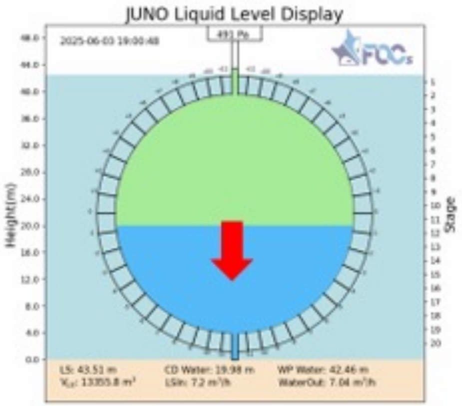
- Large statistics:
  - Huge target mass – 20 ktons LS
- Energy resolution:
  - 17,612 20-inch PMTs and 25,600 3-inch PMTs → Large PMT coverage (~78%)
  - Designed for unprecedented energy resolution (~3% at 1MeV)
  - Control of energy response systematics (≤ 1%)
- Powerful nuclear reactors (26.6 GW_{th})
- Optimized baseline (~52.5 km)
- Low background See detail in Guanda's talk on Oct. 2
  - ~650m overburden for cosmic background suppression
  - LS purification and screening of materials



JUNO status

JUNO Timeline:





Collaboration formed
2014

2015
Civil construction

Detector construction
2022

2024.12
Start of water filling

Start of LS filling
2025.2

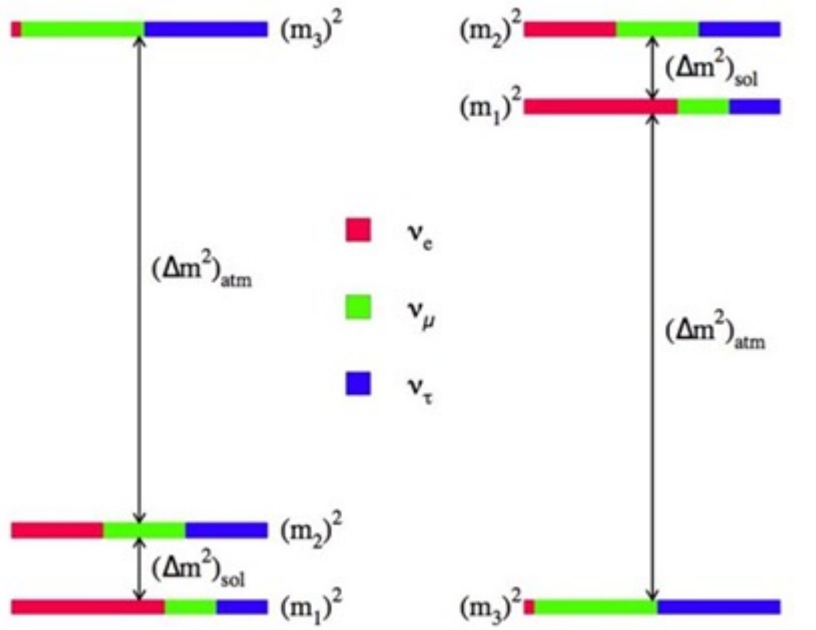
2025.8.26
Physics data-taking start

Status of ν oscillation physics

- Neutrino oscillation implies non-zero neutrino mass: beyond Standard Model

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- Known: $|\Delta m^2_{31}| \sim 2.5\times10^{-3}\mathrm{eV}^2$ $\Delta m^2_{21} \sim 7.5\times10^{-5}\mathrm{eV}^2$
  $\sin^2\theta_{23} \sim 0.5$ $\sin^2\theta_{12} \sim 0.3$ $\sin^2\theta_{13} \sim 0.02$
- Unknown:
  - sign of Δm^2_{31}, δ_{CP}, octant of θ_{23}
  - Dirac or Majorana particle, absolute mass scale



Normal ordering $m_3 > m_2 > m_1$

Inverted ordering $m_2 > m_1 > m_3$

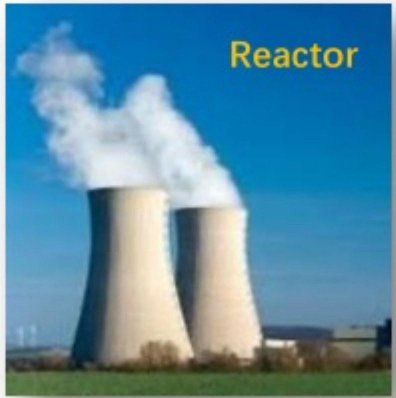
Main goals of JUNO: Determine the neutrino mass ordering (NMO), and measure Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ at <1% level via reactor antineutrinos

JUNO physics program

- JUNO can detect neutrinos and antineutrinos coming from several sources:

Covered in this talk

See Vannesa's talk

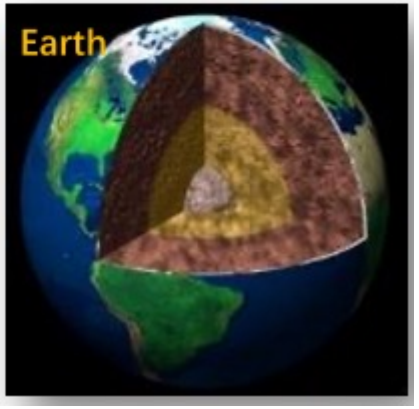


~50/day

>100/year

>100/day

$\sim 10^4$/10 s @ 10kpc



~400/year

Neutrino oscillation properties (Reactor, Atmosphere, Solar)

Neutrinos as a probe (Solar, Supernova, Earth)

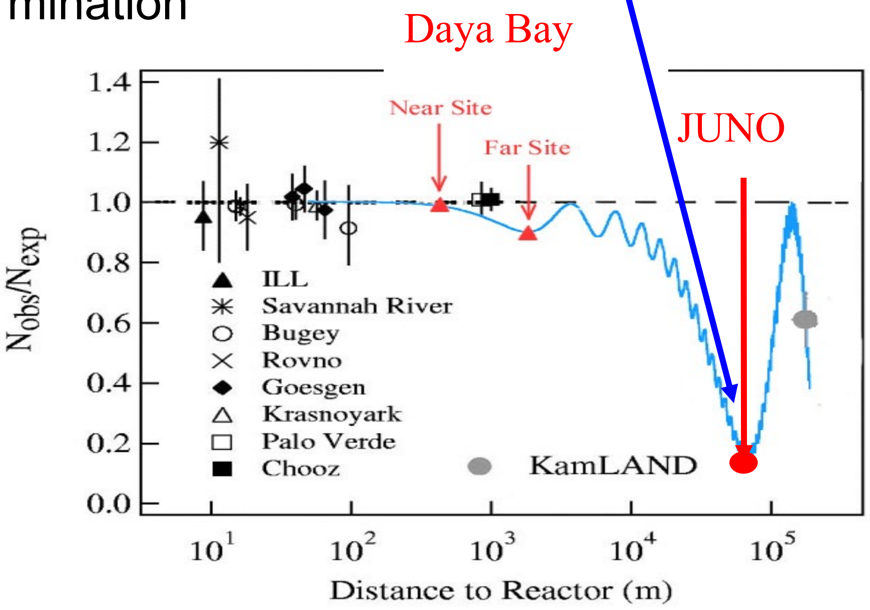
Reactor oscillations in JUNO

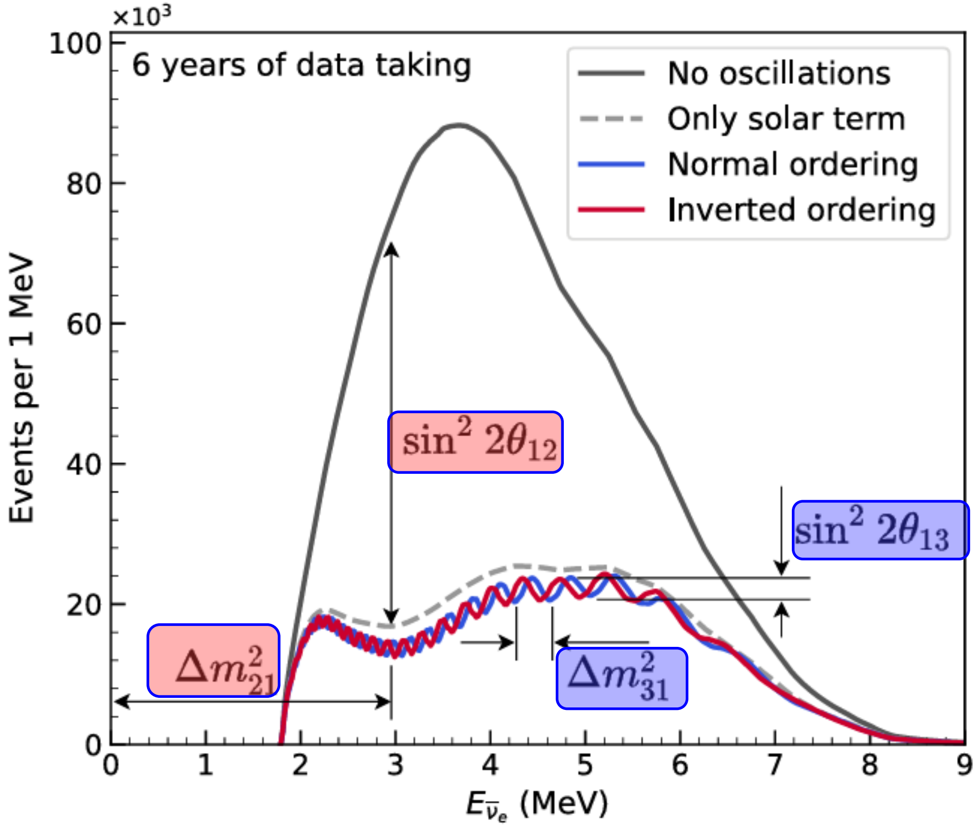
Oscillation: (quasi-vacuum)

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2(2\theta_{13})\left(\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right)$$

slow　　　　fast

- Simultaneously probe two oscillation frequencies, no dependence on δ_{CP} and θ_{23}
- Optimized baseline at first solar oscillation maximum for NMO determination





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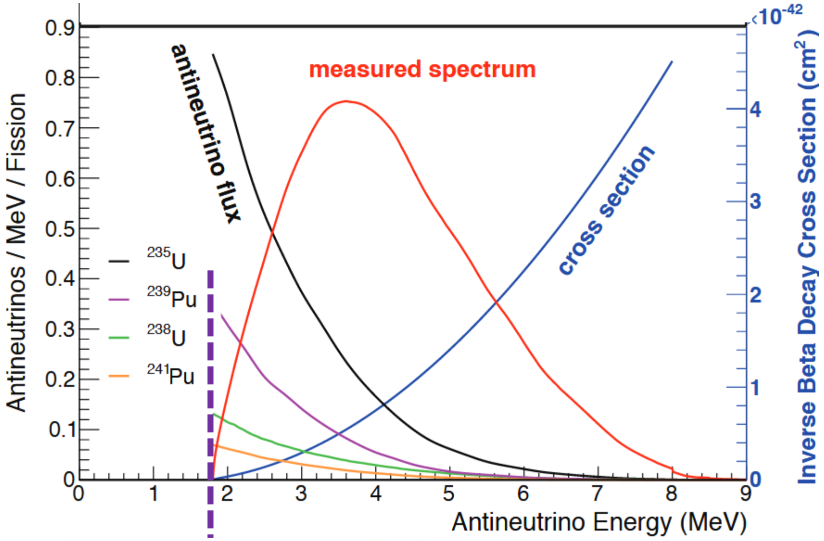
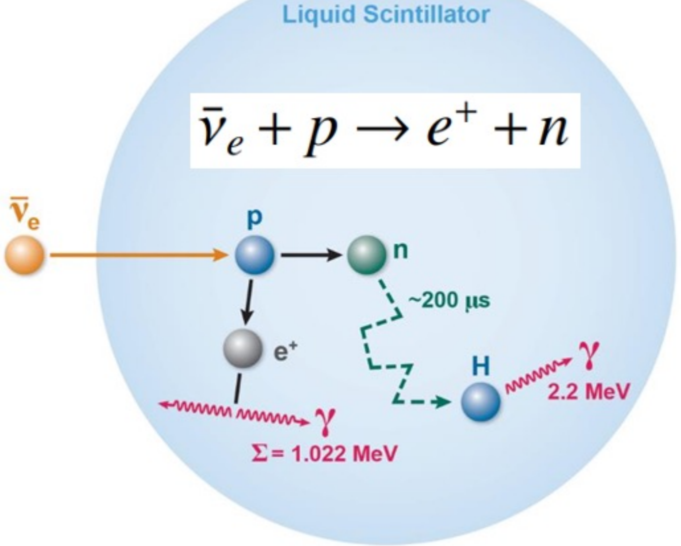
Antineutrino detection in JUNO



IBD threshold 1.8 MeV



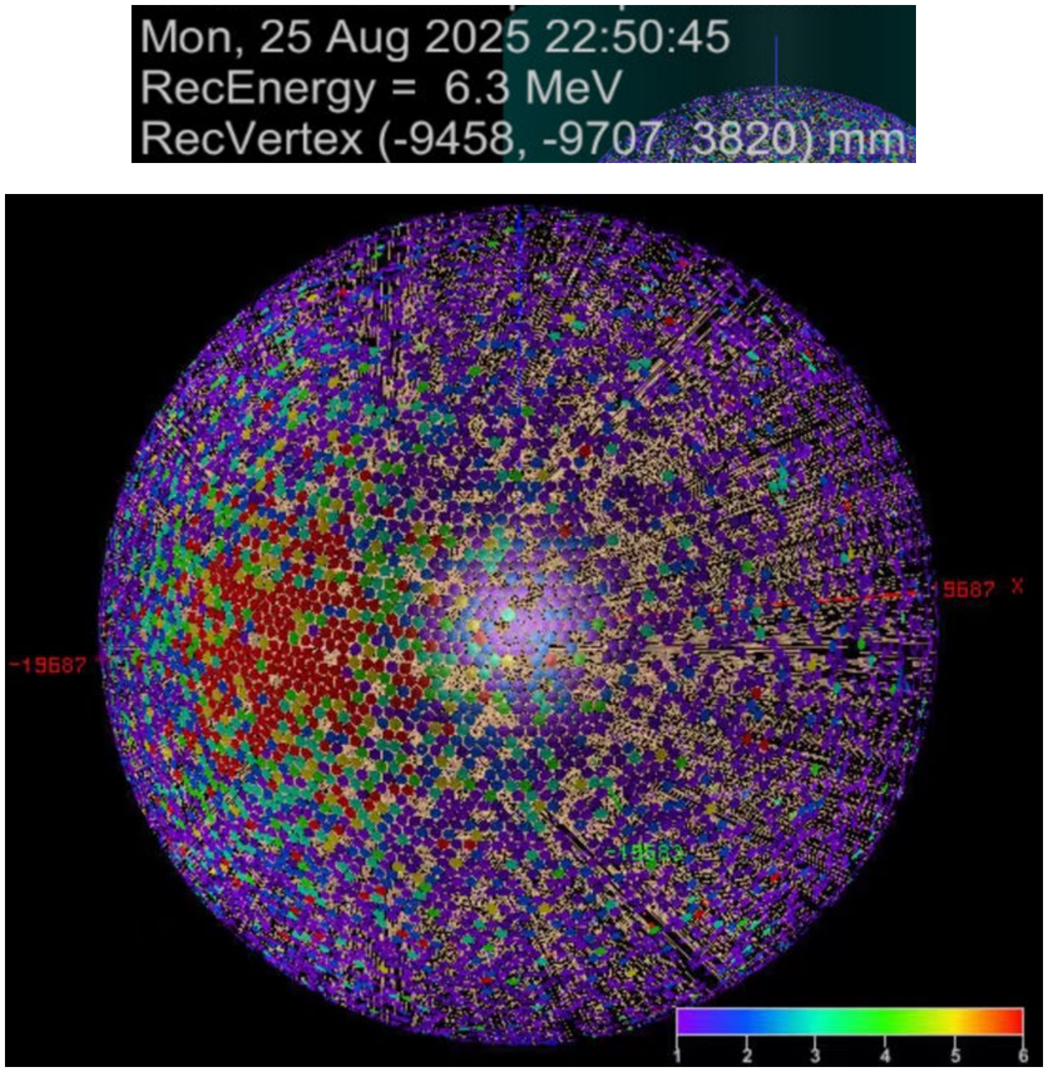
- ➢ Measure neutrinos from fissions of 4 main isotopes in reactor via Inverse Beta Decay (IBD)
- • Prompt: kinetic energy loss of e^+ and $\mathrm{e}^+\mathrm{e}^-$ annihilation γs
- • Delayed: n-capture on H (2.2 MeV) or $^{12}\mathrm{C}$ (4.95 MeV)

$$\tau \sim 200\mu s$$

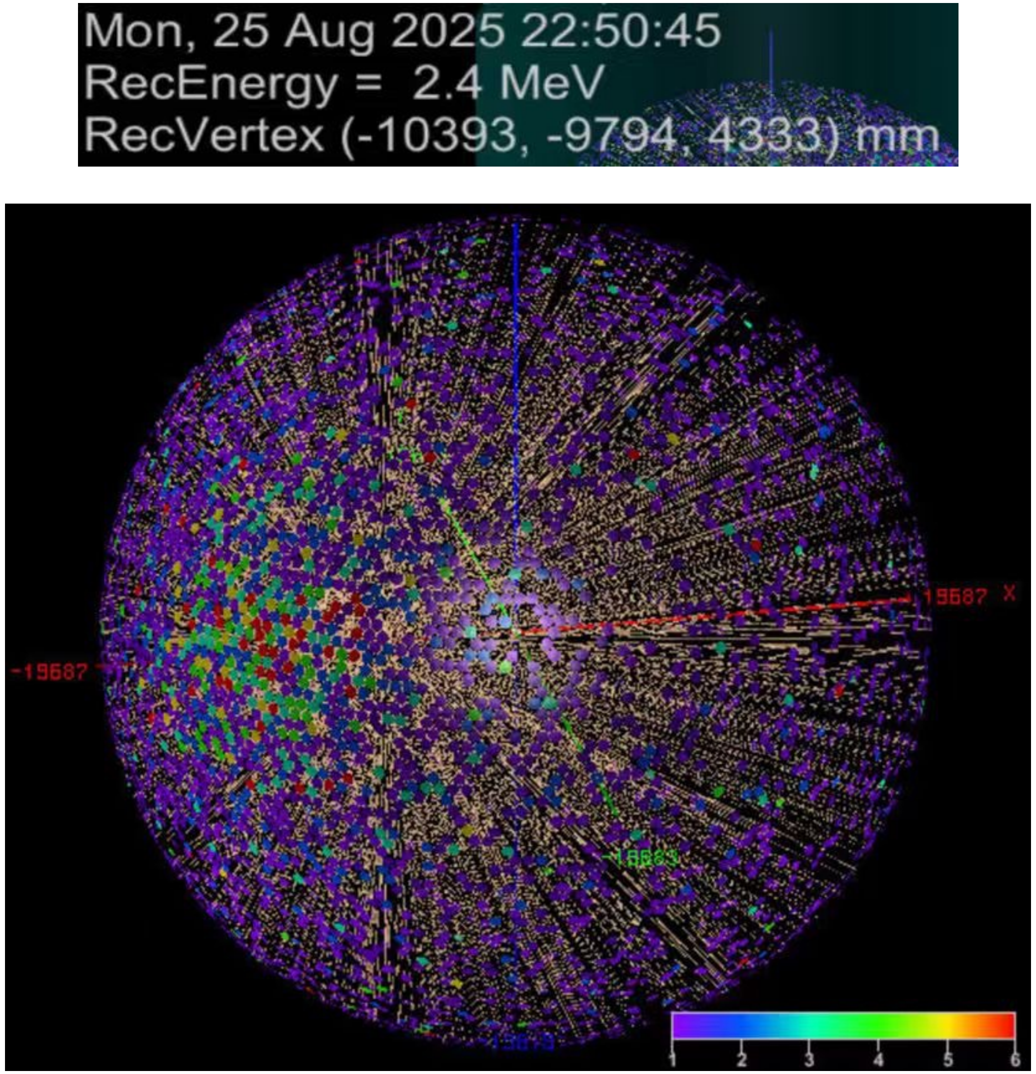
- ➢ Time-space coincidence between prompt positron and delayed neutron signals → powerful background suppression
- ➢ Relation of positron energy and neutrino energy

$$\mathrm{E_{vis}}(e^+) \sim E_{\overline{\nu}_e} - 0.78\ MeV$$

Event display of reactor neutrino



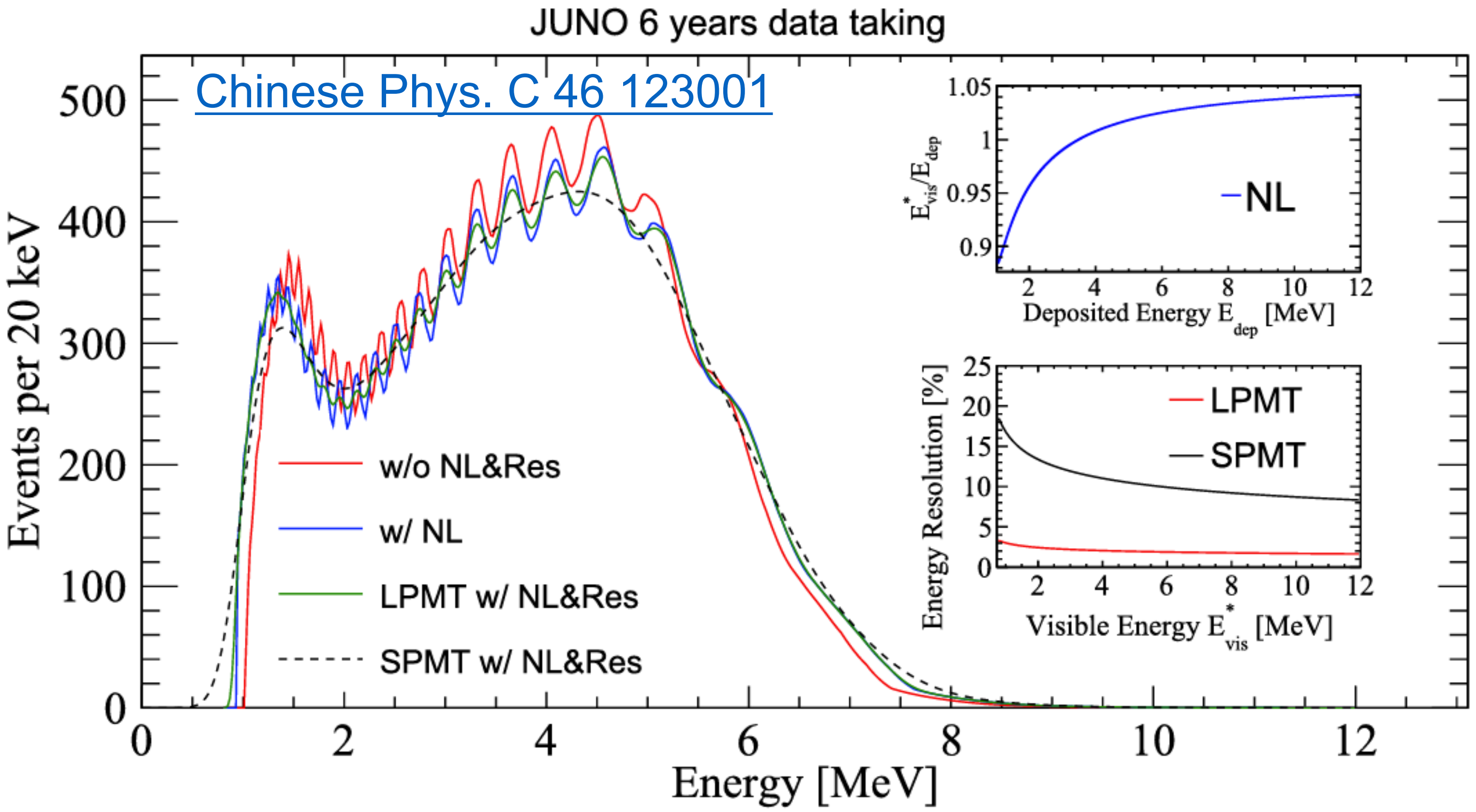
Prompt e^+ signal



Delayed neutron signal

Detector response

Antineutrino energy		Deposited energy		Visible energy		Reconstructed energy
E_ν	→	$E_{\rm dep}$	→	$E_{\rm vis}$	→	$E_{\rm rec}$
	IBD reaction		Light emission		Smearing	



- **Liquid scintillator non-linearity (LSNL)**, visible energy ∝ detected photo-electrons:

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

- **Energy resolution:**

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

a: stochastic Poisson term

b: dominated by non-uniformity

c: PMT dark noise

Signals and backgrounds

Event selection and background suppression:

- With fiducial volume (FV), energy selection, time coincidence, vertex correlation, and muon veto
- ~ 82% efficiency for IBD events

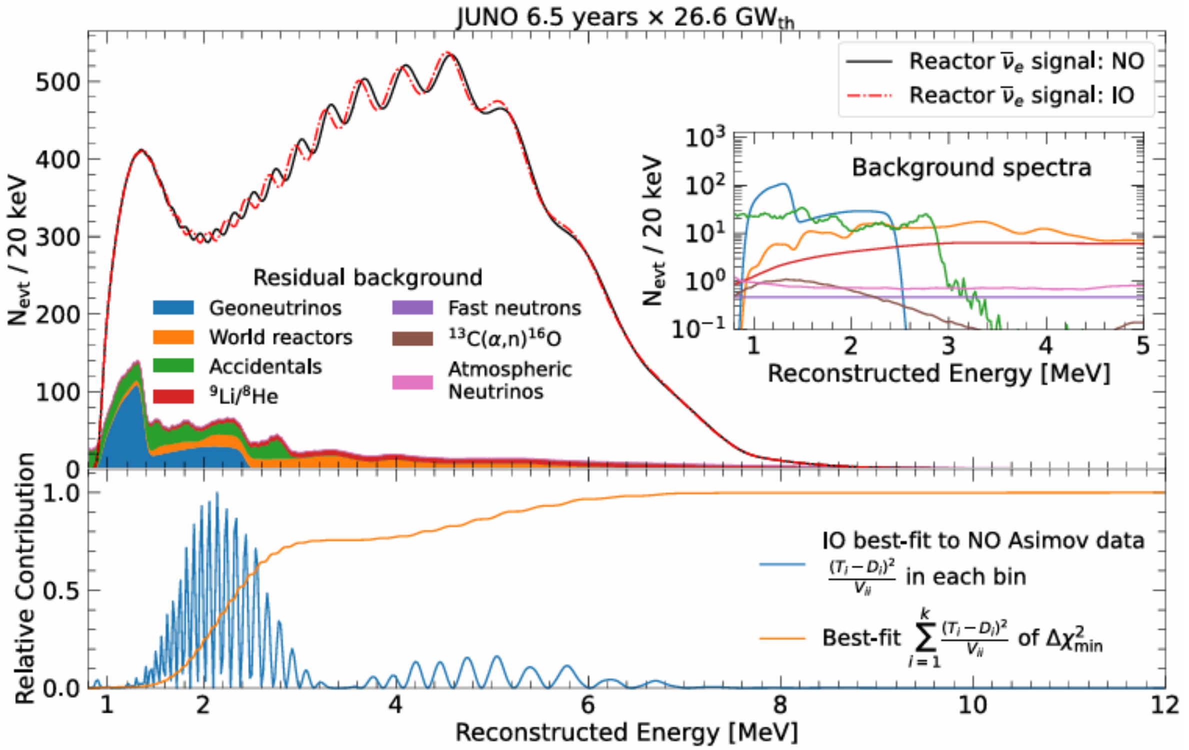
Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1

Main background:

- Accidental coincidences from radioactivity → FV cut
- Muon-induced $^{9}\text{Li}/\,^{8}\text{He}$ → muon veto
- Irreducible backgrounds: Geo-ν, World reactors (>300 km)

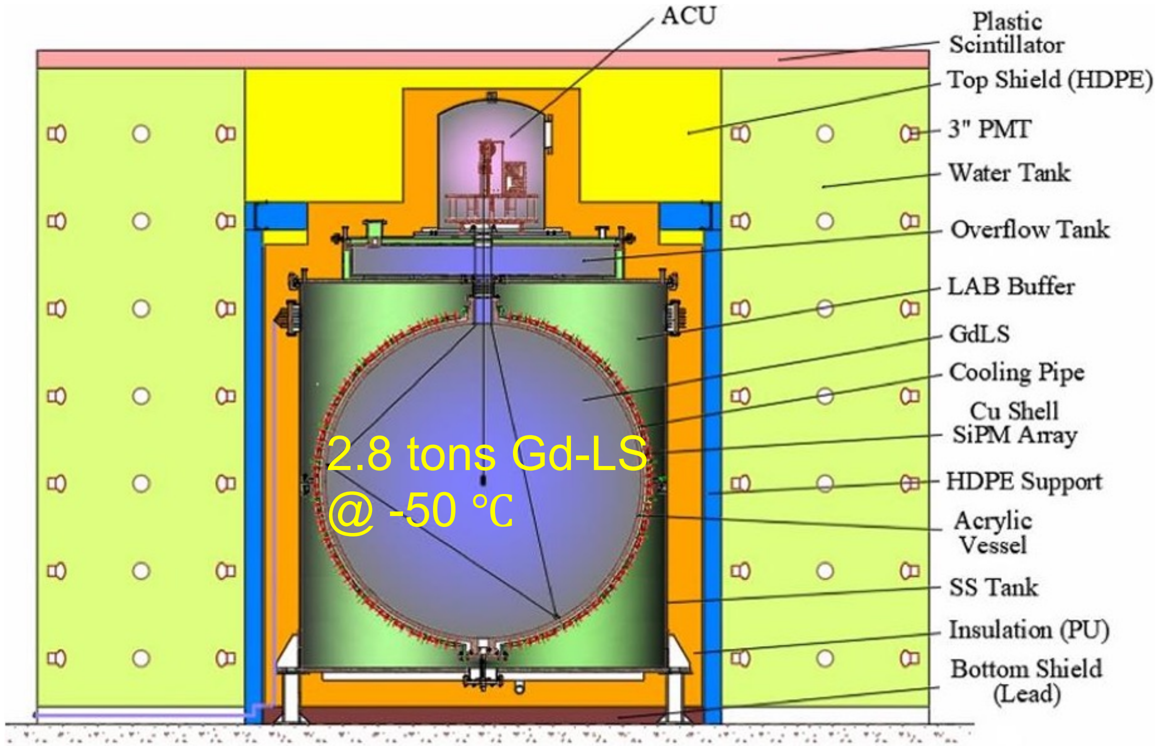
Backgrounds	Rate [day^{-1}]	B/S [%]
Geoneutrinos	1.2	2.5
World reactors	1.0	2.1
Accidentals	0.8	1.7
$^{9}\text{Li}/^{8}\text{He}$	0.8	1.7
Atmospheric neutrinos	0.16	0.34
Fast neutrons	0.1	0.21
$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$	0.05	0.01
Total backgrounds	4.11	8.7

Low B/S ratio



Taishan Antineutrino Observatory: site at 44m from one of the Taishan cores

- Primary goal: provide precise un-oscillated reactor ν spectrum for JUNO NMO sensitivity
- Expect < 2% energy resolution @ 1MeV (~94% coverage with SiPM)
- Sub-percent spectral shape uncertainty



arXiv:2005.08745

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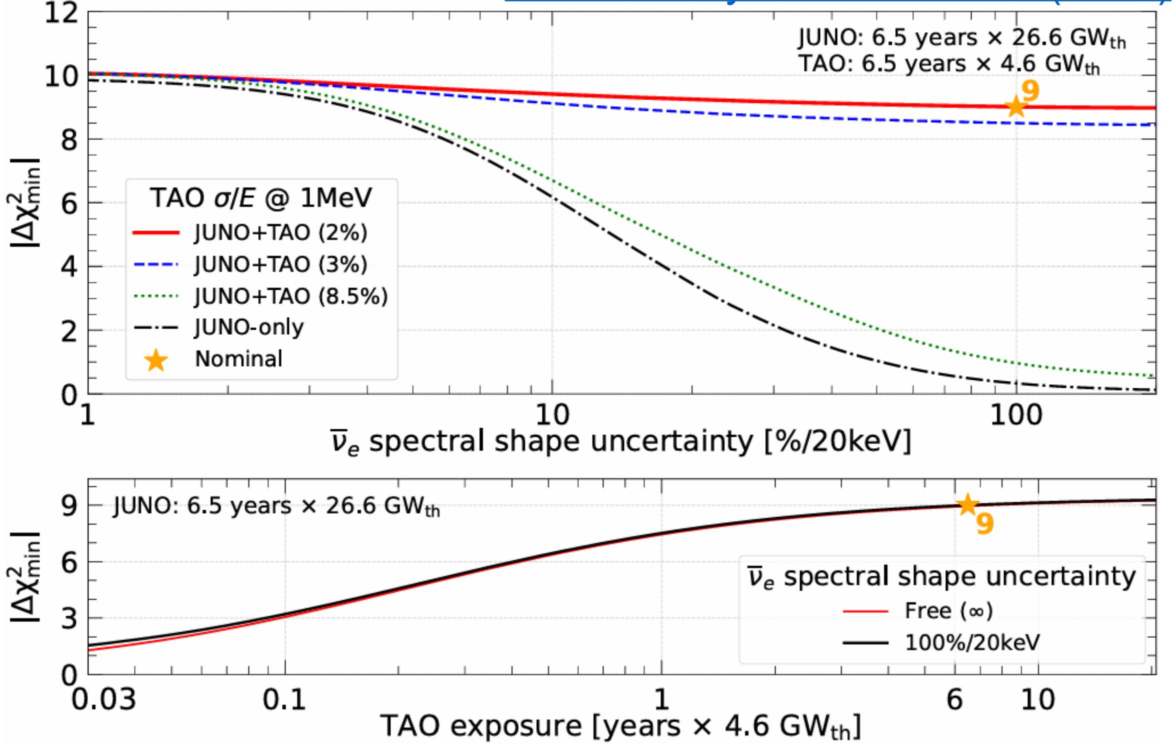
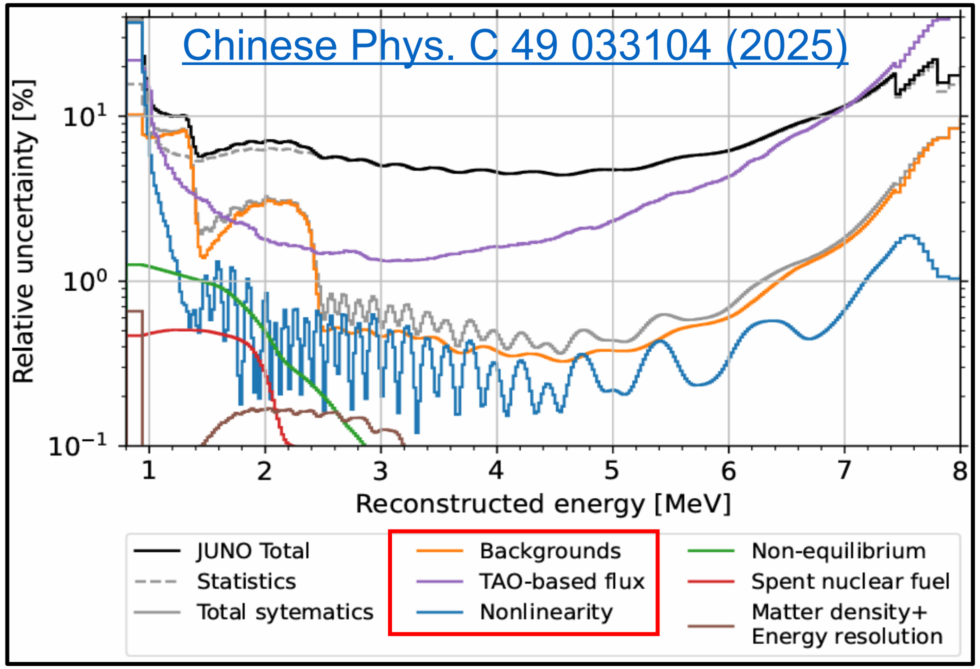


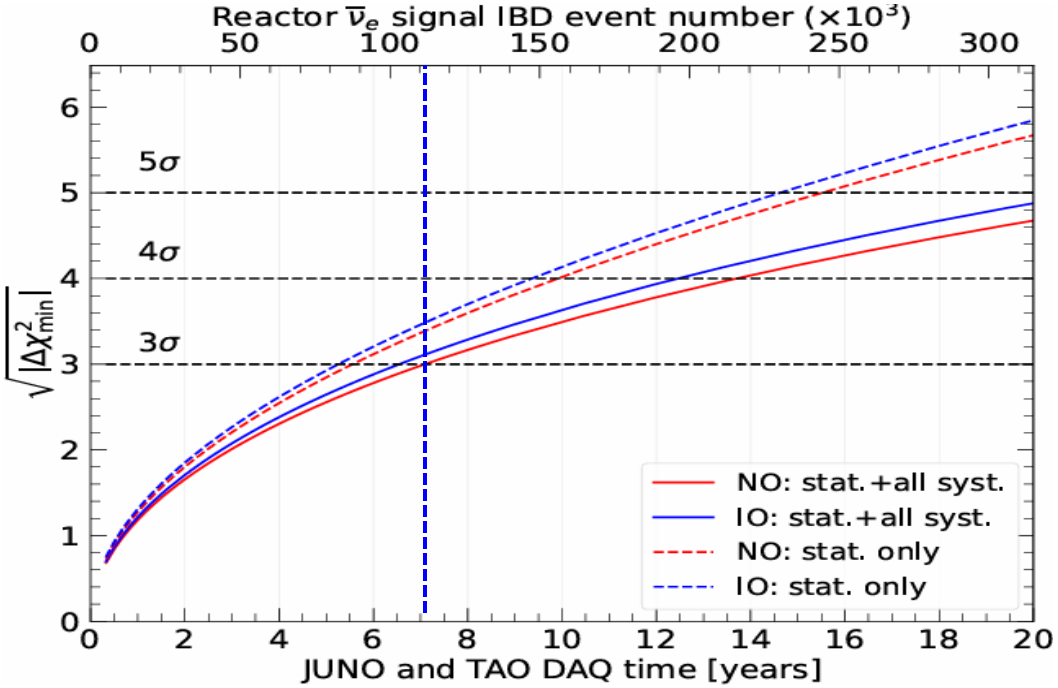
Sensitivity to neutrino mass ordering

- Fit data respectively in NO and IO scenarios
- NMO discriminator:

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

- Reactor-only: 3σ median sensitivity in ~7.1 years of data taking, with 11/12 duty cycle (6.5 years × 26.6 $\rm GW_{th}$ exposure)





- Dominant systematics: reactor spectrum uncertainty, backgrounds, and non-linearity uncertainty
- Reactor + atmospheric neutrino analysis in JUNO
  → further improve NMO sensitivity (ongoing)
- Synergy with LBL and other atmospheric experiments
  → enhance NMO sensitivity

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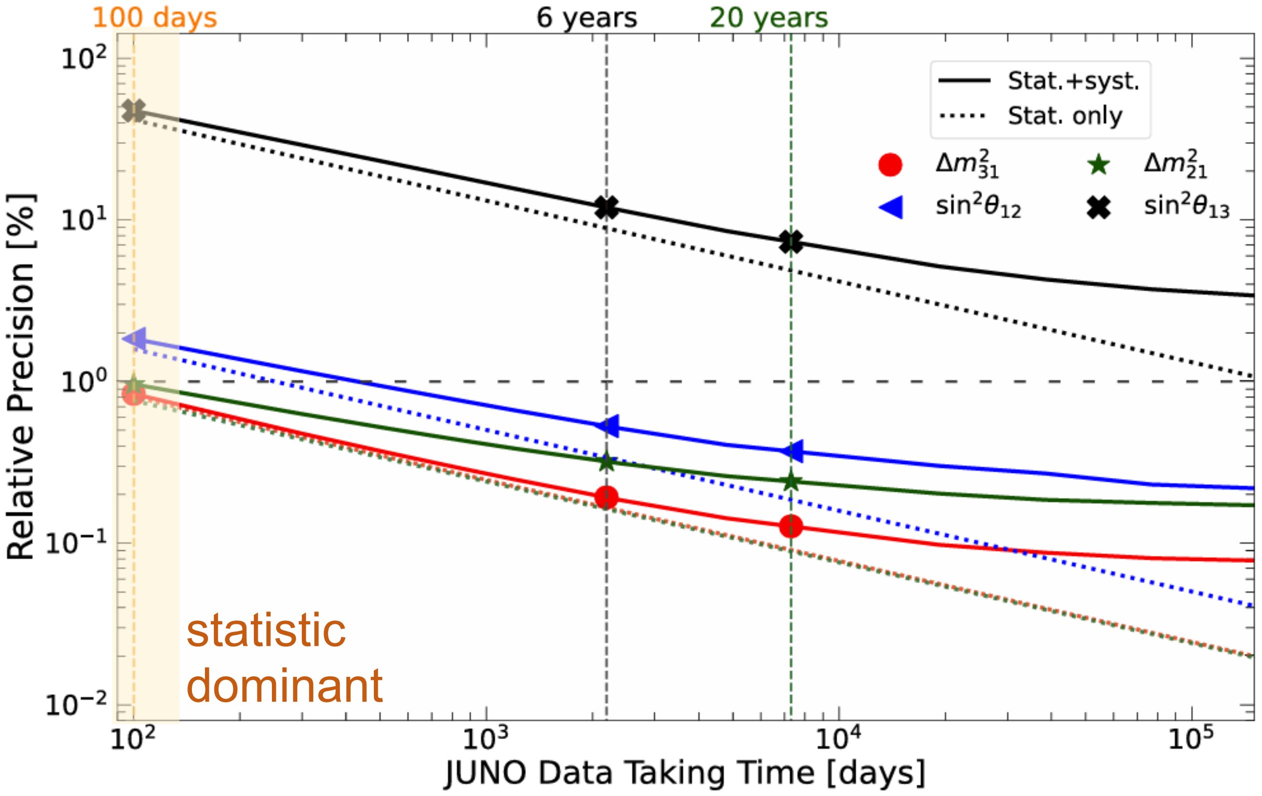
Phys. Rev. D **111**, 013008

Precision measurements on oscillation parameters



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$\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$:

- In 2 years: sub-percent precision
  → world-leading measurement
- In 6 years: precision < 0.5%, one order of magnitude improvement!

Precision	PDG 2025	100 days	6 years
Δm^2_{31}	1.1 %	0.8%	0.2 %
Δm^2_{21}	2.5 %	1.0 %	0.3 %
$\sin^2\theta_{12}$	3.9 %	1.9 %	0.5 %
$\sin^2\theta_{13}$	2.8 %	47.9 %	12.1 %

Systematic uncertainty on precision

Dominant systematic uncertainty:

- Δm^2_{31}: shape uncertainty of reactor neutrino spectrum
- Δm^2_{21}: backgrounds (especially within low energy region, i.e., geo-neutrinos)
- $\sin^2\theta_{12}$, $\sin^2\theta_{13}$: rate uncertainty of normalization factor, including flux and efficiency

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	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

Conclusion

- JUNO is a multi-purpose large liquid scintillator experiment

- Great physics potential using reactor $\bar{\nu}_e$ dataset:
  - Δm^2_{21}, $|\Delta m^2_{31}|$, and $\sin^2\theta_{12}$ measurements with **< 0.5%** precision in 6 years
  - NMO sensitivity via oscillation interference in vacuum: $\boldsymbol{3\sigma}$ in 7.1 years of data taking

- JUNO detector has been fully constructed, and LS filling has been completed.
- The physics data taking began at the end of August
  - Results from reactor neutrinos will come soon !

Backup

Detector performance

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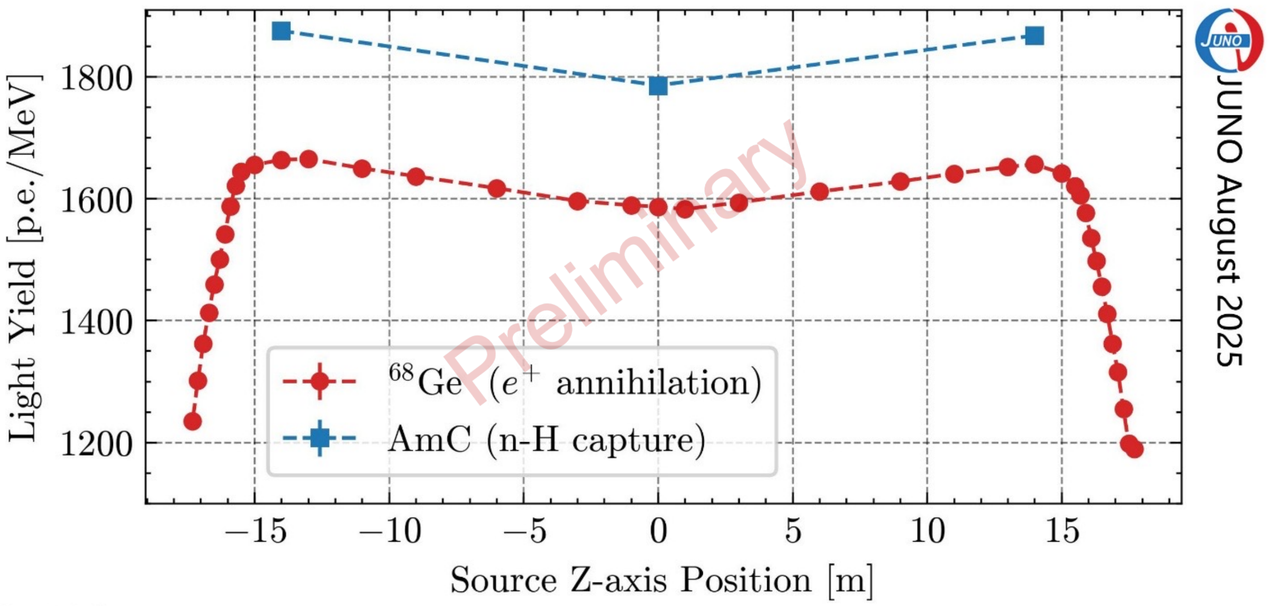
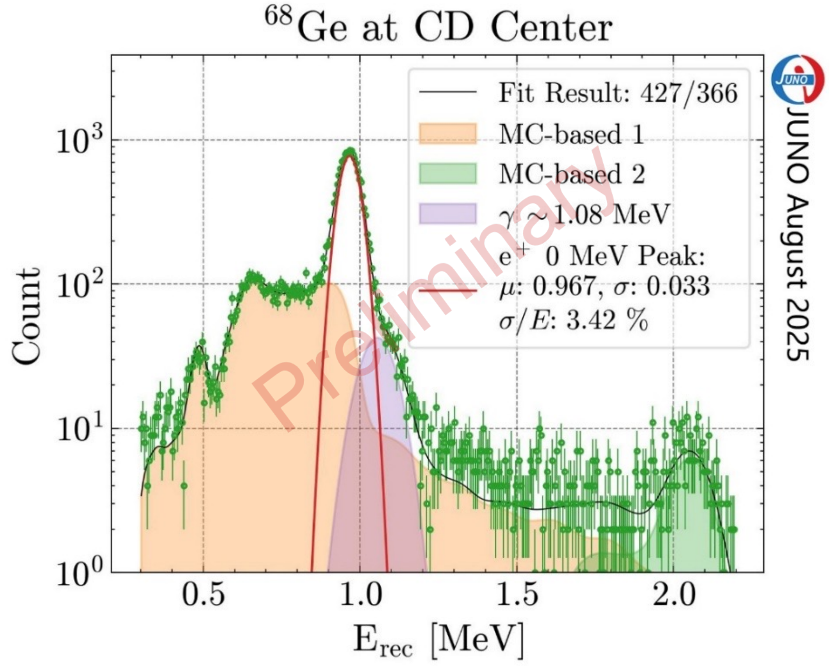
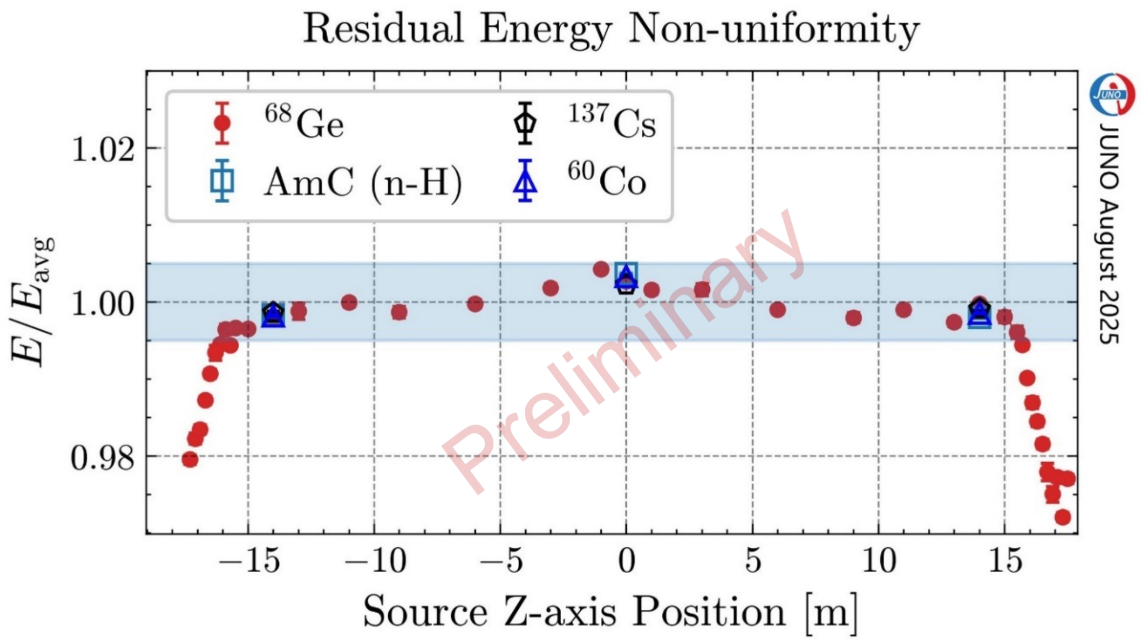
- Measured light yield better than expectations based on simulation:
  - >1600 PE/MeV for ^{68}Ge, >1800 PE/MeV for neutron capture (~1785 PE/MeV in expectations)
- Energy resolution for alpha from ^{214}Po gives ~3% @0.92MeV
- Energy resolution for ^{68}Ge ~3.4%@2×0.511 MeV, close and worse than expectation 3.1%
- Further improvement coming: more calibration data, noise/flasher removal, reconstruction and fit, …

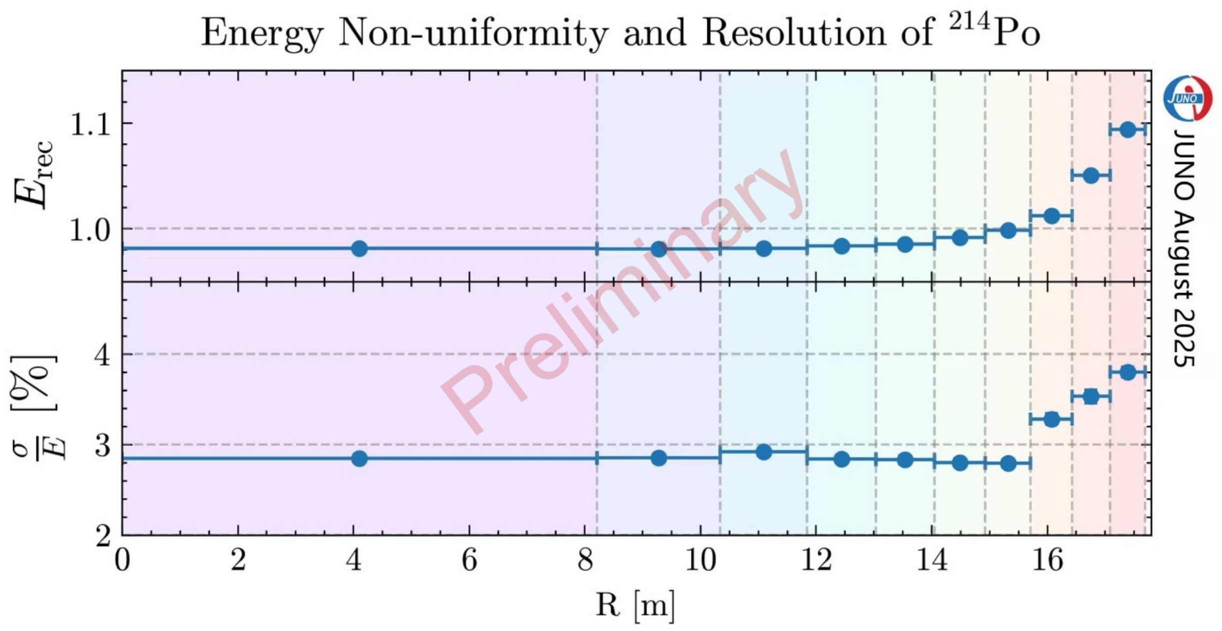
Light yield for ^{68}Ge and neutron





Detector performance





Spectral shape uncertainty from TAO