JUNO's Geoneutrino Results and Prospects

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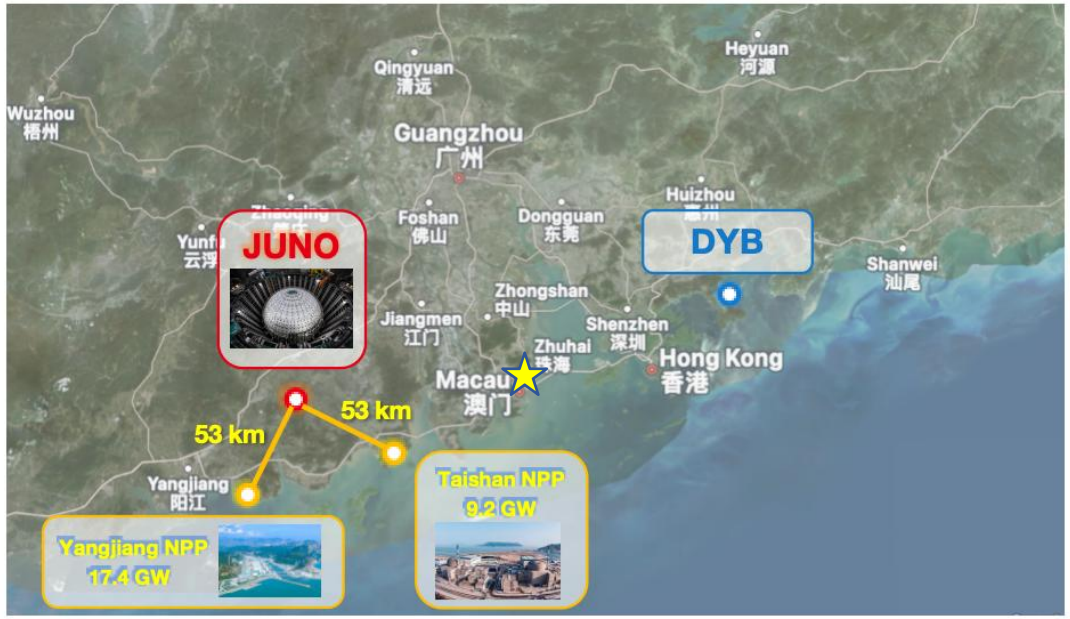
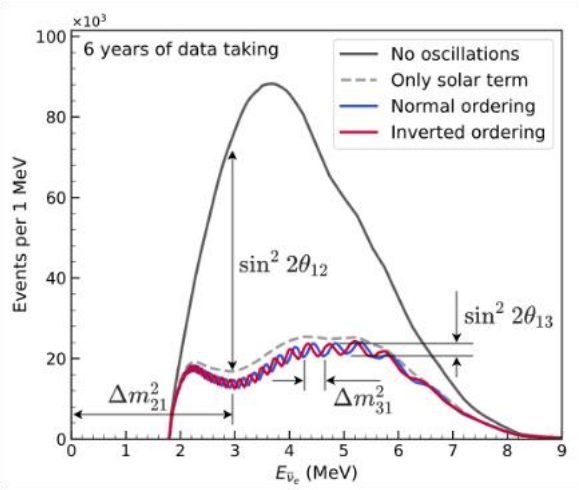
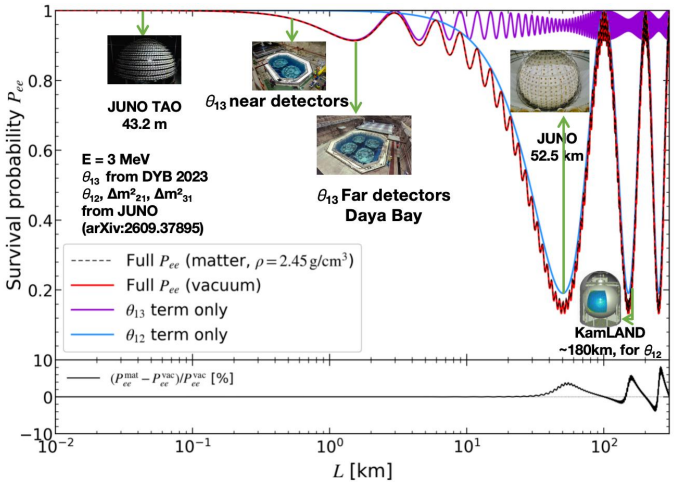
JUNO Location & Primary Goal



Primary physics goal: Use reactor neutrinos to determine the mass ordering
- Independent of θ_{23} & δ_{CP} and small matter effect



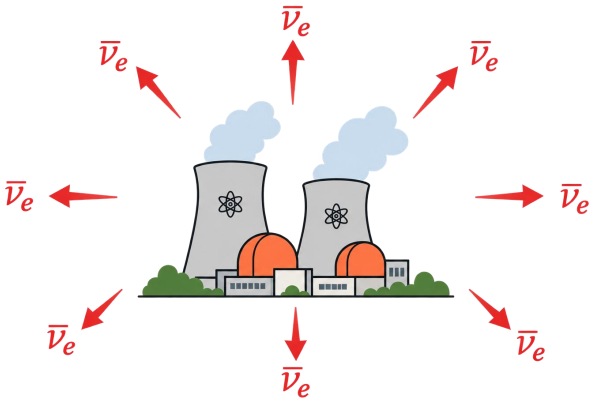


- Located in Jiangmen, Guangdong — **650 m** rock overburden
- **52.5 km** from the Yangjiang & Taishan reactor
- Equidistant from both ⇒ effectively increases the neutrino flux
- Sits at the first solar oscillation maximum ⇒ maximal spectral distortion

Reactor antineutrino production and spectrum

(Jianrun Hu's talk)

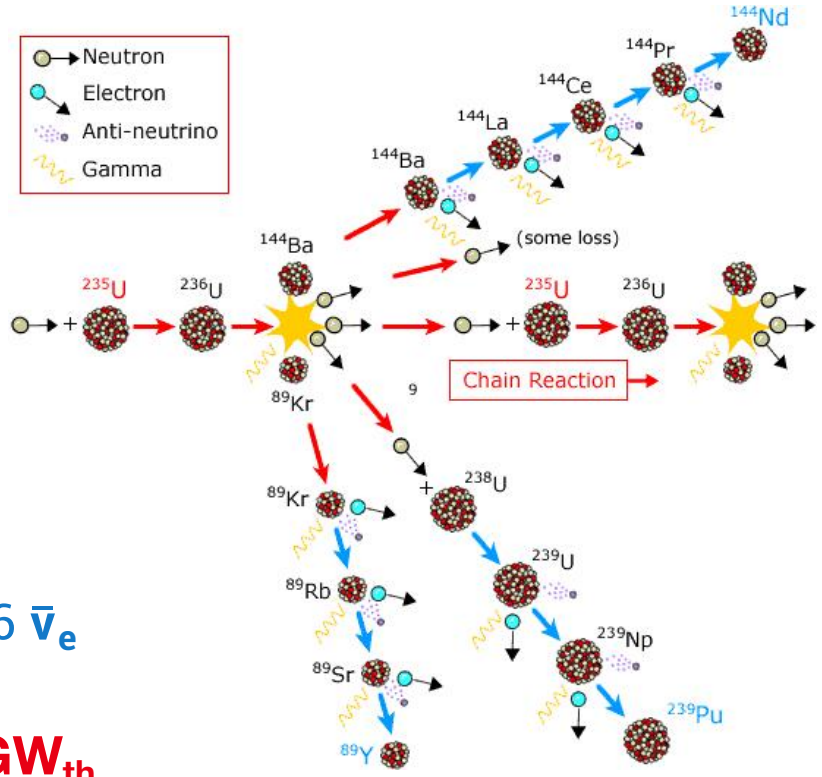
- Reactor antineutrino dominantly come from fission of ^{235}U and ^{239}Pu
- Unoscillated reactor spectrum and flux constrained by the near detector spectra from TAO and Daya Bay



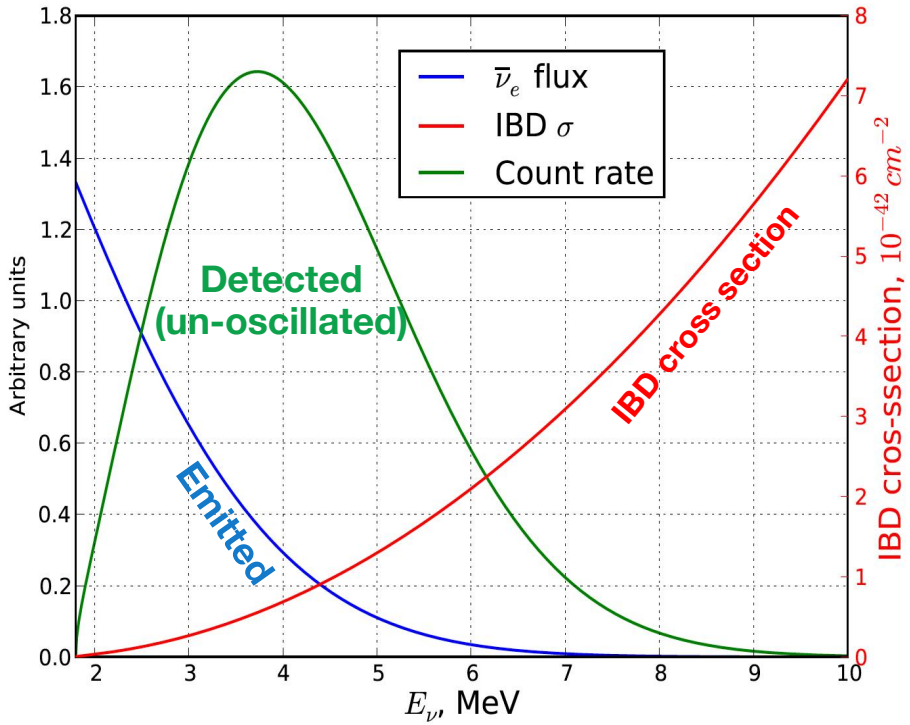
Each fission generates ~6 $\bar{\nu}_e$

↓

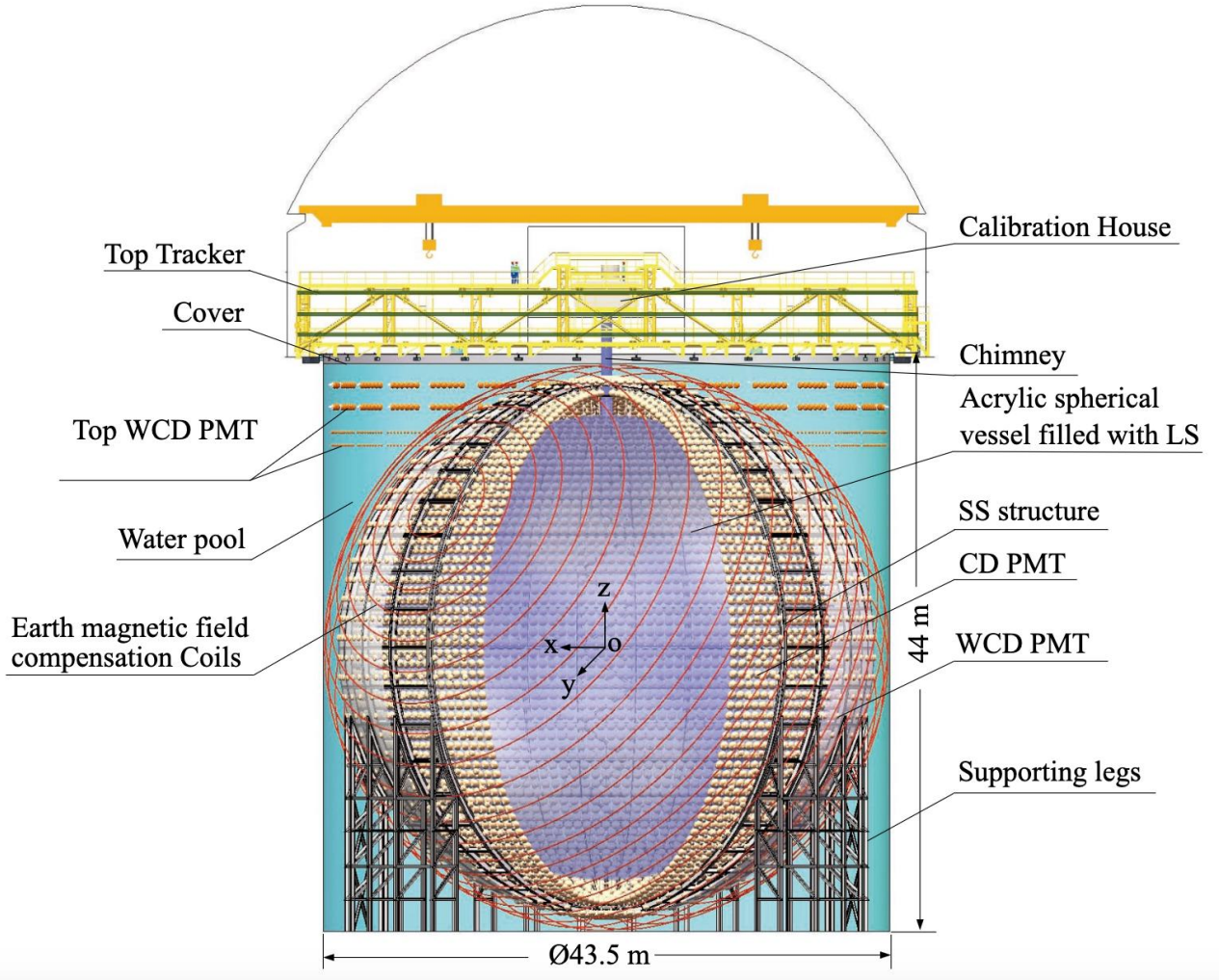
6×10^{20}/s/reactor with 3 GW_{th} power



Credit: nobelprize.org



The JUNO Detector



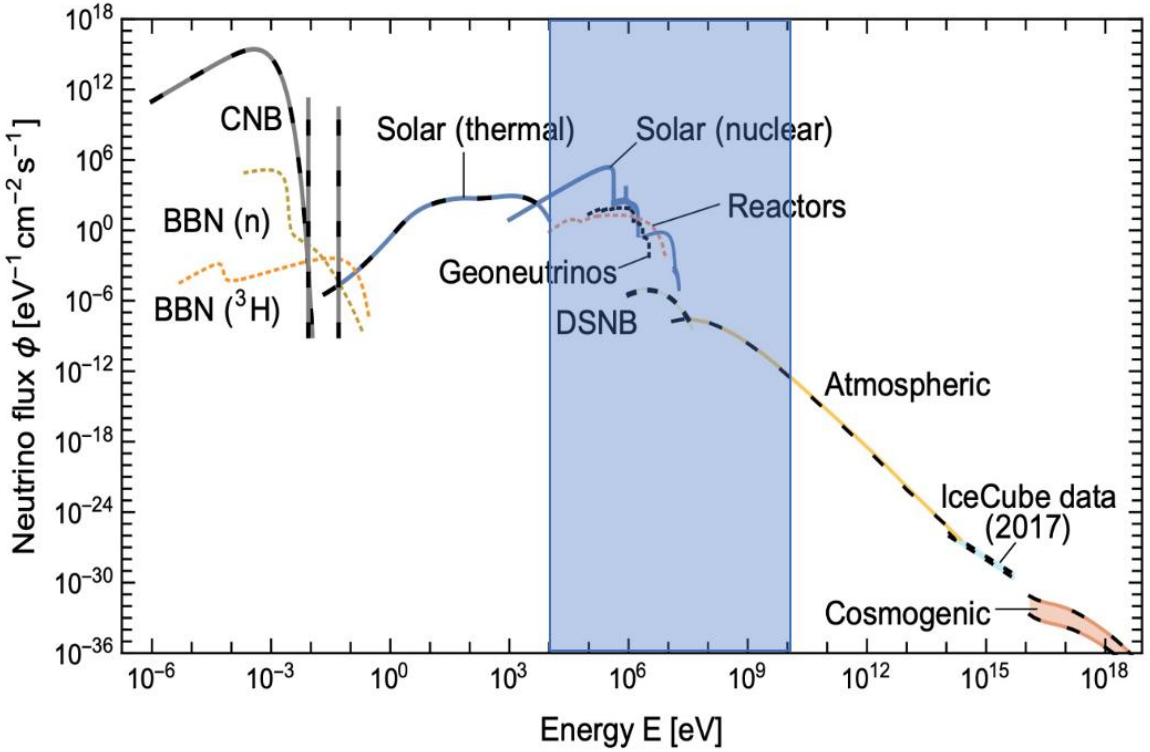
VETO System

- Top Tracker — plastic scintillator
- Water Pool: Ø43.5 m, H 44 m
- Earth magnetic-field shielding coils

Central Detector

- Stainless-steel structure · 35.4 m Ø acrylic sphere
- 20 kton LAB-based liquid scintillator
- 17,612 × 20″ PMT + 25,600 × 3″ PMT
- ⇒ 78% photocathode coverage

Neutrino Sources

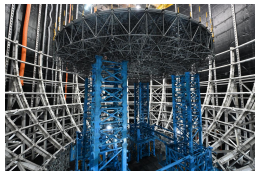


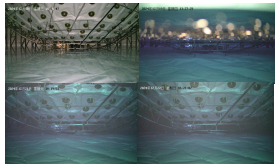
JUNO — Key Capabilities

- **20 kton** liquid-scintillator detector
- Excellent energy resolution
- Wide energy range
- Low background levels

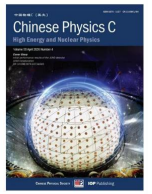
Beyond its primary physics goals, JUNO is a truly **multi-purpose detector**

Timeline









2013
Project start

2015
Start of civil construction



2022
Beginning of detector installation

Dec 2024
End of detector installation

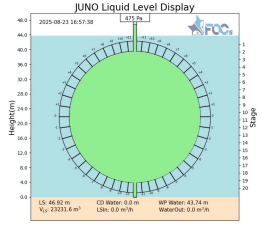


WATER FILLING

Feb 2025
End of water filling

LS FILLING

Aug 2025
End of LS filling

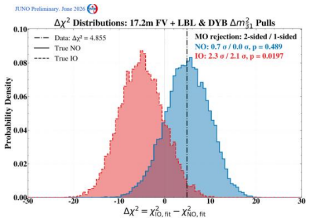


PHYSICS DATA

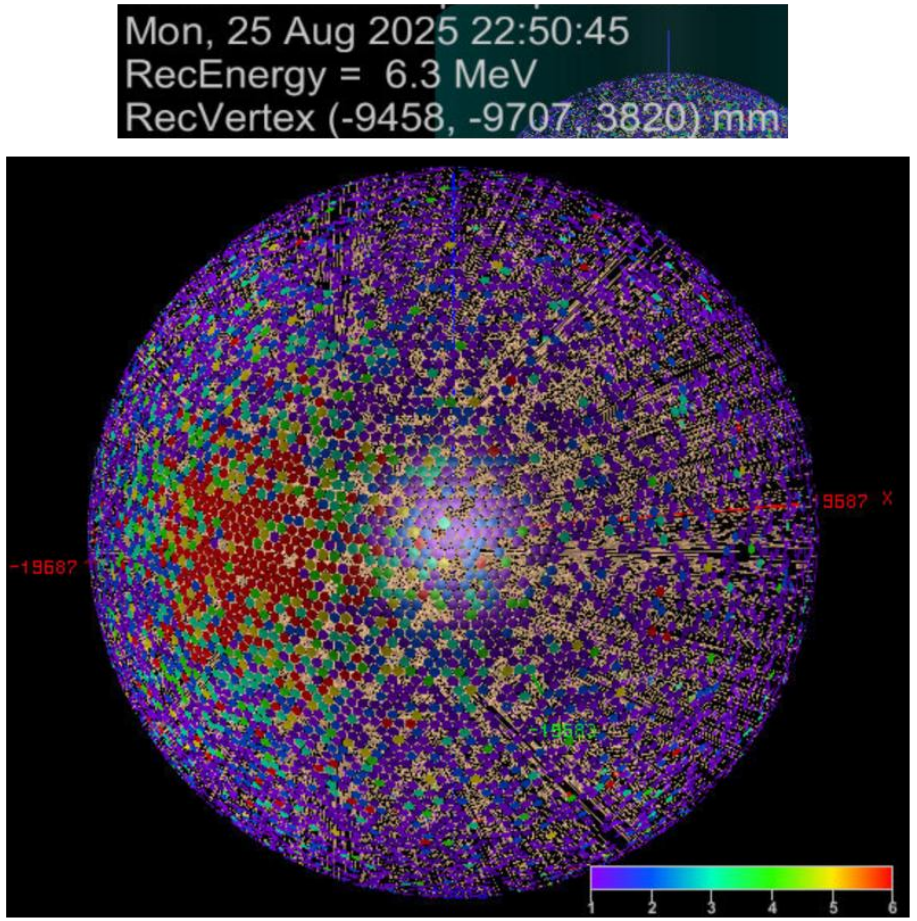
Nov 19, 2025
First results announced
59 days of data

arXiv:2609.37895

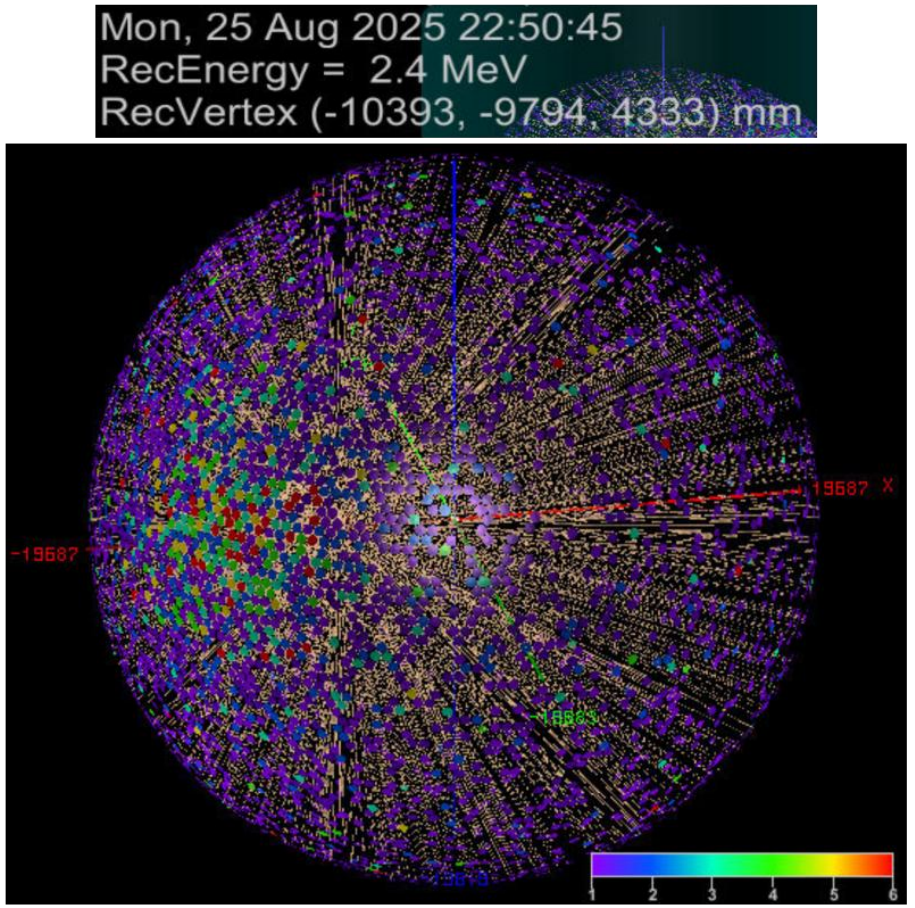
Jun 2026
Neutrino 2026
207 days of data



The First Antineutrino Event



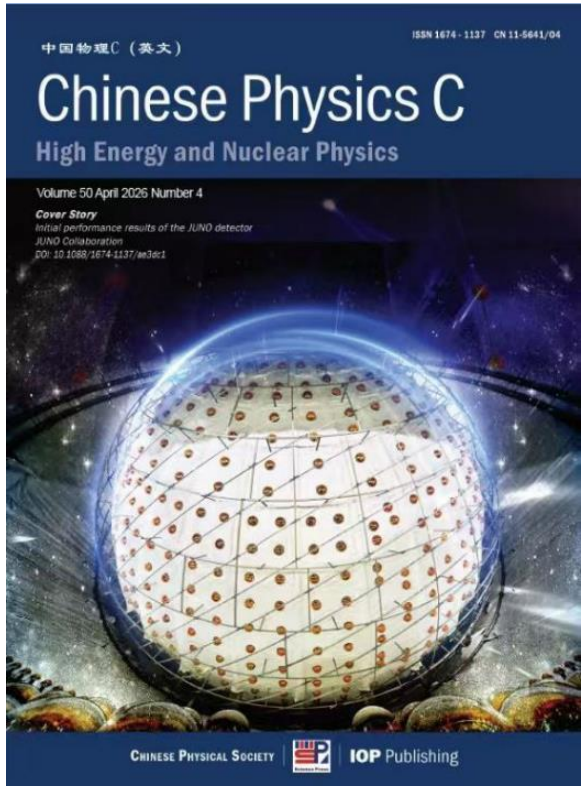
Prompt e+ signal



Delay neutron signal

First results using 59 days of data published

Initial Performance of the Detector
Chinese Physics C 50, 043001 (2026)



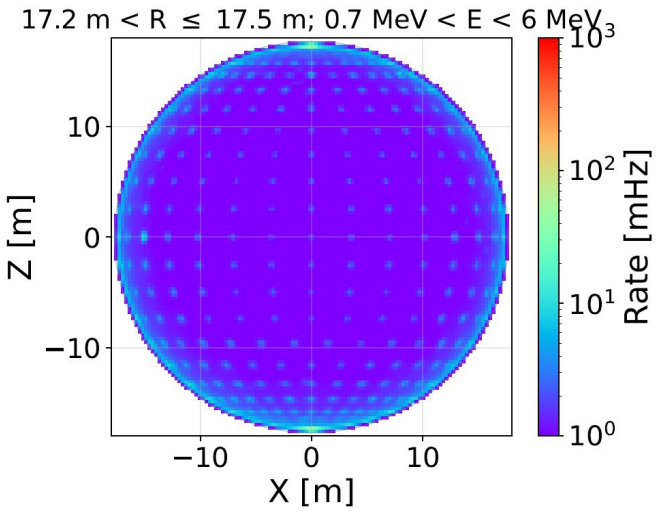
Measurement of reactor neutrino oscillation with the first JUNO data
Nature, *654*(8118), 343-348 (2026)

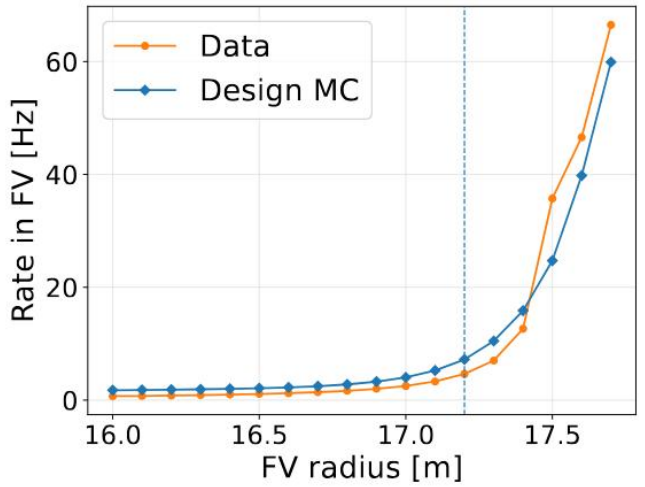


Today Results using 207 days of data based on arXiv:2609.37895

Backgrounds of the Detector

- For IBD candidates: (r < 17.2m & E > 0.7MeV)
  - ⇨ Clearly see the steel structure: acrylic surface background from dust is limited ➔ washing is effective
  - ⇨ Single event rate: < 6 Hz (design 7.2 Hz)
  - ⇨ Background simulation includes LS, PMTs, steel structure, acrylic and water (including Rn) ➔ Good agreement with data
- Ultra-low natural radioactivity





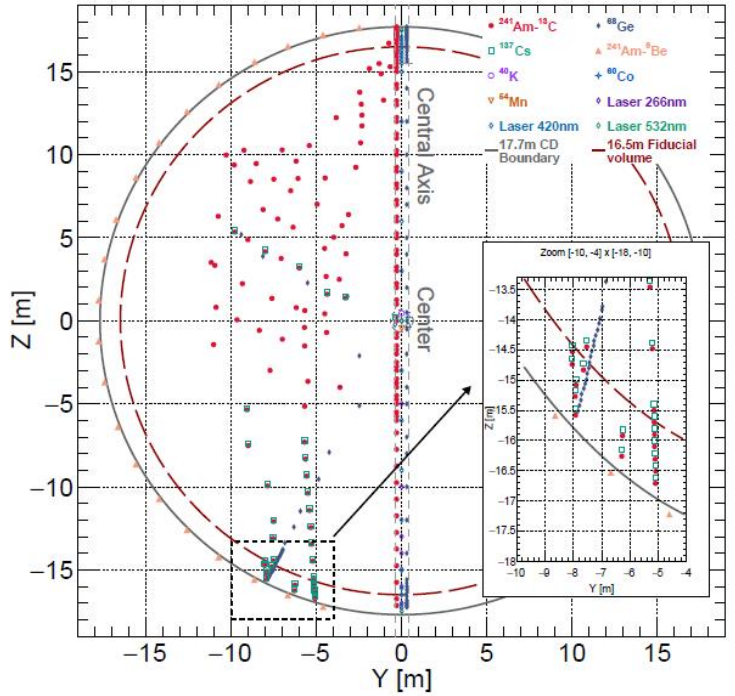
Fiducial volume	^{238}U [10^{-17} g/g]	^{232}Th [10^{-17} g/g]	^{210}Po [10^4 cpd/kt]	
			Initial	Present (Jun. 1)
r < 16.5 m	8.22±0.03±0.68	7.8±0.1±0.4	4.80±0.02±0.14	2.25±0.01±0.07
r < 15.0 m	7.79±0.03±0.70	7.8±0.2±0.4	4.78±0.02±0.14	2.28±0.01±0.07

Calibration in JUNO

Combination of different sources to calibrate JUNO:

- **1D:** Automated Calibration Unit (ACU), on z-axis
  - ^{137}Cs, ^{54}Mn, ^{40}K, ^{68}Ge, ^{60}Co, Am-C, Am-Be, sensors, laser
- **2D:** Cable Loop System, off-axis calibration
  - Am-C, 68Ge, 137Cs
- **3D:** natural radioactivity
  - Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

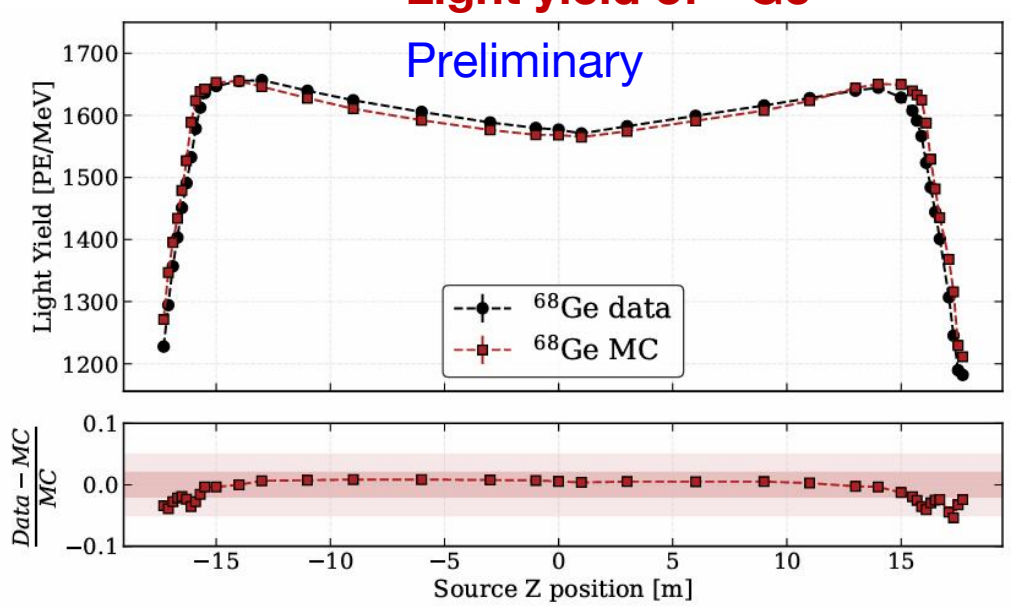
Positions at which source calibration performed



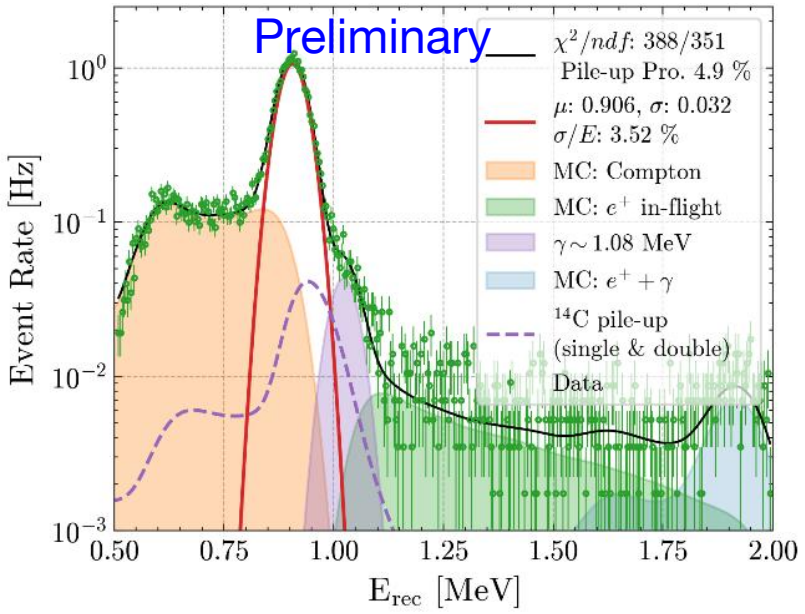
Light Yield and Energy Resolution

- Light yield at the detector center is ~1600 PE/MeV for ^{68}Ge and ~1785 PE/MeV for neutrons, in good agreement with MC
- Energy resolution for ^{68}Ge is ~3.5% @ 2× 0.511 MeV at the center, slightly worse than the expected 3.1%
  - ⇨ *Further performance improvement ongoing：Better MC; more calibration; ML to remove 14C; better recon., etc.*

Light yield of ^{68}Ge



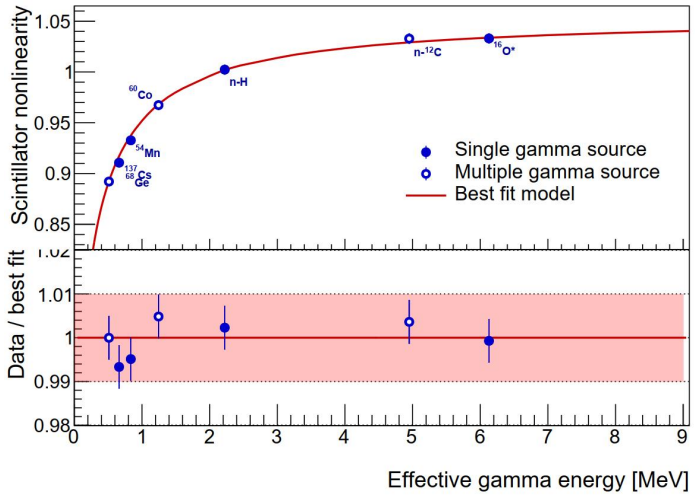
^{68}Ge Reconstructed Energy



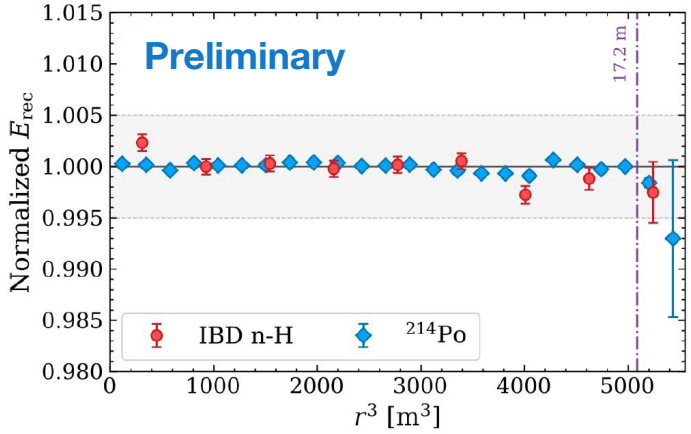
Energy Reconstruction Performance

- Energy response depends on particle type, energy, position, and time
- After calibration and correction:
  - →**Residual spatial non-uniformity is ~0.2%**
  - →**Residual time variation is ~0.3%**
  - →**Energy non-linearity uncertainty < 1%**

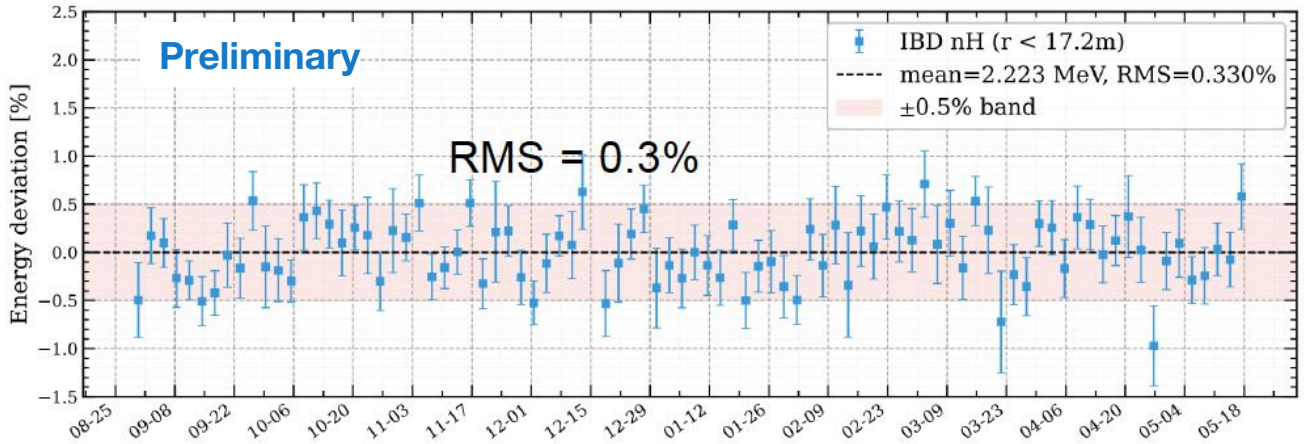
Energy Non-linearity: γ sources



Spatial non-uniformity: normalized Energy vs r³



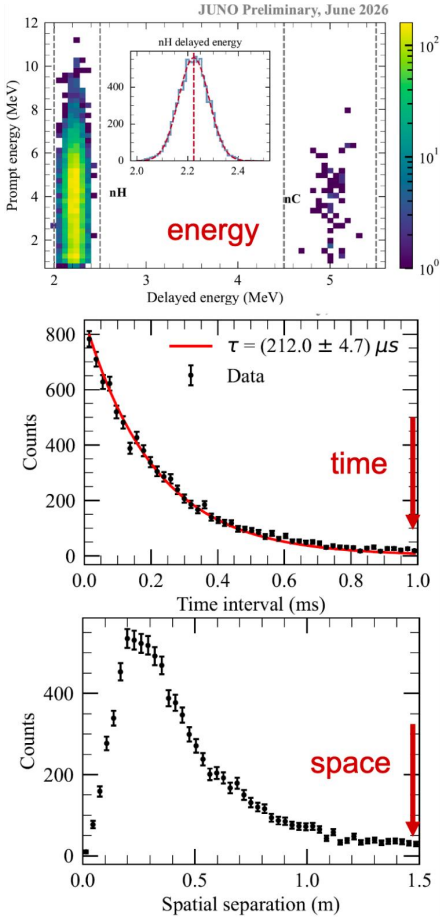
Time variation: IBD n-H after correction



IBD Event Selection

Muon (μ) and spallation neutron (spn) identification	
μ	$Q > 3 \times 10^4$ pe (CD), or $Q > 700$ pe (WP)
spn	$Q \in (3, 30) \times 10^3$ pe, $\Delta T_{spn-\mu} \in (0.02,\ 2)$ ms
IBD selection criteria	
PMT flasher removal	Using hit multiplicity and timing info
Prompt E	$0.7 < E_p < 12.0$ MeV
Delayed E	$2.0 < E_d < 2.5$ MeV (n capture on H) $4.5 < E_d < 5.5$ MeV (n capture on ^{12}C)
Coincidence	$5 < \Delta T_{p-d} < 1000$ μs, $\Delta R_{p-d} < 1.5$ m
Fiducial volume	$r_p < 17.2$ m, $\lvert z_p \rvert < 15.5$ m
Muon veto	$\Delta T_{d-\mu} > 5$ ms (CD), $\Delta T_{d-\mu} > 2$ ms (WP) $\Delta R_{d-spn} > 4$ m or $\Delta T_{d-spn} > 1.2$ s $\frac{\Delta R_{d-\mu}}{2.5\ \text{m}} + \frac{\Delta T_{d-\mu}}{0.5\ \text{s}} > 1$
Multiplicity	No additional event with $E > 0.7$ MeV (inside the FV) nor $2.0 < E < 6.0$ MeV (outside the FV) occurred within $(t_d - 2,\ t_d + 1)$ ms
L.L.R.	Likelihood-ratio selection

Improved selections

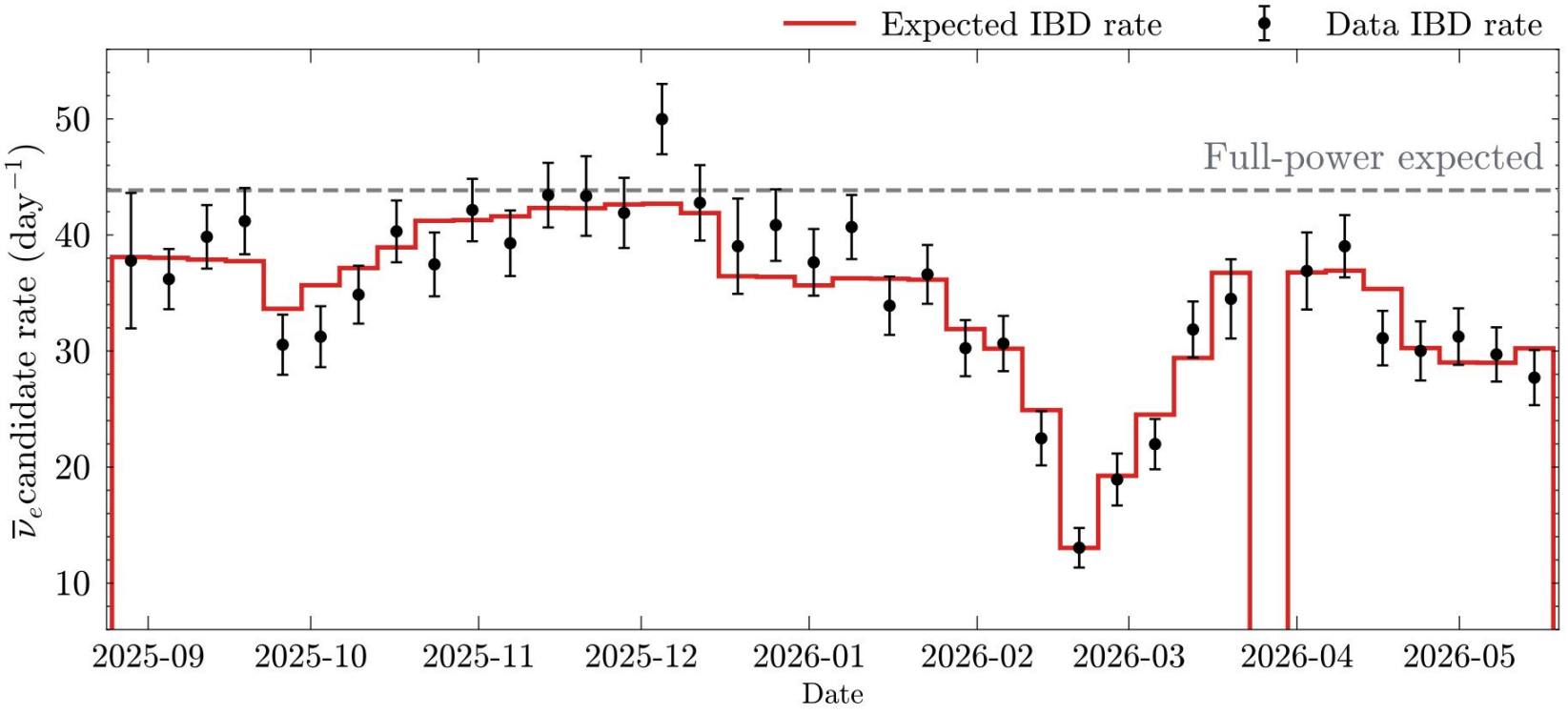


- Similar to the *Nature* paper, what's new:
  - ~10% more fiducial volume (R=16.5m→17.2m)
  - ~60% reduction of ^{9}Li bkg.
  - a factor of ~40 reduction of accidental bkg. using likelihood cut
  - model independent estimate of the ^{214}Bi bkg.

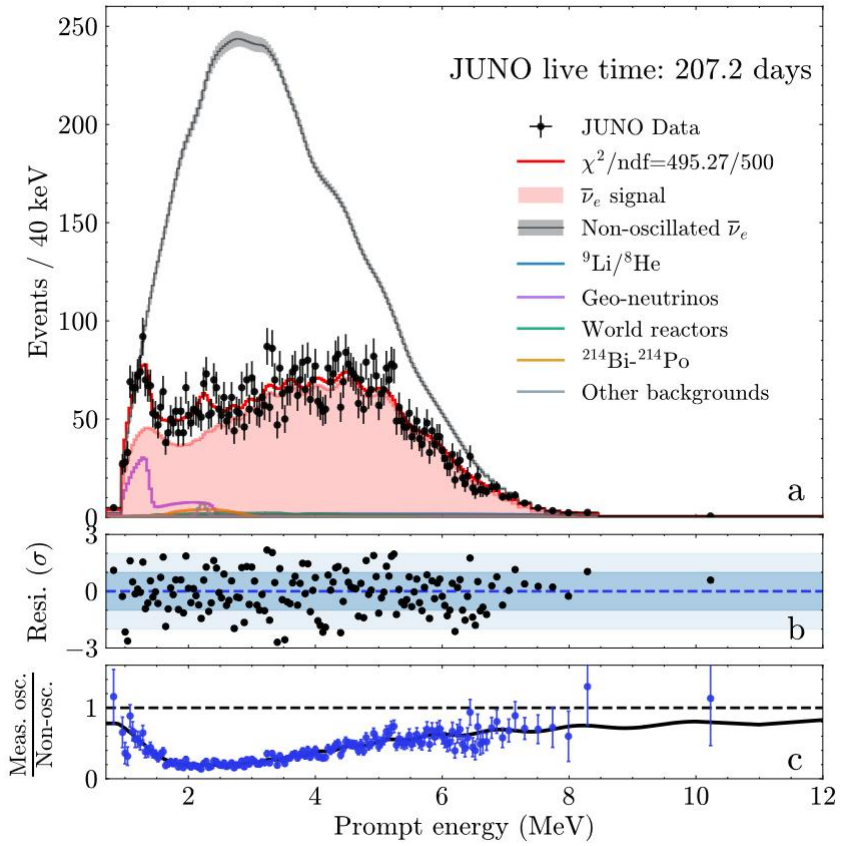
Zeyuan Yu's talk

Reactor Neutrino Event Rate

- Measured reactor neutrino event rate consistent with expectation
- Total live time is 207.2 days



Neutrino Measurement in JUNO

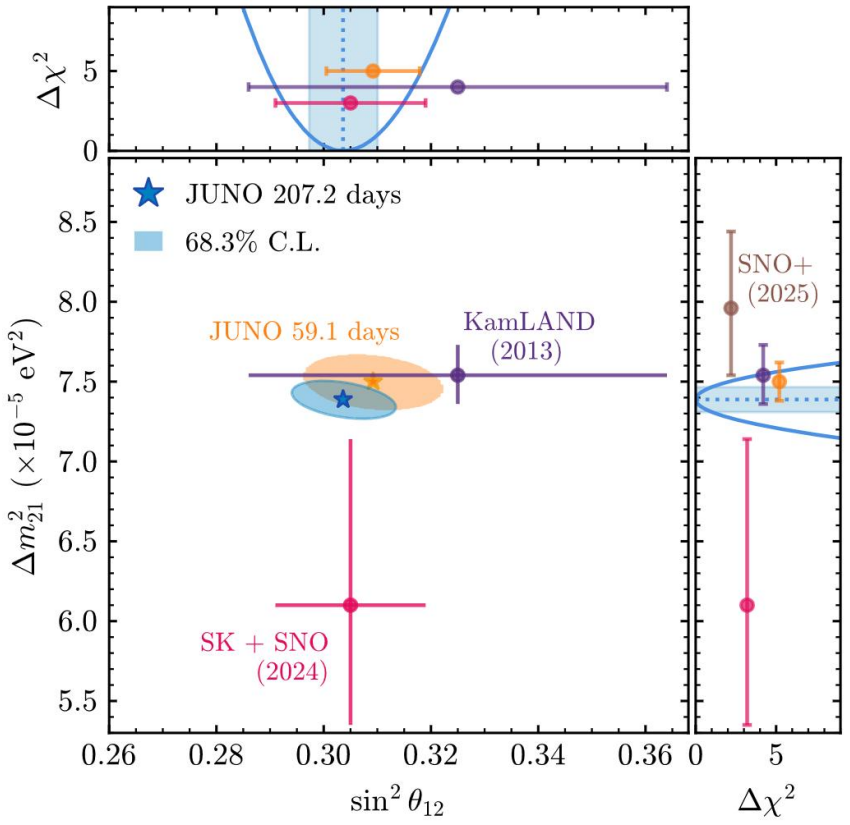


Reactor flux constrained by

- TAO satellite detector
- Daya Bay near-detector data (PRL 130, 161802)

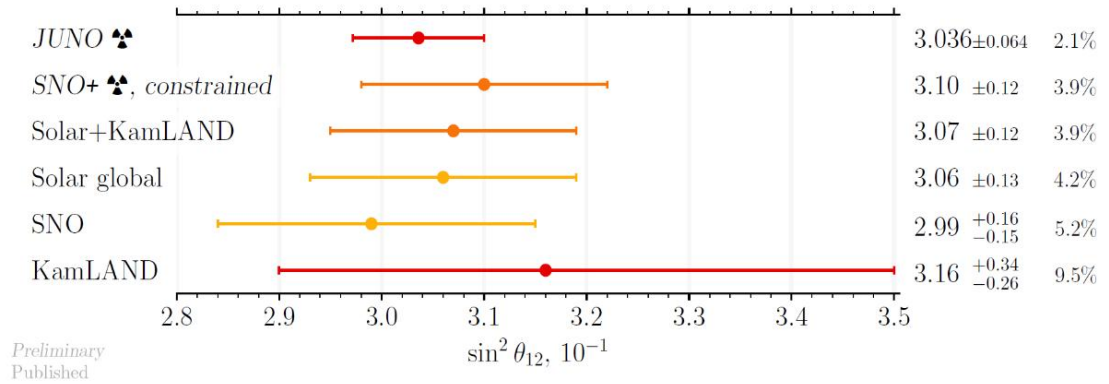
Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ε	$\sigma_{\rm rel}$
Fiducial volume	87.12%	0.96%
PMT flasher rejection	$> 99.9\%$	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency ($\varepsilon_{\rm tot}$)	74.01%	1.02%
$\bar{\nu}_e$ signal (cpd)		
w/o $\varepsilon_{\rm tot}$ corrected	36.02 ± 0.62	
w/ $\varepsilon_{\rm tot}$ corrected	48.67 ± 1.08	
Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}He	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 ± 0.09	0.92 ± 0.09
^{214}Bi-^{214}Po	0.42 ± 0.31	0.57 ± 0.34
^{13}C(α, n)^{16}O	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01

Results of Solar Oscillation Parameters

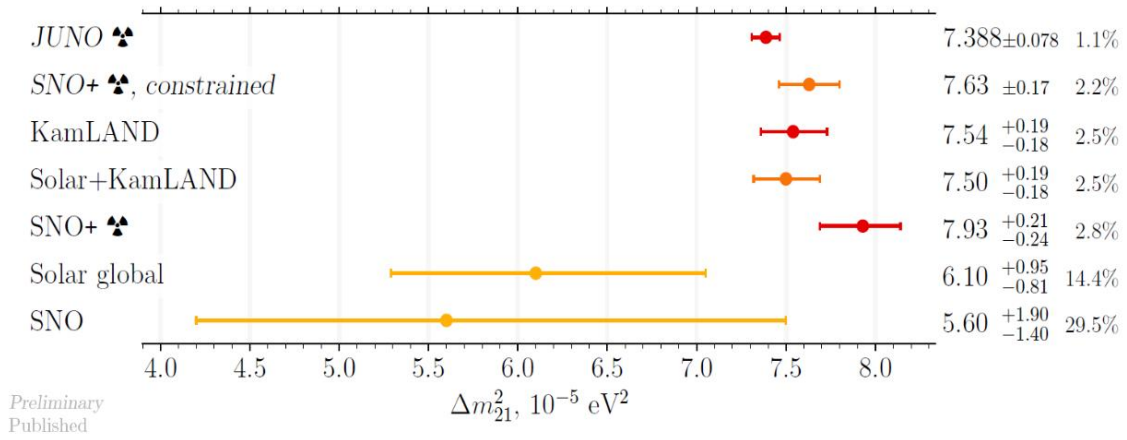


Parameter	JUNO best-fit	Precision (59.1 → 207.2 days)
Δm^2_{21}	7.388 ± 0.078	1.60% → **1.06%**
$\sin^2\theta_{12}$	0.3036 ± 0.0064	2.8% → **2.1%**

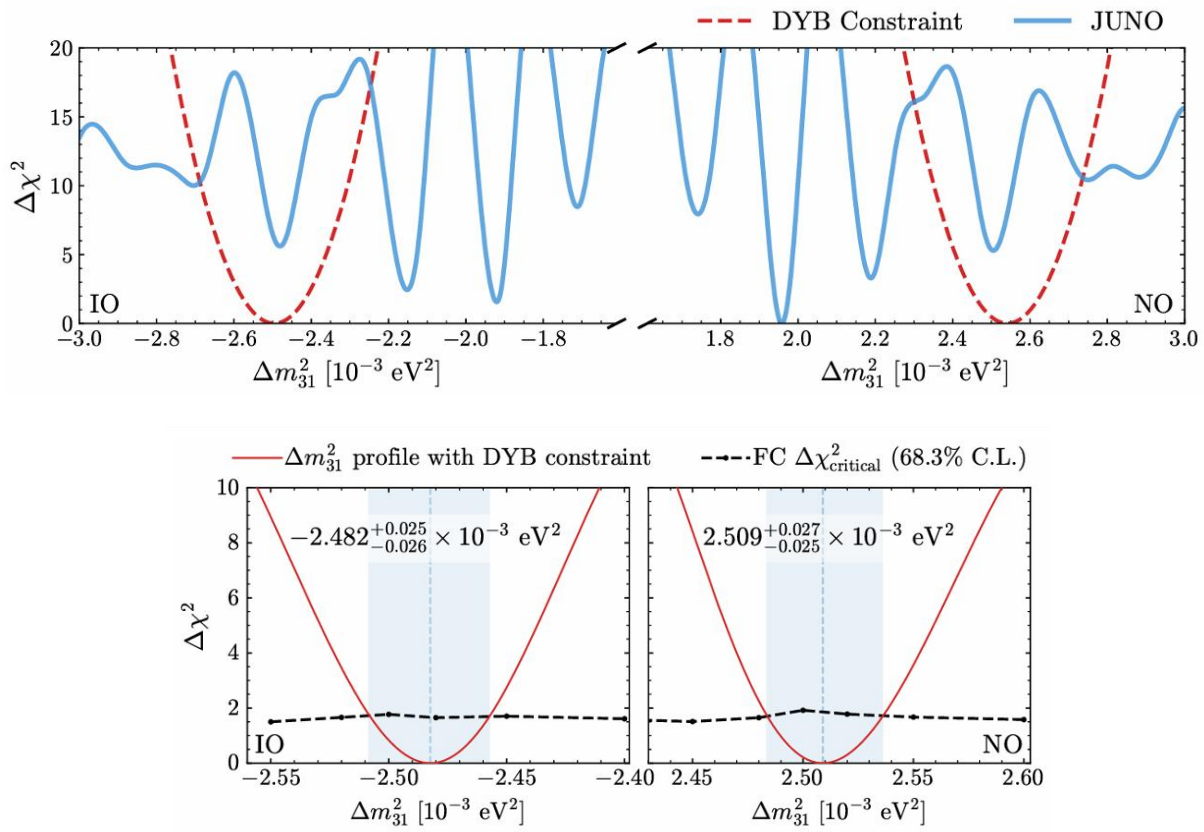
$\sin^2 2\theta_{12}$

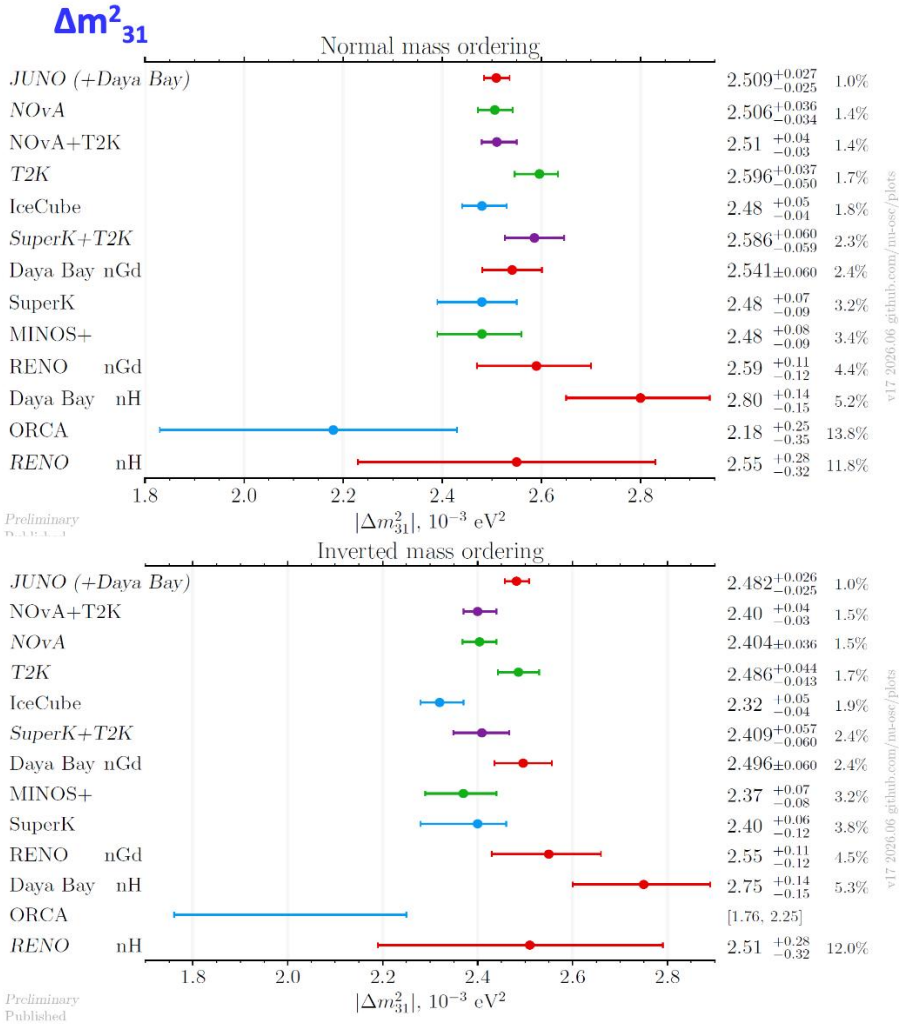


Δm^2_{21}



First Result of Δm^2_{31}

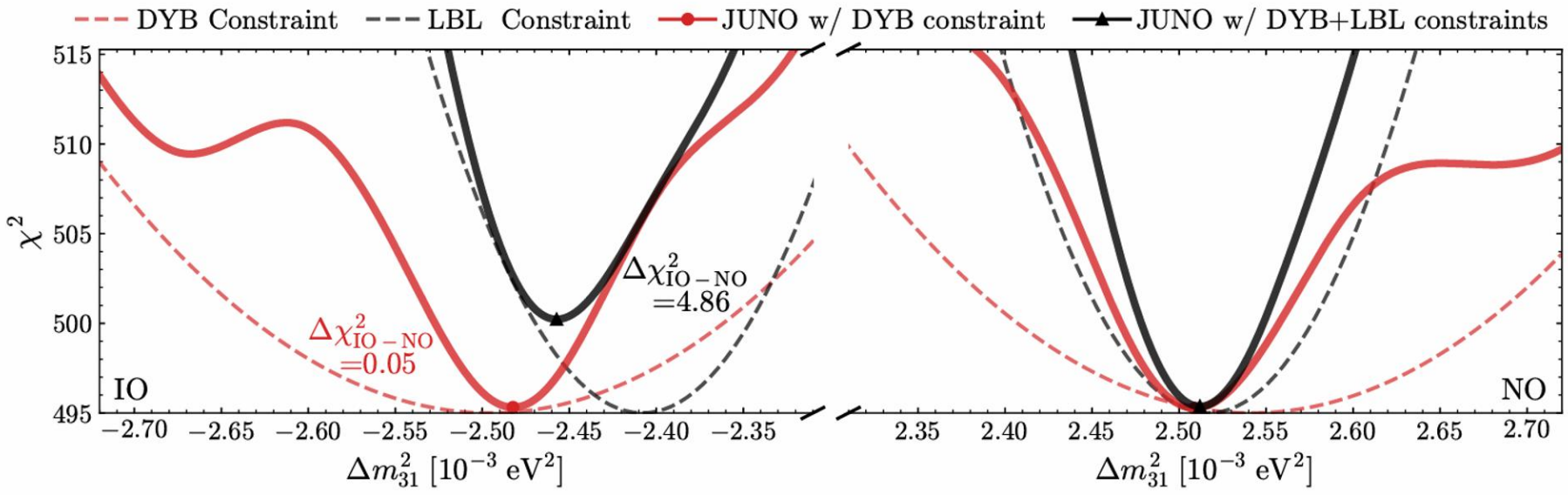




- The final minimum for each mass ordering is obtained by using the Δm^2_{31} constraint from the Daya Bay result (PRL 130 16, 161802)
- Feldman-Cousins (FC) method gives 1σ range of Δm^2_{31} ~1% precision

Adding Constraint from NuFit-LBL

- Δm^2_{31} from reactor and accelerator neutrinos should align at the right mass ordering[1]
- Adopt the NuFit-LBL results from [2]: normal mass ordering is favored at $\Delta\chi^2 = 4.86$



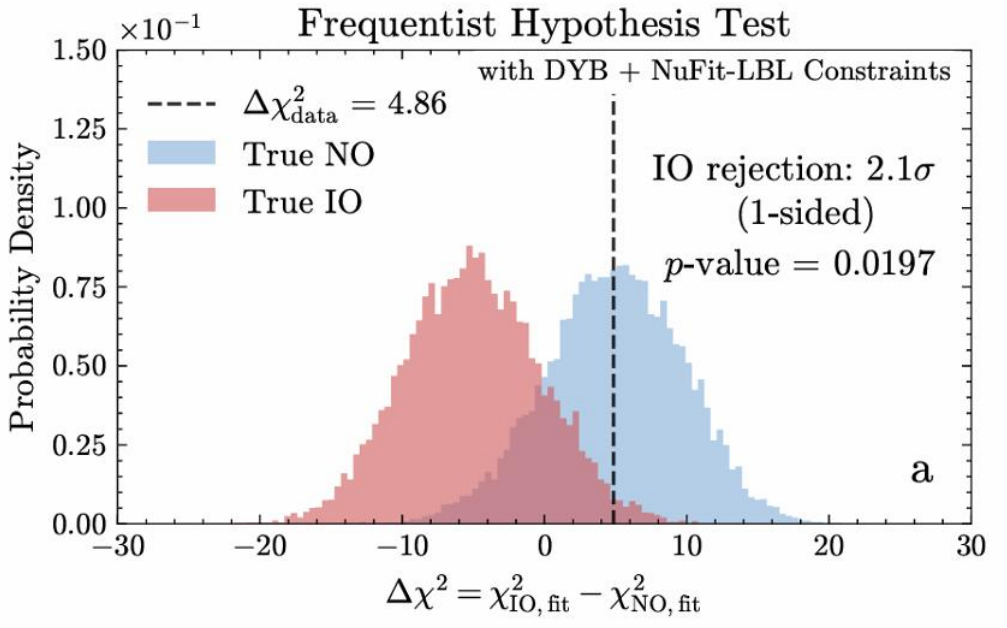
[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

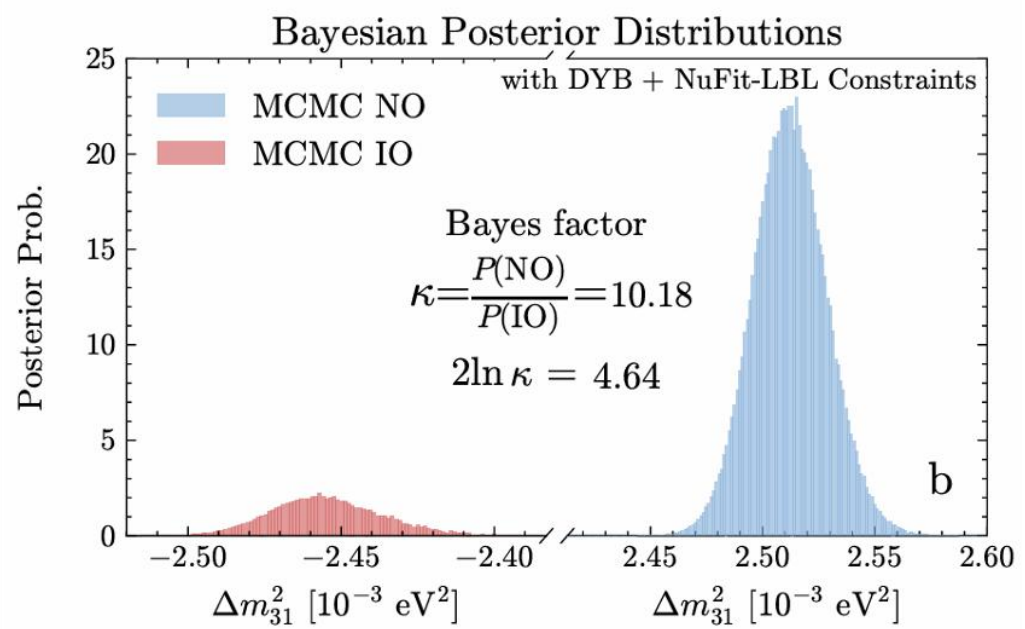
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Neutrino Mass Ordering Significance

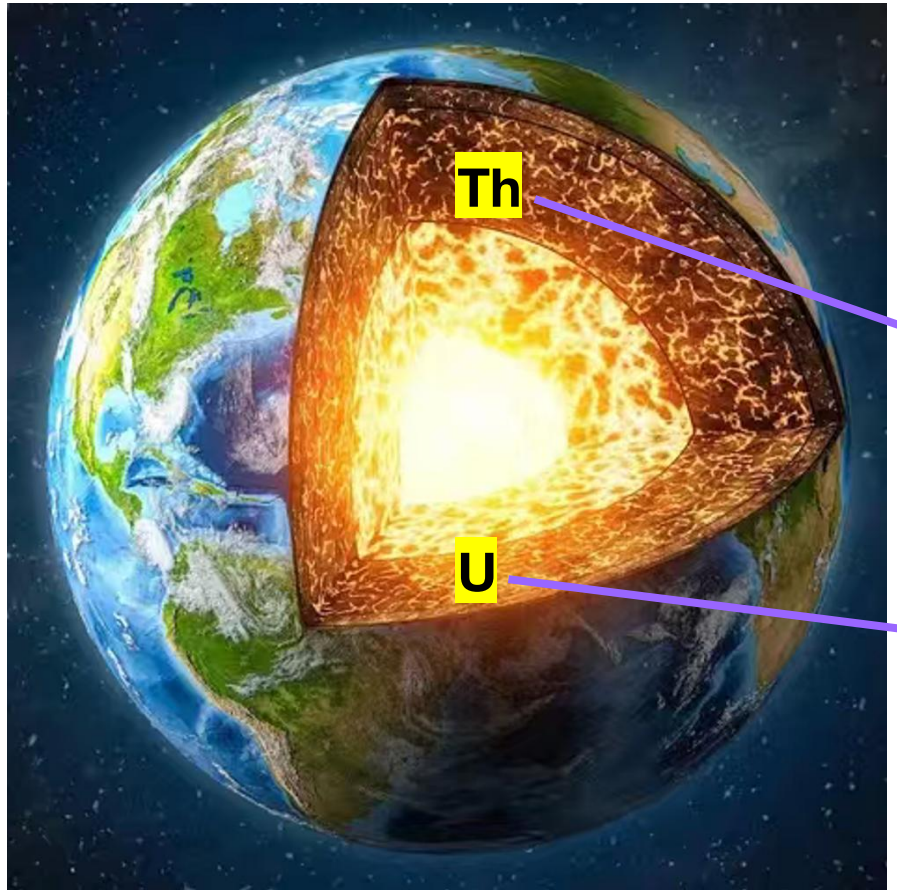
- Frequentist approach using FC method to convert $\Delta\chi^2$ to significance
- Scanned over δ_{CP}
- Normal Ordering is favored at 2.1σ/2.3σ (1-sided / 2-sided)

- Bayesian approach using Markov Chain Monte Carlo(MCMC) method
- Normal Ordering is favored with a Bayes factor of 10.18 ➔ $2\ln\kappa = 4.64$

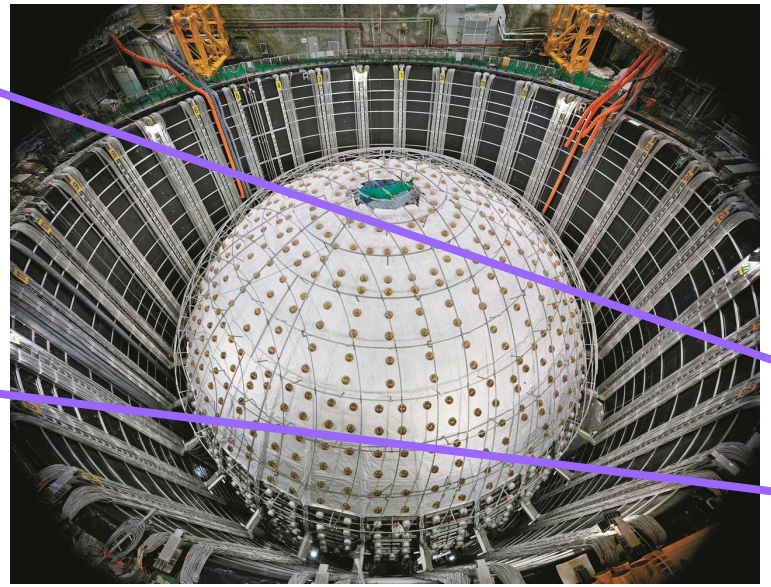


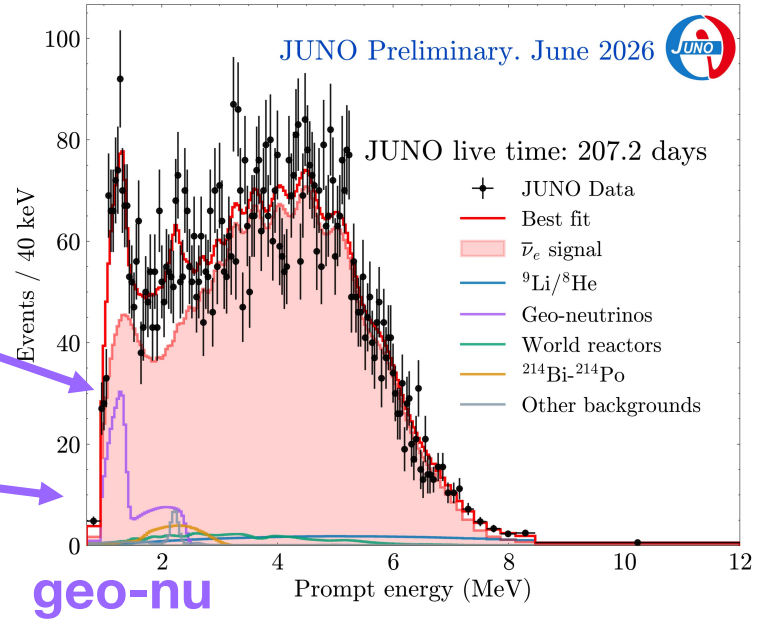


Geoneutrinos as a Probe of the Earth

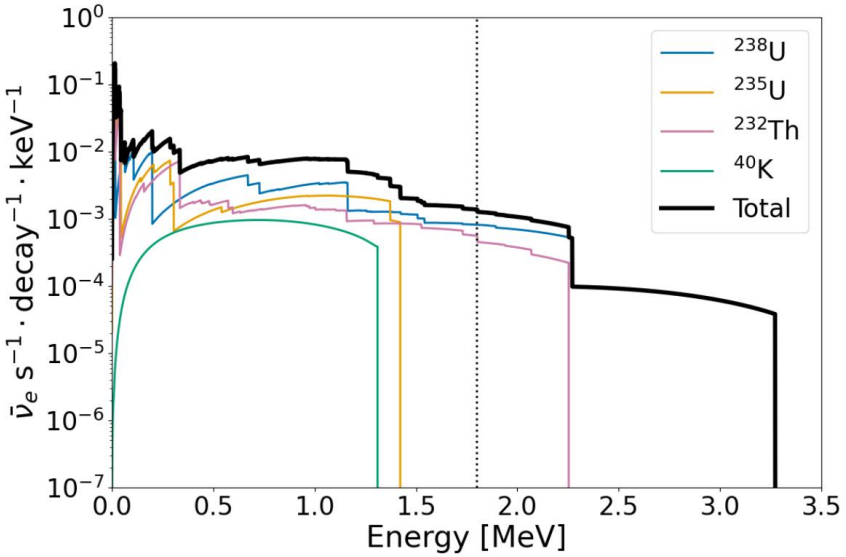


Geoneutrino provides the direct probe of the abundance and distribution of heat-producing elements(HPE) in the Earth.





Geoneutrino Production

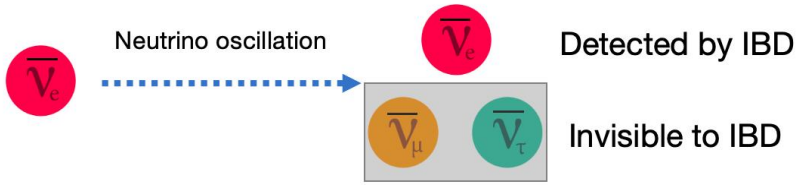


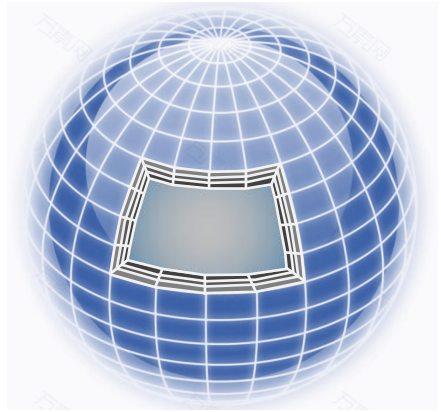
S. Enomoto, Geoneutrino spectrum and luminosity
arXiv:2511.07227
arXiv:2412.07711

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e,\ \mathrm{Q} = 51.7\,\mathrm{MeV}$$
$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e,\ \mathrm{Q} = 46.4\,\mathrm{MeV}$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e,\ \mathrm{Q} = 42.6\,\mathrm{MeV}$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e,\ \mathrm{Q} = 1.31\,\mathrm{MeV}\ (89.3\%)$$
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e,\ \mathrm{Q} = 1.504\,\mathrm{MeV}\ (10.7\%)$$

- Geoneutrinos from β-decays of **^{238}U, ^{235}U, ^{232}Th, ^{40}K** inside the Earth
- **Radiogenic heat** is in a well-known ratio to the number of emitted geoneutrinos
- IBD threshold ⇒ only **^{238}U & ^{232}Th** detectable; ^{40}K below threshold
- Distinct spectral shapes enable **U/Th separation**

Geoneutrino Signal Rate





Abundances and density (g/cm³) from geo models

Neutrino oscillation probability

Distance factor (g/cm²)

$$f\left(i, E_{\bar{\nu}}\right) = \int \boxed{P_{ee}\left(\left|\vec{r} - \vec{r}'\right|, E_{\bar{\nu}}\right)} \cdot d^3 r' \cdot \frac{\boxed{a\left(i, \vec{r}'\right) \cdot \rho\left(\vec{r}'\right)}}{4\pi\left|\vec{r} - \vec{r}'\right|^2}$$

Neutrino Flux (neutrino/s/cm²)

$$\Phi_{osc}(i, \vec{r}) = \boxed{\epsilon_{i,\bar{\nu}}} \cdot \int dE_{\bar{\nu}} \cdot \boxed{\mathrm{Sp}\left(i, E_{\bar{\nu}}\right)} \cdot f\left(i, E_{\bar{\nu}}\right)$$

Neutrino production rate (Neutrino/s/g)

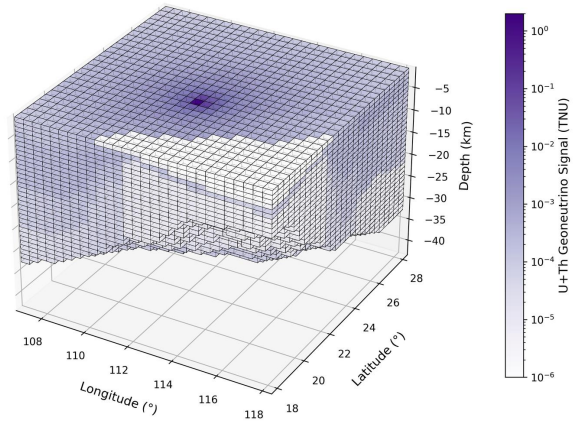
Neutrino spectrum (/MeV)

Neutrino Signal

$$R[\mathrm{TNU}] = \boxed{10^{32} \cdot \frac{\mathrm{seconds}}{\mathrm{year}}} \cdot \epsilon_{i,\bar{\nu}} \cdot \int dE_{\bar{\nu}} \cdot Sp\left(i, E_{\bar{\nu}}\right) \cdot \boxed{\sigma_{\mathrm{IBD}}\left(i, E_{\bar{\nu}}\right)} \cdot f\left(i, E_{\bar{\nu}}\right)$$

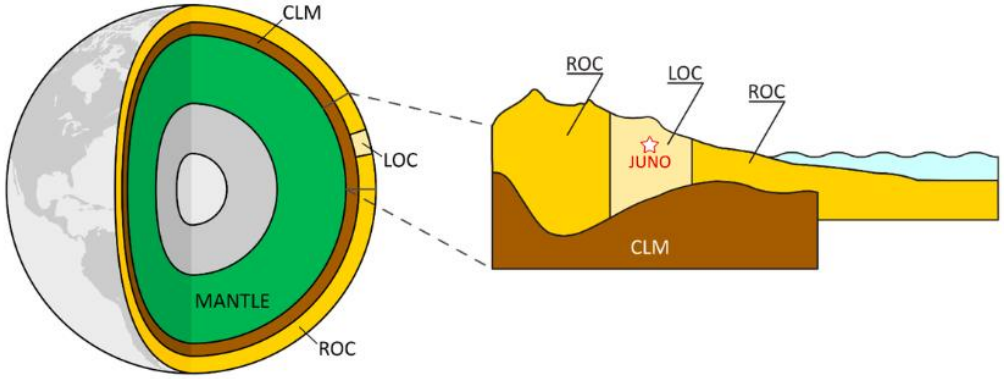
IBD events per 10^{32} free protons per year

IBD cross section (cm²)



1 terrestrial neutrino unit (TNU) corresponds to one IBD event over 1 year exposure of 10^{32} free target protons at 100% detection efficiency

Geoneutrino Signal Component



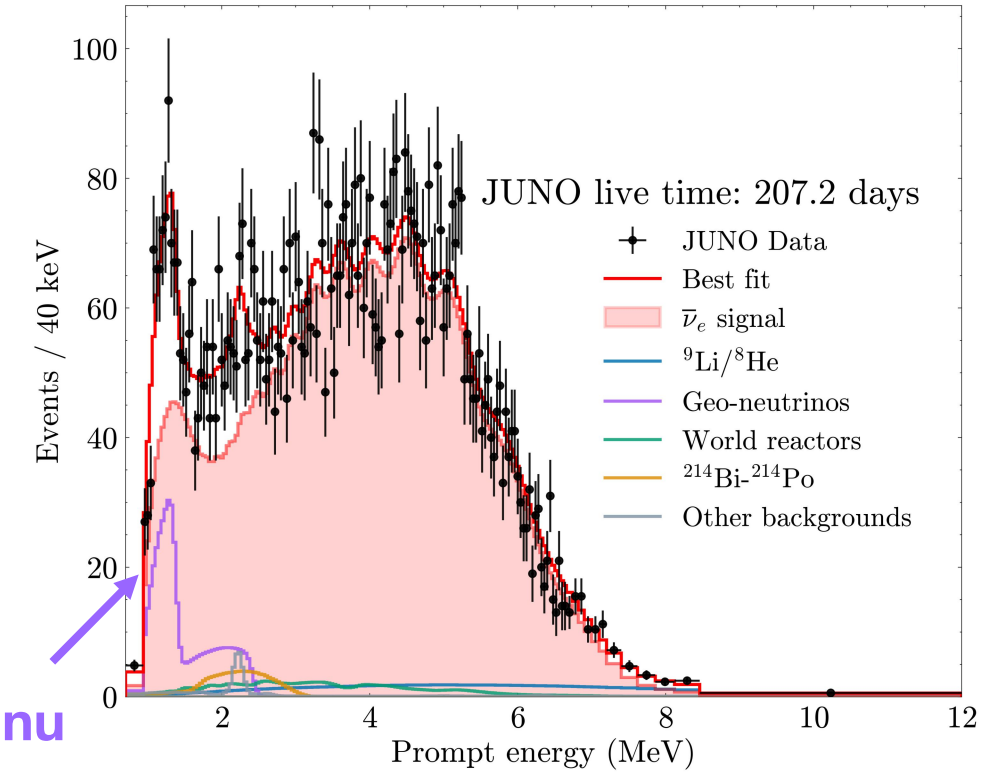
- The **lithosphere** consists of the Earth's **crust** — split into the **Local Crust (LOC)** within a few hundred km of the detector and the **Rest of the Crust (ROC)** — plus the underlying **Continental Lithospheric Mantle (CLM)**.
- The experimental signal is the sum of two components: **mantle (M)** and **lithosphere (LS)**.

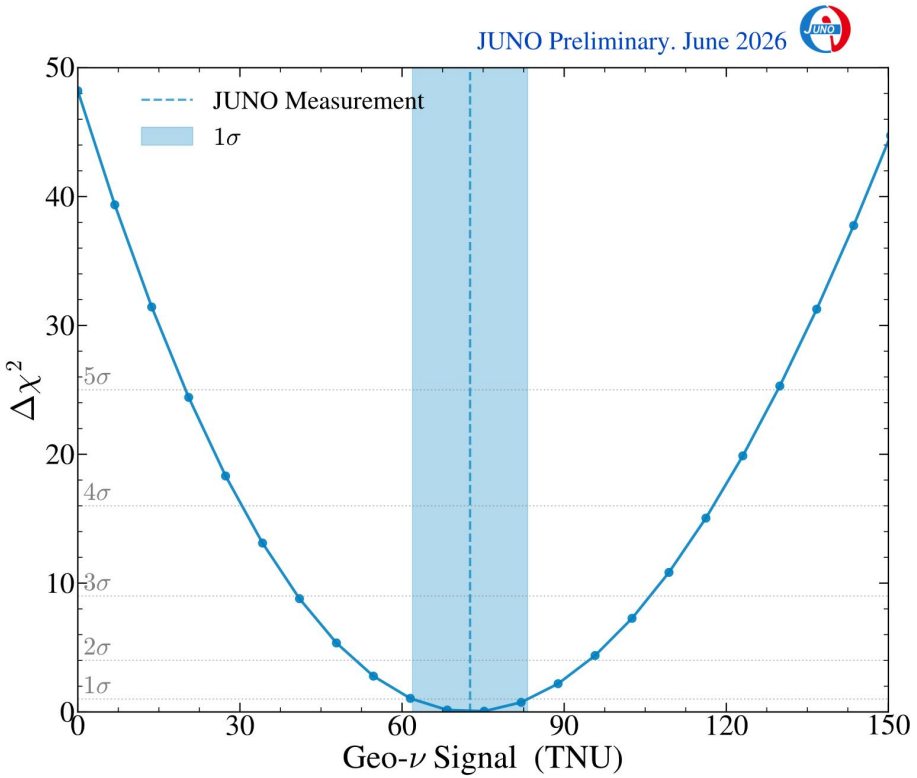
BSE class	Radiogenic heat (TW)	Predicted S_M (TNU)
Poor-H	12.4 ± 1.9	$2.8^{+2.4}_{-1.9}$
Medium-H	19.7 ± 3.1	$8.0^{+4.0}_{-3.2}$
Rich-H	31.7 ± 3.4	$17.4^{+5.7}_{-4.7}$

Model	LOC		ROC	CLM	S_{LITH} (TNU)
	Phys.	Chem.			
1	RMM	**Global Ave.**	RMM	RMM	$30.9^{+6.5}_{-6.6}$
2	CRUST 1.0	**Global Ave.**	CRUST 1.0	RMM	$32.0^{+8.2}_{-6.6}$
3	CRUST 2.0	**Global Ave.**	CRUST 1.0	RMM	$31.7^{+8.4}_{-6.6}$
4	LITHO 1.0	**Global Ave.**	LITHO 1.0	LITHO 1.0	$30.7^{+8.1}_{-0.4}$
5	GIGJ	**Global Ave.**	RMM	RMM	$31.5^{+7.2}_{-5.7}$
6	JULOC	**Local**	RMM	RMM	$40.4^{+5.6}_{-5.0}$
7	JULOC-I	**Local**	RMM	RMM	$41.2^{+4.6}_{-3.3}$

(Yufei Xi and Ruohan Gao's talks)

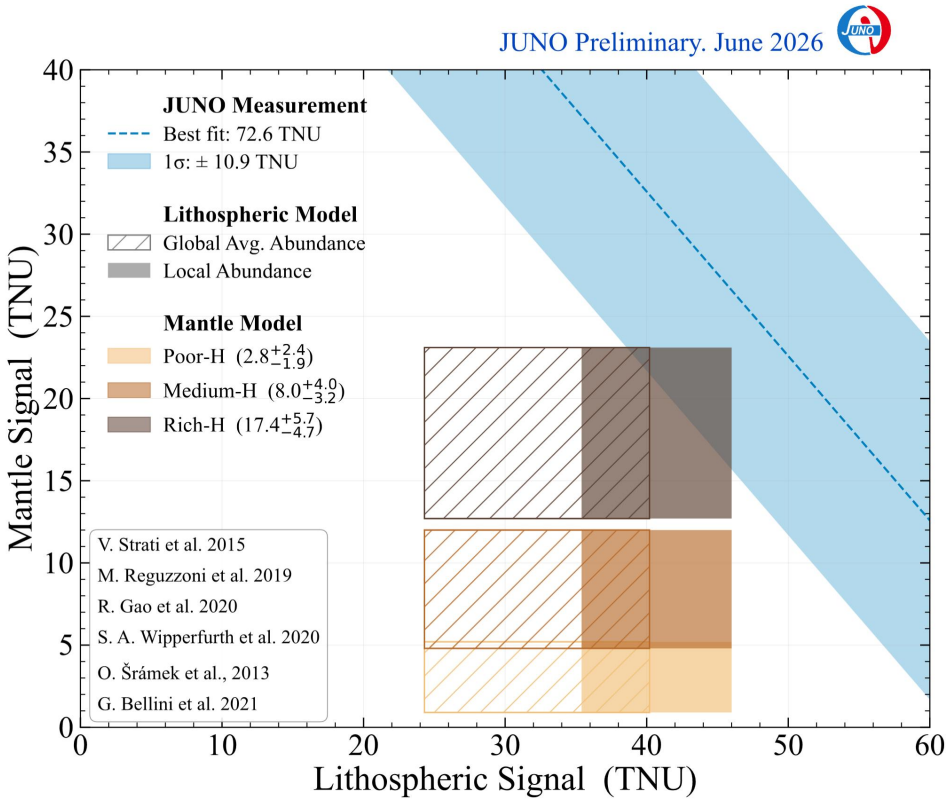
Geoneutrino Measurement in JUNO

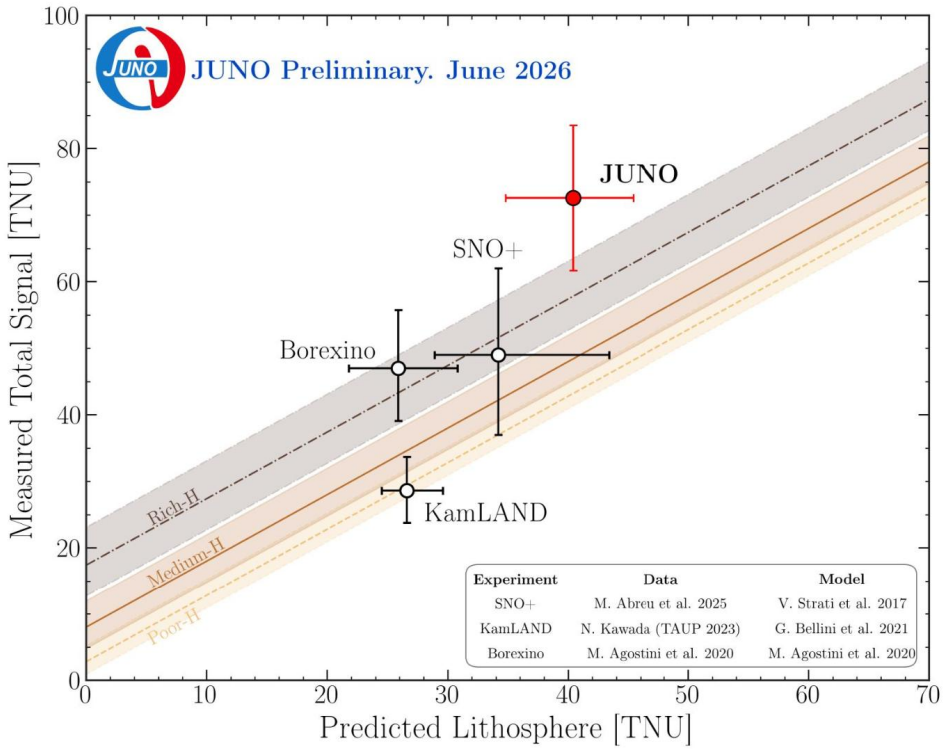




- Fit without geo flux constraint, Th/U signal ratio fixed to chondritic 0.29 (±10%)
- Clear **geo-nu** signals, giving a flux of 73 ± 11 TNU, most precise measurement ~15%
- > 5σ detection and the largest geoneutrino sample (439 ± 66) to date within 207.2 live days

Comparing the JUNO Measurement with Models

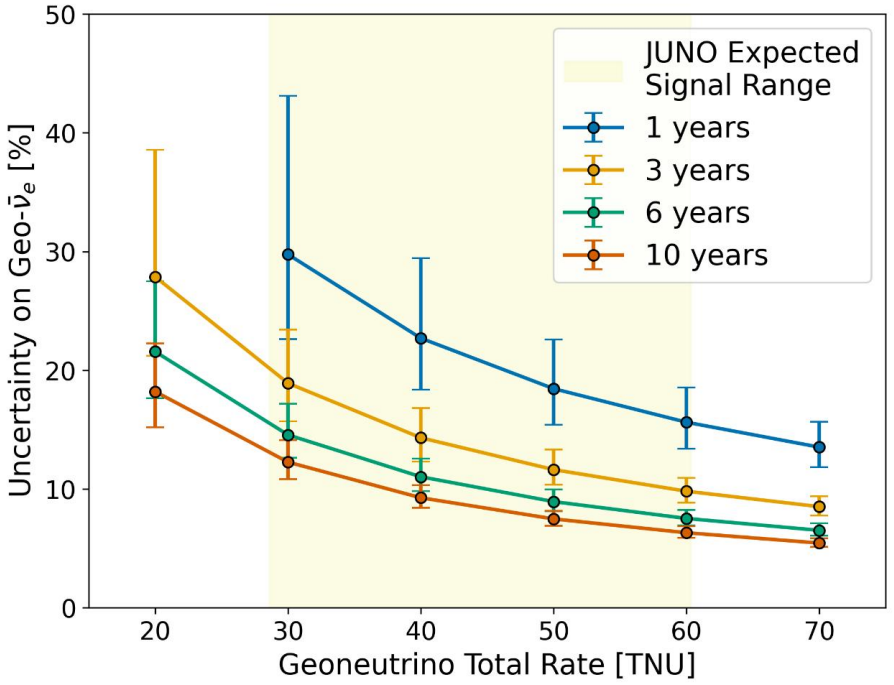


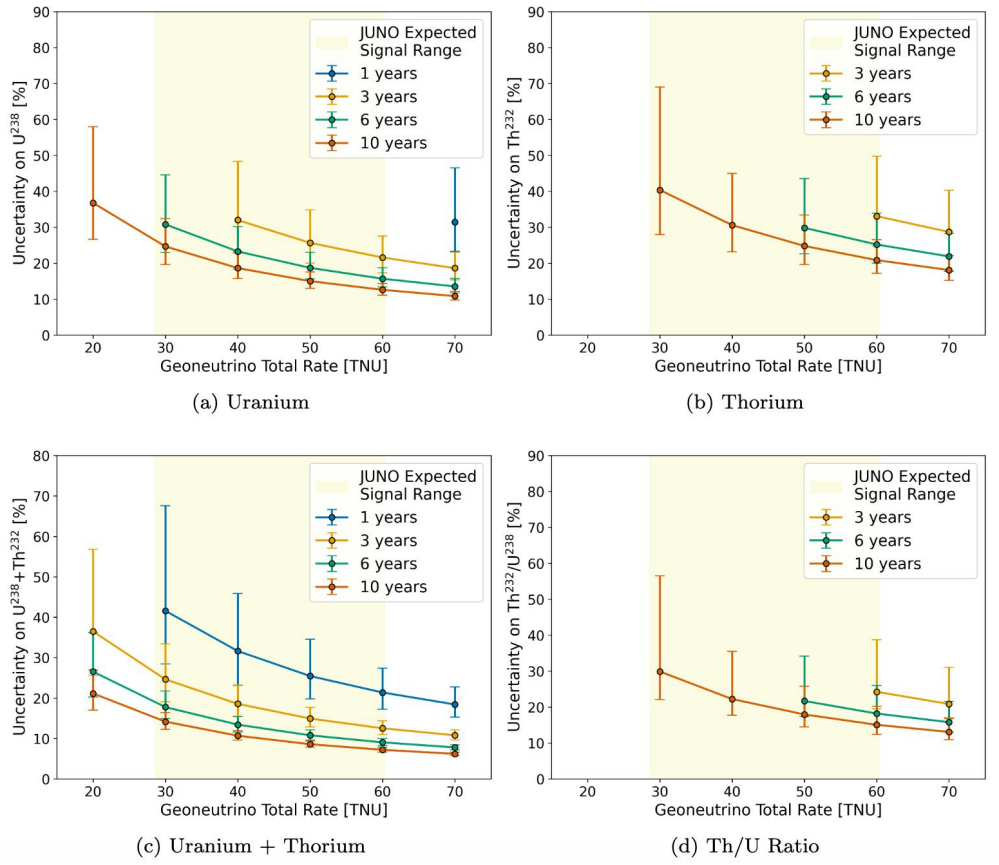


- JUNO result is higher than expectation from existing models, but not statistically significant.
- How do we interpret it? (Ruohan Gao's talk)

Prospects for Geoneutrino Detection in JUNO

arXiv:2511.07227





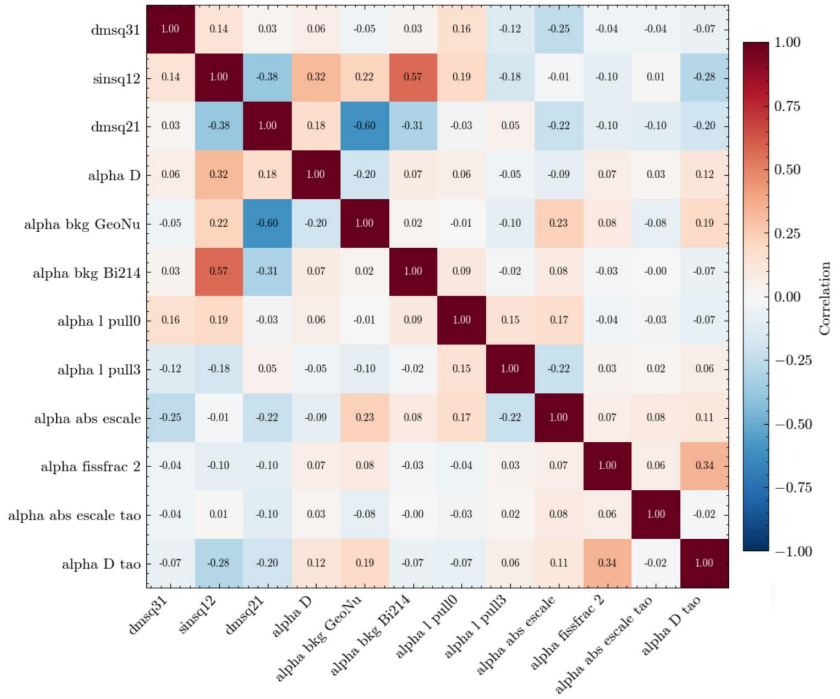
- With the high geoneutrino signal of ~70 TNU, a 10% precision on the measurement and meaningful constraints on the Th/U ratio are achievable within a three-year data taking.

Summary

- JUNO and TAO built and running smoothly, performance close to design
- Precision of solar oscillation parameters further improved by **a factor of 1.3–1.5**。First measurement on $|\Delta m^2_{31}|$ achieved a precision of **~1%**。With external constraint, **Normal Mass Ordering** is favored at **~2.1 (2.3) σ**
- JUNO is the most sensitive geoneutrino detector. JUNO measures geoneutrino signal of **73 ± 11** TNU.

Solar Oscillation Parameters

- The statistical uncertainty remains dominant, but systematic errors become important:
  - ⇨ ^{214}Bi bkg. and detection eff. can be improved



$\sin^2\theta_{12}$	Precision (%)	stat.+1 syst.
Stat-Only	1.2995	
Power	0.1368	
Spent nuclear fuel	0.0415	
Non-equilibrium	0.0631	
Fission fraction	0.1059	
Fission energy	0.0398	
Detection efficiency	0.5755	
Matter density	0.0673	
Detector response covariance	0.4081	
Reactor spectrum	0.3961	
Bkg rate	1.0781	
Bkg shape	0.2081	
AllSyst	1.6112	
Total	2.0700	

0.0 0.5 1.0 1.5 2.0

Δm^2_{21}	Precision (%)	stat.+1 syst.
Stat-Only	0.8741	
Power	0.0729	
Spent nuclear fuel	0.0261	
Non-equilibrium	0.0384	
Fission fraction	0.1069	
Fission energy	0.0194	
Detection efficiency	0.2775	
Matter density	0.0125	
Detector response covariance	0.1531	
Reactor spectrum	0.2794	
Bkg rate	0.3585	
Bkg shape	0.1043	
AllSyst	0.6090	
Total	1.0653	

0.00 0.25 0.50 0.75 1.00

Energy Non-linearity

- Non-linearities of LS and electronics are determined by calibration sources at the center: ^{68}Ge, ^{137}Cs, ^{54}Mn, ^{40}K, ^{60}Co, Am-C, and Am-Be
- The non-linearity model for e^+ is based on Geant4 and γ-sources
- The model is constrained by cosmogenic isotopes, ^{11}C(e^+), ^{10}C(e^+), ^{12}B(e^-), ^{8}Li (e^-), ^{8}B(e^+), ^{6}He(e^-), etc. in the whole volume
- Using sPMTs to correct and constrain LPMT instrumental non-linearity
- Uncertainty < 1%

Preliminary

