JUNO Experiment

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II выездное совещание Дискуссионного клуба
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Neutrino mixing

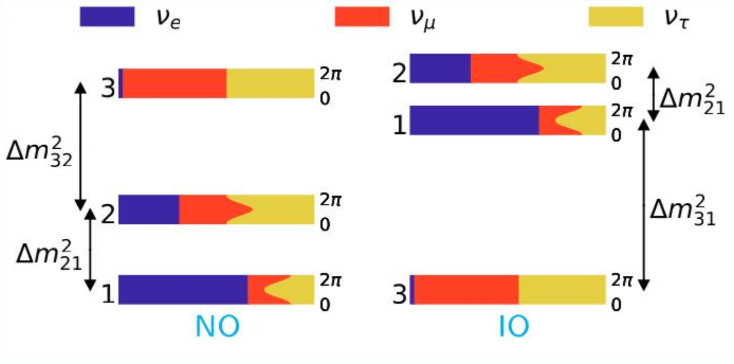
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{\rm cp}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{\rm cp}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\rm U_{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sum_j \sum_k U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left(-i\frac{\Delta m^2_{jk} L}{2E}\right)$$

Open questions & precision

[Front. Astron. Space Sci. 5:36(2018)]

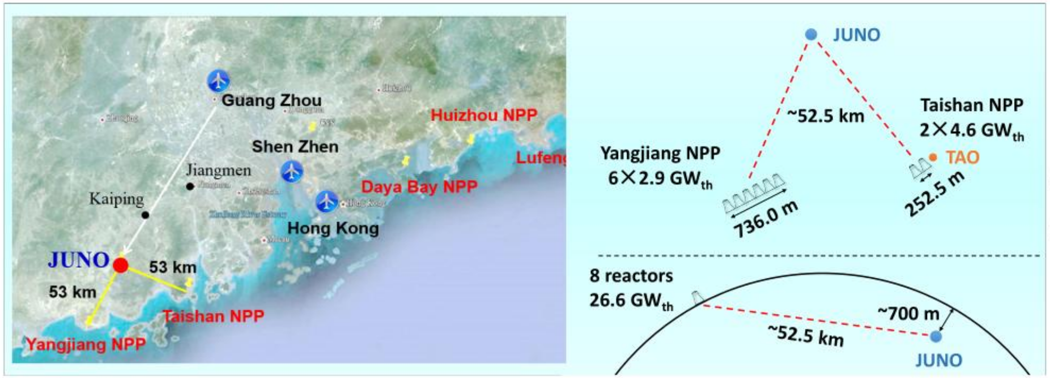
- Mass ordering:
  - Normal ordering (NO)?
  - Inverted ordering (IO)?
- Current precision: $1 \sim 5\%$
  - $< 1\%$ precision?

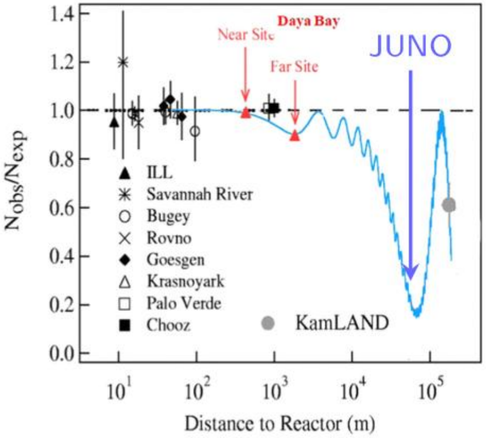


[PDG 2020]

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{23}$	$\delta_{\rm cp}$
Precision (%)	4.2	2.4	3.2	1.3	3.7	15

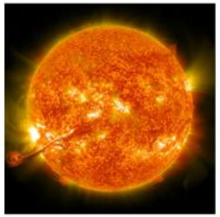
JUNO experiment overview



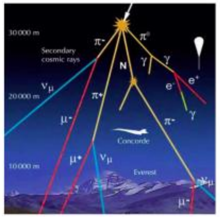


- Multi-purpose liquid scintillator experiment

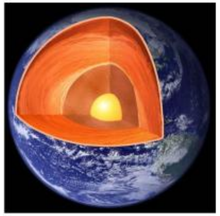
$\sim 50/\mathrm{day}$



$\mathcal{O}(1000)/\mathrm{day}$



$\sim 10/\mathrm{day}$



~ 1 - $2/\mathrm{day}$

CCSN @10kpc : $\mathcal{O}(1000)/\mathrm{s}$
DSNB: few/year

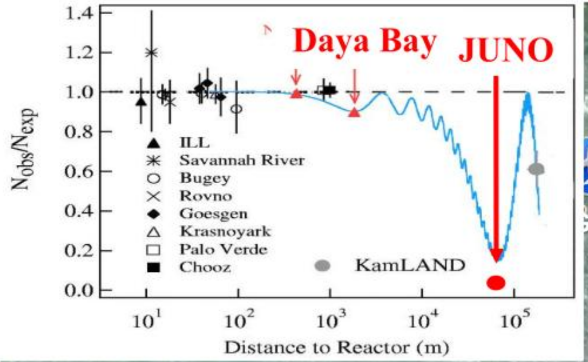
New Physics

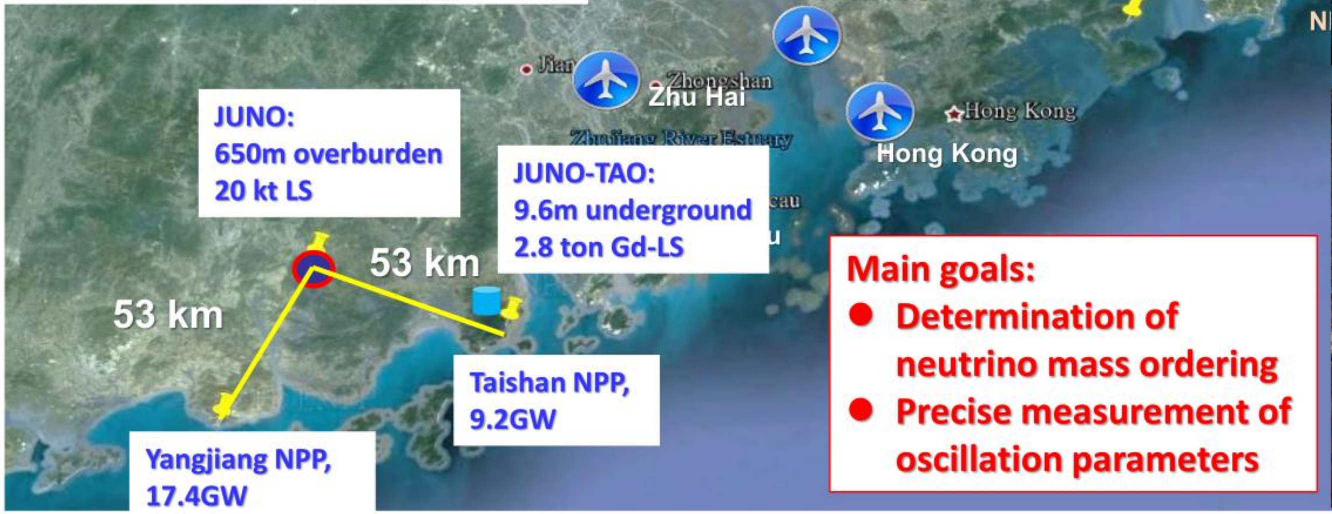
Proton decay
etc

- This talk:
  Oscillations with Reactor ($\bar{\nu}_e$), Atmospheric & Solar neutrinos (ν_e).

- See: Talk by Gaosong Li
  "JUNO non-oscillation physics".

Jiangmen Underground Neutrino Observatory





Main goals:

- **Determination of neutrino mass ordering**
- **Precise measurement of oscillation parameters**

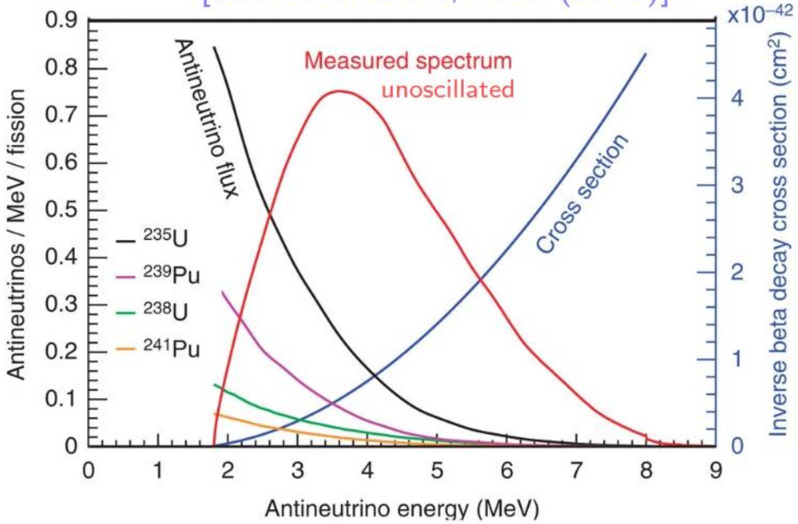
JUNO Onsite

JUNO
Overburden：700m
Vertical tunnel: 563 m
Slope tunnel：1265 m @ slope of 42%

Reactor neutrinos: flux

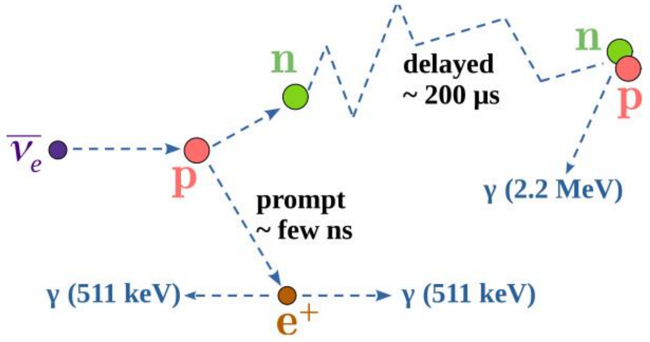
- Source: Reactor antineutrino ($\bar{\nu}_e$) from fission
  - $^{235}\mathrm{U}$, $^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$ and $^{241}\mathrm{Pu}$

[Nat Commun 6, 6935 (2015)]



- Reactors of interest to JUNO: info
  - Taishan + Yangjiang @ ~ 53 km
    26.6 $\mathrm{GW_{th}}$ (relative flux: 94%)
  - Daya Bay @ ~ 215 km
    17.4 $\mathrm{GW_{th}}$ (relative flux: 6%)

- Detection: Inverse beta decay (IBD) process.
  - $\bar{\nu}_e + p \rightarrow n + e^+$
  - Reaction threshold: 1.8 MeV
  - $E_{\mathrm{vis}}(e^+) \simeq E(\bar{\nu}) - 0.8$ MeV



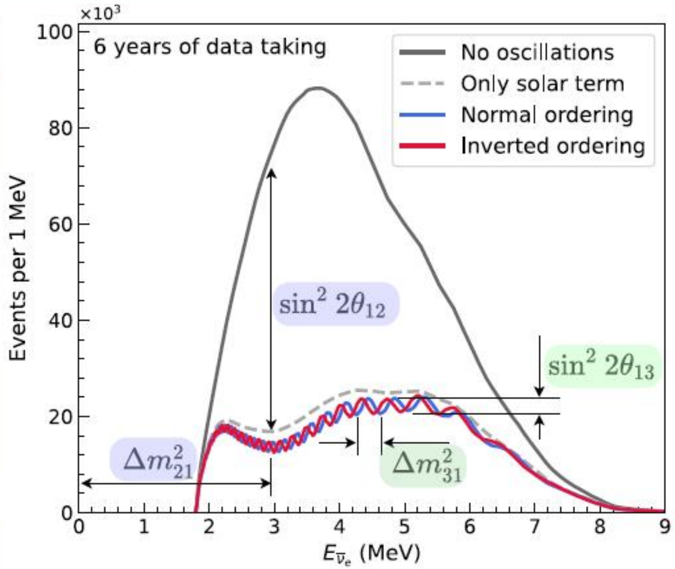
JUNO reactor spectrum

Oscillations

- Survival probability at medium baseline

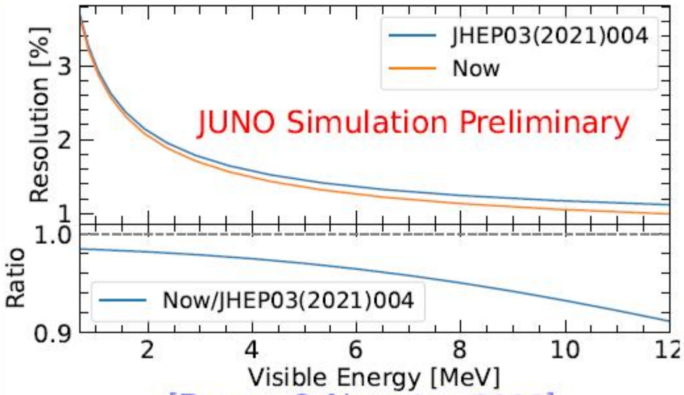
$$P_{ee} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \left[\cos^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

  - Observe two Osc. modes: slow & fast.
  - Sensitive to Mass ordering.



Detector response

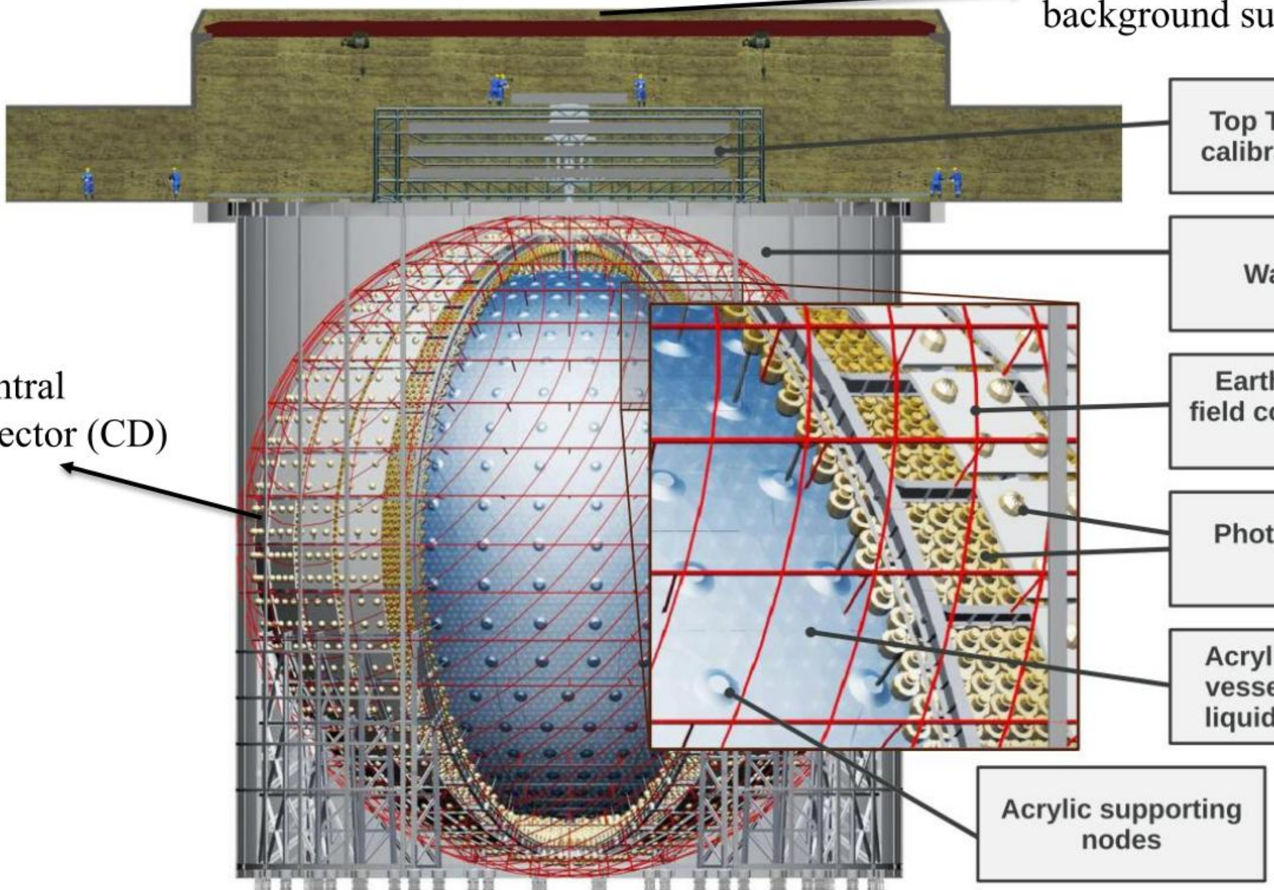
- Calibration with discrete sources. ▸ Calib
- Energy scale non-linearity: $E_{\mathrm{Visible}}/E_{\mathrm{True}}$
  - Uncertainty $< 1\%$ [J. High Energ. Phys. 2021, 4]
- Energy Resolution: 2.9% at 1 MeV ▸ Res
  - Light yield, position non-uniformity, reconstruction



[Poster @ Neutrino 2022]

JUNO detector

~650 m overburden for cosmic background suppression



Central detector (CD)

Top tracker for cosmic muon veto

Water Cherenkov detector for external background suppression and muon veto

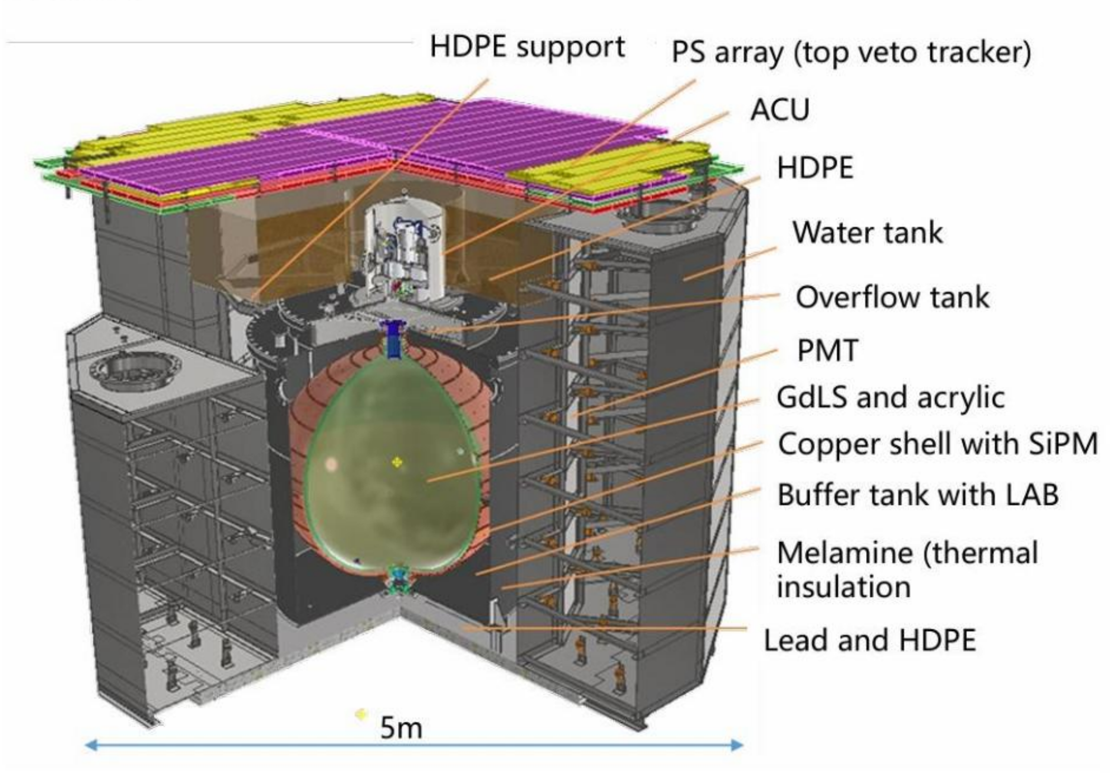
17612 20-inch CD PMTs
~ 75% coverage

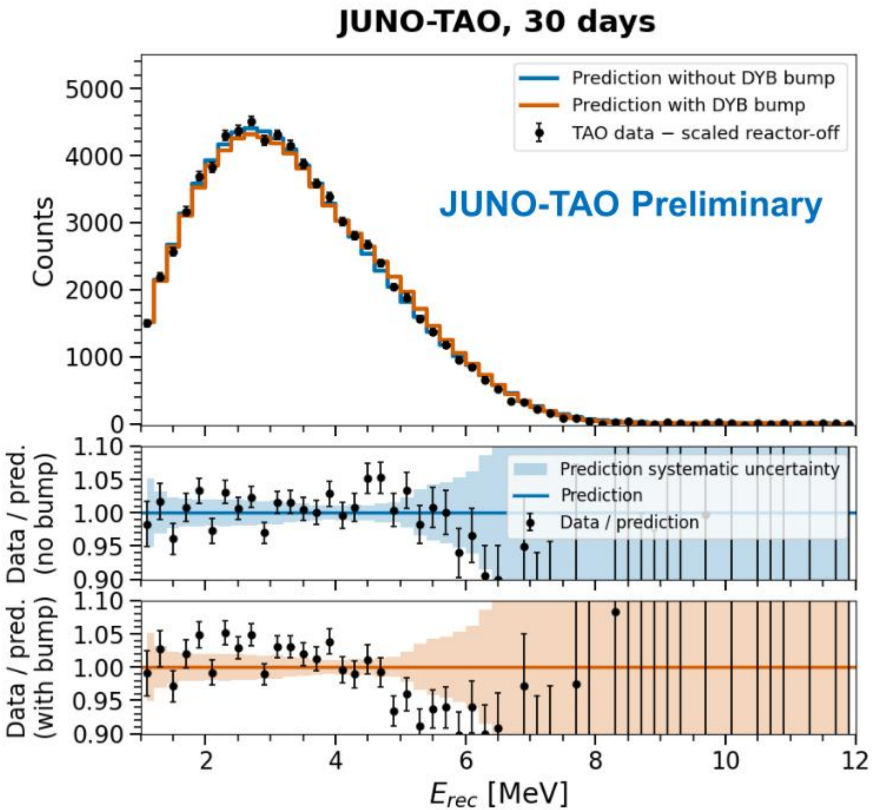
25600 3-inch CD PMTs
~ 3% coverage

20 kton liquid scintillator (LS)
LAB + 2.5 g/L PPO + 3 mg/L bis-MSB
+42 mg/L BHT

To be continued ...

Satellite detector: JUNO-TAO

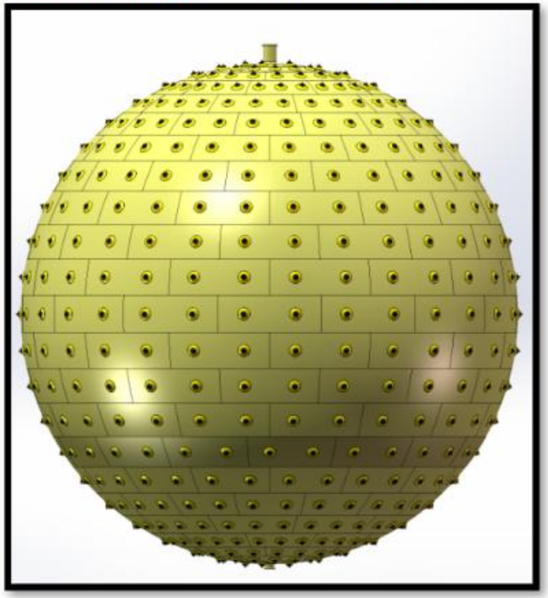


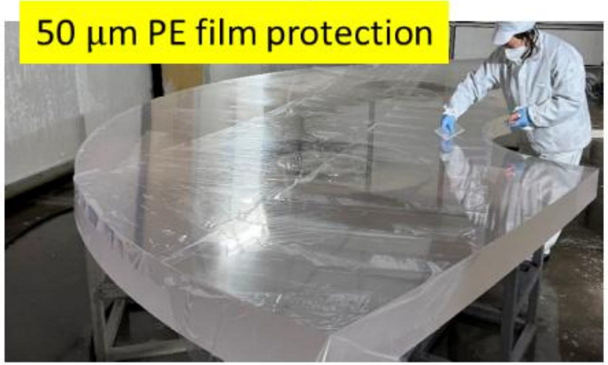


- Primary goal: provide unoscillated reactor ν spectrum for JUNO and the community.
- In stable operation since Feb. 2026: one month of data used for this analysis

Central Detector

- The acrylic sphere is composed of 265 pieces of spherical panels;
- Thickness:120mm, Net weight: ~600 tons;
- Transparency > 96% in pure water;
- Radiopurity: U/Th/K < 1 ppt





Liquid scintillator

- *Using a recipe optimized from Daya Bay's experience, tested and changed to be more suitable for JUNO;*
- *Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.*

5000 m³ LAB tank

Al_2O_3 to remove particles

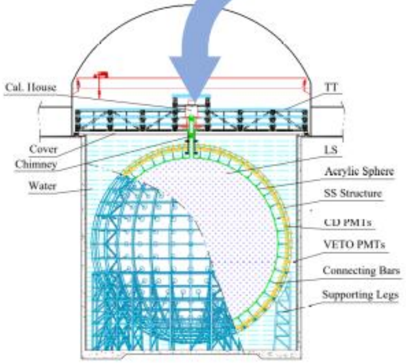

Distillation to remove radioactive impurities


Add 2.5 g/L PPO and 3 mg/L bis-MSB

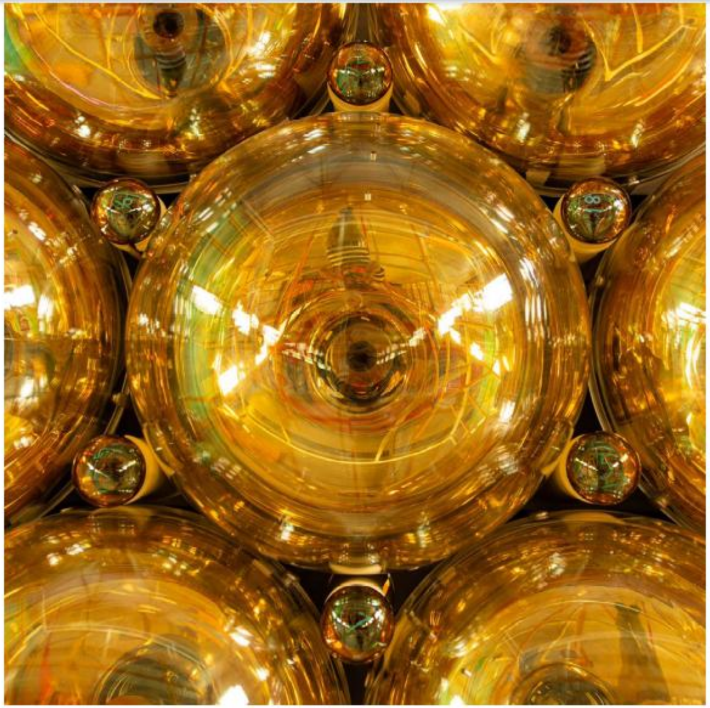

Water extraction to remove radioactive impurities


Gas stripping to remove Rn and O_2

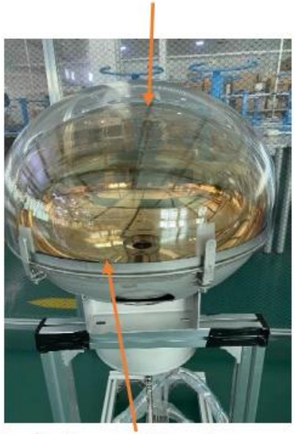

OSIRIS for LS qualification



PMT



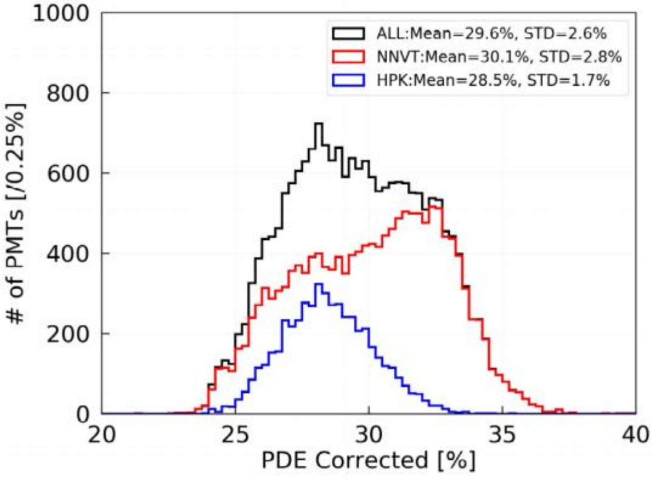
Acrylic cover

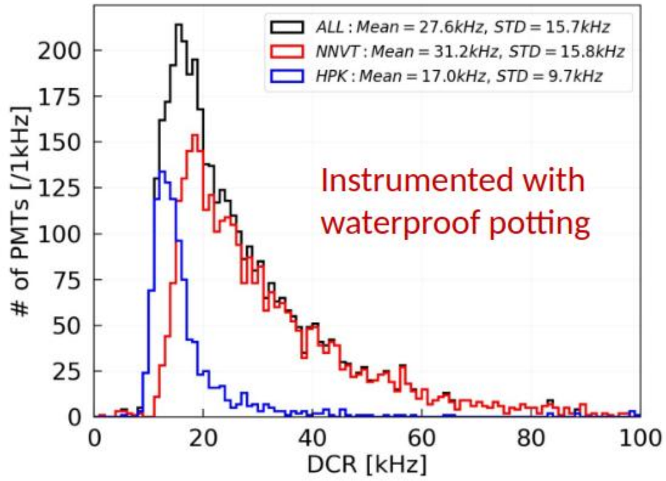


Stainless Steel cover

- Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity；
- Clearance between PMTs: 3mm；
- **Assembly precision: < 1mm；**

PMT performance



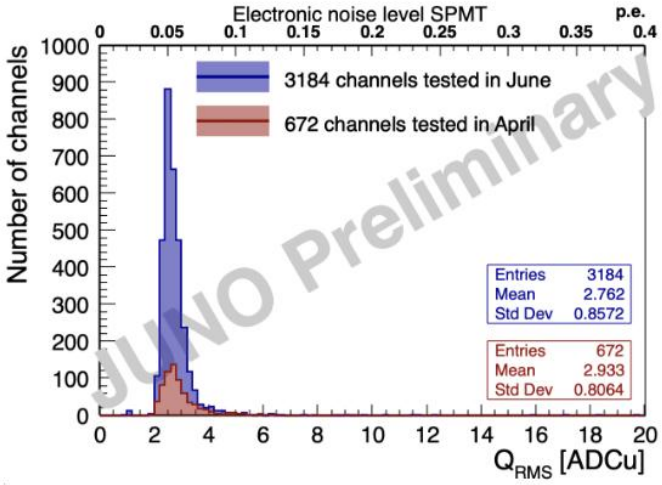


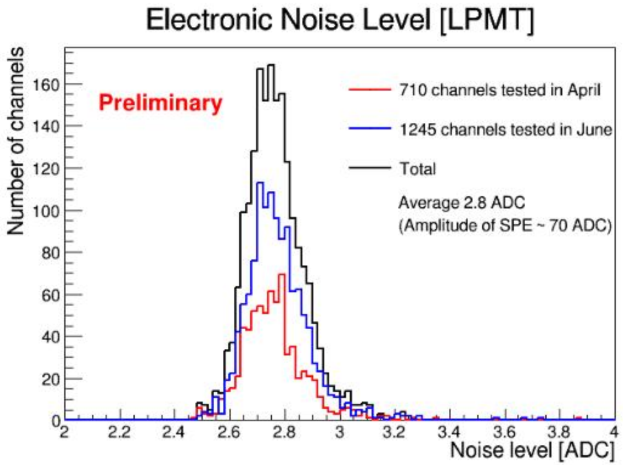
		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

- *All PMTs produced, tested, and instrumented with waterproof potting ;*
- *12.6k NNVT PMTs with higher PDE are selected for CD and the rest are used in the Water Cherenkov detector;*

Commissioning

- *Regular light-off tests and lunch tests during detector assembly started;*
  - *Light off tests: full data taking and processing chain with PMT HV on;*
  - *Light on tests: joint elec./trigger/DAQ/DCS test with PMT HV off during lunch time;*
- *Very good electronics, shielding, and grounding;*
  - *Electronics noise of LPMT is 2.8 ADC counts, 4% of SPE ➔Much better than the design of 10%;*
  - *Electronics noise of SPMT is 2.8 ADC counts, ~5% of SPE ➔Much lower than the trigger threshold of 1/3 p.e. ;*
- *All tested PMTs were working well;*





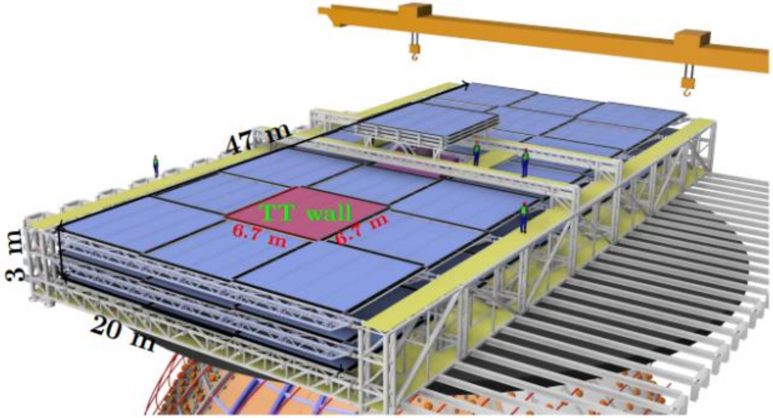
Water Cherenkov Detector

Water room on the ground

Water room underground

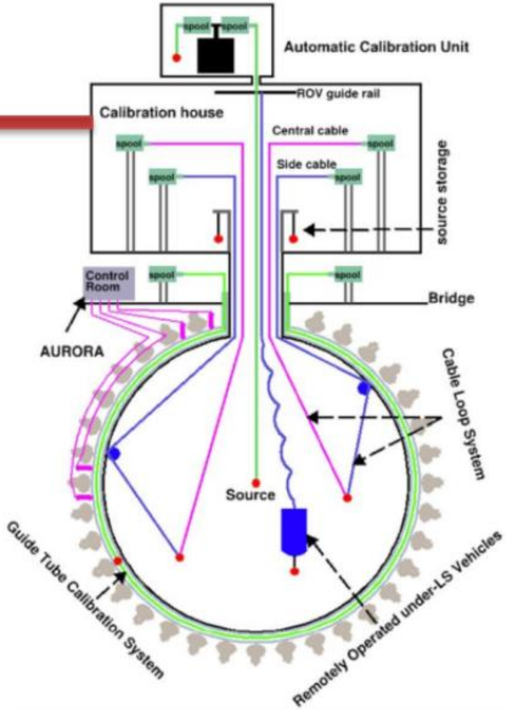
- 35 kton of ultrapure water and 2400 MCP-PMTs are used to form the Water Cherenkov Detector;
- ~6000m^2 HDPE served as Rn barrier;
- 100t/h ultrapure water system is equipped to
  - Keep the temperature at 21 ± 1°C ；
  - Reduce the radon concentration inside the water to less than 10mBq/m^3;

Top Tracker



- *Reusing the plastic scintillators from OPERA Target Tracker ;*
- *About 50% coverage on the top, three layers to reduce accidental coincidence;*
- *Provide control muon samples to validate the track reconstruction and study cosmogenic backgrounds ;*
- *All scintillator panels arrived on site in 2019;*
- *The TT support bridge is ready for production;*

Calibration systems

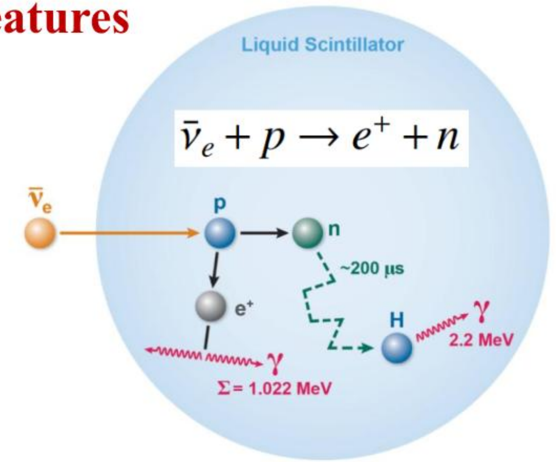


- *Four complementary subsystems will reduce the energy scale uncertainty < 1%;*
  - ✓ *1-D: Automated Calibration Unit(ACU);*
    - *Scan the central axis;*
  - ✓ *2-D: Cable Loop System(CLS);*
    - *Scan vertical plane;*
  - ✓ *2-D: Guide Tube Calibration System(GTCS);*
    - *Scan CD outer surface;*
  - ✓ *3-D: Remotely Operated Vehicle(ROV);*
    - *Full detector scan;*

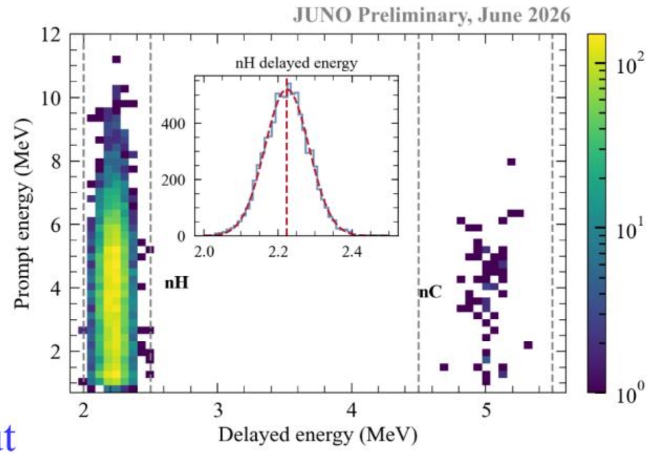
Reactor antineutrino candidate selection

- Prompt and delayed coincidence in time, space with **energy features**

Criterion	Selection
PMT flasher	Applied
Fiducial volume	$r_p < 17.2$ m, $\lvert z_p \rvert < 15.5$ m
Prompt energy	(0.7, 12) MeV
Delayed energy	(2.0, 2.5) ∪ (4.5, 5.5) MeV
Coincidence time	(5, 1000) μs
Relative distance	< 1.5 m
Multiplicity cut	No other events > 0.7 MeV in the FV or (2.0, 6.0) MeV outside the FV within 2 ms before and 1 ms after the delayed event
Water pool muon veto	Veto if the delayed is within (0, 2) ms after NPE > 700 in WP
CD muon veto	Veto if the delayed is within (0, 5) ms after NPE > 3×10^4 in CD
Spallation neutron veto	Veto if the delayed satisfies $\Delta r < 4$ m and $\Delta t < 1.2$ s after spallation neutrons with $\text{NPE}_{\text{spn}} \in (3000, 30000)$ and $T_{\text{spn}2\mu} \in (20, 2000)$ μs
Muon track veto	Veto if the delayed event: $\frac{\Delta r_{d2\mu}}{2.5\text{m}} + \frac{\Delta t_{d2\mu}}{0.5\text{s}} < 1$
Correlated discriminator	log(L.R.) > -1.26



- Optimized selection criteria:
  - ~10% more fiducial volume (R = 16.5m → 17.2m)
  - ~60% reduction of ^{9}Li bkg. with muon track veto
  - a factor of 50 reduction of accidental bkg. using likelihood ratio cut



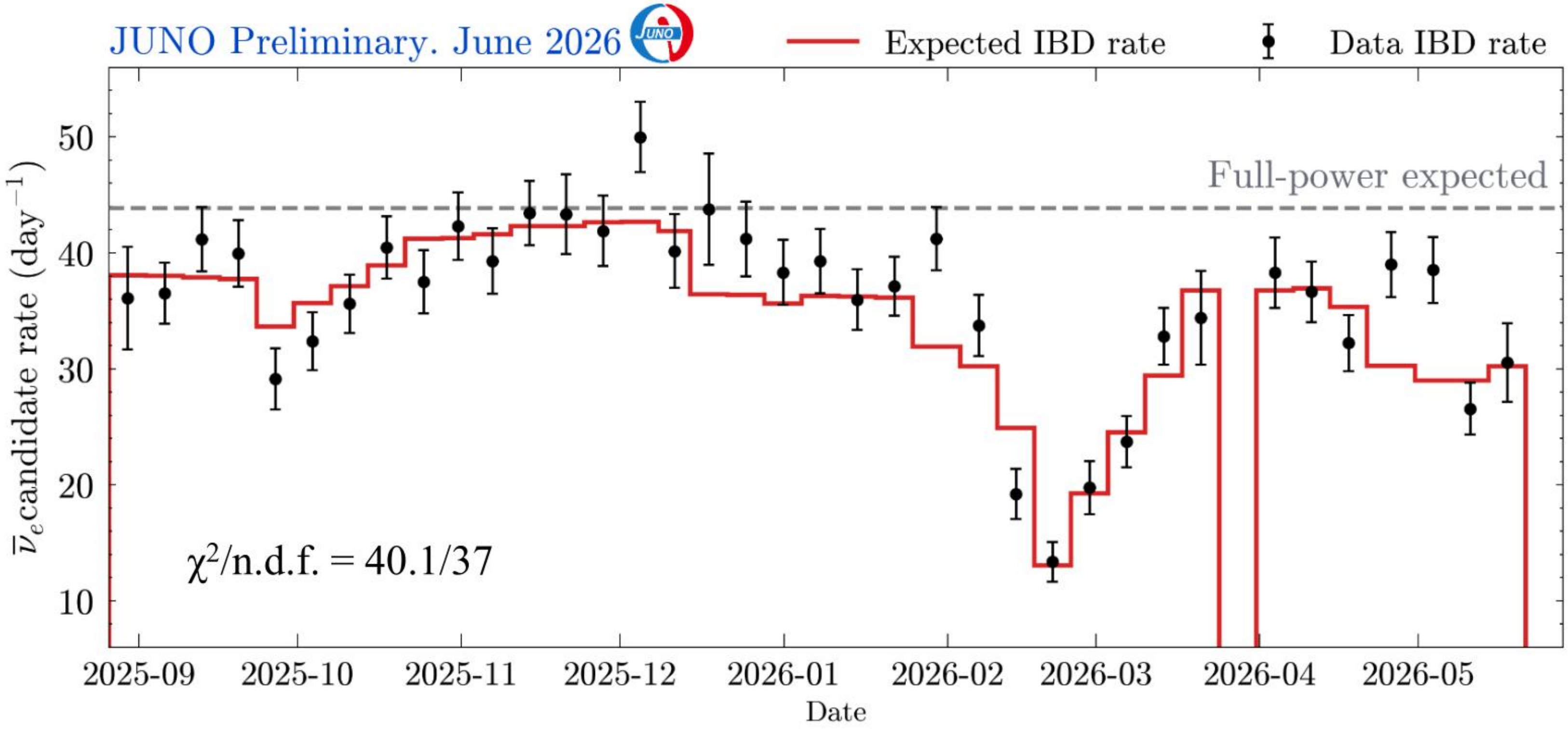
Efficiency and background analysis

Main updates in this analysis:

- More precise estimation of fiducial volume cut (σ_{FV} ~ 1.6% → ~1.0%)
- Combine time and spatial distributions since adjacent muons to estimate $^{9}Li/^{8}He$ bkg.
- Model independent estimate of the ^{214}Bi bkg. (spectrum shape model → enriched samples)
- Free geo-nu rate for their measurement

Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\overline{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ε	σ_{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 (ε_{tot})	74.01%	1.02%
$\overline{\nu}_e$ signal (cpd)		
w/o ε_{tot} corrected	36.02 ± 0.62	
w/ ε_{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
$^{13}C(\alpha, n)^{16}O$	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

Reactor Neutrino Event Rate versus Time



- After the background subtraction, measured reactor neutrino event rate consistent with expectation

Fitting strategy

- Reactor antineutrino oscillation probability

$$\mathcal{P}_{ee} = 1 - \sin^2 2\tilde{\theta}_{12}\, \tilde{c}_{13}^4 \sin^2 \tilde{\Delta}_{21} - \sin^2 2\tilde{\theta}_{13} (\tilde{c}_{12}^2 \sin^2 \tilde{\Delta}_{31} + \tilde{s}_{12}^2 \sin^2 \tilde{\Delta}_{32})$$

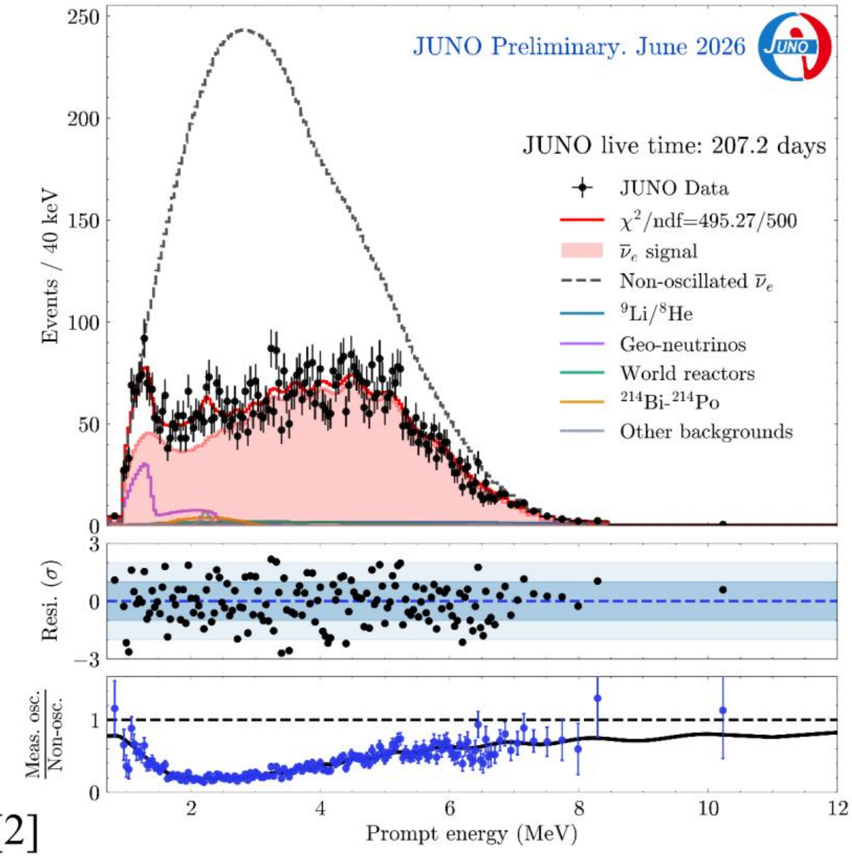
$\tilde{\theta}$: w/ matter effect

- χ^2 combined with DYB and TAO

$$\chi^2(\vec{p}, \vec{\eta}, \vec{\alpha}) = \sum_X (\mu^X - D^X)^T V_X^{-1} (\mu^X - D^X) + \lambda^2_{\text{nuis}}(\vec{\eta}) + \lambda^2_{\text{flux}}(\vec{\alpha}) + \chi^2_{\text{osc}}(\sin^2\theta_{13}, \Delta m^2_{31}). \quad (1)$$

(X = JUNO, DYB, TAO)

- External constraint χ^2_{osc}
  - External θ_{13} constraint from DYB [1]
  - Δm^2_{31} measurement: DYB Δm^2_{31} constraint [1]
  - NMO: Δm^2_{31} constraints from DYB and NuFit-LBL [2]

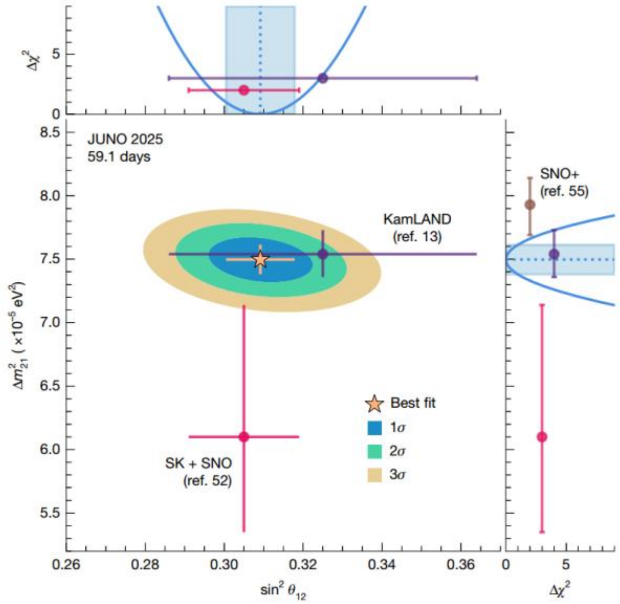


[1] DYB collaboration, PRL 130, 161802 (2023)
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380])

What is new

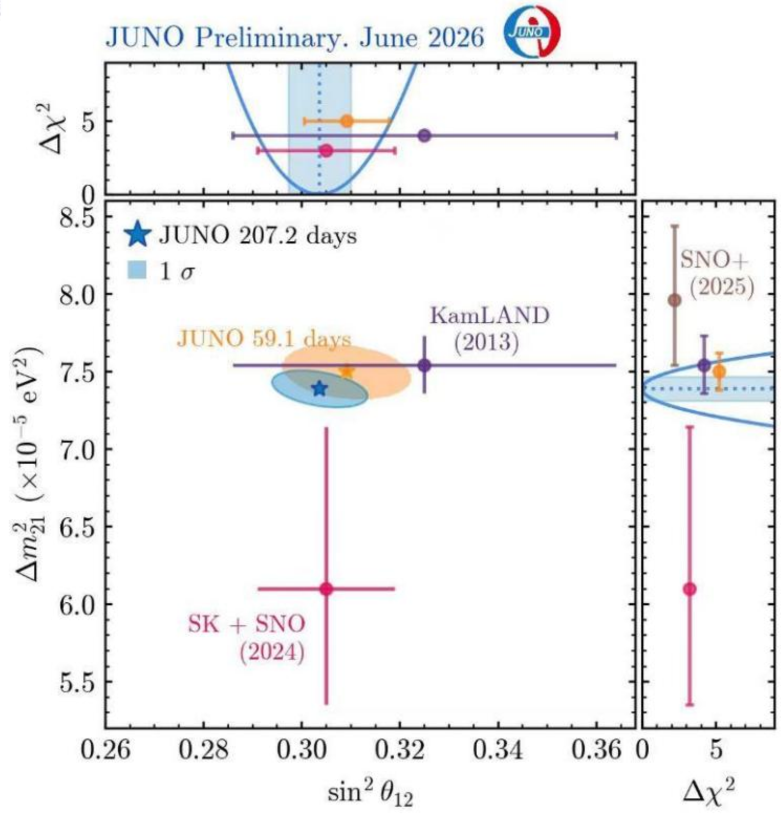
- JUNO's first results with 59 days of data released in Nov. 2025 [Nature 654, 343 (2026)]

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087, \quad (2.8\%)$$
$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\,\mathrm{eV}^2. \quad (1.6\%)$$



- This analysis focus on new results with 207 days of data
  - Data taking period: 2025.08.30-2026.05.18
  - Golden data is selected for physics analysis
- New things: first measurement of Δm^2_{31} and neutrino mass ordering (NMO) at JUNO

Updated measurement on solar parameters



$\sin^2\theta_{12}$	Precision (%)
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

stat.+1 syst. (0.0 0.5 1.0 1.5 2.0)

^{214}Bi dominate

Syst. dominate

Δm^2_{21}	Precision (%)
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

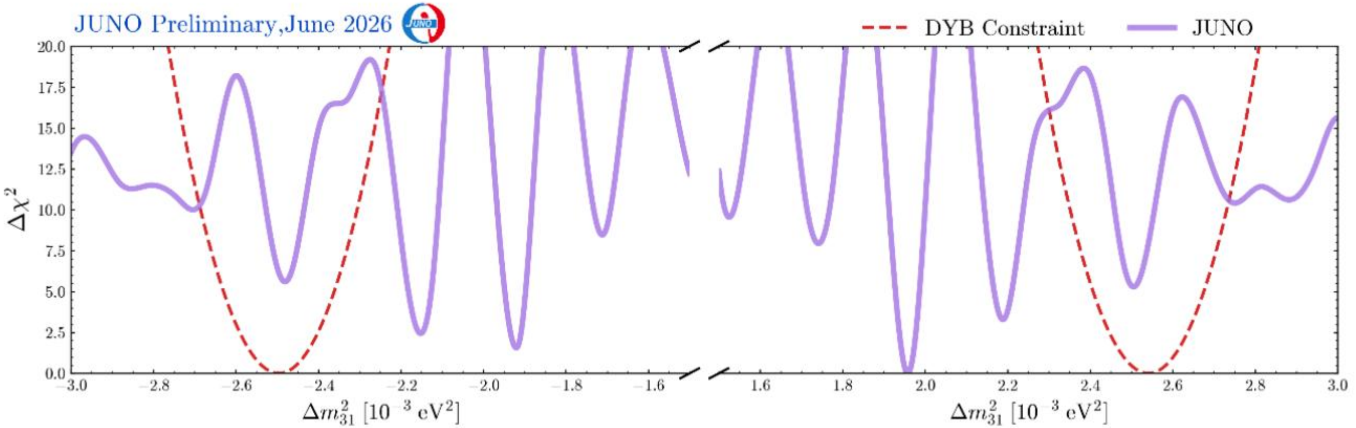
stat.+1 syst. (0.00 0.25 0.50 0.75 1.00)

Δm^2_{21}	7.388 ± 0.078 (1.60% → 1.06%)
$\sin^2\theta_{12}$	0.3036 ± 0.0064 (2.8% → 2.1%)

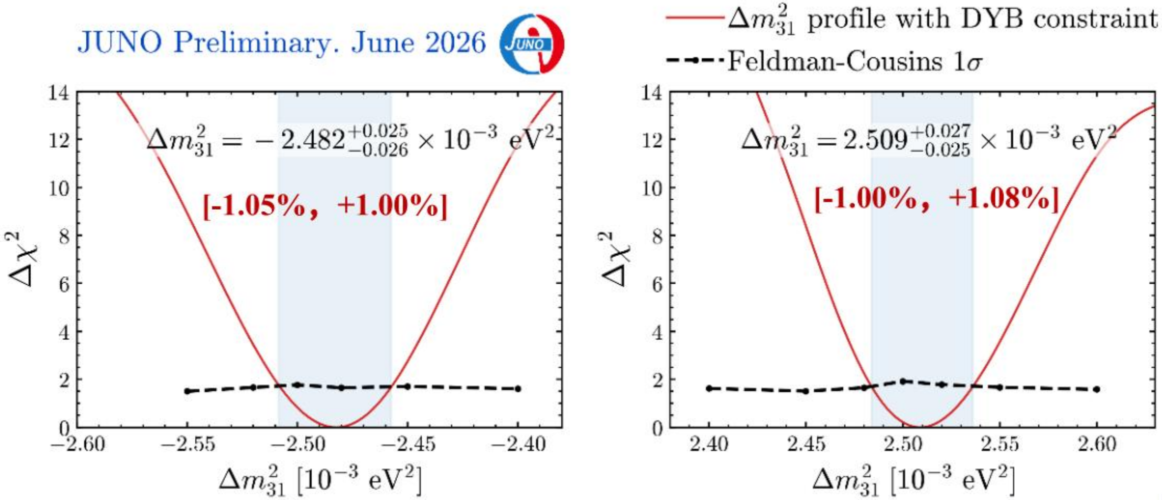
- ^{214}Bi bkg. and detection eff. can be improved

First result of Δm^2_{31}

- Due to statistical fluctuations, JUNO-only profiles of Δm^2_{31} have multiple minima

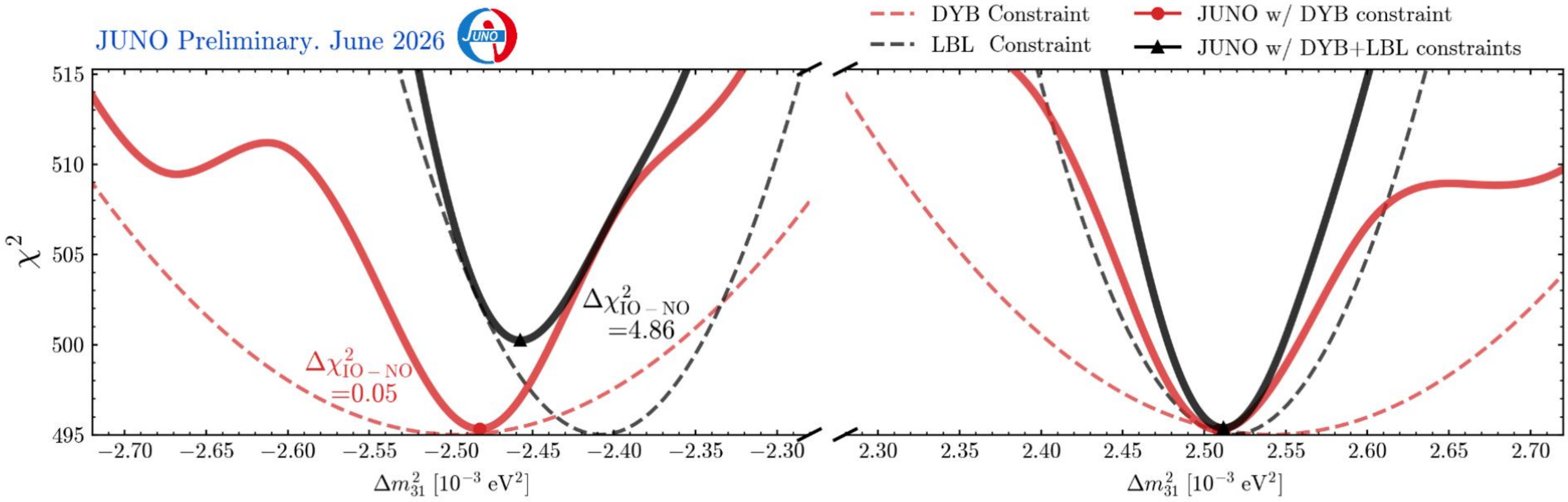


- Using the Δm^2_{31} constraint from DYB to obtain final minimum for each mass ordering.
- Feldman-Cousins (FC) method is used to determine the 1σ range of Δm^2_{31}: ~1% precision achieved



Adding constraint from NuFit-LBL

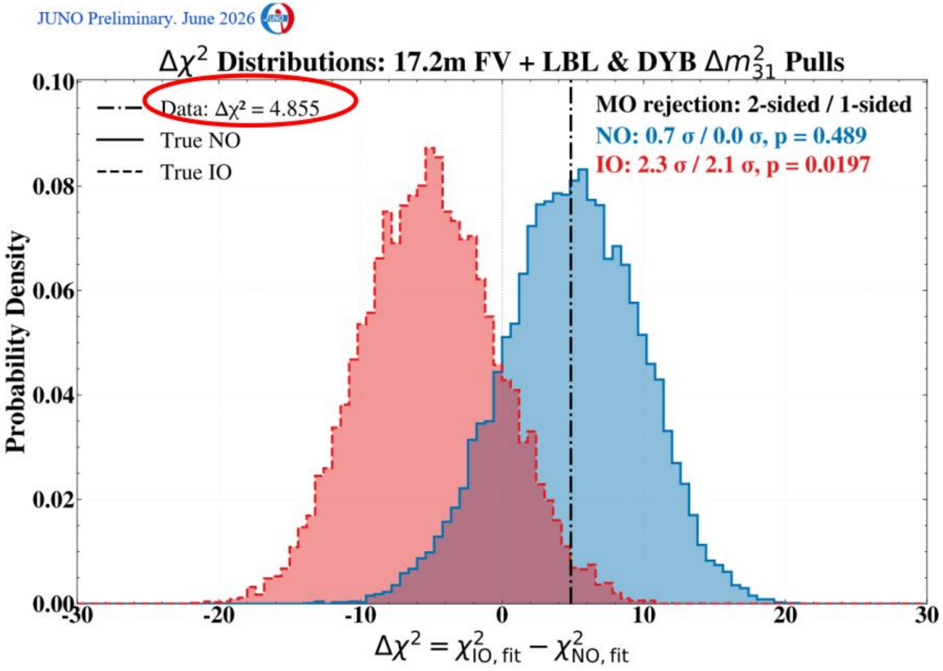
- Δm^2_{31} from reactor and accelerator neutrinos should align at the right mass ordering[1]
- Adopt the NuFit-LBL results from [2]: normal mass ordering is favored at $\Delta\chi^2 = 4.86$



[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

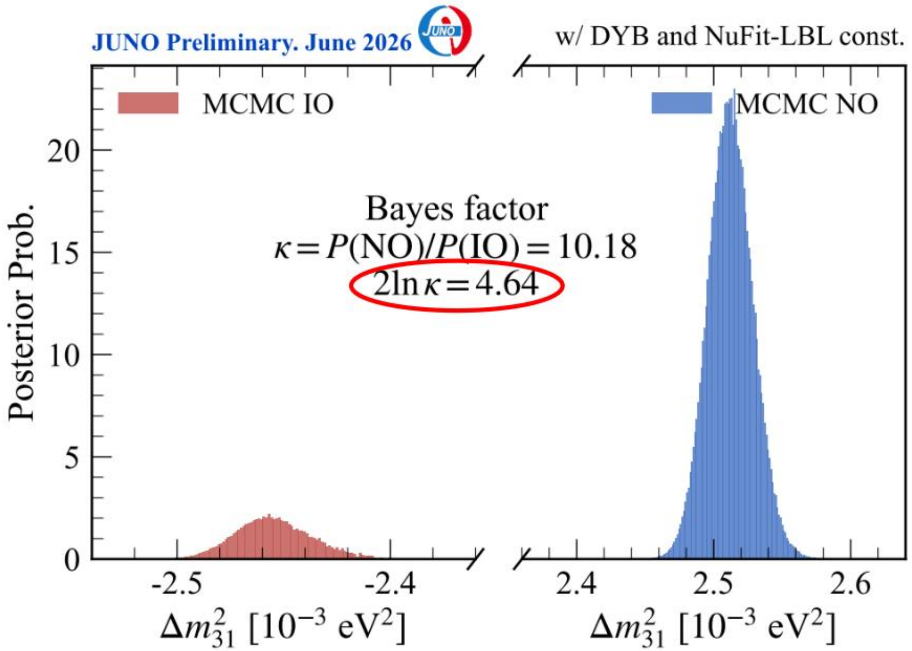
Significance of neutrino mass ordering

- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
- Influence of δ_{CP} considered (scanned)
- Normal Ordering is favored at **2.3σ**



- Bayesian approach using Markov Chain Monte Carlo (MCMC) method
- Normal Ordering is favored with a Bayes factor of 10.18 → 2lnκ= 4.64

⇨ **Consistent with the frequentist $\Delta\chi^2$**



Summary

- 207 days of golden data was used in this analysis
- Precision of solar oscillation parameters further improved by a factor of 1.3-1.5

$$\sin^2\theta_{12} = 0.3036 \pm 0.0064\,, \quad (2.1\%)$$
$$\Delta m^2_{21} = (7.388 \pm 0.078) \times 10^{-5}\ \mathrm{eV}^2\,, \quad (1.1\%)$$

- First measurement on Δm^2_{31} achieved a precision of ~1%

$$\Delta m^2_{31} = -2.482^{+0.025}_{-0.026} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})\,,$$
$$\Delta m^2_{31} = +2.509^{+0.027}_{-0.025} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})\,,$$

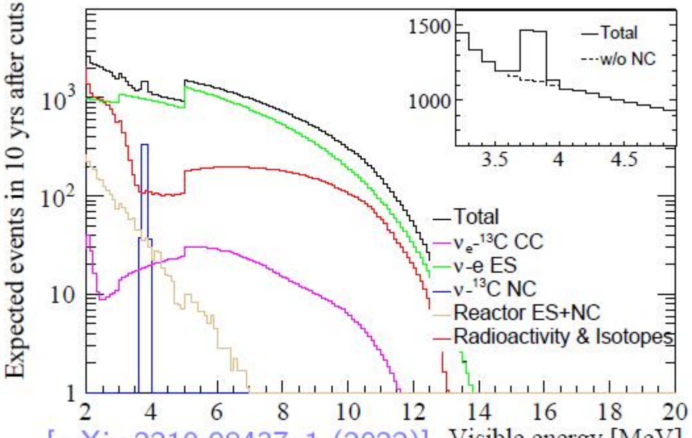
- With external constraints from DYB and NuFit-LBL, Normal Mass Ordering is favored at ~2.3σ

Solar neutrinos

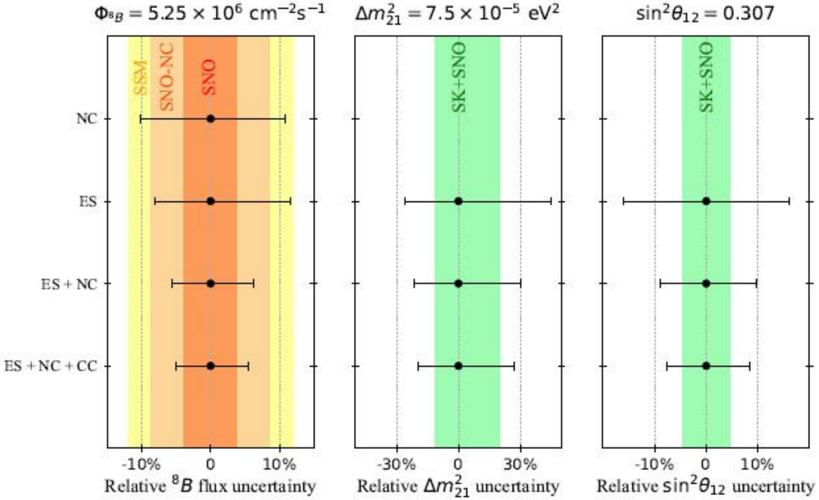
- JUNO to measure Δm^2_{21} & $\sin^2\theta_{12}$ from solar and reactor neutrinos.
- Oscillations with ^{8}B solar neutrinos
  - Main channel: ν-e **ES**
  - Other visible channels:

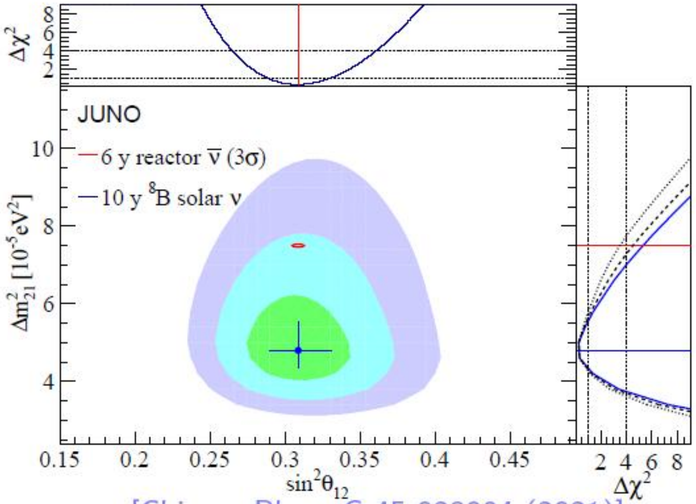
    $\nu_\alpha +$ ^{13}C **NC**: $3.7\ \mathrm{MeV}\ \gamma$

    $\nu_e +$ ^{13}C **CC**: e^- & $2.2\ \mathrm{MeV}\ \beta^+$



[arXiv:2210.08437v1 (2022)]





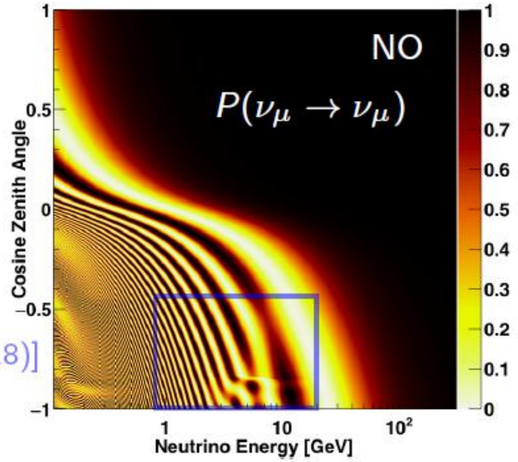
[Chinese Phys. C 45 023004 (2021)]

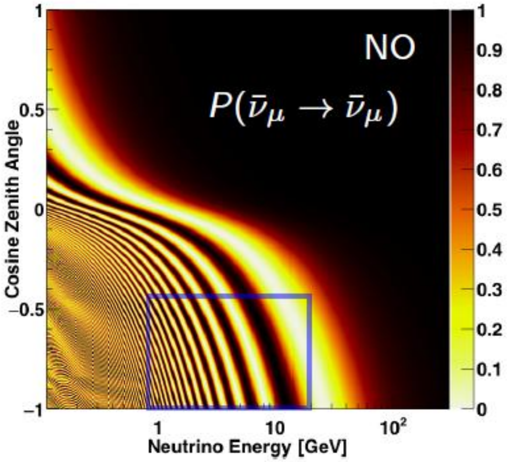
- JUNO can also measure ^{7}Be, pep, CNO.

Atmospheric neutrinos

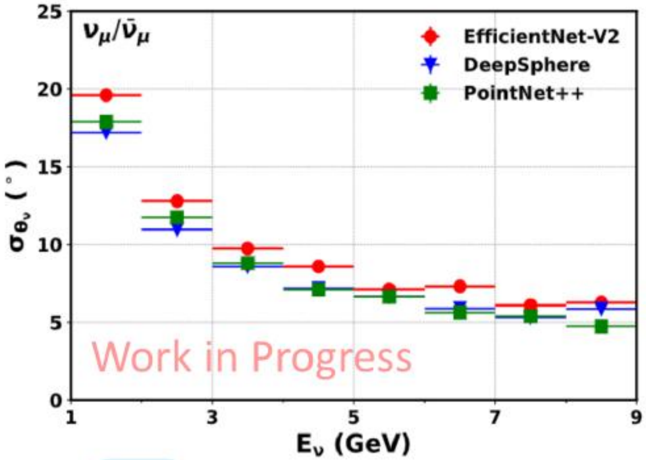
- Neutrino mass ordering:
  - Complementary to reactor neutrino
  - Earth matter effects

  [Phys. Rev. D97, 072001 (2018)]





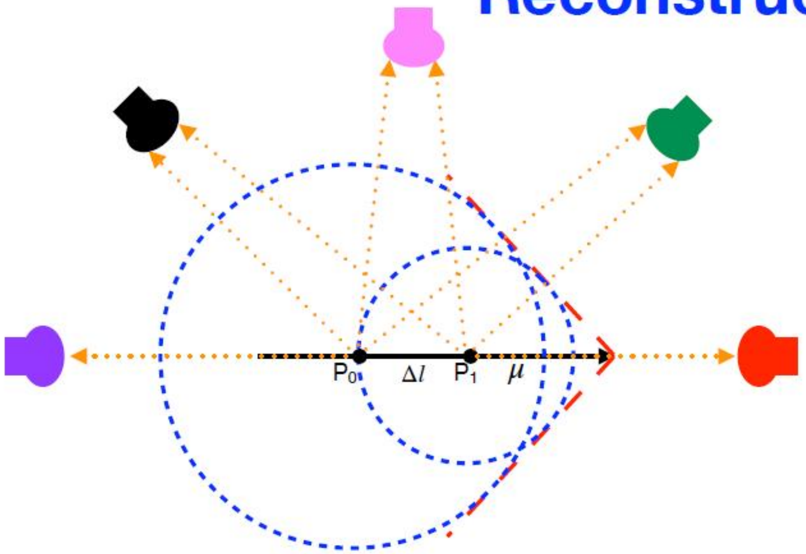
- Event classification and reconstruction:
  - Various methods (Machine learning *etc.*)
  - PMT waveform features, first hit time, neutron multiplicity
  - PID efficiency $\nu/\bar{\nu}$: 60% $\sim$ 80%
    - See: Poster by Xinhai He (376)
  - Direction resolution: $\sigma_{\theta_\nu} < 10^\circ$ ($E_\nu > 3$ GeV)

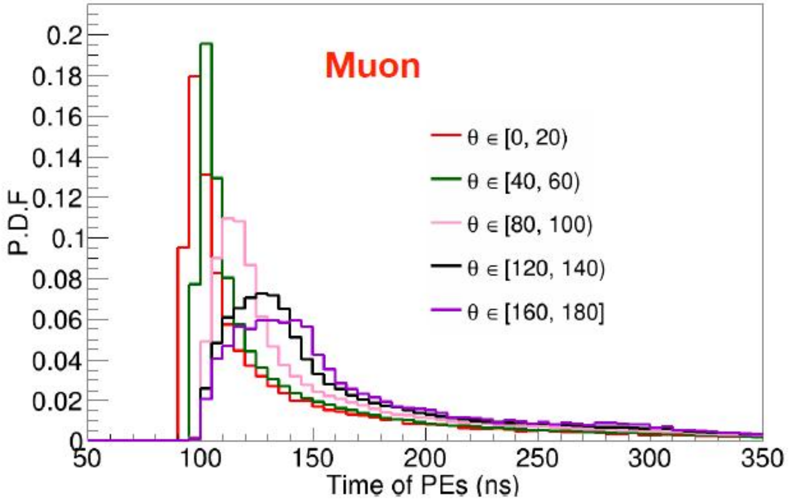


- Neutrino mass ordering sensitivity be released soon. Old

[NuFACT 2023]

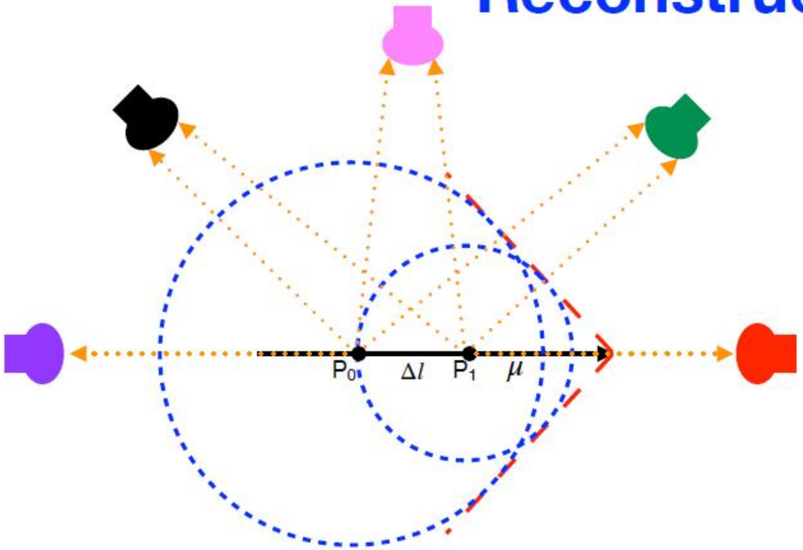
Reconstruction Principle

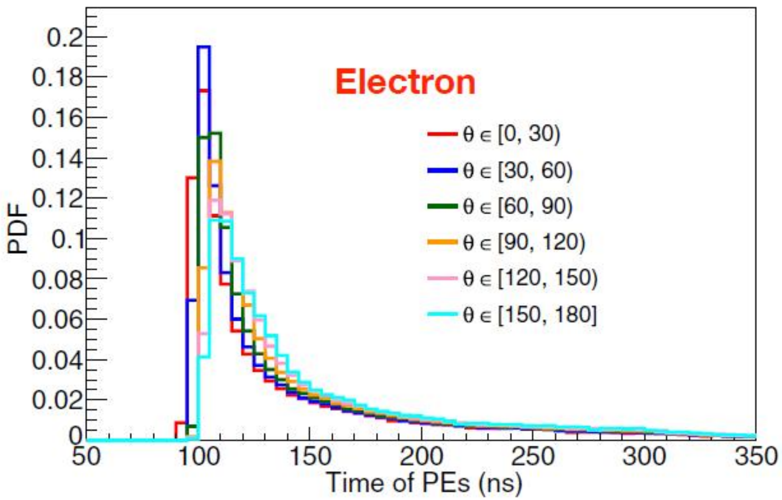




- PMTs at different angles wrt the track see distinct shapes of nPE(t), and therefore the waveforms.
- Exactly how waveforms look depends on:
  - Track direction;
  - Track starting and stopping points;
  - Track dE/dx…

Reconstruction Principle





- PMTs at different angles wrt the track see distinct shapes of nPE(t), and therefore the waveforms.
- Exactly how waveforms look depends on:
  - Track direction;
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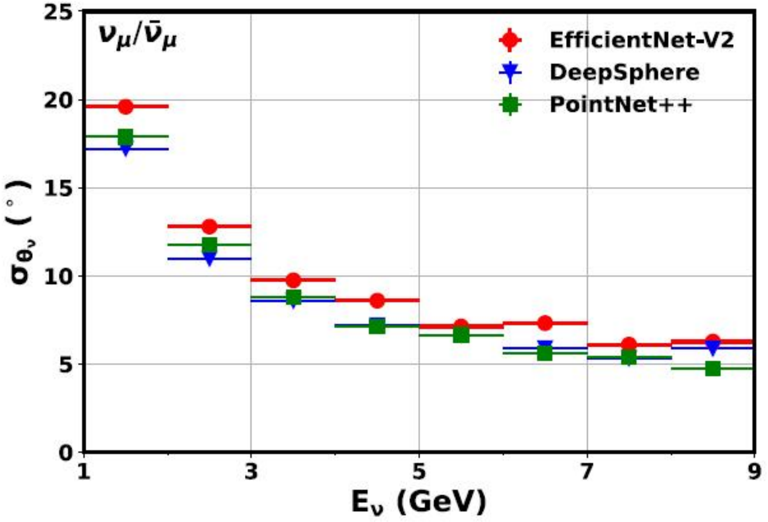
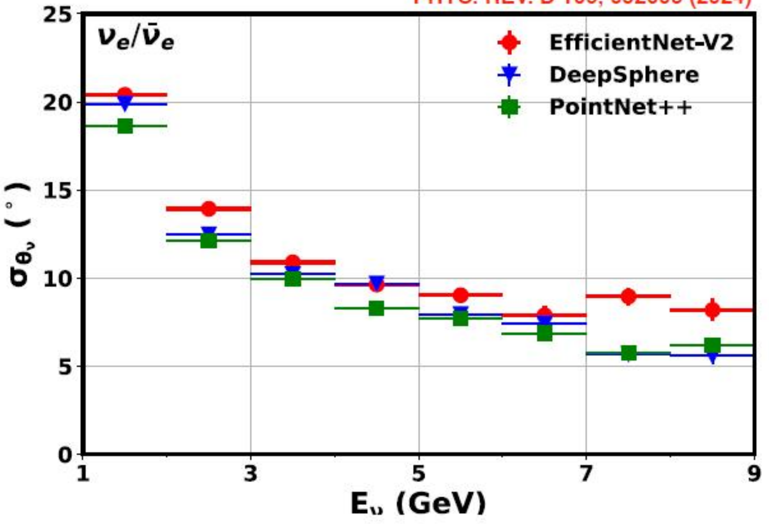
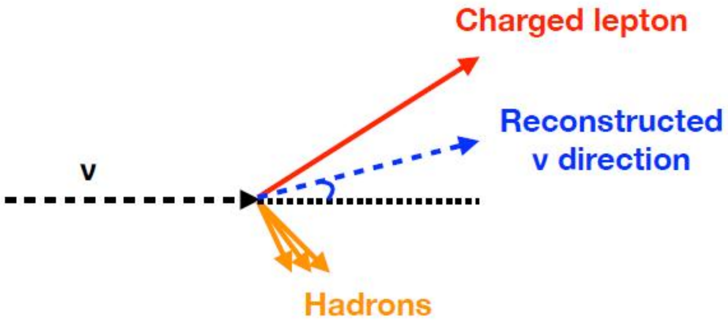
  - Track dE/dx…

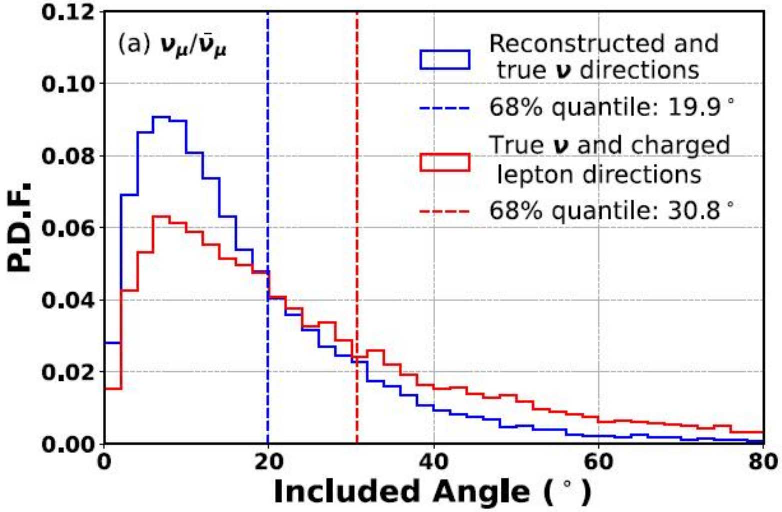
Direction Reconstruction Performance

PHYS. REV. D 109, 052005 (2024)

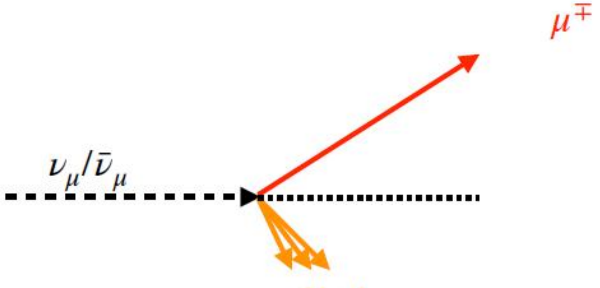


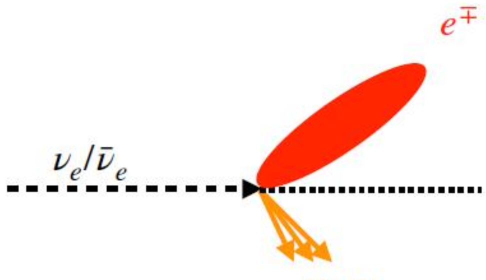






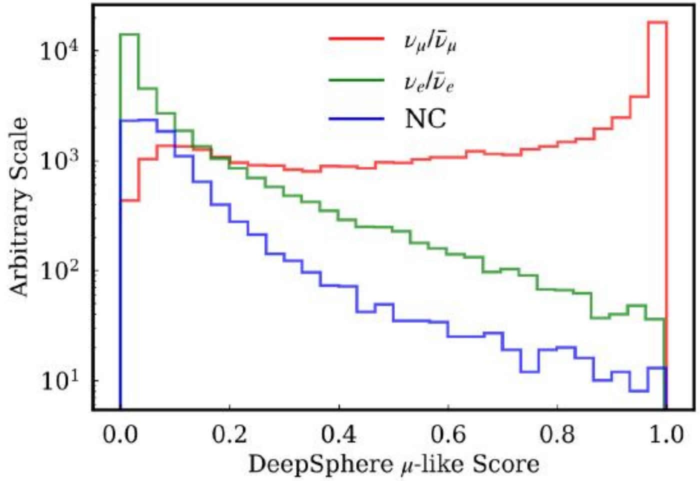
Flavor identification

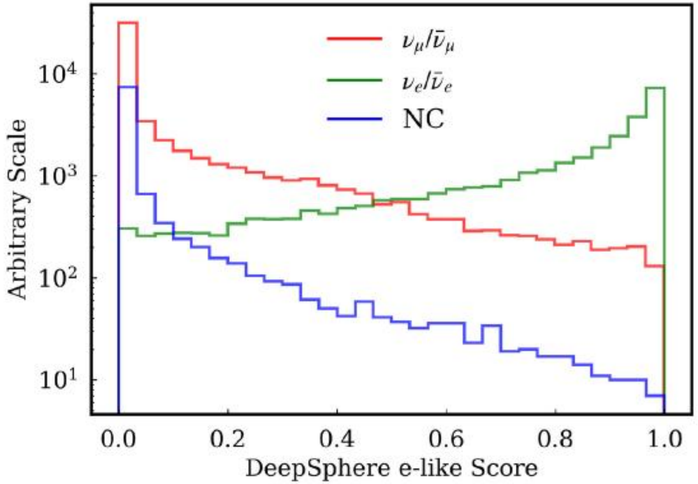




Neutrino flavors are reflected in the flavor of outgoing charged leptons in CC interactions, leading to different waveform features

PHYS. REV. D 112, 012018 (2025)

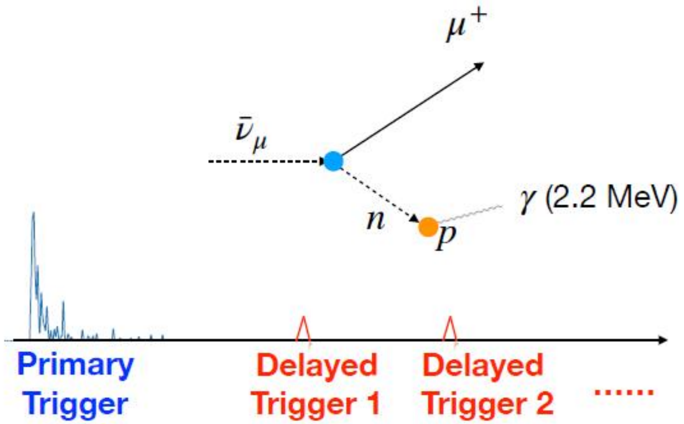




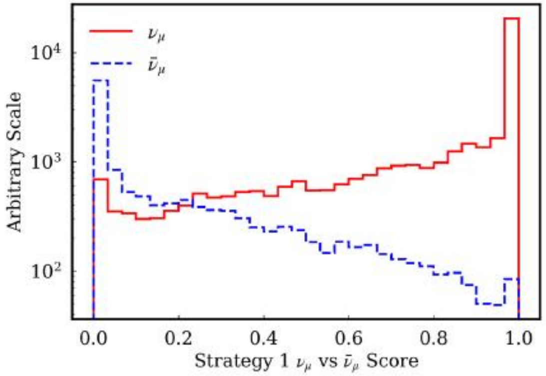
Both $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$-CC events can be well separated from background.

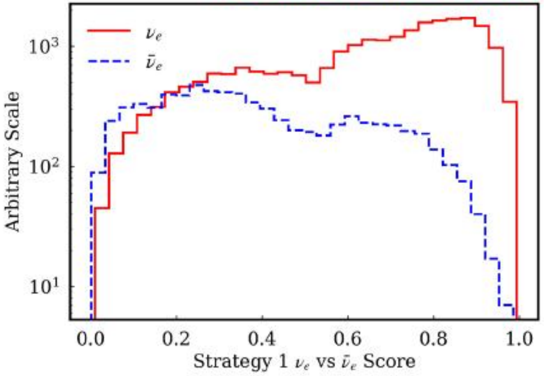
Neutrino vs Anti-neutrino

	ν_μ-CC	$\bar{\nu}_\mu$-CC
QE	$\nu_\mu + n \rightarrow \mu^- + p$	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
RES	$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$	$\bar{\nu}_\mu + p \rightarrow \mu^+ + p + \pi^-$
	$\nu_\mu + n \rightarrow \mu^- + p + \pi^0$	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n + \pi^0$
	$\nu_\mu + n \rightarrow \mu^- + n + \pi^+$	$\bar{\nu}_\mu + n \rightarrow \mu^+ + n + \pi^-$
DIS	$\nu_\mu + N \rightarrow \mu^- + X$	$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$



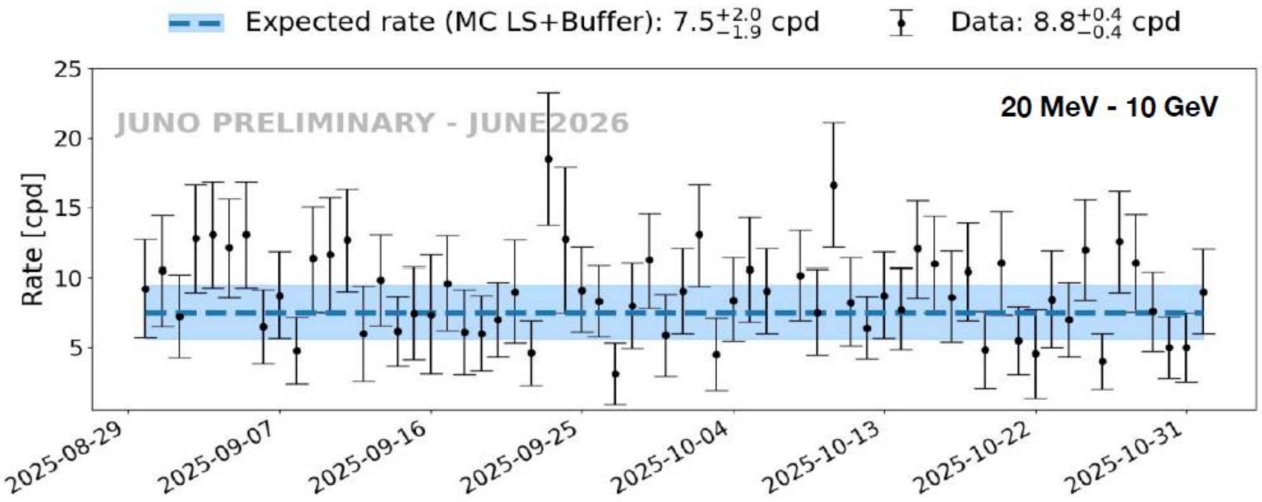
PHYS. REV. D 112, 012018 (2025)

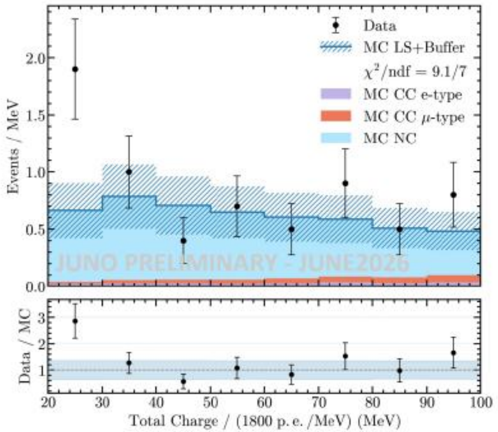


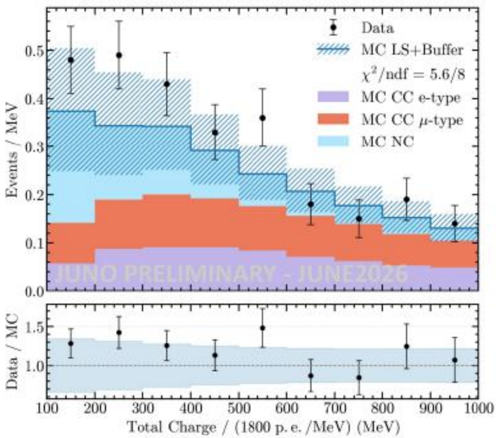


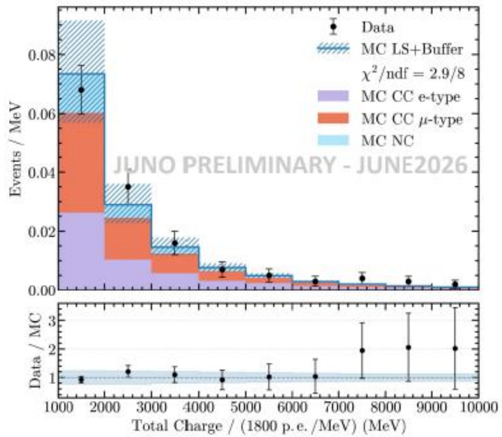
- It is possible to statistically separate ν and $\bar{\nu}$ with helps from
  - Hadronic energy fraction (reflected in waveform features);
  - neutron-capture informations.

First Atmospheric Candidate Events in JUNO



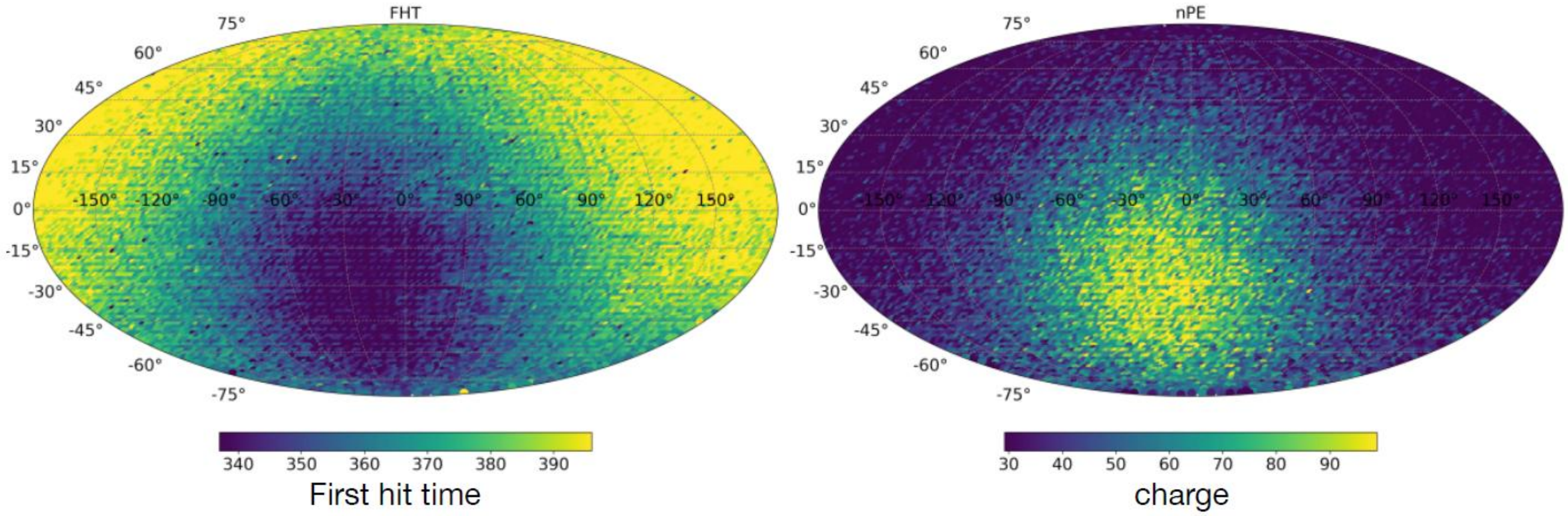






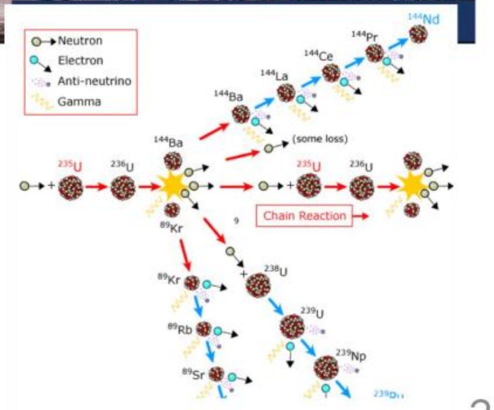
MC prediction: HONDA flux, GENIE v3.04.02 with G18 10a 02 11b tune, oscillated using PDG2025 (NO)

First Atmospheric Candidate Events in JUNO



Example of atmospheric neutrino candidate events in JUNO

JUNO-TAO (Taishan Antineutrino Observatory)



- TAO is the satellite experiment of JUNO
- TAO is deployed near Unit 1 with a baseline of 43.2 m
- In reactors, beta decay chain of fission fragments of U/Pu releases ~6 $\overline{\nu}_e$/ fission

Introduction: Roadmap

2018
Choose Taishan NPP

2020.3
Concept Design Report

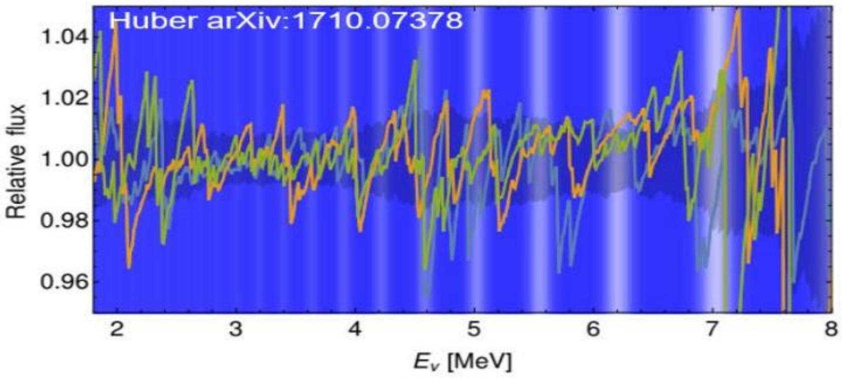
2023.10
1:1 Prototype

2024.11
Installation Starts

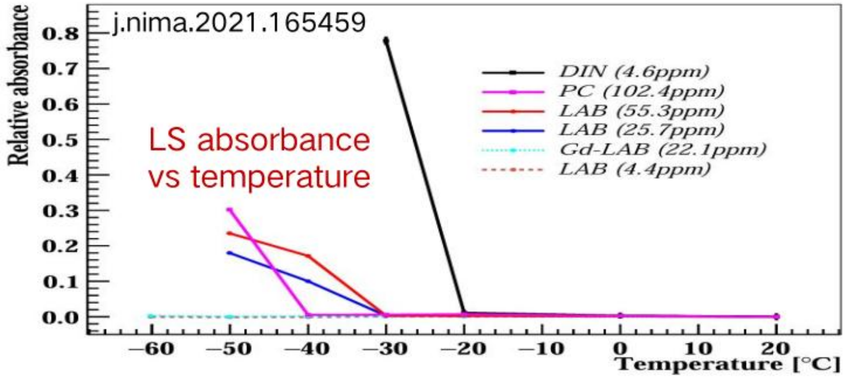
2025.9
Installation Completes

2026.2
Commissioned Data-taking Starts

- Unknown intrinsic fine structures could bias JUNO's neutrino mass ordering (NMO) measurement

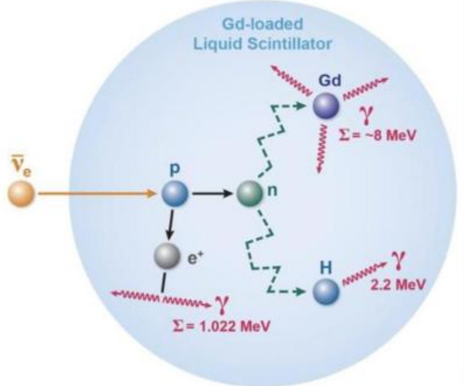


- ☐ LS+PMT (JUNO) → Low-temperature LS + SiPM (TAO)
  - ■ Photo-electron yield (PE/MeV) ~4500 (JUNO ~1700)
  - ■ Low temperature: -50℃, dark count rate: < 100 Hz/mm^2

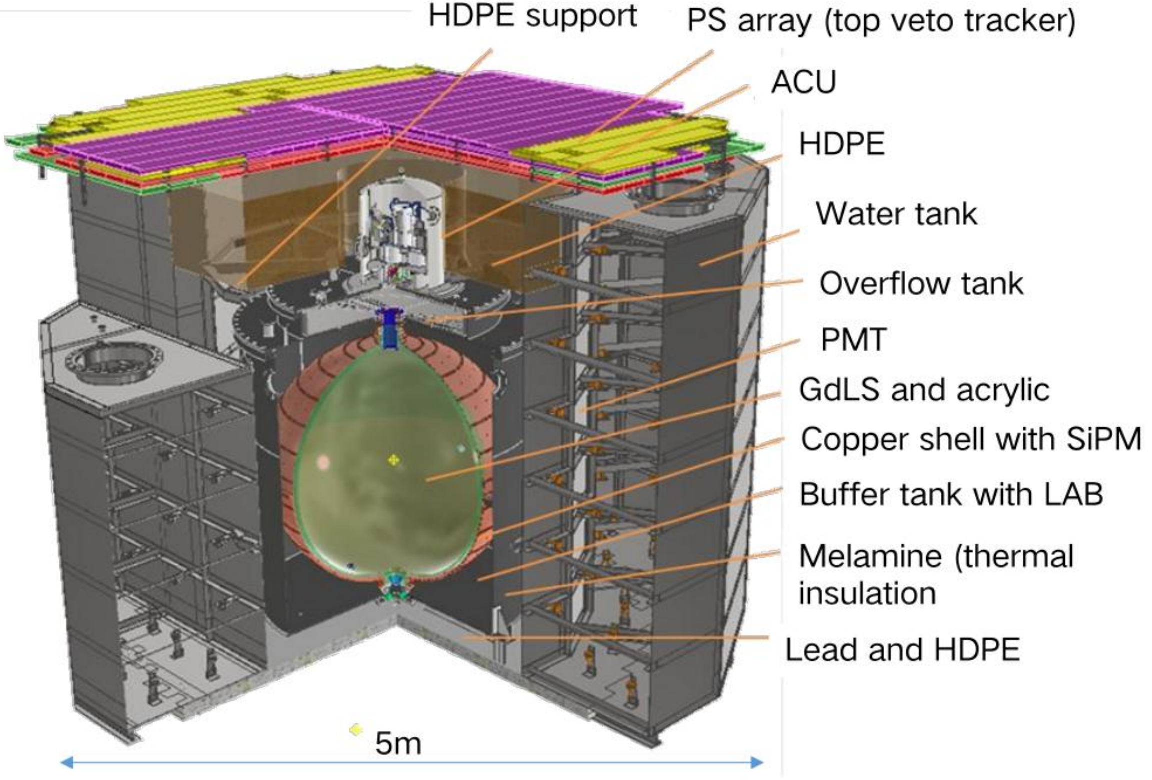


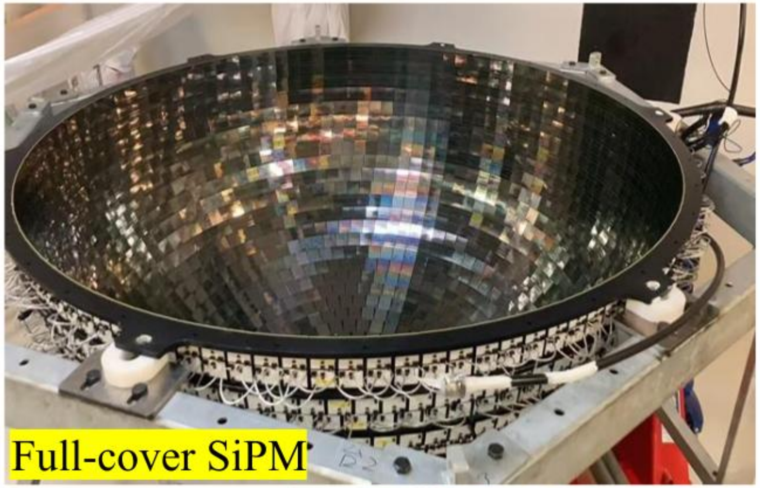
Introduction: Detector Design

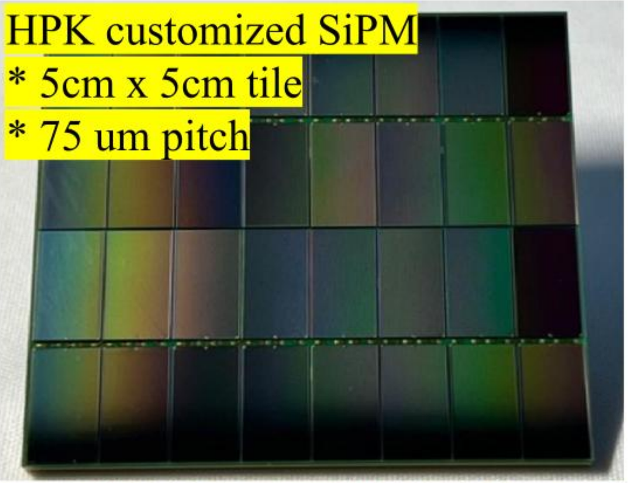
- Central detector (CD)
  - 2.8 t GdLS in an acrylic vessel (∅ = 1.8m)
  - 10 m^2 SiPM on a copper shell
  - Tank filled with buffer LAB
  - Automated Calibration Unit (from Daya Bay) and Cable Loop System
- 2 veto detectors
  - 3 water Cerenkov detectors
  - 4 layers of plastic scintillator bars



- IBD to detect reactor $\overline{\nu}_e$
- neutron captured by Gd

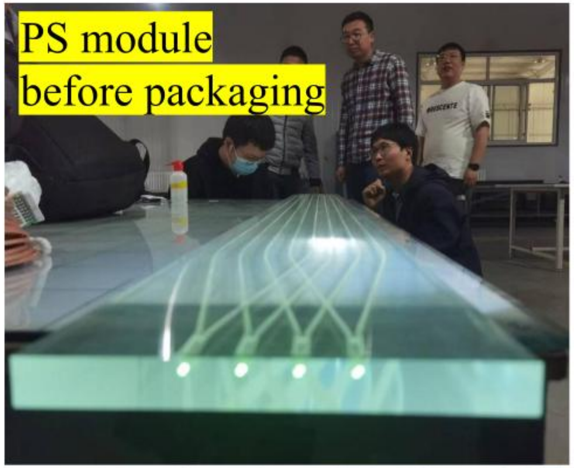




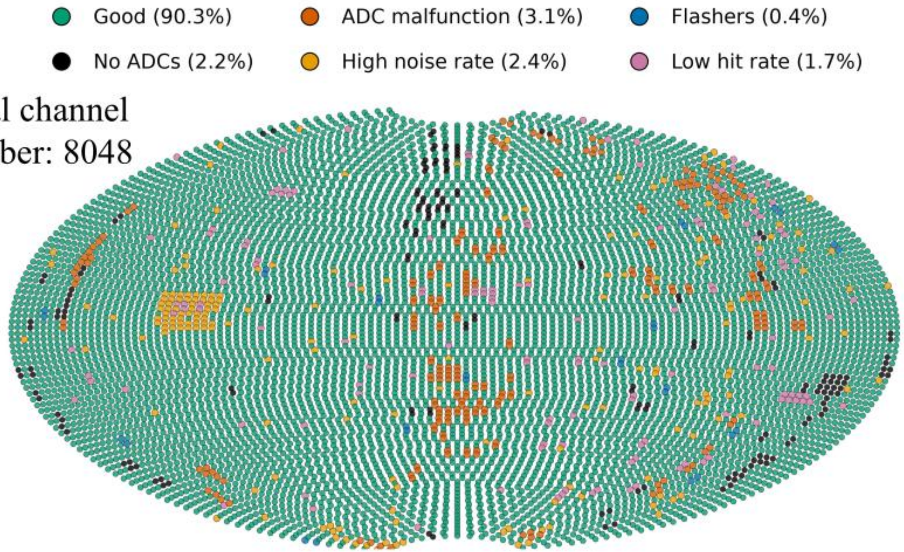


Calibration and Veto Systems

Calibration and Veto Systems

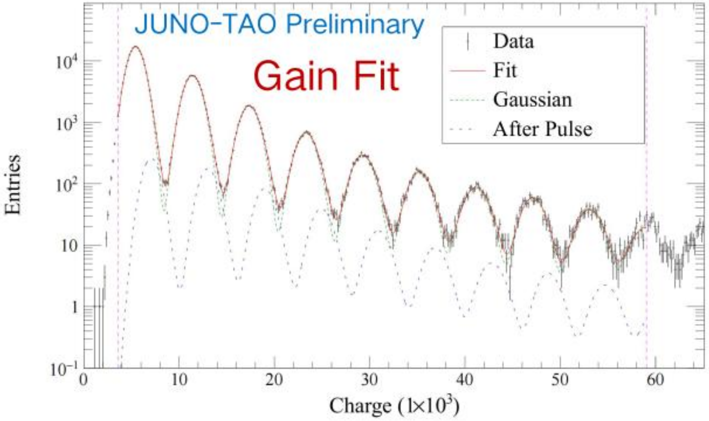


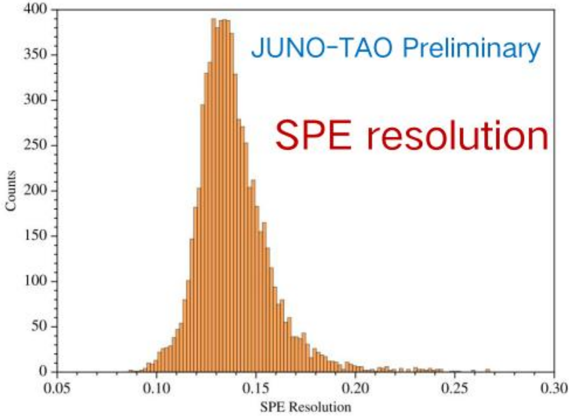
Detector Performance: Channel Calibration



Total channel number: 8048

- **SiPM over voltage V_{ov}**: 3.5 V
- **Gain**: 6000 ± 130 LSB, uniformity ~2%, stability: ~0.1%
- **Single photo-electron (SPE) resolution**: ~14% (15% in CDR)
- **DCR**: ~50 Hz/mm^2 (100 Hz/mm^2 in CDR)
- **PDE**: ~50% (SiPM QA/QC), uniformity ~5%

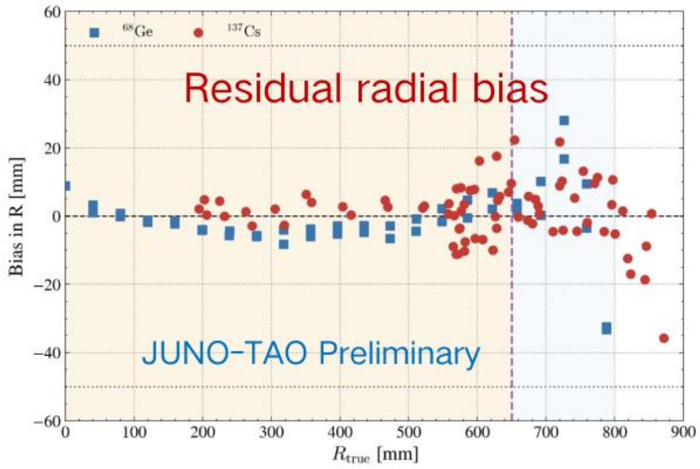


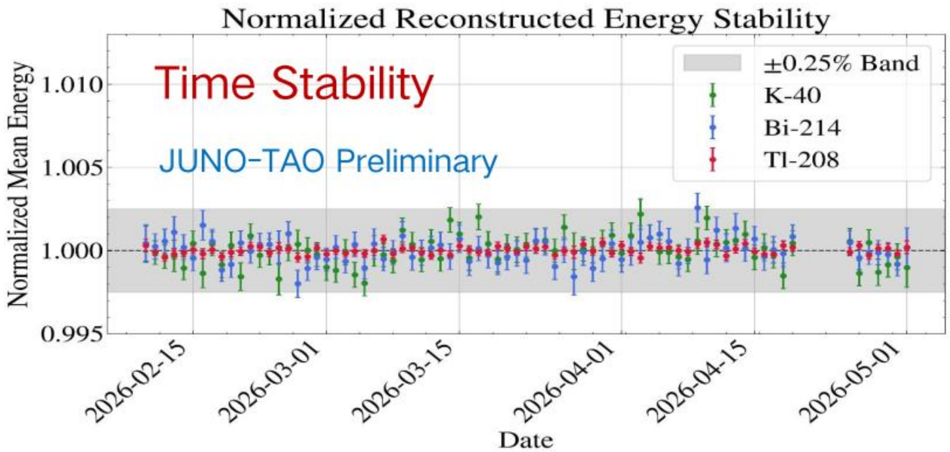


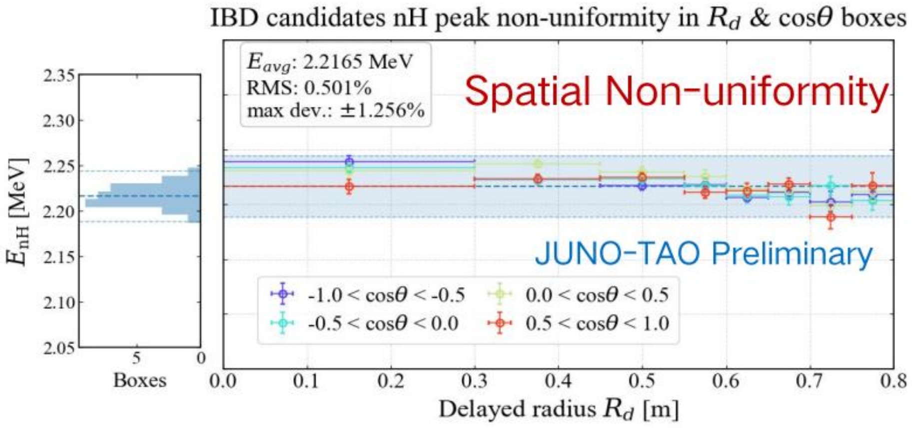
- **Cross-talk**: ~25% (preliminary)
- **After-pulse**: < 5% (SiPM QA/QC)

Detector Performance: Event Reconstruction

- **Procedure**:
  1) PE counting in channel; 2) PE sum in event;
  3) Charge Center method to recontruct vertex
  4) non-uniformity correction (calibration data and Tl-208);
  5) time variation correction (Tl-208);
  6) fix energy scale (nH peak @2.223 MeV)
- **Energy scale performance**:
  time stability < 0.25% (natural radioactive events)
  non-uniformity 0.6% (IBD nH events)

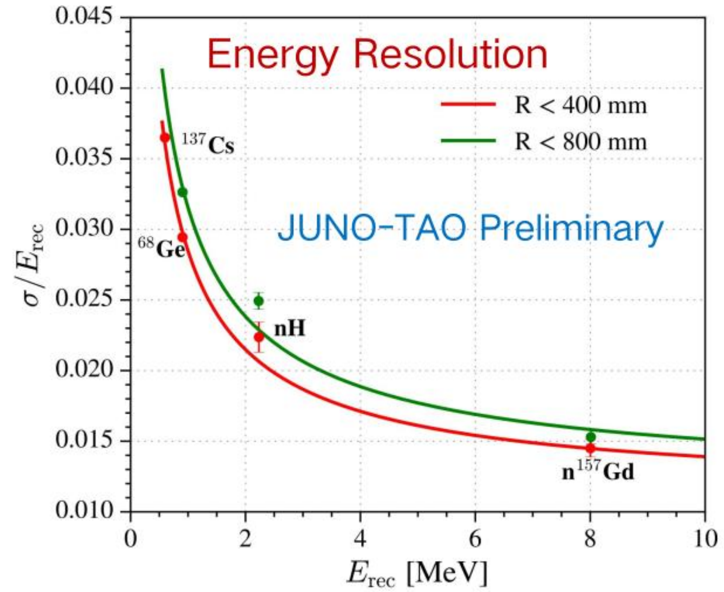


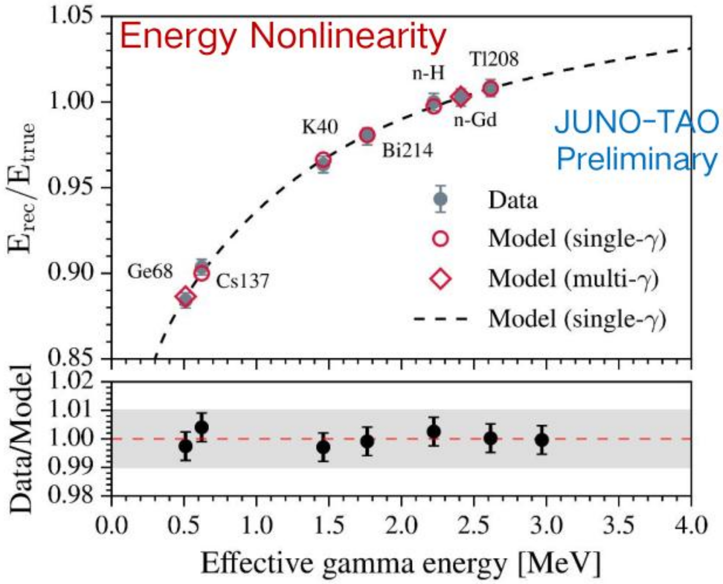


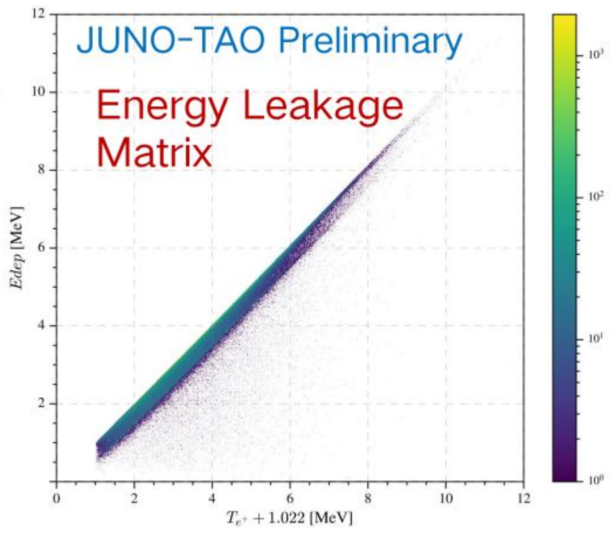


Detector Performance: Energy Response

- **Energy resolution**: 1. **Ge-68 @R = 0**: 2.82% @1MeV; 2. γ curve → e^+ curve using MC
- **Energy nonlinearity**: 1. fit single-γ nonlinearity (NL) model, convert to positron nonlinearity with MC; 2. uncertainty 1~2%
- **Energy leakage**: 1. Generated by MC, validation with CLS Cs-137 MC/data; 2. Shape systematics: fiducial volume uncertainty + energy leakage → IBD prompt spectrum uncertainty

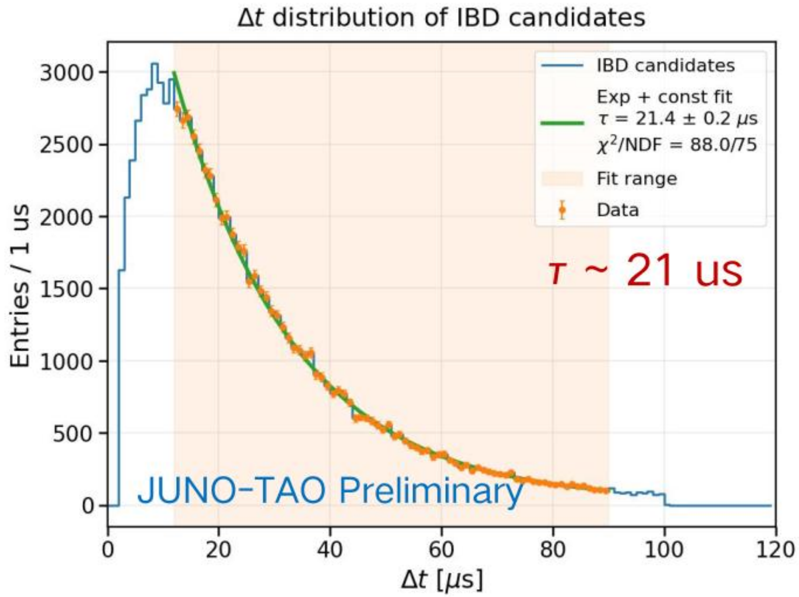


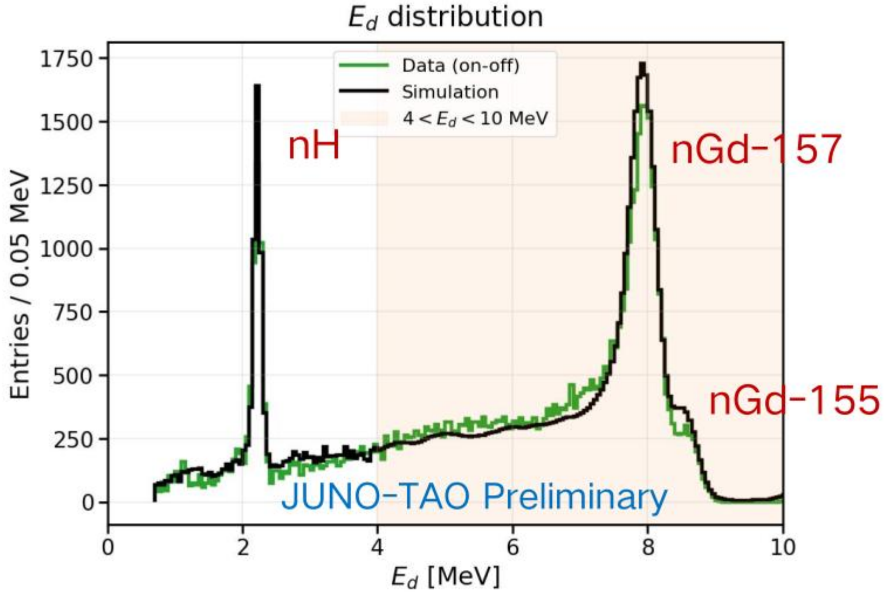




IBD Analysis: Time / Distance / Energy Cut

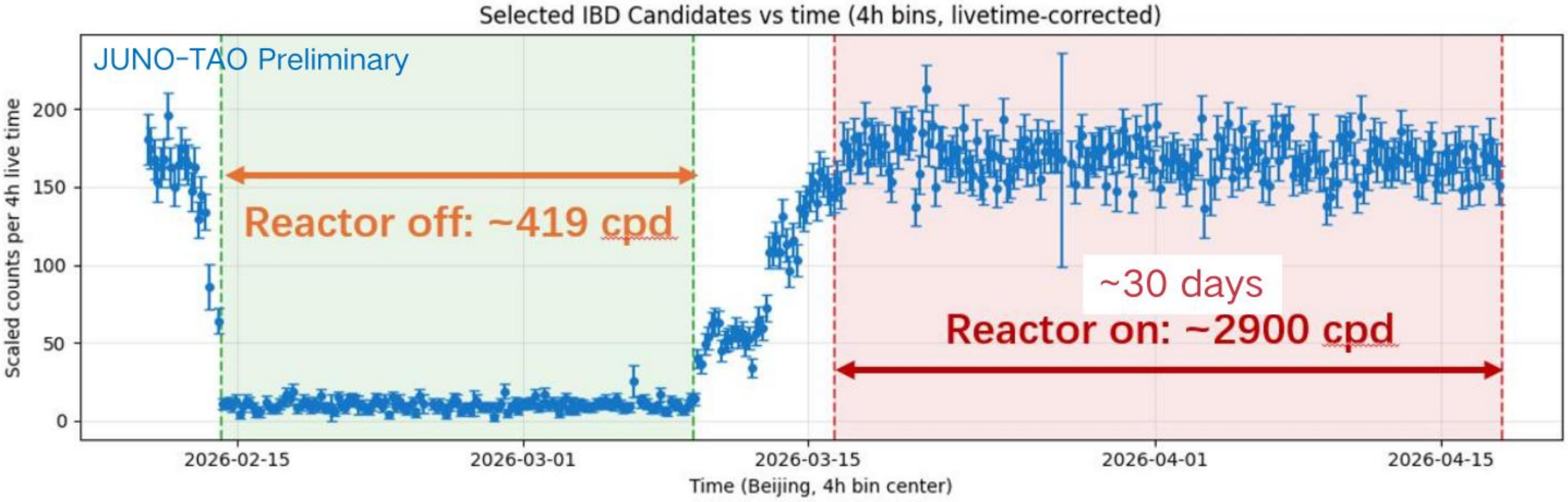
- **Time**: ΔT(prompt, delayed) in (2, 100) us time window, veto events in (0,100) us after muon
- **Space**: ΔR(prompt, delayed) < 500 mm, R(prompt) < 800 mm (Fiducial Volume Cut)
- **Energy**: E(delayed) in (4,10) MeV
- **Total efficiency**: 46.6 ± 5.0 %, **systematics**: FV cut on R(prompt), energy cut on E(delayed)





IBD Analysis: Observed IBD Signal Rate

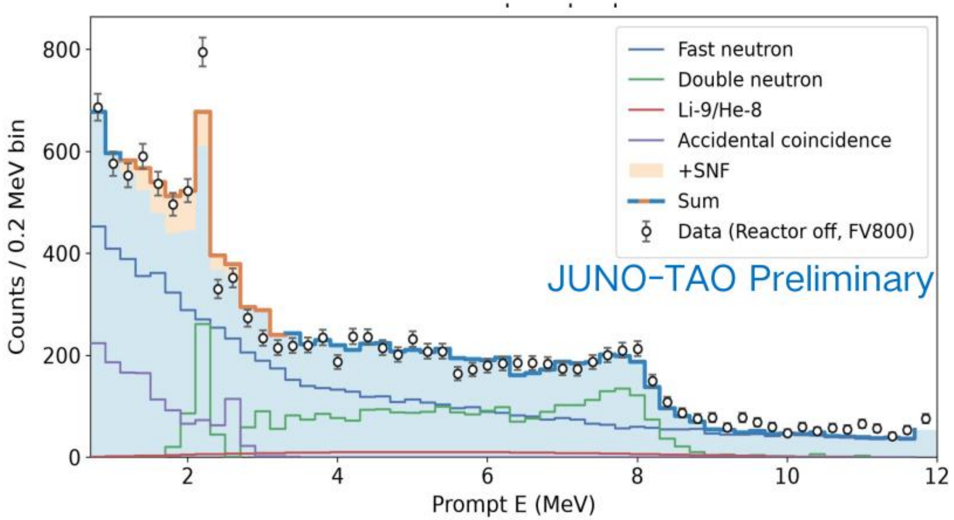
- **Observed IBD signal rate**: ~2500/day, from reactor-on data minus (scaled) reactor-off data.
- **S:B = 6:1 w/o PSD (pulse shape discrimination)**,
  - Really good for shallow overburden experiment
  - could be improved in future



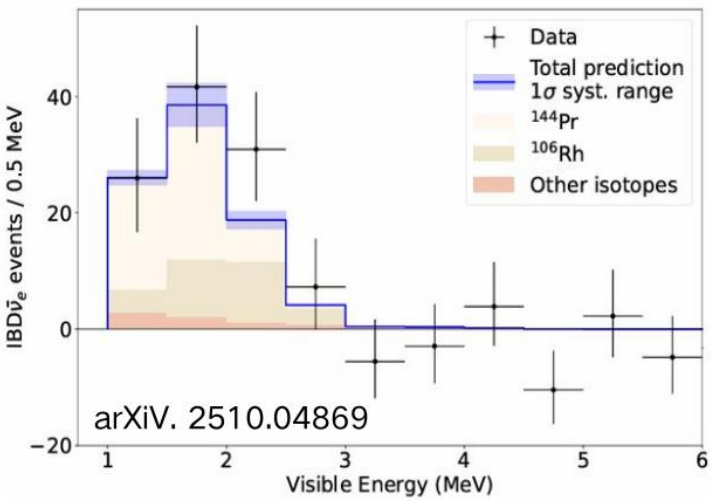
IBD Analysis: Reactor-off & SNF Neutrino

- **Direct measurement of background**
- **Direct measurement of spent nuclear fuel (SNF) neutrino**
  - Background: date-driven estimation except for Li-9/He-8, can be further suppressed
  - Remote reactor OFF makes SNF neutrino signal more clear

TAO Reactor-off Data

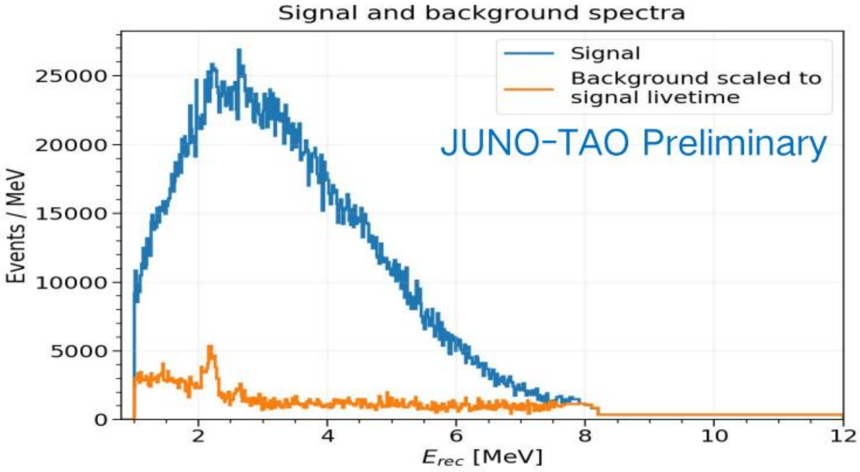


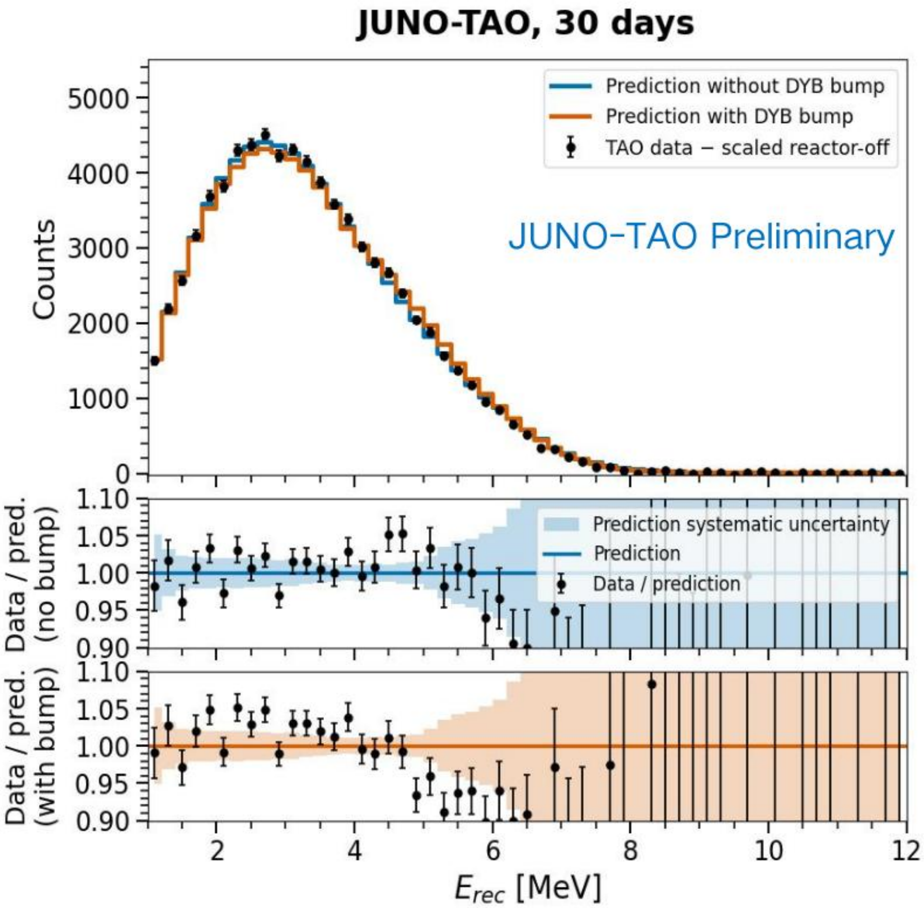
SNF neutrino observed by Double Chooz



IBD Analysis: Prompt Event Energy Spectrum

- **Prediction**: Huber-Mueller model (PRC, 83:054615, 2011, PRC, 84:024617, 2011) + Daya Bay correction (PRL 123(11):111801, 2019) + non-equillibrium correction, convoluted with TAO detector response
- **Results**: good data/prediction agreement, sign of 5 MeV bump, small difference in high energy tail





Summary

- TAO detector is constructed and in stable operation since Feb. 10th, 2026
- World leading energy resolution 2.8% @Ge-68, further improvements expected
- Excellent background control, further background suppression expected
- Preliminary IBD analysis with 1 month data, good data/prediction agreement

  → spectrum used in JUNO physics analysis (JUNO OA Talk later)