The JUNO Detector and its Physics Results

NNN26 · 25th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

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On behalf of the JUNO Collaboration



Chung-Ang University, Seoul, Republic of Korea · October 28–30, 2026

JUNO Project and the Collaboration

- **Project firstly approved in China in 2013 and later in other countries. Civil construction started in 2015.**
- **Collaboration established in 2014, now >700 collaborators from 70 institutions in 16 countries/regions.**

Country	Institute	Country	Institute	Country	Institute
Armenia	YerPhI	China	SDU	Italy	INFN-CT
Belgium	ULB	China	SJTU	Italy	INFN-FE
Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile	UNAB	China	SYSU	Italy	INFN-MI
China	BISEE	China	THU	Italy	INFN-MIB
China	CDUT	China	UCAS	Italy	INFN-PD
China	CNPRI	China	WHU	Italy	INFN-PG
China	CUGB	China	WuYiU	Italy	INFN-Roma3
China	DGUT	China	XJTU	Pakistan	PINSTECH (PAEC)
China	ECUT	China	XMU	Russia	JINR
China	GXU	China	ZZU	Slovakia	FMFI-UK
China	HIT	Czech	Charles U.	Taiwan-China	NCTU
China	HunanU	Finland	JyU	Taiwan-China	NKNU
China	IGGCAS	France	CPPM	Taiwan-China	NTU
China	IHEG-CAGS	France	IJCLab	Taiwan-China	NTUT
China	IHEP	France	IPHC	Thailand	CHULA
China	IMP	France	LP2iB	Thailand	NARIT
China	JNU	France	Subatech	Thailand	SUT
China	JXNU	Germany	EKUT	U.K.	U. Liverpool
China	KNRC	Germany	GSI	U.K.	U. Warwick
China	Nankai U.	Germany	U. Hamburg	USA	UC-Irvine
China	NCEPU	Germany	JGUMainz	USA	UMD-G
China	NJU	Germany	RWTH-AC		
China	RNCG	Germany	TUM		

+Observers: USTC, Peking Uni., Jilin Uni., Beijing Normal Uni., CIAE (China), PUC, UEL (Brazil)

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Outline

01 Detector Design & Performance

JUNO overview, central detector, veto system, TAO satellite, current status

02 Latest Physics Results

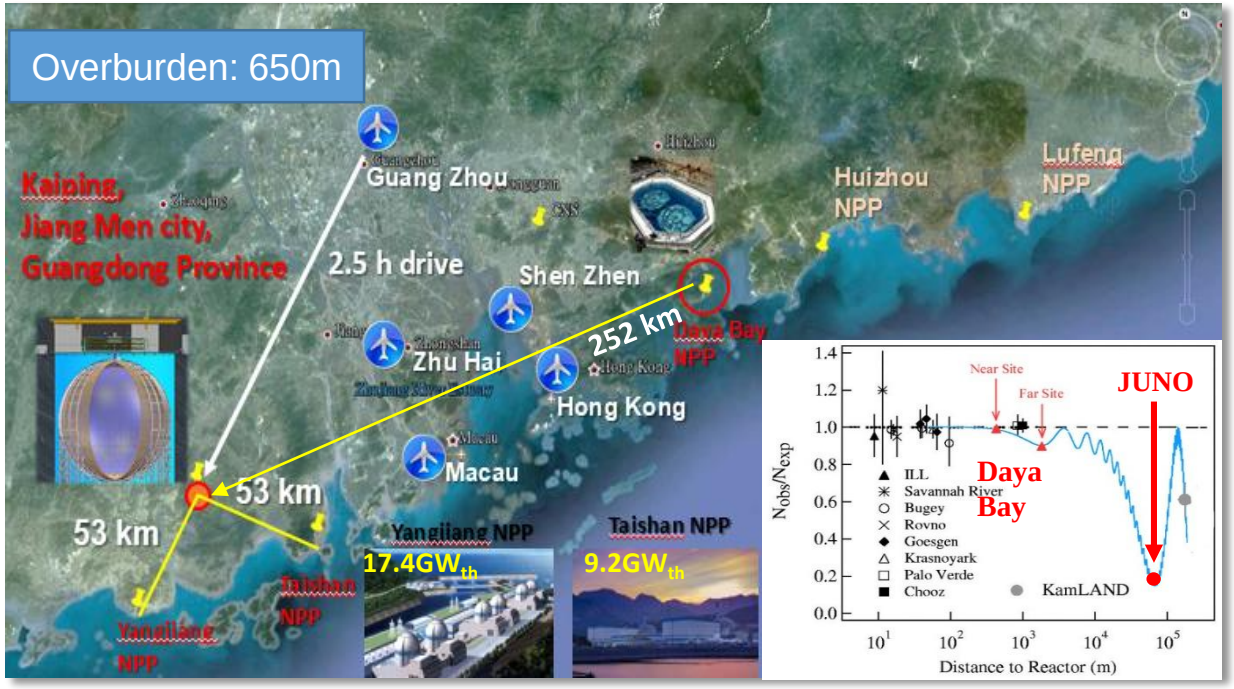
Reactor antineutrinos, mass ordering, geo-neutrinos

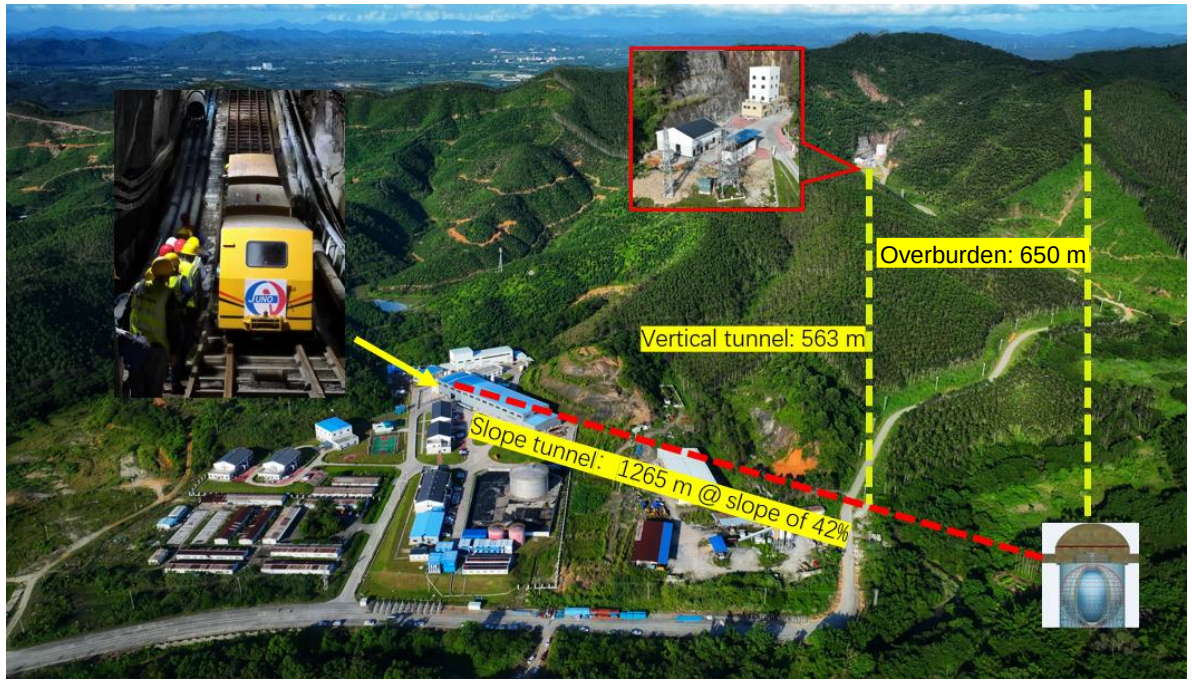
03 Upgrade Plans & Future Program

0νββ searches with isotope loading

01 Detector Design & Performance

JUNO: Location & Primary Physics Goal



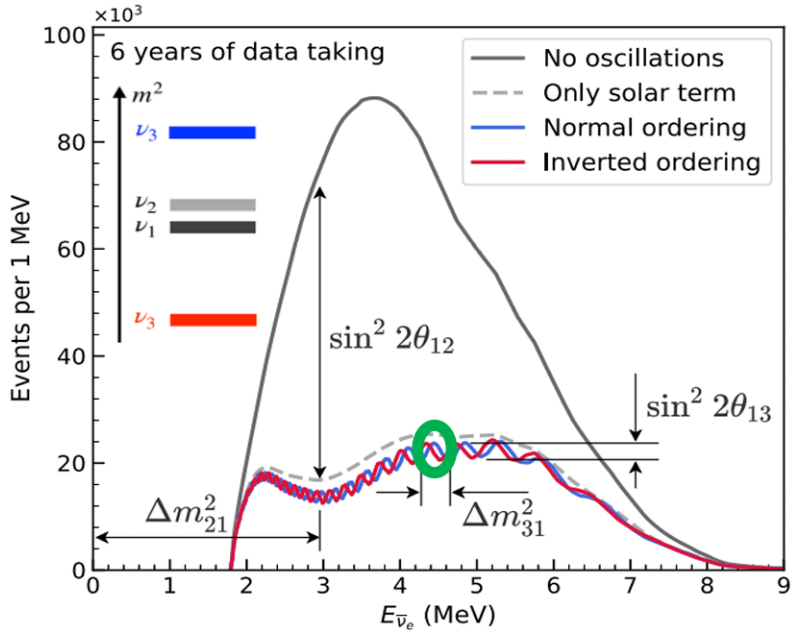


- ✓ Use reactor neutrinos to determine the mass ordering (sign of Δm^2_{32}), independent of matter effects and CP phase;
- ✓ Equal distance to two reactor power plants for doubling the ν flux;
- ✓ With an overburden of 650 m, reducing the muon rate to 4 mHz/m^2 with an average energy of 207 GeV;

JUNO: An unique approach to determine neutrino mass ordering

KEY PARAMETERS

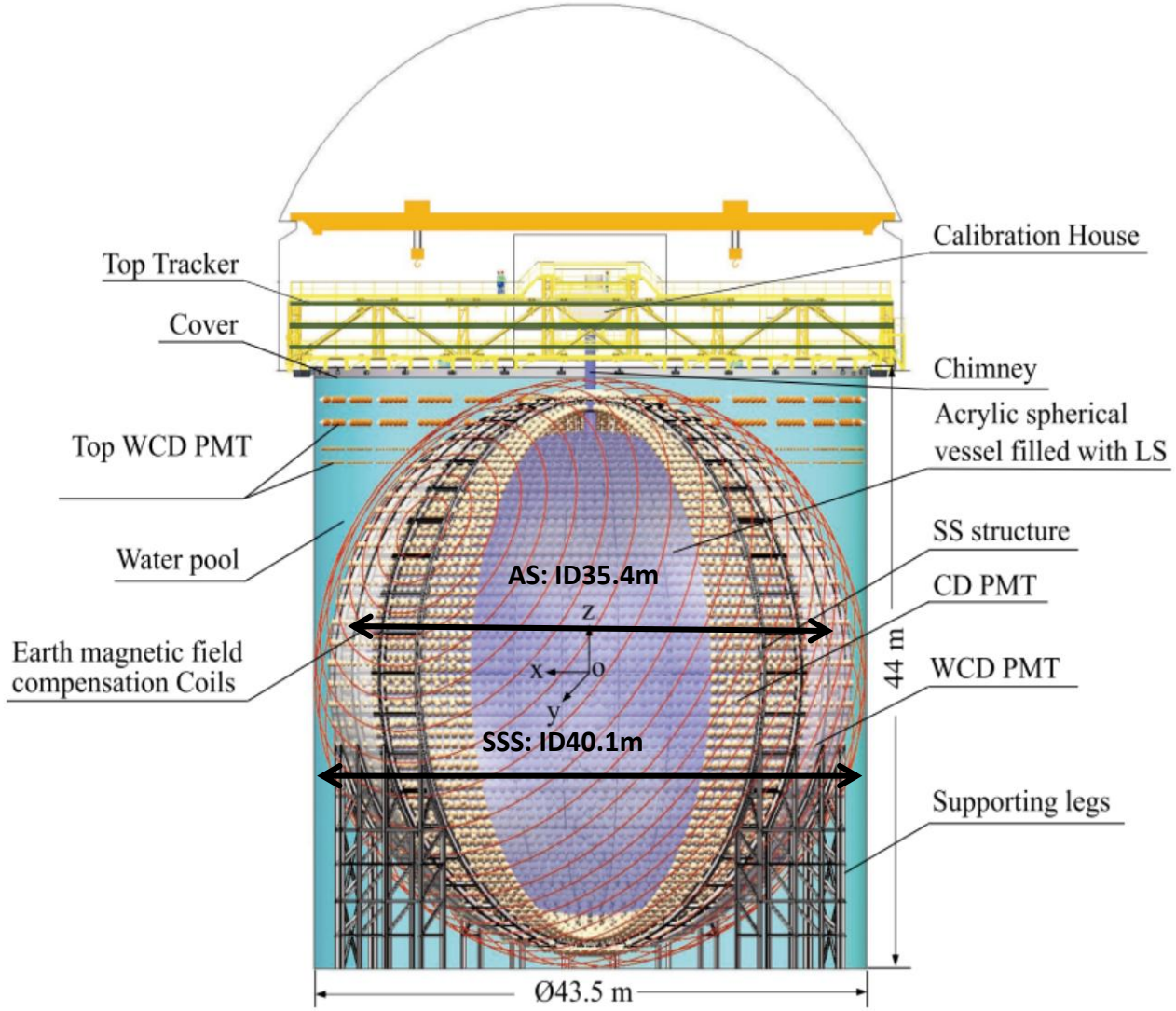
- Large statistics
  - ✓ 20 ktons of LS
- 3%@1MeV energy resolution
  - ✓ LS light yield >1200 P.E./MeV
  - ✓ LS attenuation length > 20m
  - ✓ PMT coverage 75%
- 1% energy scale uncertainty
  - ✓ Four complementary calibration systems
- Low background
  - ✓ A "clean" central detector
  - ✓ Veto detector



$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

JUNO Detector

- Central Detector:
  - ✓ 20 ktons of LS + Acrylic Sphere;
  - ✓ 17612 20” PMT + 25600 3 ” PMT;
    - ➢ Coverage: 78%;
- Veto Detector:
  - ✓ Water Cherenkov detector
    - ➢ 41 ktons of ultrapure water;
    - ➢ 2404 20” PMT + 348 20” PMT + 600 8” PMT;
    - ➢ Earth magnetic field compensation coils;
  - ✓ Top tracker detector
    - ➢ Plastic scintillator covering ~half of the WP;



Liquid scintillator



1) Al_2O_3 for optical transparency



2) Distillation for radiopurity

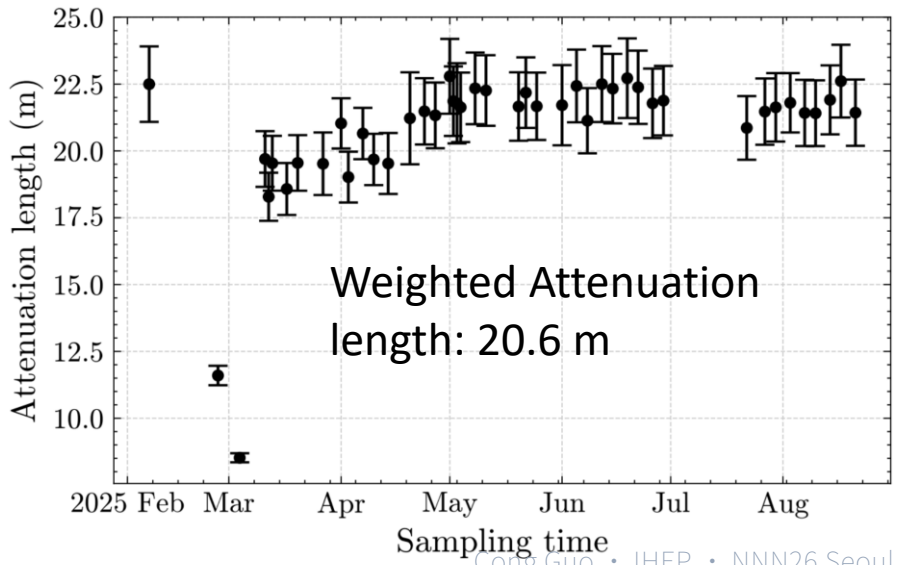


3) Water extraction to remove radioactive impurities

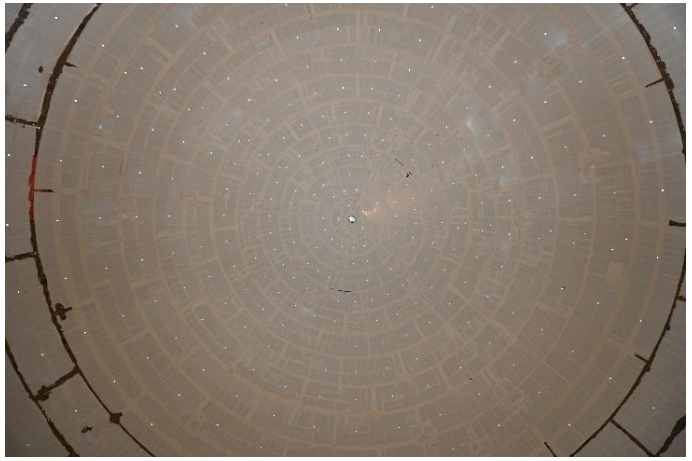
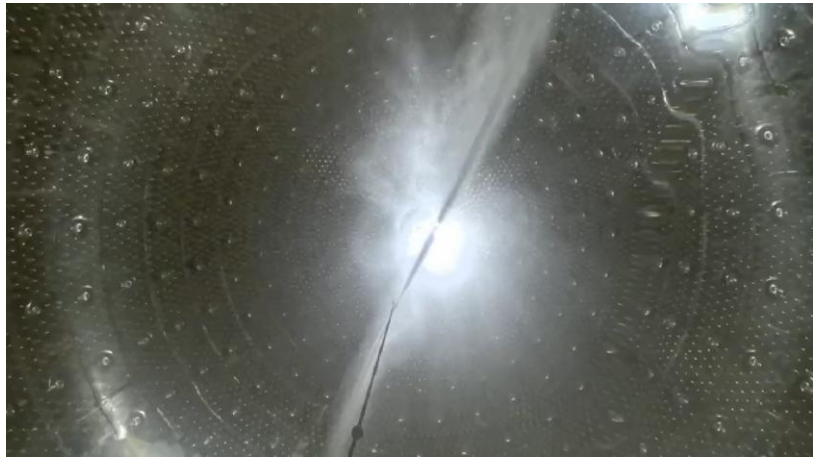


4) Gas stripping to remove Rn and O_2

- For optimal transparency and light yield:
  - ✓ Recipe: LAB + 2.5g/L PPO + 3 mg/L bis-MSB + 0.005% BHT;
  - ✓ Production: Four purification plants + LS Mixing ;
  - ✓ Auxiliary device: HPN plant + UPW system;
  - ✓ Background: U/Th < 10^{-16}g/g, Rn<1mBq/m^3;

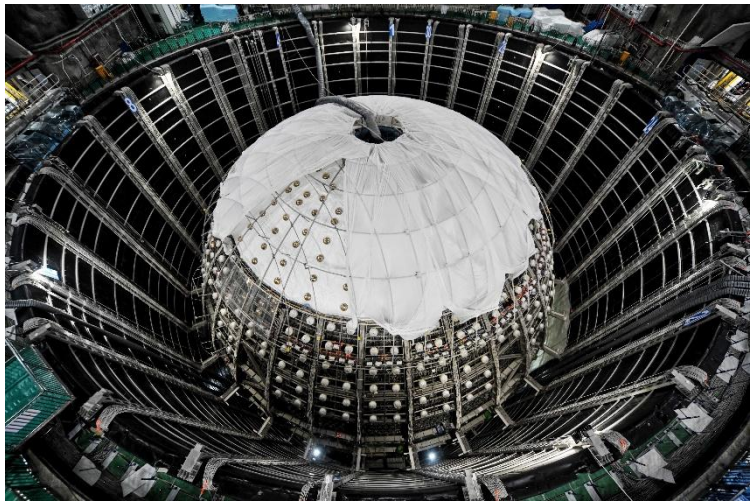


Central detector

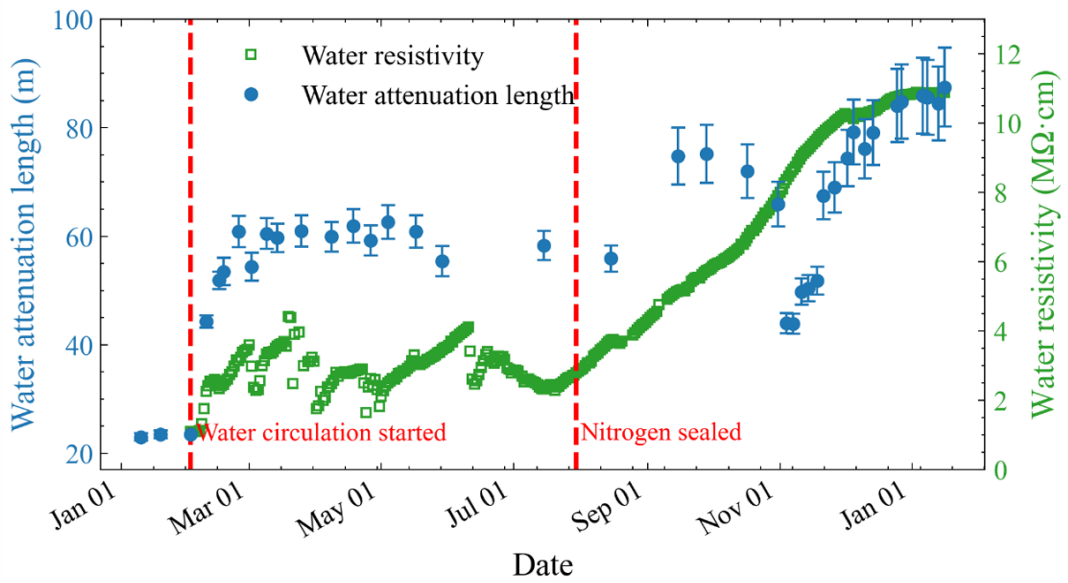




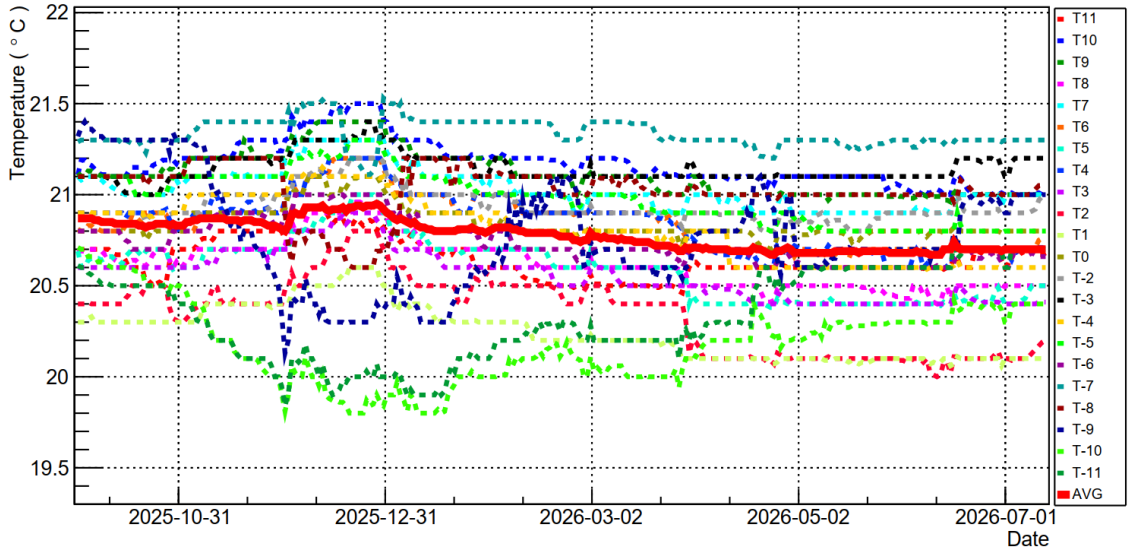
- 263 Acrylic panels thermally pressed and machined to the spherical shape, bonded together in-situ through PMMA polymerization;
- SS structure to hold the acrylic tank and PMTs, through steel bars with springs and rotating heads;
- Clearance between PMTs is ~3 mm, to maximize coverage;
- Water soluble paper film on acrylic to stop Rn decay daughters, high-pressured UPW is used to remove dust and paper film before water filling ;
  - Resistivity~18 MΩ*cm, U/Th < 10^{-15} g/g, Rn < 10mBq/m^3 ;

Water Cherenkov detector

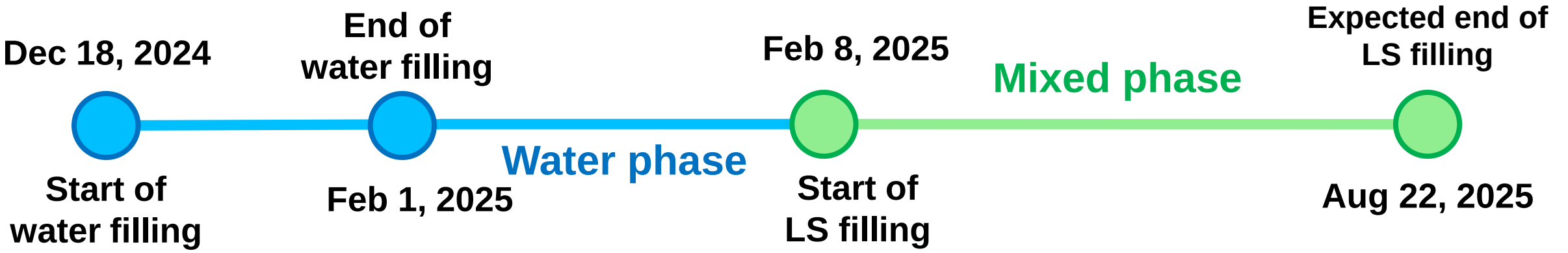


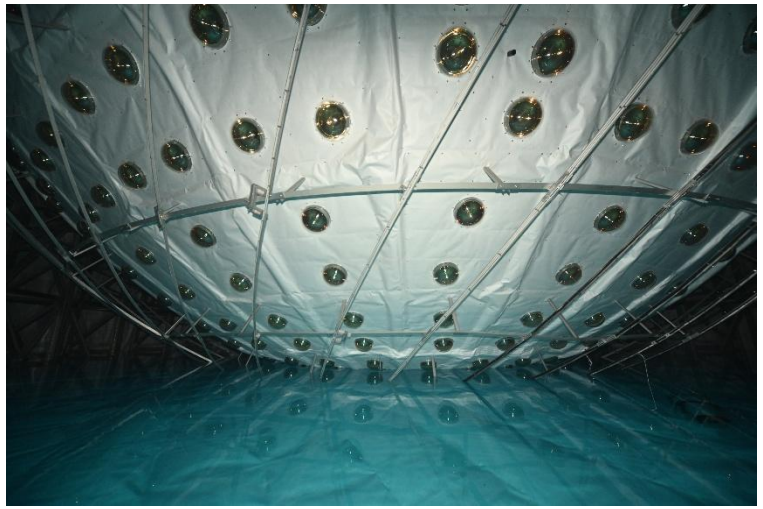
- The WCD uses 41 ktons UPW to tag muon and passive shielding;
- The water in the WCD is circulated and purified by an UPW system at a flow rate of ~100 t/h;
- Muon trigger rate in CD ~5 Hz, in Water Pool (only) ~4 Hz;
- Muon detection efficiency of CD through-going muons > 99.5%;



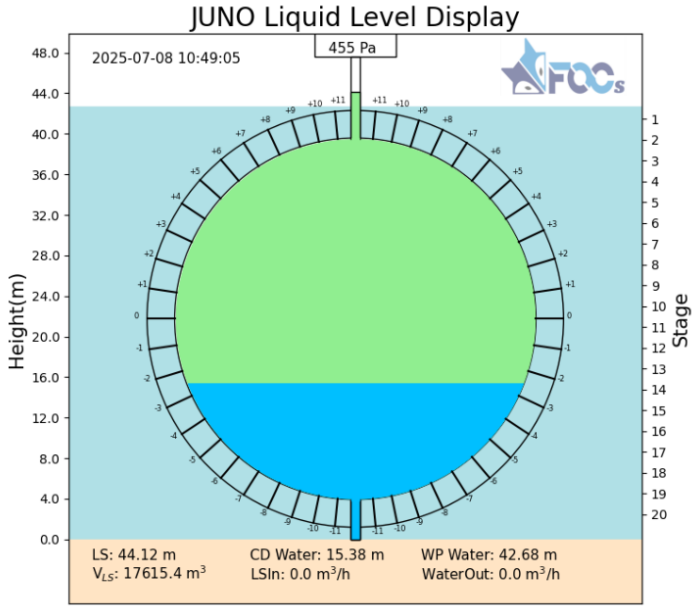


Detector filling



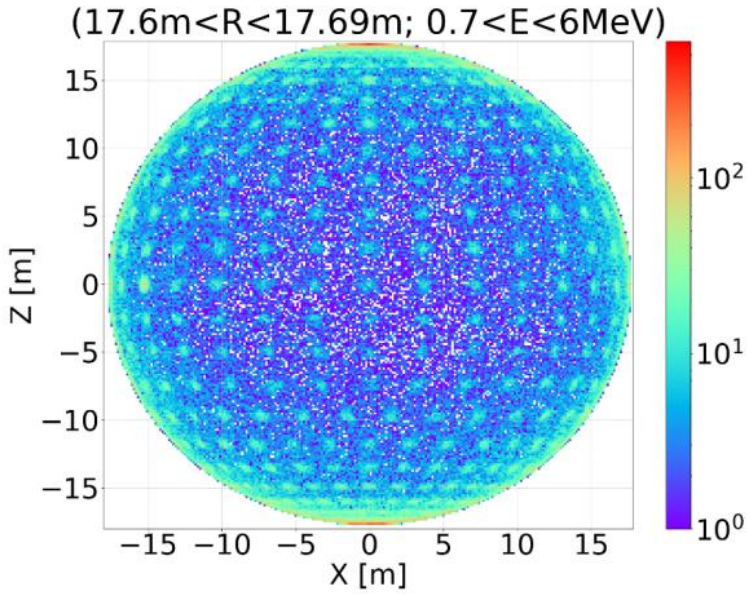


- UPW filled in CD:
  - ✓ $^{226}Ra < 10\ \mu Bq/m^3$;
  - ✓ $^{222}Rn < 10 mBq/m^3$;
- The LS filling speed is 7 m^3/h;
- LS in the CD: 23231.6 m^3 ;
- Water in the pool: 41225.1 m^3;



A very clean detector

- For reactor neutrinos: (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
- LS purity:

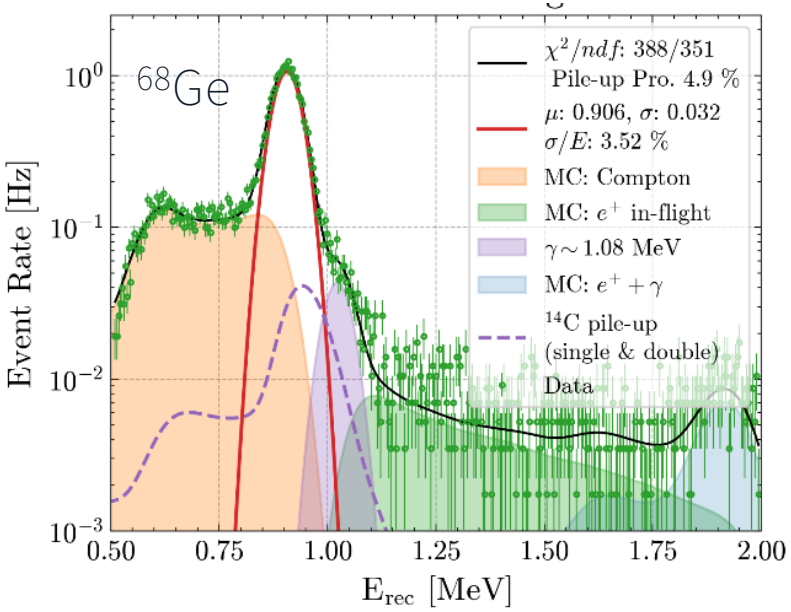


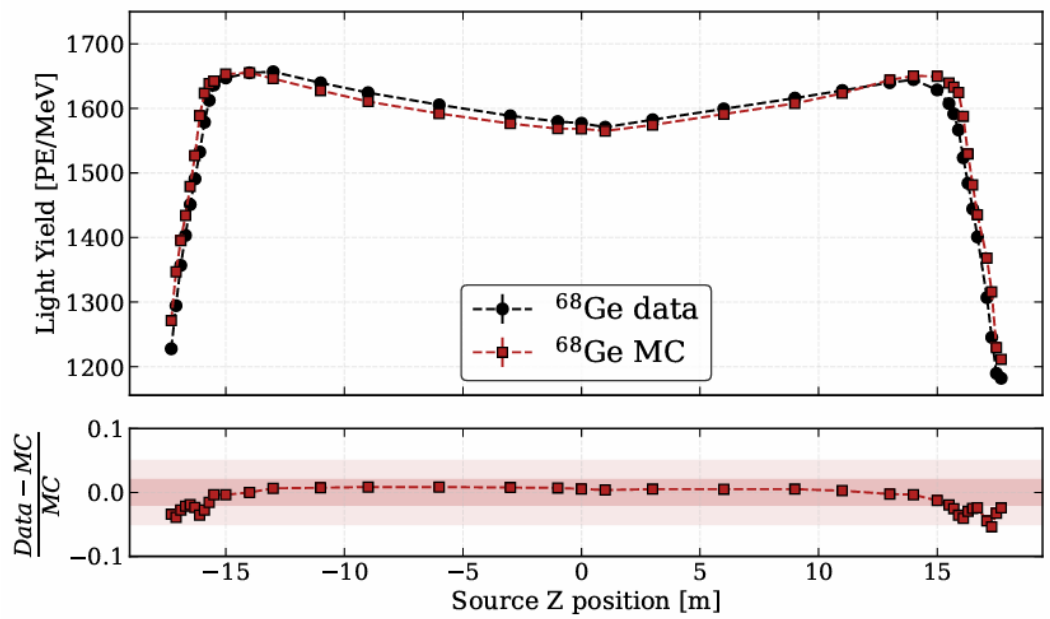
Fiducial volume	^{238}U [10^{-17} g/g]	^{232}Th [10^{-17} g/g]	^{210}Po [10^4 cpd/kt]	
			Initial	Present (Jun. 1)
r < 16.5 m (+ remove top hot spot)	3.6±0.1	1.4±0.1	4.80±0.1	2.0±0.1

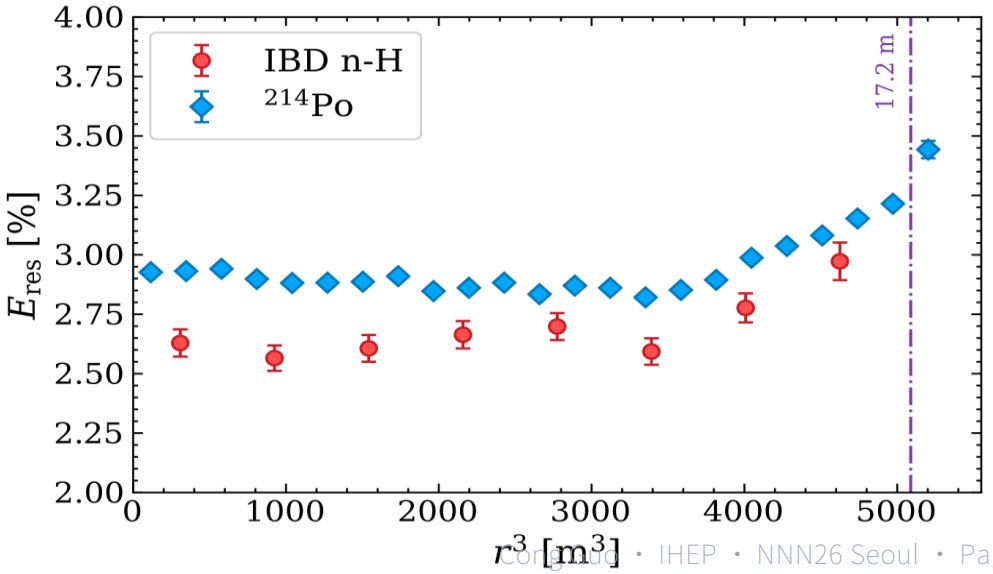
02 Latest Physics Results

Light yield and energy resolution

- Light yield at the detector center is ~1600 P.E./MeV for ^{68}Ge and ~1785 P.E./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%;
- Energy resolution for α from ^{214}Po is ~2.9% @0.93MeV;

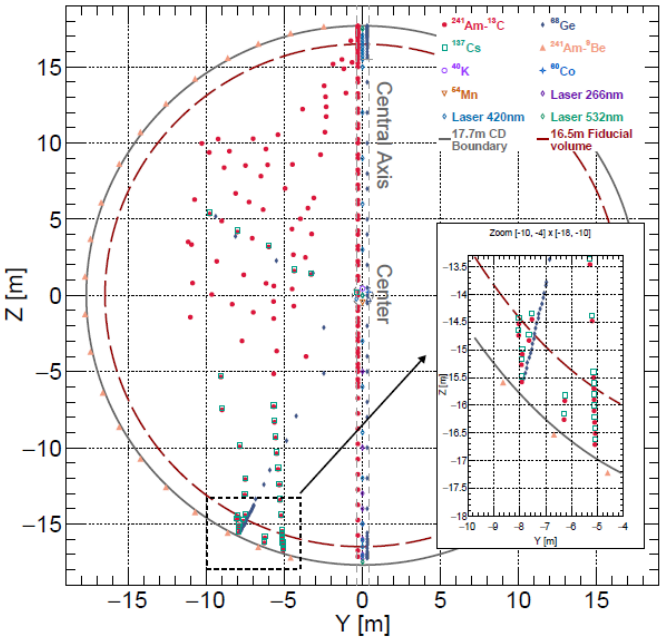


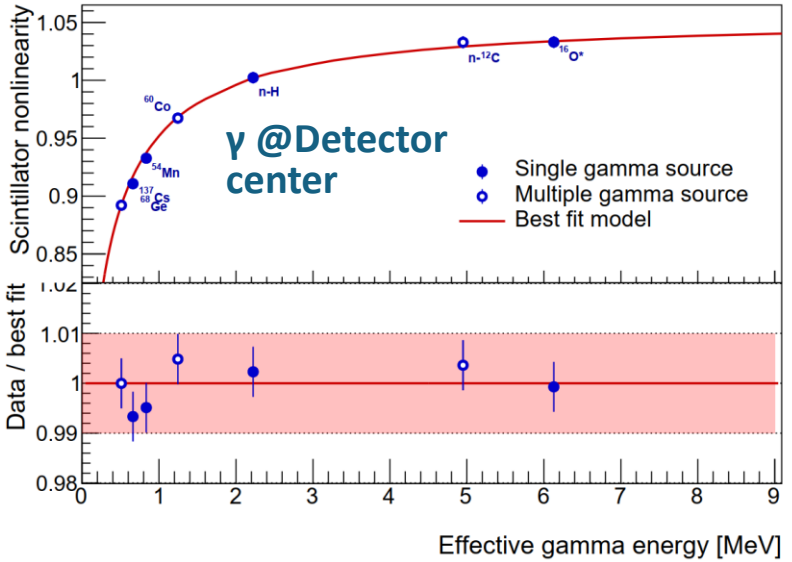




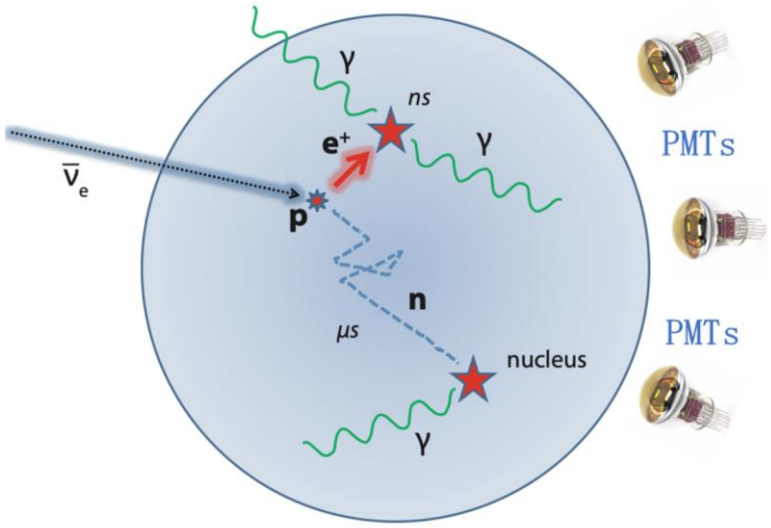
Calibration and energy uncertainty

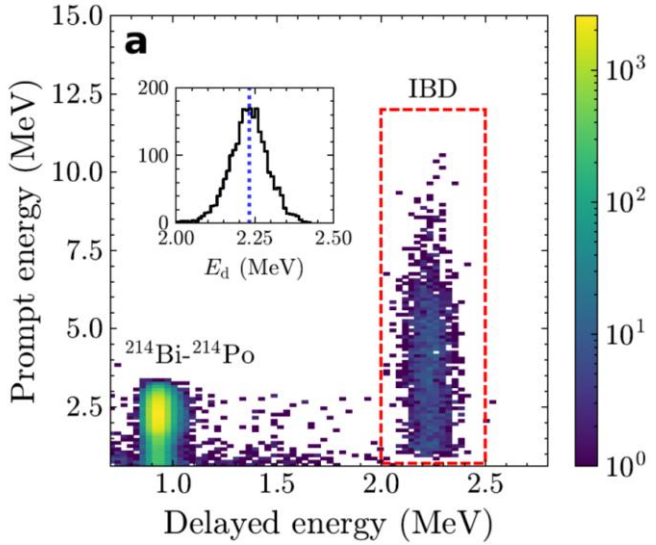
- Four complementary subsystems, Automated Calibration Unit (1D), Cable Loop Systems (2D), Guide Tube Calibration System (2D), and Remotely Operated Vehicle (3D);
- Performed calibration:
  - ✓ 1D (ACU, central axis): ^{137}Cs, ^{54}Mn, ^{40}K, ^{68}Ge, ^{60}Co, Am-C, Am-Be, sensors, laser
  - ✓ 2D (CLS, vertical plane): Am-C, ^{68}Ge, ^{137}Cs
  - ✓ 3D using cosmogenic backgrounds:
    - ➢ Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes
- 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;
- Uncertainty < 1%;

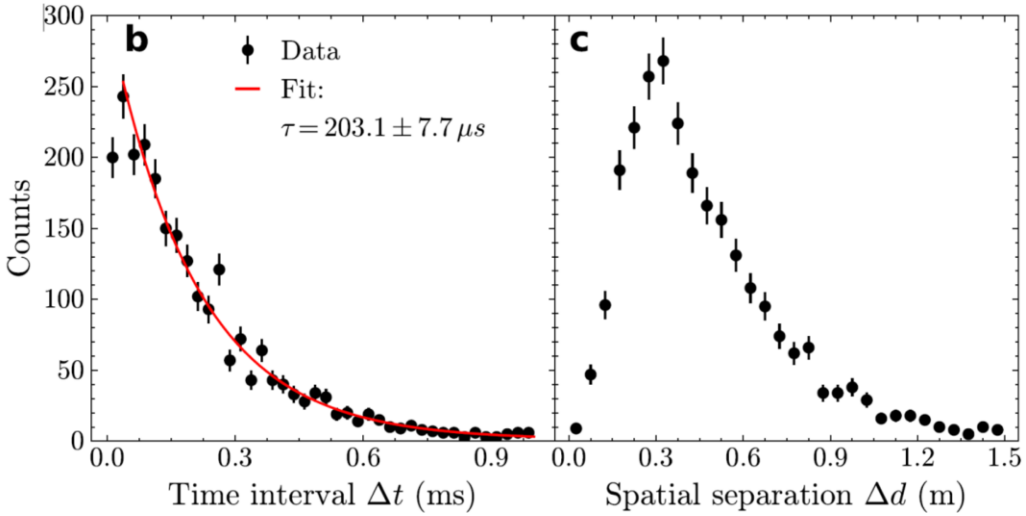


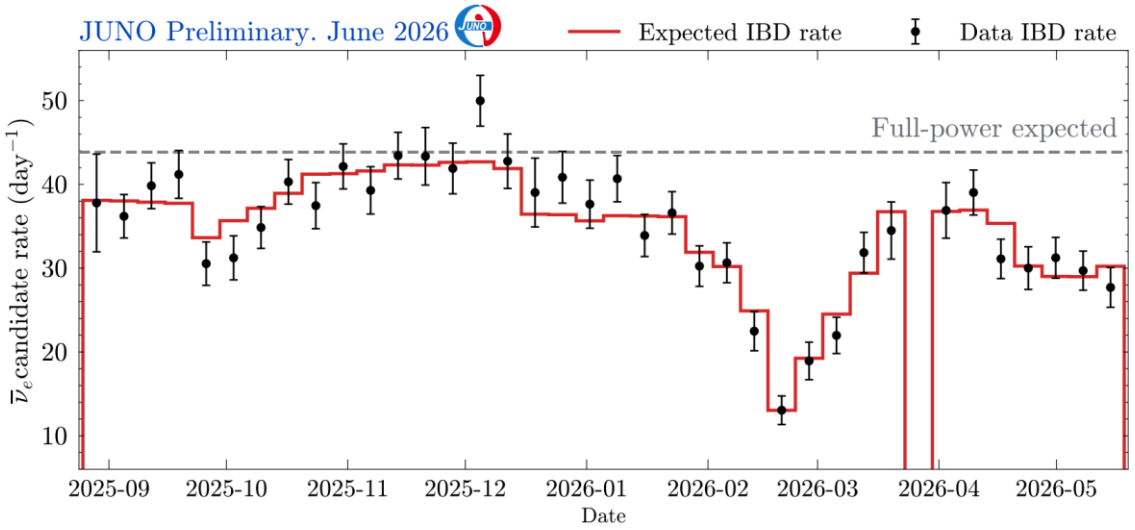


Reactor neutrino selection



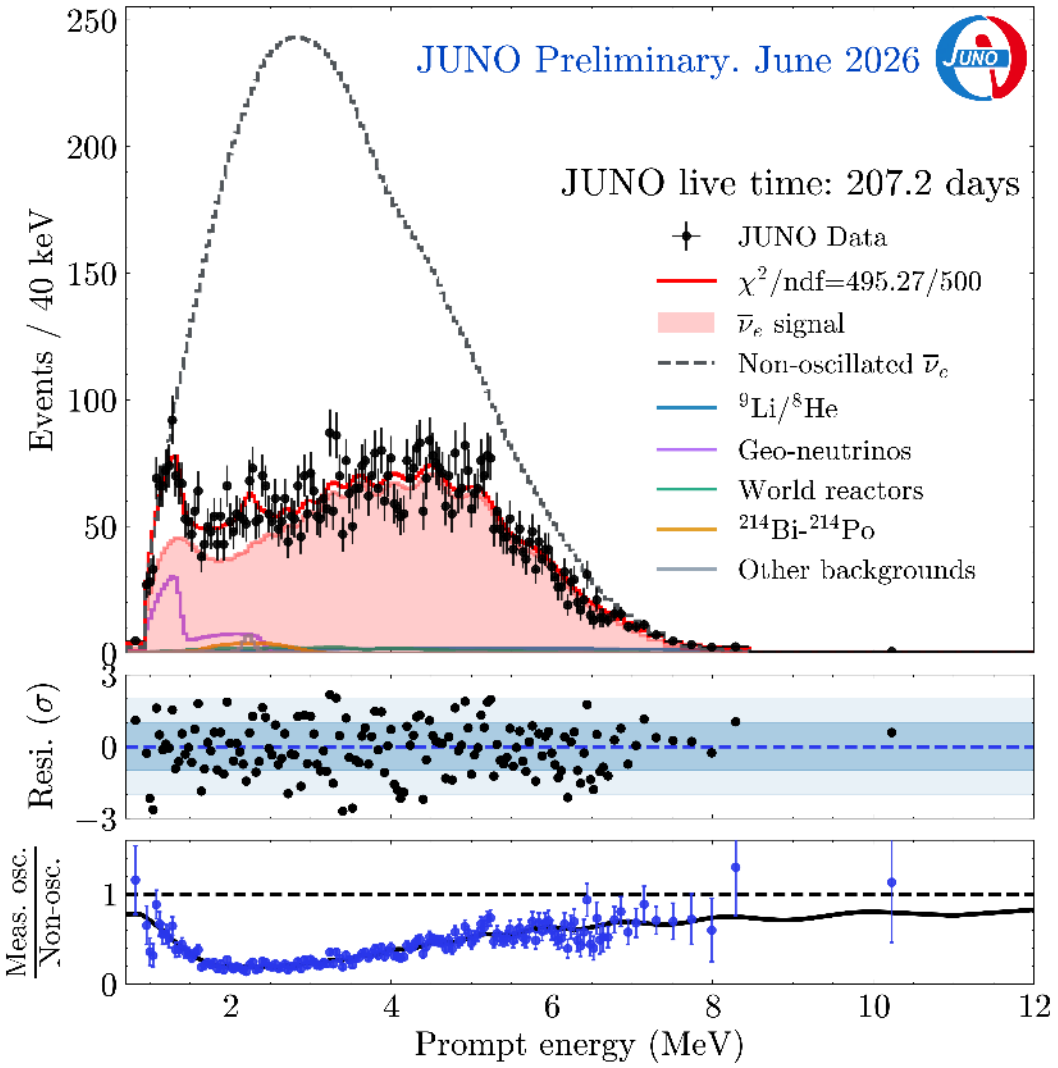






- Prompt and delayed coincidence in time, space with energy features;
- Measured reactor neutrino event rate consistent with expectation;
- Total live time is 207.2 days;

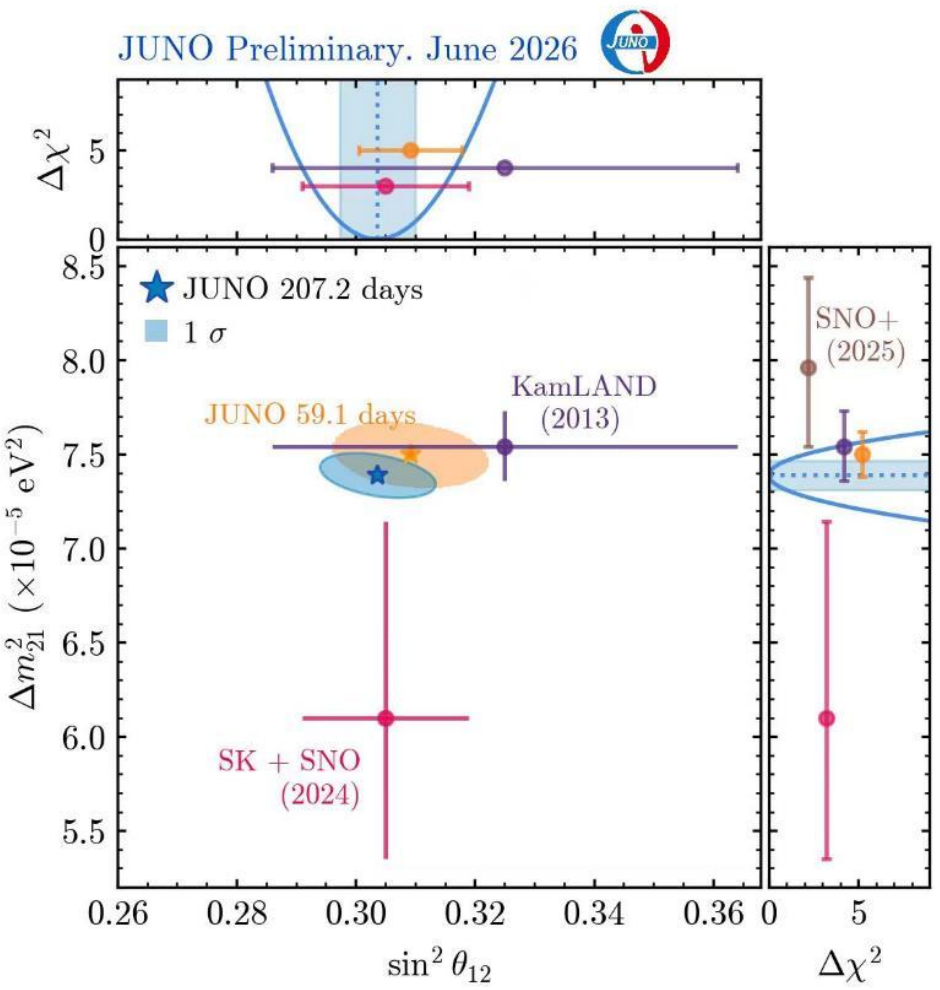
Measured reactor neutrino spectrum



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(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

Fitting constrained by the near detector spectra from JUNO-TAO measurement results and Daya Bay measurement result (PRL 130 16, 161802)

Results of the solar oscillation parameters



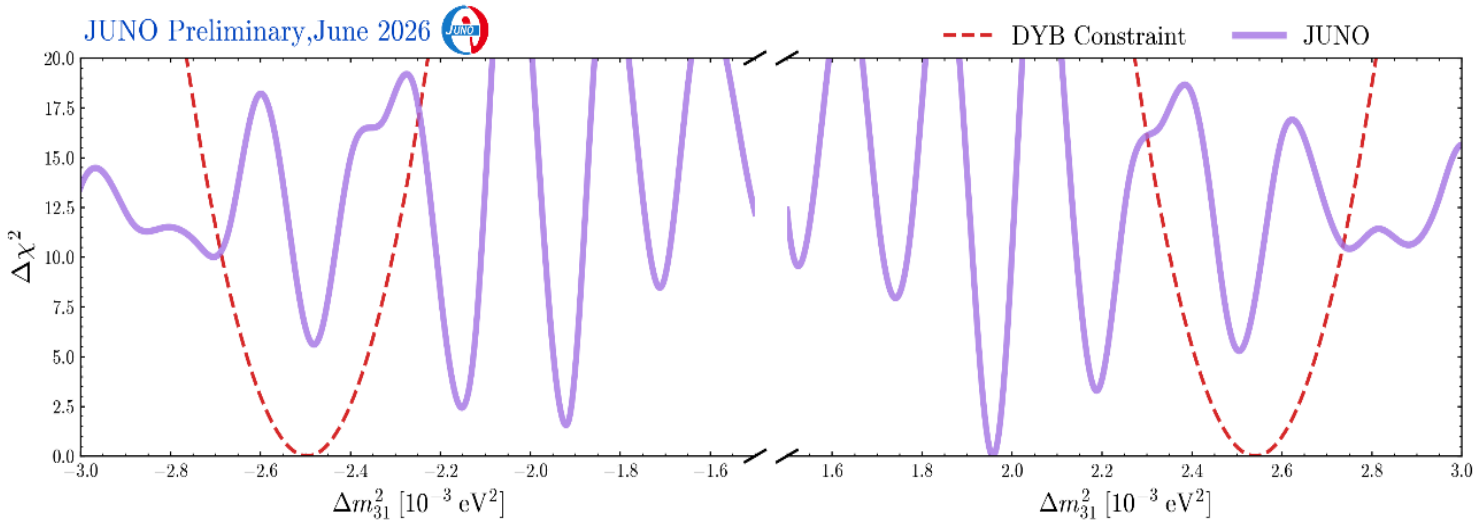
Δm^2_{21}	7.388 ± 0.078 (1.60% → 1.06%)
$\sin^2\theta_{12}$	0.3036 ± 0.0064 (2.8% → 2.1%)

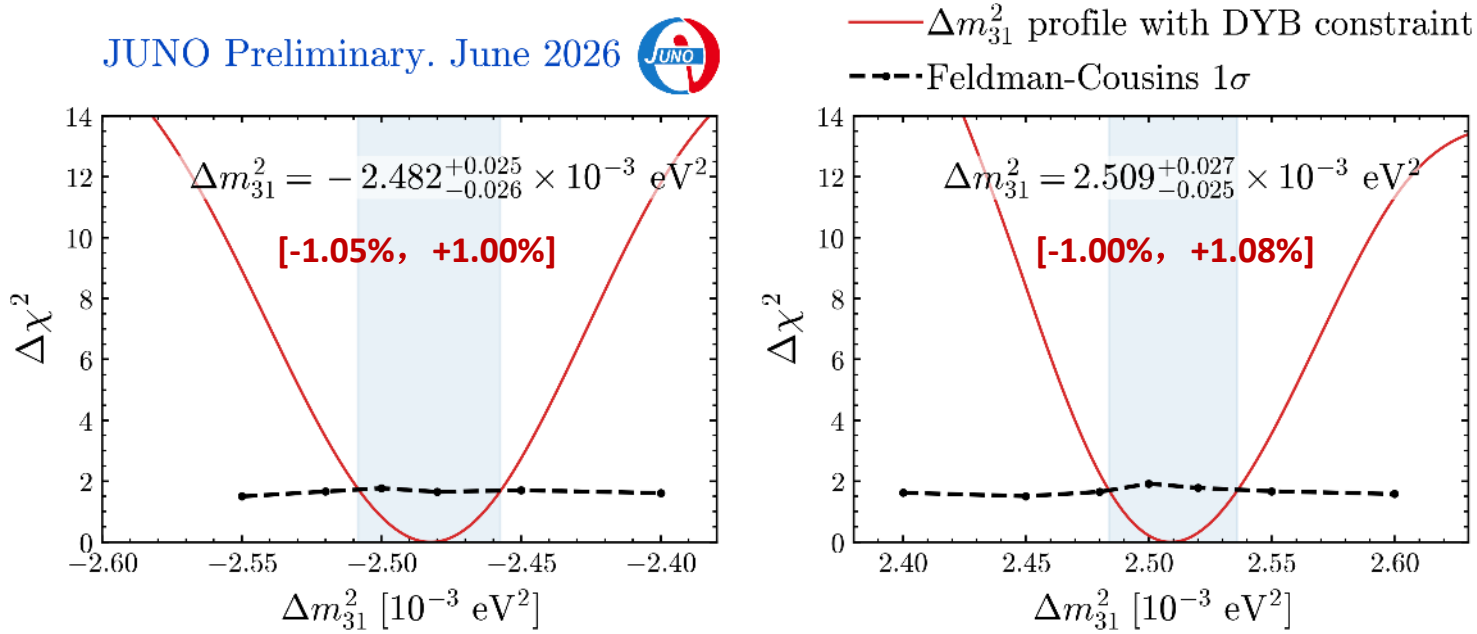
- Even though the statistical uncertainty is dominant, systematic errors become important:
  - ✓ ^{214}Bi bkg. and detection eff. can be improved

$\sin^2\theta_{12}$	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

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

Result of Δm^2_{31}

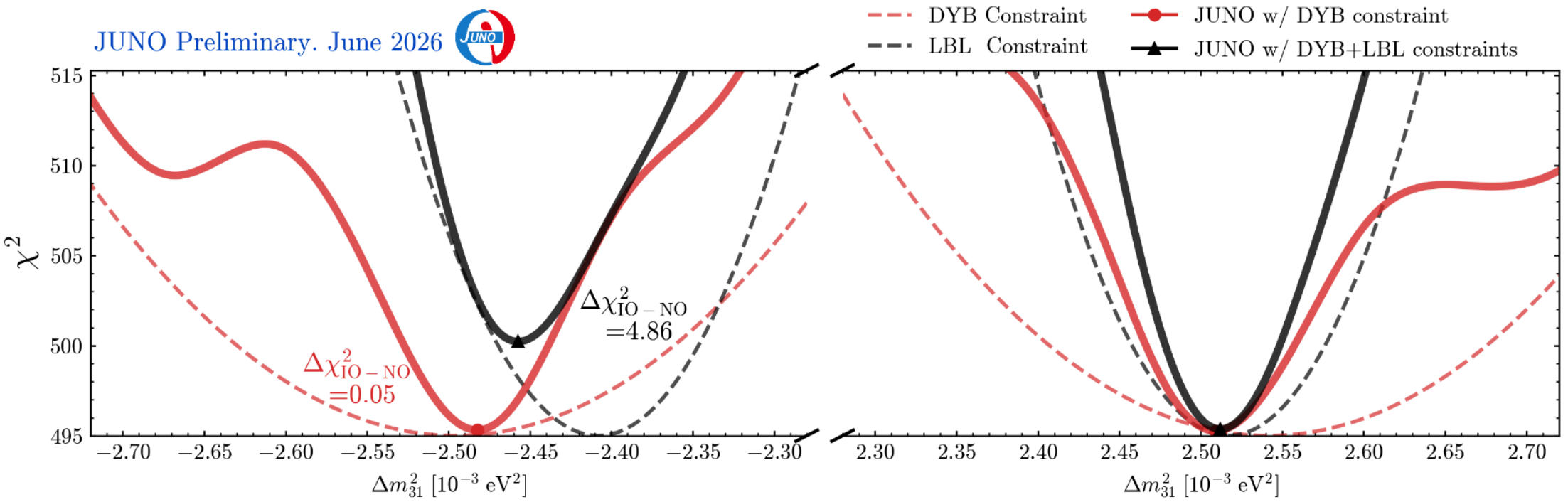




- Due to statistical fluctuations, JUNO only profiles of Δm^2_{31} have multiple minimal;
- The final minimum for each mass ordering is obtained by using the Δm^2_{31} constraint from the Daya Bay result (PRL 130 16, 161802);
- Feldman-Cousins (FC) method is used to determine the 1σ range of Δm^2_{31} : ~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 $\Delta\chi^2 = 4.86$



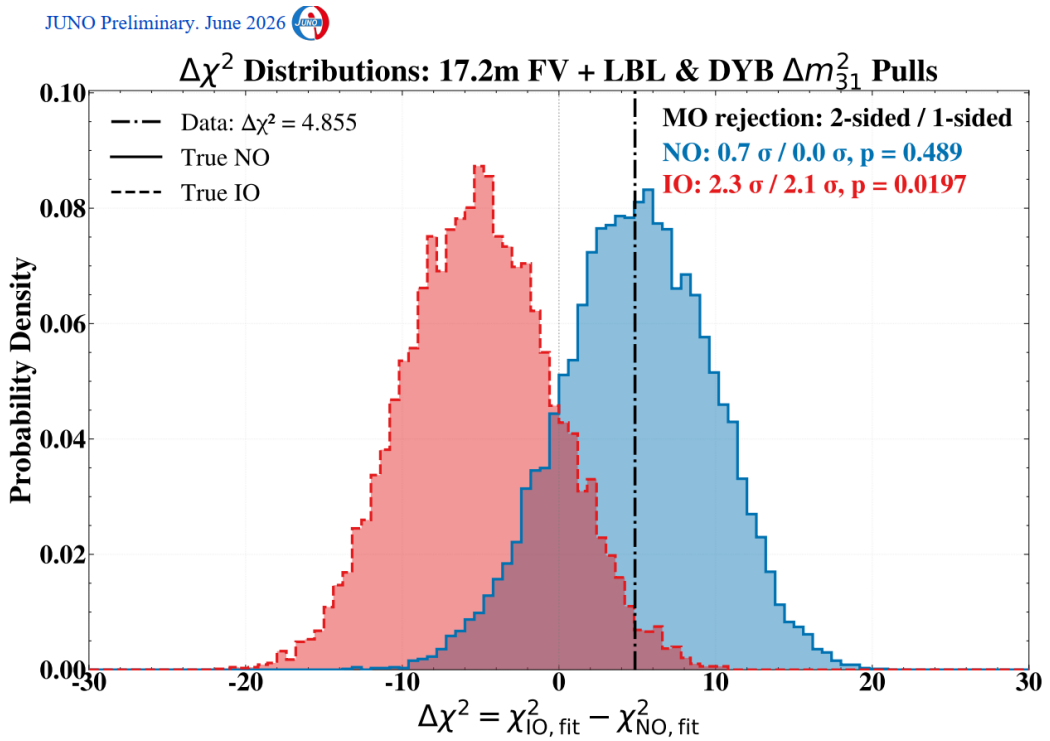
[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

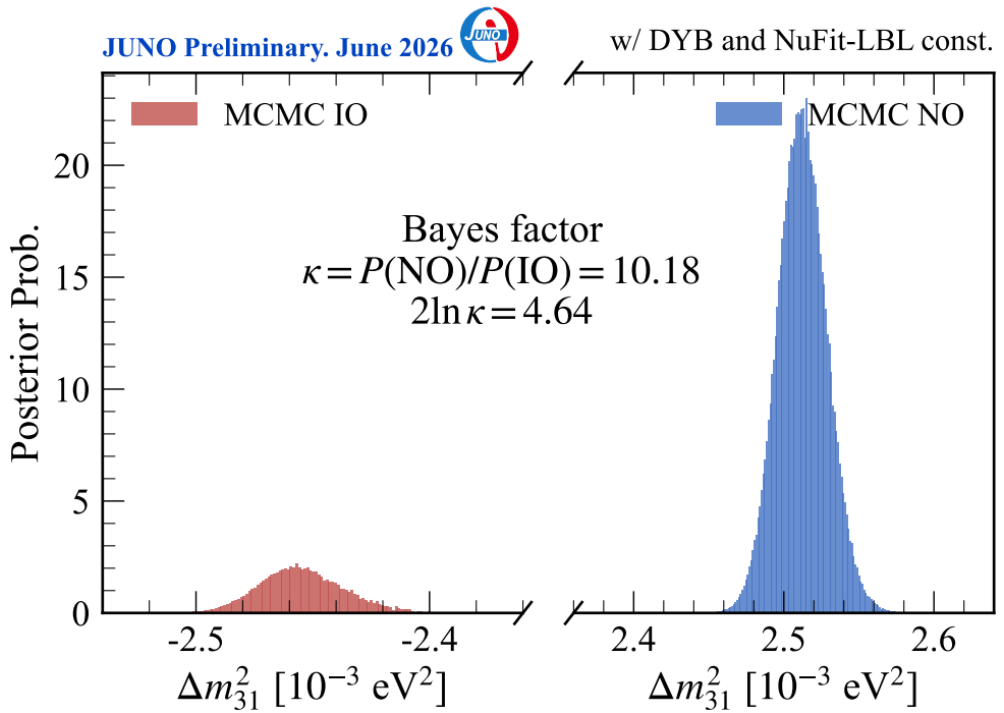
Neutrino Mass Ordering Significance

- Frequentist approach using pseudo exp. to convert $\Delta\chi^2$ to significance
- Influence of δ_{CP} considered (scanned)
- Normal Ordering is favored at 2.1σ (one-sided)

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

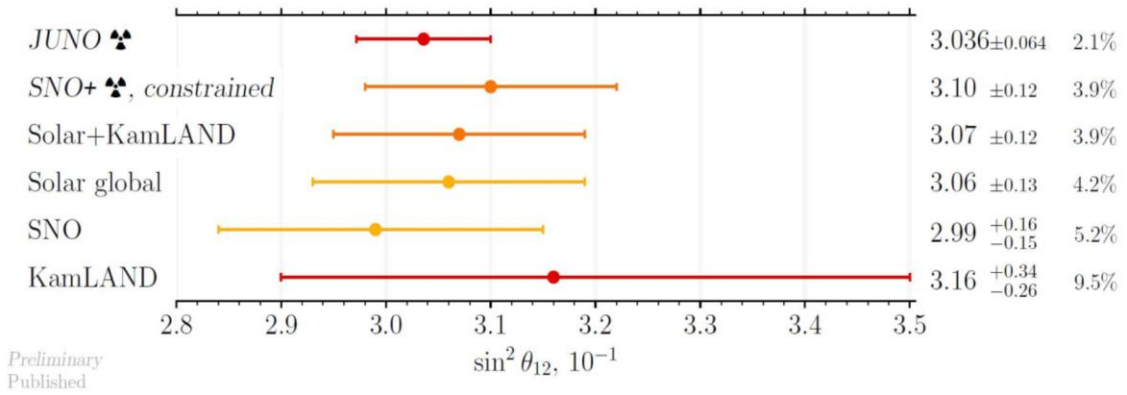
➔ $2\ln k = 4.64$ Consistent with the frequentist $\Delta\chi^2$



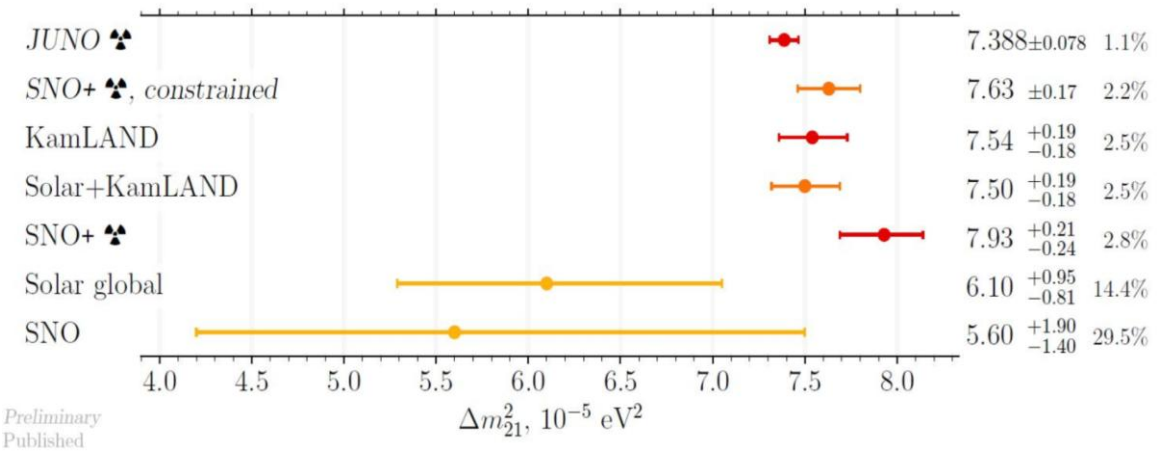


Comparison of Results on Oscillation Parameters

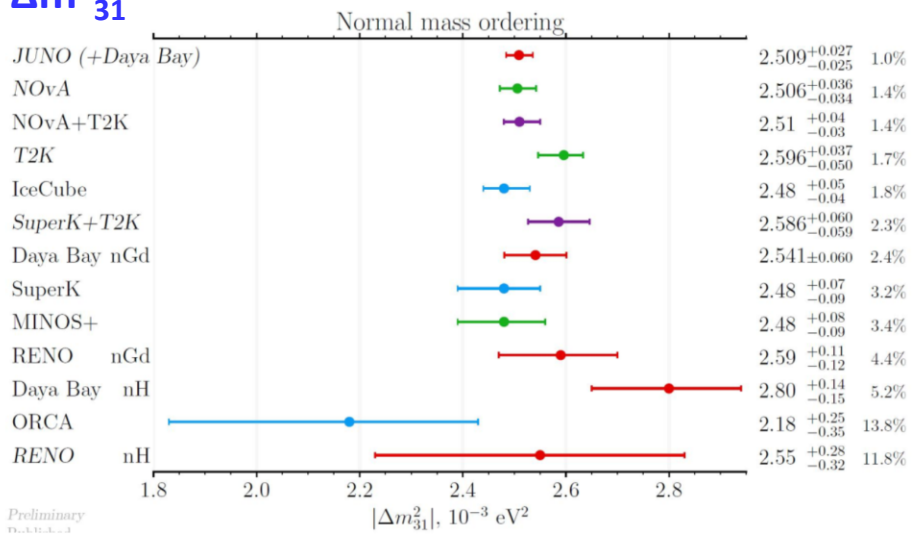
$\sin^2 2\theta_{12}$

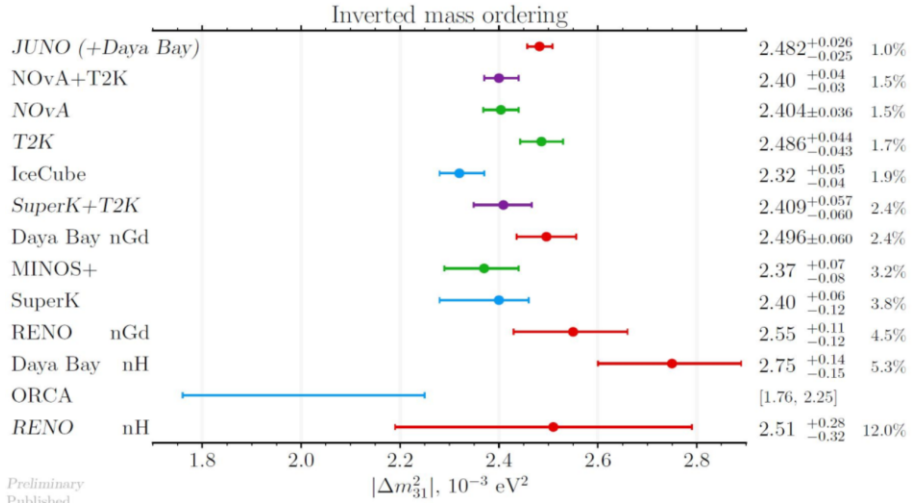


Δm^2_{21}



Δm^2_{31}

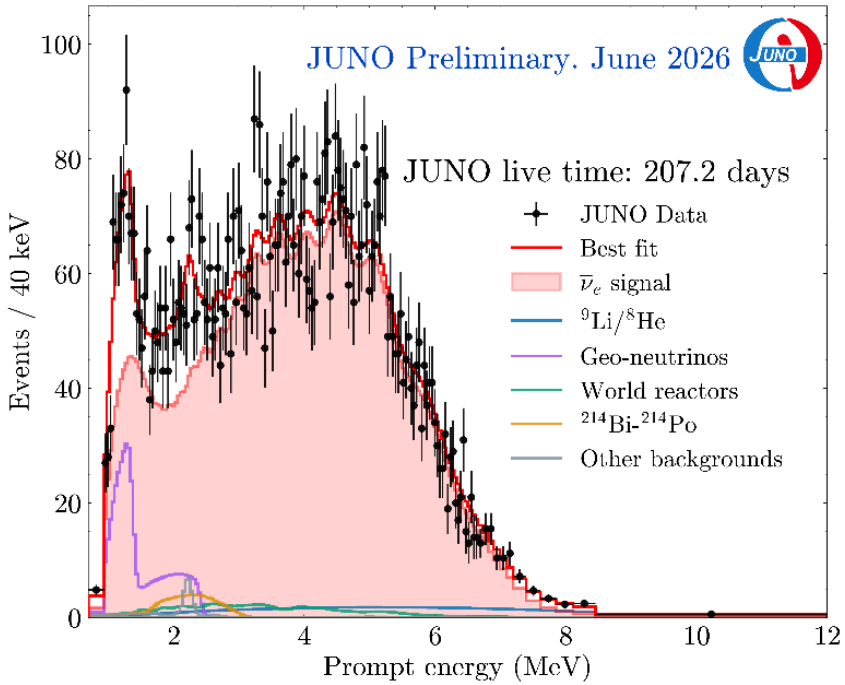


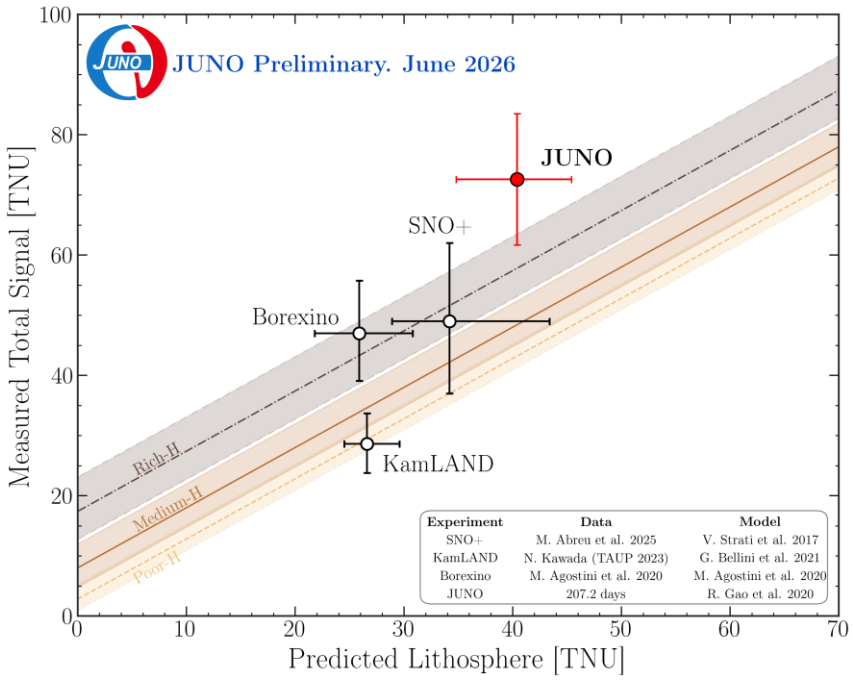


Results from JUNO have smallest uncertainties

Results on Geo-neutrinos

- Fits are performed without constraint on geo-neutrino flux, but with 3.4(±10%) U/Th ratio
  - ✓ Constraining the geo-nu flux does not change oscillation results;
- Clear geo-nu signals at 1-3 MeV, giving a flux of 73 ± 11 TNU;
  - ✓ Largest geo-neutrino samples so far, and most precise measurement
- JUNO result is higher than expectation from existing models, but not statistically significant;
- Need more JUNO data and more refined geological model predictions;



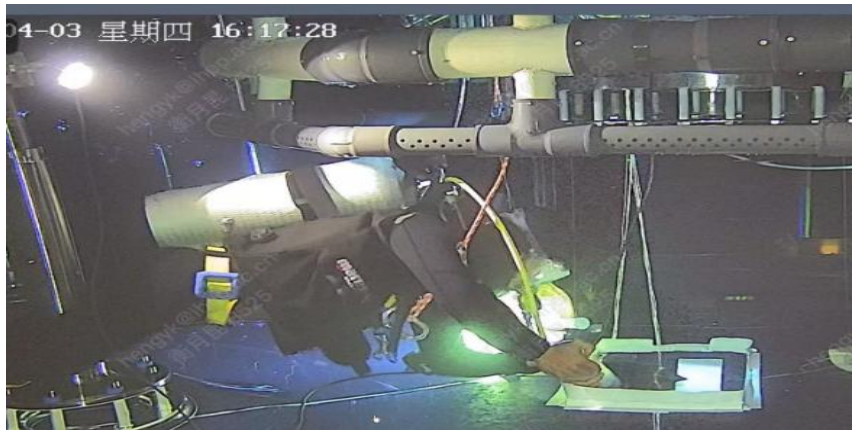


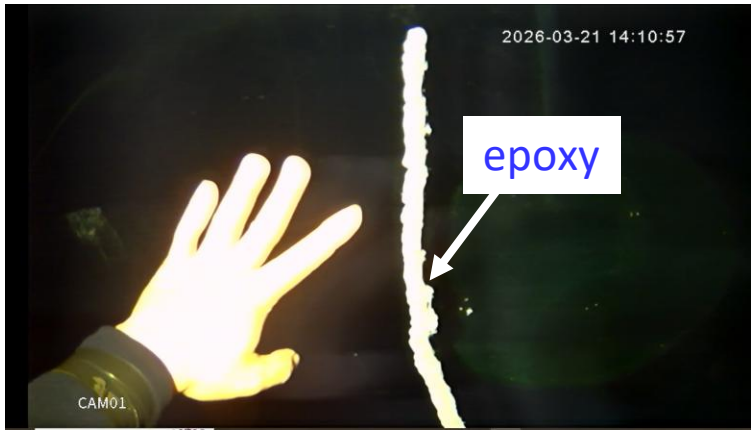
Life is not always easy!

Cracks on the Acrylic Tank

- However, a LS leak to water happened on March 21, 2025:
  - ✓ Abnormal trigger rate observed and confirmed by under water robot;
  - ✓ Leak was stopped within 1 week using epoxy and tape by divers;
  - ✓ Further repair by epoxy and acrylic plate to reduce the stress (pulling open the crack) by 50% ;
- Another leak of water to LS happened on March 19, 2026:
  - ✓ Experienced divers were called to stop the leak within 2 days;
  - ✓ Further repair in the following two days ;
  - ✓ A total of ~1Bq ^{222}Rn went into LS, 13 days of data excluded;
  - ✓ No other increase of radioactive backgrounds in LS;
- Main structure is safe, stress within expectations;

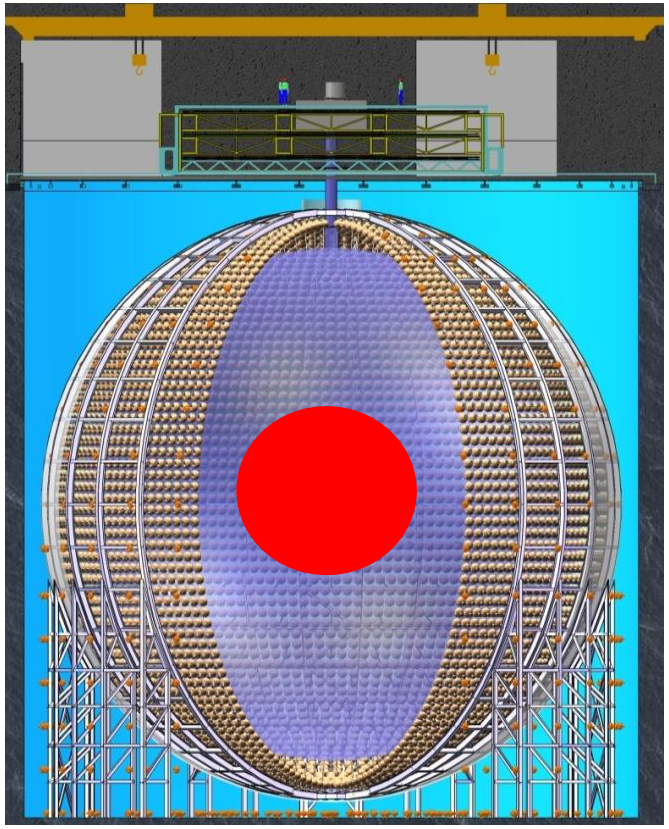




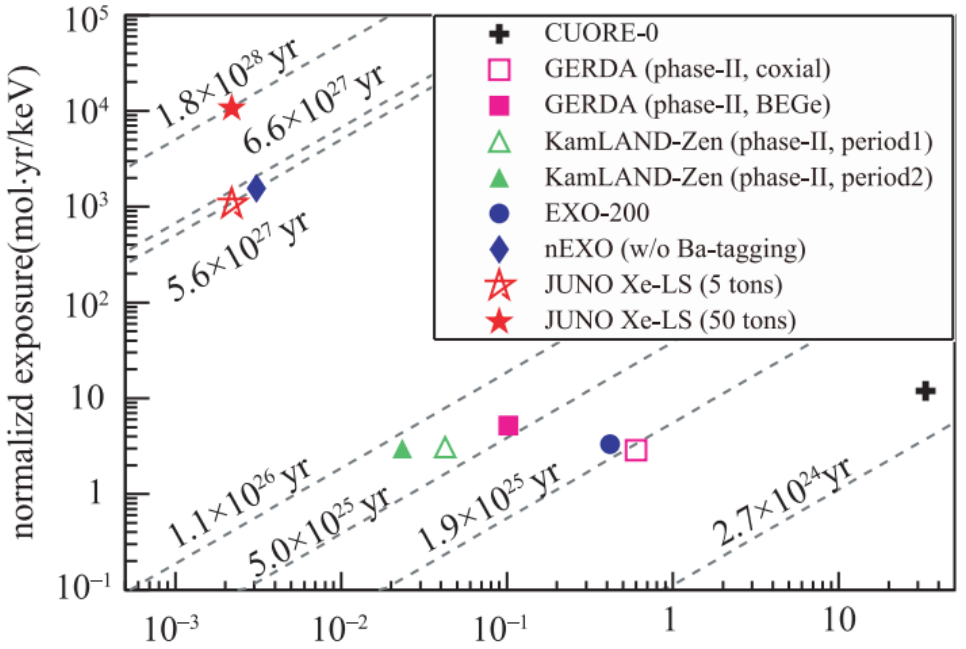


03 Upgrade Plans & Future Program

JUNO-ββ



Insert a balloon/Directly filled with ^{136}Xe-loaded LS(or ^{130}Te) into the JUNO detector



- Once mass ordering is determined (~2030), JUNO will be upgraded for ββ-decays, in addition to existing capabilities;
- ^{130}Te/^{136}Xe will be loaded into the LS;
- R&D about the Te/Xe-LS is under going;

Summary

- The JUNO detector and TAO are successfully built and operating smoothly;
- Initial performance shows that the detector works well as designed;
- Precision of solar oscillation parameters further improved by a factor of 1.3-1.5;
- First measurement on Δm^2_{31} achieved a precision of ~1% ;
- With external constraint, Normal Mass Ordering is favored at ~2.1σ(one-sided);
- First geo-neutrino results yield a flux of 73 ± 11 TNU;
- JUNO will be working for 30 years and it will be upgraded to 0νββ searching experiment at ~2030;

Thanks for your attention!

