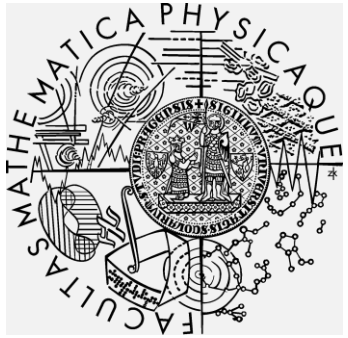


Recent Results from Neutrino Experiment JUNO



Vít Vorobel on behalf of JUNO collaboration
Institute of Particle and Nuclear Physics
Charles University



Co-funded by the European Union



Ministry of Education, Youth and Sports of the Czech Republic

Neutrino mixing

flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$

mass eigenstates

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{Majorana}}$$

Atmospheric $\theta_{23} = 45°$

Reactor $\theta_{13} = 9°$

Solar $\theta_{12} \approx 34°$

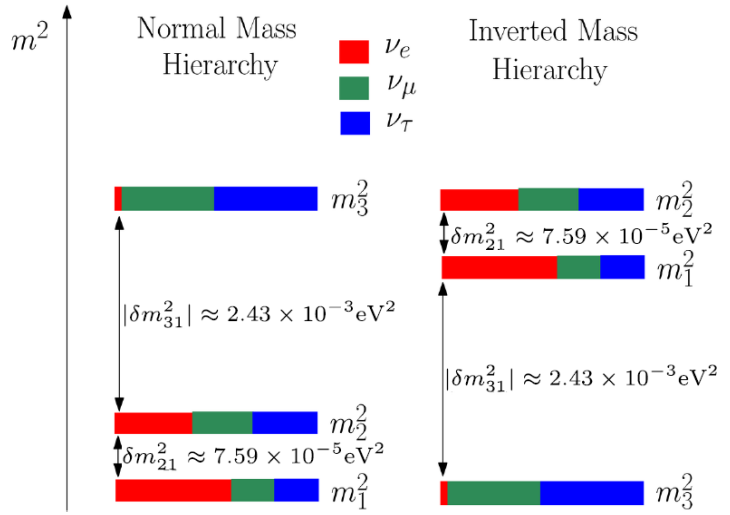
Majorana $0\nu\beta\beta$

Neutrino mixing complete information (9 parameters):

- Masses (3) $m_1 \quad m_2 \quad m_3$

PMNS matrix parameters

- Mixing angles (3) $\theta_{12} \quad \theta_{23} \quad \theta_{13}$
- Dirac phase (1) δ
- Majorana phases (2) $\alpha_1 \quad \alpha_2$



Open questions

- Neutrino mass ordering (NO or IO)
- Leptonic CP violation (δ_{CP})
- Octant of θ_{23}
- Precision tests of three-flavour oscillations
- Physics beyond the three-neutrino framework
- Majorana neutrino $\nu \equiv \overline{\nu}$

Neutrino mixing parameters

PDG data 2025 – before JUNO

Parameter	Value	Precision
$sin^2(\theta_{12})$	0.307 ± 0.012	3.9%
Δm^2_{21}	$(7.50 \pm 0.19) \times 10^{-5}\ eV^2$	2.5%
$sin^2(\theta_{23})$	$0.534^{+0.015}_{-0.019}$	3.2%
Δm^2_{32}	$(2.527 \pm 0.034) \times 10^{-3}\ eV^2$	1.3%
$sin^2(\theta_{13})$	0.0216 ± 0.0006	2.8%

JUNO aims

- In 2 years $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ precision → unprecedented < 1% level.
- In 6 years $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ precision → 0.5%, 0.3% and 0.2%.
- Determine the neutrino mass ordering with 3σ in about 6 years.
- Search for deviations from the standard 3-neutrino paradigm.
- Guide the design of future neutrino experiments.
- Constrain and discriminate between theoretical models.

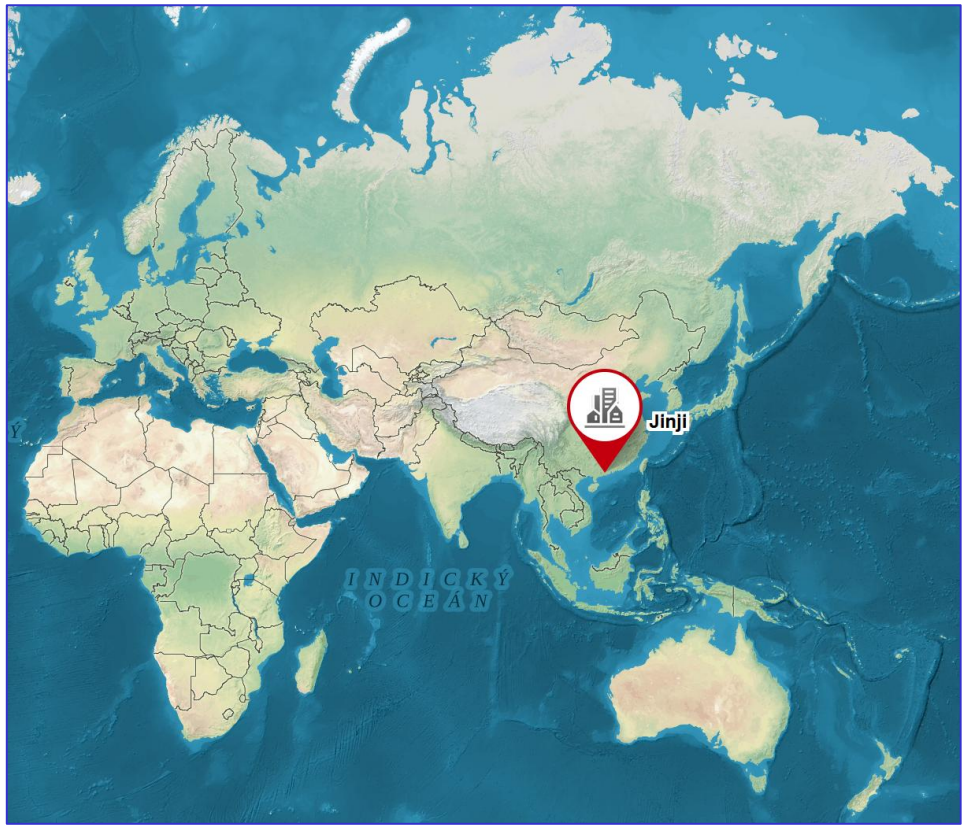
JUNO EXPERIMENT

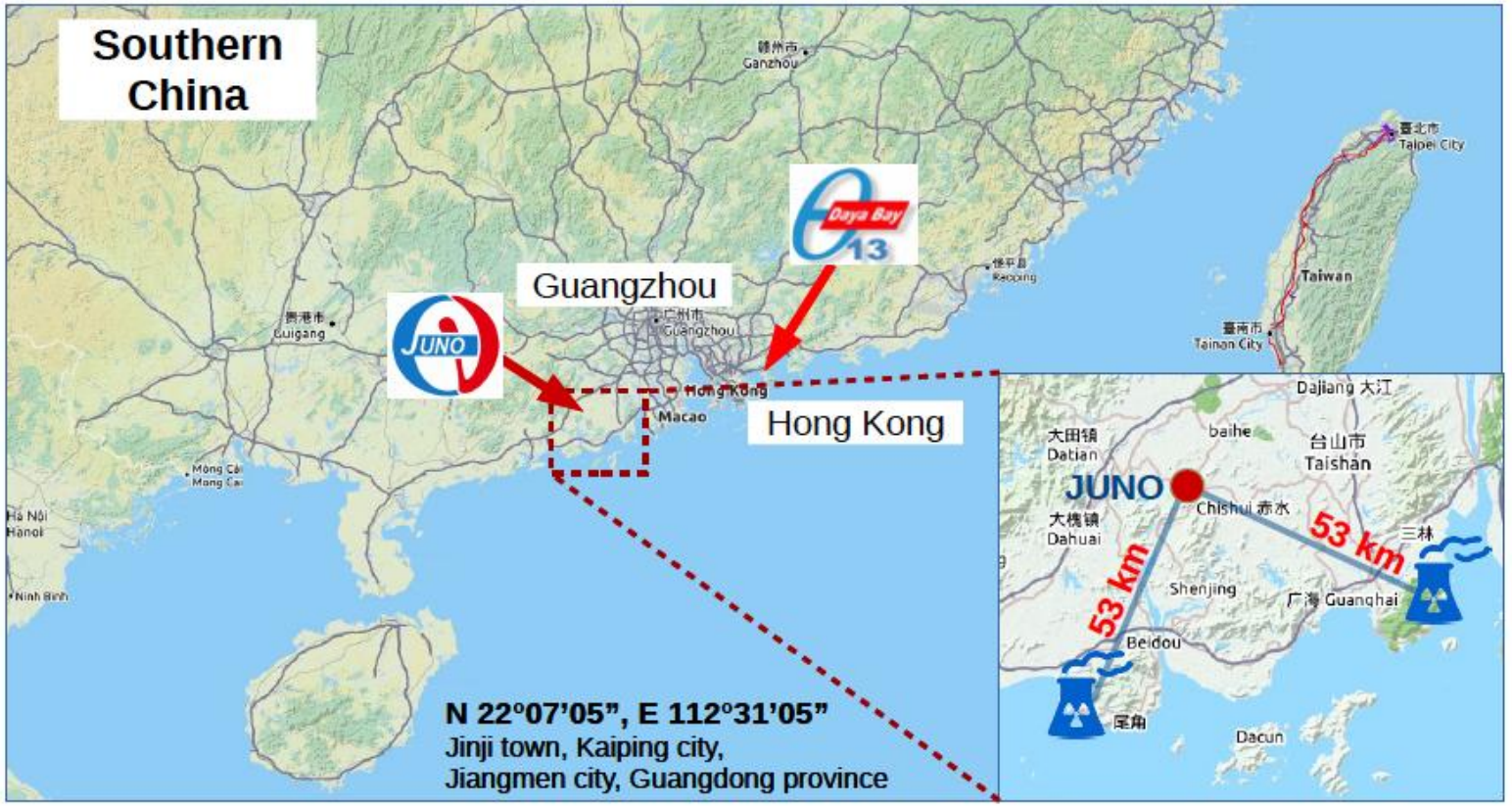


JUNO – Jiangmen Underground Neutrino Observatory

- Jiangmen Underground Neutrino Observatory
- a multi-purpose neutrino experiment,
- approved in Feb. 2013,
- data taking: Aug. 2025.

- Neutrino sources: 10 nuclear reactors (Yangjiang+Taishan: 26.6 GWth),
- baseline: 53 km,
- detector is ~700 m underground.



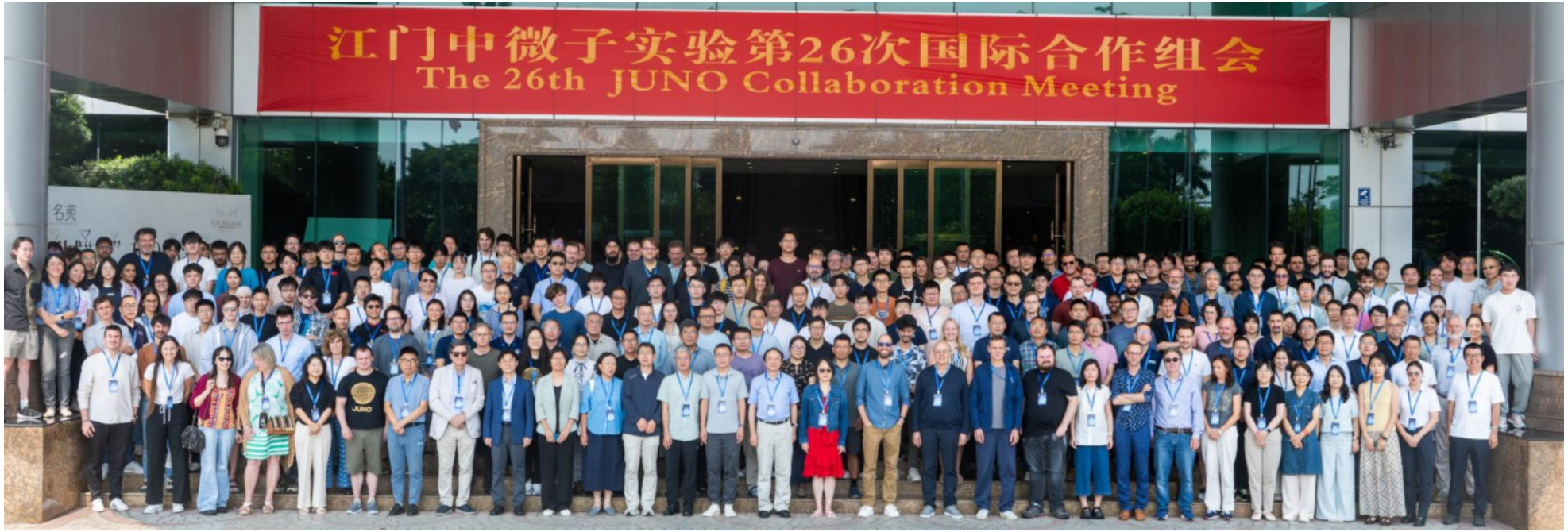


JUNO – Collaboration

- Established in 2014
- About 70 institutions
- 750 collaborators
- 17 countries and regions

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

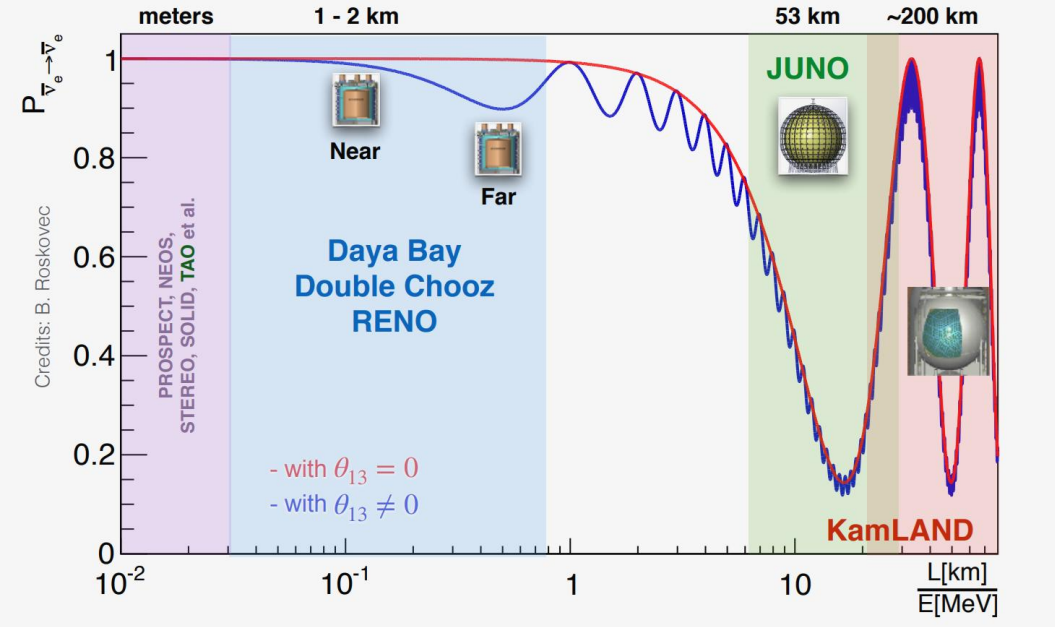
+Observers: USTC, Peking Uni., Jilin Uni., Beijing Normal Uni., CIAE (China), PUC, UEL (Brazil), Oxford Uni. (UK)



JUNO – Jiangmen Underground Neutrino Observatory

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

slow oscillation — fast oscillation



Neutrino Mass Ordering (NMO)

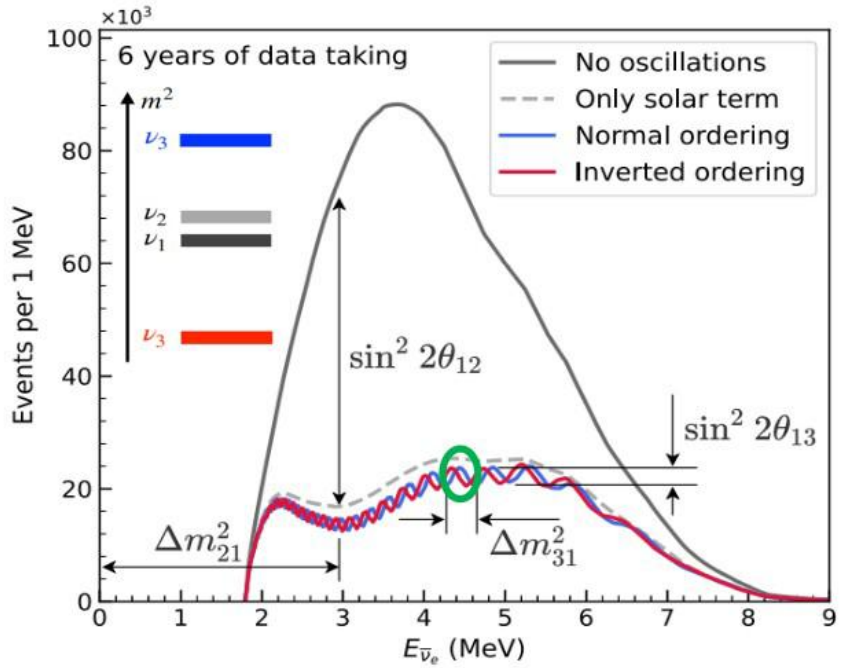
NMO sensitivity manifests as an energy dependent phase

◊ JUNO sits at the baseline maximizing NMO sensitivity

◊ Investigation of reactor antineutrino oscillation on long baseline ~53 km

Main physics goals

- 3σ measurement of the **neutrino mass ordering** with reactor antineutrinos in ~6 yeas
- Measuring **oscillation parameters** with precision <0.5 % ($\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31}) in ~6 yeas



JUNO requirements

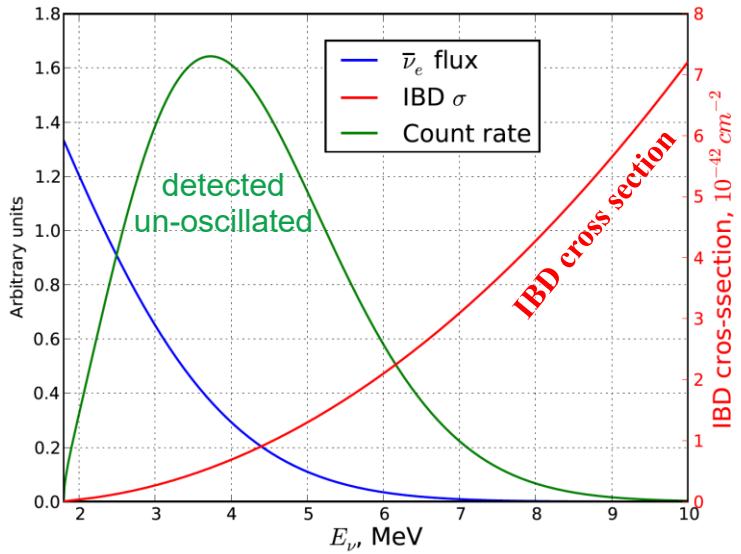
- Large signal statistics
- High **energy resolution ~3% @ 1 MeV**
- Highly controlled **energy scale non-linearity uncertainty <1%** for small spectral features identification
- Low background for low spurious events
- Low reactor antineutrino spectrum shape uncertainty

Electron-antineutrino detection

Detection of $\bar{\nu}_e$ – Inverse beta-decay (IBD) in LAB liquid scintillator:

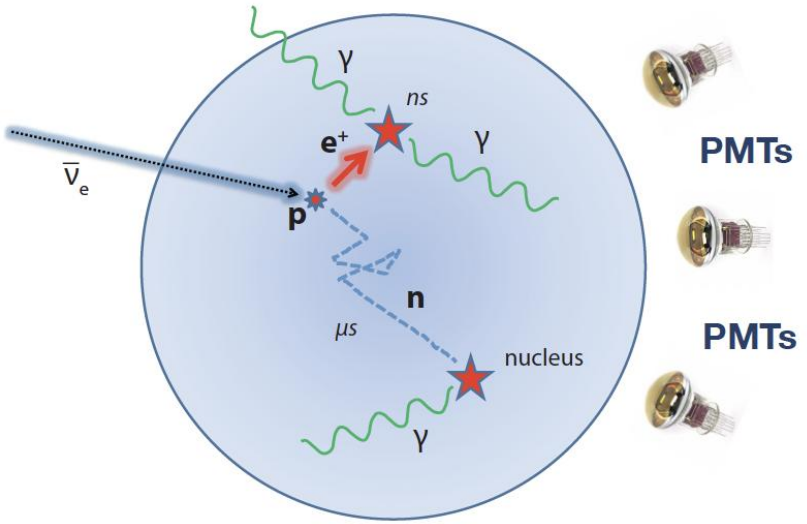
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\hookrightarrow$ + p $\rightarrow$ D + γ(2.2 MeV) (t~200 μs)



Treshold $E_{\bar{\nu}} \approx 1.8$

$E_{\bar{\nu}} \approx E_{prompt} + 0.8$



Coincidence between prompt positron and delayed neutron signals allows for **powerful background suppression.**

Energy of positron preserves information about energy of incoming $\bar{\nu}_e$.

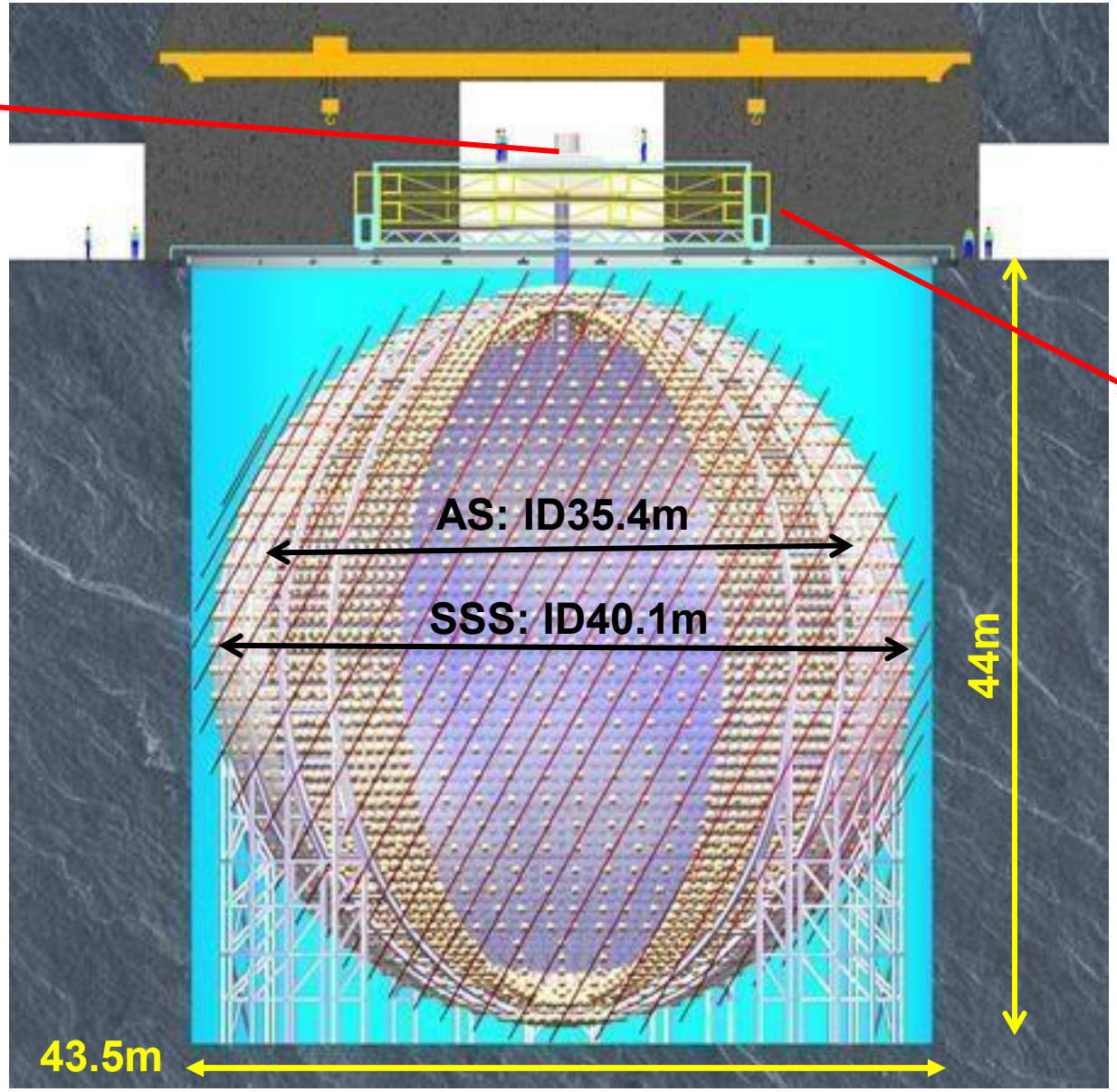
JUNO studies how incoming $\bar{\nu}_e$'s oscillate (disappear) into other flavors.

JUNO – Jiangmen Underground Neutrino Observatory

Calibration

Central detector

- Acrylic sphere + 20kt Liquid scintillator
- 17612 20” PMTs
- 25600 3” PMTs
- Stainless steel structure (SSS)



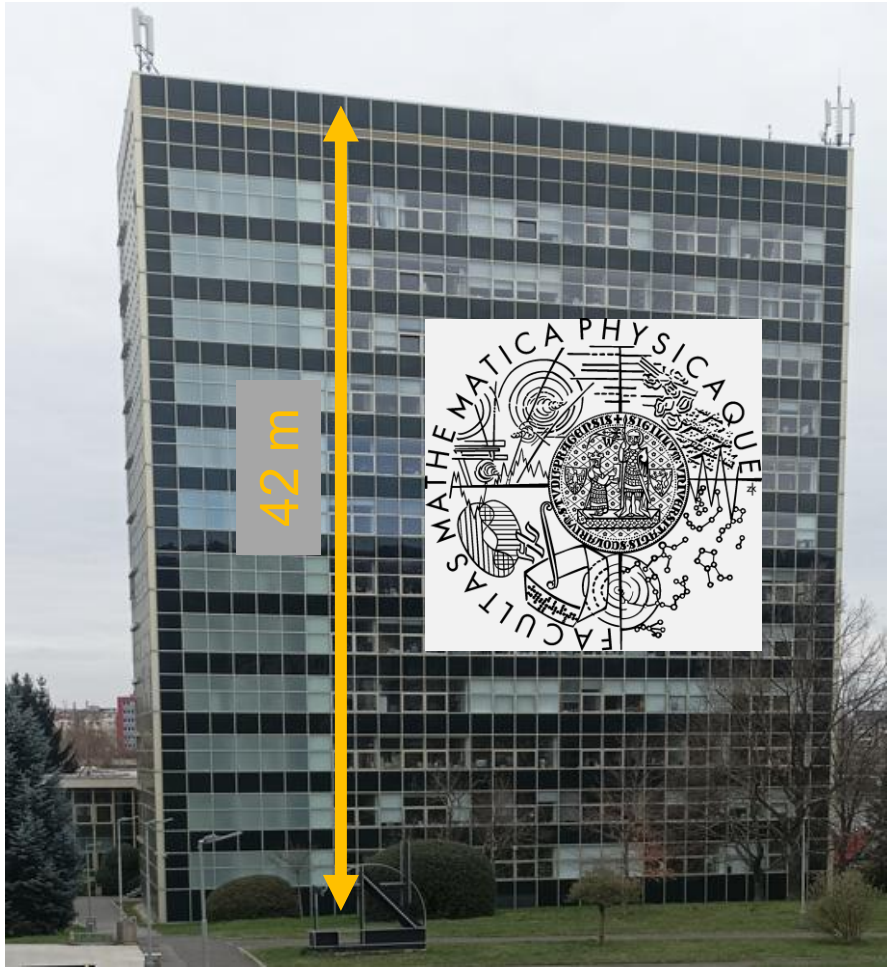
VETO system

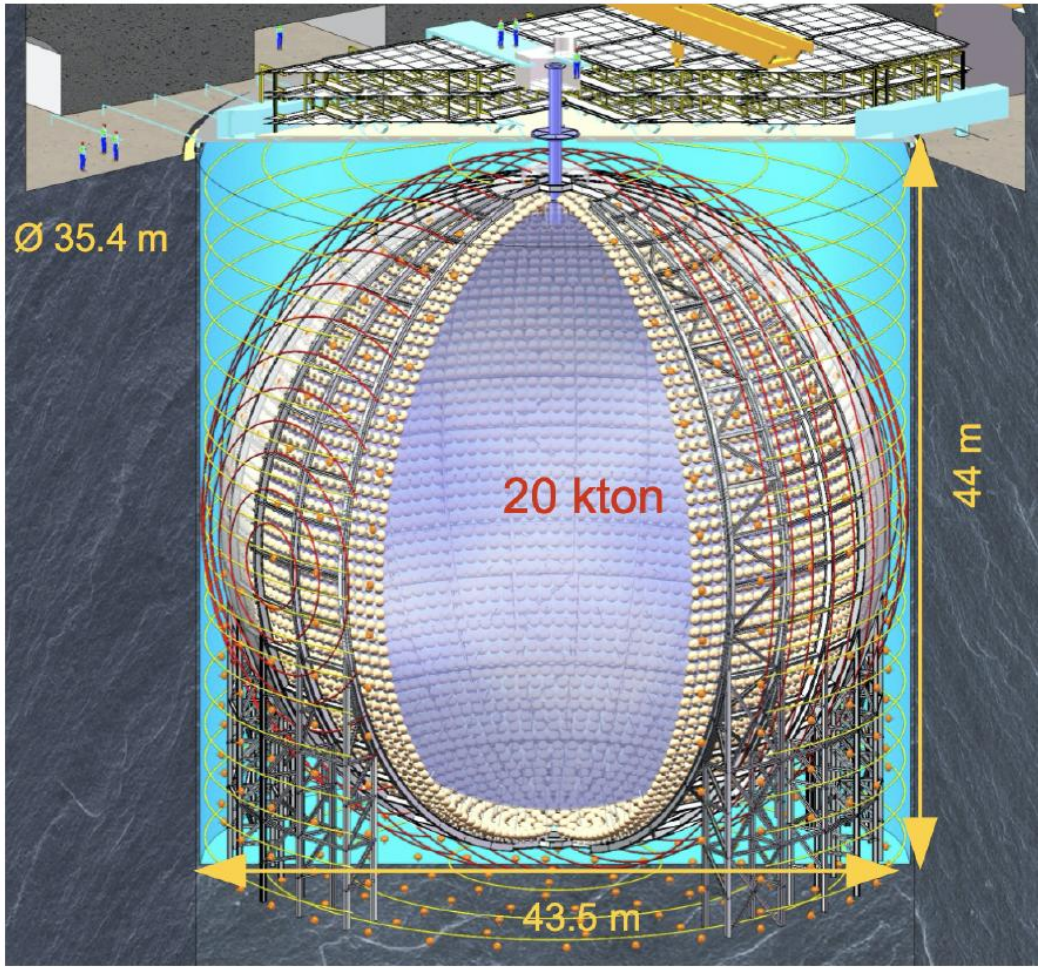
Top Tracker: plastic scintillator

Water Cherenkov Detector
- SSS: 2400 20” PMTs
- WP wall for atmospheric ν:
- 348 20” spare PMTs
- 600 8” PMTs from Daya Bay

Earth Magnetic Field shielding coils

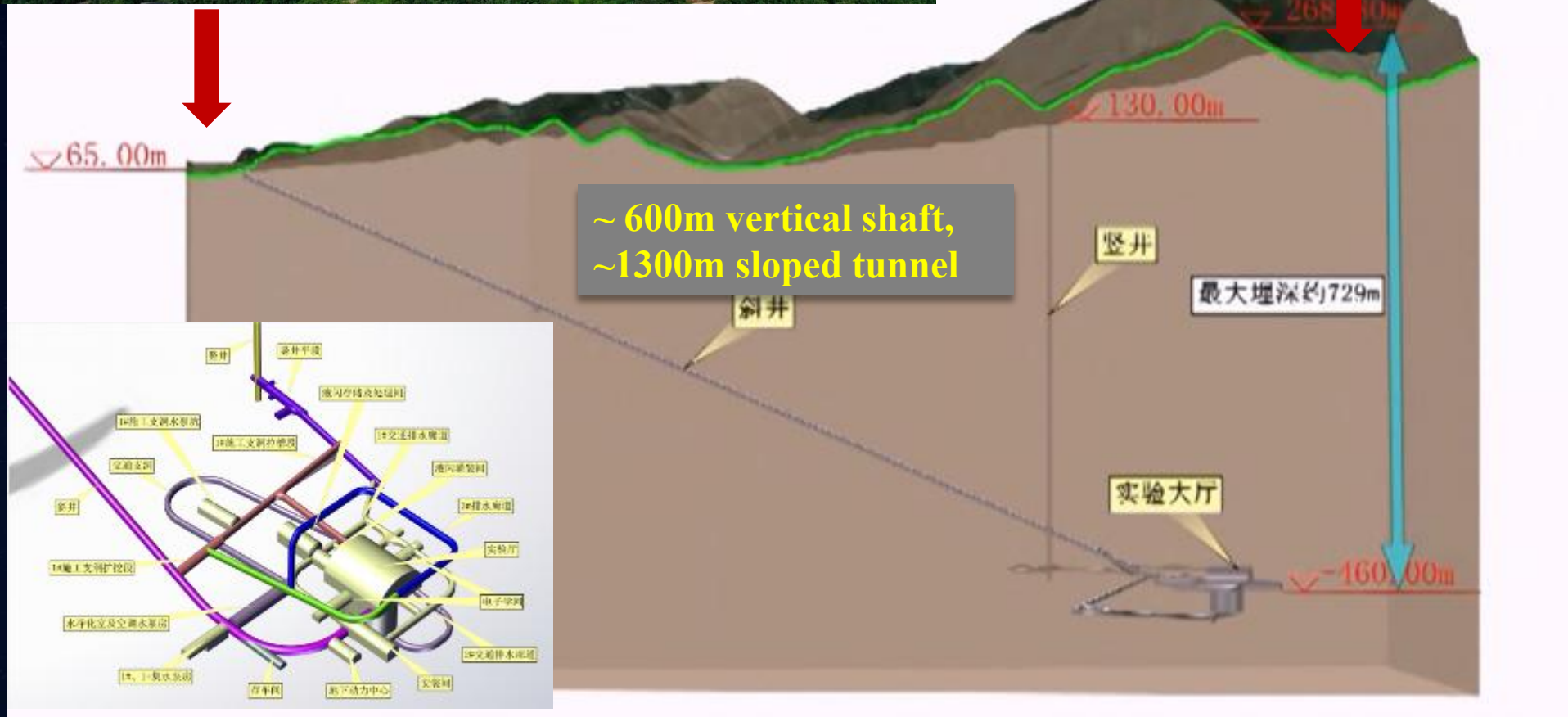
JUNO – Jiangmen Underground Neutrino Observatory






700 meter




65.00m
130.00m
~ 600m vertical shaft,
~1300m sloped tunnel
竖井
斜井
最大埋深约729m
实验大厅
-160.00m

PMTs and Electronics

	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Charge Collection	Dynode	MCP	Dynode
Photon Efficiency	28.5%	30.1%	25%
Dynamic range	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347





LPMT & sPMT





PMT and Underwater box installation



LPMT Underwater box

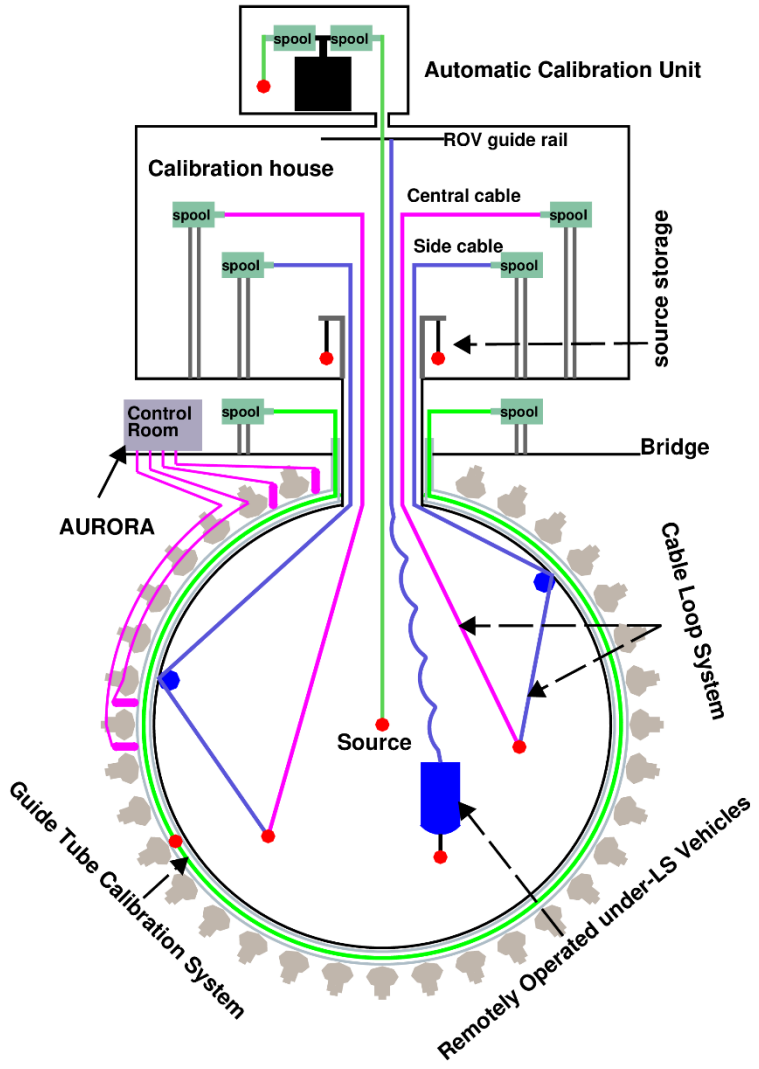


sPMT Underwater box

Central Detector Calibration

More info in talk T. Těmj on Saturday

JUNO also needs to **keep the systematics under control.**



Have a **comprehensive calibration program** consisting of four complementary systems:

- 1D: Automated Calibration Unit (ACU) deploys radioactive and laser (1ns, keV-TeV range) sources along the vertical axis. ^{137}Cs, ^{54}Mn, ^{40}K, ^{68}Ge, ^{60}Co, Am-C, Am-Be, sensors, laser
- 2D: Cable Loop System (CLS) to scan a vertical plane. Am-C, ^{68}Ge, ^{137}Cs
- 2D: Guide Tube to scan the outer surface of the central detector (where the CLS cannot reach).
- 3D: Remotely Operated Vehicle (ROV) operating inside the LS to scan the full volume.
- 3D using cosmogenic backgrounds:

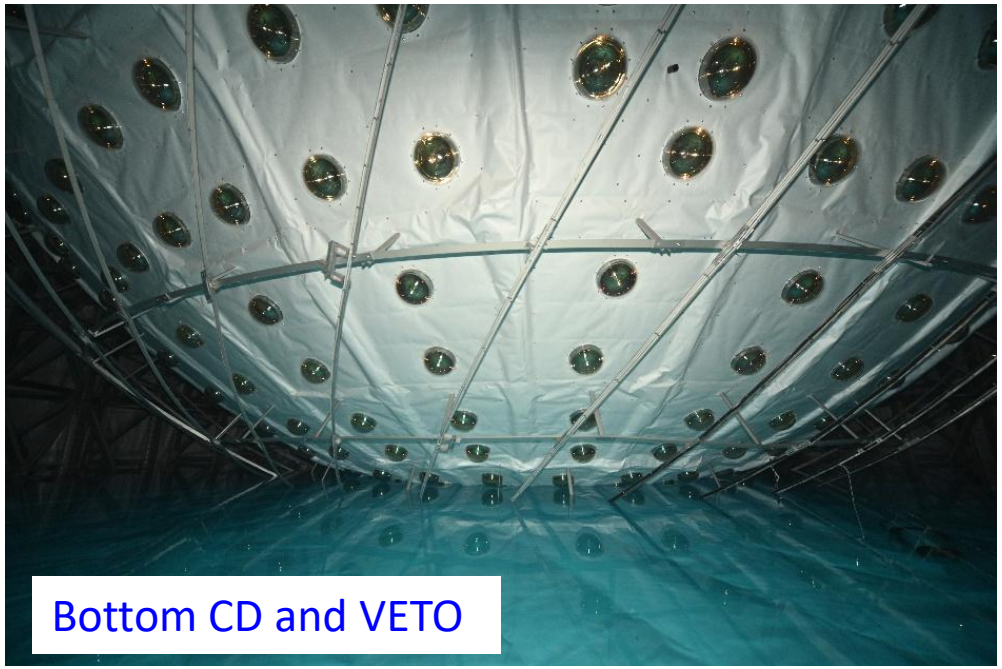
  Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

Goal is to keep the energy scale uncertainty < 1%

Veto Systems







- Water VETO:
  - ⇨40 kt pure water for backgrounds shielding & tagging
  - ⇨2400 20” PMTs on the SS trust +348 20” PMTs + 600 8” PMTs on the pool wall
  - ⇨pool lining using 5mm HDPE + Tyvek
  - ⇨100t/h pure water production system with Rn & Ra removal system
- Top tracker: refurbished OPERA plastic scintillators
- Earth magnetic field compensation coil

Liquid Scintillator


5000 m³ LAB tank

Operations on surface

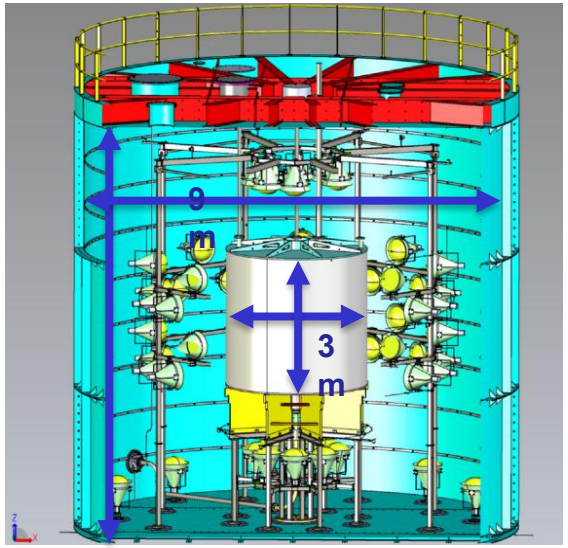
- Al2O3 filter to remove particles
- Distillation to remove radioactive impurities
- Add 2.5g/L PPO, 3mg/L bis-MSB

- Stainless pipe to underground

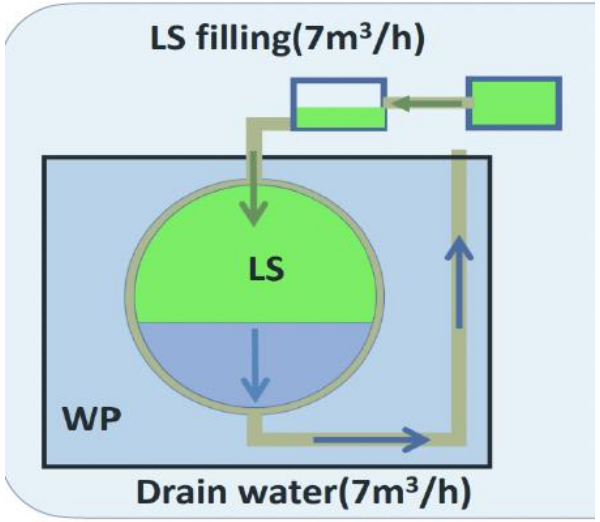

Distillation to remove radioactive impurities

Operation underground

- Water extraction to remove radioactive impurities
- Gas stripping to remove Rn and O2
- OSIRIS for LS qualification
- LS filling



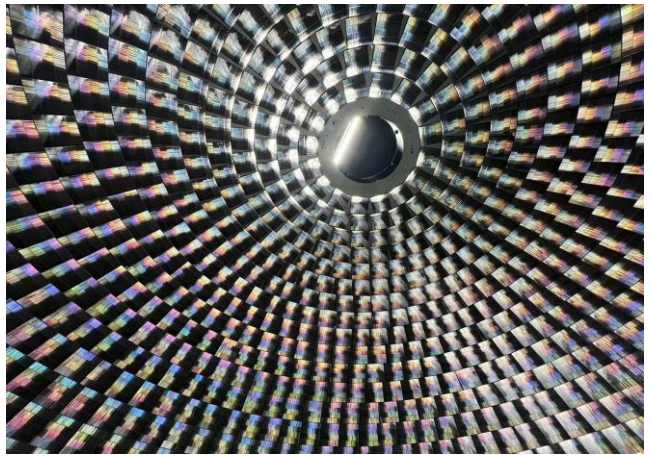
Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

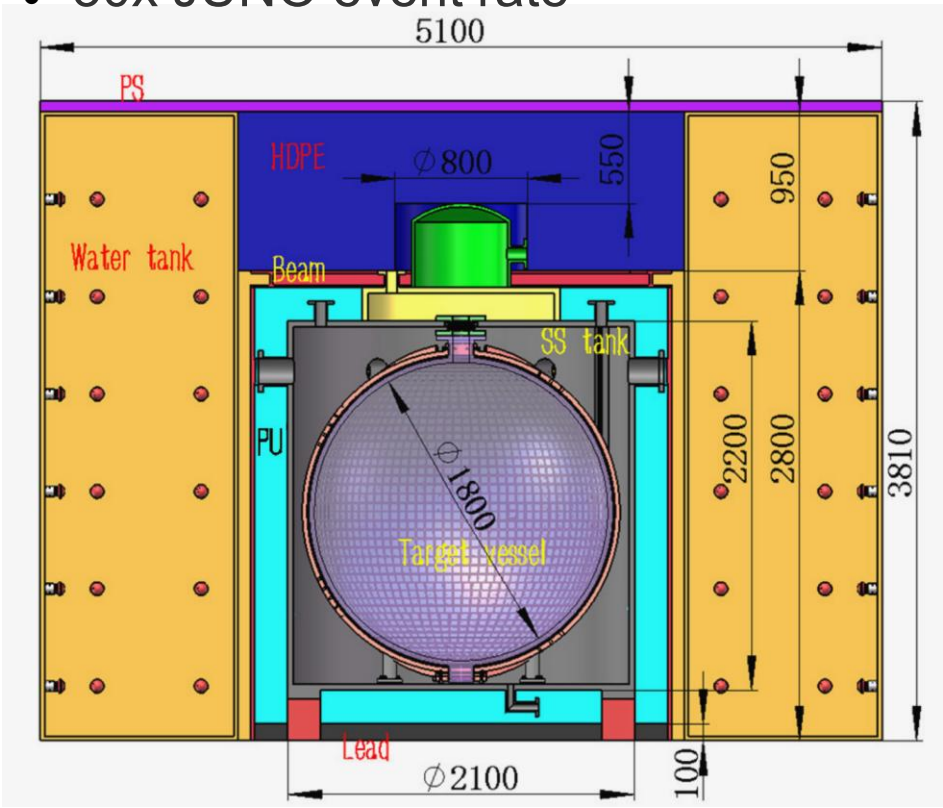


Four purification plants for a radio-purity of 10^{-17} g/g (U/Th) and 20 m attenuation length @ 430 nm.

TAO - Taishan Antineutrino Observatory

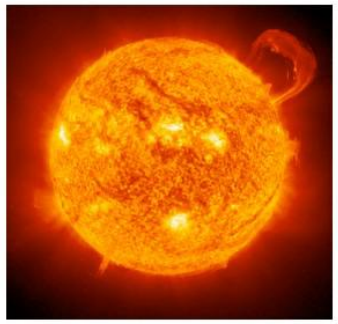
- Satellite detector for JUNO: provide precise measurement of unoscillated reactor antineutrino spectrum
- ~40 m from one of Taishan 4.6 GW_{th} reactor core
- 1 ton fiducial volume with Gd-LS
- 10 m^2 SiPM of 50% photon detection efficiency operated at -50°C
- ≥94% photo-coverage , <2%/√E
- 30x JUNO event rate

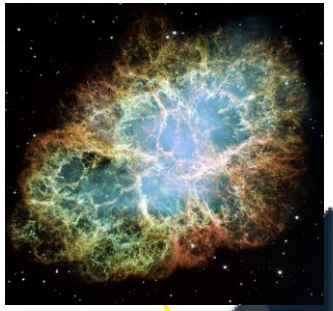




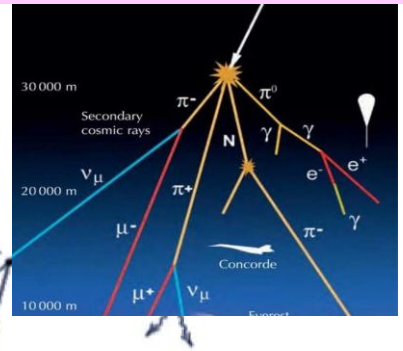


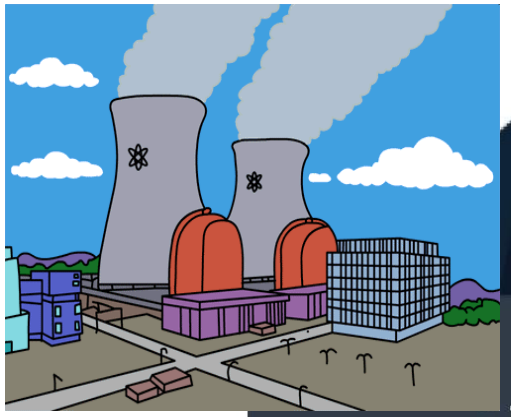
JUNO multi-purpose neutrino experiment











SuperNova ν
5k in 10 s (10 kpc)

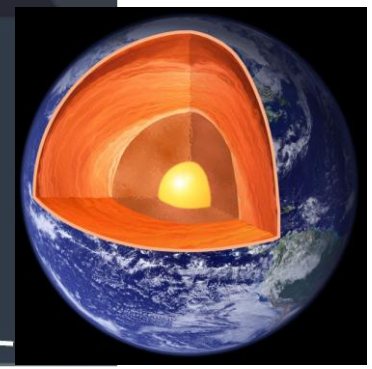
Wimp
(dark matter)
?

Solar ν
$O(10-1000)$/day

Atmospheric ν
10-20/day

Reactor ν
$\sim 60-80$/day

Geo-ν
$\sim 1-2$/day



New physics

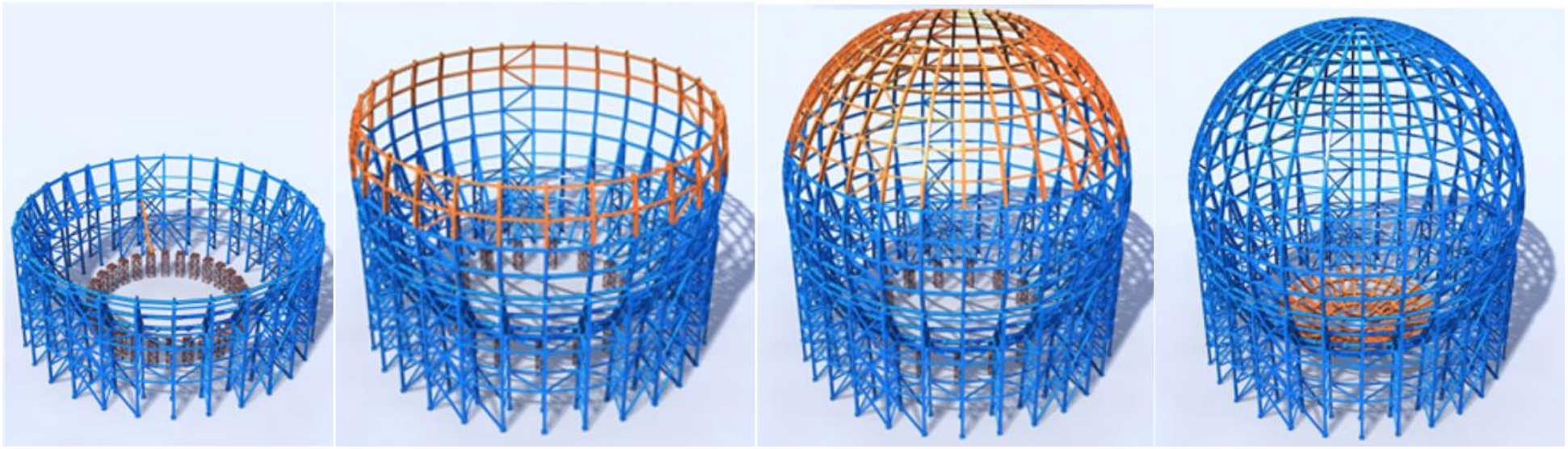
DETECTOR CONSTRUCTION

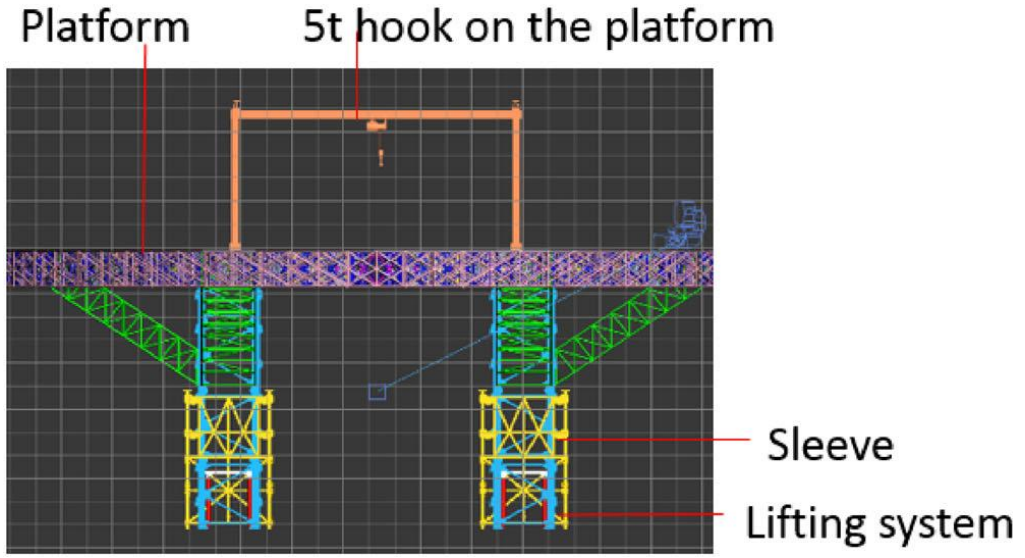


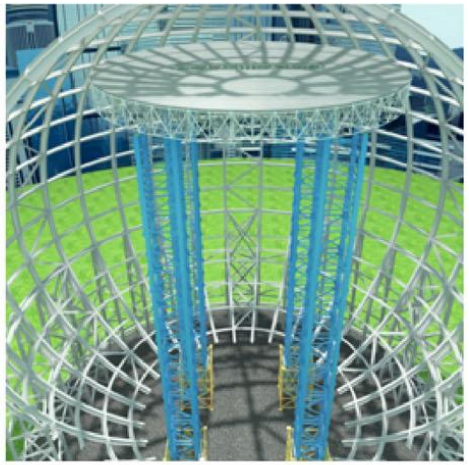
Slope tunnel access, 1300 m, 15 min.



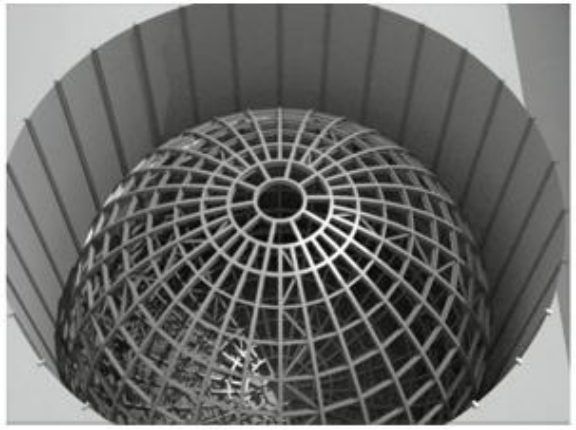
Stainless Steel Structure – from bottom to top



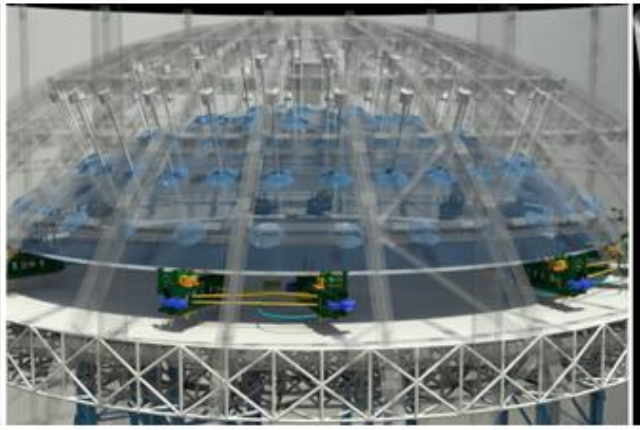




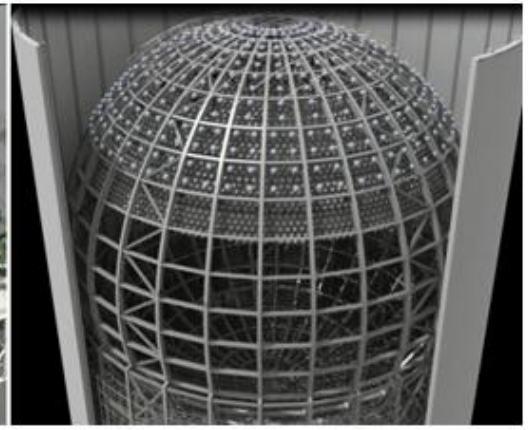
Acrylic Sphere and PMTs – from top to bottom



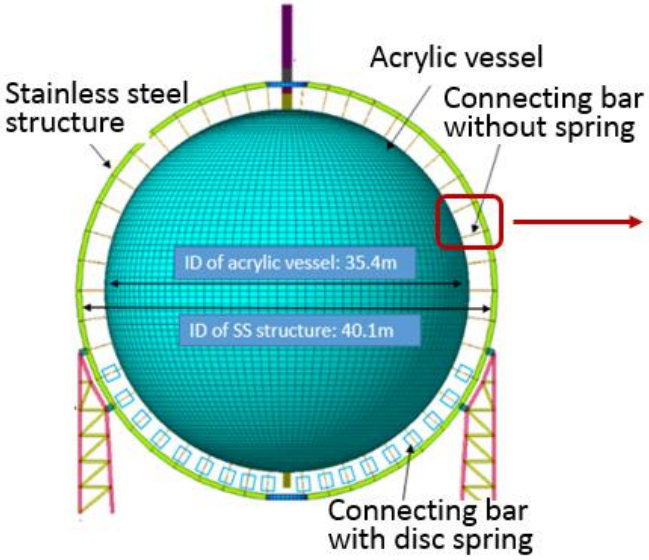
Stainless steel structure installed.

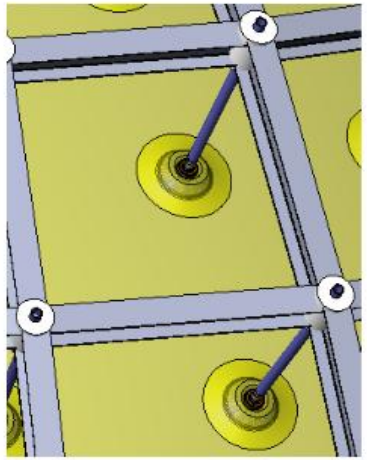


Acrylic vessel installed.

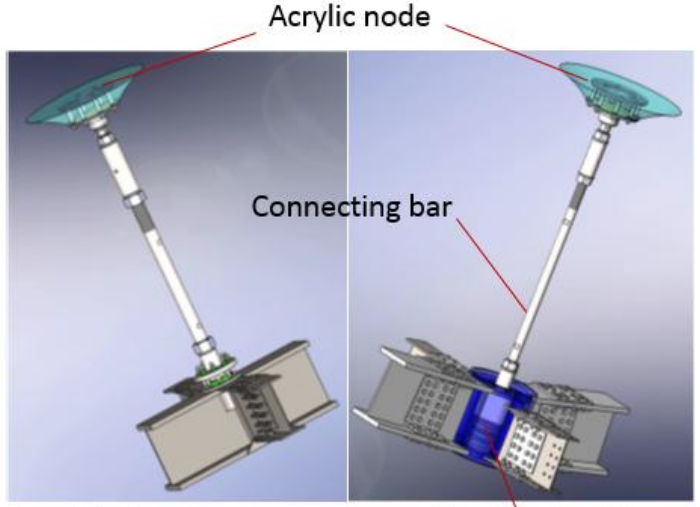


PMT installed.





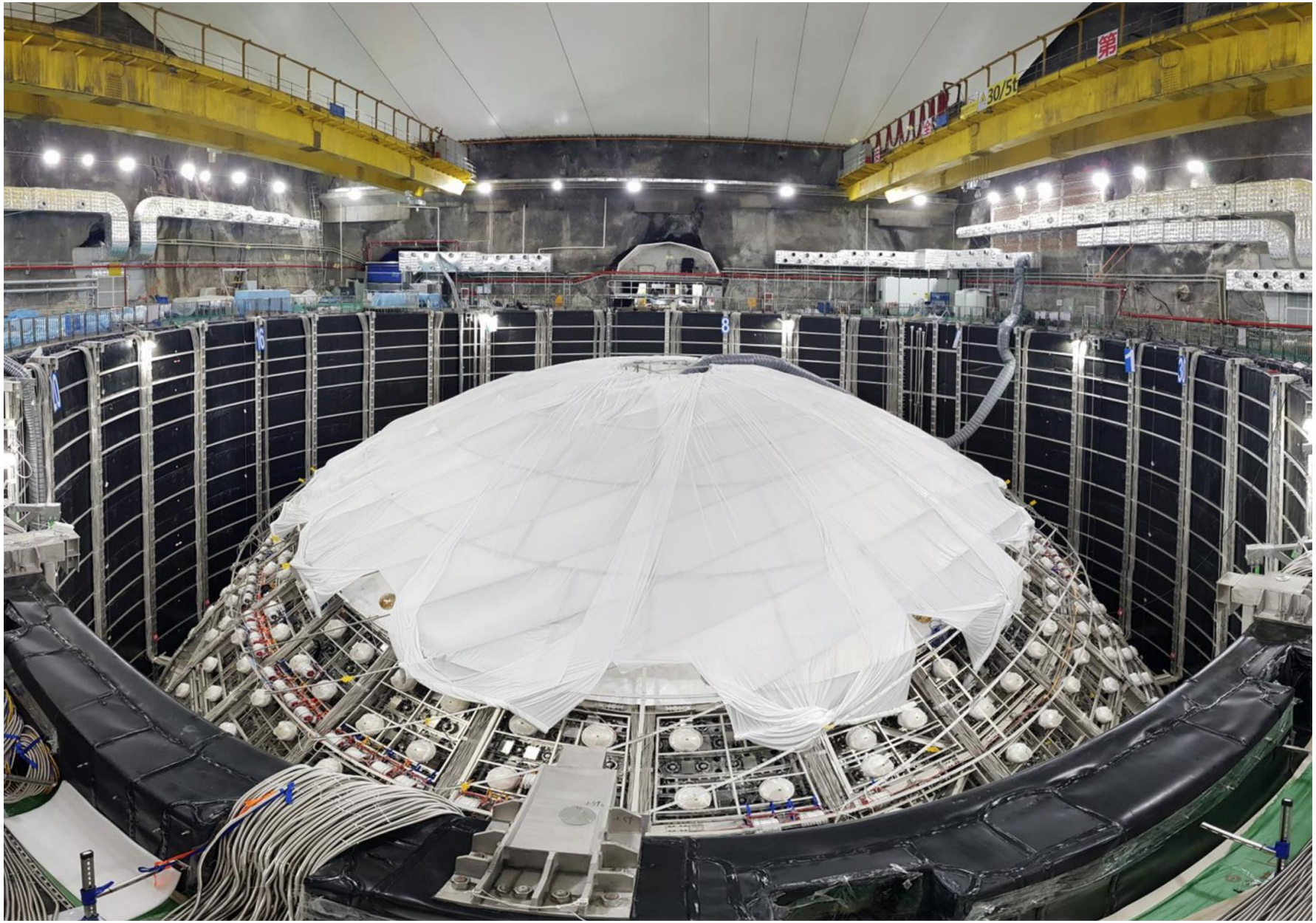
Connecting structure



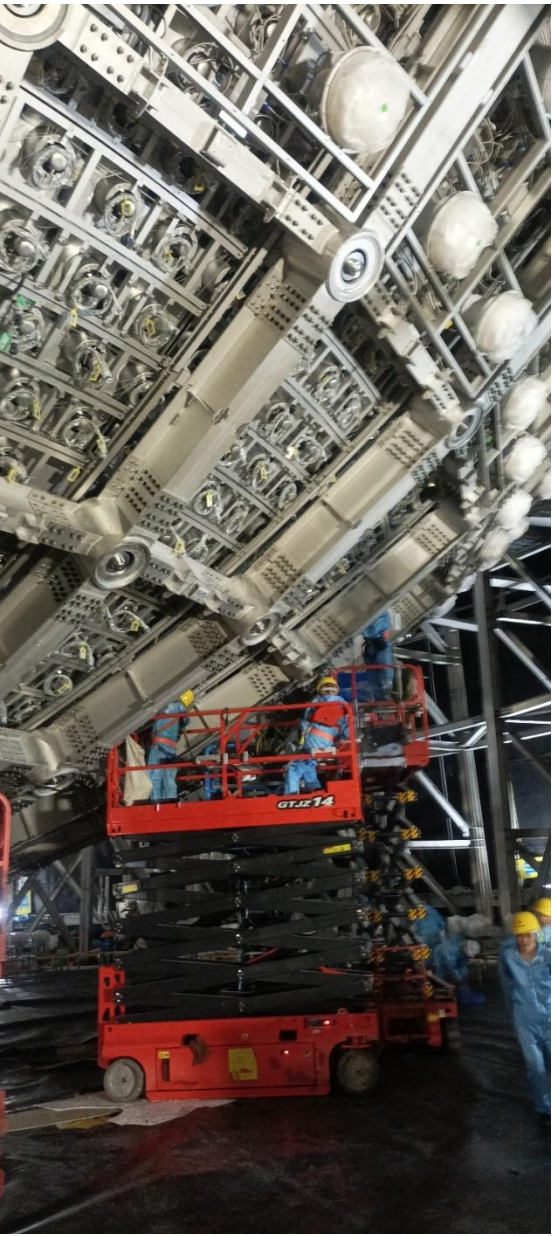
Steel node without spring

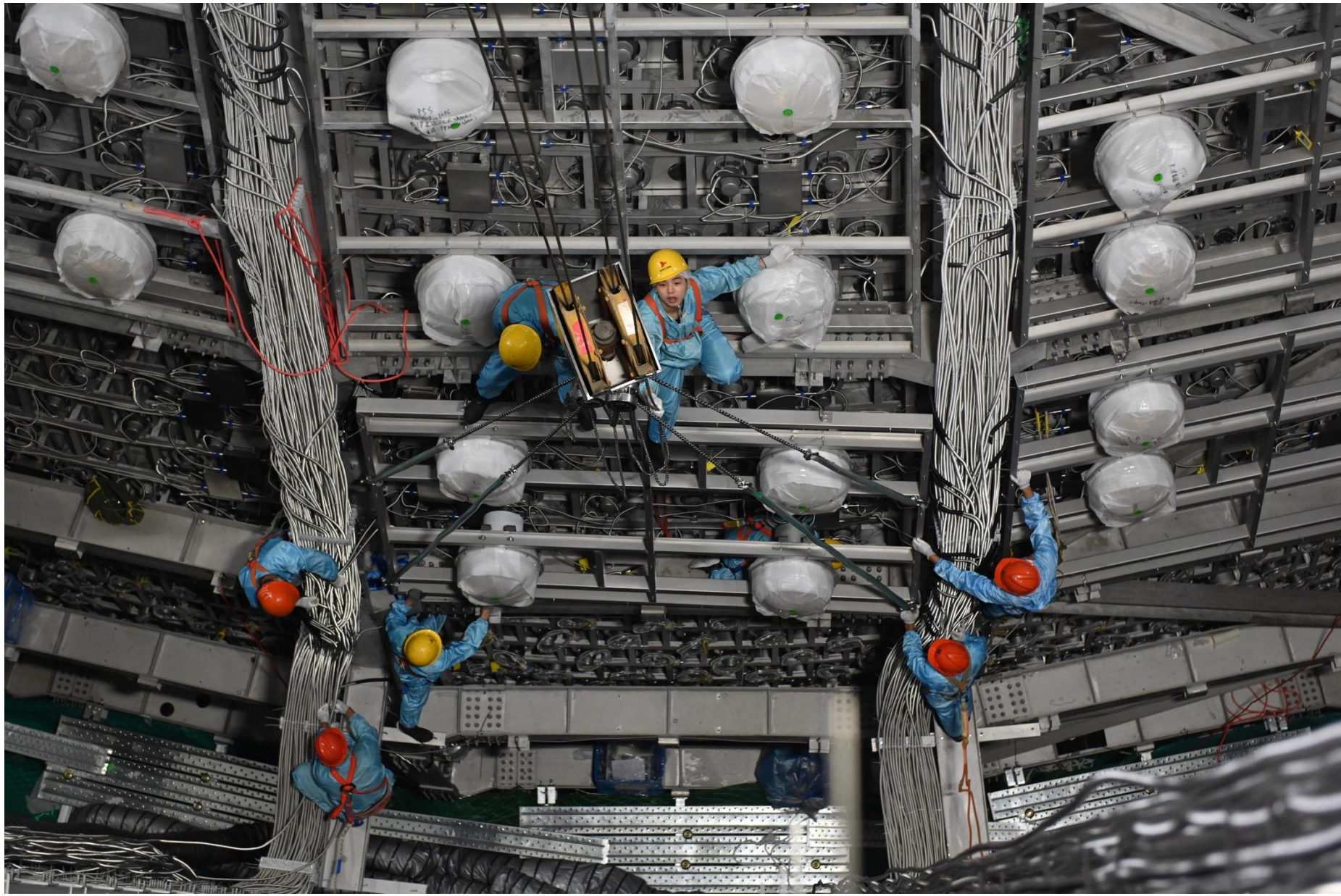
Steel node with disc spring

Experimental Hall = Clean Room



Installations in height





Check and repair the outer surface of the acrylic sphere



JUNO detector water phase

Achievements:

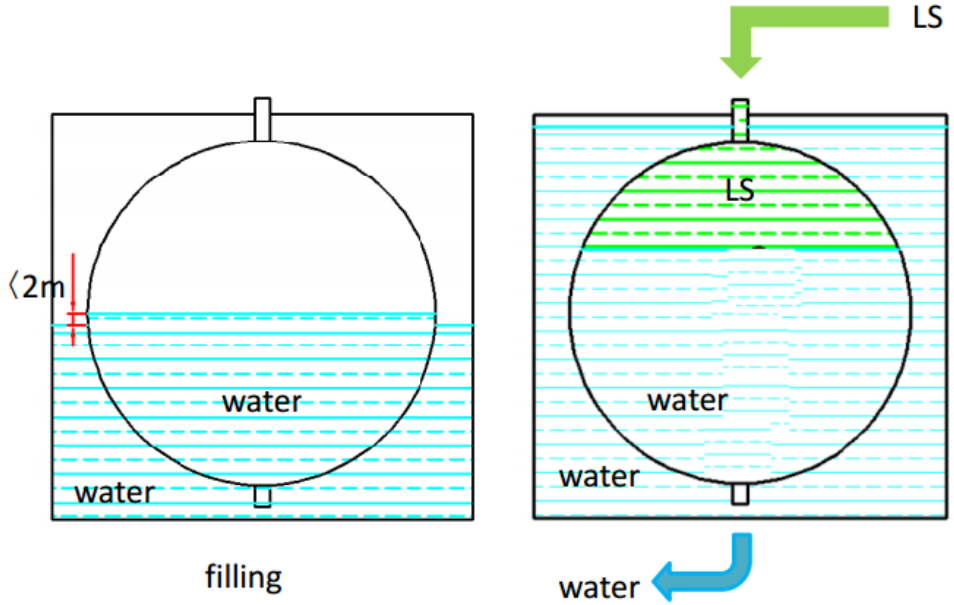
Christmas 2024 – start of water filling
Chinese New Year – water filling finished

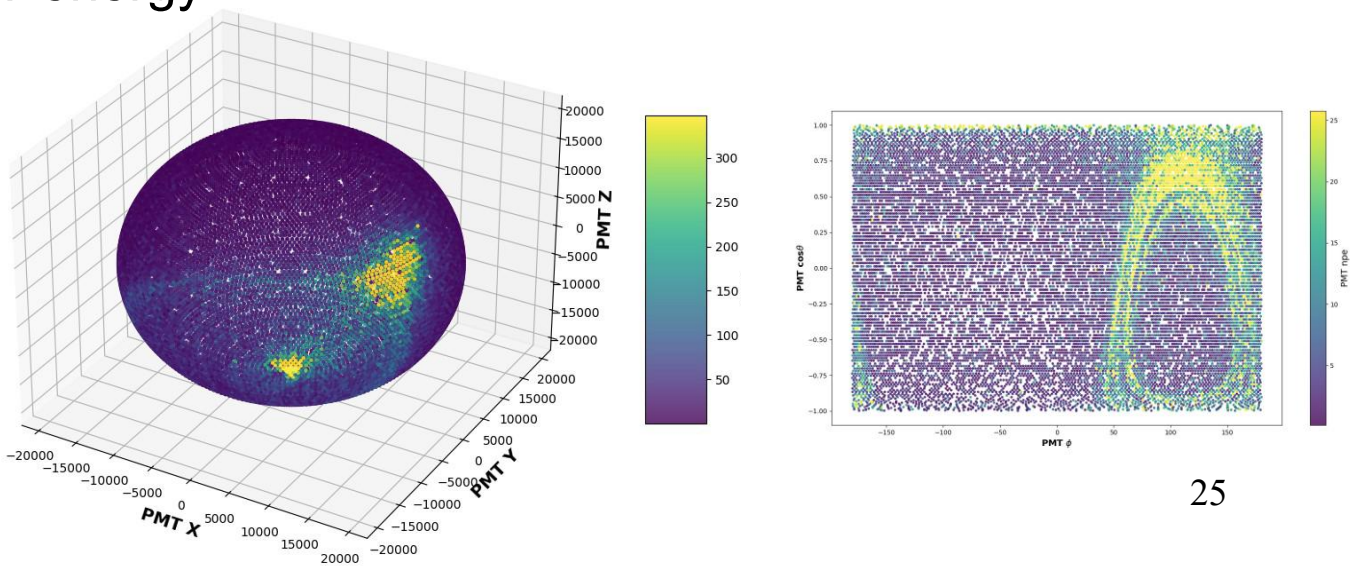
Very small failure PMT rate: ~20/20k
(0.1% loss at installation/due to high dark rate)

Successful identification of neutrons from Am-Be and Am-C sources demonstrates the detector's low-energy detection capabilities

We see the first muon candidates

February 2025 – start of LS filling

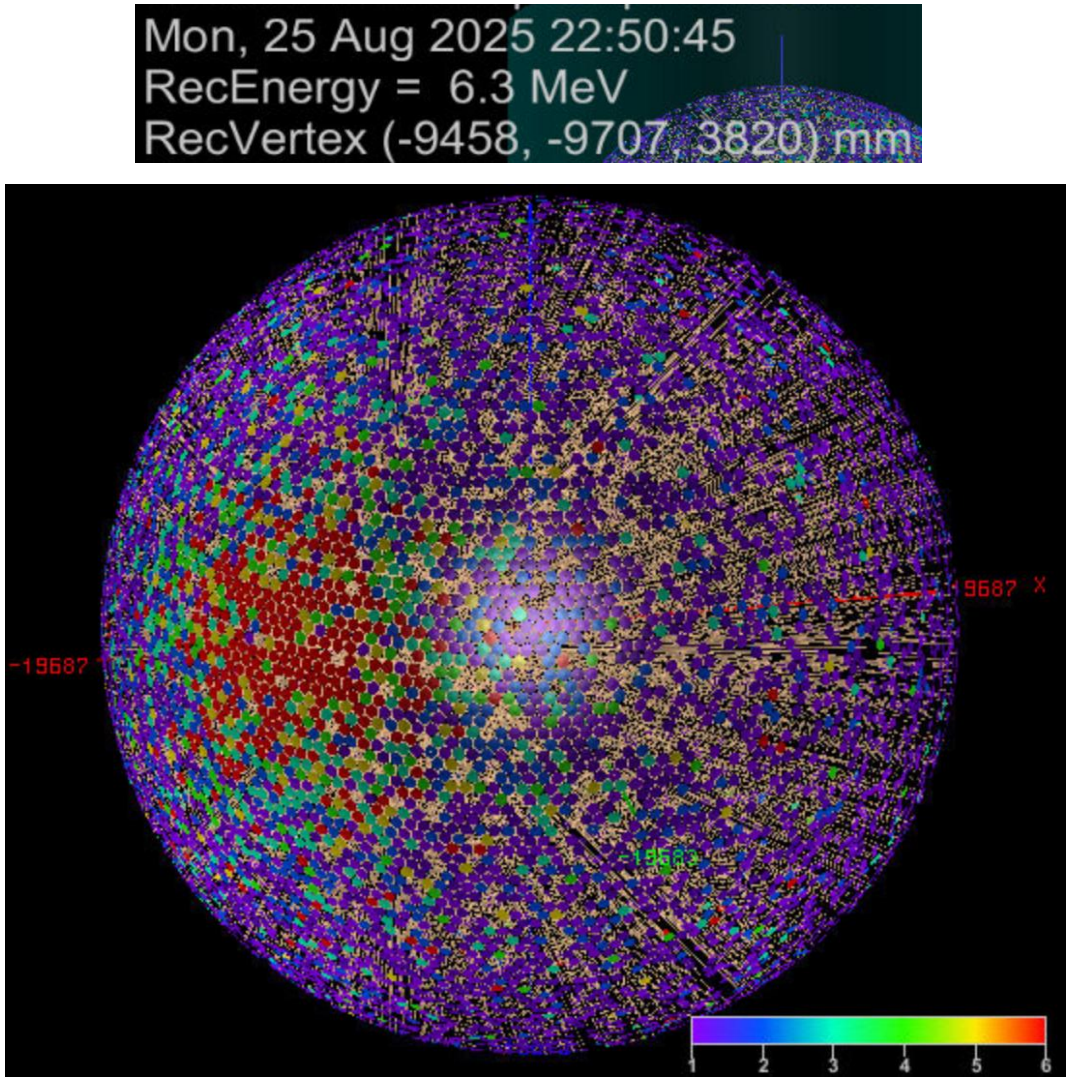




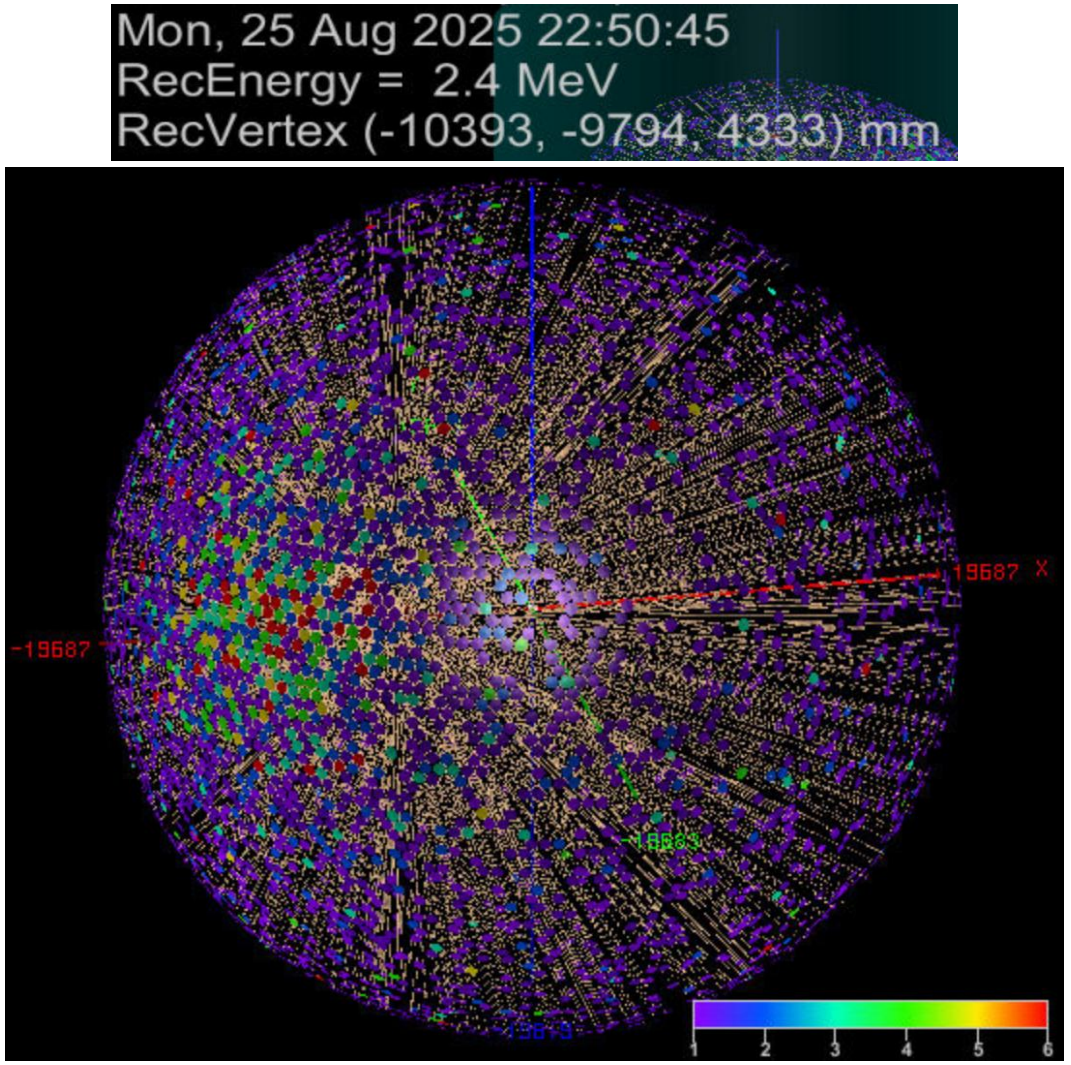
JUNO RESULTS



A Golden Reactor Neutrino Event



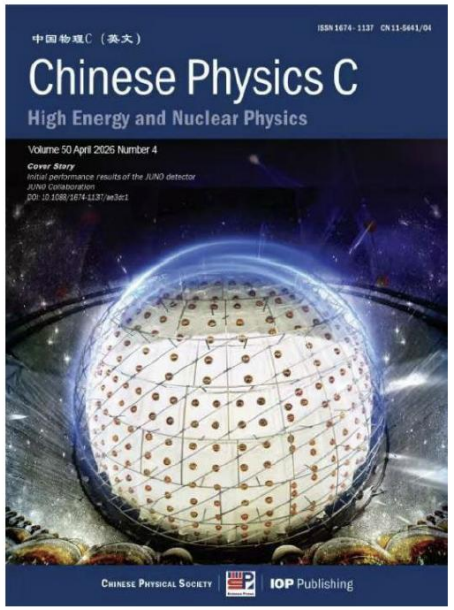
Prompt e+ signal



Delay neutron signal

November 2025: First results using 59 days of data released!

"***Initial performance results of the JUNO detector***"
CPC Vol. 50, No. 4 (2026) 043001



"***First measurement of reactor neutrino oscillations at JUNO***" Nature, Vol 654, 11 June 2026, 343



In this first release the 'solar" oscillation parameters measured with the best precision

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087 \quad \textbf{2.8\%}$$

$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \mathrm{eV}^2 \quad \textbf{1.6\%}$$

Good agreement with previous results! Precision improved of a factor 1.6

Today New Results using 207 days of data

"Measurement of Neutrino Oscillation Parameters at JUNO and Indication of the Neutrino Mass Ordering" arXiv:2609.37895v1 (2026)

Updated preliminary results released in June @ NEUTRINO 2026

"Measurement of Neutrino Oscillation Parameters at JUNO and Indication of the Neutrino Mass Ordering" arXiv:2609.37895v1 (2026)

- Consistent results from three independent analyses (starting from event reconstruction).
- Blinding strategy to conceal the oscillation parameters throughout the analysis.

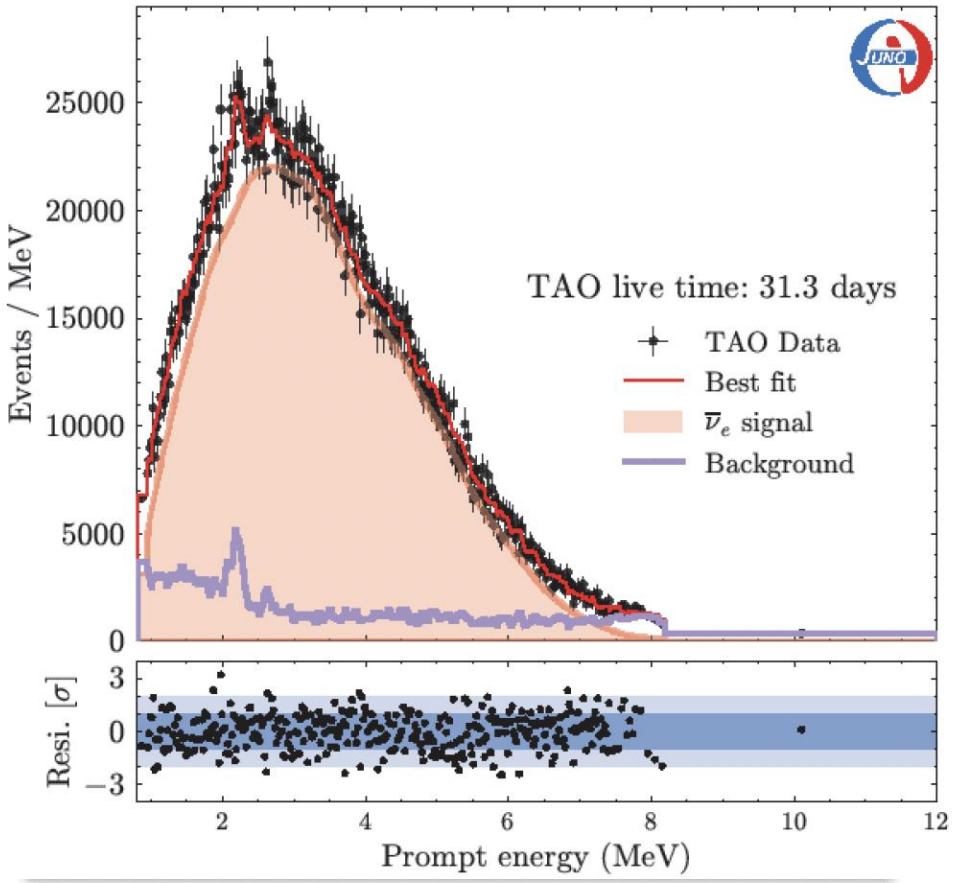
What is new in this analysis?

- TAO data included: unoscillated reactor spectrum
- More JUNO data! (207 days, August 30 2025 - May 24 2026 vs 59 days)
- More calibration -> better reconstruction
- 10% larger fiducial volume (R < 17.2 m vs 16.5 m)
- Better IBD selection
  - 60% reduction of cosmogenic ^{9}Li background
  - Suppression (factor 50) of accidental background at larger FV using likelihood cut
  - Model independent estimate of the 214BiPo- correlated background

February 2026: TAO online

Unoscillated reactor neutrino spectrum

- **REFERENCE FOR JUNO SPECTRAL FIT,**
- search for sterile neutrinos,
- improve nuclear databases.

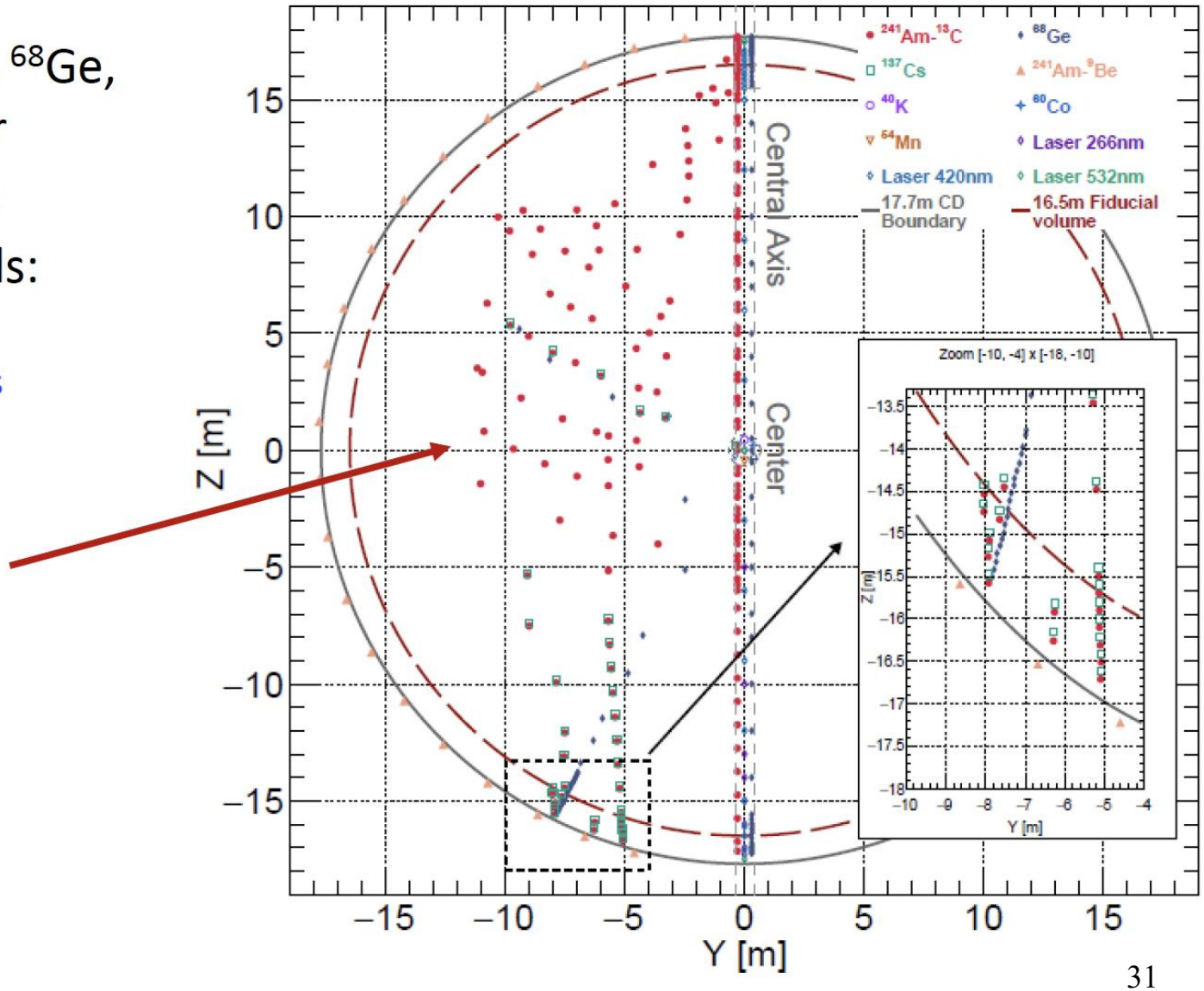




More JUNO calibration data

- 1D (central axis): ^{137}Cs, ^{54}Mn, ^{40}K, ^{68}Ge, ^{60}Co, Am-C, Am-Be, sensors, laser
- 2D (cable loop): Am-C, ^{68}Ge, ^{137}Cs
- 3D using cosmogenic backgrounds:
  - ⇨ Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

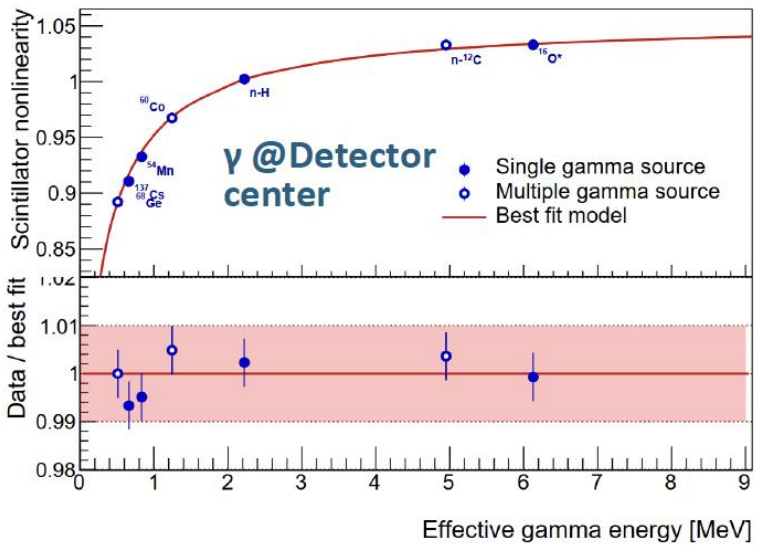
- Positions at which source calibration performed
- No ^{222}Rn leakage or other contaminations introduced during calibration

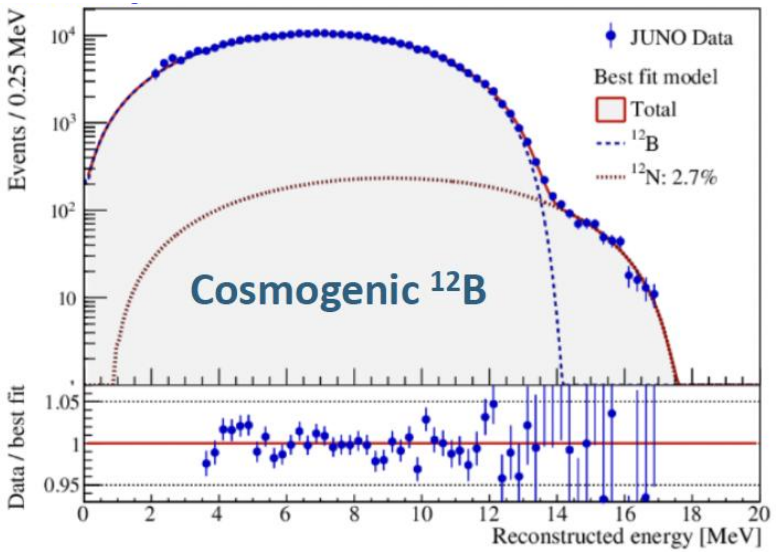


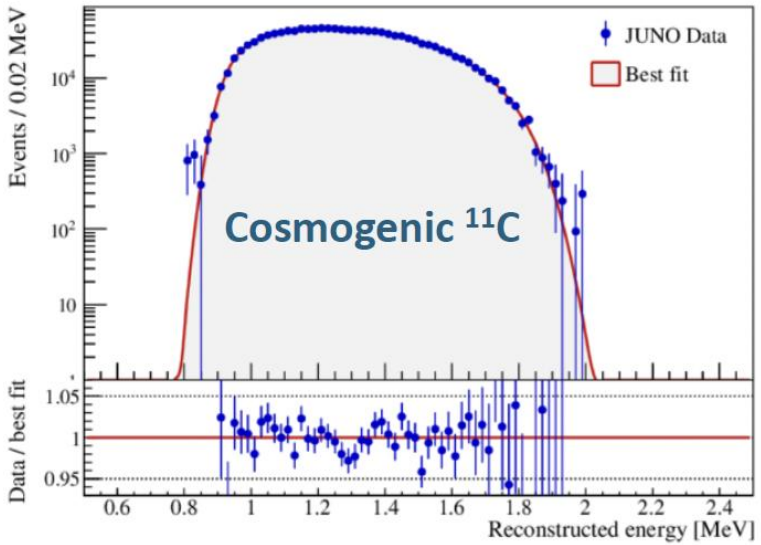
Energy Scale Non-linearity

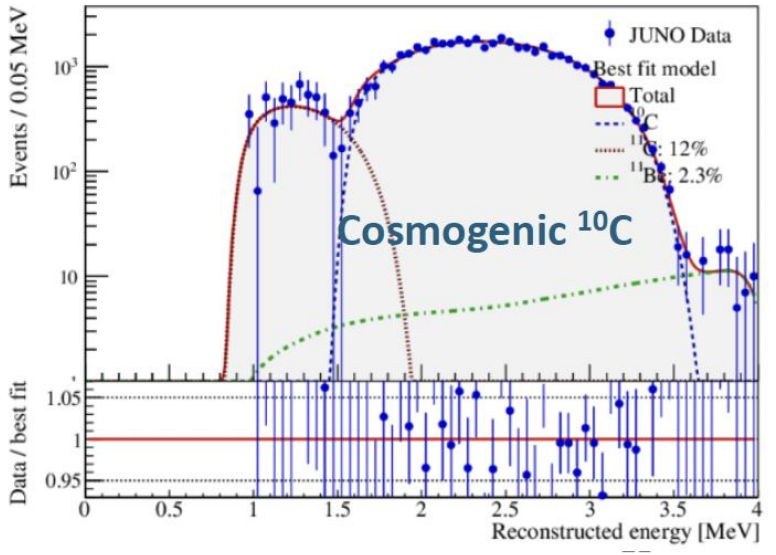
See also talk by T. Tměj on Saturday

arXiv:2609.37895v1 (2026)









<u>Energy scale is intrinsically non-linear and particle dependent:</u>

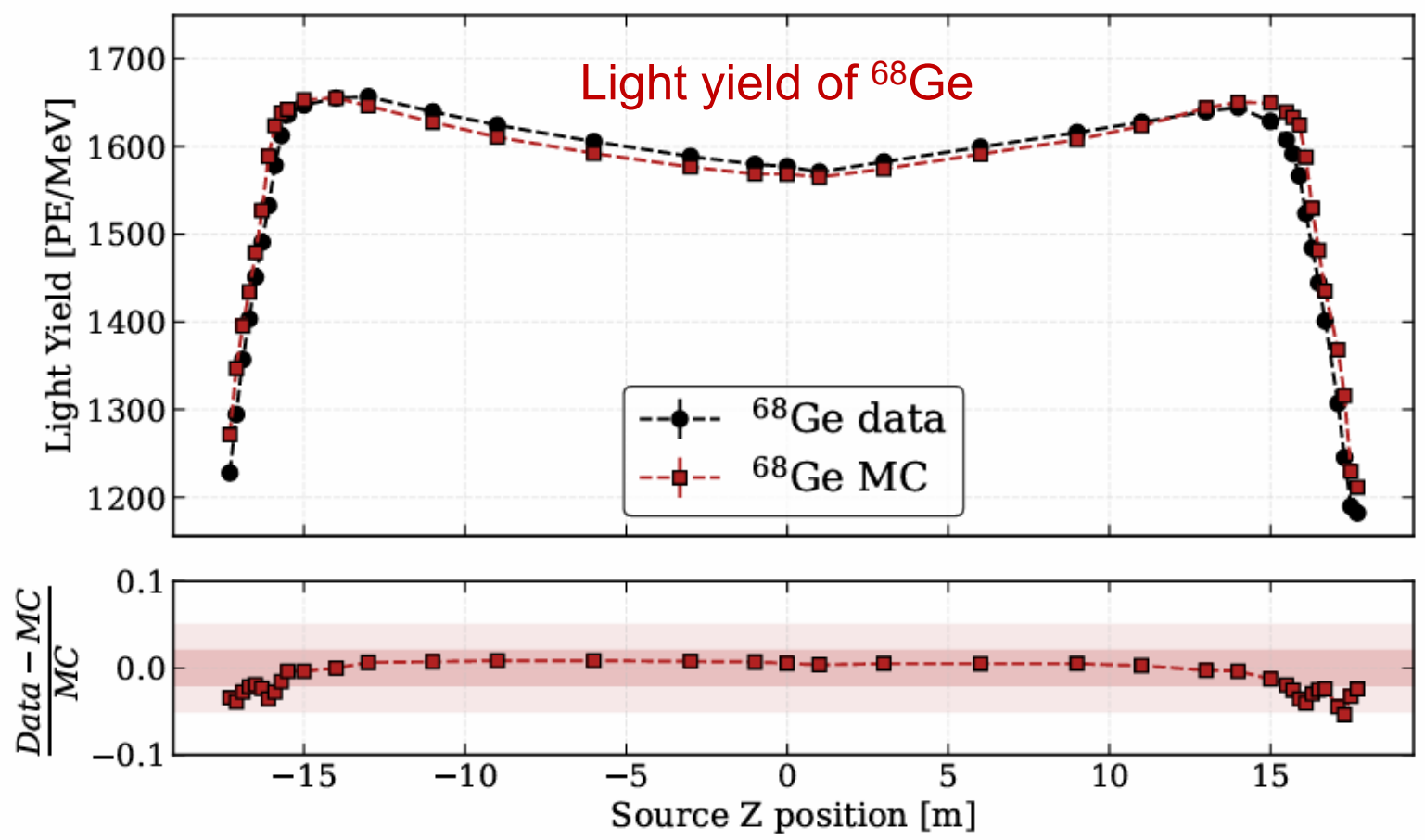
- ionisation quenching
- Cherenkov light
- minor: instrumental effects

Energy scale non-linearity is characterized with better than 1% precision

- gamma calibration sources
- cosmogenic ^{12}B (e^-)
- cosmogenic ^{11}C, ^{10}C (e^+)

Light Yield and Energy Resolution

- LY at the detector center is ~1600 PE/MeV for ^{68}Ge and ~1785 PE/MeV for n-H capture, in good agreement with MC simulations
- Energy resolution for ^{68}Ge is ~3.5% @ 2× 0.511 MeV at the center (expectation from MC was 3.1%)
- Energy resolution for alpha from ^{214}Po is ~2.9% @0.93MeV

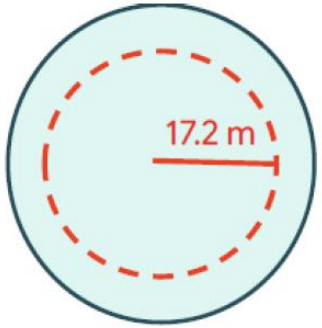


IBD Event selection

Enlarged!

Fiducial Volume cut

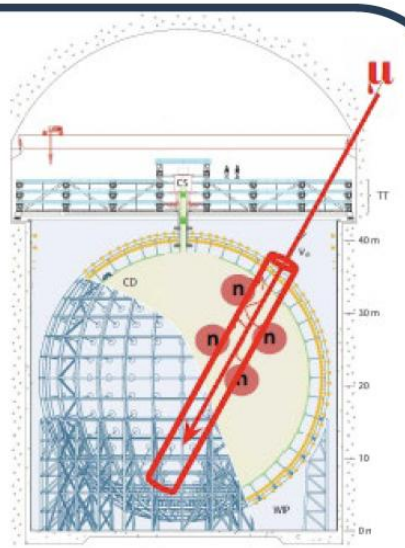
- To remove external radioactivity
- R<17.2 m +|z|<15.5 m



Improved!

Removal of muons and muon correlated events

- Veto after muon of 5ms (short lived + noise)
- Space/ time correlation with muon track and n (long lived cosmogenics);



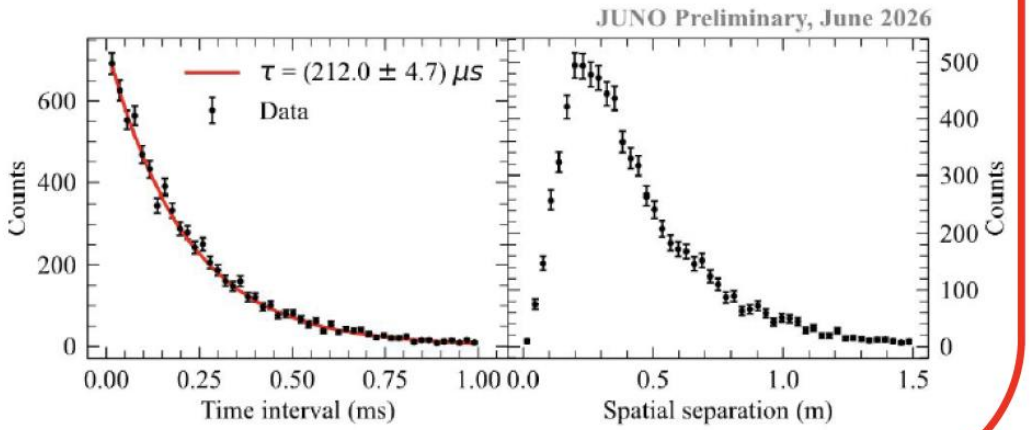
IBD selection (space+time+energy)

5μs <Δt < 1 msec

ΔR<1.5 m

0.7 MeV <E_{prompt} <12 MeV

2 MeV<,$E_{delayed}$ < 2.5 MeV

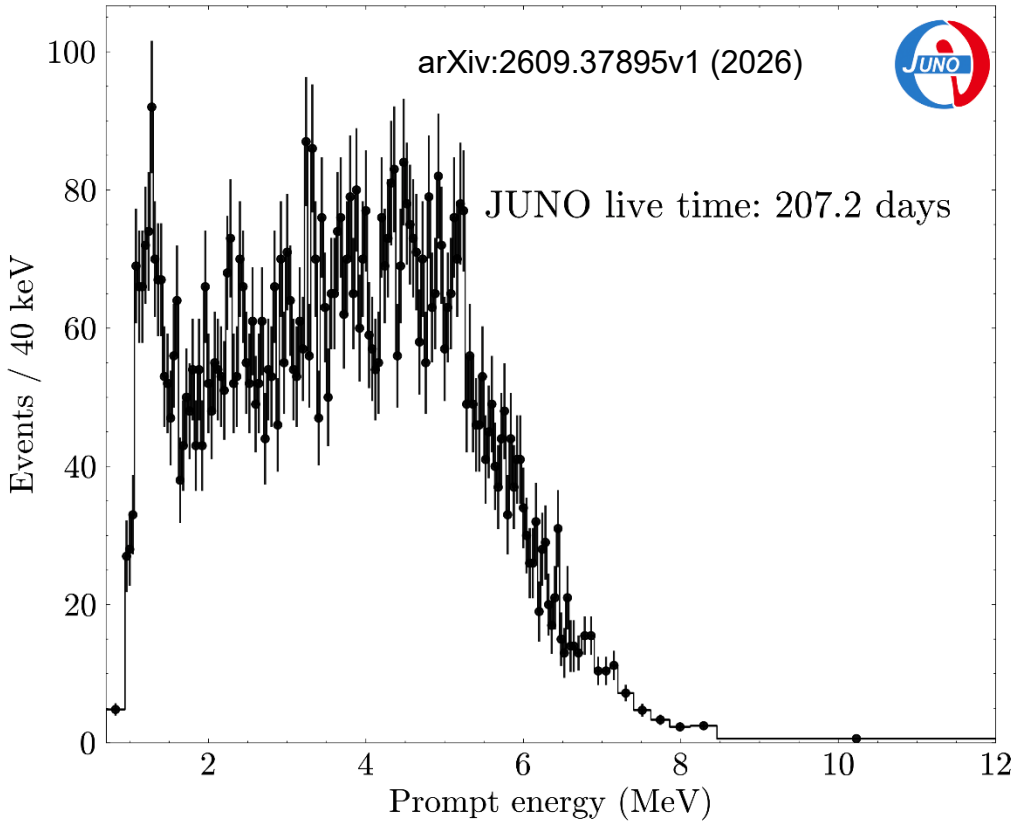


Efficiency of all the cuts ε_{tot} ~ 74%

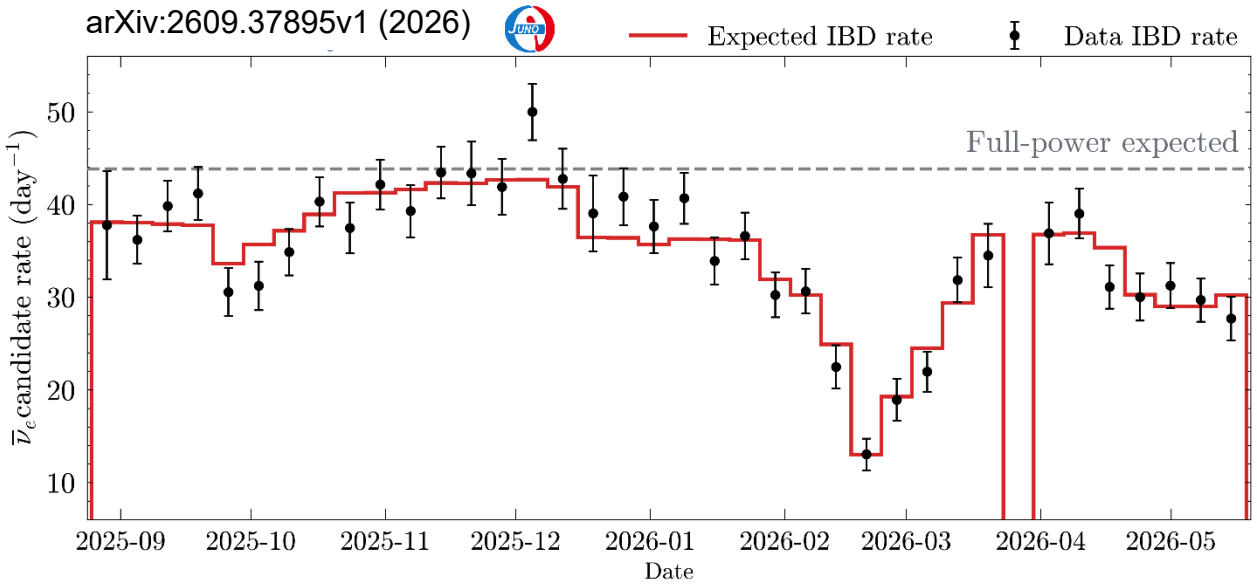
Total number of target protons in 20 kton: (1.442 ± 0.014) x 10^{33}

Selected IBD Candidates

N of $\bar{\nu}_e$ candidates = 8294 (~40 ev/day)

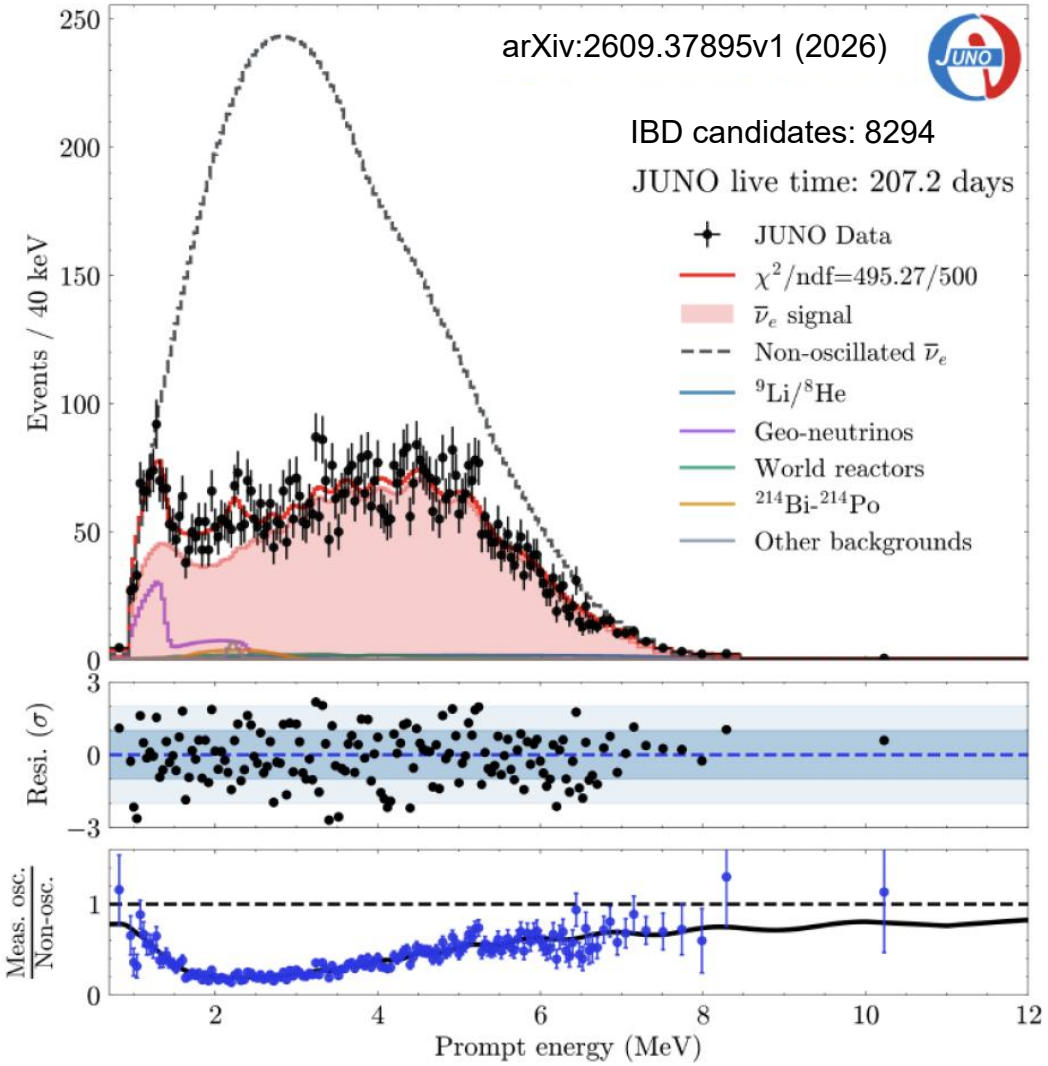


Time evolution of the background-subtracted IBD rate follows the expectations, based on the delivered power to nuclear power plants:



JUNO IBD prompt energy spectrum

Fitting constrained by the near detector spectra from TAO and Daya Bay



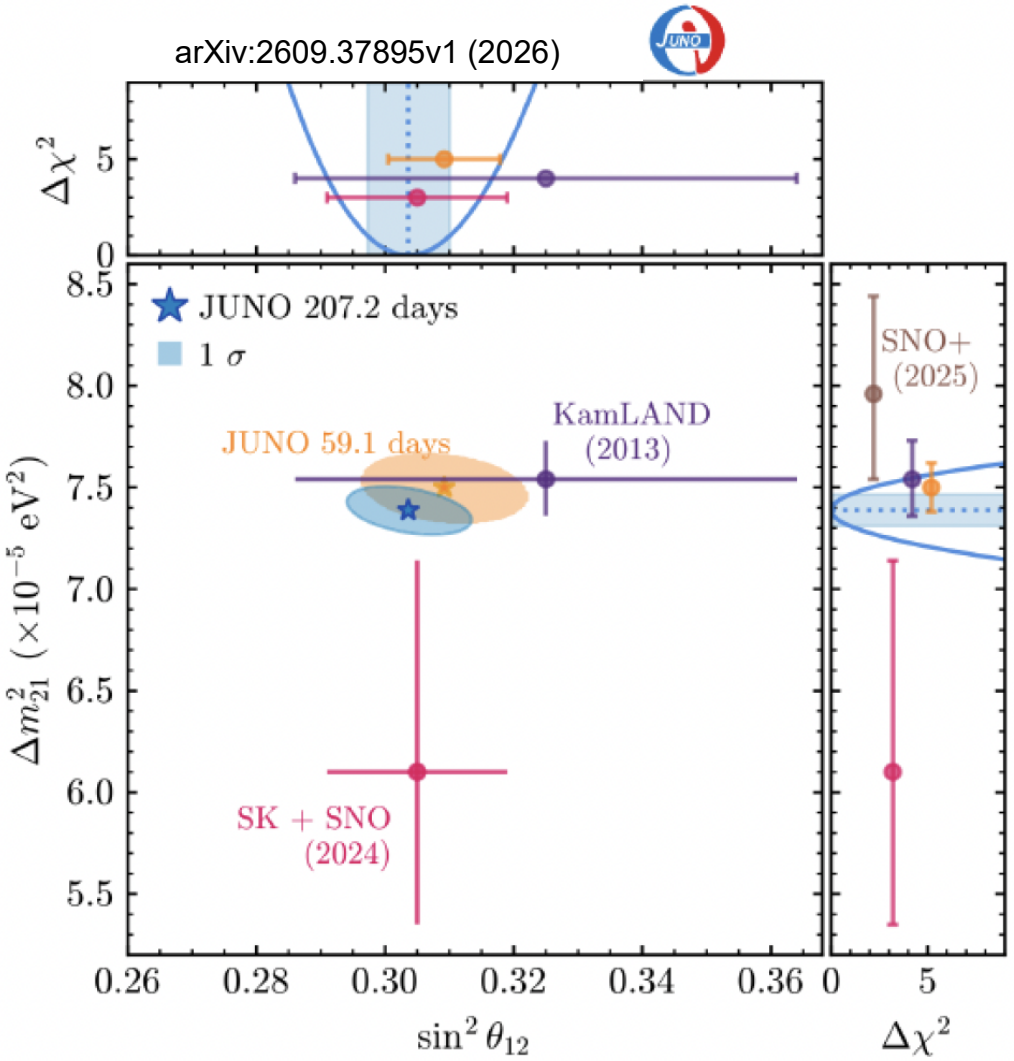
The signal and background RATES are

Reactor $\bar{\nu}_e$ (cpd)	**34.62 ± 0.64**

Backgrounds (cpd)	Best-fit
^{9}Li/^{8}He	1.41 ± 0.26
Geoneutrinos	2.12 ± 0.32
World reactors	0.92 ± 0.09
^{214}Bi-^{214}Po	0.57 ± 0.34
^{13}C(α, n)^{16}O	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02
Double neutrons	0.13 ± 0.10
Atmospheric neutrinos	0.11 ± 0.05
Accidentals	0.07 ± 0.01

New results on solar oscillation parameters

Improved precision with respect to JUNO "Nature" paper



Fit results for 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%)

2.5% (PDG 2025)
3.9% (PDG 2025)

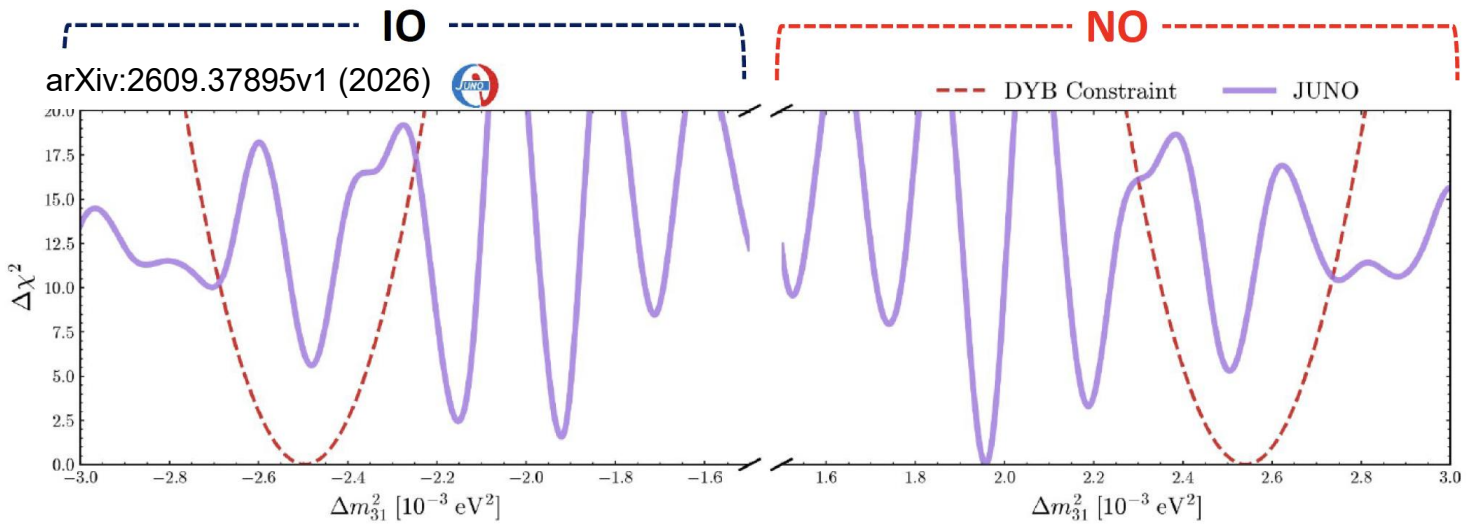
World's best precision

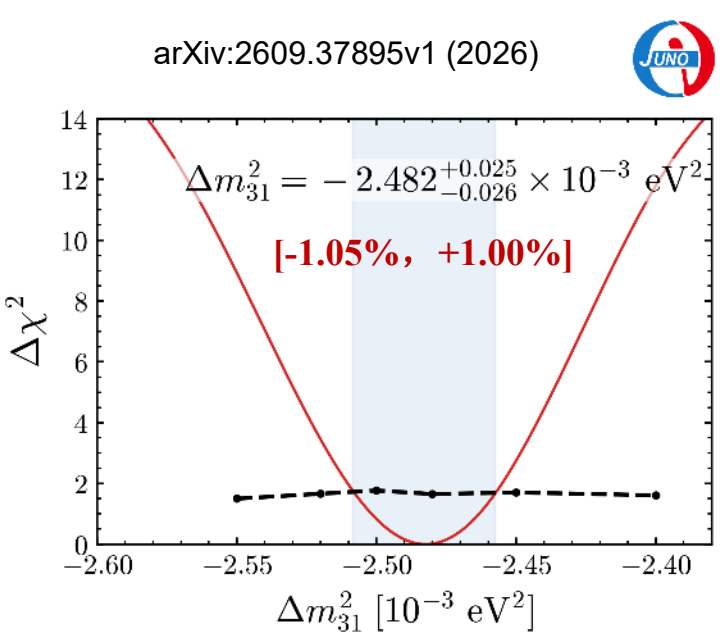
First Result of Δm^2_{31}

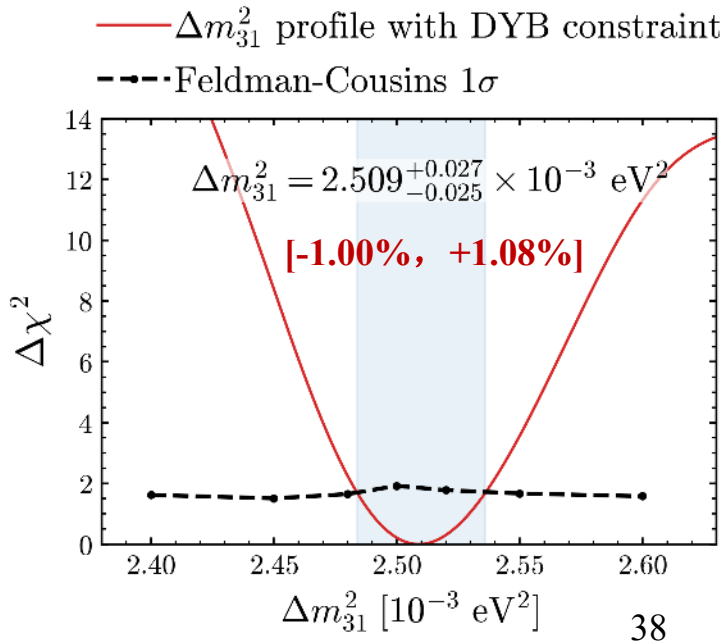
Due to statistical fluctuations, JUNO-only profiles of Δm^2_{31} have **multiple minima.**

Daya Bay result Δm^2_{31} constraint (PRL 130 16, 161802) allows us to focus on one minimum for each mass ordering.

Feldman-Cousins (FC) method is used to determine the 1σ range of Δm^2_{31}: ~1% precision achieved



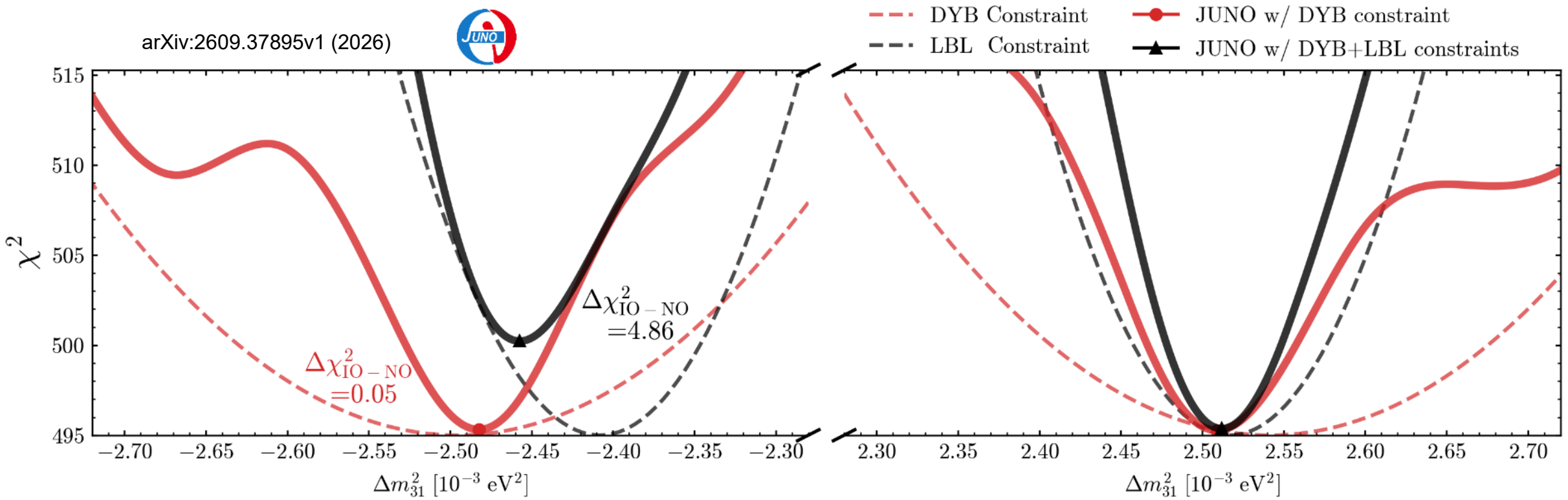




Adding Constraint from NuFit-LBL

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)

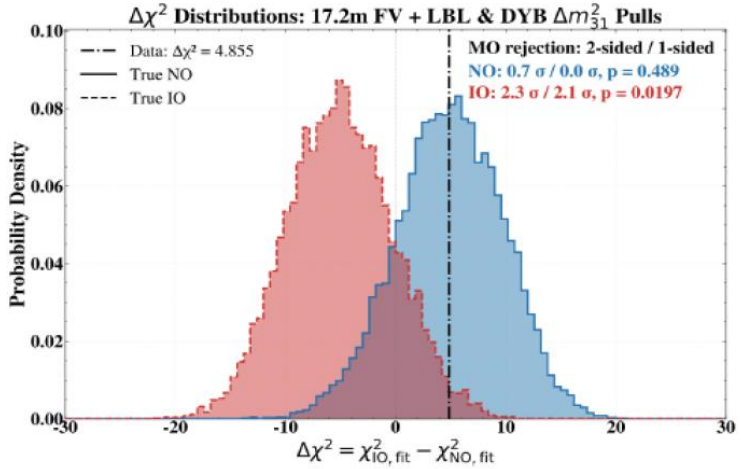
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Neutrino Mass Ordering Significance

QUANTITATIVELY: significance calculated with both Frequentist and Bayesian approach

Frequentist

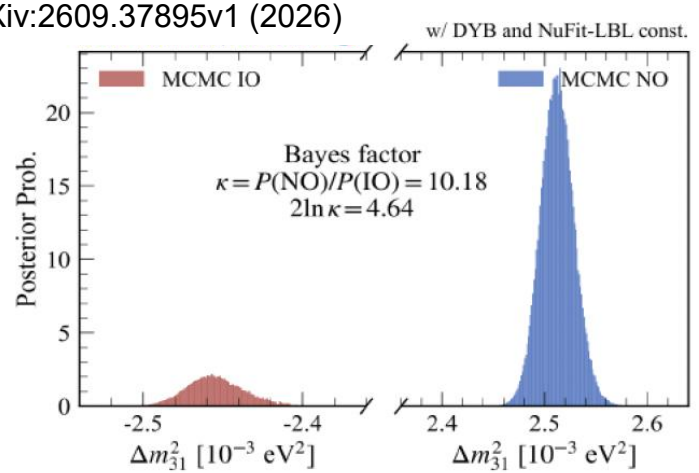
arXiv:2609.37895v1 (2026)



- Inferred with generation of many pseudo-experiments;
- **Normal Ordering preferred at 2.3σ (2 sided)**

Bayesian

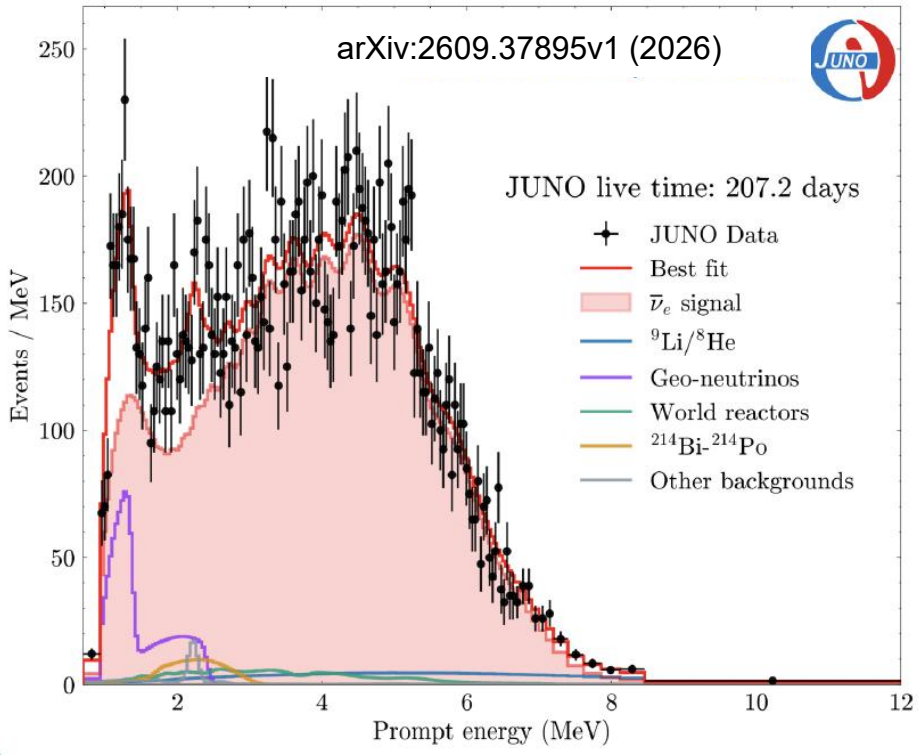
arXiv:2609.37895v1 (2026)



- Inferred through Markov-Chain Montecarlo (MCMC);
- **Normal Ordering preferred with Bayes Factor of 10.18**

→ Preference for the Normal Ordering scenario

JUNO results on geoneutrinos



Terrestrial Neutrino Unit

1 TNU = 1 IBD event / 10^{32} target protons / year

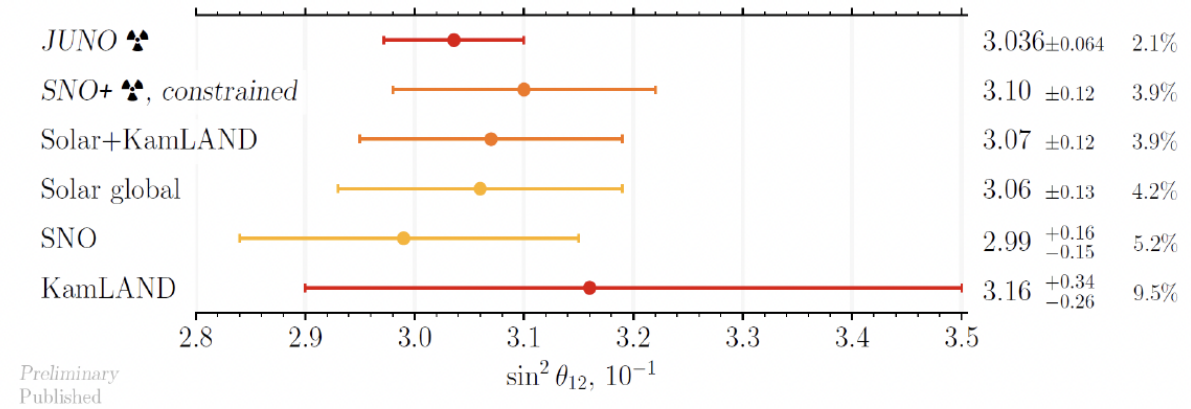
(cca 1 IBD event / 1 kton of liquid scintillayor / 1 year)

with 100% detection efficiency

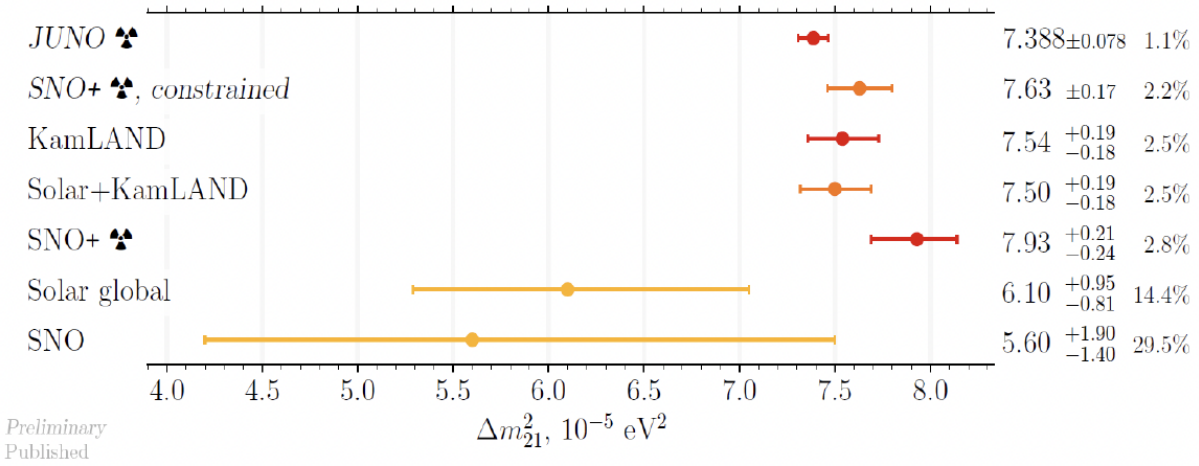
- Fits are performed without constraint on geo-neutrino flux, but with 3.4 ± 10% U/Th chondritic ratio.
- Constraining the geo-nu flux within geological model predictions doesn't change oscillation results.
- Clear geo-nu signal at 1-3 MeV, giving a flux of 73 ± 11 TNU
- Largest geo-neutrino sample so far.
- JUNO result is higher than expectation from existing models, but not statistically significant.
- Need more JUNO data and more refined geological model predictions.

Comparison with existing results

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

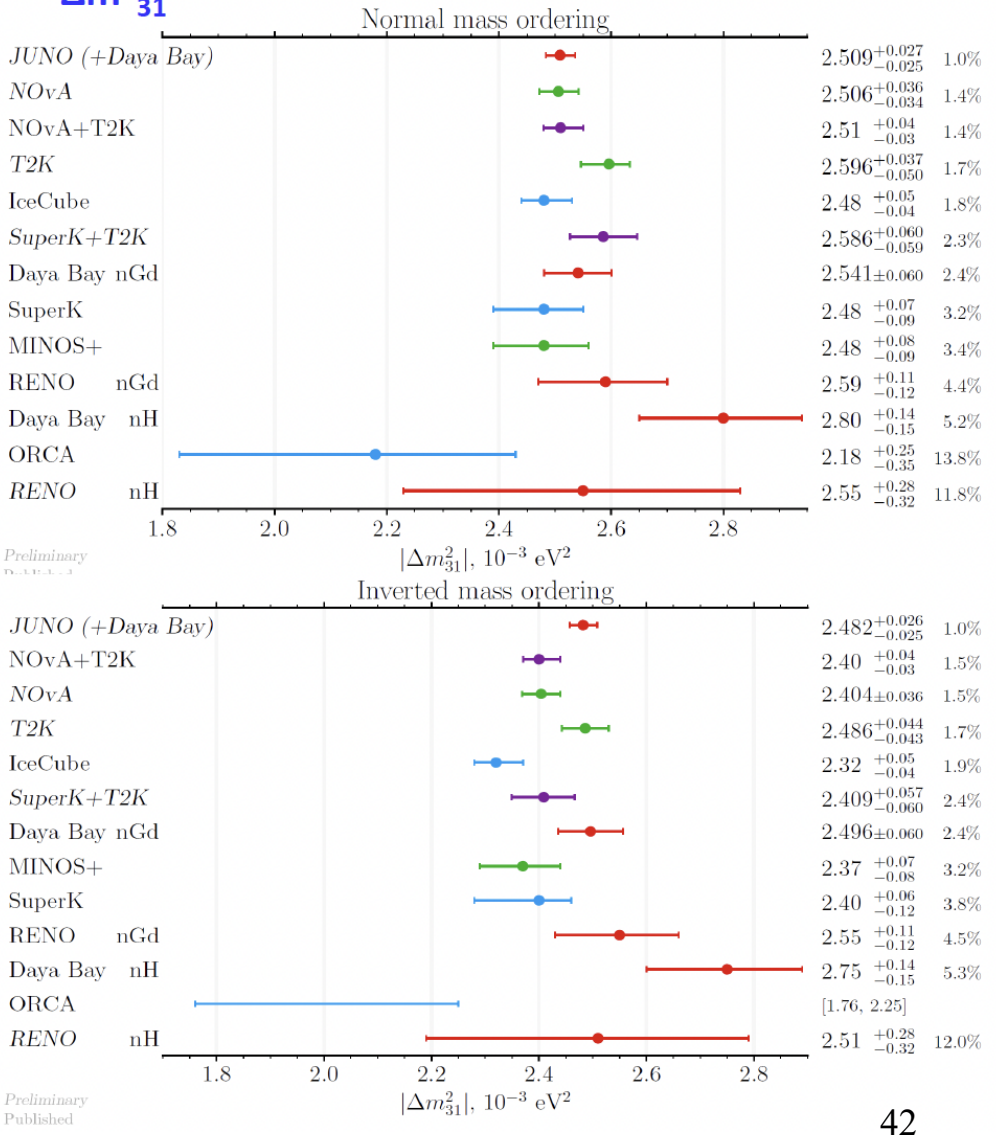


Δm^2_{21}



Results from JUNO have smallest uncertainties

Δm^2_{31}



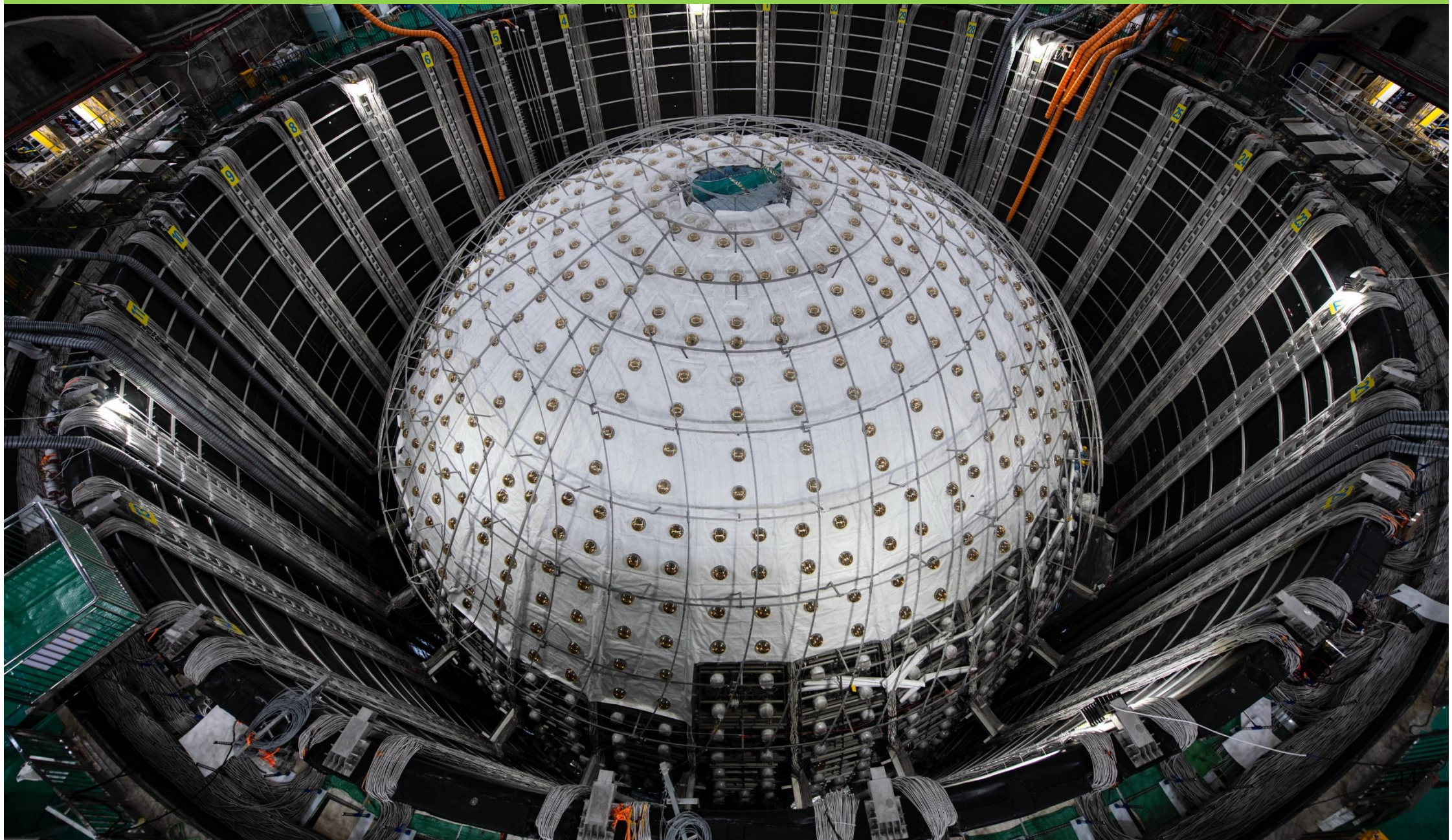
Summary

- After 13 years of effort, the JUNO and TAO detectors have been successfully completed and are operating smoothly.
- The initial JUNO performance results show that the detector is working well and largely as designed.

- **The first 59 days** of reactor-neutrino data already established JUNO as a **world-leading experiment in the precision measurement of solar oscillation parameters**.

- **The 207-day** dataset provides further improvements in precision: $\boldsymbol{\Delta m^2_{21}: 1.06\%, \sin^2\theta_{12}: 2.1\%.}$
- Combining JUNO + JUNO-TAO + Daya Bay achieves world-leading precision of about **1% on $\boldsymbol{\Delta m^2_{31}}$**.
- **Normal mass ordering (NO) is favored at 2.3σ** when additional constraints on Δm^2_{31} from Daya Bay and long-baseline (LBL) accelerator experiments are included.
- **The first geoneutrino measurement** achieves a precision of approximately 15%, with a relatively high measured signal.

Thank you for your attention.



BACKUPS

Neutrino mixing parameters

PDG data 2025 – before JUNO

Parameter	Value	Precision
$sin^2(\theta_{12})$	0.307 ± 0.012	3.9%
Δm^2_{21}	$(7.50 \pm 0.19) \times 10^{-5}\ eV^2$	2.5%
$sin^2(\theta_{23})$	$0.534^{+0.015}_{-0.019}$	3.2%
Δm^2_{32}	$(2.527 \pm 0.034) \times 10^{-3}\ eV^2$	1.3%
$sin^2(\theta_{13})$	0.0216 ± 0.0006	2.8%

JUNO aims

- In 2 years $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ precision → unprecedented < 1% level
- In 6 years $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ precision → 0.5%, 0.3% and 0.2%

Neutrino mass constraints

Neutrino oscillations - Inverted ordering	Σm_ν	> 0.10 eV
- Normal ordering	Σm_ν	> 0.059 eV
Cosmology	Σm_ν	< 0.0642 eV
Beta decay	$m_\beta = \sqrt{\sum_i \lvert U_{ei}\rvert^2 m_i^2}$	< 0.45 eV
Double beta decay	$m_{\beta\beta} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	< 0.028-0.122 eV

Why pursue ever higher precision?

- Determine the neutrino mass ordering and constrain the mass scale.
- Search for deviations from the standard 3-neutrino paradigm.
- Guide the design of future neutrino experiments.
- Constrain and discriminate between theoretical models.

Neutrino oscillations provide the only direct evidence for non-zero neutrino masses and establish lower bounds on the masses of the heavier eigenstates.

MAJOR INPUTS TO THE SPECTRAL FIT

Unoscillated reactor spectrum and flux (constrained in the fit)

- Hueber –Mueller prediction
- TAO data + detector response
- Daya Bay near detector data + detector response (PRL 130 16, 161802)
- Reactors time dependent thermal power, fission fractions, and baselines.

Oscillation physics

- Free: $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31}
- $\sin^2\theta_{13}$ constrained by Daya Bay
- Matter effects included

IBD and normalization

- Energy-dependent IBD cross section
- Number of target protons
- Live time and selection efficiency

Detector response matrix

- Energy scale and nonlinearity
- Energy resolution
- Spatial nonuniformity
- Time-dependent stability
- Analytical treatment of ^{14}C pile-up

Other spectral components

with shape and rate uncertainties

FREELY FITTED MAJOR COMPONENT

Geoneutrinos: U/Th ratio constrained to chondritic value with 10% error

MAJOR CONSTRAINED BACKGROUNDS

$^9Li/^8He$ and $^{214}Bi–^{214}Po$ from data
World reactors from simulation and reactor-operation data

MINOR BACKGROUNDS

$^{13}C(\alpha,n)^{16}O$, fast and double neutrons, atmospheric neutrinos and accidentals

Spectral fit

Predicted oscillated prompt-energy spectrum.

Likelihood fit to JUNO data

Nuisance parameters encode systematic constraints

Normal and inverted ordering are fitted separately

Output:

Signal and background rates

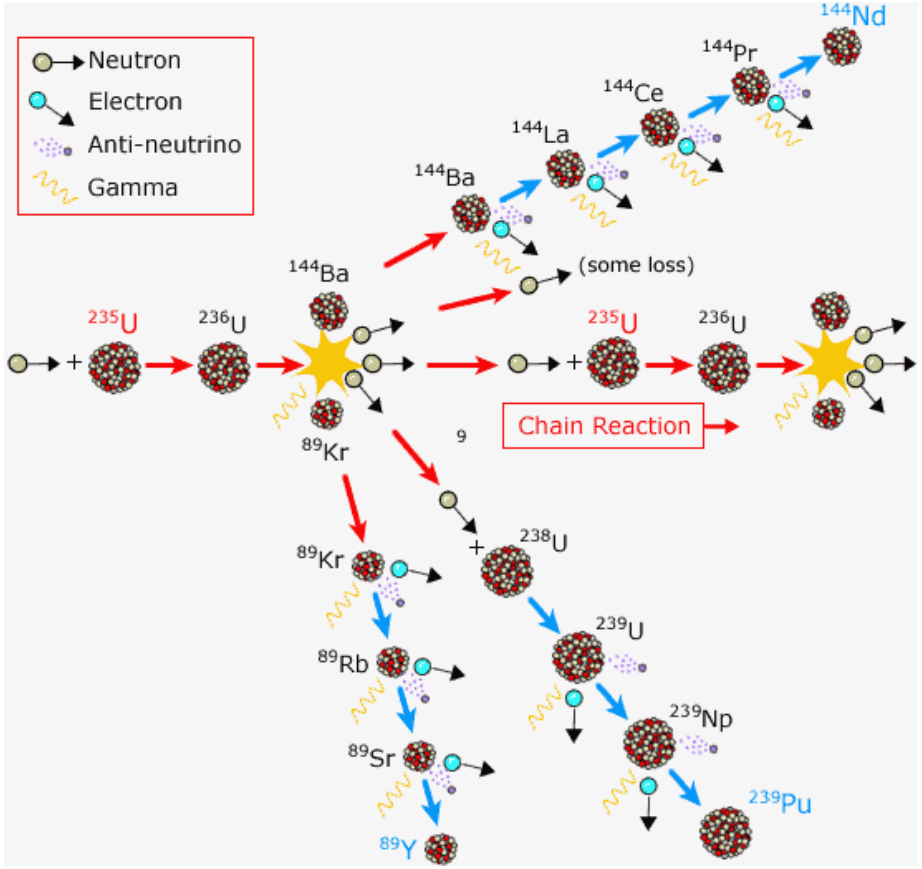
Oscillation parameters

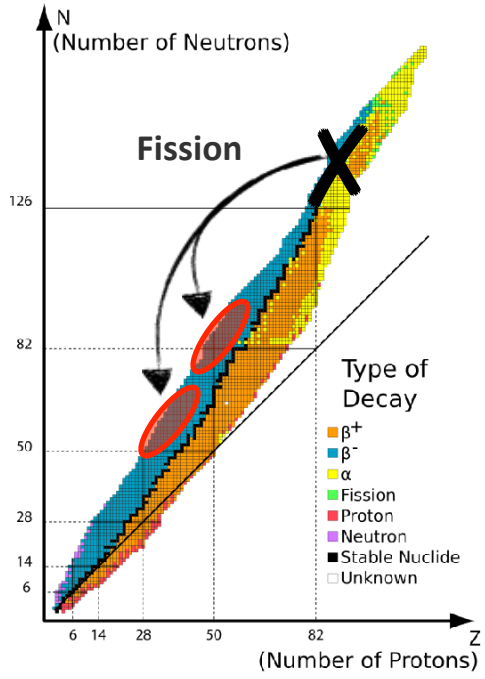
Production of reactor neutrinos

Nuclear reactors are a flavor-pure, widely available, cost-effective, extremely intense and well-understood source of electron antineutrinos



~10^{20} ν_e /GW_{th} / s





- Fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- β-decay of neutron rich products

$n \rightarrow p + e^- + \nu_e$

February 2026: TAO online

Novel technology:

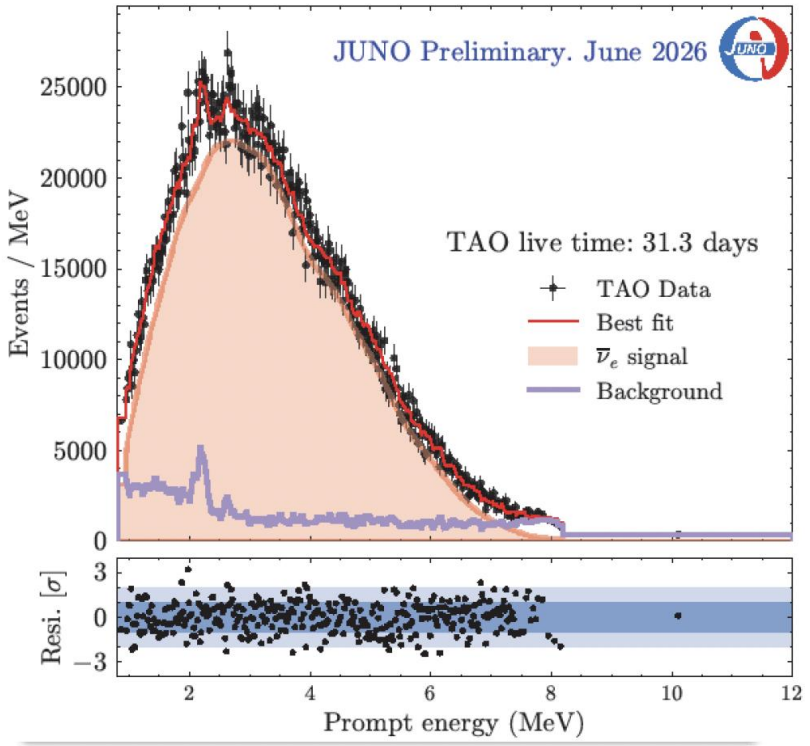
- ✓ SiPM (94% coverage)
- ✓ 2.8 ton of Gd-loaded LS @ -50°C
- ✓ **44 m from 4.6 GW_{th} Taishan 1 core – unoscillated spectrum**
- ✓ 4500 p.e./MeV
- ✓ Energy resolution: <2%/√E
- ✓ 1000 IBD / day

To measure unoscillated reactor neutrino spectrum

- ✓ Better resolution to constrain fine structure and spectral shape.
- ✓ **REFERENCE FOR JUNO SPECTRAL FIT**

Improve nuclear databases, search for sterile neutrinos.



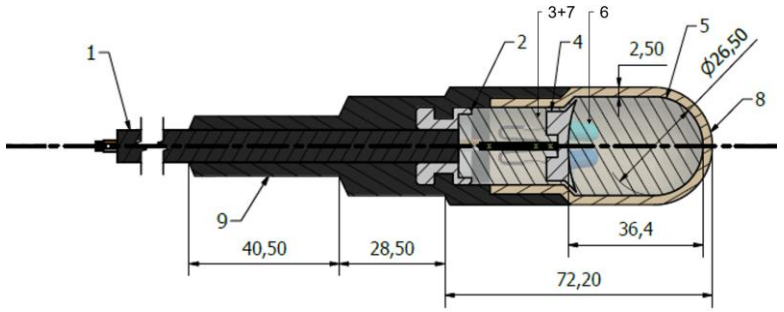


Water Pool PMT Calibration System

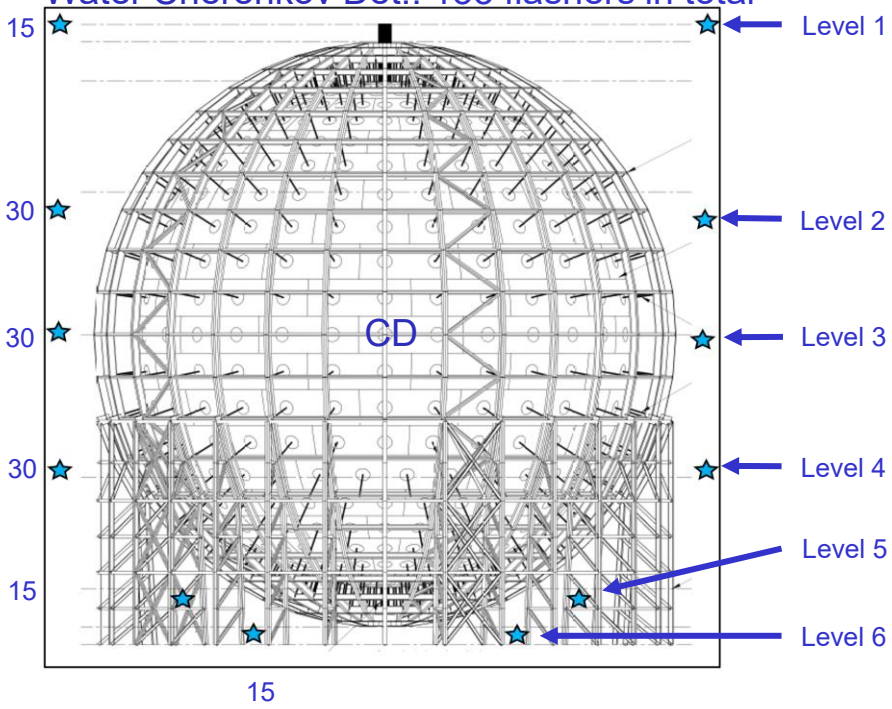
Timing calibration and gain monitoring – system of nanosecond light pulse sources.

- A total of 135 LED flashers are installed in the JUNO Water Cherenkov Detector.
- Each flasher is equipped with four different LEDs.
- 4 flashers are used for light attenuation measurement in WP.
- 15 flashers are in TAO Water Tanks.





Water Cherenkov Det.: 135 flashers in total



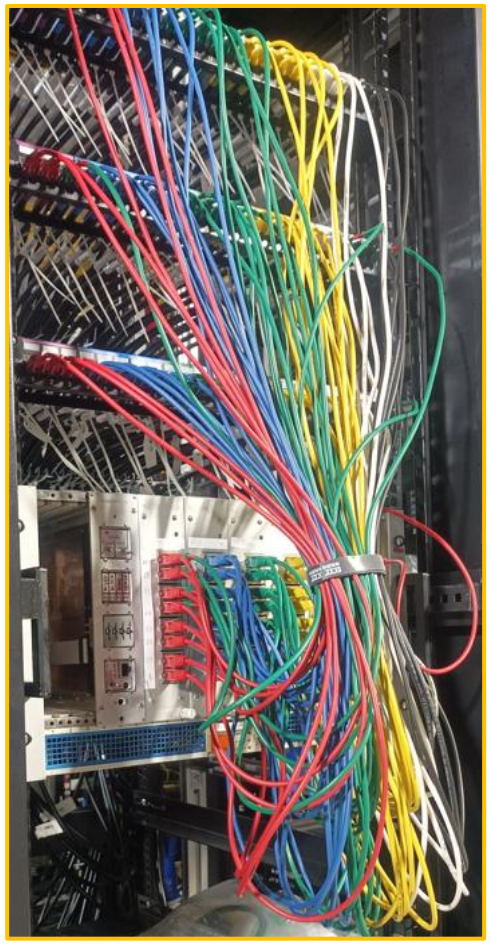
Requirements for the flashers

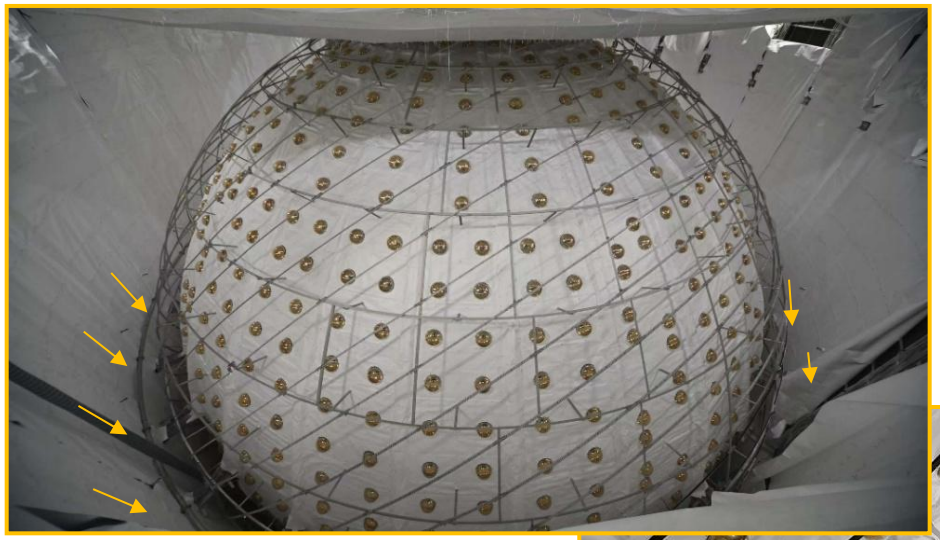
- Electronic – light pulse timing better then the PMT TTS, on the order of ~ns
- Optical – isotropic emission within +/- 10%, adjustable intensity
- Chemical – stability in ultra-pure (UP) water, with no water contamination
- Radiopurity

The biggest challenge was to ensure waterproofness and reliable functionality throughout the entire lifetime of the experiment, with no possibility of repair in 40m depth of UP water.

Installation of LED flashers

Nov.-Dec. 2024 – the 135 flashers installed in Water Pool.



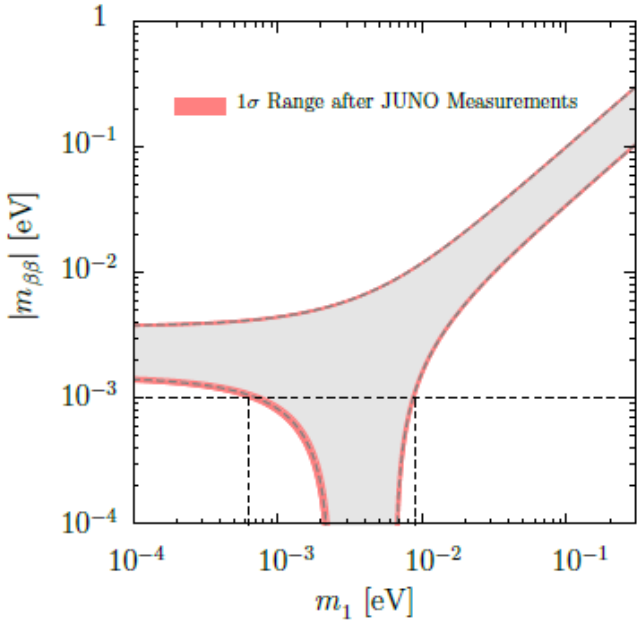






Neutrino Physics Prospects

- In 5 years from now, Nova, T2K, SuperK, ORCA, Icecube, JUNO are likely to constrain the mass ordering to very high significance
- In 10 years from now, DUNE, HyperK are likely to determine the CP phase to high precision
- 0νββ decay will be the next breakthrough



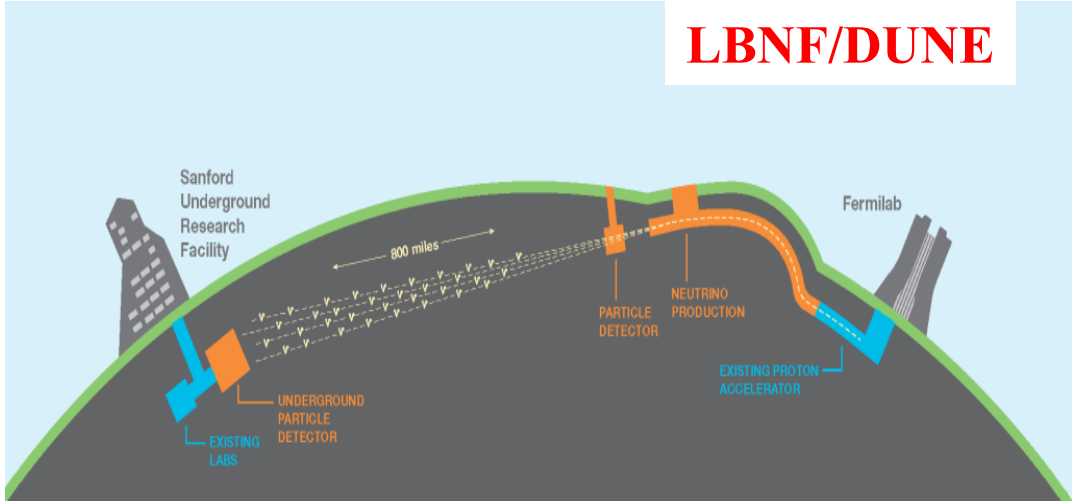
J. Cao et al., arXiv:1908.08355

- **Hints from cosmology: < ~1 eV**
- **Guess from Oscillation: ~1 meV**
- **Katrin will probe to ~ 0.2 eV**

$$(m_{\nu_e})^{eff} = [\Sigma_i \, | U_{ei} |^2 \, m^2_{\nu_i}]^{1/2}$$

- **0ν ββ decay should target for ~ 1meV**

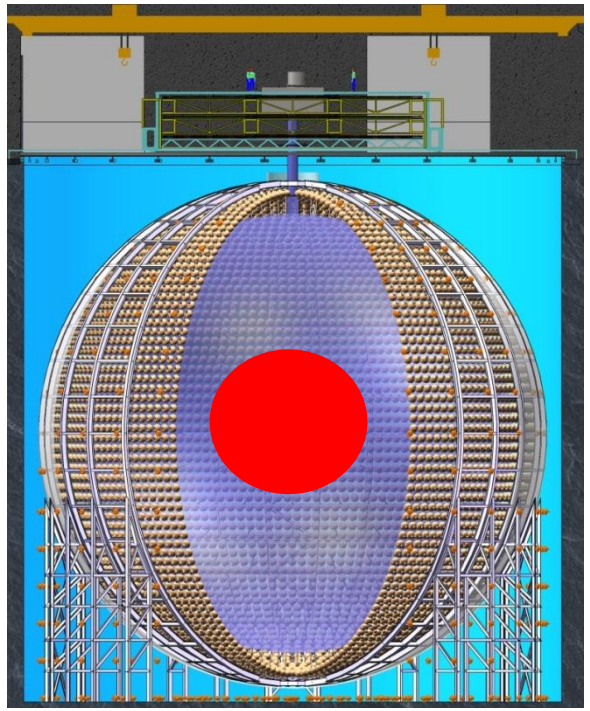
$$| M_{\beta\beta} | = | \Sigma_i \; (U_{ei})^2 \, m_{\nu_i} |$$



Future JUNO Upgrade to JUNO-ββ

- Once mass ordering is determined (~2030), JUNO will be upgraded for ββ-decays, in addition to existing capabilities
- Cosmogenic backgrounds can be removed by a cut of LS volume along the muon track for seconds

	Isotope	Mass(t)	$<m_{\beta\beta}>$,meV
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
Darwin/Panda-nT	^{136}Xe	3-5	7-22
LEGEND-1000/CDEX-1t	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO-ββ	^{136}Xe	50	4-10
	^{130}Te	100	3-14



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

Zhao et al., arXiv: 1610.07143, CPC 41（2017）5