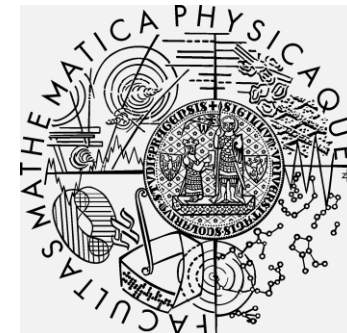




Recent Results from Neutrino Experiment JUNO



Vít Vorobel on behalf of JUNO collaboration
Ústav částicové a jaderné fyziky, MFF UK



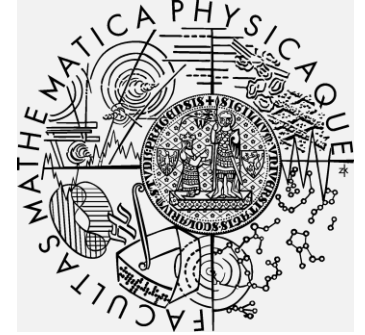
Co-funded by
the European Union





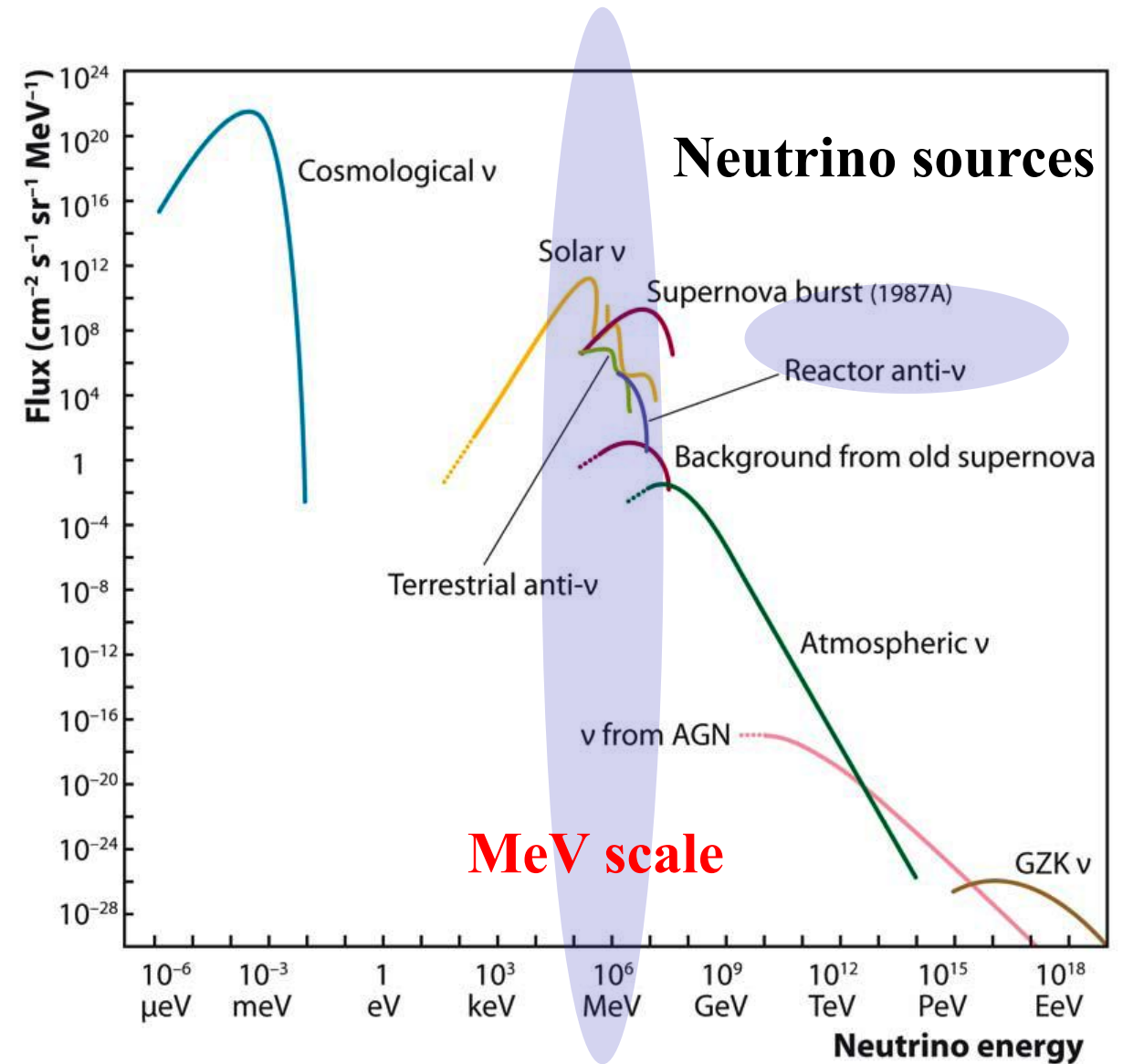
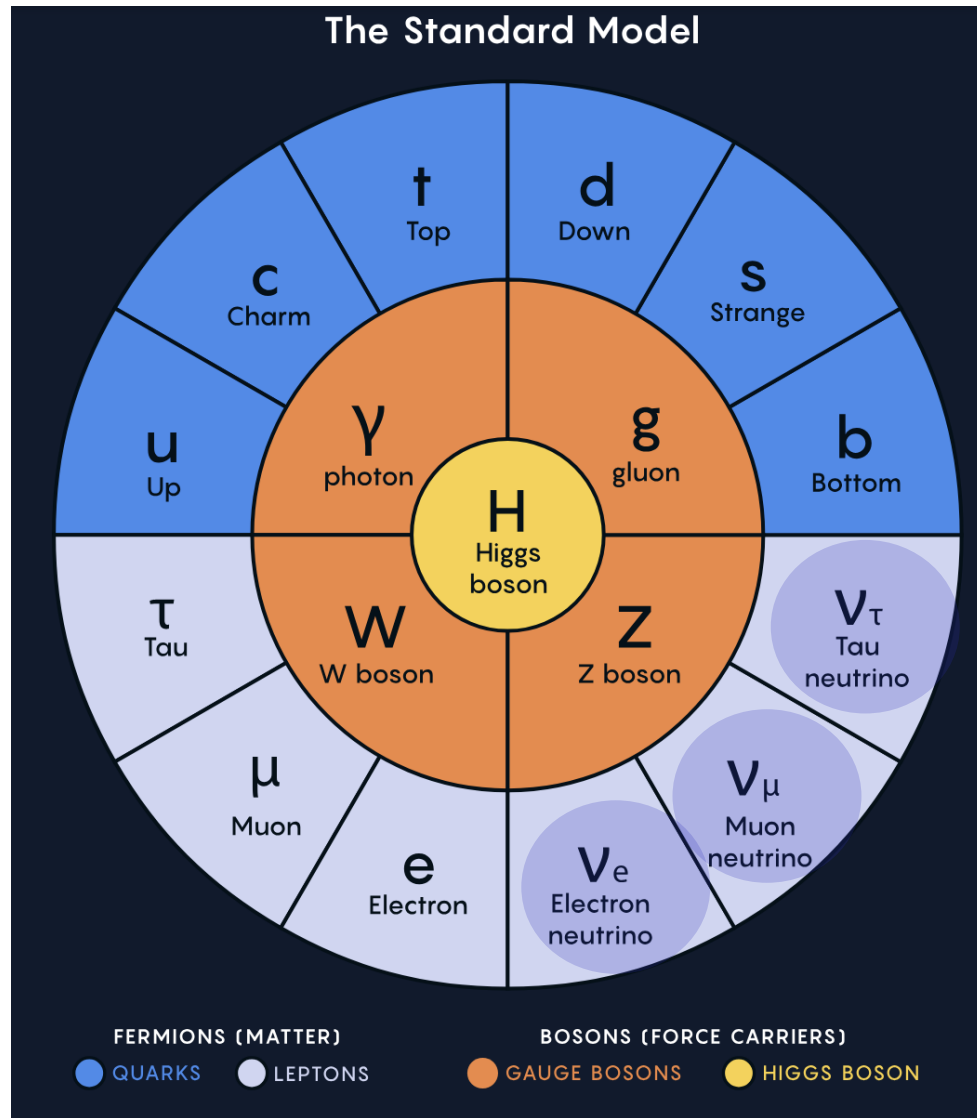
Outline

- Neutrino mixing
- Neutrino mass
 - β -decay, $0\nu 2\beta$ -decay, cosmology, ν -oscillations
 - Constraints on neutrino parameters
- JUNO
 - Physics aim, requirements, design
 - Multipurpose neutrino experiment
 - Construction
 - Results
- Future JUNO- $\beta\beta$



NEUTRINO INTRODUCTION

Neutrinos



Neutrino milestones

- **1930 Pauli** – postulates light neutral particle, spin $\frac{1}{2}$, in β -decay
- 1937 Majorana – what if $\nu = \text{anti-}\nu$?
- 1956 Reines, Cowan – observation of reactor anti- ν
- 1957 Pontecorvo – hypotesis of neutrino oscillation
- 1968 Davis – solar neutrino observation (deficit)

- many experiments, big effort

- 1998 Super-Kamiokande – oscillation of atmospheric ν
- SNO – precision measurement of solar neutrino oscillation
- 2012 Daya Bay – short baseline reactor neutrino oscillation

.....

□ **96 years later**

- CP? Hierarchy? Majorana? Mass? Why so small? ...



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

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric } \theta_{23} = 45^\circ} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor } \theta_{13} = 9^\circ} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar } \theta_{12} \approx 34^\circ} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{Majorana } 0\nu\beta\beta}$$

Neutrino mixing complete information (9 parameters):

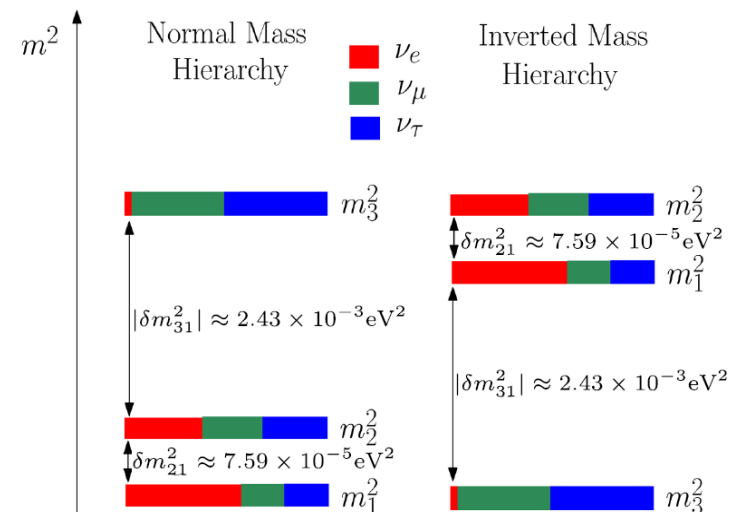
- Mass (3)
- Mixing angle (3)
- Dirac phase (1)
- Majorana phase (2)

m_1 m_2 m_3

θ_{12} θ_{23} θ_{13}

δ

α_1 α_2



NEUTRINO MASS

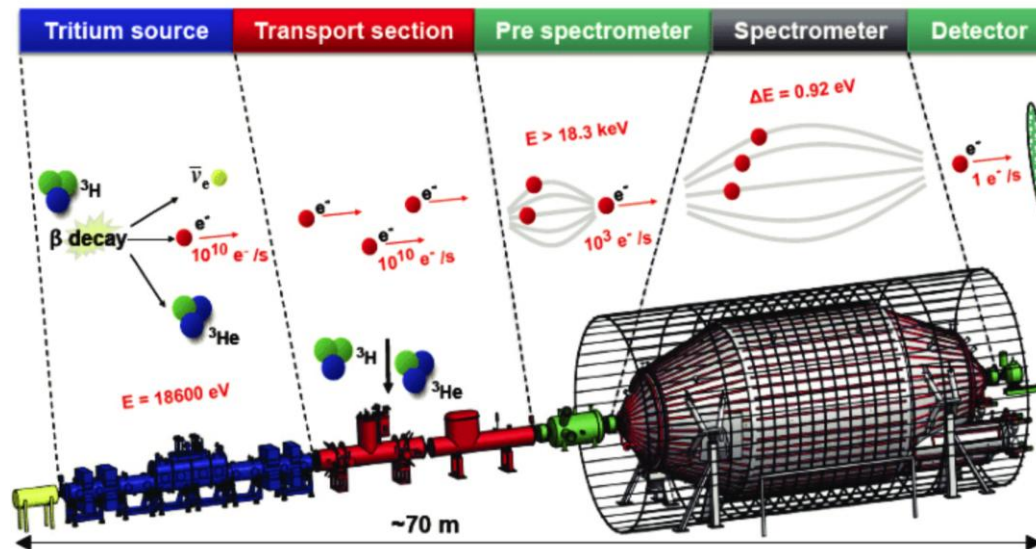
Kinematic measurement

$$m_{\nu\alpha}^2 = \sum_i |U_{\alpha i}|^2 m_i^2$$

- Beta decay ^3H – energy spectrum endpoint measurement

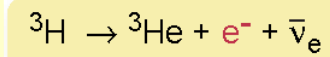
$$N(E) \propto F(E, Z) \cdot p E (Q - E) \cdot \sqrt{(Q - E)^2 - m_{\nu_e}^2}$$

- KATRINE 0.45 eV/c² at 90% confidence level
- Planned sensitivity 0.2 eV/c²



$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

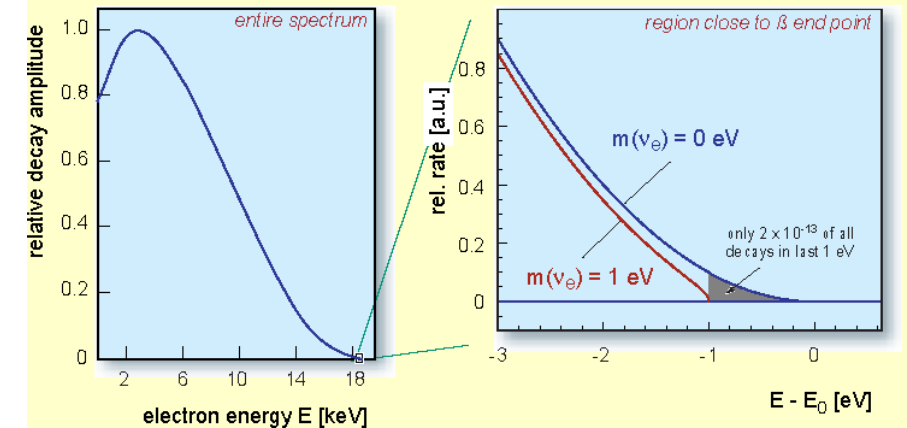
tritium β -decay and the neutrino rest mass



superallowed

half life : $t_{1/2} = 12.32 \text{ a}$

β end point energy : $E_0 = 18.57 \text{ keV}$



- Rozpad π – PSI, $m_{\nu_\mu} < 170 \text{ keV}/c^2$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2m_\pi \sqrt{p_\mu^2 + m_\mu^2}$$

- Rozpad τ – OPAL, DELPHI, ALEPH
 $m_{\nu_\tau} < 18 \text{ MeV}/c^2$

$$\tau \rightarrow \nu_\tau + 5\pi^\pm (\pi^0) \quad \tau \rightarrow \nu_\tau + 3\pi^\pm$$

Cosmology constraint

$$\sum m_i = m_1 + m_2 + m_3$$

CMB + Large-Scale Structure (LSS) → constrain the sum of neutrino masses

CMB

Planck – early Universe & initial conditions

ACT (*Atacama Cosmology Telescope*) – complementary CMB observations

LSS

Gravitational lensing – growth of cosmic structure

DESI (*Dark Energy Spectroscopic Instrument*) – 3D mapping of LSS

galaxy clustering

BAO (*Baryon Acoustic Oscillations*)

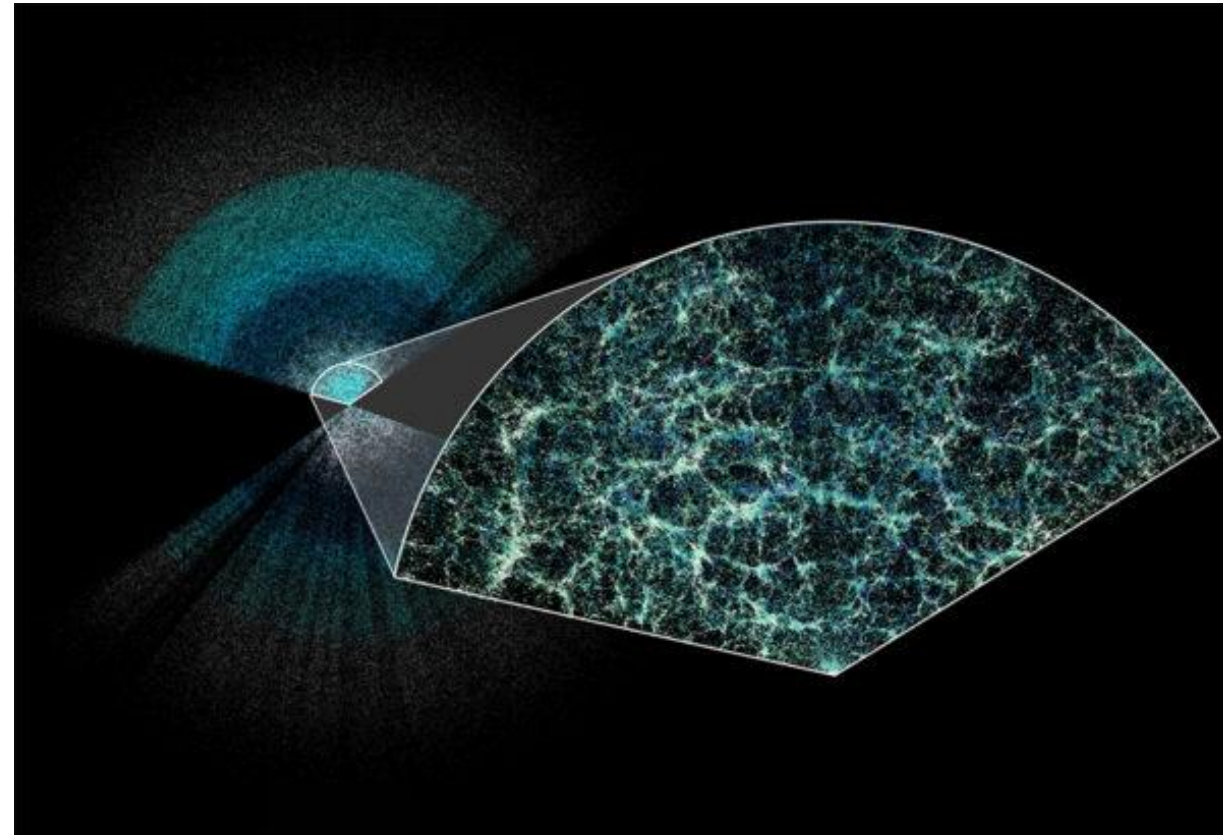
Lyman- α forest of distant quasars

Cosmological model Λ -CDM+ $\sum m_\nu$

$$\sum m_\nu = m_1 + m_2 + m_3 < 0.0642 \text{ eV} \quad (95\% \text{CL})$$

DESI DR2 BAO + CMB assuming Λ -CDM+ $\sum m_\nu$

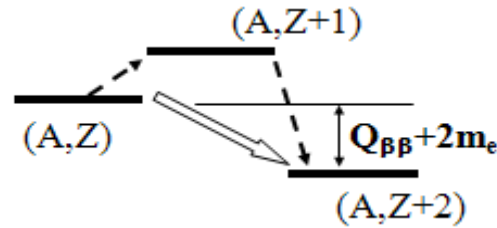
Constraints on neutrino physics from DESI DR2 BAO and DR1 full shape. Physical Review D, 112, 083513. <https://doi.org/10.1103/w9pk-xsk7>



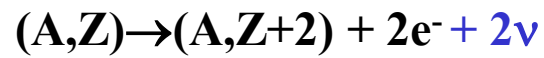


$\beta\beta$ -decay

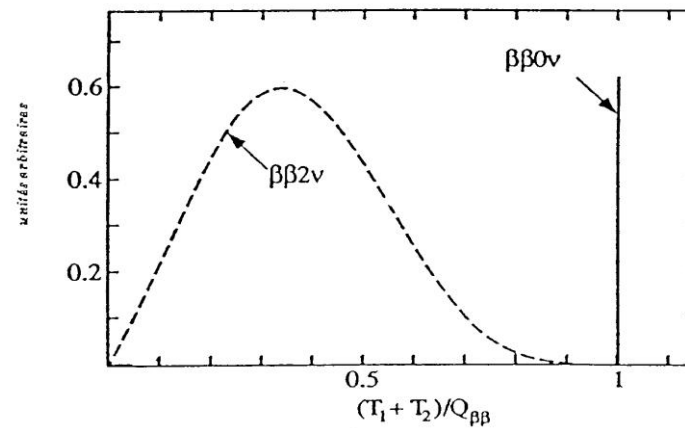
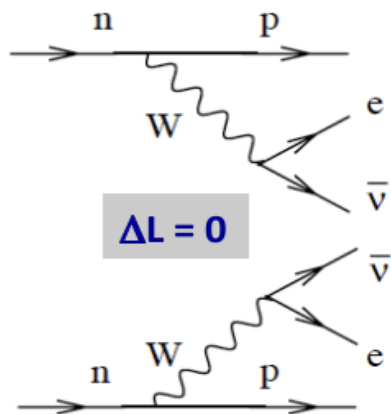
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$



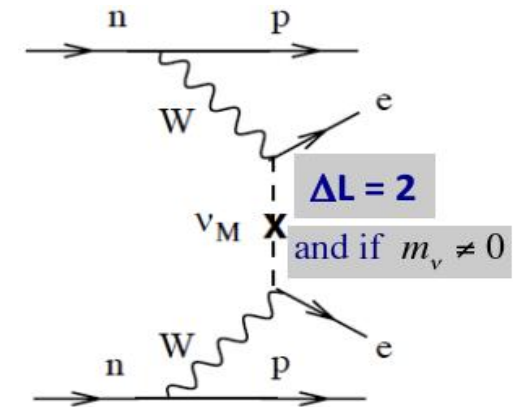
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}, Z) \times |M_{0\nu}|^2 \times \langle m_{\nu e} \rangle^2$$



$\beta\beta 2\nu$: proces allowed in SM, $T_{1/2} \sim 10^{20}y$



$\beta\beta 0\nu$: proces beyond SM, $T_{1/2} \geq 10^{25}y$



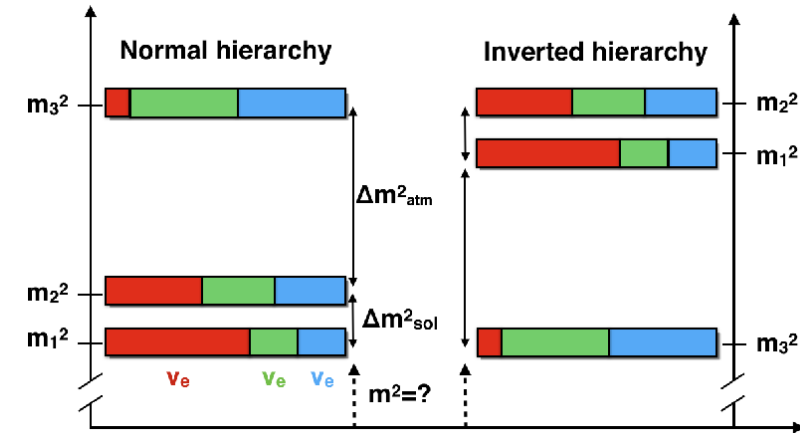
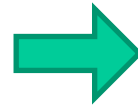
$0\nu\beta\beta$ and neutrino fundamental properties

Probe of neutrino nature.

Neutrinos are Majorana fermions (particle $\equiv$ antiparticle) if $\beta\beta 0\nu$ takes place $\Rightarrow$ See-Saw mechanism, Leptogenesis, Baryon asymmetry, CP violation

Neutrino mass hierarchy.

$\beta\beta 0\nu$ measurements might help to establish the right one.

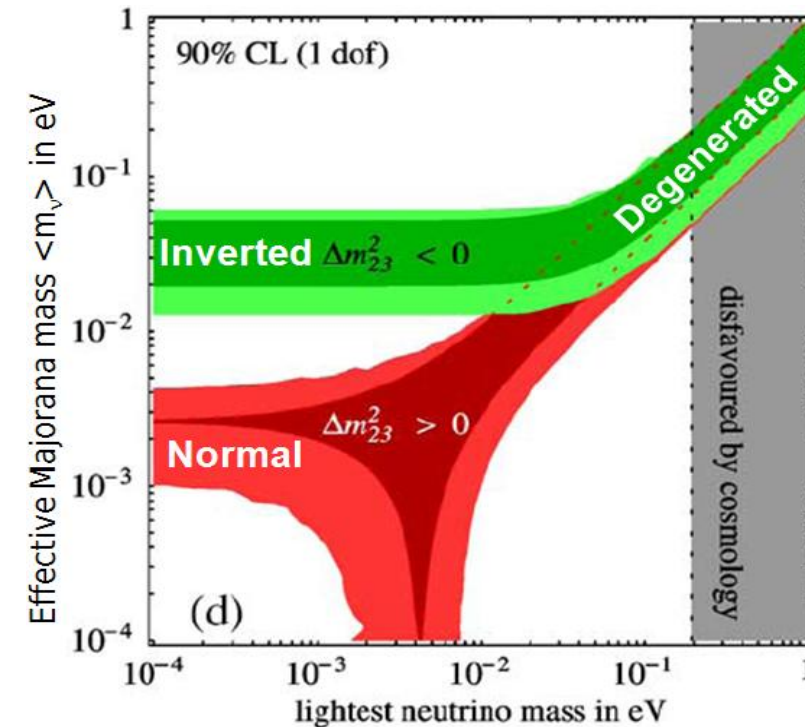


Absolute mass scale.

$\beta\beta 0\nu$ experiments are among the most sensitive ones.



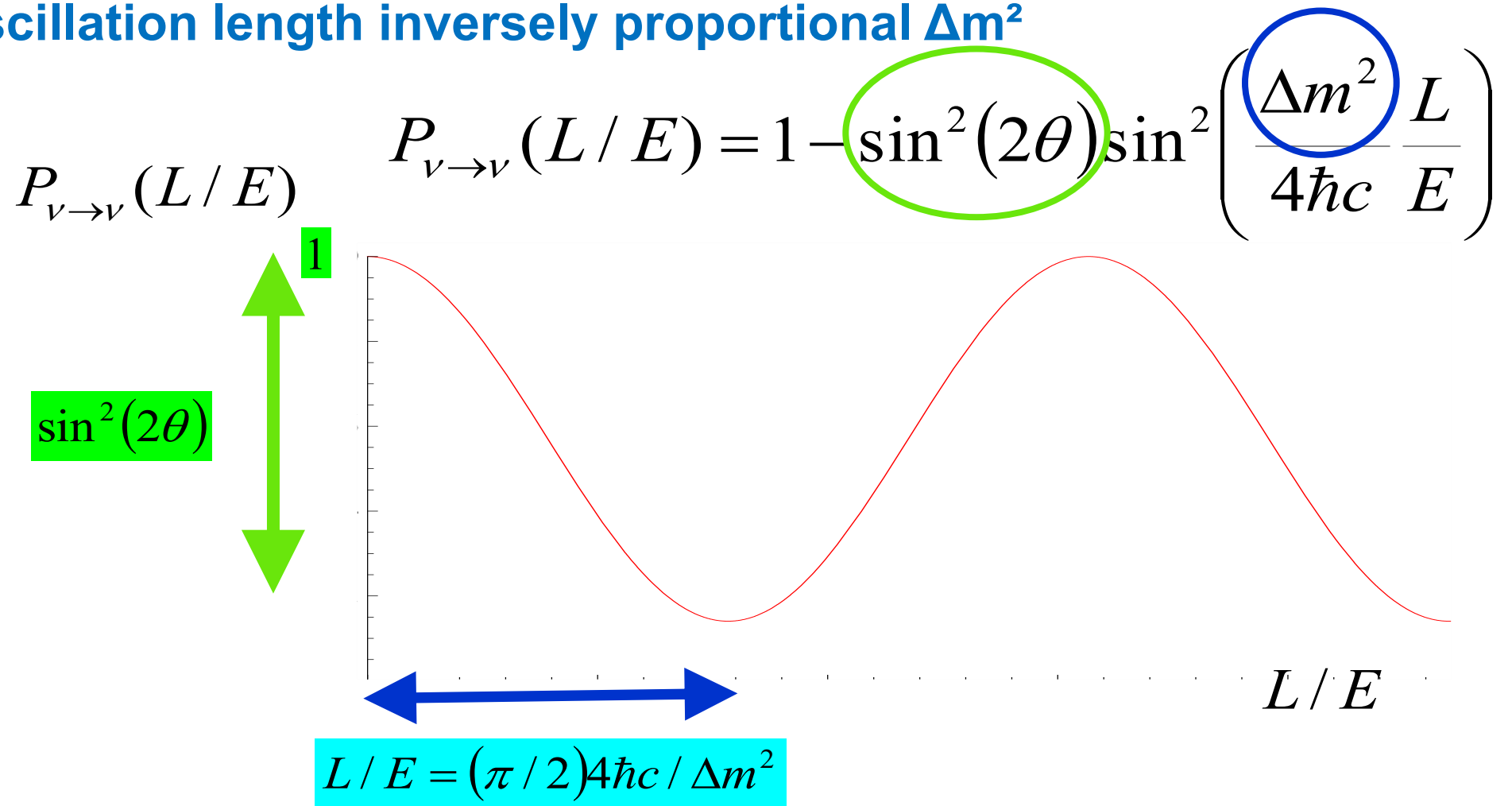
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| < 0.028-0.122 \text{ eV}$$



Mixing and oscillations – two neutrinos

Oscillation amplitude = $\sin^2(2\theta)$,

Oscillation length inversely proportional Δm^2



Oscilace neutrin (ve vakuu)

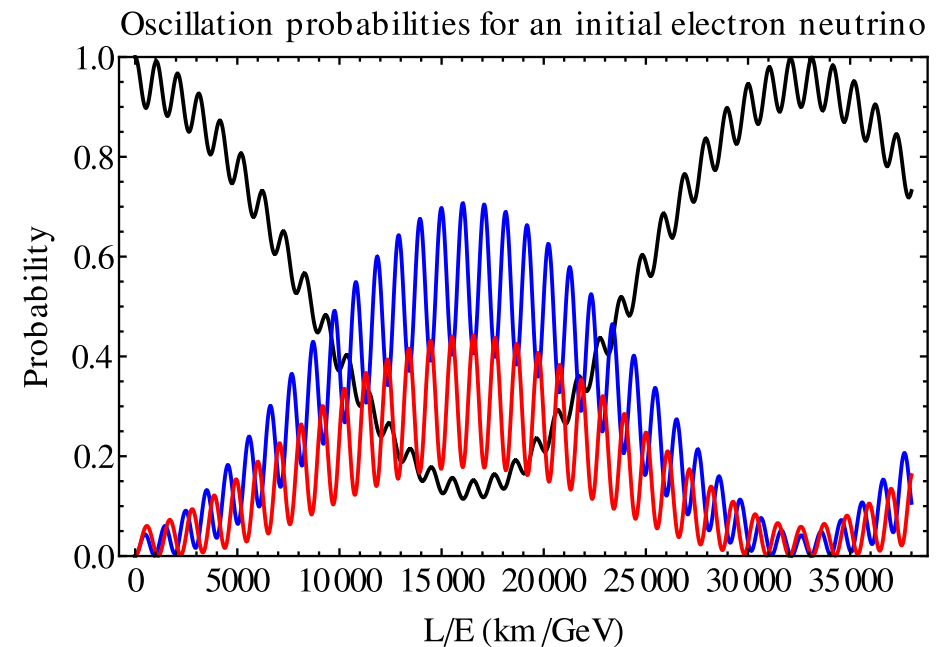
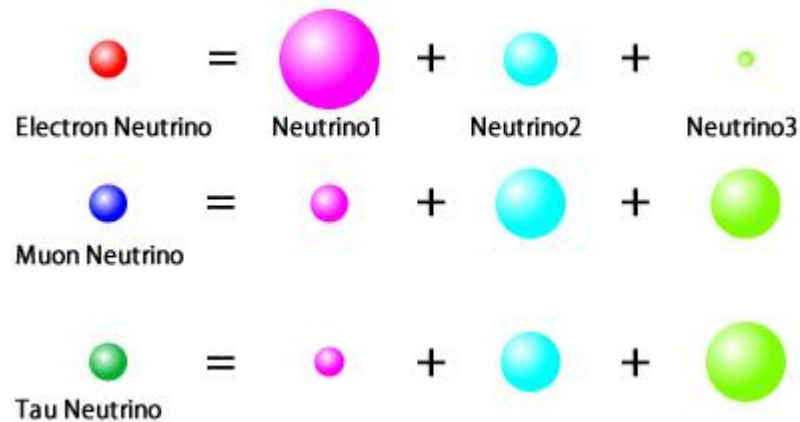
n-neutrin

$$|\nu_i(\tau_i)\rangle = \exp\left(-\frac{i}{\hbar} m_i c^2 \tau_i\right) |\nu_i(0)\rangle = \exp\left(-\frac{i}{\hbar} (E_i t - p x)\right) |\nu_i(0)\rangle \approx \exp\left(-\frac{i}{\hbar} \frac{m_i^2 c^3}{2E} x\right) |\nu_i(0)\rangle \quad E \gg m_i c^2 \quad x \approx ct \quad pc = \sqrt{E^2 - m_i^2 c^4} \approx E - \frac{m_i^2 c^4}{2E}$$

$$|\nu_\alpha(x)\rangle \approx \sum_i U_{\alpha i}^* \exp\left(-\frac{i}{\hbar} \frac{m_i^2 c^3}{2E} x\right) |\nu_i\rangle = \sum_\beta \left[\sum_i U_{\alpha i}^* \exp\left(-\frac{i}{\hbar} \frac{m_i^2 c^3}{2E} x\right) U_{\beta i} \right] |\nu_\beta\rangle$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | \nu_\alpha(x) \rangle \right|^2 = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left[\frac{\Delta m_{ij}^2 c^3}{4\hbar E} x \right] + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left[\frac{\Delta m_{ij}^2 c^3}{2\hbar E} x \right] \quad \Delta m_{ij}^2 = m_i^2 - m_j^2$$

3-neutrina



Neutrino mixing parameters

PDG data 2025 – before JUNO

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

JUNO aims

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

Neutrino mass constraints

Neutrino oscillations

- Inverted ordering Σm_ν $> 0.10 \text{ eV}$

- Normal ordering Σm_ν $> 0.059 \text{ eV}$

Cosmology Σm_ν $< 0.0642 \text{ eV}$

Beta decay $m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$ $< 0.45 \text{ eV}$

Double beta decay $m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$ $< 0.028\text{-}0.122 \text{ eV}$

Why pursue ever higher precision?

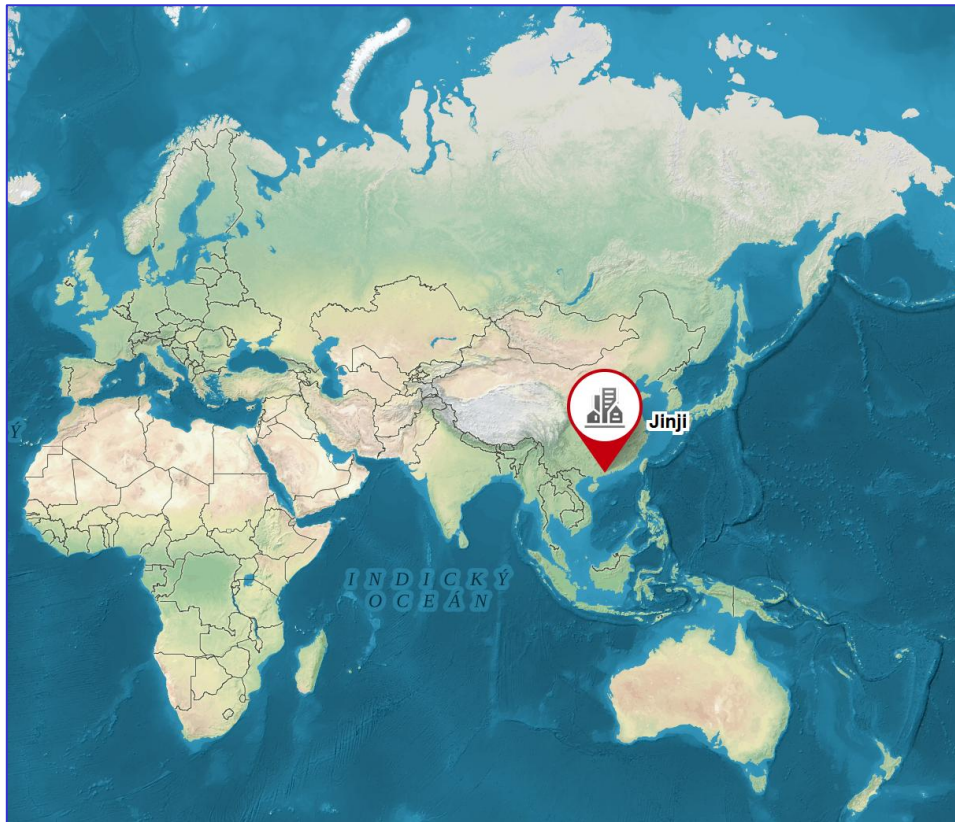
- Determine the neutrino mass ordering and constrain the mass scale.
- Search for deviations from the standard 3-neutrino paradigm.
- Guide the design of future neutrino experiments.
- Constrain and discriminate between theoretical models.

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

JUNO EXPERIMENT

JUNO – Jiangmen Underground Neutrino Observatory

- Jiangmen Underground Neutrino Observatory
- a multi-purpose neutrino experiment,
- approved in Feb. 2013,
- ~ 300 M\$,
- data taking: ~2025.
- Neutrino source: 10 nuclear reactors (Yangjiang+Taishan: 26.6-35.7 GWth),
- baseline: 53 km,
- overburden: ~700 m.



JUNO – Collaboration

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		

**=67 institutes
> 700 participants**

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

JUNO – Collaboration

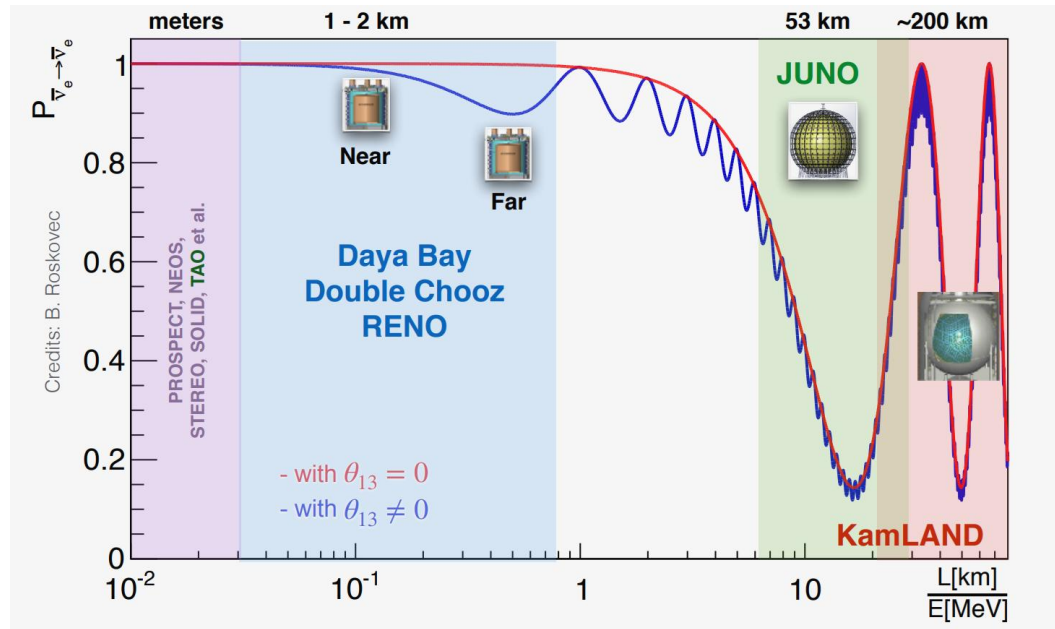


JUNO surface infrastructure



JUNO – Jiangmen Underground Neutrino Observatory

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



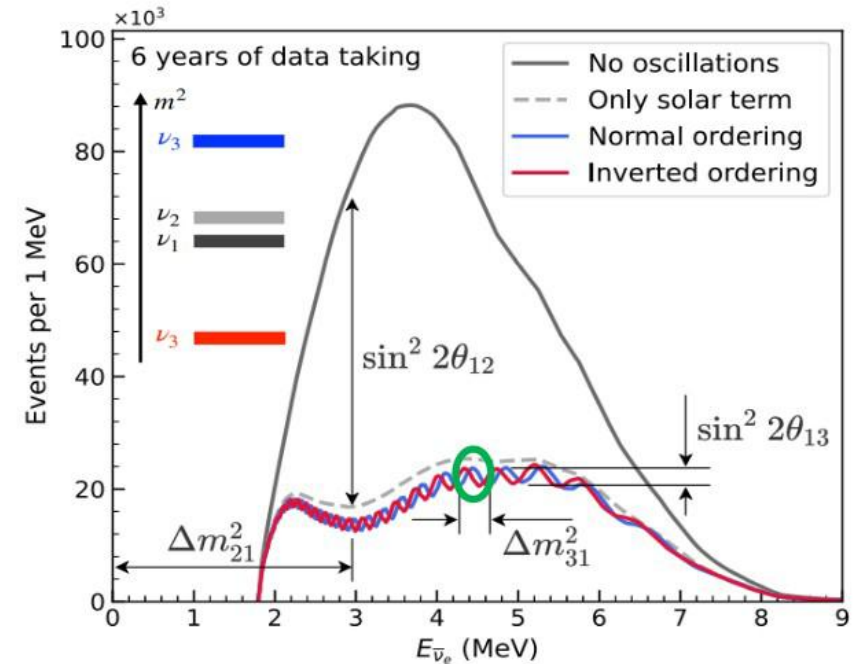
Neutrino Mass Ordering (NMO)

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

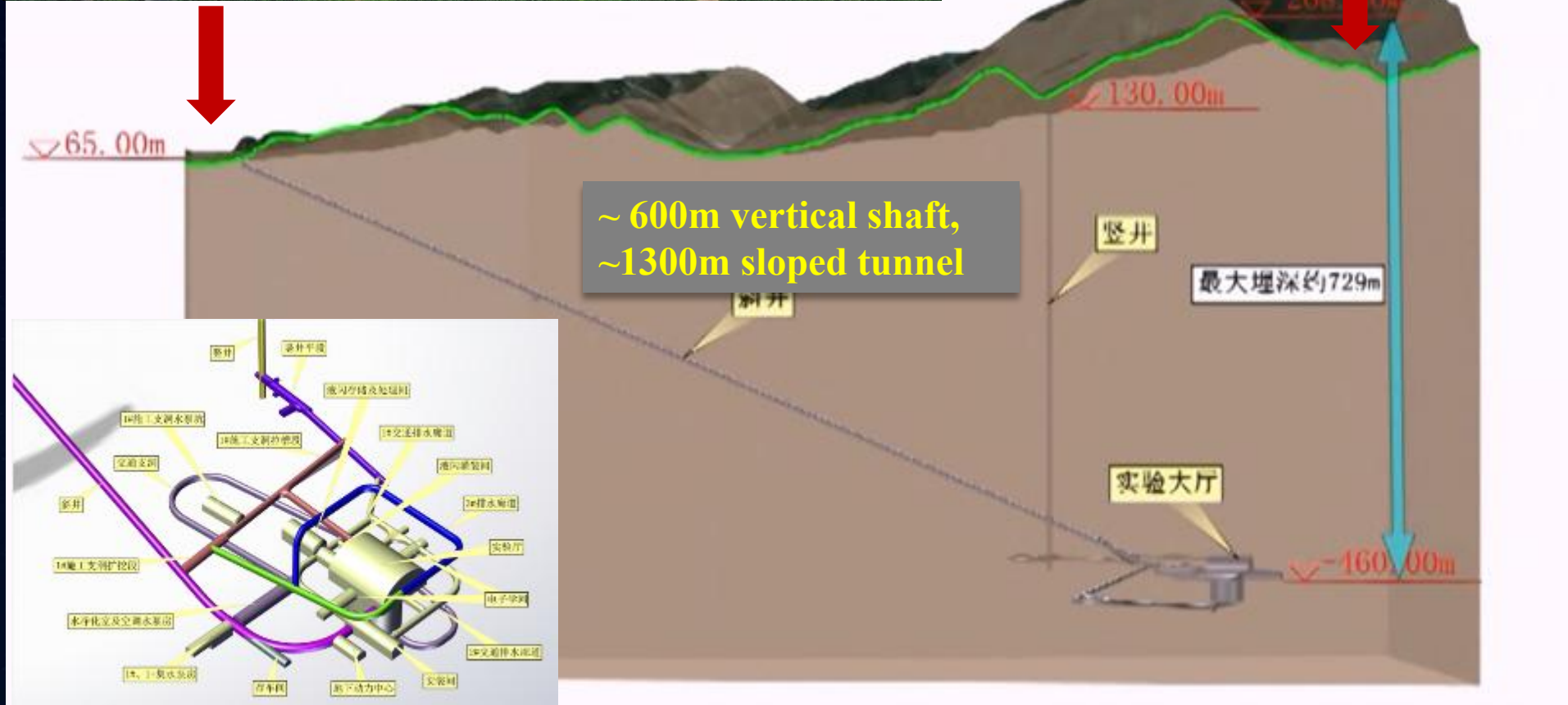
Main physics goals

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



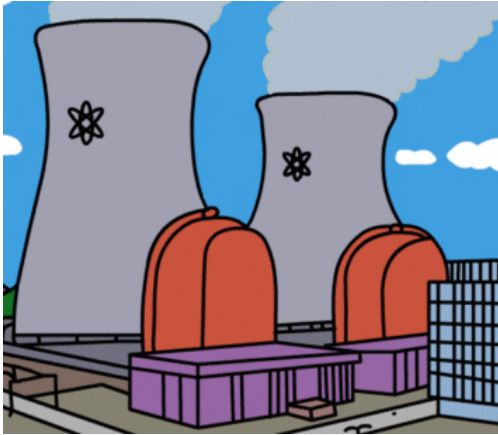
JUNO requirements

- 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



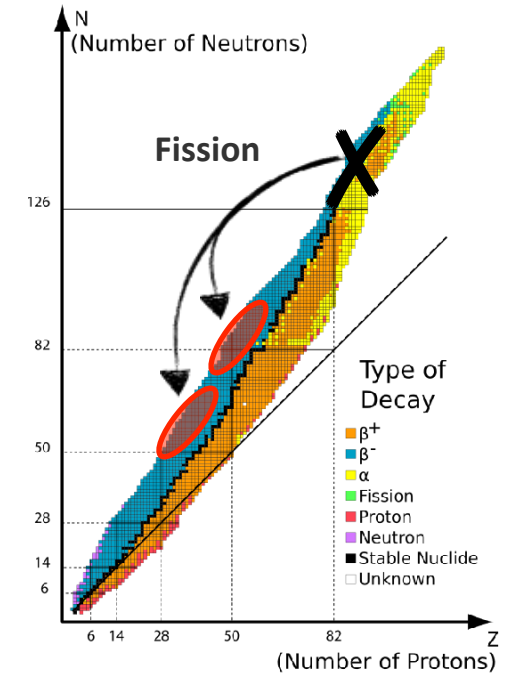
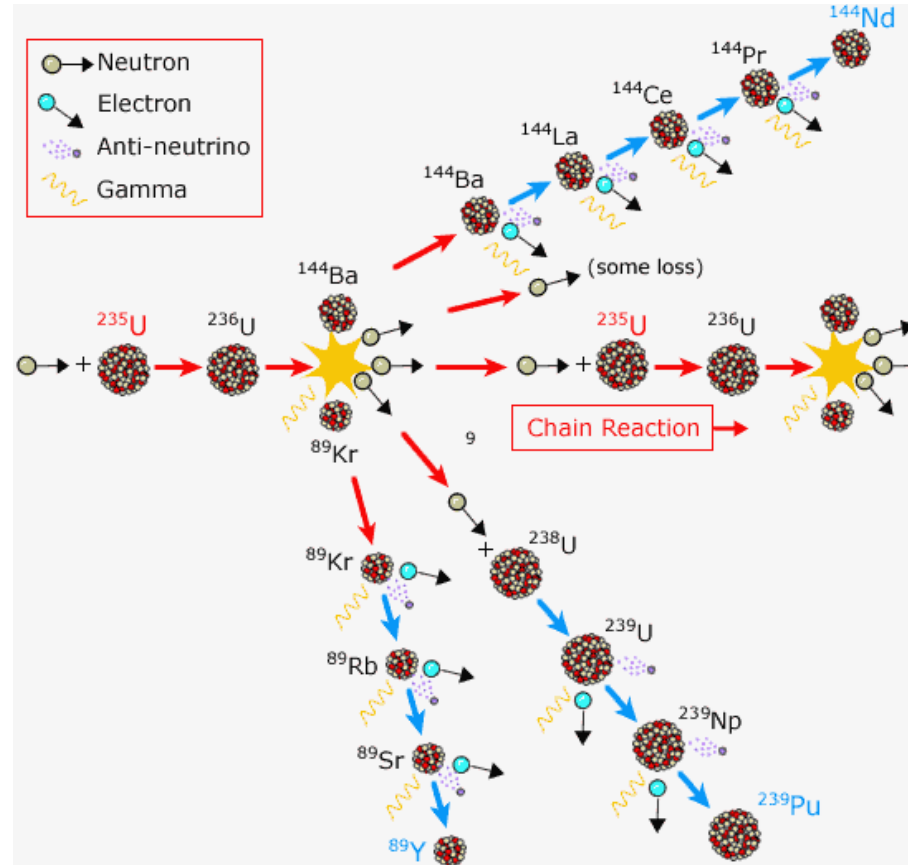
Production of reactor neutrinos

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



$$\sim 10^{20} \nu_e / \text{GW}_{\text{th}} / \text{s}$$

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



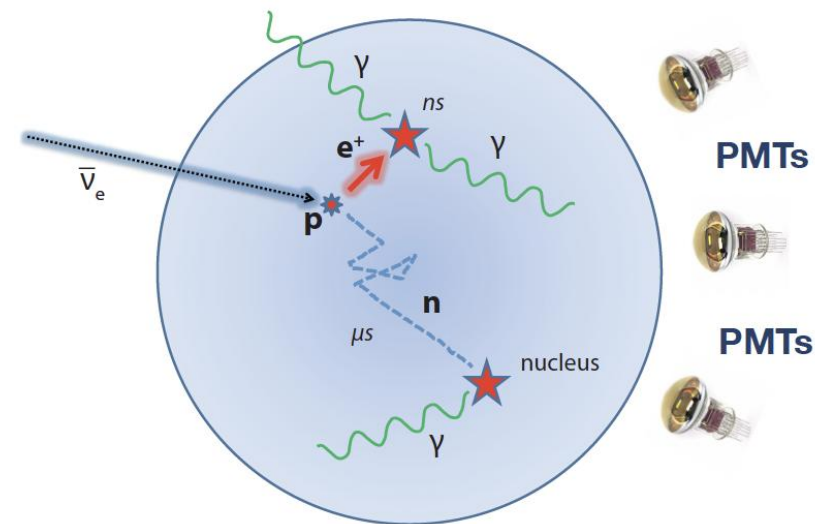
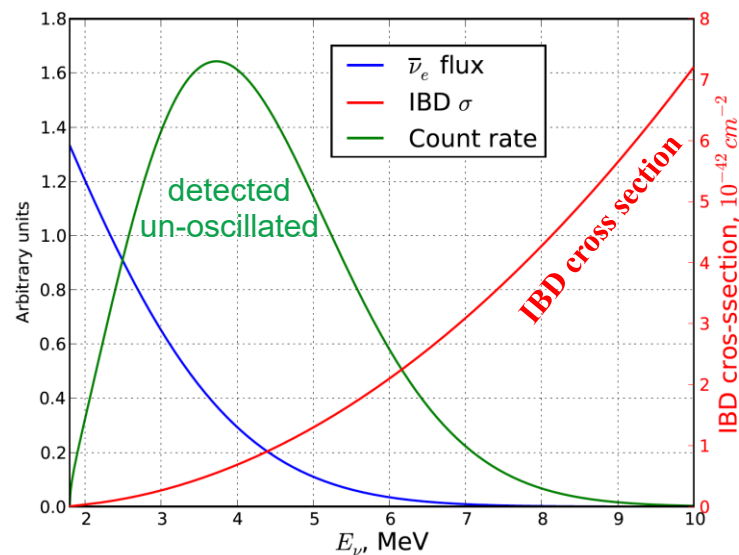
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Electron-antineutrino detection

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

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

$$\rightarrow + p \rightarrow D + \gamma(2.2 \text{ MeV}) \quad (t \sim 200 \mu\text{s})$$



Threshold $E_{\bar{\nu}} \approx 1.8 \text{ MeV}$

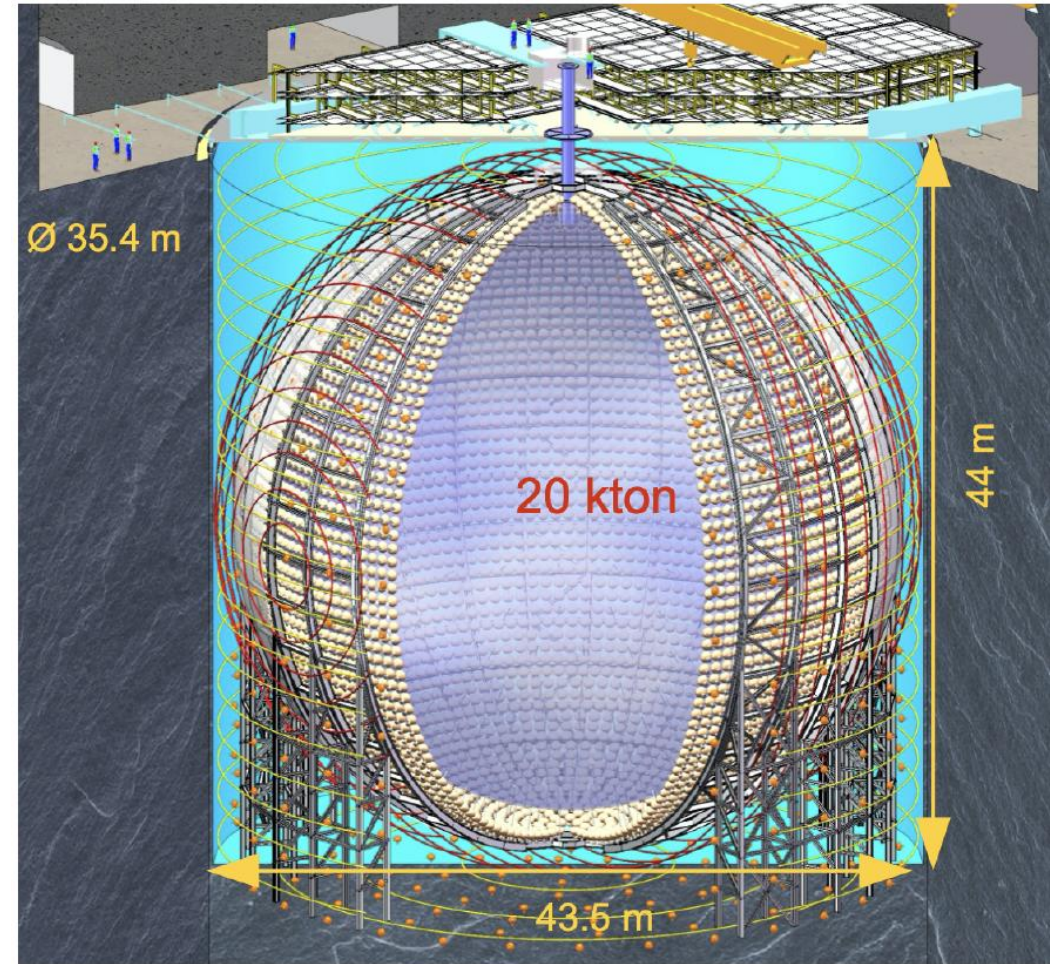
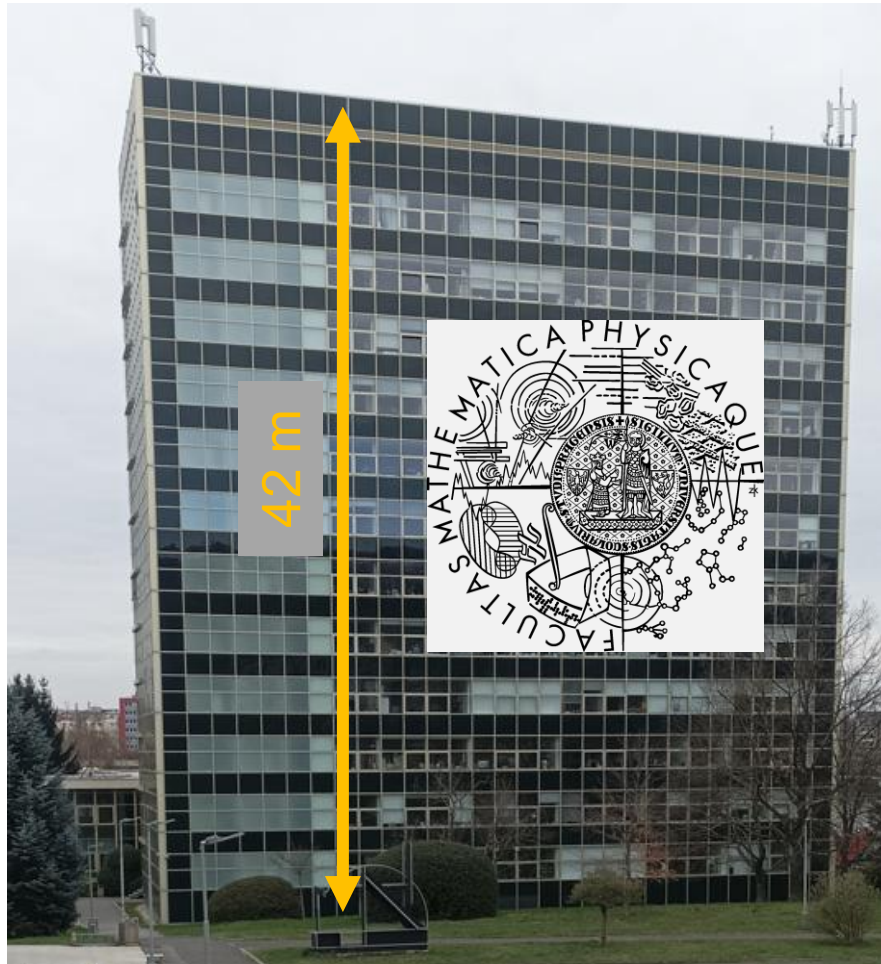
$E_{\bar{\nu}} \approx E_{\text{prompt}} + 0.8 \text{ MeV}$

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

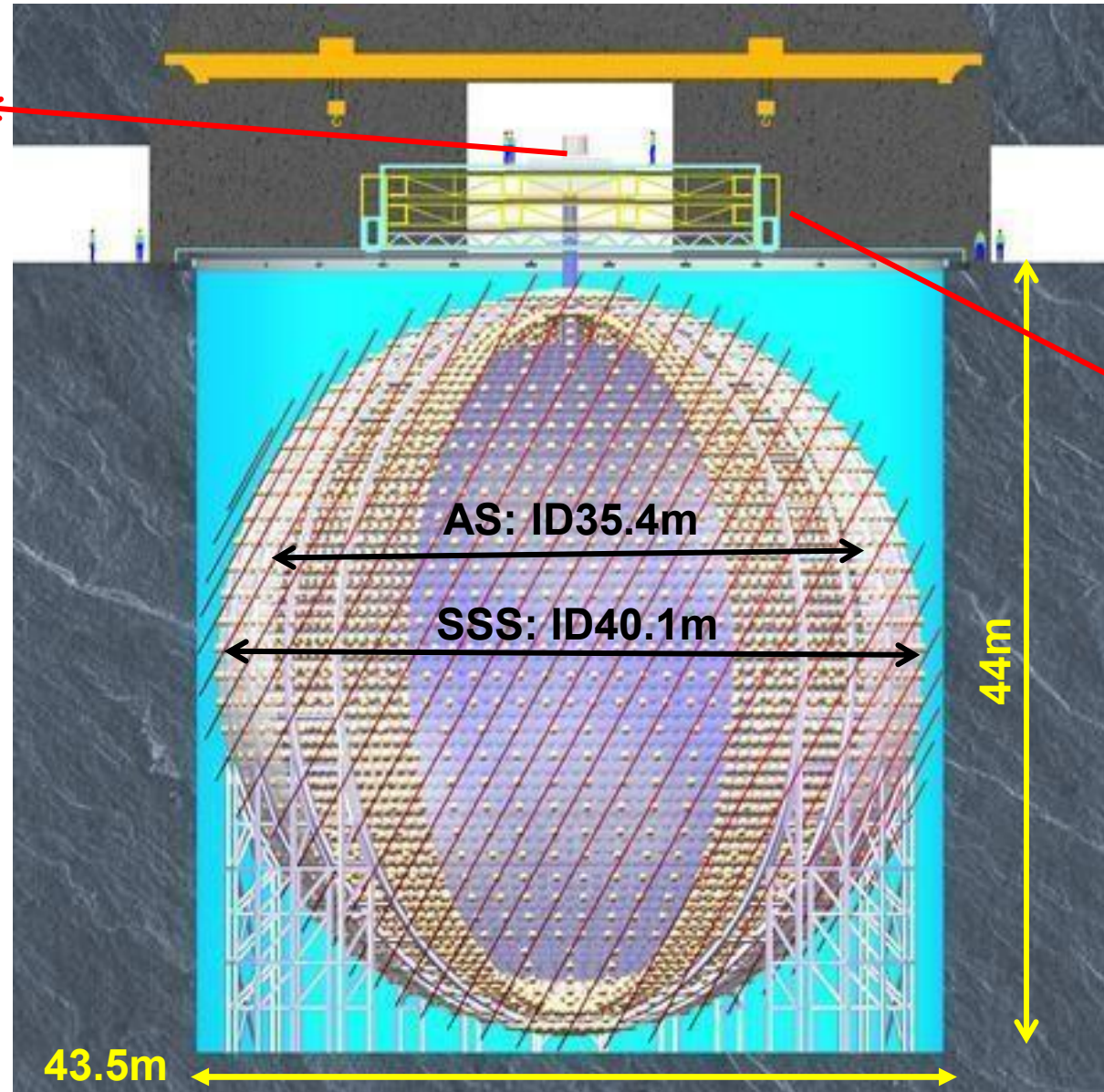


JUNO – Jiangmen Underground Neutrino Observatory

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

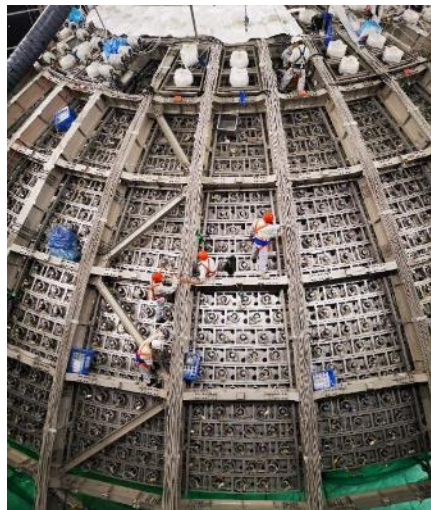
Earth Magnetic Field shielding coils

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



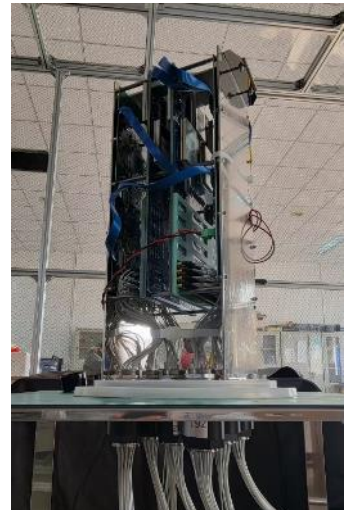
LPMT & sPMT



PMT and Underwater box installation



LPMT Underwater box



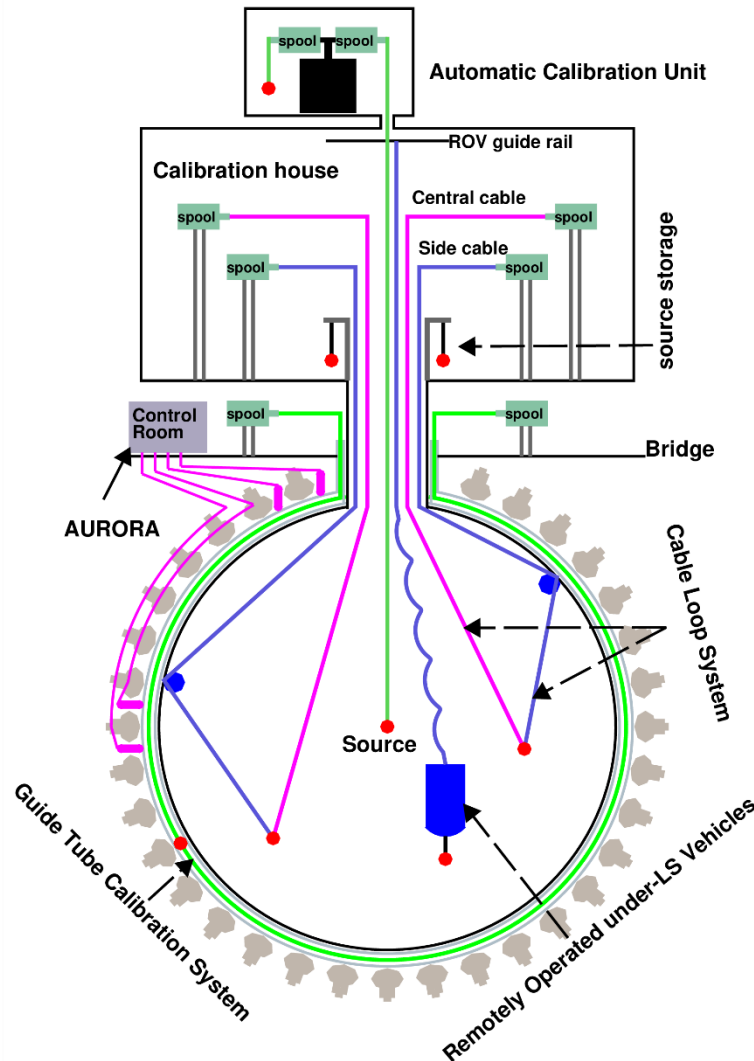
SPMT Underwater box

Central Detector Calibration

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

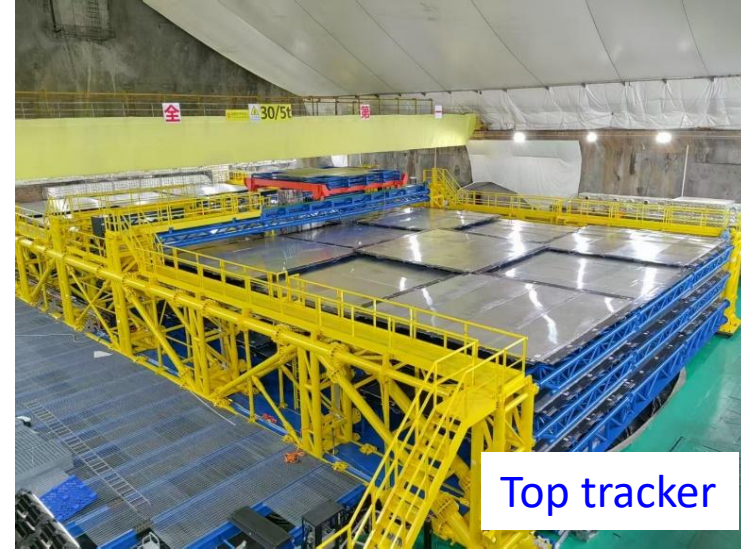
Have a **comprehensive calibration program** consisting of four complementary systems:

- 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 vertical planes. 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

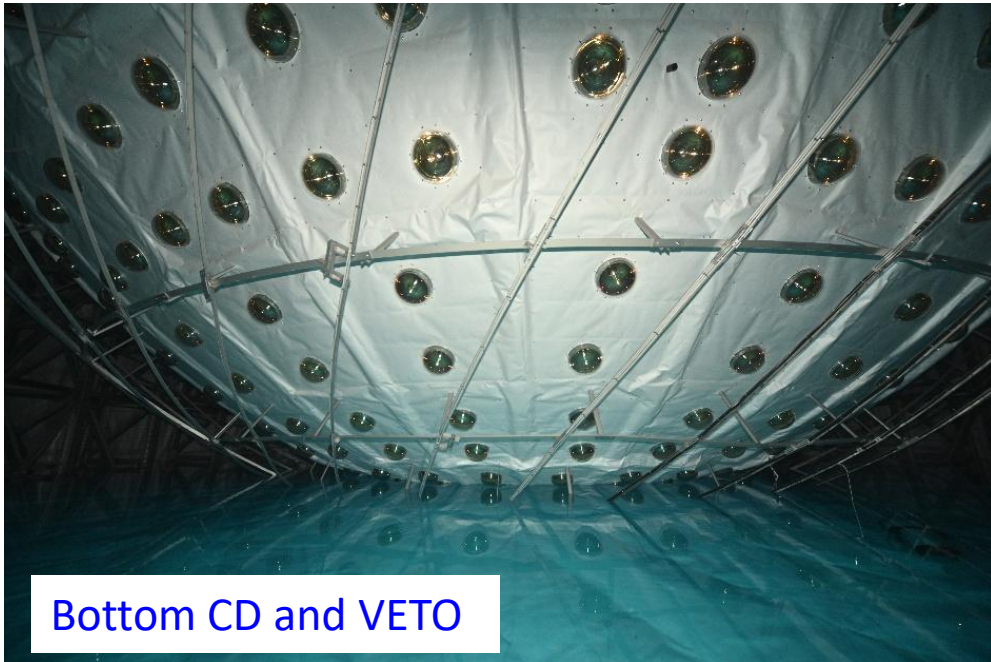


Goal is to keep the energy scale uncertainty < 1%

Veto



Top tracker



Bottom CD and VETO

◆ 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

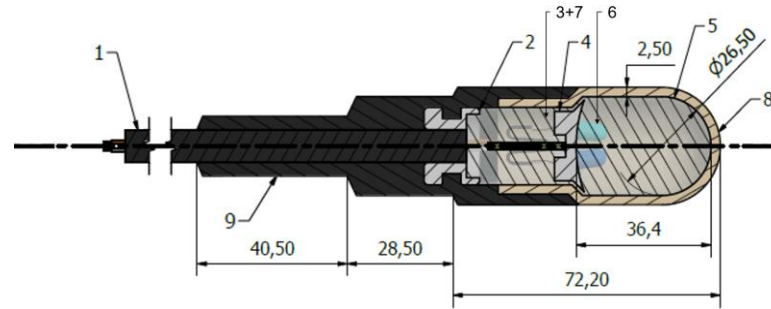
◆ Earth magnetic field compensation coil

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.

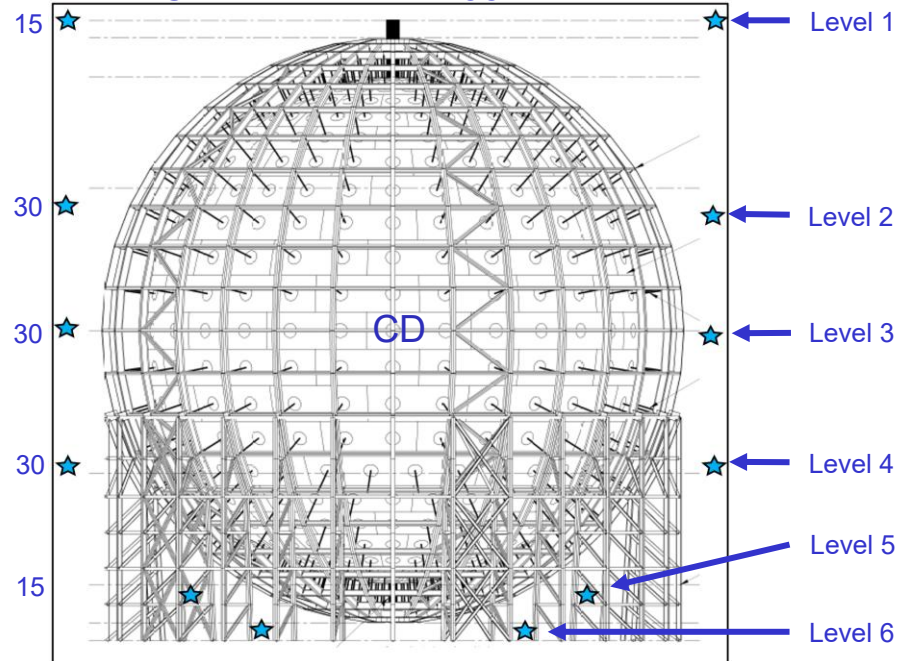


Requirements for the flashers

- Electronic – light pulse timing better than 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.

Water Cherenkov Det.: 135 flashers in total



Liquid Scintillator



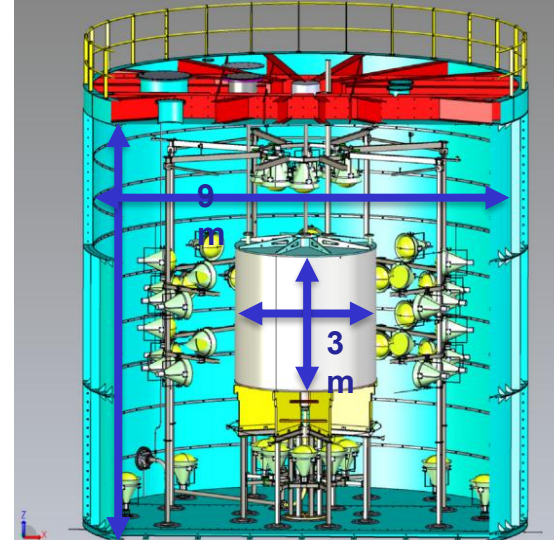
Operations on surface

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

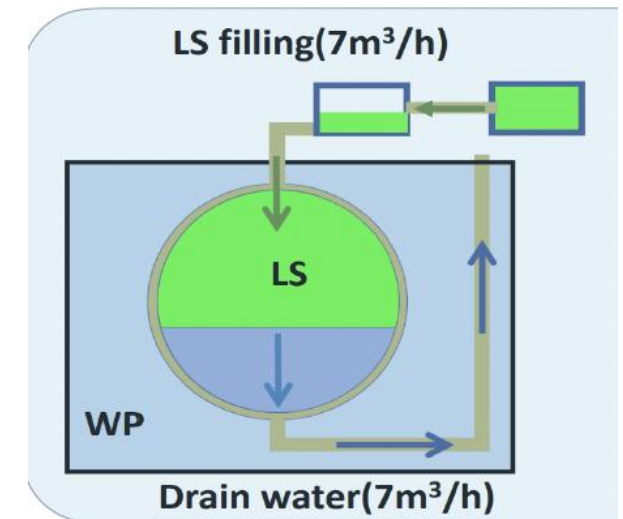


Operation underground

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



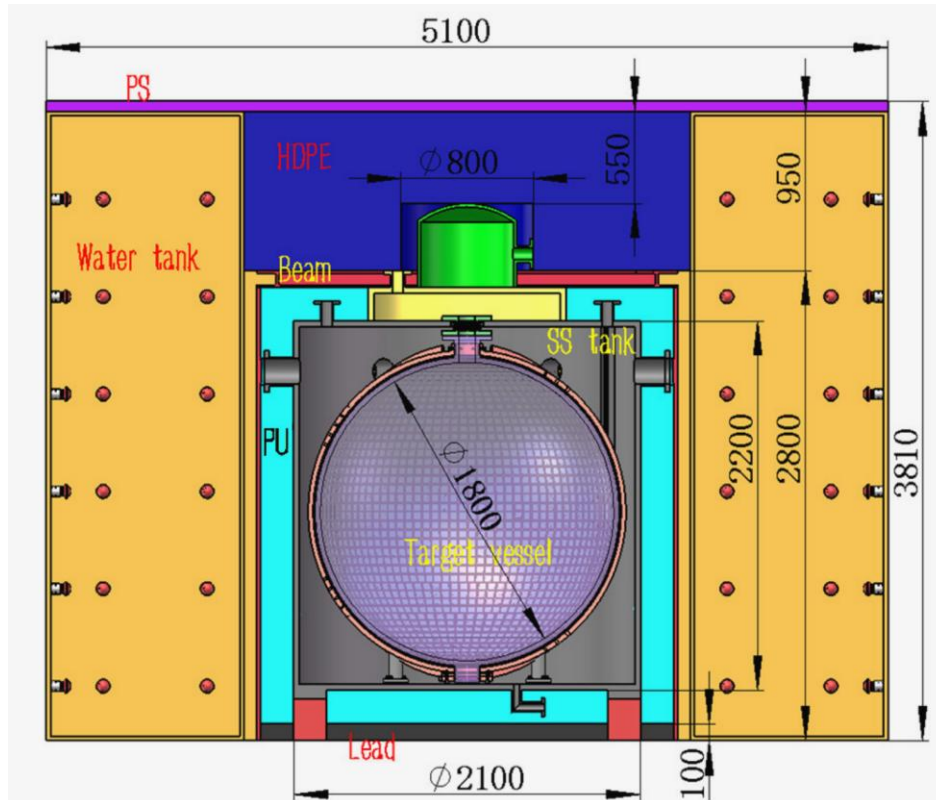
Online
Scintillator
Internal
Radioactivity
Investigation
System (OSIRIS)



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

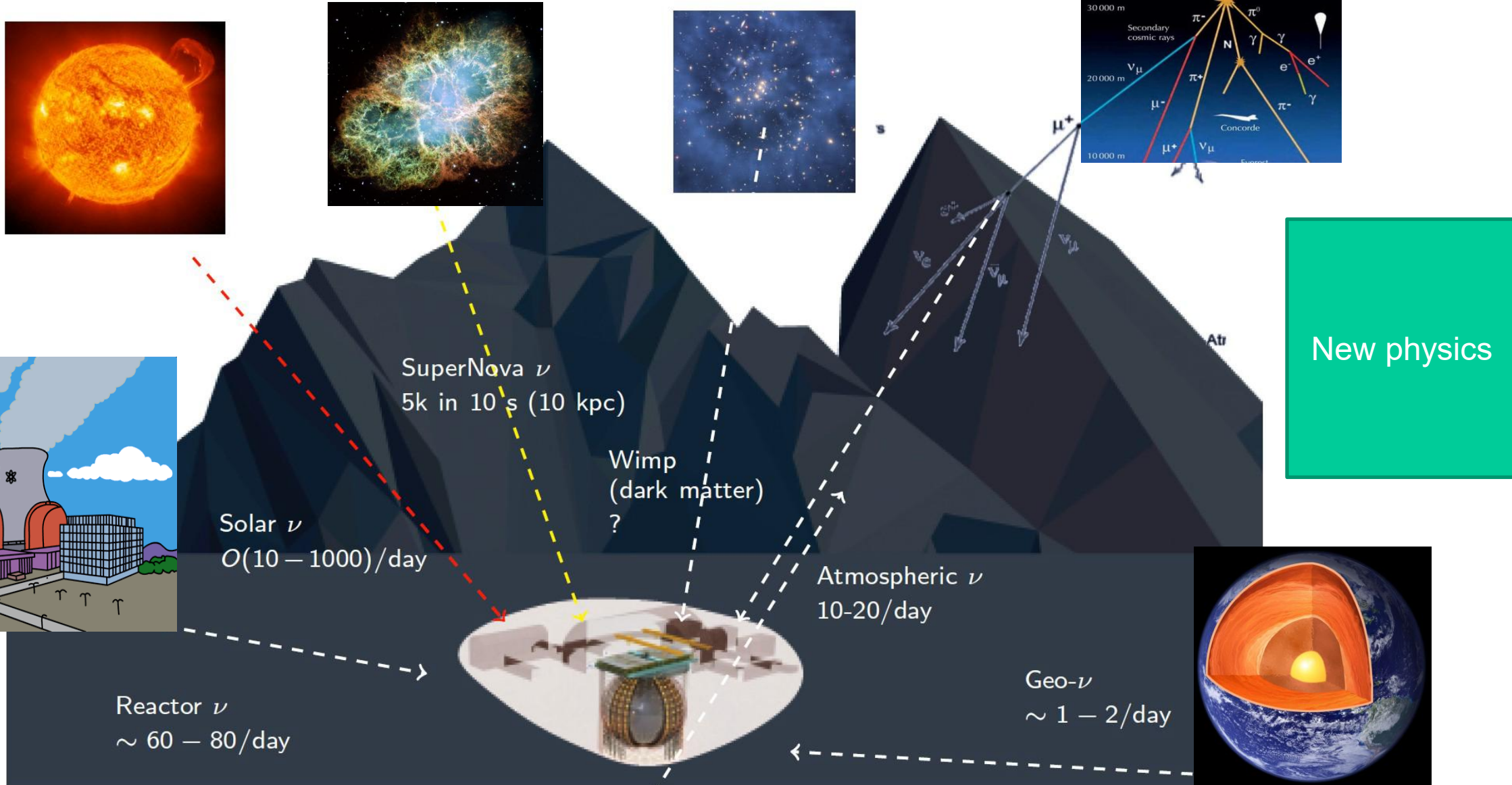
TAO - Taishan Antineutrino Observatory

- Satellite detector to JUNO: provide precise measurement of reactor antineutrino spectrum
- ~40 m from one of Taishan 4.6 GW_{th} reactor core
- 1 ton fiducial volume with Gd-LS
- 10 m² SiPM of 50% photon detection efficiency operated at -50°C
- ≥94% photo-coverage
- 30x JUNO event rate

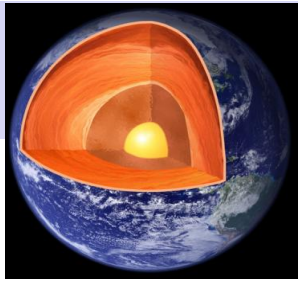


JUNO - MULTIPURPOSE

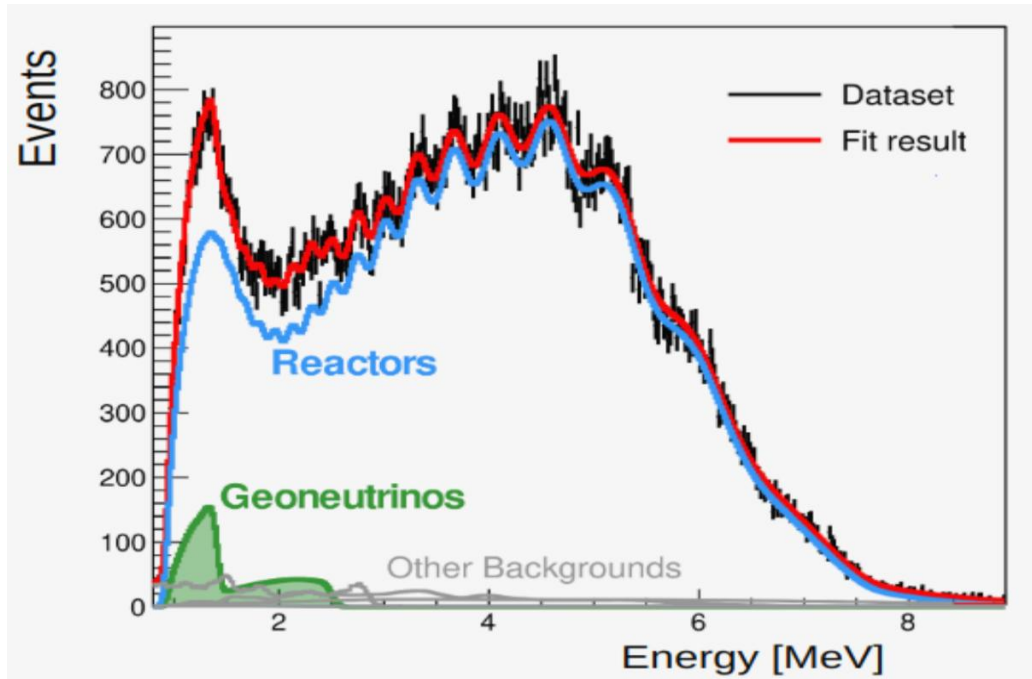
JUNO multi-purpose neutrino experiment



Geoneutrinos

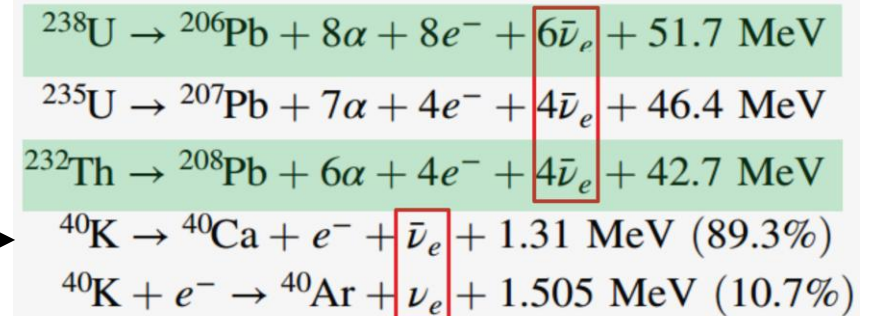


- Geoneutrinos give us information about the abundance of radioactive elements inside the crust and mantle, as well as the amount of heat emitted from them
- High statistics: more events in one year (~400 ν 's) than global geoneutrino sample accumulated to date
- Good sensitivity to mantle geoneutrinos due to the higher precision and relatively well-known knowledge of the crust



	Preliminary expected sensitivity [%]				
	Th/U fixed	Th/U free			
Time	U+Th	U	Th	U+Th	U/Th
1y	~22	-	-	-	-
6y	~10	~35	~40	~18	~70
10y	~8	~30	~35	~15	~55

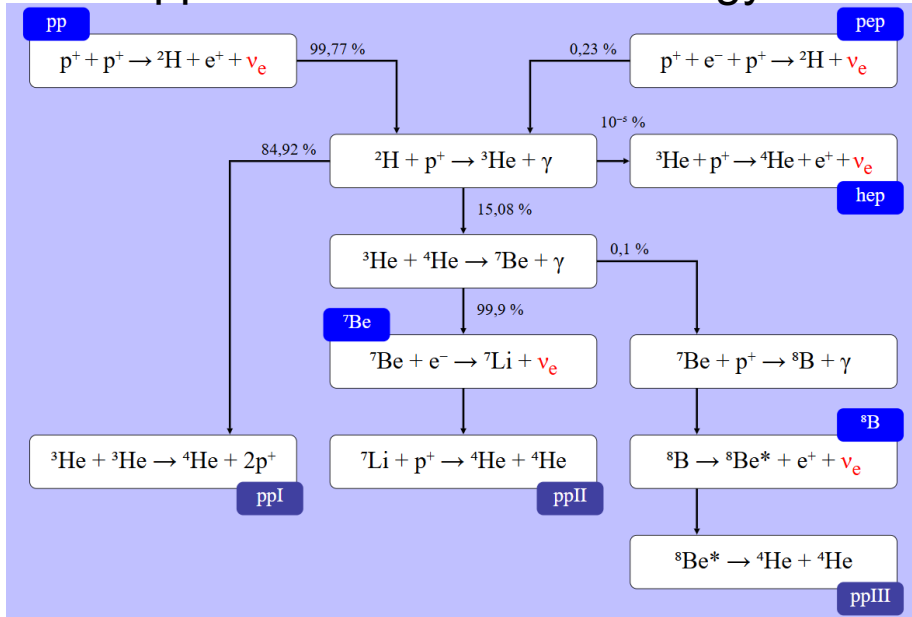
Below threshold
for IBD



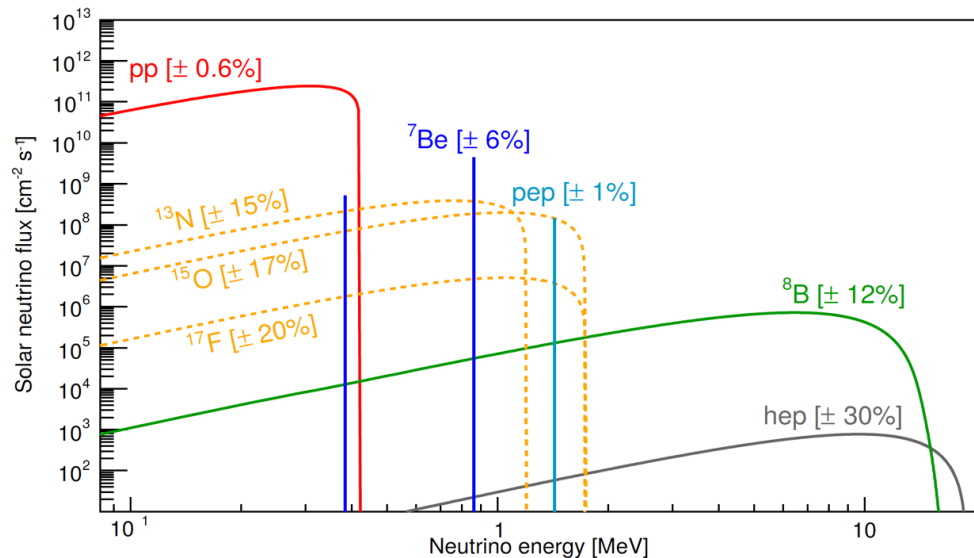
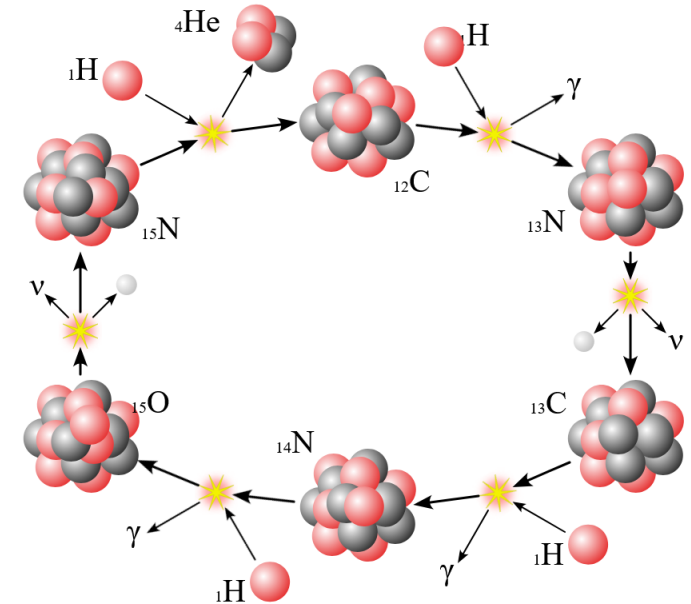
The largest background: **Reactor neutrinos**

Solar Neutrinos

pp-chain: ~99% solar energy

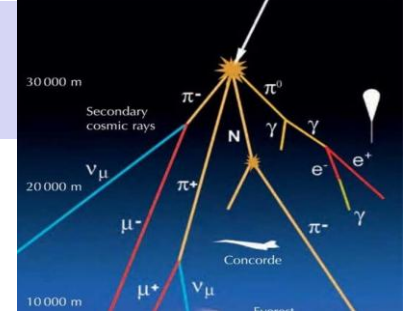


CNO-cycle: < 1% solar energy



- ${}^7\text{Be}$, *pep*, and CNO neutrino flux precision may exceed current precision levels, given good control of radiopurity
- Simultaneous measurement of ${}^8\text{B}$ solar neutrinos, Δm^2_{21} , and $\sin^2\theta_{12}$: ${}^8\text{B}$ flux can be measured with $\sim 5\%$ precision using ES+NC+CC channels in 10 years. $\sin^2\theta_{12}$: 8%, Δm^2_{21} : 20%

Atmospheric Neutrinos

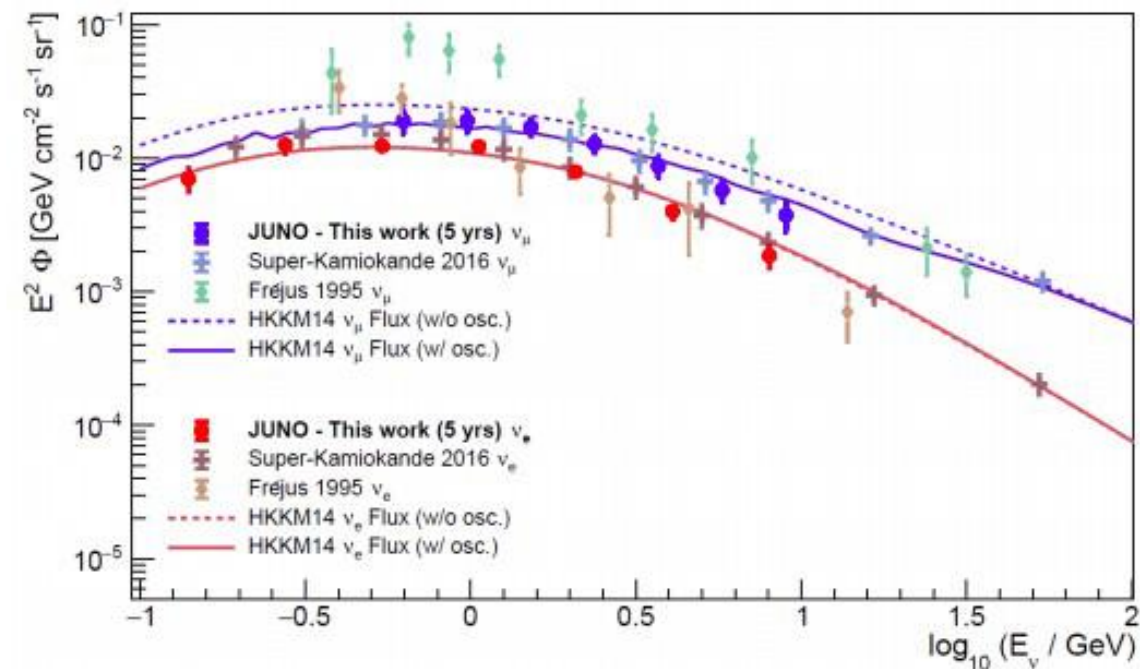


Neutrino oscillations investigation using atmospheric neutrinos

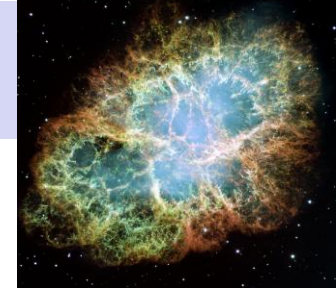
- Complementary detection channel to reactor: independent measurements and systematics
- Exploit matter effects on oscillations
- Additional parameters: $\sin 2\theta_{23}$ and δ_{CP}
- Boost of NMO sensitivity using both channels

Flux measurements

- Flavor - dependent energy spectrum can be measured in the (0.1 - 10) GeV energy range
- ν_e/ν_μ discrimination possible using based on time pattern of scintillation light

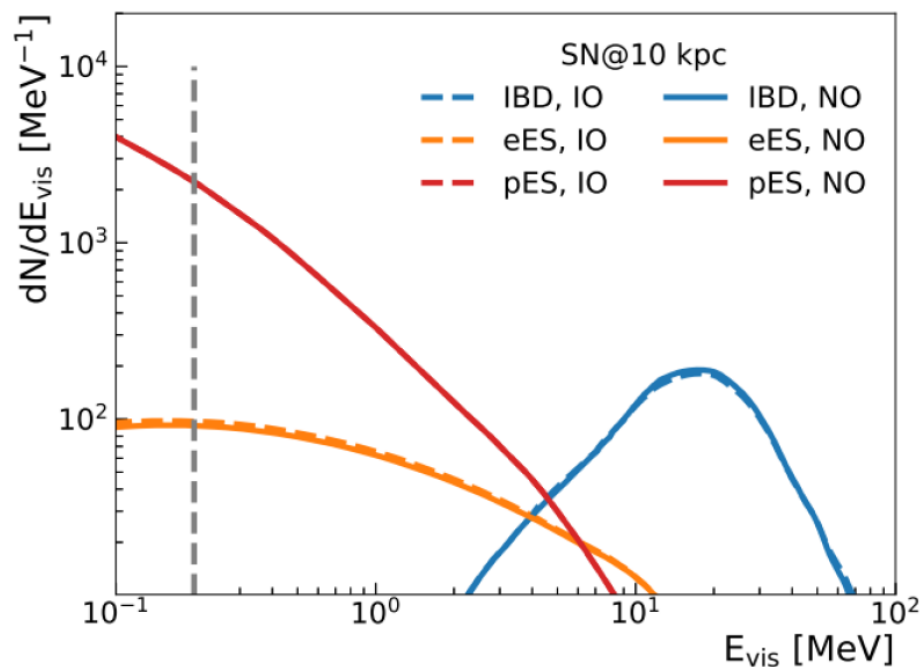


Super-Nova Neutrinos



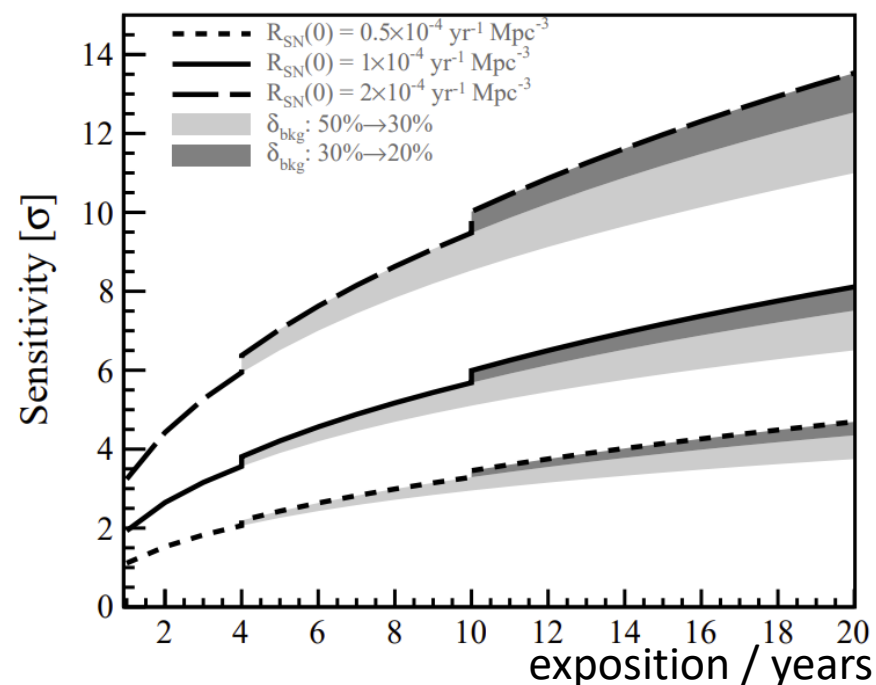
Core-collapse Supernova (SN) in our vicinity:

- Large SN neutrino sample with high energy resolution and low threshold (~ 0.02 MeV with multi-messenger trigger)
- 3 detection channels sensitive to all flavors, 10^4 detected events (5000 IBDs) for SN @ 10 kpc
- Capability to detect pre-SN neutrinos from close SN-candidates: ~ 1.6 (0.9) kpc for normal (inverted) ordering



Diffuse Supernova Background (DSNB):

- DSNB: flux of neutrinos reaching the Earth from all the core-collapse supernovae in the universe
- Potential to make first observation of DSNB with $\sim 3\sigma$ significance in ~ 3 years assuming a nominal reference model

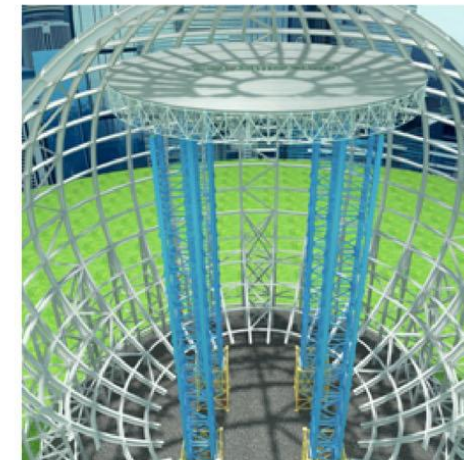
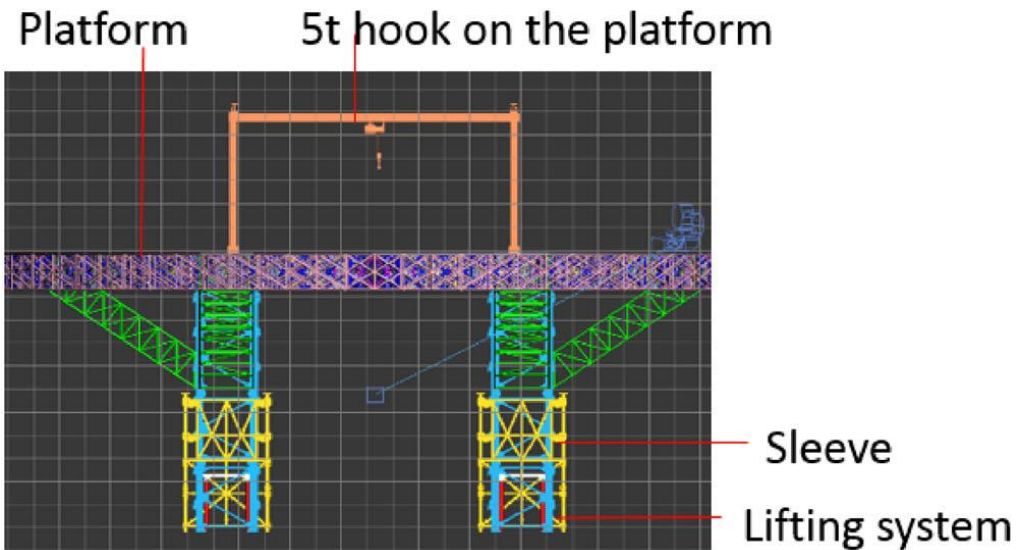
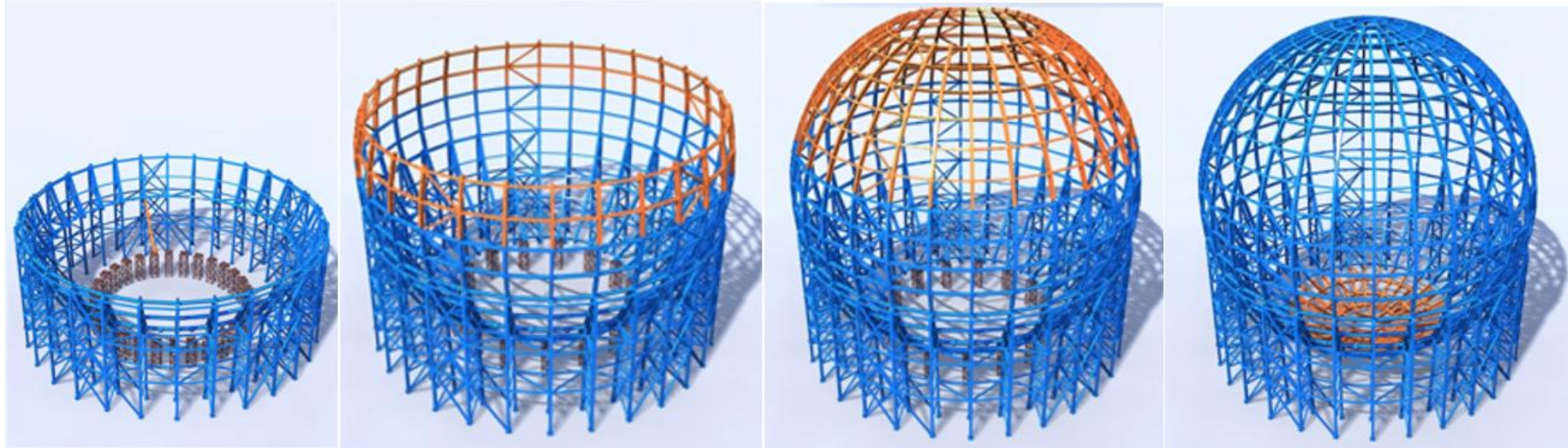


DETECTOR CONSTRUCTION

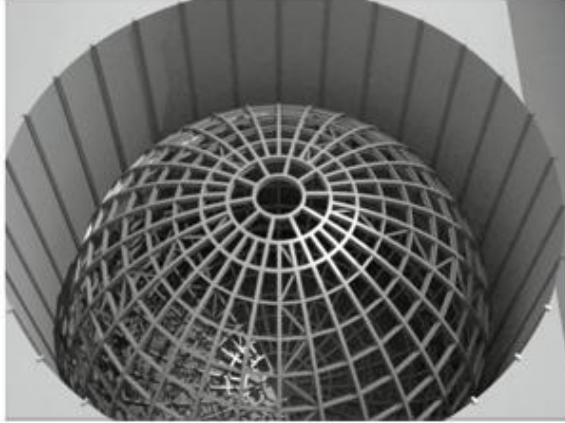
Slope tunnel access, 1300 m, 15 min.



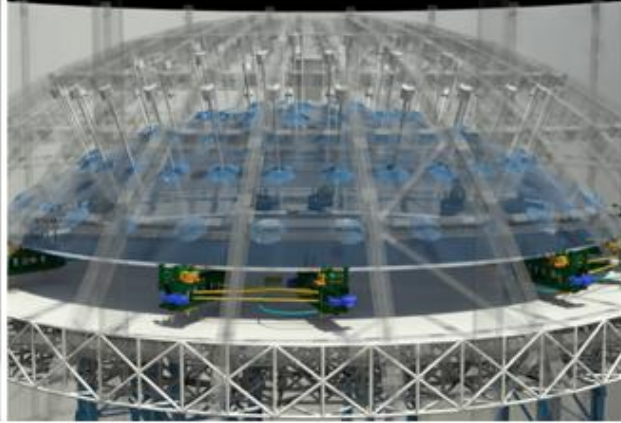
Stainless Steel Structure – from bottom to top



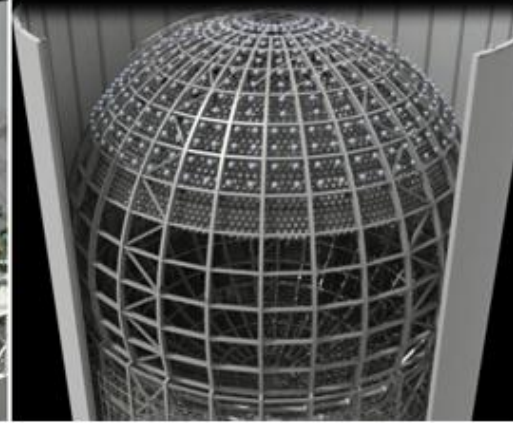
Acrylic Sphere and PMTs – from top to bottom



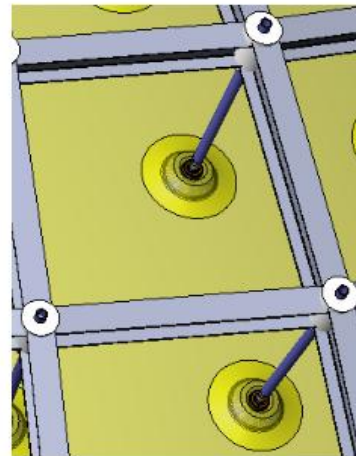
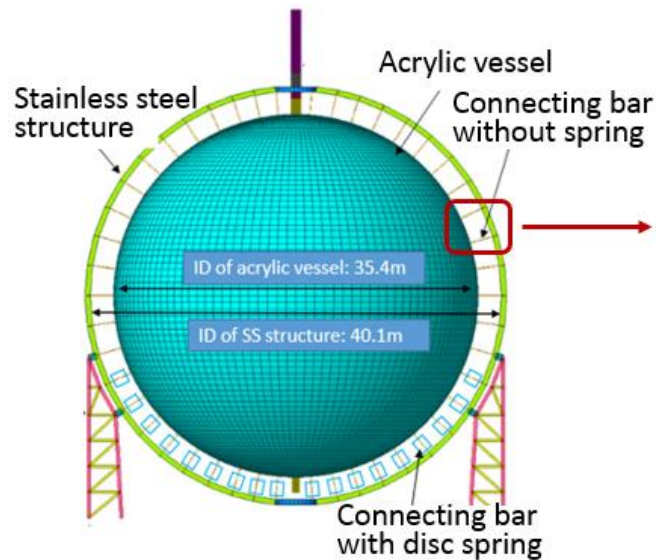
Stainless steel structure installed.



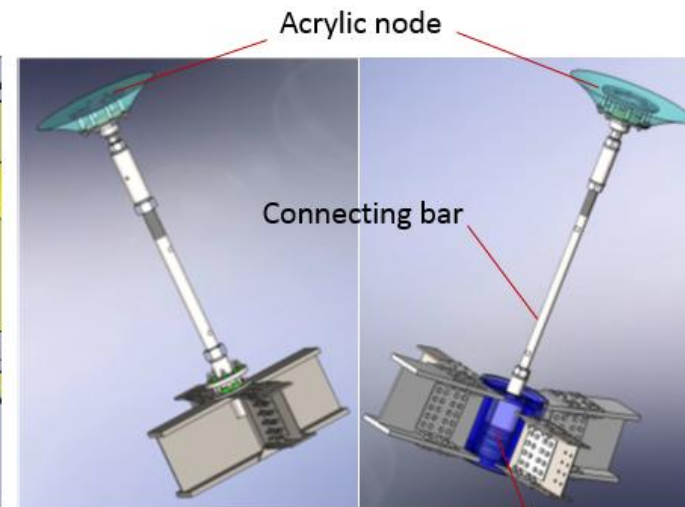
Acrylic vessel installed.



PMT installed.



Connecting structure



Steel node without spring

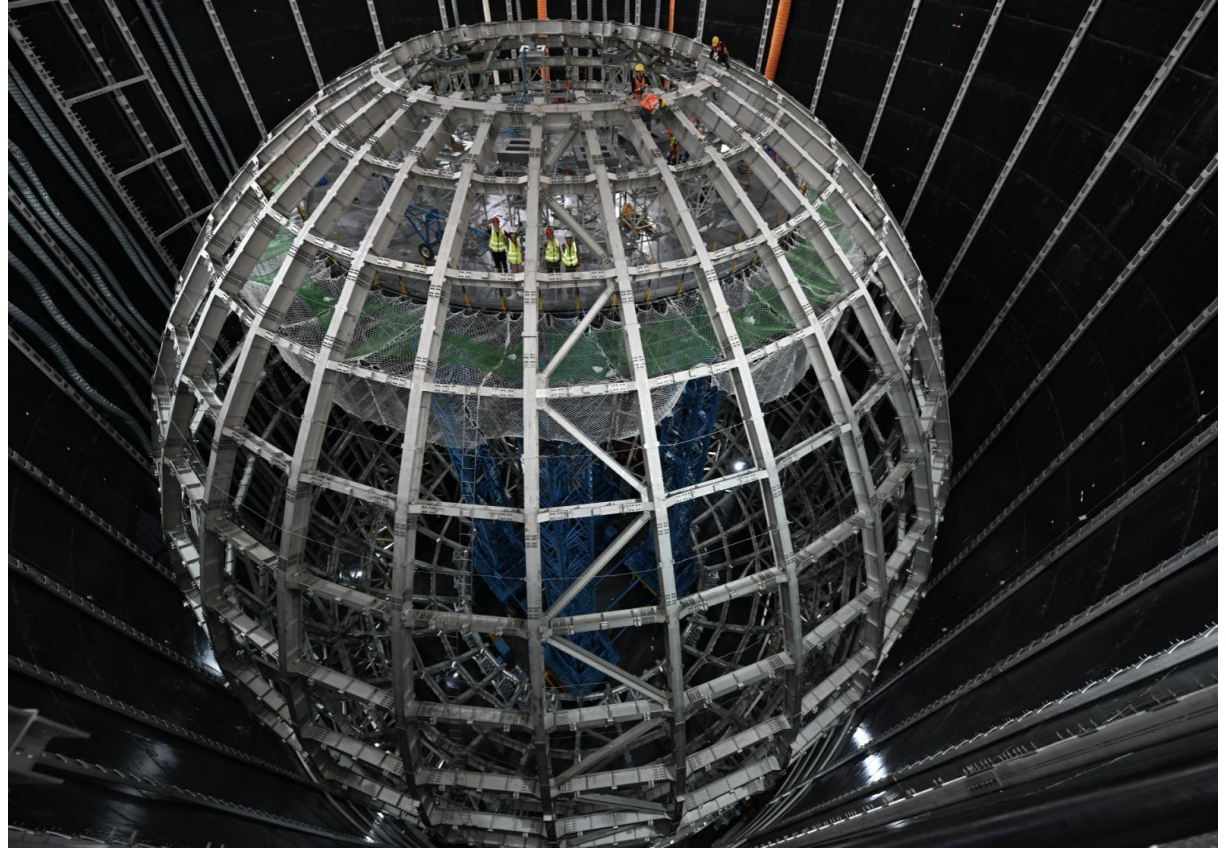
Steel node with disc spring

Detector Construction

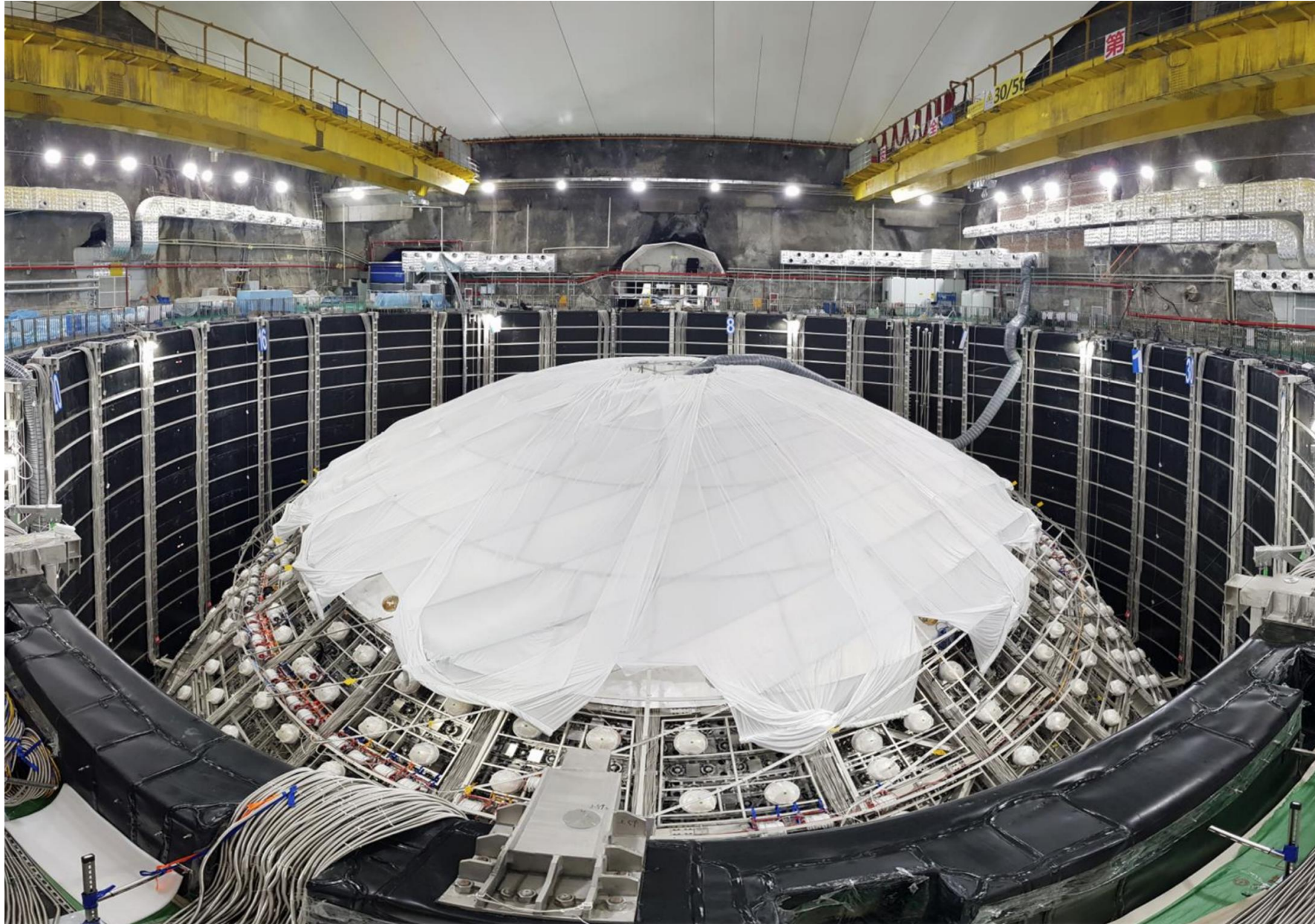
Installation platform finished (May 2022)



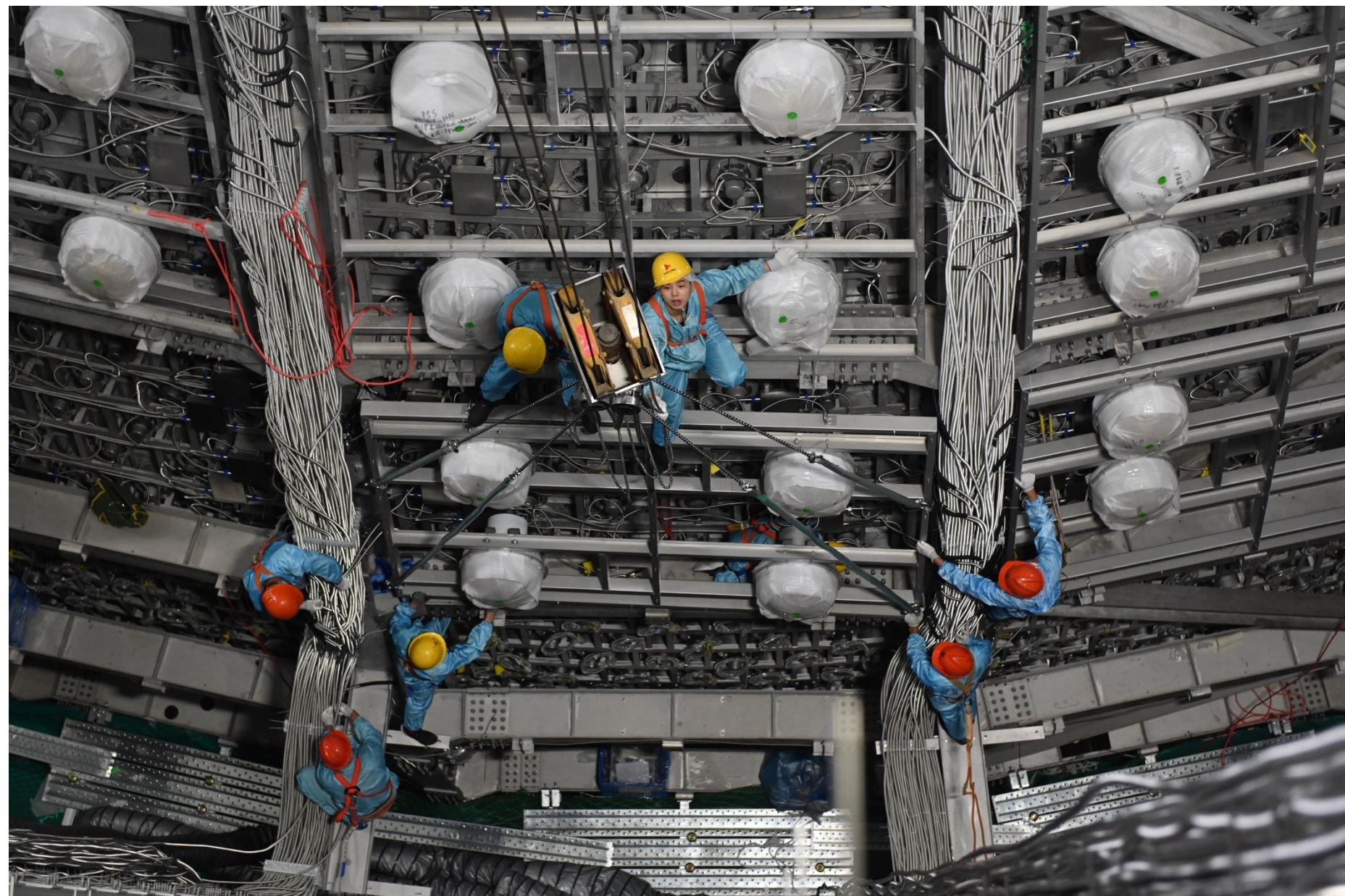
Support structure finished (June 2022)



Experimental Hall = Clean Room



Installations in height



Check and repair the outer surface of the acrylic sphere



Surface test of cleaning construction



Removal of temporary protective paper from the inner surface

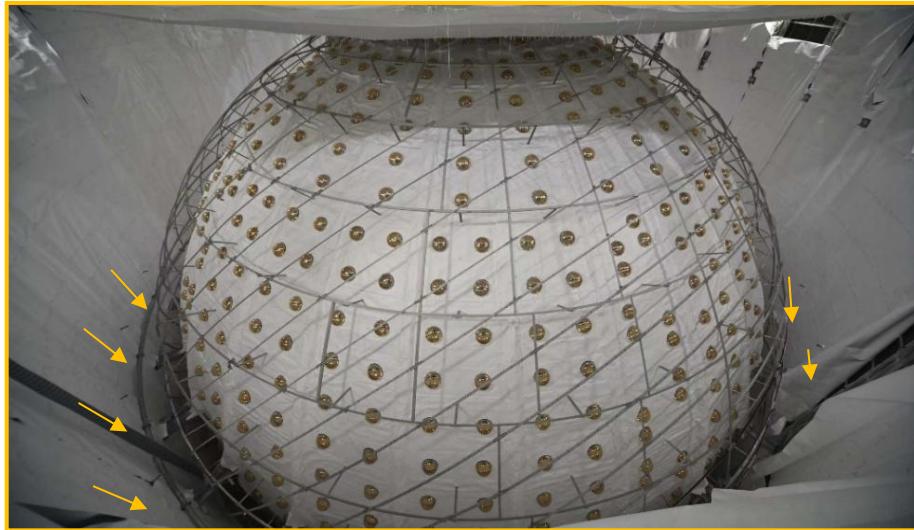
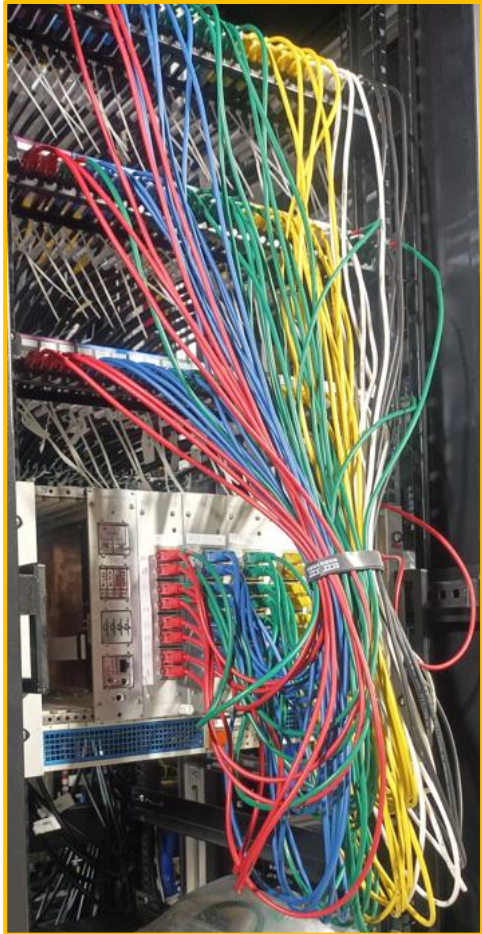


Final residual paper were taken by hand



Installation of LED flashers

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



JUNO detector water phase

Achievements:

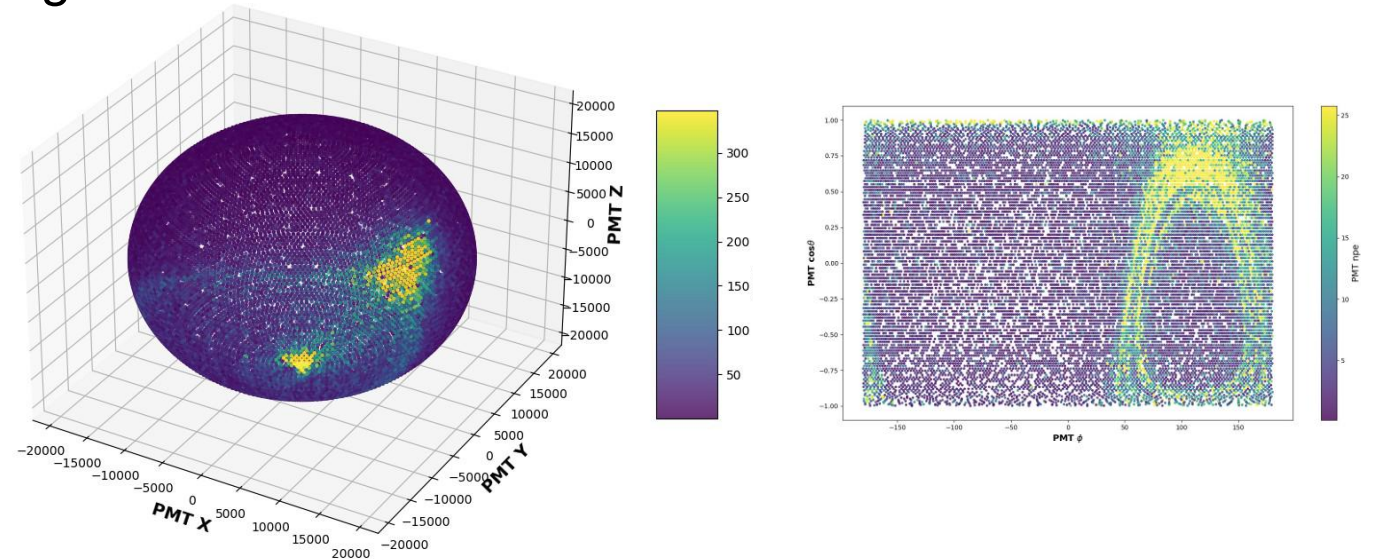
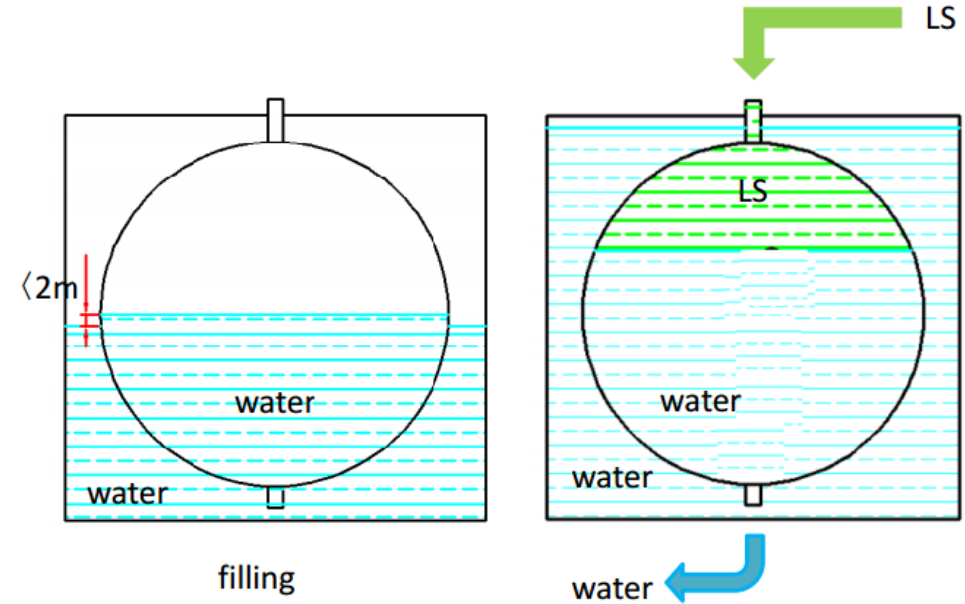
Christmas 2024 – start of water filling
Chinese New Year – water filling finished

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

Calibration sources working as expected (Am-Be and Am-C) probe low-energy threshold by identifying these neutron sources

We see the first muon candidates

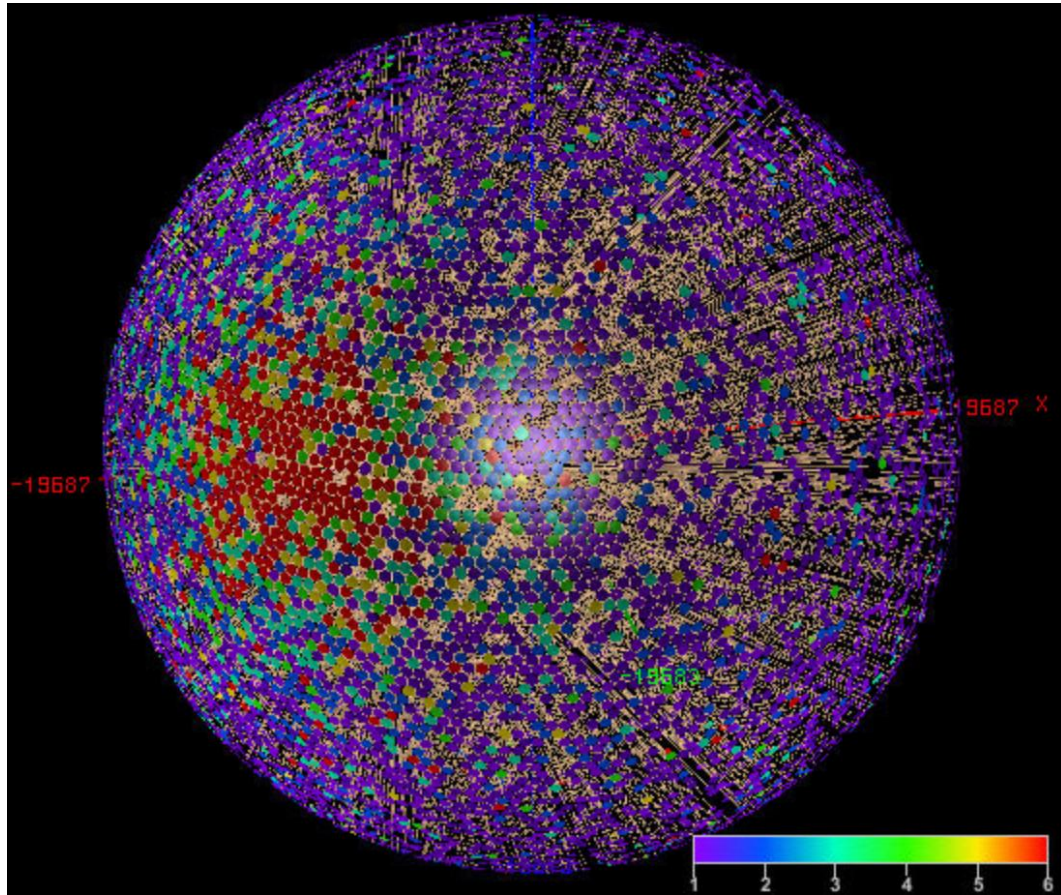
February 2025 – start of LS filling



JUNO RESULTS

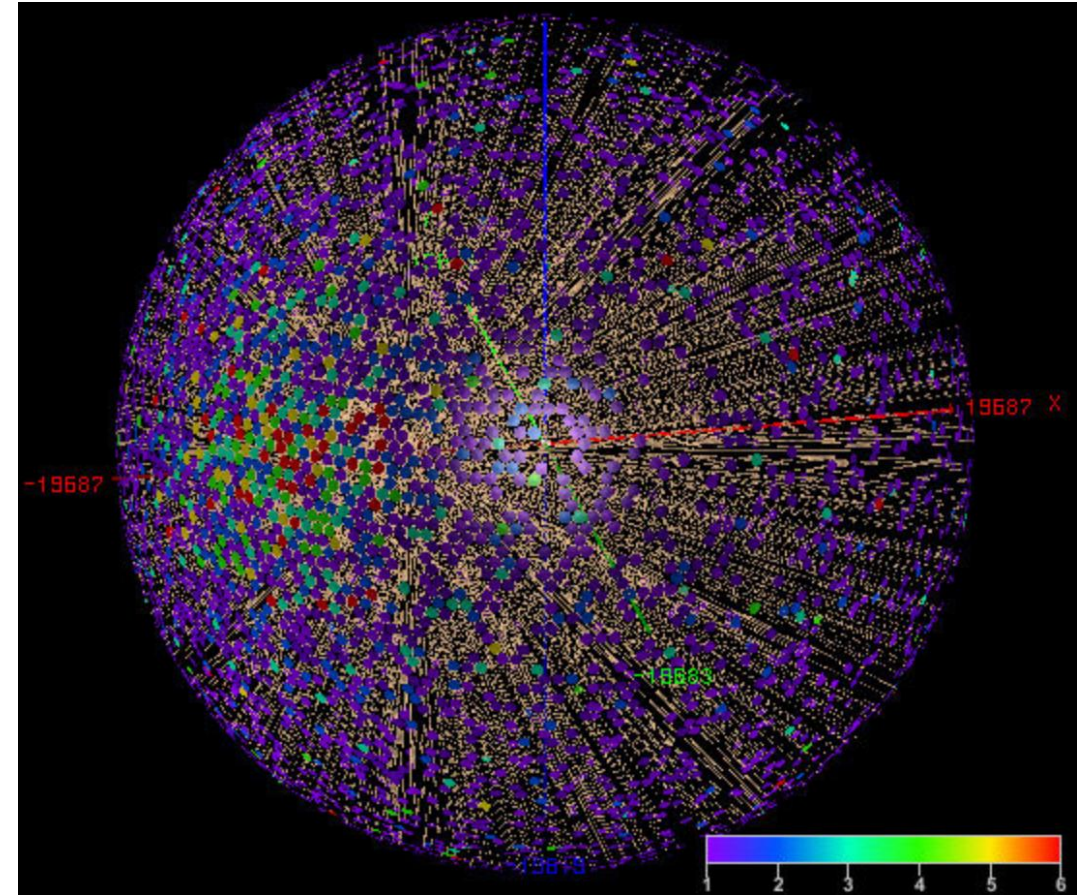
A Golden Reactor Neutrino Event

Mon, 25 Aug 2025 22:50:45
RecEnergy = 6.3 MeV
RecVertex (-9458, -9707, 3820) mm



Prompt e⁺ signal

Mon, 25 Aug 2025 22:50:45
RecEnergy = 2.4 MeV
RecVertex (-10393, -9794, 4333) mm

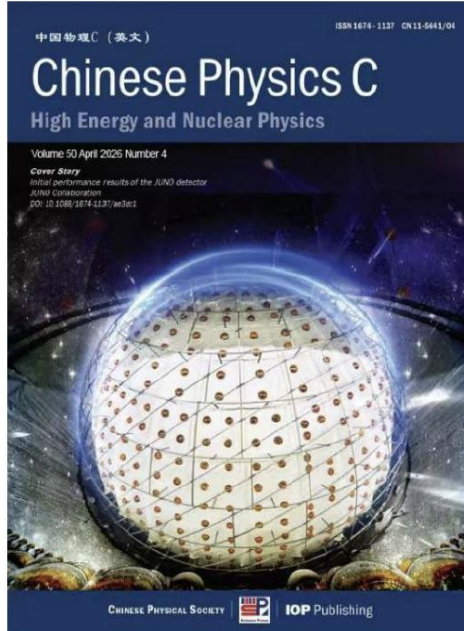


Delay neutron signal

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

"Initial performance results of the JUNO detector"

CPC Vol. 50, No. 4 (2026) 043001



In this first release the ‘solar’ oscillation parameters measured with the best precision

"First measurement of reactor neutrino oscillations at JUNO"

Nature, Vol 654, 11 June 2026, 343



$$\sin^2 \theta_{12} = 0.3092 \pm 0.0087$$

2.8%

$$\Delta m_{21}^2 = (7.50 \pm 0.12) \times 10^{-5} \text{ eV}^2$$

1.6%

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

Today New Results using 207 days of data

Updated preliminary results released in June @ NEUTRINO 2026

(publication under preparation)

- 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 ^9Li background
 - Suppression (factor 50) of accidental background at larger FV using likelihood cut
 - Model independent estimate of the $^{214}\text{BiPo}$ - correlated background

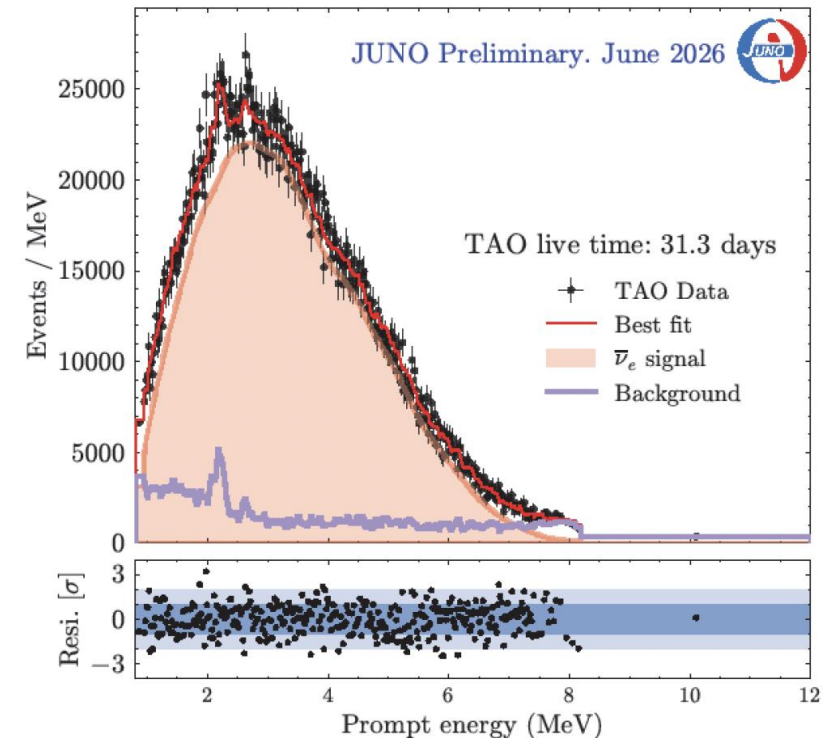
February 2026: TAO (Taishan Neutrino Observatory) online

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: $<2\%/\sqrt{E}$
- ✓ 1000 IBD / day

To measure unoscillated reactor neutrino spectrum

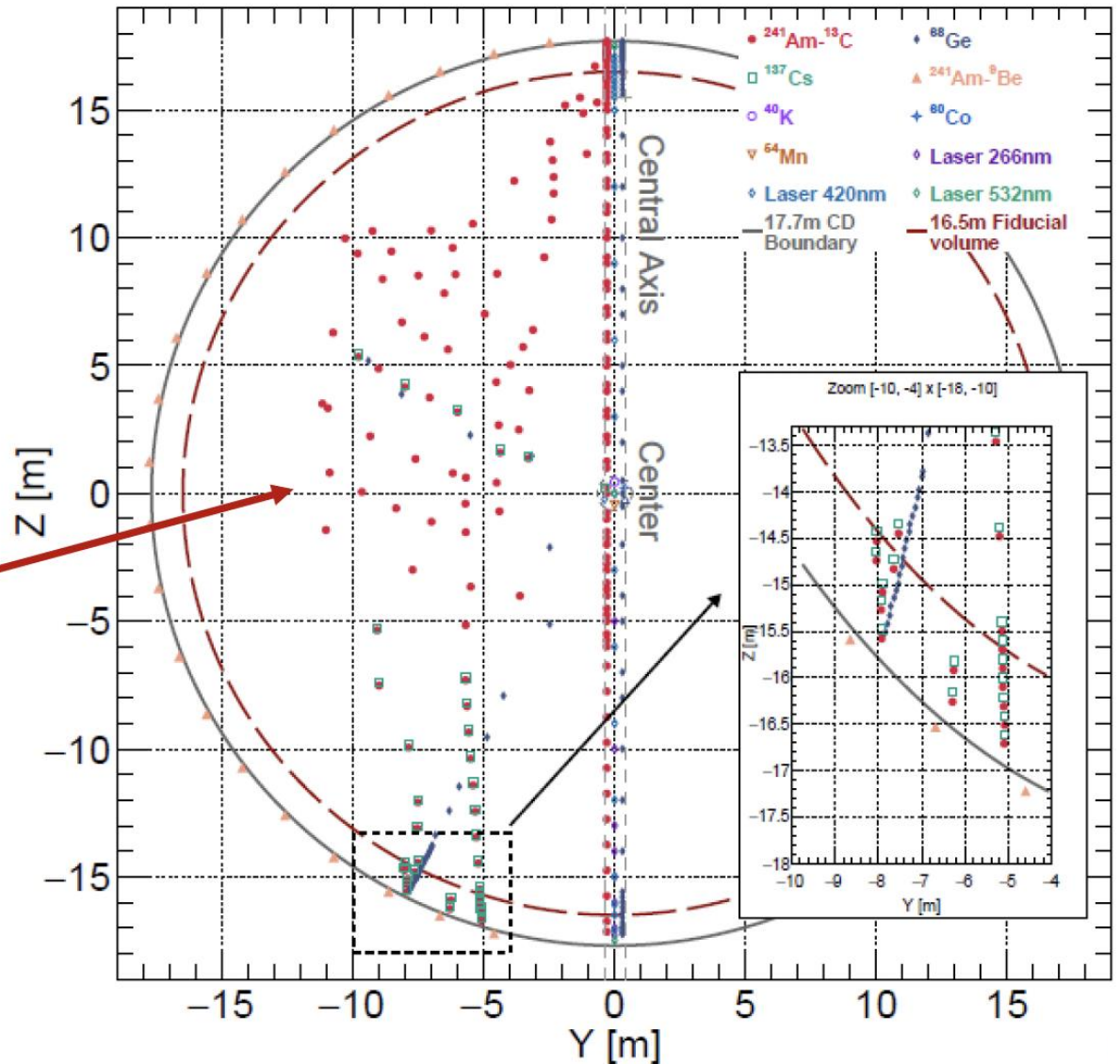
- ✓ Better resolution to constrain fine structure and spectral shape.
 - ✓ **REFERENCE FOR JUNO SPECTRAL FIT**
- Improve nuclear databases, search for sterile neutrinos.



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

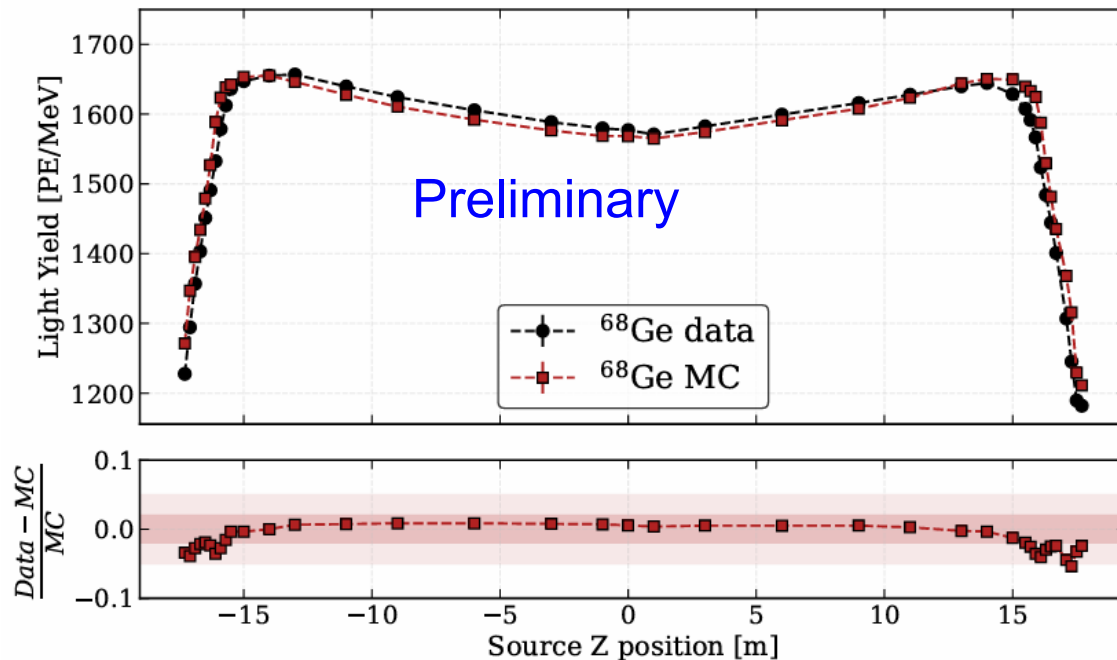
- Positions at which source calibration performed
- No ^{222}Rn leakage or other contaminations introduced during calibration



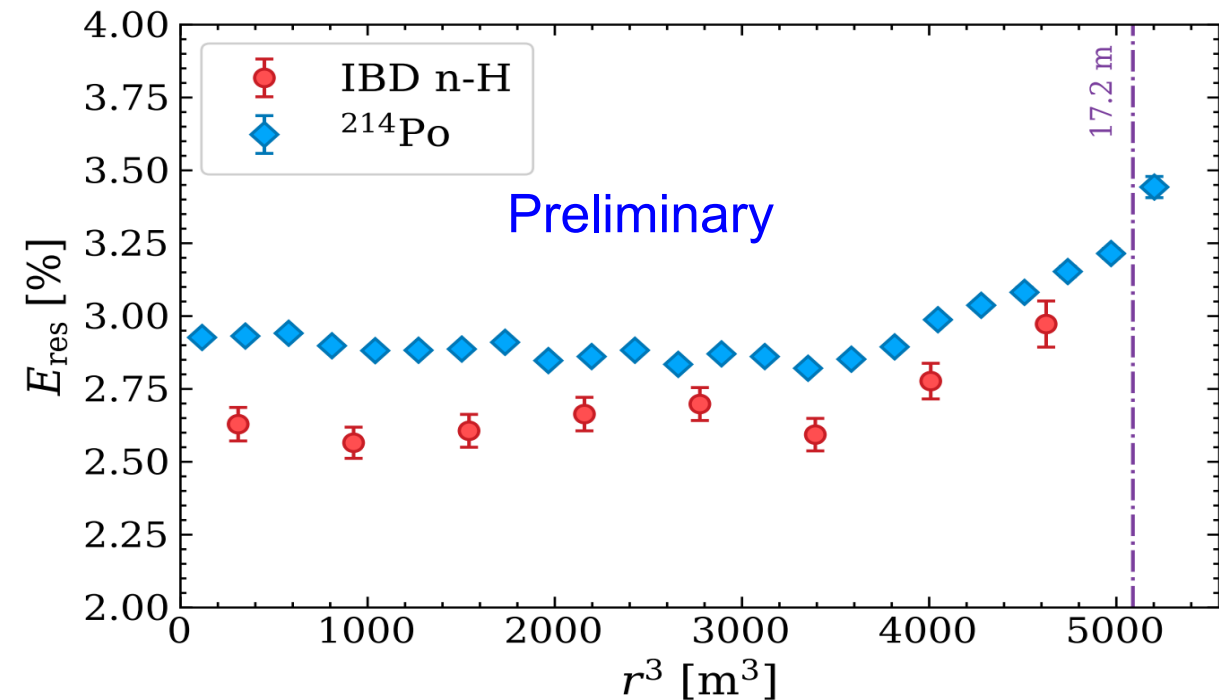
Light Yield and Energy Resolution

- 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 $\sim 3.5\%$ @ 2×0.511 MeV at the center (expectation from MC was 3.1%)
- Energy resolution for alpha from ^{214}Po is $\sim 2.9\%$ @ 0.93 MeV

Light yield of ^{68}Ge

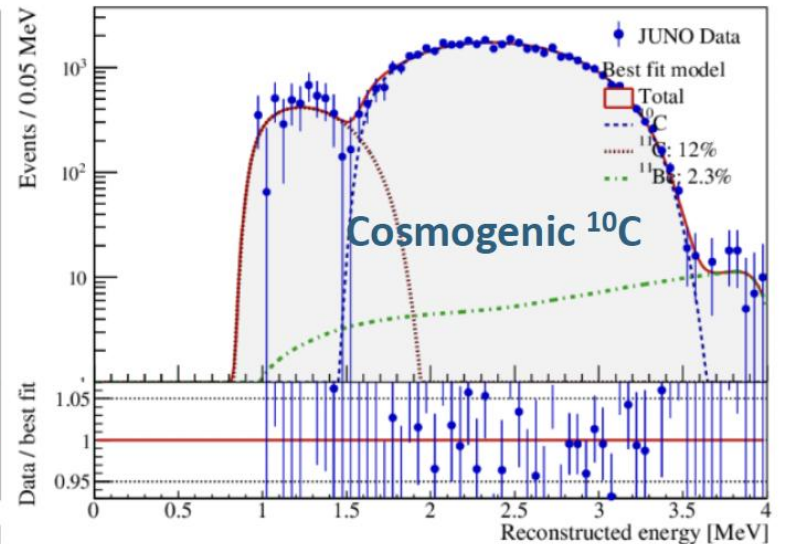
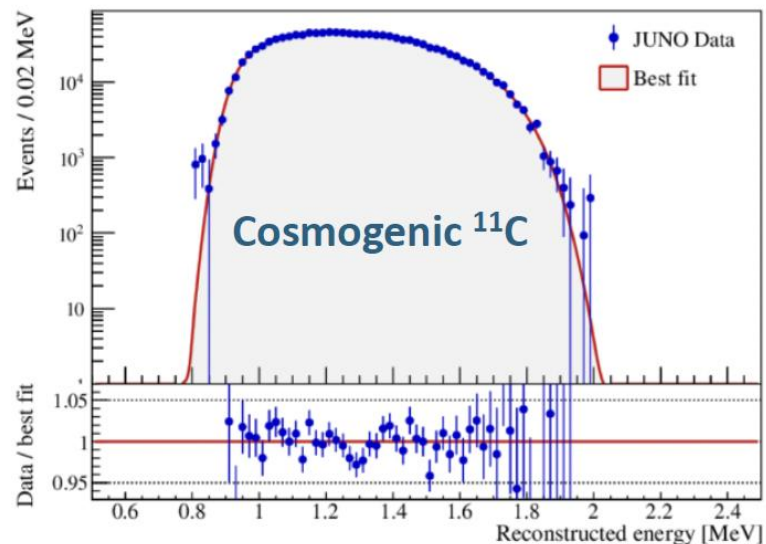
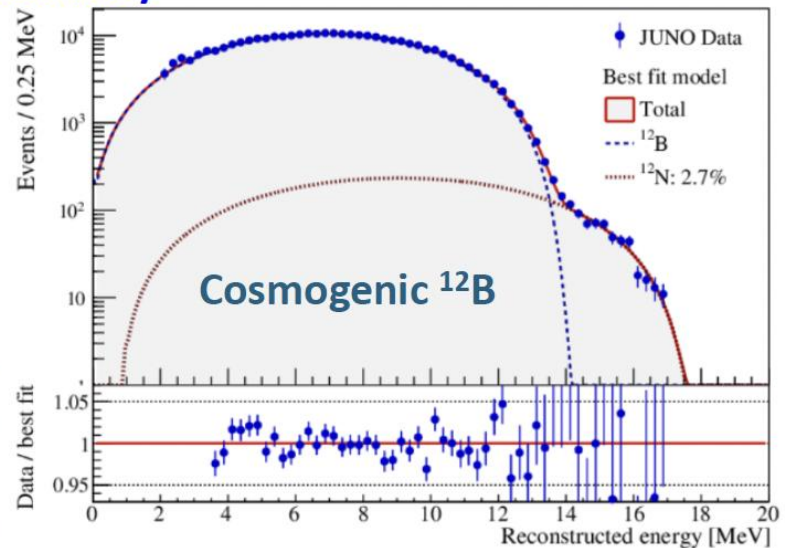
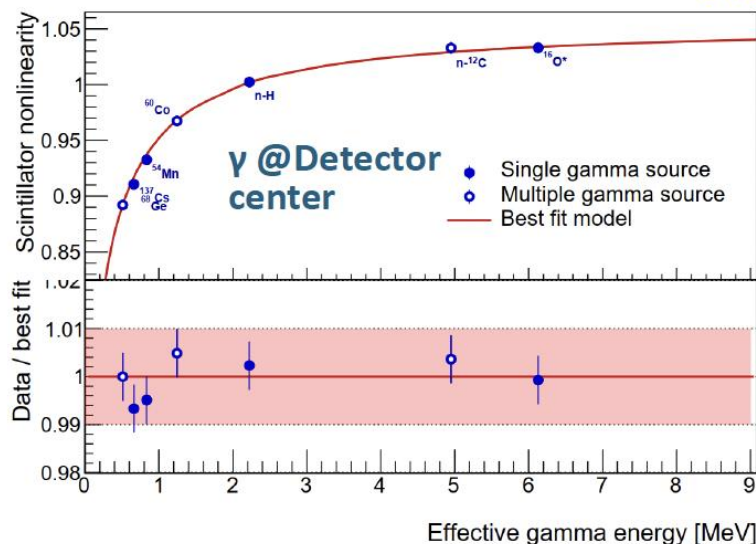


Energy resolution vs r^3



Energy Scale Non-linearity

Preliminary



Energy scale is intrinsically non-linear and particle dependent:

- ionisation quenching
- Cherenkov light
- minor: instrumental effects

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

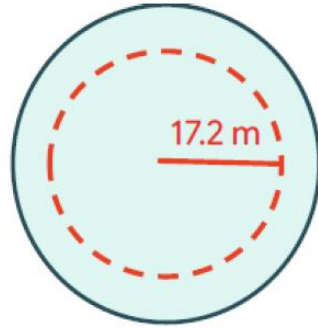
- gamma calibration sources
- cosmogenic ^{12}B (e^-)
- cosmogenic ^{11}C , ^{10}C (e^+)

IBD Event selection

Enlarged!

Fiducial Volume cut

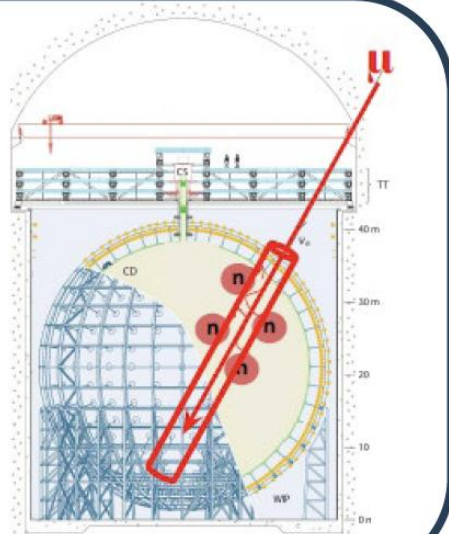
- To remove external radioactivity
- $R < 17.2 \text{ m} + |z| < 15.5 \text{ m}$



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);



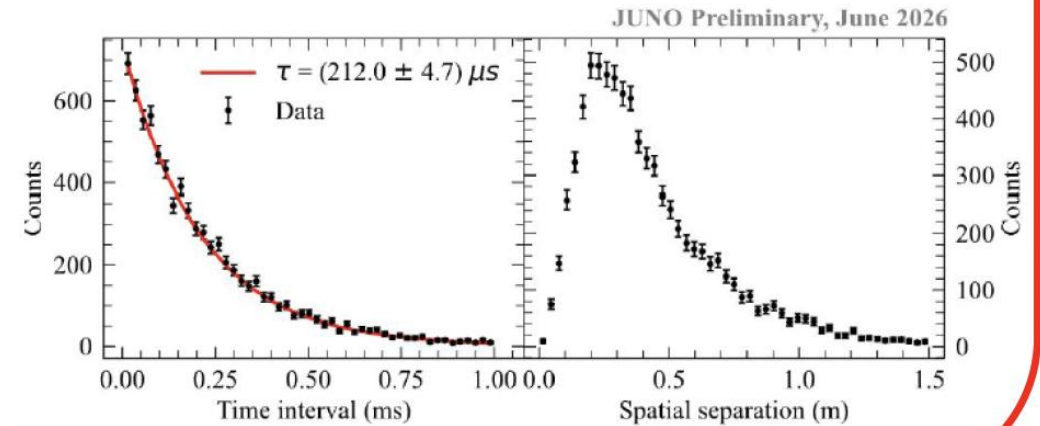
IBD selection (space+time+energy)

$$5 \mu\text{s} < \Delta t < 1 \text{ msec}$$

$$\Delta R < 1.5 \text{ m}$$

$$0.7 \text{ MeV} < E_{\text{prompt}} < 12 \text{ MeV}$$

$$2 \text{ MeV} < E_{\text{delayed}} < 2.5 \text{ MeV}$$

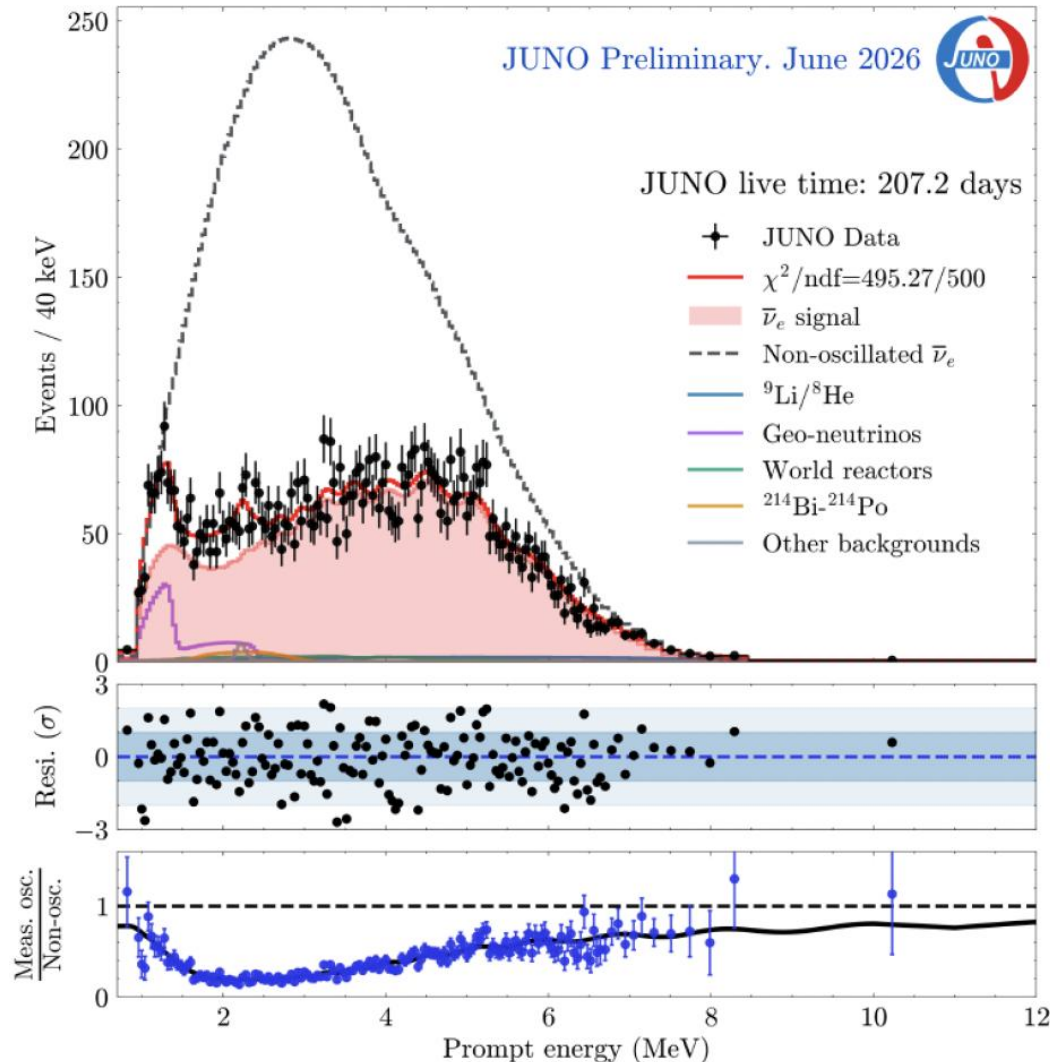


Efficiency of all the cuts $\epsilon_{\text{tot}} \sim 74\%$

Total number of target protons in 20 kton: $(1.442 \pm 0.014) \times 10^{33}$

JUNO IBD prompt energy spectrum

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



The signal and background RATES are

$\bar{\nu}_e$ signal (cpd)

w/o ϵ_{tot} corrected 36.02 ± 0.62

w/ ϵ_{tot} corrected 48.67 ± 1.08

Backgrounds (cpd)

Best-fit

${}^9\text{Li}/{}^8\text{He}$ 1.41 ± 0.26

Geoneutrinos 2.12 ± 0.32

World reactors 0.92 ± 0.09

${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$ 0.57 ± 0.34

${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ 0.05 ± 0.02

Fast neutrons 0.02 ± 0.02

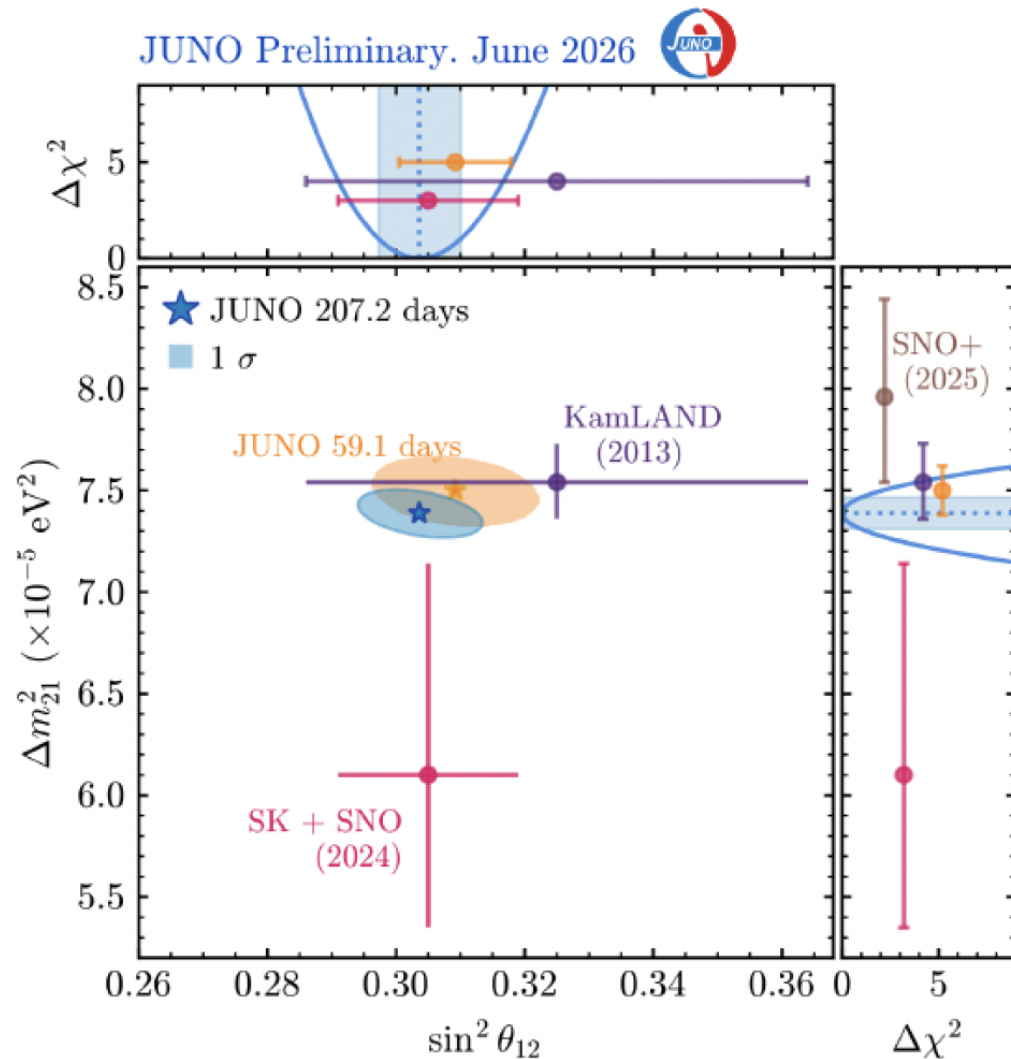
Double neutrons 0.13 ± 0.10

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

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

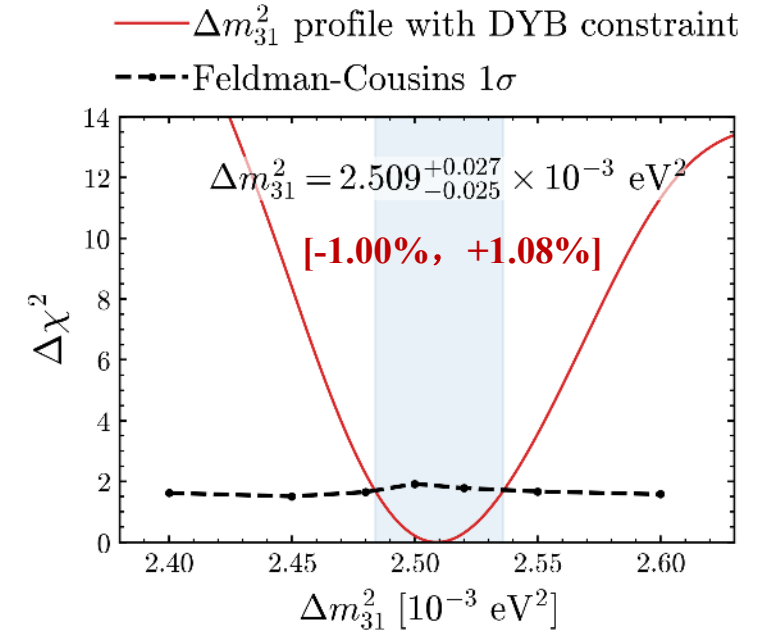
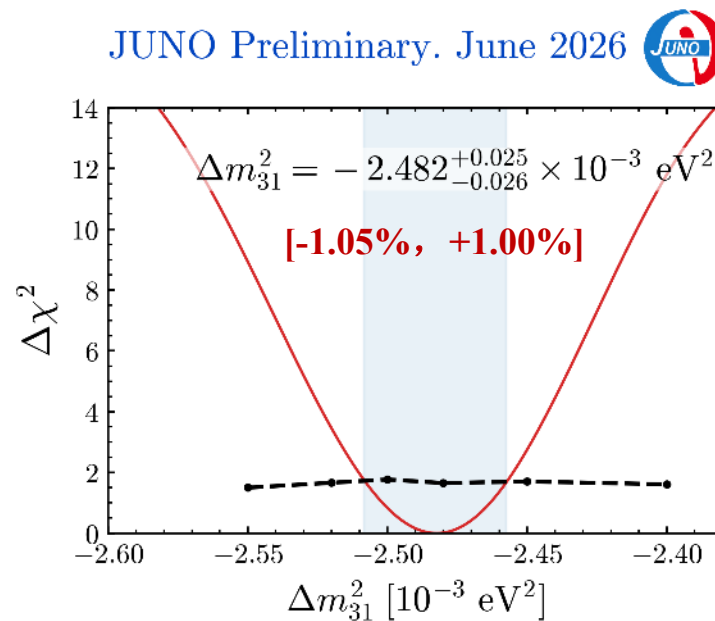
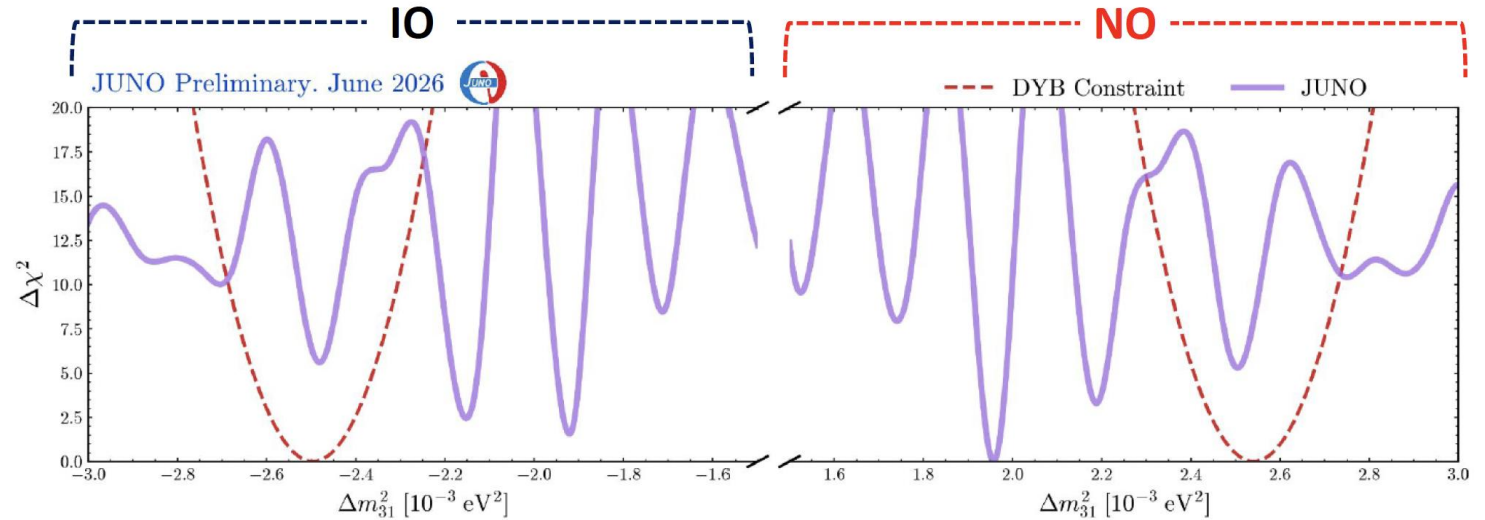
World's best precision

First Result of Δm^2_{31}

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

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)

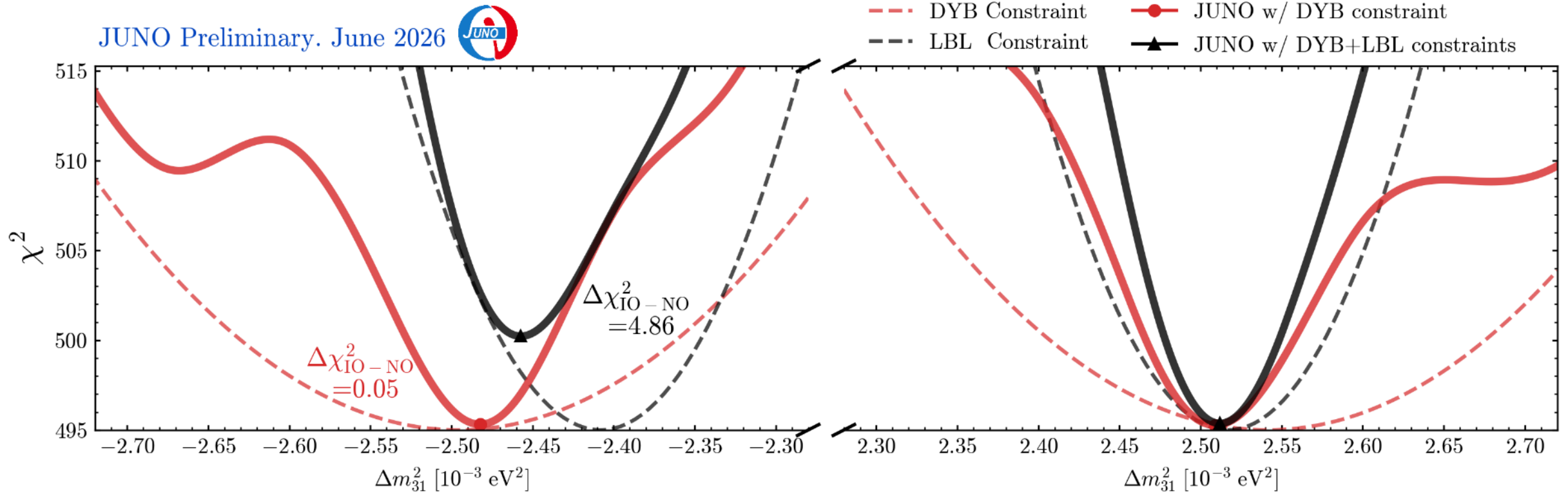
Feldman-Cousins (FC) method is used to determine the 1σ range of Δm^2_{31} : $\sim 1\%$ precision achieved



Adding Constraint from NuFit-LBL

Δm_{31}^2 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 $\Delta\chi^2 = 4.86$**



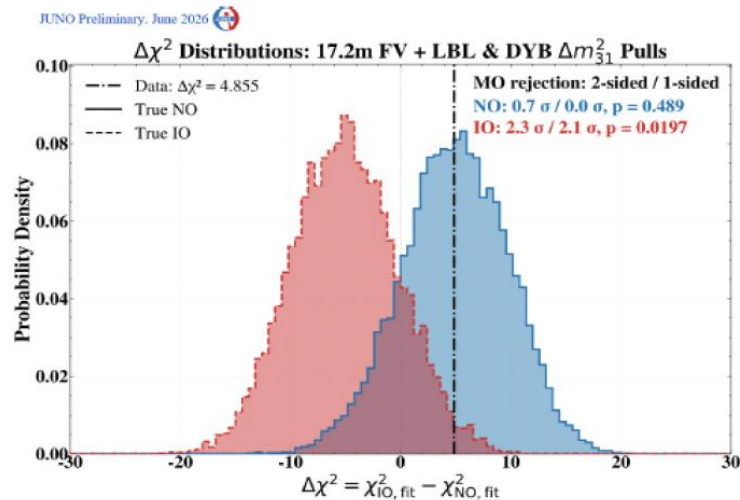
[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

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

Neutrino Mass Ordering Significance

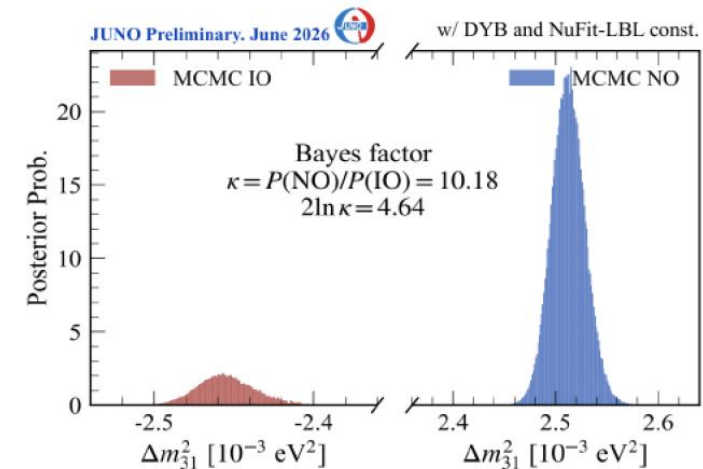
QUANTITATIVELY: significance calculated with both Frequentist and Bayesian approach

Frequentist



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

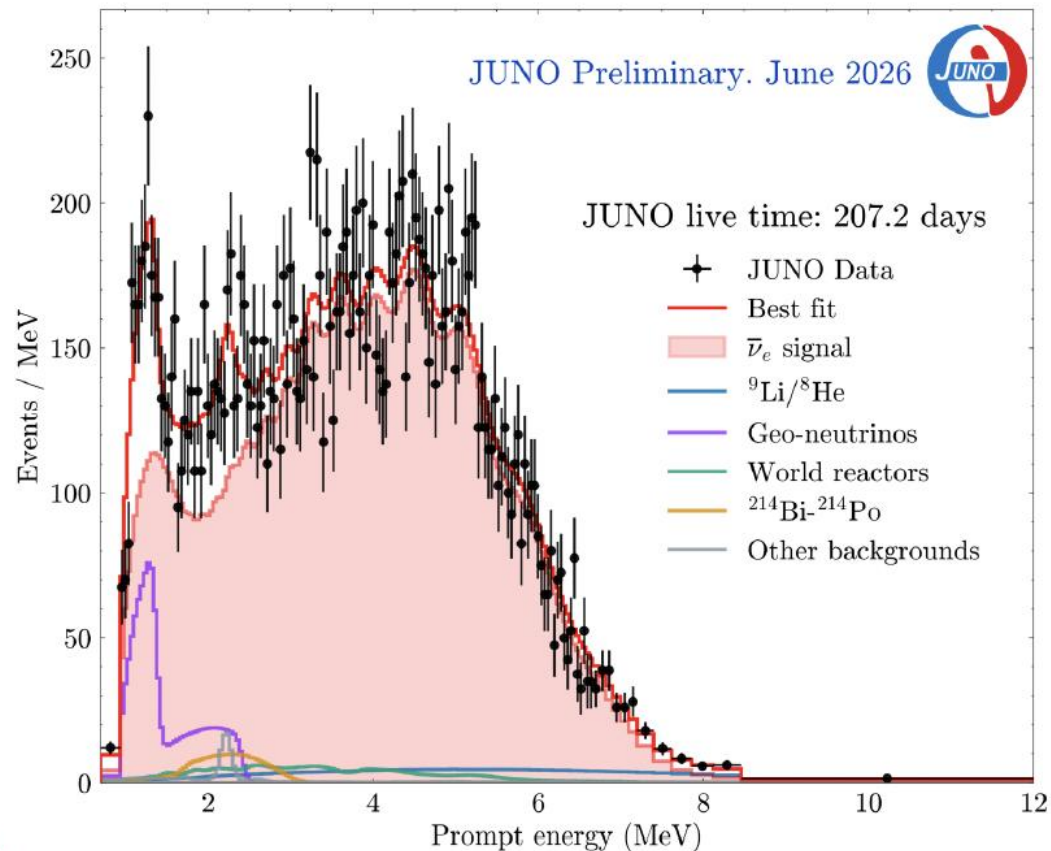
Bayesian



- 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



- Fits are performed without constraint on geo-neutrino flux, but with $3.4 \pm 10\%$ 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 samples 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.

Terrestrial Neutrino Unit

1 TNU = 1 IBD event / 10^{32} target protons / year
(cca 1 IBD event / 1 kton of liquid scintillator / 1 year)
with 100% detection efficiency

FUTURE

Expected Future of Neutrino

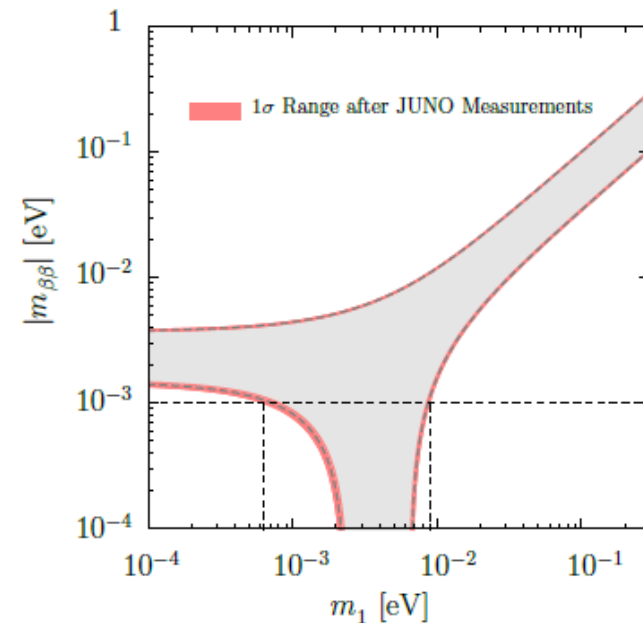
- ◆ In 5 years from now, **Nova+T2K/SuperK +ORCA/Icecube +JUNO** will determine the mass hierarchy
- ◆ In 10 years from now, **DUNE+HyperK** will determine the CP phase
- ◆ $0\nu\beta\beta$ decay will be the next breakthrough

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

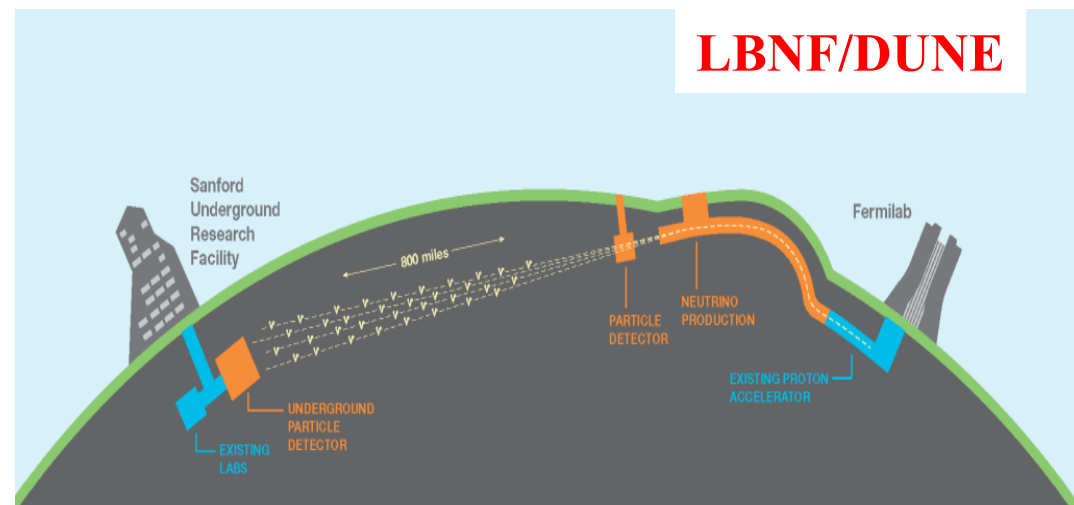
$$(m_{\nu_e})^{\text{eff}} = [\sum_i |U_{ei}|^2 m_{\nu_i}^2]^{1/2}$$

- **$0\nu\beta\beta$ decay should target for $\sim 1\text{meV}$**

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



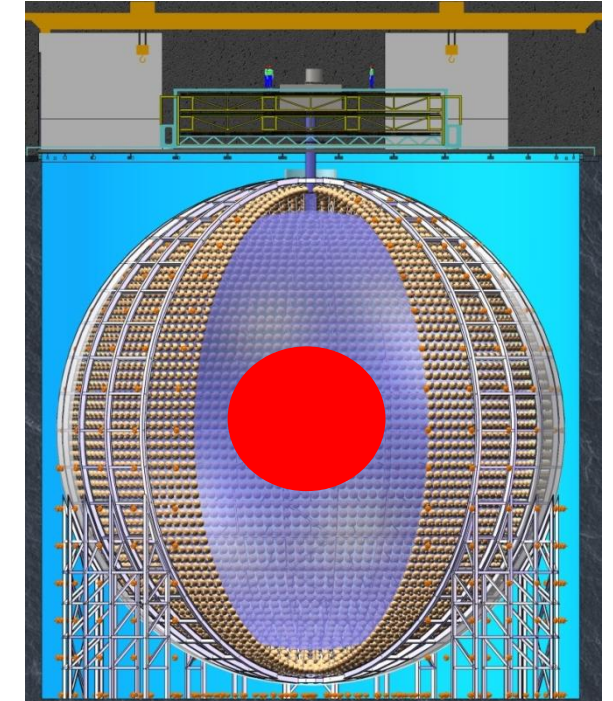
J. Cao et al.,
arXiv:1908.08355



Future JUNO Upgrade to JUNO- $\beta\beta$

- ◆ Once mass ordering is determined (~ 2030), JUNO will be upgraded for $\beta\beta$ -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)	$\langle m_{\beta\beta} \rangle, \text{meV}$
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- $\beta\beta$	^{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

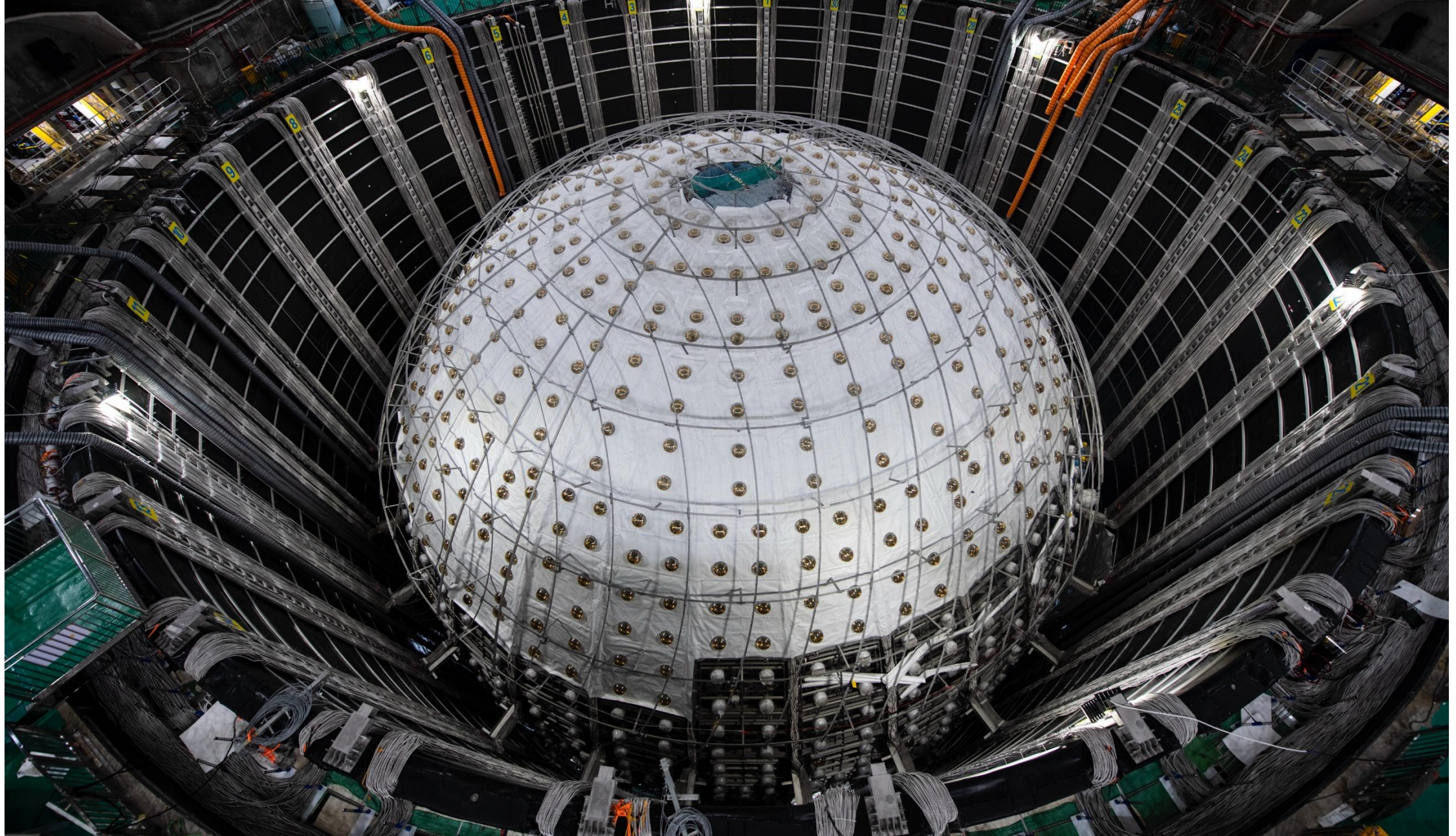
Zhao et al., arXiv: 1610.07143, CPC 41 (2017) 5

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: **Δm_{21}^2 : 1.06%, $\sin^2 \theta_{12}$: 2.1%.**
- Combining JUNO + JUNO-TAO + Daya Bay achieves world-leading precision of about **1% on Δm_{31}^2** .
- **Normal mass ordering (NO) is favored at 2.3σ** when additional constraints on Δm_{31}^2 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

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

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

MINOR BACKGROUNDS

$^{13}\text{C}(\alpha, n)^{16}\text{O}$, 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

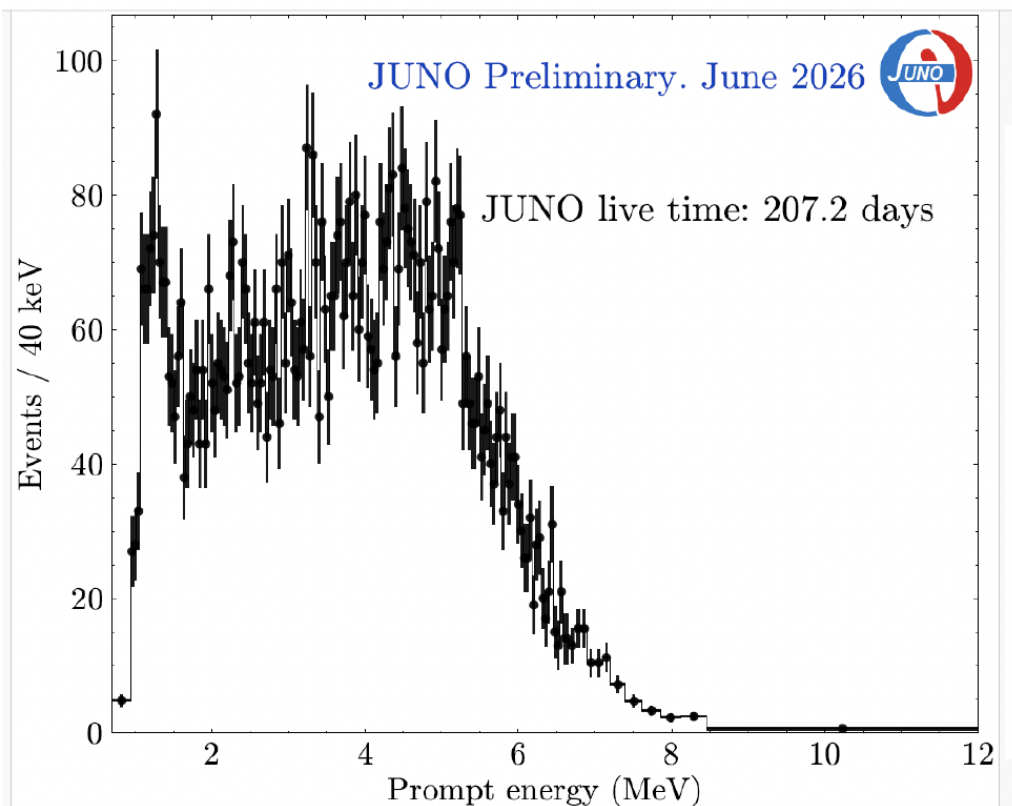
Output:

Signal and background rates

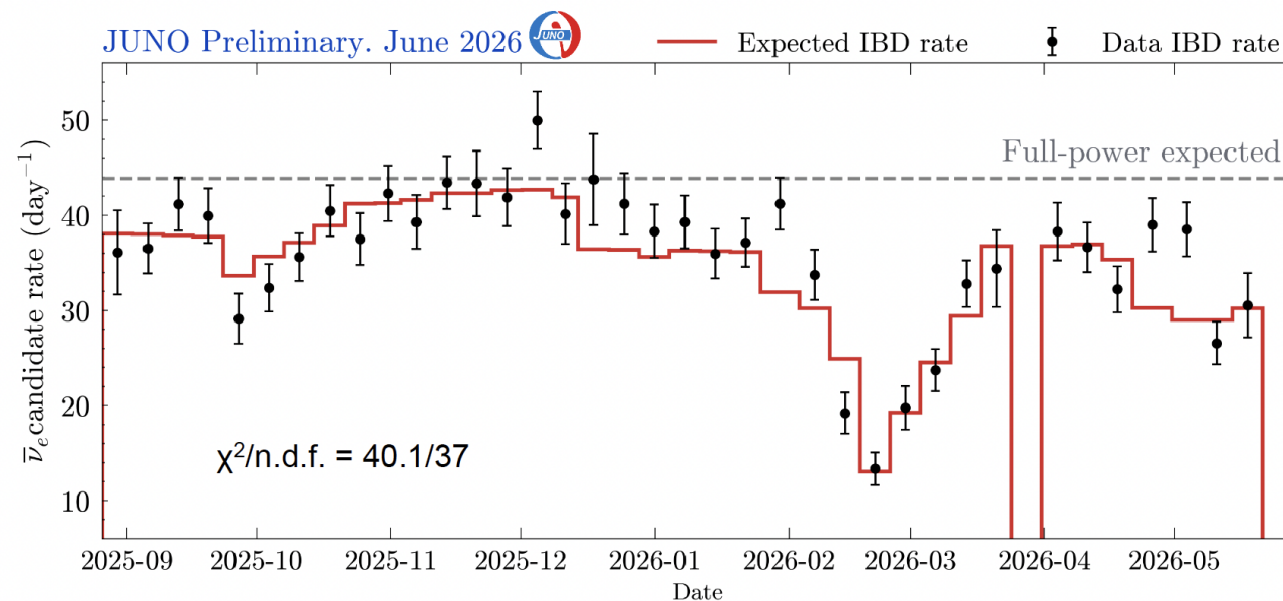
Oscillation parameters

SELECTED IBD CANDIDATES

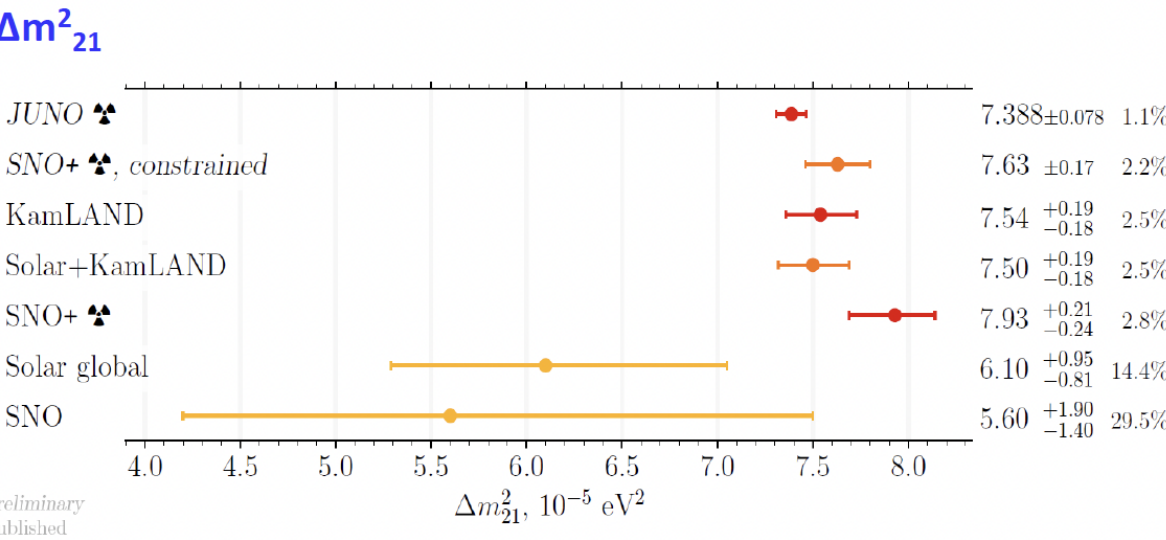
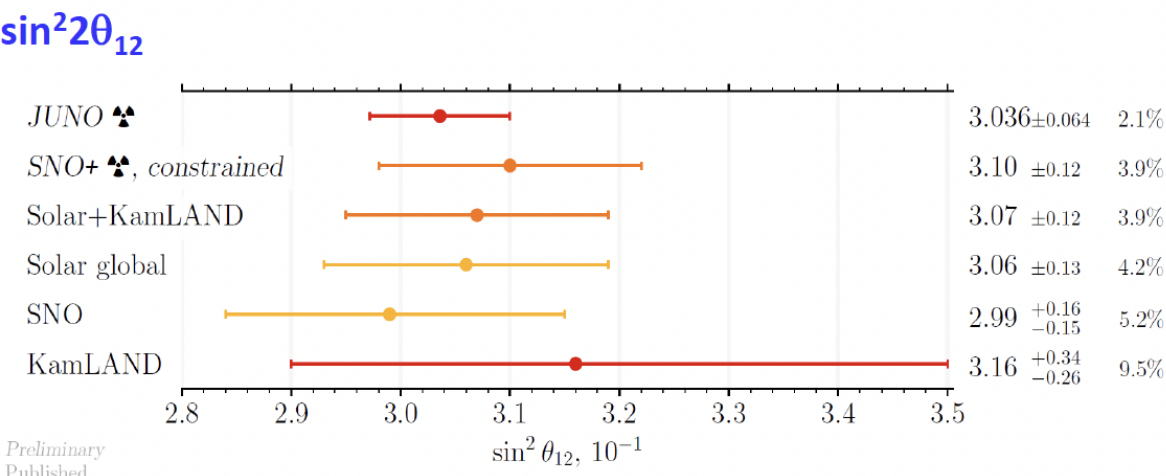
N of ν candidates = 8294 (~ 40 ev/day)



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



COMPARISON WITH EXISTING RESULTS



Results from JUNO have smallest uncertainties

