

REACTOR NEUTRINOS AND THE ROAD TO PRECISION:



Livia Ludhova on behalf of the JUNO collaboration

GSI Darmstadt & JGU Mainz

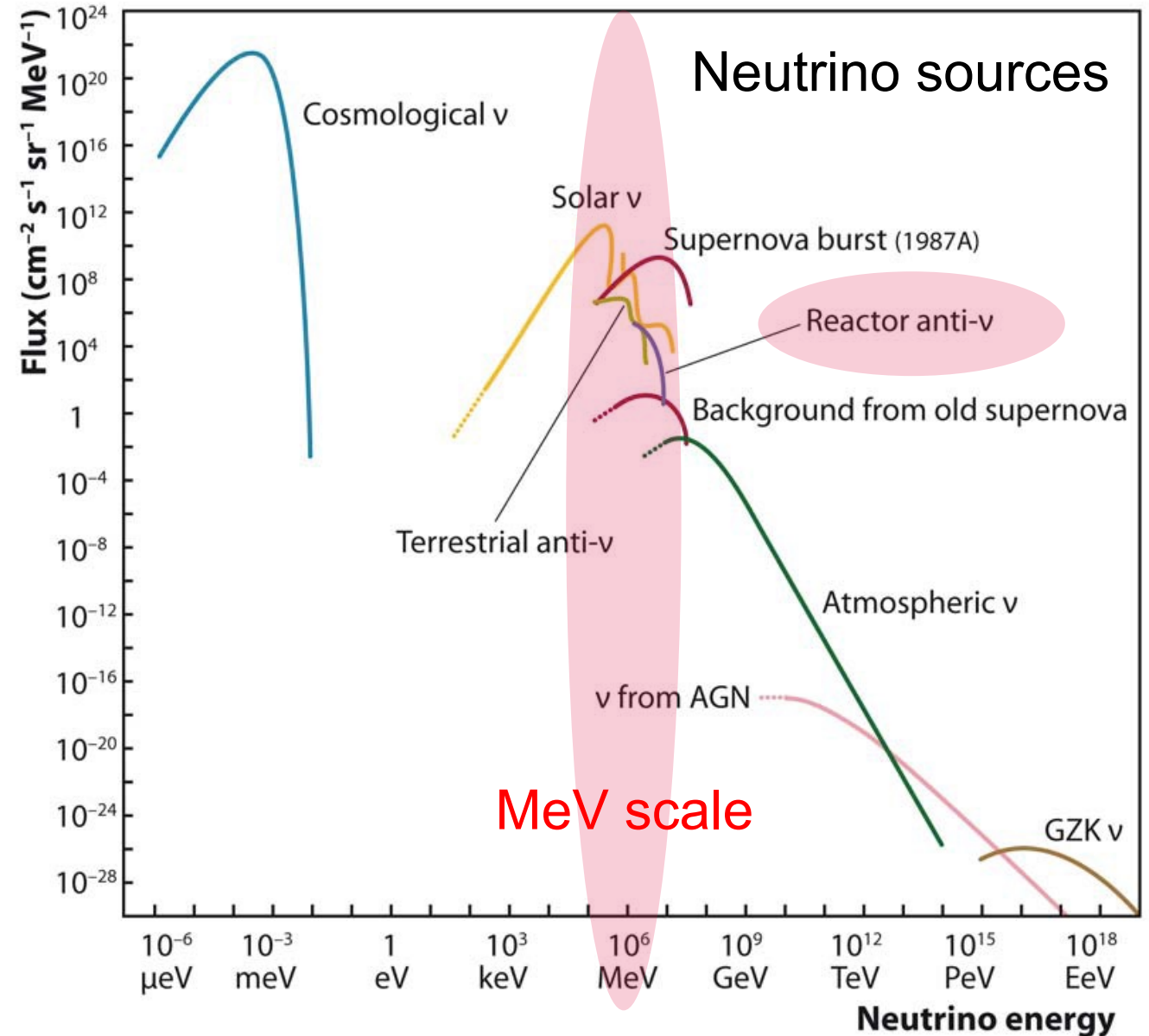
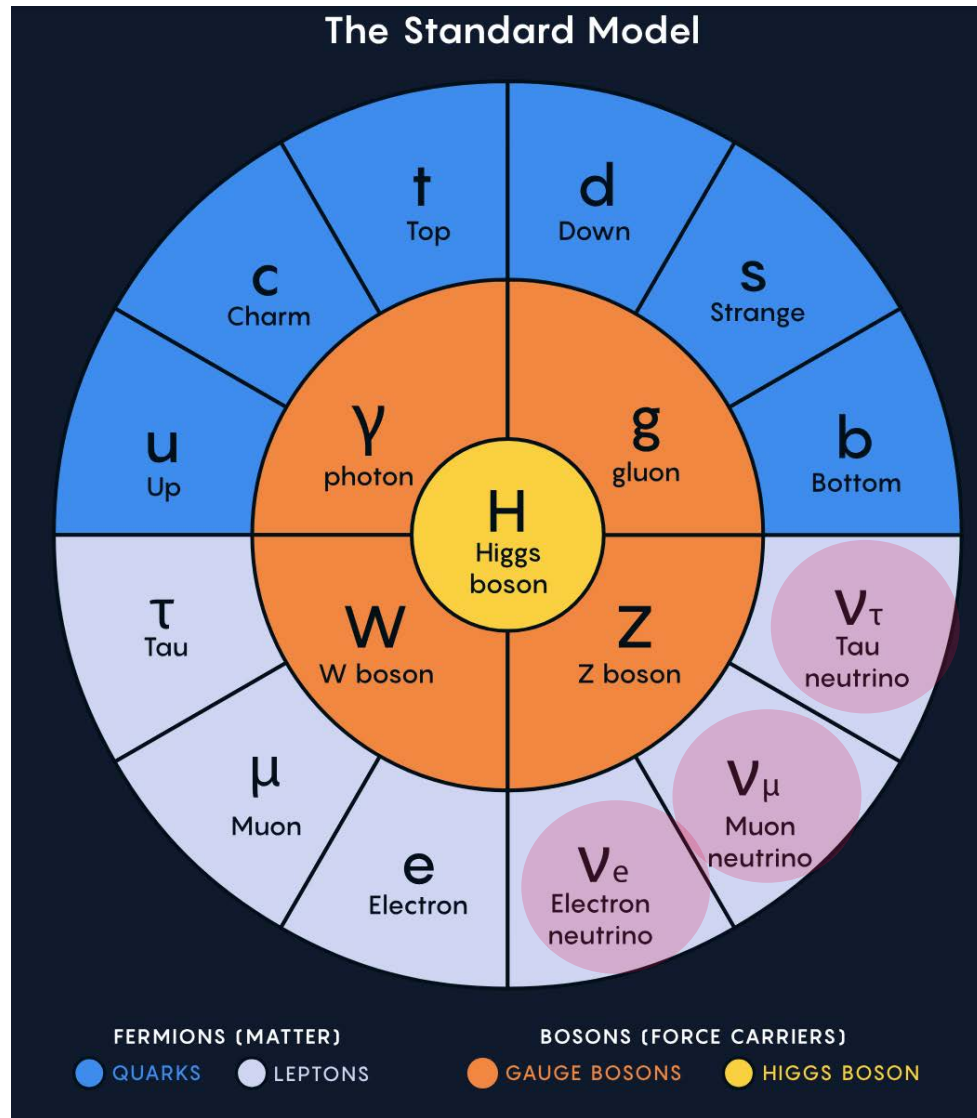
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th COURSE, Erice, Italy, 20/09/2026



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

INTRODUCING NEUTRINOS

2



NEUTRINO MIXING

3

Overview on neutrino mixing,
see talk of Mariam Tórtola.

Flavour eigenstates

$\alpha = e, \mu, \tau$

(INTERACTIONS)

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\nu_i\rangle$$

Mass eigenstates

$i = 1, 2, 3$

(PROPAGATION)

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix}}_{\text{Reactor}} \times \underbrace{\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \times \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana}}$$

Atmospheric

rotation $R_{23}(\theta_{23})$
dominant $\nu_\mu \leftrightarrow \nu_\tau$
mixing

Reactor

rotation $R_{13}(\theta_{13}, \delta)$
couples ν_e to ν_3
introduces CP phase δ

Solar

rotation $R_{12}(\theta_{12})$
dominant $\nu_e \leftrightarrow \nu_\mu$
mixing

Majorana

diagonal phase matrix
 $\text{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$
(only if Majorana neutrinos)

Mixing angles θ_{ij}

$\theta_{23} \sim 45^\circ$ (atmospheric, which quadrant?)

$\theta_{13} \sim 9^\circ$ (reactor, non-zero confirmed in 2012)

$\theta_{12} \sim 33^\circ$ (solar)

CP-violating phase δ

(unknown)

governs CP violation in
neutrino oscillations

Majorana phases α_1, α_2

(only if neutrinos are
Majorana particles)

Dirac vs Majorana

If Dirac particles:

$\alpha_1 = \alpha_2 = 0$ (unphysical)

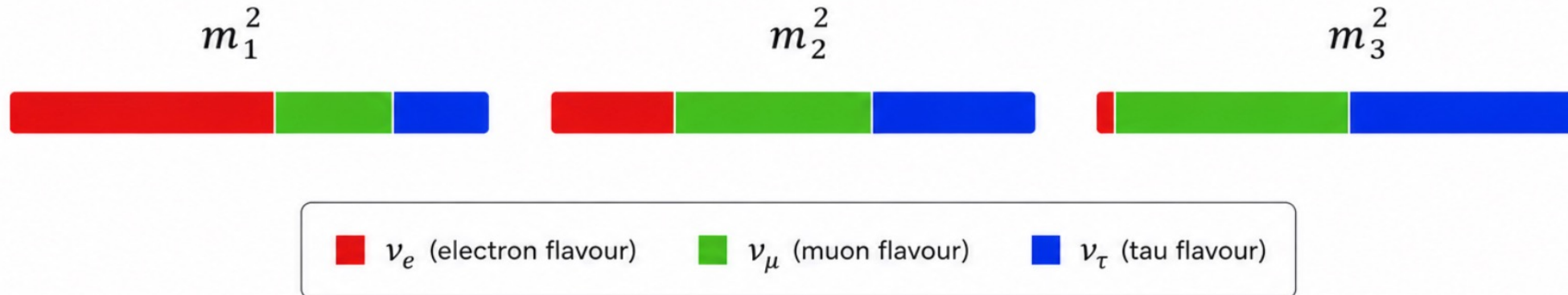
If Majorana particles:

$\alpha_1, \alpha_2 \in [0, 2\pi)$ (physical)

NEUTRINO MIXING

Flavour content of mass eigenstates

Each mass eigenstate m_i^2 is a mixture of flavour eigenstates (ν_e , ν_μ , ν_τ)

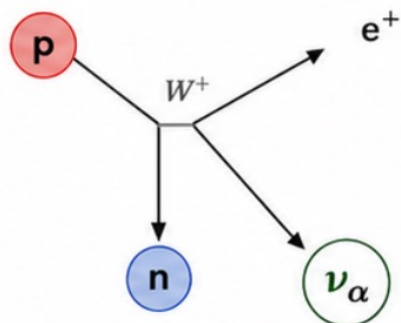


Our definition: we call the 1st mass eigenstate the one with the **largest electron flavour component**.

NEUTRINO OSCILLATIONS

ν production

e.g. β^+ -decay



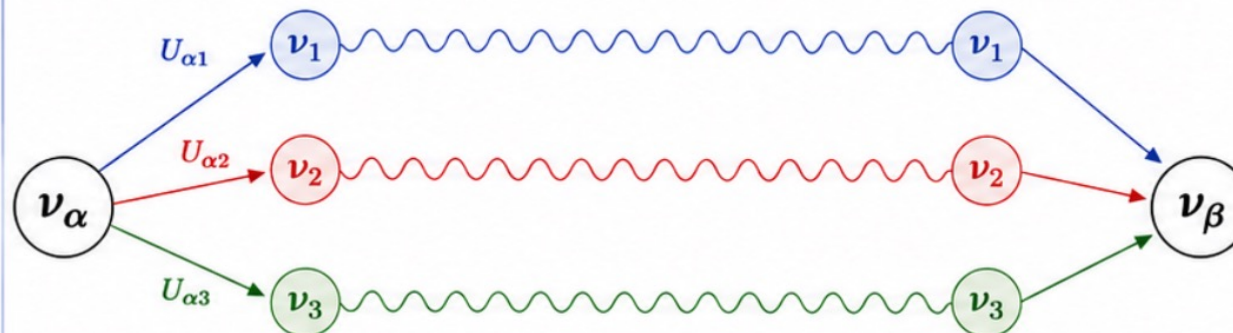
Weak interaction creates neutrino in **flavor-eigenstate**

ν_α ($\alpha = e, \mu, \tau$).

$P(\nu_\alpha) = 100\%$ at production.

ν propagation (oscillation)

As a coherent superposition of **mass-eigenstates**.



During propagation over distance L with energy E , mass-eigenstates accumulate different phases.

Phase difference between mass-eigenstates:

$$\Delta\phi_{ij} = \phi_i - \phi_j = \frac{\Delta m_{ij}^2 L}{2E}$$

Mass-squared difference:

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \quad (i, j = 1, 2, 3; i \neq j)$$

ν detection

As **flavor-eigenstate**:

Superposition of mass-eigenstates has changed because of phase factors.

$$P_{\alpha\beta} = P(\nu_\alpha \rightarrow \nu_\beta)$$

$$P_{\alpha e} : \nu_e$$

$$P_{\alpha\mu} : \nu_\mu$$

$$P_{\alpha\tau} : \nu_\tau$$

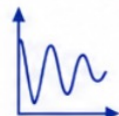
Finite probability to detect a different **neutrino-flavor**!

Oscillation probability (vacuum)

$$P_{\alpha\alpha} = 1 - 4 \sum_{i>j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right)$$



Neutrinos have non-zero rest **mass** (Nobel Prize 2015).



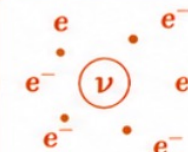
$P(\nu_\alpha \rightarrow \nu_\alpha)$
= f(baseline L ,
energy E_ν).



Different (L, E_ν) $\Rightarrow$
sensitivity to different
($\theta_{ij}, \Delta m_{ij}^2$).



Appearance /
disappearance.



Oscillations in matter:
effective ($\theta_{ij}, \Delta m_{ij}^2$)
parameters = f(e^- density N_e ,
energy E_ν).

$i, j = 1, 2, 3$ (mass eigenstates)

$U_{\alpha i}$: lepton mixing matrix (PMNS) element

$\Delta m_{ij}^2 = m_i^2 - m_j^2$

L : baseline (distance)

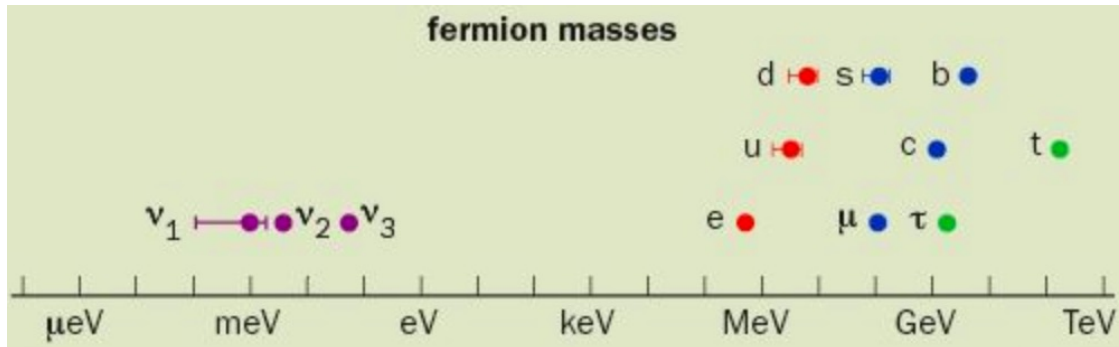
E_ν : neutrino energy

N_e : electron number density

NEUTRINO PHYSICS & OPEN QUESTIONS

Absolute neutrino mass scale

See talk of
Christian Weinheimer!



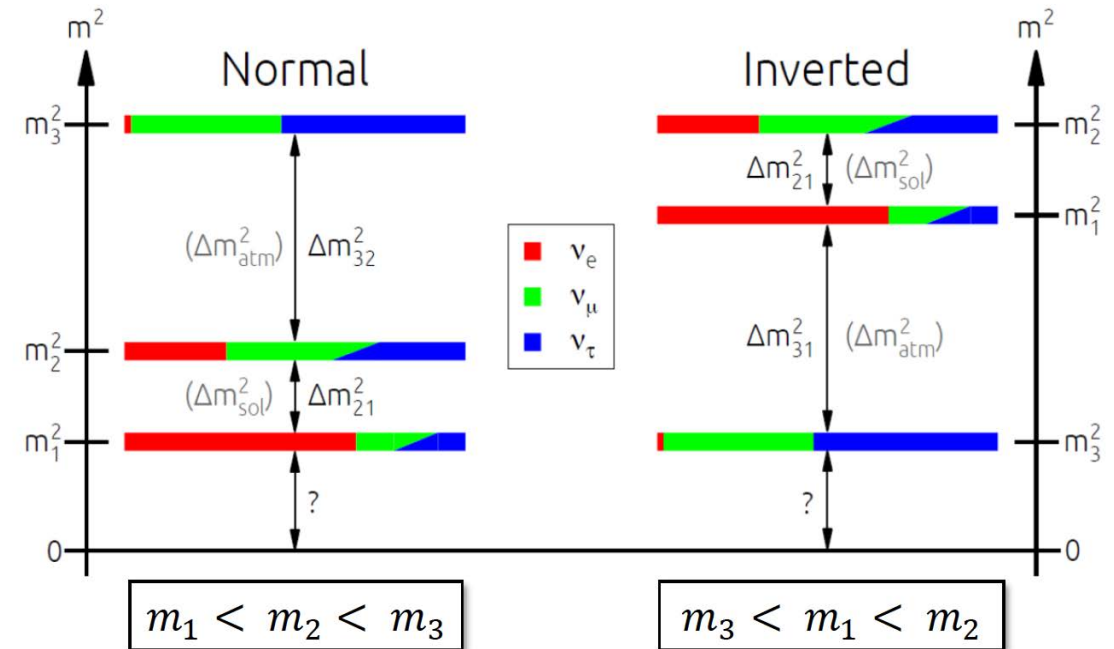
Open questions in neutrino physics

Neutrino Mass Ordering (NMO)

Linked
↑
↓

- ✓ CP-violating phase
- ✓ Octant of θ_{23} mixing angle
- ✓ Absolute mass-scale
- ✓ Origin of neutrino mass
- ✓ $0\nu\beta\beta$ & (Dirac vs Majorana)
- ✓ Existence of sterile neutrino
- ✓ Non-Standard Interactions in lepton sector

NMO: the main goal of JUNO



$$\Delta m_{31,\text{normal}} > \Delta m_{31,\text{inverted}}$$

$|\Delta m_{31}^2| = m_3^2 - m_1^2$ has opposite signs in the two hierarchies!

CURRENT KNOWLEDGE OF OSCILLATION PARAMETERS

PDG 2025*	Value	Precision	
$\sin^2 \theta_{12}$	0.307 ± 0.012 ($\theta_{12} \sim 33^\circ$)	3.9%	"solar"
Δm_{21}^2	$7.50 \pm 0.19 \times 10^{-5} eV^2$	2.5%	
$\sin^2 \theta_{13}$	0.0216 ± 0.0006 ($\theta_{13} \sim 9^\circ$)	2.8%	"atmospheric"
$\sin^2 \theta_{23}$	$0.534^{+0.015}_{-0.019}$ ($\theta_{23} \sim 45^\circ$)	3.2%	
Δm_{32}^2	$2.527 \pm 0.034 \times 10^{-3} eV^2$	2.8%	

*State of the art BEFORE JUNO

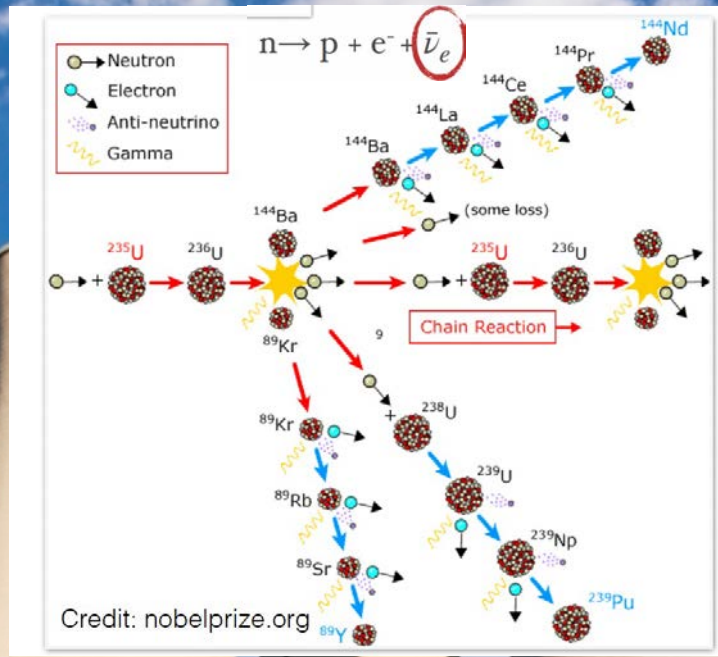
Why to pursue ever higher precision?

- Reveal neutrino properties with unprecedented accuracy.
- Provide powerful consistency checks across experiments and theoretical frameworks.
- Probe possible deviations from the standard 3-neutrino paradigm.

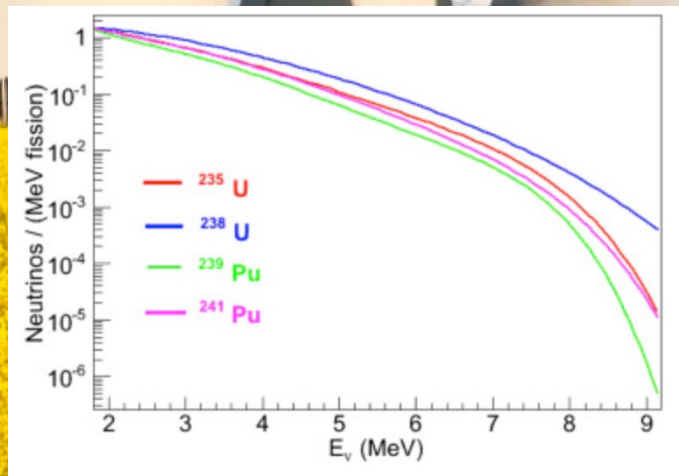
The strongest human-made source of neutrinos

A typical reactor emits every second about 10^{20} electron flavour antineutrinos.

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

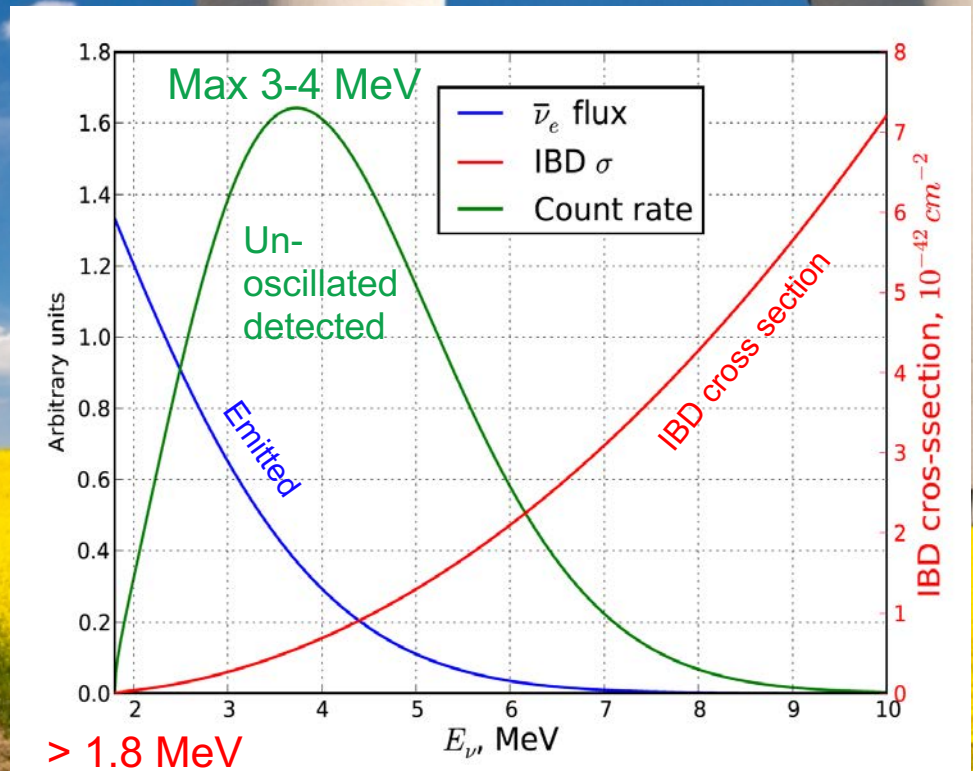


Credit: nobelprize.org



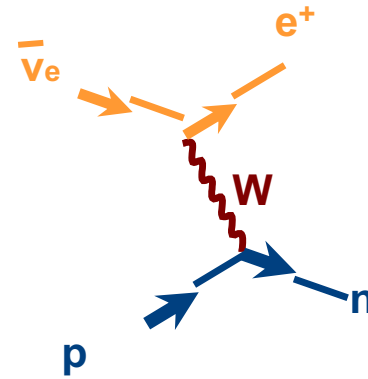
Energy spectrum up to ~ 9 MeV,
detectable >1.8 MeV,
Inverse Beta Decay (IBD) on proton.

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



INVERSE BETA-DECAY ON PROTON (IBD)

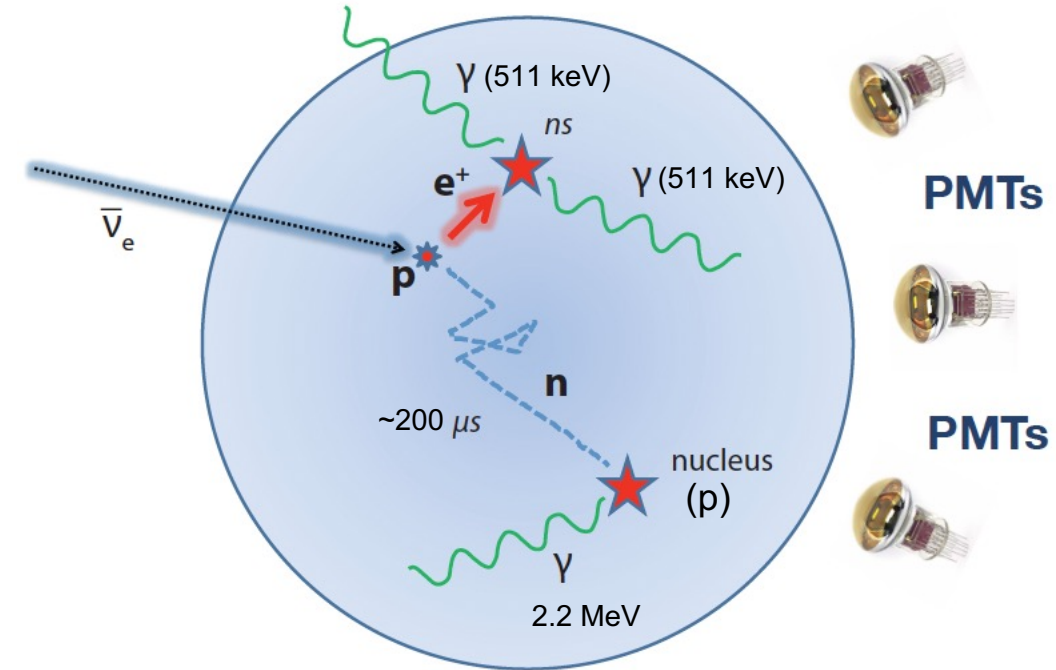
- CC interaction mediated by W bosons
- Sensitive only to **electron flavour**
- Cross section very well known
- Powerful **background suppression** tool
- Geoneutrinos – irreducible background with ~ 3.3 MeV end-point



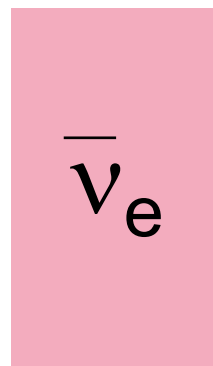
Energy threshold = 1.8 MeV

σ @ few MeV: $\sim 10^{-42} \text{ cm}^2$

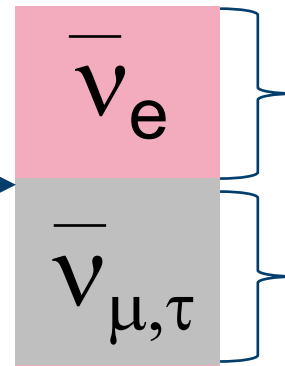
(~ 100 x more than elastic scattering on e^-)



Emitted reactor neutrino:



Neutrino oscillation

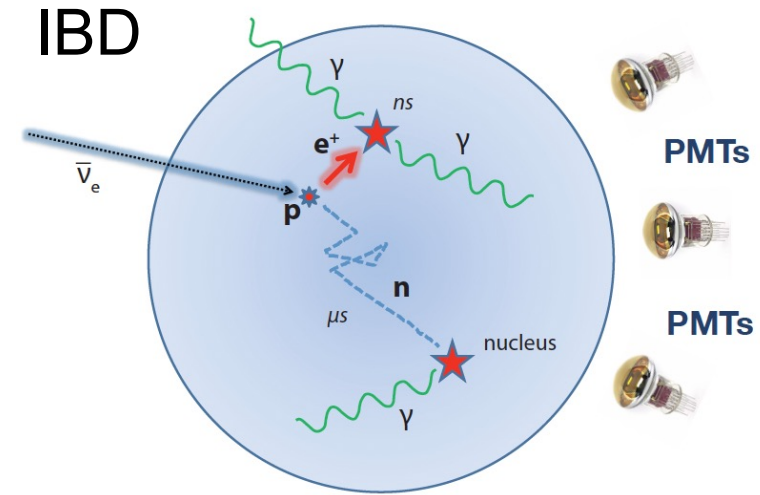


Detection with IBD

Invisible to IBD

$$\begin{aligned}
 E_{\text{prompt}} &= E_{\text{visible}} \\
 &= T_{e^+} + 2 \times 511 \text{ keV} \\
 &\sim E_{\text{antineutrino}} - 0.784 \text{ MeV}
 \end{aligned}$$

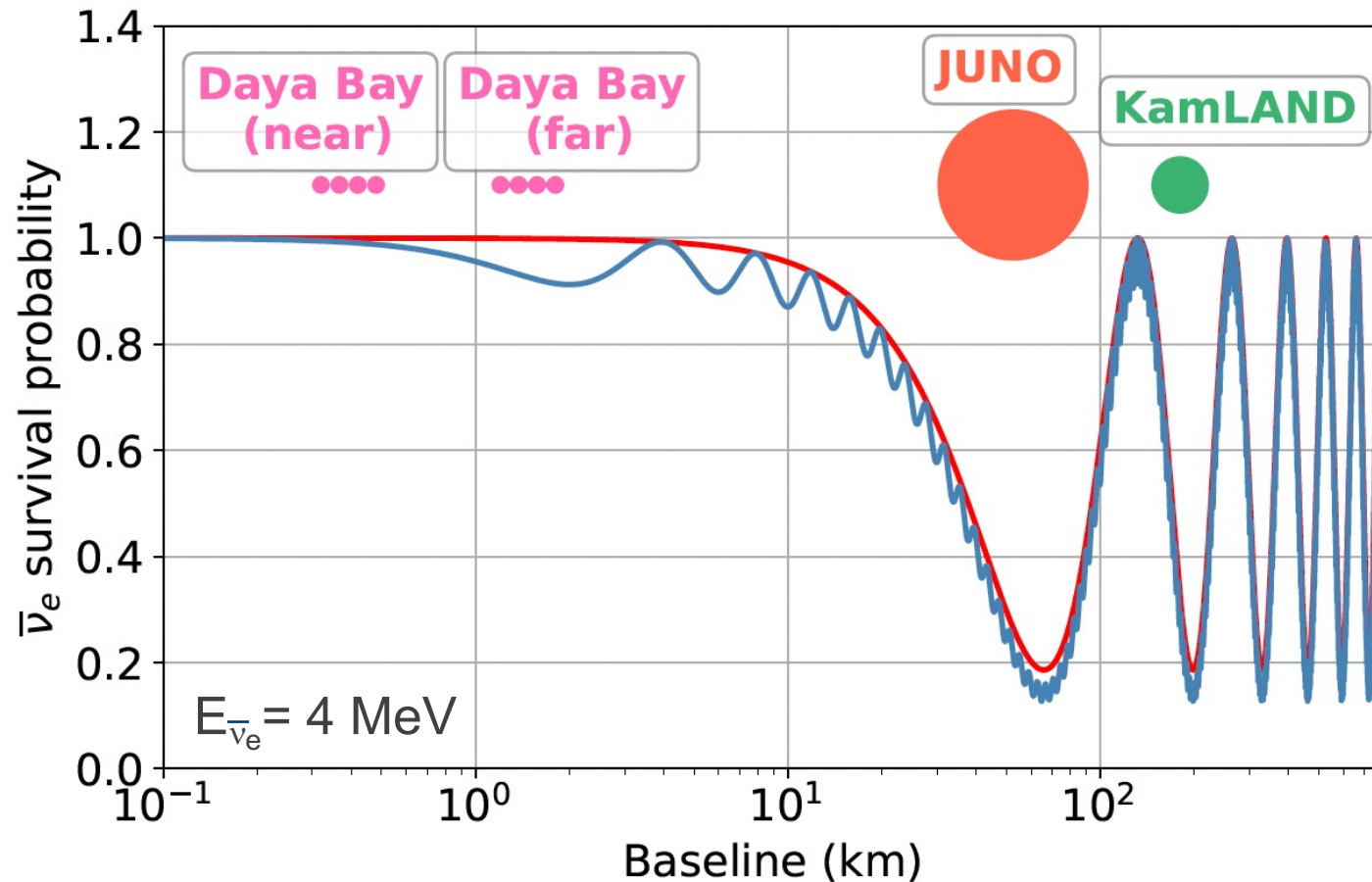
PARTICLE DETECTION WITH LARGE LIQUID SCINTILLATOR DETECTORS



- **Charged particles** lose energy in the scintillator through ionization and excitation of molecules, producing **scintillation light**;
- **Gamma rays** are neutral particles, but in the scintillator they interact mainly via **Compton scattering**, producing secondary electrons (charged particles);
- Scintillation light is detected by an array of **photomultiplier tubes (PMTs)**, converting optical signals into electrical signals;
- The number of hit PMTs is related to the deposited energy → **energy reconstruction**
- The PMT hit-time pattern is used for → **event vertex reconstruction**
- Each trigger is associated with a GPS timestamp → **absolute event time**

JUNO AMONG REACTOR NEUTRINO EXPERIMENTS

AT DIFFERENT BASELINES



Electron survival probability for reactor antineutrinos:

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

**Slow
(solar)**

$$P_{21} = \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

**Fast
(atm.)**

$$P_{31} = \cos^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{31}$$

$$P_{32} = \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{32}$$

Normal ordering: $\Delta m_{31}^2 > 0$

Inverted ordering: $\Delta m_{31}^2 < 0$

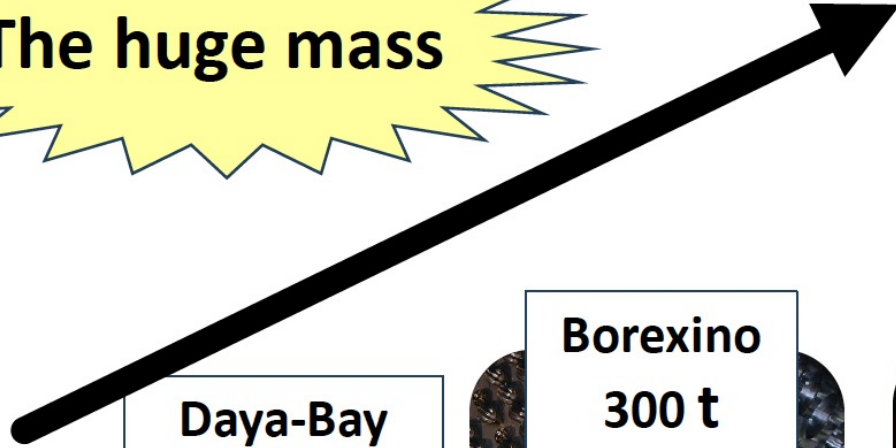
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

- 52.5 km baseline used only by JUNO.
- **1st maximum of slow solar oscillation** (P_{ee} minimum).
- **Fast oscillation pattern dependent on the NMO (sign of $\Delta m_{31/2}^2$).**
Independent from δ_{CP} and θ_{23} .

THE JUNO DETECTOR

What makes JUNO a truly remarkable detector?

The huge mass



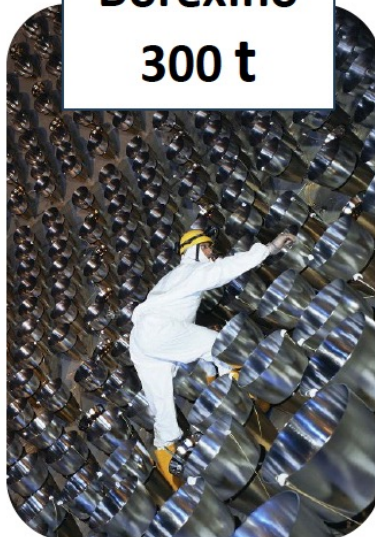
Cowan
Reines300L



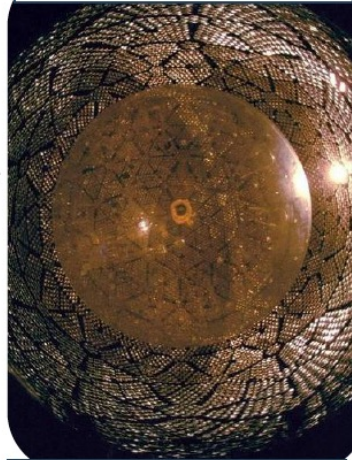
Daya-Bay
8 x 20 tons



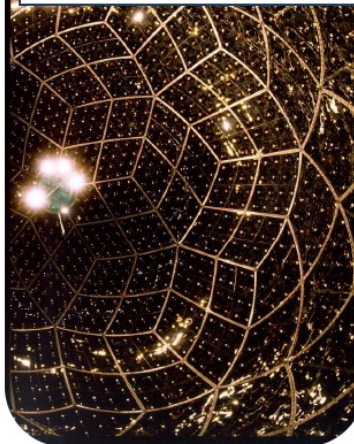
Borexino
300 t



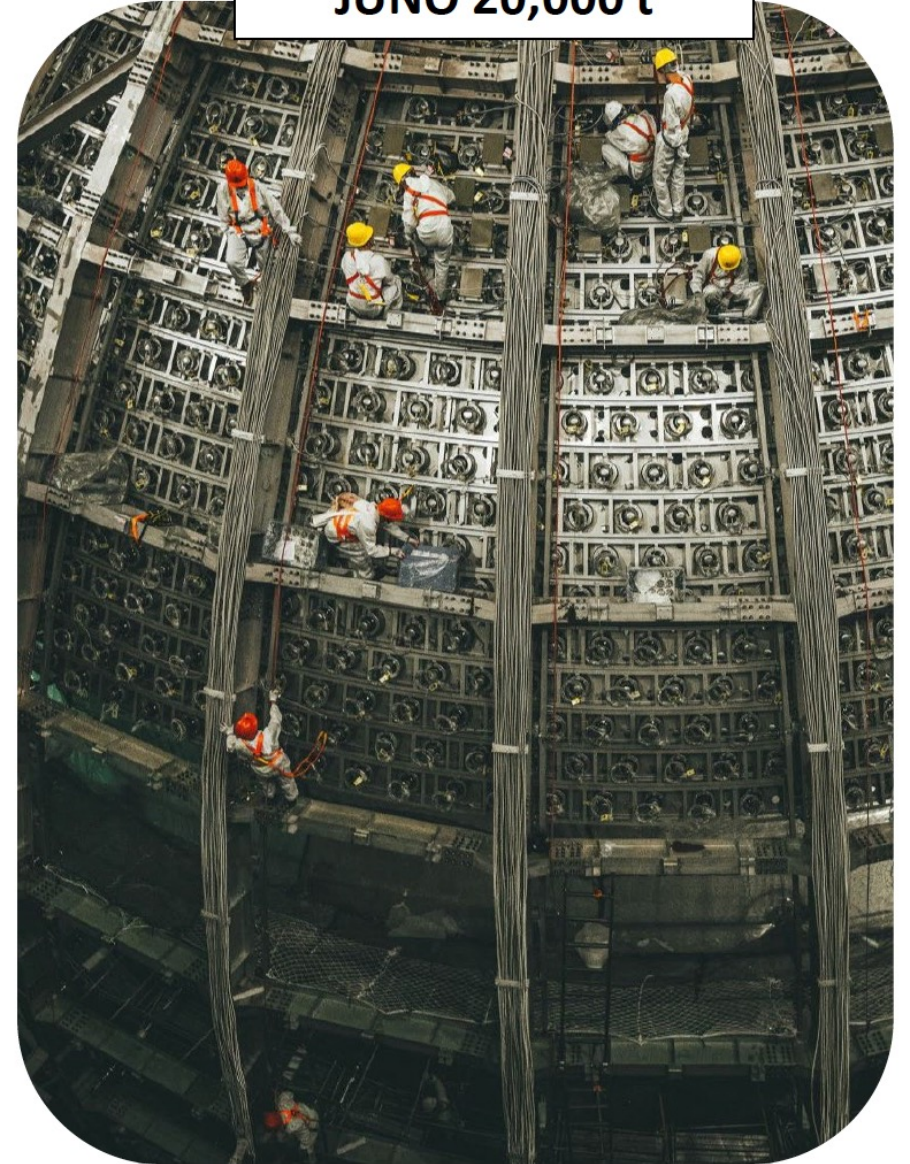
SNO 1000 t



KamLAND
1000 t



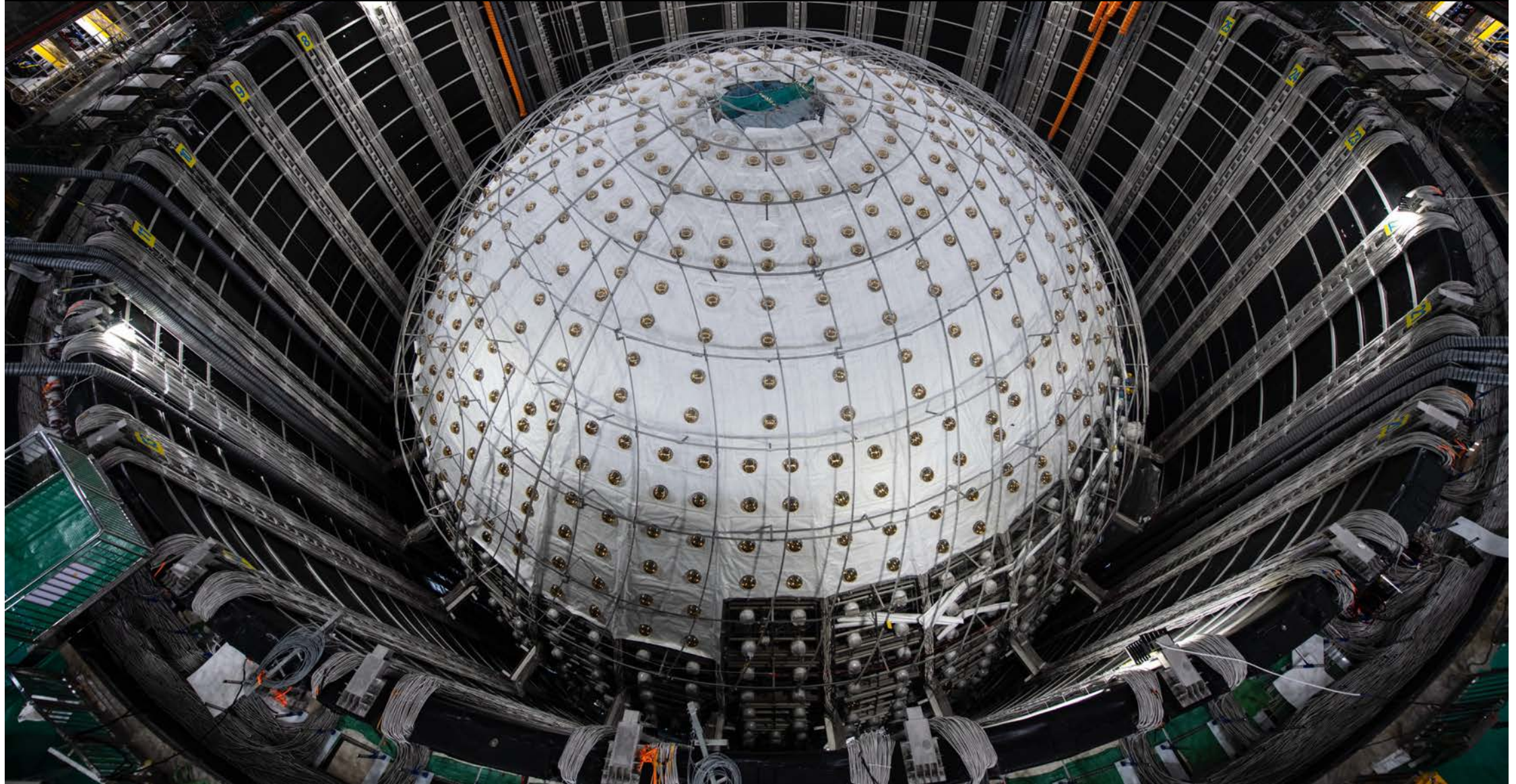
JUNO 20,000 t



Jiangmen Underground Neutrino Observatory

The first multi-kton liquid scintillator detector ever built.
Data taking started on August 26, 2025.

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JUNO: A MULTI-PURPOSE OBSERVATORY

Reactor anti- ν



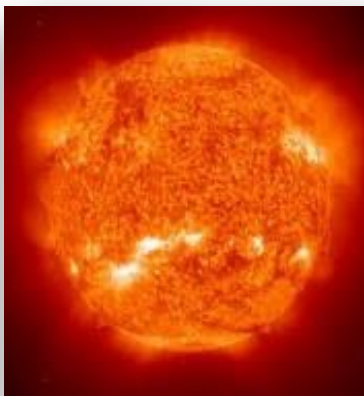
~55 / day

Atmospheric ν



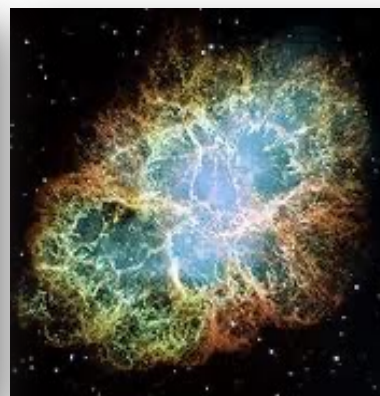
Several / day

Solar ν



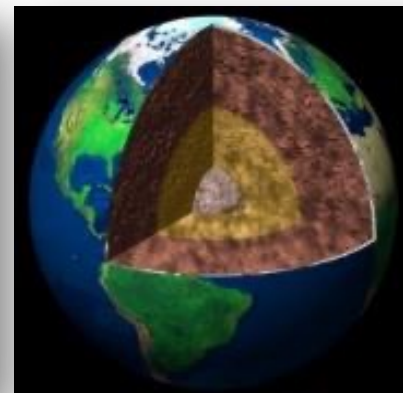
^8B : ~50/day
CNO: ~1000/day
 ^7Be : ~10000/day

Supernovae (SN) ν



Core Collapse SN
@ 10 kpc:
thousands in few sec.
Diffuse SN signal:
few / year

Geoneutrinos



~400 / year

+

New
physics

Proton decay
Neutrino magnetic
moment
Sterile neutrinos
Non-standard
interactions
Lorentz invariance
violation

Neutrino oscillation & properties

Neutrinos as a probe

JUNO: A MULTI-PURPOSE OBSERVATORY

First results!

Reactor anti- ν



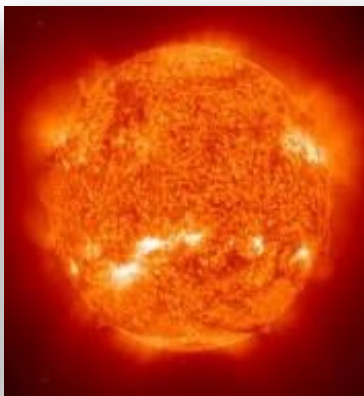
~55 / day

Atmospheric ν



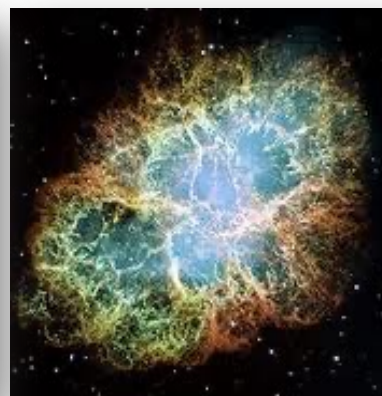
Several / day

Solar ν



^8B : ~50/day
CNO: ~1000/day
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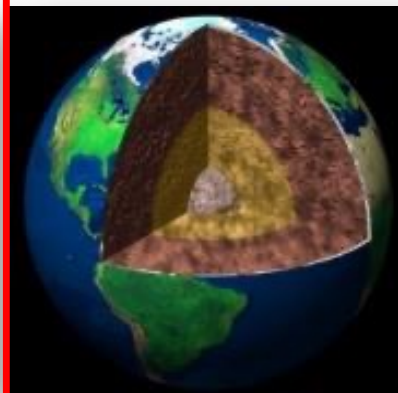
Supernovae (SN) ν



Core Collapse SN
@ 10 kpc:
thousands in few sec.
Diffuse SN signal:
few / year

First results!

Geoneutrinos



~400 / year

+

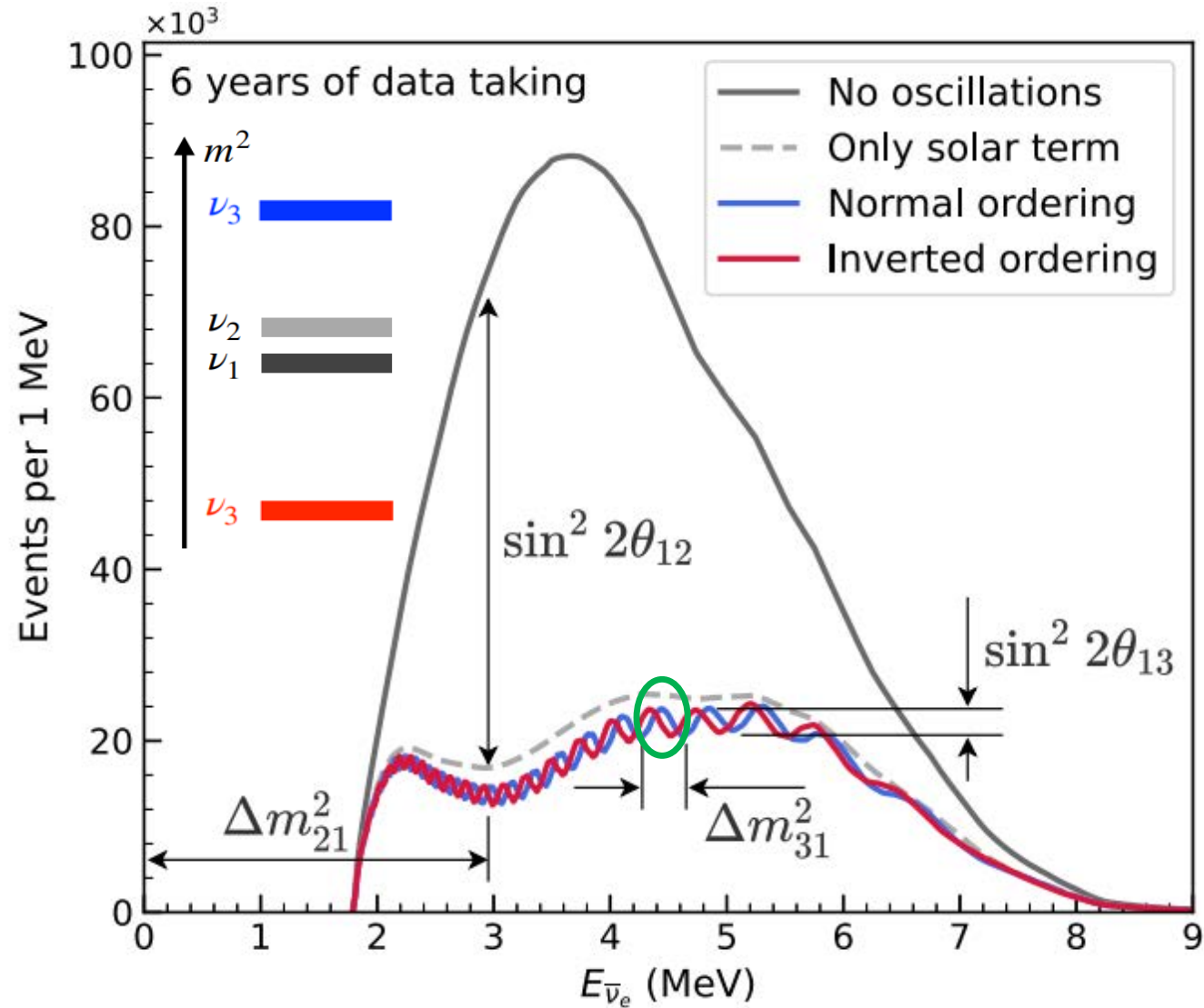
**New
physics**

Proton decay
Neutrino magnetic
moment
Sterile neutrinos
Non-standard
interactions
Lorentz invariance
violation

Neutrino oscillation & properties

Neutrinos as a probe

JUNO & NEUTRINO OSCILLATIONS



JUNO PHYSICS CHALLENGES

- ❑ Large antineutrino statistics $O(100k)$ @ 52.5 km baseline: **powerful reactors (26.6 GW_{th}) & large target mass (20 kton)**
- ❑ Resolving signature wiggles of the fast oscillation in the energy spectrum:
 - excellent **energy resolution ~3% @ 1 MeV (at least 1300 pe / MeV)**,
 - better than **1% understanding of the intrinsically non-linear energy scale of the liquid scintillator (LS)**,
 - **possible micro-structures in the reactor spectrum under control** (*PRL 114 (2015) 012502*).
- ❑ **Backgrounds:**
 - cosmogenic background: rock overburden of 650 m,
 - radio-purity of all materials: $< 10^{-15} / 10^{-17}$ g of U/Th /g of LS for NMO/solar physics (*JHEP 11 (2021) 102*).
- ❑ **Time stability** over several years.

Stochastic terms in the energy resolution (photon statistics):

- **High light yield** (LY $\sim 10^4$ photons/MeV).
- **LS transparency:** $\lambda_{\text{att}} > 20$ m @ 430 nm.
- **PMT geometrical coverage: 78%.**
- **PMT quantum efficiency & collection efficiency: ~30%.**

Systematic effects in the energy scale / spectra:

- **Calibration** (*JHEP 03 (2021) 004*)
 - ✓ $\alpha/\beta/\gamma$ sources, light pulses, UV-laser
 - ✓ 5 complementary systems
- **Double calorimetry concept**
 - ✓ large 20" and small 3" PMTs
- **TAO** – Taishan Antineutrino Observatory with an excellent energy resolution $< 2\%$ (stat) @ 1MeV (*arXiv:2005.08745, 2020*)

JUNO COLLABORATION



- established in 2014
- 74 institutions
- 750 collaborators
- 17 countries and regions

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Wu Yi U.	Italy	INFN di Frascati
Belgium	Universite Libre de Bruxelles	China	Wuhan U.	Italy	INFN-Ferrara
Brazil	PUC	China	Xi'an JT U.	Italy	INFN-Milano
Brazil	UEL	China	Xiamen University	Italy	INFN-Milano Bicocca
Chile	SAPHIR	China	Zhengzhou U.	Italy	INFN-Padova
Chile	UNAB	China	NUDT	Italy	INFN-Perugia
China	BISEE	China	CUG-Beijing	Italy	INFN-Roma 3
China	CAGS	China	ECUT-Nanchang City	Pakistan	PINSTECH (PAEC)
China	ChongQing University	China	CDUT-Chengdu	Russia	INR Moscow
China	DGUT	China	SUSTech-Shenzhen	Russia	JINR
China	Guangxi U.	China	KNRC	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyväskylä	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nankai U.	France	CPM Marseille	Taiwan-China	NKNU
China	NCEPU	France	IPHC Strasbourg	Taiwan-China	NTUT
China	Shandong U.	France	Subatech Nantes	Thailand	NARIT
China	Shanghai JT U.	Germany	RWTH Aachen U.	Thailand	PPRLCU
China	IGG-Beijing	Germany	TUM	Thailand	SUT
China	SYSU	Germany	U. Hamburg	U.K.	U. Liverpool
China	Tsinghua U.	Germany	GSI	U.K.	U. Warwick
China	UCAS	Germany	U. Mainz	USA	UMD-G
China	U. of South China	Germany	U. Tuebingen	USA	UC Irvine
China	IMP	Italy	INFN Catania		

+Observers: USTC, Pekin Uni., Jilin Uni., Beijing Normal Uni., CIAE (China)



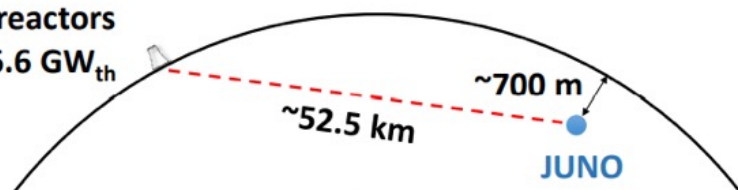
JUNO SITE



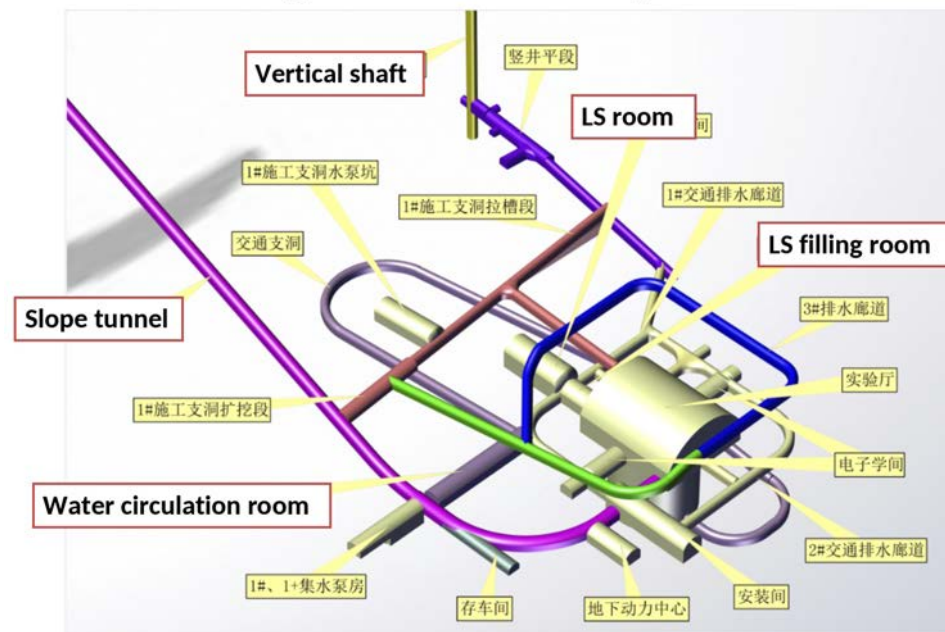
Baseline difference for all cores should be < 500 m.

	Yangjian						Taishan			
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

8 reactors
26.6 GW_{th}



Dedicated underground laboratory
~650 m rock overburden (1800 m w.e)



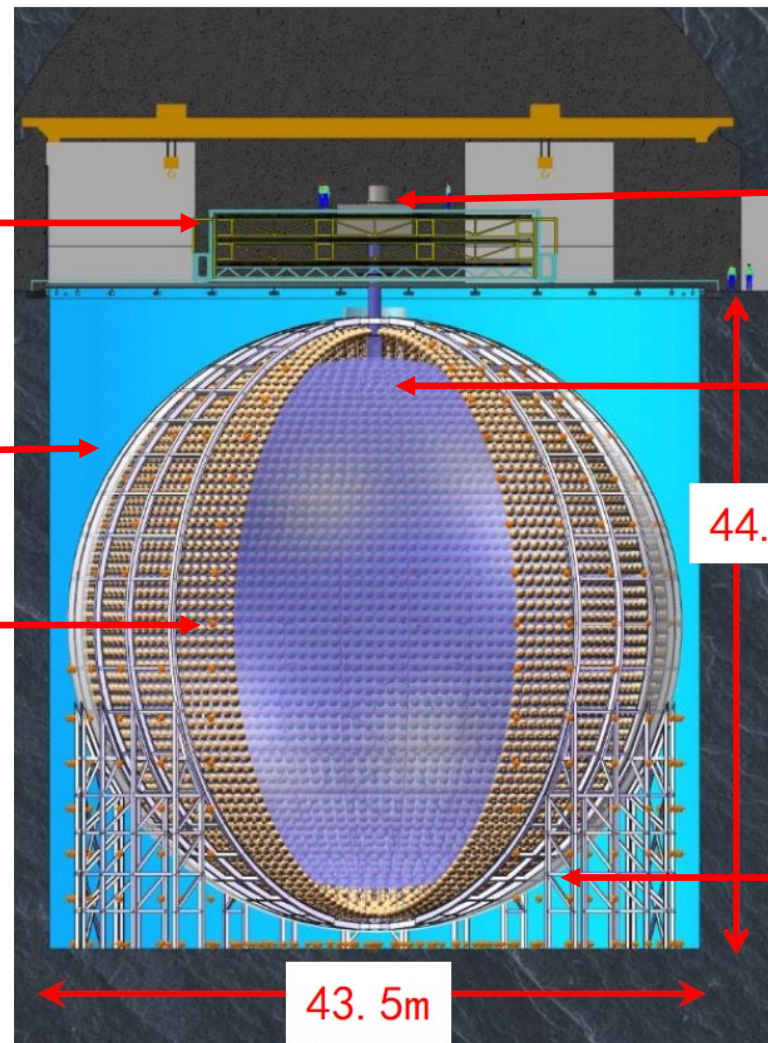
JUNO CIVIL CONSTRUCTION FINISHED IN 12/2021

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JUNO DETECTOR

DESIGN



Top Tracker

Water Pool
Water Cherenkov μ veto
2404 20" PMTs

Central Detector
20 kton of LS

Linear Alkali Benzene (LAB)
 + *PPO* + *bis-MSB* + *BHT*

17596 20" PMTs (large) +
25587 3" PMTs (small)

Calibration house

Acrylic Sphere
Diameter = 35.4 m

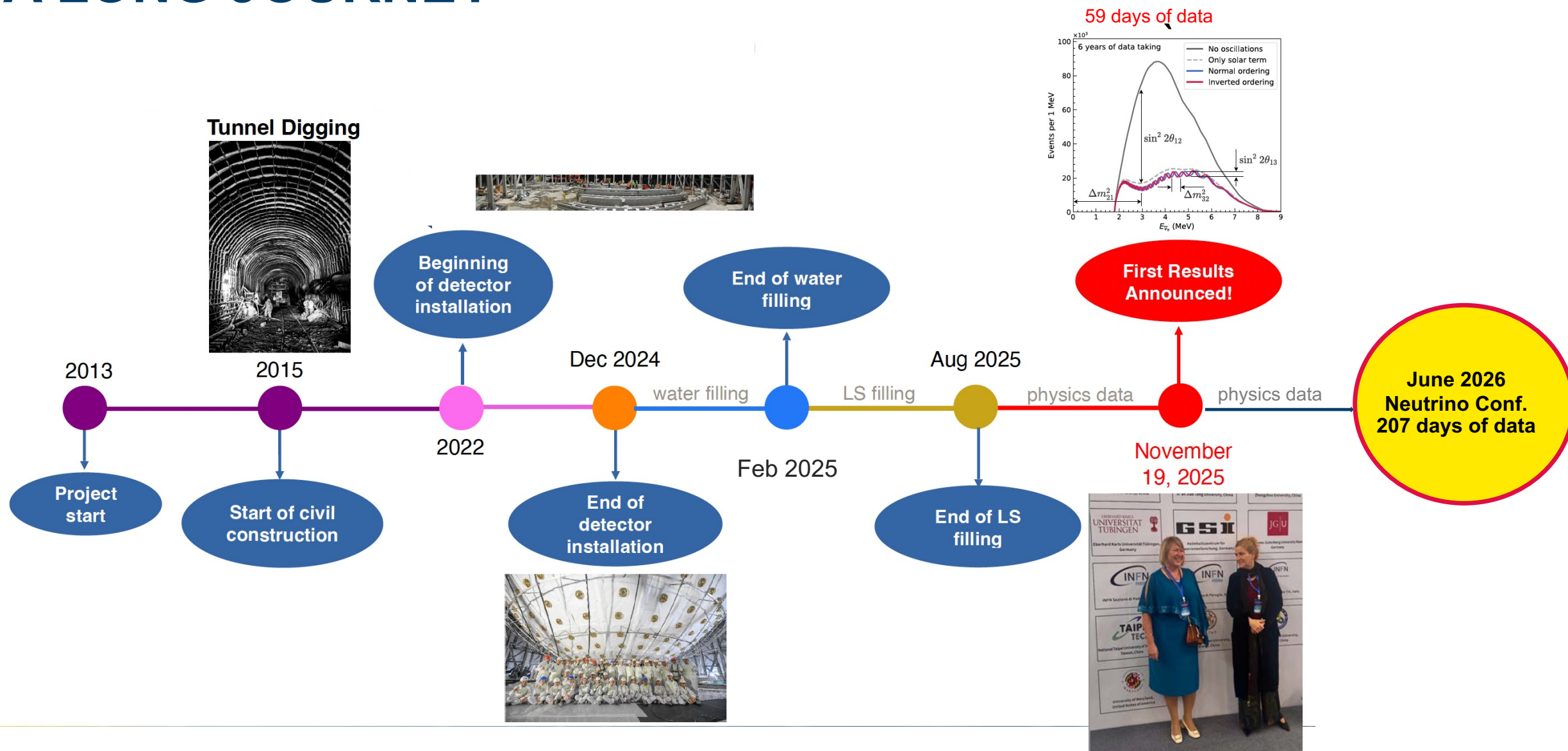
Stainless steel Latticed Shell

44.5m

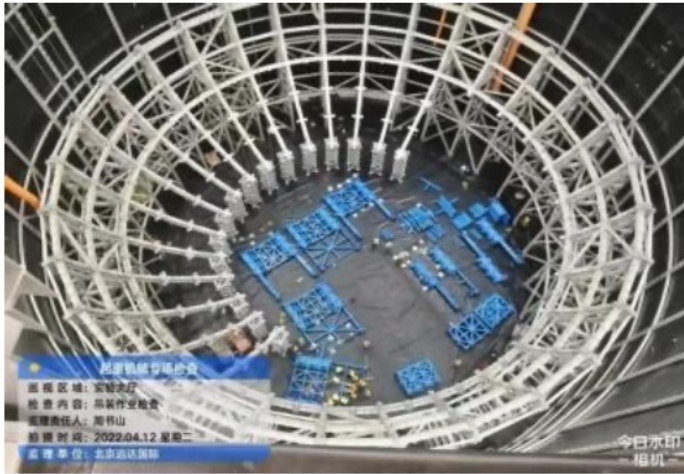
43.5m

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	8x20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	78%
Energy resolution	8.5% / $\sqrt{E}$ MeV	~5%/ $\sqrt{E}$ MeV	~6%/ $\sqrt{E}$ MeV	~3%/$\sqrt{E}$ MeV
Eff. Light yield	~160 p.e. / MeV	~500 p.e. / MeV	~250 p.e. / MeV	>1300 p.e./MeV

A LONG JOURNEY



CONSTRUCTION OF THE CENTRAL DETECTOR



Bottom structure



Platform for Acrylic assembly



Top structure



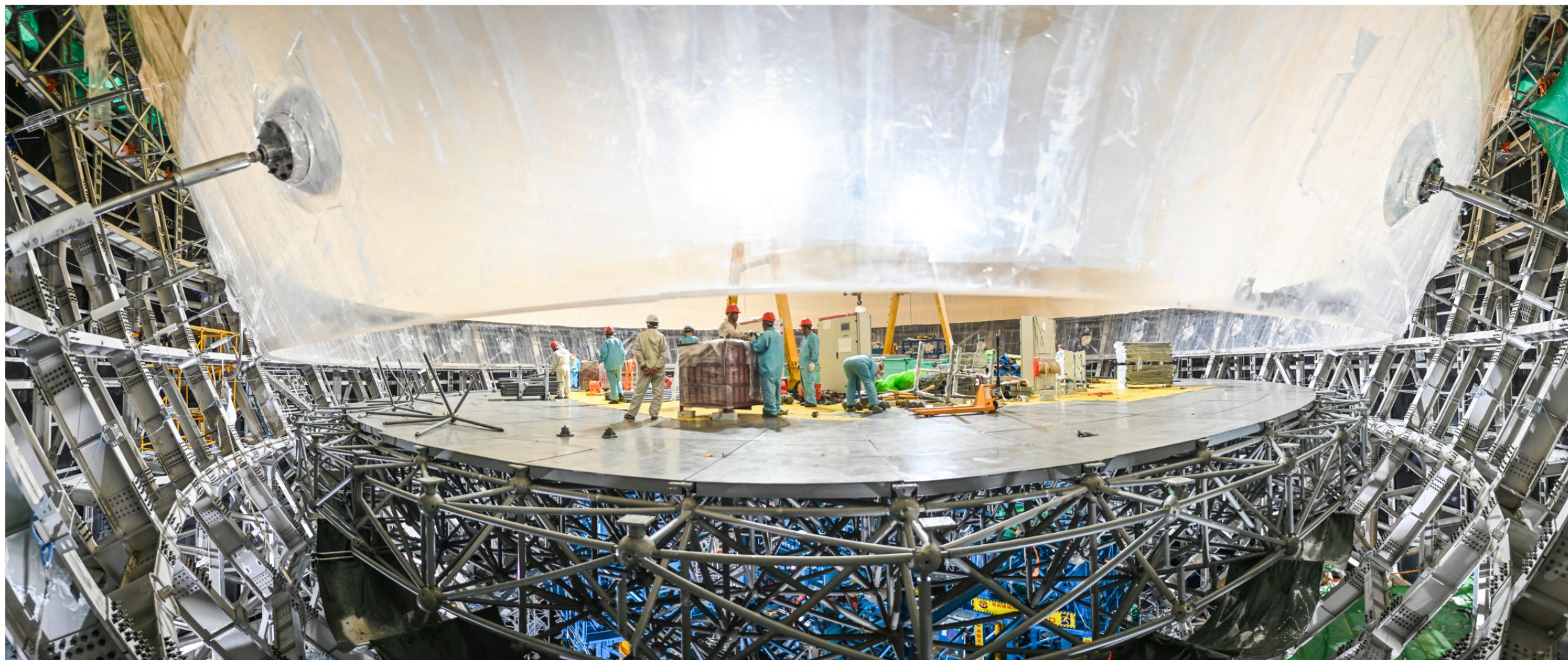
5 layers of Acrylic

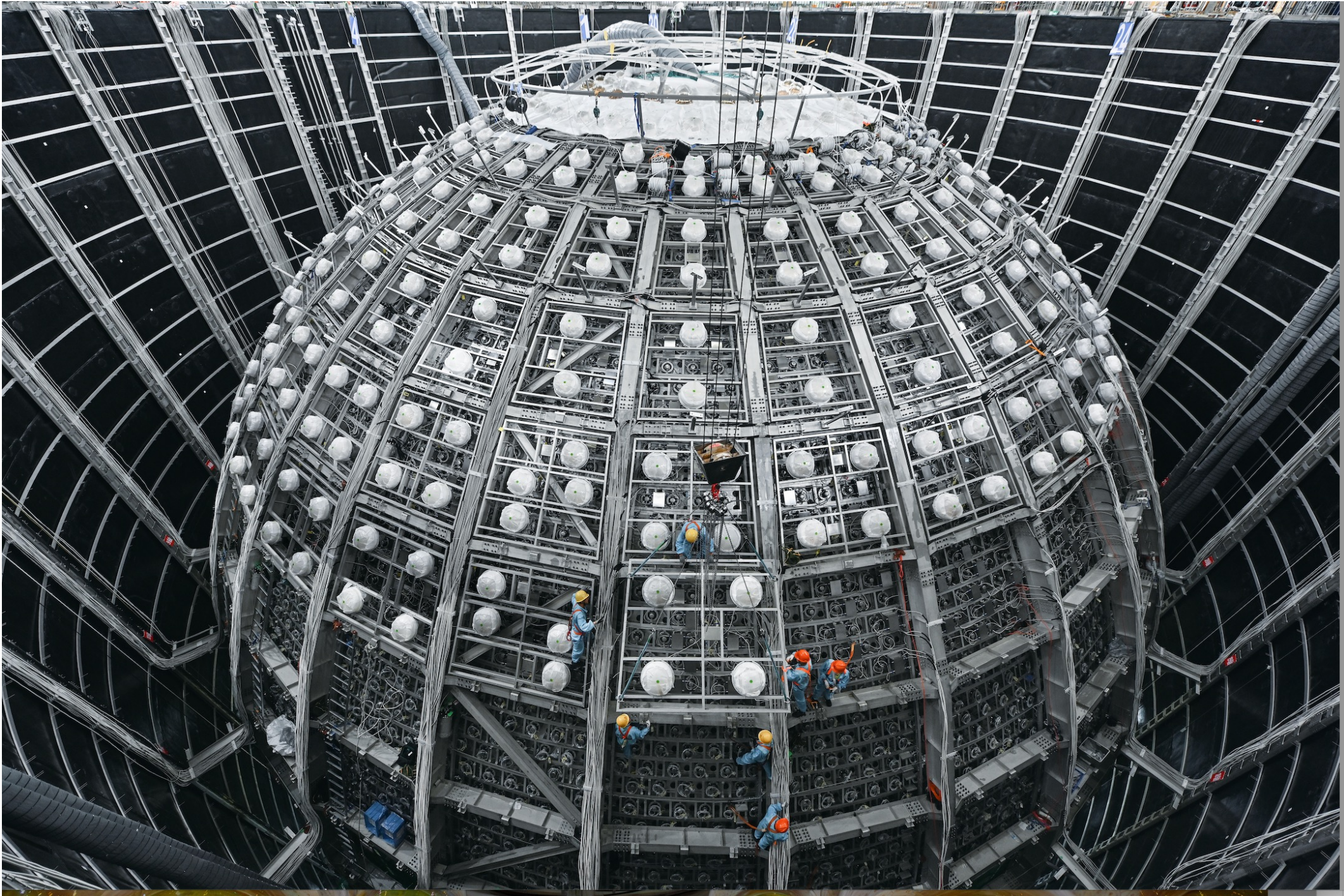


20 layers of Acrylic

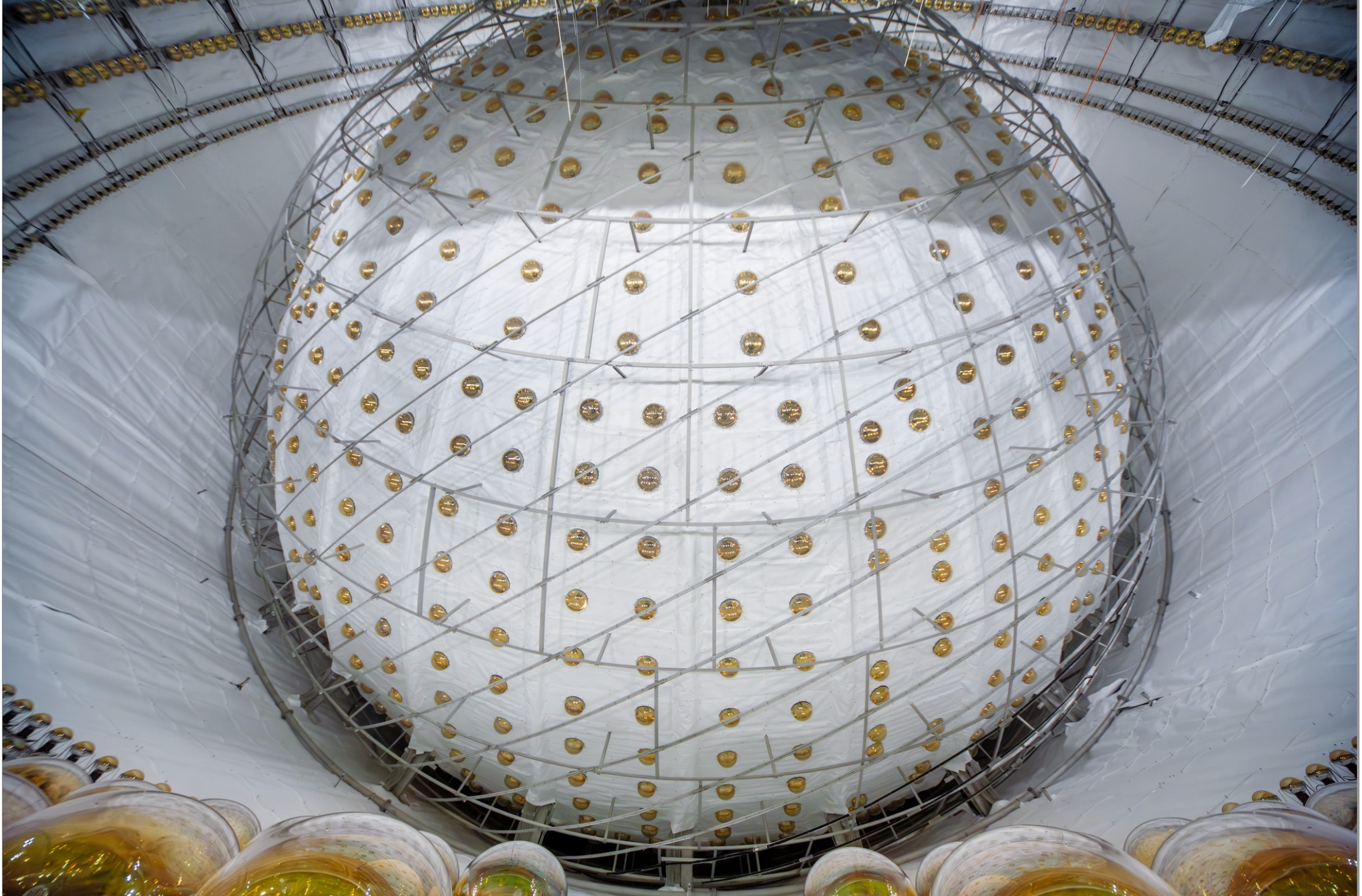


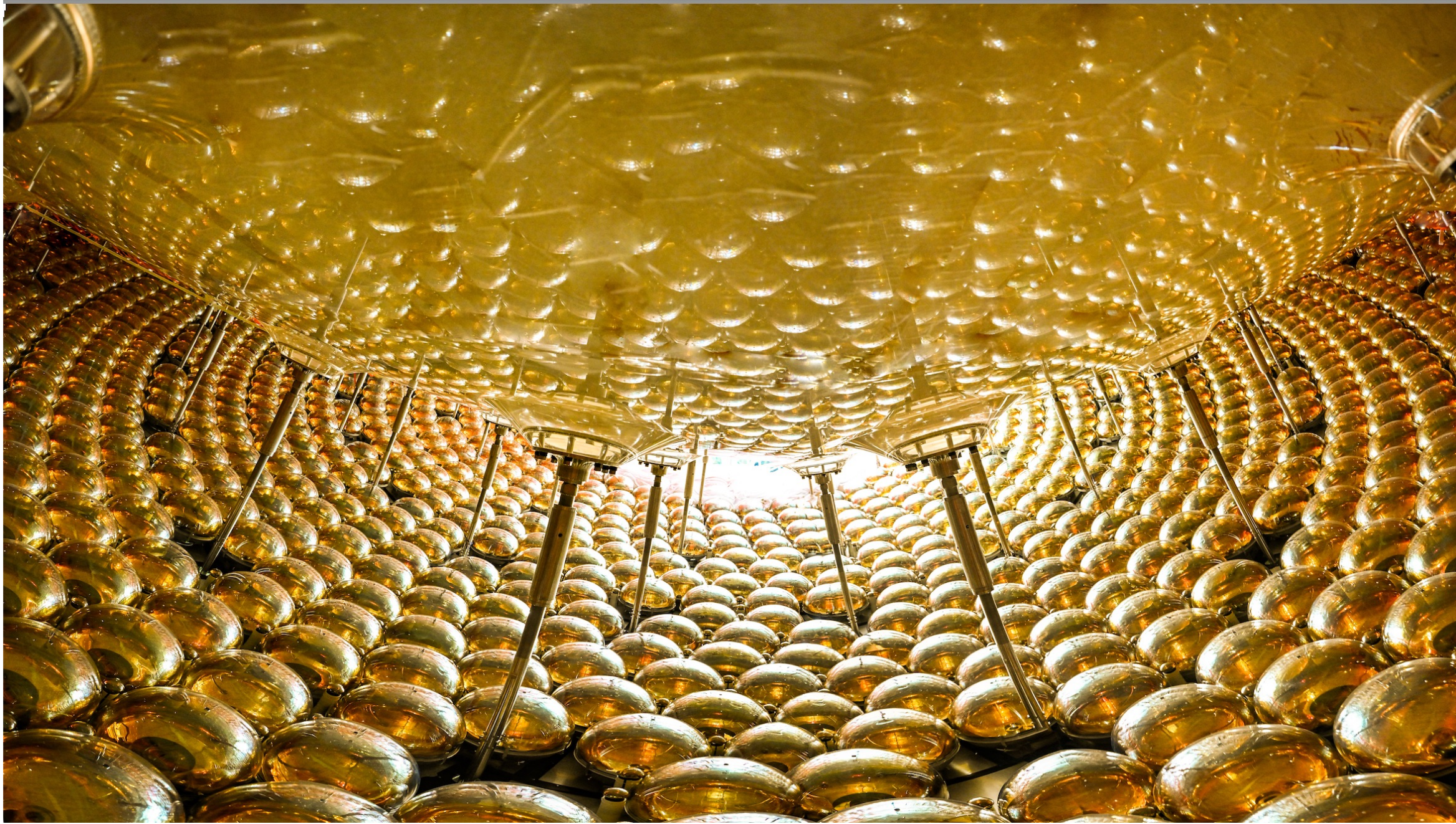
23 layers of acrylic





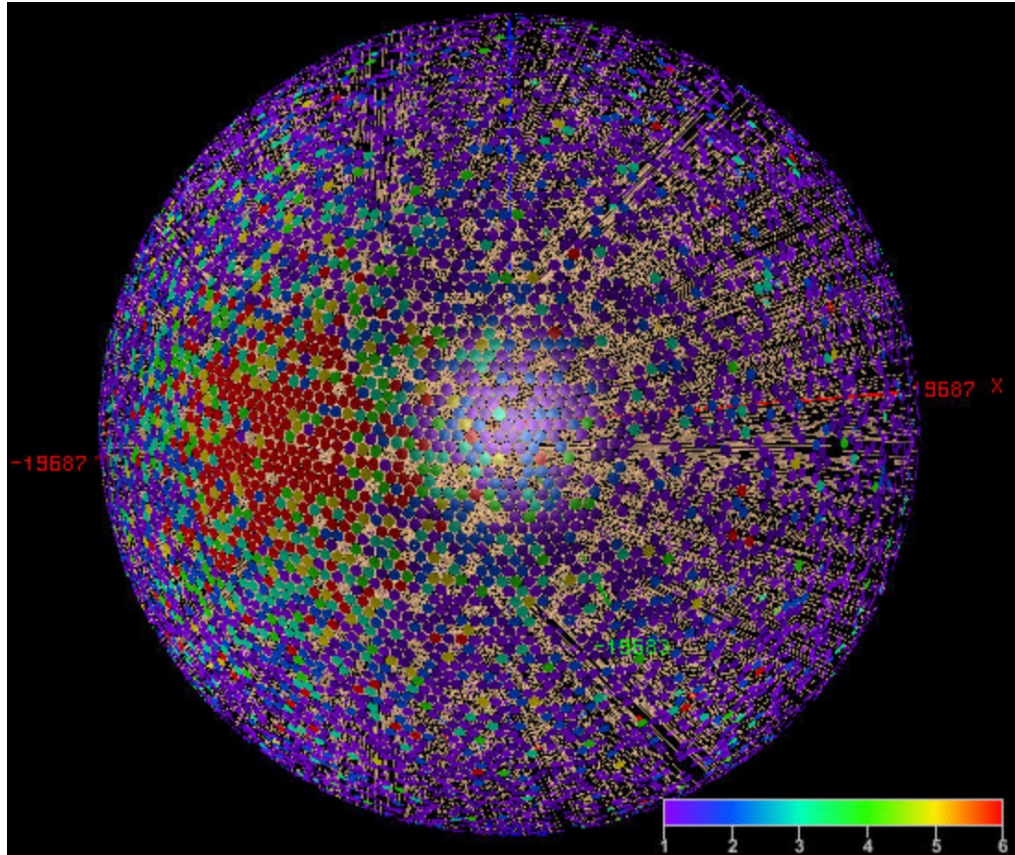






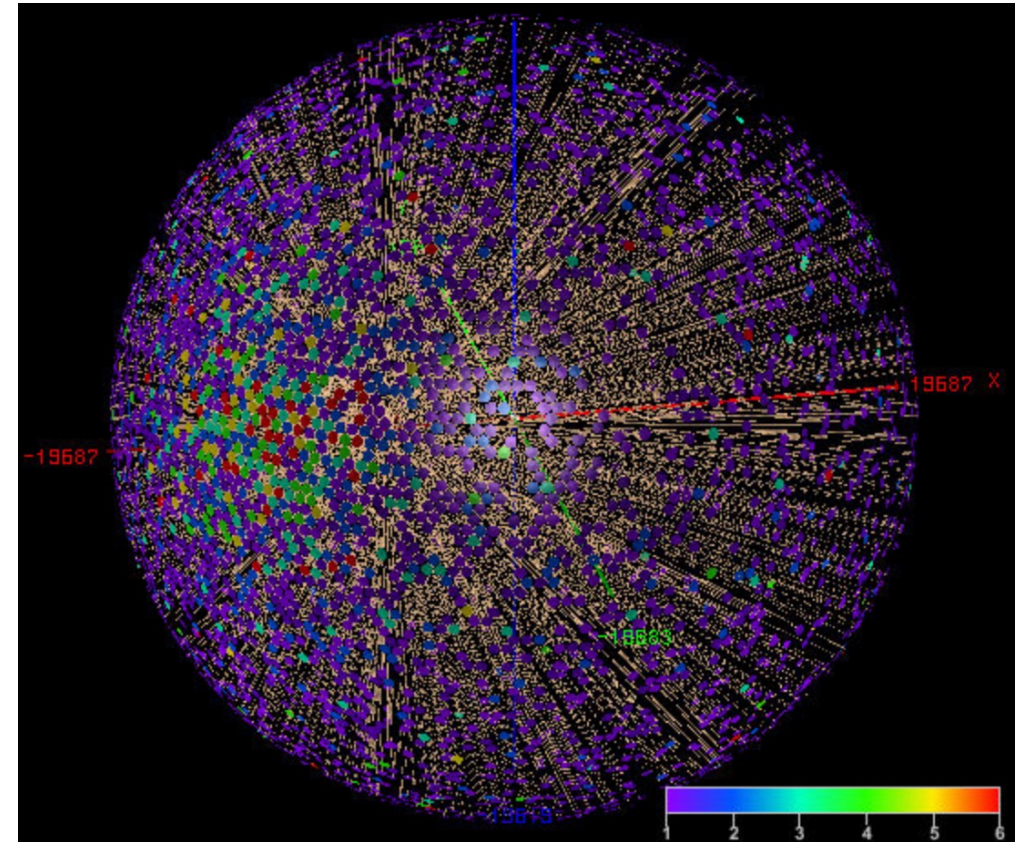
THE FIRST ANTINEUTRINO EVENT

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

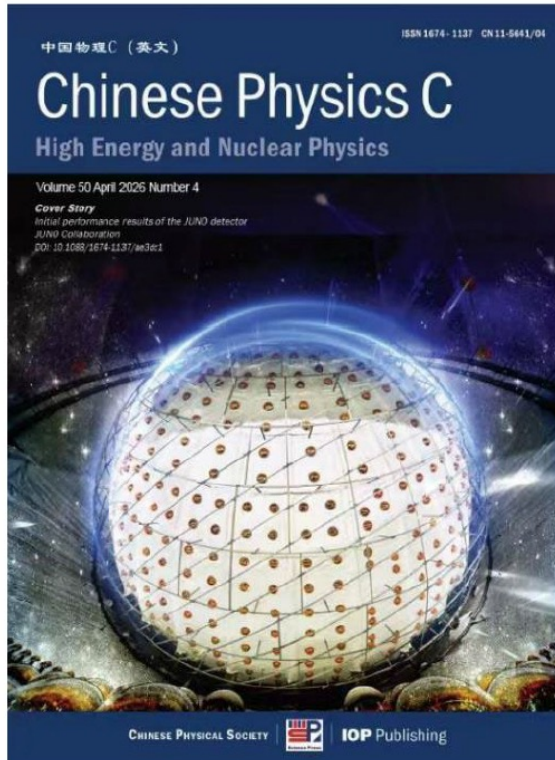


Delayed neutron signal

NOVEMBER 2025: FIRST JUNO RESULTS 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

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

2.8%

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

1.6%

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

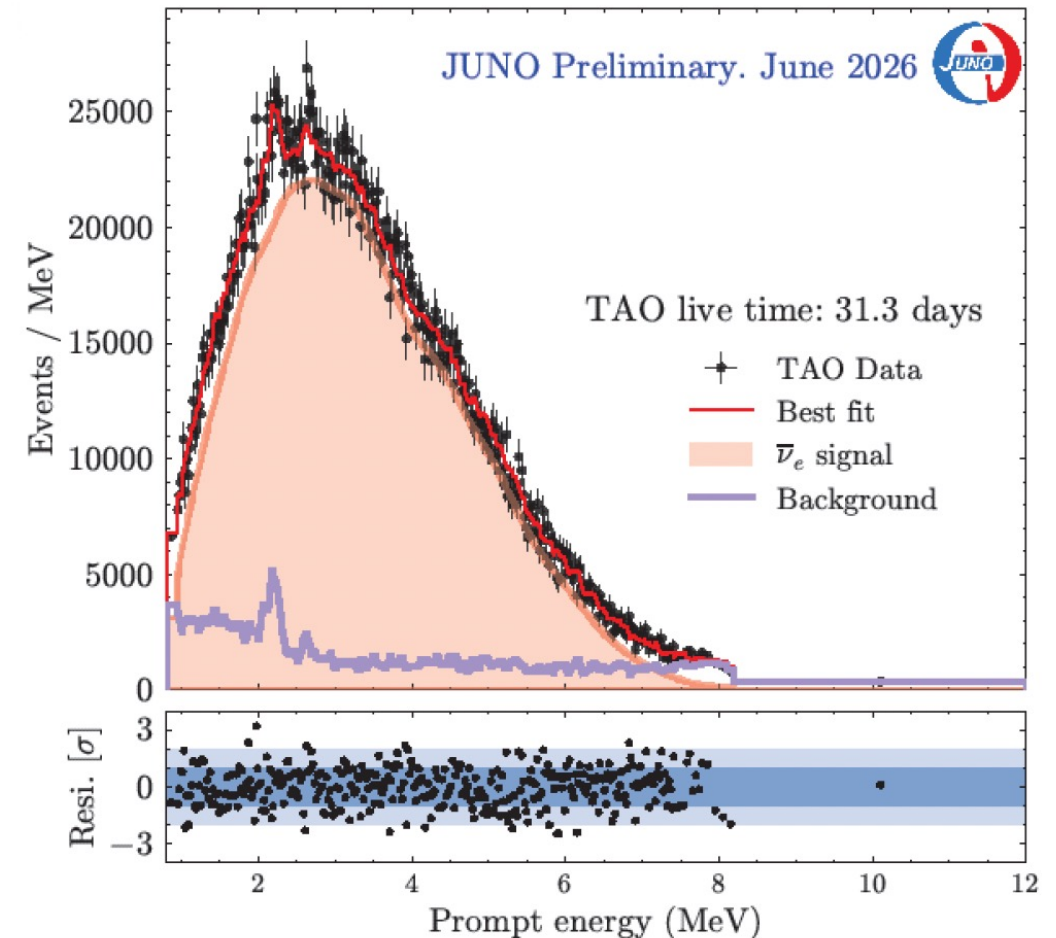
FEBRUARY 2026: TAO (TAISHAN NEUTRINO OBSERVATORY) ONLINE!

Novel technology: 2.8 ton of Gd-loaded LS @ -50°C

- ✓ **SiPM (94% coverage)**
- ✓ **30 m from 4.6 GW_{th} Taishan 1 core – unoscillated spectrum**
- ✓ Energy resolution: $<2\%/\sqrt{E}$
- ✓ 1000 anti- ν / day



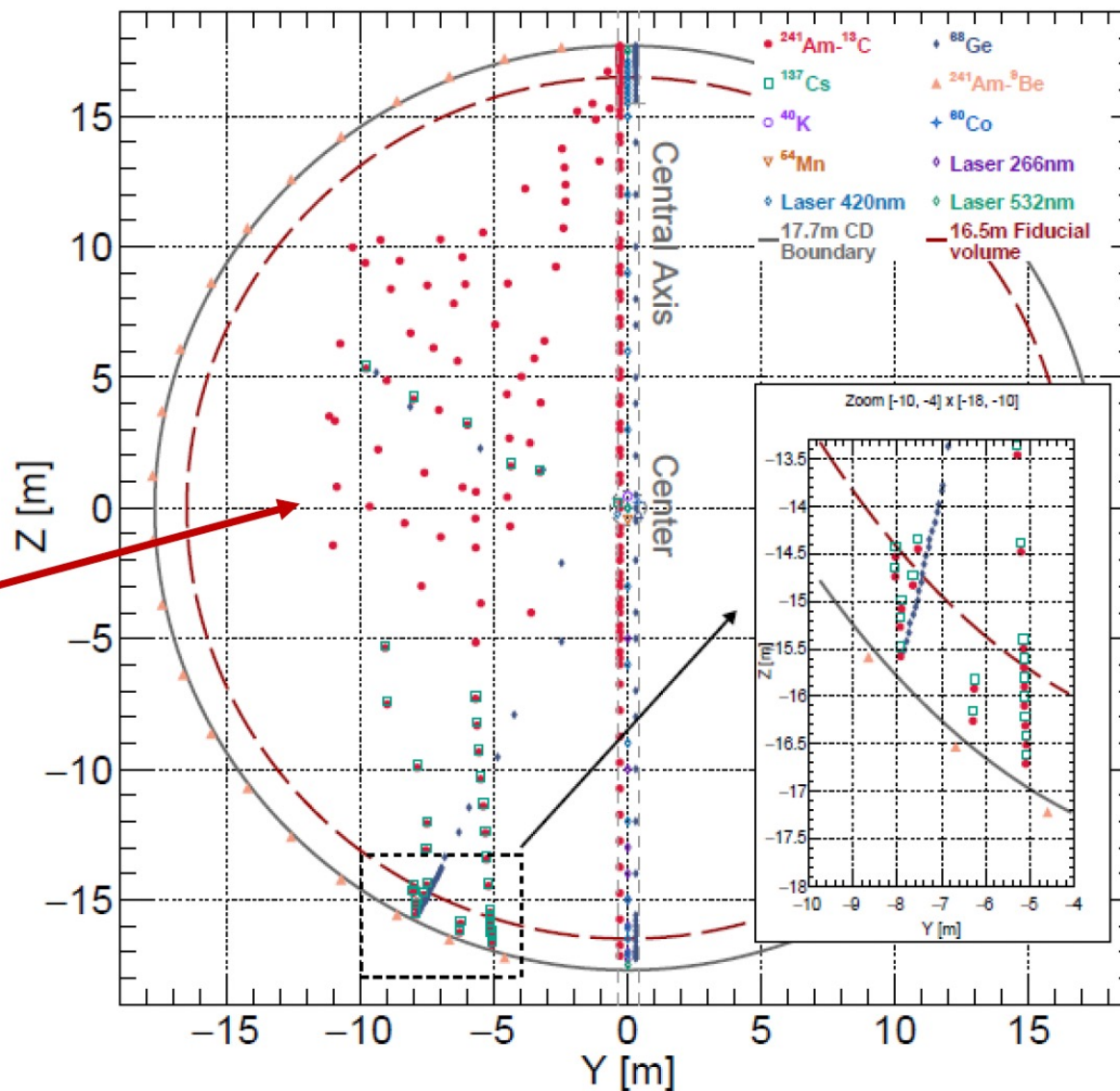
- **To measure unoscillated reactor neutrino spectrum**
 - ✓ Better resolution to constrain fine structure and spectral shape.
 - ✓ **REFERENCE FOR JUNO SPECTRAL FIT**
- **Improve nuclear databases, search for sterile neutrinos.**



MORE JUNO CALIBRATION DATA

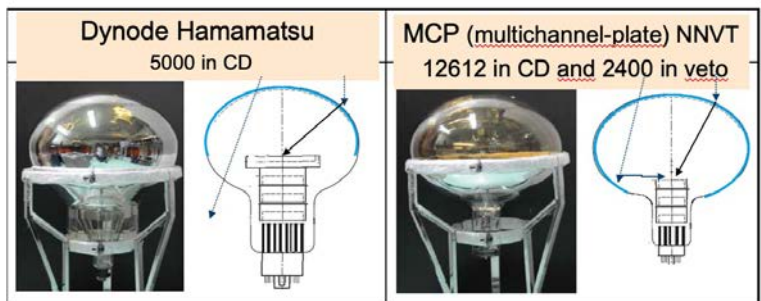
- 1D (central axis): ^{137}Cs , ^{54}Mn , ^{40}K , ^{68}Ge , ^{60}Co , Am-C, Am-Be, sensors, laser
- 2D (cable loop): Am-C, ^{68}Ge , ^{137}Cs
- 3D using cosmogenic backgrounds:
 ⇒ Bi-Po214 from Rn decays, spallation neutrons, other cosmogenic isotopes

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



ACHIEVED DETECTOR PERFORMANCE

Large 20-inch PMTs

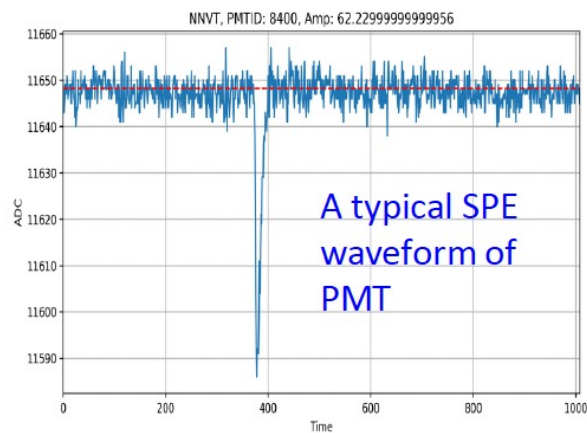


TRANSMISSION ONLY

TRANSMISSION + REFLECTION

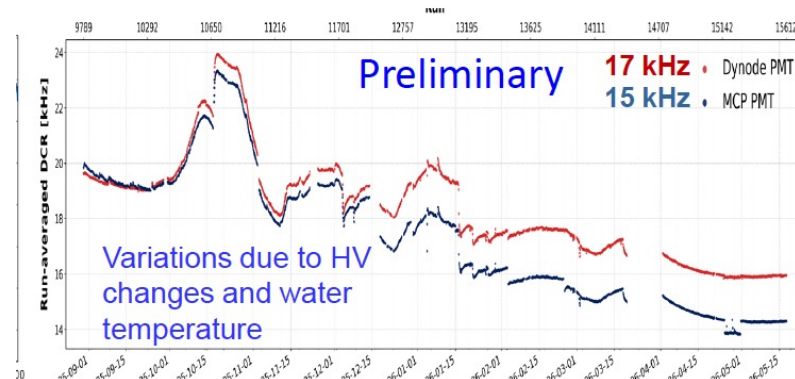
	CD		WCD		Total
	Hamamatsu R12860-50	NNVT GDB6201	NNVT GDB6201		
Installed	4939	12657	2404	348	20348

- ~ 26 dead PMTs/electronics, ~1.2/month
- ~ 600 flashing PMTs (turned off)

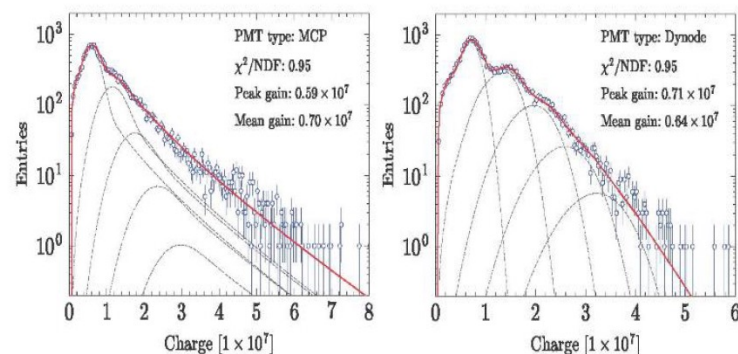


A typical SPE
waveform of
PMT

LPMT Dark Count Rate



LPMT calibration with laser



- Mean gain stable within 0.2%
- Time alignment < 1 ns
- Time resolution of a few ns

Electronics

- Low noise levels (roughly 0.05 pe)
- Single channel threshold 0.2-0.3 pe

Trigger

- Multiplicity trigger 350 hits in 305 ns window
- Threshold at ~200 keV
- 500 Hz rate
- 1006 ns DAQ gate window
- Online Event Classification
- Data stream ~900 MB/s

ACHIEVED DETECTOR PERFORMANCE

Chin. Phys. C 50, 043001 (2026).

Ultra-low radioactivity

^{238}U : $(7.8 \pm 0.4) \times 10^{-17}$ g/g
 ^{232}Th : $(8.2 \pm 0.7) \times 10^{-17}$ g/g
 ^{210}Po (June 2026):
 $(2.25 \pm 0.07) \times 10^4$ /day /kton

LS

$^{238}\text{U}/^{232}\text{Th} < 10^{-15}$ g/g
 ^{222}Rn : < 10 mBq/m³
 ^{226}Ra : < 50 $\mu\text{Bq/m}^3$

High-purity water

High transparency

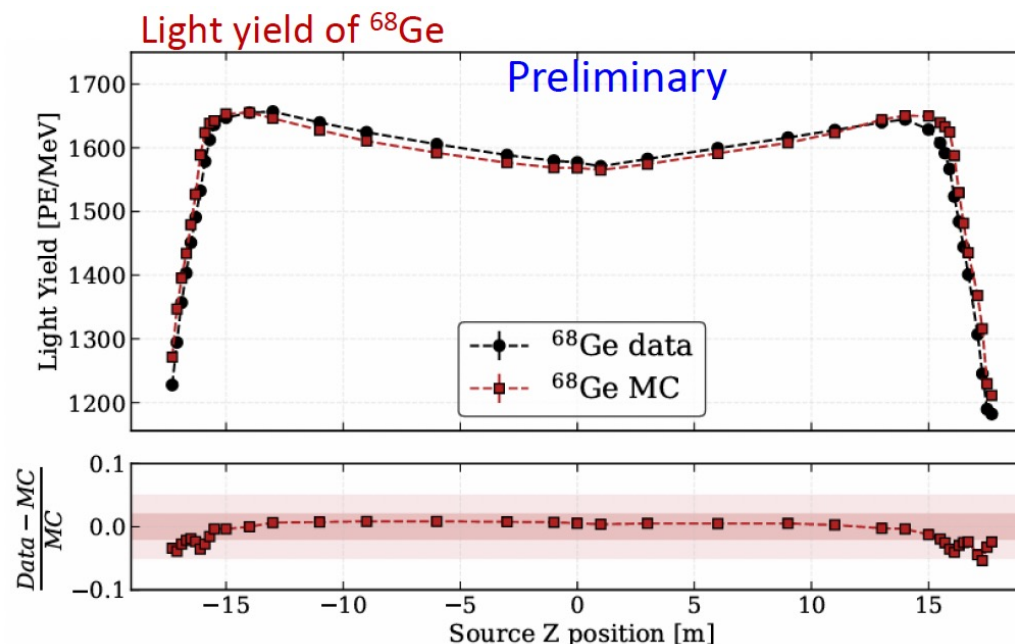
Attenuation length in LS
 > 20.6 m @ 430 nm

Attenuation length in water
 > 75 m

Muon veto > 99.9% efficiency

- ~5 Hz crossing Central Detector, additional ~4 Hz Water Pool only
- Directionality in agreement with expectations

Light yield: a lot of light!



Light yield
at (0,0,0):

~1600 PE/MeV for
 ^{68}Ge

~1785 PE/MeV for
neutrons,

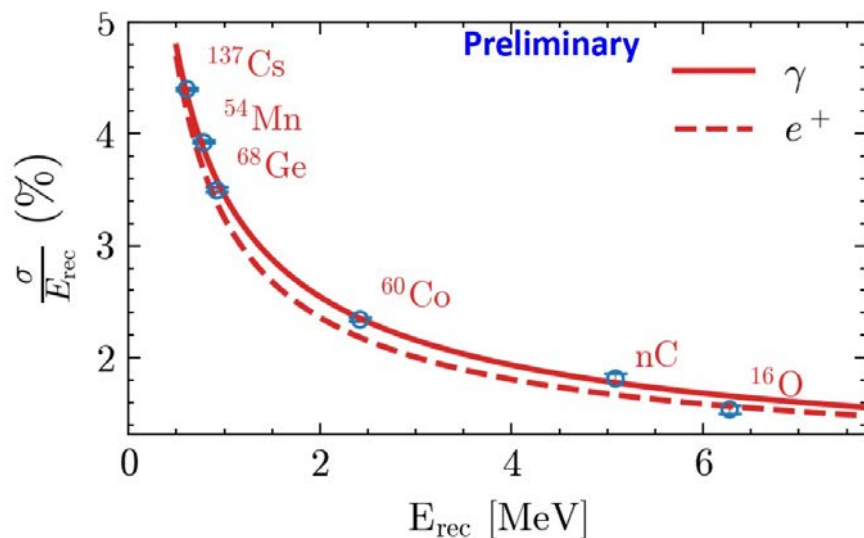
in good agreement
with MC

EVENT RECONSTRUCTION PERFORMANCE

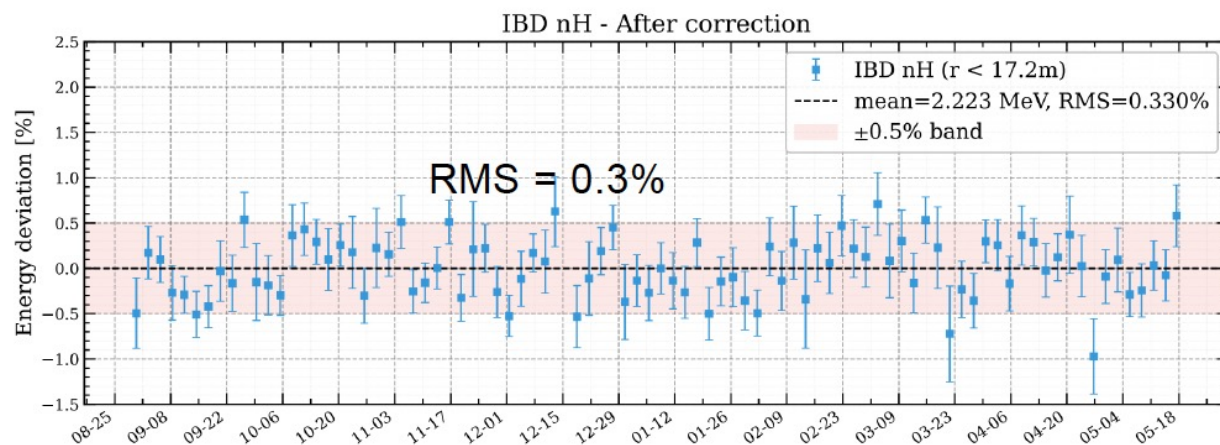
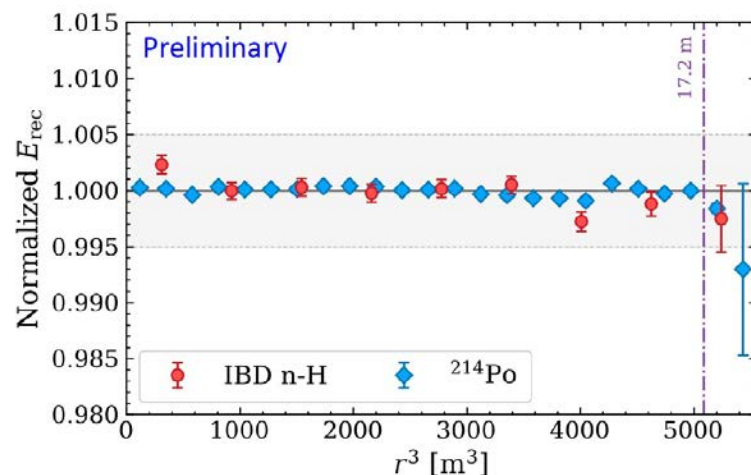
- Vertex and energy: from reconstructed PMT hit times & charges
- Time dependent variations & r- θ -t dependence corrected by ^{214}Po

Energy resolution:

- Particle type, energy, and space dependent.
- An analytical R-dependent resolution model for e^+ was built using Geant4 simulation and data from calibration sources (α , γ).



Slightly worse than the design
– in focus now!



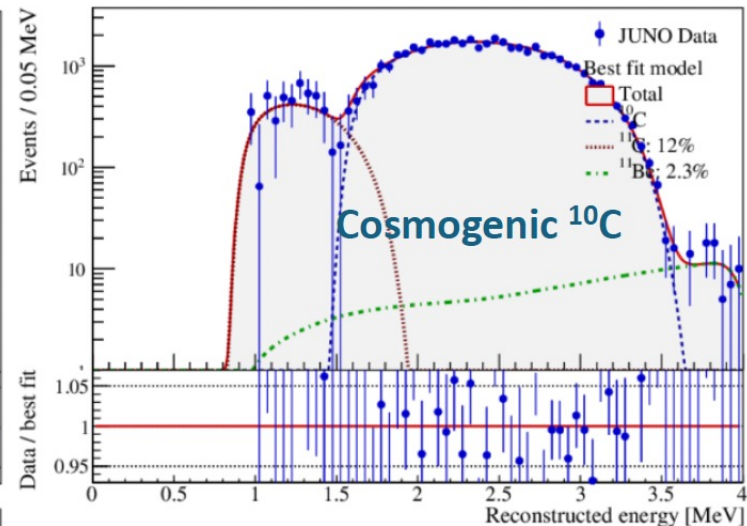
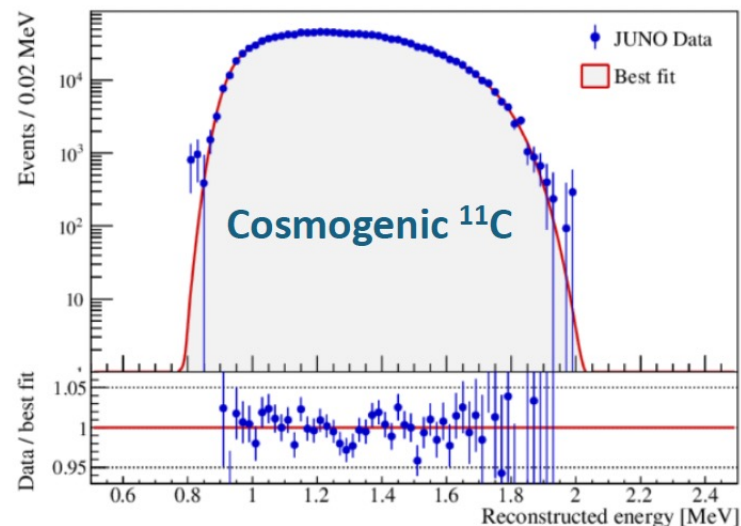
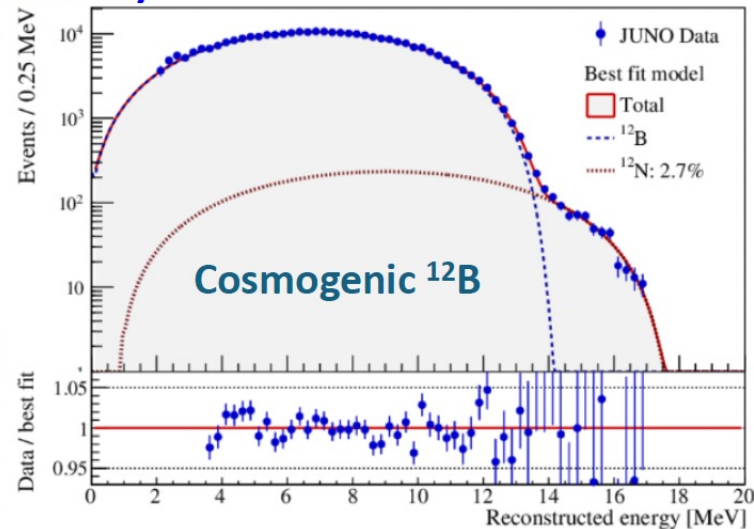
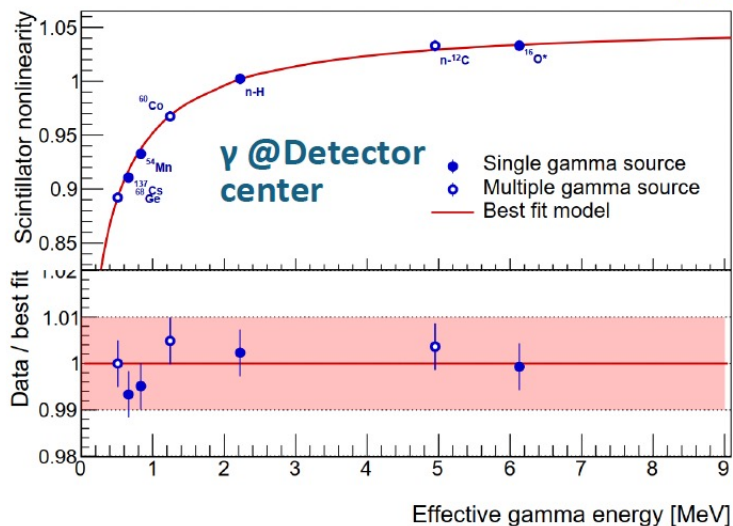
Energy scale stability
(after correction)
checked by 2.2 MeV gamma
from n-H (IBDs, ^9Li)

Spatial non-uniformity:
 $\sim 0.2\%$

Time variation:
 $\sim 0.3\%$

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

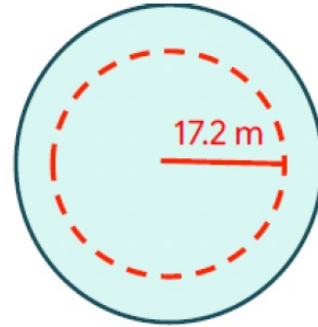
- gamma calibration sources
- cosmogenic ^{12}B (e^-)
- cosmogenic $^{11/10}\text{C}$ (e^+)

IBD EVENT SELECTION

Enlarged!

Fiducial Volume cut

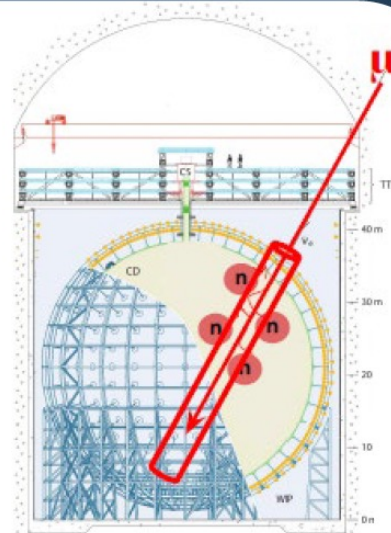
- To remove external radioactivity
- $R < 17.2 \text{ m} + |z| < 15.5 \text{ m}$



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);



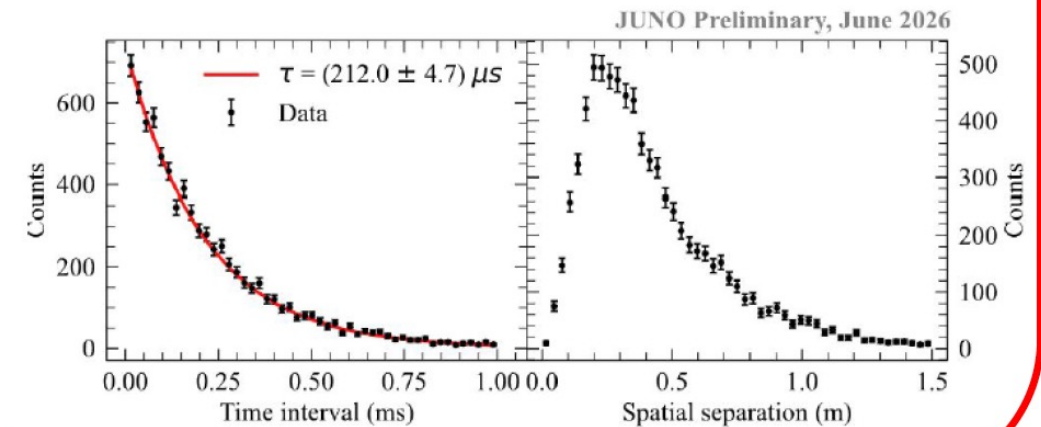
IBD selection (space+time+energy)

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

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

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

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

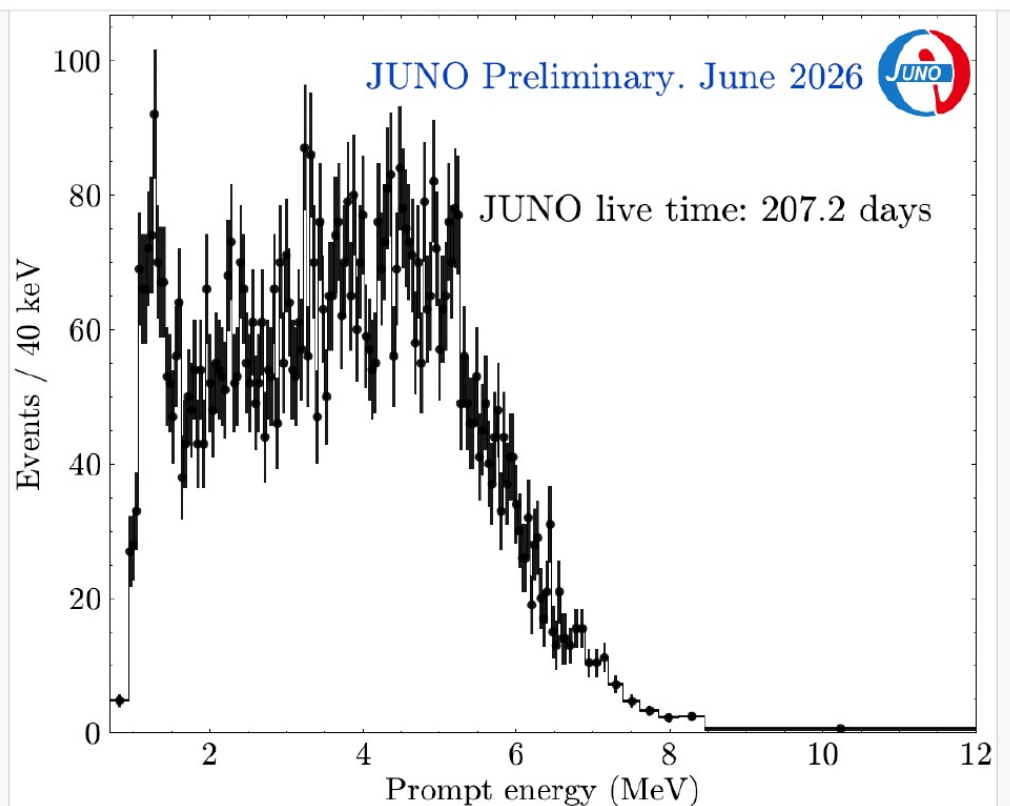


Efficiency of all the cuts $\epsilon_{\text{tot}} \sim 74\%$

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

SELECTED IBD CANDIDATES

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



→ Contain not only reactor signal, but also residual backgrounds

Geoneutrinos: antineutrinos from ^{238}U and ^{232}Th decay chains in the Earth $\rightarrow$ geological models provide predictions with large systematic uncertainties,

MAJOR backgrounds: independently evaluated

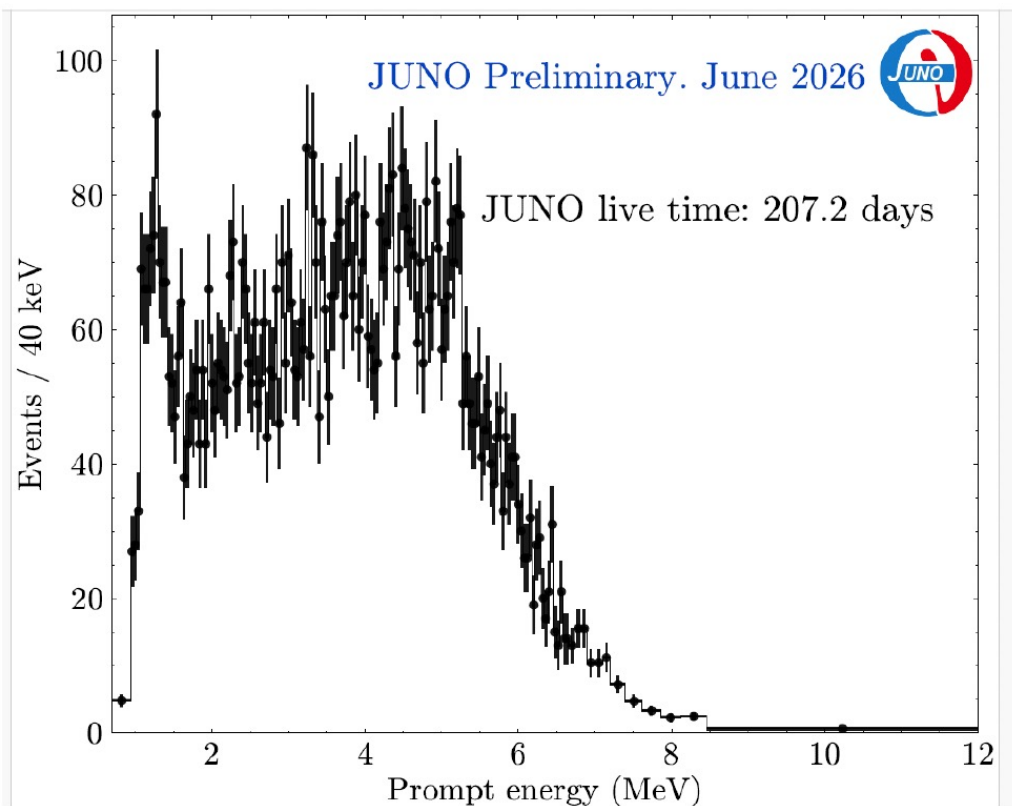
- **Cosmogenic $^9\text{Li}/^8\text{He}$: (e^- + neutron) decay**, constrained based on IBDs after muons
- **World reactors:** reactor-antineutrino background from far away reactors
- **$^{214}\text{Bi}/\text{Po}$** correlated radioactive background, constrained using data

MINOR backgrounds: independently evaluated

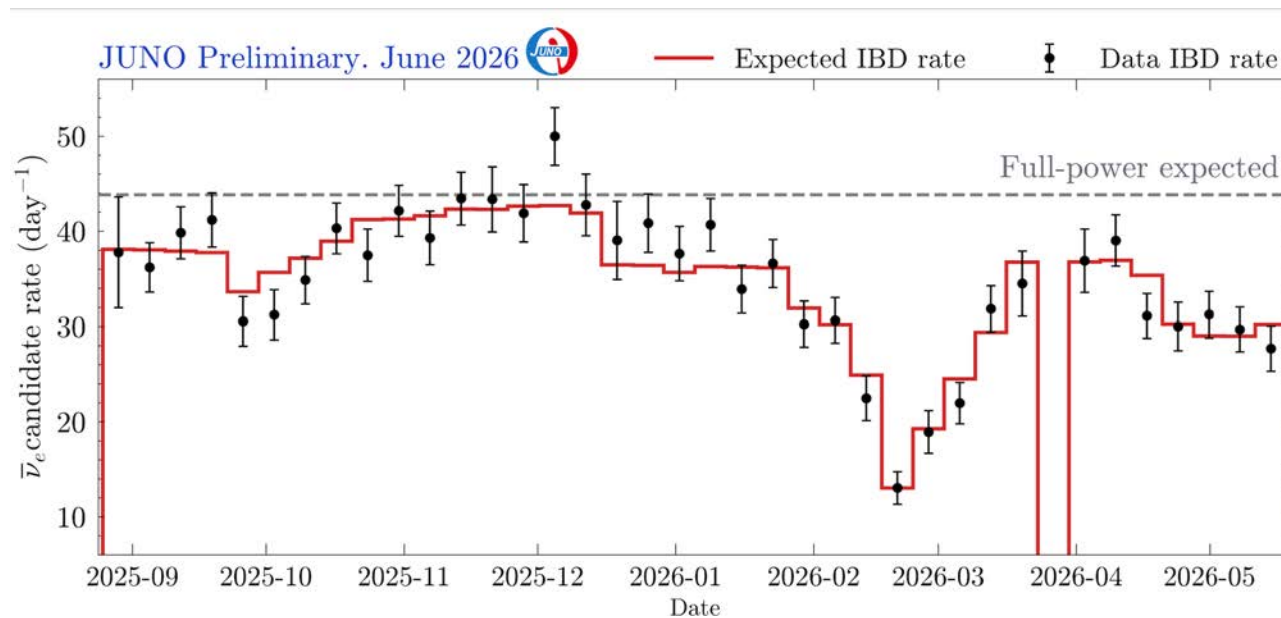
- **$^{13}\text{C}(\alpha, n)^{16}\text{O}$:** $^{210}\text{Po}(\alpha)$ -induced neutron background
- **Fast neutrons:** muon-induced background
- **Double neutrons:** correlated neutron background
- **Atmospheric neutrinos:** atmospheric-neutrino background
- **Accidentals:** random coincidences, determined from data

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:



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}Bi – ^{214}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

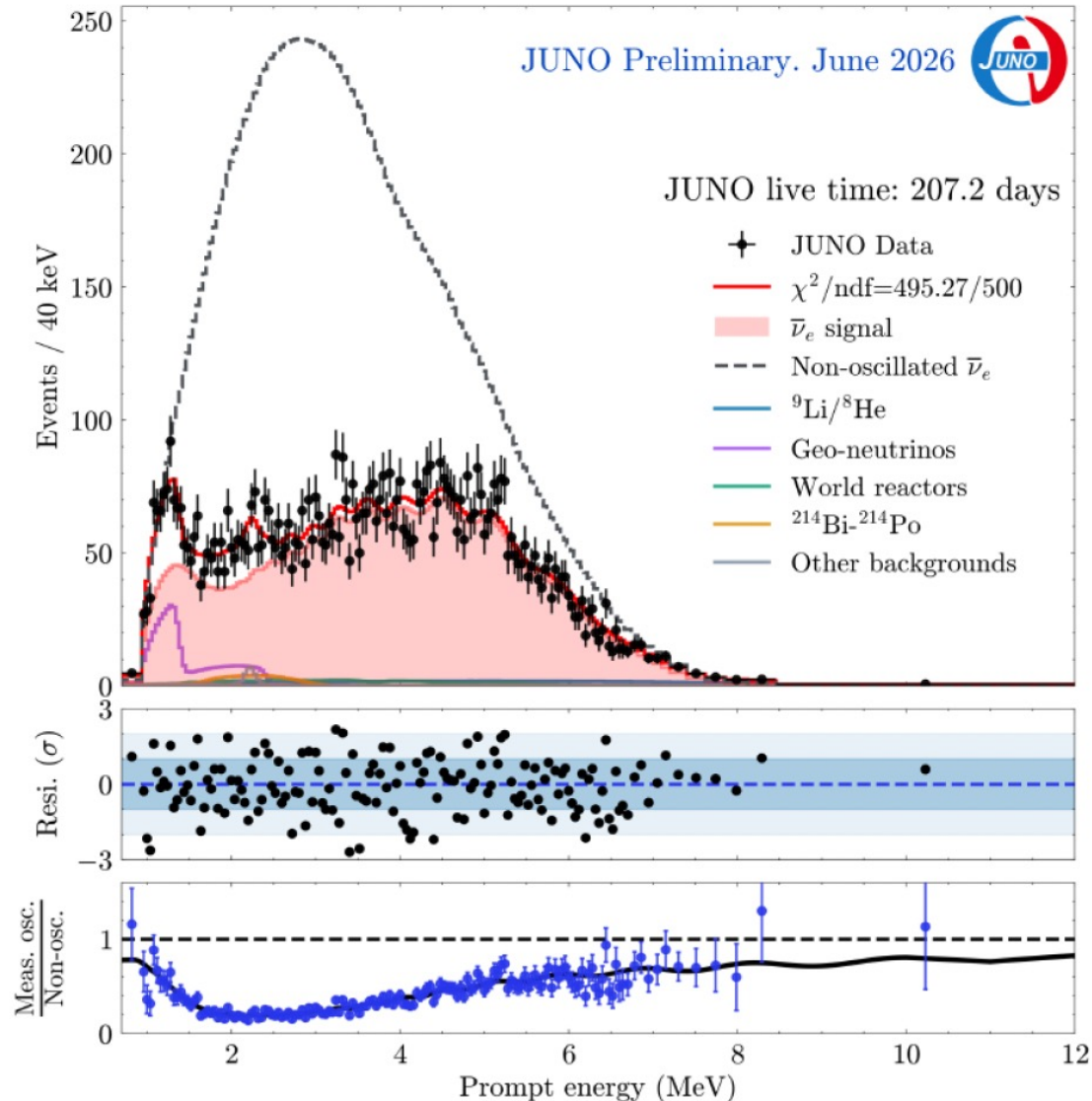
Normal and inverted ordering are fitted separately

Output:

Signal and background rates

Oscillation parameters

RESULTS: SIGNAL AND BACKGROUND RATES



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

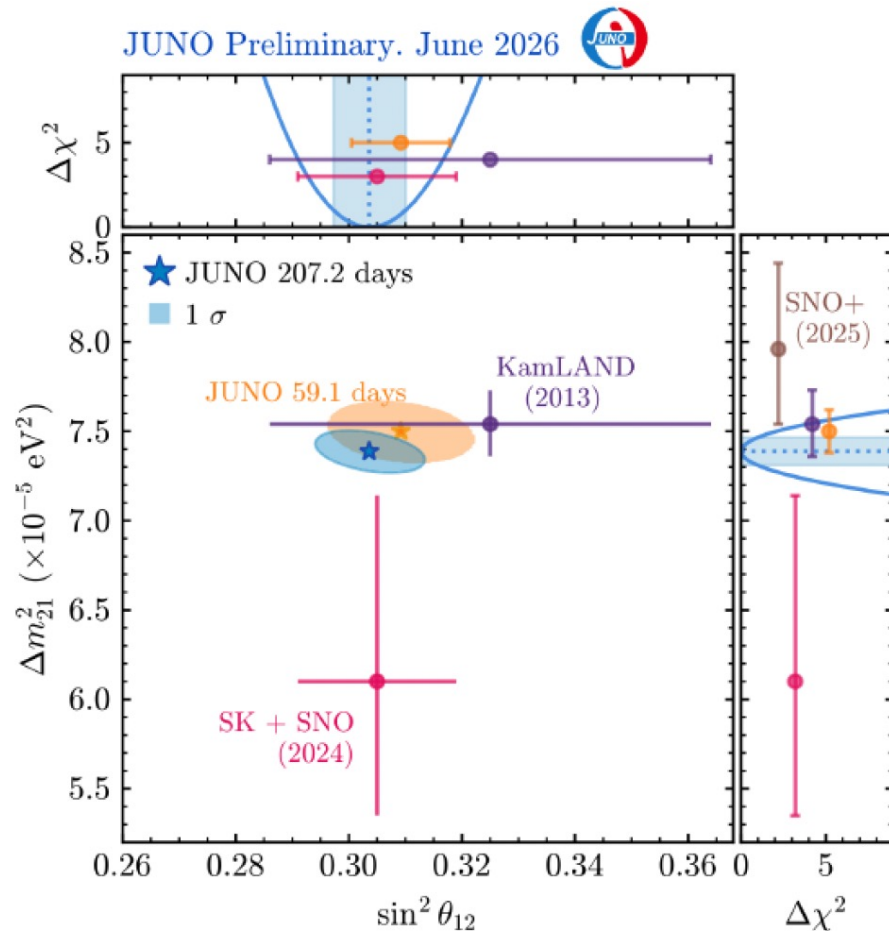
Fast neutrons 0.02 ± 0.02

Double neutrons 0.13 ± 0.10

Atmospheric neutrinos 0.11 ± 0.05

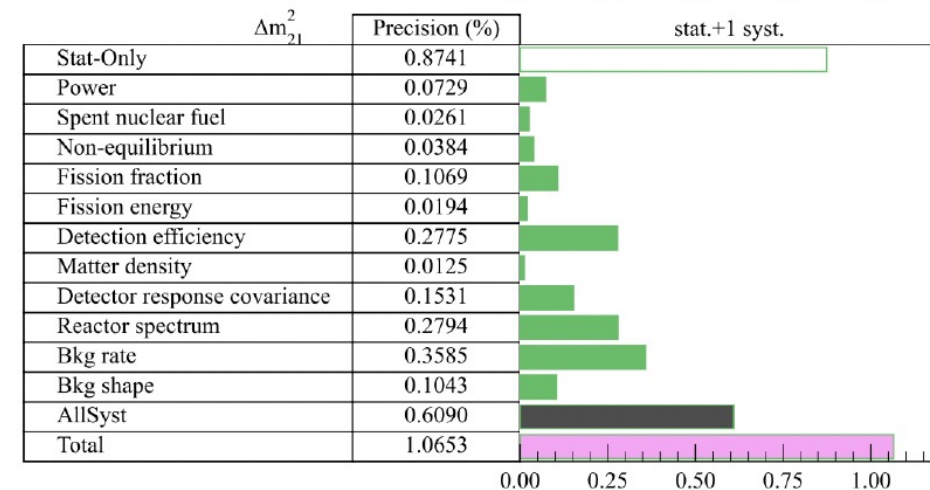
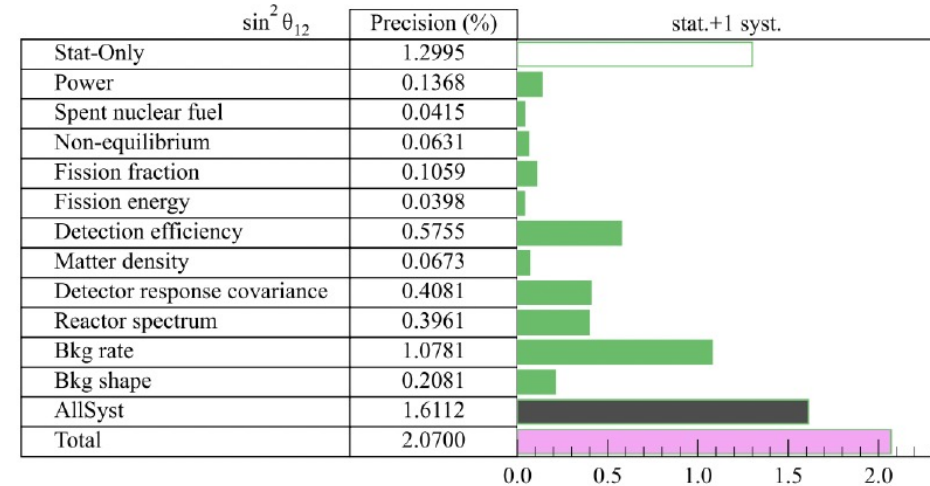
Accidentals 0.07 ± 0.01

RESULTS ON SOLAR OSCILLATION PARAMETERS

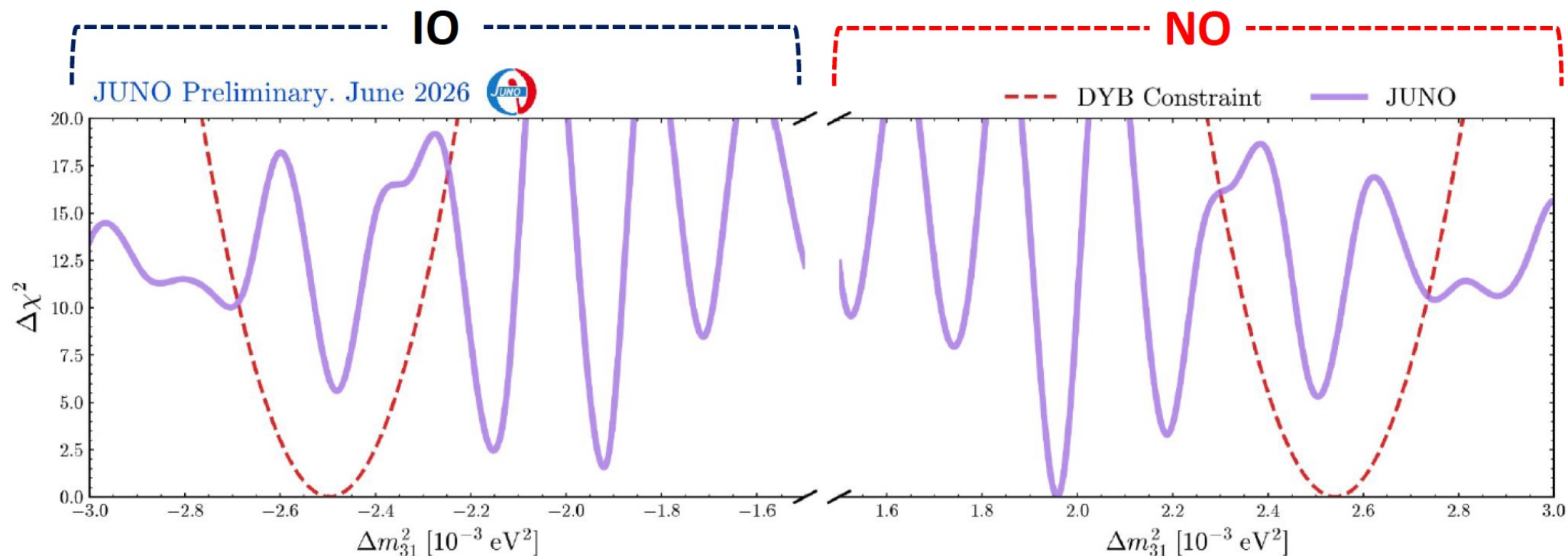


Δm_{21}^2	7.388 ± 0.078 (1.60% $\rightarrow$ 1.06%)	2.5% (PDG 2025)
$\sin^2 \theta_{12}$	0.3036 ± 0.0064 (2.8% $\rightarrow$ 2.1%)	3.9% (PDG 2025)

Statistical uncertainty still dominant, but **systematic errors** become important (^{214}Bi bkg., detection eff. – can be improved)

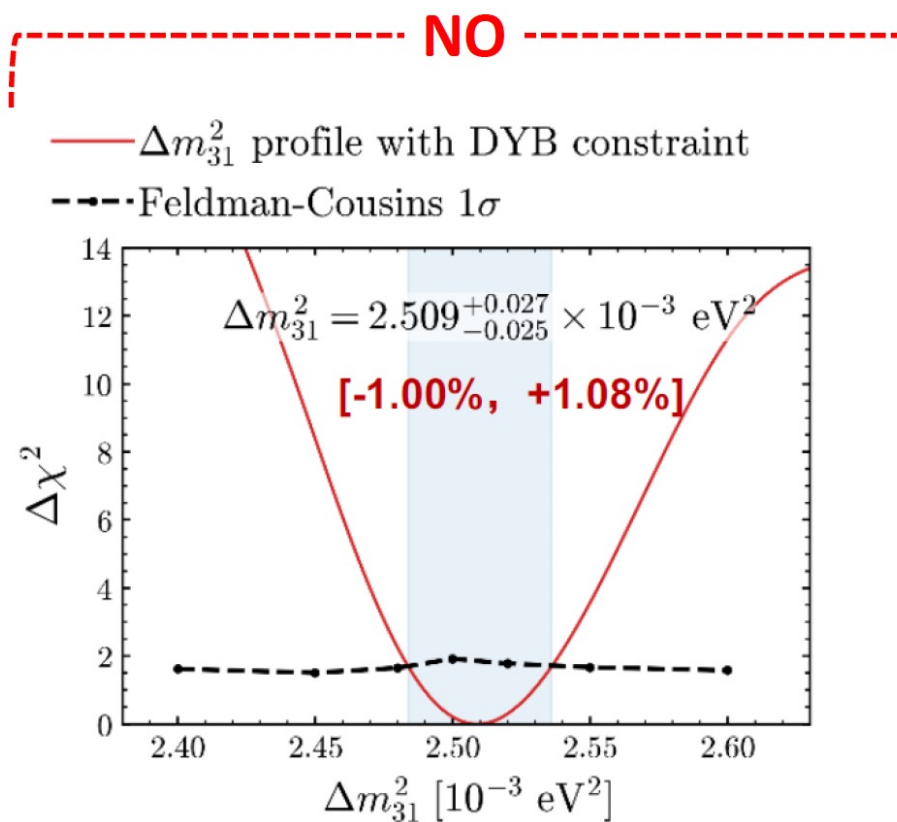
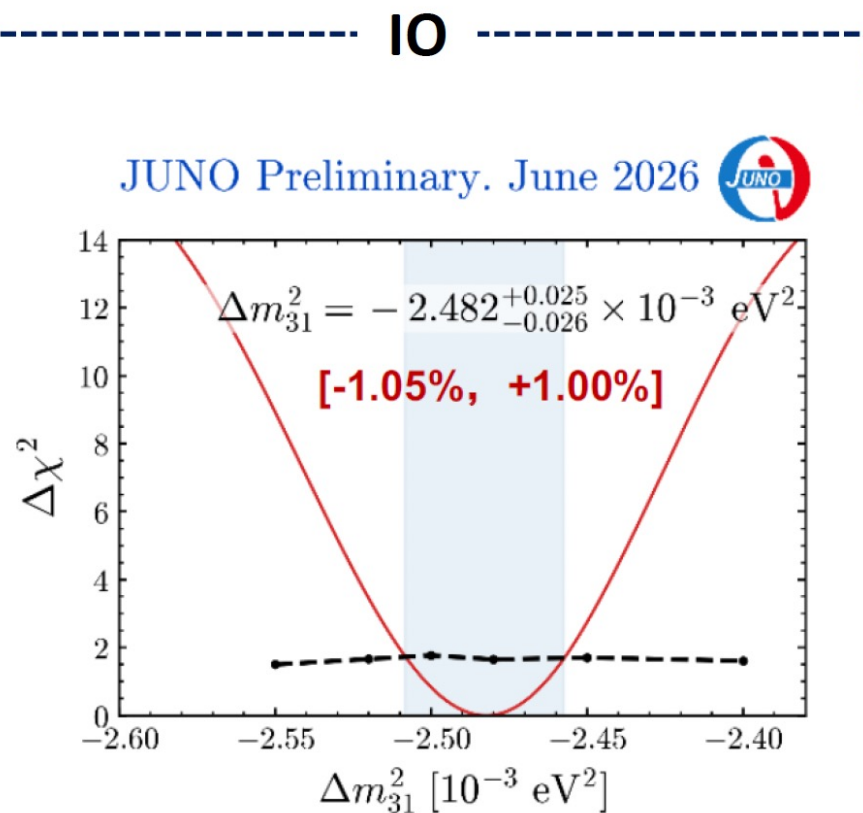


RESULTS ON ATMOSPHERIC MASS SPLITTING



- Without external constraints on Δm_{31}^2 , JUNO $\Delta\chi^2$ profiles for Δm_{31}^2 feature multiple minima: this is expected at the low statistics of 207 days.
- Daya Bay constraints on Δm_{31}^2** identify the compatible JUNO minima, while the precision within each minimum is largely determined by the JUNO profile.

RESULTS ON ATMOSPHERIC MASS SPLITTING

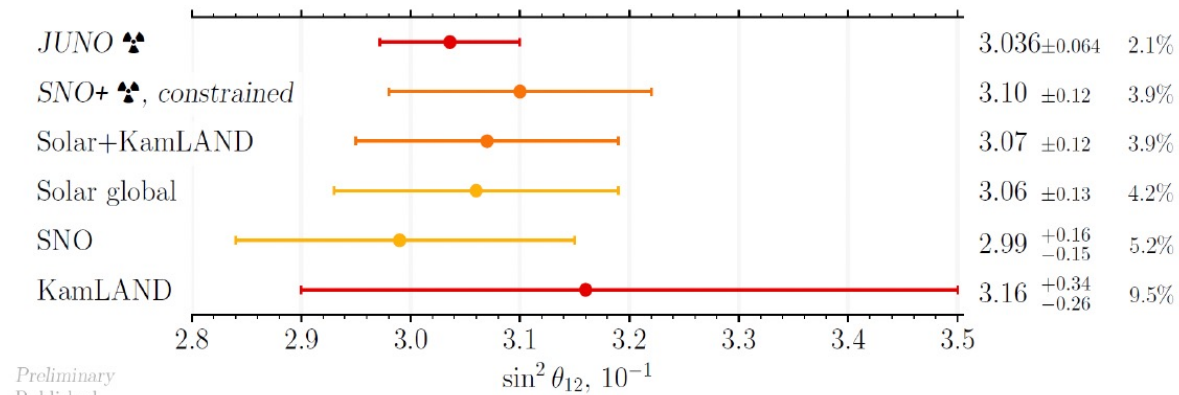


Feldman-Cousins (FC) method is used to determine the 1σ range of Δm_{31}^2

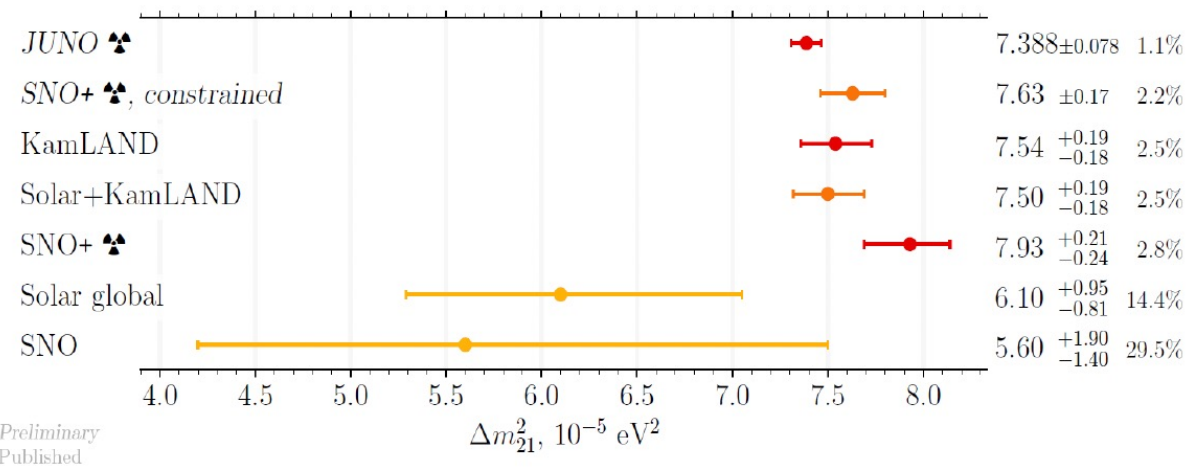
~1% precision achieved for Δm_{31}^2 (in both IO and NO scenarios)

COMPARISON WITH EXISTING RESULTS

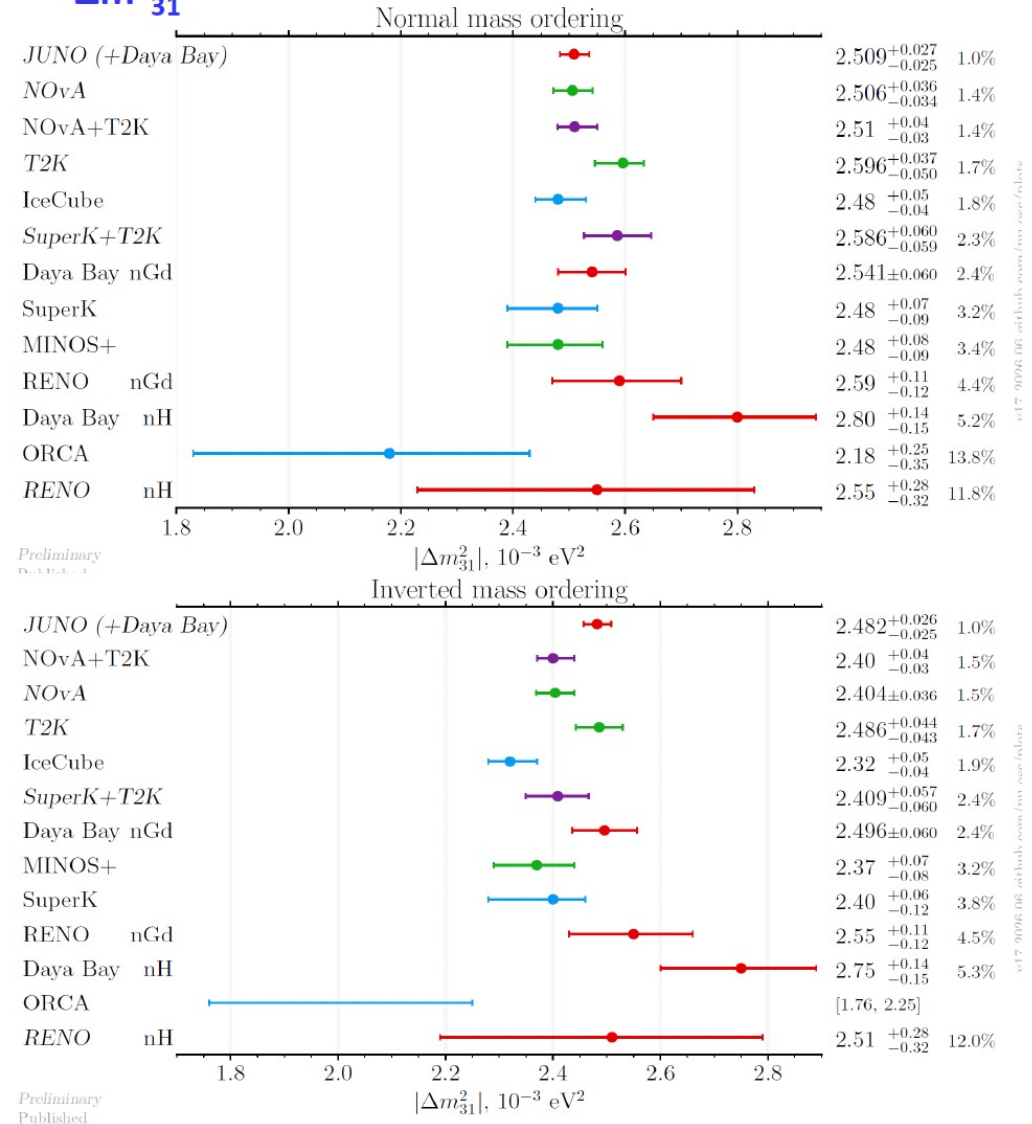
$\sin^2 2\theta_{12}$



Δm^2_{21}



Δm^2_{31}



Results from JUNO have smallest uncertainties

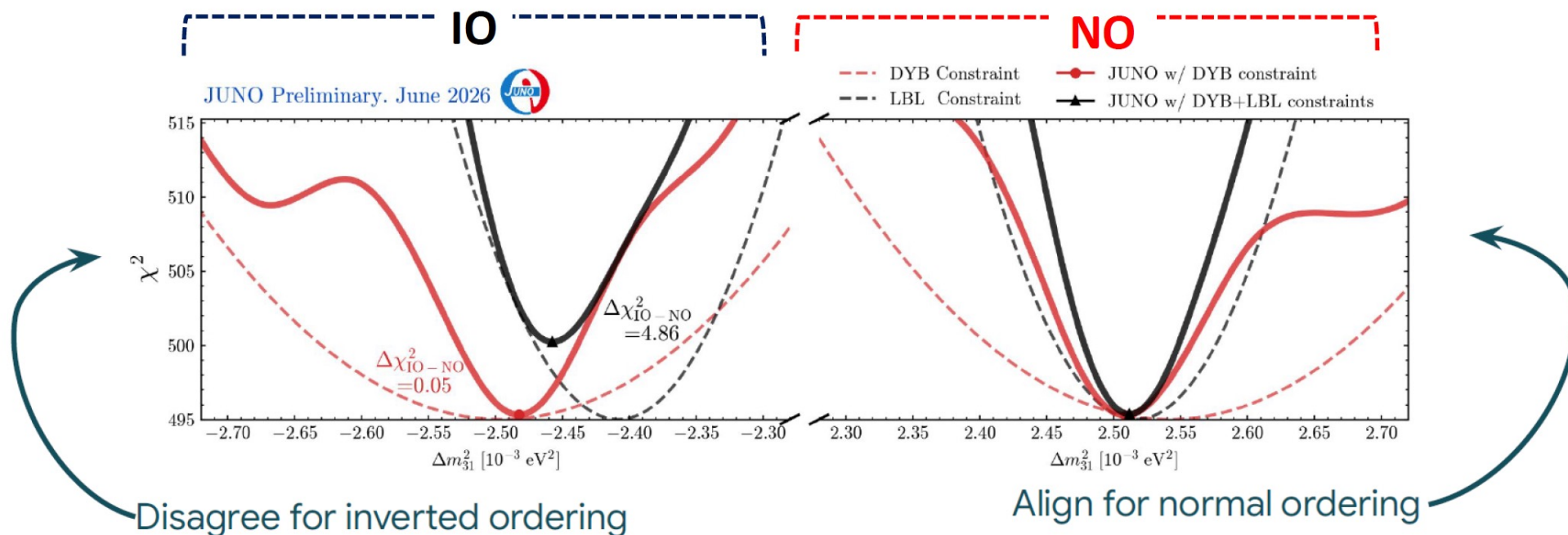
NEUTRINO MASS ORDERING: ADDING CONSTRAINT FROM LBL EXPERIMENTS

Overview on accelerator- ν experiments, see talk of Elizabeth Worcester.

Long BaseLine (LBL) accelerator experiments (NoVA, MINOS, T2K..) and reactor experiments (JUNO, Daya Bay) are complementary $\rightarrow \Delta m_{31}^2$ profiles should align at the right mass ordering [1] !!

We adopted the NuFit-LBL Δm_{31}^2 results from [2] as additional constraint in our fit:

NORMAL ORDERING IS PREFERRED WITH $\Delta\chi^2 = 4.86$



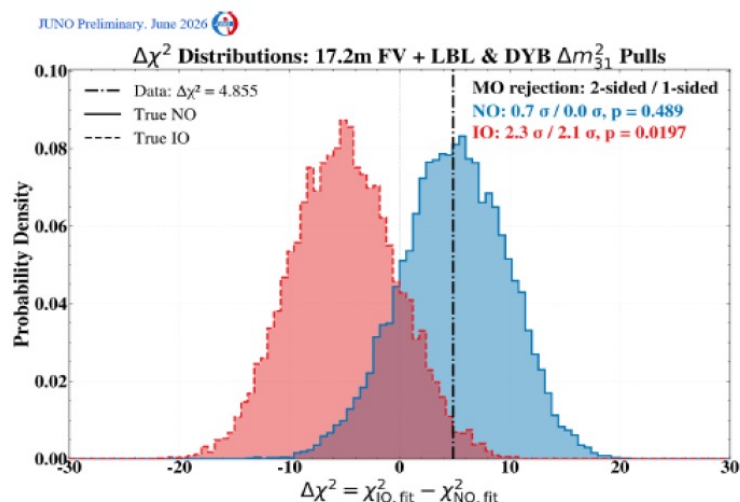
[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

[2] NuFIT6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

NEUTRINO MASS ORDERING SIGNIFICANCE

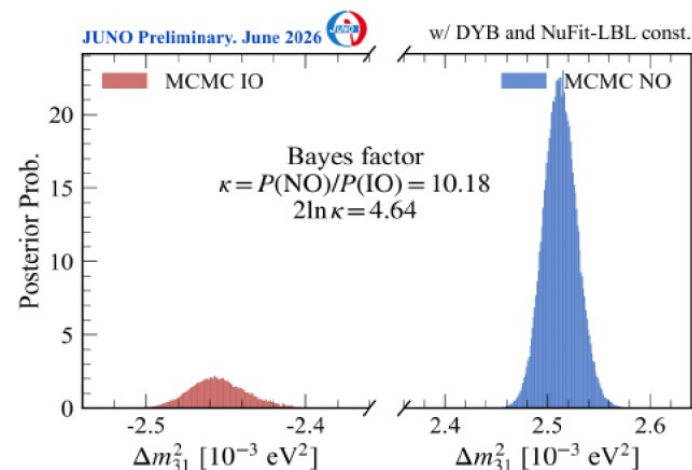
QUANTITATIVELY: significance calculated with both Frequentist and Bayesian approach

Frequentist



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

Bayesian

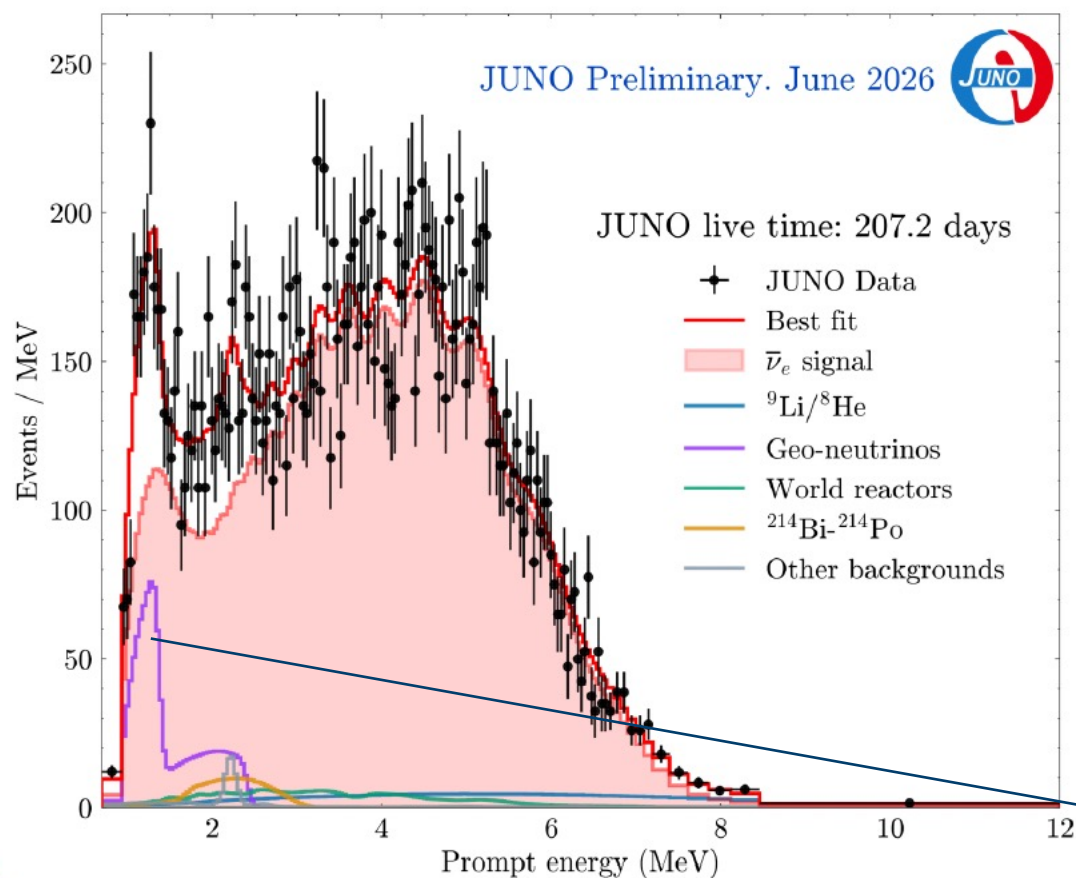


- Inferred through Markov-Chain Montecarlo (MCMC);
- **Normal Ordering preferred with Bayes Factor of 10.18**

→ Preference for the Normal Ordering scenario

JUNO RESULTS ON GEONEUTRINOS

Overview on geoneutrinos, see talk of Mark Chen.

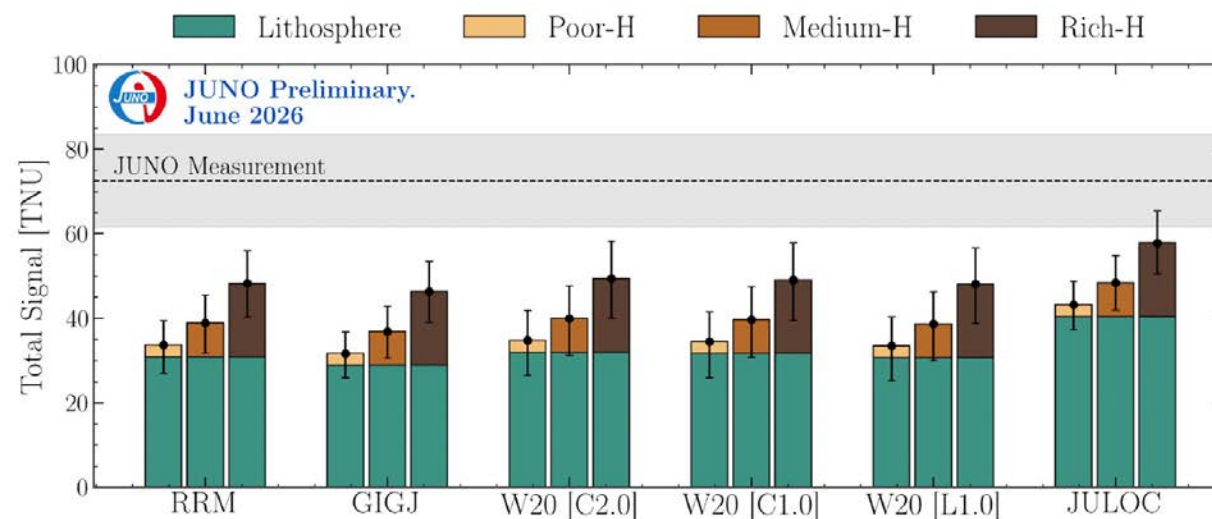


Fits are performed without constraint on geo-neutrino flux, but with $3.4 \pm 10\%$ U/Th chondritic ratio.

Constraining the geo-nu flux within geological model predictions doesn't change oscillation results.

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



- 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.

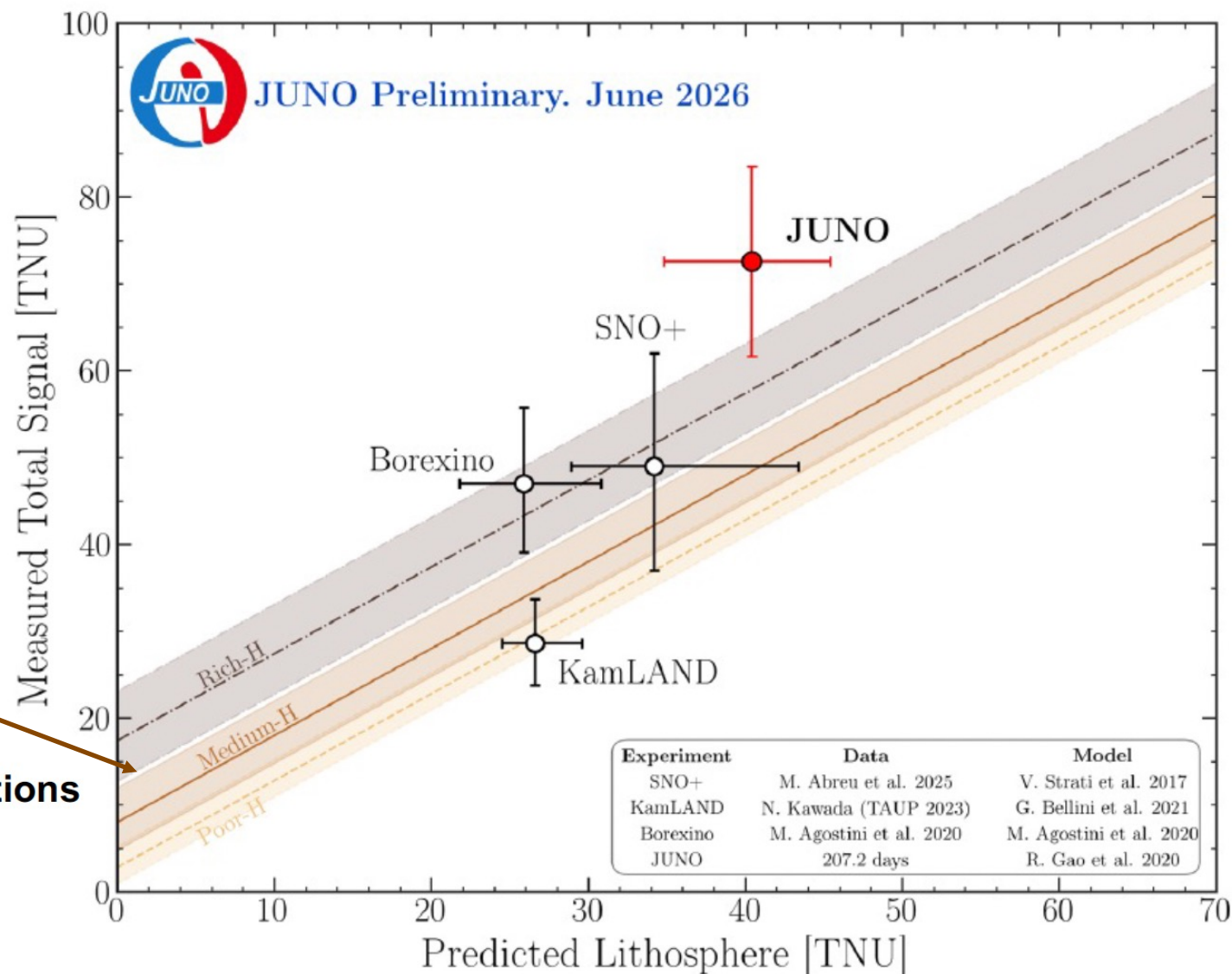
MULTISITE MEASUREMENTS & MANTLE SIGNAL

Is the mantle laterally homogeneous?

We need more statistics and improved prediction of the lithospheric signal.

The 3 bands:
Prediction of mantle signal based on different Bulk Silicate Earth models.
Rich, Medium, and Poor
in U and Th content.

Y-offset = mantle contributions
(assumes homogenous mantle)



SUMMARY & OUTLOOK

August 2025: JUNO & February 2026: JUNO-TAO started their taking data.

With 207 days of JUNO data, we have obtained:

- World leading precision on solar oscillation parameters (Δm^2_{21} of 1.06% & $\sin 2\theta_{12}$ of 2.1%);
- Combining JUNO + JUNO-TAO + Daya-Bay near detector $\rightarrow$ world-leading precision on Δm^2_{31} of $\sim 1\%$
- **Normal mass ordering is favored at 2.3σ** when additional constraint on Δm^2_{31} from Daya-Bay and LBL accelerator experiments is used;
- **First geoneutrino measurement** with $\sim 15\%$ precision and rather high signal value.

What's next?

- Focus on further calibrations, low level analysis, and reconstruction methods towards and improved energy resolution.
- Additional physics analysis are also in the pipeline.



Livia Ludhova on behalf of the JUNO collaboration

GSI Darmstadt & JGU Mainz

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th COURSE, Erice, Italy, 20/09/2026

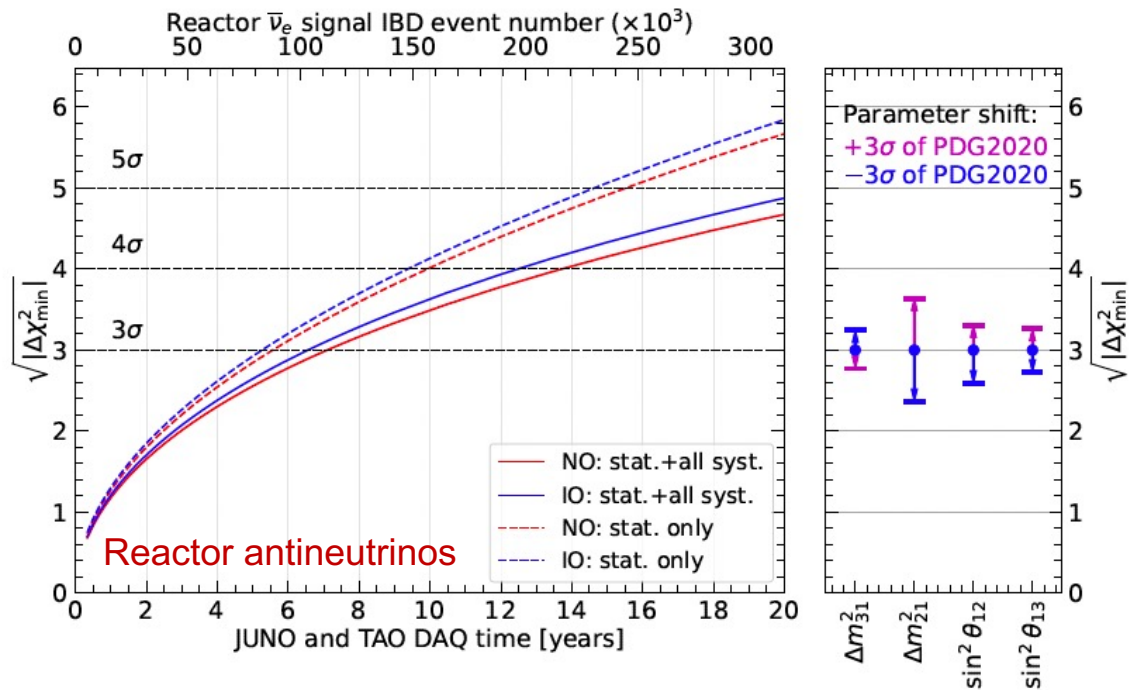


JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Back up slides

JUNO SENSITIVITY & NEUTRINO OSCILLATION

Neutrino Mass Ordering

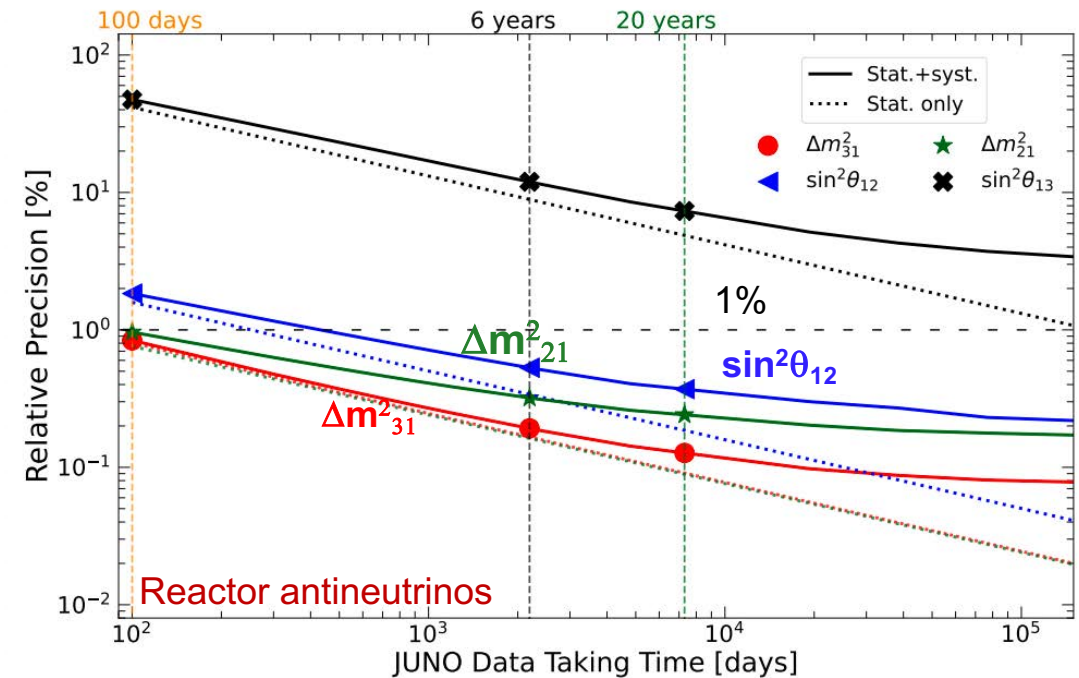


3 σ (reactors only) @ ~6 years * 26.6 GW_{th} exposure

Combined reactor + atmospheric neutrino analysis in progress:
further improvement of the NMO sensitivity.

Chin. Phys. C 49 (2024) 033104.

Oscillation Parameters



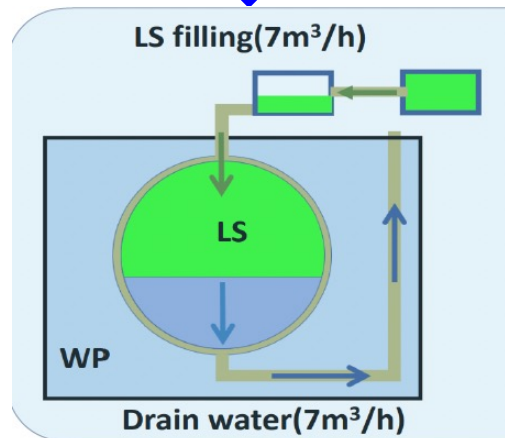
Precision of Δm^2_{21} , $\sin^2 \theta_{12}$, Δm^2_{31} < 0.5% in 6 years.

Solar parameters **ALSO** with ^8B solar neutrinos

$\sin^2 \theta_{12} (+9\% / -8\%)$ and $\Delta m^2_{21} (+27\% / -17\%)$

Chin. Phys. C 46 (2022) 123001.

LIQUID SCINTILLATOR PLANTS ON SITE



85%

15%



SS pipes to underground

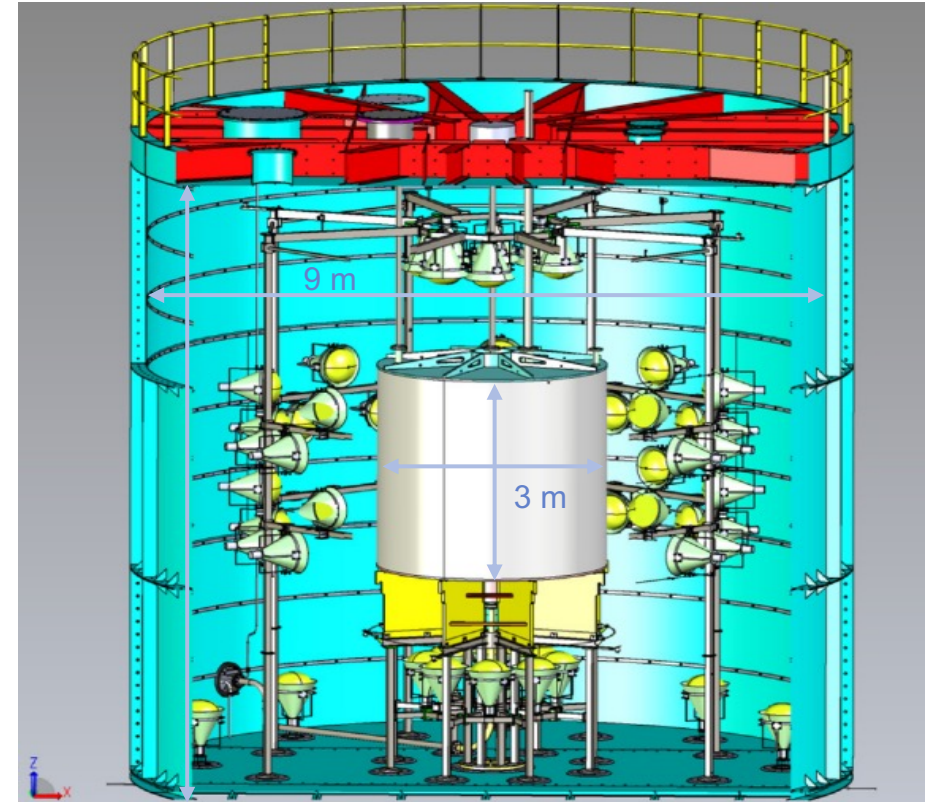
Four purification plants for a radio-purity of 10⁻¹⁷ g/g (U/Th) and 20 m attenuation length @ 430 nm.

ONLINE SCINTILLATOR INTERNAL RADIOACTIVITY INVESTIGATION SYSTEM (OSIRIS)

A 20-t detector to monitor radiopurity of LS
before and during filling to the central detector

- ✓ RADON CONTAMINATION
- ✓ OPTICAL PROPERTIES

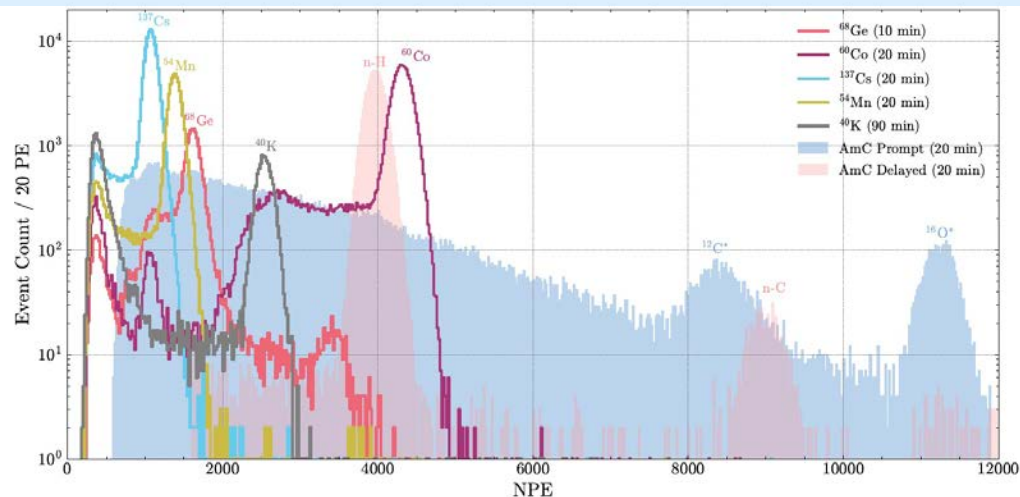
Eur.Phys.J.C 81 (2021) 11, 973.



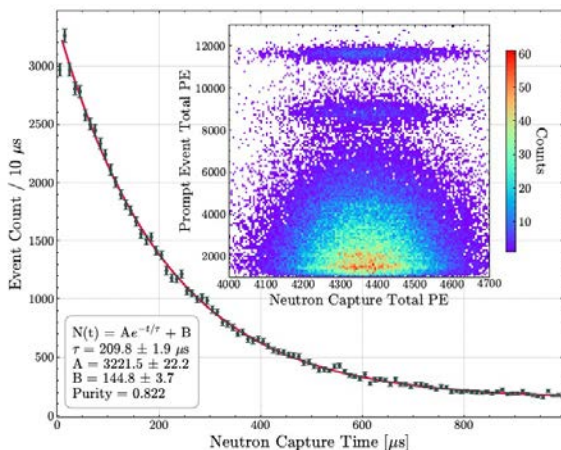
KEY CONTRIBUTION OF GERMAN GROUPS WITH LEADERSHIP BY M. WURM (JGU)

JUNO CALIBRATION DATA

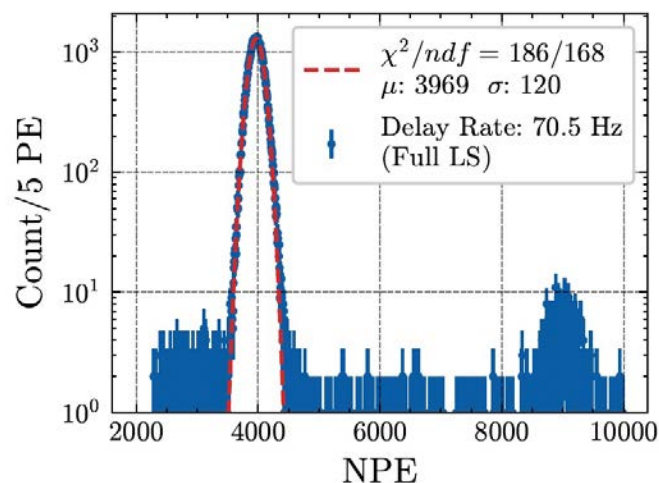
Charge distributions (NPE) from different γ and neutron calibration sources, after dark-noise (DCR) subtraction.



Neutron capture time with AmC source.



Neutron capture peaks.

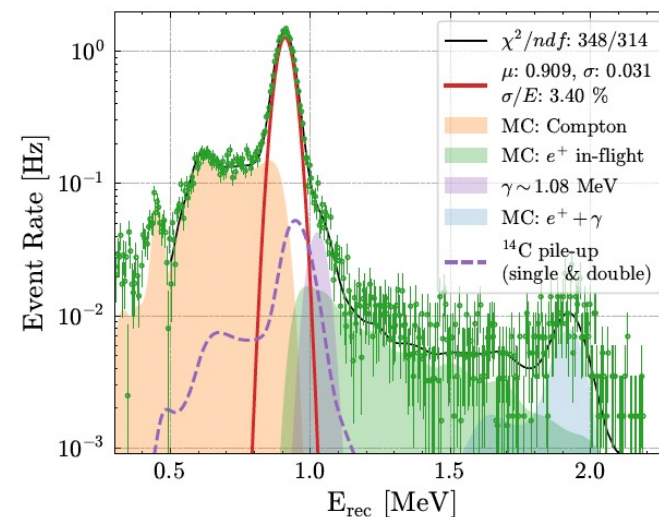


Source	Energy	System	Activity
Gamma Sources			
^{68}Ge	$0.511 \times 2 \text{ MeV}$	ACU	595 Bq ^a
^{137}Cs	0.662 MeV	ACU	140 Bq ^b
^{54}Mn	0.835 MeV	ACU	521 Bq ^a
^{40}K	1.460 MeV	ACU	13 Bq
^{60}Co	1.173+1.333 MeV	ACU	165 Bq ^b
Neutron Sources			
$^{241}\text{Am}-^{13}\text{C}$	neutron + 6.13 MeV ($^{16}\text{O}^*$)	ACU	130 Bq
	(n,γ)p 2.223 MeV	CLS	100 Bq
	(n,γ) ^{12}C 4.94 MeV		
	(n,γ) ^{56}Fe 7.63 MeV, etc.		
$^{241}\text{Am}-^9\text{Be}$	neutron + 4.43 MeV ($^{12}\text{C}^*$)	GT	30 Bq
	(n,γ)p 2.22 MeV		
Optical Calibration			
Laser	Optical pulses (420 nm and 266 nm)	ACU	50 Hz

^a Reference activity measured on 6/21/2023.

^b Reference activity measured on 4/6/2021.

^{68}Ge source in the detector centre.



MODEL INDEPENDENT MEASUREMENT OF ^8B SOLAR NEUTRINOS

Interaction channels of $^8\text{B}-\nu$:

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

- No threshold
- All flavours & $\sigma(\nu_{\mu,\tau}) / \sigma(\nu_e) = 1/6$
- Single events - continuous spectrum

CC: $\nu_e + ^{13}\text{C} \rightarrow e^- + ^{13}\text{N}$

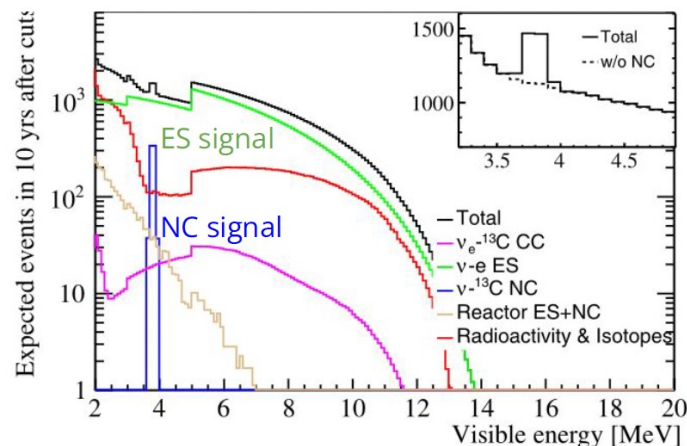
- $E_{\text{thr}} = 2.2 \text{ MeV}$
- Possible only with ν_e
- Prompt: e^- ; Delayed: ^{13}N decay

NC: $\nu_x + ^{13}\text{C} \rightarrow \nu_x + ^{13}\text{C}^*$

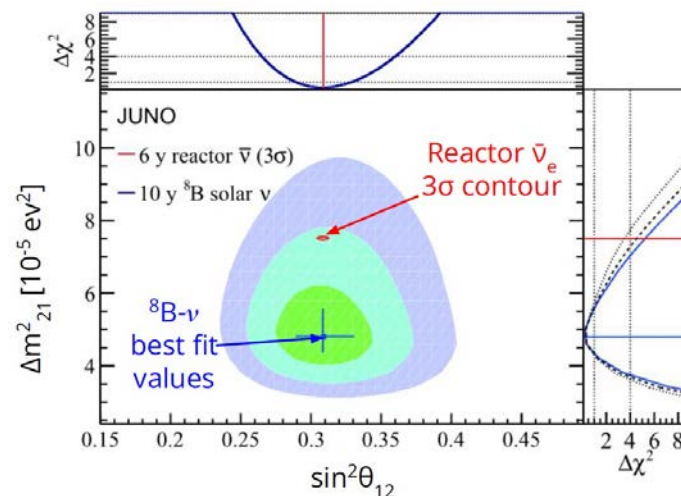
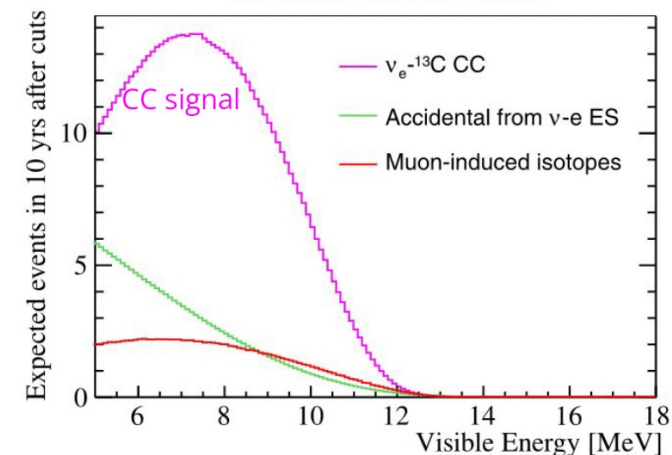
- $E_{\text{thr}} = 3.685 \text{ MeV}$
- All flavors & equal σ
- Single events - monochromatic γ

ES: *Chinese Phys. C* 45 (2021) 1
 ES+NC+CC: *Ap. J.* 965 (2024) 122

10 years, single events
after cuts



10 years, correlated prompt
events after cuts



Potential to search for possible discrepancies

Expected precision in 10 years:

^8B flux: 5% JUNO & 3% JUNO + SNO

$\sin^2 \theta_{12}$: +9% / -8%

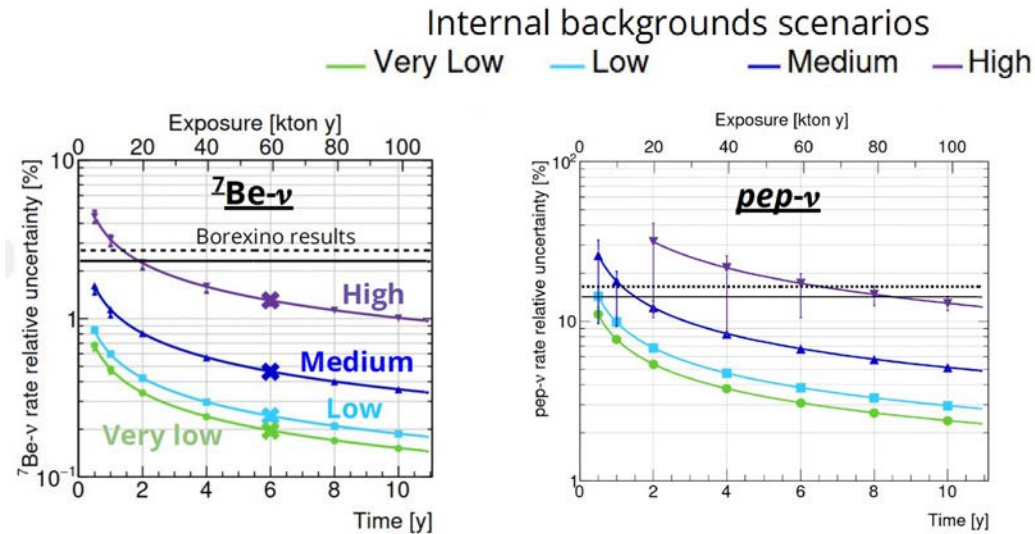
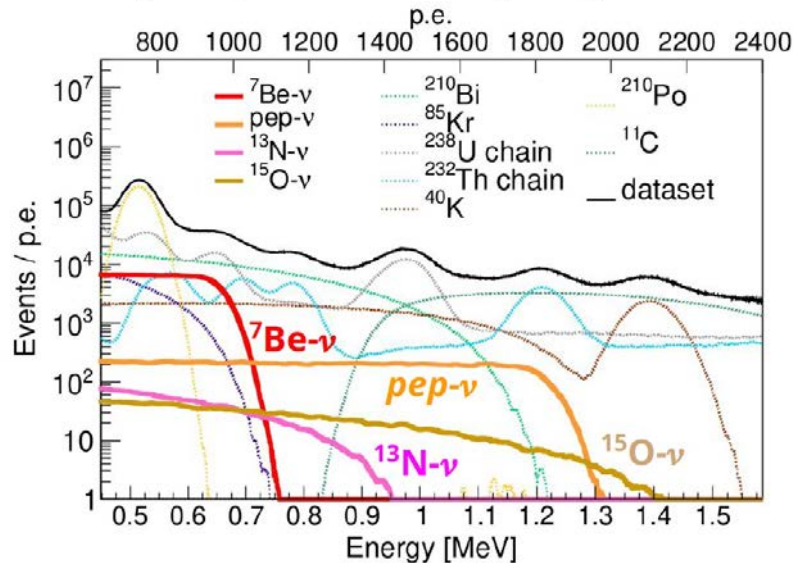
Δm^2_{21} : +27% / -17%

SENSITIVITY TO ${}^7\text{Be}$, pep, CNO SOLAR NEUTRINOS

60

$$\text{ES: } \nu_x + e^- \rightarrow \nu_x + e^-$$

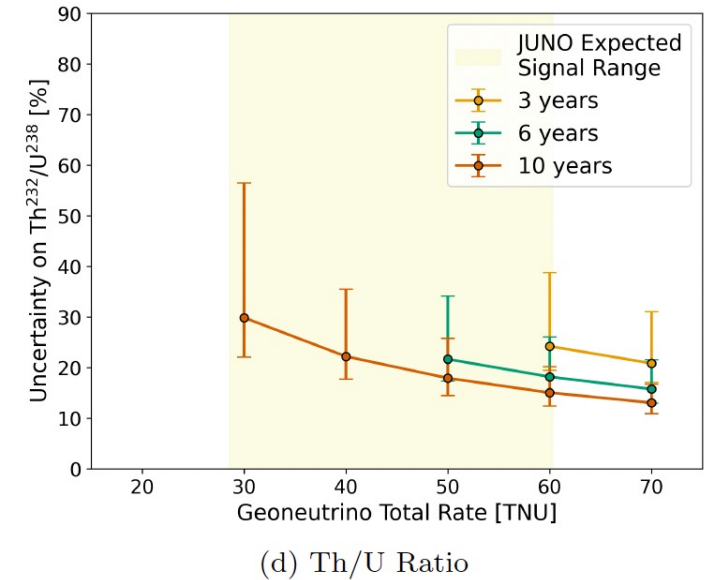
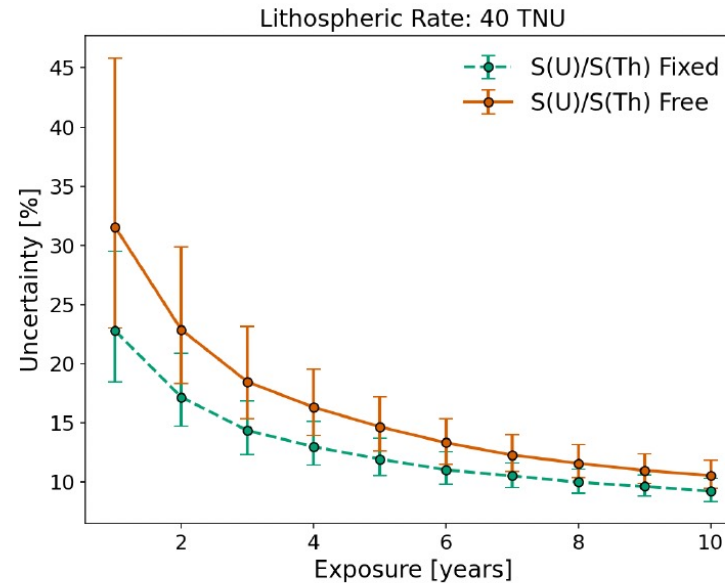
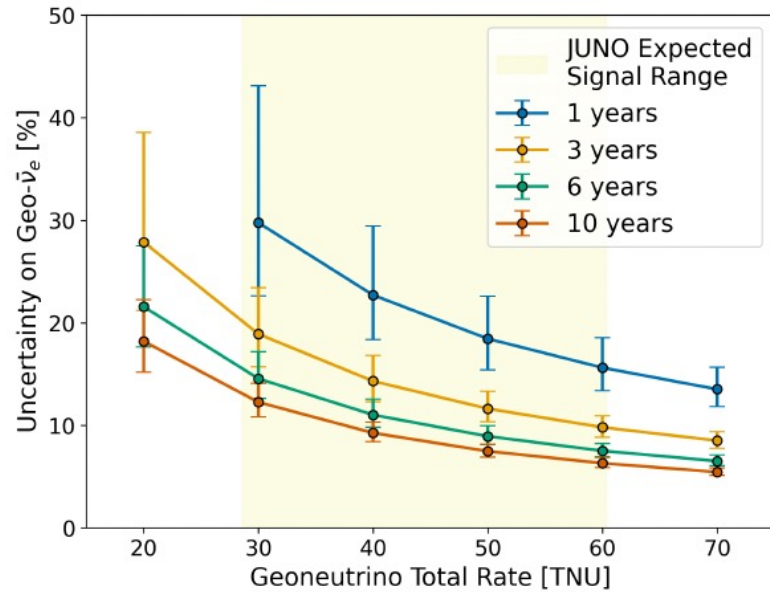
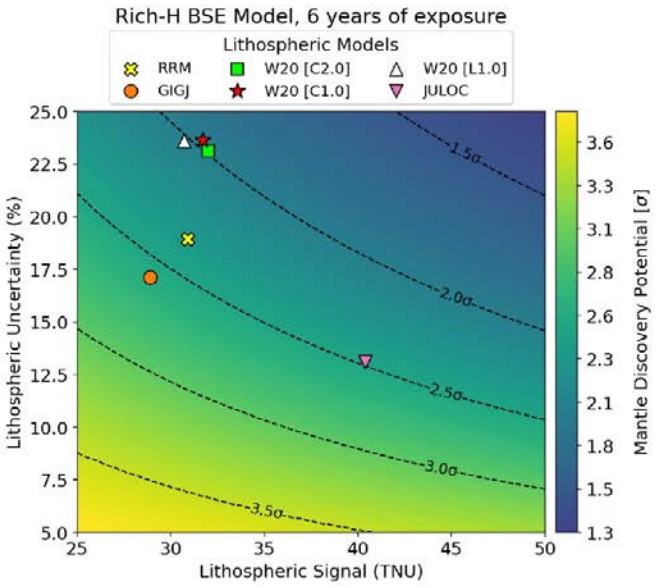
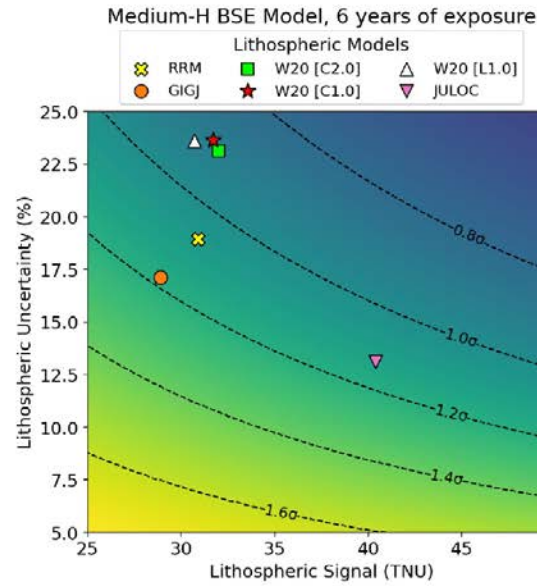
6 years, Medium radiopurity scenario



J. Cos. Astro. Phys. 10 (2023) 022.

- Several radio-purity scenarios: from the Borexino level up to the “IBD” one (minimum required for the NMO)
- JUNO has potential to improve the precision of the existing Borexino measurements
 - **${}^7\text{Be}$** : in 1-2 years time $< 2.7\%$ (current Borexino precision) for all radiopurity scenarios
 - **pep**: in 1-2 years time $< 17\%$ (current Borexino precision), only in IBD scenario after more than 6 years
 - **CNO**: constraining pep rate is crucial, precision of 20% possible in 2 to 4 years (except for the IBD scenario)
 - constraint of ${}^{210}\text{Bi}$ radioactive background not needed (applied in Borexino analysis *Nature* 587 (2020) 577–582)
 - Independent measurement of ${}^{13}\text{N}$ and ${}^{15}\text{O}$ might be possible for the first time.

	S(U) [TNU]	S(Th) [TNU]	S(U+ Th) [TNU]	S(Th)/S(U)
Poor-H	$28.1^{+8.2}_{-6.2}$	$8.1^{+2.3}_{-1.8}$	$36.0^{+9.6}_{-7.4}$	0.29
Medium-H	$32.0^{+7.9}_{-6.4}$	$9.1^{+2.4}_{-1.9}$	$41.0^{+9.5}_{-7.7}$	0.29
Rich-H	$39.1^{+8.3}_{-6.9}$	$11.3^{+2.5}_{-2.1}$	$50.2^{+10.1}_{-8.5}$	0.29



SUPERNOVAE (SN)

- **Pre-SN neutrinos:** emitted *in the last hours before the collapse*. Never detected. Alert of SN.
- **Core-collapse SN:** emitted *during the SN explosion*, **burst of few tens of seconds** in three phases (shock breakout, accretion, cooling). Observed from SN1987A.
- **SN rate in our Galaxy:** ~ 3 per century.

Dominant detection channel: IBD

Integrated signal for a $30M_{\odot}$ progenitor:

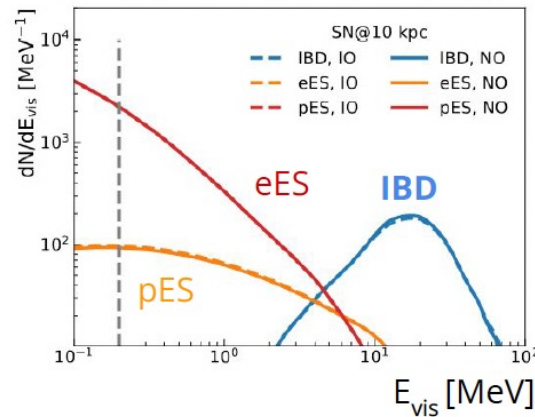
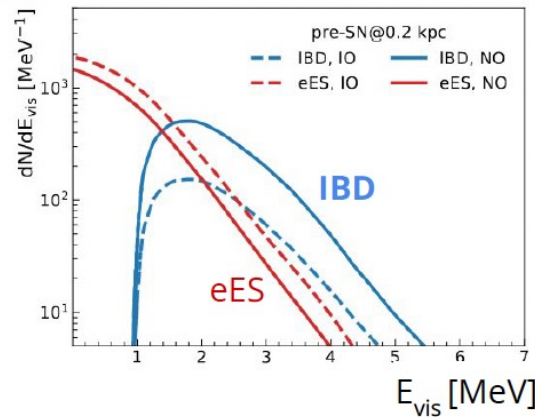
- **Pre-SN @0.2 kpc:** 400 - 1200 IBDs in a few hours
- **SN @10 kpc:** ~ 5000 IBDs in few seconds

Alert efficiency: probability to identify Pre-SN/SN neutrinos burst
Sensitivity: distance at which the alert efficiency is 50%

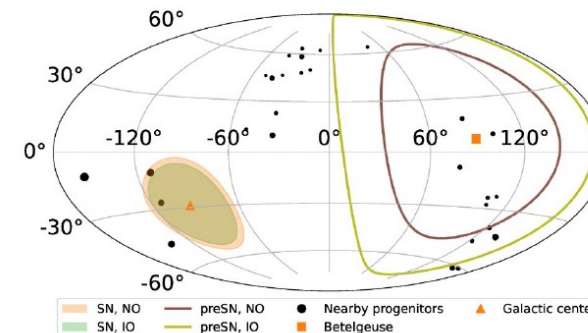
For an exploding star of $30M_{\odot}$ JUNO is sensitive to:

- ❖ **Pre-SN up to 1.6 kpc (0.9 kpc)** in case of NO (IO)
- ❖ **SN up to 370 kpc (360 kpc)** in case of NO (IO)

Pre-SN interaction channels SN interaction channels



Directionality of IBD events $\rightarrow$
Possible to **point** to the **source**,
crucial to help telescopes to detect
early electromagnetic radiation

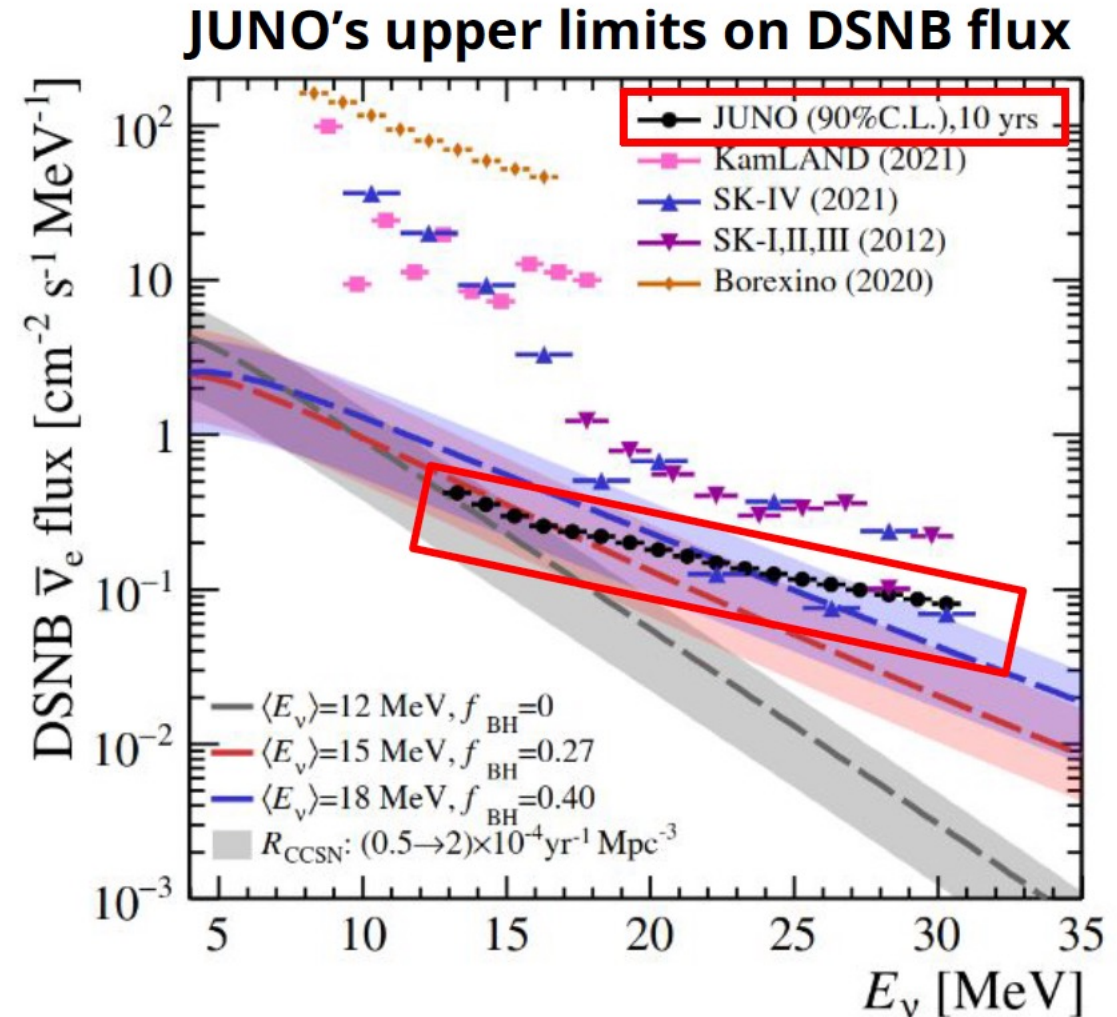


DIFFUSE SUPERNOVAE BACKGROUND SIGNAL (DSNB)

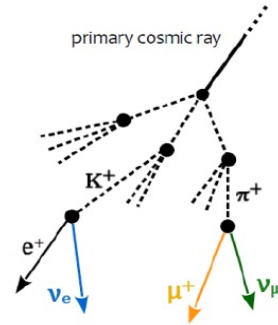
- Integrated neutrino flux from the past SN in the visible Universe.
- ~10 core collapse SN/s in the visible Universe.
- Info about the star formation rate.
- Expected signal: few IBD events / year.
- Main background:
 - ✓ reactor anti- $\bar{\nu}$ $\rightarrow$ go above 10 MeV
 - ✓ NC atmospheric ν - pulse shape discrimination (eff 50% $\rightarrow$ 80%),

**JUNO DSNB discovery potential:
3 σ in 3 years with nominal models**

J. Cos. Astro. Phys. 10 (2022) 033.



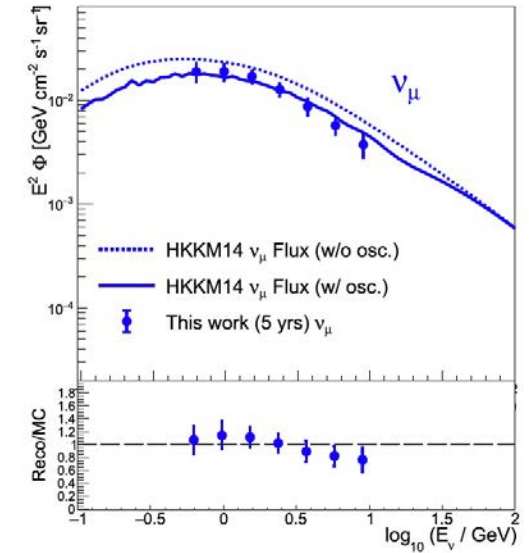
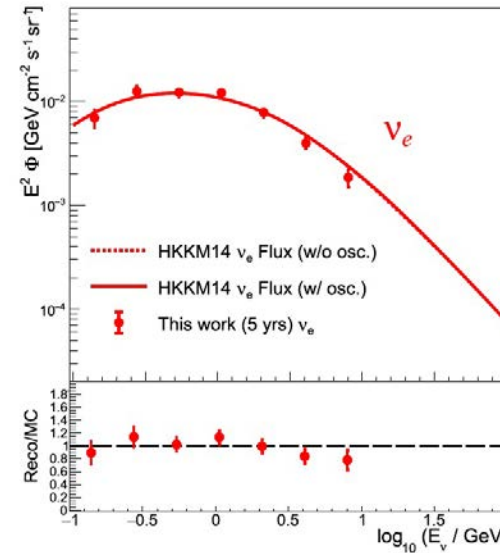
ATMOSPHERIC NEUTRINOS



- Expected ~10/15 events per day before the cuts.
- Will be the first measurement with LS: can play a major role in GeV range, possibly pushing to MeV region.
- CC and NC interactions.

Motivation: boost the sensitivity to NMO:

- Atmospheric neutrinos provide an independent channel exploiting the Earth matter effect on oscillation of ~GeV neutrinos.
- Requirement of the reconstruction of neutrino
 - Direction (*Phys. Rev. D* 109.052005).
 - Energy and flavour (*Eur. Phys. J. C* 81 (2021) 887).



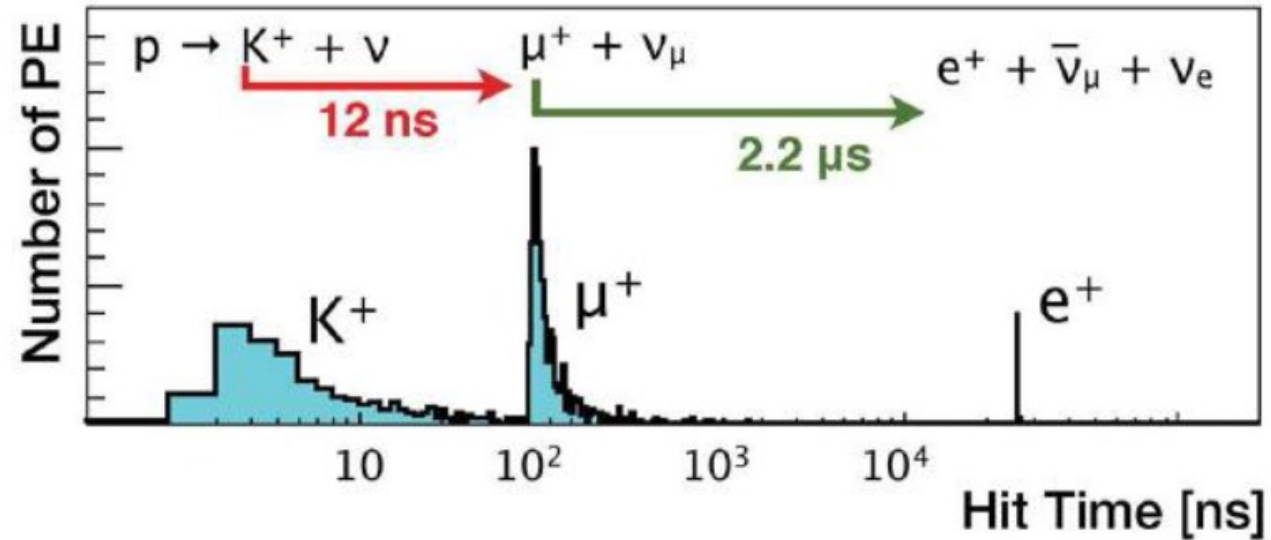
CC events

- ✓ Muon/electron flavour discrimination.
- ✓ ν_e and ν_μ energy spectra: 25% precision after 5 years
- ✓ θ_{23} with 6 degree precision.

JUNO NMO sensitivity with combined reactor and atmospheric neutrinos is ongoing.

PROTON DECAY

Tripple signal



- Possible decay channels:
 $p \rightarrow \pi^0 + e^+$ (GUT flavored)
 $p \rightarrow K^+ + \nu$ (SUSY flavored)
- current best limits set by Super-Kamiokande in $p \rightarrow \pi^0 + e^+$ and $p \rightarrow \pi^0 \mu^+$
 (K. Abe *et al.*, Phys. Rev. D 95 (2017) 012004)
- JUNO has potentials in the other channel, by detecting K^+ in LS
- signals can be separated from background thanks to a triple coincidence signal
- JUNO will reach a sensitivity of about 8×10^{33} years with 10 year exposure *Chin. Phys. C* 47 (2023) 113002.

Cracks on the Acrylic Tank



- Main structure is safe, stress within expectations
- 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 $\sim 1\text{Bq } ^{222}\text{Rn}$ went into LS, 13 days of data excluded
 - ⇒ No other increase of radioactive backgrounds in LS

