



First Results from the Jiangmen Underground Neutrino Observatory (JUNO)

LU Xianguo 卢显国

University of Warwick

On behalf of the JUNO Collaboration

江門中微子實驗

Niels Bohr Lunch Seminar

Manchester Particle Physics Group

2026 October 2, Manchester

Faceless Neutrino

Neutrinos and antineutrinos in Standard Model

1. Charge neutral
2. Massless

❖ How can we tell all 6 of them apart?

❑ How did we know there were 6 of them in the first place?

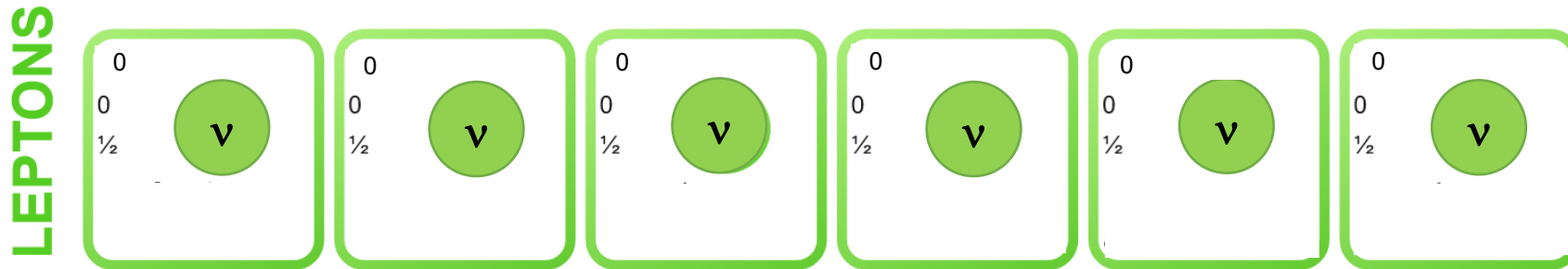


Image source: Wikipedia

Neutrino's *Familiar Face*

Neutrinos and antineutrinos in Standard Model

1. Charge neutral
2. Massless
- ❖ How can we tell all 6 of them apart?
 - ❑ How did we know there were 6 of them in the first place?
3. **Flavour**, defined by charged-current interactions

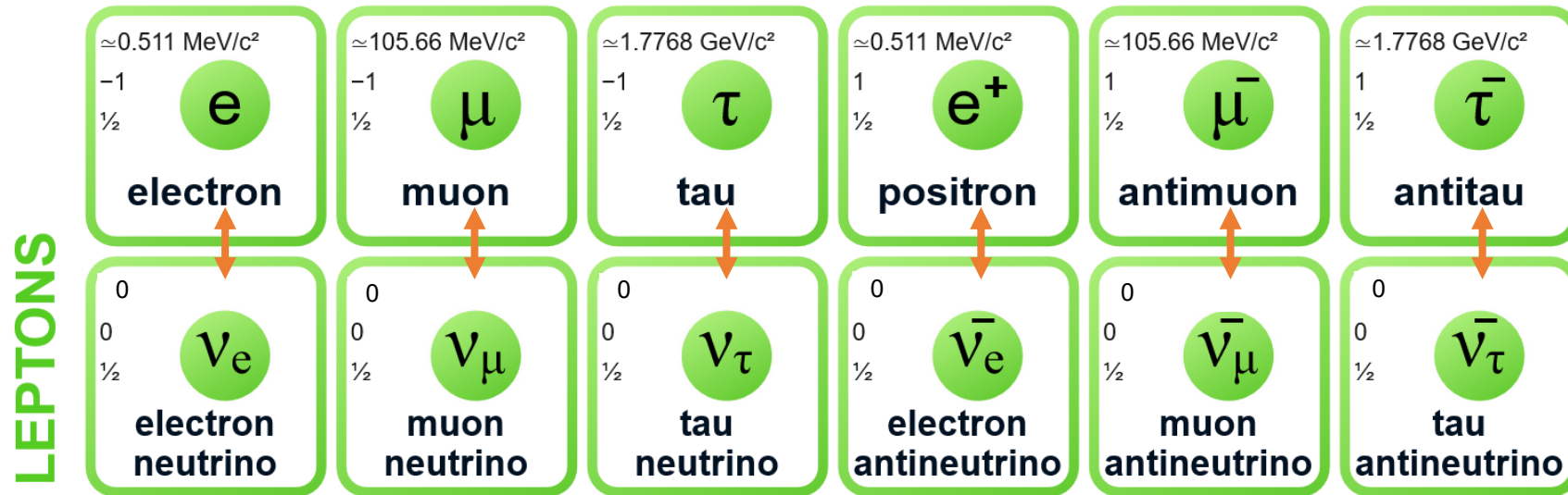
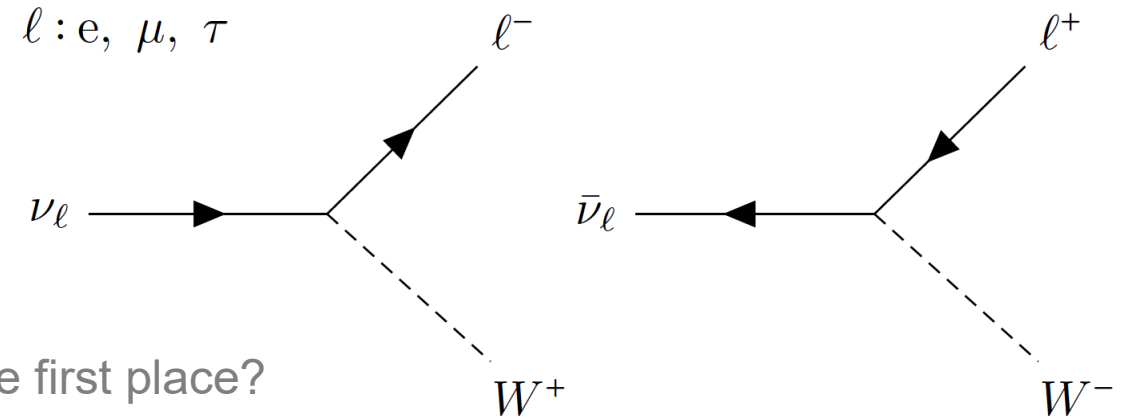


Image source: Wikipedia

Neutrino's *Two Faces*

Neutrinos and antineutrinos in *Nature*

1. Charge neutral
2. ~~Massless~~ turns out to have tiny but not zero *mass*!
- ❖ How can we tell all 6 of them apart? *One more face (too many)*
 - ❑ How did we know there were 6 of them in the first place?
3. *Flavour*, defined by charged-current interactions → *Oscillate*!

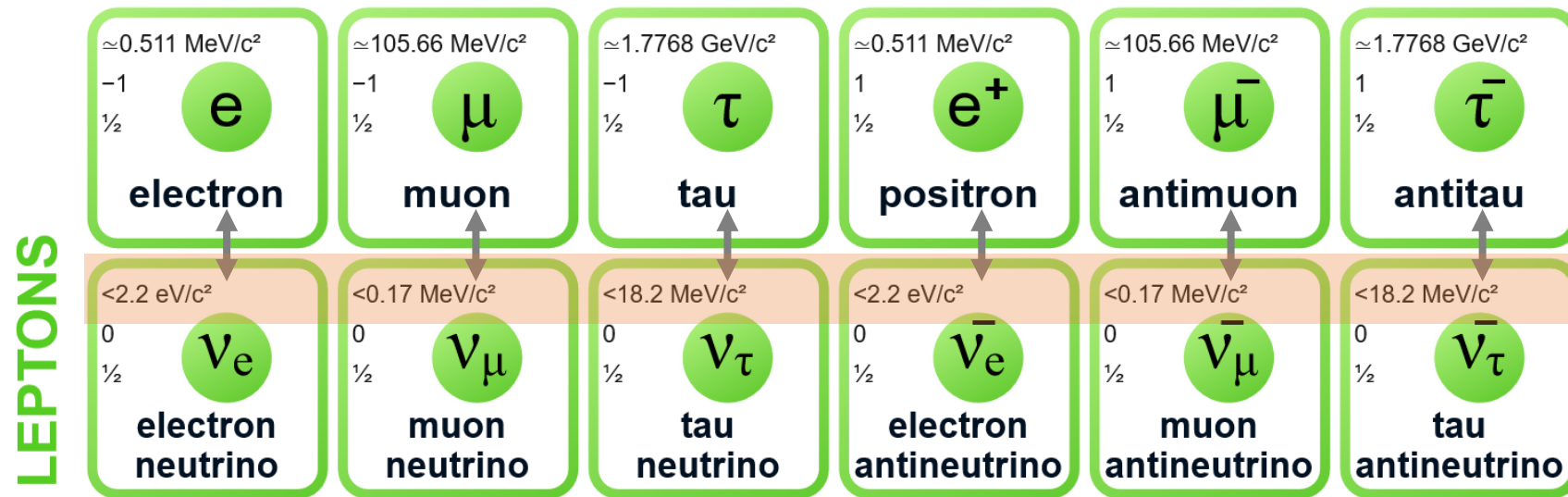


Image source: Wikipedia

Neutrino Mass and Mixing

Standard Model

Beyond Standard Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$\pm$

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

Mass “levels”

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino Mass and Mixing

Standard Model

Beyond Standard Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass “levels”



Normal / Inverted
Mass Ordering (MO, or Hierarchy)

A problem only when there are more than 2 masses!

Neutrino Mass and Mixing

Standard Model

Beyond Standard Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

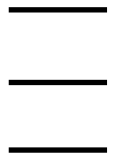
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Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

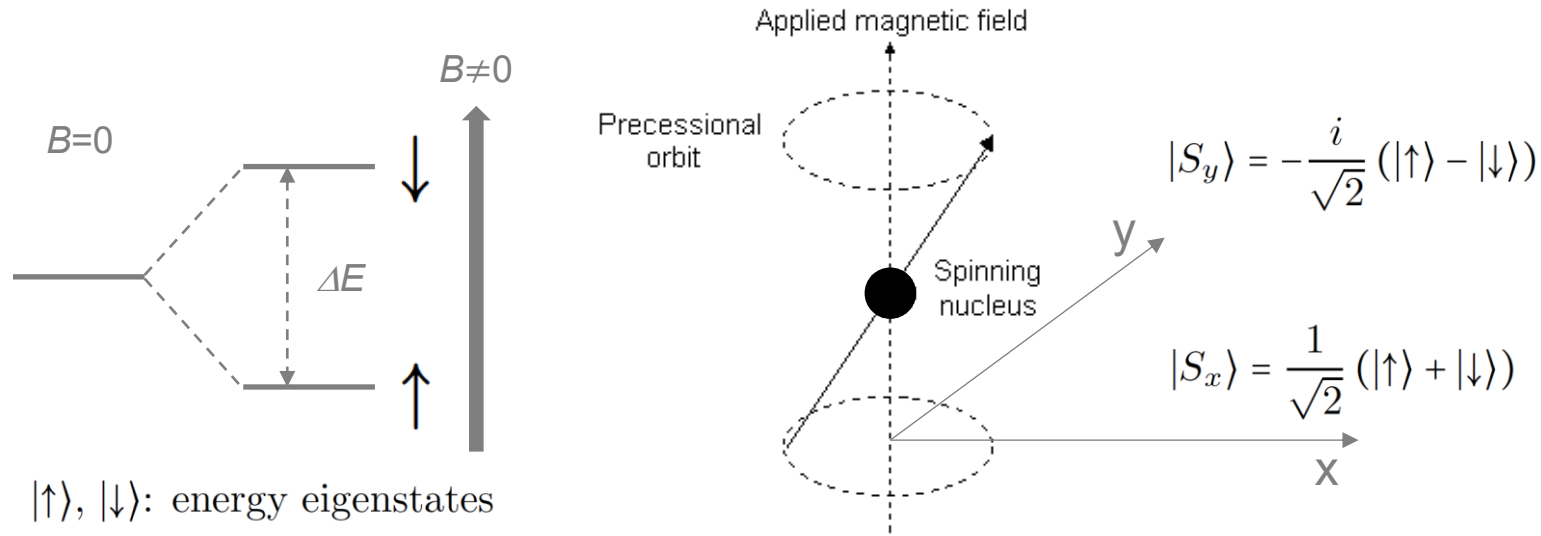
Mass “levels”

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Mass gap (Δm^2) **and** mixing lead to neutrino flavour oscillations

Analogy: spin rotation in a magnetic field, e.g. in MRI



Animated gif source: <https://teaching.shu.ac.uk/hwb/chemistry/tutorials/molspec/nmr1.htm>

$$|S_x\rangle_t = \cos \frac{\Delta E}{2} t |S_x\rangle_0 - \sin \frac{\Delta E}{2} t |S_y\rangle_0$$

Oscillation probability

$$P_{S_x \rightarrow S_x}(t) = \cos^2 \frac{\Delta E}{2} t$$

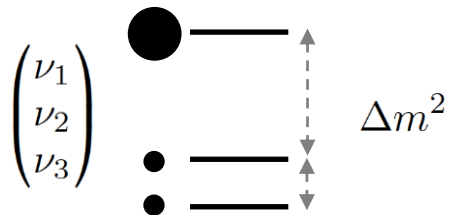
$$P_{S_x \rightarrow S_y}(t) = \sin^2 \frac{\Delta E}{2} t$$

Energy gap

$$\begin{pmatrix} |\uparrow\rangle_t \\ |\downarrow\rangle_t \end{pmatrix} = \begin{pmatrix} e^{i\frac{\Delta E}{2}t} & 0 \\ 0 & e^{-i\frac{\Delta E}{2}t} \end{pmatrix} \begin{pmatrix} |\uparrow\rangle_0 \\ |\downarrow\rangle_0 \end{pmatrix}$$

Mixing

$$\begin{pmatrix} |S_x\rangle \\ |S_y\rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -i & i \end{pmatrix} \begin{pmatrix} |\uparrow\rangle \\ |\downarrow\rangle \end{pmatrix}$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Survival $P_{\nu_\mu \rightarrow \nu_\mu} \left(\frac{L}{E} \right)$

Appearance $P_{\nu_\mu \rightarrow \nu_e} \left(\frac{L}{E} \right)$

Phase $\sim \Delta m^2 L/E$

Neutrino Mass and Mixing

Standard Model

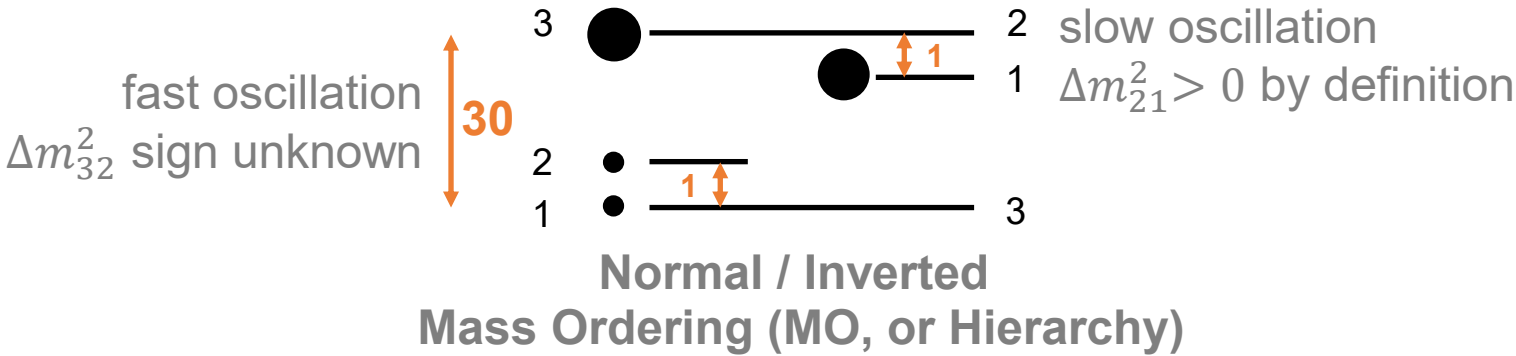
Beyond Standard Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata
PMNS matrix

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass “levels”



Survival $P_{\nu_\mu \rightarrow \nu_\mu} \left(\frac{L}{E} \right)$

Appearance $P_{\nu_\mu \rightarrow \nu_e} \left(\frac{L}{E} \right)$

Phase $\sim \Delta m^2 L/E$

Neutrino Mass and Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \bullet \quad \begin{array}{c} \text{---} \\ \text{---} \\ \bullet \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array}$$

$\theta_{13} \neq 0 \rightarrow \delta_{CP} \text{ can be observed}$

θ_{12} : mixing between ν_1 and ν_2

θ_{23} : mixing between ν_μ and ν_τ

θ_{13} : if 0, effective 2 flavour mixing
 ➤ No CPV!

$$\begin{pmatrix} \nu_e \\ \nu_{\mu'} \\ \nu_{\tau'} \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mass and Mixing

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$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

Open questions

❑ Neutrino *mass* structure

❖ Mass gaps (Δm_{21}^2 , $|\Delta m_{32}^2|$) and ordering ($\text{sgn } \Delta m_{32}^2$)?

❑ Neutrino *flavour* structure

❖ Mixing angles (θ_{12} , θ_{23} , θ_{13}) and CP-phase (δ_{CP})?

👤 Not accessible through oscillation measurements:

❑ Absolute mass

❑ Dirac/Majorana nature

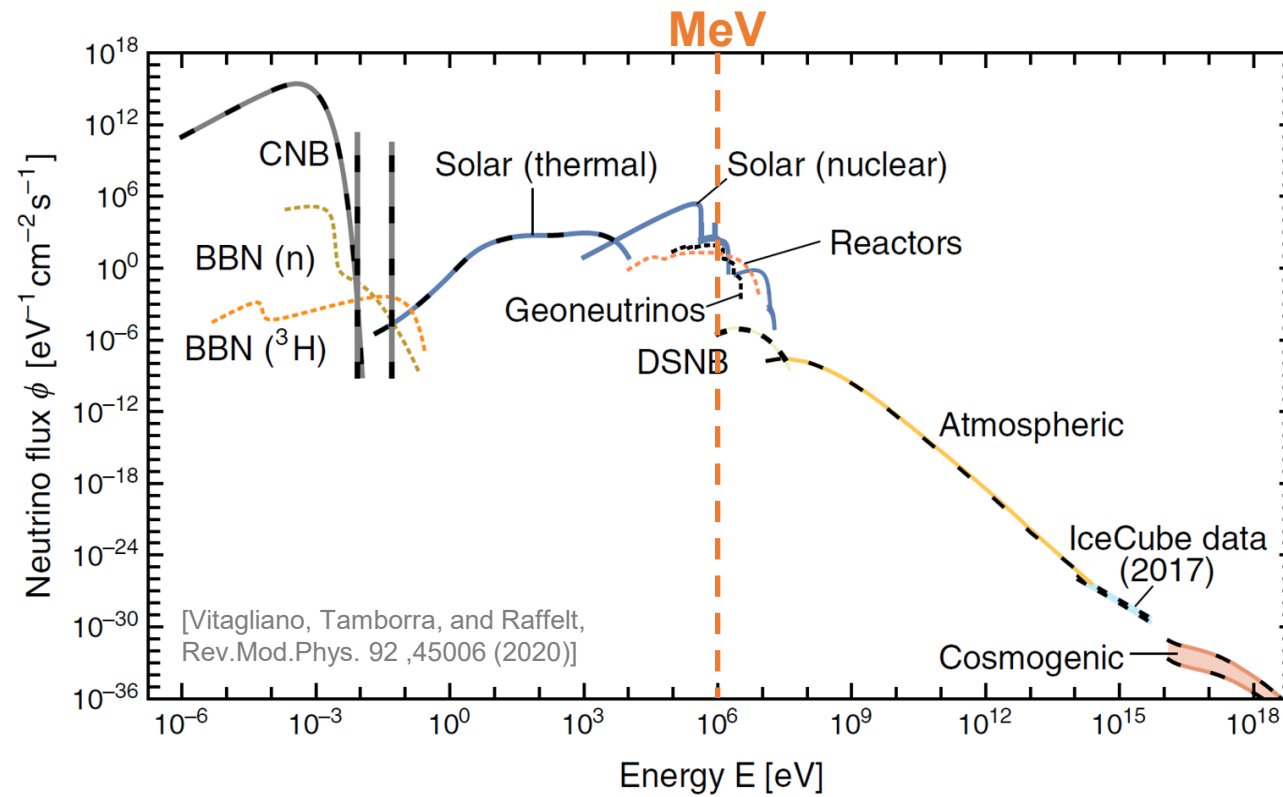
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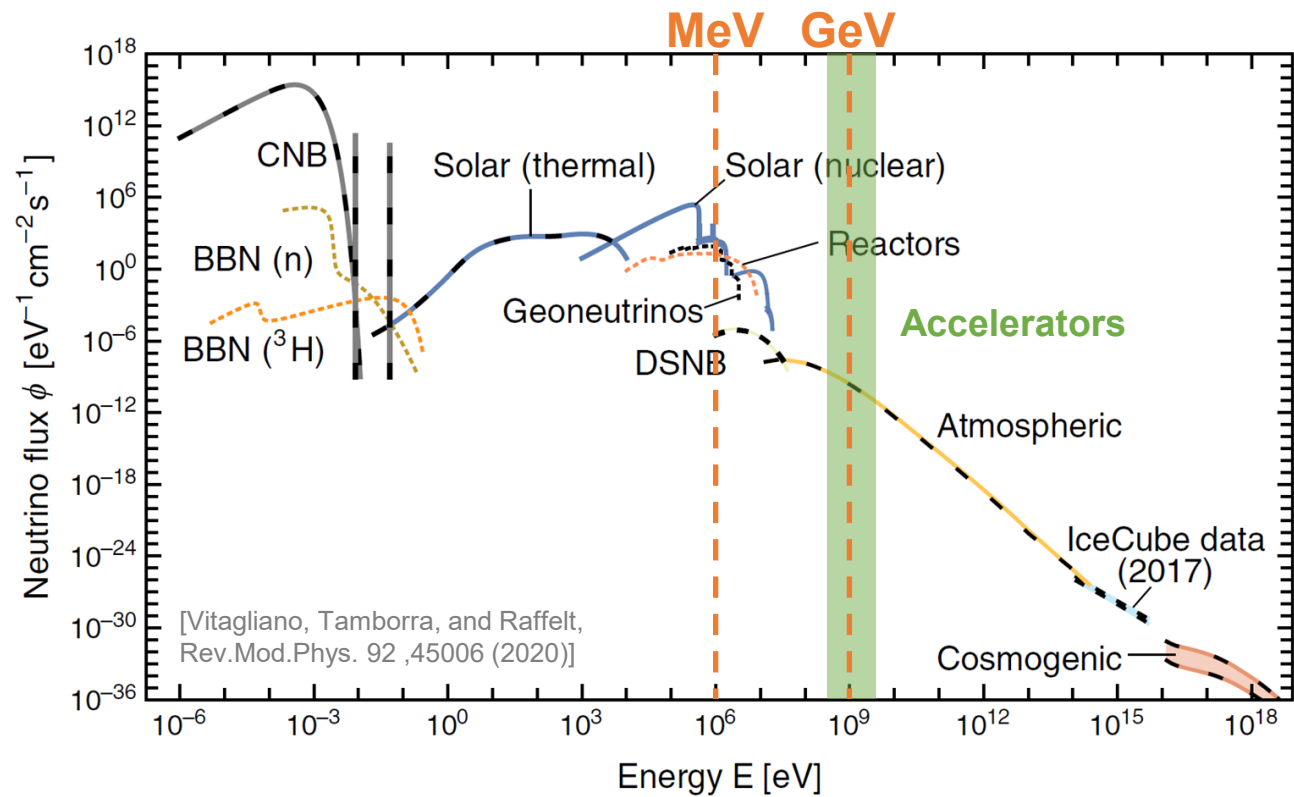
Neutrino Sources



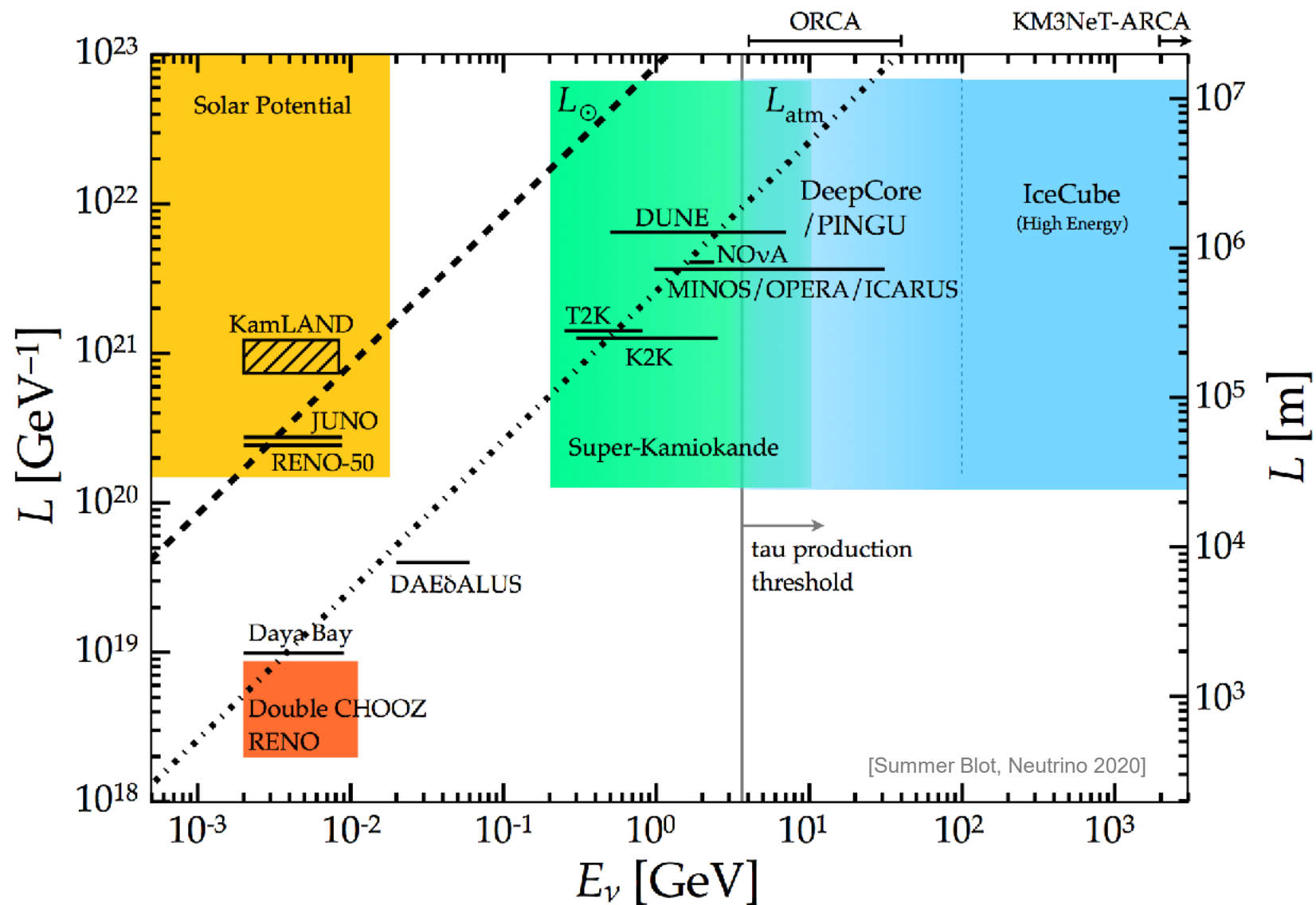
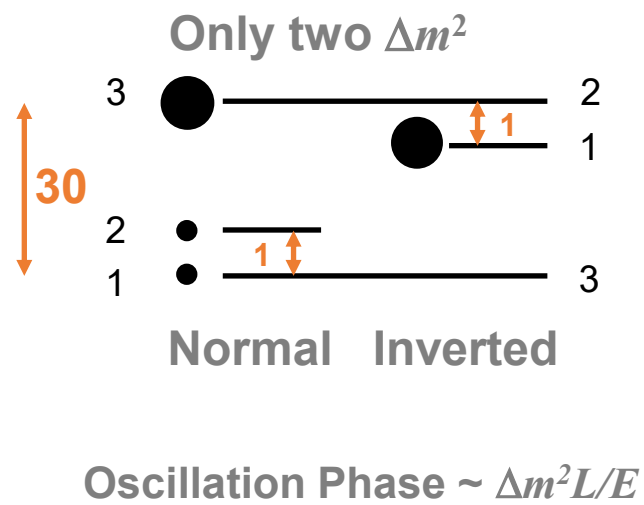
Neutrino Sources

(Oscillation-relevant) Types at source

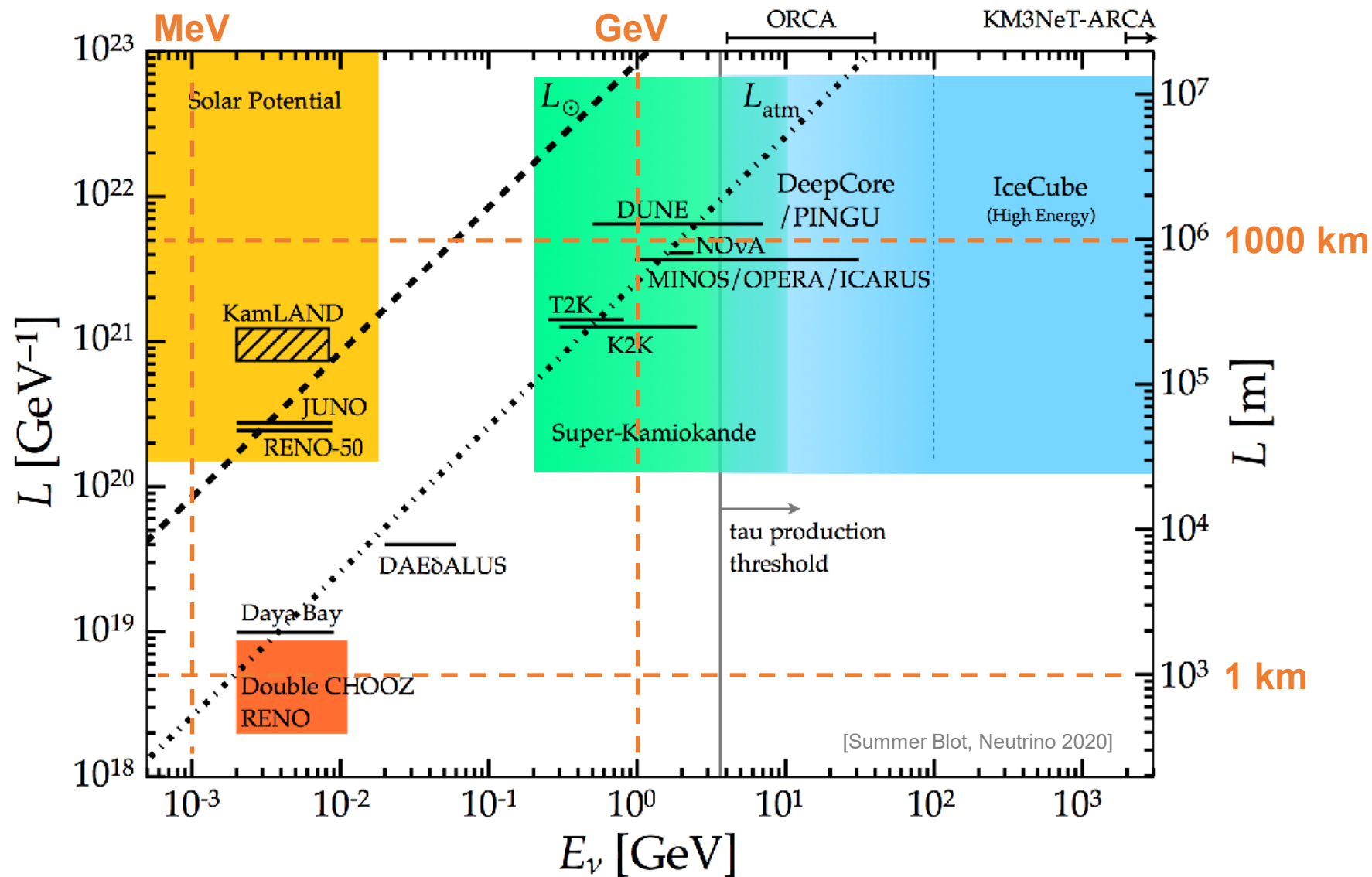
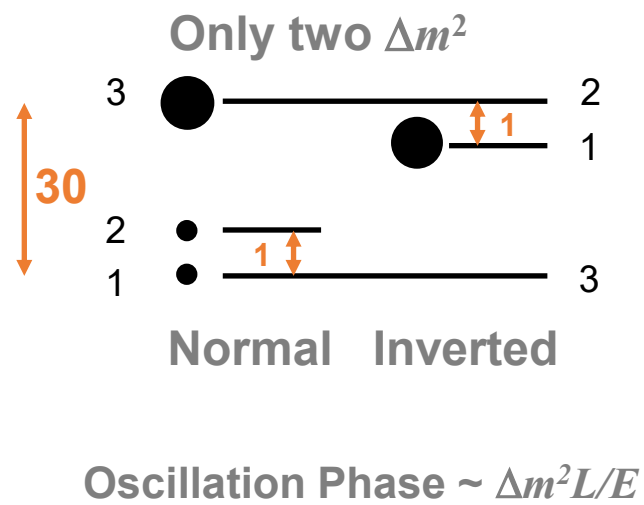
Solar	Reactor	Acc. & Atmo.
ν_e		
	$\bar{\nu}_e$	
		ν_μ
		$\bar{\nu}_\mu$



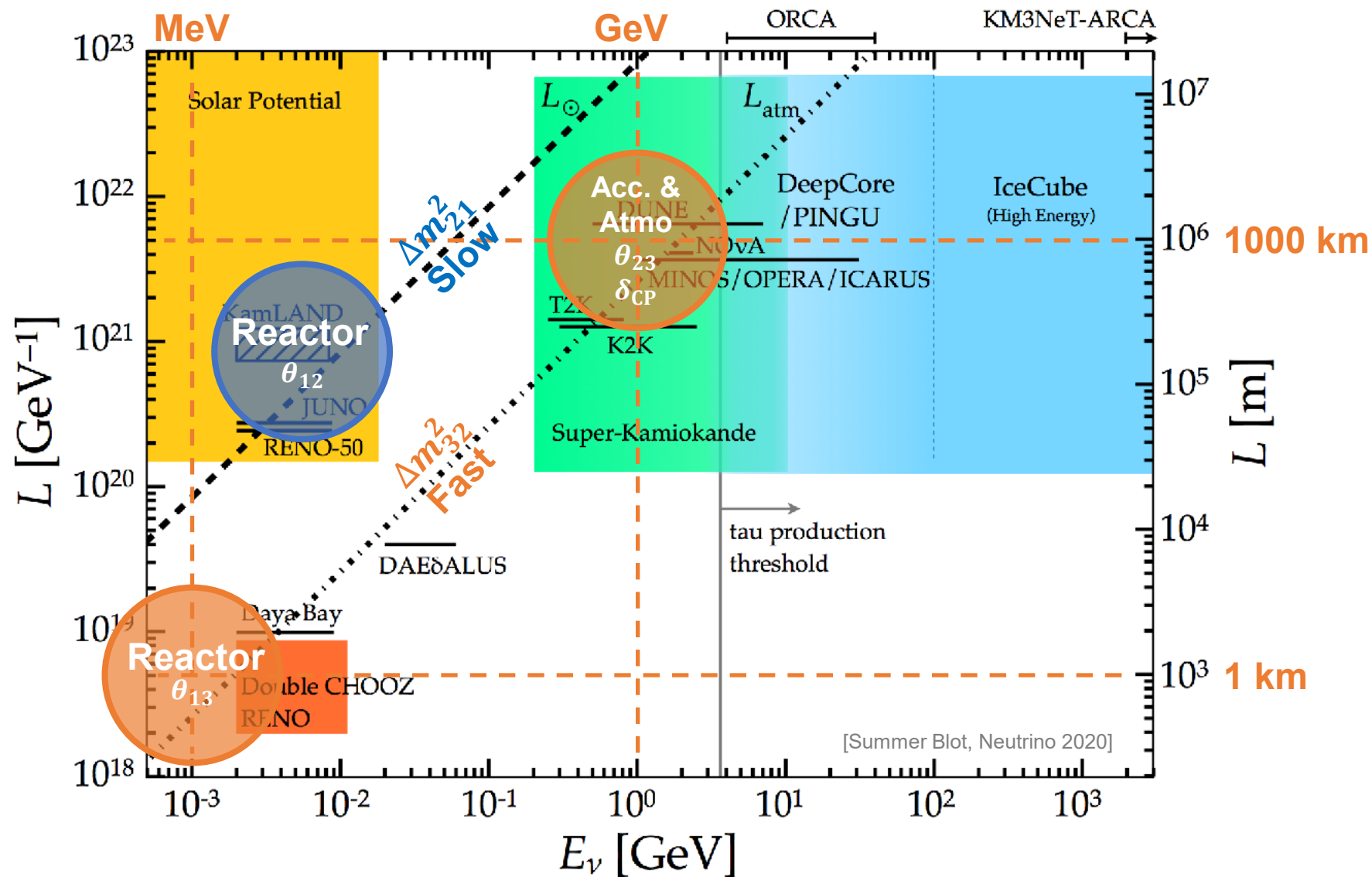
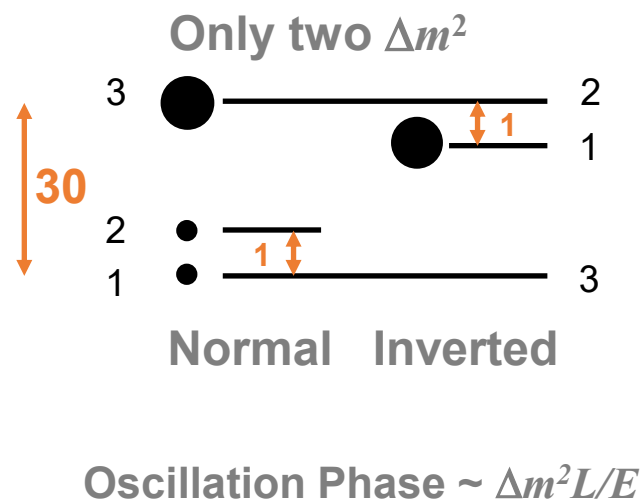
Neutrino Oscillation Experiments



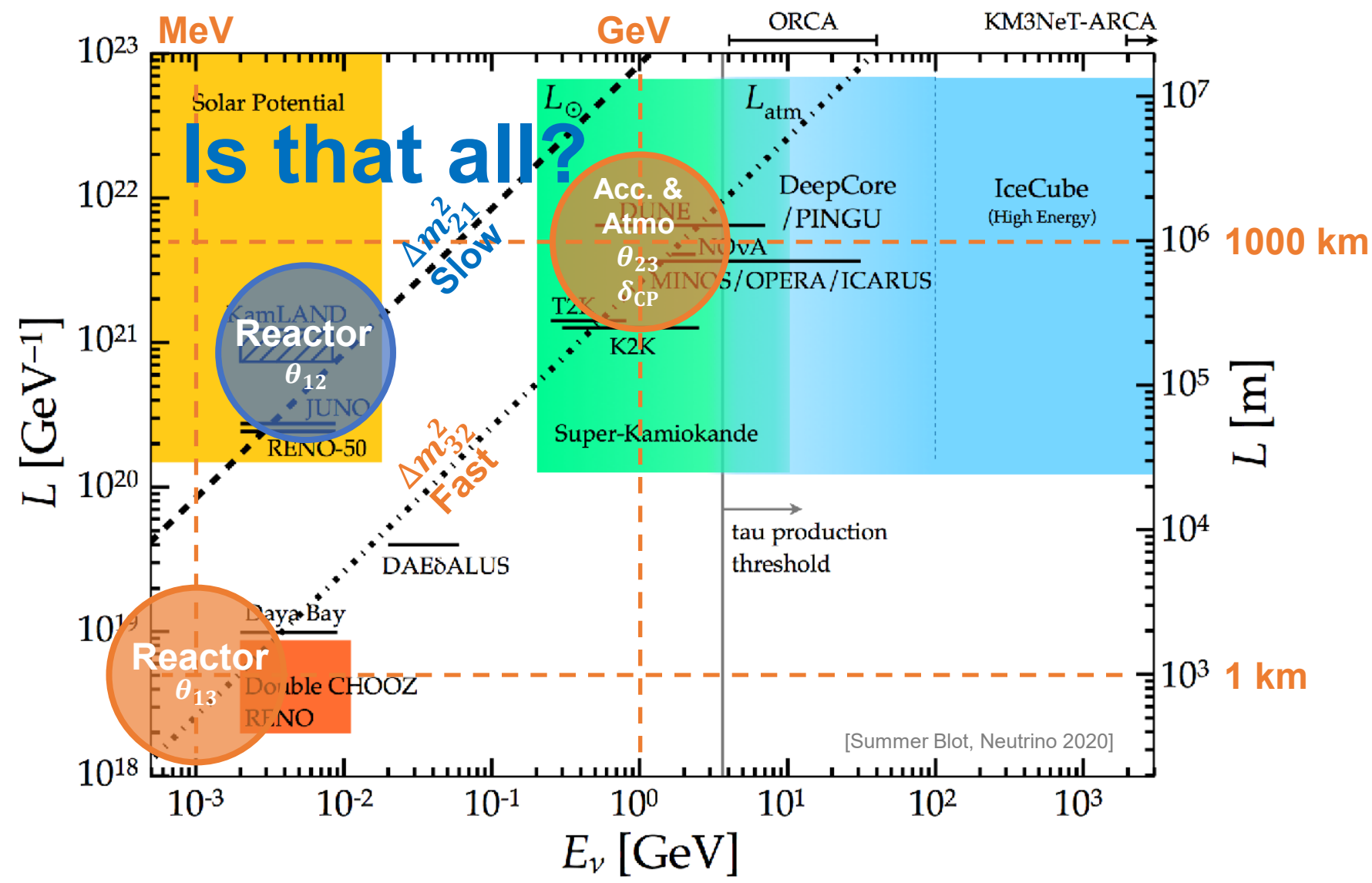
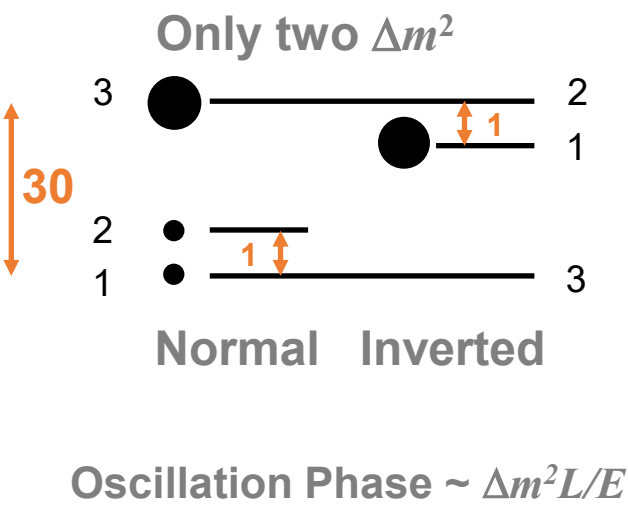
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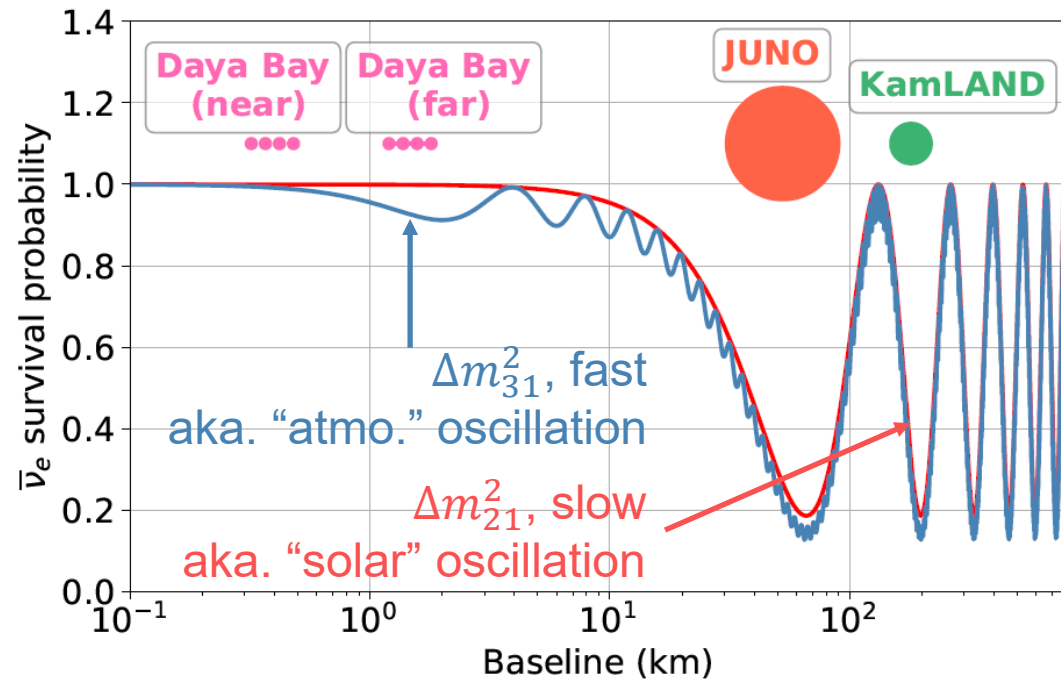
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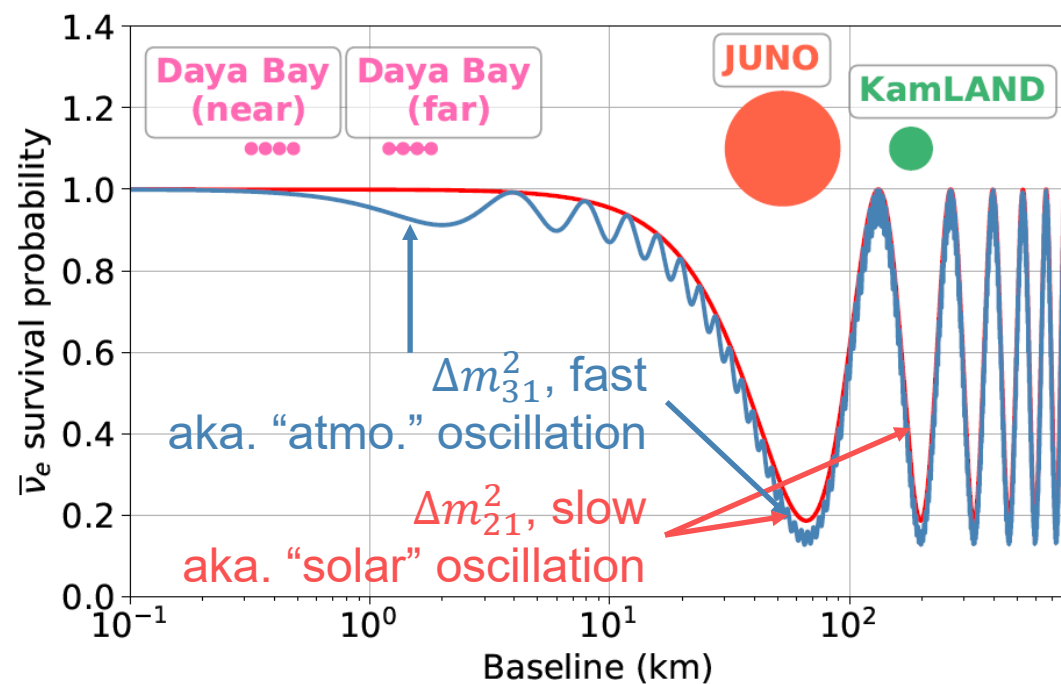
Neutrino Oscillation Experiments



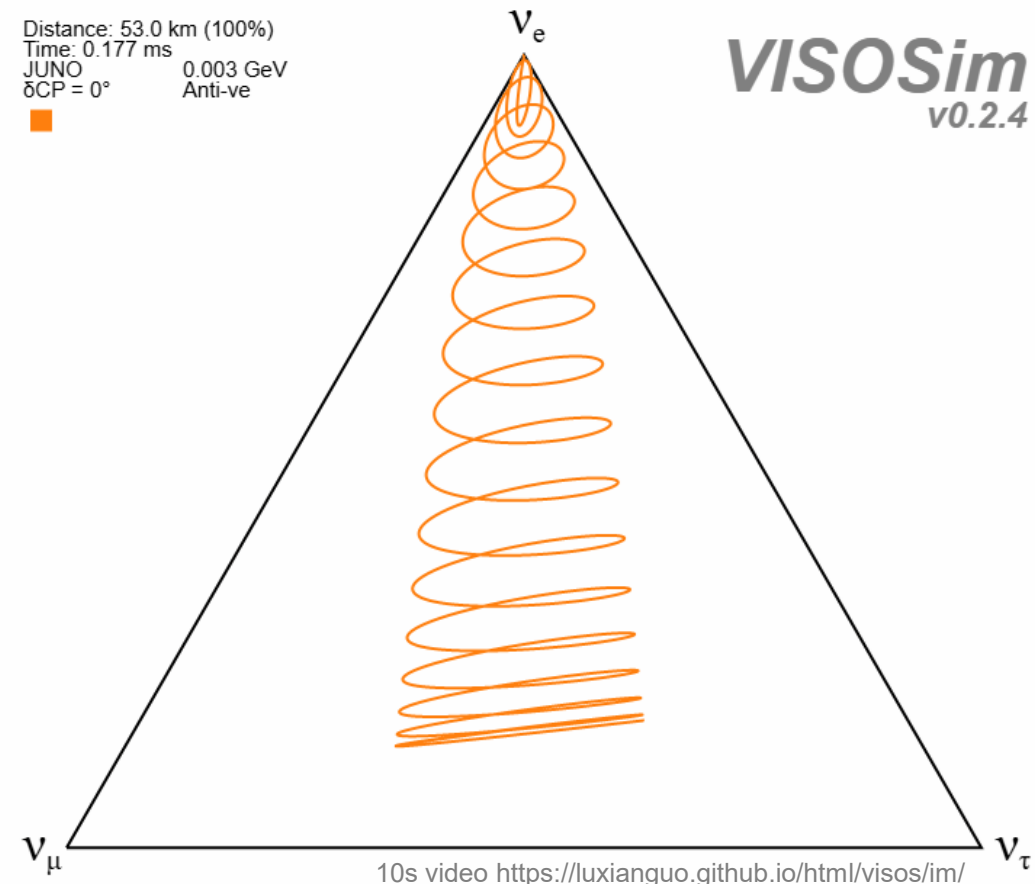
Neutrino Oscillation at JUNO



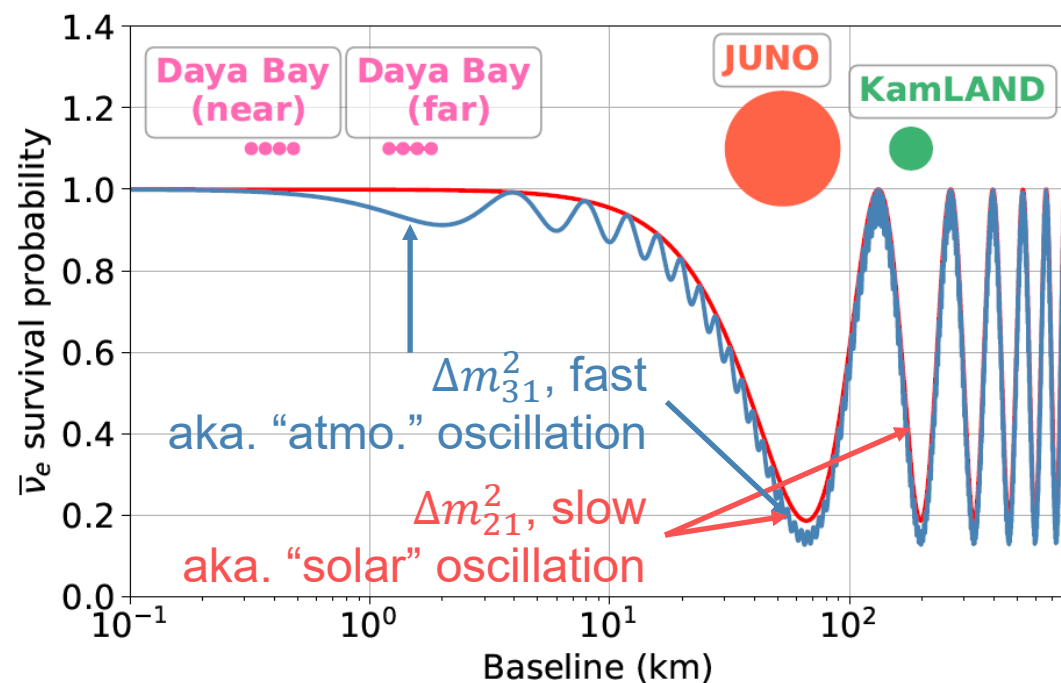
Neutrino Oscillation at JUNO



Distance: 53.0 km (100%)
Time: 0.177 ms
JUNO
 $\delta\text{CP} = 0^\circ$
0.003 GeV
Anti- ν_e

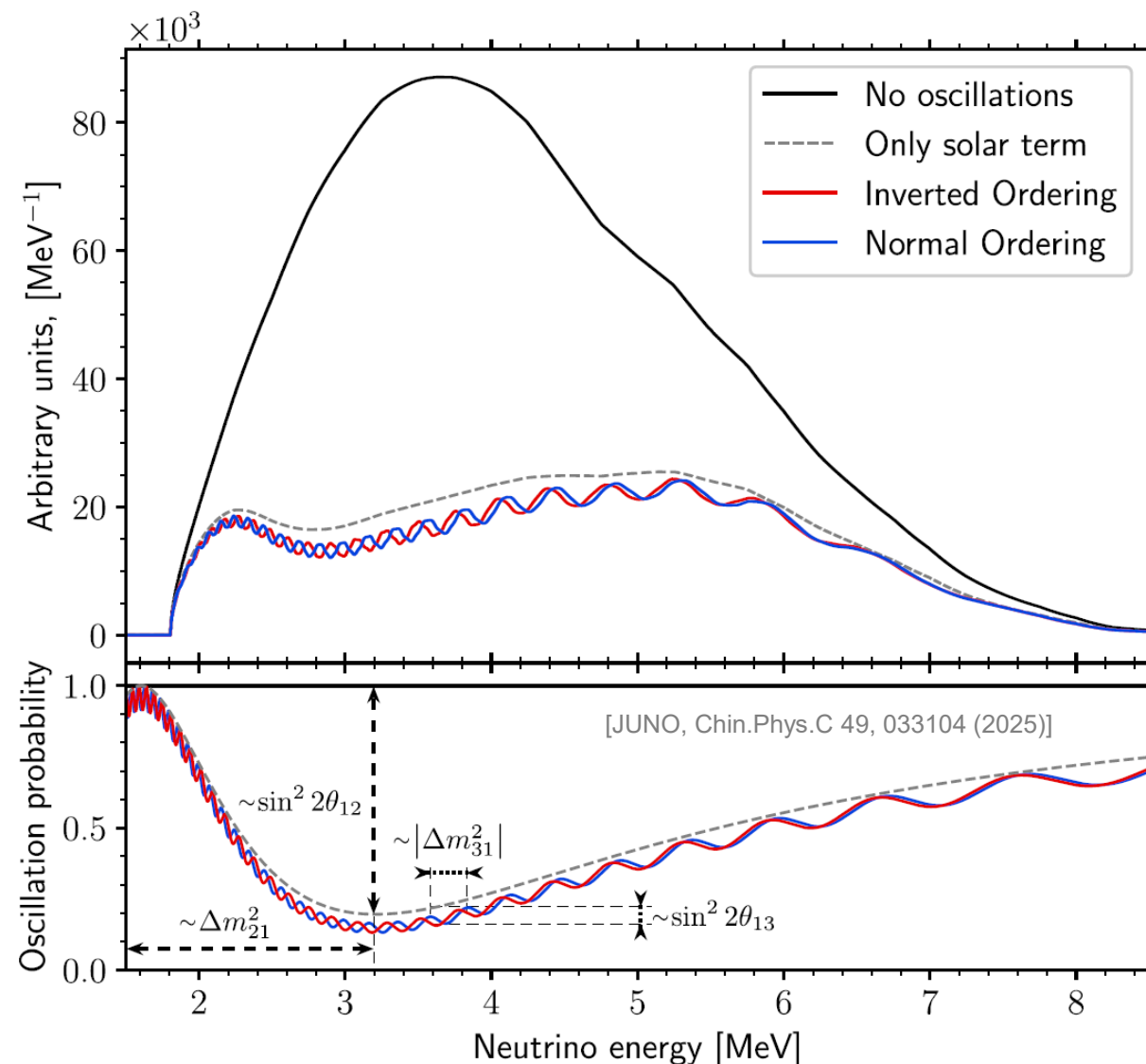


Neutrino Oscillation at JUNO



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

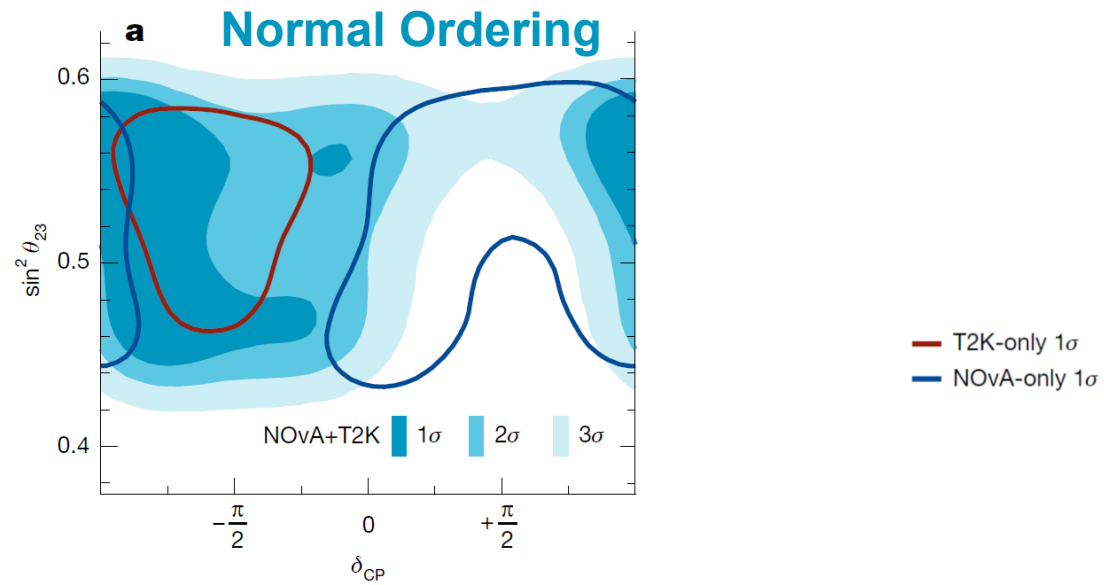
S. Petcov and Piai, Phys. Lett. B 553, 94-106 (2002)
 J. Learned et al., PRD 78(2008)071302
 L. Zhan, Y. Wang et al., PRD 78(2008)111103



JUNO's main goal: Neutrino Mass Ordering

Why Neutrino Mass Ordering?

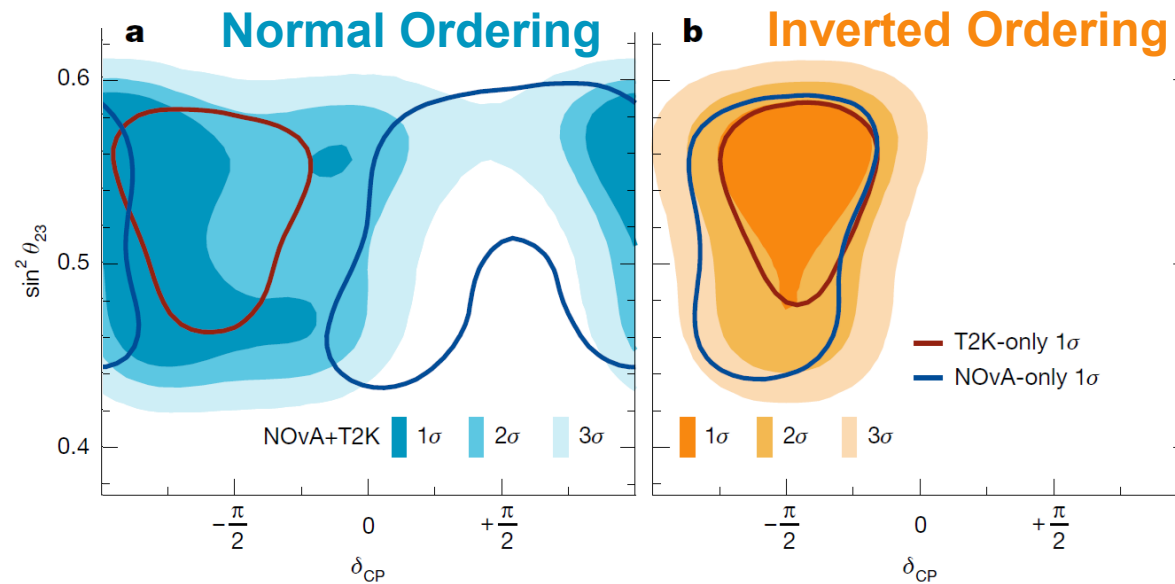
[T2K and NOvA, Nature 646, 818 (2025)]



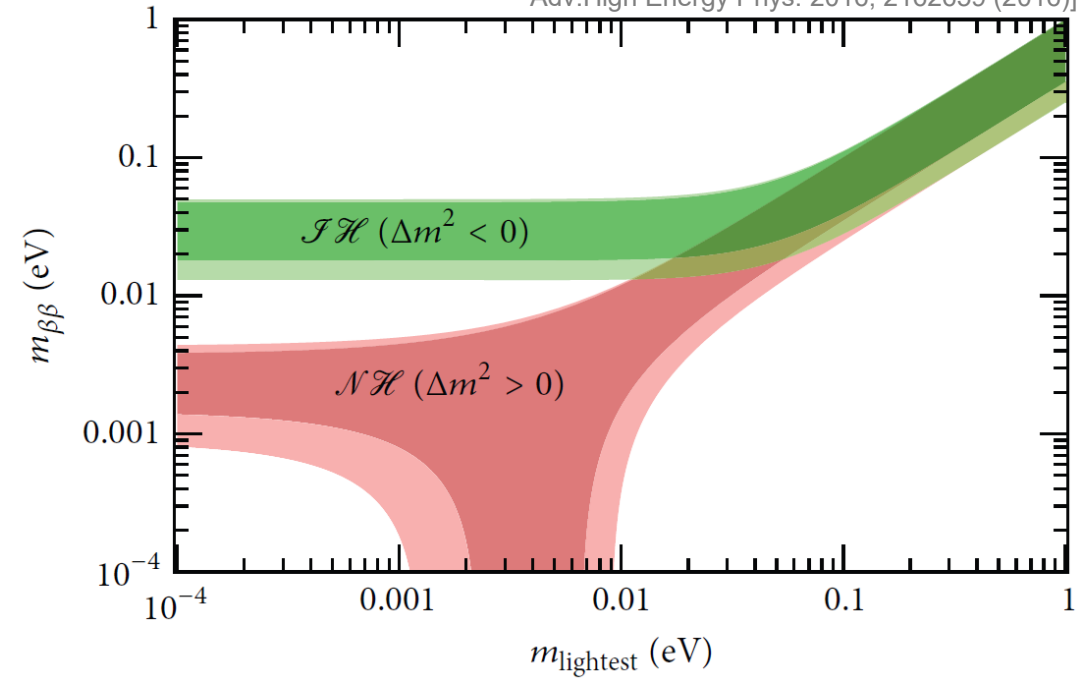
❑ CP violation with neutrinos is already extremely difficult to measure even with a known NMO

Why Neutrino Mass Ordering?

[T2K and NOvA, Nature 646, 818 (2025)]



[Dell'Oro, Marcocci, Viel, and Vissani, Adv.High Energy Phys. 2016, 2162659 (2016)]



- ❑ CP violation with neutrinos is already extremely difficult to measure even with a known NMO
- ❑ Neutrinoless double beta decay interpretation depends on NMO
- ❑ Cosmological input for sum of neutrino masses
- ❑ Astrophysical input for supernova neutrino flavour evolution

JUNO's Location

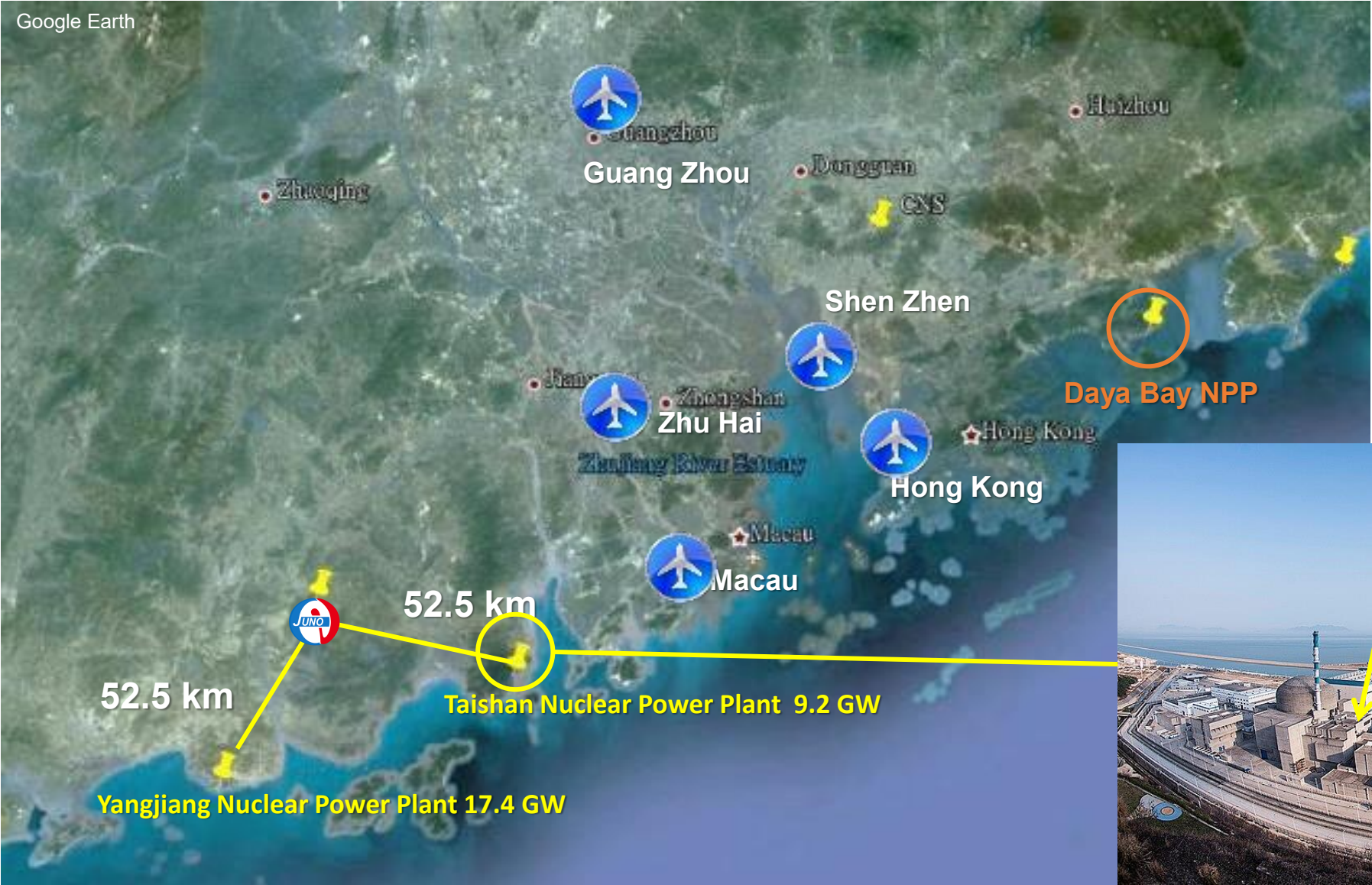


JUNO's Location

Guangdong–Hong Kong–Macao Greater Bay Area



JUNO's Location



- JUNO-TAO: Taishan Antineutrino Observatory**
- ☐ Satellite experiment of JUNO
 - ☐ Data taking since Feb. 2026



The JUNO Collaboration

= 68 institutes
> 700 participants

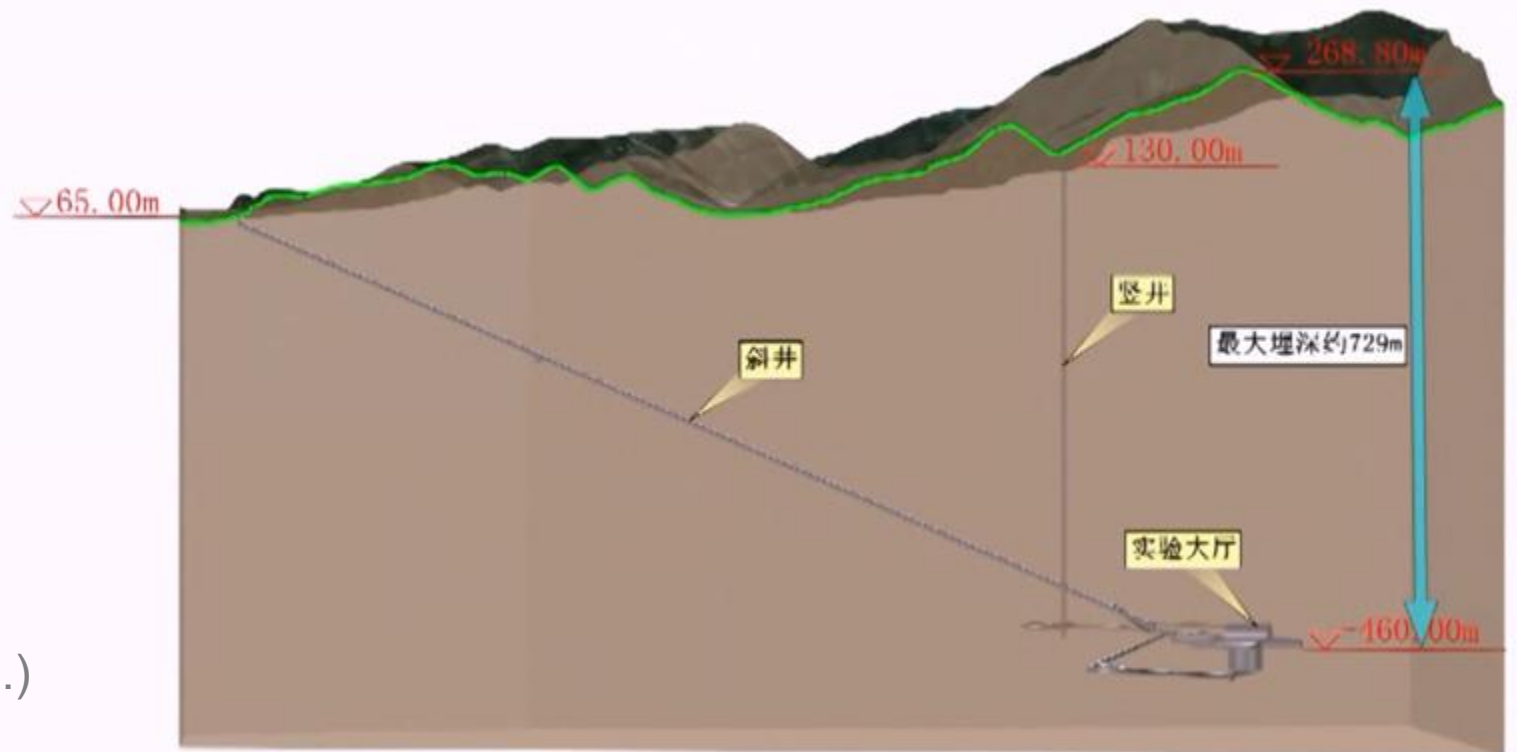
UK involvement
Warwick 2022/07 –
Liverpool 2024/07 –
Oxford 2026/01 –

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

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

The JUNO Lab

- ❑ ~500 m underground
- ❑ ~700 m rock overburden (1800 m.w.e.)



The JUNO Lab



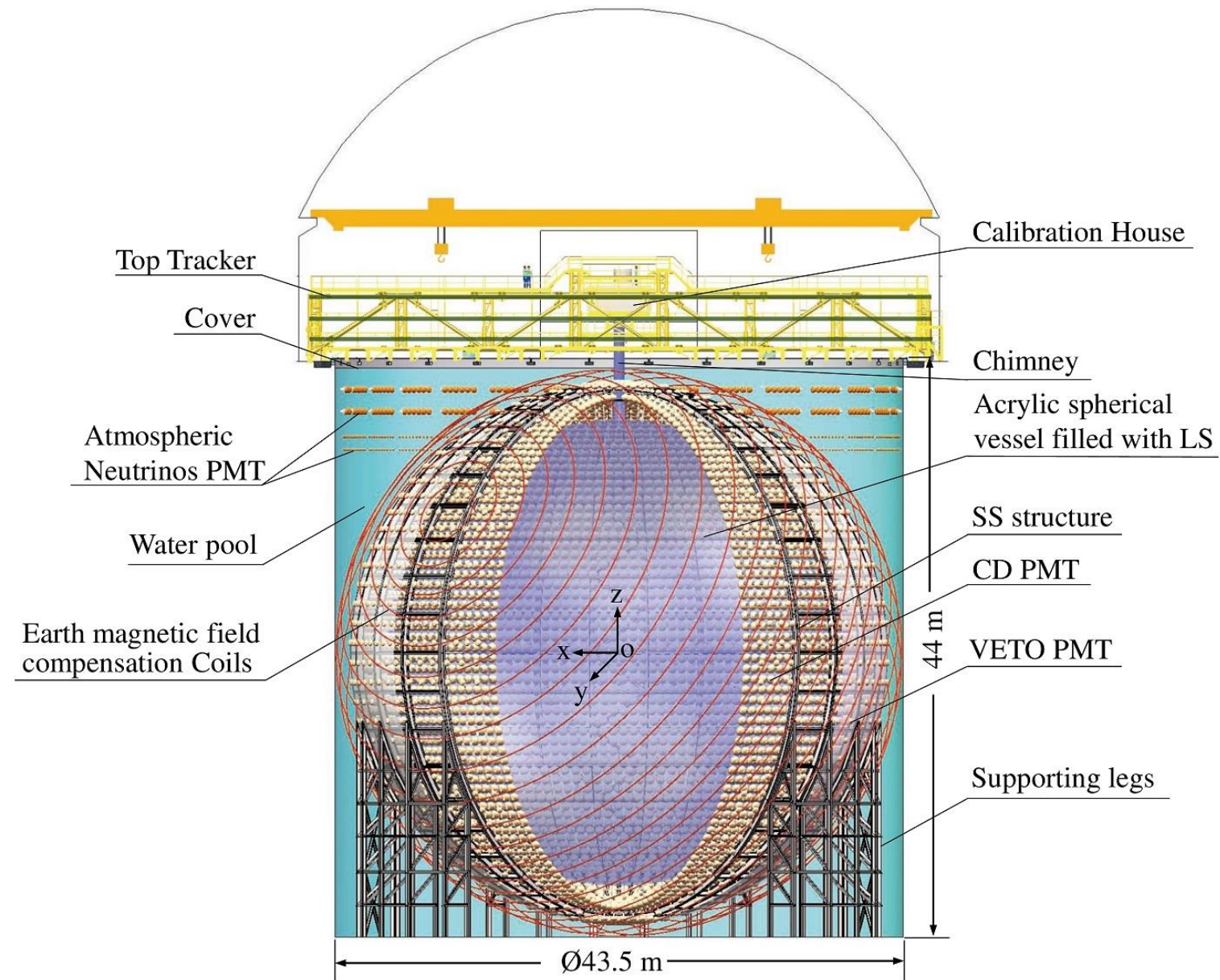
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The JUNO Lab

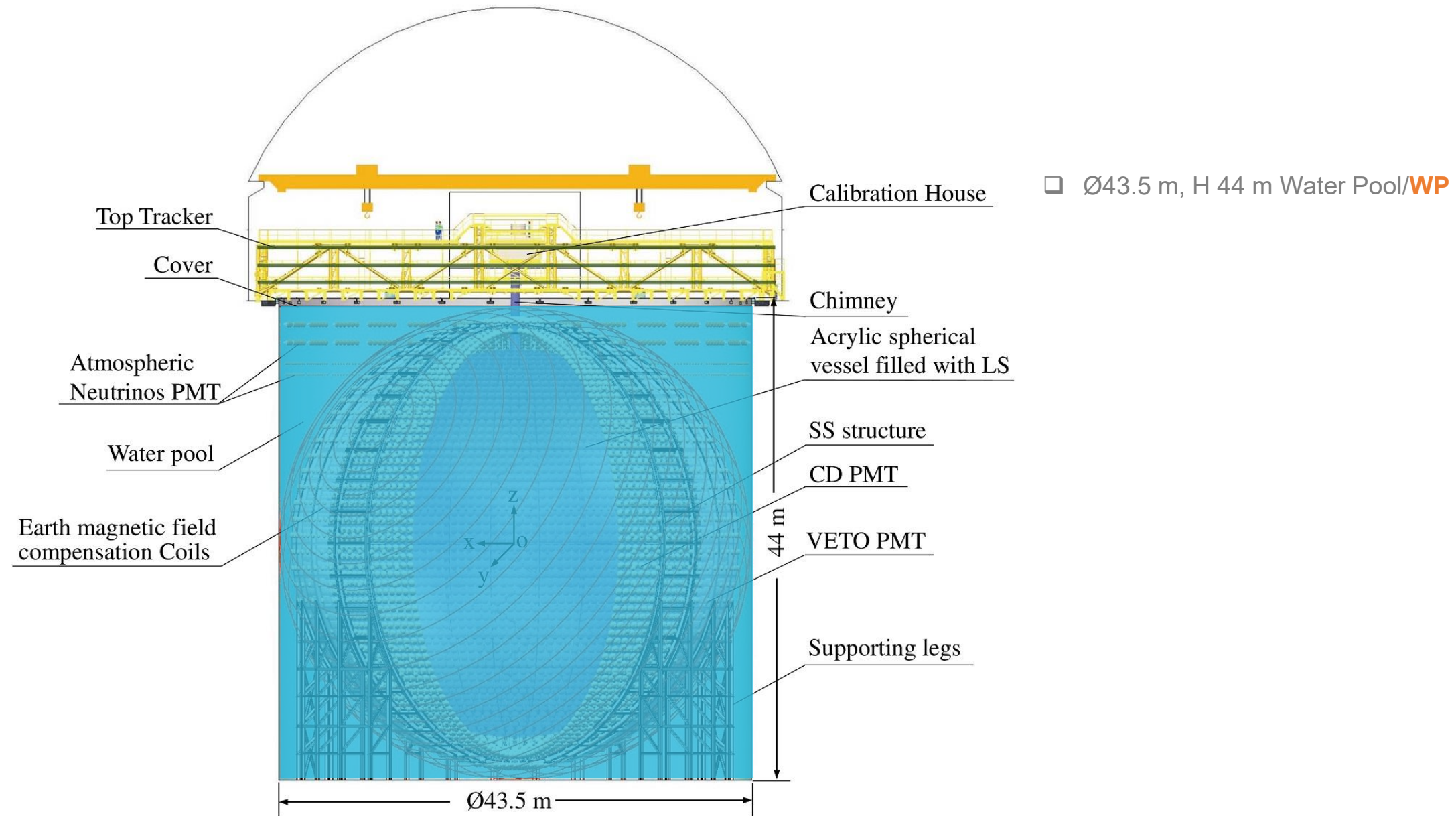


- ❑ ~500 m underground
- ❑ ~700 m rock overburden (1800 m.w.e.)
- ❑ ~1300 m sloped tunnel
- ❑ ~600 m vertical shaft

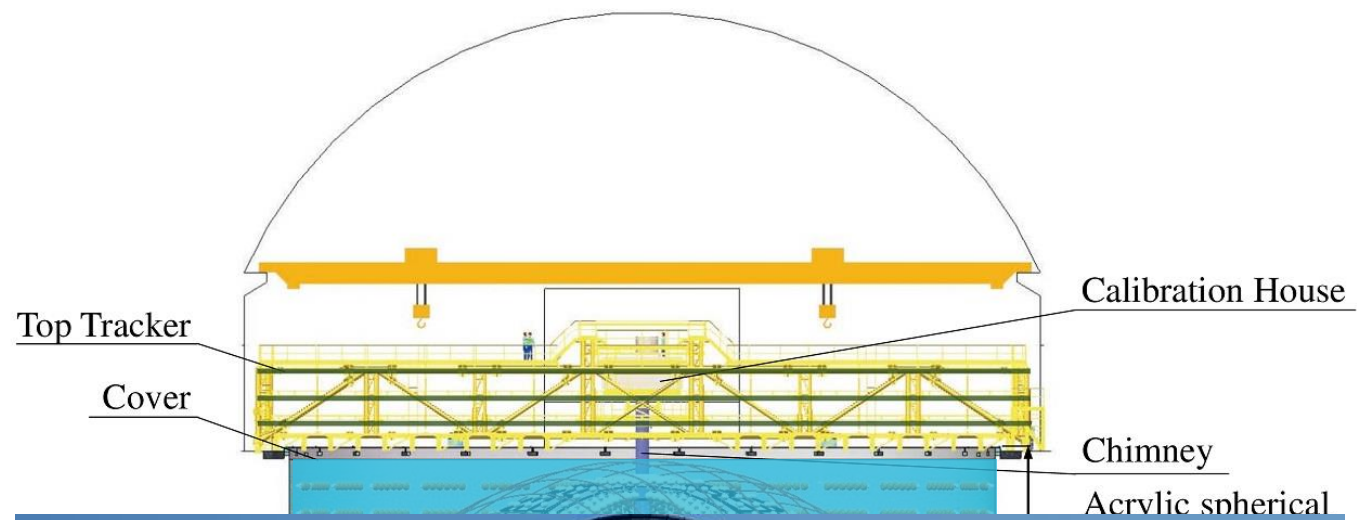
The JUNO Detector



The JUNO Detector



The JUNO Detector



□ Ø43.5 m, H 44 m Water Pool/ WP

At
Ne

Wiki: Royal Albert Hall

LS

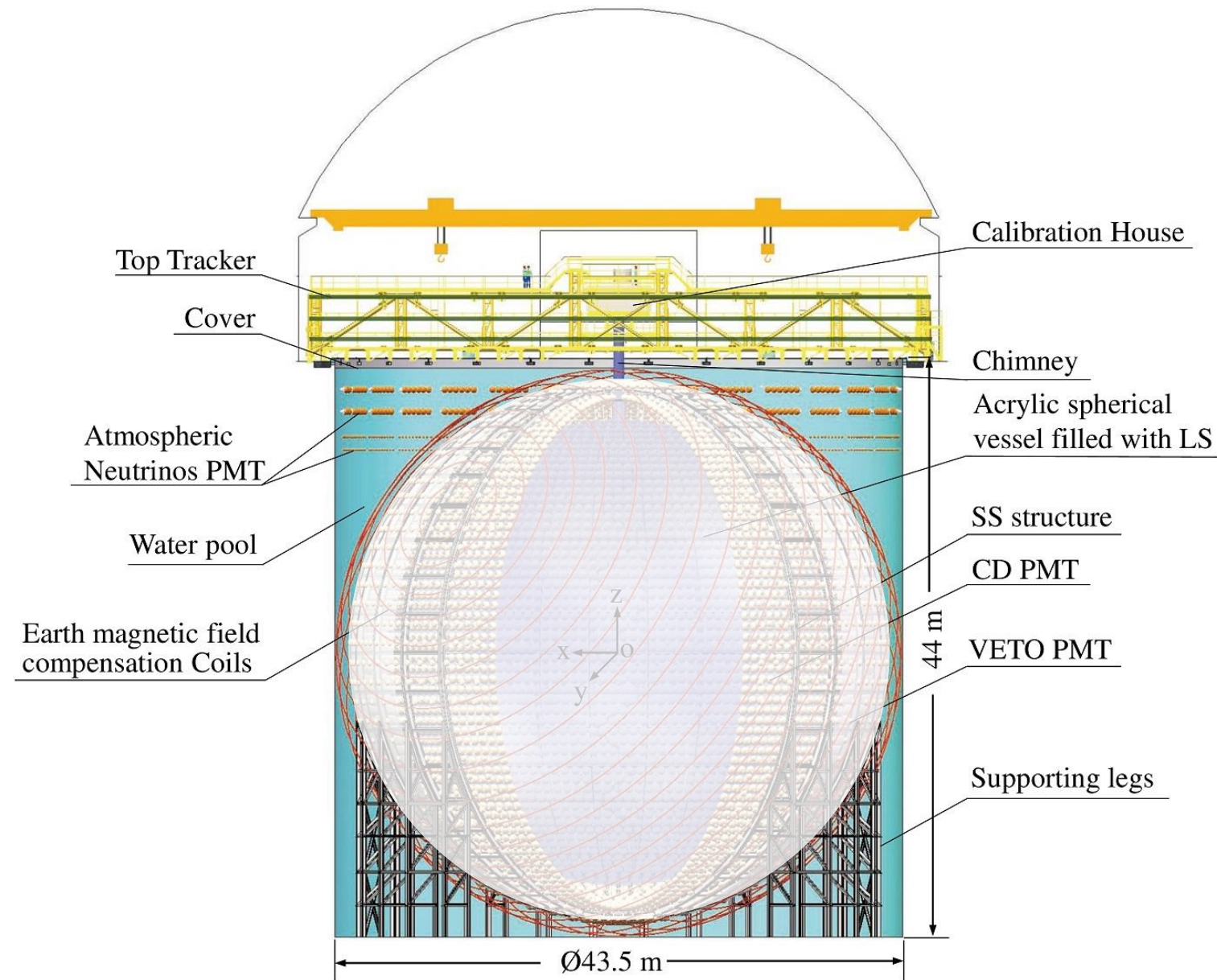


← Ø43.5 m →

2026 October 2, Manchester

LU Xianguo 卢显国, Warwick

The JUNO Detector



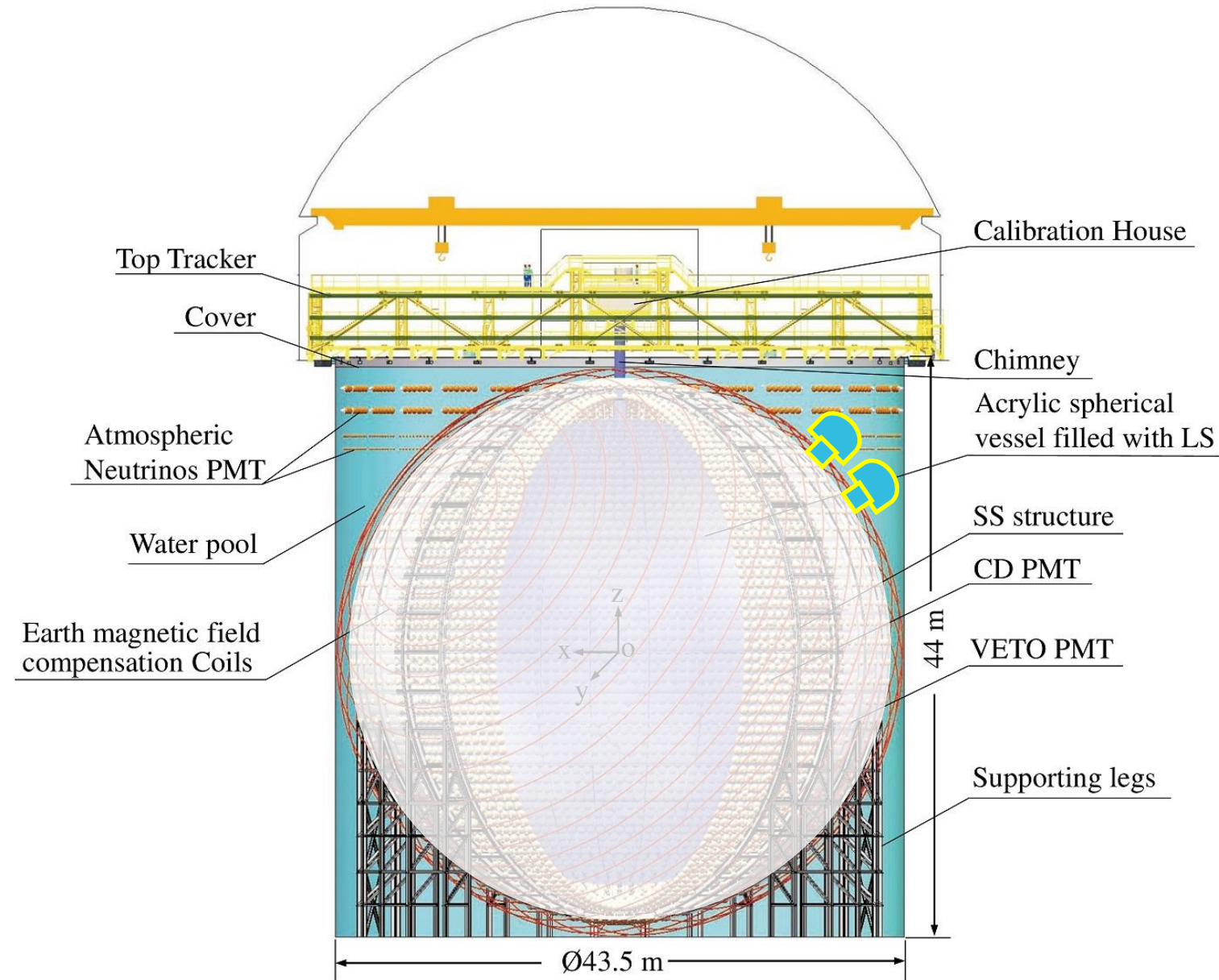
□ Ø43.5 m, H 44 m Water Pool/WP

----- Tyvek -----

□ Stainless Steel Structure/**SSS**

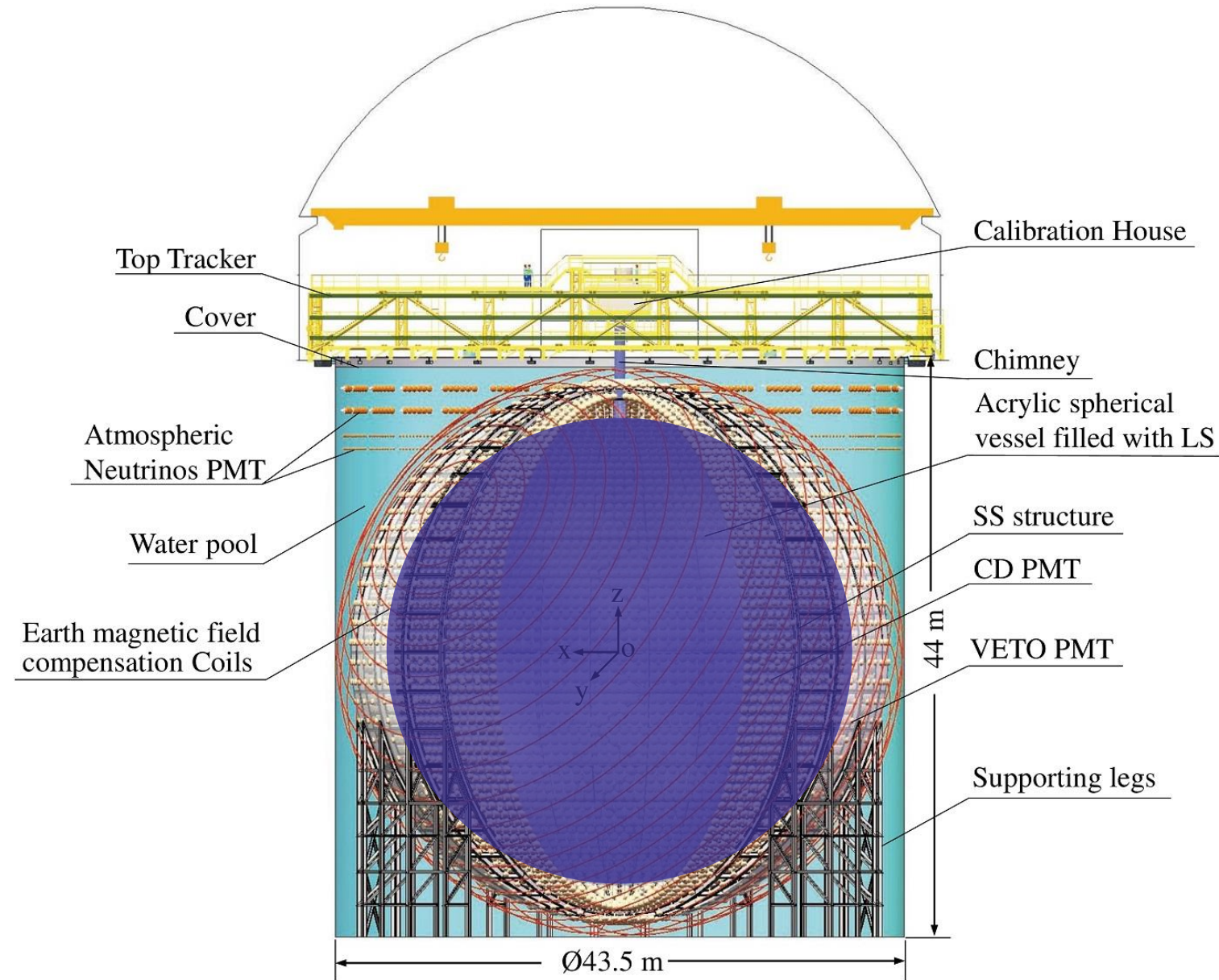
----- Tyvek -----

The JUNO Detector



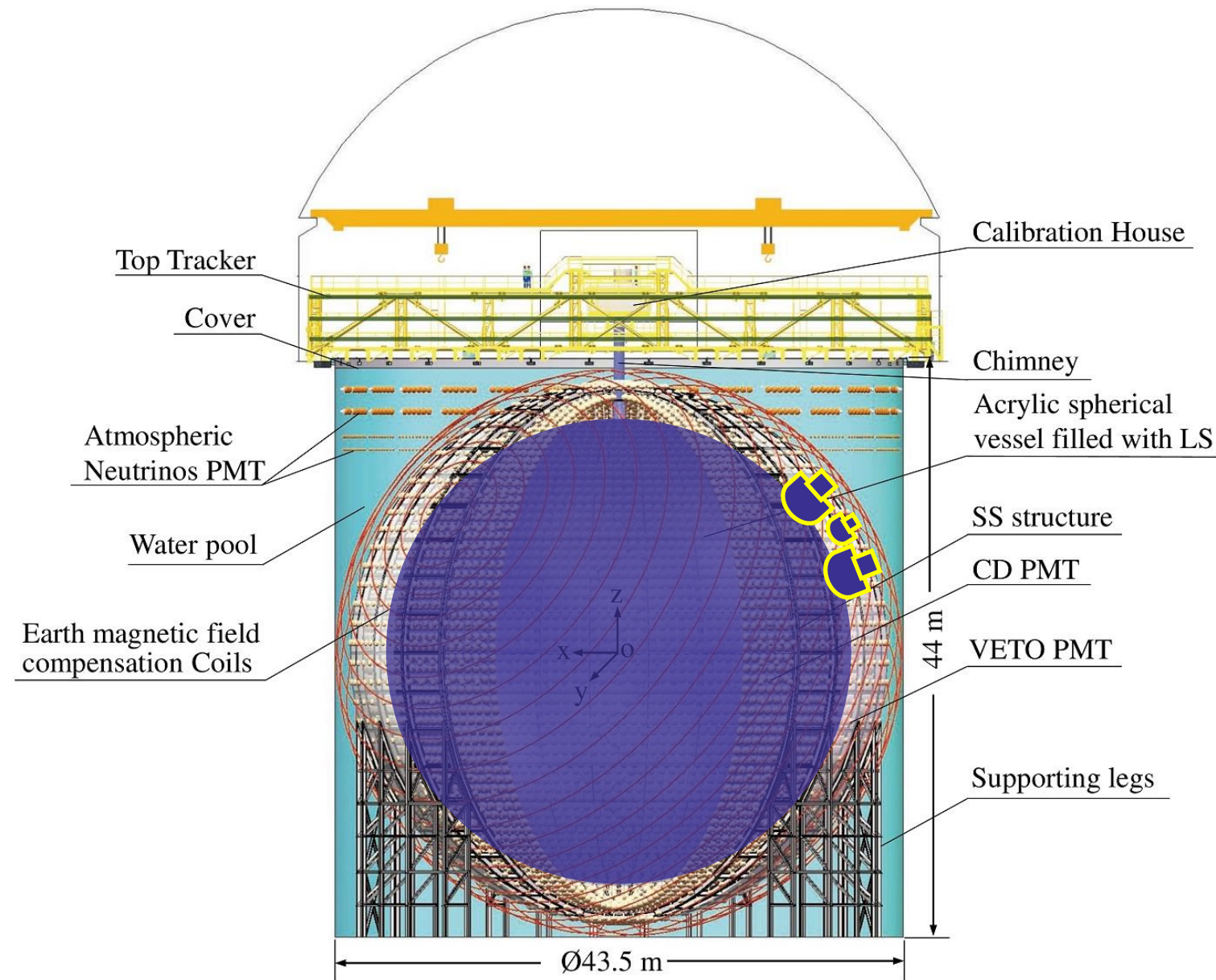
- Ø43.5 m, H 44 m Water Pool/WP
 - ❖ 35 kt water—Water Cher' Detector/**WCD**
 - Tyvek -----
- Stainless Steel Structure/SSS
 - ❖ **WCD PMTs** viewing outwards
 - 2,404 20" large PMTs (Micro-Channel Plate/MCP)
 - Tyvek -----

The JUNO Detector



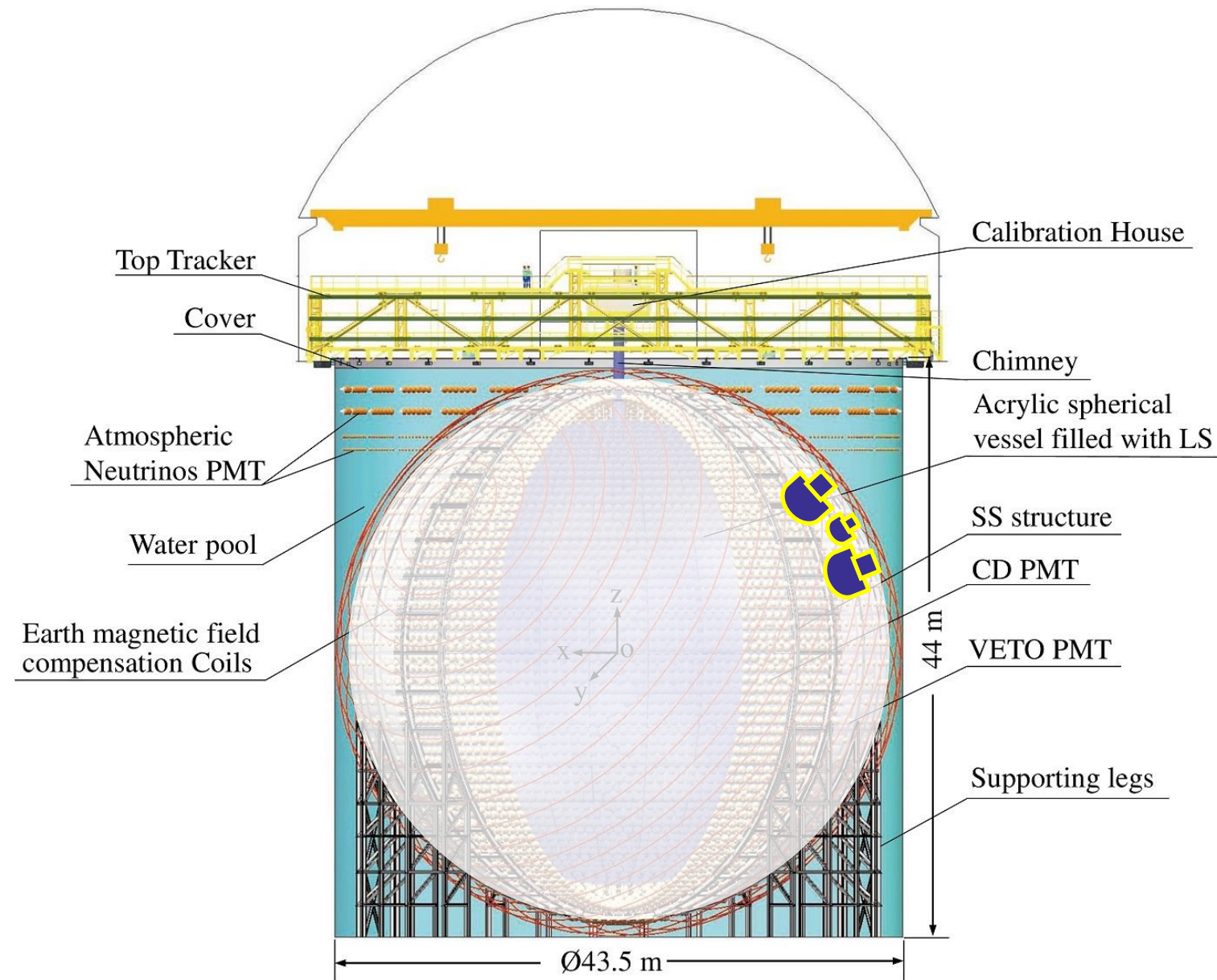
- Ø43.5 m, H 44 m Water Pool/WP
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 - Tyvek -----
- Stainless Steel Structure/SSS
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 - 2,404 20" large PMTs (Micro-Channel Plate/MCP)
 - Tyvek -----
- Ø35.4 m Acrylic Vessel/**AV**
 - ❖ 20 kt liquid scintillator/**LS**—Central Detector/**CD**
 - Fluorescence emission peak 430 nm (violet-blue)

The JUNO Detector



- ❑ Ø43.5 m, H 44 m Water Pool/WP
 - ❖ 35 kt water—Water Cherenkov Detector/WCD
 - Tyvek -----
 - ❖ 5 kt **water buffer** between WCD and AV
- ❑ Stainless Steel Structure/SSS
 - ❖ WCD PMTs viewing outwards
 - 2,404 20" large PMTs (Micro-Channel Plate/MCP)
 - Tyvek -----
 - ❖ **CD PMTs** viewing inwards
 - 17,596 20" large PMTs: 4939 dynode + MCP (w/ ×2 photon detection efficiency)
 - 25,587 3" small PMTs (higher dynamic range, calibration for large PMTs; a problem due to the connections: add N₂ into water)
- ❑ Ø35.4 m Acrylic Vessel/AV
 - ❖ 20 kt liquid scintillator/LS—Central Detector/CD
 - Fluorescence emission peak 430 nm (violet-blue)

The JUNO Detector



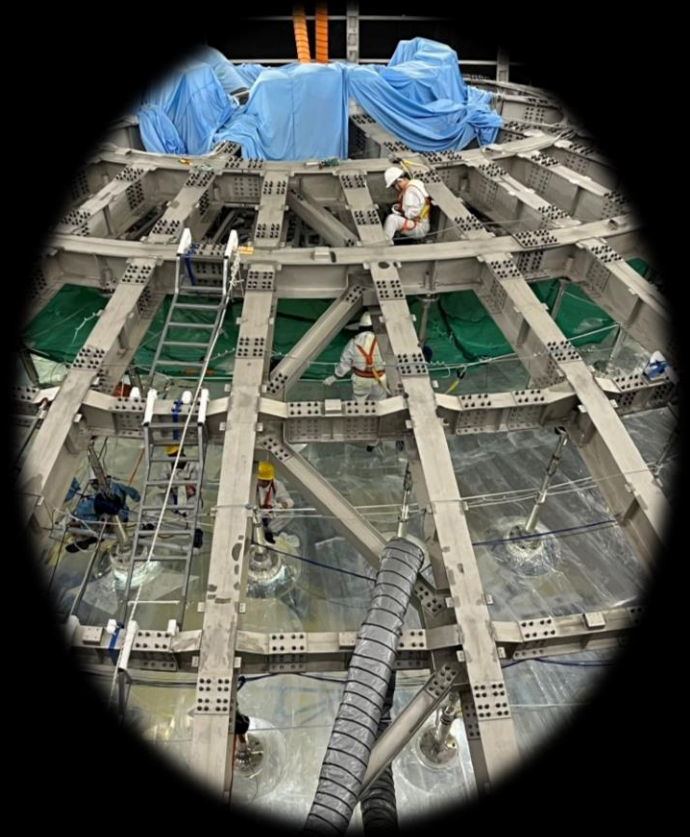
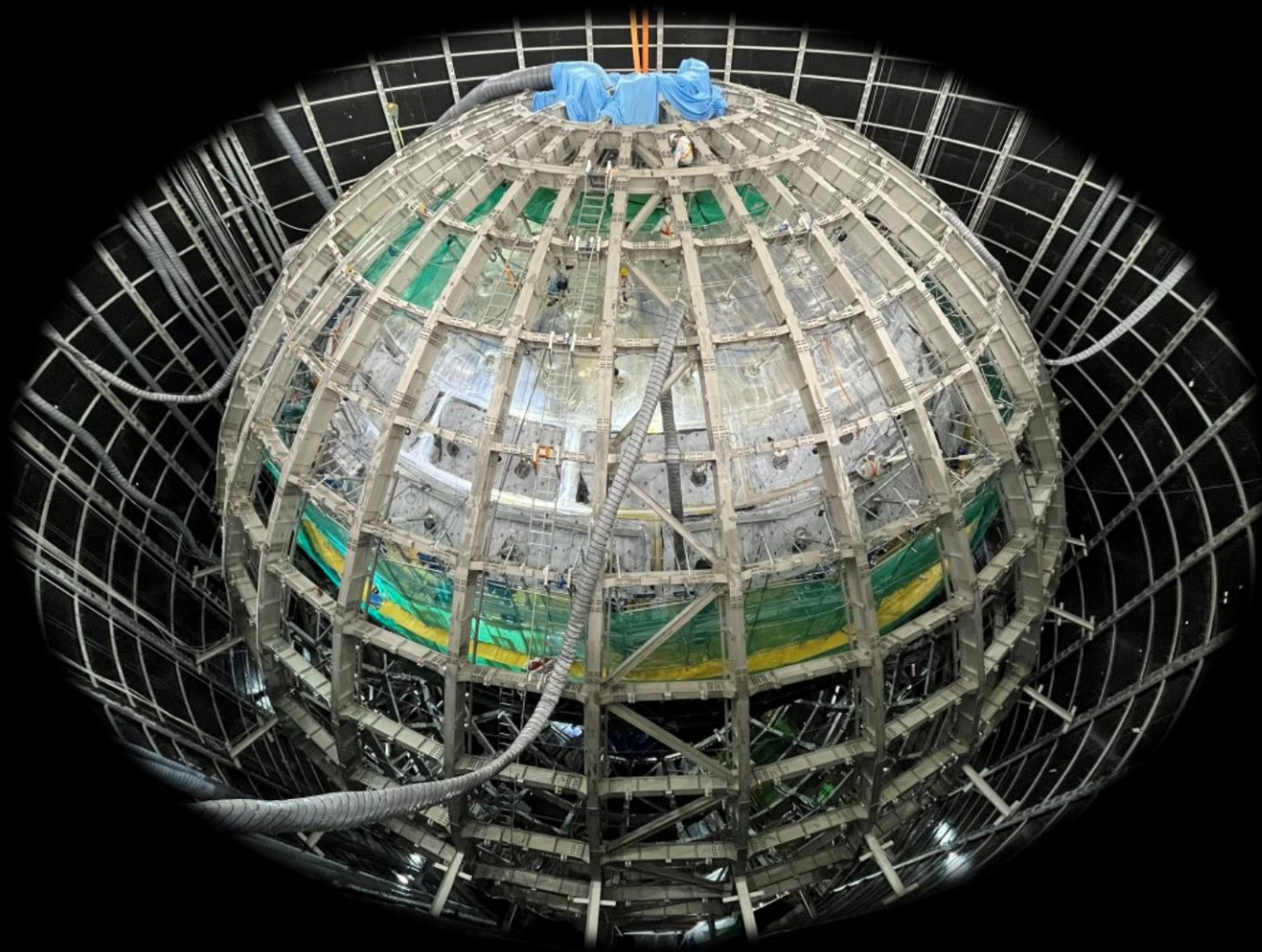
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 - 25,587 3" small PMTs (higher dynamic range, calibration for large PMTs; a problem due to the connections: add N_2 into water)
 - ✓ **75%+3% geometrical coverage ← SSS**
 - mechanical precision ~3 mm**



Photo credit: LIU Yuexiang@IHEP

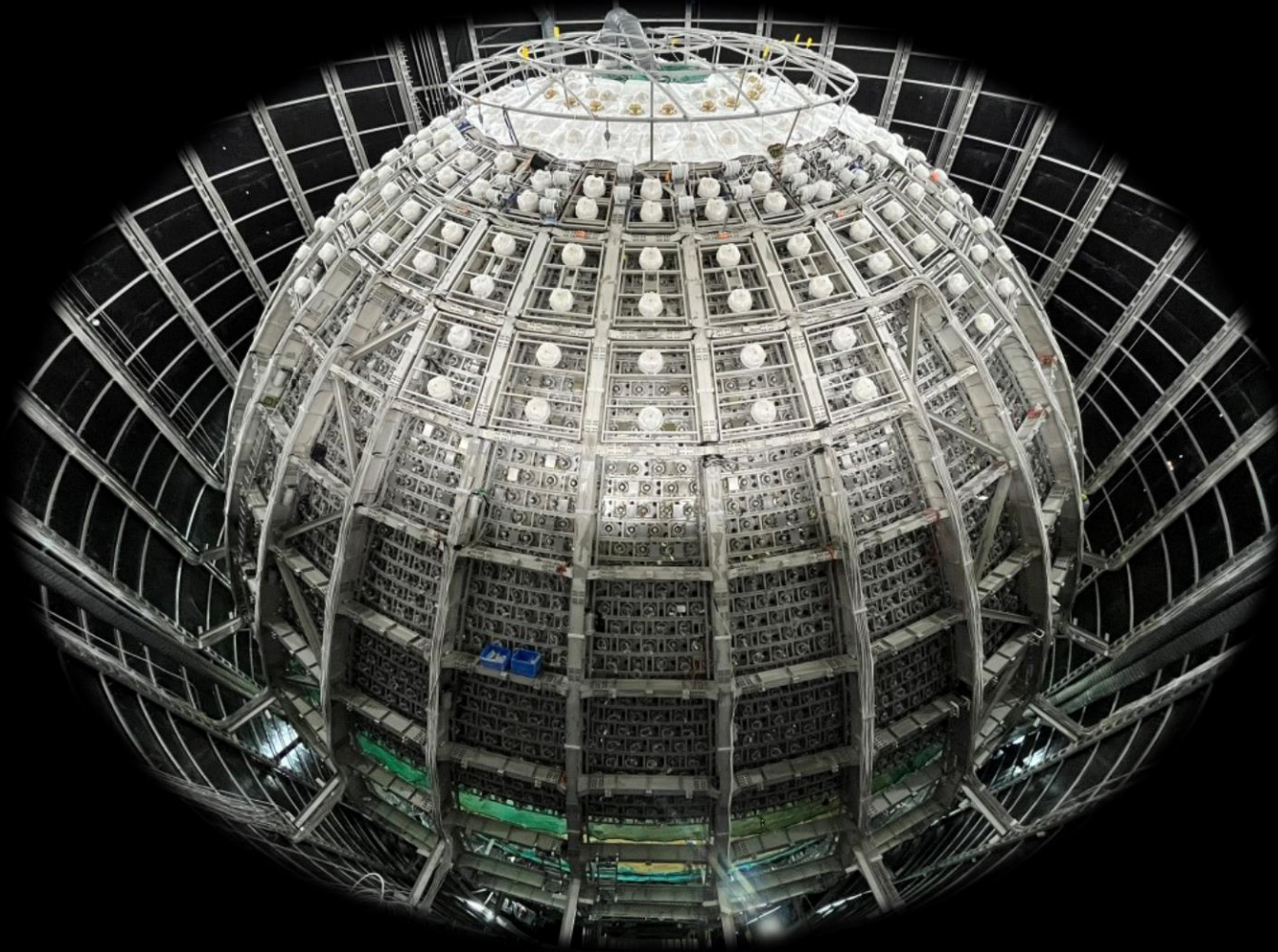
The JUNO Detector

□ SSS and AV



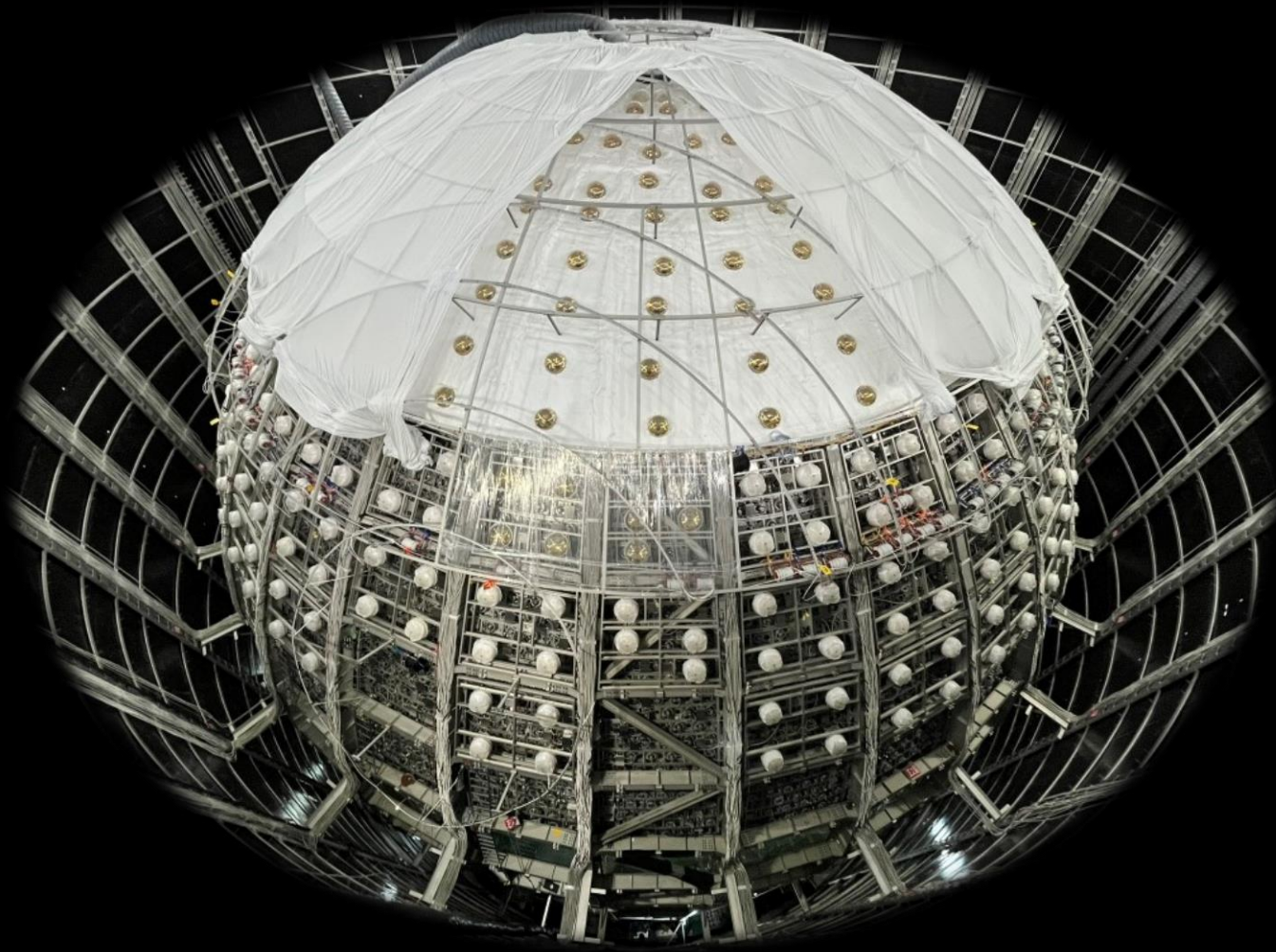
The JUNO Detector

□ WCD PMTs (and back of CD PMTs)



The JUNO Detector

- Tyvek and earth magnetic field compensation coils (and temporary protector)

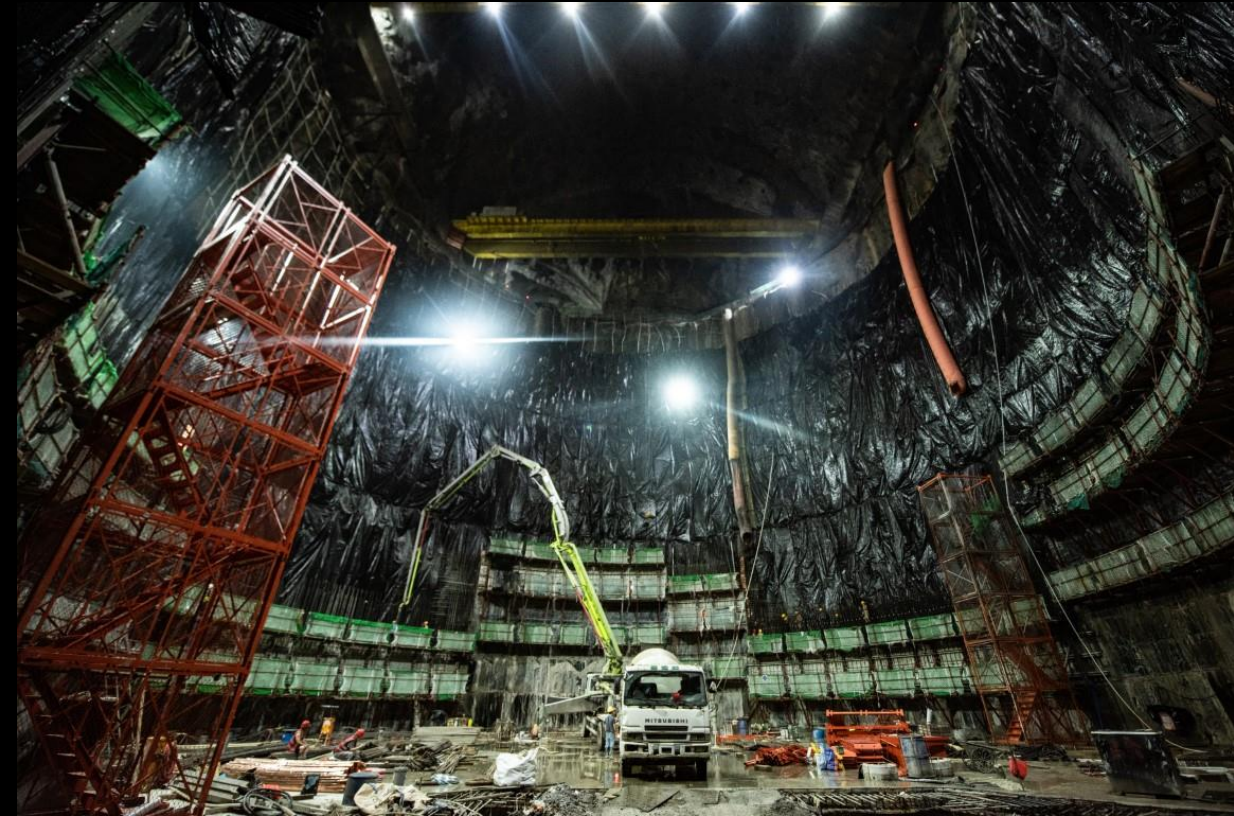
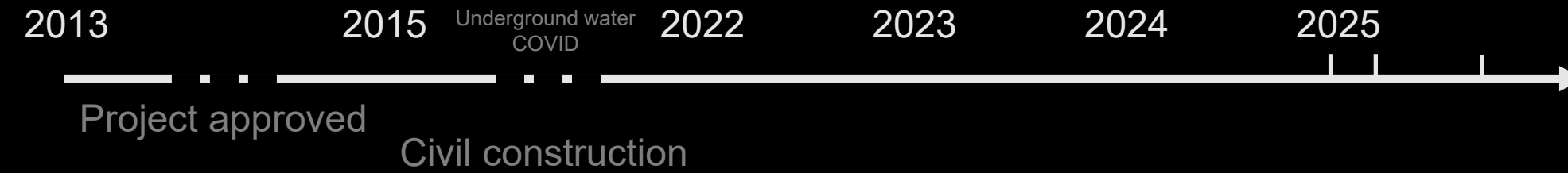


The JUNO Detector

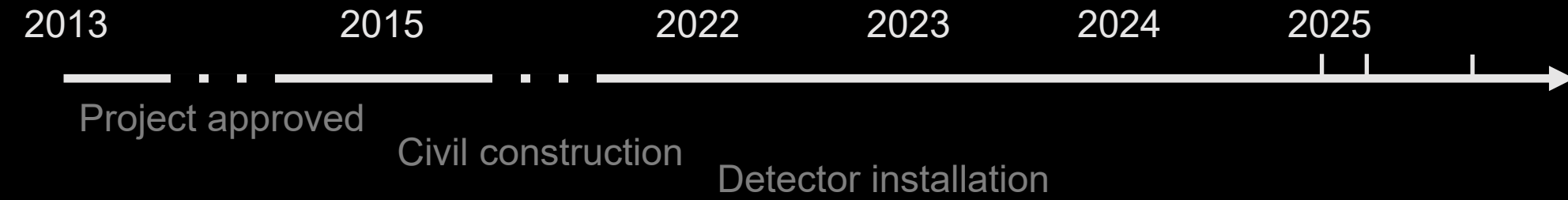
□ Large and small PMTs (and water buffer region)



Towards JUNO's First Results

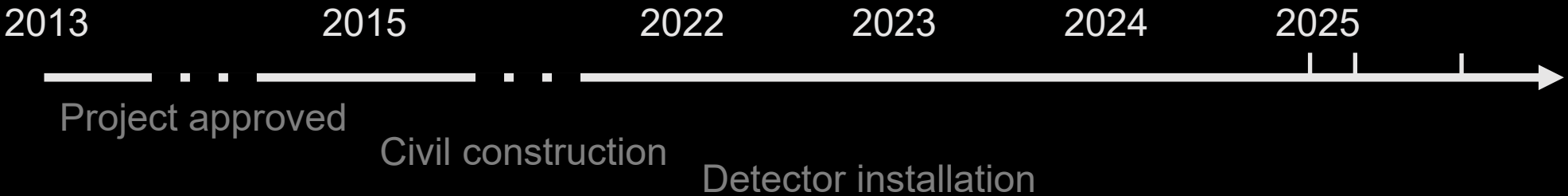


Towards JUNO's First Results



30s video

Towards JUNO's First Results



2022/08/15



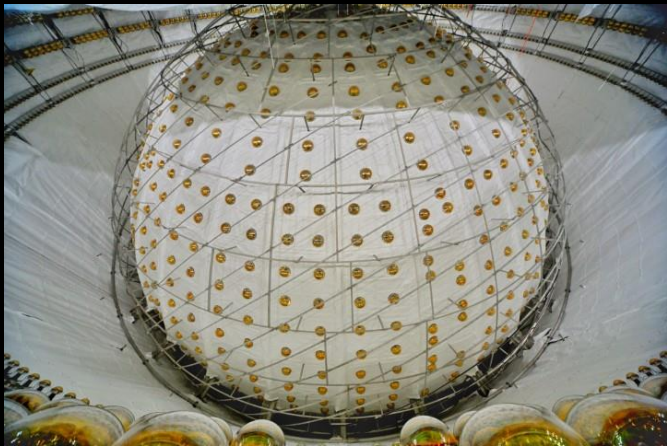
2023/08/04



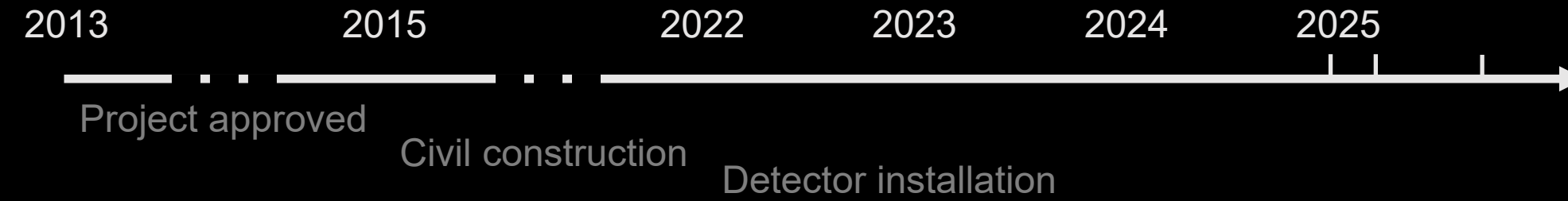
2024/09/27



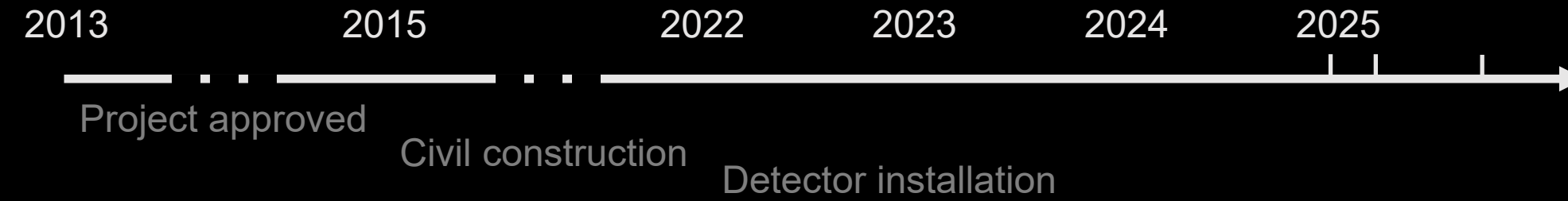
2024/12/19



Towards JUNO's First Results



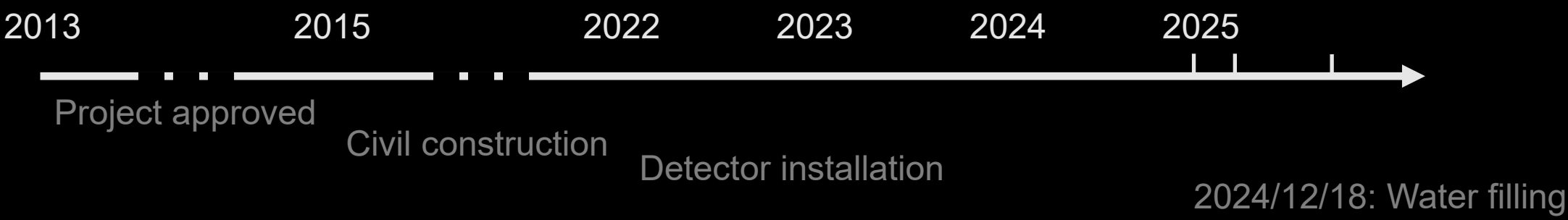
Towards JUNO's First Results



1m video



Towards JUNO's First Results



10s video

Towards JUNO's First Results

2013

2015

2022

2023

2024

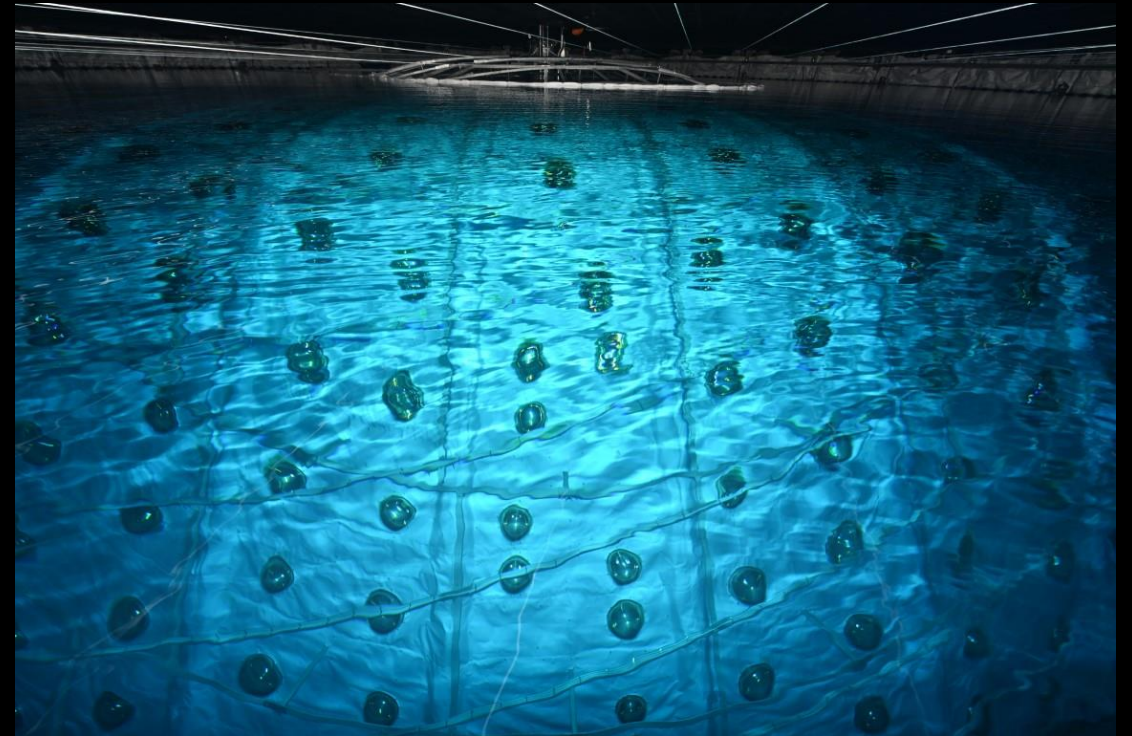
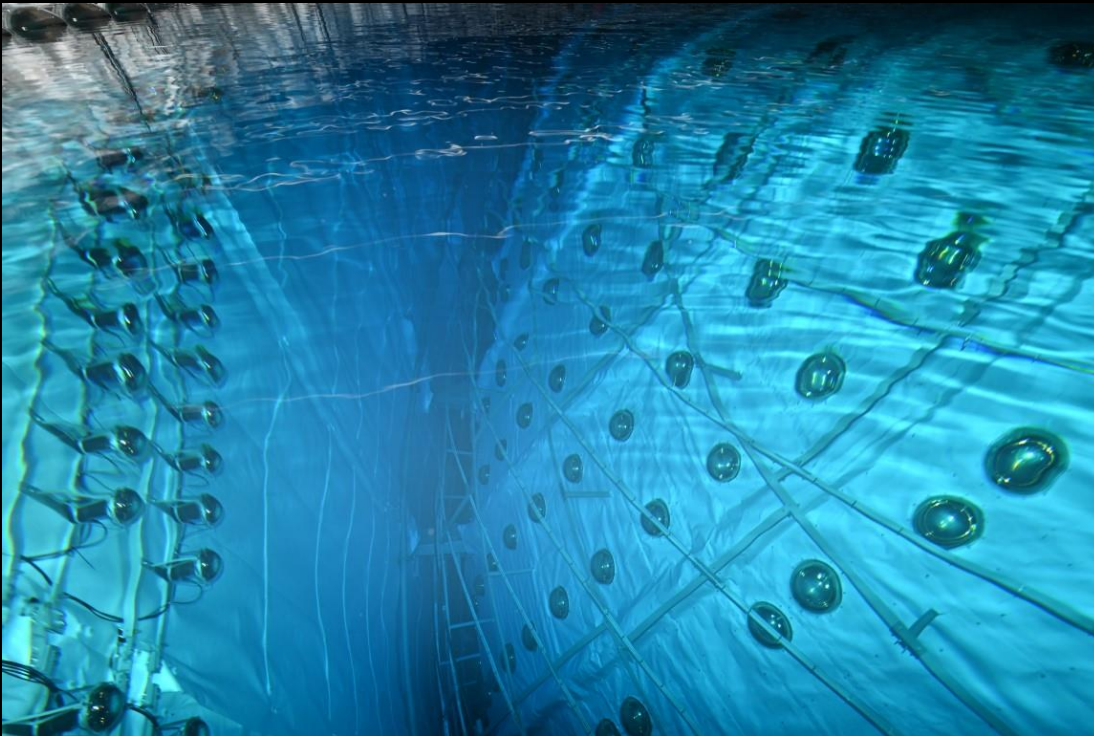
2025

Project approved

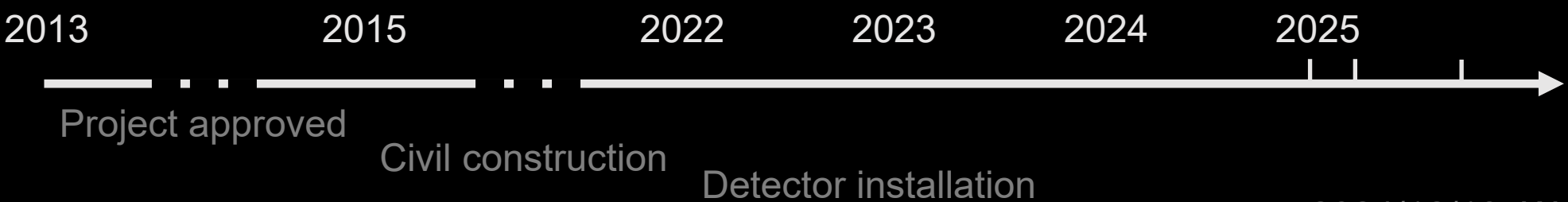
Civil construction

Detector installation

2024/12/18: Water filling



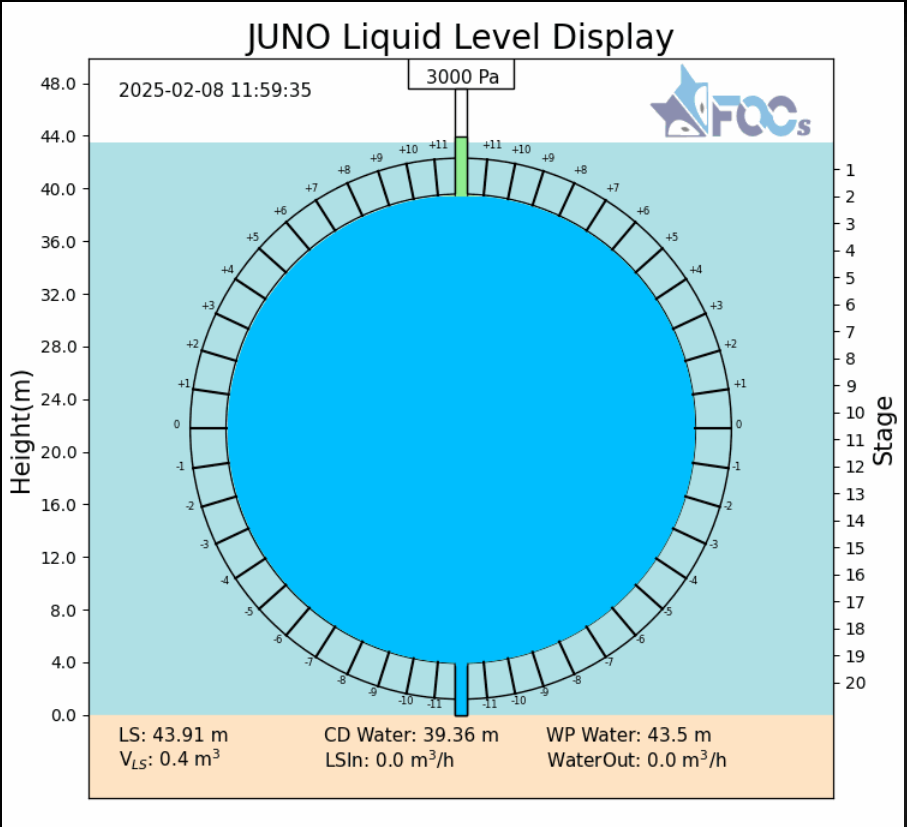
Towards JUNO's First Results



2024/12/18: Water filling

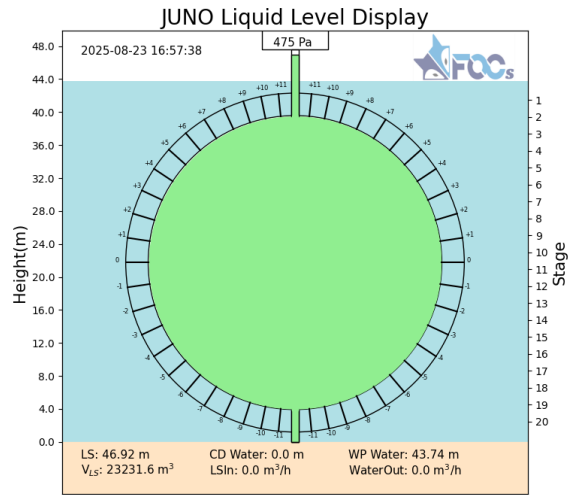
2025/02/01: Water/LS exchange

2025/08/22: LS filling complete

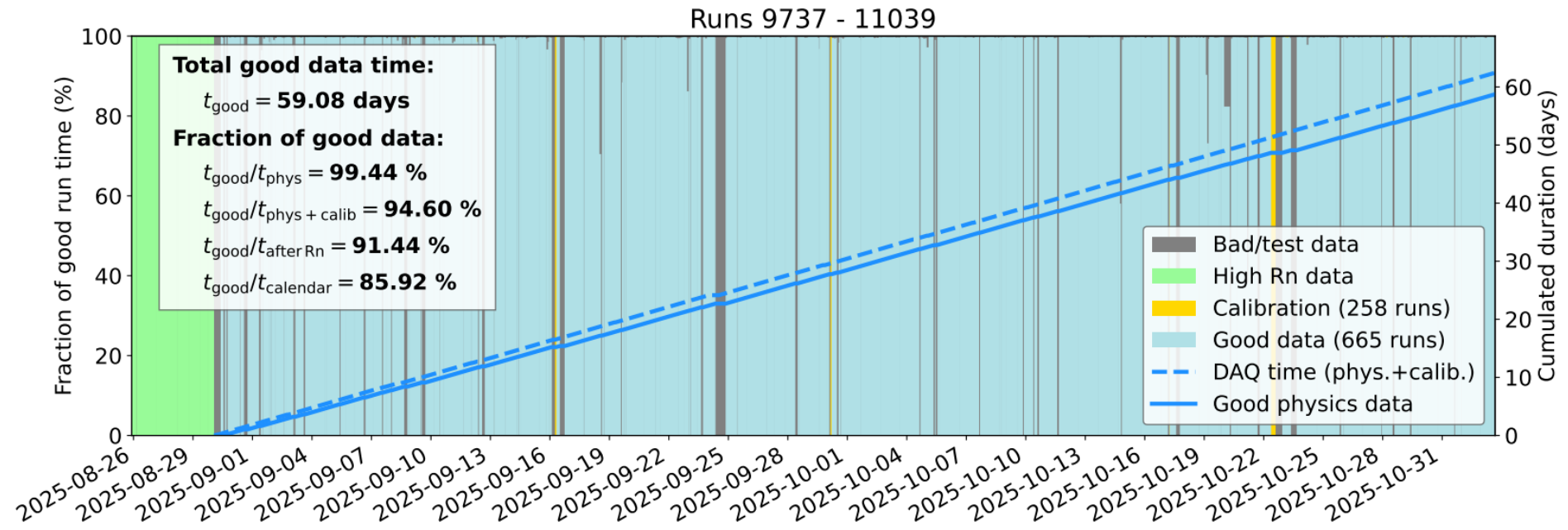


Animated gif

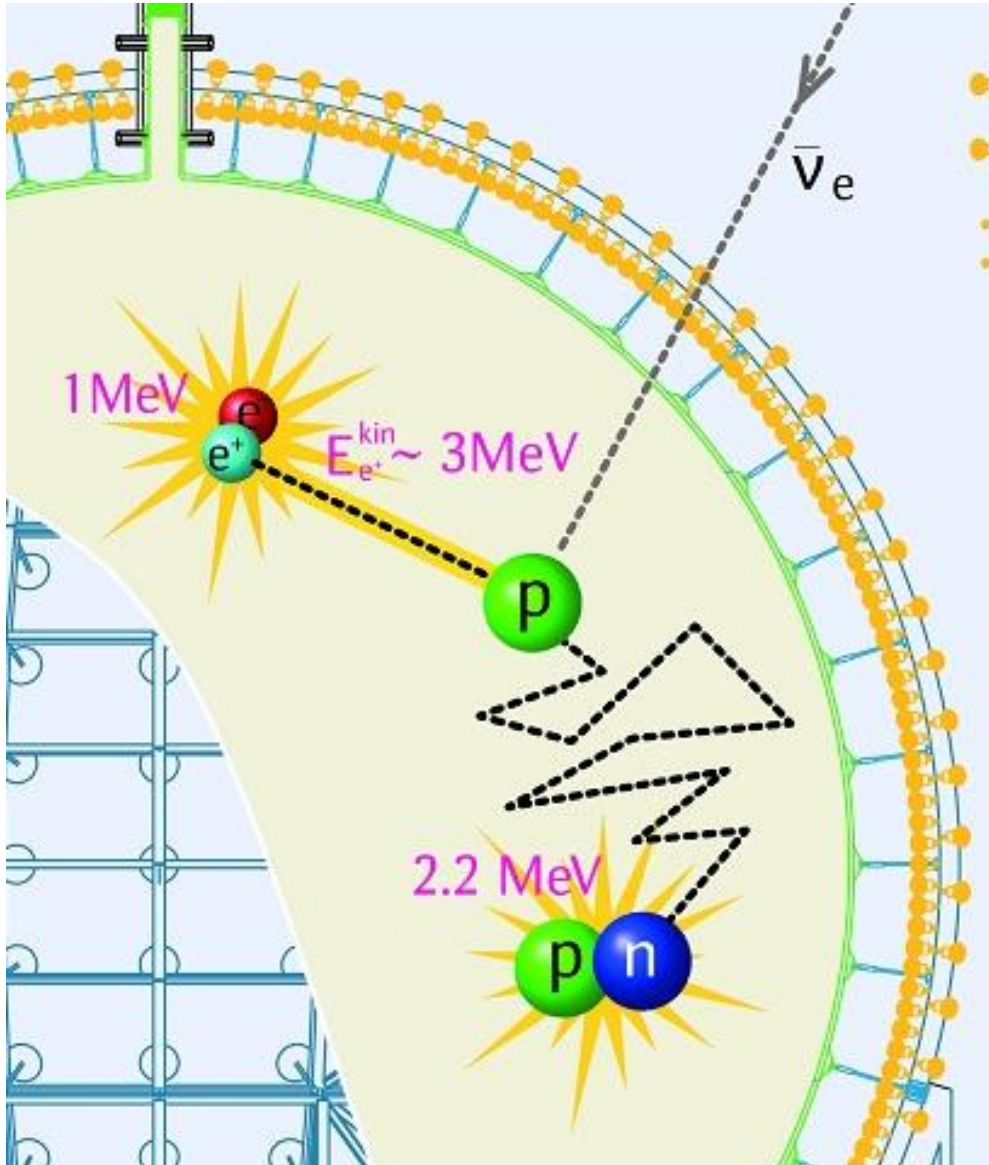
Towards JUNO's First Results



- 2025/08/22 (22:12): LS filling completed; water in CD fully replaced by LS
- 2025/08/23 (14:00): Detector calibration began
- 2025/08/26 (05:30): Start of physics data taking
 - ❖ LS in CD: 23,231.6 m³
 - ❖ Water in WP: 41,225.1 m³
- ❖ Data set used for First Result: 08/26–11/02 (69 calendar days)
 - Detector uptime > 97.8%
 - Physics-quality data: 59.1 days



Reactor $\bar{\nu}_e$ Event Characteristics at JUNO



Inverse beta decay (IBD)

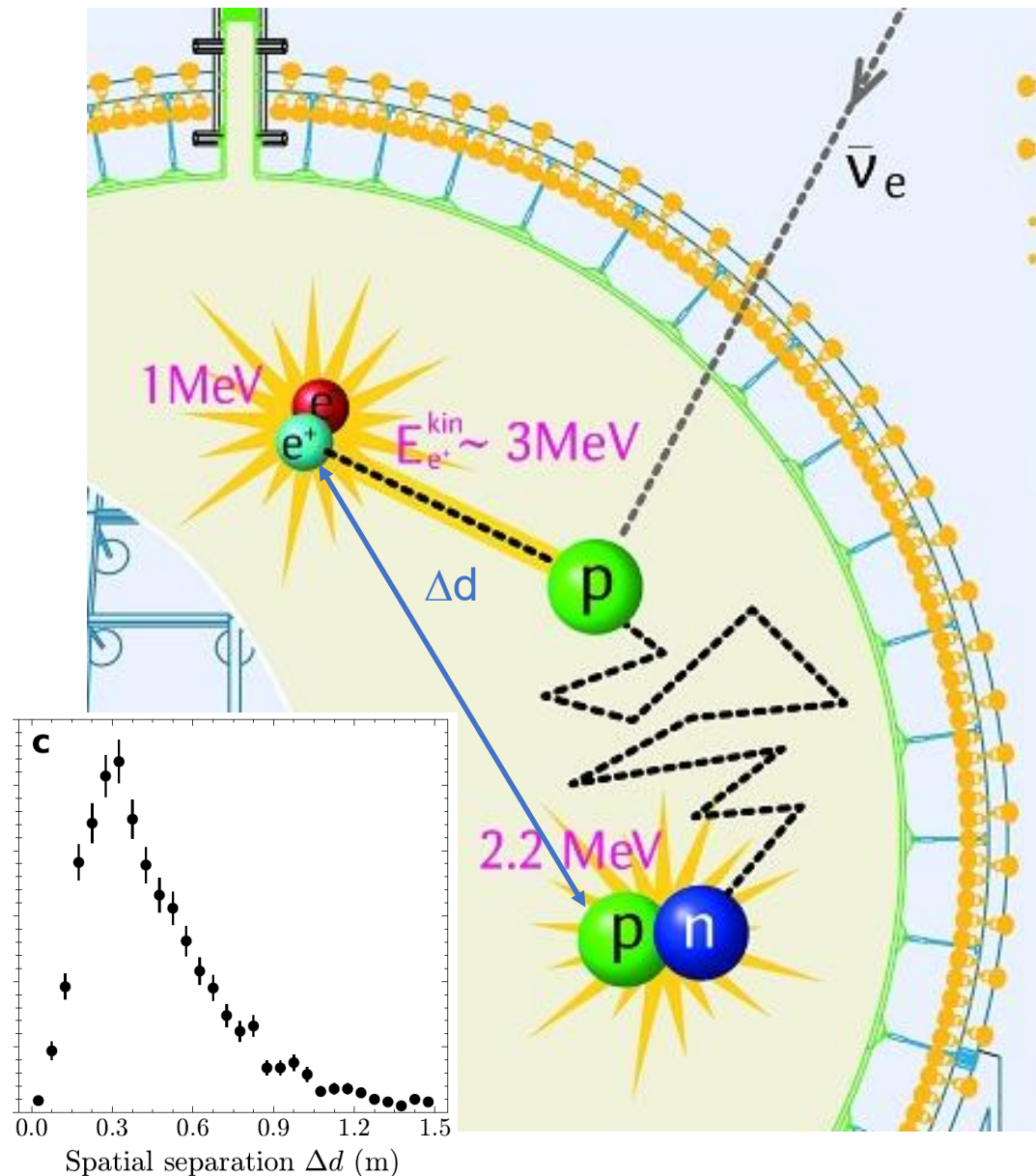
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

❑ Only on hydrogen, not carbon

❑ Prompt signal: e^+

❖ Prompt energy + $0.78\text{ MeV} \sim E_\nu$

Reactor $\bar{\nu}_e$ Event Characteristics at JUNO



Inverse beta decay (IBD)

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

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❑ Prompt signal: e^+

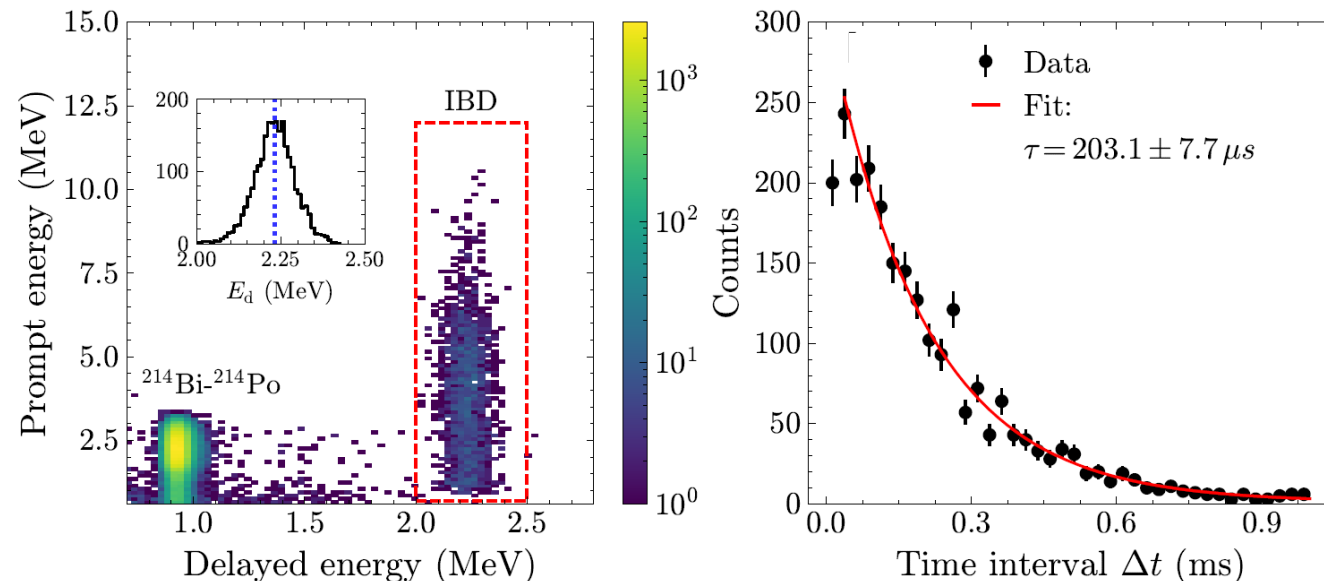
❖ Prompt energy + 0.78 MeV $\sim E_{\nu}$

❑ Delayed signal: $n + \text{H} \rightarrow \text{d} + \gamma$

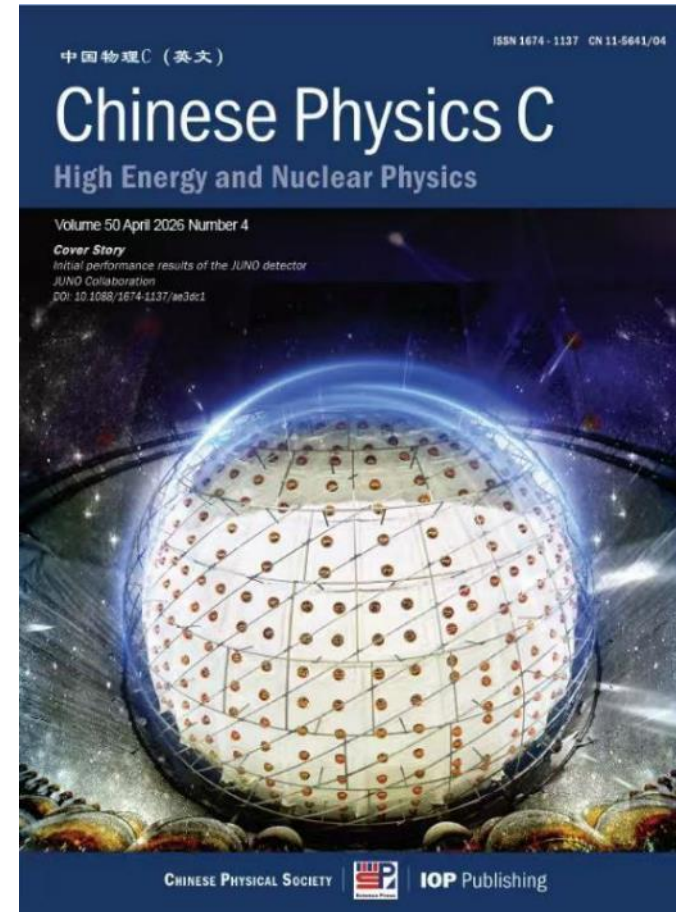
❖ 2.2 MeV neutron capture peak

❖ Mean capture time $\sim 200 \mu\text{s}$

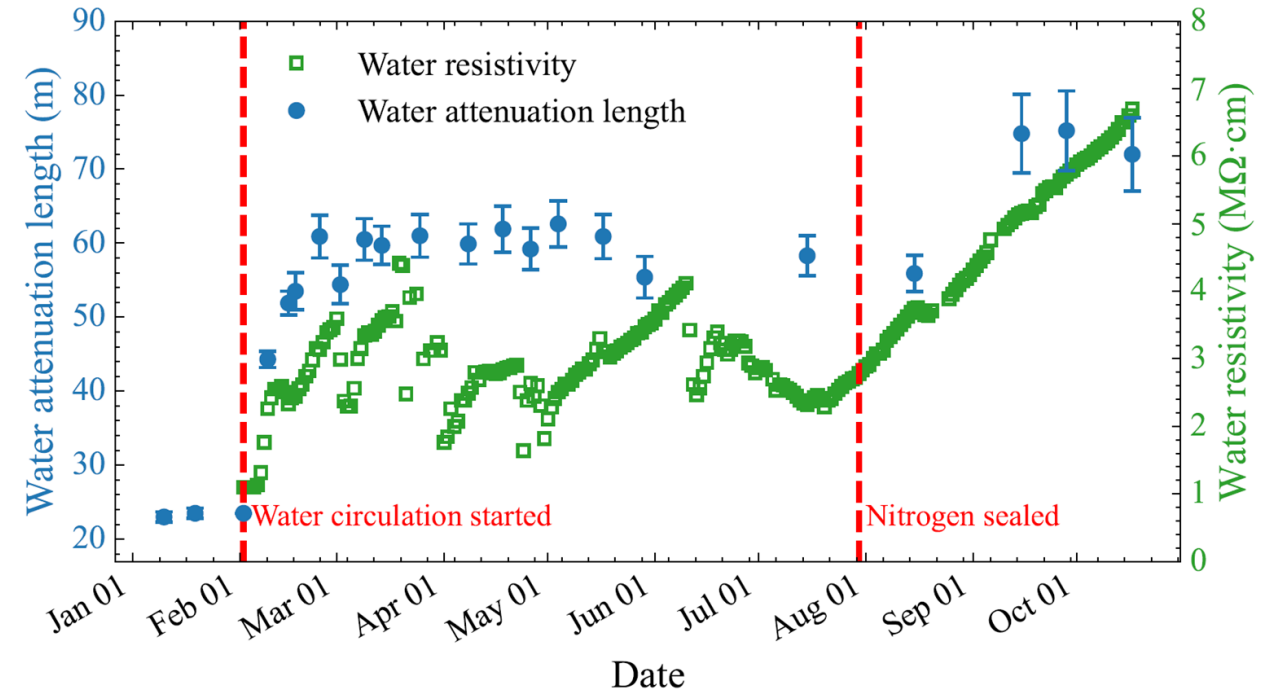
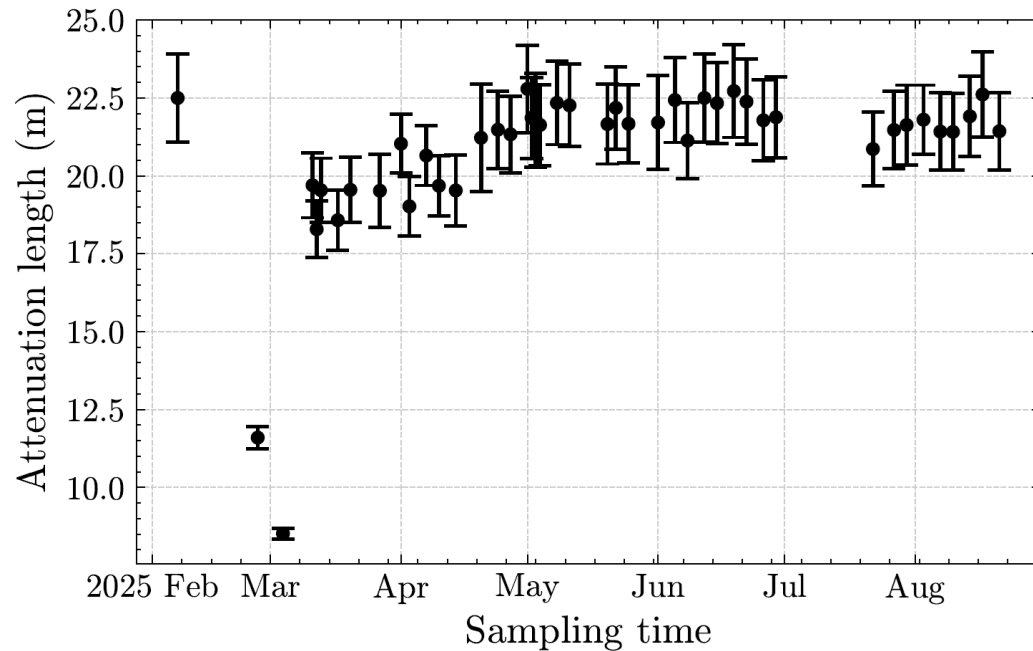
❖ Separation between vertices up to $\sim 1 \text{ m}$



First JUNO results using 59 days of data recently published



Detector Performance

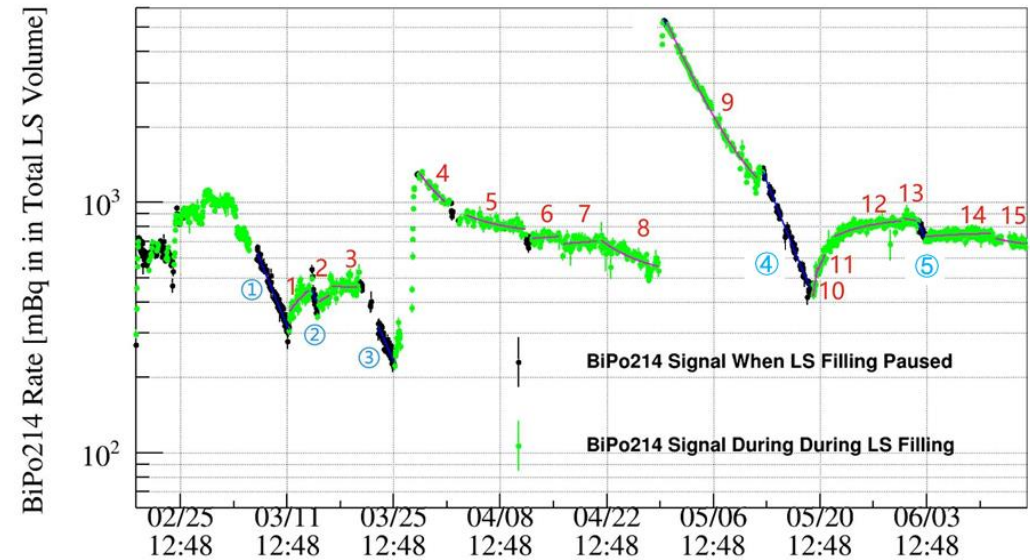


- ❑ LS attenuation length average: 20.6m @430 nm
 - ❖ Sensitive indicator of LS quality
 - ❖ Critical for light yield and energy scale uniformity
 - ❖ Designed goal 20 m for a good energy resolution

- ❑ WCD water attenuation length > 70 m @400 nm
 - ❖ Excellent optical transparency
 - ❖ Ultra-pure water
 - ❖ Design goal 40 m

Detector Performance

■ 2025 02/19 – 06/16 (Run3840 - 6495)



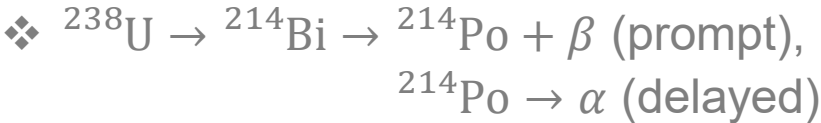
CD	Design	Measured	WCD	Design	Measured
Singles* (Hz)	< 7.2	<7	²²² Rn (mBq/m ³)	< 10	<10
²³⁸ U/ ²³² Th (×10 ⁻¹⁵ g/g)	<1	<0.1	²²⁶ Ra (mBq/m ³)	<1	<0.01
²¹⁰ Po (×10 ⁴ cpd/kt)	<8	<5	²³⁸ U/ ²³² Th (×10 ⁻¹⁵ g/g)	<10	<0.4

* For E>0.7 MeV and r < 17.2 m

Internal radioactivity

❑ Cosmogenic spallation n/¹²B/¹¹C from $\mu + ^{12}\text{C}$

❑ Natural radioactivity

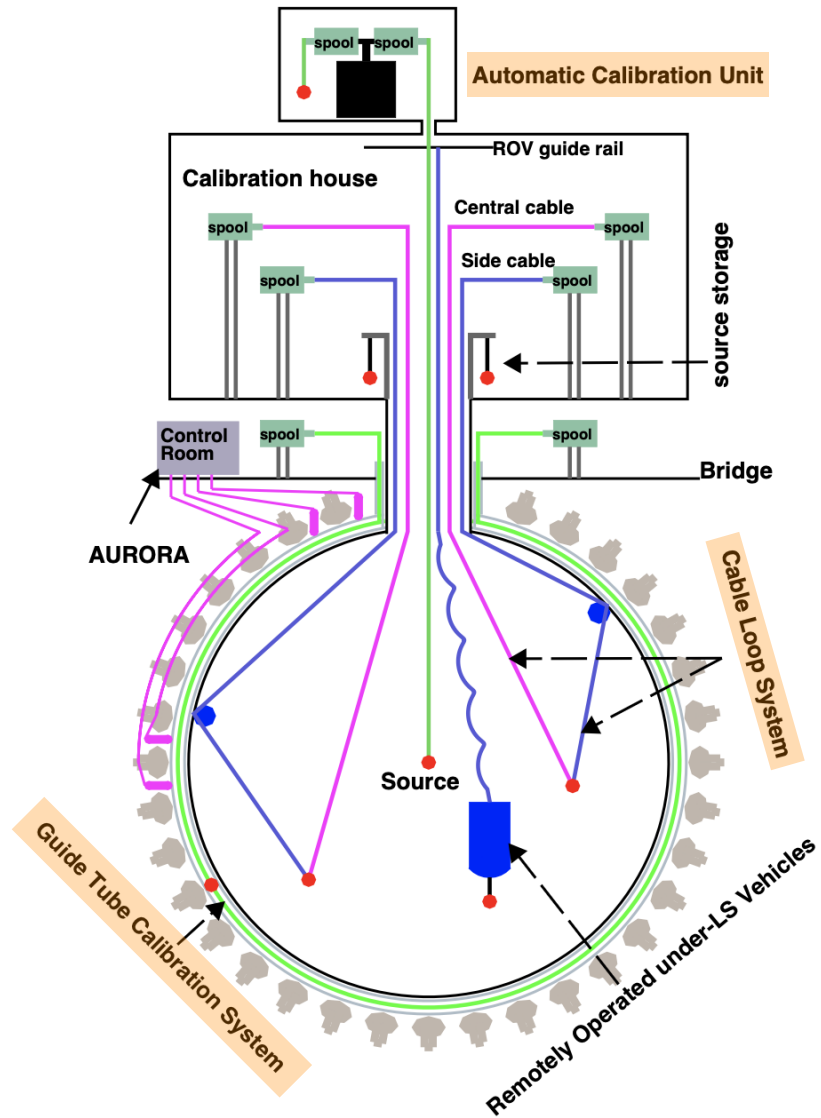


➤ Calibration α source

➤ BiPo214 very distinctive coincidence signal, easy to identify, very useful tool

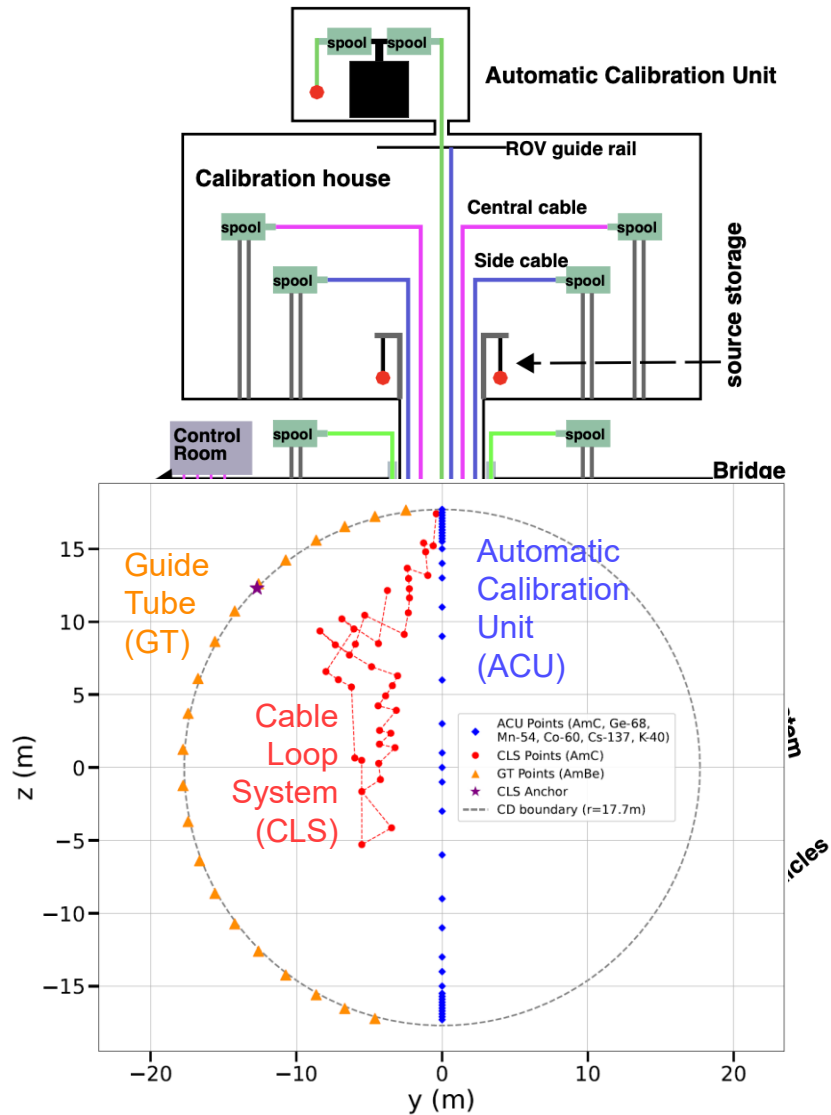
❑ Very clean detector: < 10 mg dust in 20 kt LS

Energy Calibration

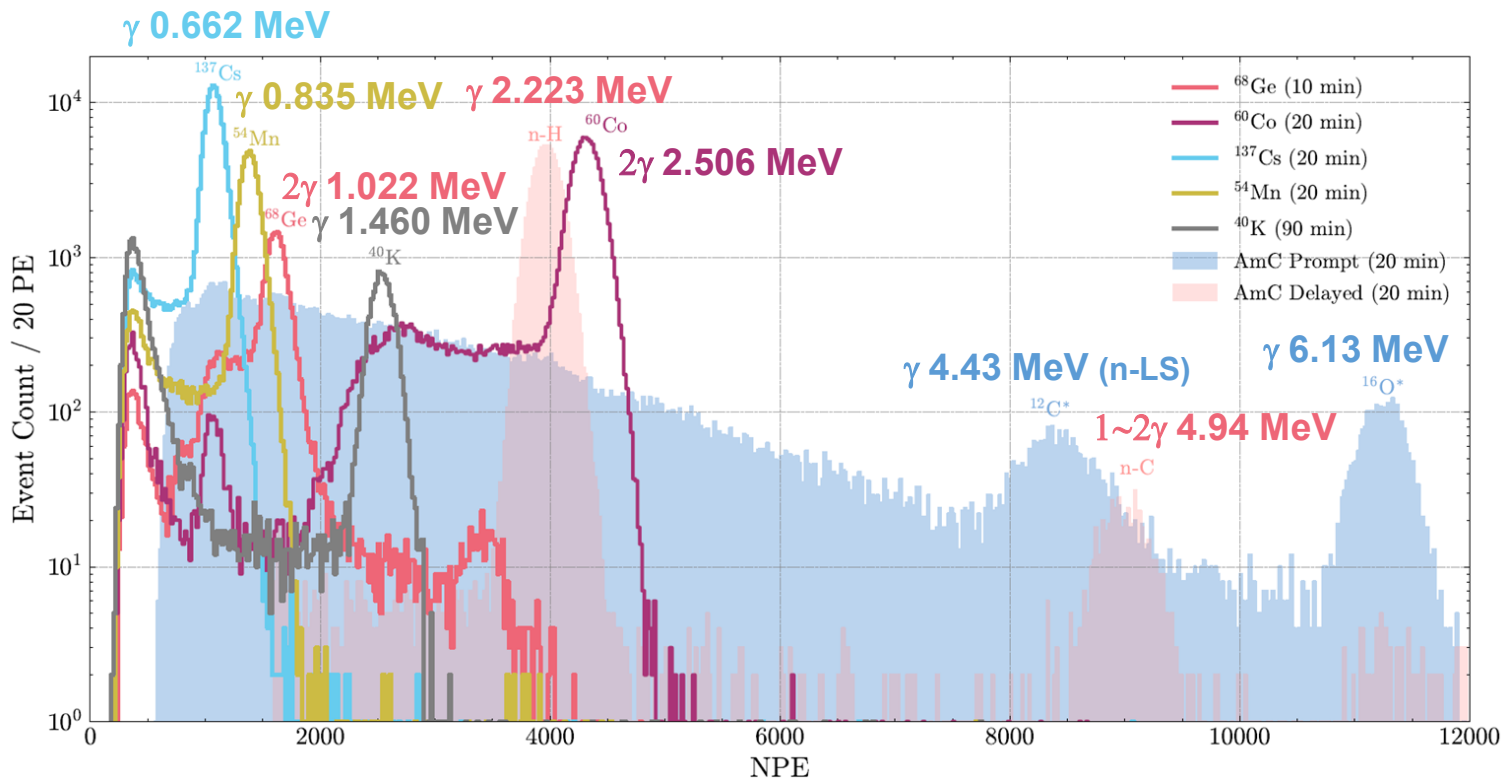


- ❑ External calibration sources deployed by ACU, CLS, and GT
 - ❖ E.g. AmC: $\alpha + {}^{13}\text{C} \rightarrow {}^{16}\text{O}^* + \text{n}$

Energy Calibration



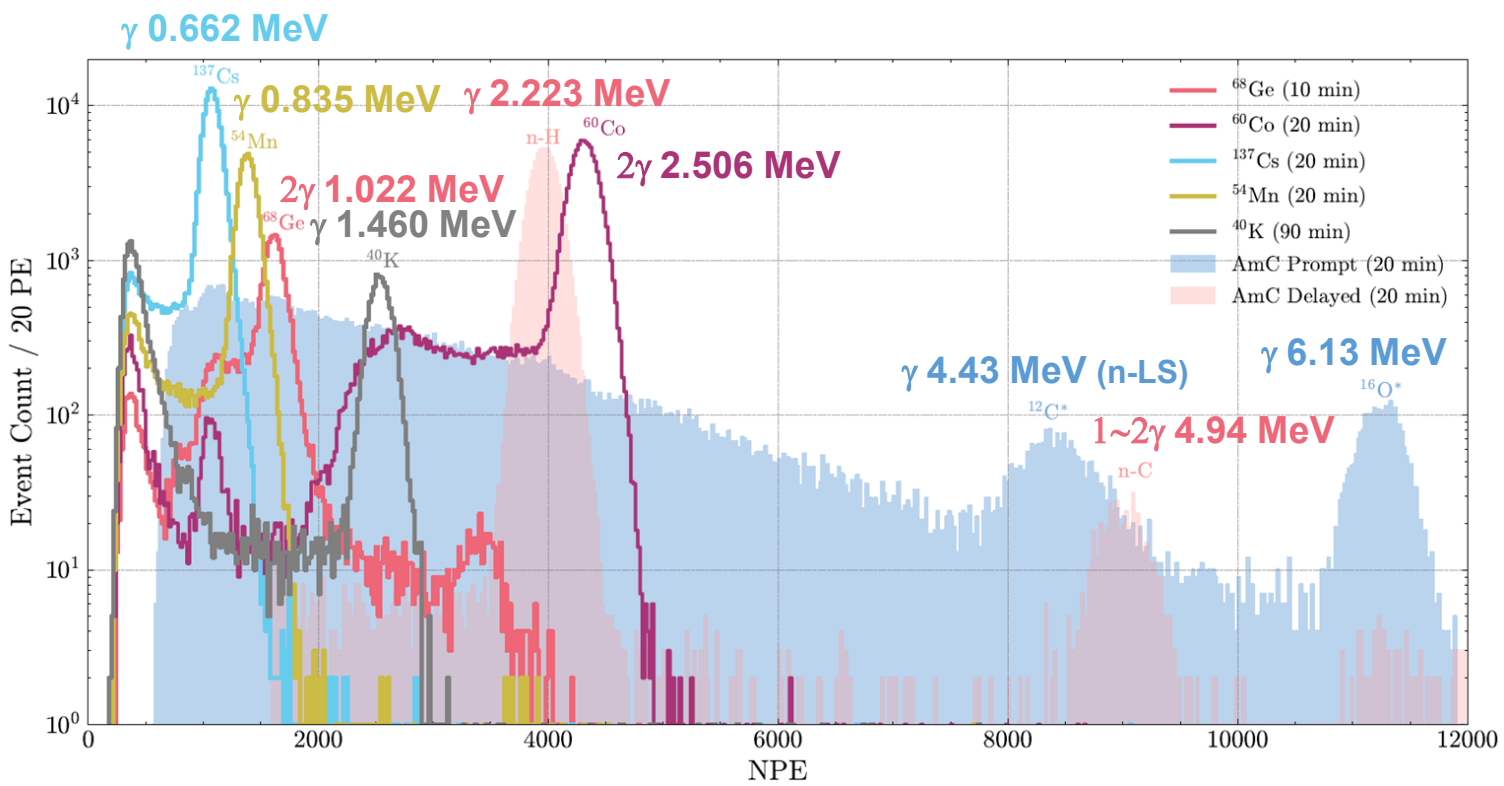
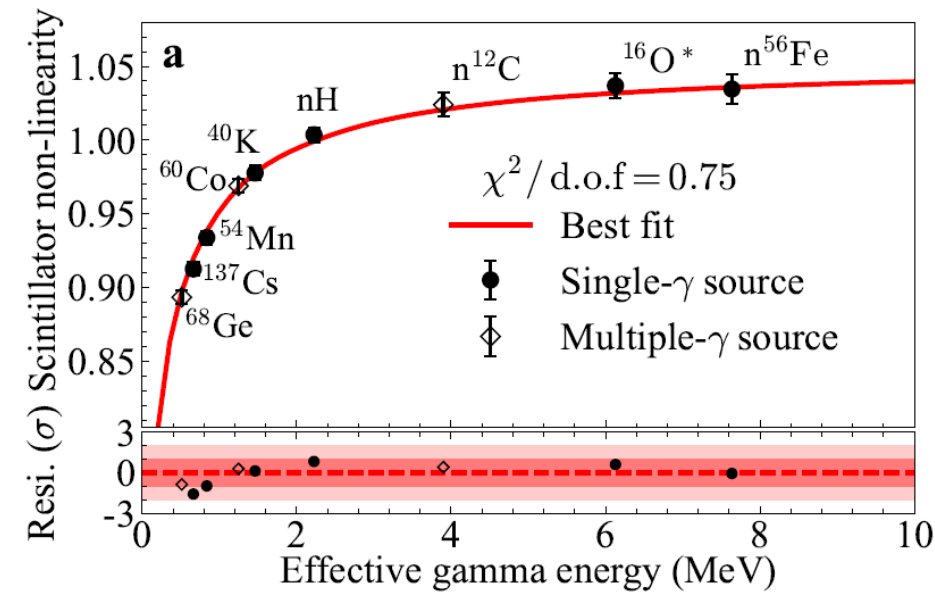
- ❑ External calibration sources deployed by ACU, CLS, and GT
 - ❖ E.g. AmC: $\alpha + {}^{13}\text{C} \rightarrow {}^{16}\text{O}^* + \text{n}$
- ❑ Various locations
- ❑ A wide range of energy covered



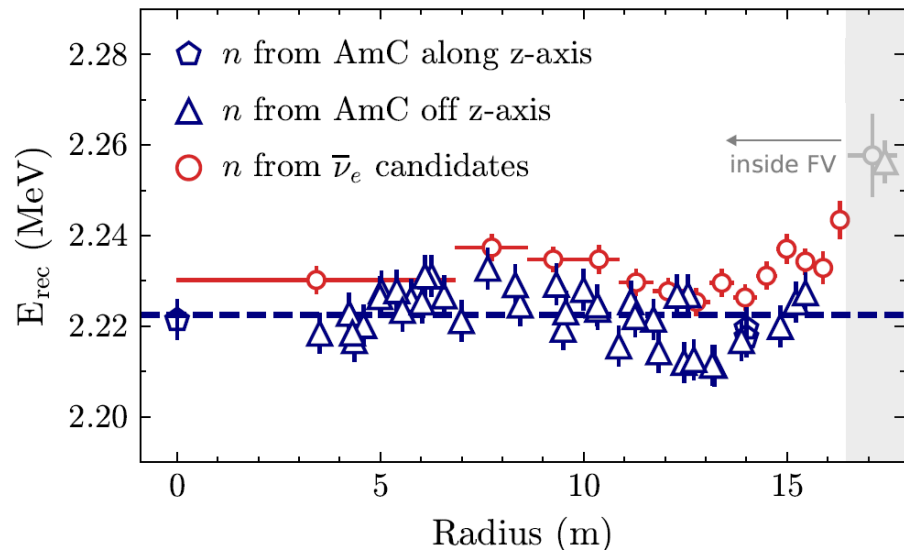
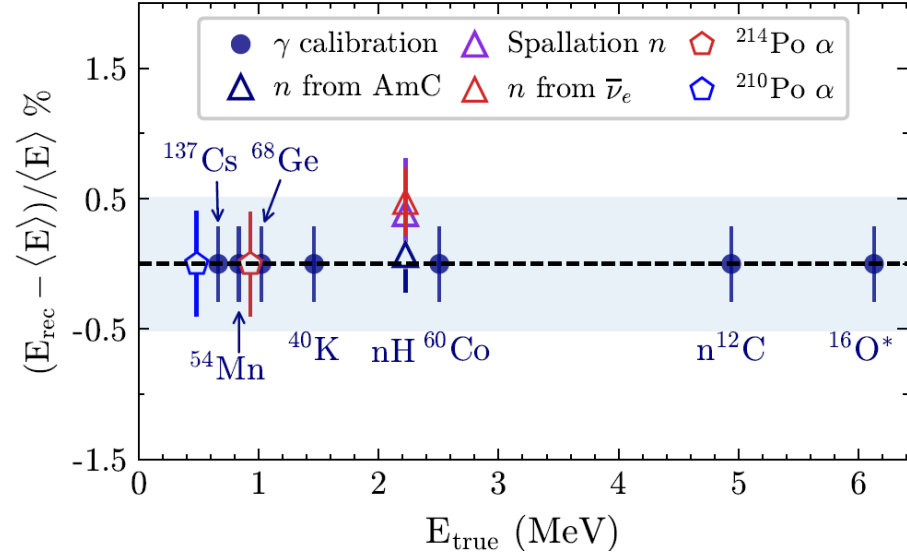
Energy Calibration

$$E_{\text{rec}} = \underbrace{k}_{\text{absolute scale}} \underbrace{[1 + f(E)]}_{\text{non-linearity}} E_{\text{true}}$$

- Non-linearity (due to Birks, Cherenkov, etc.) well described
- ❖ Characterised to <1% precision



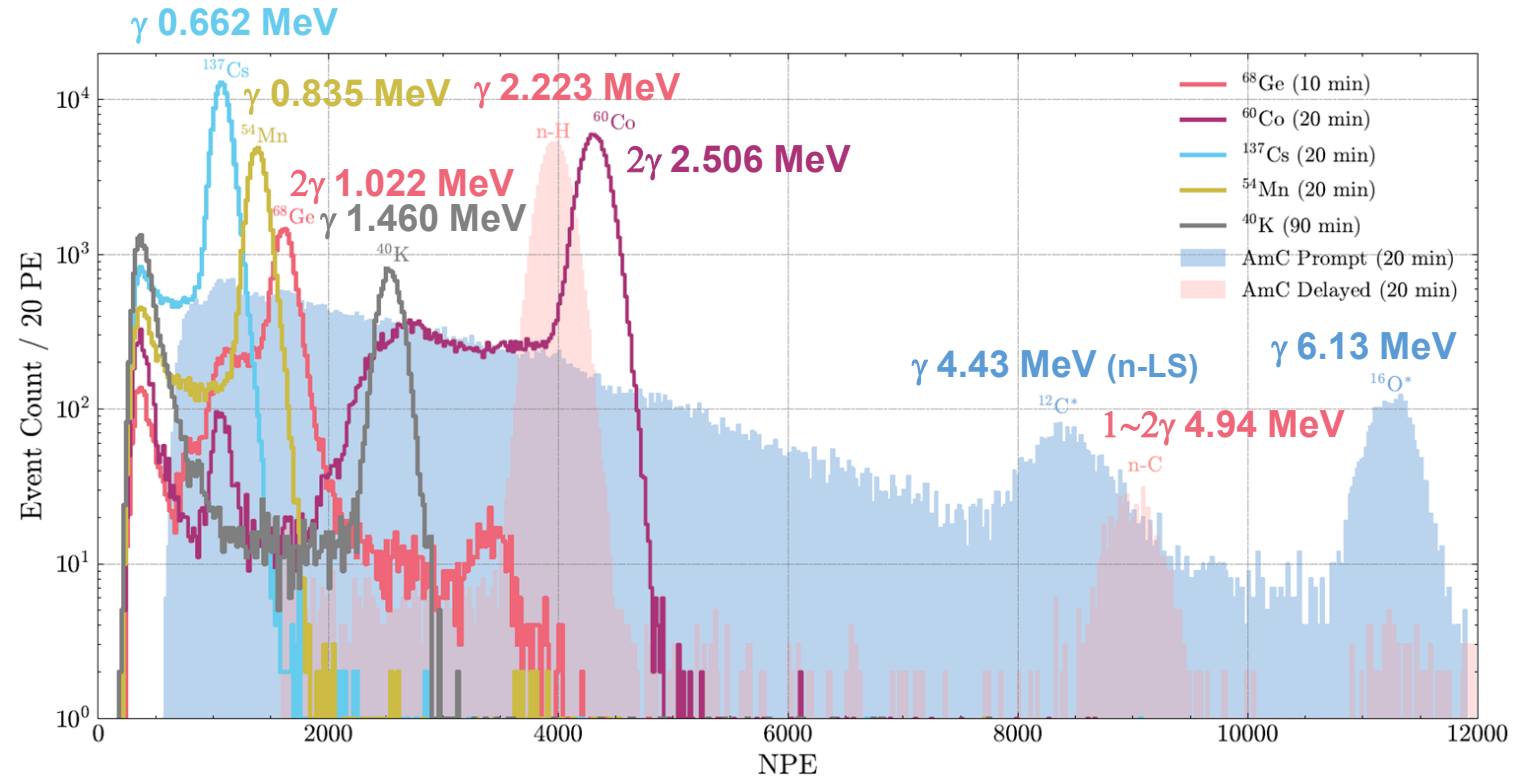
Energy Calibration



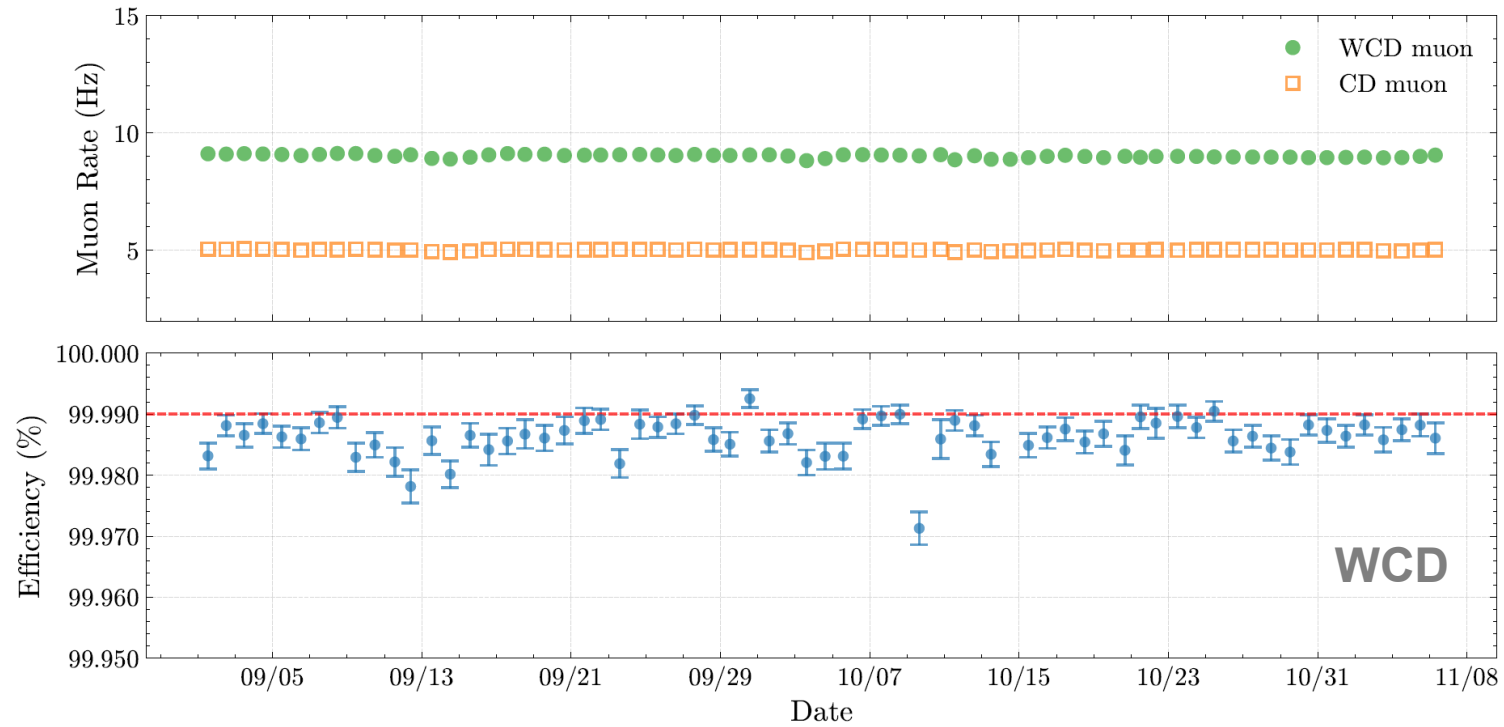
$$E_{\text{rec}} = \underbrace{k}_{\text{absolute scale}} \underbrace{[1 + f(E)]}_{\text{non-linearity}} E_{\text{true}}$$

□ Energy scale is known to 0.5%

- ❖ Good spatial uniformity
- ❖ Consistent energy response between calibration data and IBD candidates



Muon Veto



Muon tagging:

❑ WCD

❖ Cherenkov light

❖ 9 Hz

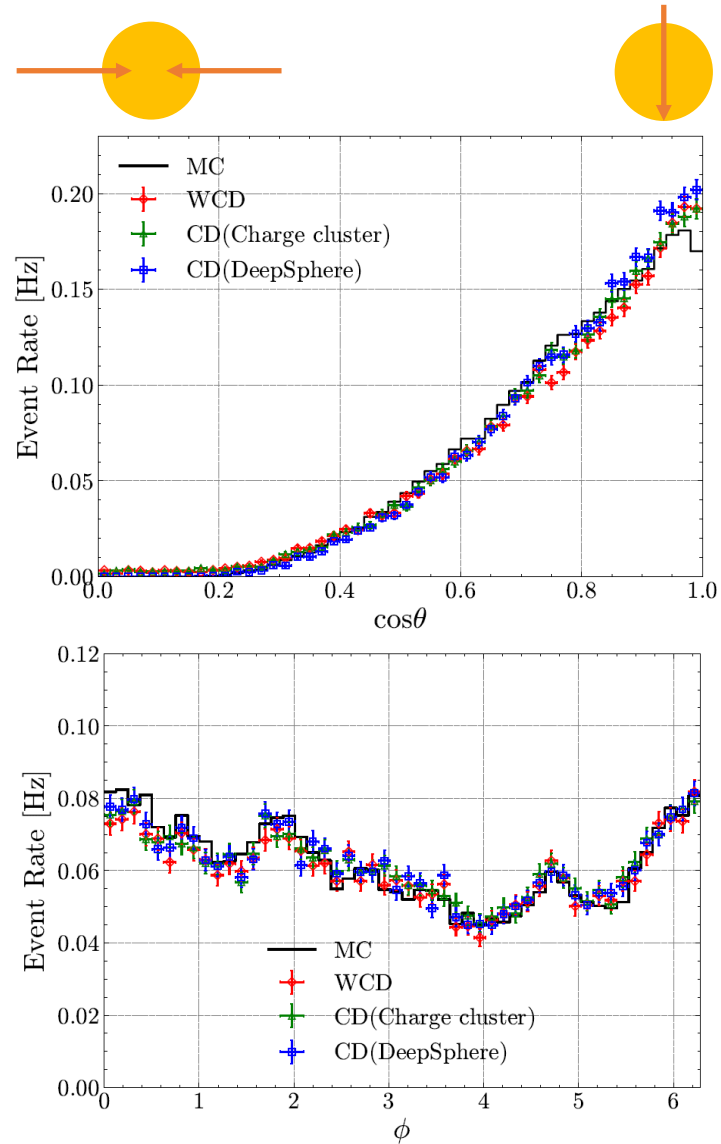
❑ CD

❖ Very large and track-like energy deposition

❖ 5 Hz

❑ Stable performance and almost 100% tagging efficiency in WCD

Muon Veto



Single muon reconstruction

□ WCD and CD reconstruction consistent with MC

❖ Normalisation and shape

❖ Validating models of muon flux and rock overburden

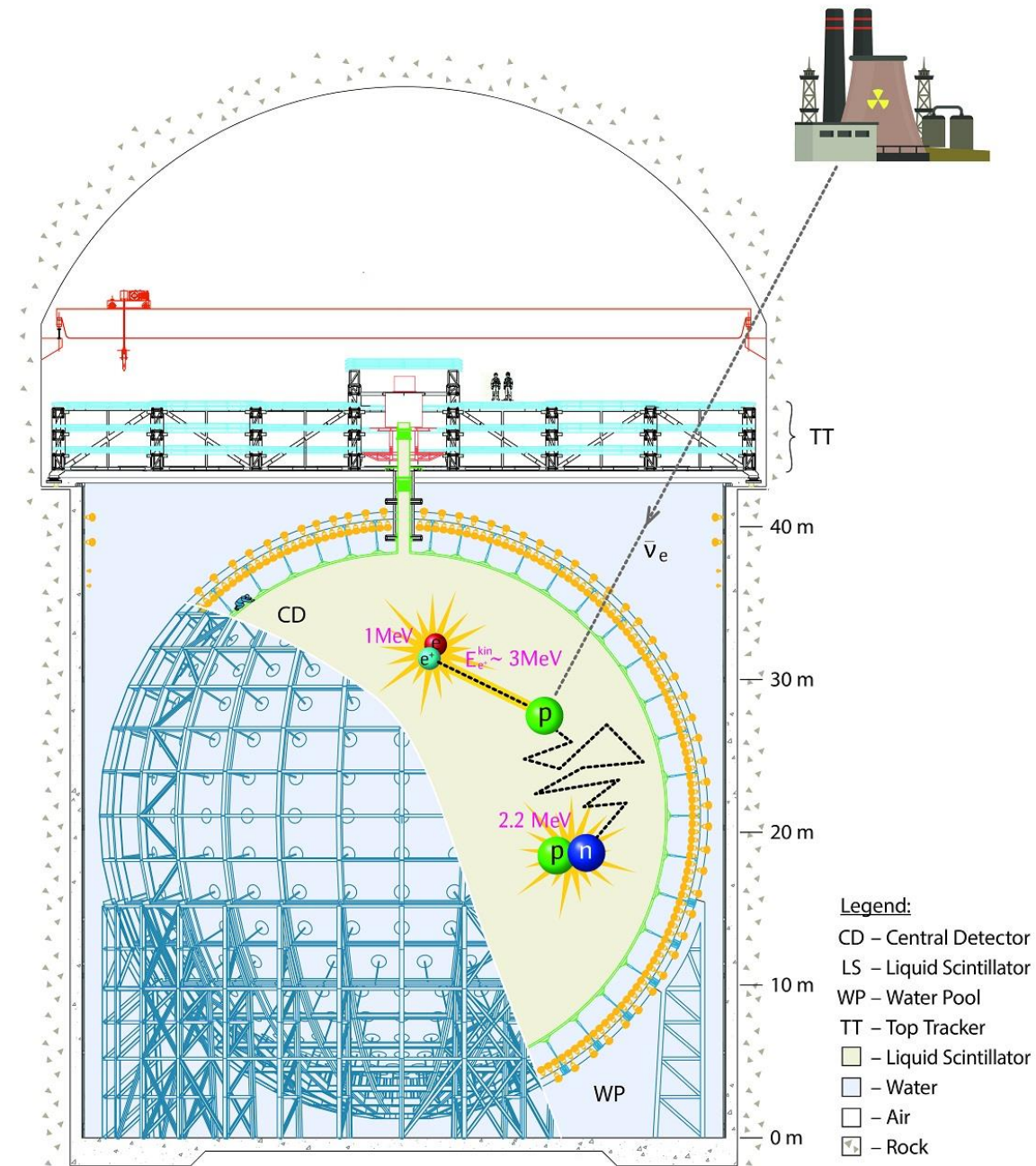
Event Selection

Background

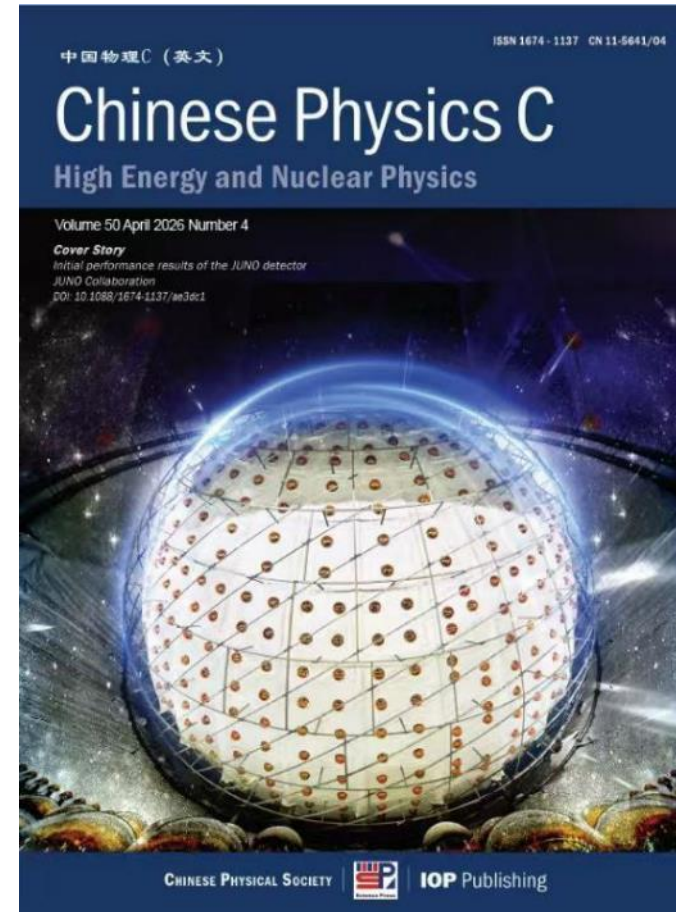
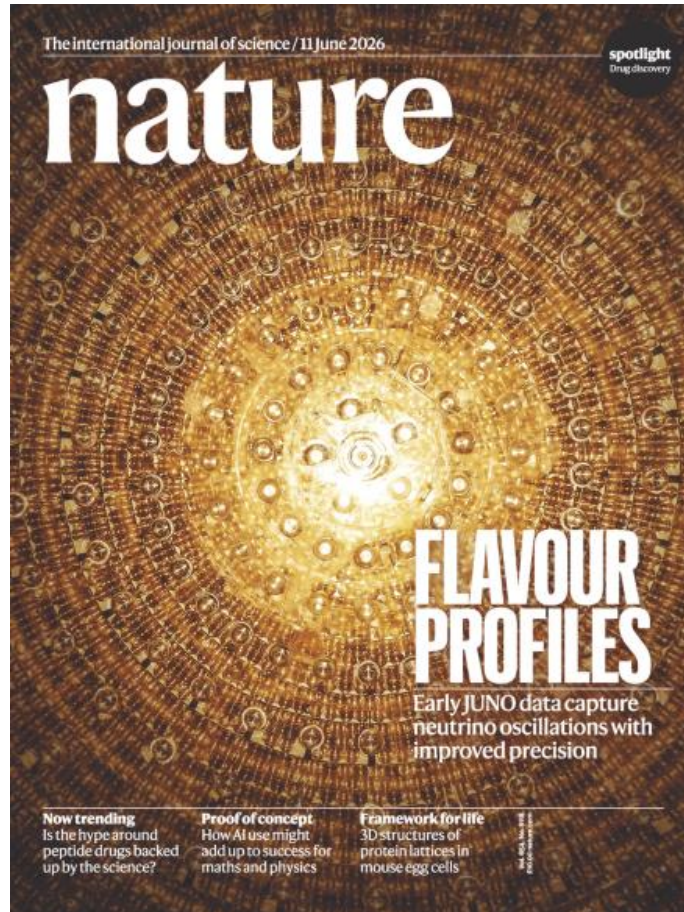
- ❑ Cosmogenic spallation products
 - ❖ $^9\text{Li}/^8\text{He}$: β -n decay most dangerous
- ❑ Natural radioactivity
- ❑ Geoneutrinos from decay of U/Th
- ❑ World reactors

Event selection

- ❑ Fiducial volume cut
 - ❖ Remove events near CD boundary where external backgrounds enters; to keep the best performance region only
- ❑ PMT flasher rejection
 - ❖ Remove events produced by flashing PMTs
- ❑ Muon veto
 - ❖ Remove events after a cosmic-ray muon
 - ❖ Spallation neutron space-time veto
- ❑ Multiplicity cut
 - ❖ Remove events with more than 2 triggers expected for IBD
- ❑ Triple coincidence for IBD

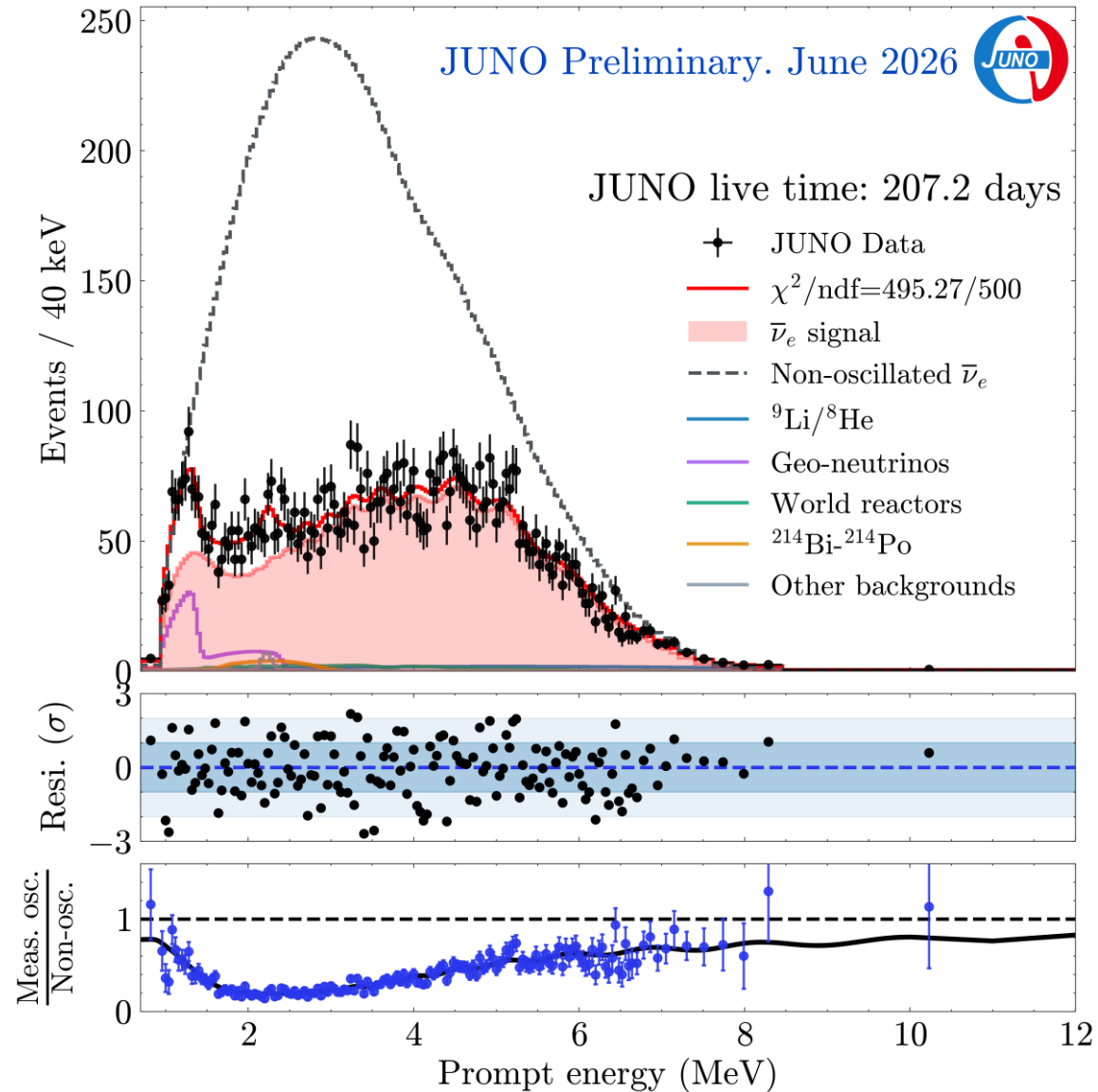


First JUNO results using 59 days of data recently published



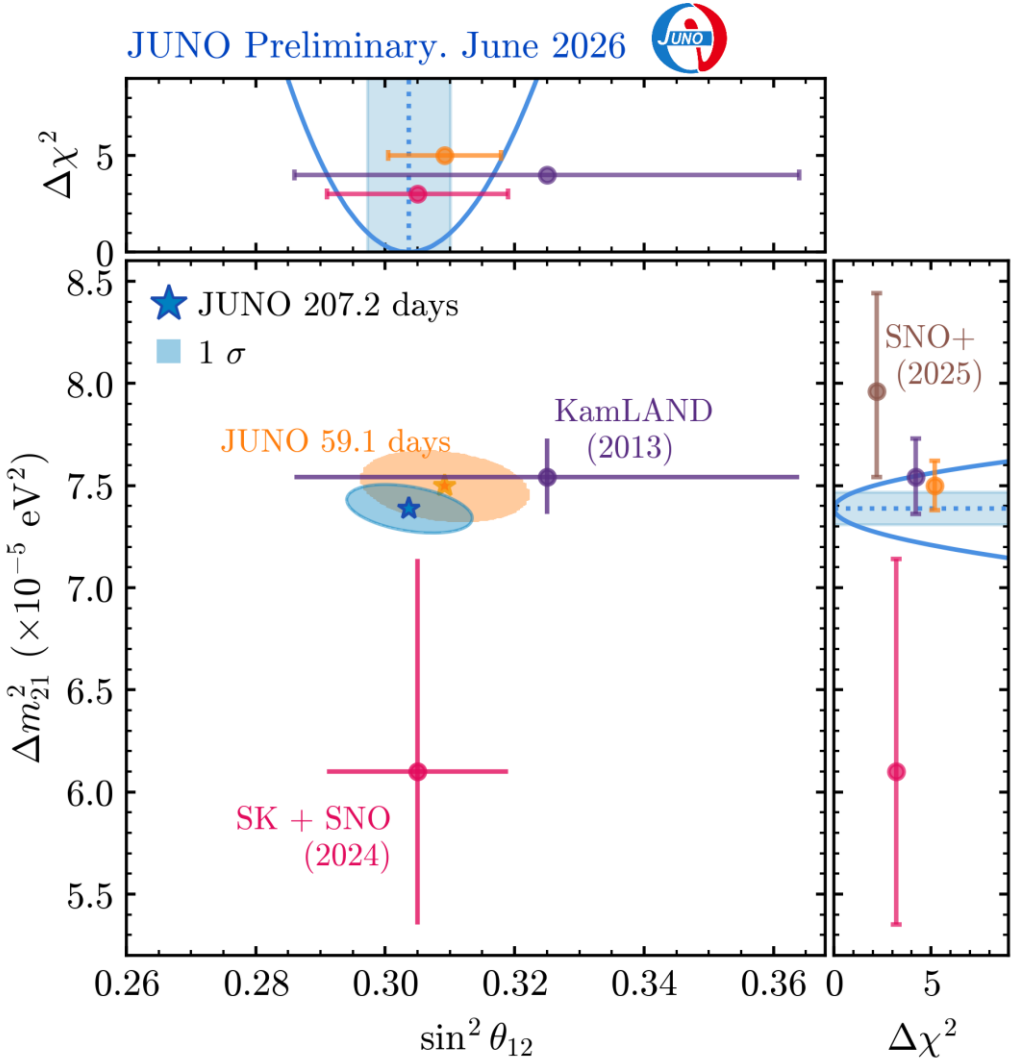
New results released in June 2026 with 207 days of data

Reactor $\bar{\nu}_e$ Energy Spectrum at JUNO



- Fitting constrained by the near detector spectra from TAO and Daya Bay (PRL 130 16, 161802)
- Consistent results from three independent analyses

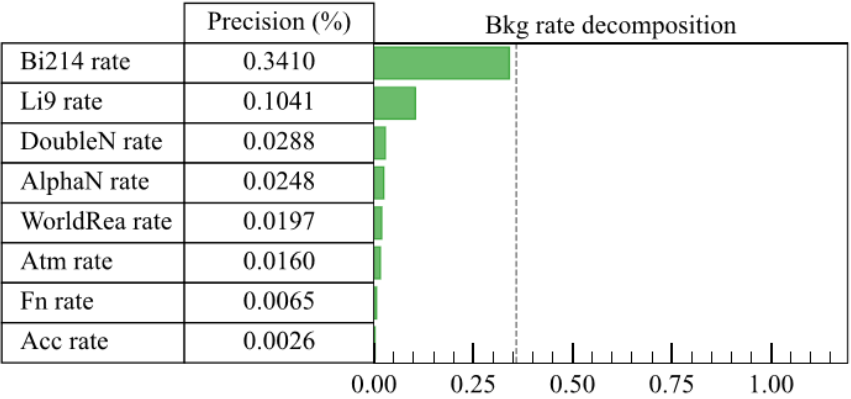
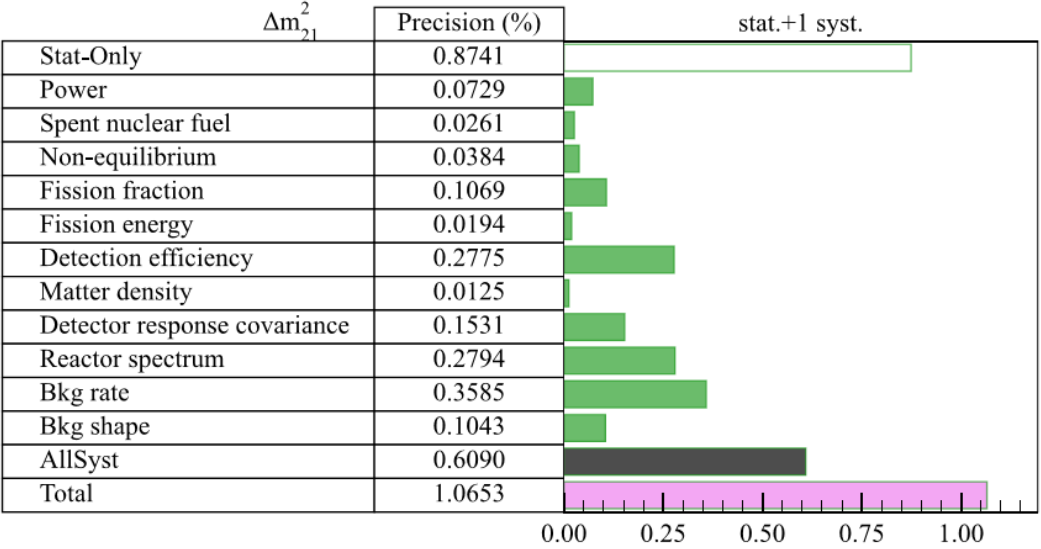
JUNO's New Results of Solar Mixing Parameters



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%)

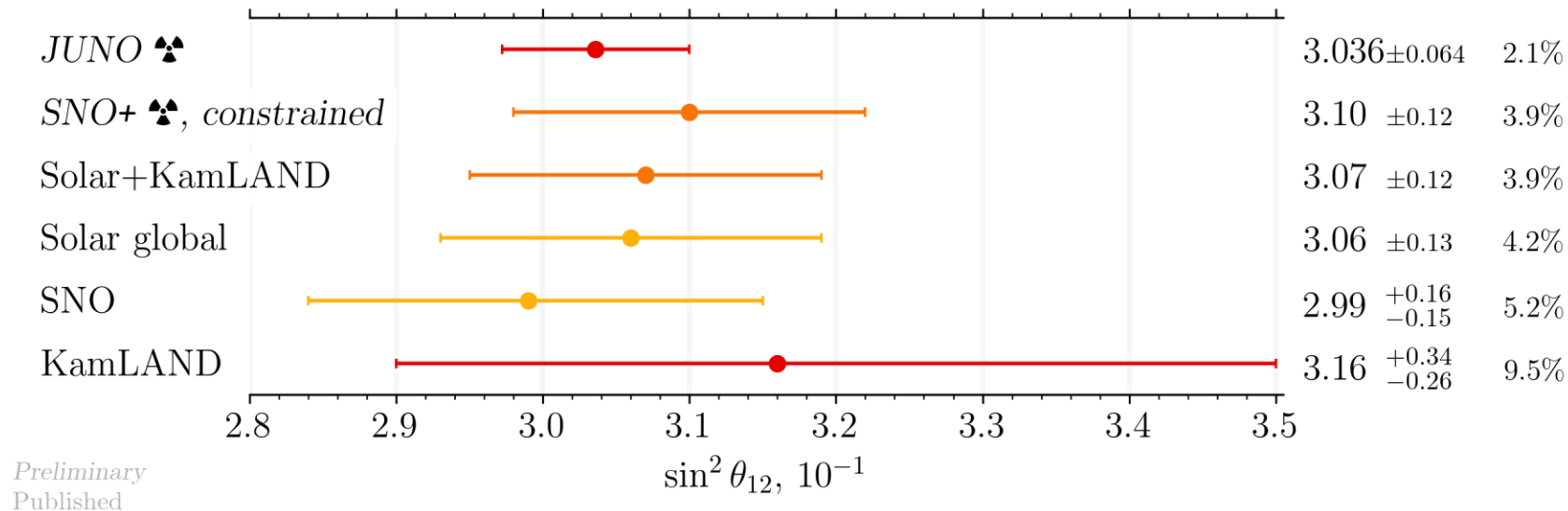
2026 October 2, Manchester

- Even though the statistical uncertainty is dominant, systematic errors become important:
 - ²¹⁴Bi background and detection eff. can be improved

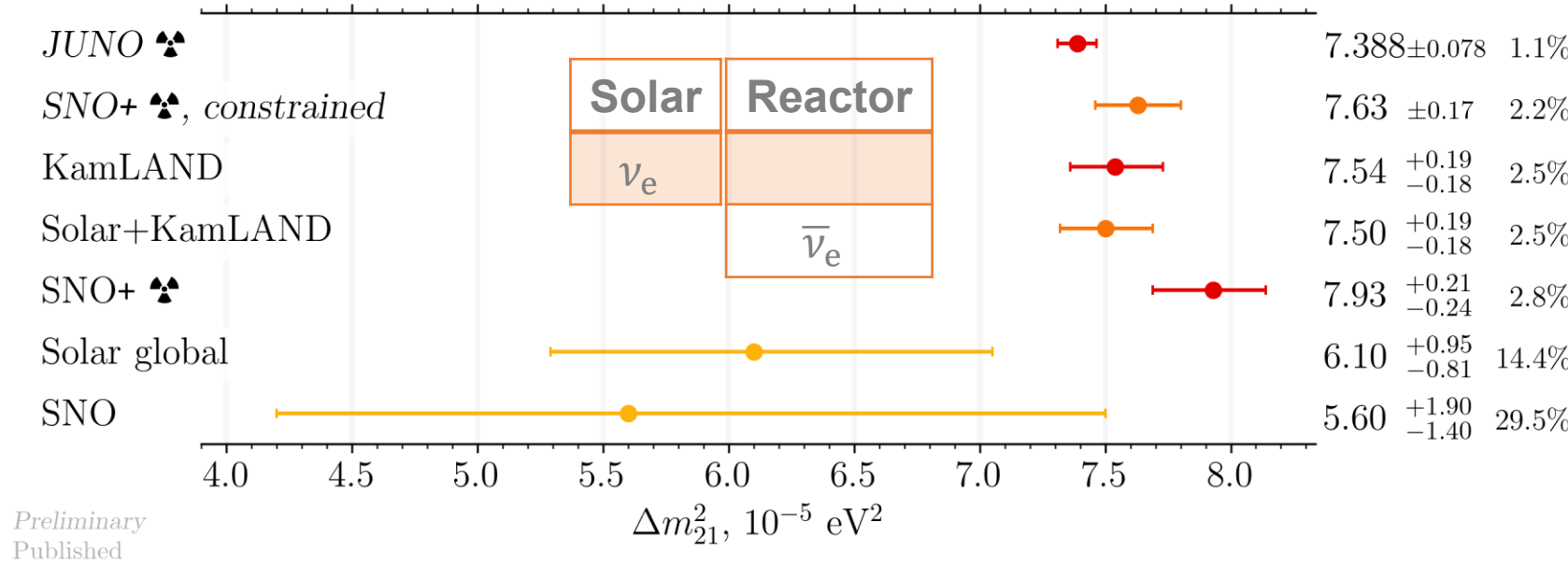


Stat-Only: JUNO+TAO+DYB; Free GeoNu rate; JUNO 207.2 d, TAO 31.3 d

JUNO's New Results of Solar Mixing Parameters



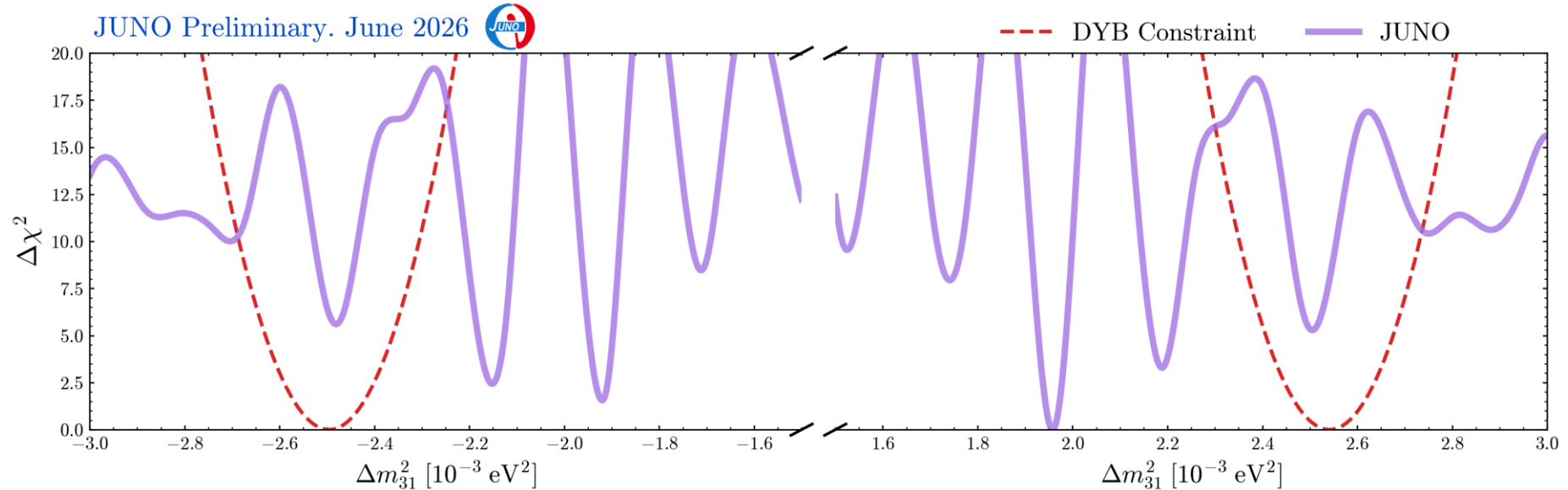
v9 2026.06 github.com/nu-osc/plots



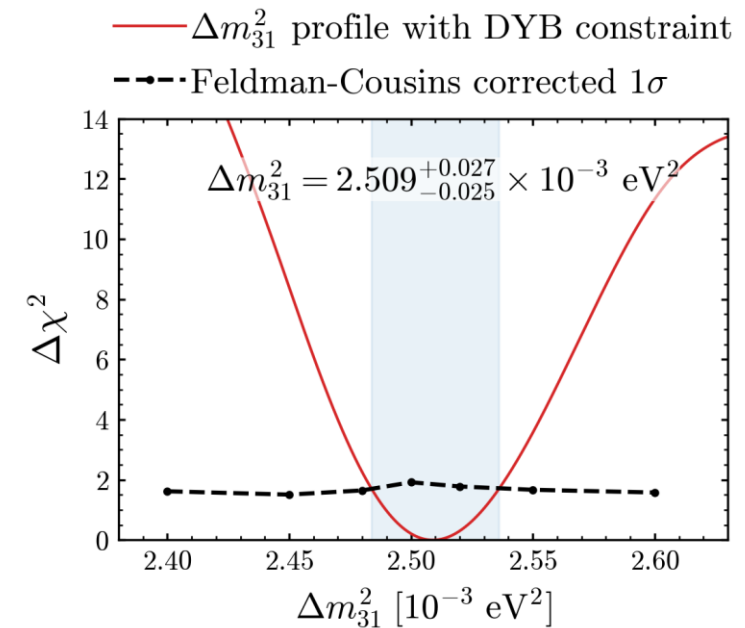
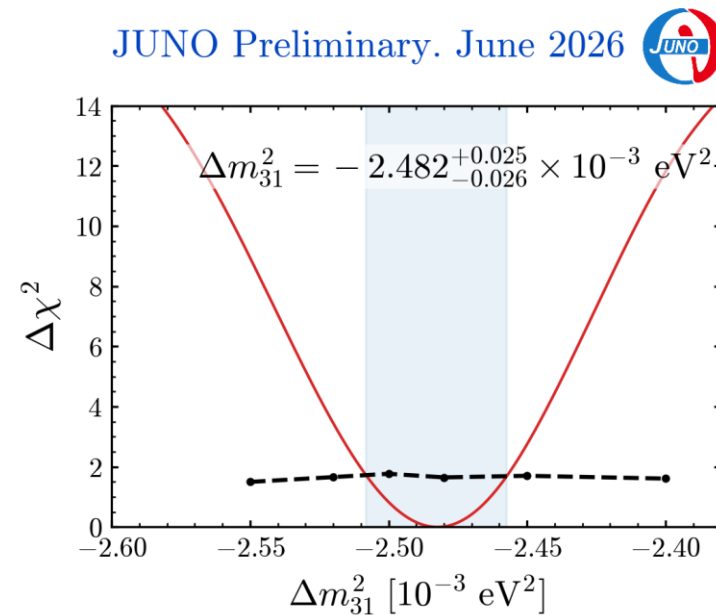
v11 2026.06 github.com/nu-osc/plots

JUNO First Measurement of Δm_{31}^2

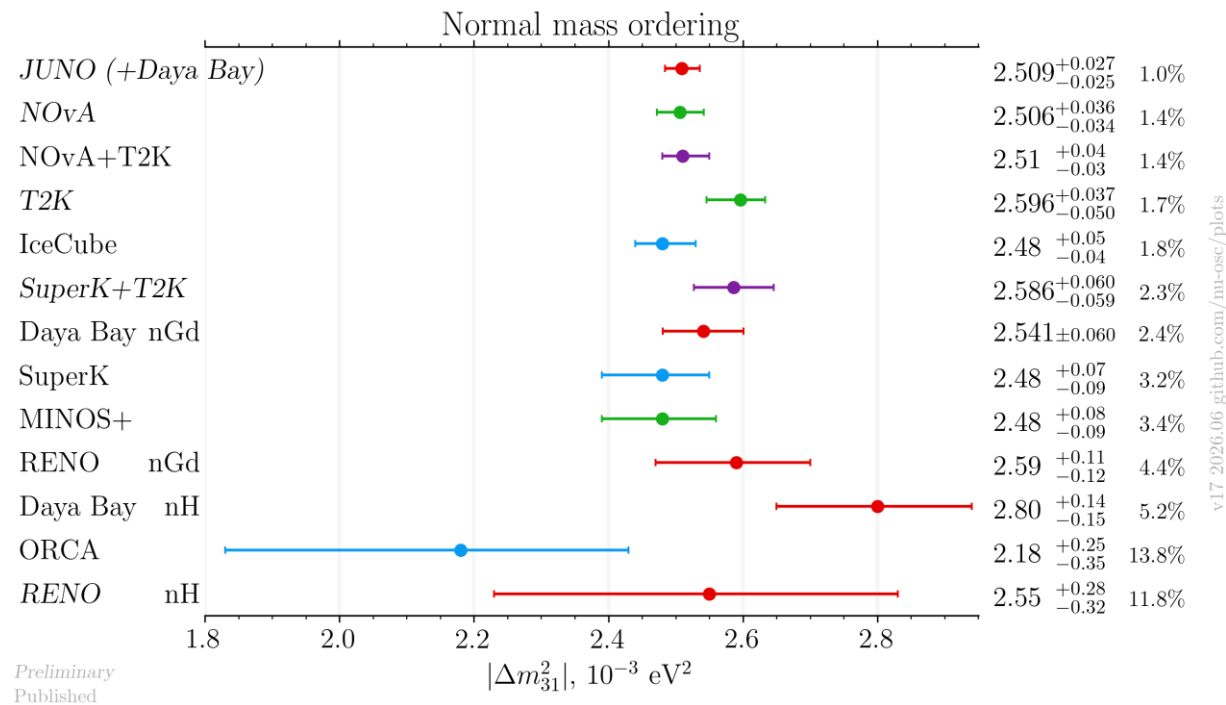
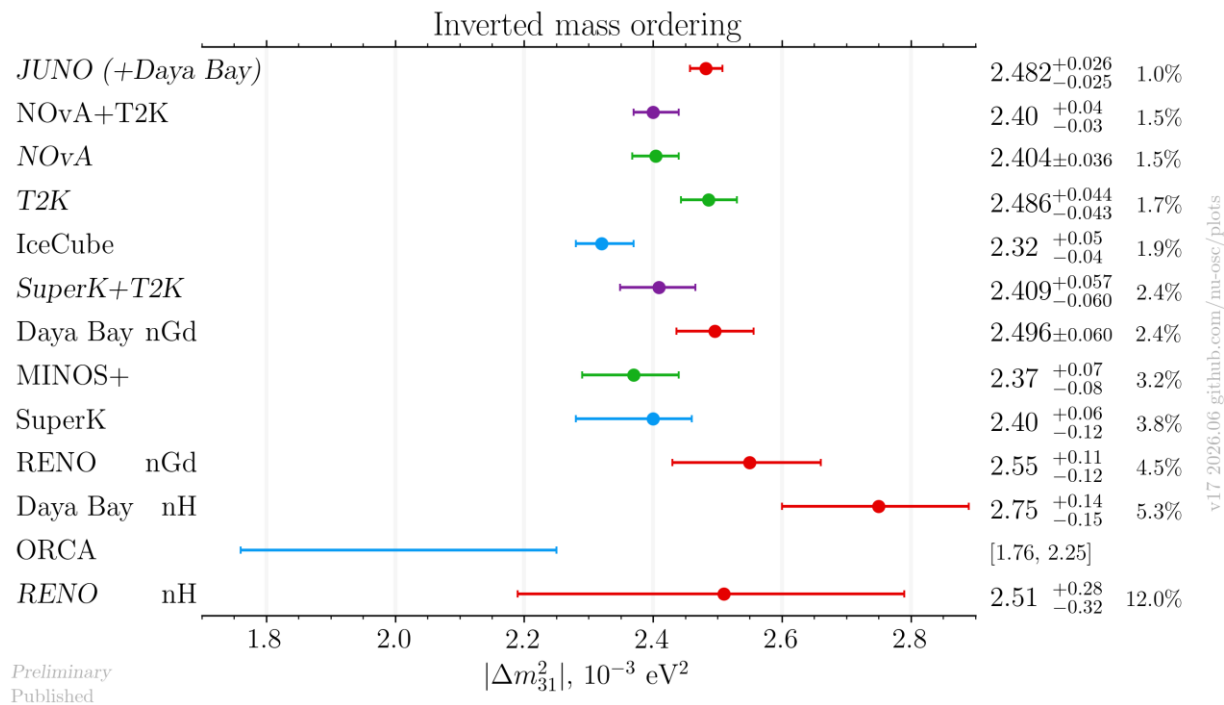
- Due to statistical fluctuations, JUNO-only profiles of Δm_{31}^2 have multiple minima



- The final minimum for each mass ordering is obtained by using the Δm_{31}^2 constraint from the Daya Bay result (PRL 130 16, 161802)
- Feldman-Cousins (FC) method is used to determine the 1σ range of Δm_{31}^2 : $\sim 1\%$ precision achieved



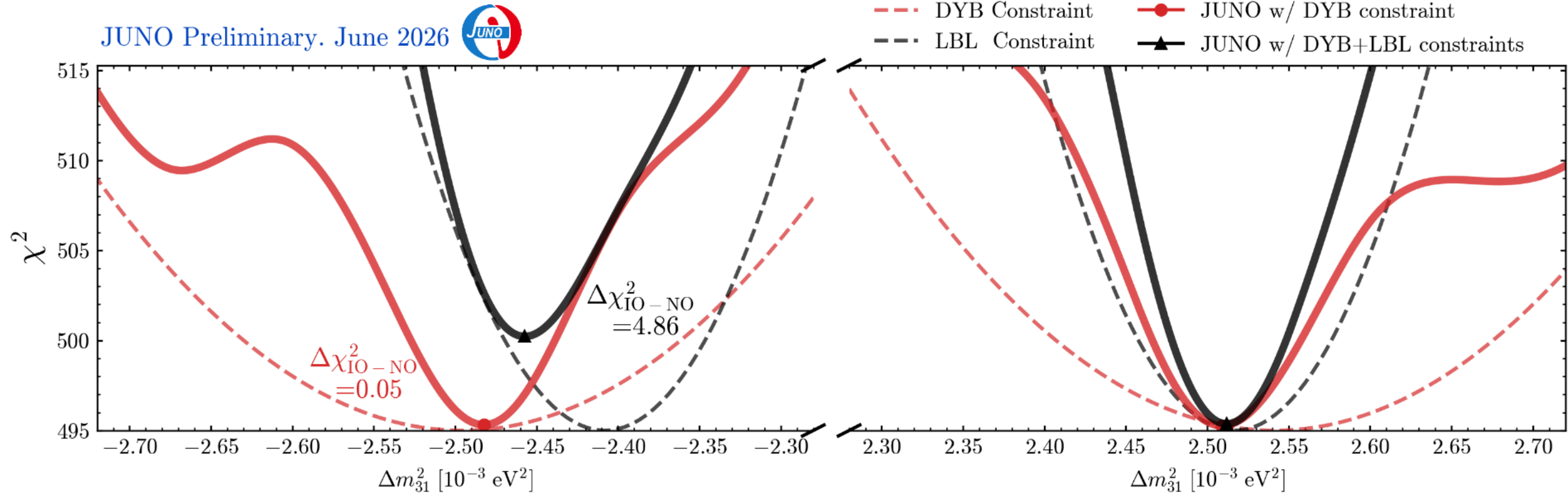
JUNO First Measurement of Δm_{31}^2



➤ Results from JUNO have smallest uncertainties

JUNO First Measurement of Δm_{31}^2

- 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)

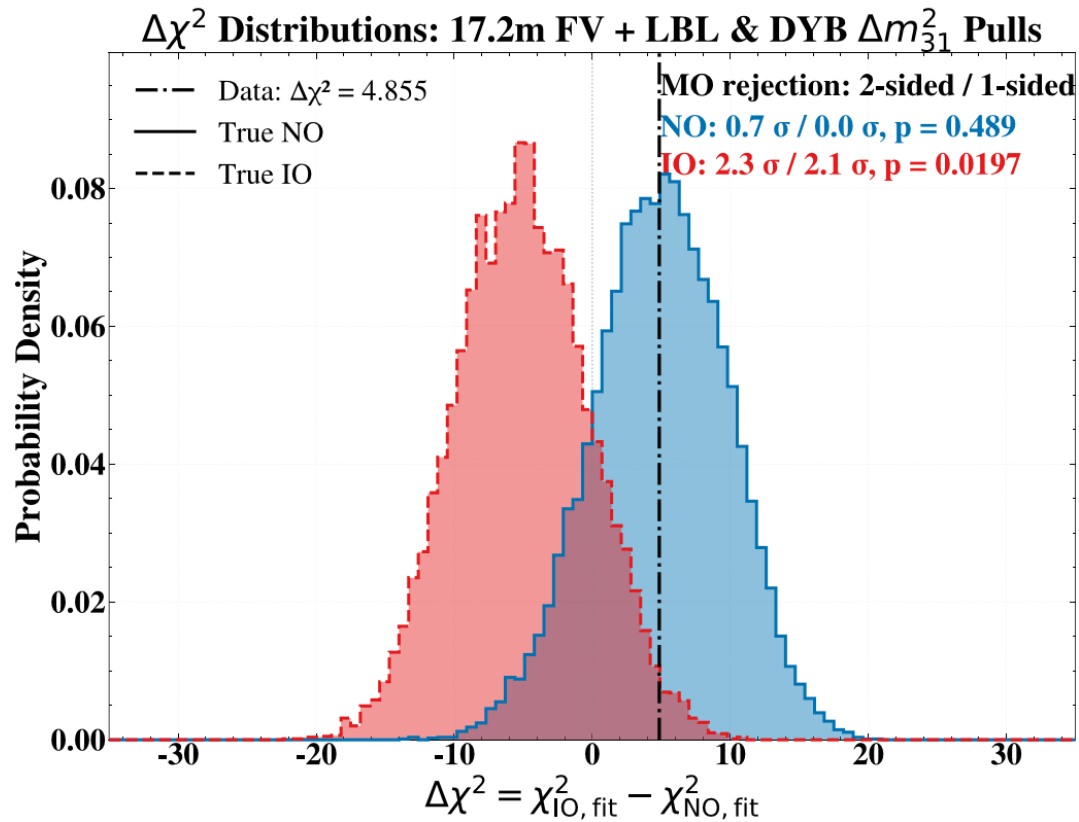
[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

JUNO's Neutrino Mass Ordering Significance

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

- ❑ Bayesian approach using Markov Chain Monte Carlo (MCMC) method
- ❑ Normal Ordering is favored with a Bayes factor of **10.18**
→ $2\ln \kappa = 4.64$, consistent with the frequentist $\Delta\chi^2$

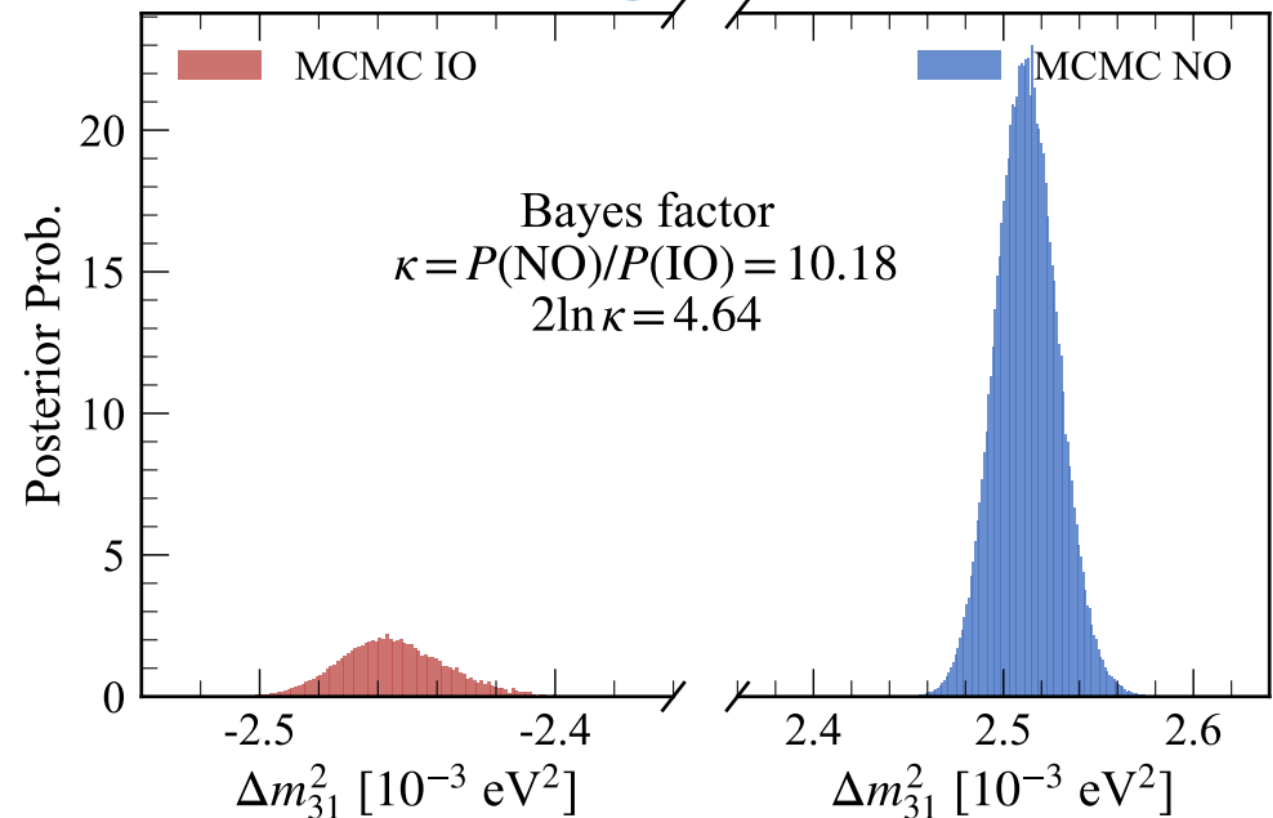
JUNO Preliminary. June 2026



JUNO Preliminary. June 2026



w/ DYB and NuFit-LBL const.



Neutrino Oscillations in 2026

Normal ordering is favoured, with fit-dependent significance

Valencia

2.7σ

[Beccaria, NOW2026](#), w/ JUNO 59 days

NuFIT 7 prelim.

$\Delta\chi^2 \approx 11.6$

[Martinez-Soler, NOW2026](#), w/ JUNO 207 days

Bari prelim.

4.0σ

[Marcone, NOW2026](#), w/ JUNO 207 days

An Observatory for 30 Years

[JUNO, J.Phys.G 43, 030401 (2016)]
[JUNO, Prog.Part.Nucl.Phys. 123,103927 (2022)]

Earth



~400/year

Sun



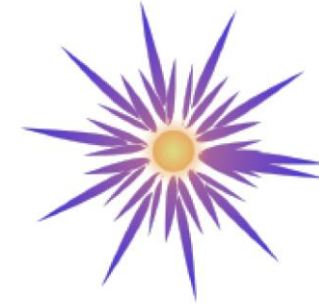
>100/day

Atmosphere



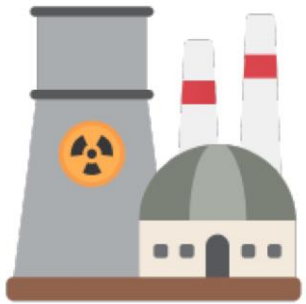
>100/year

Supernovae



~10⁴/10 s @ 10kpc

Reactor



~60/day

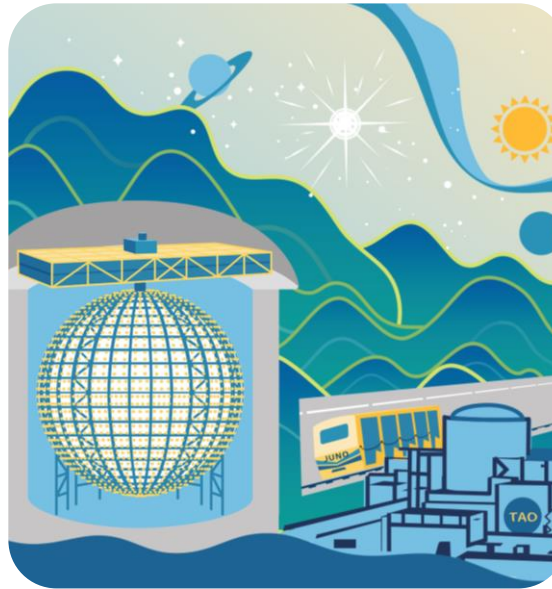


Image by CAS, published by China Daily

LU Xianguo 卢显国, Warwick

More!! (BSM)

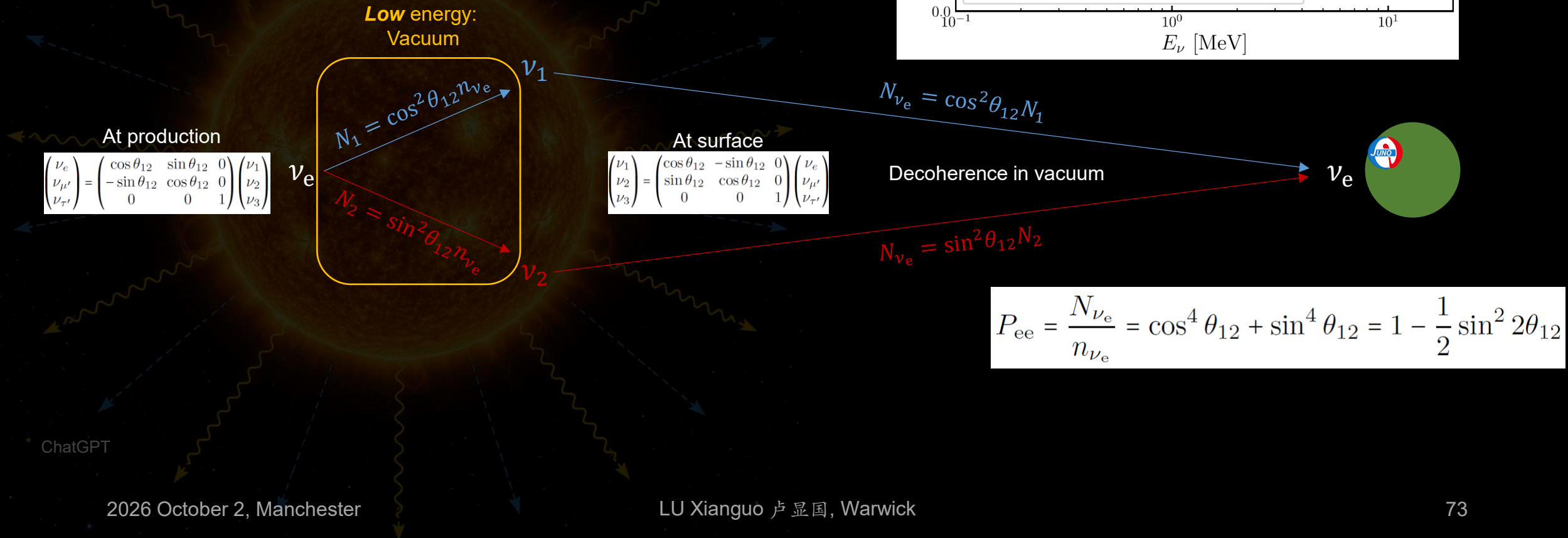
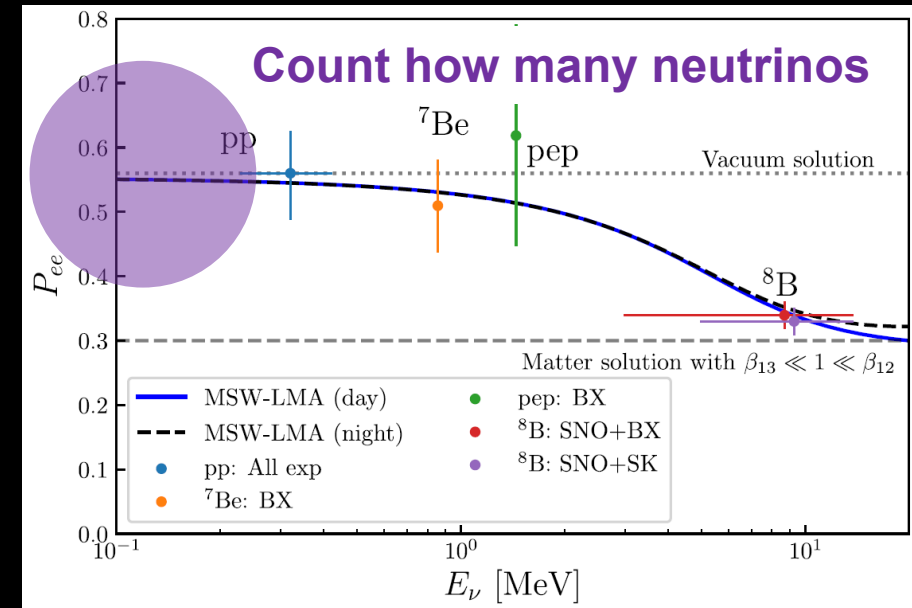


2026 October 2, Manchester

Cartoon from Barbara Caccianiga@INFN- Milano

Mixing of Solar Neutrinos

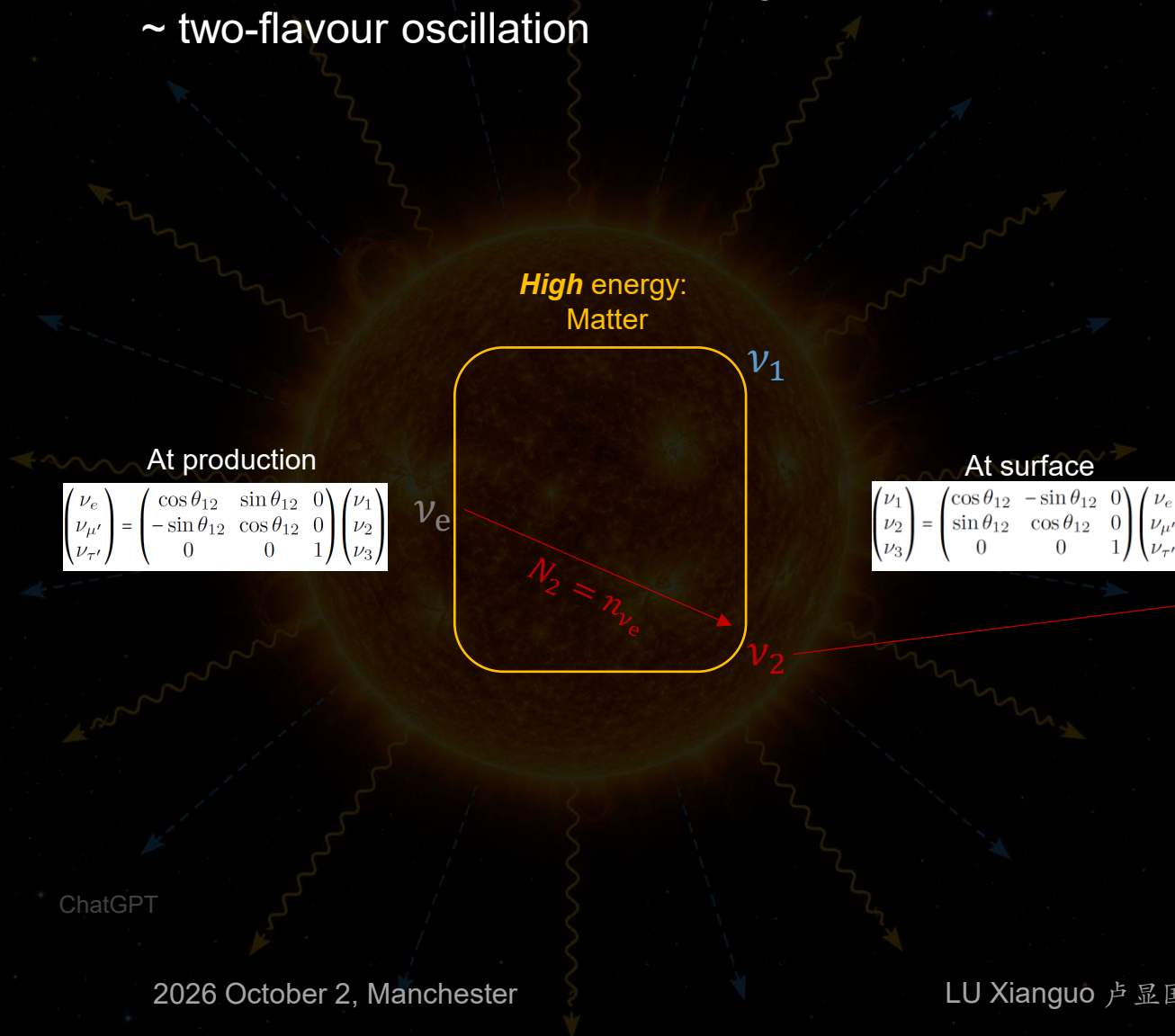
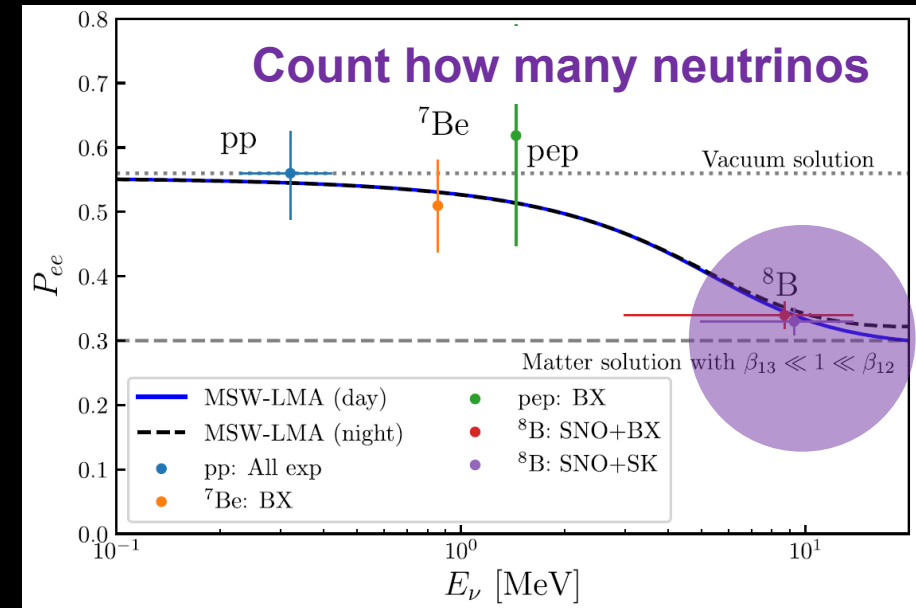
- Insensitive to μ - and τ -flavours, $\theta_{13} \approx 0$
 $\sim$ two-flavour oscillation



$$P_{ee} = \frac{N_{\nu_e}}{n_{\nu_e}} = \cos^4 \theta_{12} + \sin^4 \theta_{12} = 1 - \frac{1}{2} \sin^2 2\theta_{12}$$

Mixing of Solar Neutrinos

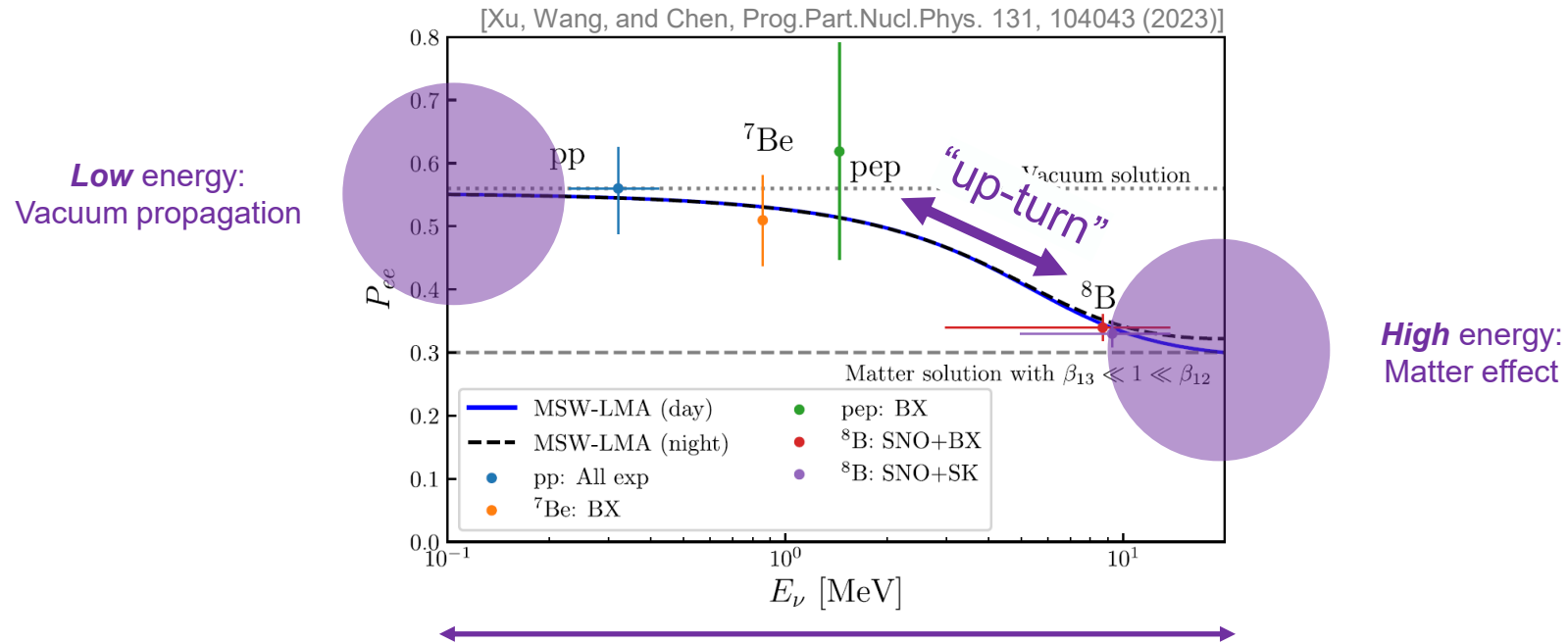
- Insensitive to μ - and τ -flavours, $\theta_{13} \approx 0$
 $\sim$ two-flavour oscillation



Decoherence in vacuum



Mixing of Solar Neutrinos

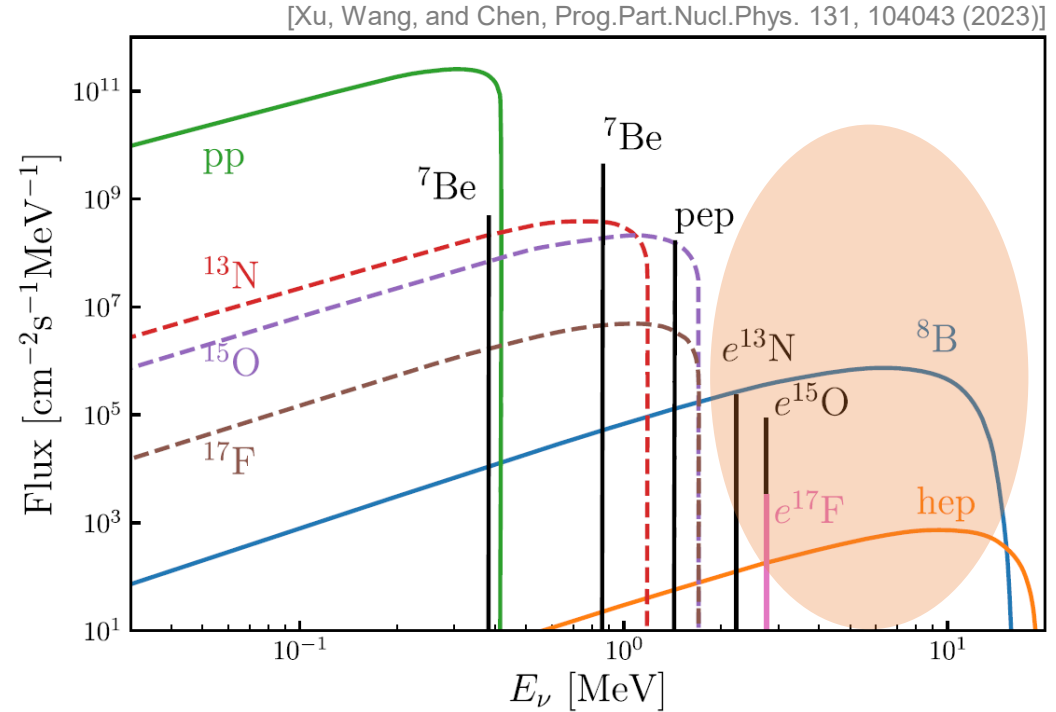
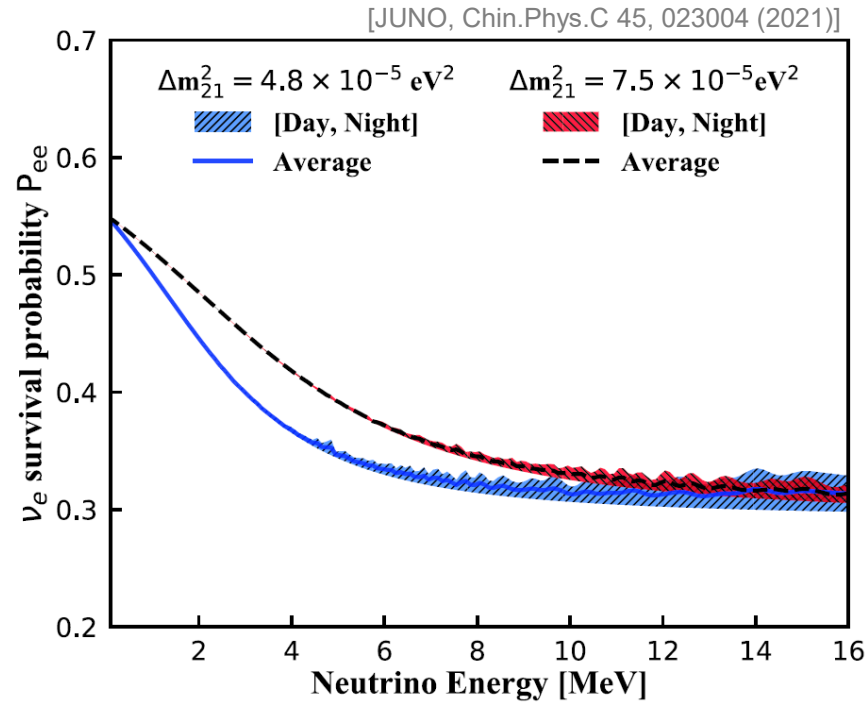


□ Insensitive to μ - and τ -flavours, $\theta_{13} \approx 0$
~ two-flavour oscillation

$$\begin{pmatrix} \nu_e \\ \nu_{\mu'} \\ \nu_{\tau'} \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

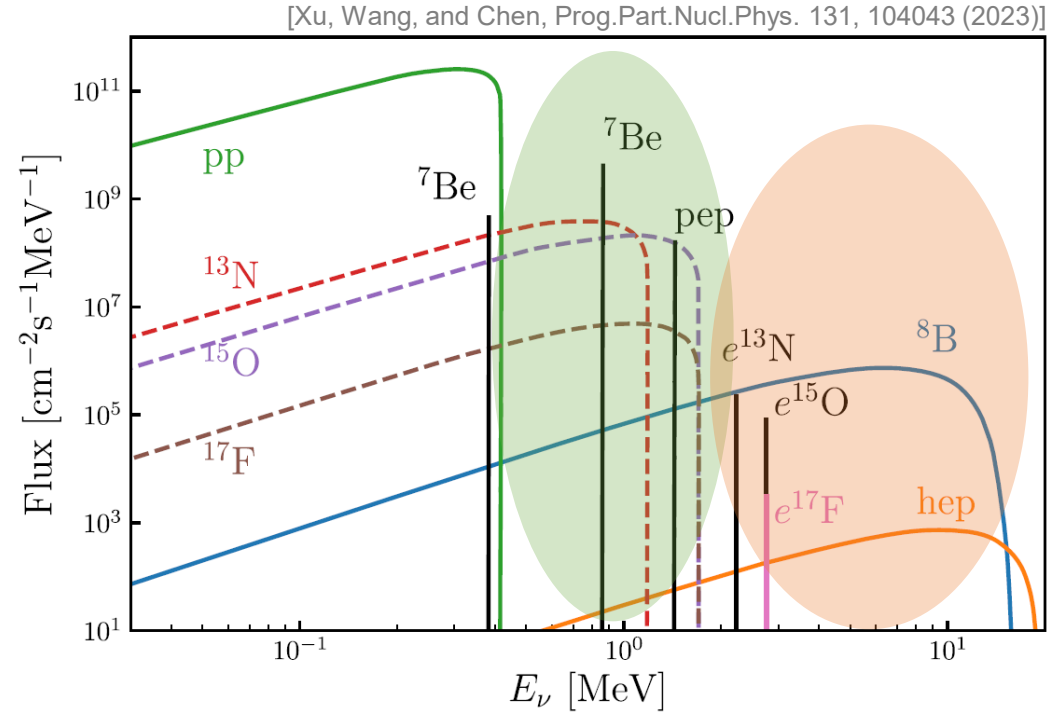
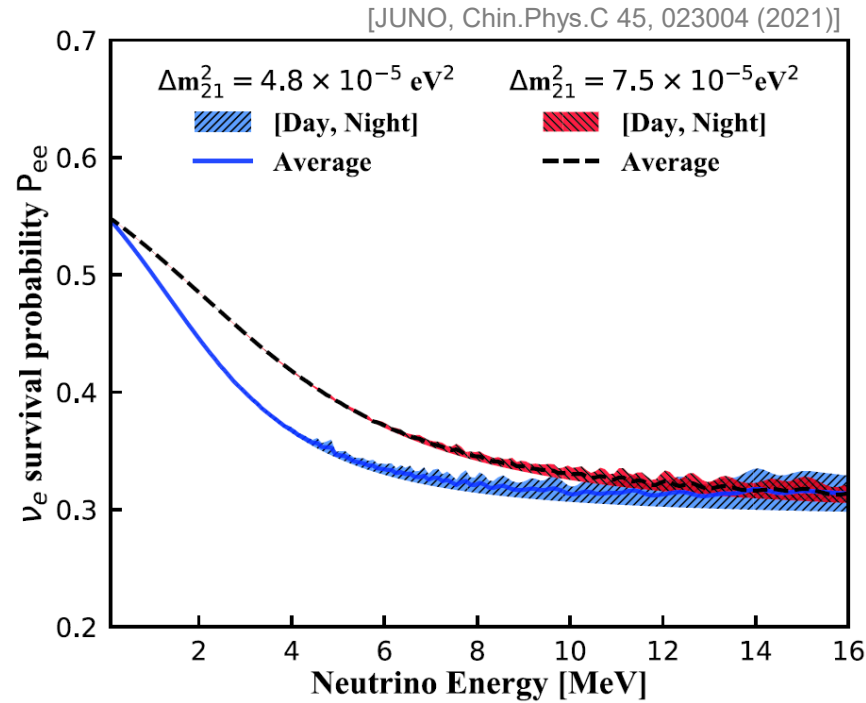
- How high is high?
- The only energy scale in this two-flavour mixing: Δm_{21}^2
- Stretching between limits, aka “up-turn”, tell us about Δm_{21}^2

Solar Neutrinos at JUNO



- Up-turn-sensitive energy with ${}^8\text{B}$
 - ❖ Reactor-solar consistency test of solar mixing/oscillations in a *single* experiment (matter effects, ν vs. $\bar{\nu}$, new physics, etc.)

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- ❑ CNO neutrinos to probe the Sun [JUNO, JCAP 10, 022 (2023)]
- ❑ Solar only ν , not $\bar{\nu}$
 - ❖ No reaction on hydrogen nor carbon: only ES on electron (+ %-level CC/NC w/ carbon)
 - ❖ No IBD coincidence: demanding on background (internal, cosmogenic) control

Beyond the Oscillation Measurements: JUNO- $\beta\beta$

Table 1. Comparison of the parameters of the assumed JUNO Xe-LS detector and KamLAND-Zen detector.

[Zhao *et al.*, Chin.Phys.C 41, 053001 (2017)]

	KamLAND-Zen	JUNO Xe-LS
energy resolution	6.6%/ $\sqrt{E}$ [10] 7.3%/ $\sqrt{E}$ [17]	3%/ $\sqrt{E}$
Xe-doping	2.5% (phase I [10]) 2.9% (phase II [17])	5%
^{136}Xe enrichment	$\sim 91\%$ [10, 17]	80%
$0\nu\beta\beta$ ROI	(2.3, 2.7) MeV [17]	(2403, 2513) keV
$\varepsilon_{0\nu\beta\beta}$ in ROI	89.9%*	75.8%

*corresponding to $\sigma \sim 7.3\%\sqrt{E}$ resolution

❑ After JUNO oscillation measurements, search for $0\nu\beta\beta$ will be the next focus

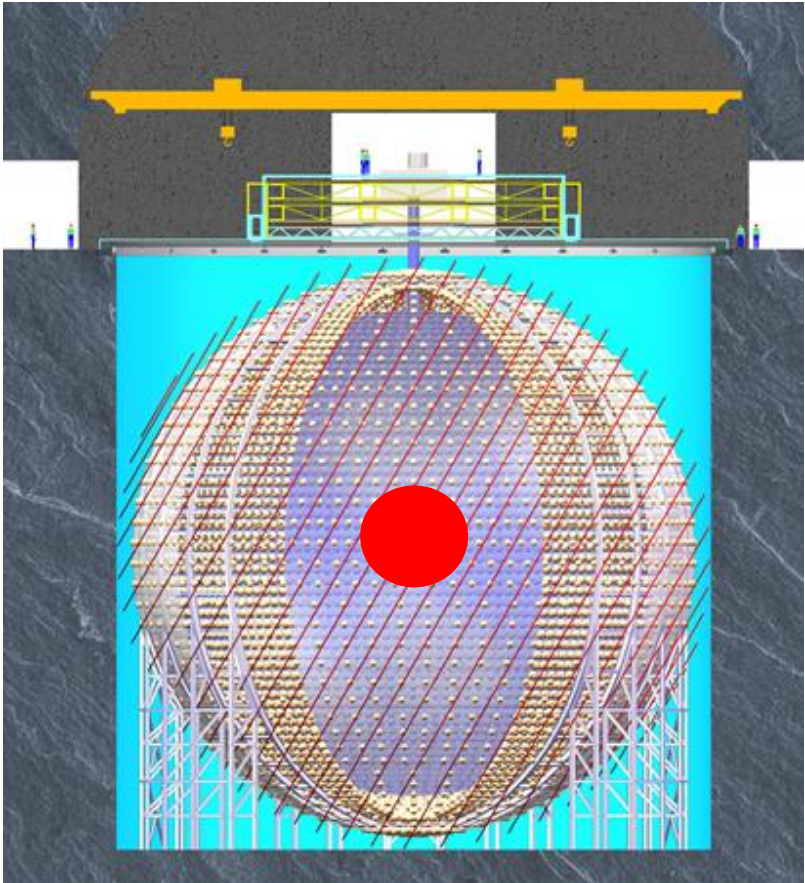


Figure from Yifang Wang, FNAL seminar, April 2025

❑ Future upgrade: Insert a balloon filled with ^{136}Xe -loaded LS (or ^{130}Te) into JUNO CD

[Zhao *et al.*, Chin.Phys.C 41, 053001 (2017)]

Summary and Outlook

- ❖ After 13 years of efforts, from idea to construction, JUNO detector is fully completed, despite numerous challenges (water in the excavation, covid...)
 - The Collaboration is very excited to have started the physics data taking
- ❖ First JUNO physics result with 60 days of data: world-leading measurement of the solar mixing parameters ($\sin^2\theta_{12}$ and Δm_{21}^2).
- ❖ Demonstrates precision reactor neutrino measurements with a 20-kton liquid-scintillator detector at a 52.5 km baseline.
- ❖ Validates detector performance: calibration strategy, energy response, and background control required for precision oscillation measurements.
 - Key specifications have been mostly met.
- ❖ Precision of solar oscillation parameters further improved
- ❖ First measurement on Δm_{31}^2 achieved a precision of **~1%**
- ❖ With external constraint, **Normal Mass Ordering** is favored at **~2.3 σ**
- ❖ Enables a diverse neutrino programme in the next 30 years



The 27th JUNO Collaboration Meeting
Wuhan University

