



The Jiangmen Underground Neutrino Observatory (JUNO): Status and First Physics Results

LU Xianguo 卢显国

University of Warwick

On behalf of the JUNO Collaboration

江門中微子實驗

EPP Seminar

2026 May 28, Warwick

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?

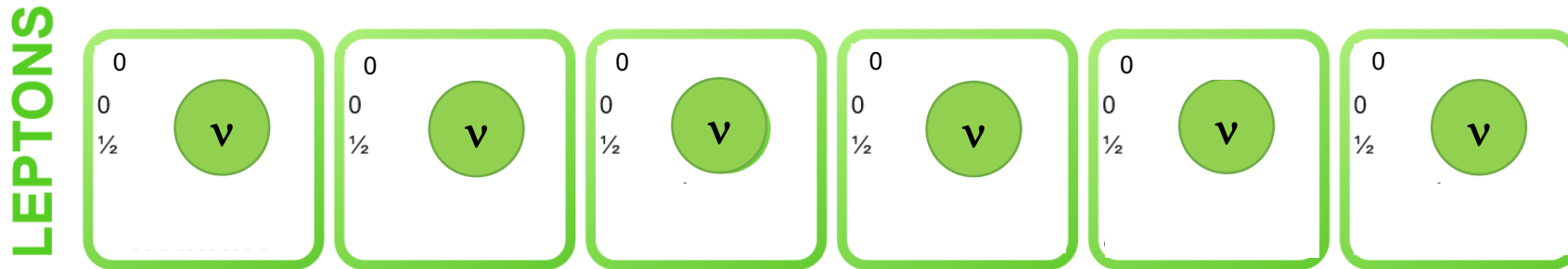


Image source: Wikipedia

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

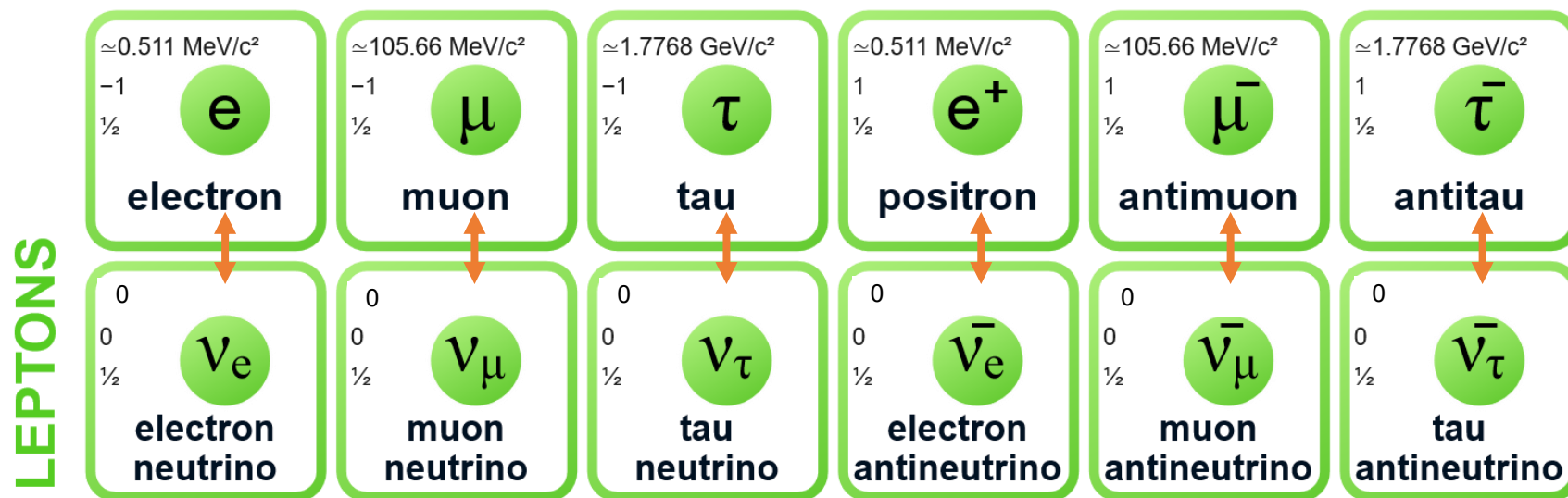
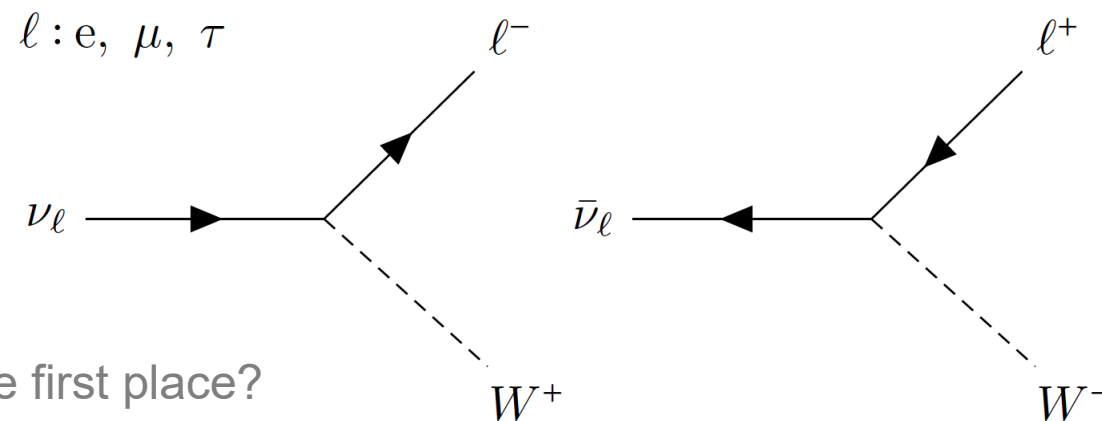


Image source: Wikipedia

Neutrino's *Two Faces*

Neutrinos and antineutrinos in *Nature*

1. Charge neutral
2. ~~Massless~~ turns out to be tiny but not zero!
 - ❖ 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

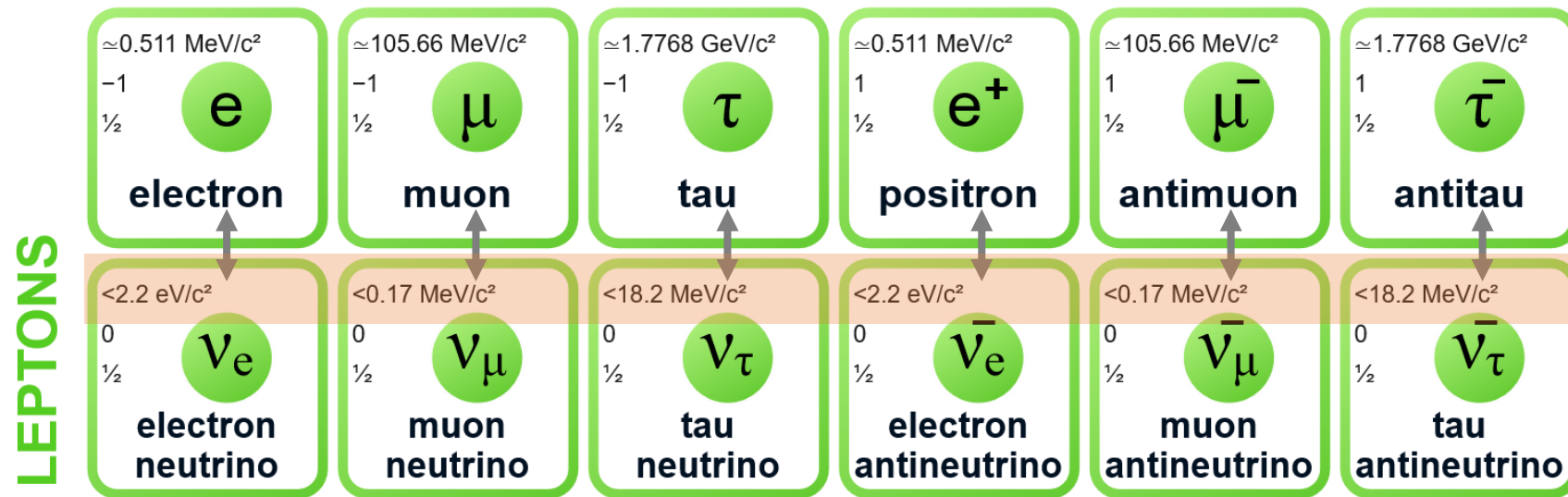


Image source: Wikipedia

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

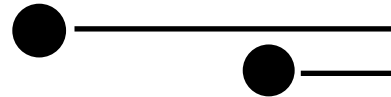
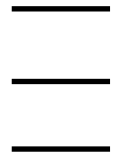
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

$$\text{PMNS matrix}$$

Mass “levels”

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

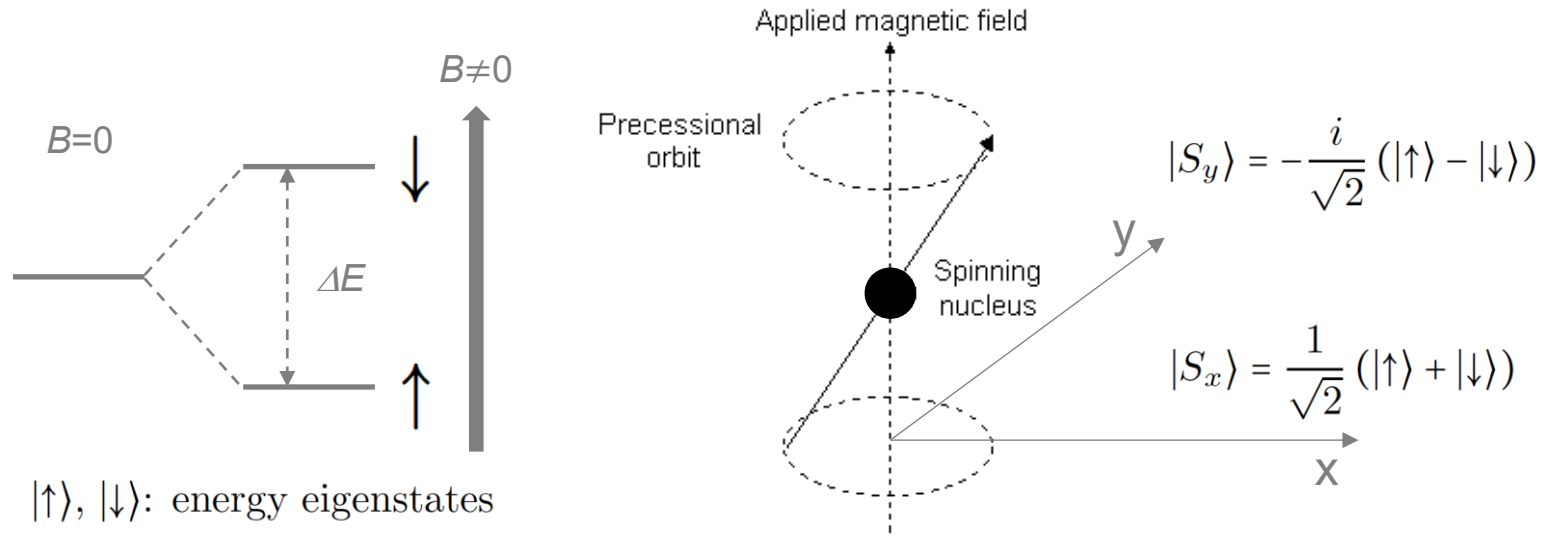


Normal / Inverted
Mass Ordering (MO, or Hierarchy)

A problem only when there are more than 2 masses!

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

Analogy: spin rotation in a magnetic field



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

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

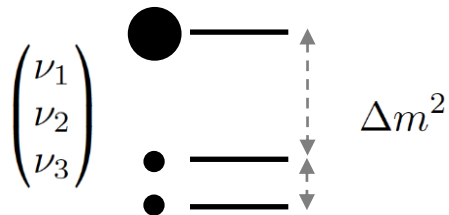
$$P_{S_x \rightarrow S_y}(t) = \sin^2 \frac{\Delta E}{2} t$$

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

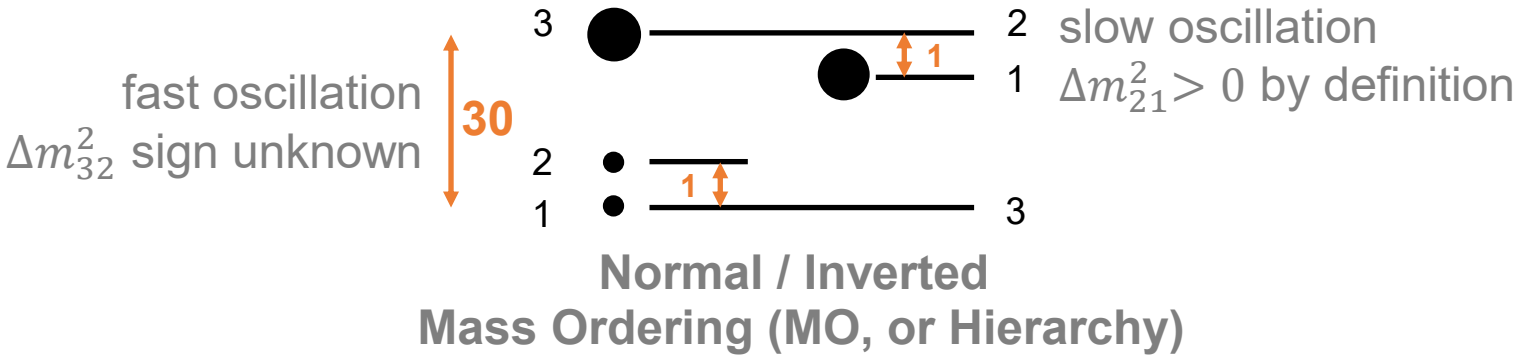
Beyond Standard Model

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

Pontecorvo–Maki–Nakagawa–Sakata
PMNS matrix

Mass “levels”

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



Neutrino Mass and Mixing

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

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

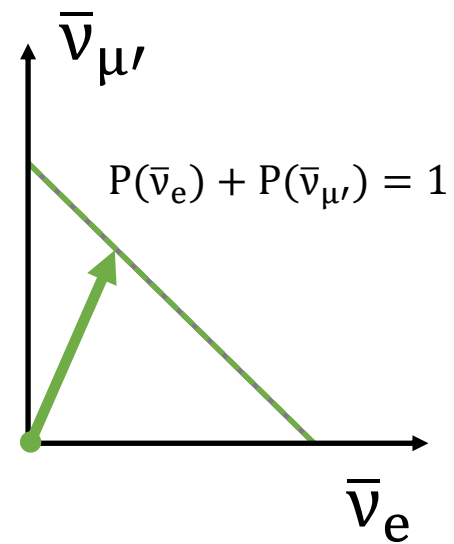
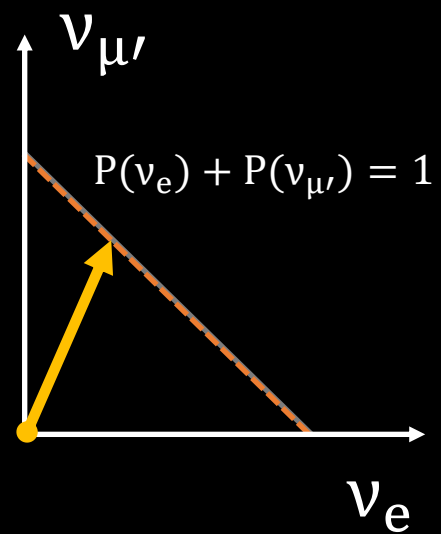
θ_{12} : mixing between ν_1 and ν_2

θ_{23} : mixing between ν_μ and ν_τ

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

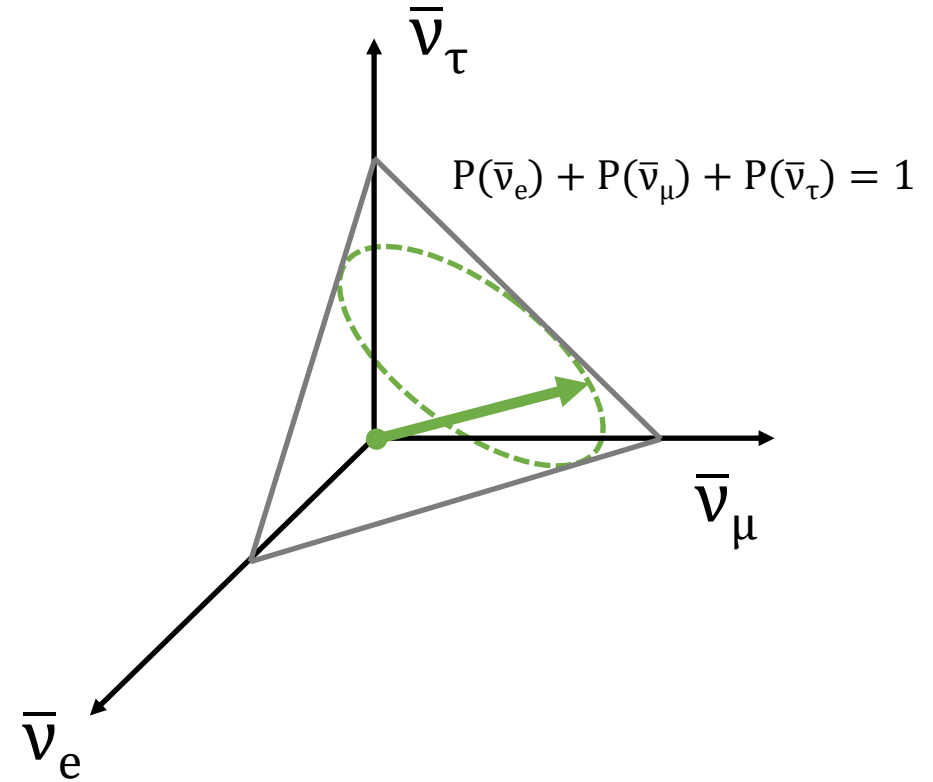
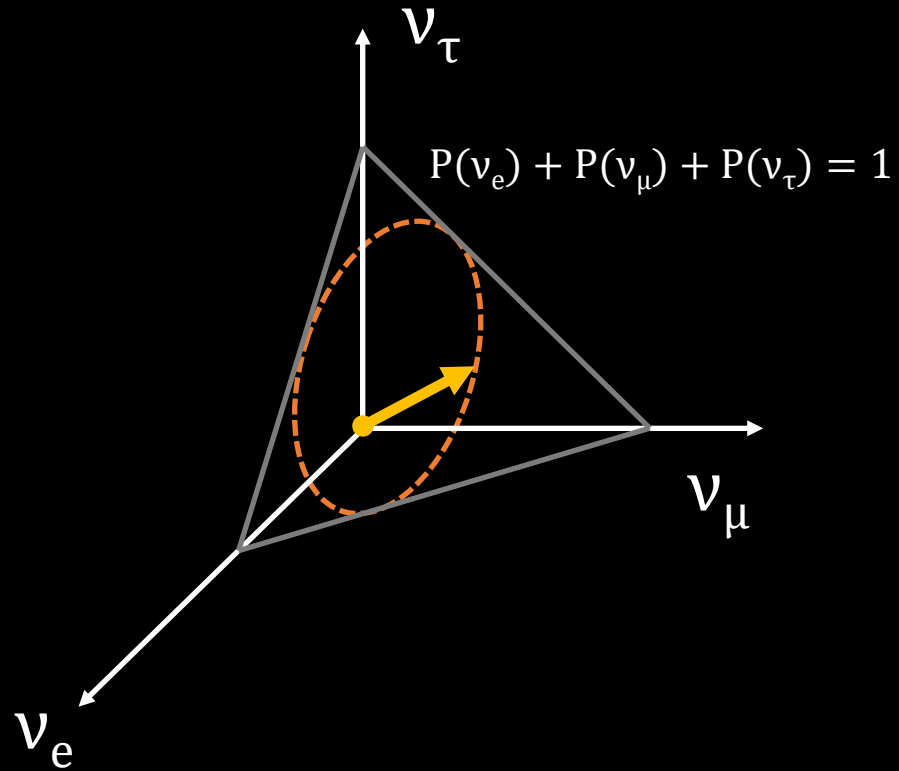
$$\begin{pmatrix} \nu_e \\ \nu_{\mu'} \\ \nu_{\tau'} \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

2-flavor oscillation



Oscillation as a function of *time*
line-in-**line** $\rightarrow$ same trivia

3-flavor oscillation



Oscillation as a function of *time*
 line-in-plane $\rightarrow$ CP-violation possible

Neutrino Mass and Mixing

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

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

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

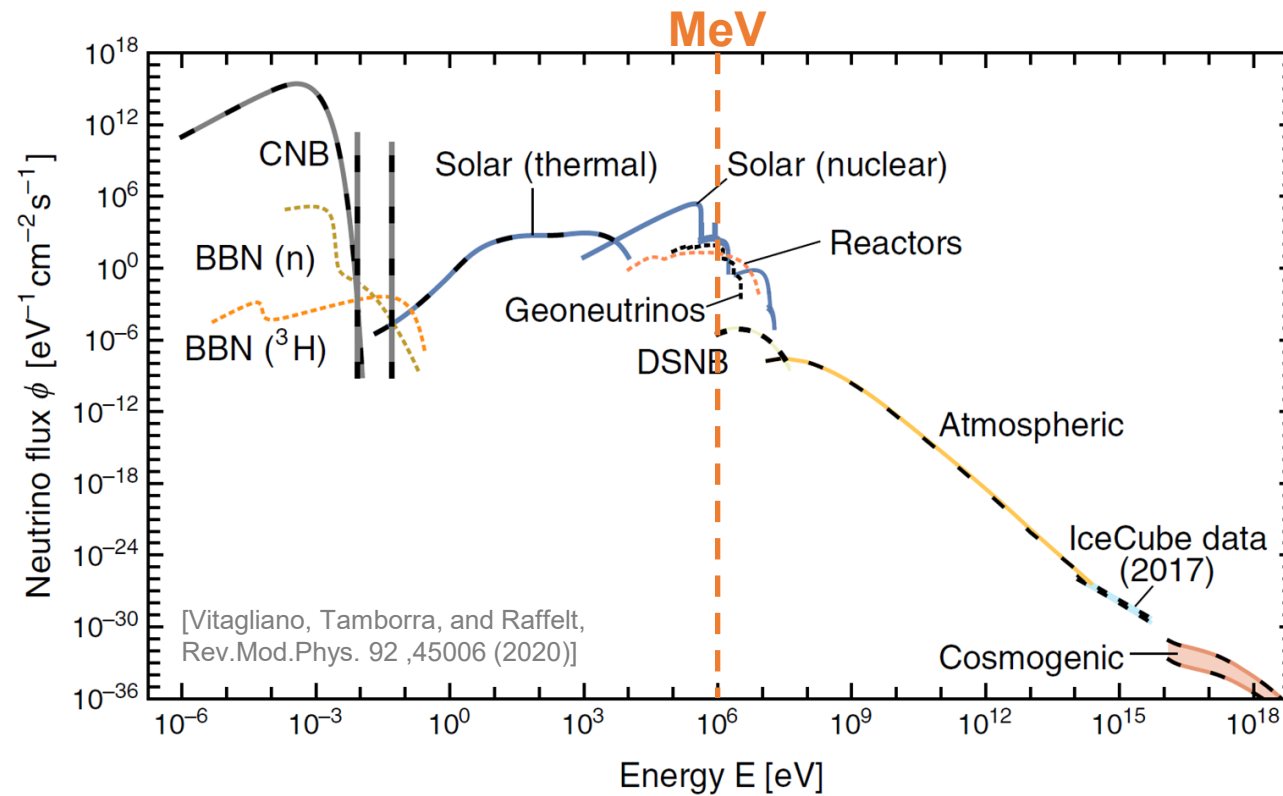
θ_{12} : mixing between ν_1 and ν_2

θ_{23} : mixing between ν_μ and ν_τ

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

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

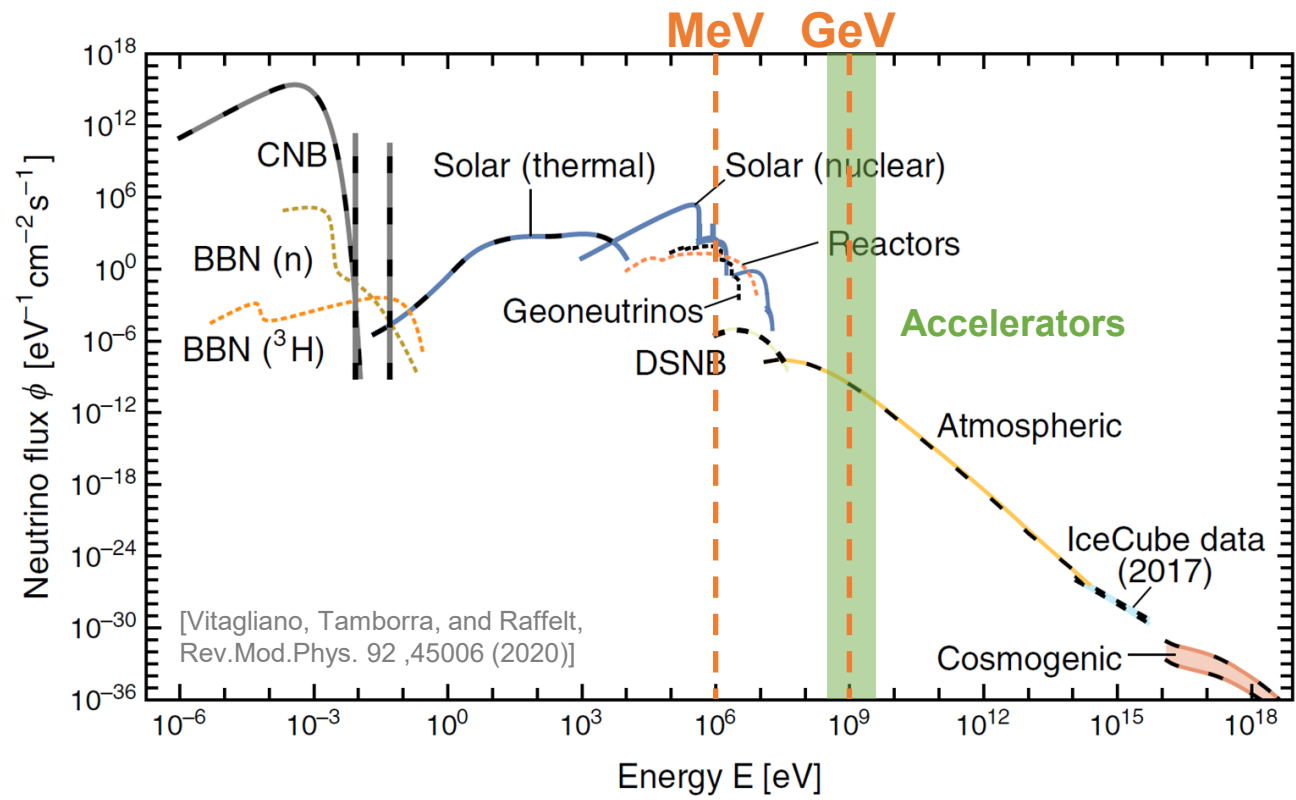
Neutrino Sources



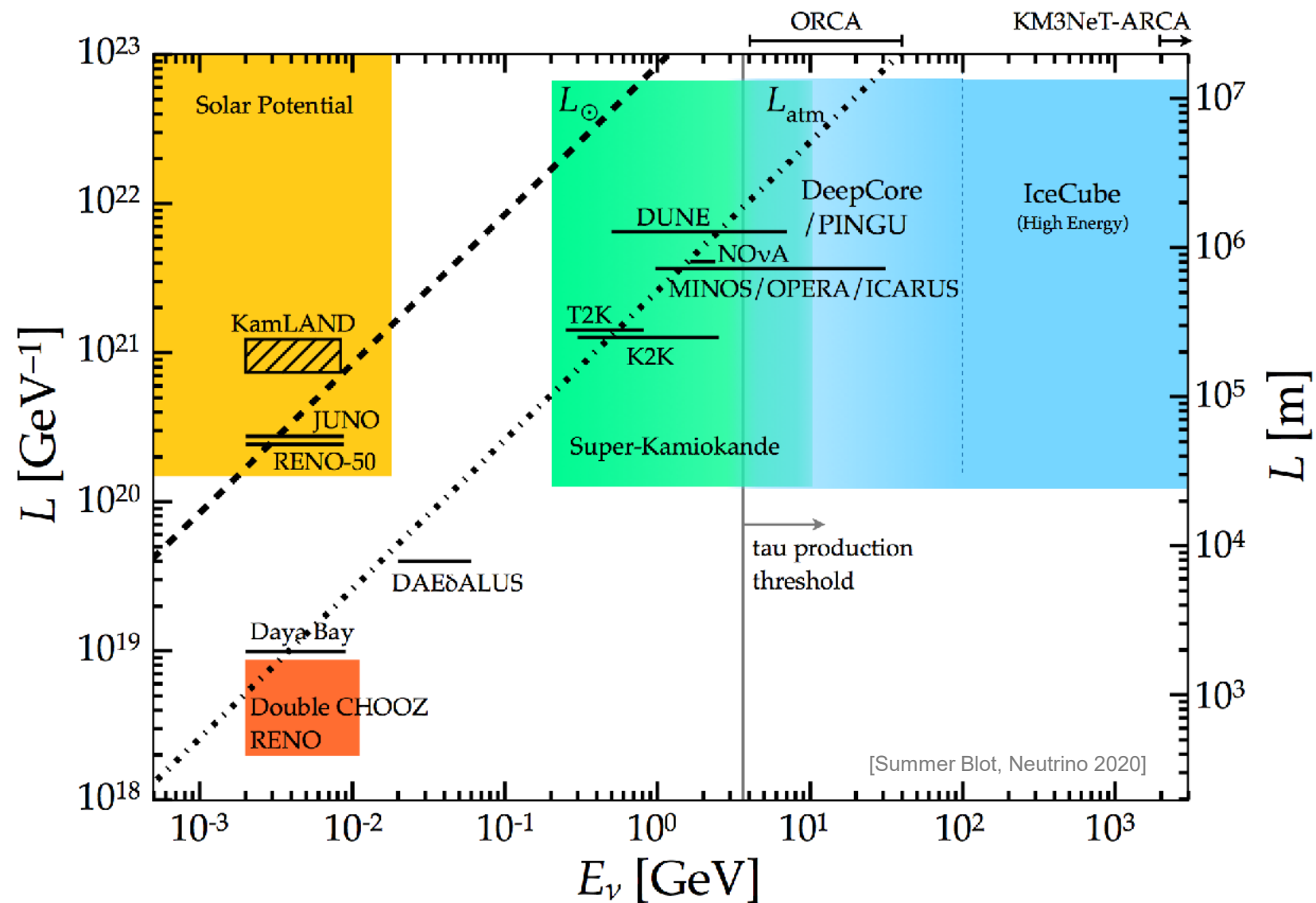
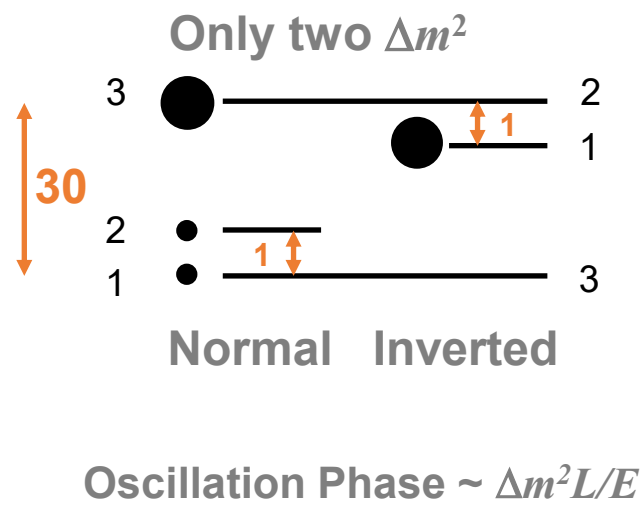
Neutrino Sources

(Oscillation-relevant) Types at source

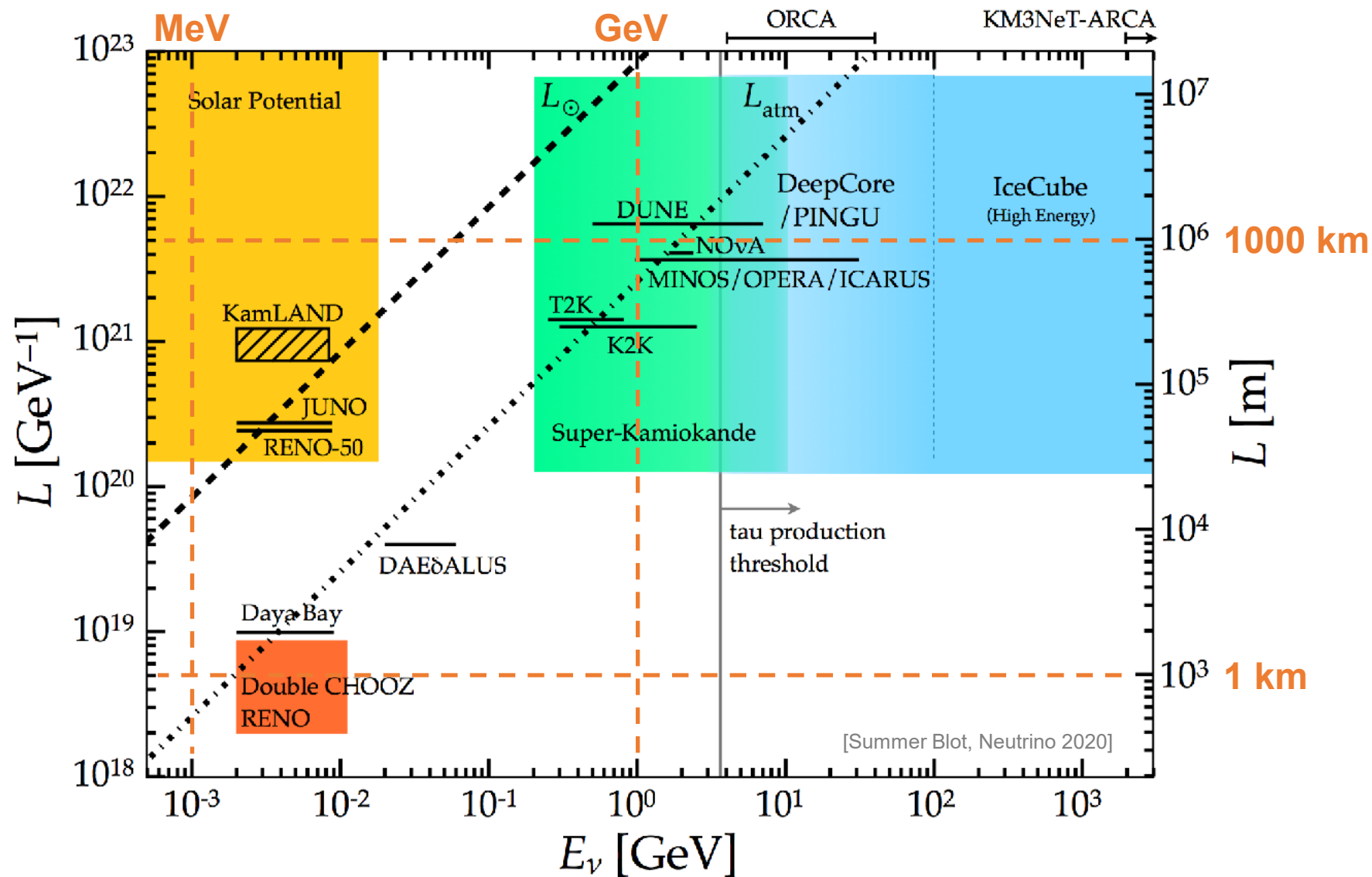
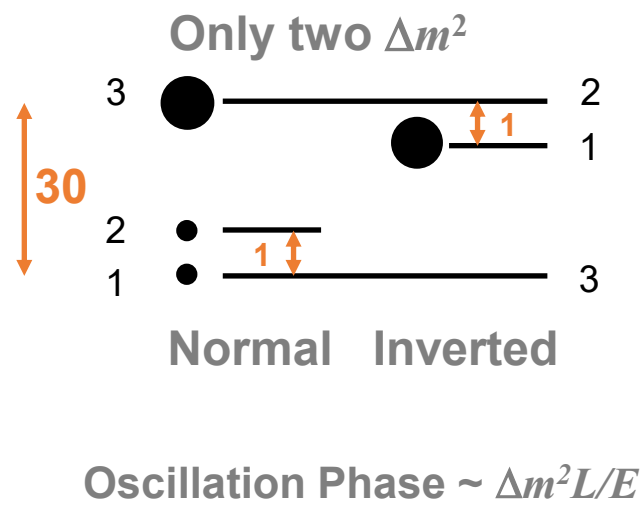
Solar	Reactor	Acc. & Atmo.
ν_e		
	$\bar{\nu}_e$	
		ν_μ
		$\bar{\nu}_\mu$



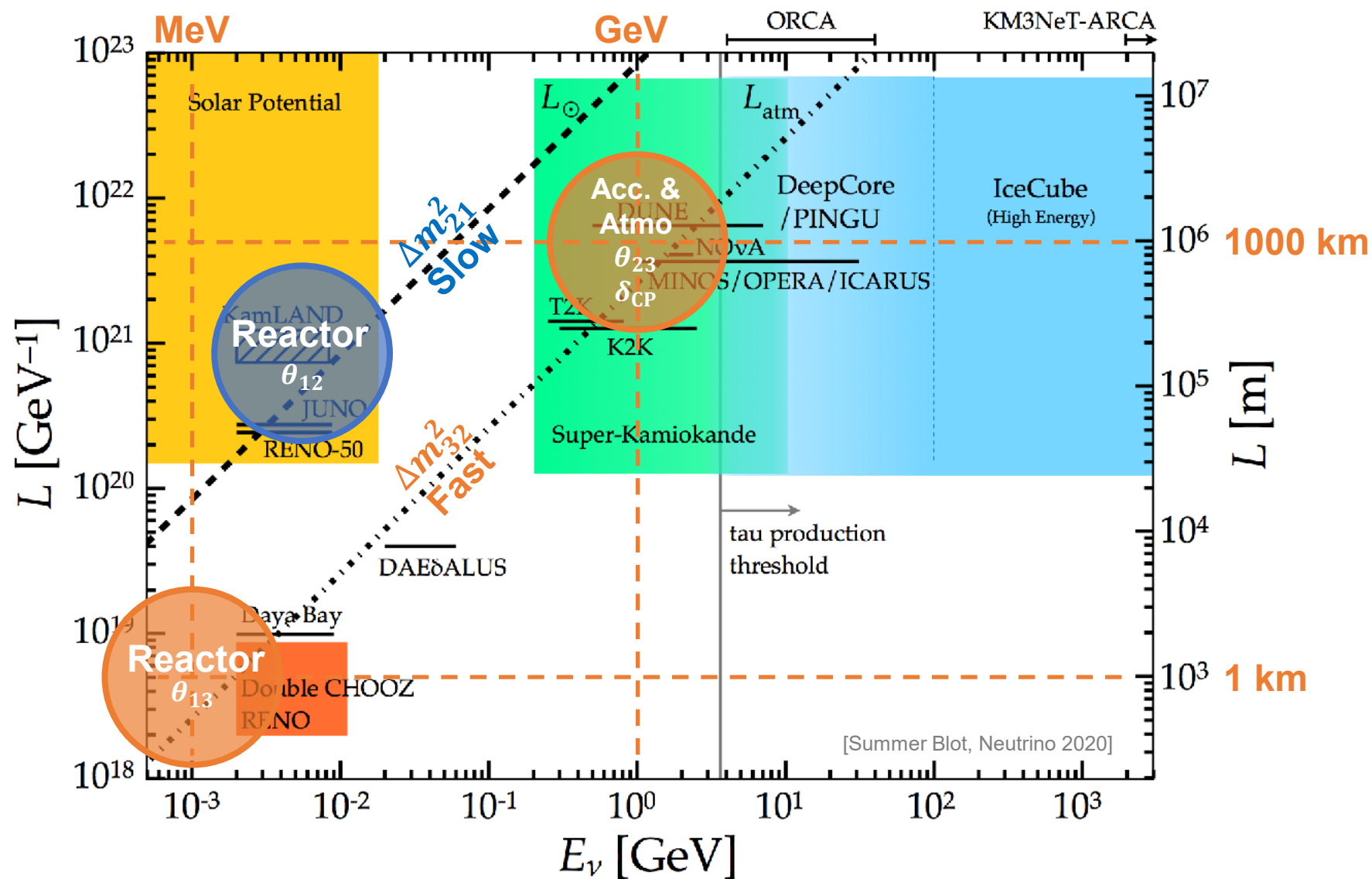
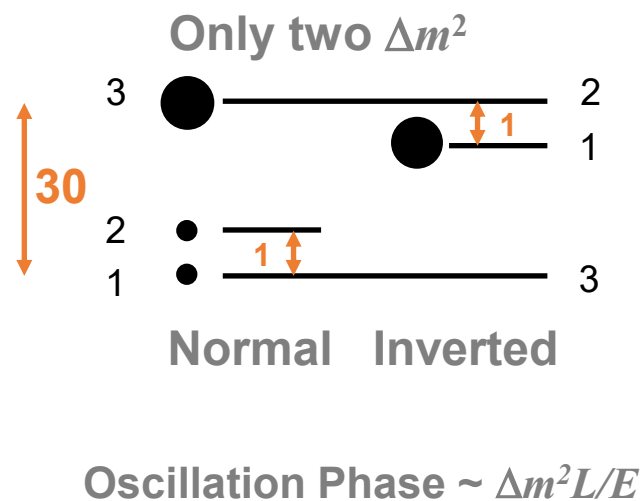
Neutrino Oscillation Experiments



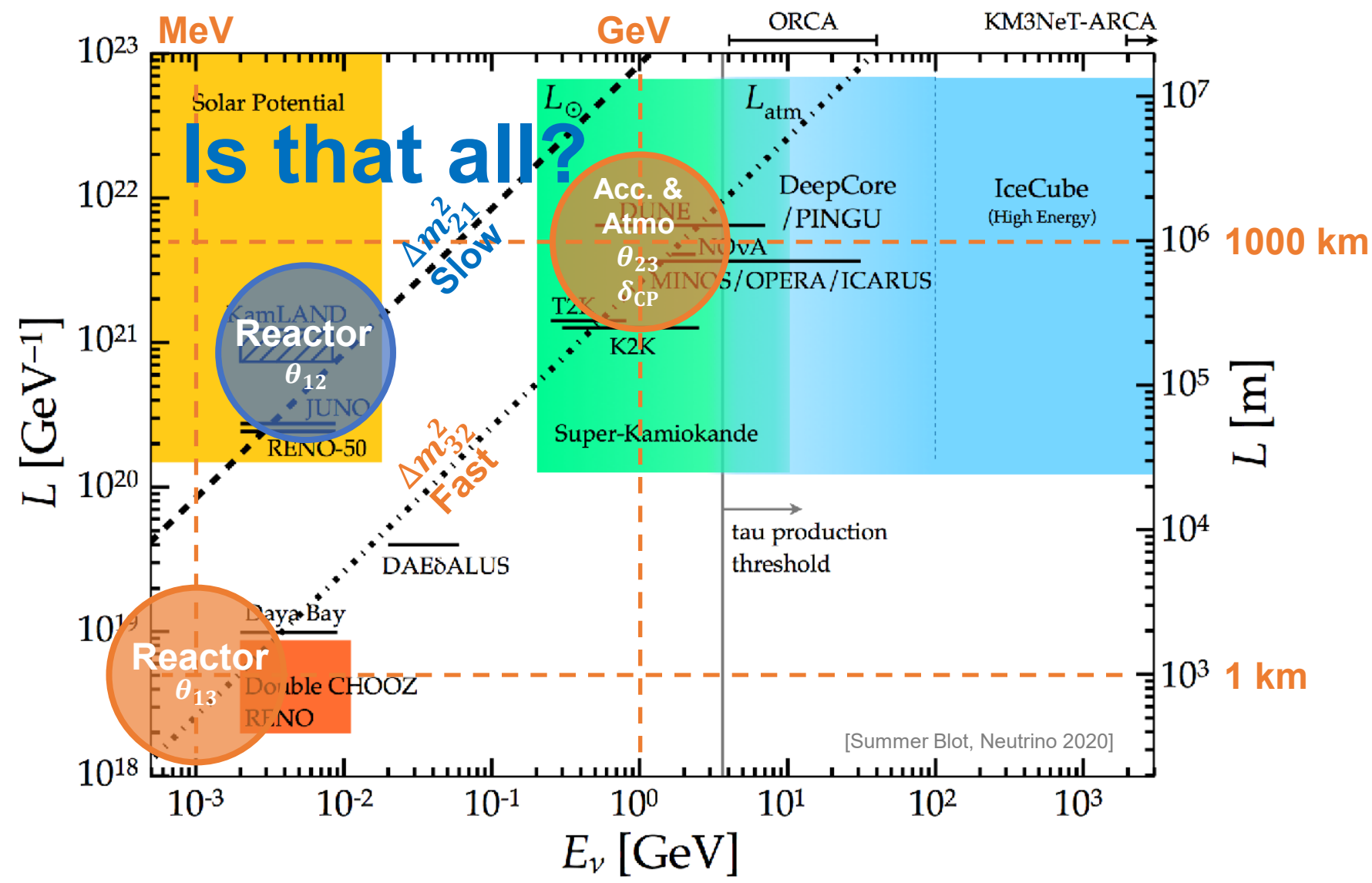
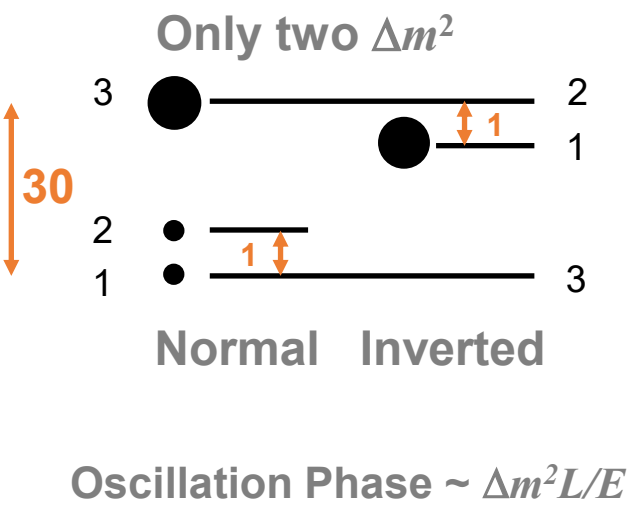
Neutrino Oscillation Experiments



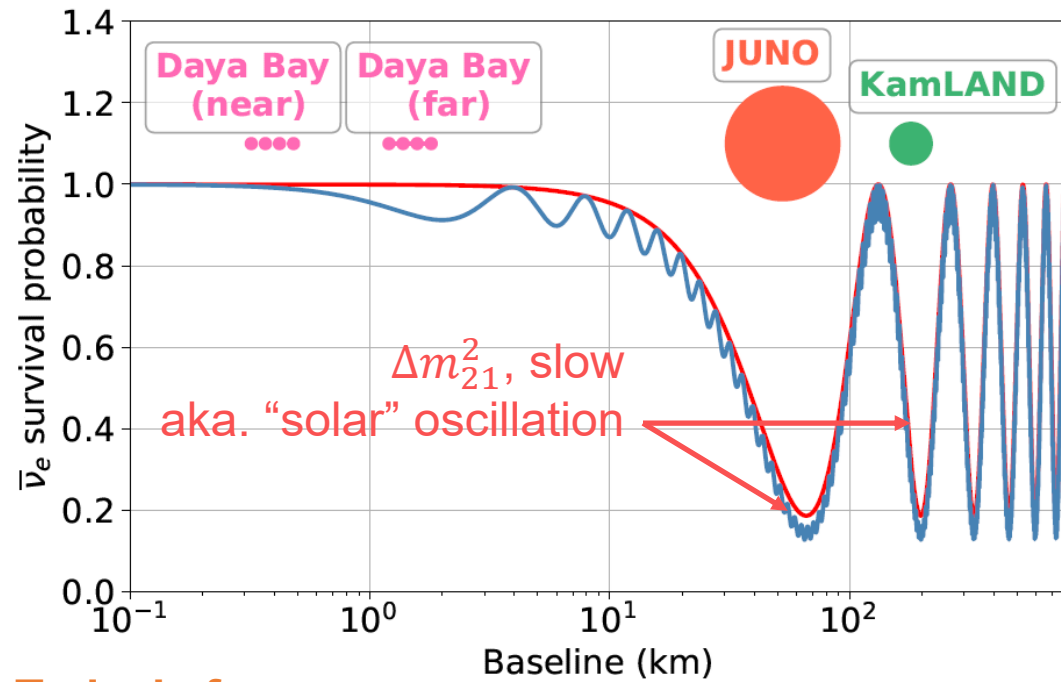
Neutrino Oscillation Experiments



Neutrino Oscillation Experiments



Neutrino Oscillation at JUNO



Today's focus

arXiv > hep-ex > arXiv:2511.14593

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

First measurement of reactor neutrino oscillations at JUNO

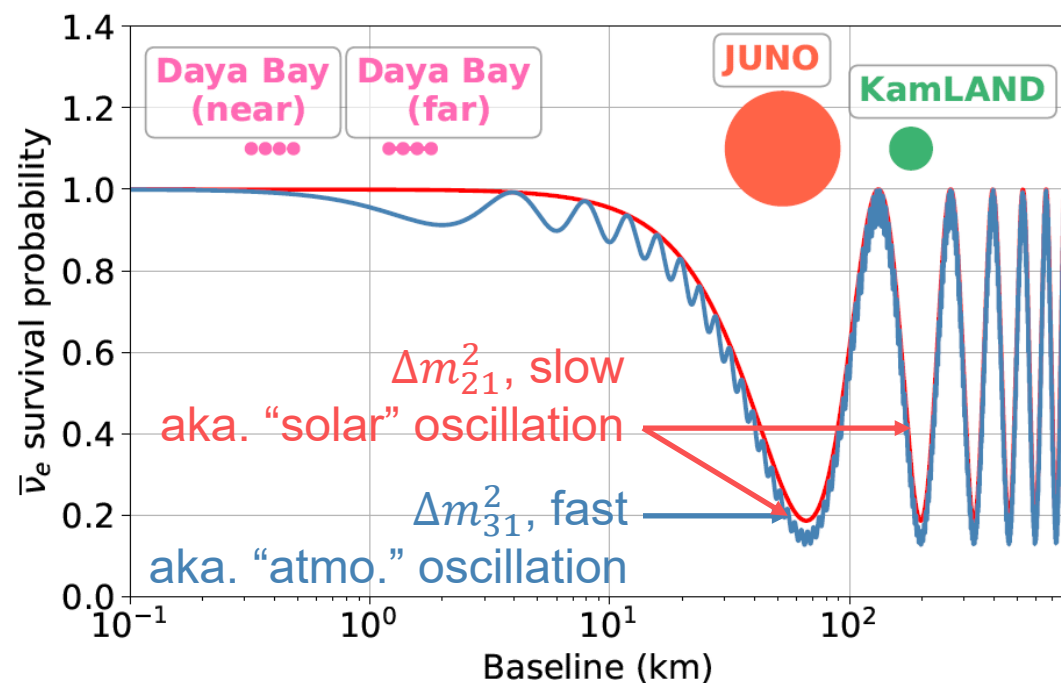
arXiv > hep-ex > arXiv:2511.14590

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

Initial performance results of the JUNO detector

Neutrino Oscillation at JUNO



Today's focus

arXiv > hep-ex > arXiv:2511.14593

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

First measurement of reactor neutrino oscillations at JUNO

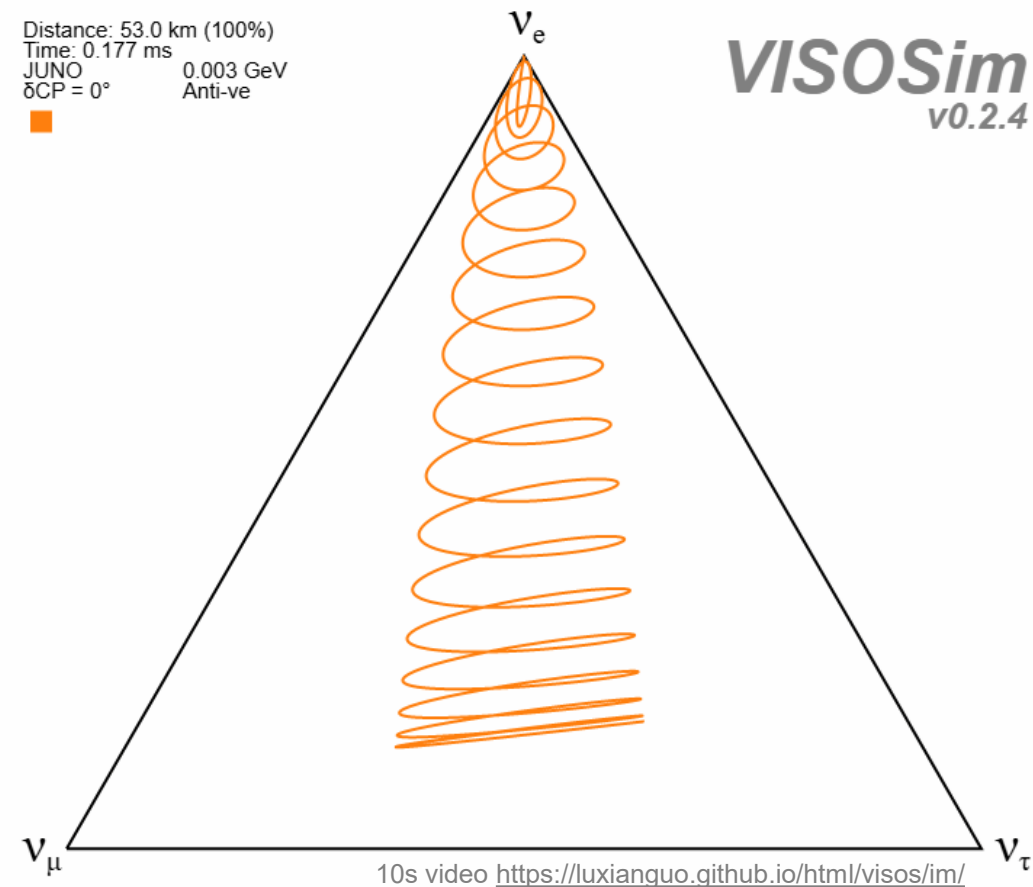
arXiv > hep-ex > arXiv:2511.14590

High Energy Physics - Experiment

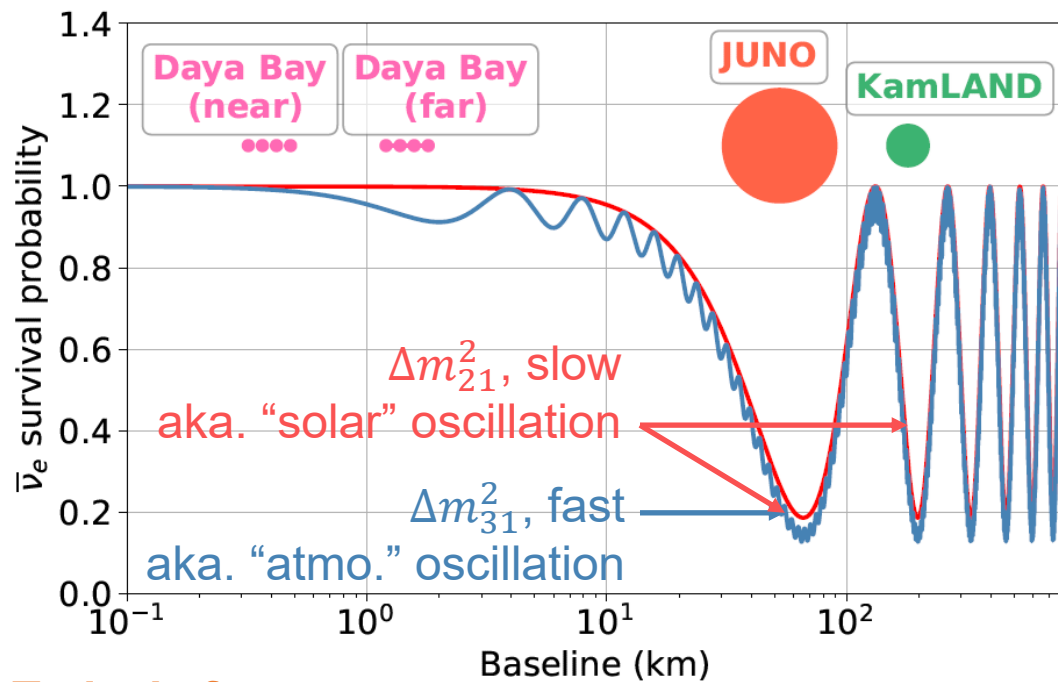
[Submitted on 18 Nov 2025]

Initial performance results of the JUNO detector

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



Today's focus

arXiv > hep-ex > arXiv:2511.14593

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

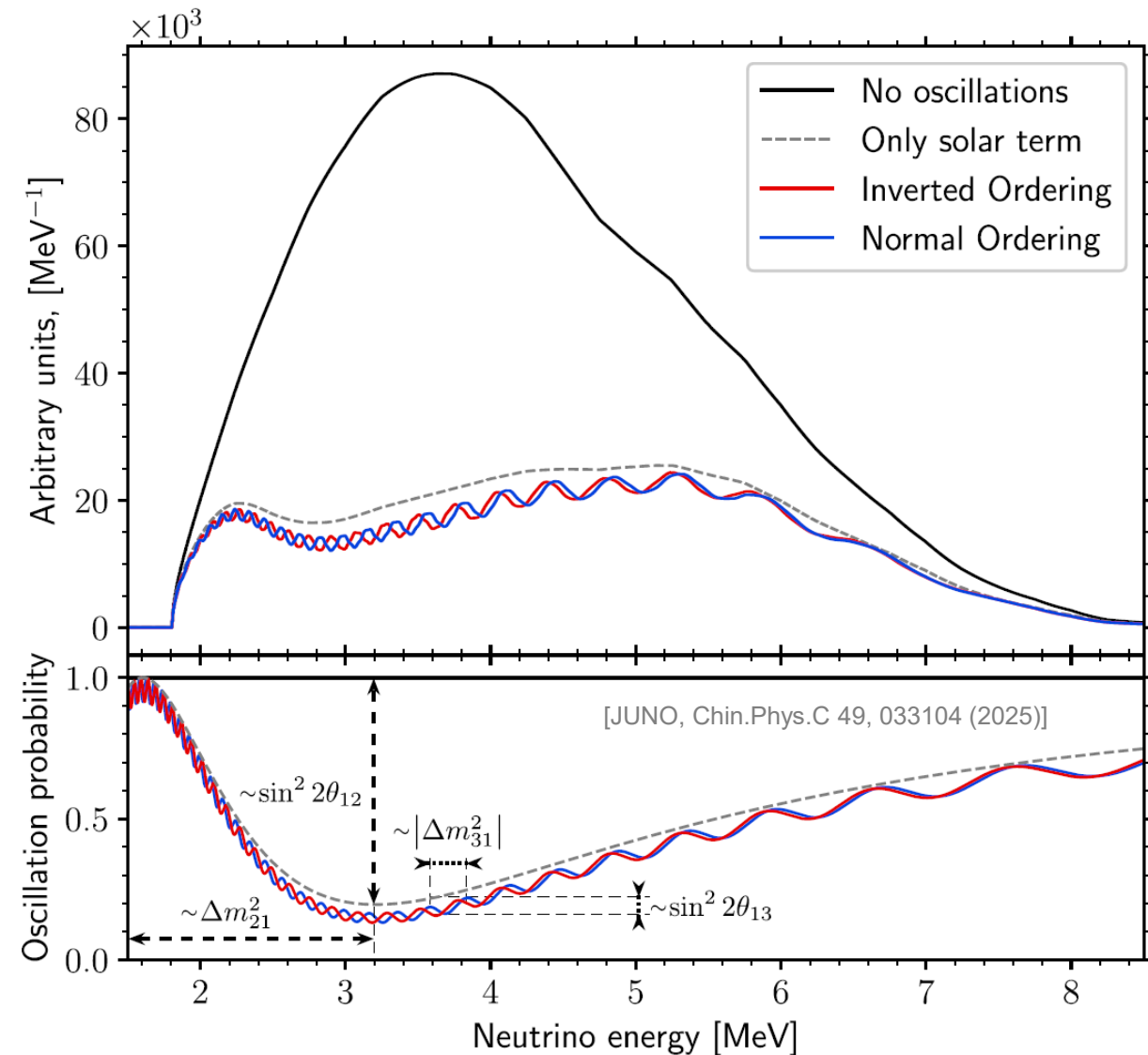
First measurement of reactor neutrino oscillations at JUNO

arXiv > hep-ex > arXiv:2511.14590

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

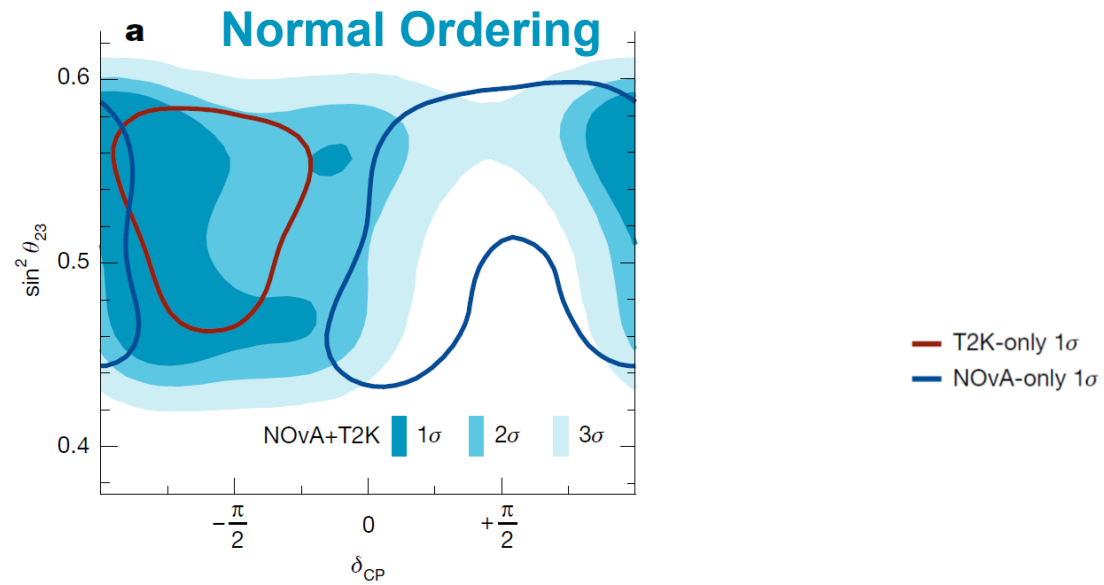
Initial performance results of the JUNO detector



JUNO's main goal: Neutrino Mass Ordering

Why Neutrino Mass Ordering?

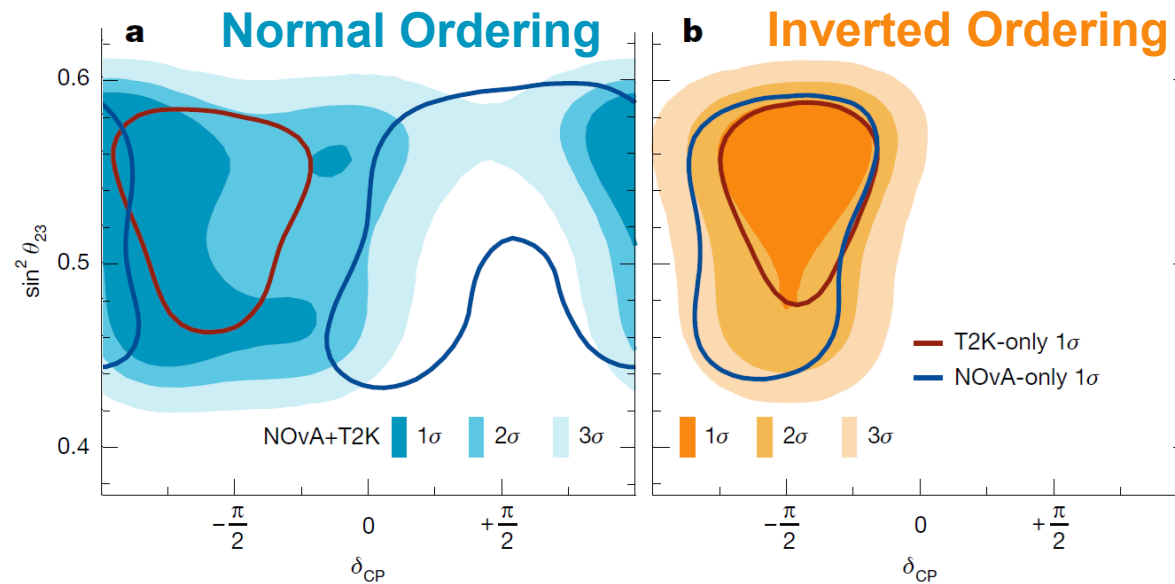
[T2K and NOvA, Nature 646, 818 (2025)]



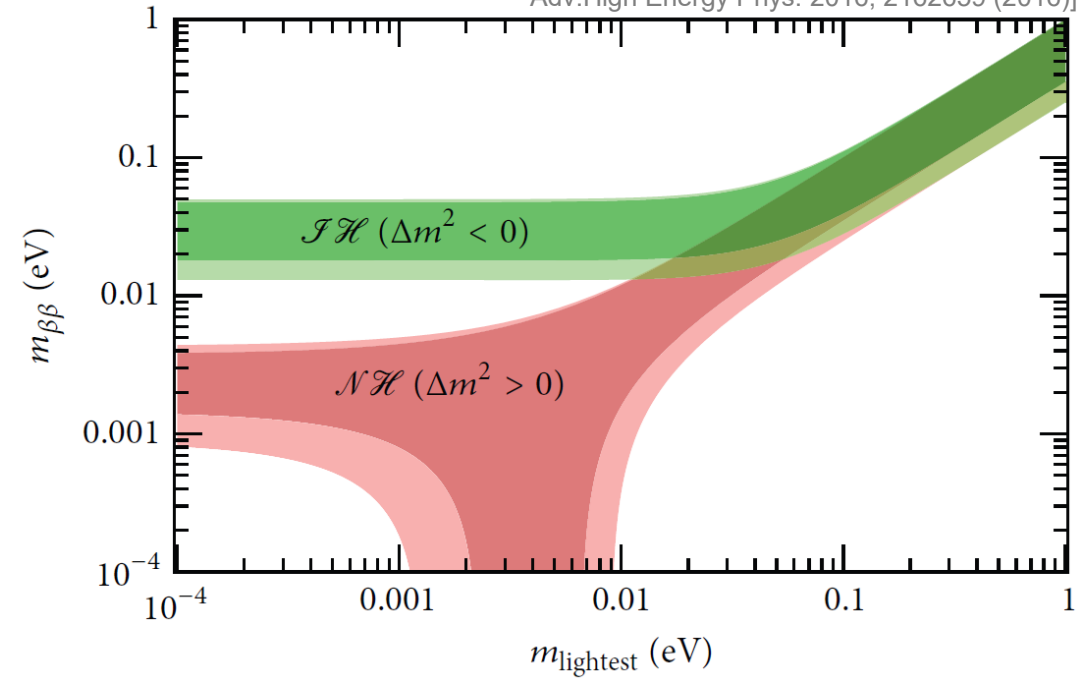
❑ CP violation with neutrinos is already extremely difficult to measure even with a known NMO

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



The JUNO Collaboration

UK involvement
Warwick 2022/07 –
Liverpool 2024/07 –

= 70 institutes
> 700 participants

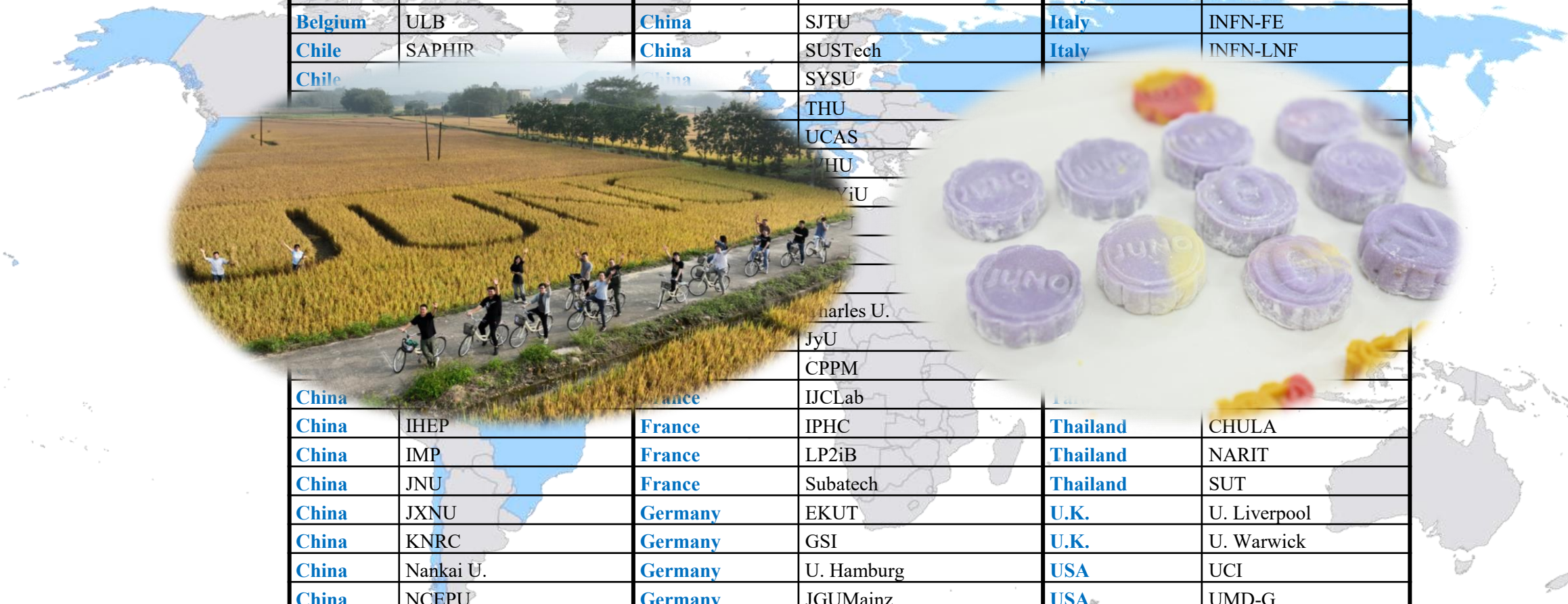
Country	Institute	Country	Institute	Country	Institute
Armenia	YerPhI	China	SDU	Italy	INFN-CT
Belgium	ULB	China	SJTU	Italy	INFN-FE
Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile	UNAB	China	SYSU	Italy	INFN-MI
China	BISEE	China	THU	Italy	INFN-MIB
China	CDUT	China	UCAS	Italy	INFN-PD
China	CNPRI	China	WHU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

The JUNO Collaboration

UK involvement
Warwick 2022/07 –
Liverpool 2024/07 –

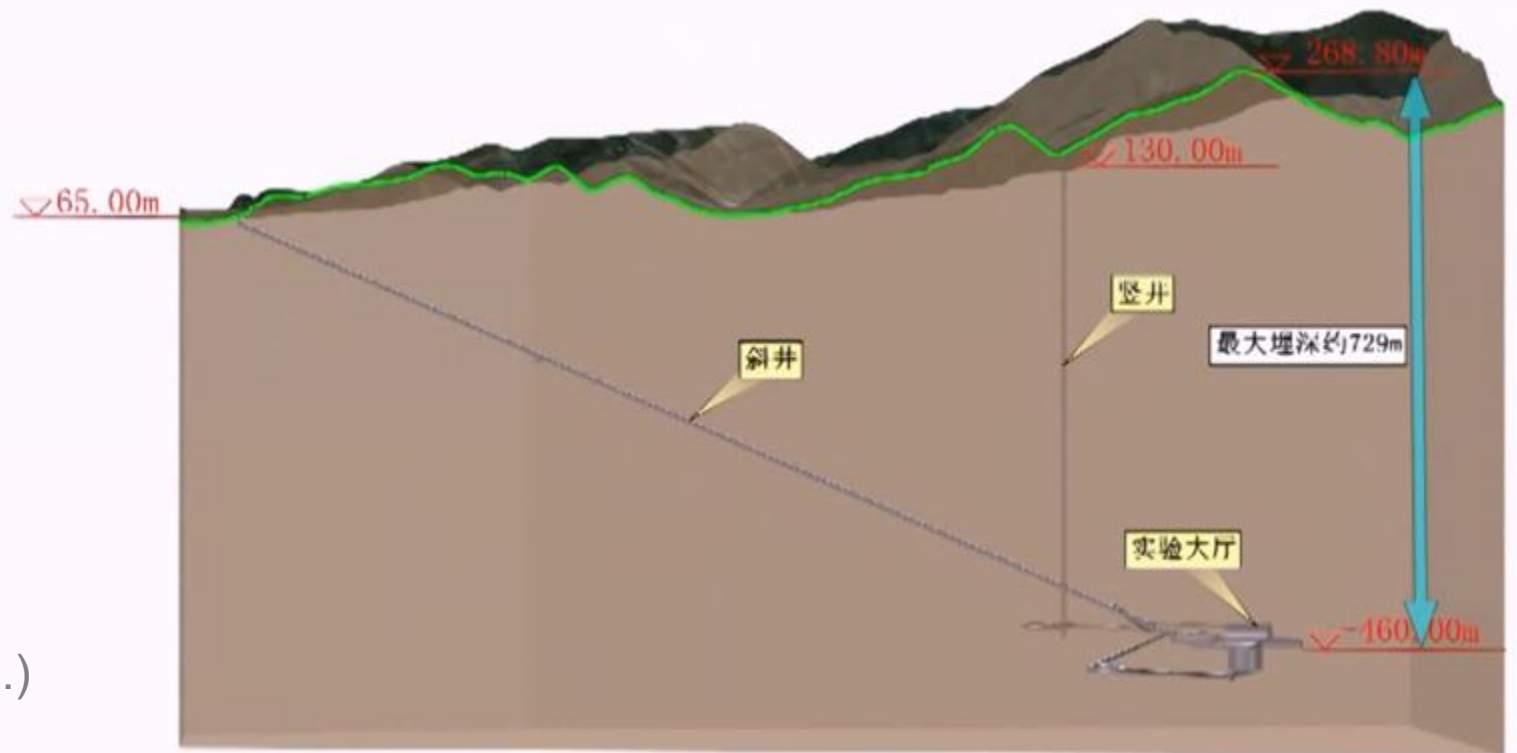
= 70 institutes
> 700 participants

Country	Institute	Country	Institute	Country	Institute
Armenia	YerPhI	China	SDU	Italy	INFN-CT
Belgium	ULB	China	SJTU	Italy	INFN-FE
Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile		China	SYSU		
		China	THU		
		China	UCAS		
		China	THU		
		China	ZJU		
		China	YiU		
		China	Charles U.		
		China	JyU		
		China	CPPM		
China		France	IJCLab	Thailand	CHULA
China	IHEP	France	IPHC	Thailand	NARIT
China	IMP	France	LP2iB	Thailand	SUT
China	JNU	Germany	Subatech	U.K.	U. Liverpool
China	JXNU	Germany	EKUT	U.K.	U. Warwick
China	KNRC	Germany	GSI	USA	UCI
China	Nankai U.	Germany	U. Hamburg	USA	UMD-G
China	NCEPU	Germany	JGUMainz		
China	NJU	Germany	RWTH-AC		
China	RNCG	Germany	TUM		

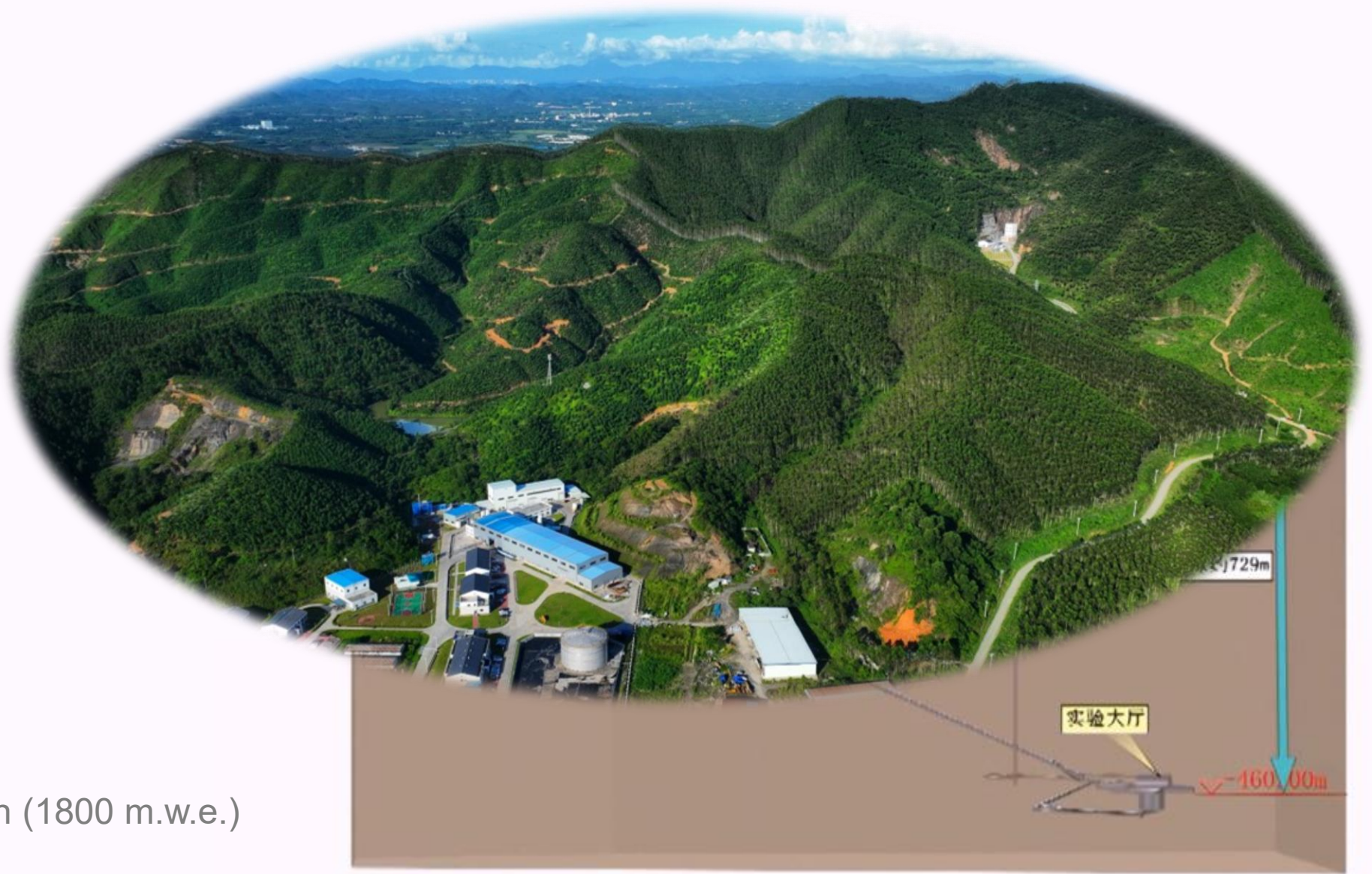


The JUNO Lab

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



The JUNO Lab



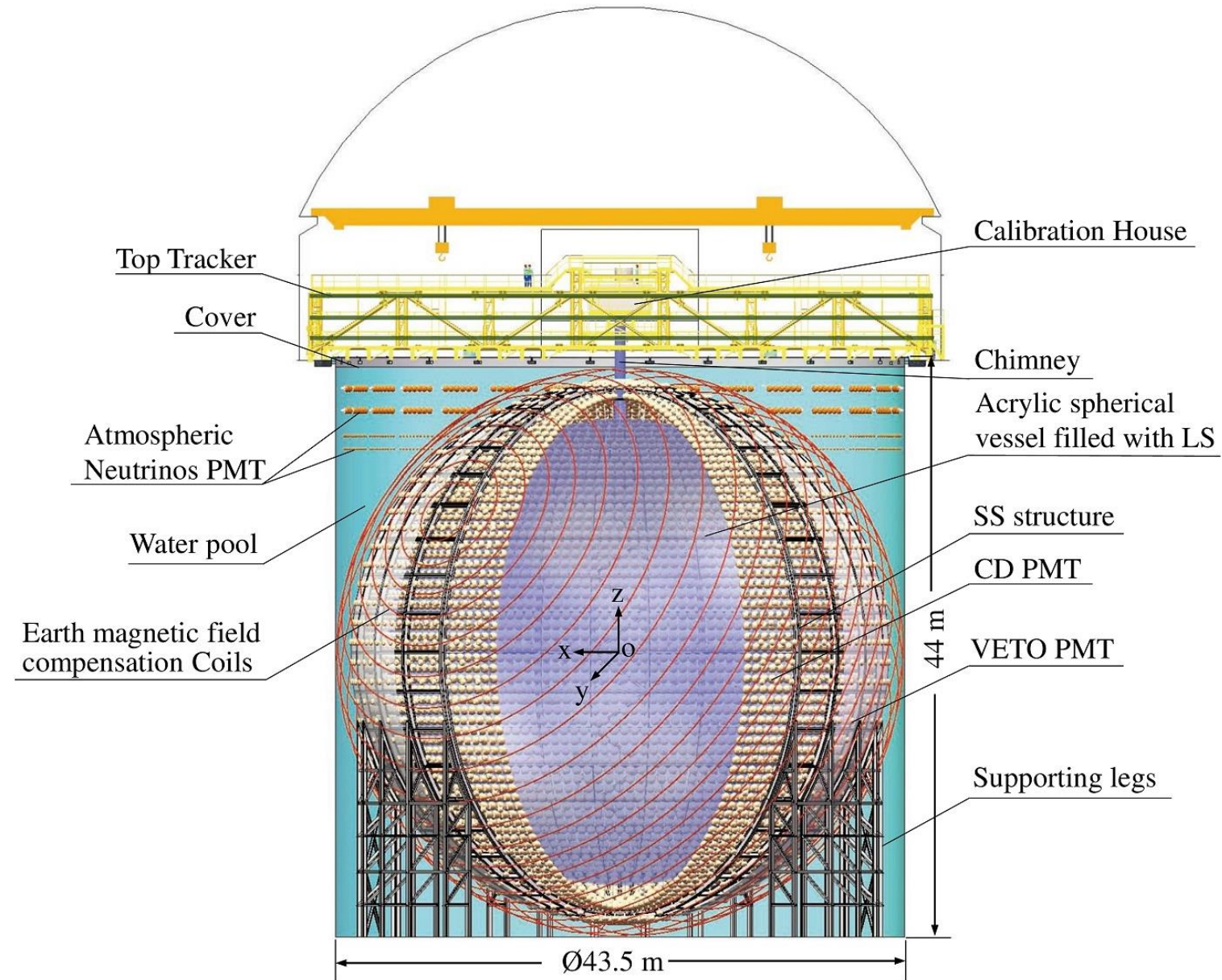
- ❑ ~500 m underground
- ❑ ~700 m rock overburden (1800 m.w.e.)

The JUNO Lab

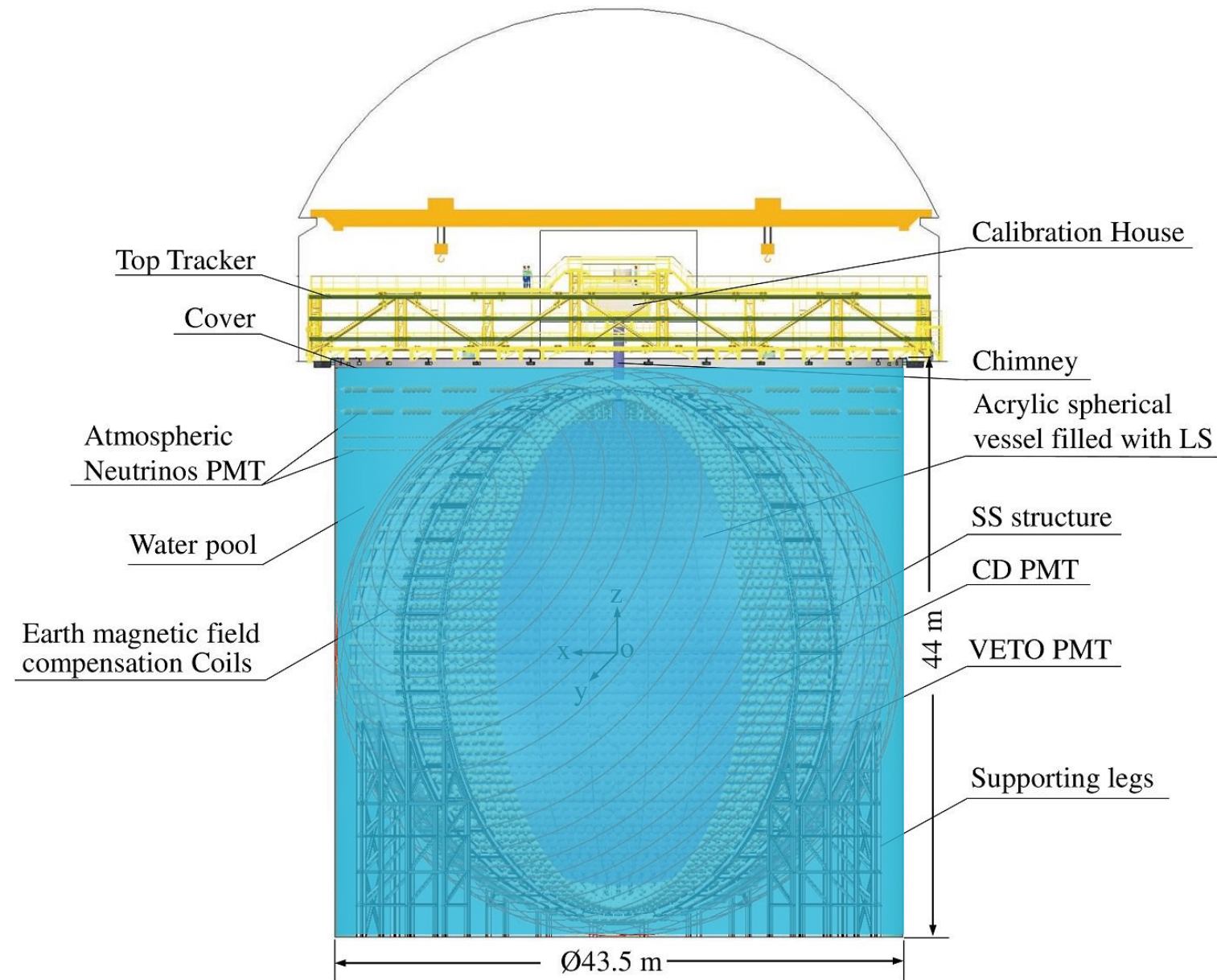


- ❑ ~500 m underground
- ❑ ~700 m rock overburden (1800 m.w.e.)
- ❑ ~1300 m sloped tunnel
- ❑ ~600 m vertical shaft

The JUNO Detector

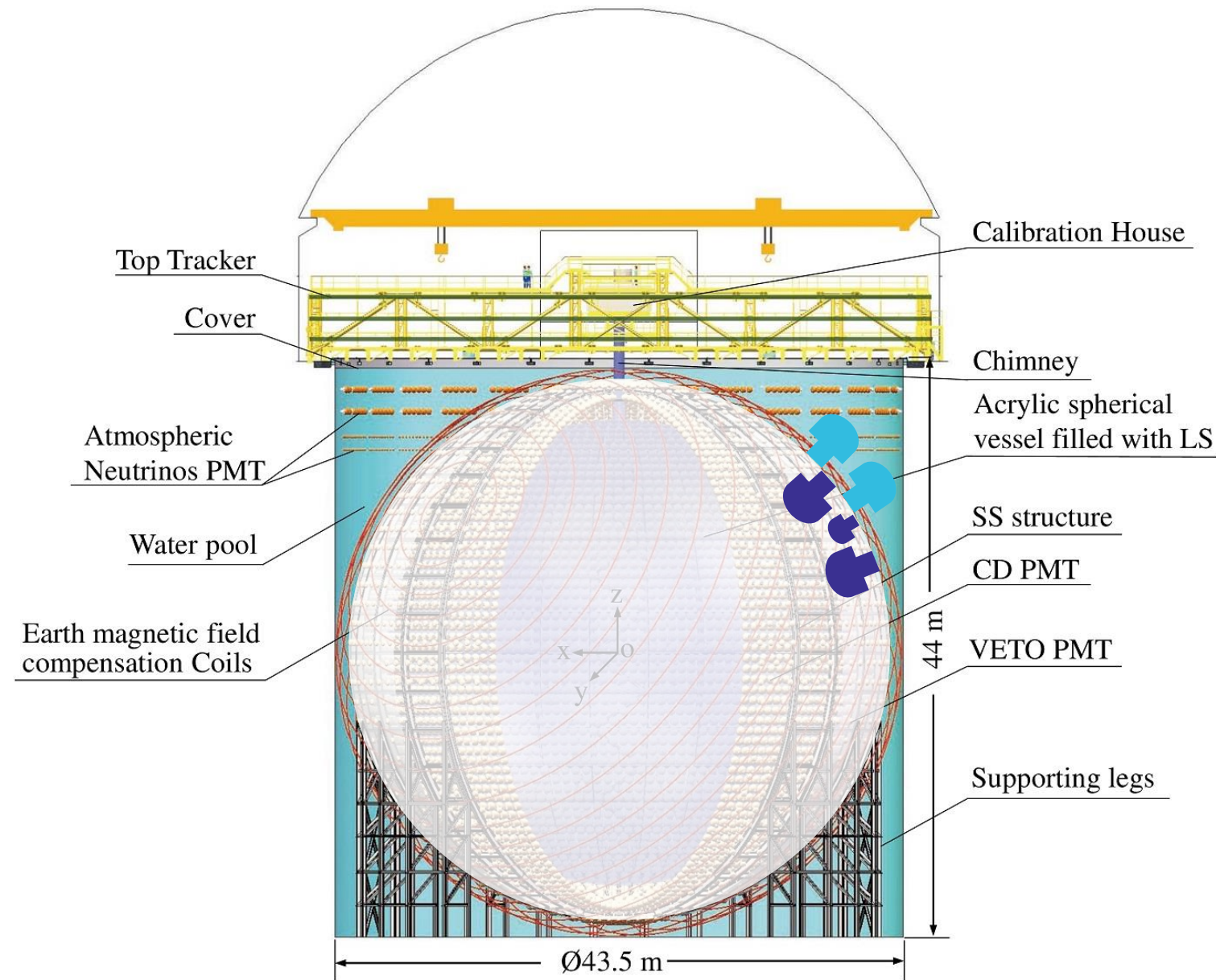


The JUNO Detector



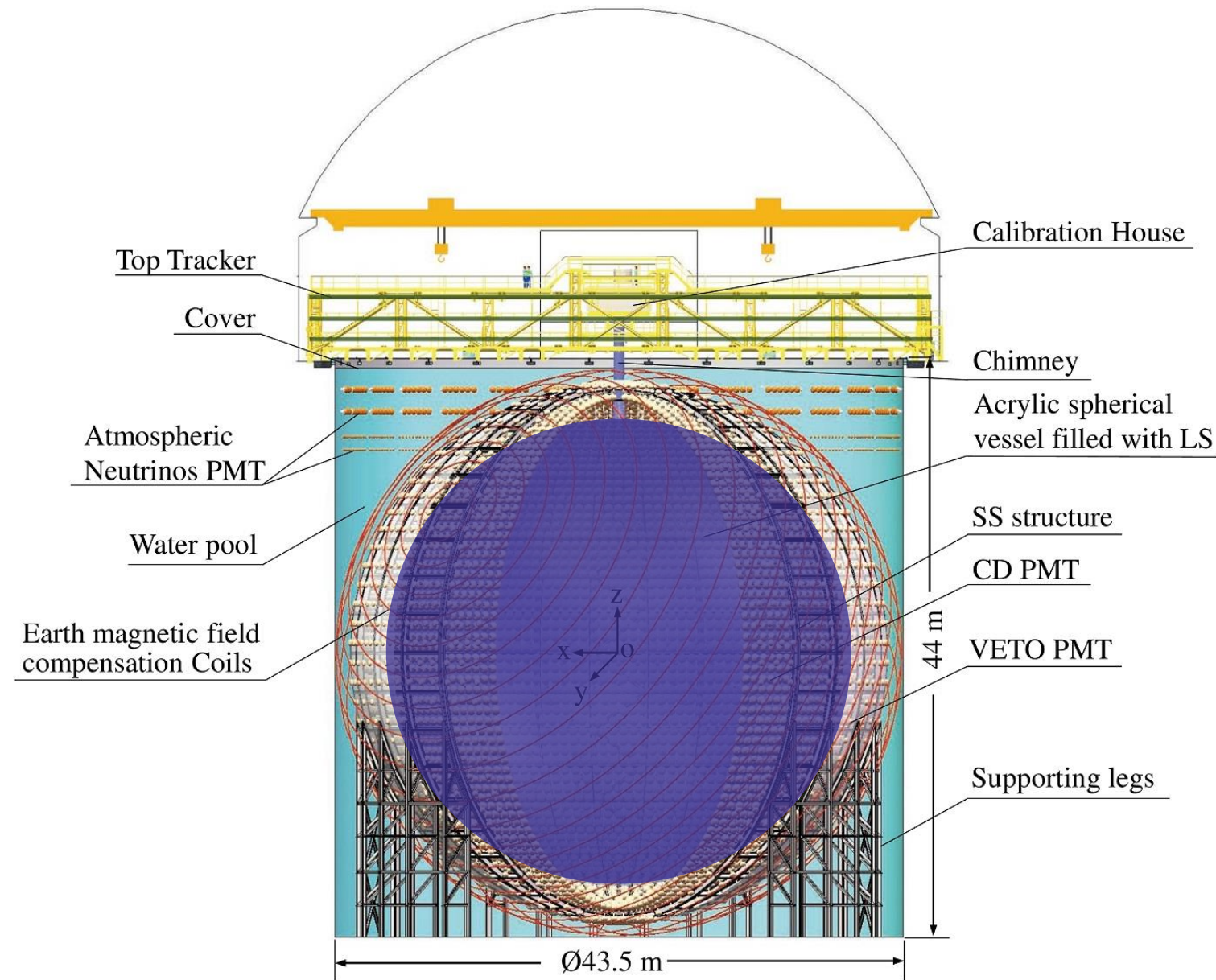
- Ø43.5 m, H 44 m Water Pool/WP
 - ❖ 35 kt water—Water Cherenkov Detector/WCD
 - Tyvek -----
 - ❖ 5 kt water buffer between WCD and AV

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" veto PMTs (Micro-Channel Plate/MCP)
 - Tyvek -----
 - ❖ CD PMTs viewing inwards
 - 17,596 20" large PMTs: 4939 dynode + MCP (w/ $\times 2$ photon detection efficiency)
 - 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 $\leftarrow$ SSS mechanical precision ~ 3 mm

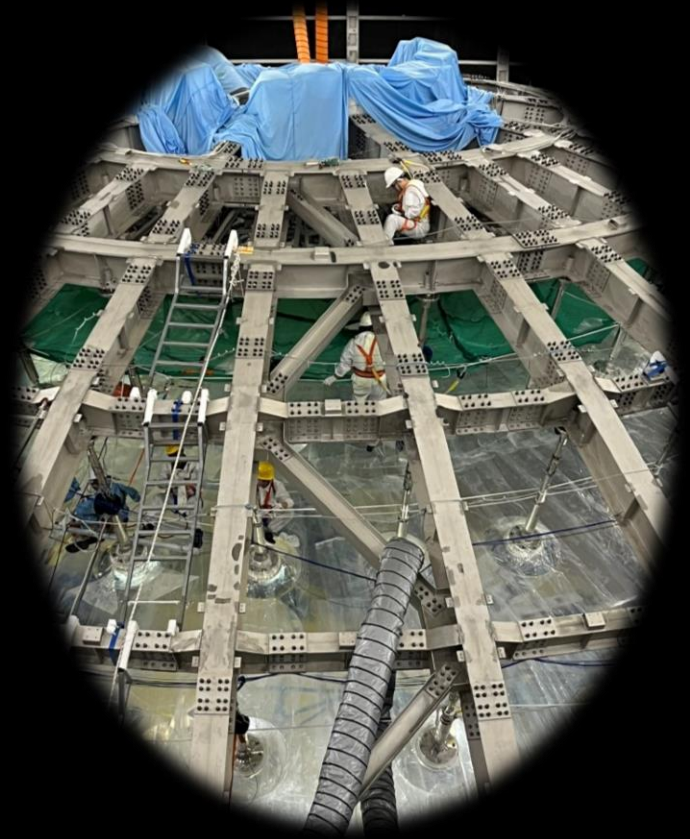
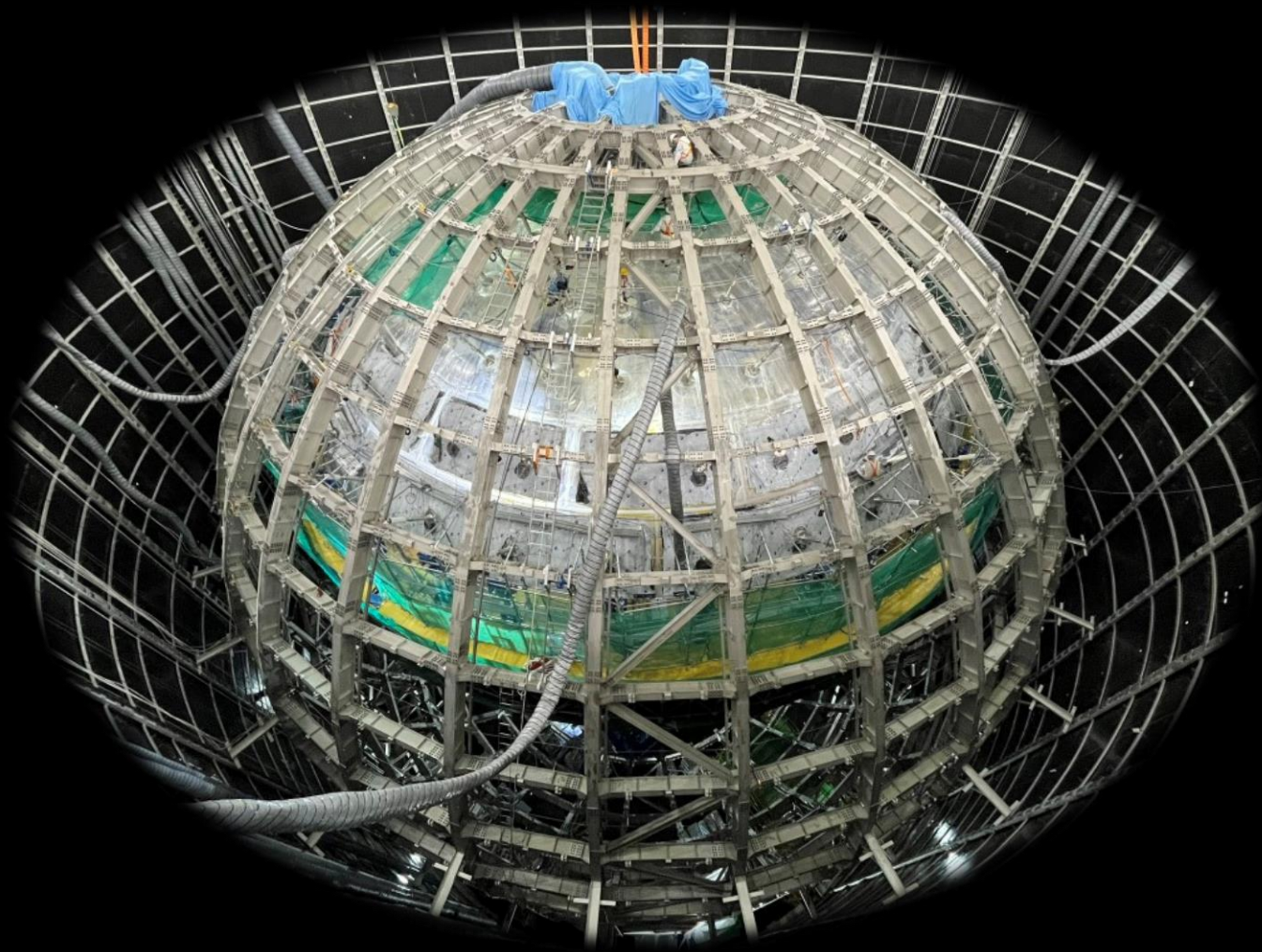
The JUNO Detector



- ❑ 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" veto PMTs (Micro-Channel Plate/MCP)
 - Tyvek -----
 - ❖ CD PMTs viewing inwards
 - 17,596 20" large PMTs: 4939 dynode + MCP (w/ $\times 2$ photon detection efficiency)
 - 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 $\leftarrow$ SSS
 - mechanical precision ~ 3 mm
- ❑ Ø35.4 m Acrylic Vessel/AV
 - ❖ 20 kt liquid scintillator—Central Detector/CD
 - Fluorescence emission peak 430 nm (violet-blue)

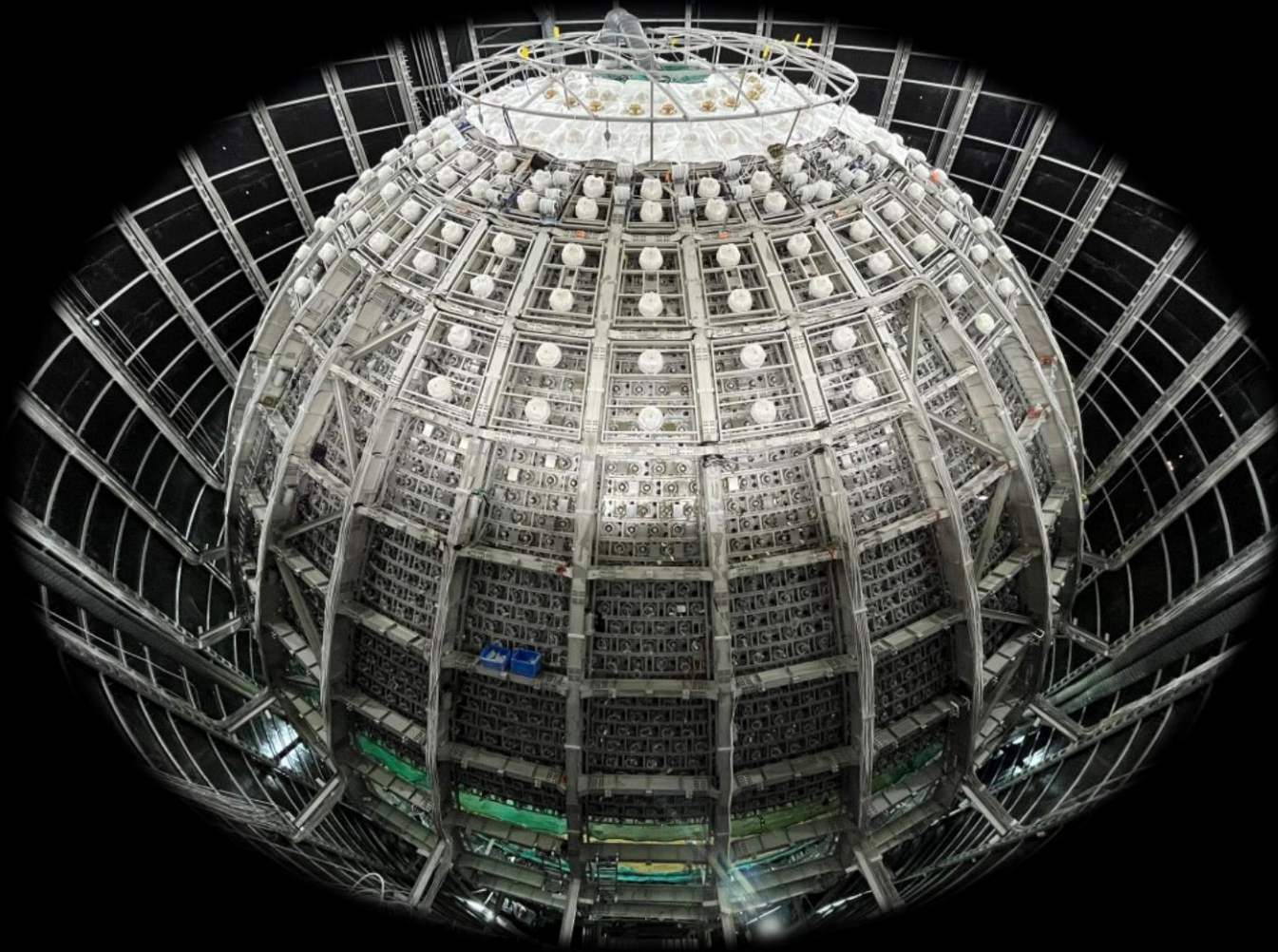
The JUNO Detector

□ SSS and AV



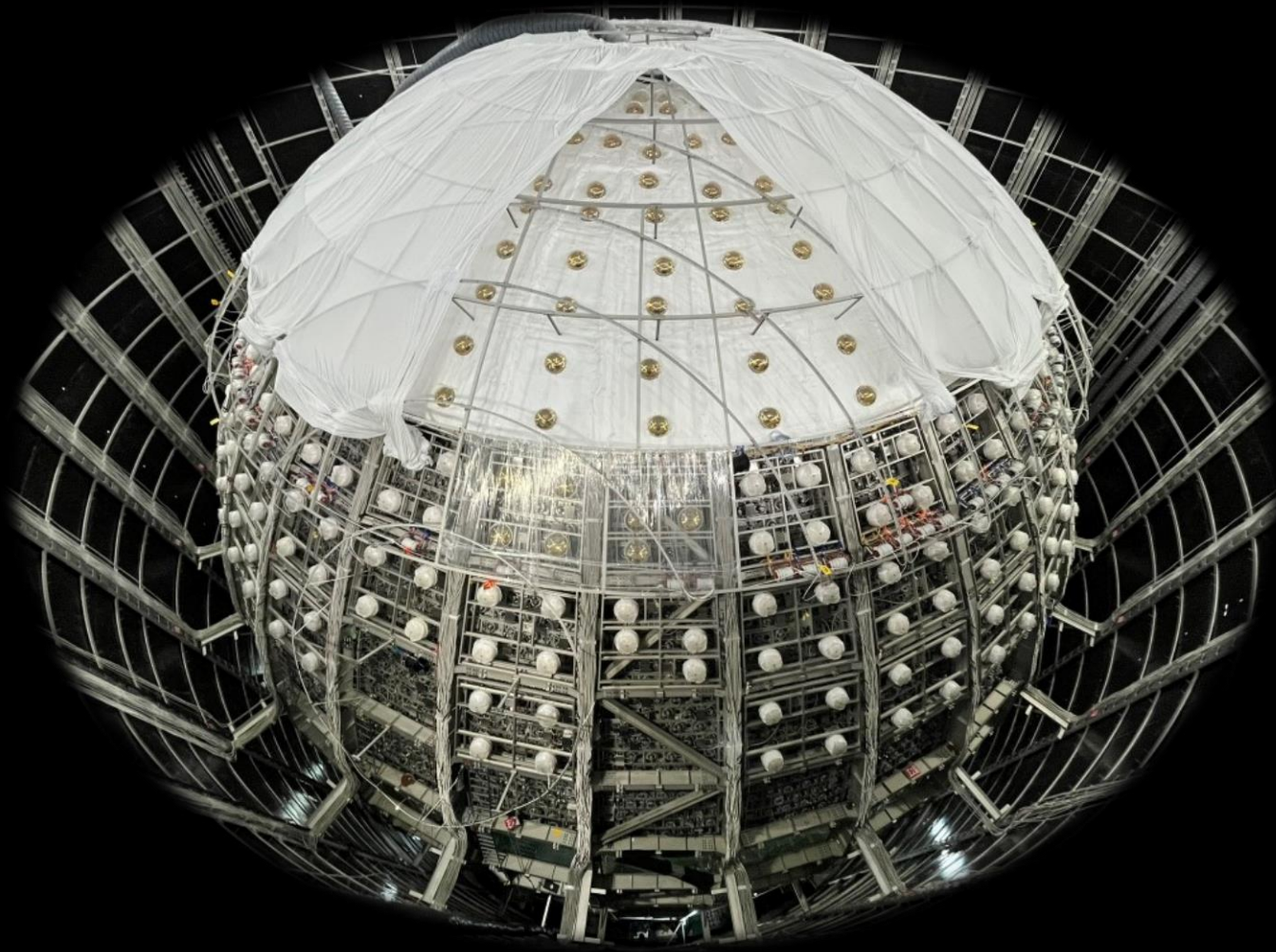
The JUNO Detector

□ Veto PMTs (and back of large PMTs)



The JUNO Detector

□ Tyvek (and earth magnetic field compensation coils)

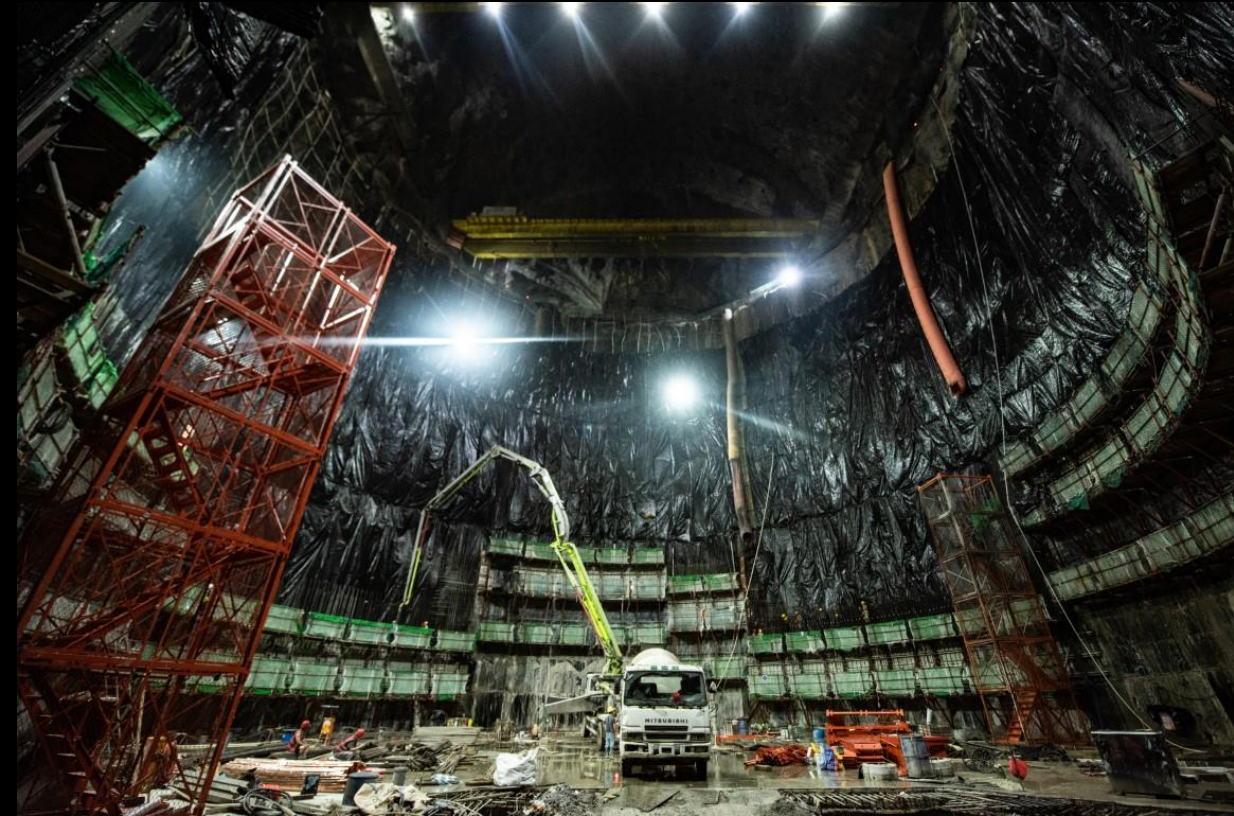
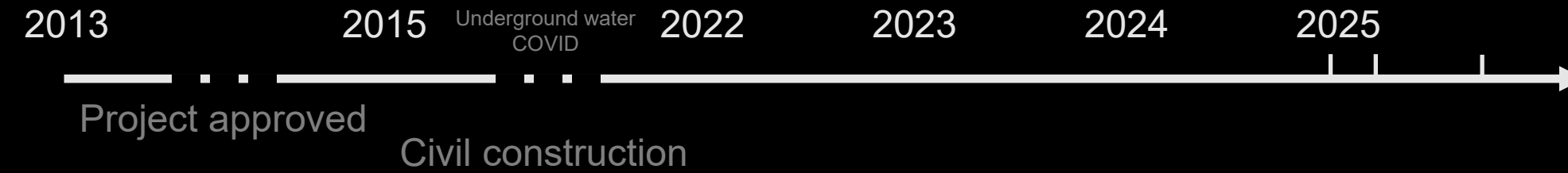


The JUNO Detector

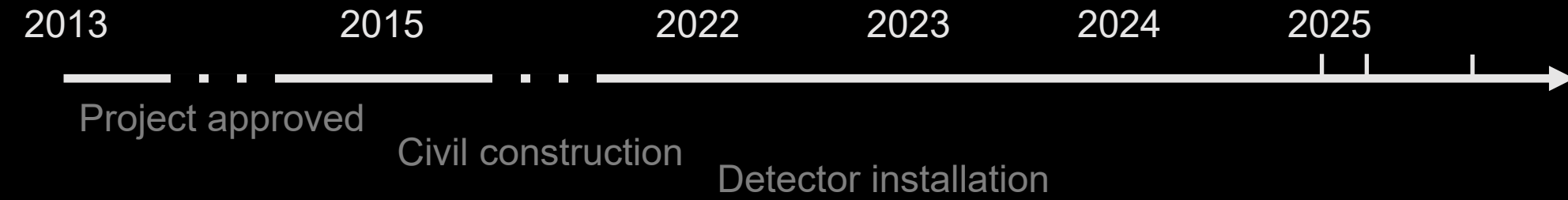
□ Large and small PMTs (and water buffer region)



Towards JUNO's First Results



Towards JUNO's First Results



30s video

Towards JUNO's First Results

2013

2015

2022

2023

2024

2025

Project approved

Civil construction

Detector installation

2022/08/15



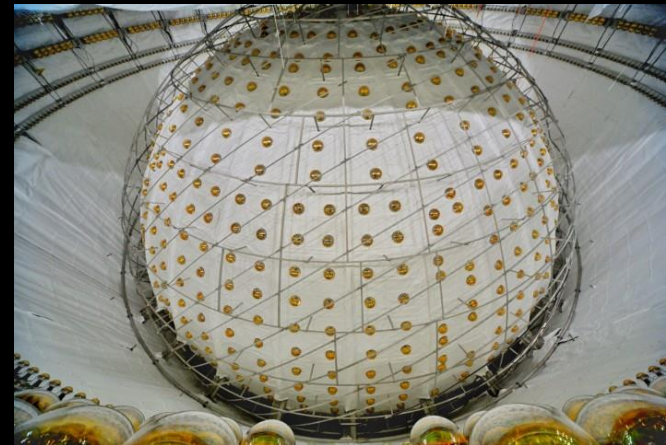
2023/08/04



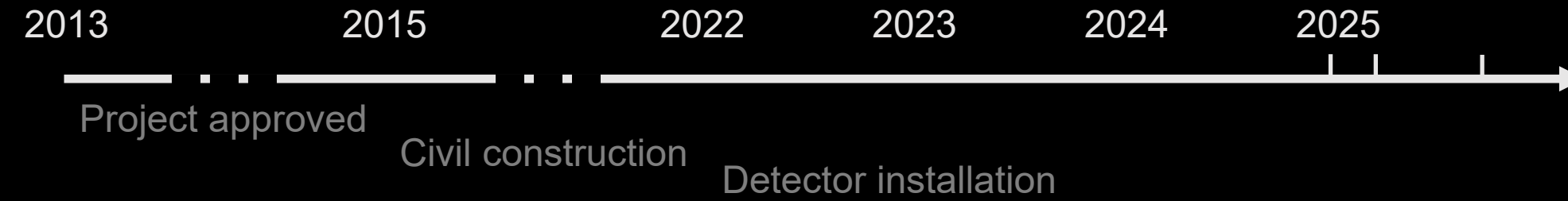
2024/09/27



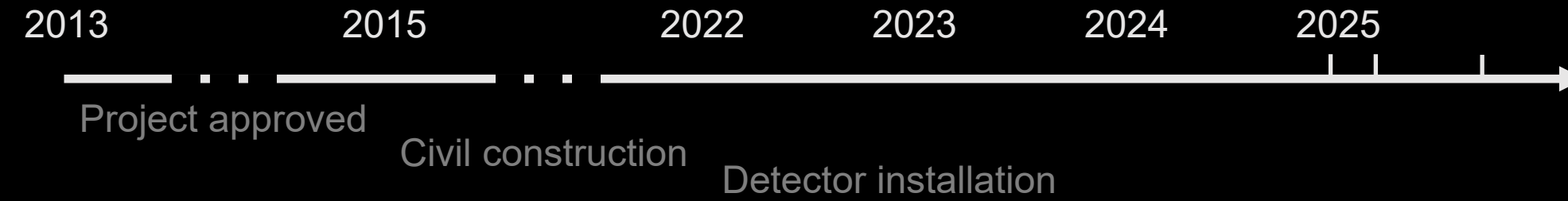
2024/12/19



Towards JUNO's First Results



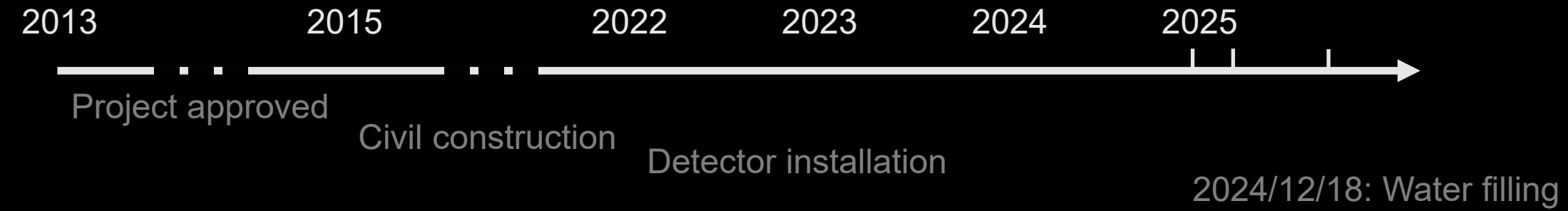
Towards JUNO's First Results



1m video



Towards JUNO's First Results



10s video

Towards JUNO's First Results

2013

2015

2022

2023

2024

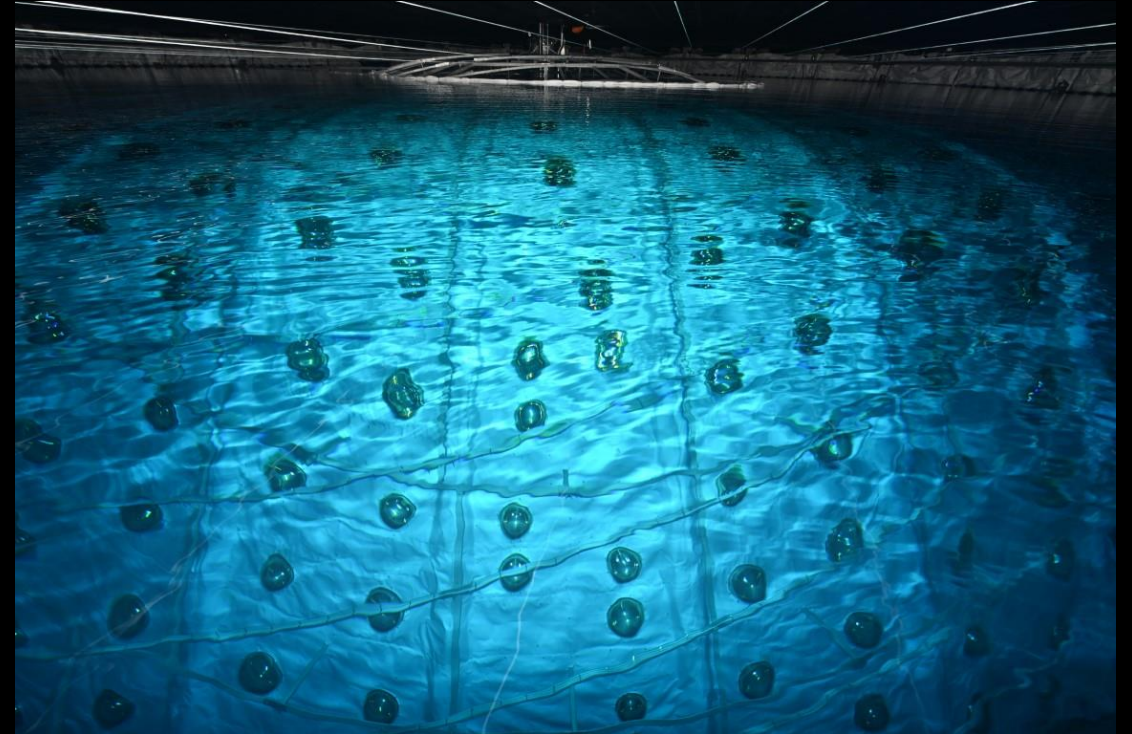
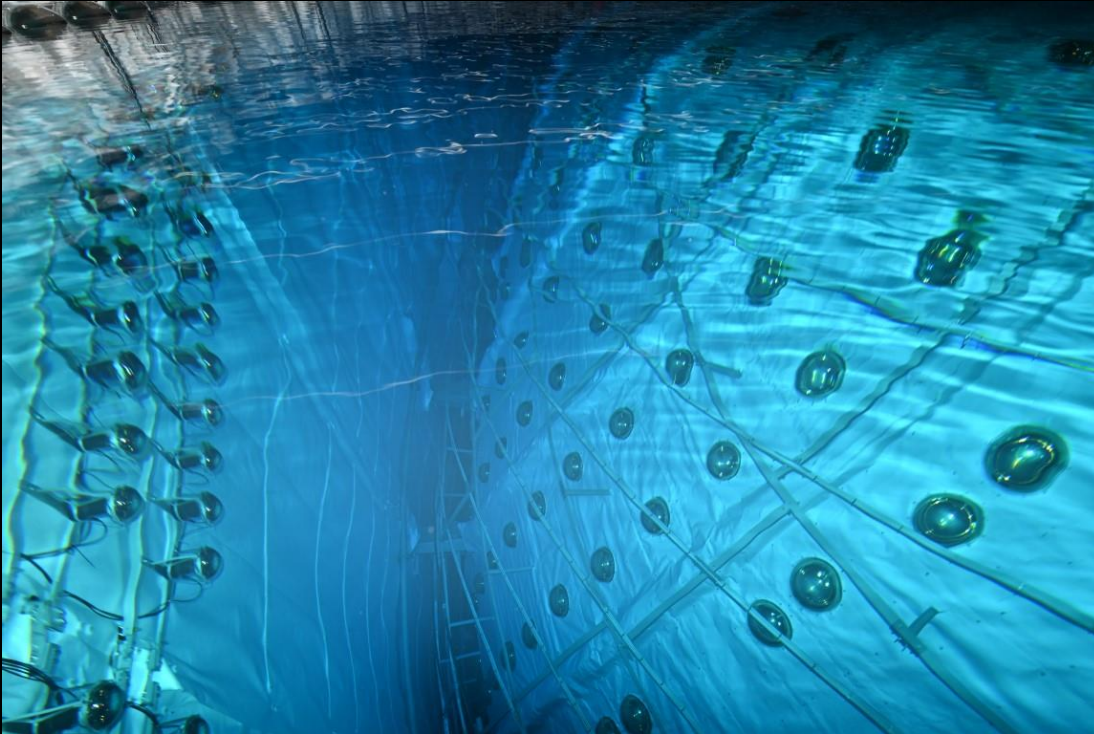
2025

Project approved

Civil construction

Detector installation

2024/12/18: Water filling



Towards JUNO's First Results



Project approved

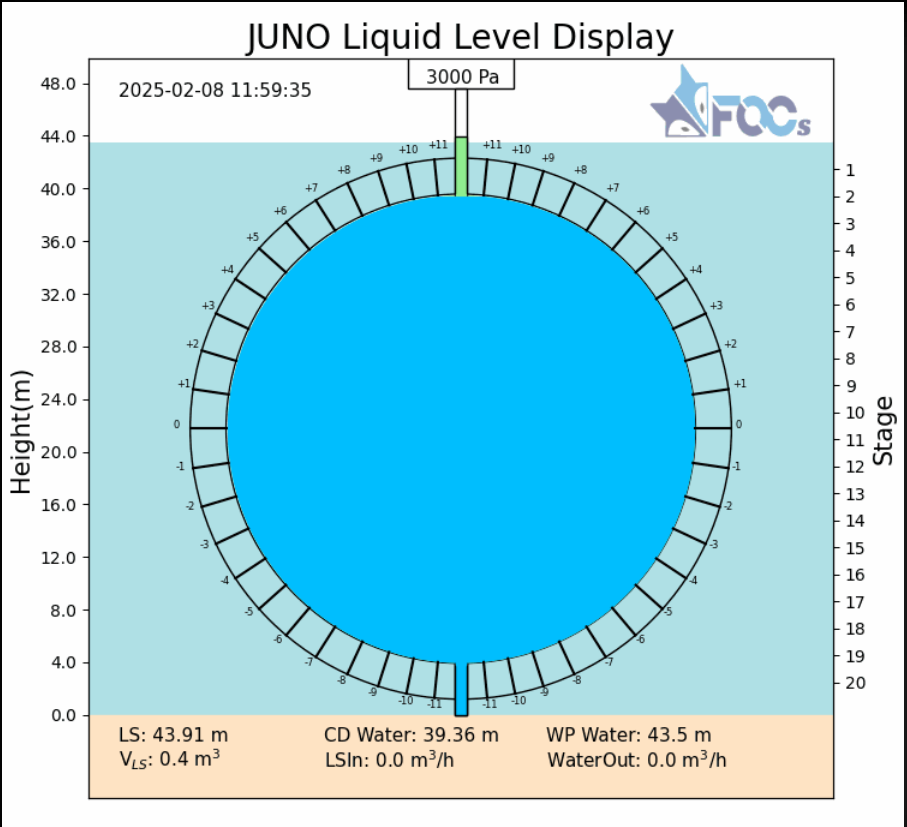
Civil construction

Detector installation

2024/12/18: Water filling

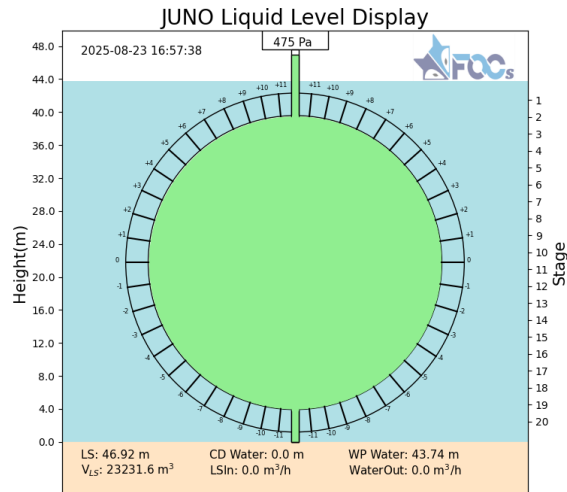
2025/02/01: Water/LS exchange

2025/08/22: LS filling complete

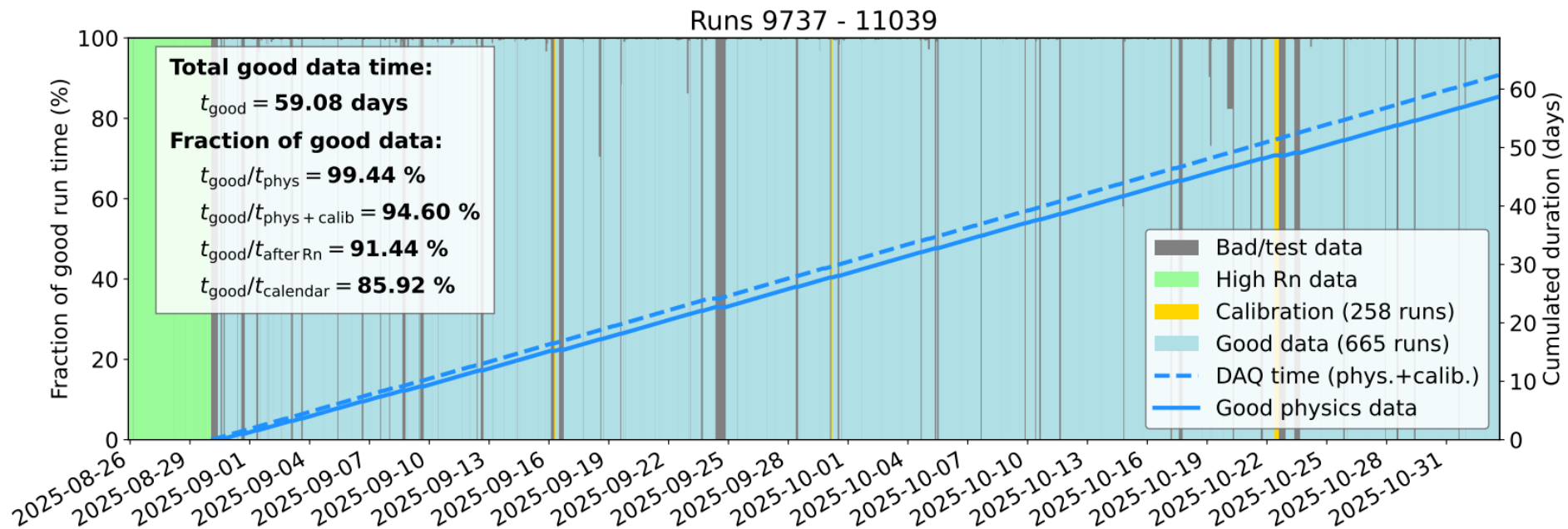


Animated gif

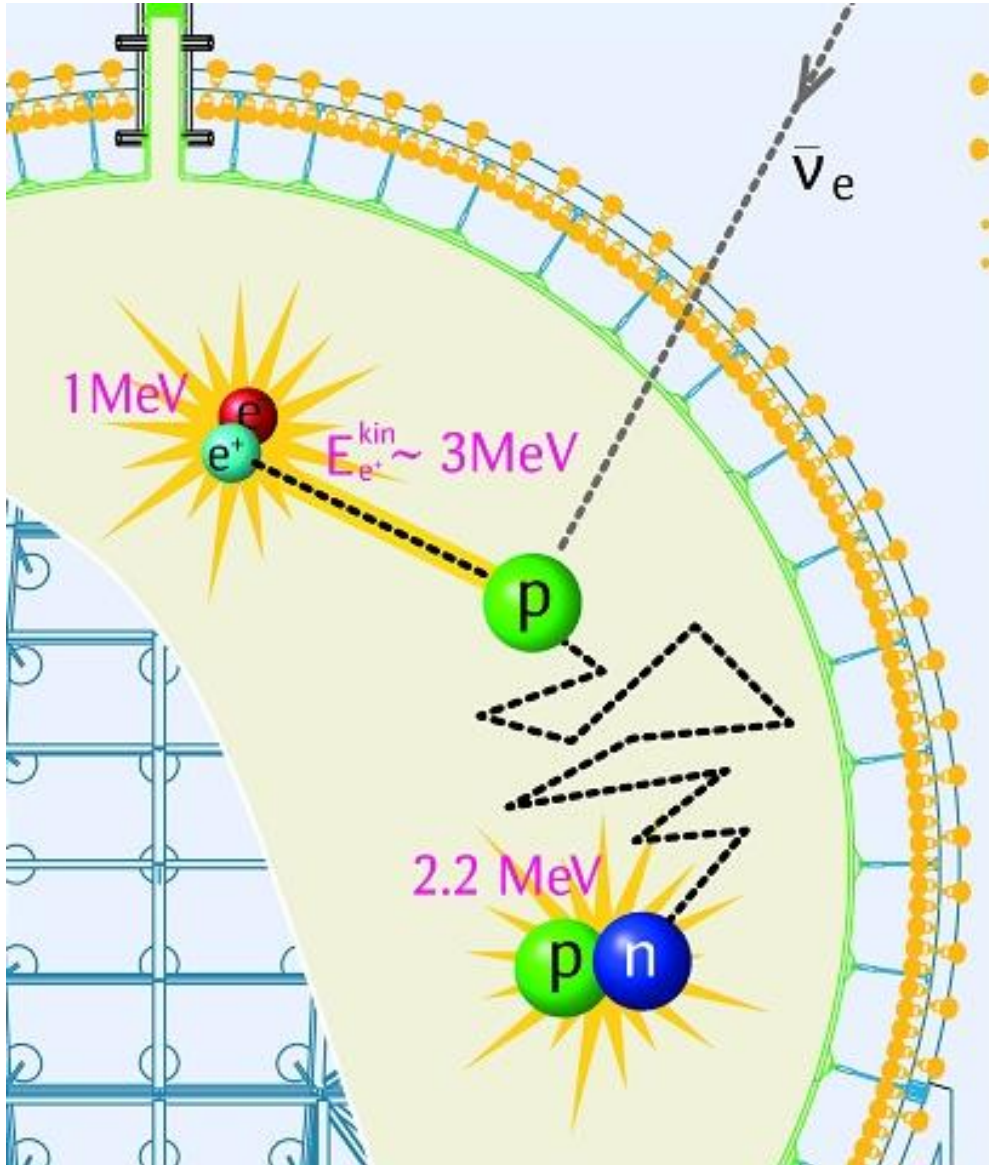
Towards JUNO's First Results



- ❑ 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)

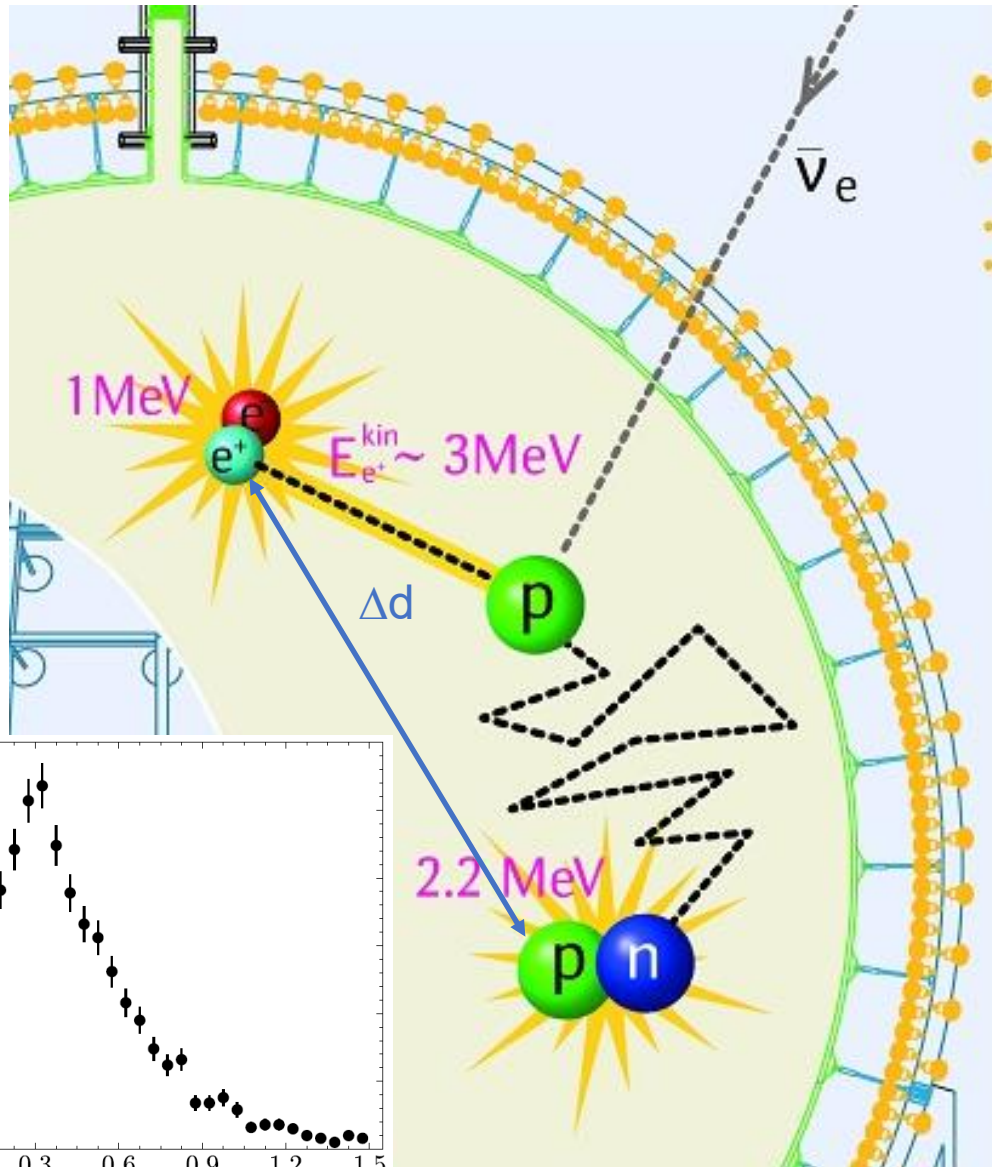
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

❑ Only on hydrogen, not carbon

❑ Prompt signal: e^+

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

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^+

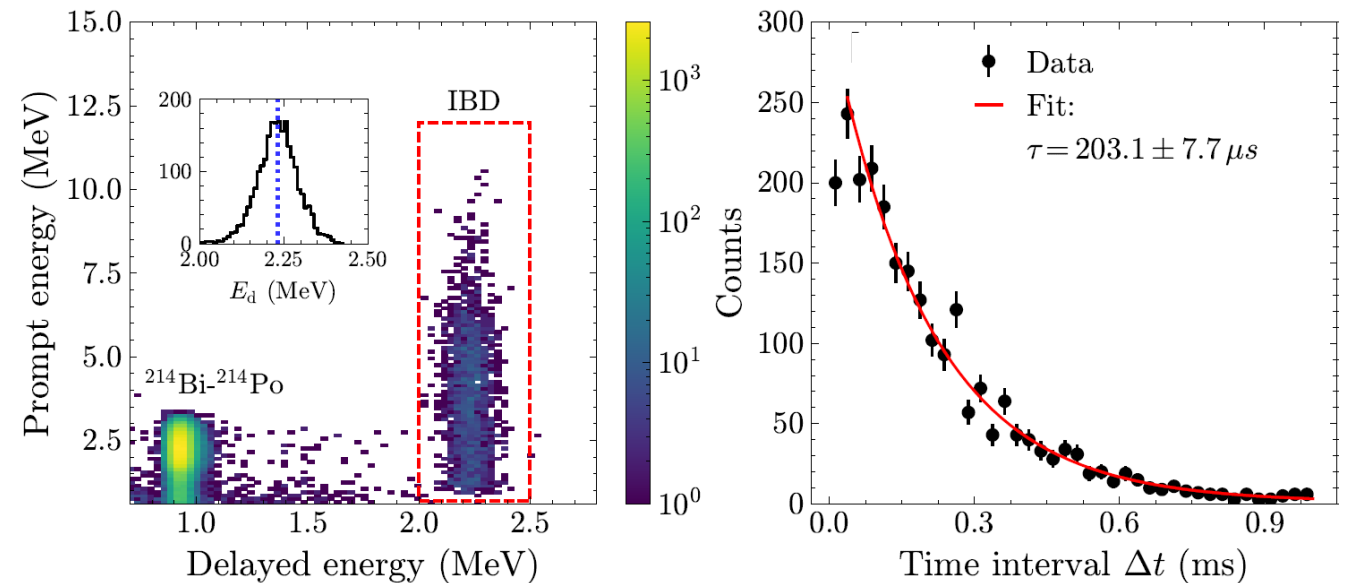
❖ Prompt energy + $0.78 \text{ MeV} \sim E_\nu$

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

❖ 2.2 MeV neutron capture peak

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

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

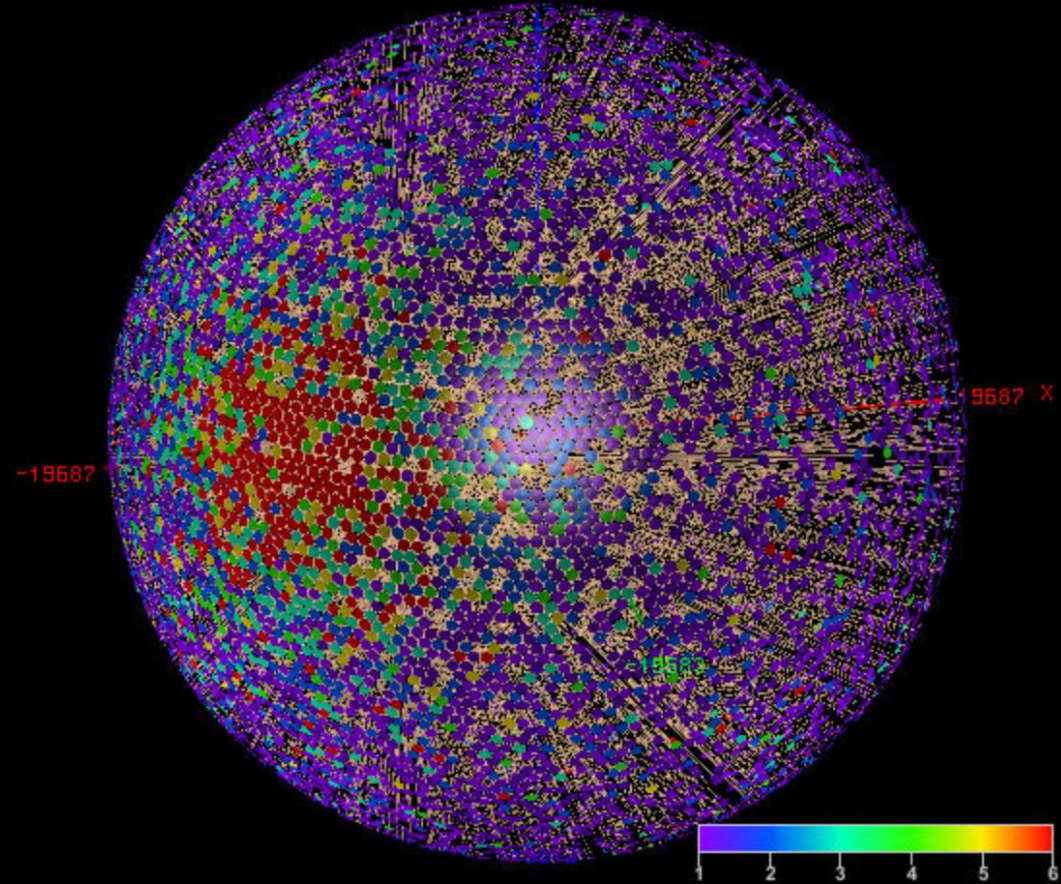


Spatial separation Δd (m)

2020 May 20, Warwick

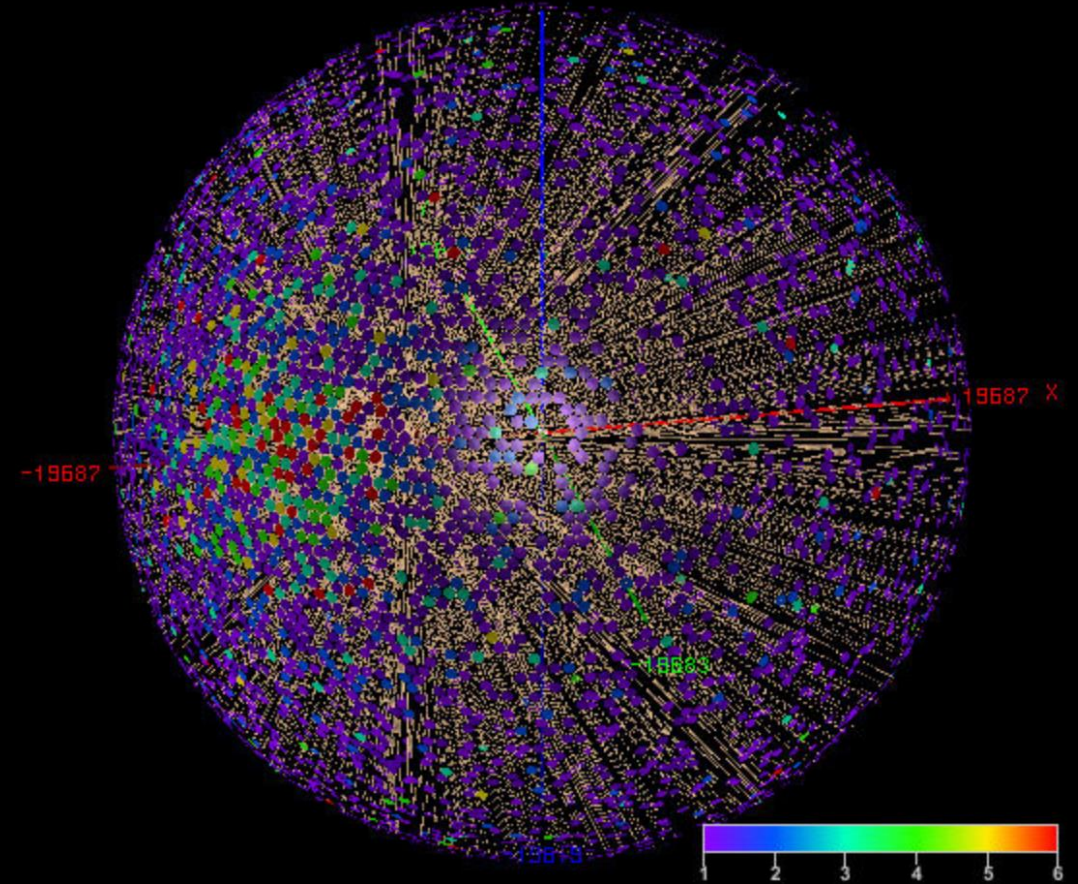
A Golden Reactor Neutrino Event

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



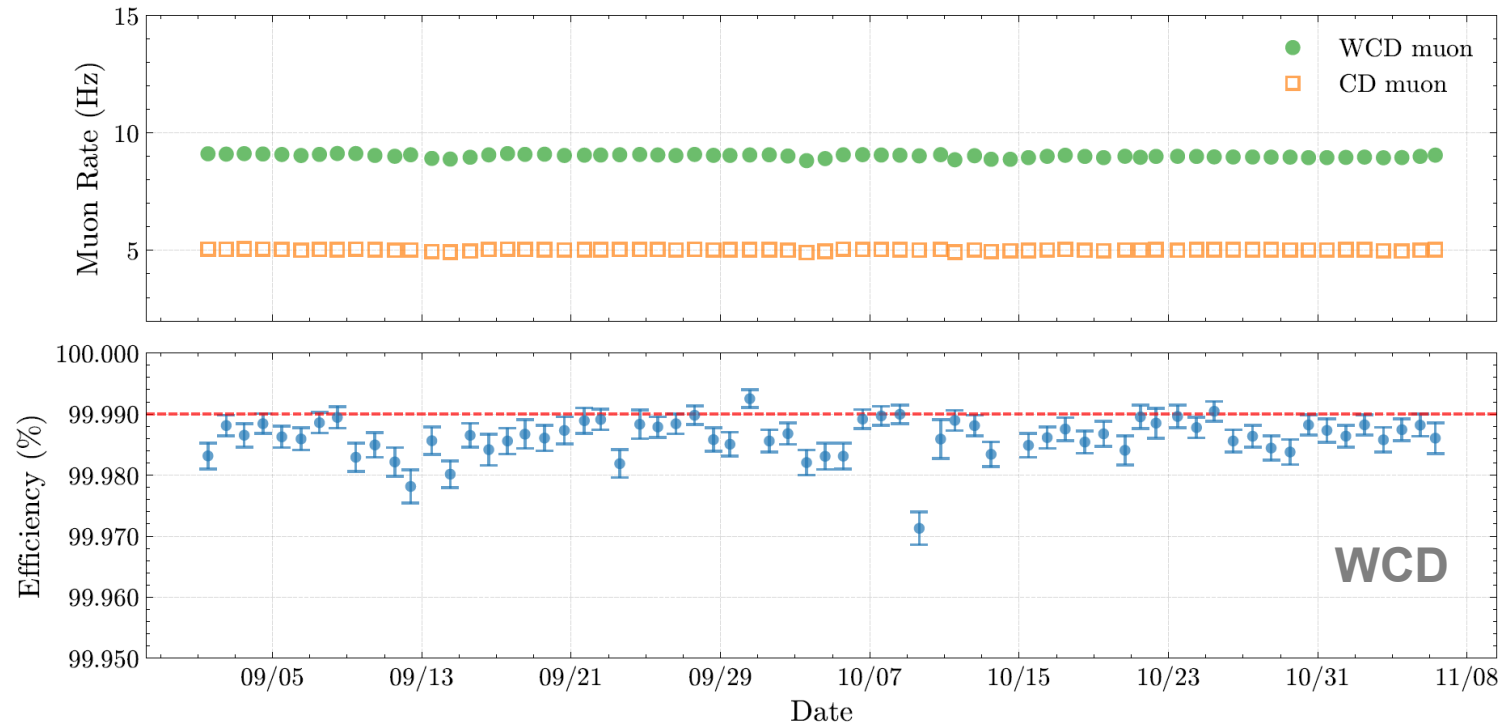
Prompt positron signal

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



Delayed neutron signal

Muon Veto



Muon tagging:

☐ WCD

❖ Cherenkov light

❖ 9 Hz

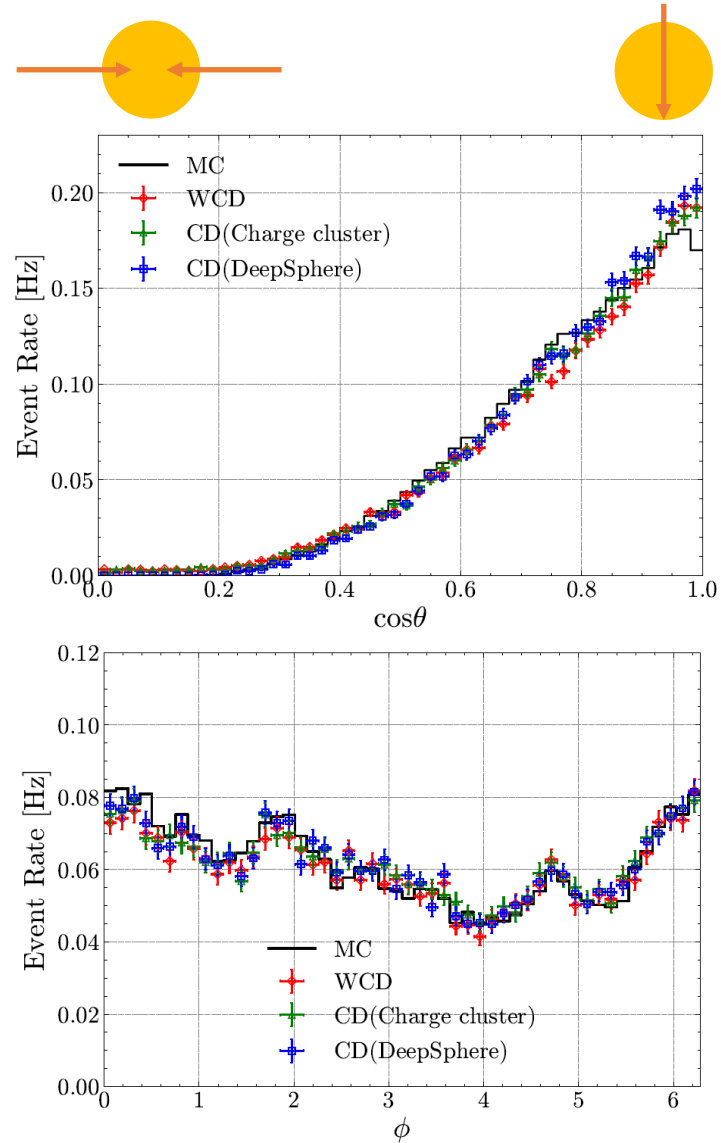
☐ CD

❖ Very large and track-like energy deposition

❖ 5 Hz

☐ Stable performance and almost 100% tagging efficiency in WCD

Muon Veto



Single muon reconstruction

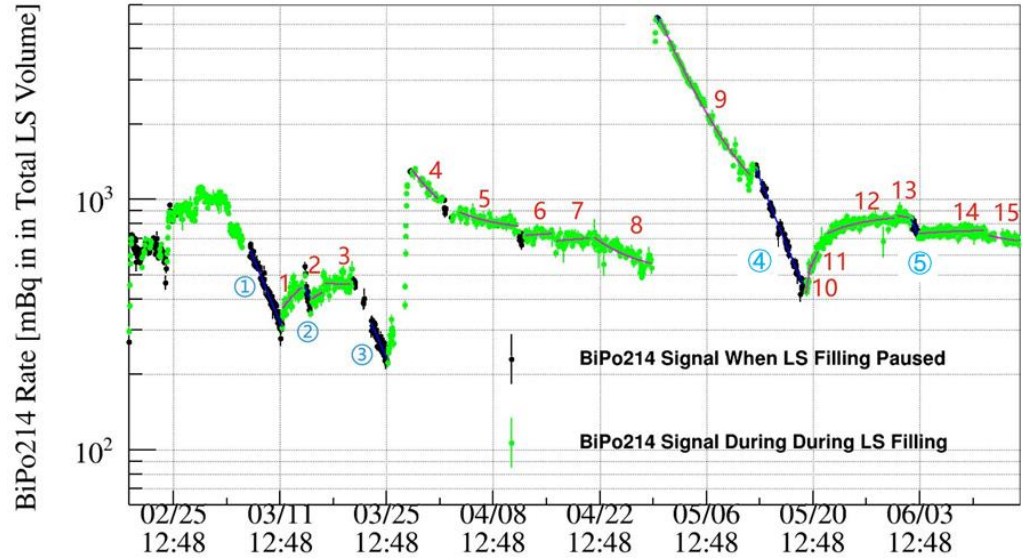
□ WCD and CD reconstruction consistent with MC

❖ Normalisation and shape

❖ Validating models of muon flux and rock overburden

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

❑ Natural radioactivity

❖ $^{238}\text{U} \rightarrow ^{210}\text{Po} \rightarrow \alpha$

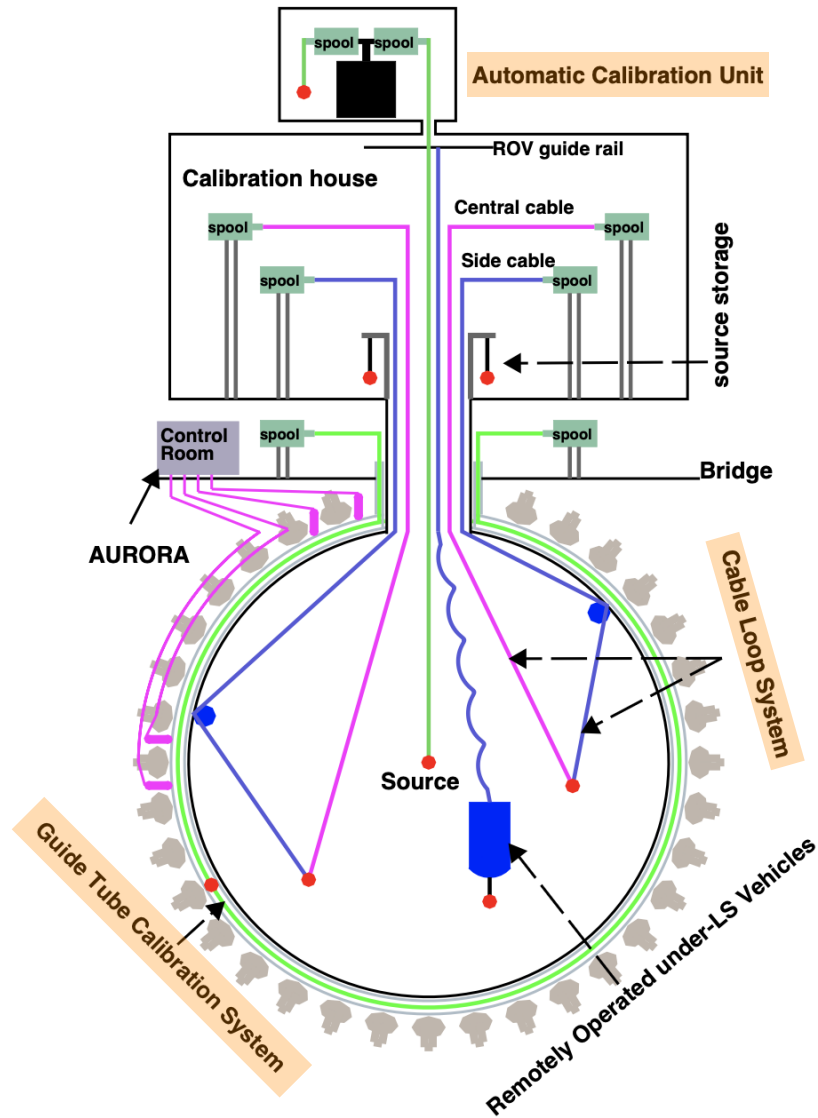
❖ $^{238}\text{U} \rightarrow ^{214}\text{Bi} \rightarrow ^{214}\text{Po} + \beta$ (prompt),
 $^{214}\text{Po} \rightarrow \alpha$ (delayed)

➤ Calibration α source

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

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

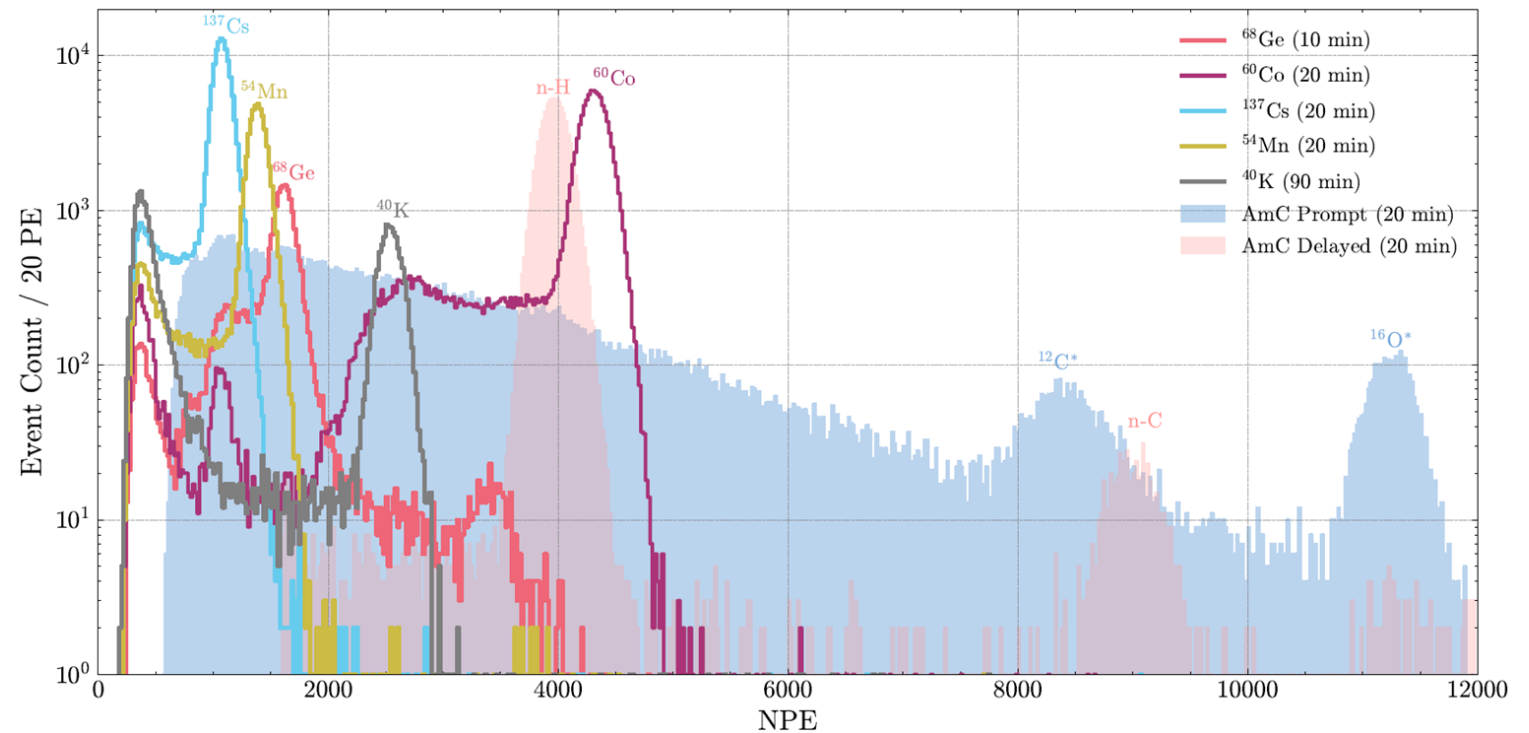
Energy Calibration



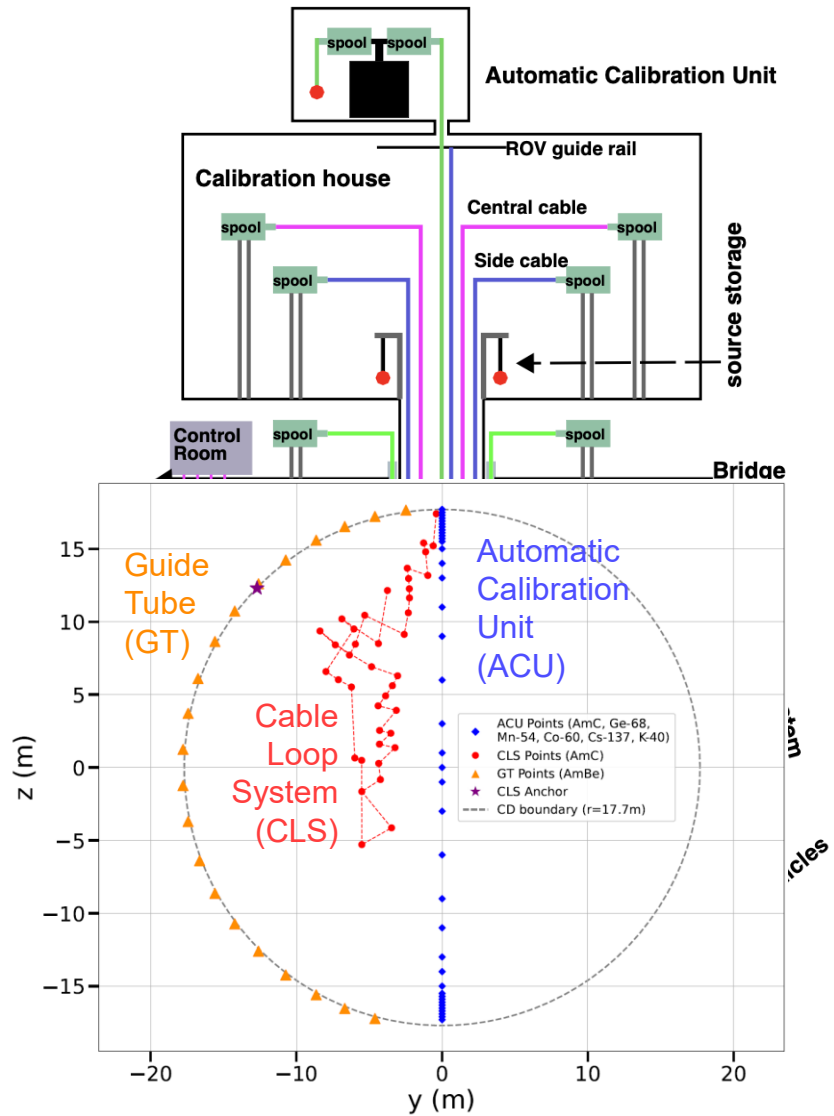
❑ External calibration sources deployed by ACU, CLS, and GT



❑ A wide range of energy covered

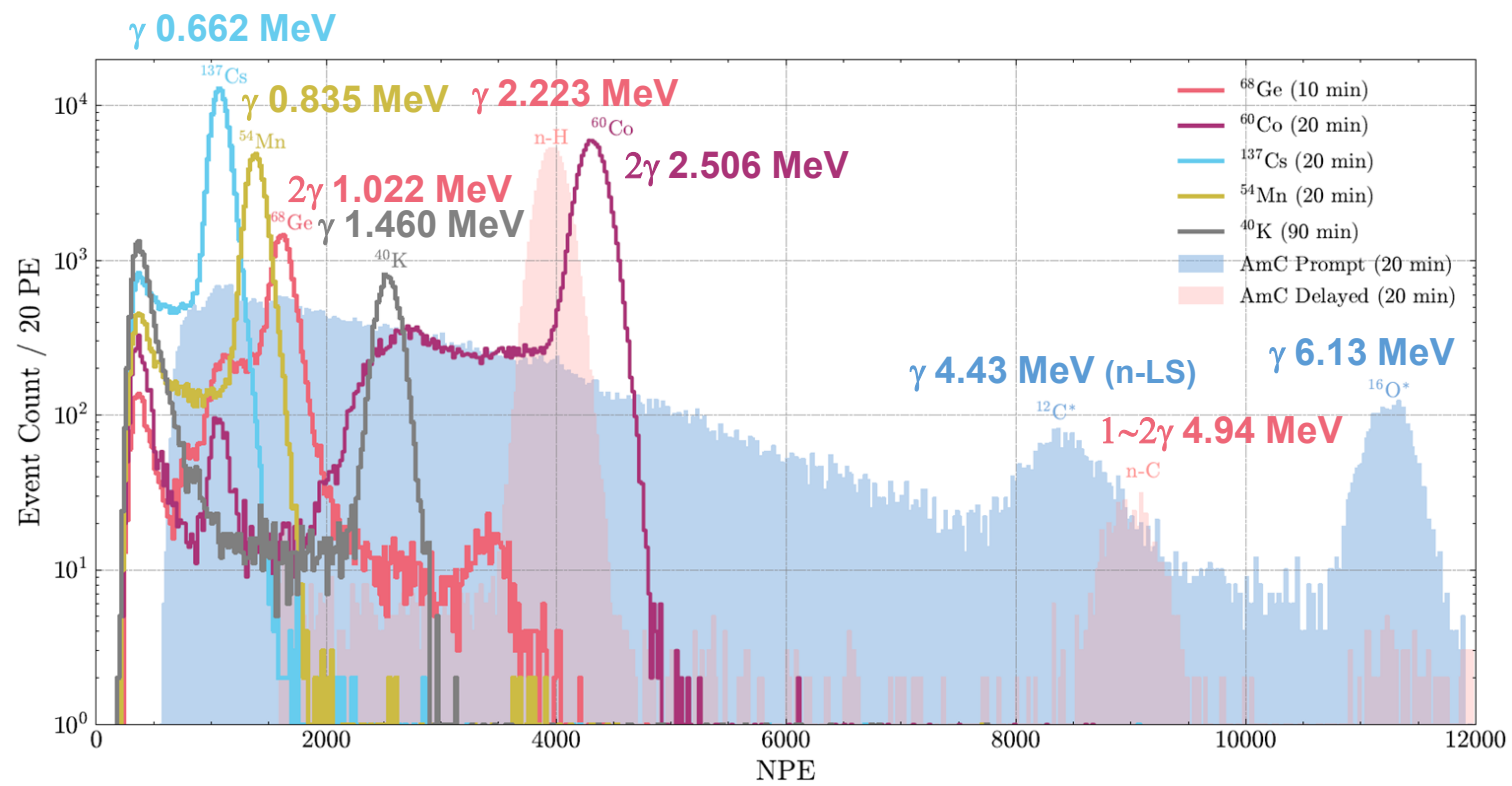


Energy Calibration



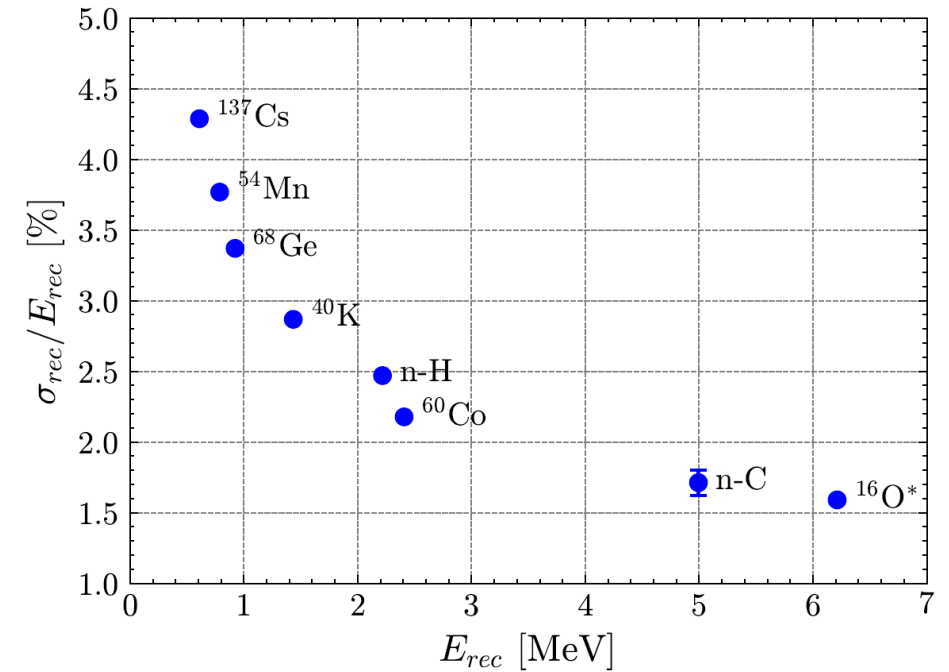
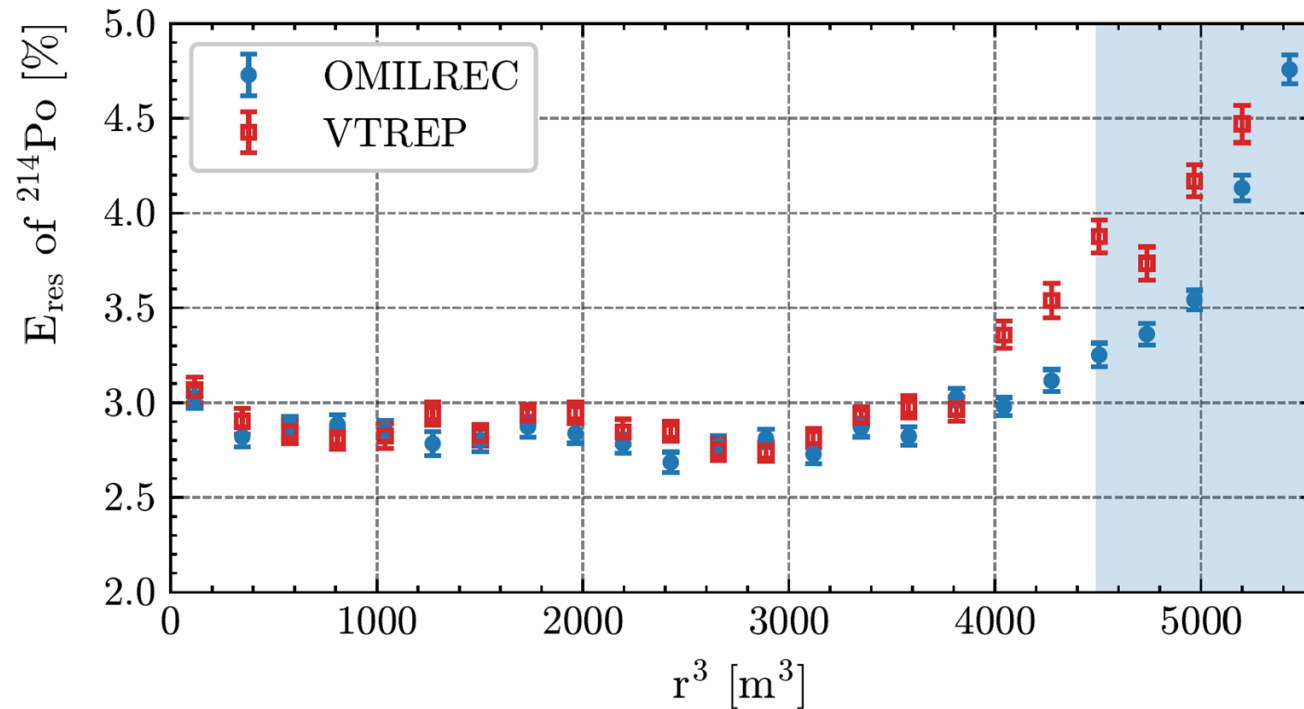
2026 May 28, Warwick

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



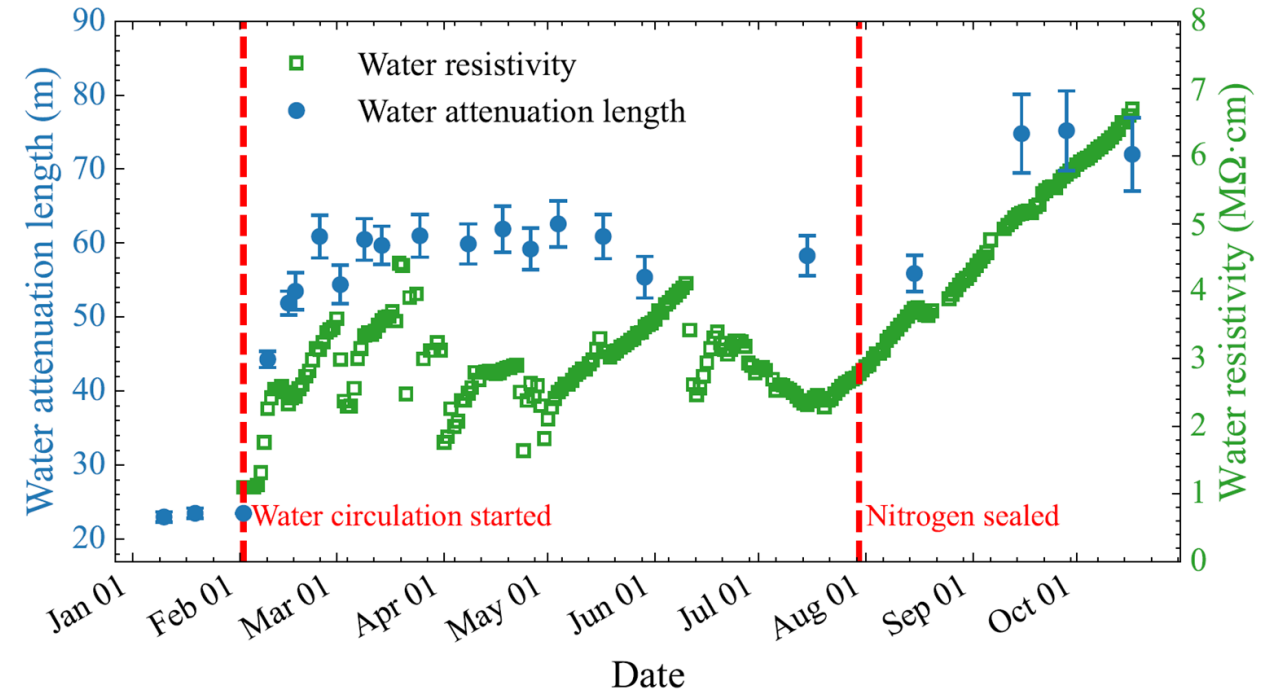
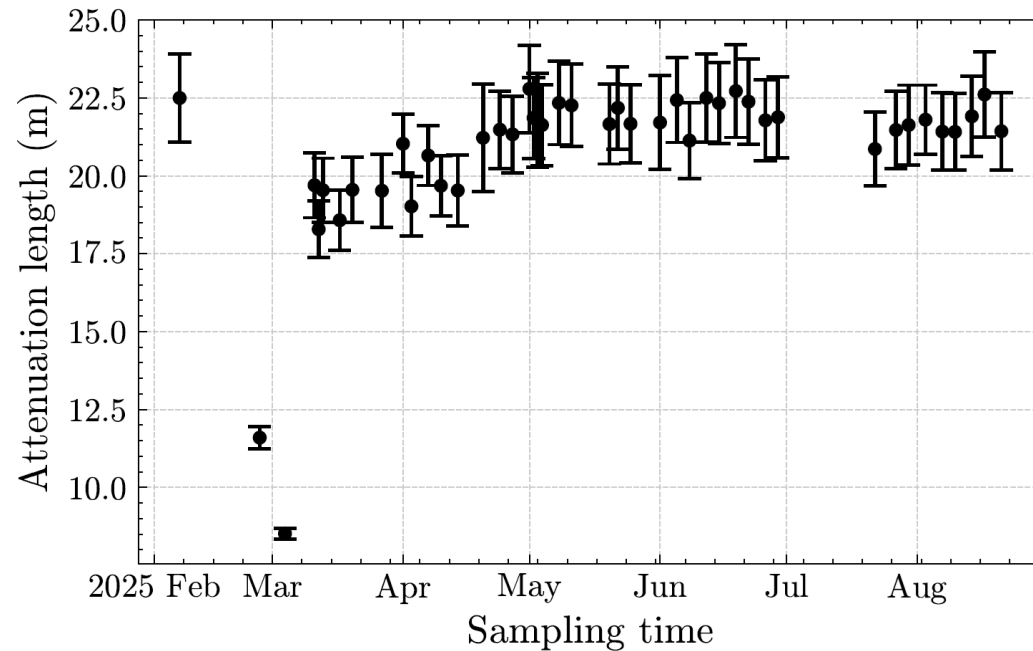
EPP Seminar | LU Xianguo 卢显国, Warwick

Energy Calibration



- Energy resolution for α from ^{214}Po is $< 3\%$ @0.93MeV
- Energy resolution for γ from ^{68}Ge is $\sim 3.4\%$ @0.90 MeV
 - ❖ Already close to but slightly worse than the expectation of 3.1%
 - ❖ Further improvements expected with better calibration and energy reconstruction

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

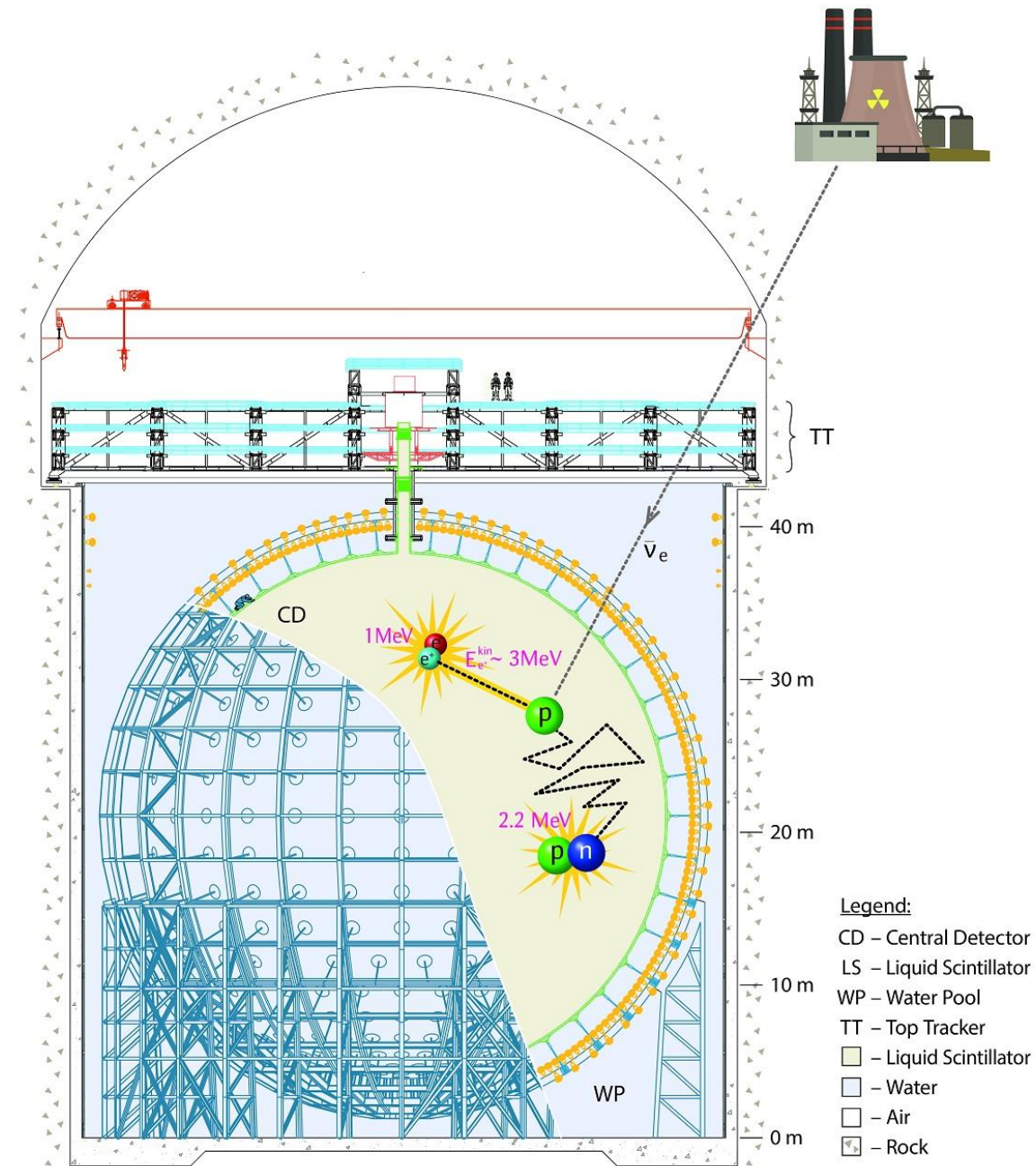
Event Selection

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



Reactor $\bar{\nu}_e$ Rate at JUNO

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\bar{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ε_{tot} corrected	33.5 ± 1.7	
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\bar{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
^{214}Bi - ^{214}Po	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3

Reactor $\bar{\nu}_e$ Rate at JUNO

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	~ 40 per day
$\bar{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ε_{tot} corrected	33.5 ± 1.7	~ 6 per day
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\bar{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
${}^9\text{Li}/{}^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
${}^{214}\text{Bi}$ - ${}^{214}\text{Po}$	0.18 ± 0.10	0.20 ± 0.10
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3

❑ Uncertainties on predicted non-oscillated signal rate

- ❖ Proton counting in LS (geometric, chemical, etc.)
- ❖ Flux constrained by released Daya Bay near detector data
- ❖ Residual reactor specific systematics

❑ S/B ~ 5

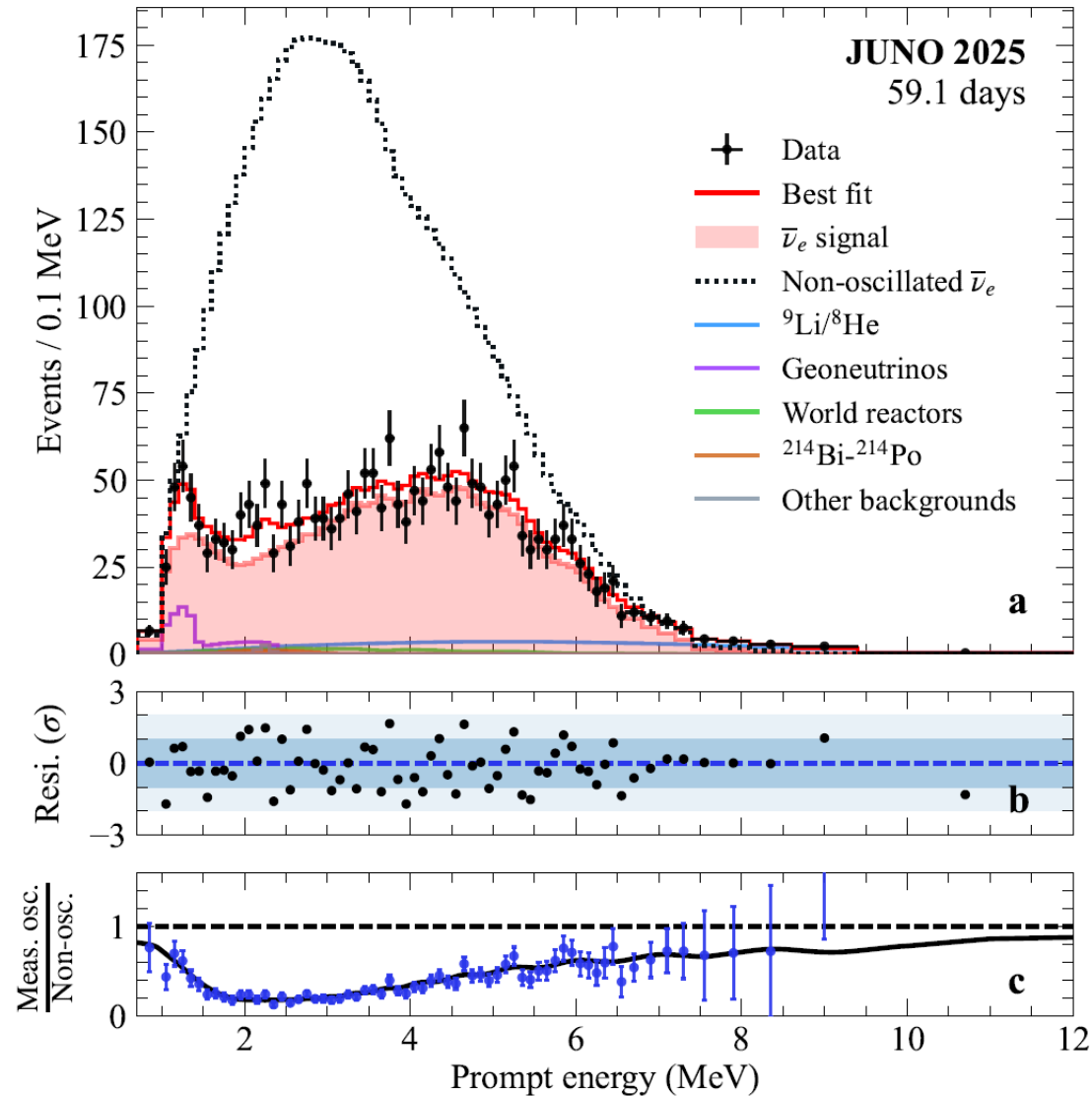
- ❖ Cosmogenic ${}^9\text{Li}/{}^8\text{He}$ S/B ~ 8, vert good given shallow depth!
- ❖ Geo-v irreducible but itself interesting!

Reactor $\bar{\nu}_e$ Rate at JUNO

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\bar{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ε_{tot} corrected	33.5 ± 1.7	
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\bar{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
^{214}Bi - ^{214}Po	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3

- ❑ Uncertainties on predicted non-oscillated signal rate
 - ❖ Proton counting in LS (geometric, chemical, etc.)
 - ❖ Flux constrained by released Daya Bay near detector data
 - ❖ Residual reactor specific systematics
- ❑ S/B ~ 5
 - ❖ Cosmogenic $^9\text{Li}/^8\text{He}$ S/B ~ 8 , vert good given shallow depth!
 - ❖ Geo- ν irreducible but itself interesting!
- ❑ Efficiency $\sim 70\%$
 - ❖ Dominated by fiducial volume

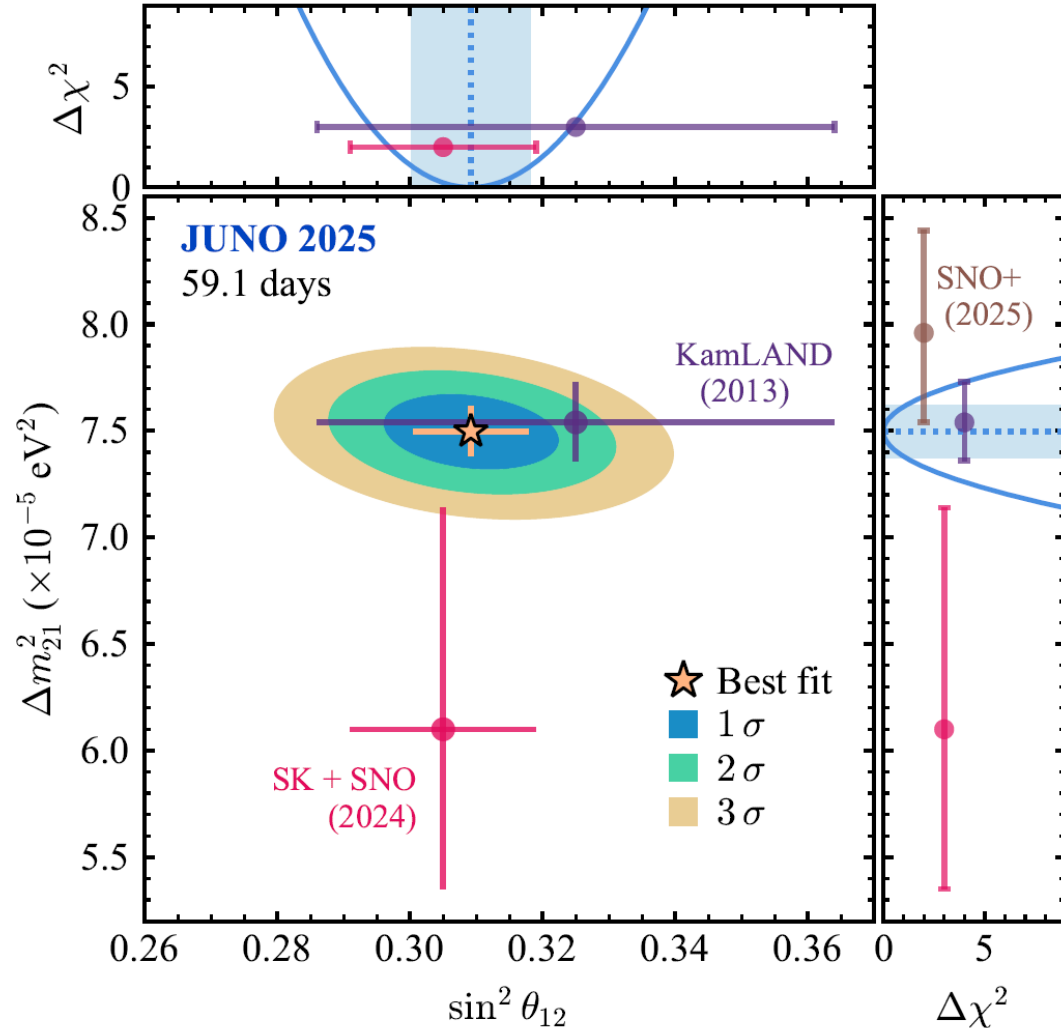
Reactor $\bar{\nu}_e$ Energy Spectrum at JUNO



- Dominant distortion driven by θ_{12} and Δm_{21}^2
- Backgrounds under control
- Consistent results from three independent analyses

❖ Own selections, reconstructions, background estimations, detector response characterisations, and fitting implementation

JUNO First Measurement of Solar Mixing Parameters



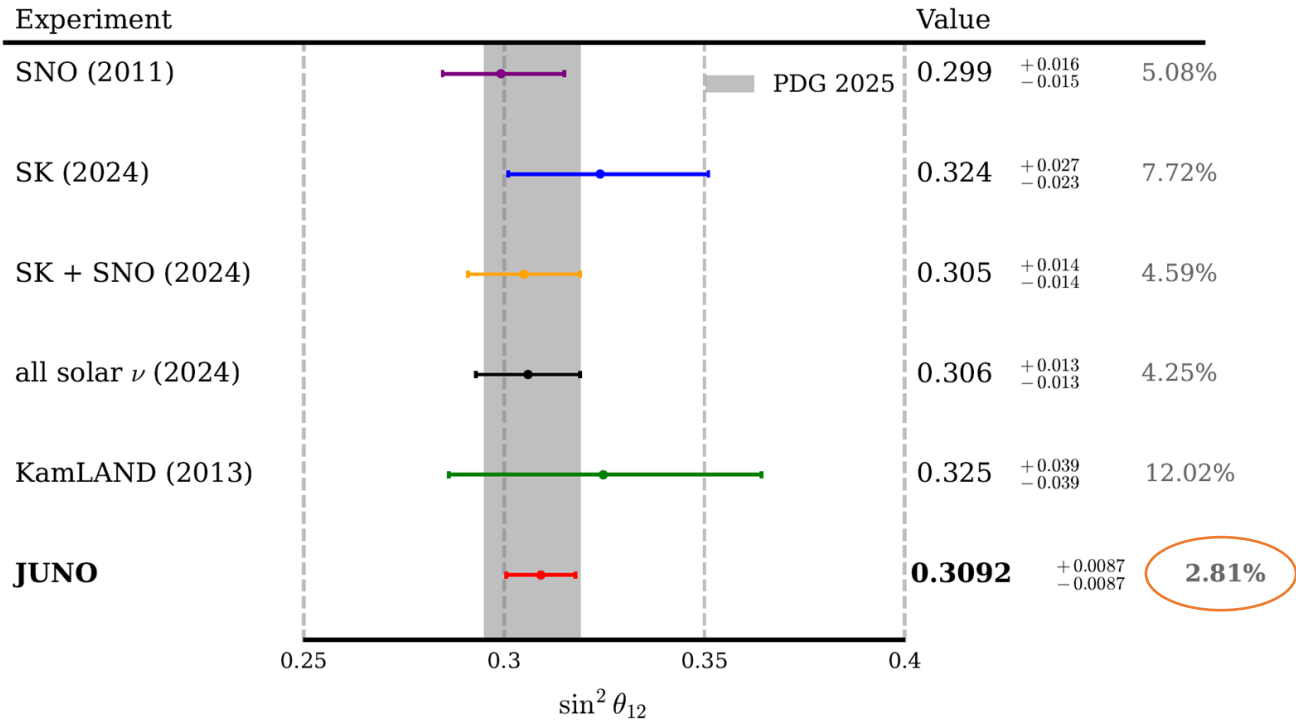
- Most precise single-experiment measurement of solar mixing parameters
 - 1.6× improvement in precision
- Significant improvement over previous reactor measurements
 - With only 59.1 days of data

SK+SNO (2024): SK, Phys. Rev. D 109, 092001 (2024)

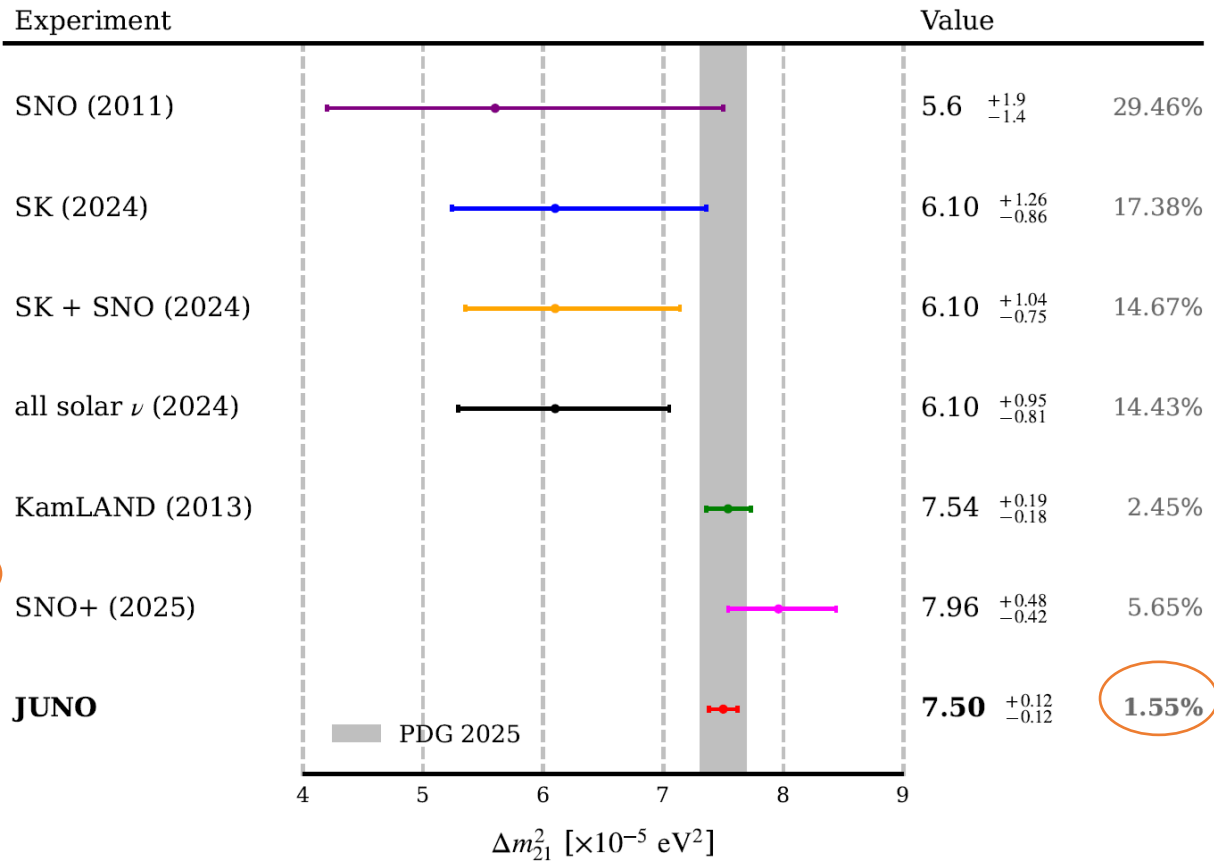
KamLand (2013): KamLAND, Phys. Rev. D 88, 033001 (2013)

SNO+ (2025): SNO+, Phys. Rev. Lett. 135, 121801 (2025)

JUNO First Measurement of Solar Mixing Parameters

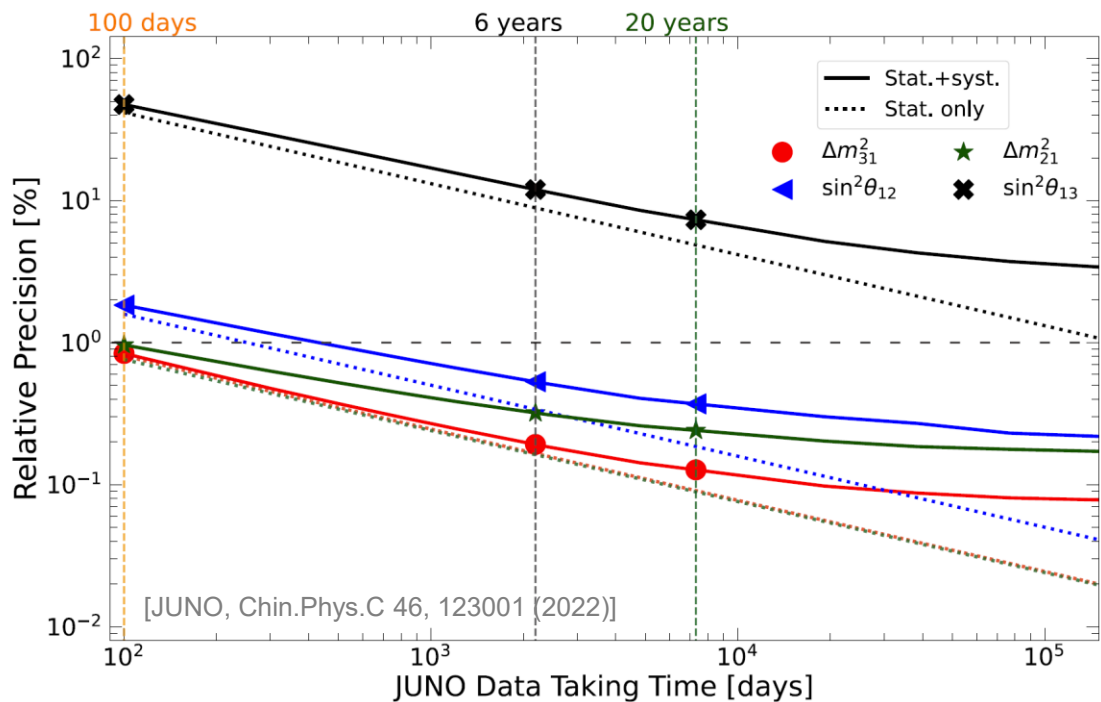


SNO (2011): SNO, Phys. Rev. C 88, 025501 (2013)
SK (2024), SK+SNO (2024), all solar ν (2024): SK, Phys. Rev. D 109, 092001 (2024)
KamLand (2013): KamLAND, Phys. Rev. D 88, 033001 (2013)
SNO+ (2025): SNO+, Phys. Rev. Lett. 135, 121801 (2025)

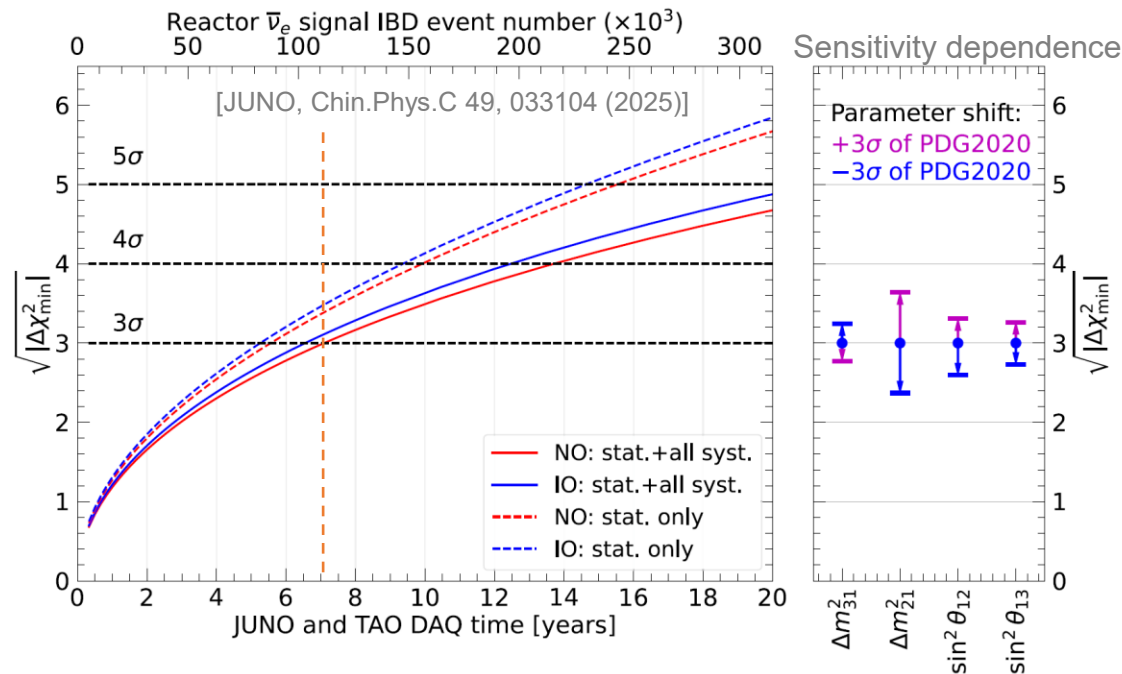


❖ Mild difference still between solar and reactor

Beyond the First Measurement



NMO sensitivity



7.1 years

□ NO: 3σ

□ IO: 3.1σ

□ Sub-percent measurements of Δm^2_{31} , Δm^2_{21} , $\sin^2 \theta_{12}$

An Observatory for 30 Years

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

Earth



~400/year

Sun



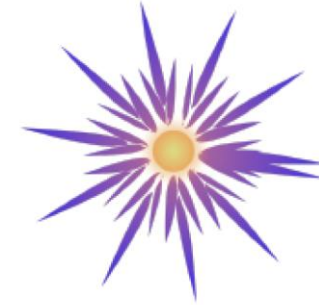
>100/day

Atmosphere



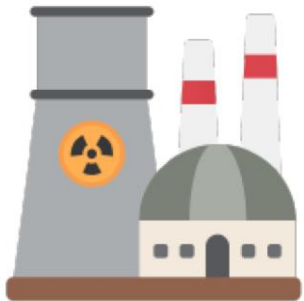
>100/year

Supernovae



~10⁴/10 s @ 10kpc

Reactor



~60/day

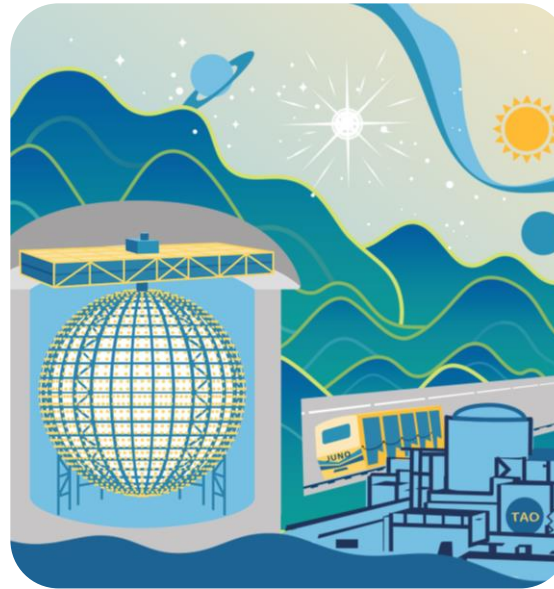


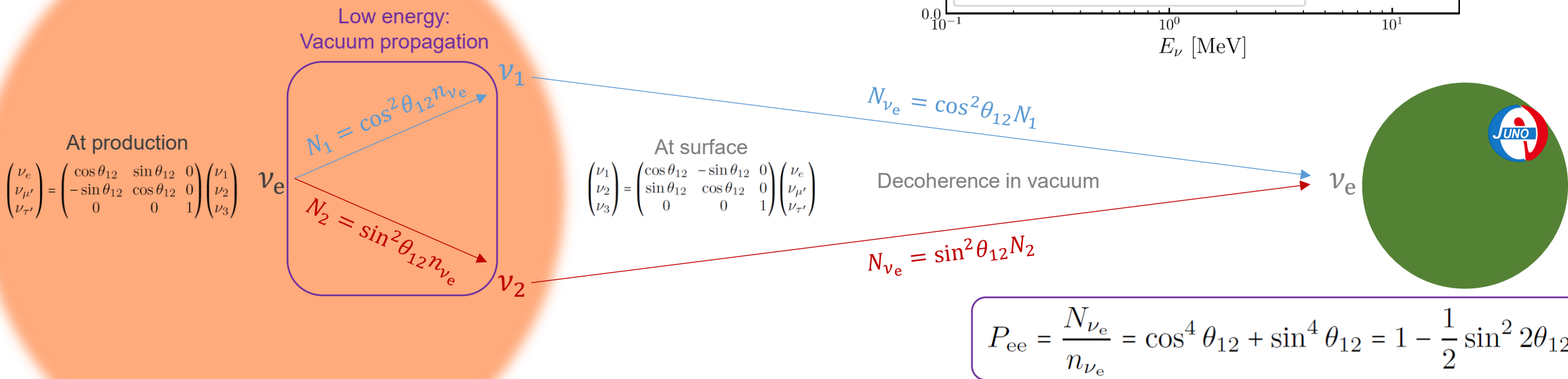
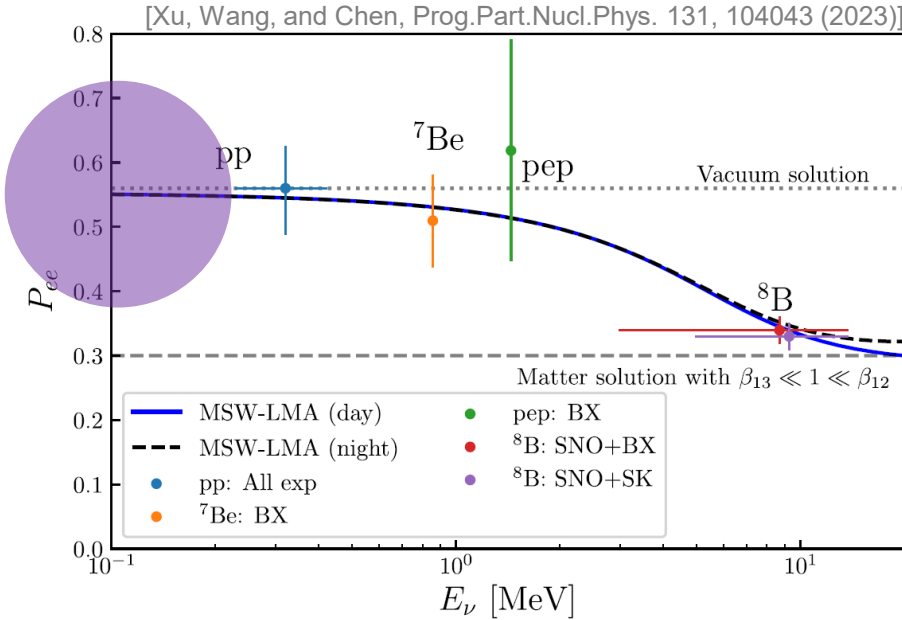
Image by CAS, published by China Daily

More!! (BSM)



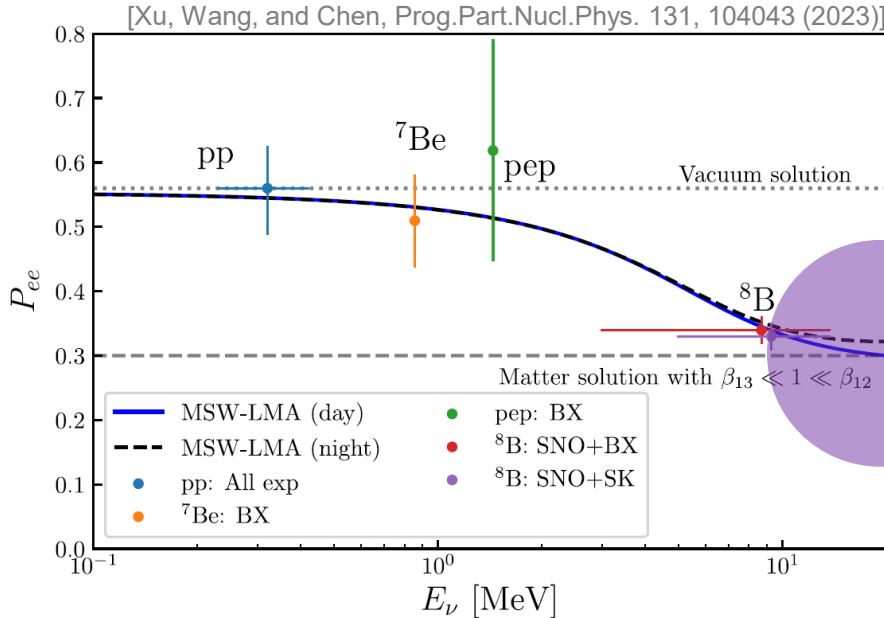
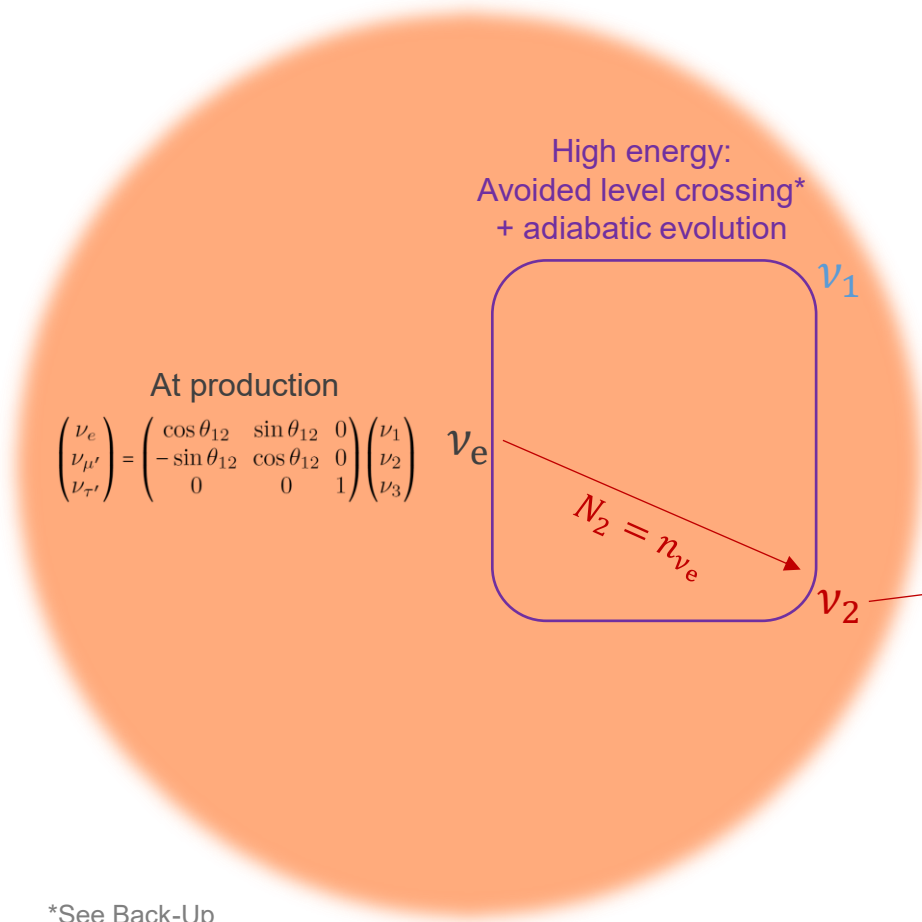
Mixing of Solar Neutrinos

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



Mixing of Solar Neutrinos

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

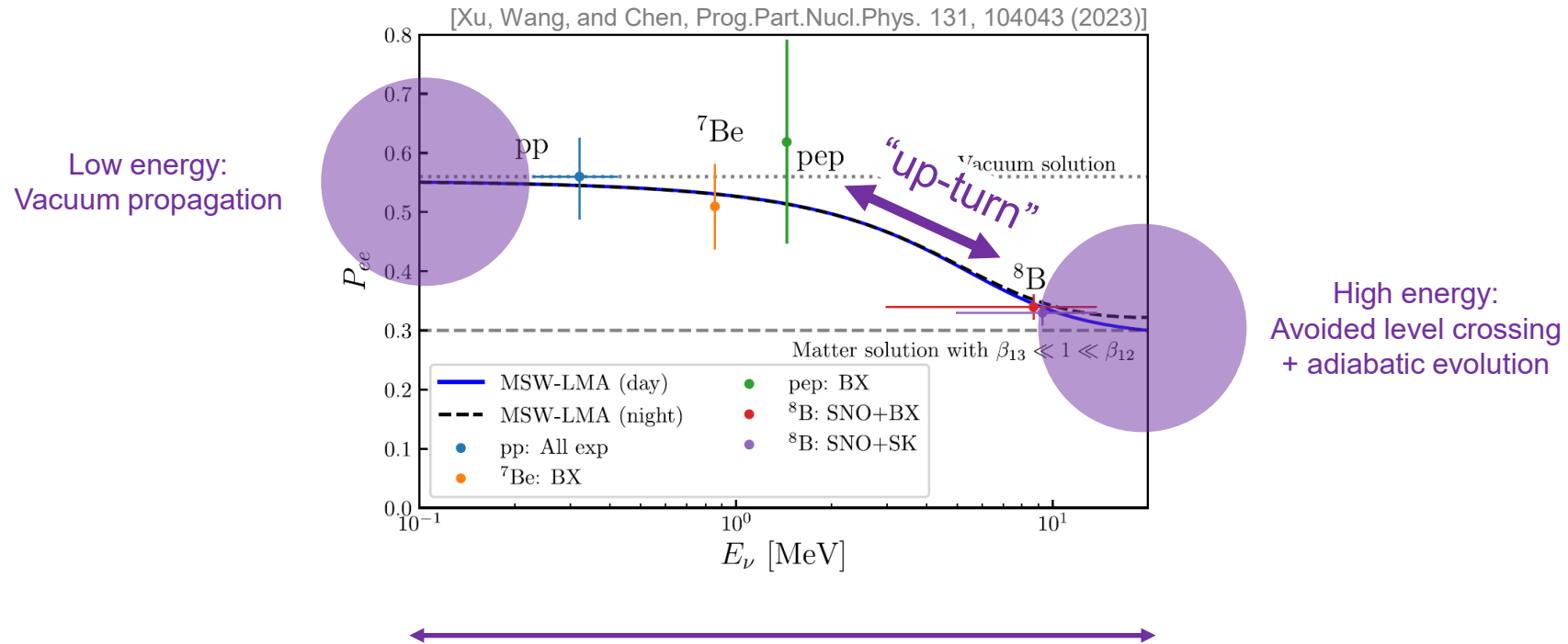


Decoherence in vacuum

$$P_{ee} = \frac{N_{\nu_e}}{n_{\nu_e}} = \sin^2 \theta_{12}$$

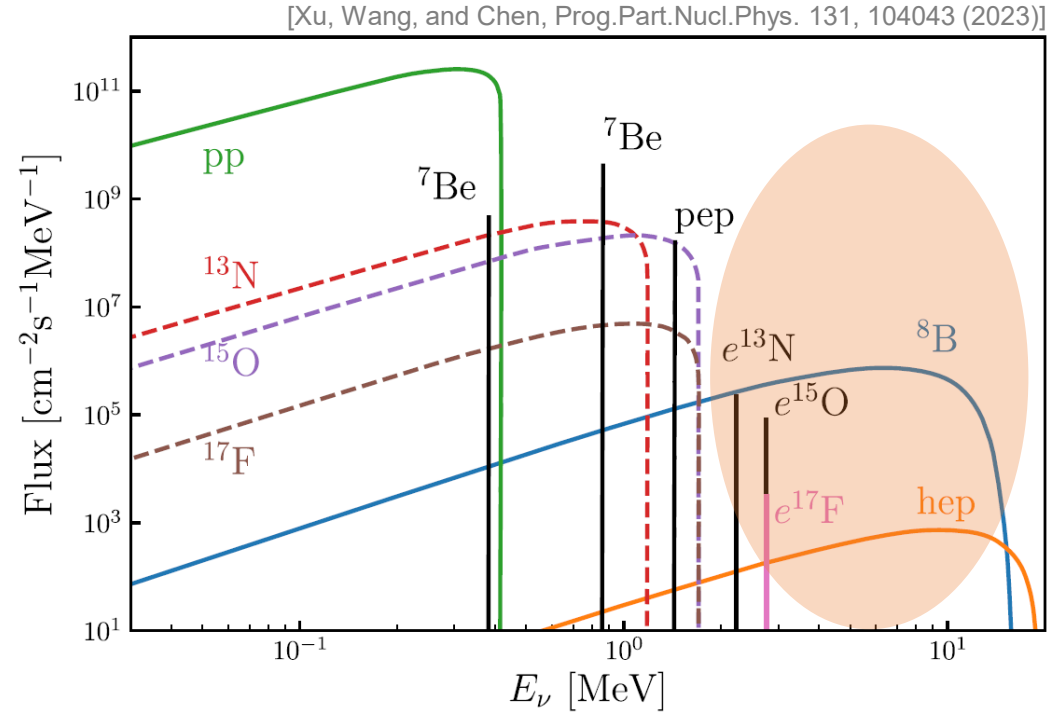
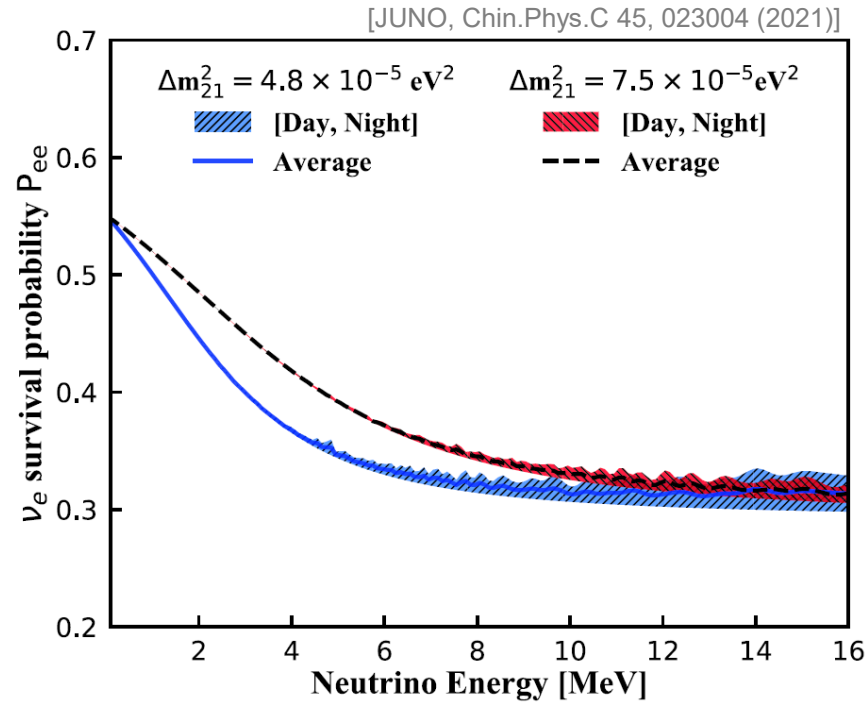
*See Back-Up

Mixing of Solar Neutrinos



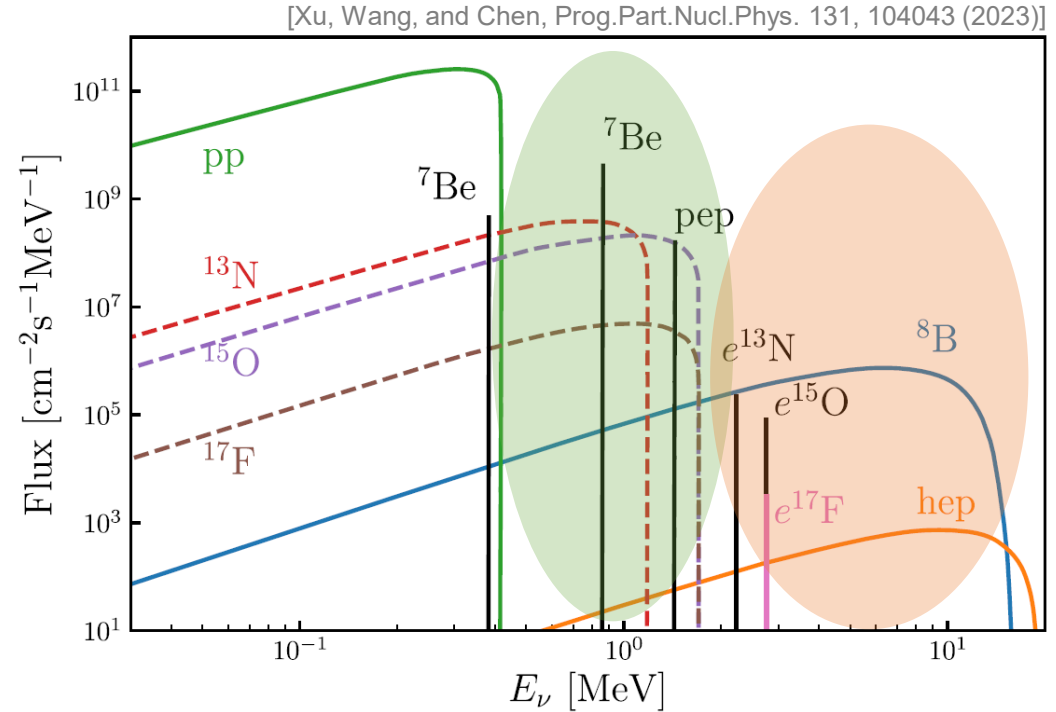
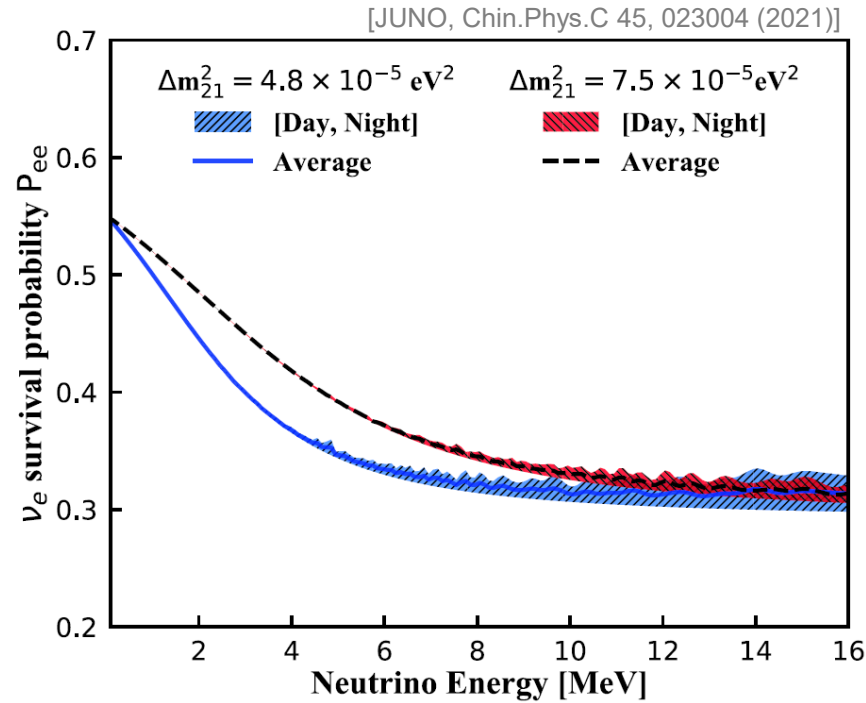
- How high is high?
- Relative to the only energy scale in this two-flavour mixing: Δm_{21}^2
- Stretching between limits, aka “up-turn”, gives us Δm_{21}^2

Solar Neutrinos at JUNO



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

Solar Neutrinos at JUNO



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

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.
- ❖ Establishes the foundation for the main JUNO goal: determining the neutrino mass ordering with
 - Larger statistics
 - Further optimised detector performance
 - TAO: near detector at Taishan NPP site to provide reference spectrum
 - ❖ -9.8 m (V, 5 m.w.e.), ~30 m (H) from 4.6 GW_{th}, 2.8 t Gd-LS, >95% photo-coverage, >50% photon detection efficiency [JUNO, arXiv:2005.08745]
 - ❖ Started data taking on 2026/02/10!
- ❖ Enables a diverse neutrino programme in the next 30 years



BACKUP

More on Neutrino Mass: MSW Matter Effect

Before getting into atmospheric ν ...

All neutrinos experience the same NC matter potential in medium.

Additional CC potential for ν_e (“+”) and $\bar{\nu}_e$ (“-”)

$$V_{CC} = \pm\sqrt{2}G_F n_e$$

Electron density n_e

Fermi constant $\sqrt{2}G_F \simeq 7.63 \times 10^{-14} \frac{\text{eV cm}^3}{N_A}$

$$A_{CC} \equiv 2EV_{CC}$$

Homework: Write down the Feynman diagrams of ν_e and $\bar{\nu}_e$ CC interactions with electrons.

Extremely relativistic kinematics

$$E \simeq p + \frac{m^2}{2p}, \quad p \simeq E$$

As usual, $\Delta m^2 \equiv m_2^2 - m_1^2$

1. No mixing: $\nu_1 = \nu_e, \nu_2 = \nu_\mu$

ν_e Hamiltonian in matter

$$H = E + V_{CC} \equiv E + \frac{m_M^2}{2E}$$

Effective mass $m_M^2 = m^2 + A_{CC}$

(NC induces the same A_{NC} for all neutrino flavours)

Effective mass gap $\Delta m_M^2 = \Delta m^2 - A_{CC}$

- When the matter potential fills up the mass gap

$$A_{CC} = \Delta m^2$$

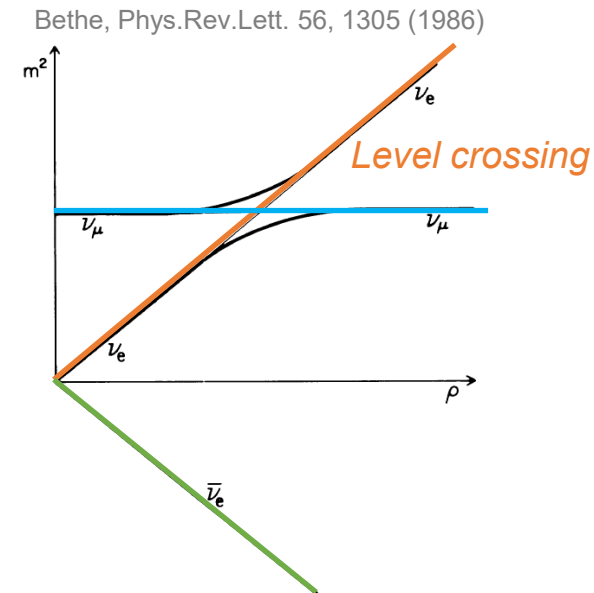
$$E [\text{GeV}] n_e \left[\frac{N_A}{\text{cm}^3} \right] = \frac{\Delta m^2 [10^{-5} \text{eV}^2]}{2 \times 7.63 \times 10^{-14} \left[\frac{\text{eV cm}^3}{N_A} \right]}$$

$$En_e \simeq \frac{\Delta m^2}{15}, \quad E \text{ in GeV}, n_e \text{ in } \frac{N_A}{\text{cm}^3}, \Delta m^2 \text{ in } 10^{-5} \text{eV}^2$$

$$\text{Water } n_e = \frac{5}{9} \frac{N_A}{\text{cm}^3}$$

$$\text{For } \Delta m^2 = 10^{-5} \text{eV}^2, E = 0.12 \text{ GeV}$$

- For $A_{CC} > \Delta m^2, \Delta m_M^2 < 0$
- For $A_{CC} \gg \Delta m^2, \Delta m_M^2 \simeq -A_{CC}$



More on Neutrino Mass: MSW Matter Effect

Extremely relativistic kinematics

$$E \simeq p + \frac{m^2}{2p}, \quad p \simeq E$$

As usual, $\Delta m^2 \equiv m_2^2 - m_1^2$

1. No mixing: $\nu_1 = \nu_e, \nu_2 = \nu_\mu$

ν_e Hamiltonian in matter

$$H = E + V_{CC} \equiv E + \frac{m_M^2}{2E}$$

Effective mass $m_M^2 = m^2 + A_{CC}$

(NC induces the same A_{NC} for all neutrino flavours)

Effective mass gap $\Delta m_M^2 = \Delta m^2 - A_{CC}$

- When the matter potential fills up the mass gap

$$A_{CC} = \Delta m^2$$

$$E [\text{GeV}] n_e \left[\frac{N_A}{\text{cm}^3} \right] = \frac{\Delta m^2 [10^{-5} \text{eV}^2]}{2 \times 7.63 \times 10^{-14} \left[\frac{\text{eV cm}^3}{N_A} \right]}$$

$$E n_e \simeq \frac{\Delta m^2}{15}, \quad E \text{ in GeV}, n_e \text{ in } \frac{N_A}{\text{cm}^3}, \Delta m^2 \text{ in } 10^{-5} \text{eV}^2$$

$$\text{Water } n_e = \frac{5}{9} \frac{N_A}{\text{cm}^3}$$

$$\text{For } \Delta m^2 = 10^{-5} \text{eV}^2, E = 0.12 \text{ GeV}$$

- For $A_{CC} > \Delta m^2$, $\Delta m_M^2 < 0$
- For $A_{CC} \gg \Delta m^2$, $\Delta m_M^2 \simeq -A_{CC}$

2. Mixing: Vacuum Hamiltonian in $\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$ basis

$$H \supset \frac{\Delta m^2}{4E} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

Full Hamiltonian in $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$ basis

$$H' \supset \frac{\Delta m^2}{4E} U \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} U^\dagger + \frac{A_{CC}}{4E} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\ \equiv \frac{\Delta m_M^2}{4E} U_M \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} U_M^\dagger,$$

with effective mass gap Δm_M^2 and mixing

$$U_M \equiv \begin{pmatrix} \cos \theta_M & \sin \theta_M \\ -\sin \theta_M & \cos \theta_M \end{pmatrix}$$

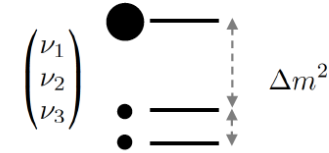
- When $A_{CC} \gg \Delta m^2$, U becomes irrelevant,

$$\frac{A_{CC}}{4E} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \frac{\Delta m_M^2}{4E} U_M \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} U_M^\dagger$$

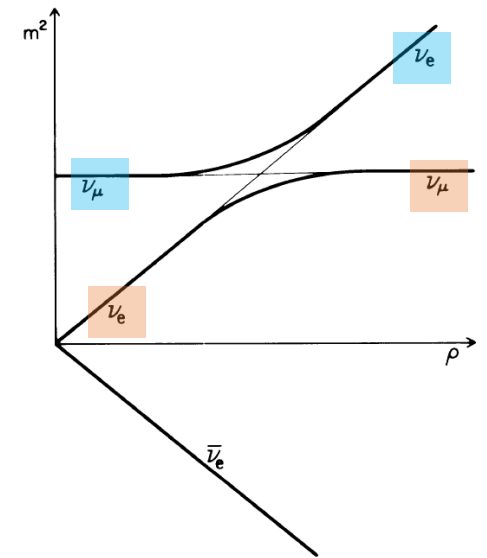
- $\Delta m_M^2 = -A_{CC}$, $\theta_M = 0$, falling back to the previous no mixing case, or
- $\Delta m_M^2 = A_{CC}$, $\theta_M = \pm \frac{\pi}{2}$, naming $\nu_1 = \nu_\mu$, $\nu_2 = \nu_e$.

Quiz: Is there oscillation when the mixing angle is $\pi/2$?

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



Bethe, Phys.Rev.Lett. 56, 1305 (1986)



More on Neutrino Mass: MSW Matter Effect

Extremely relativistic kinematics

$$E \simeq p + \frac{m^2}{2p}, \quad p \simeq E$$

As usual, $\Delta m^2 \equiv m_2^2 - m_1^2$

1. No mixing: $\nu_1 = \nu_e, \nu_2 = \nu_\mu$

ν_e Hamiltonian in matter

$$H = E + V_{CC} \equiv E + \frac{m_M^2}{2E}$$

Effective mass $m_M^2 = m^2 + A_{CC}$

(NC induces the same A_{NC} for all neutrino flavours)

Effective mass gap $\Delta m_M^2 = \Delta m^2 - A_{CC}$

- When the matter potential fills up the mass gap

$$A_{CC} = \Delta m^2$$

$$E [\text{GeV}] n_e \left[\frac{N_A}{\text{cm}^3} \right] = \frac{\Delta m^2 [10^{-5} \text{eV}^2]}{2 \times 7.63 \times 10^{-14} \left[\frac{\text{eV cm}^3}{N_A} \right]}$$

$$E n_e \simeq \frac{\Delta m^2}{15}, \quad E \text{ in GeV}, n_e \text{ in } \frac{N_A}{\text{cm}^3}, \Delta m^2 \text{ in } 10^{-5} \text{eV}^2$$

$$\text{Water } n_e = \frac{5}{9} \frac{N_A}{\text{cm}^3}$$

$$\text{For } \Delta m^2 = 10^{-5} \text{eV}^2, E = 0.12 \text{ GeV}$$

- For $A_{CC} > \Delta m^2$, $\Delta m_M^2 < 0$
- For $A_{CC} \gg \Delta m^2$, $\Delta m_M^2 \simeq -A_{CC}$

2. Mixing: Vacuum Hamiltonian in $\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$ basis

$$H \supset \frac{\Delta m^2}{4E} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

Full Hamiltonian in $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$ basis

$$\begin{aligned} H' &\supset \frac{\Delta m^2}{4E} U \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} U^\dagger + \frac{A_{CC}}{4E} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\ &\equiv \frac{\Delta m_M^2}{4E} U_M \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} U_M^\dagger, \end{aligned}$$

with effective mass gap Δm_M^2 and mixing

$$U_M \equiv \begin{pmatrix} \cos \theta_M & \sin \theta_M \\ -\sin \theta_M & \cos \theta_M \end{pmatrix}$$

- When $A_{CC} \gg \Delta m^2$, U becomes irrelevant,

$$\frac{A_{CC}}{4E} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \frac{\Delta m_M^2}{4E} U_M \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} U_M^\dagger$$

- $\Delta m_M^2 = -A_{CC}$, $\theta_M = 0$, falling back to the previous no mixing case, or
- $\Delta m_M^2 = A_{CC}$, $\theta_M = \pm \frac{\pi}{2}$, naming $\nu_1 = \nu_\mu$, $\nu_2 = \nu_e$.

- In general, with

$$U \equiv \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

The effective mass gap and mixing angle are

$$\begin{aligned} \Delta m_M^2 &= \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2} \\ \tan 2\theta_M &= \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}} \quad \text{e.g. Giunti \& Kim (2007)} \end{aligned}$$

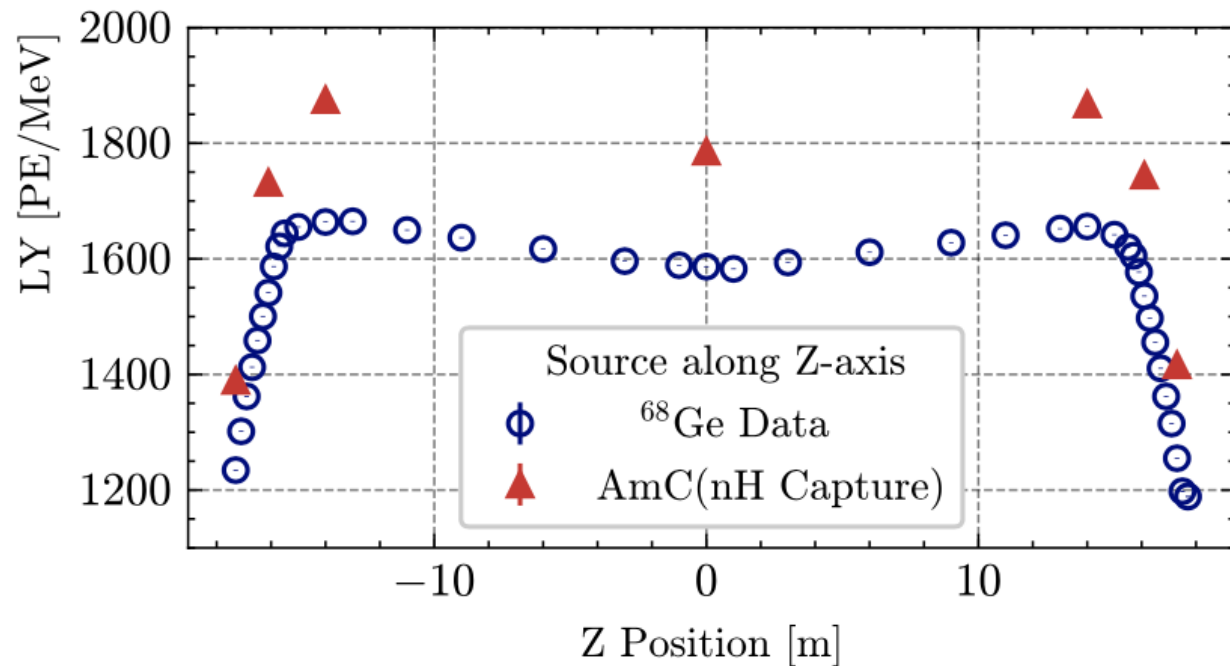
Mikheyev-Smirnov-Wolfenstein effect

Resonance at $A_{CC}^R = \Delta m^2 \cos 2\theta$

$$\theta_M^R = \frac{\pi}{4}, \text{ regardless of } \theta$$

... will come back to this later

Homework: Recover the previous no-mixing and small gap cases with the general effective mass gap and mixing angle.



Measured light yield along the z-axis

Better light yield than expected!
 ~1600 PE/MeV for ^{68}Ge and ~1780 PE/MeV for neutrons

	Borexino
^{238}U	$(1.6 \pm 0.1) \times 10^{-17} \text{ g/g}$
^{232}Th	$(6.8 \pm 1.5) \times 10^{-18} \text{ g/g}$
^{210}Po	$8 \times 10^4 \text{ cpd/kt}$

[Borexino, Phys.Rev.Lett. 101, 091302 (2008)]

- ☐ Construction & installation team size > 1000
 - ☐ Installation ~ 400
- ☐ Taishan: 2 EPRs (European Pressurised Reactor)
 - ☐ Yangjiang: 6 PWRs (pressurized water reactor)
- ☐ Data size: 60 MB/s ~ 5 TB/day
- ☐ Tyvek® < HDPE (High-Density Polyethylene)
 - ☐ WP wall: HDPE + Tyvek
 - ☐ SSS: Tyvek
- ☐ SN alert → continue data taking, DAQ saves triggerless TQ into disks for alert +/- 1min
- ☐ SSS 3 mm tolerance can be maintained during filling?
- ☐ Calibration vehicle controlled via umbilical cable
- ☐ What dominates NMO/oscillation uncertainty now: FV, energy resolution, flux uncertainty

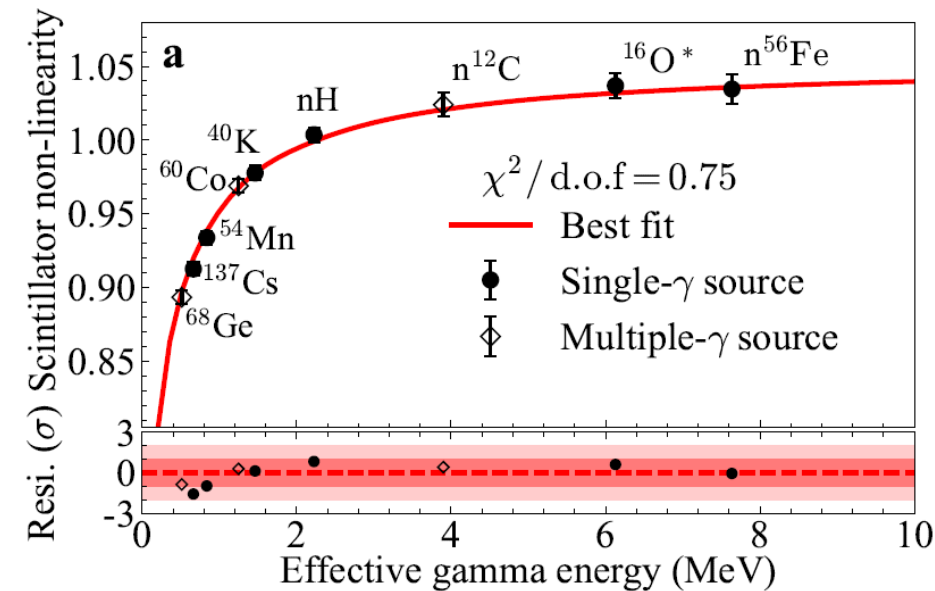
Table 1

Typical CC, NC, and ES Detection Channels of the ^8B Solar Neutrinos Together with the Final States, Neutrino Energy Threshold, Typical Signatures in the Detector, and Expected Event Numbers with 10 yr of Data Taking

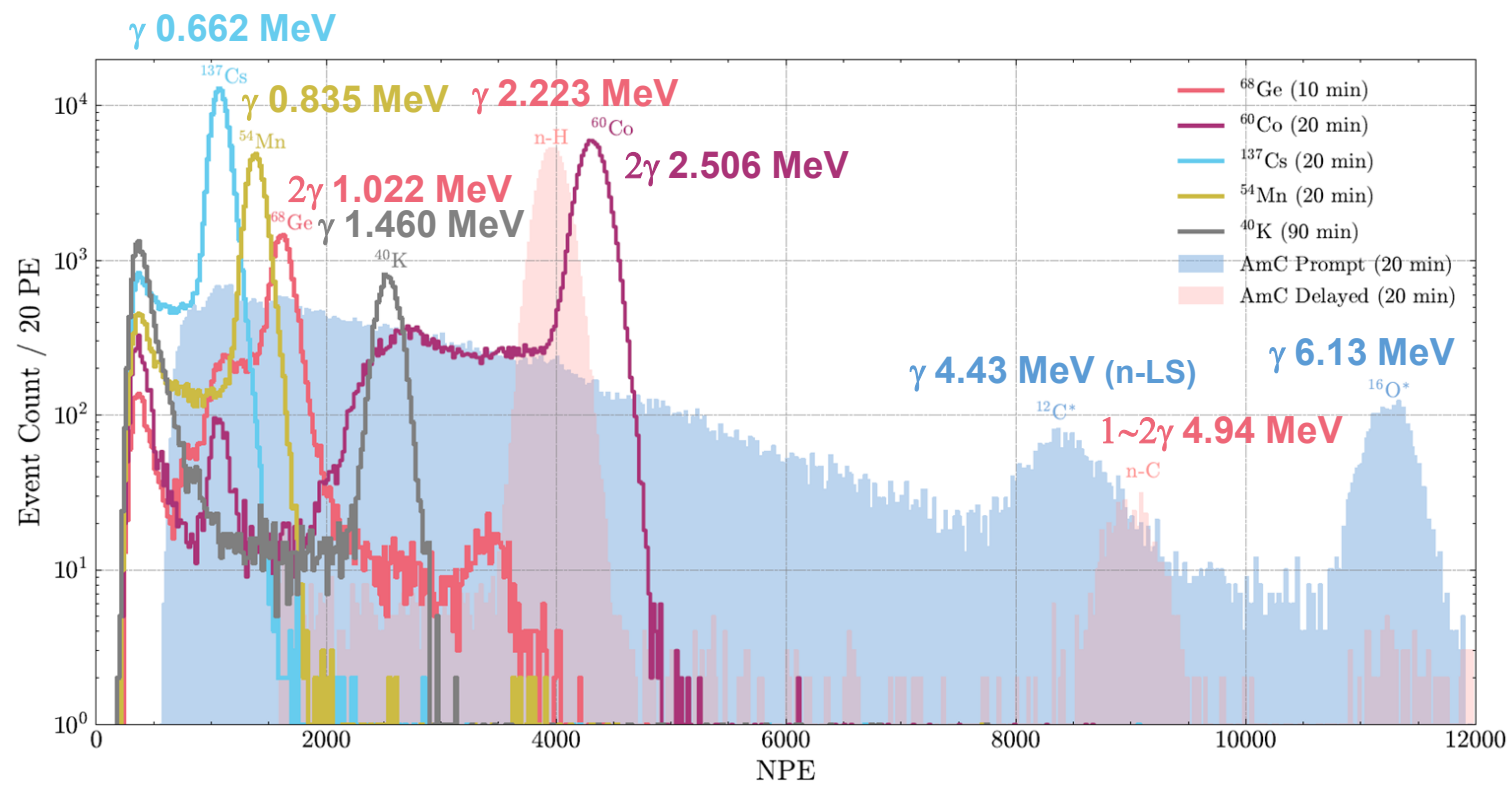
No.		Channels	Threshold (MeV)	Signal	Event Numbers (10 yr)
1	CC	$\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}(1^+; \text{gnd})$ (Fukugita et al. 1988)	16.827	$e^- + ^{12}\text{N}$ decay (β^+ , $Q = 17.338$ MeV)	0.43
1		$\nu_e + ^{13}\text{C} \rightarrow e^- + ^{13}\text{N}(\frac{1}{2}^-; \text{gnd})$ (Suzuki et al. 2012)	2.2	$e^- + ^{13}\text{N}$ decay (β^+ , $Q = 2.22$ MeV)	3929
2		$\nu_e + ^{13}\text{C} \rightarrow e^- + ^{13}\text{N}(\frac{3}{2}^-; 3.5 \text{ MeV})$ (Suzuki et al. 2012)	5.7	$e^- + p$	2464
4	NC	$\nu_x + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}(1^+; 15.11 \text{ MeV})$ (Fukugita et al. 1988)	15.1	γ	4.8
3		$\nu_x + ^{13}\text{C} \rightarrow \nu_x + n + ^{12}\text{C}(2^+; 4.44 \text{ MeV})$ (Suzuki et al. 2019)	6.864	$\gamma + n$ capture	65
4		$\nu_x + ^{13}\text{C} \rightarrow \nu_x + ^{13}\text{C}(\frac{1}{2}^+; 3.089 \text{ MeV})$ (Suzuki et al. 2012)	3.089	γ	14
5		$\nu_x + ^{13}\text{C} \rightarrow \nu_x + ^{13}\text{C}(\frac{3}{2}^-; 3.685 \text{ MeV})$ (Suzuki et al. 2012)	3.685	γ	3032
6		$\nu_x + ^{13}\text{C} \rightarrow \nu_x + ^{13}\text{C}(\frac{5}{2}^+; 3.854 \text{ MeV})$ (Suzuki et al. 2012)	3.854	γ	2.8
7	ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5

Note. Note that ν_x with ($x = e, \mu, \tau$) denotes all three active flavor neutrinos. The spin and parity of the daughter nuclei at the gnd or excited states, denoted as the corresponding excited energies, are also provided.

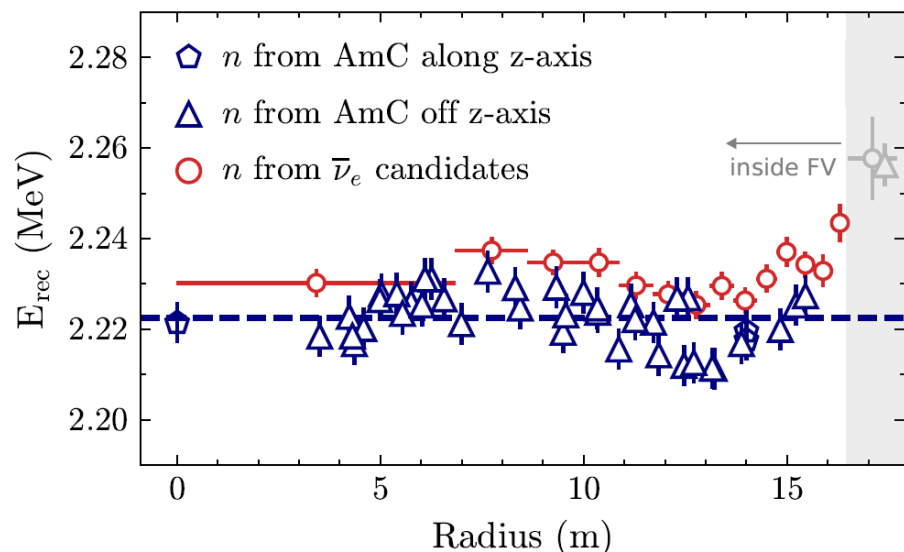
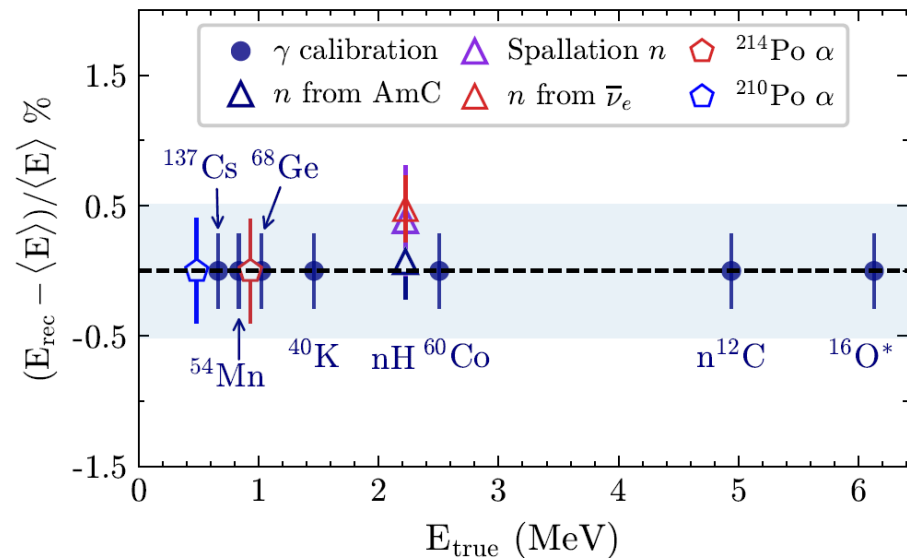
Energy Calibration



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



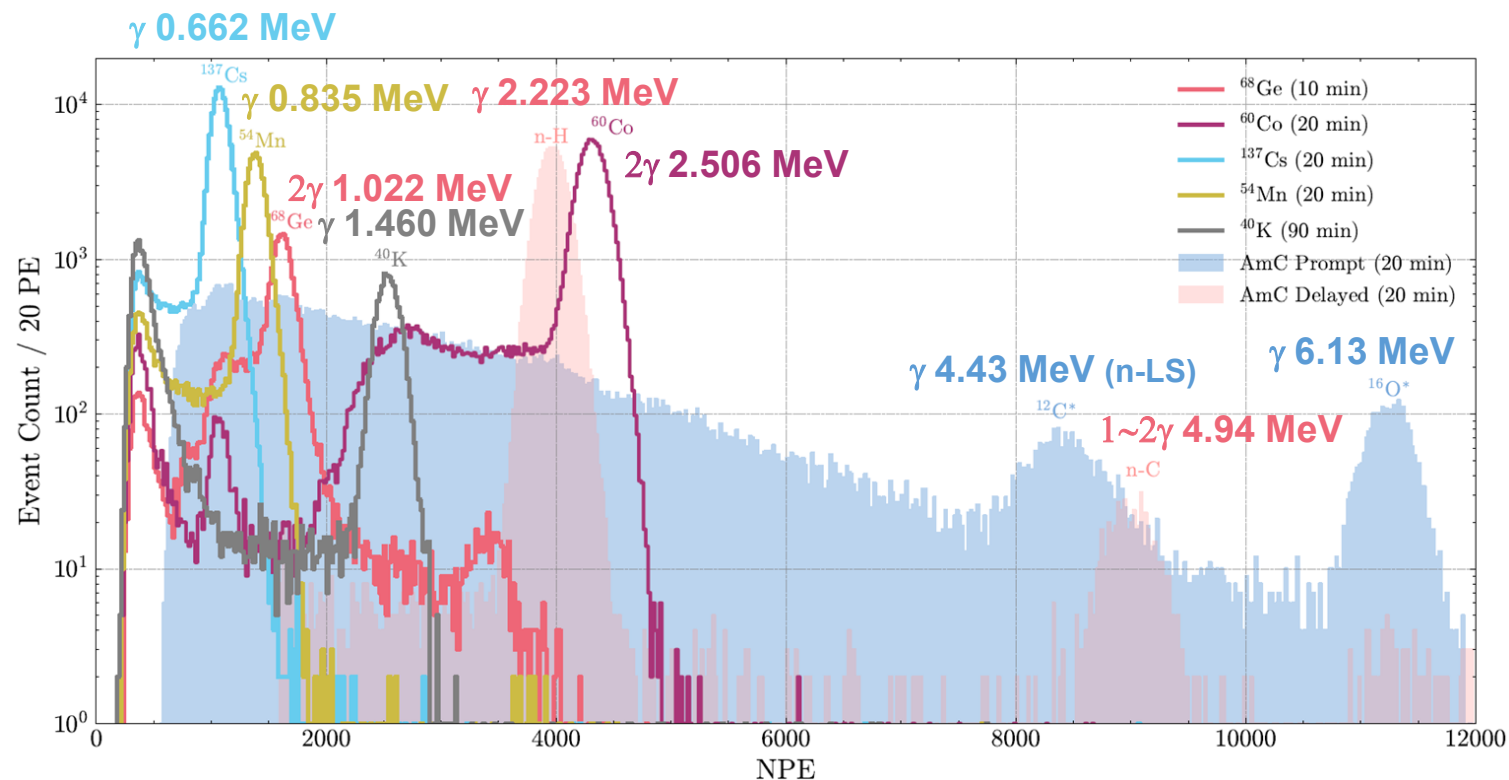
Energy Calibration



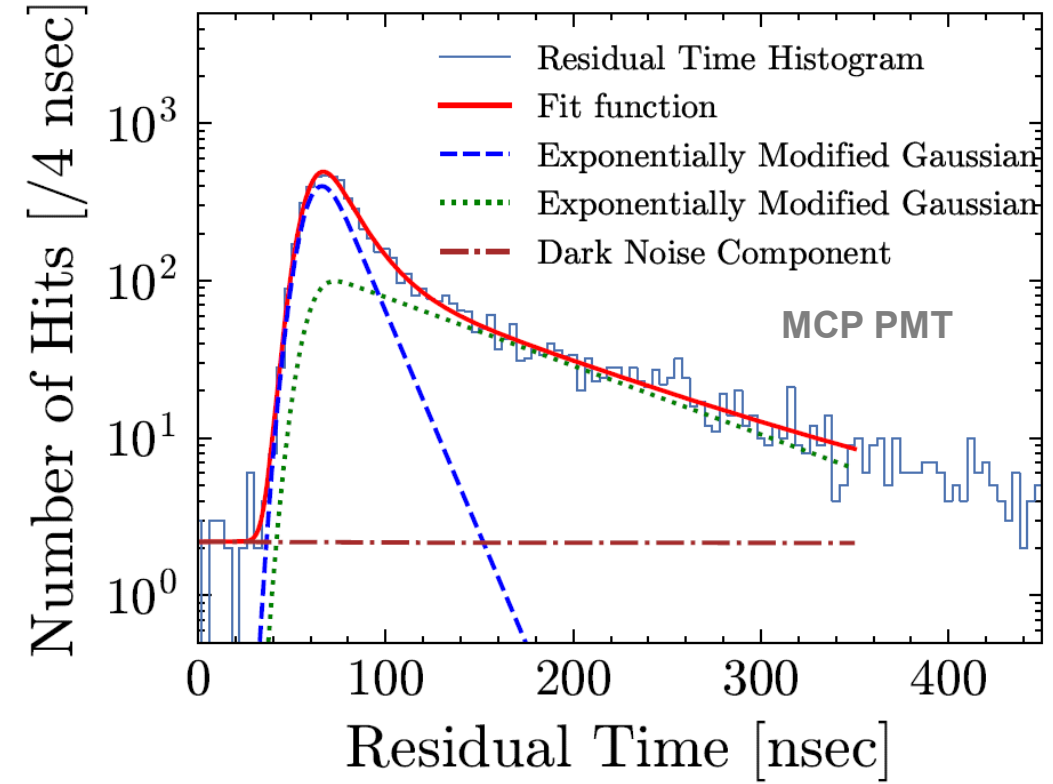
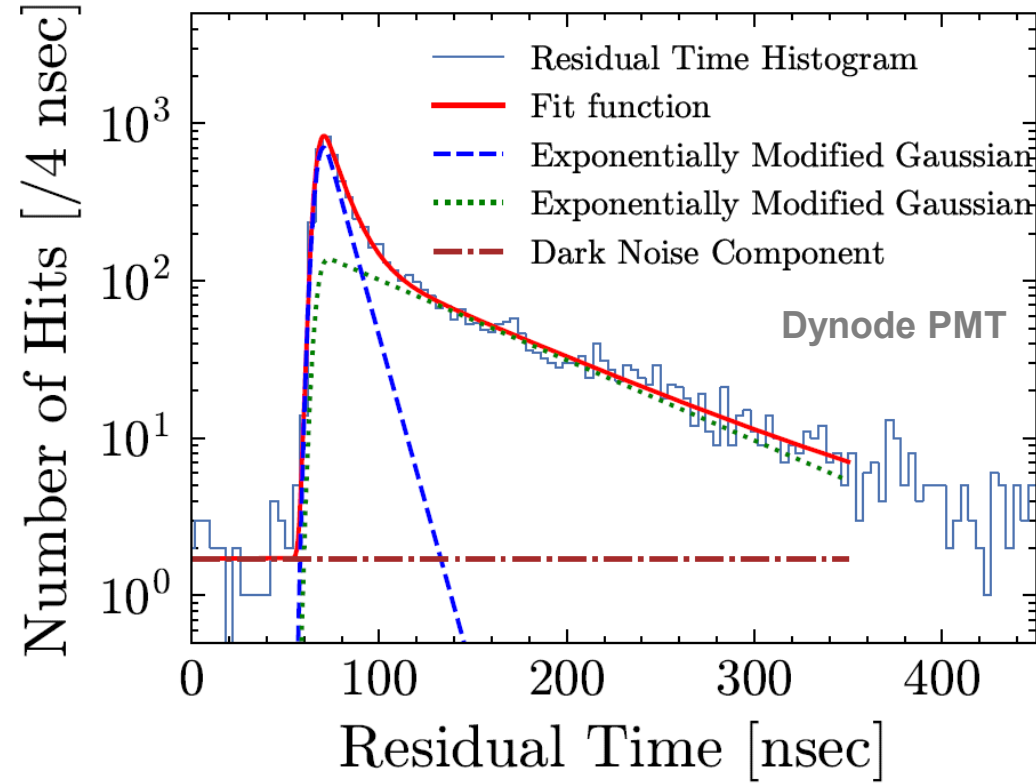
□ Energy scale is known to 0.5%

❖ Good spatial uniformity

❖ Consistent energy response between calibration data and IBD candidates

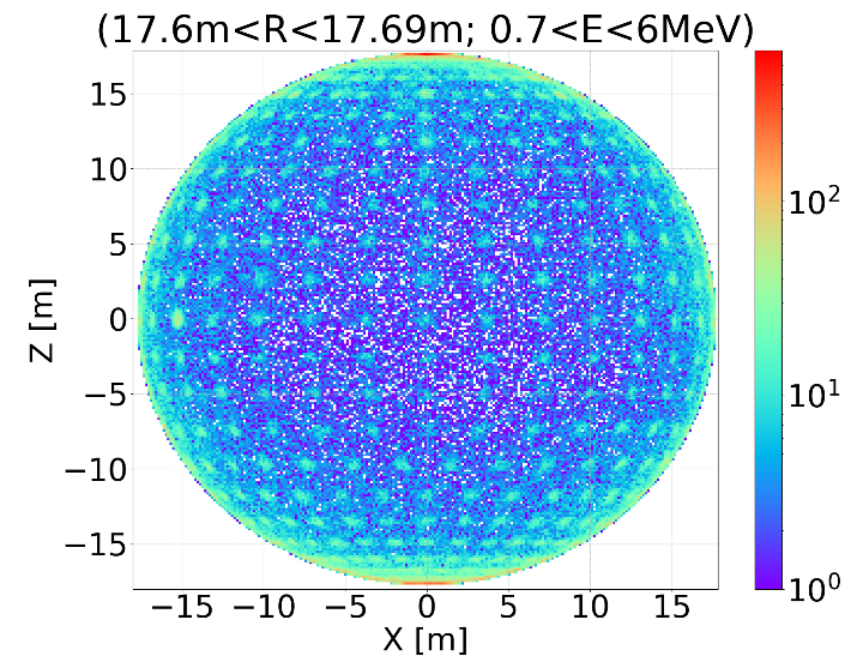
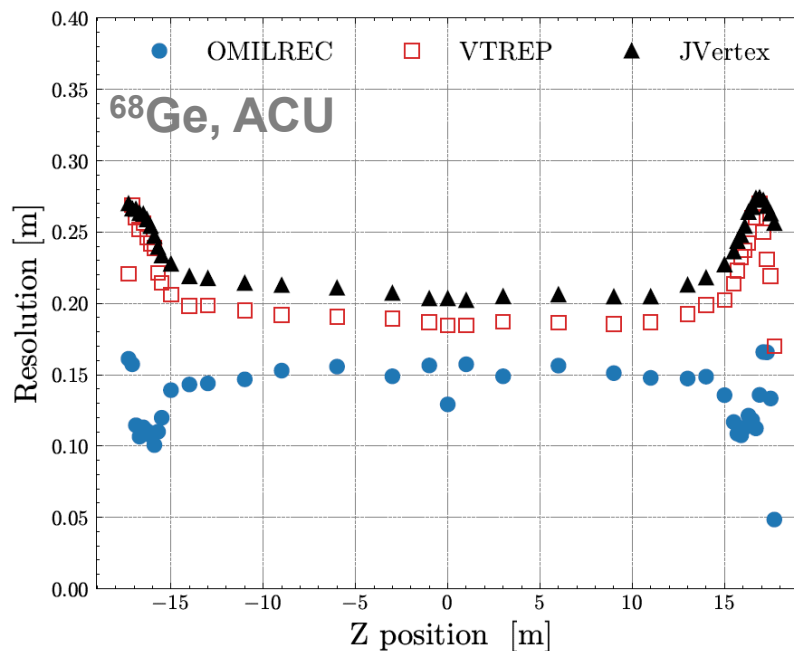
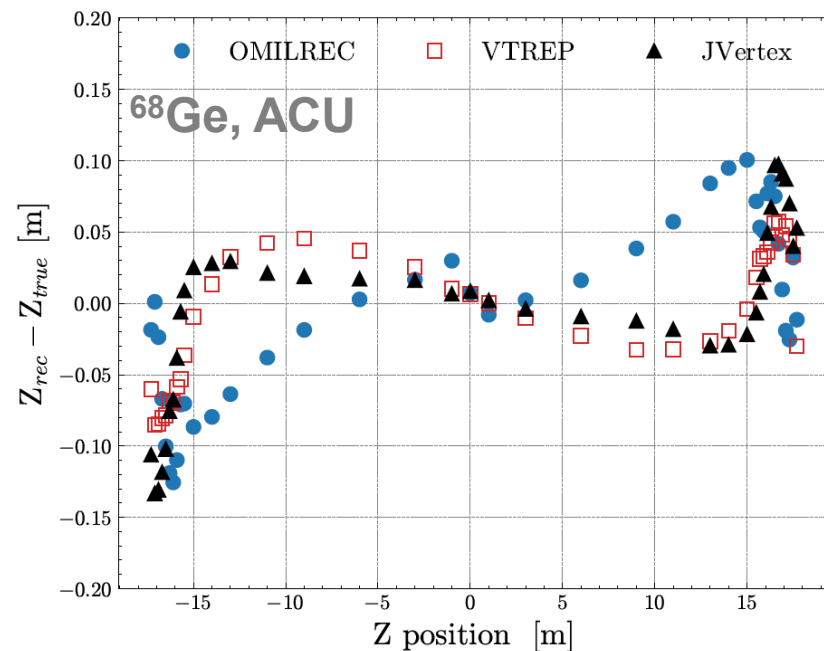


Timing Performance



- Event residual time = $t_{\text{first-hit}} - t_{\text{TOF}} - t_{\text{ref-PMT}}$
- Well-defined prompt timing peaks
- Consistent with design, not limiting factor
- Sufficient for background veto and vertex reconstruction

Vertex Reconstruction



Vertex of "singles" at outermost 10 cm of CD
External radioactivity from joints of AV support

- Z-bias within 10 cm across detector
 - ❖ Deviation near boundary due to less uniform photon collection
- Resolution 10-20 cm
 - ❖ Optical boundary effects
- Sufficient for event selection, defining fiducial volume, and correcting energy non-uniformity.

Reactor $\bar{\nu}_e$ Rate at JUNO

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\bar{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ε_{tot} corrected	33.5 ± 1.7	
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\bar{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
^{214}Bi - ^{214}Po	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3

Source	Uncertainties
Target protons	1.0%
Reference spectrum	1.2%
Thermal power	0.5%
Fission fraction	0.6%
Spent nuclear fuel	0.3%
Non-equilibrium	0.2%
Different fission fraction	0.1%

- ❑ Uncertainties on predicted non-oscillated signal rate
 - ❖ Proton counting in LS (geometric, chemical, etc.)
 - ❖ Flux constrained by released Daya Bay near detector data

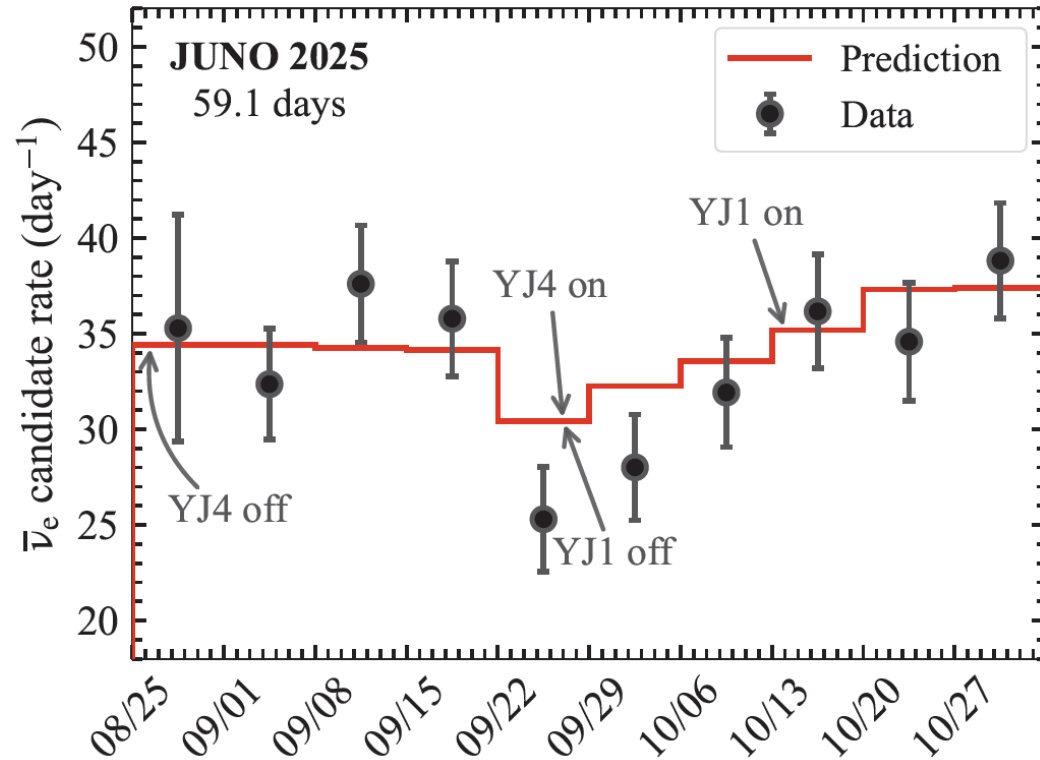
Reactor $\bar{\nu}_e$ Rate at JUNO

Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\bar{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\bar{\nu}_e$ signal (cpd¹)		
w/o ε_{tot} corrected	33.5 ± 1.7	
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\bar{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
^{214}Bi - ^{214}Po	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3

Source	Uncertainties
Target protons	1.0%
Reference spectrum	1.2%
Thermal power	0.5%
Fission fraction	0.6%
Spent nuclear fuel	0.3%
Non-equilibrium	0.2%
Different fission fraction	0.1%

- ❑ Uncertainties on predicted non-oscillated signal rate
 - ❖ Proton counting in LS (geometric, chemical, etc.)
 - ❖ Flux constrained by released Daya Bay near detector data
 - ❖ Residual reactor specific systematics

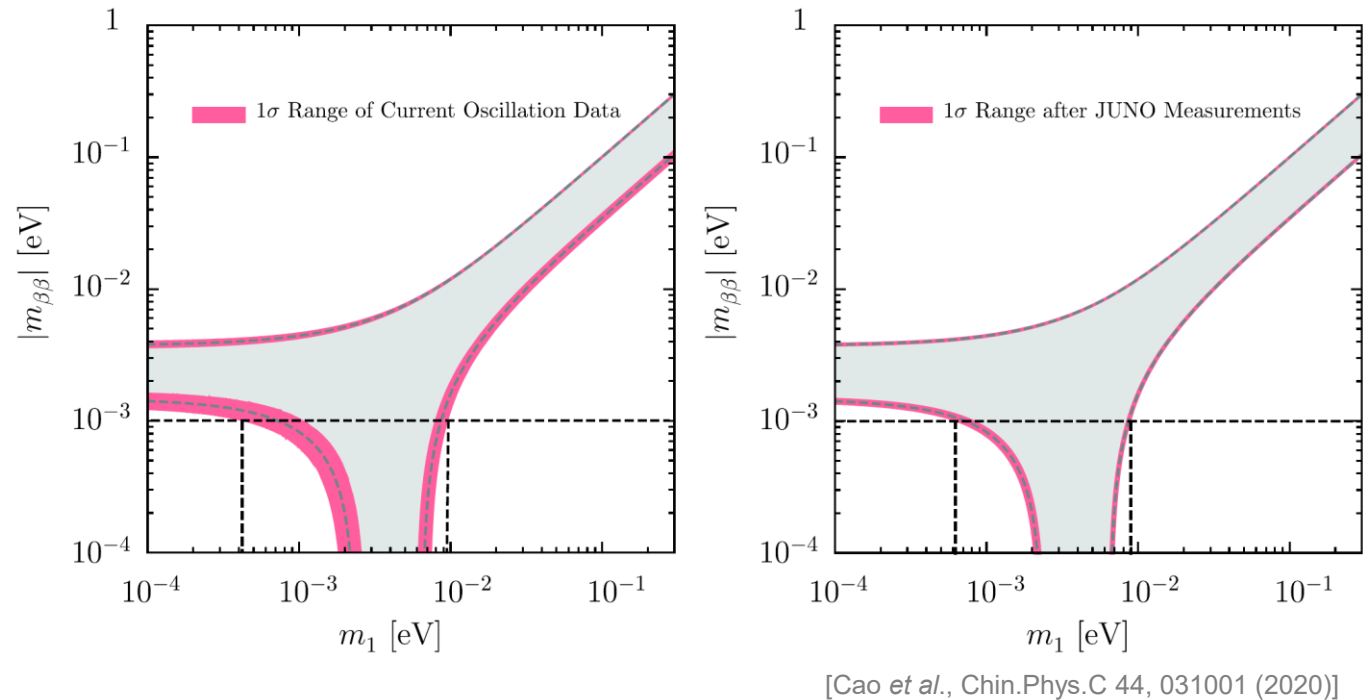
Reactor $\bar{\nu}_e$ Rate at JUNO



* Background subtracted

- Neutrino rate follows reactor operations in real time
 - ❖ Events are indeed from reactors
 - ❖ Backgrounds do not dominate the signal
 - ❖ Flux modelling is correct
 - ❖ Detector stability is good
- Reactor real-time monitoring
 - ❖ Sensitive to single core at 50 km (8 cores, 27 GW_{th})

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



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

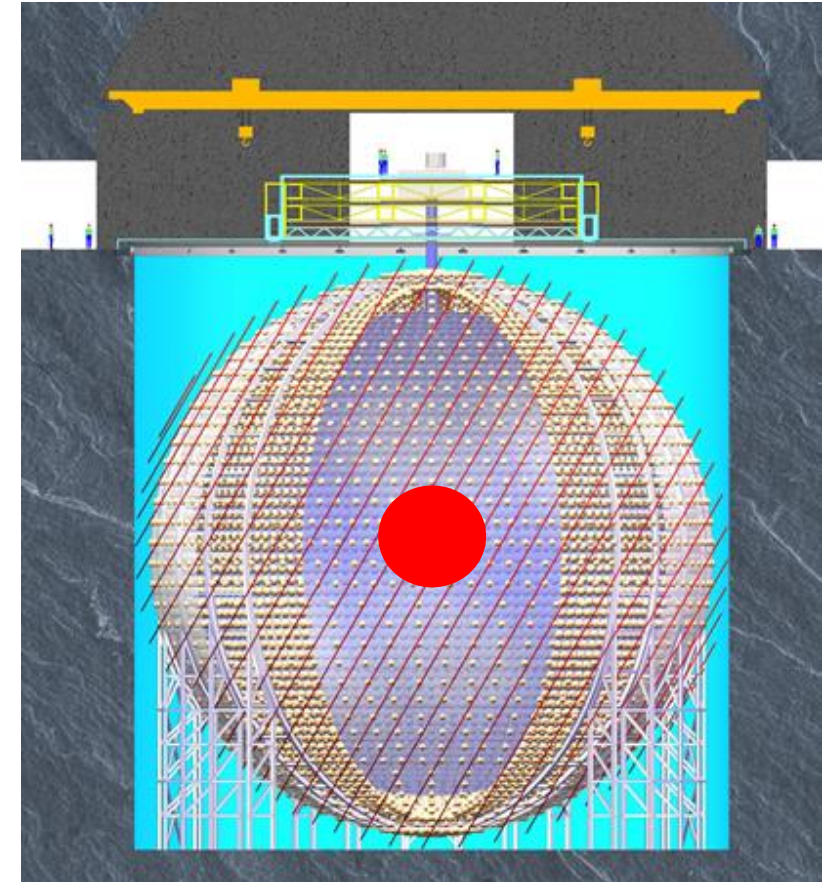


Figure from Yifang Wang, FNAL seminar, April 2025

- ❑ 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)]