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

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University of Warwick

On behalf of the JUNO Collaboration

江門中微子實驗

PPD Seminar, RAL

2026 March 25, Didcot

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?

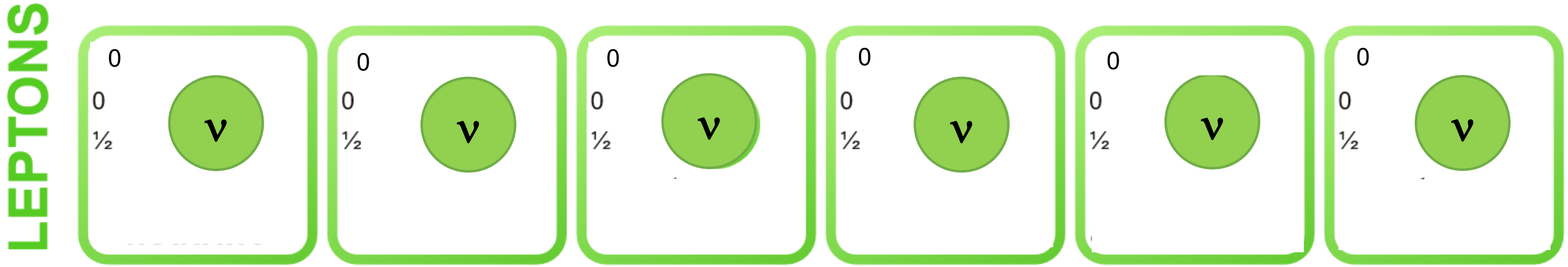
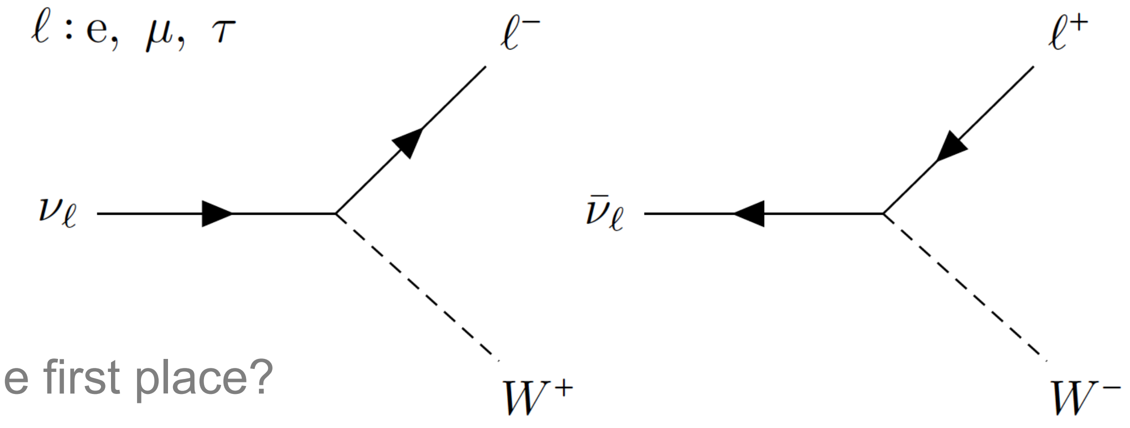


Image source: Wikipedia

Neutrino's *Familiar Face*



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3. Flavour, defined by charged-current interactions

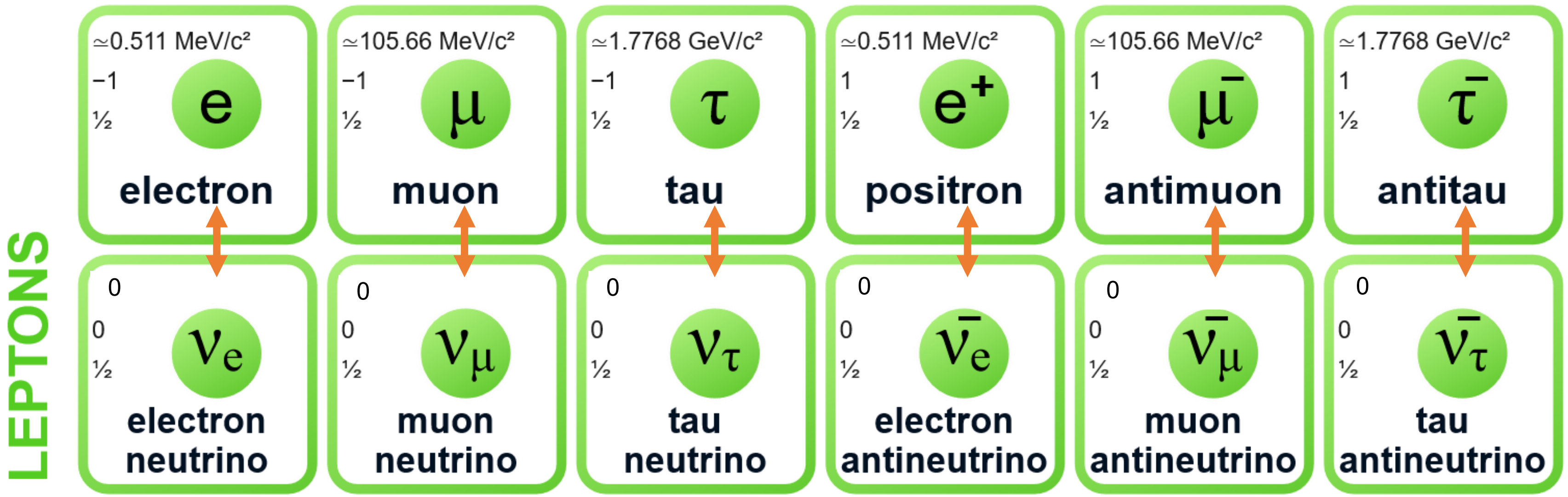

Image source: Wikipedia

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

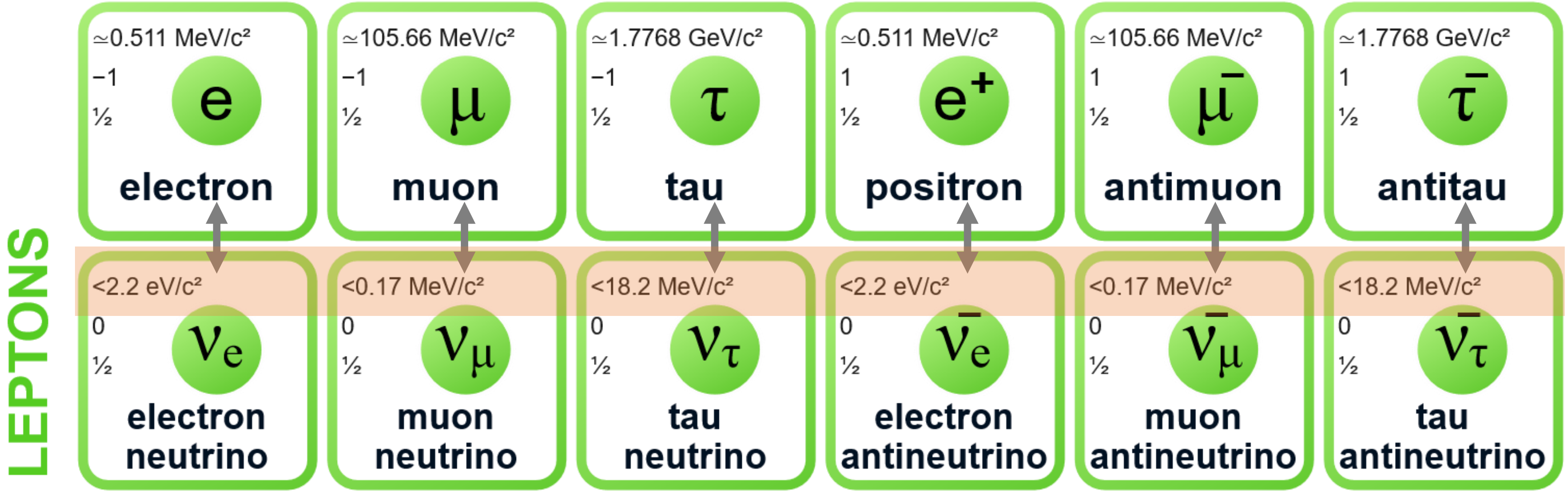

Image source: Wikipedia

Neutrino Mass and Mixing

Standard Model | Beyond Standard Model

Mass "levels"

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

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

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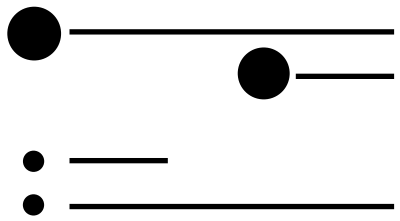
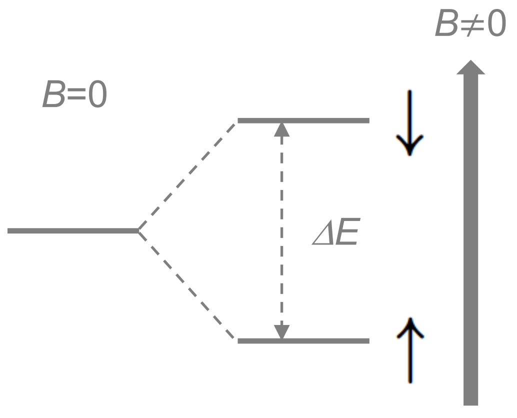


Normal / Inverted
Mass Ordering (MO, or Hierarchy)

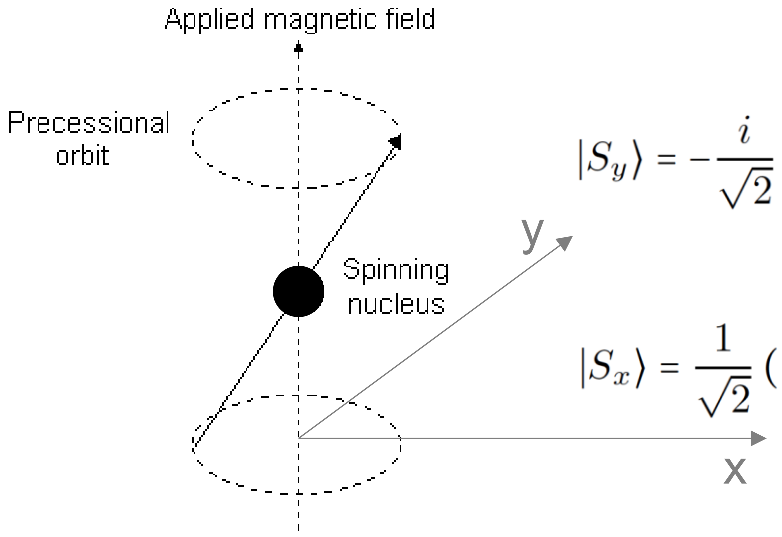
A problem only when there are more than 2 masses!

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

Analogy: spin rotation in a magnetic field



$|\uparrow\rangle, |\downarrow\rangle$: energy eigenstates



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

$$|S_y\rangle = -\frac{i}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle)$$

$$|S_x\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$$

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

Oscillation probability

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

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

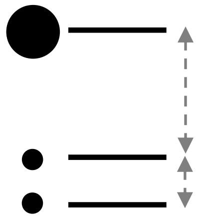
Energy gap

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

Mixing

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

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



Δm^2

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

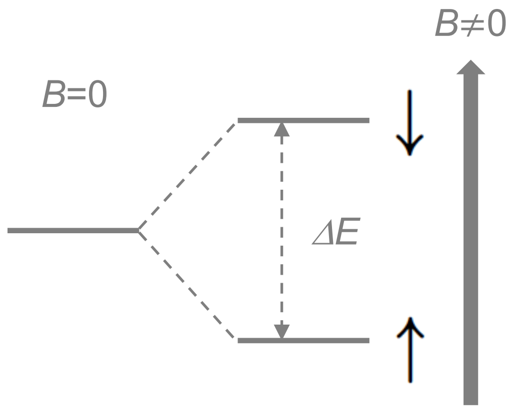
Survival $P_{\nu_\mu\to\nu_\mu}\left(\frac{L}{E}\right)$

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

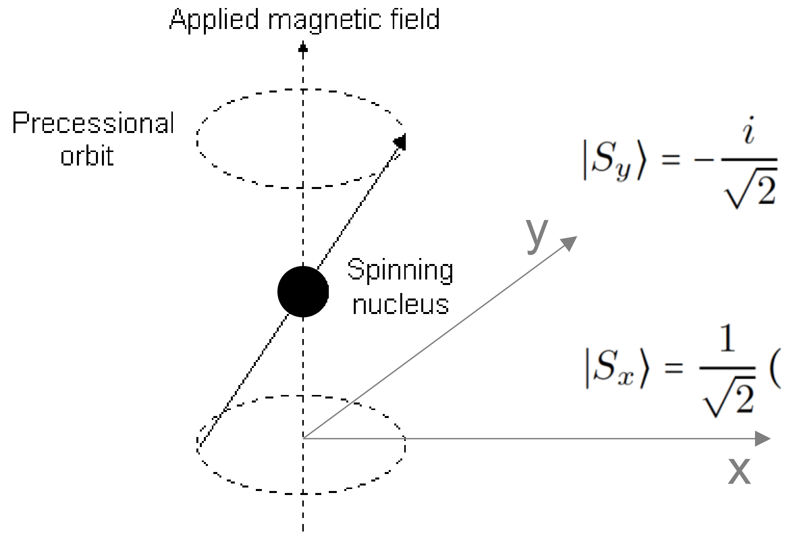
Phase ~ $\Delta m^2 L/E$

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

Analogy: spin rotation in a magnetic field



$|\uparrow\rangle, |\downarrow\rangle$: energy eigenstates



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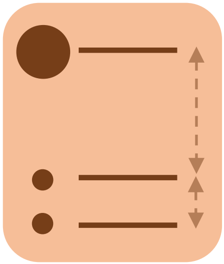
$\begin{pmatrix}\nu_1\\\nu_2\\\nu_3\end{pmatrix}$  Δm^2

2- or 3-flavour oscillation?

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

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

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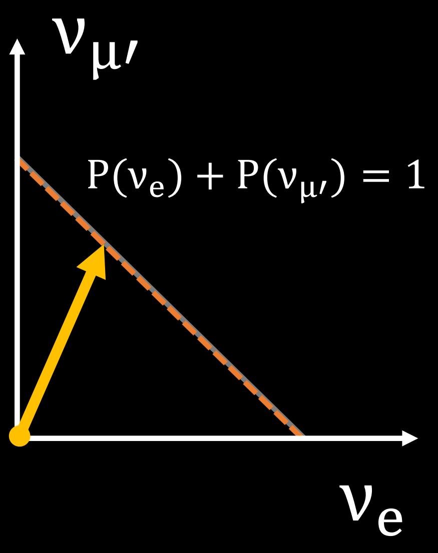
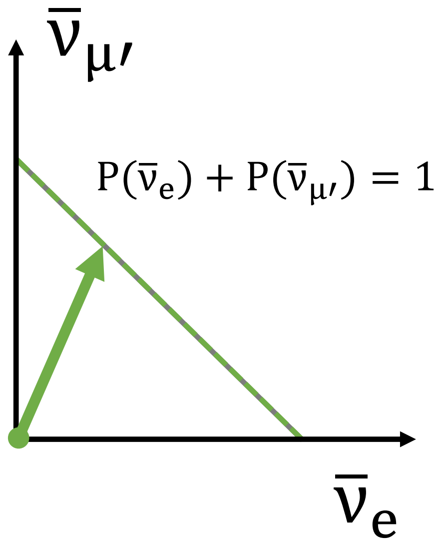
Phase ~ $\Delta m^2 L/E$

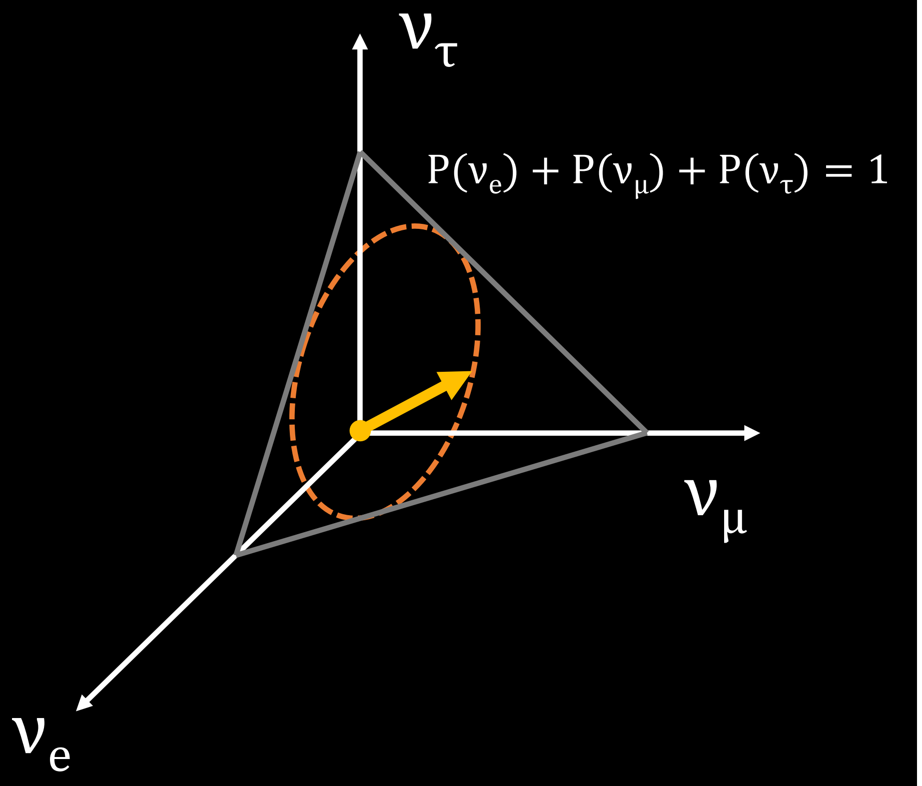
2-flavor oscillation

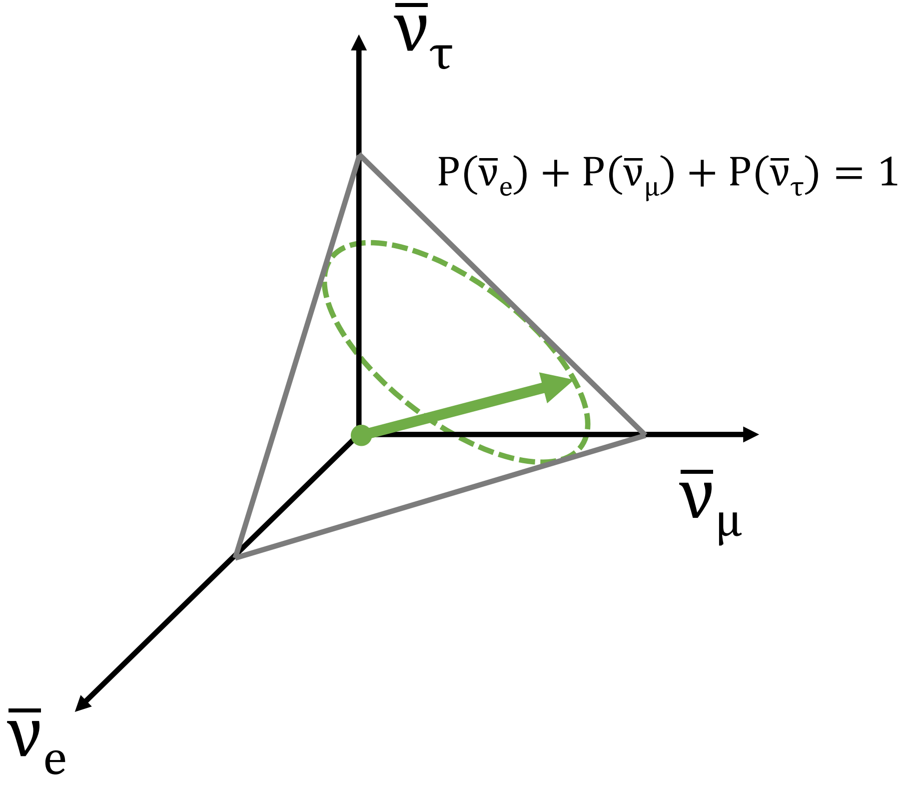




Oscillation as a function of *time*
line-in-**line** → same trivia

3-flavor oscillation





Oscillation as a function of *time*
line-in-**plane** → CP-violation possible

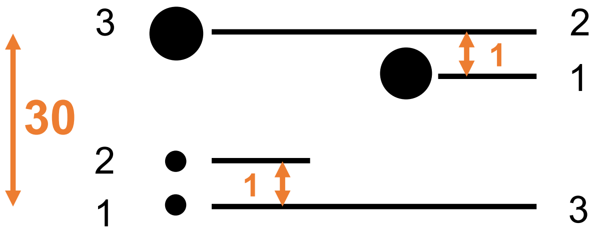
Neutrino Mass and Mixing

Standard Model | Beyond Standard Model

Mass "levels"

$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} =$ Pontecorvo–Maki–Nakagawa–Sakata **PMNS matrix** $\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

fast oscillation
Δm^2_{32} sign unknown

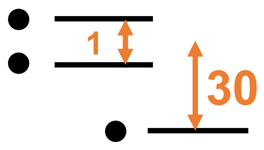


slow oscillation
$\Delta m^2_{21} > 0$ by definition

Normal / Inverted
Mass Ordering (MO, or Hierarchy)

Neutrino Mass and Mixing

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



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

Open questions

❑ What are the neutrino masses?

❖ Mass gaps (Δm^2_{21}, $|\Delta m^2_{32}|$) and ordering (sgn Δm^2_{32})?

❑ What are the mixing parameters?

❖ 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

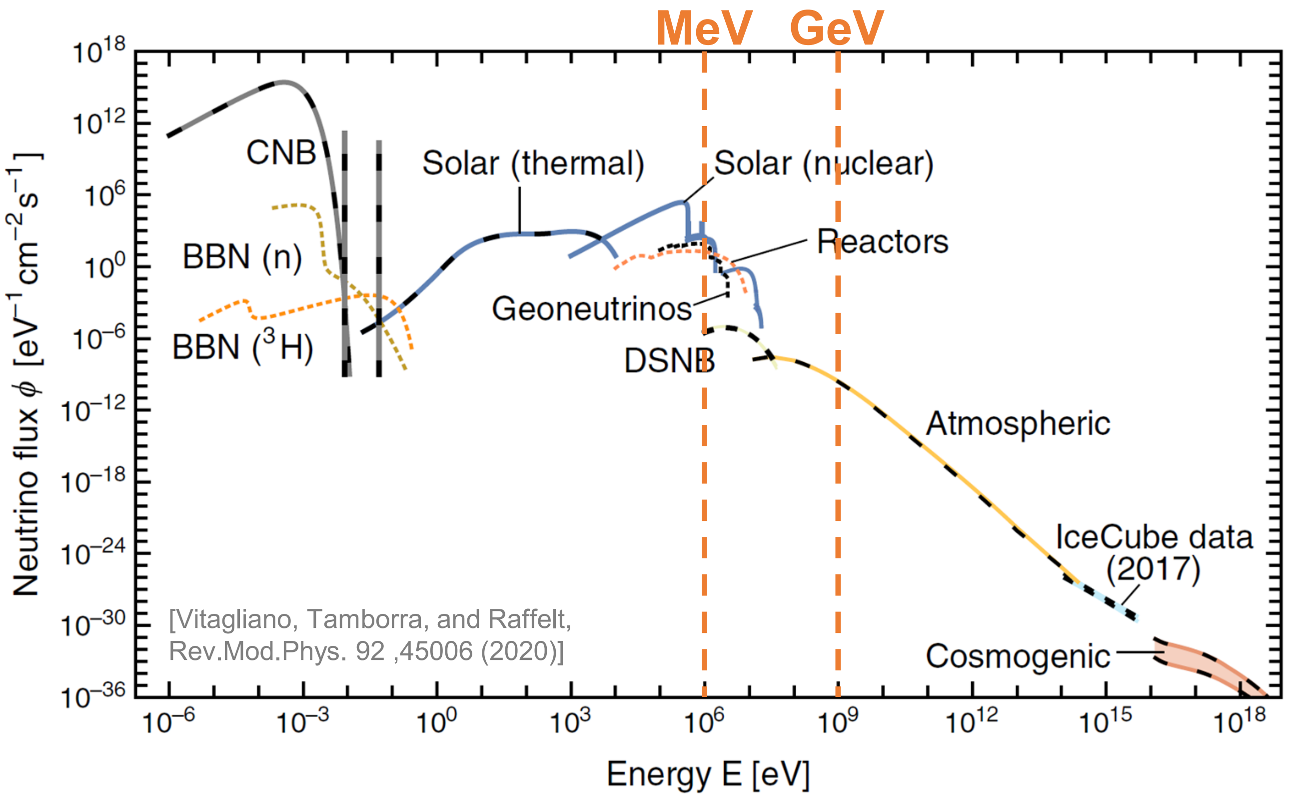
θ_{23}: mixing between ν_μ and ν_τ

θ_{13}: if 0, effective 2 flavour mixing

➢ No CPV!

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

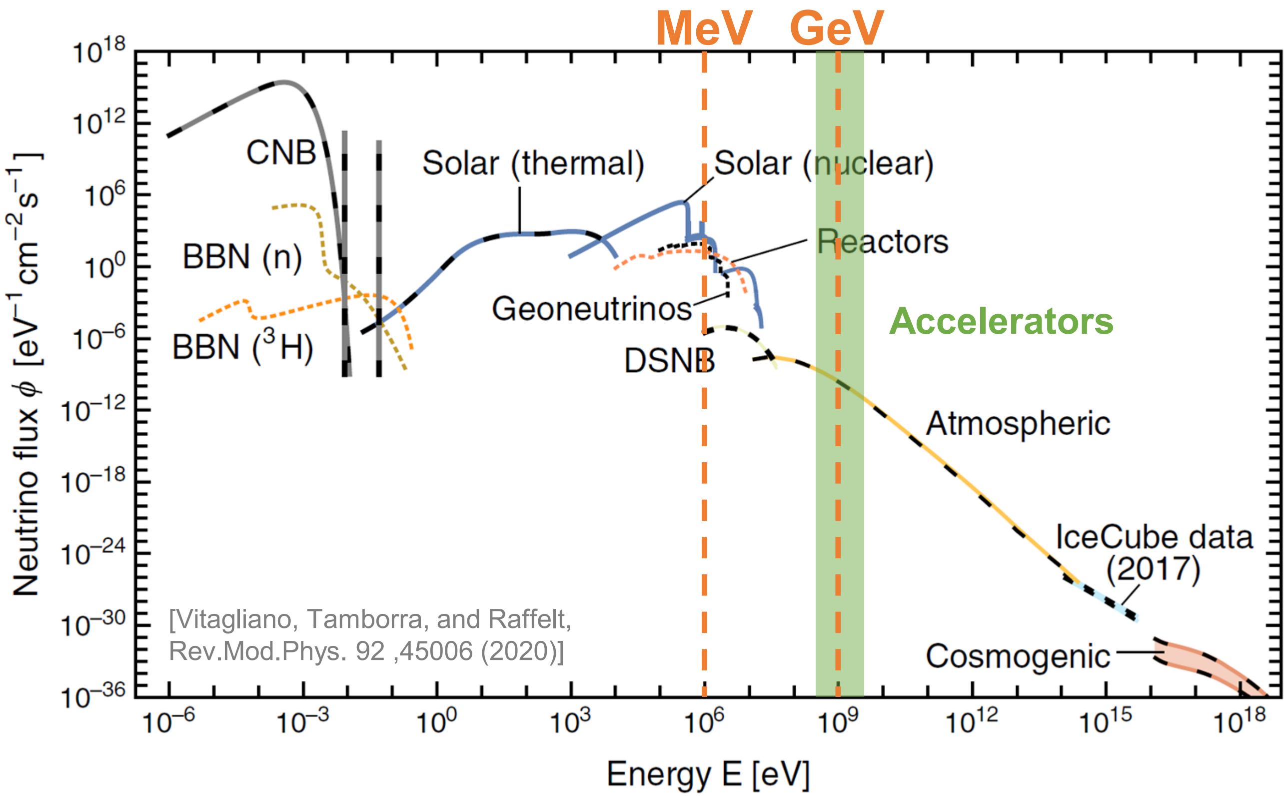
Neutrino Sources



Neutrino Sources

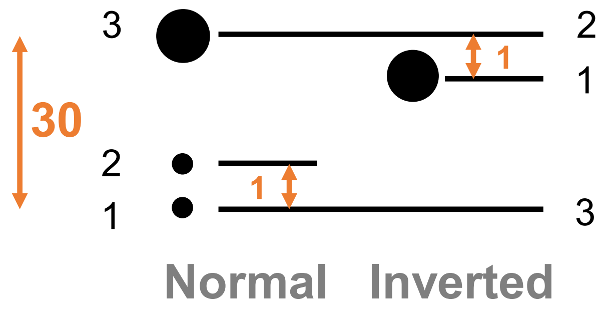
(Oscillation-relevant) Types at source

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

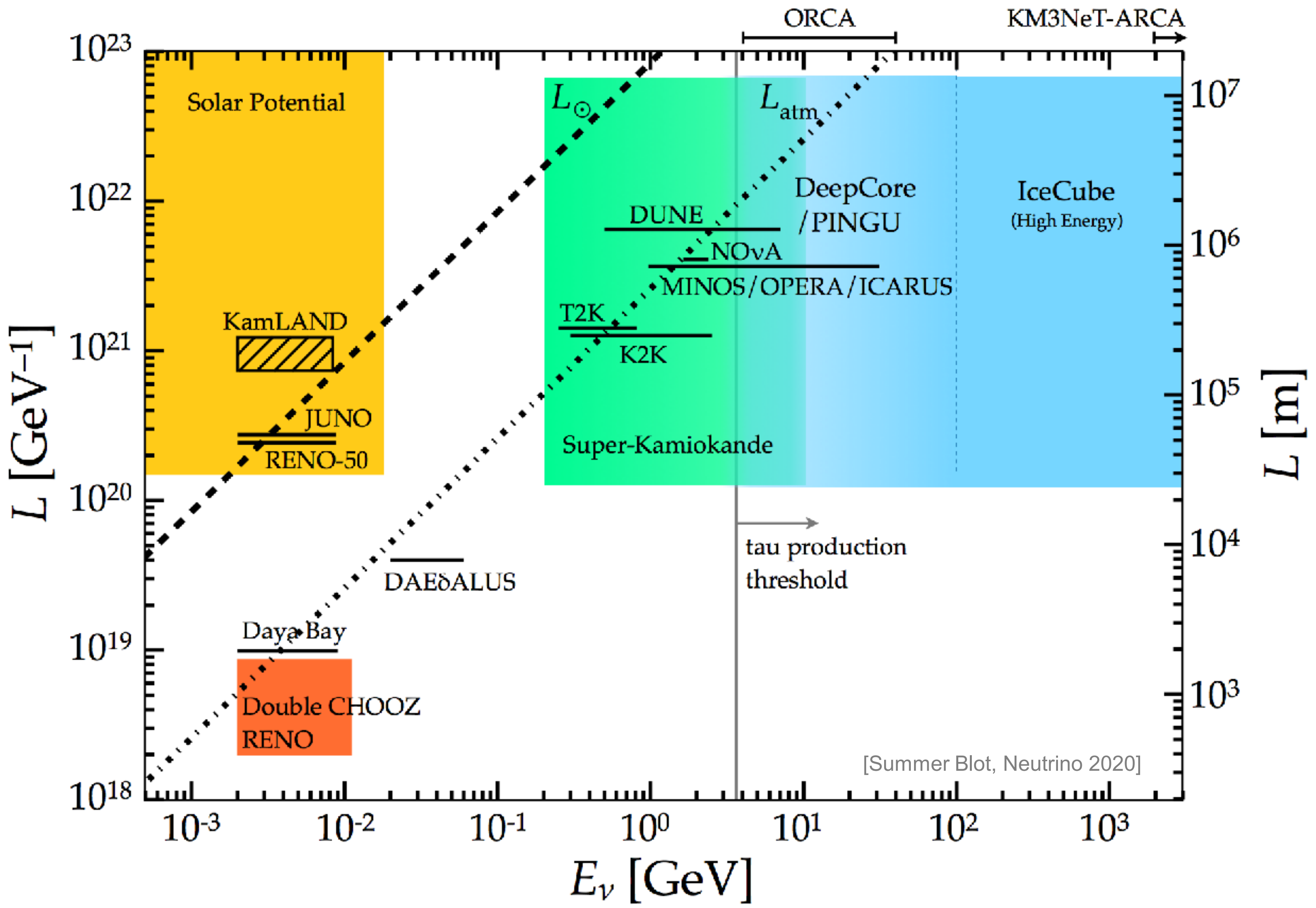


Neutrino Oscillation Experiments

Only two Δm^2



Oscillation Phase ~ $\Delta m^2 L/E$



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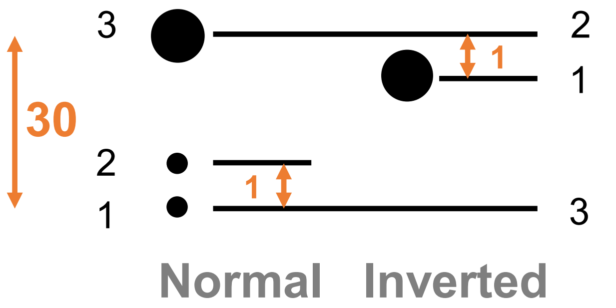

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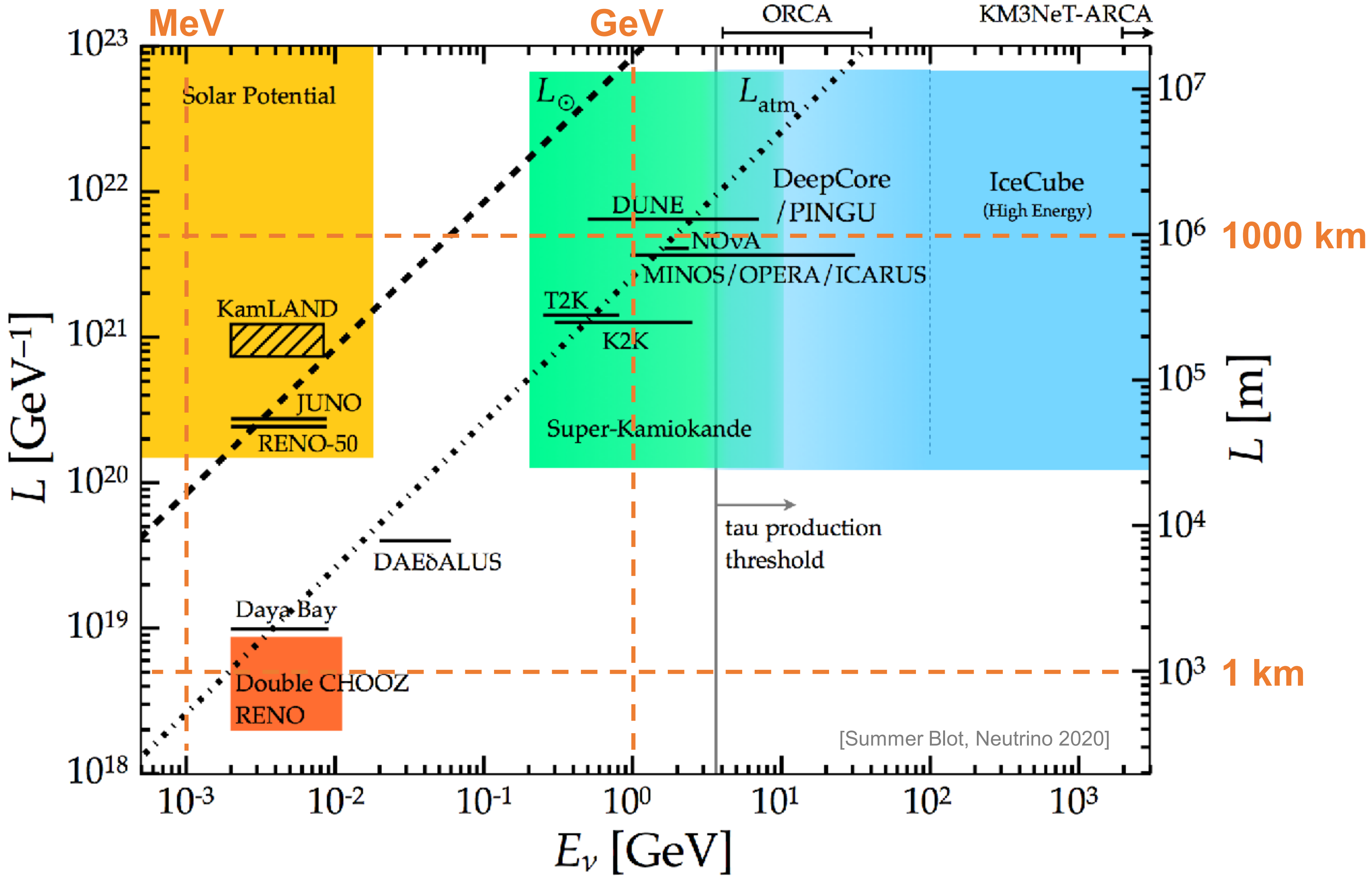

Neutrino Oscillation Experiments

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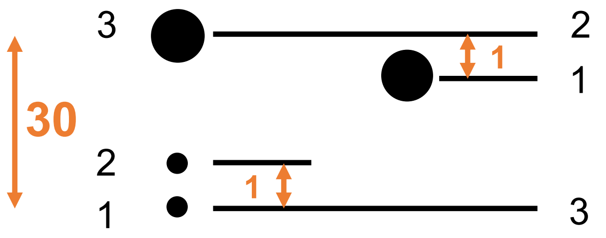
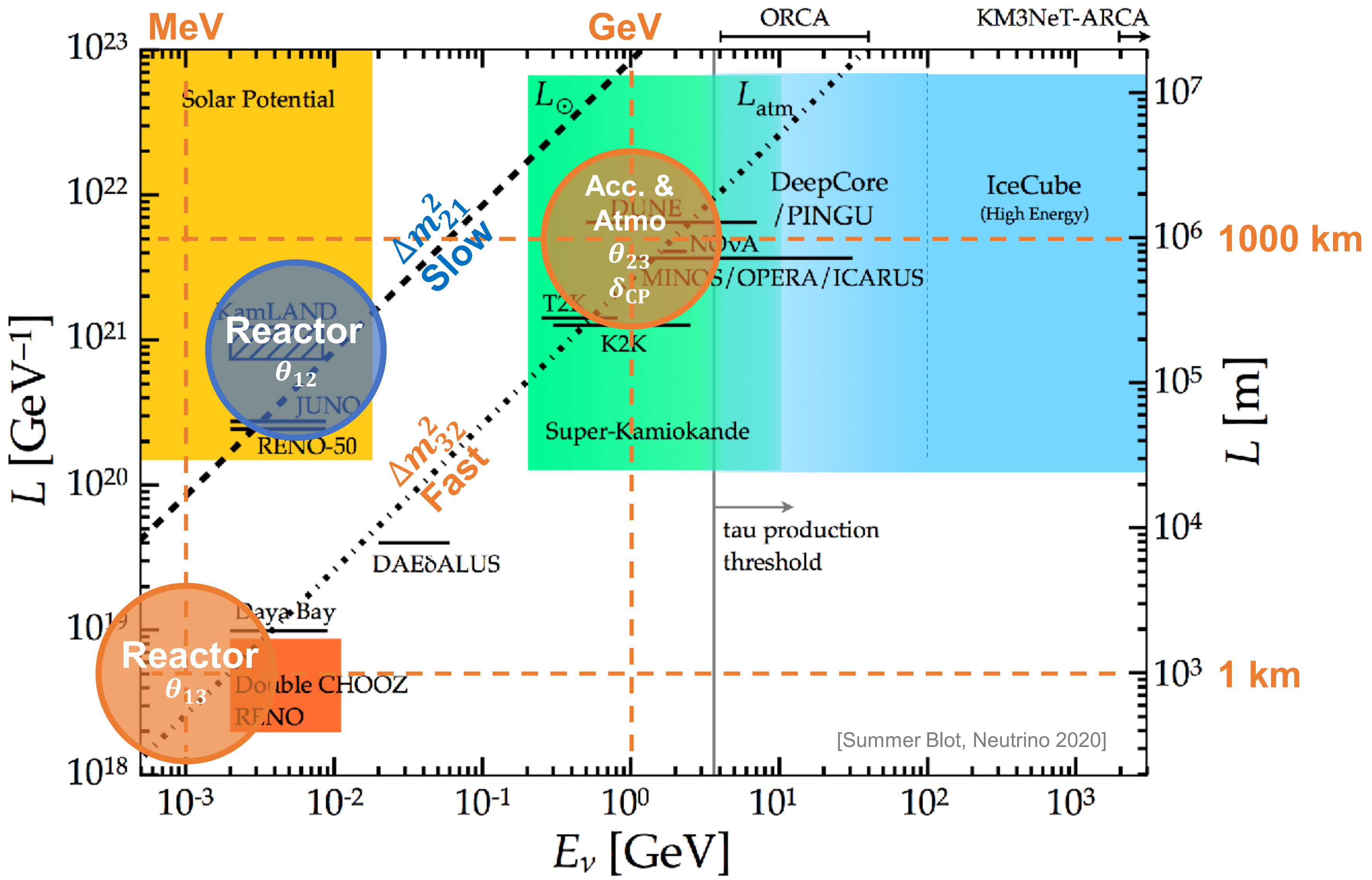


Normal **Inverted**

Oscillation Phase ~ $\Delta m^2 L/E$



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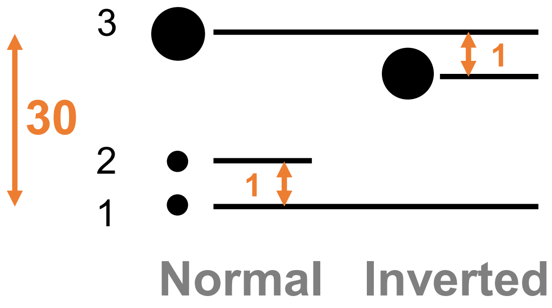

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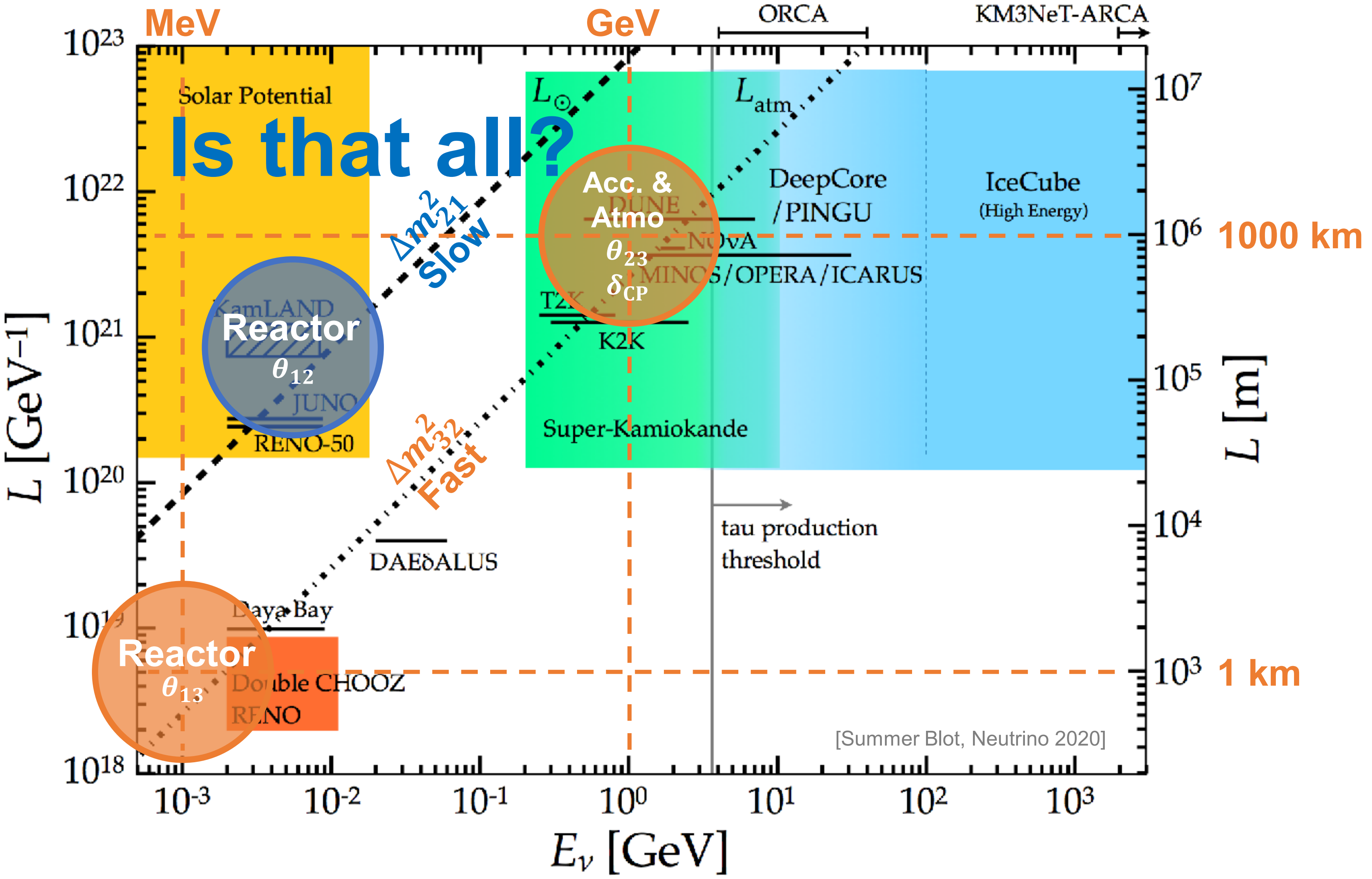
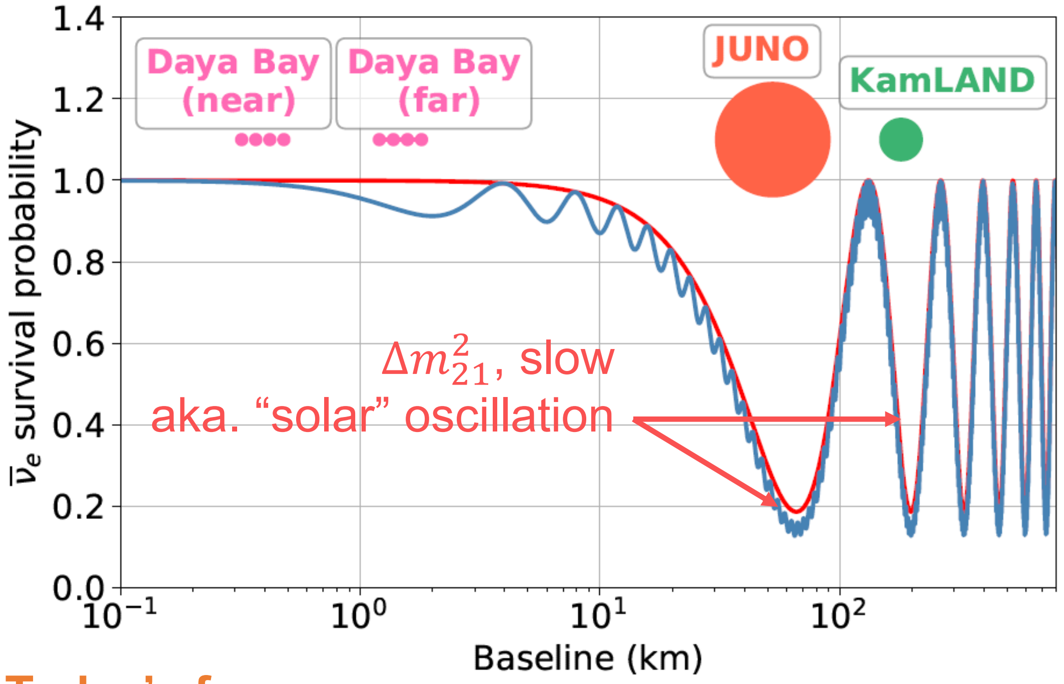


Neutrino Oscillation at JUNO



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

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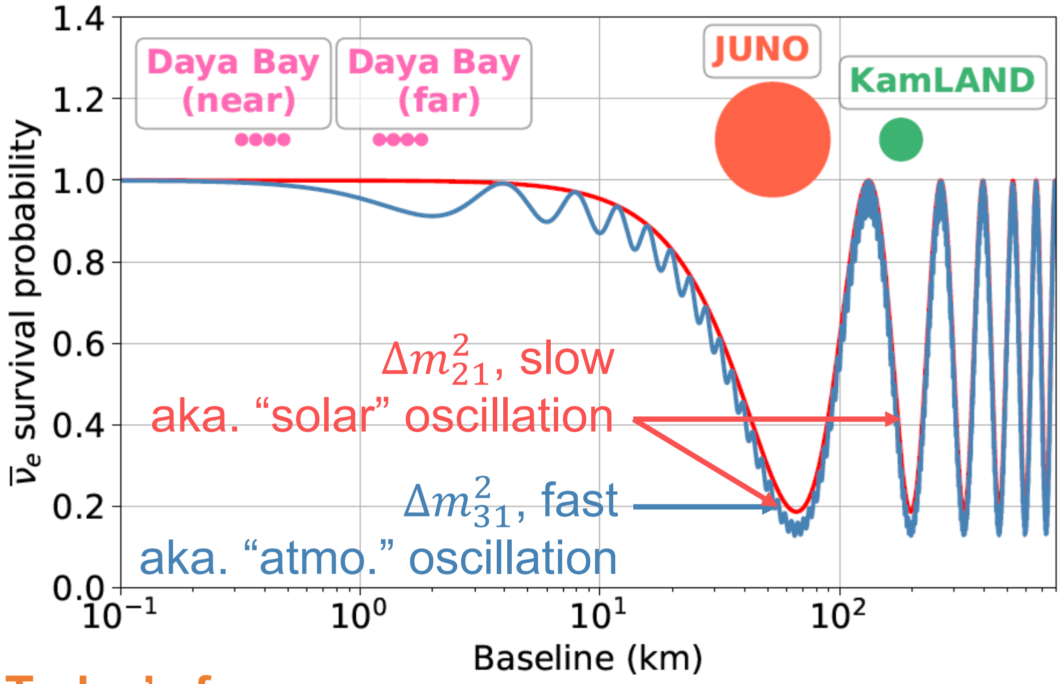
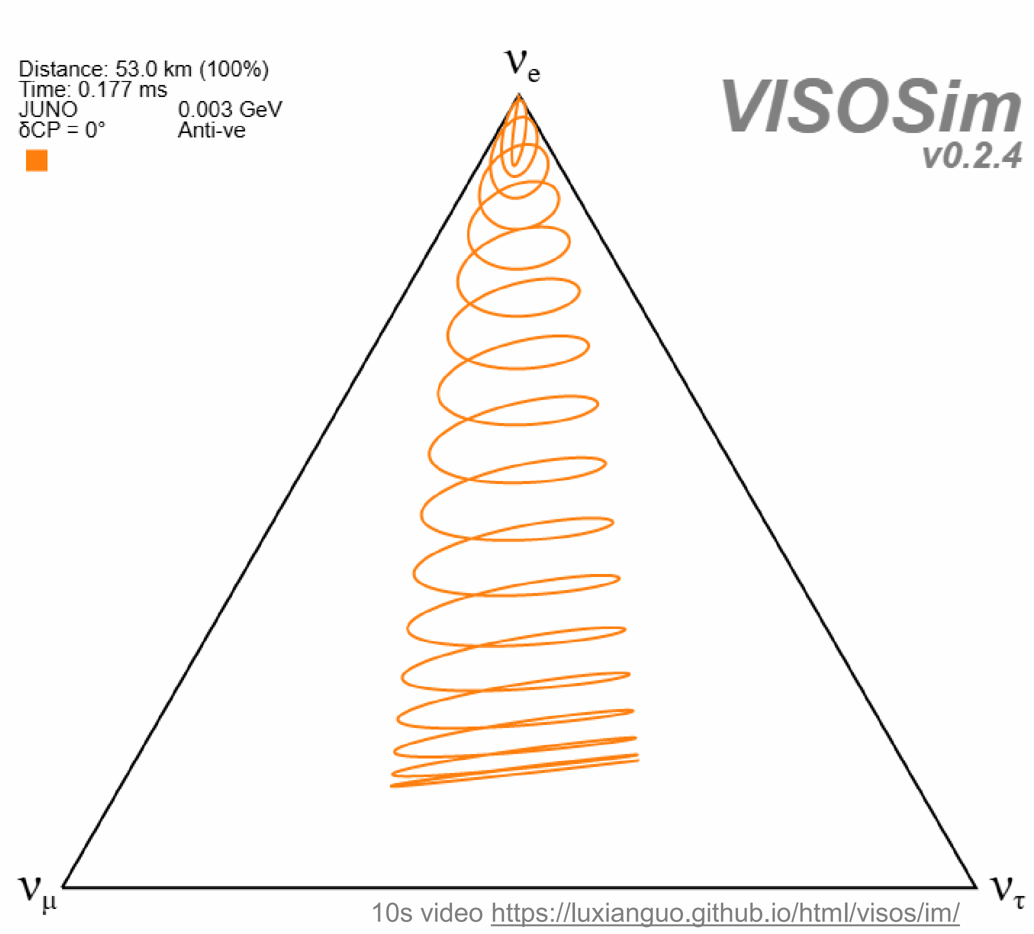
Initial performance results of the JUNO detector

Neutrino Oscillation at JUNO





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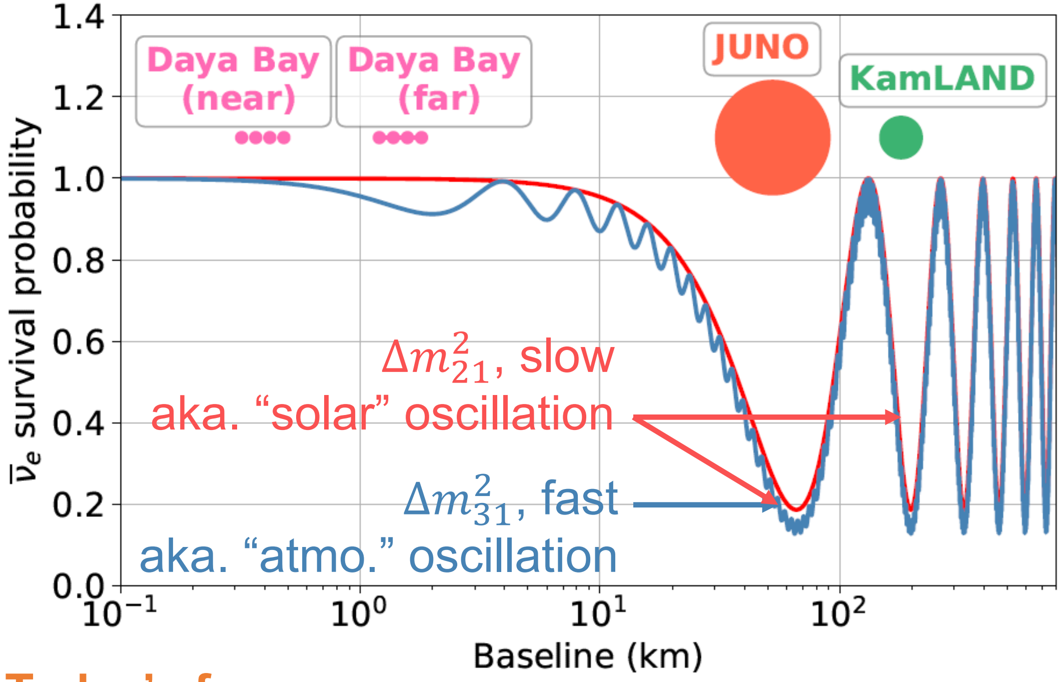

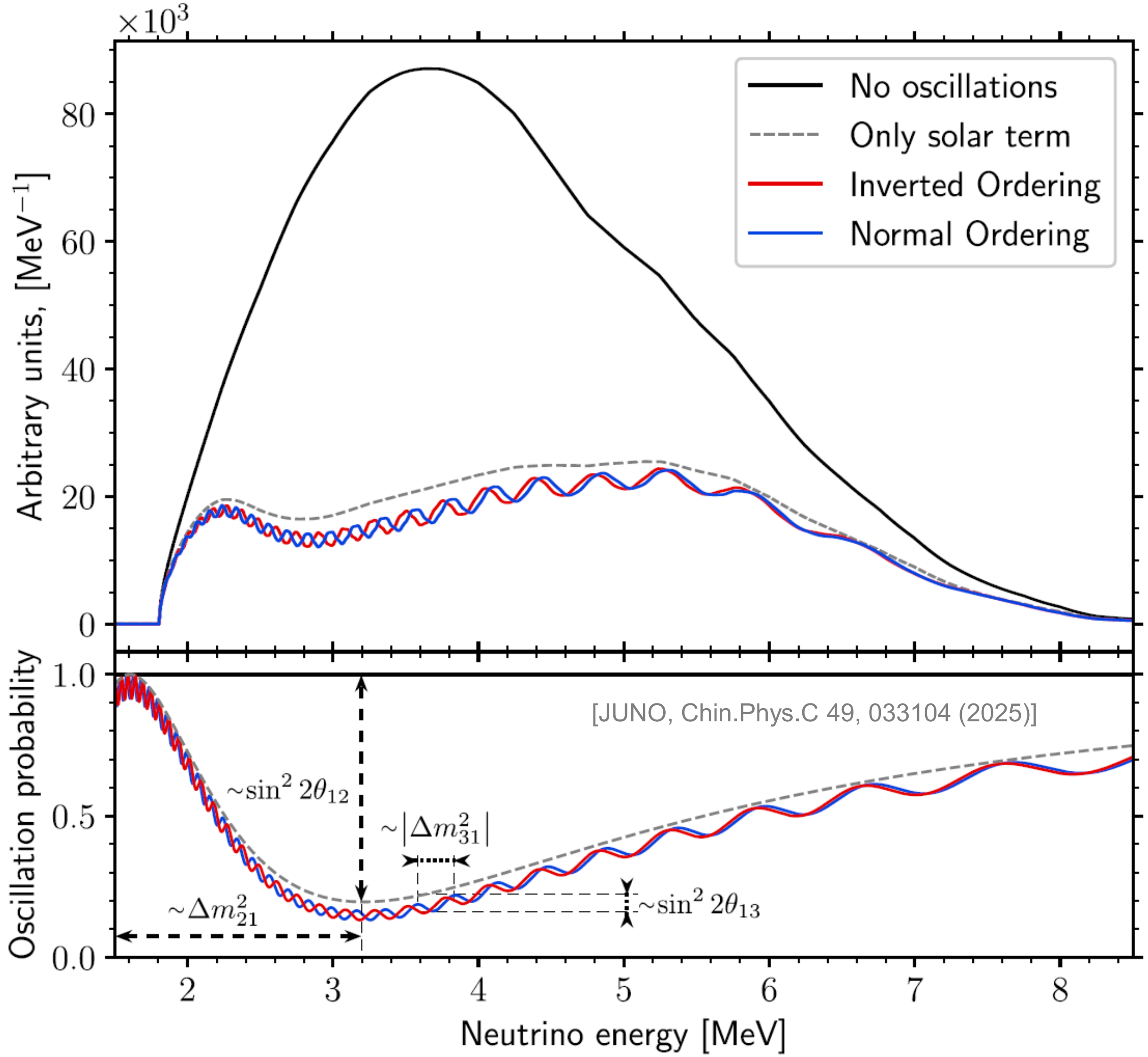

JUNO's main goal: Neutrino Mass Ordering

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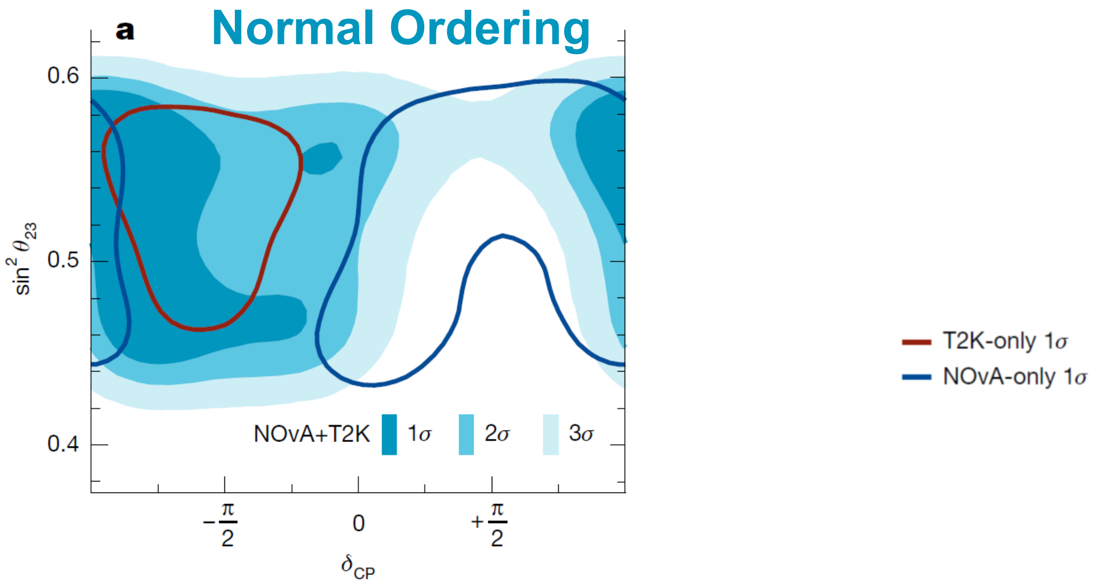
Why Neutrino Mass Ordering?

[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?

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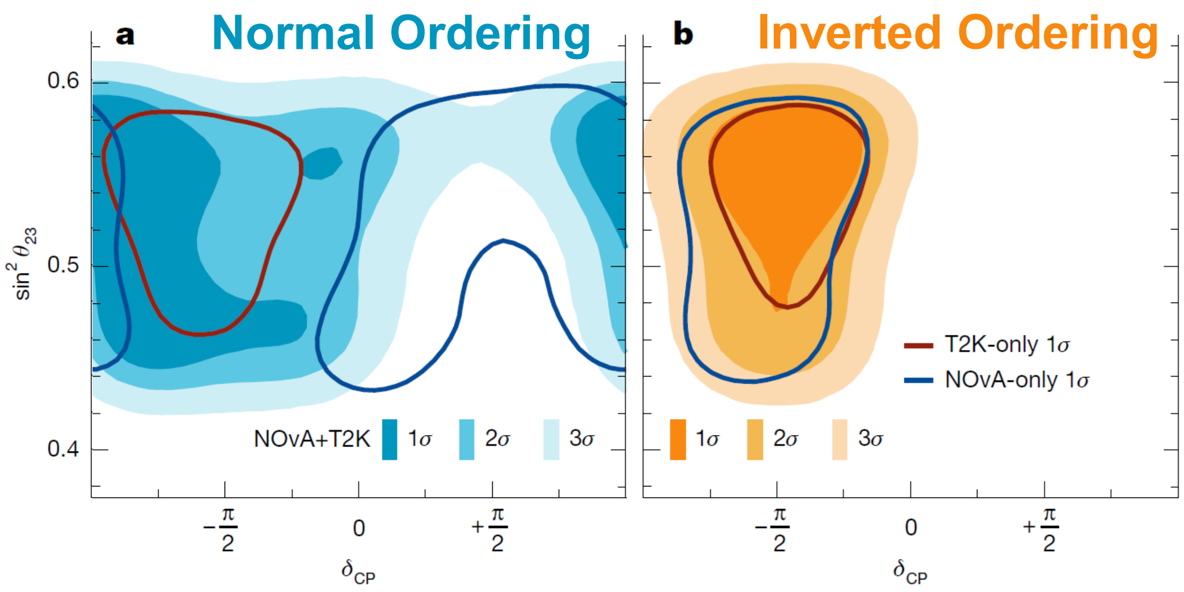
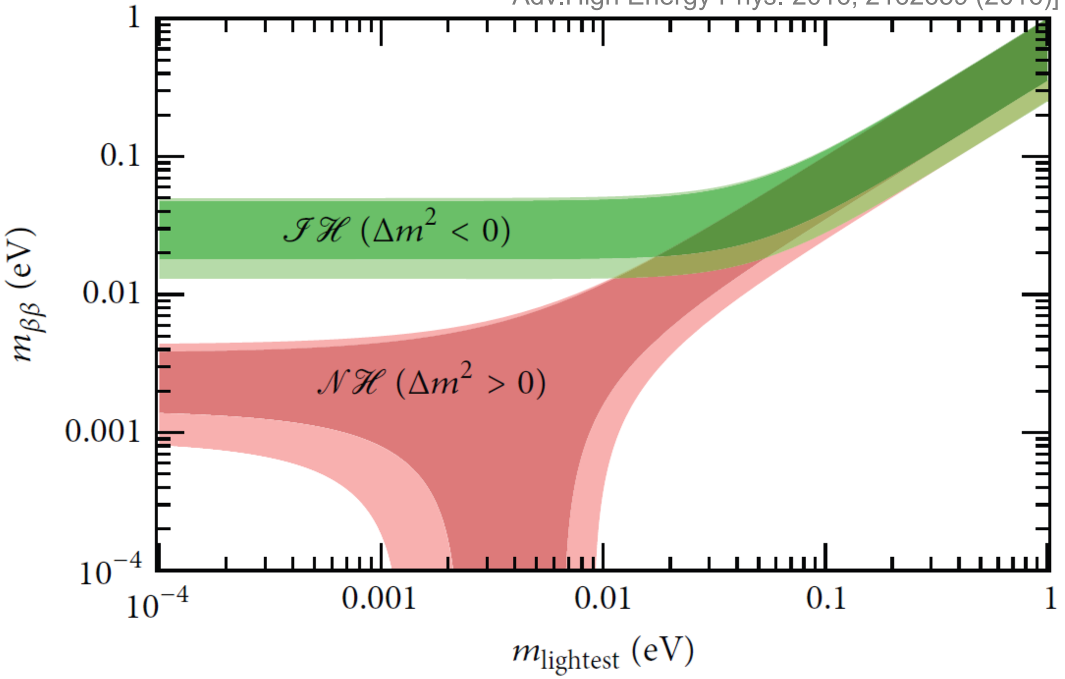


[Dell'Oro, Marcocci, Viel, and Vissani, Adv.High Energy Phys. 2016, 2162659 (2016)]



- ❑ 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

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Guangdong–Hong Kong–Macao Greater Bay Area

The JUNO Collaboration

= 70 institutes
> 700 participants

- UK involvement

Warwick 2022/07 –
Liverpool 2024/07 –

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		

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Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile	[illegible]	China	SYSU	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	THU	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	UCAS	[illegible]	[illegible]
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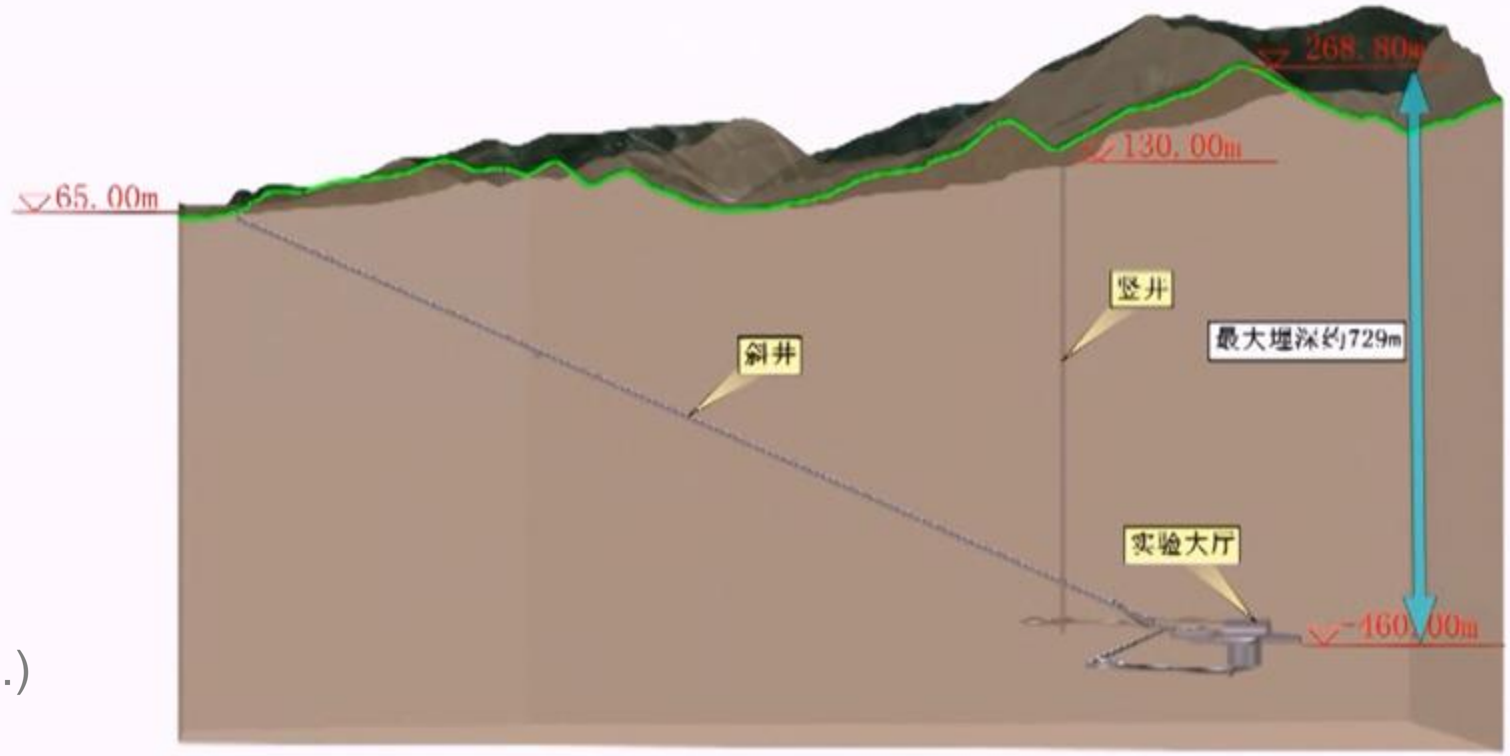
China	NCEPU	Germany	JGUMainz	USA	UMD-G
China	NJU	Germany	RWTH-AC		
China	RNCG	Germany	TUM		

Photo credit: LIU Yuexiang@IHEP

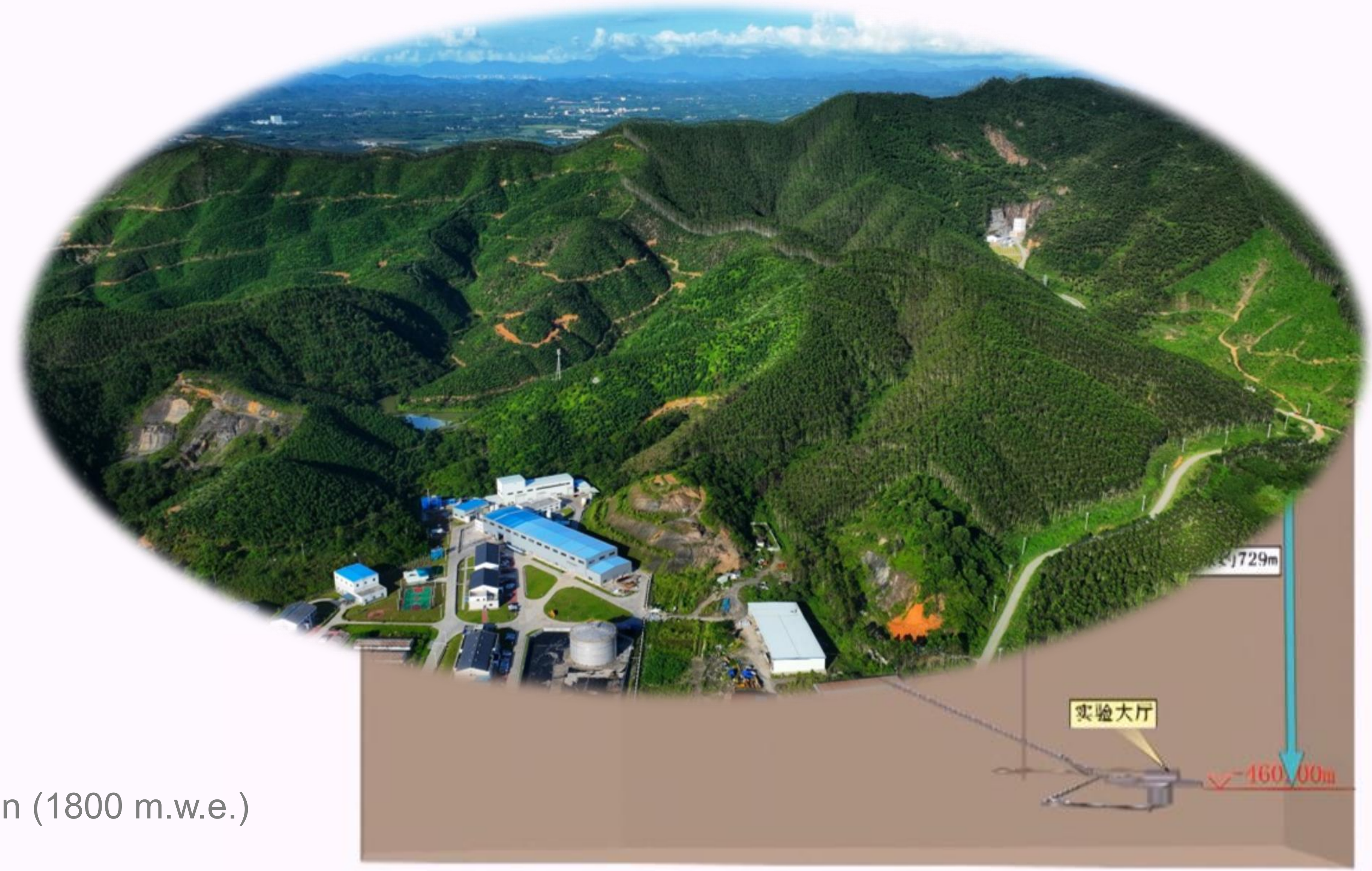
The JUNO Lab



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

Photo credit: LIU Yuexiang@IHEP

The JUNO Lab



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

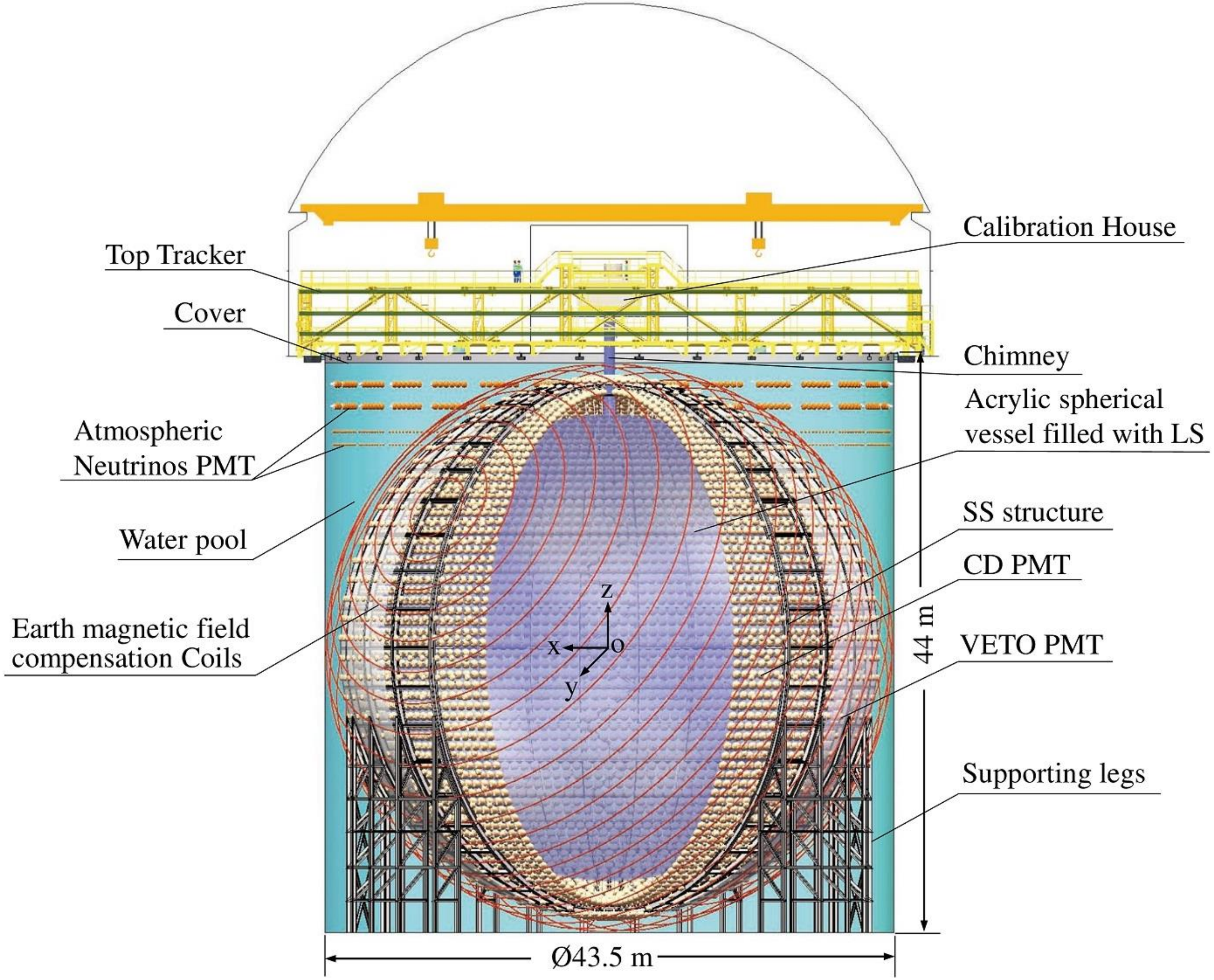
Photo credit: LIU Yuexiang@IHEP

The JUNO Lab

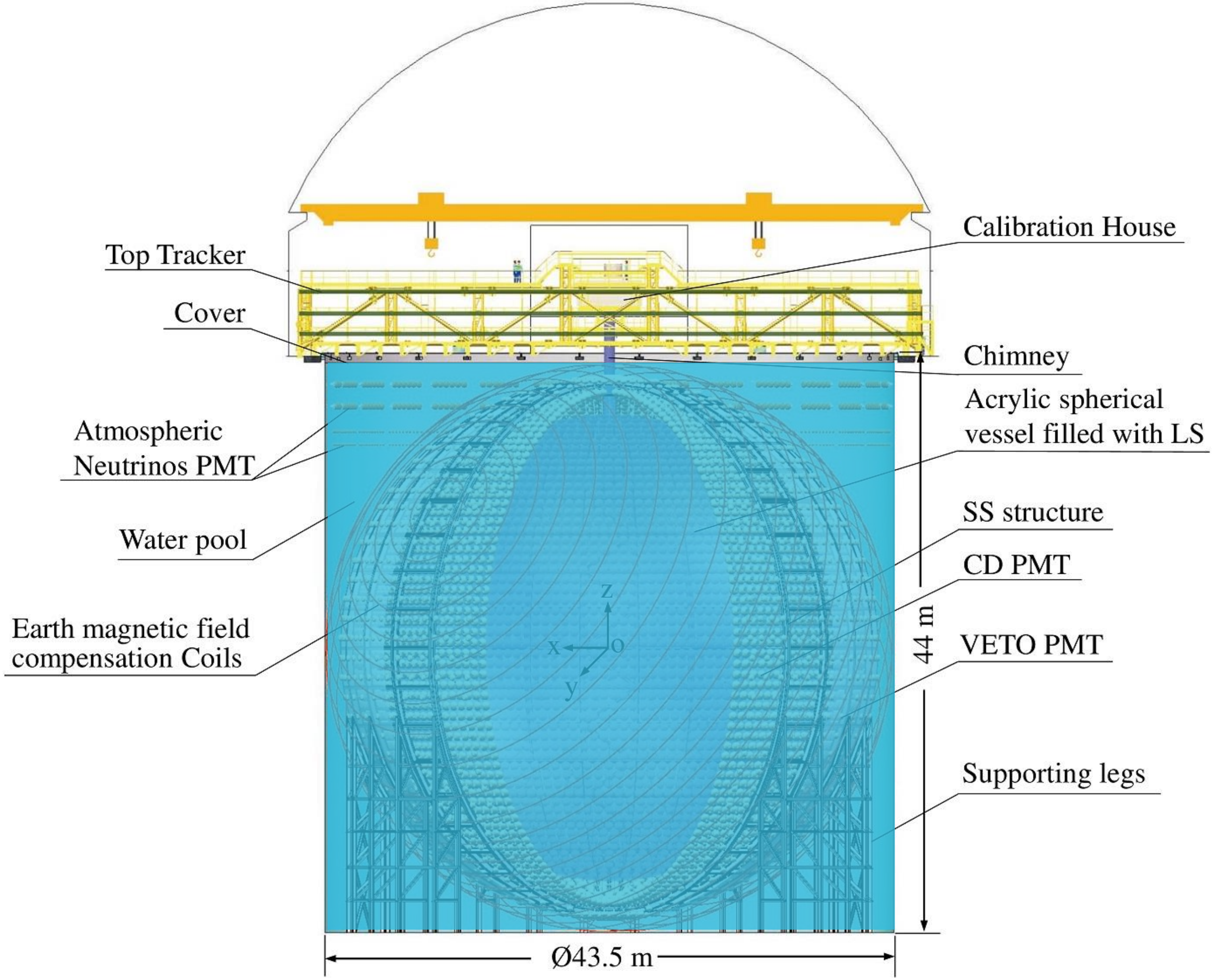
- ~500 m underground
- ~700 m rock overburden (1800 m.w.e.)
- ~1300 m sloped tunnel
- ~600 m vertical shaft

Photo credit: LIU Yuexiang@IHEP

The JUNO Detector



The JUNO Detector

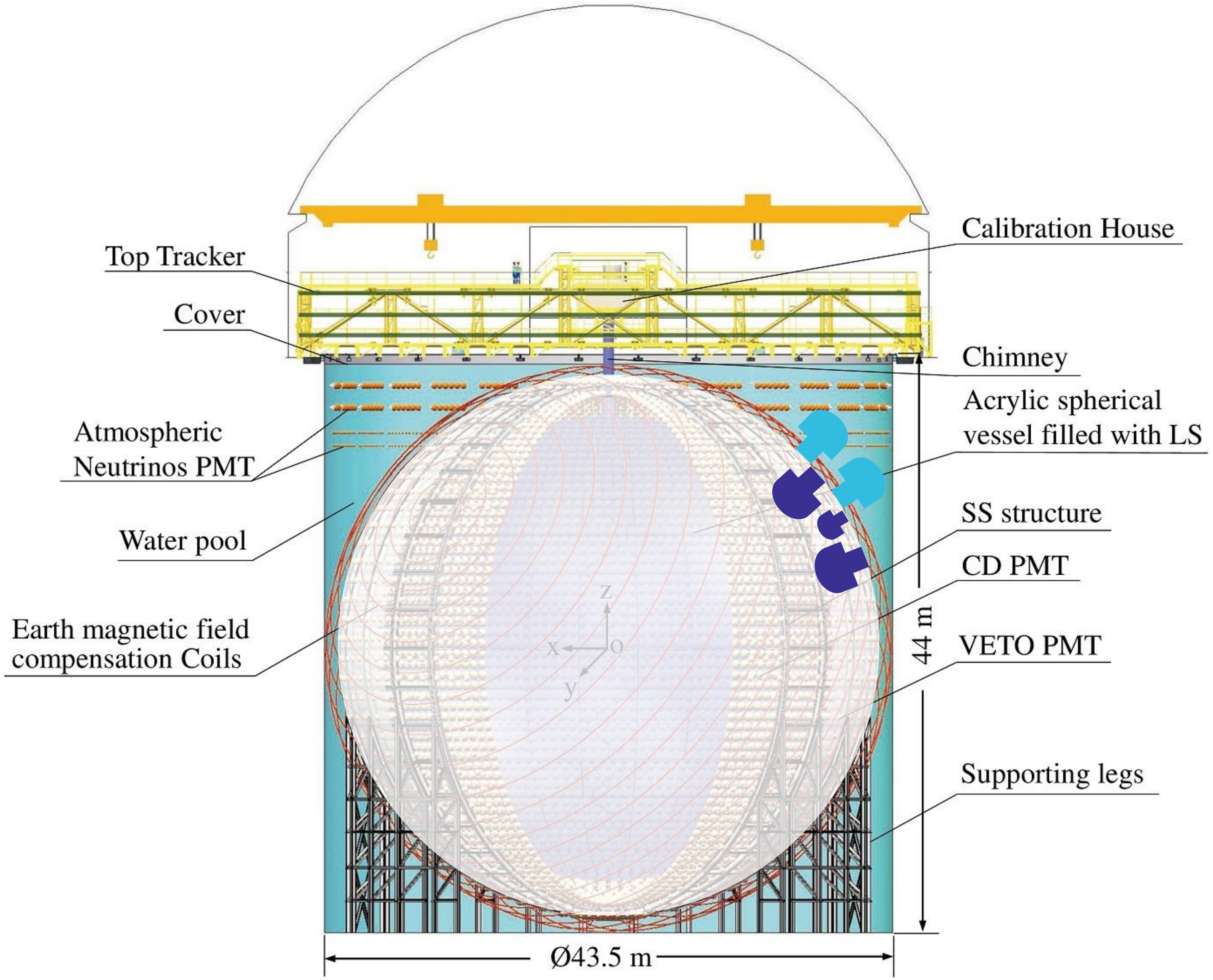


- ❑ Ø43.5 m, H 44 m Water Pool/WP
  - ❖ 35 kt water—Water Cher' Detector/WCD

---------------------------- 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 Cher' Detector/WCD

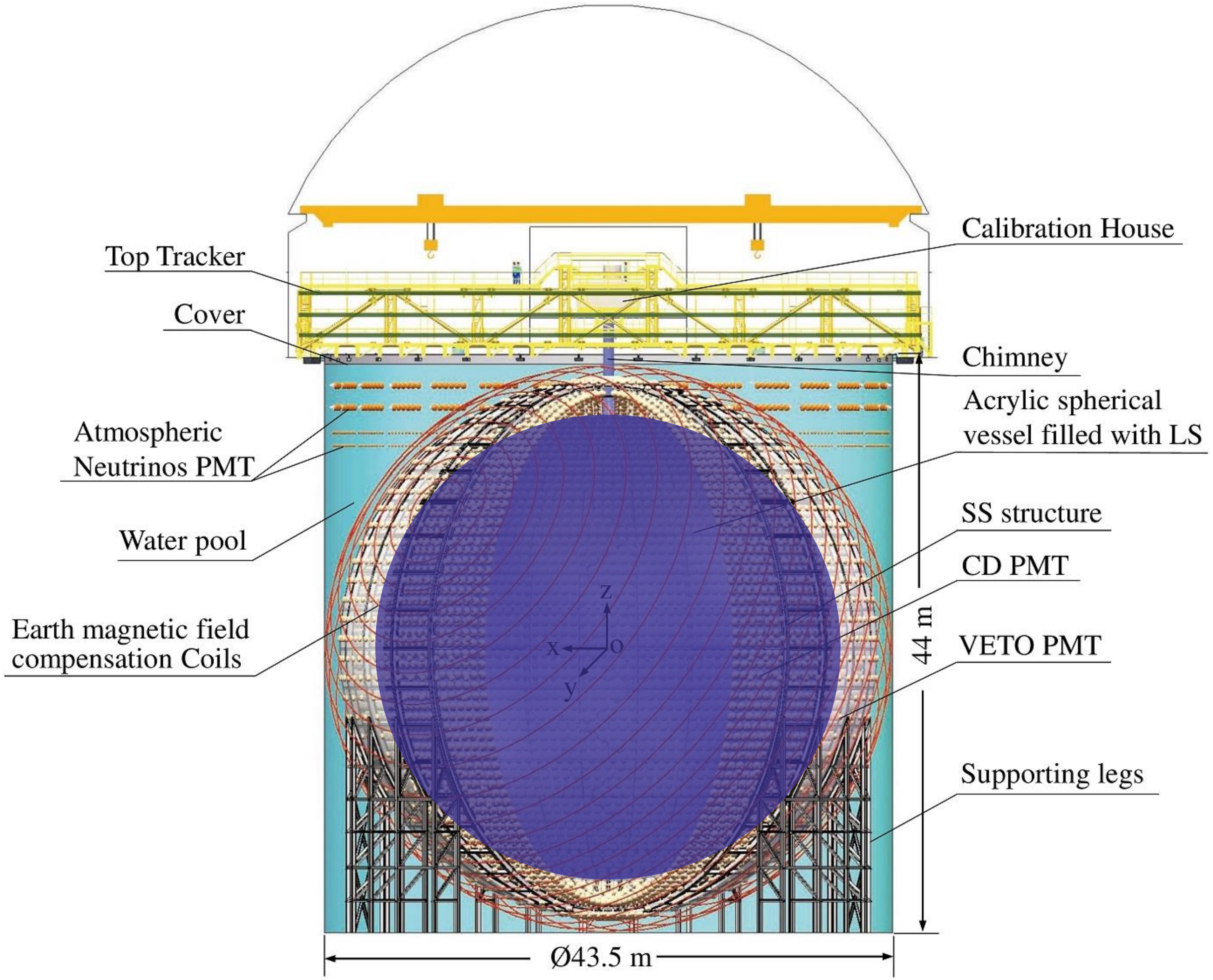
  ---------------------------- Tyvek ----------------------------

  - ❖ 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/ ×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 ← SSS mechanical precision ~3 mm

The JUNO Detector



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  ---------------------------- Tyvek ----------------------------

  - ❖ CD PMTs viewing inwards
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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
- ❑ 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

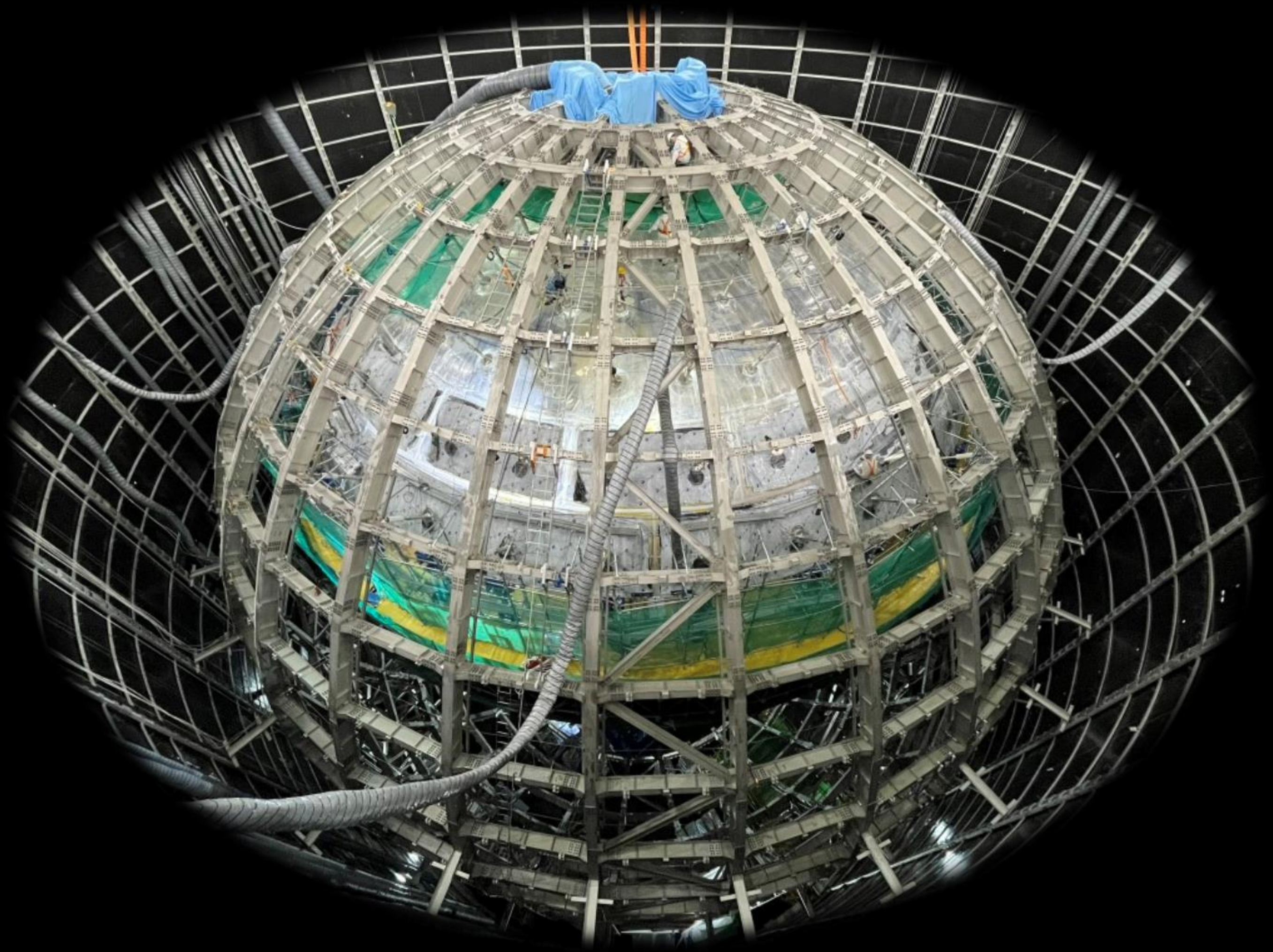


Photo credit: XL

The JUNO Detector

- Veto PMTs (and back of large PMTs)

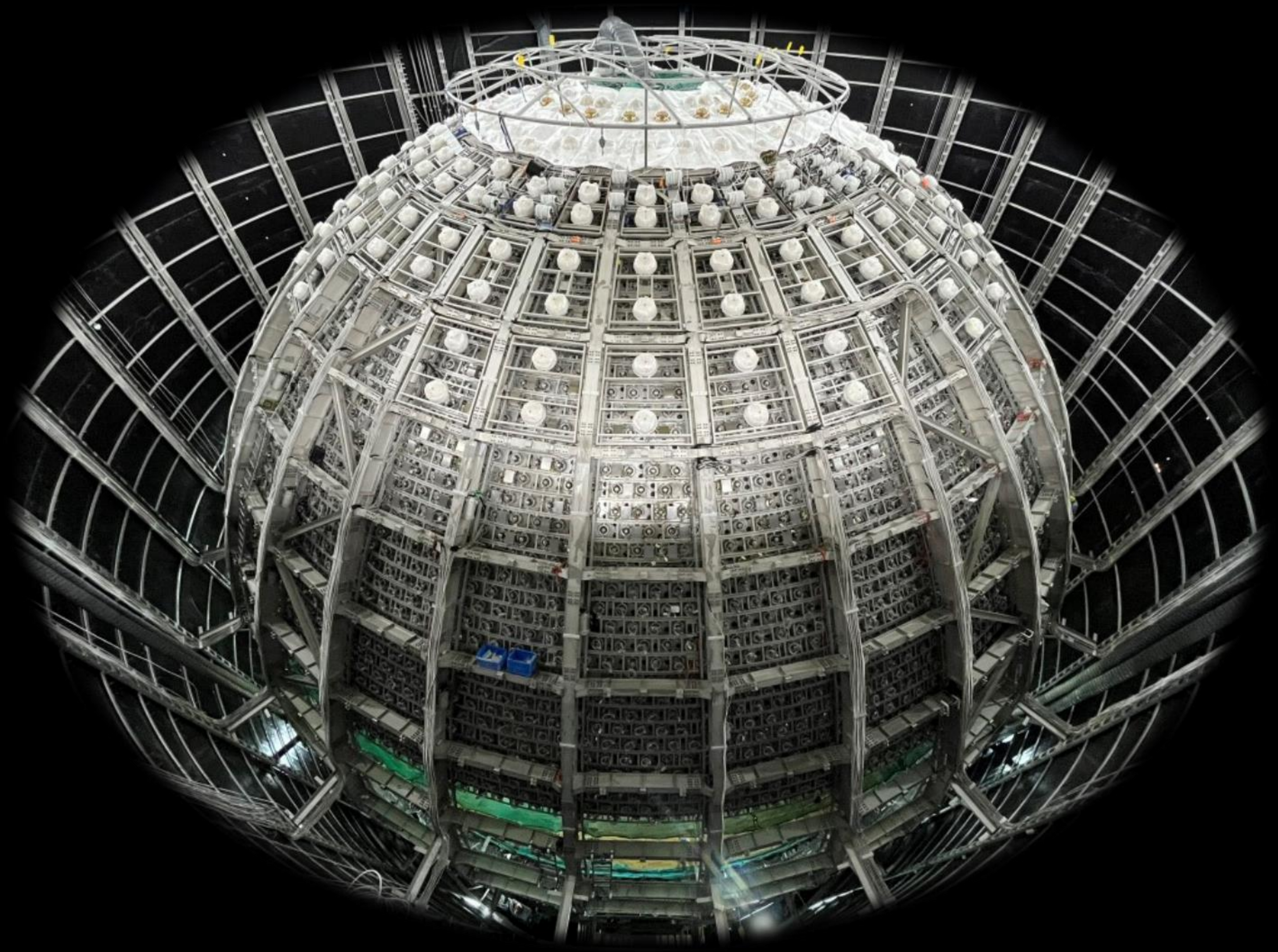


Photo credit: XL

The JUNO Detector

- Tyvek (and earth magnetic field compensation coils)

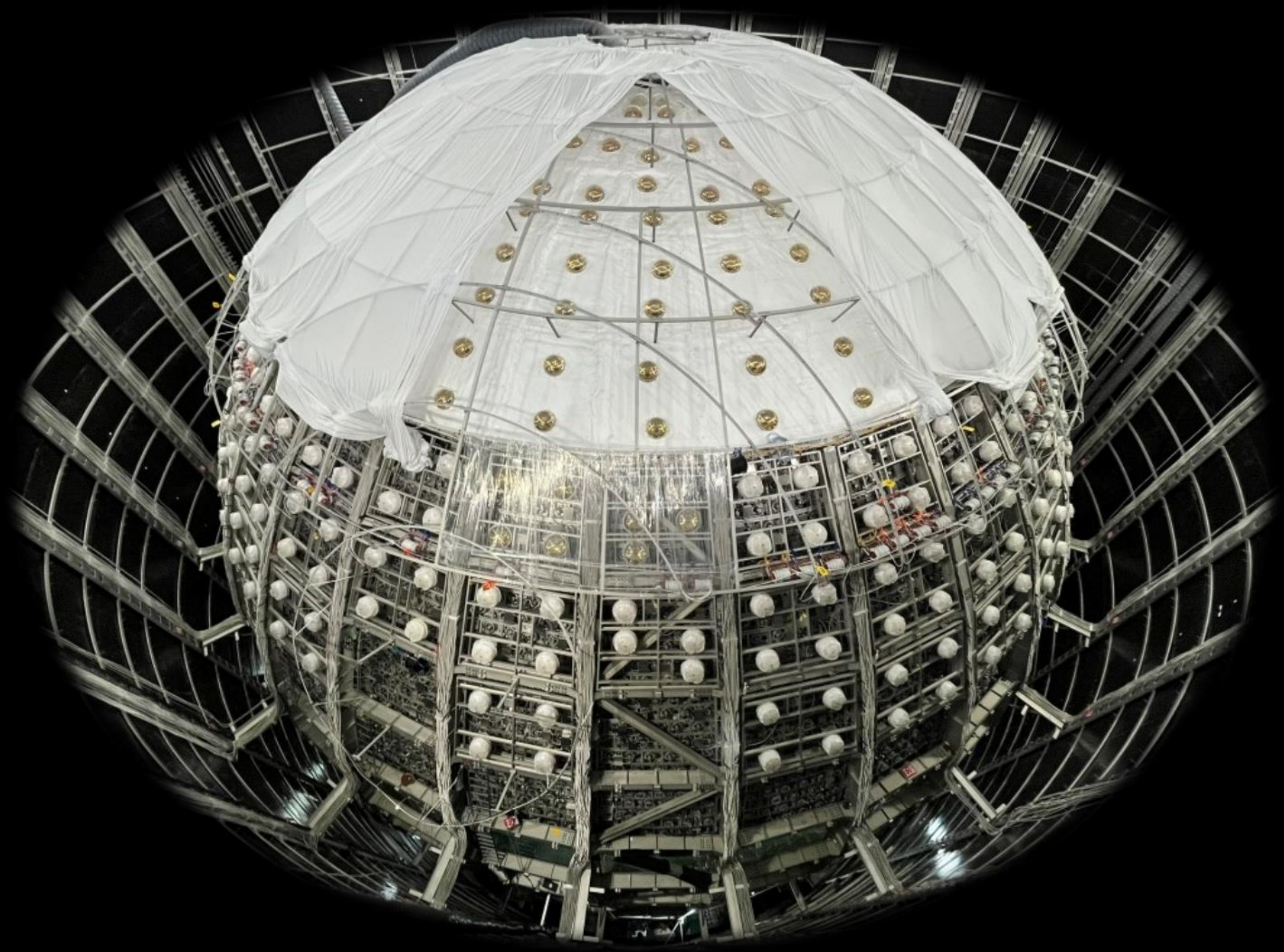


Photo credit: XL

The JUNO Detector

- Large and small PMTs (and water buffer region)

Photo credit: LIU Yuexiang@IHEP

Towards JUNO's First Results

2013 · · · 2015 · · · 2022 2023 2024 2025

Underground water
COVID

Project approved

Civil construction

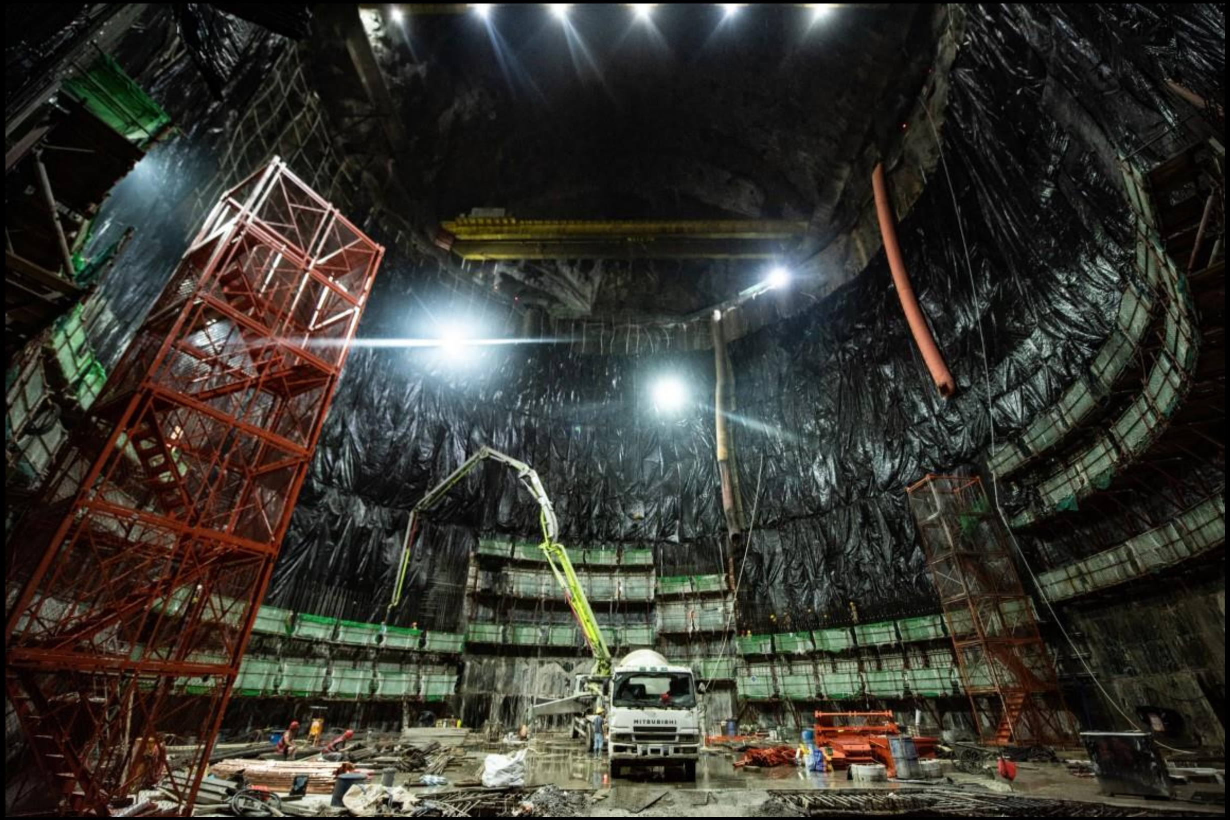


Photo credit: LIU Yuexiang@IHEP

Towards JUNO’s First Results

2013 — Project approved

2015 — Civil construction

2022 — Detector installation

2023

2024

2025

30s video

Towards JUNO's First Results

2013 — 2015 — 2022 — 2023 — 2024 — 2025

Project approved

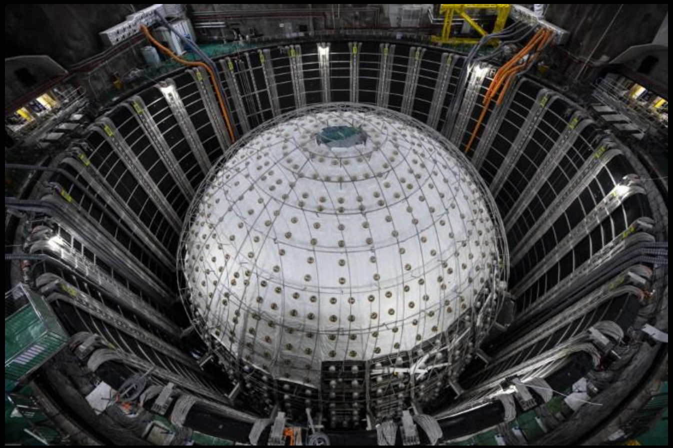
Civil construction

Detector installation

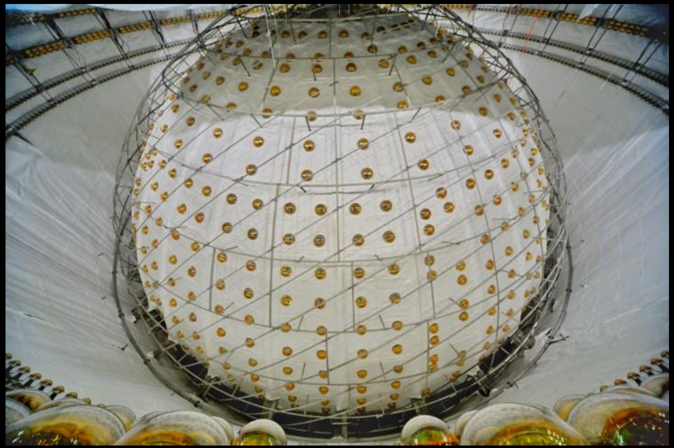
2022/08/15

2023/08/04

2024/09/27



2024/12/19



Towards JUNO's First Results

2013 2015 2022 2023 2024 2025

Project approved

Civil construction

Detector installation

Photo credit: LIU Yuexiang@IHEP

Towards JUNO’s First Results

2013 2015 2022 2023 2024 2025

Project approved

Civil construction

Detector installation

1m video

Photo credit: LIU Yuexiang@IHEP

Towards JUNO's First Results

2013 2015 2022 2023 2024 2025

Project approved

Civil construction

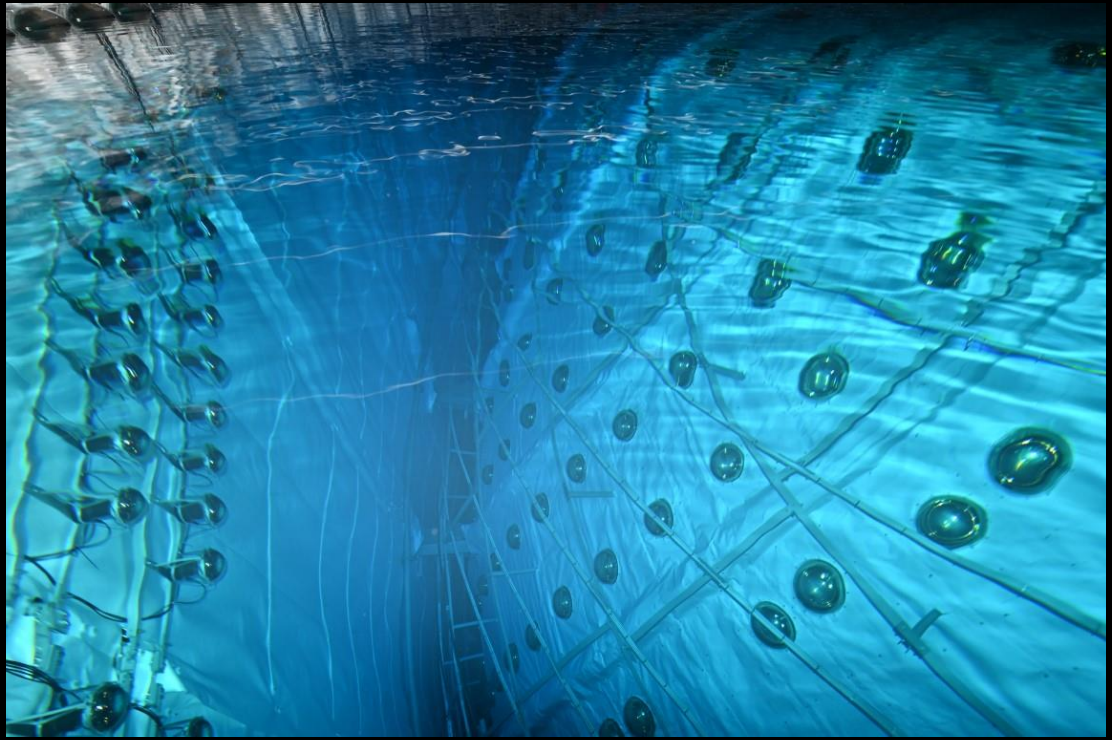
Detector installation

2024/12/18: Water filling

10s video

Towards JUNO's First Results

2013 — Project approved
2015 — Civil construction
2022 — Detector installation
2023
2024
2025
2024/12/18: Water filling



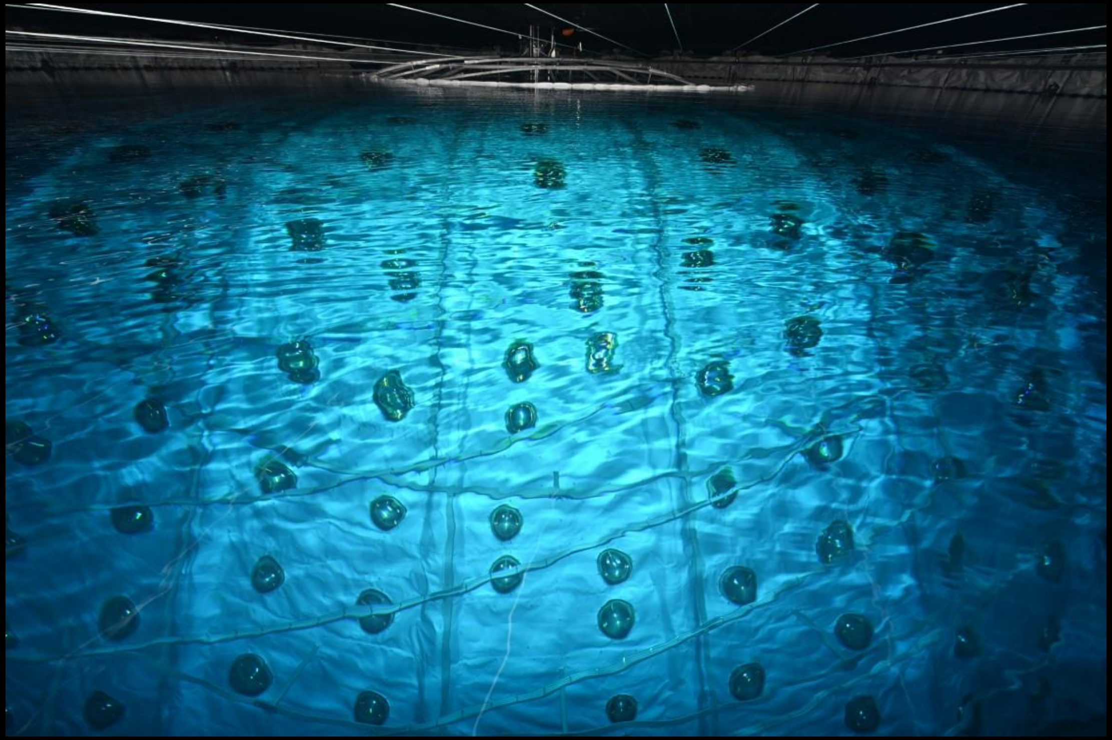


Photo credit: LIU Yuexiang@IHEP

Towards JUNO's First Results

2013 — Project approved

2015 — Civil construction

2022 — Detector installation

2023

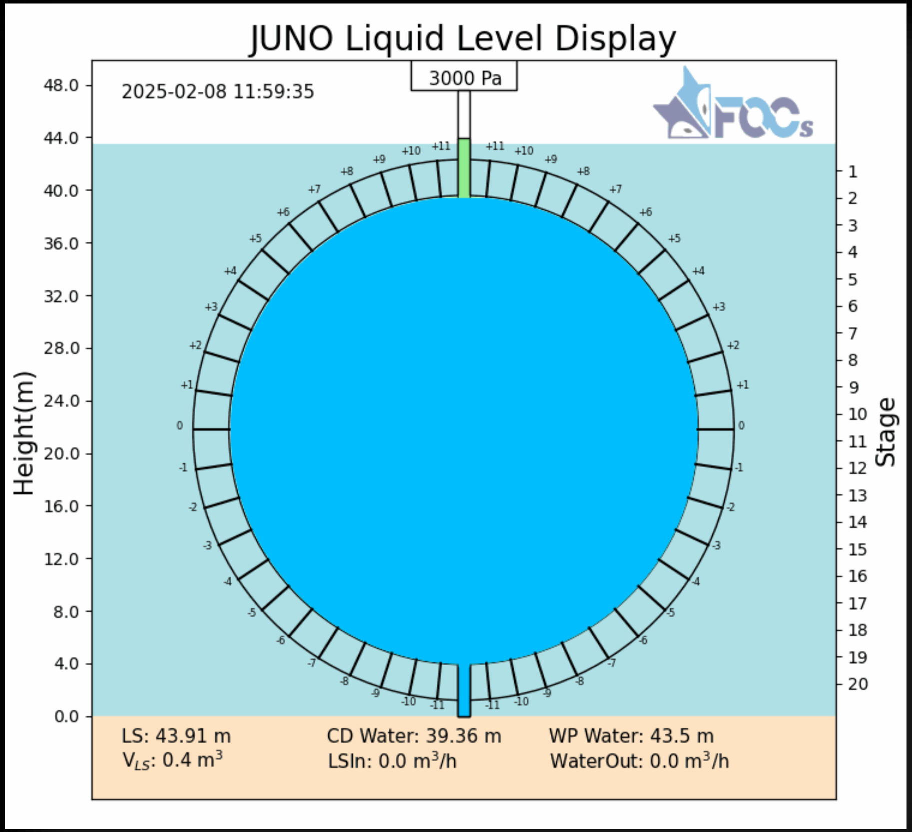
2024

2025

2024/12/18: Water filling

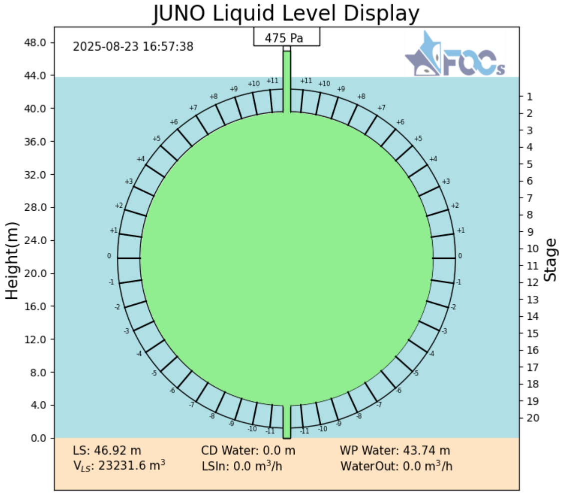
2025/02/01: Water/LS exchange

2025/08/22: LS filling complete

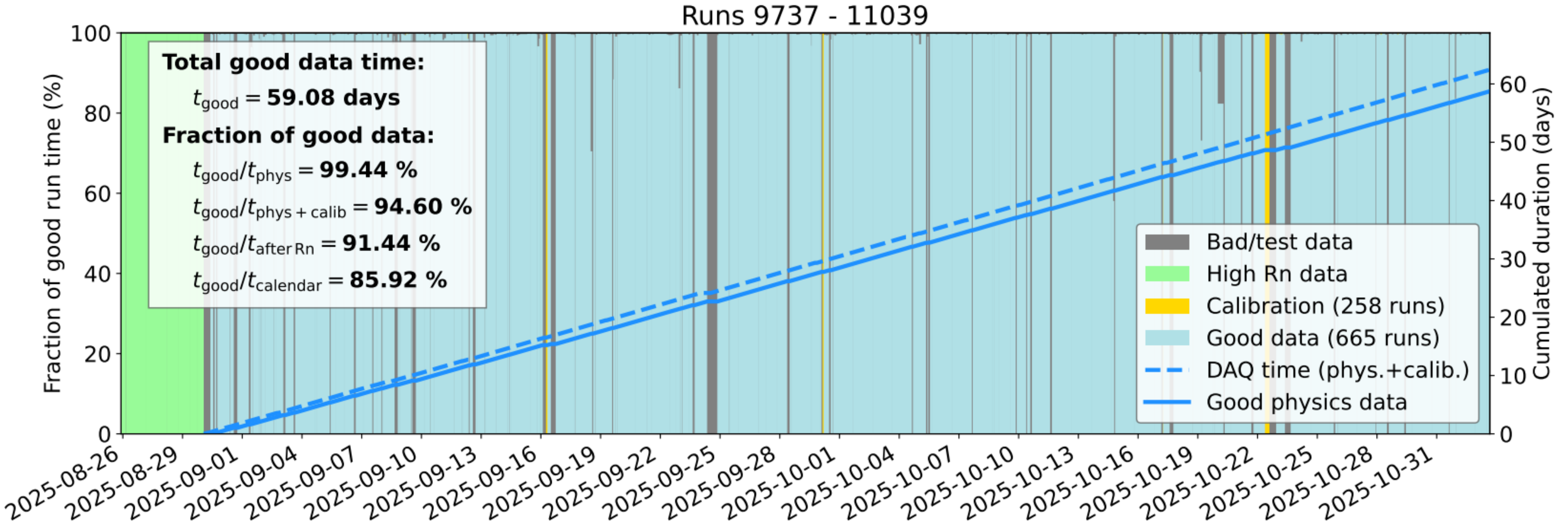


Animated gif

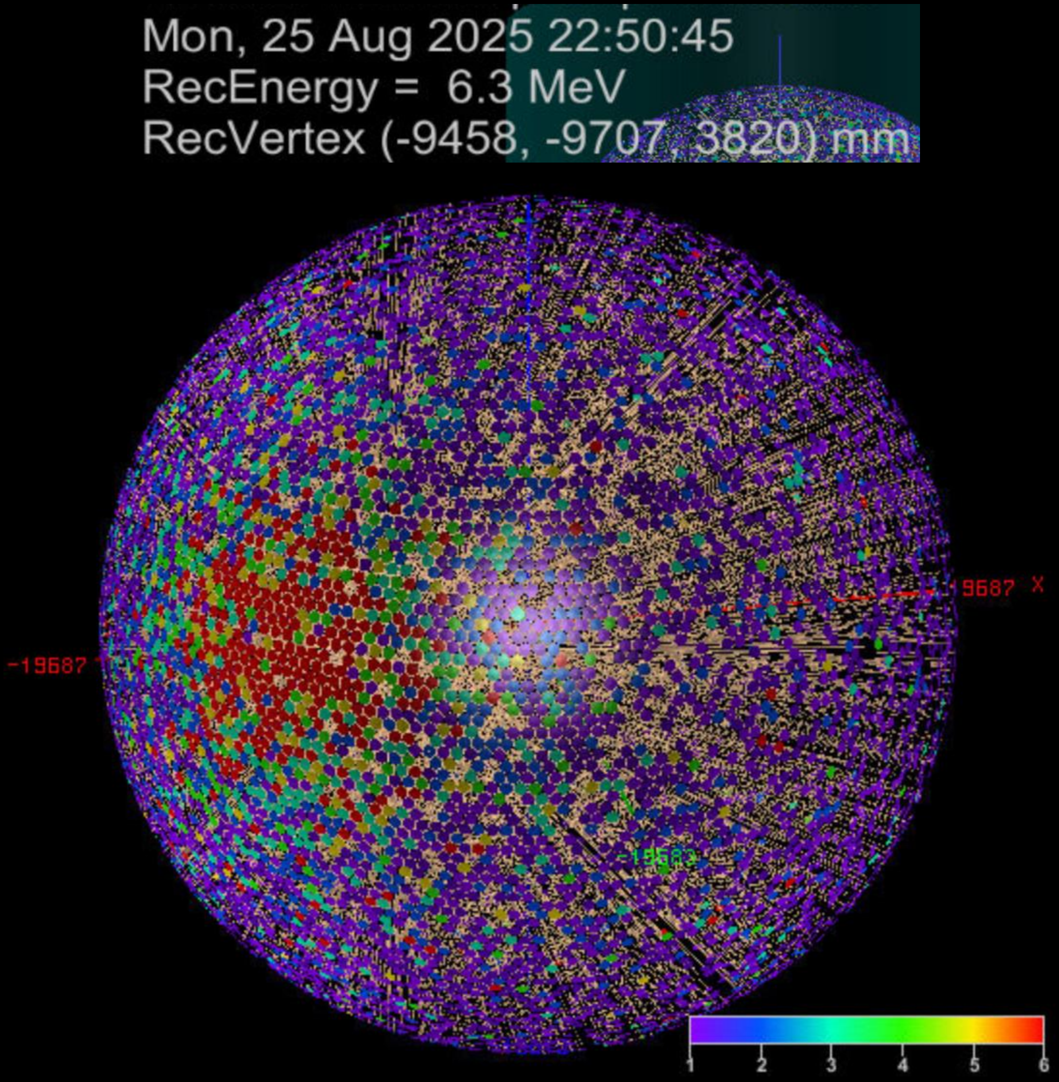
Towards JUNO's First Results



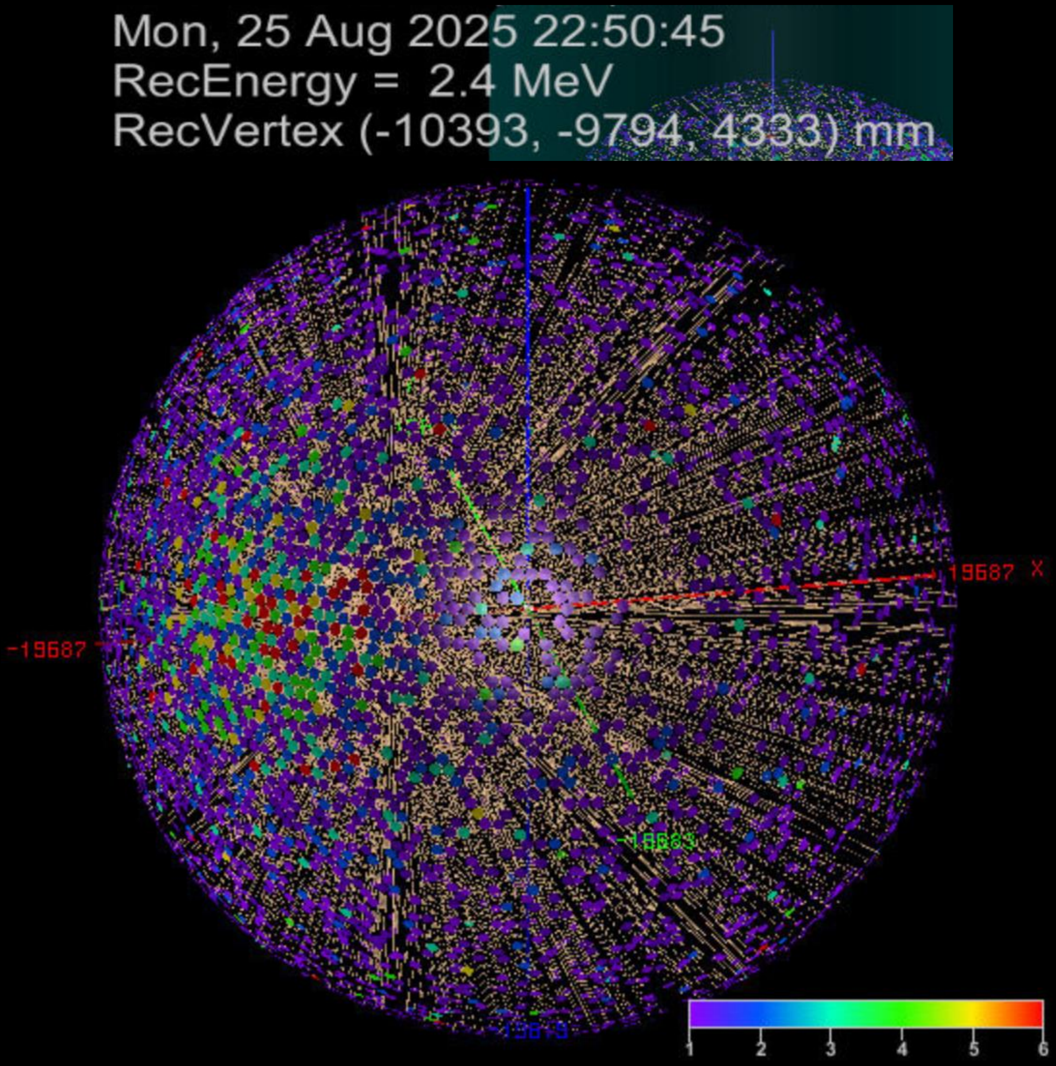
- ❑ 2025/08/22 (22:12): LS filling completed; water in CD fully replaced by LS
- ❑ 2025/08/23 (14:00): Detector calibration began
- ❑ 2025/08/26 (05:30): Start of physics data taking
  - ❖ LS in CD: 23,231.6 m³
  - ❖ Water in WP: 41,225.1 m³
- ❖ Data set used for First Result: 08/26–11/02 (69 calendar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



A Golden Reactor Neutrino Event

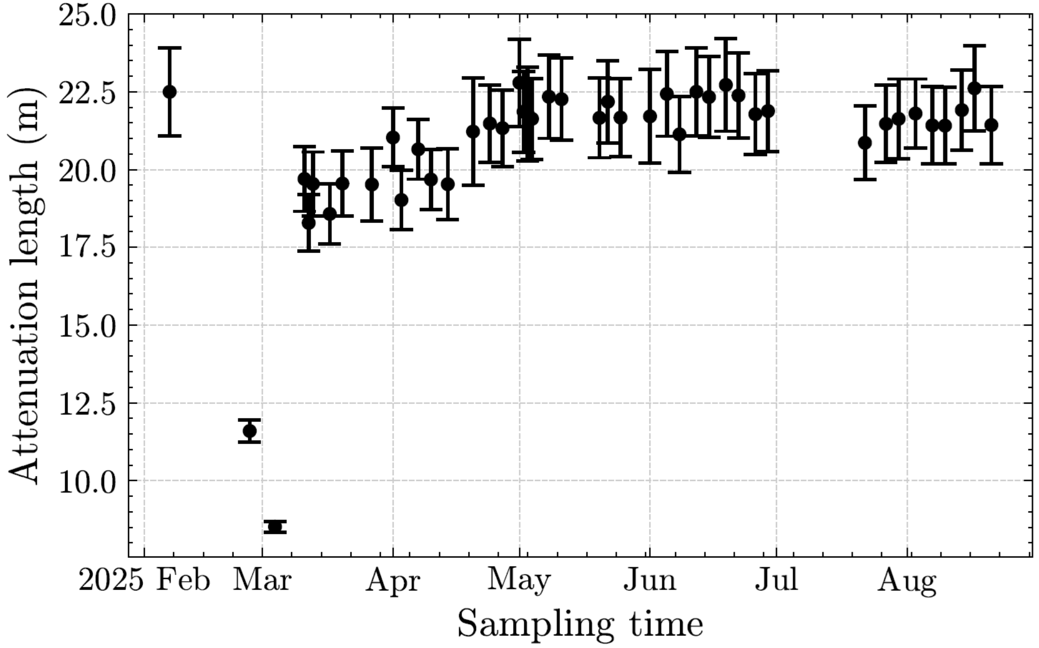


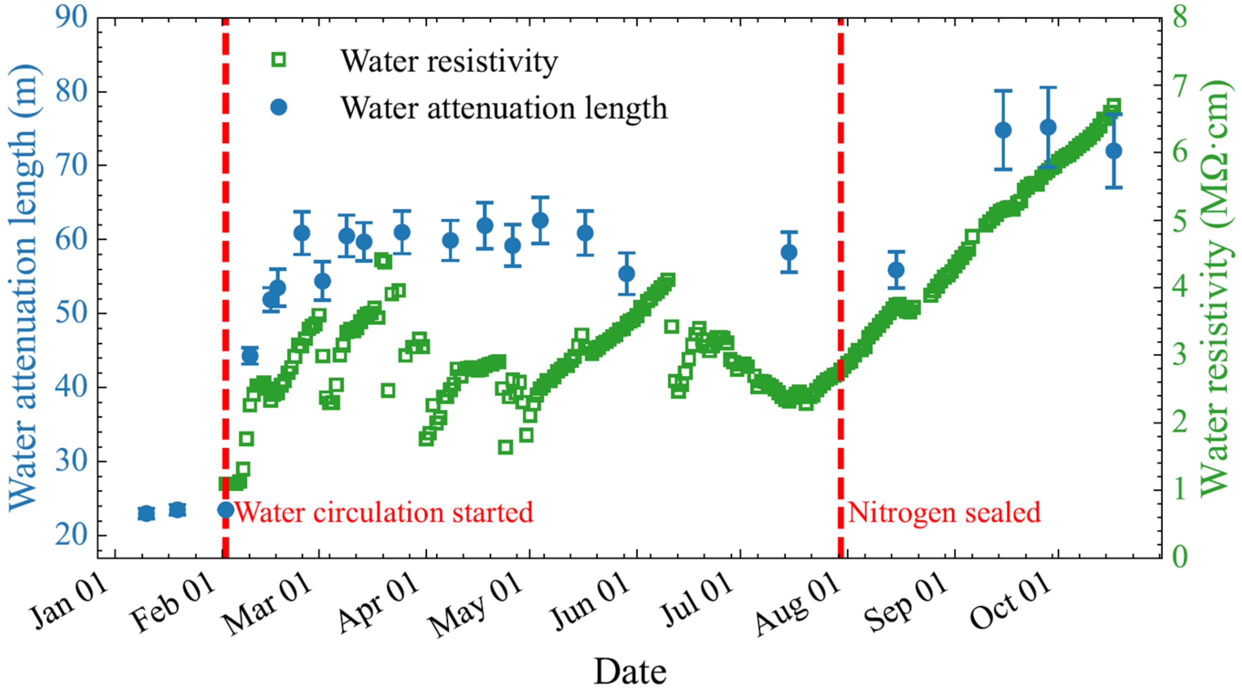
Prompt positron signal



Delayed neutron signal

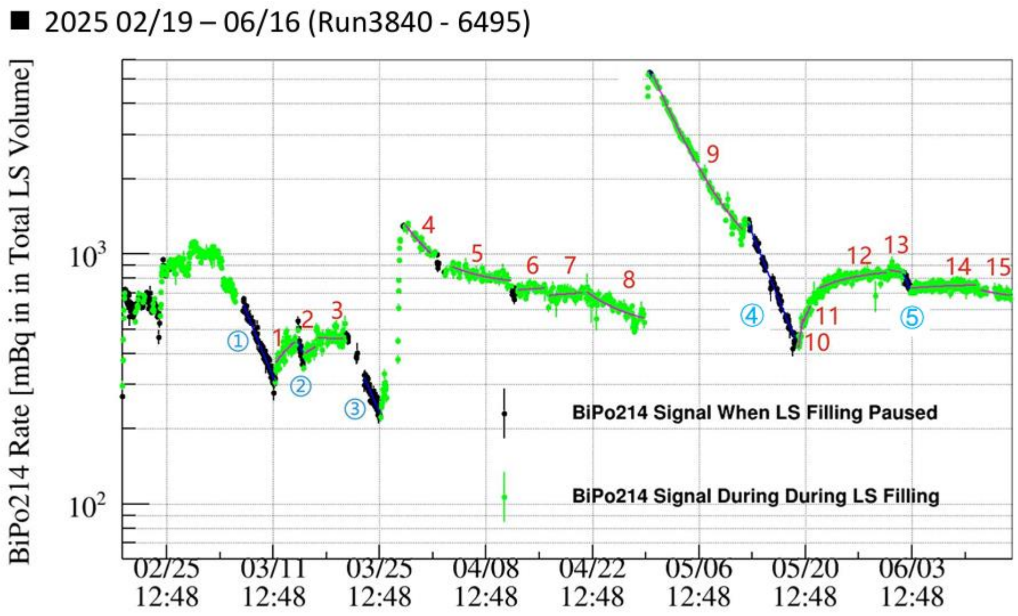
Detector Performance





- ❑ 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



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

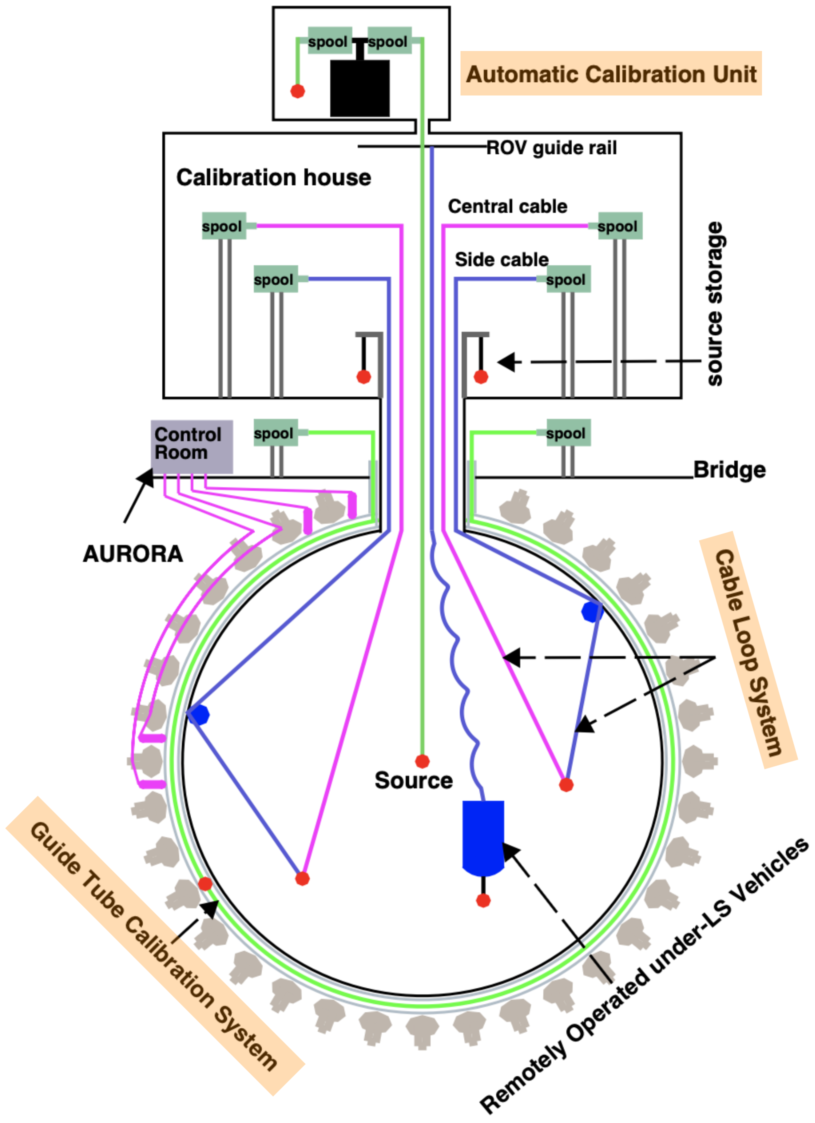
* For E>0.7 MeV and r < 17.2 m

Internal radioactivity

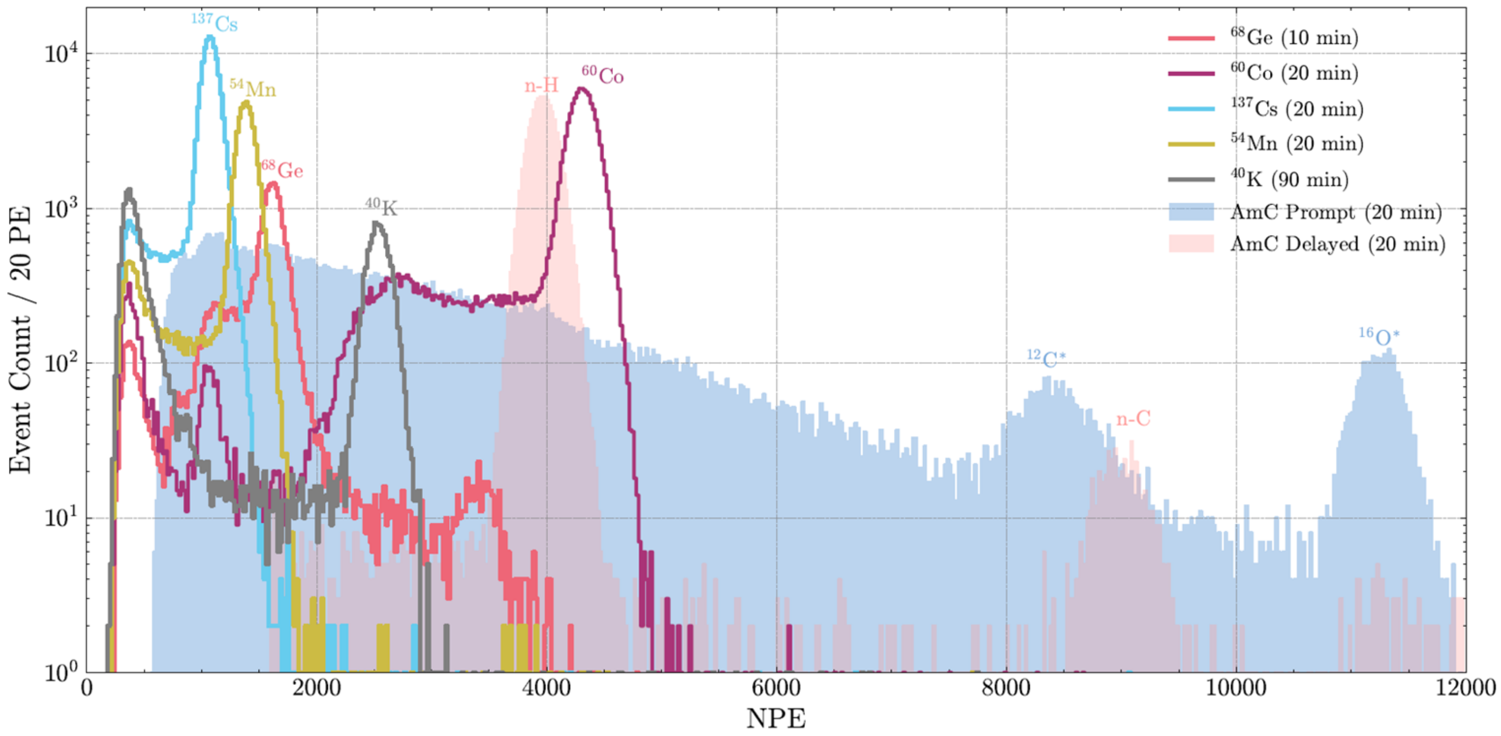
- Cosmogenic spallation $\mathrm{n}/^{12}\mathrm{B}/^{11}\mathrm{C}$ from $\mu + {}^{12}\mathrm{C}$
- Natural radioactivity
  - $^{238}\mathrm{U} \rightarrow {}^{210}\mathrm{Po} \rightarrow \alpha$
  - $^{238}\mathrm{U} \rightarrow {}^{214}\mathrm{Bi} \rightarrow {}^{214}\mathrm{Po} + \beta$ (prompt), $^{214}\mathrm{Po} \rightarrow \alpha$ (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

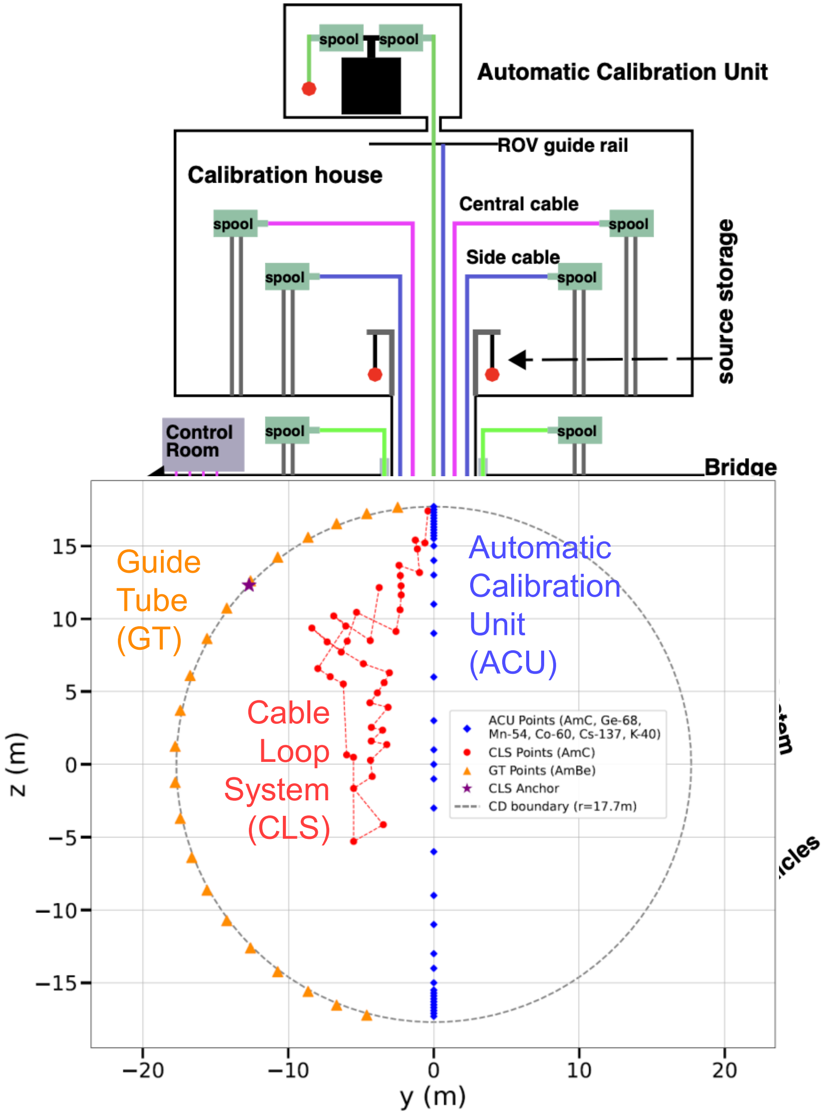
Energy Calibration



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



Energy Calibration



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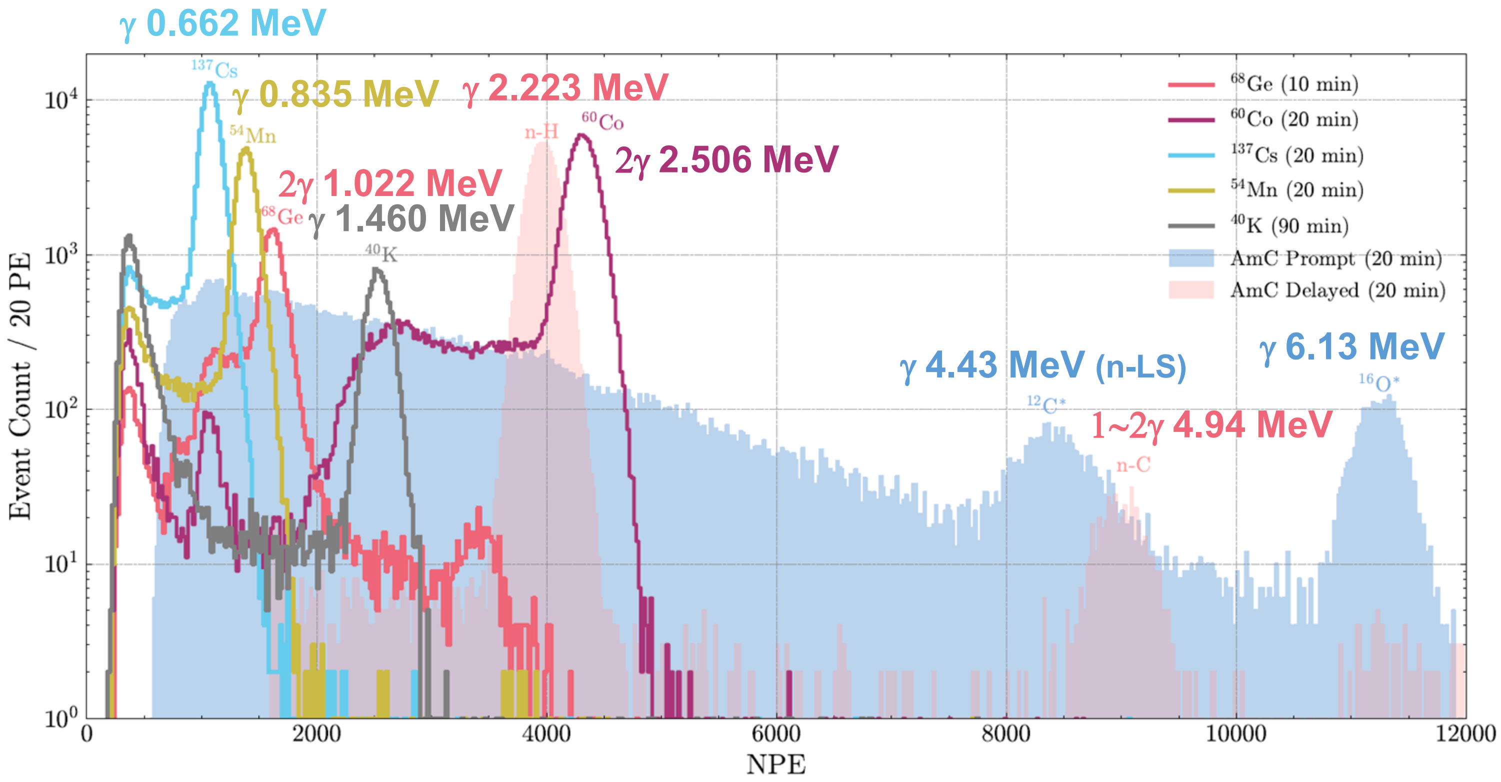
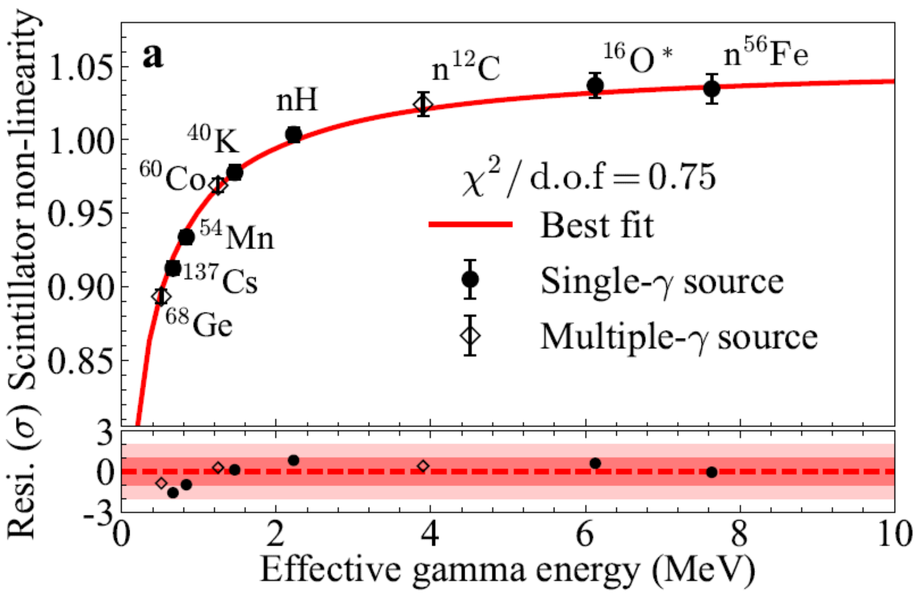
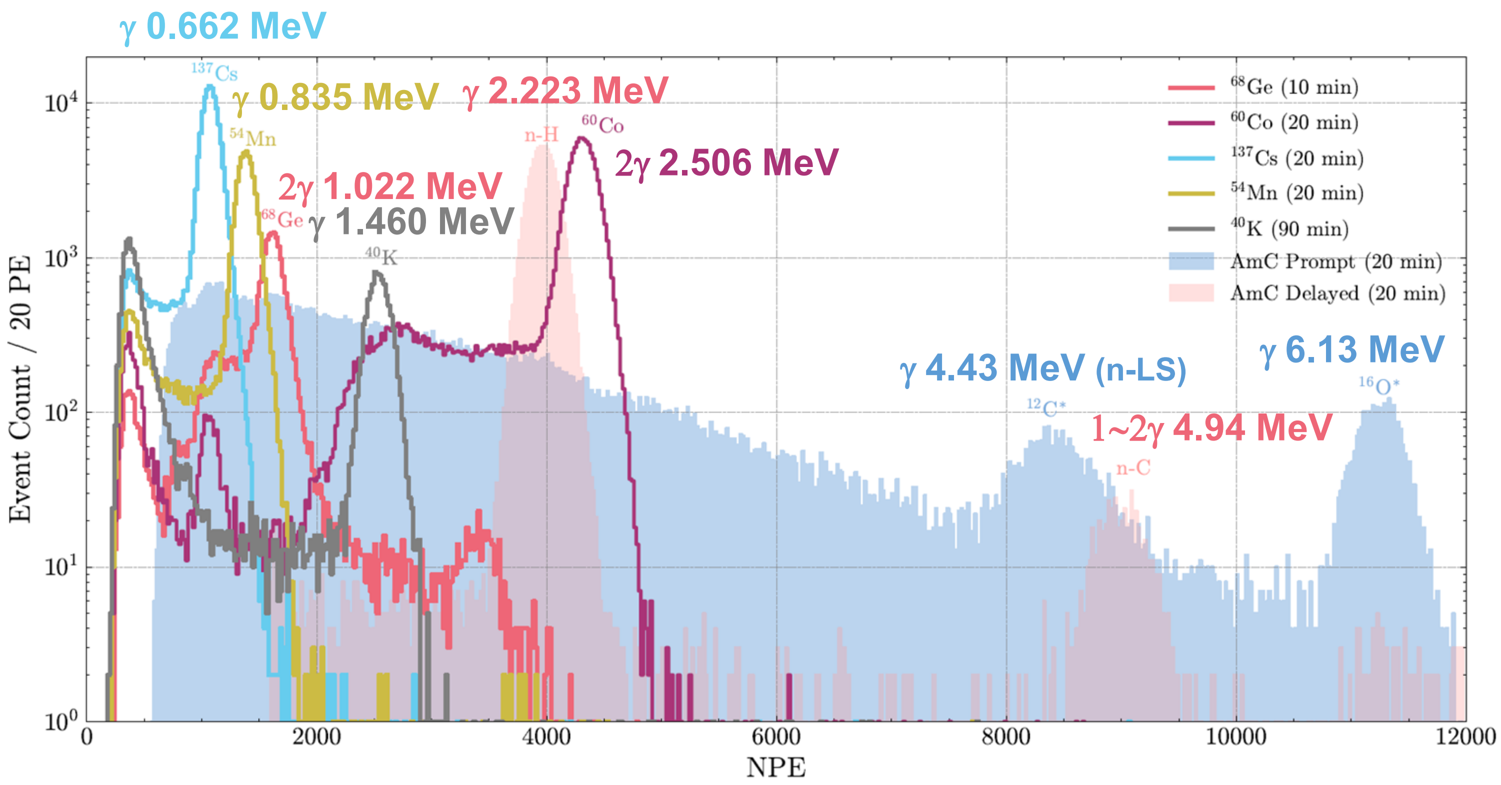


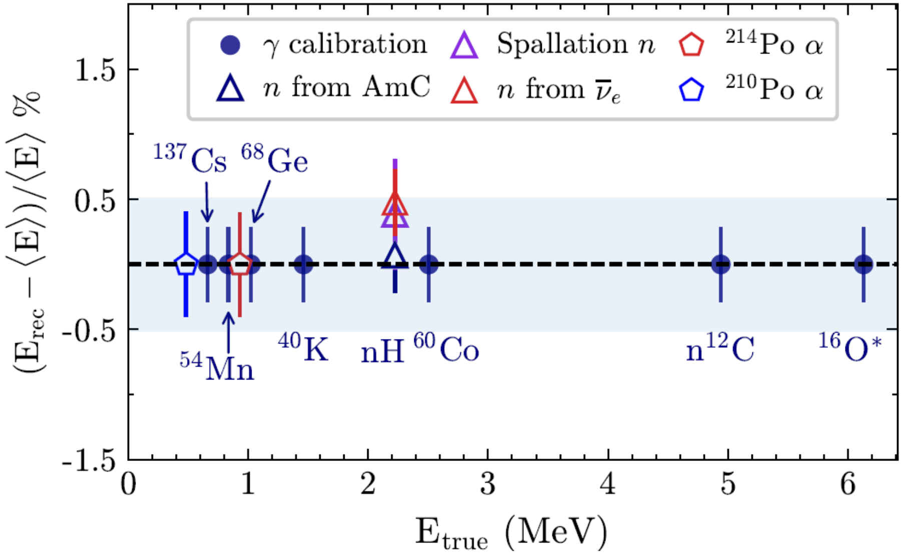
Energy Calibration

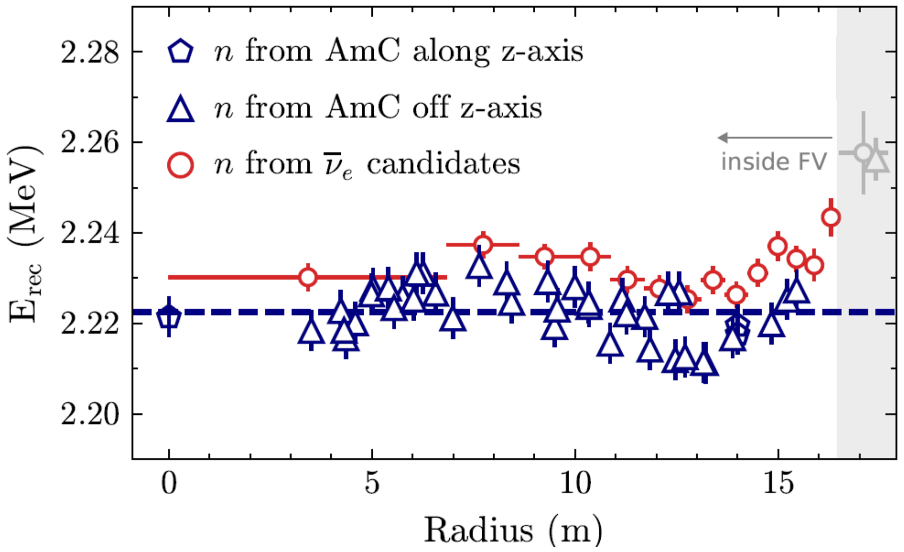


- Non-linearity (due to Birks, Cherenkov, etc.) well described
  - Characterised to <1% precision

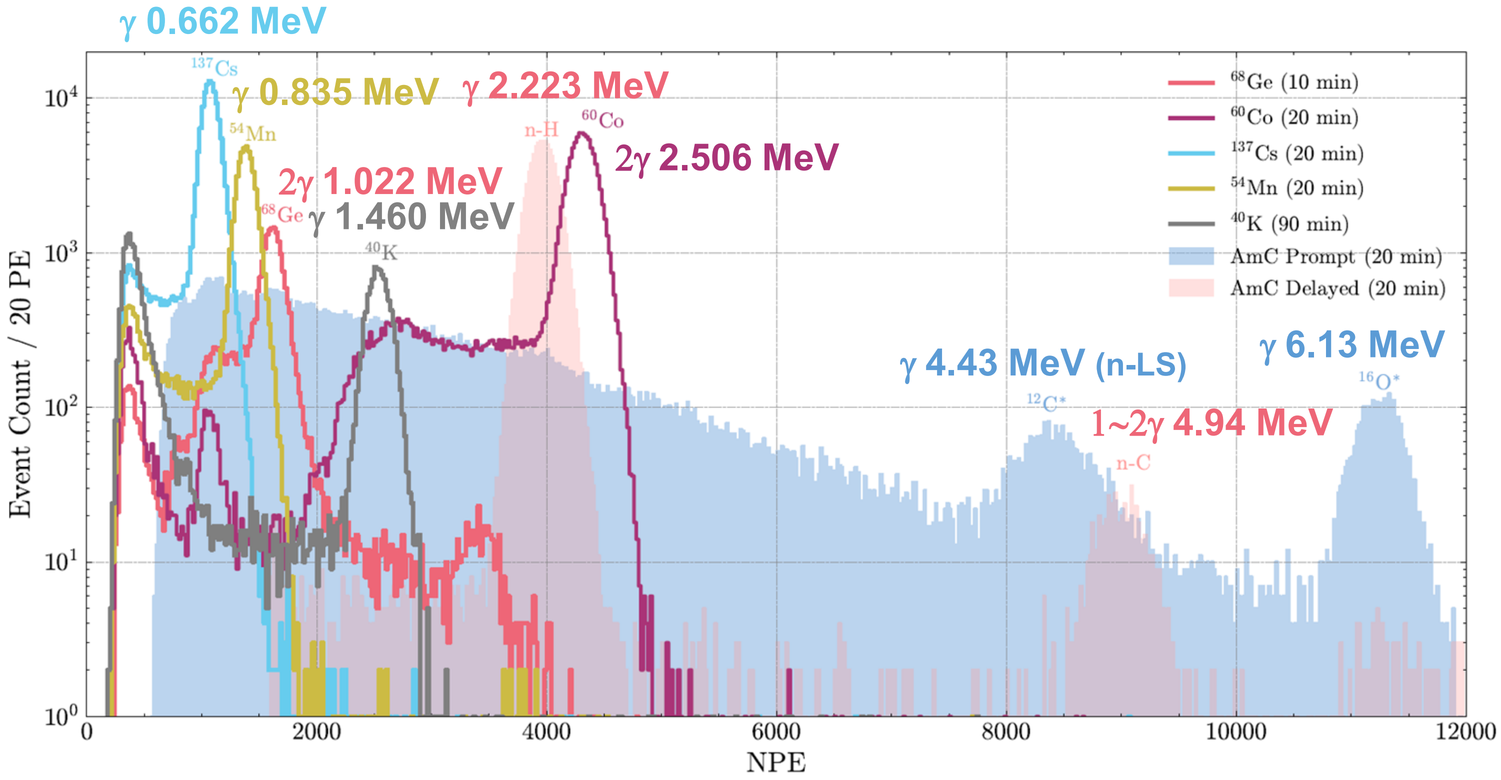


Energy Calibration

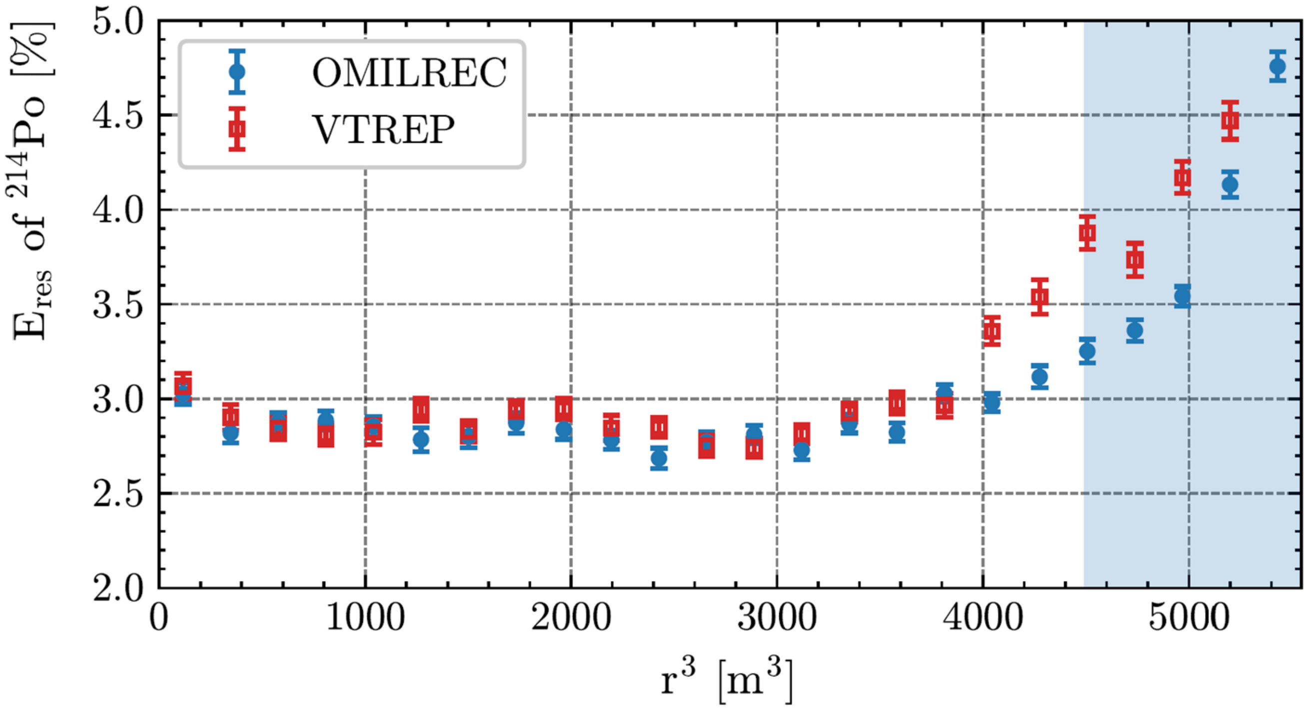


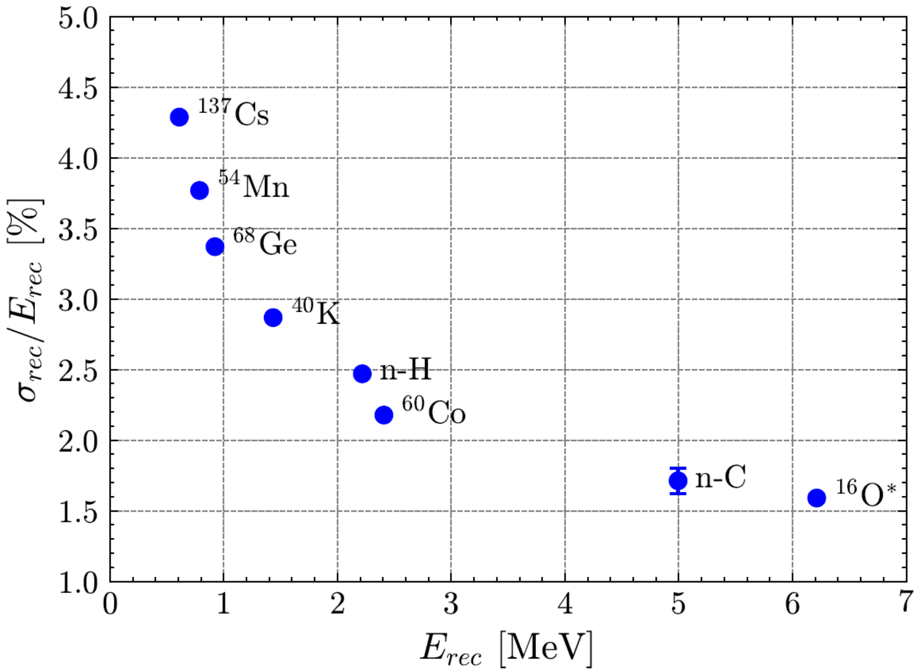


- Energy scale is known to 0.5%
  - Good spatial uniformity
  - Consistent energy response between calibration data and IBD candidates



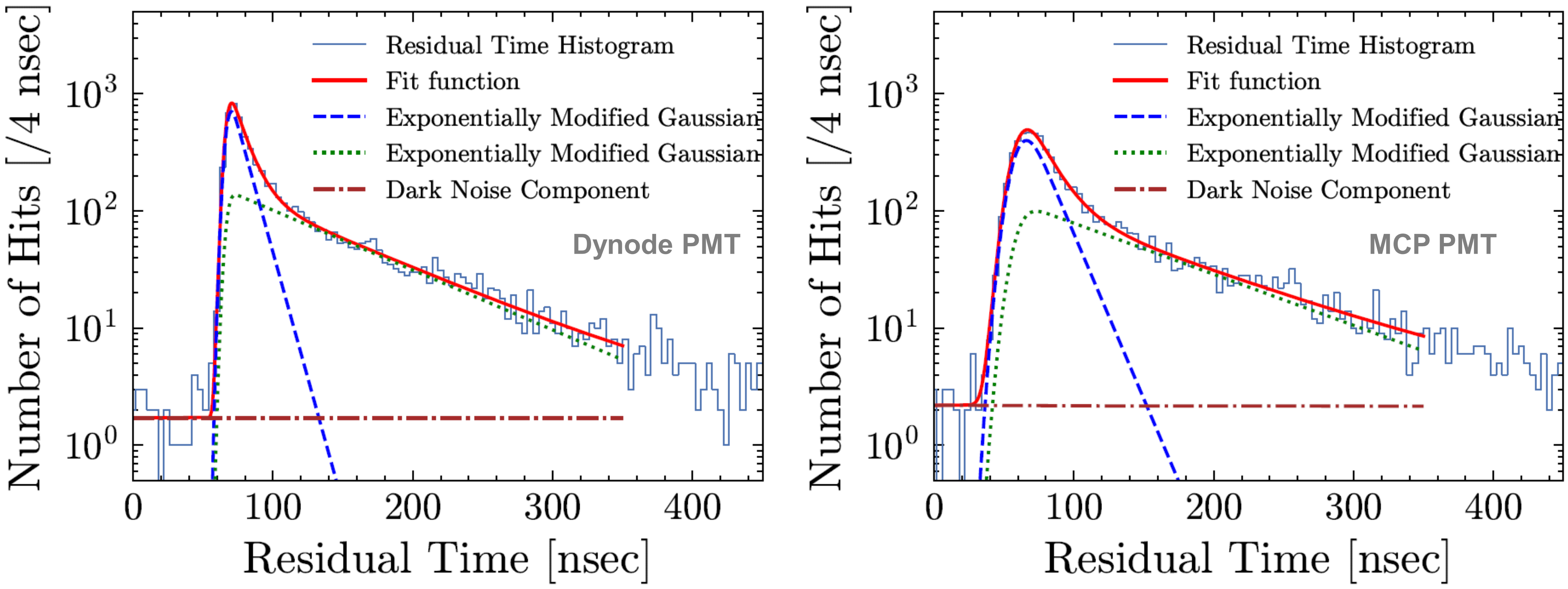
Energy Calibration





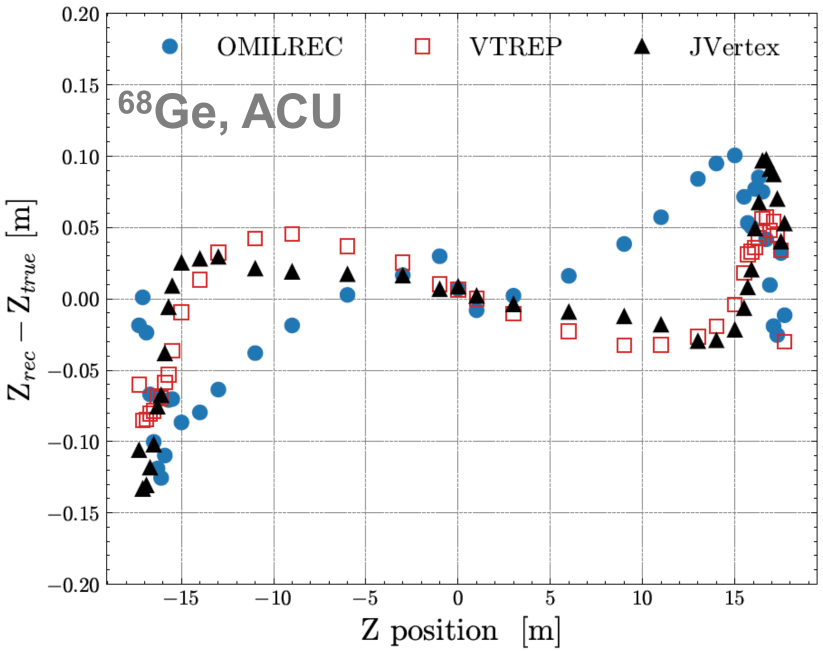
- ❑ Energy resolution for α from ^{214}Po is < 3% @0.93MeV
- ❑ Energy resolution for γ from ^{68}Ge is ~3.4% @0.90 MeV
  - ❖ Already close to but slightly worse than the expectation of 3.1%
  - ❖ Further improvements expected with better calibration and energy reconstruction

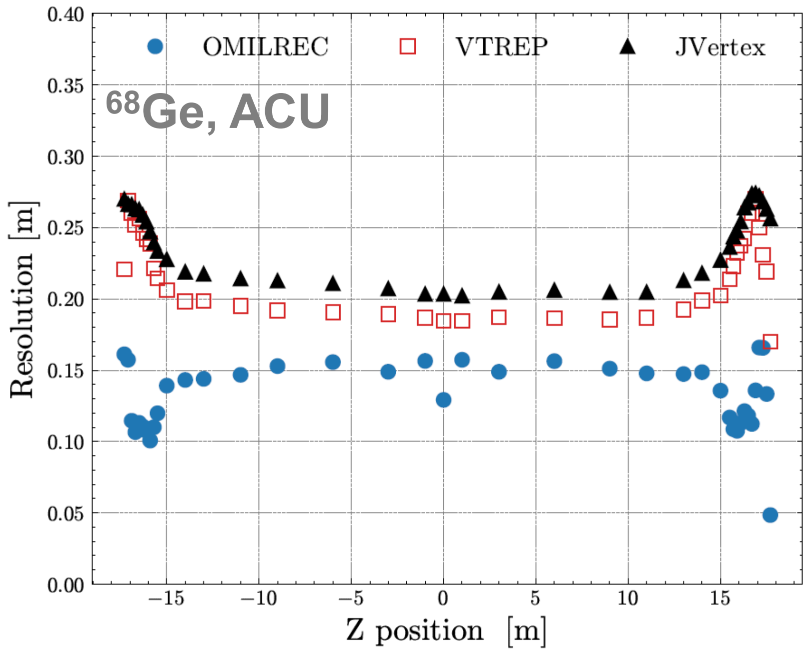
Timing Performance

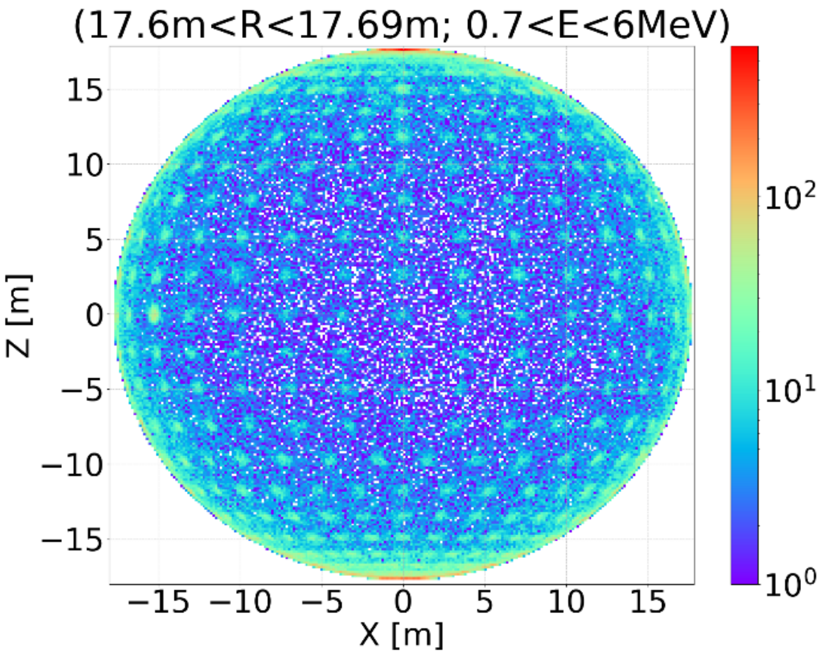


- Event residual time = $t_{first\text{-}hit} - t_{TOF} - t_{ref\text{-}PMT}$
- Well-defined prompt timing peaks
- Consistent with design, not limiting factor
- Sufficient for background veto and vertex reconstruction

Vertex Reconstruction



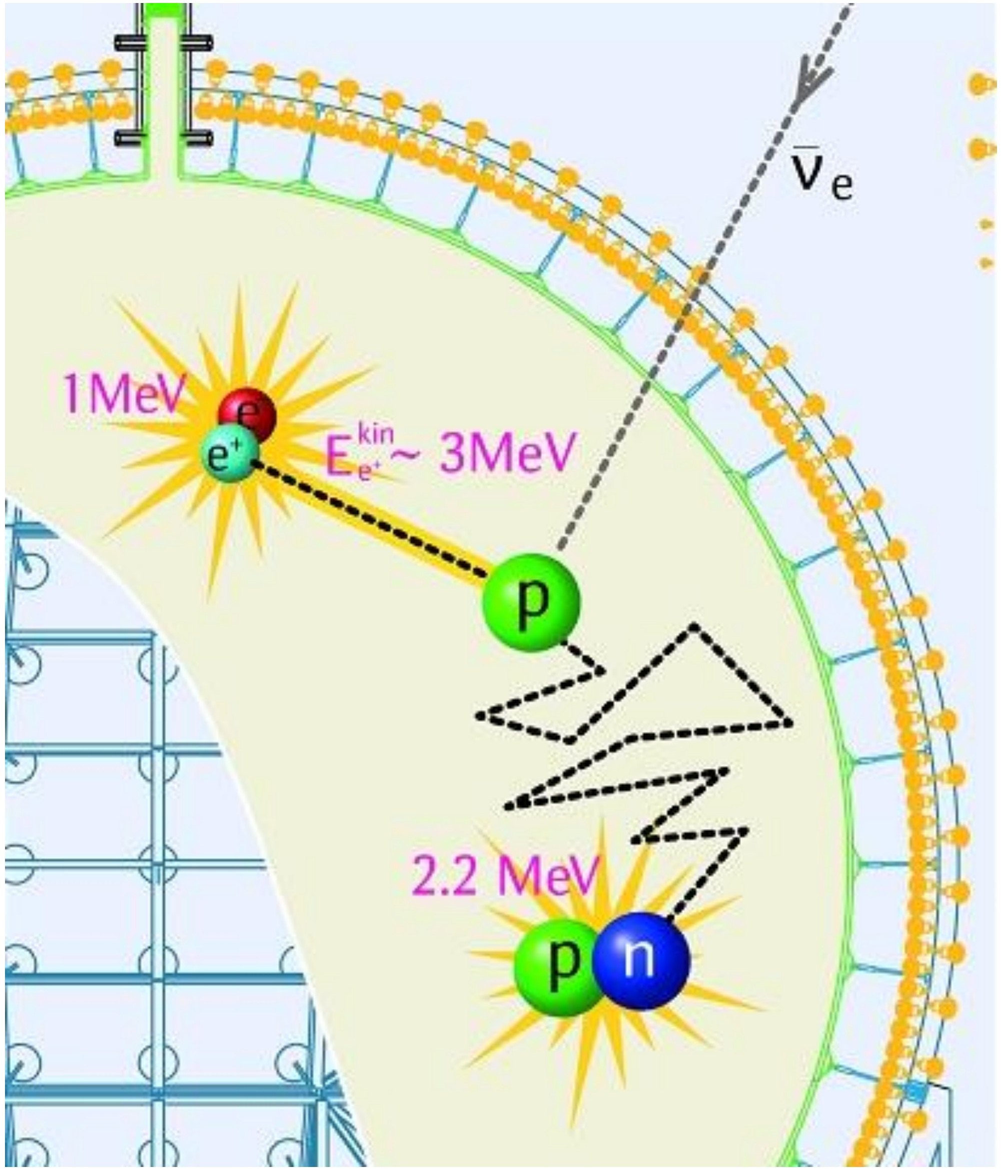




Vertex of "singles" at outermost 10 cm of CD
External radioactivity from joints of AV support

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

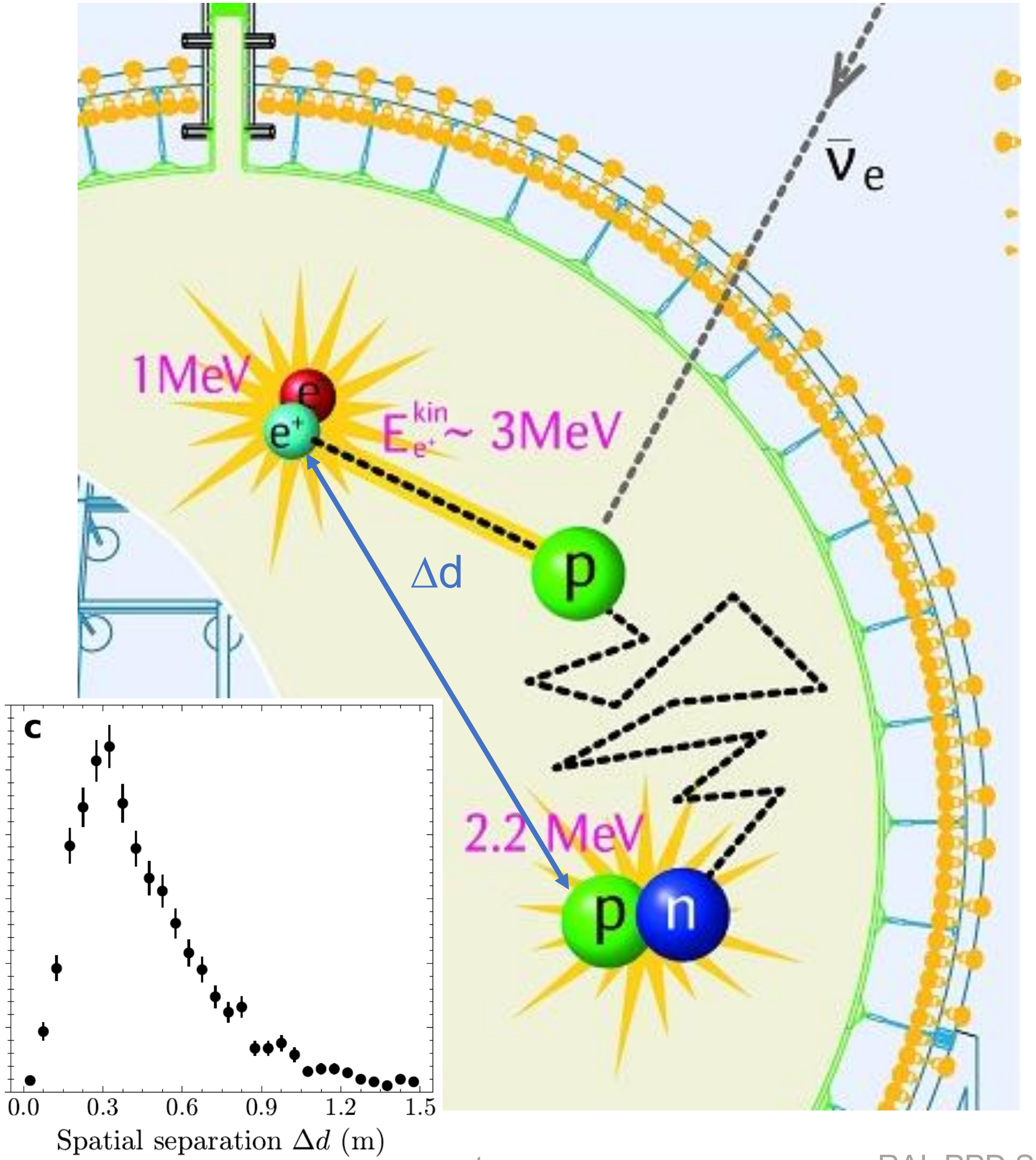


Inverse beta decay (IBD)

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

- ❑ Only on hydrogen, not carbon
- ❑ Prompt signal: e^+
  - ❖ Prompt energy + 0.78 MeV ~ E_ν

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



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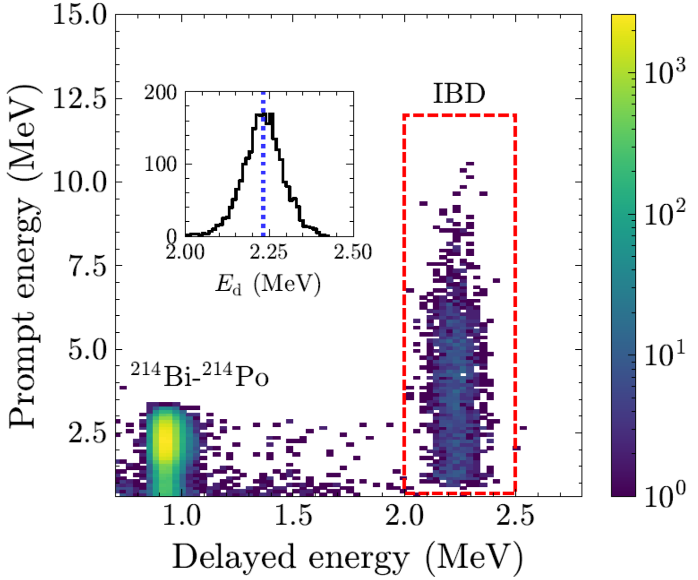
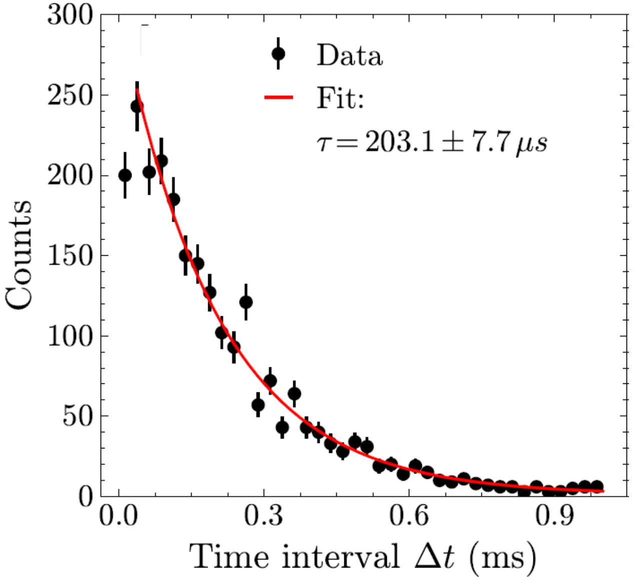
$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$$

- ❑ Only on hydrogen, not carbon
- ❑ Prompt signal: e^+
  - ❖ Prompt energy + 0.78 MeV ~ E_ν
- ❑ Delayed signal: $\mathrm{n} + \mathrm{H} \rightarrow \mathrm{d} + \gamma$
  - ❖ 2.2 MeV neutron capture peak
  - ❖ Mean capture time ~ 200 µs
  - ❖ Separation between vertices up to ~1 m





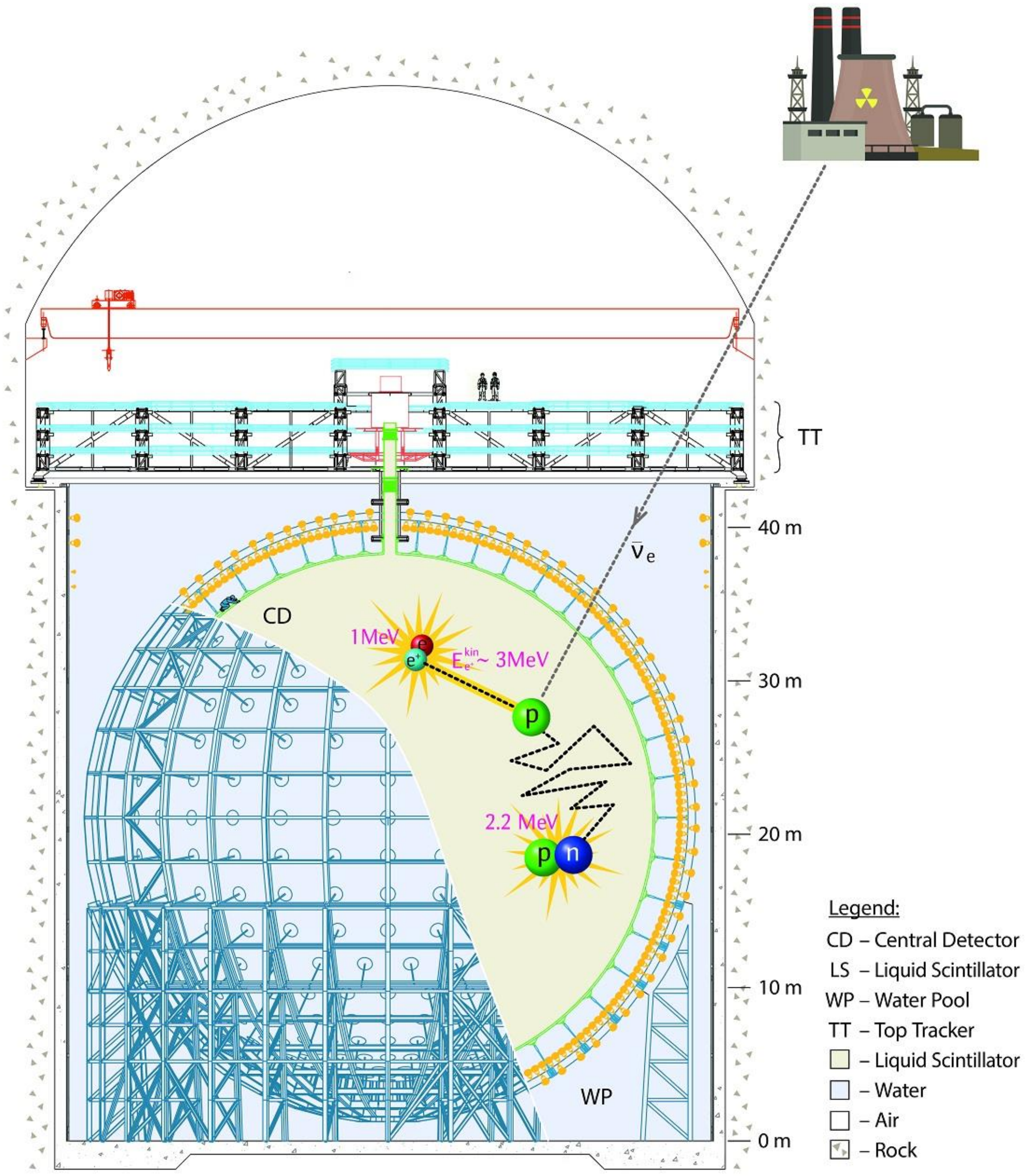
Event Selection

Background

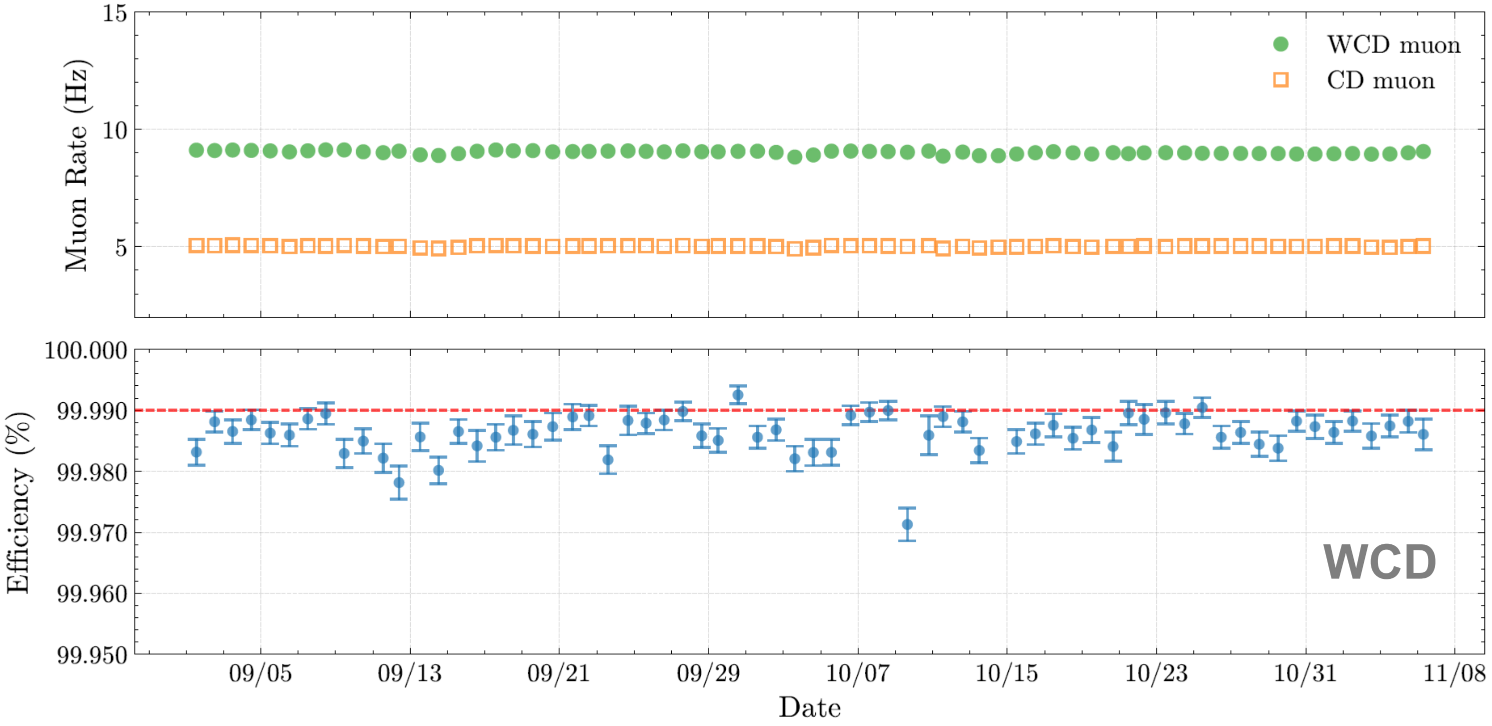
- ❑ Cosmogenic spallation products
  - ❖ $^{9}Li/^{8}He$: β-n decay most dangerous
- ❑ Natural radioactivity
- ❑ Geoneutrinos from decay of U/Th
- ❑ World reactors

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



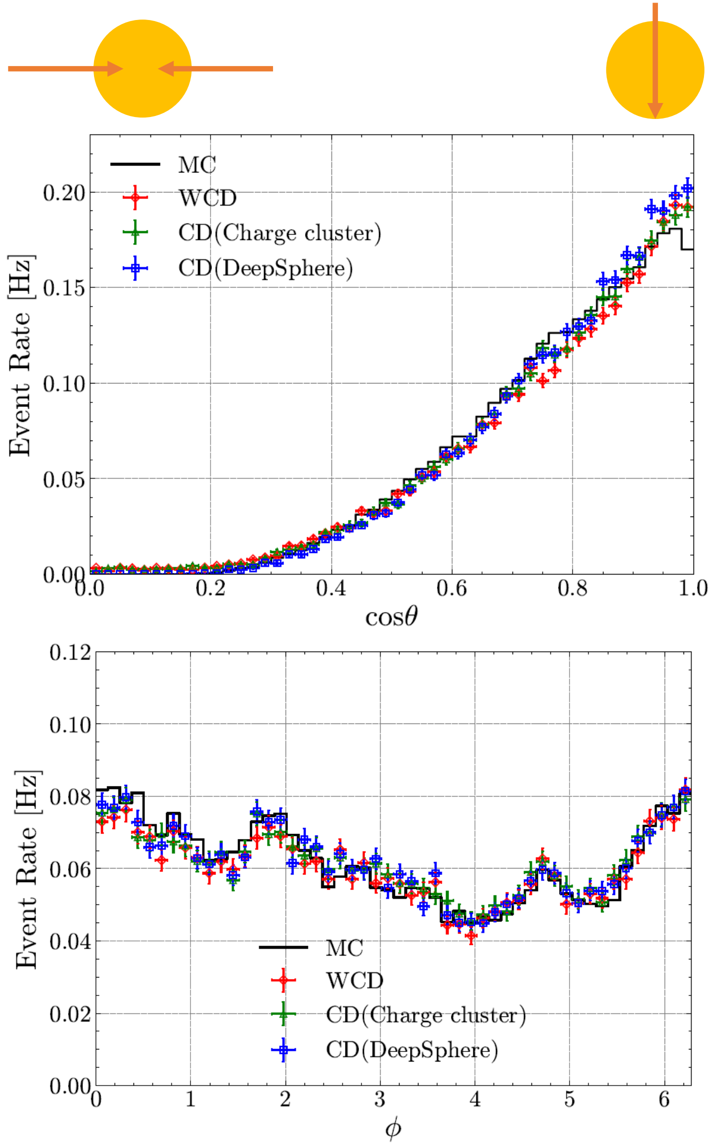
Event Selection: Muon Veto



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

Event Selection: Muon Veto



Single muon reconstruction

- ❑ WCD and CD reconstruction consistent with MC
  - ❖ Normalisation and shape
  - ❖ Validating models of muon flux and rock overburden

Photo credit: LIU Yuexiang@IHEP

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

Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\overline{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	$\sigma_{\rm rel}$
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 ($\varepsilon_{\rm tot}$)	69.9	1.6
$\overline{\nu}_e$ signal (cpd[1])		
w/o $\varepsilon_{\rm tot}$ corrected	33.5 ± 1.7	
w/ $\varepsilon_{\rm tot}$ corrected	47.9 ± 2.6	
Non-oscillated $\overline{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}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}C(α, n)^{16}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%

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

Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\overline{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	$\sigma_{\rm rel}$
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 ($\varepsilon_{\rm tot}$)	69.9	1.6
$\overline{\nu}_e$ signal (cpd[1])		
w/o $\varepsilon_{\rm tot}$ corrected	33.5 ± 1.7	
w/ $\varepsilon_{\rm tot}$ corrected	47.9 ± 2.6	
Non-oscillated $\overline{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}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}C(α, n)^{16}O	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
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  - Proton counting in LS (geometric, chemical, etc.)
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- ❑ 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

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~ 40 per day

~ 6 per day

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- Uncertainties on predicted non-oscillated signal rate
  - Proton counting in LS (geometric, chemical, etc.)
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  - Residual reactor specific systematics
- S/B ~ 5
  - Cosmogenic ^{9}Li/^{8}He S/B ~ 8, vert good given shallow depth!
  - Geo-ν irreducible but itself interesting!

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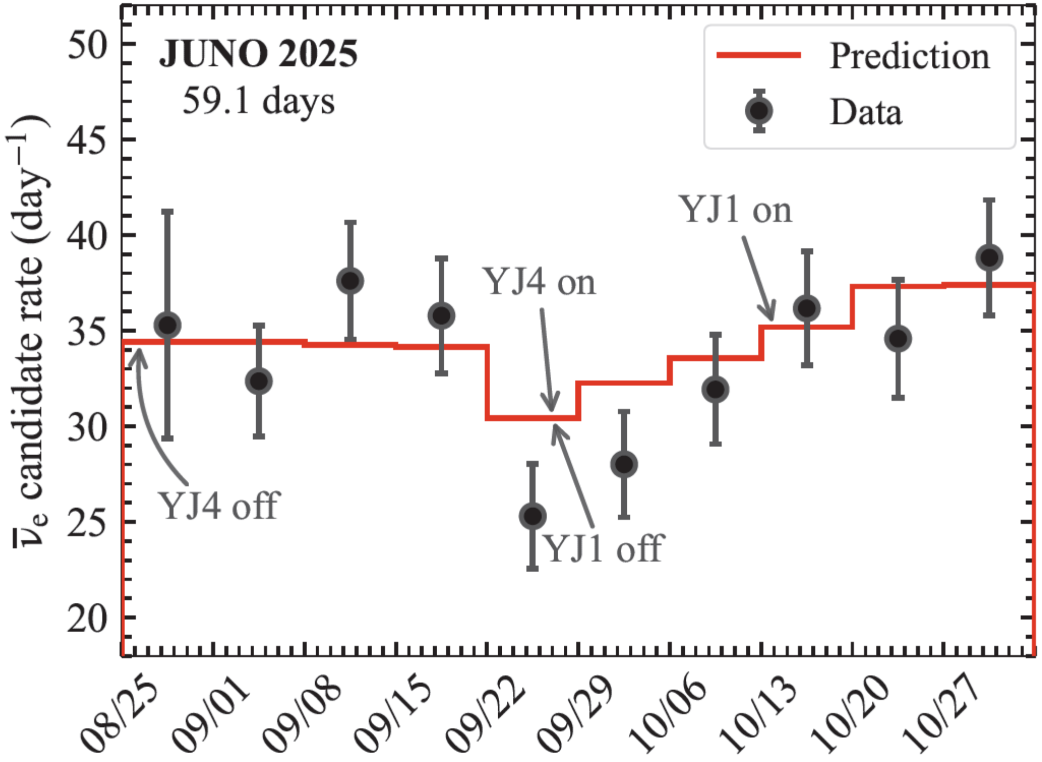
- S/B ~ 5
  - Cosmogenic ^{9}Li/^{8}He S/B ~ 8, vert good given shallow depth!
  - Geo-ν irreducible but itself interesting!
- Efficiency ~ 70%
  - Dominated by fiducial volume

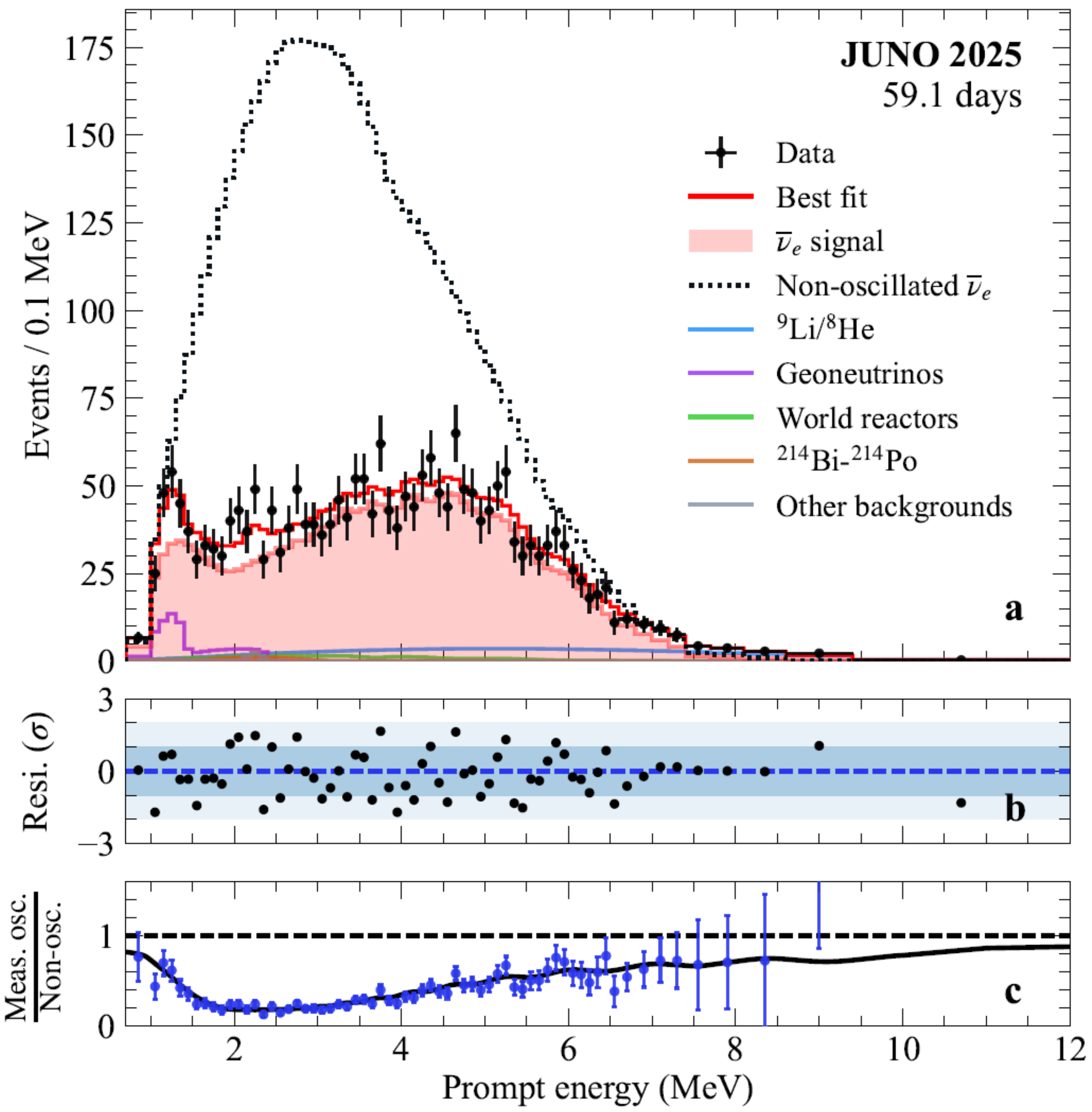
Reactor $\bar{\nu}_e$ Rate at JUNO



* Background subtracted

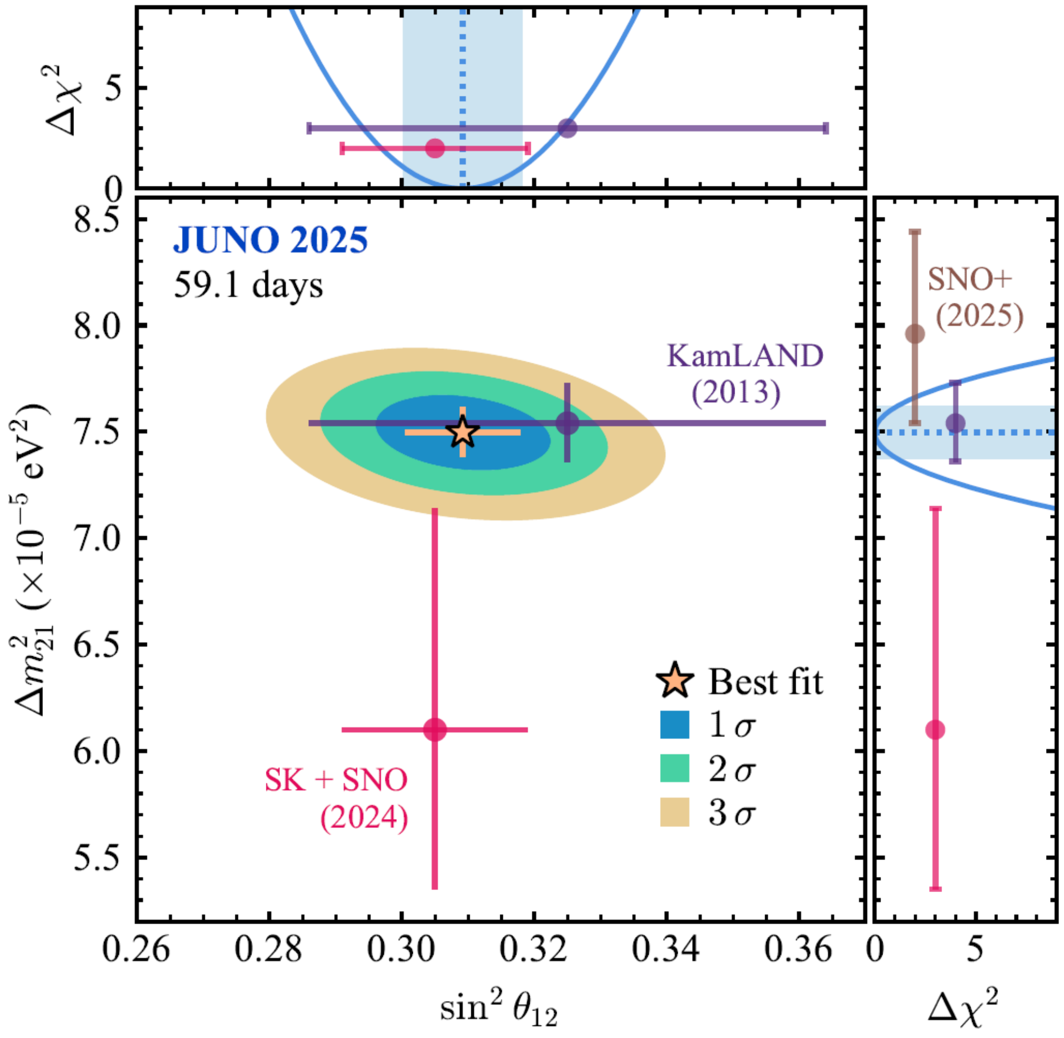
- ❑ Neutrino rate follows reactor operations in real time
  - ❖ Events are indeed from reactors
  - ❖ Backgrounds do not dominate the signal
  - ❖ Flux modelling is correct
  - ❖ Detector stability is good
- ❑ Reactor real-time monitoring
  - ❖ Sensitive to single core at 50 km (8 cores, 27 GW_{th})

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



- ❑ Dominant distortion driven by θ_{12} and Δm^2_{21}
- ❑ 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)

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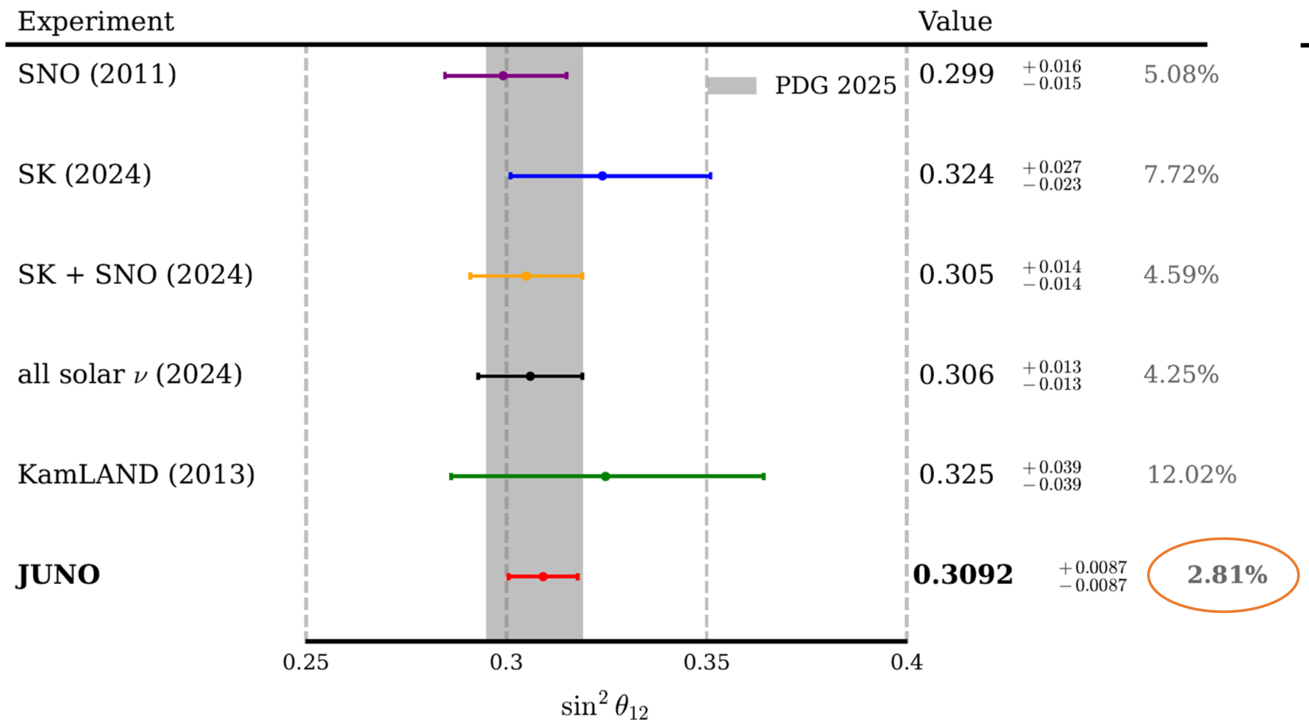
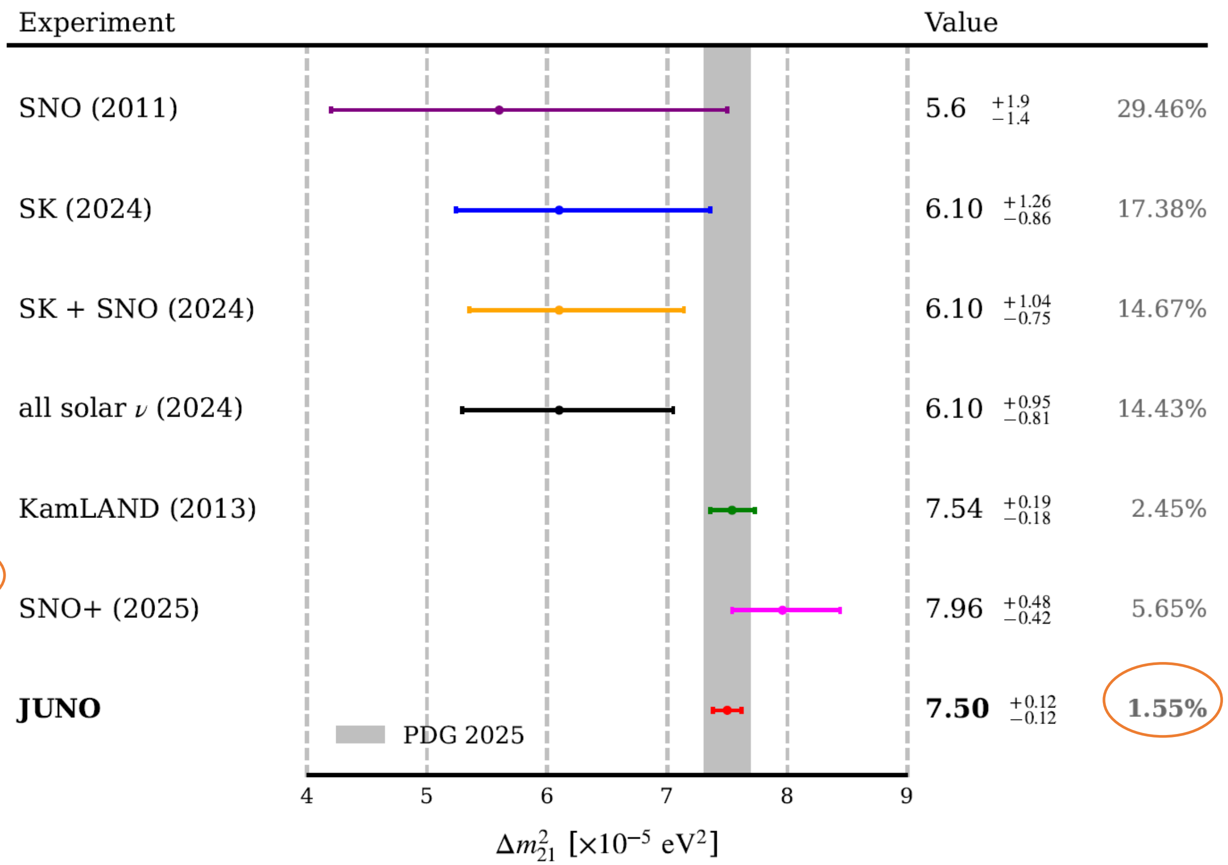


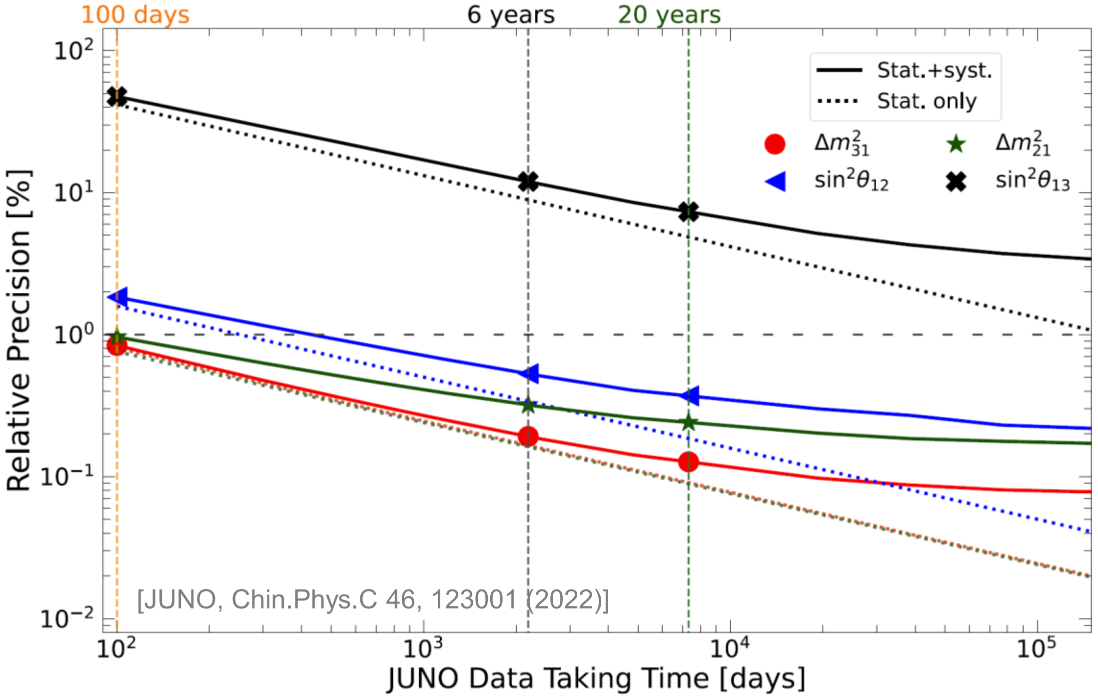


SNO (2011): SNO, Phys. Rev. C 88, 025501 (2013)
SK (2024), SK+SNO (2024), all solar ν (2024): SK, Phys. Rev. D 109, 092001 (2024)
KamLand (2013): KamLAND, Phys. Rev. D 88, 033001 (2013)
SNO+ (2025): SNO+, Phys. Rev. Lett. 135, 121801 (2025)

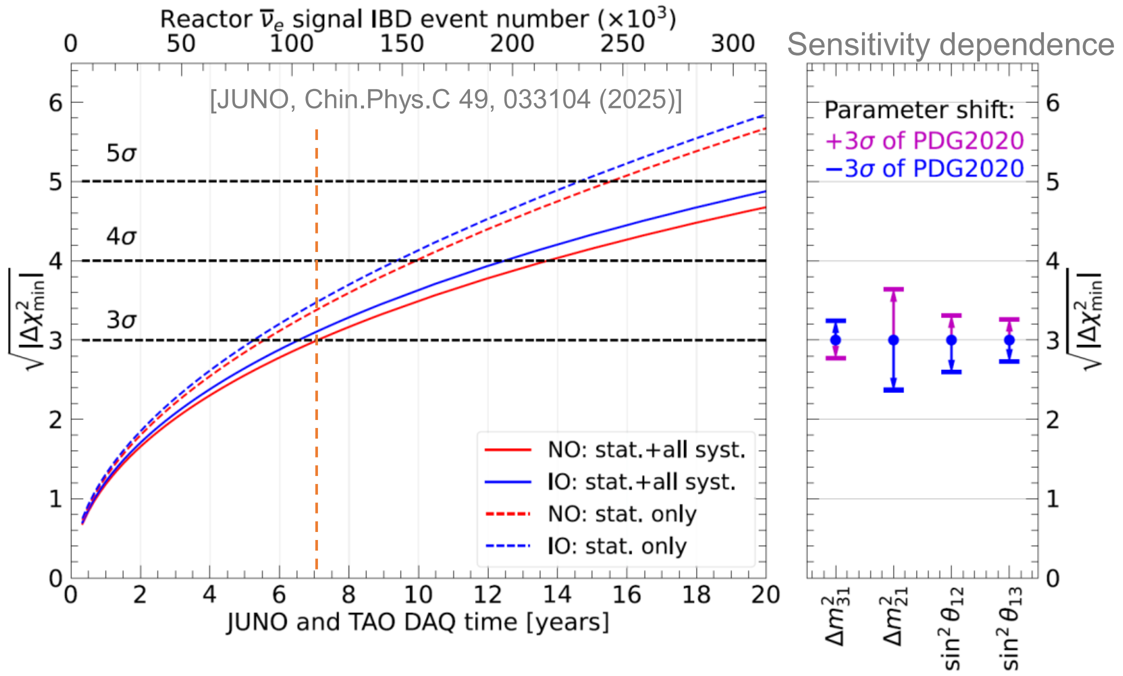
- ❖ Mild difference still between solar and reactor

- ❑ Transition to precision era of neutrino solar mixing parameter measurements
  - ❖ Reactors can be used to measure at the sub-percent level, w/
    - ➢ Much larger detector
    - ➢ Higher statistics

Beyond the First Measurement



NMO sensitivity

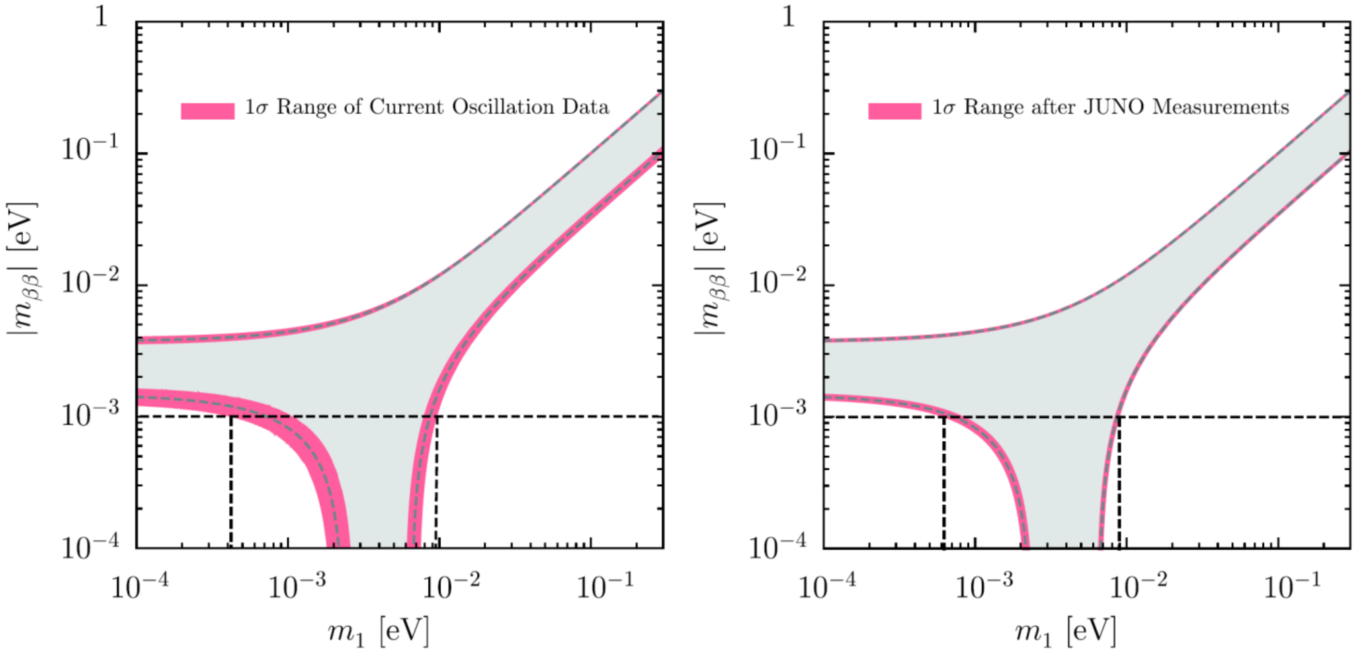


- ❑ Sub-percent measurements of Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$

7.1 years

- ❑ NO: 3σ
- ❑ IO: 3.1σ

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



[Cao *et al.*, Chin.Phys.C 44, 031001 (2020)]

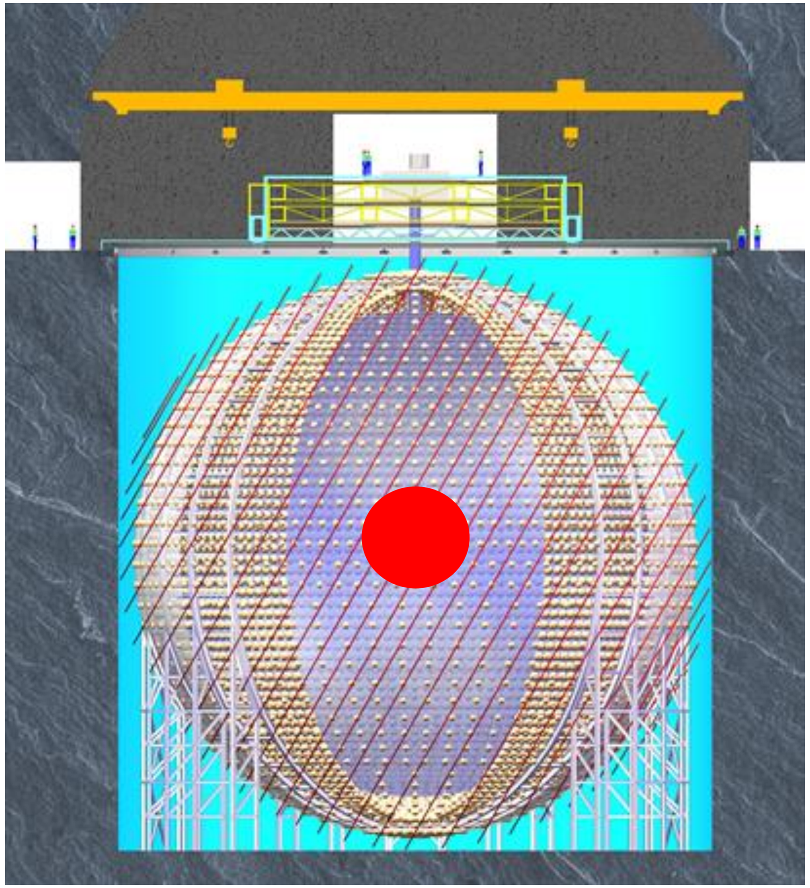


Figure from Yifang Wang, FNAL seminar, April 2025

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

An Observatory for 30 Years

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

Earth

~400/year

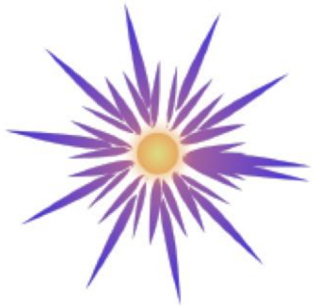
Sun

>100/day

Atmosphere

>100/year

Supernovae



~10^4/10 s @ 10kpc

Reactor

~60/day

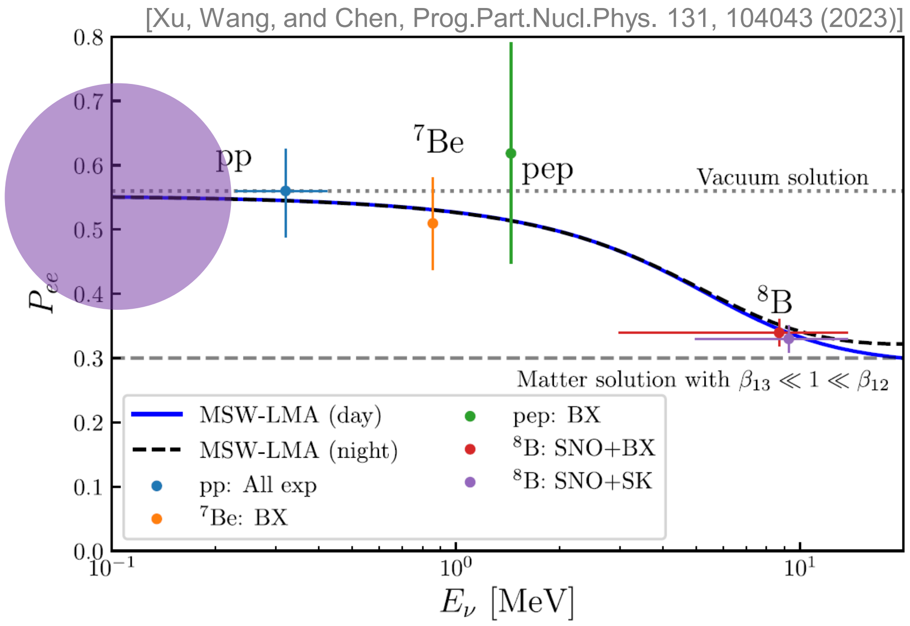
Image by CAS, published by China Daily

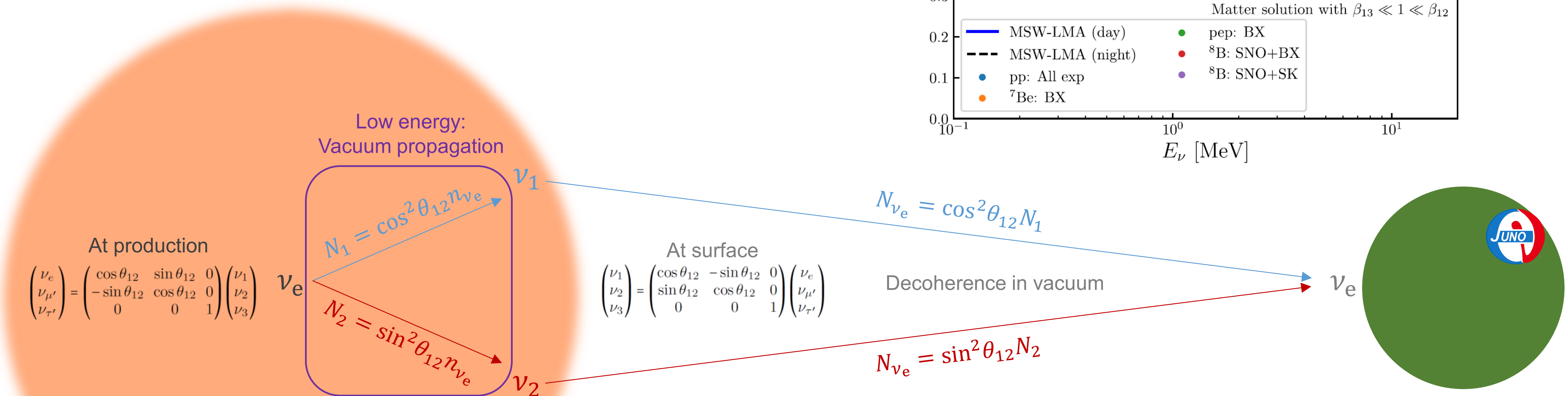
More!! (BSM)

Cartoon from Barbara Caccianiga@INFN- Milano

Mixing of Solar Neutrinos

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





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

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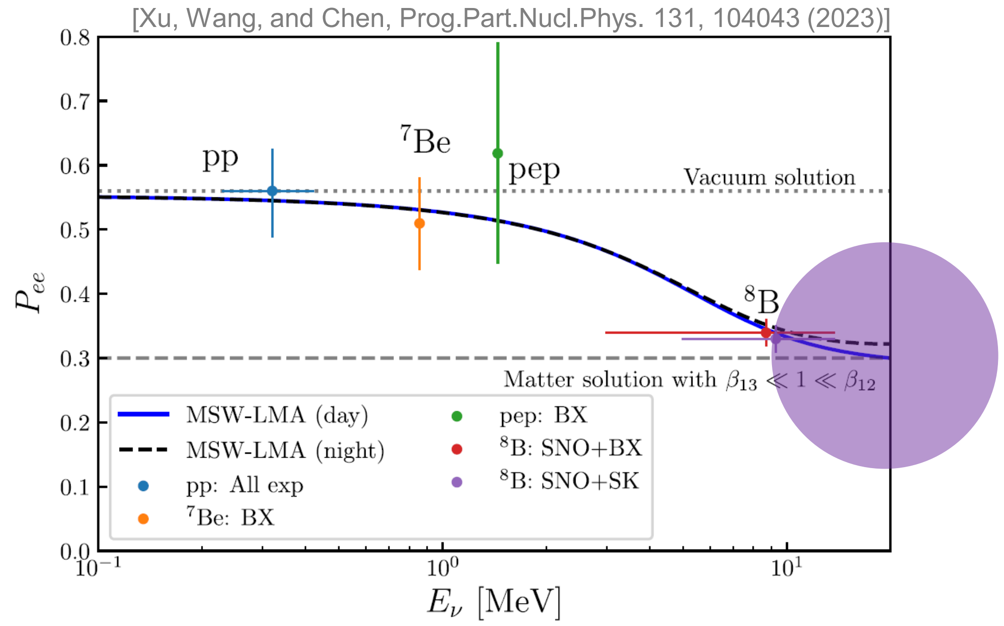
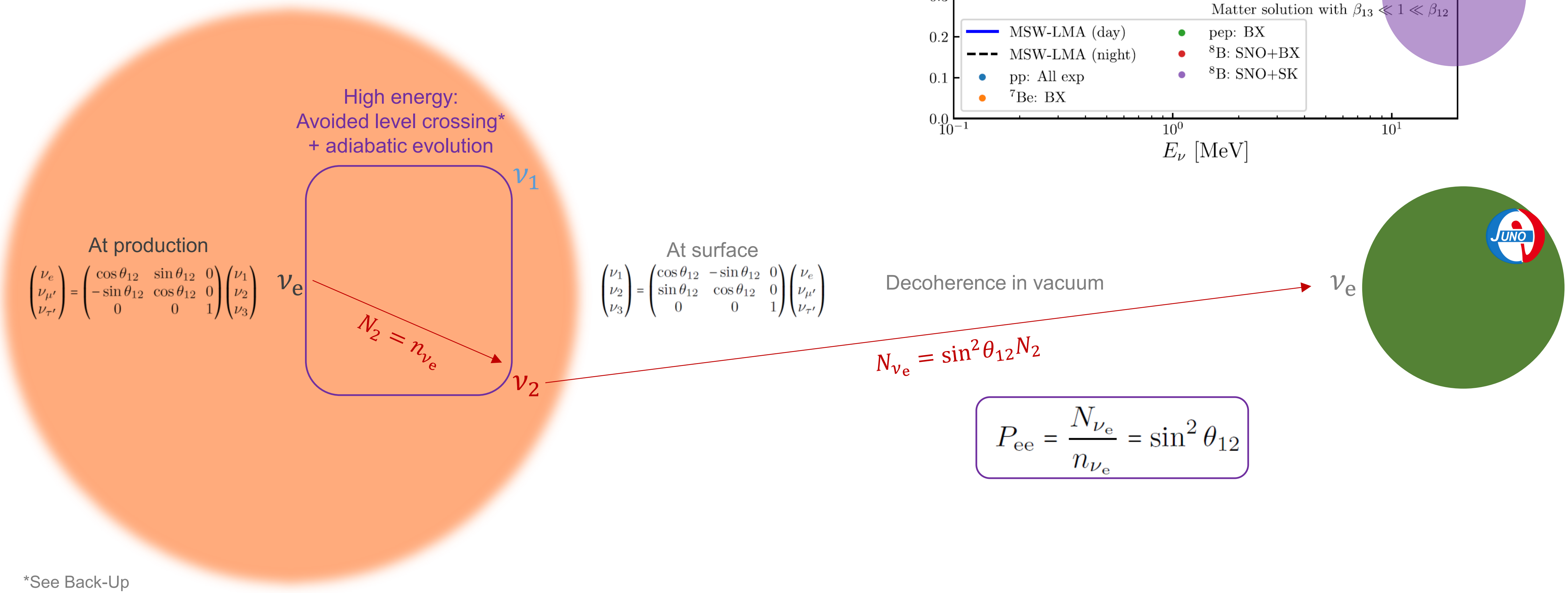


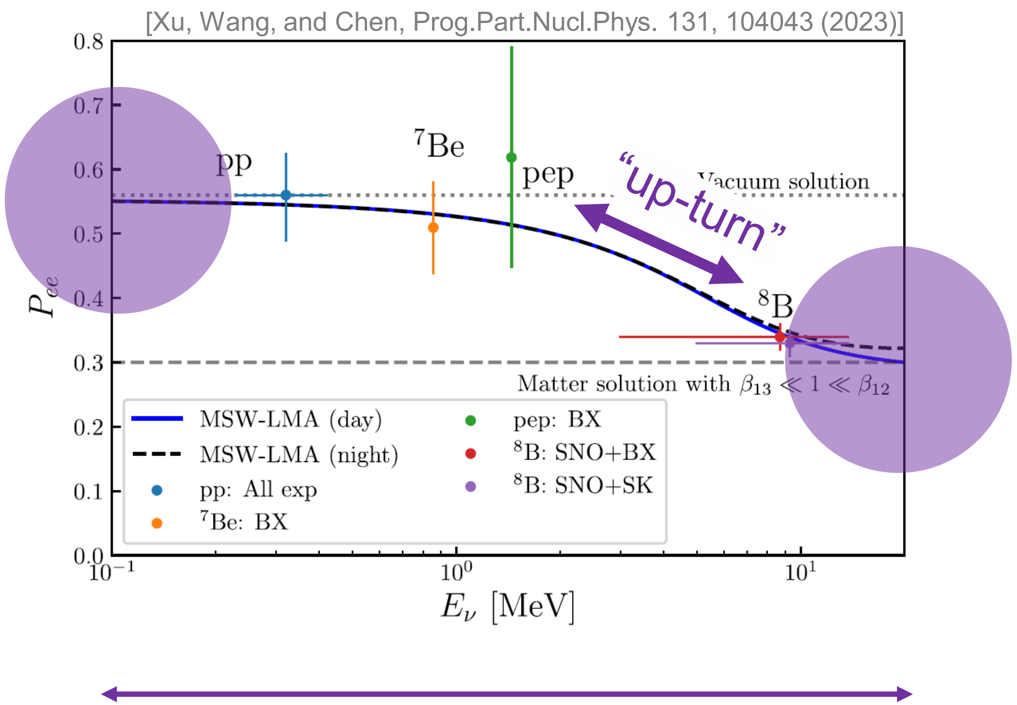


$$P_{ee} = \frac{N_{\nu_e}}{n_{\nu_e}} = \sin^2\theta_{12}$$

*See Back-Up

Mixing of Solar Neutrinos

Low energy:
Vacuum propagation



High energy:
Avoided level crossing
+ adiabatic evolution

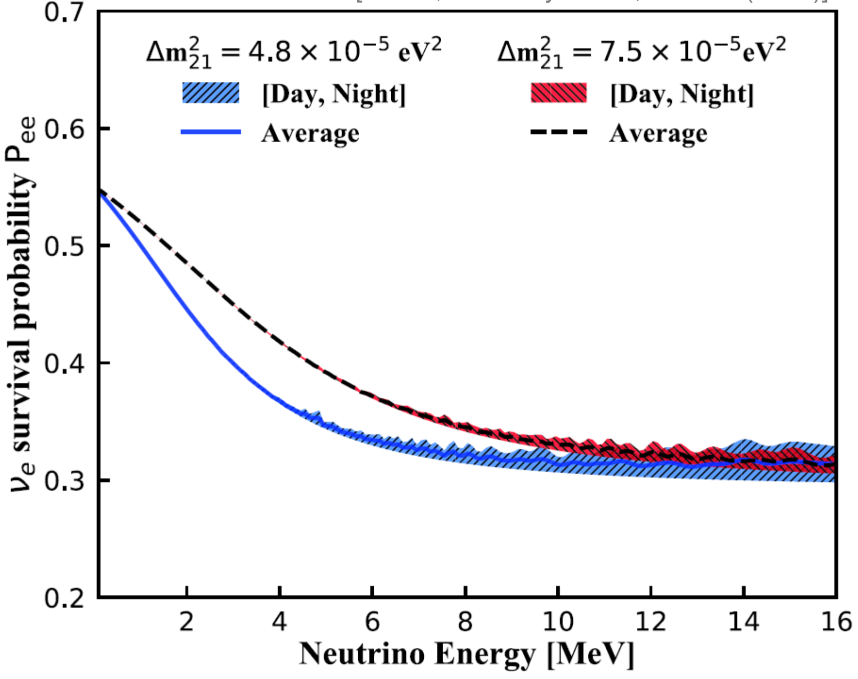
— How high is high?

— Relative to the only energy scale in this two-flavour mixing: Δm^2_{21}

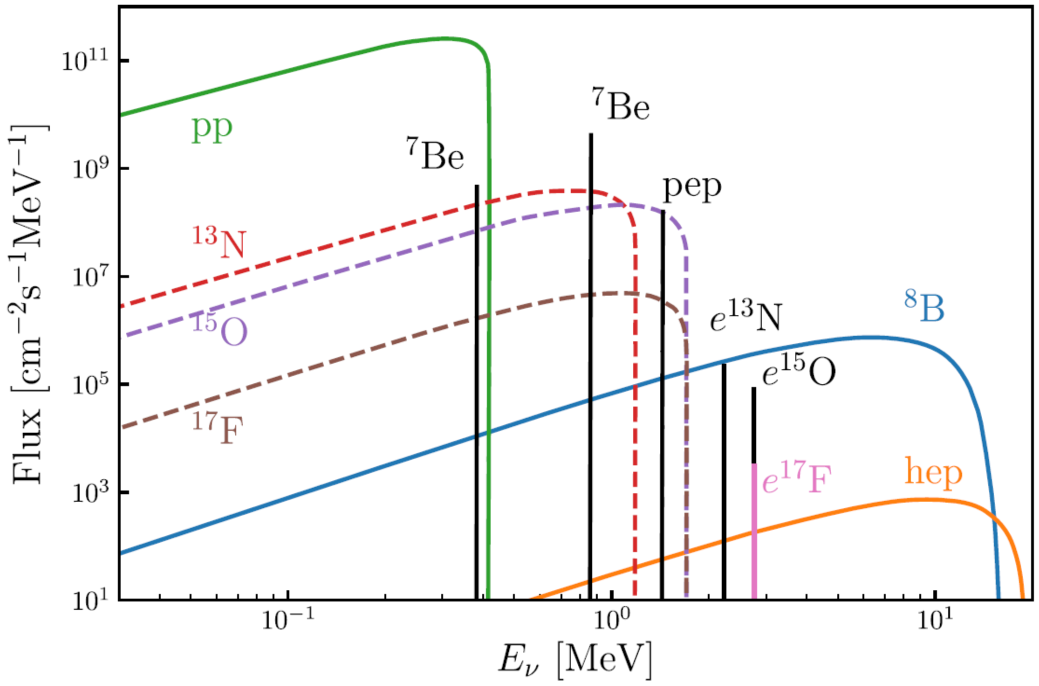
❑ Stretching between limits, aka "up-turn", gives us Δm^2_{21}

Solar Neutrinos at JUNO

[JUNO, Chin.Phys.C 45, 023004 (2021)]



[Xu, Wang, and Chen, Prog.Part.Nucl.Phys. 131, 104043 (2023)]



- Up-turn-sensitive energy with ^{8}B
  - Reactor-solar consistency test of solar mixing/oscillations (matter effects, ν vs. $\bar{\nu}$, new physics, etc.)
  - Other neutrinos to probe the Sun [JUNO, JCAP 10, 022 (2023)]

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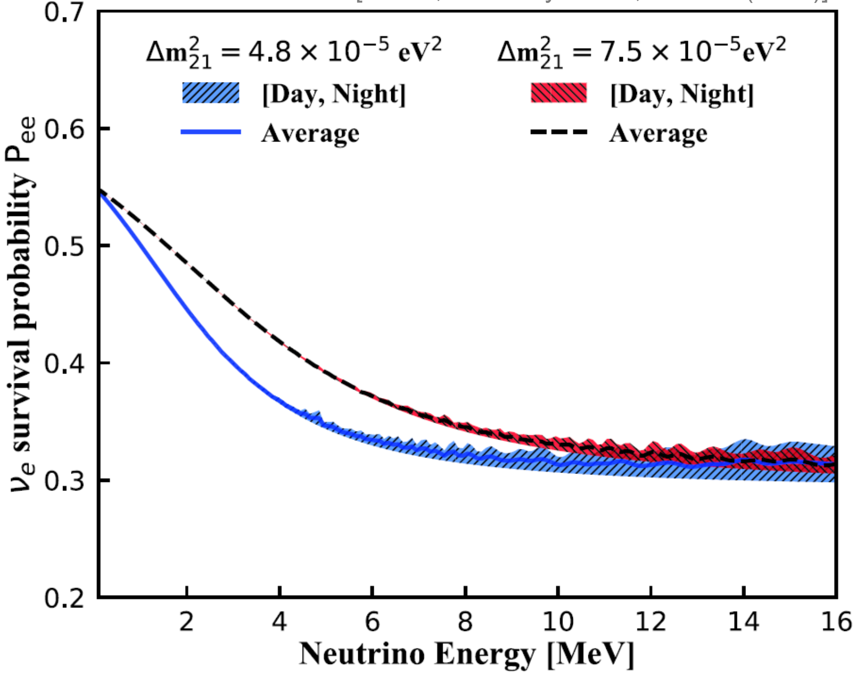

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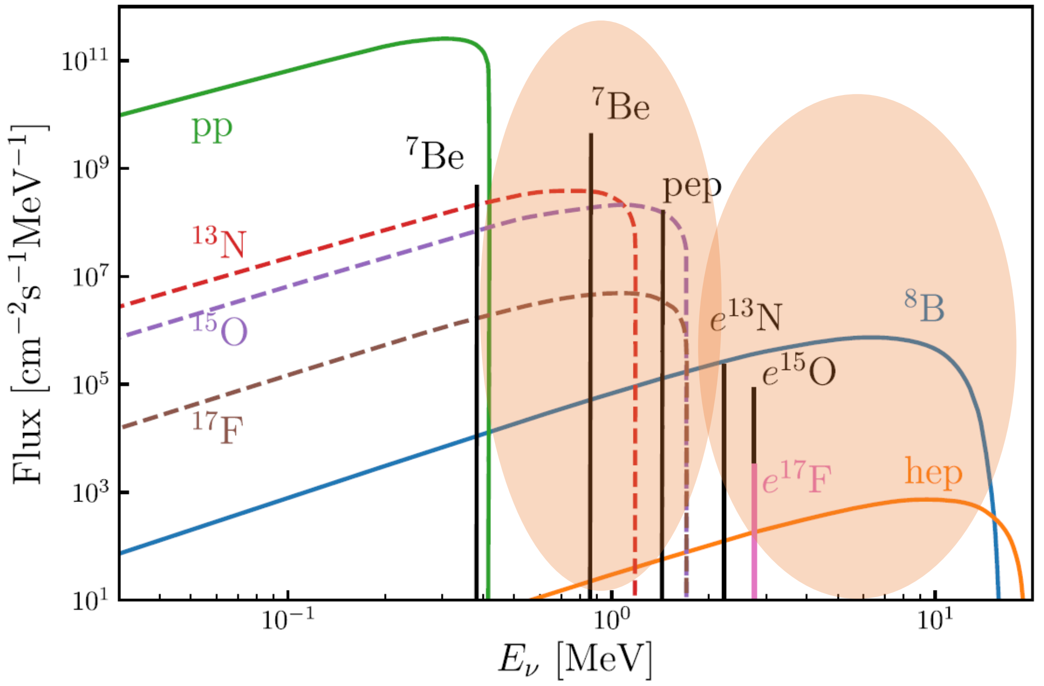

- ❑ Up-turn-sensitive energy with ^{8}B
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  - ❖ Other neutrinos to probe the Sun [JUNO, JCAP 10, 022 (2023)]
- ❑ Solar only ν, not $\overline{\nu}$
  - ❖ No reaction on hydrogen nor carbon: only ES on electron
  - ❖ No IBD coincidence: demanding on background (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^2_{21}).
- 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

Photo credit: LIU Yuexiang@IHEP

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 $\bar{\nu}_e$ (“−”)

$$V_{\rm CC} = \pm\sqrt{2}G_{\rm F}n_{\rm e}$$

Electron density $n_{\rm e}$
Fermi constant $\sqrt{2}G_{\rm F} \simeq 7.63\times 10^{-14}\,\frac{\rm eV\ cm^3}{N_{\rm A}}$
$A_{\rm CC} \equiv 2EV_{\rm CC}$

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

Extremely relativistic kinematics

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

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

1. No mixing: $\nu_1 = \nu_{\rm e}$, $\nu_2 = \nu_\mu$
   ν_e Hamiltonian in matter

$$H = E + V_{\rm CC} \equiv E + \frac{m_{\rm M}^2}{2E}$$

Effective mass $m_{\rm M}^2 = m^2 + A_{\rm CC}$
(NC induces the same $A_{\rm NC}$ for all neutrino flavours)
Effective mass gap $\Delta m_{\rm M}^2 = \Delta m^2 - A_{\rm CC}$

- When the matter potential fills up the mass gap

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

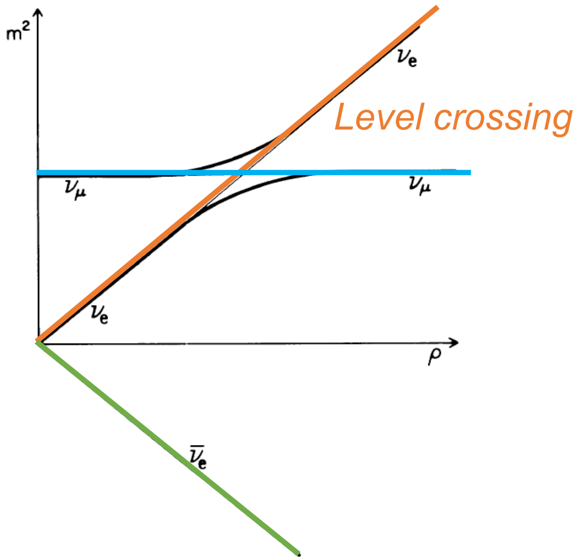
$$E\,[\rm GeV]\,n_{\rm e}\left[\frac{N_{\rm A}}{\rm cm^3}\right] = \frac{\Delta m^2\left[10^{-5}{\rm eV}^2\right]}{2\times 7.63\times 10^{-14}\left[\frac{\rm eV\ cm^3}{N_{\rm A}}\right]}$$

$$En_{\rm e} \simeq \frac{\Delta m^2}{15},\ E \text{ in GeV}, n_{\rm e} \text{ in } \frac{N_{\rm A}}{\rm cm^3}, \Delta m^2 \text{ in } 10^{-5}{\rm eV}^2$$

Water $n_{\rm e} = \frac{5}{9}\frac{N_{\rm A}}{\rm cm^3}$
For $\Delta m^2 = 10^{-5}{\rm eV}^2$, $E = 0.12$ GeV

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

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



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   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

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

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

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

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

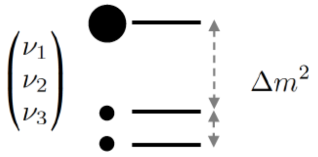
     For $\Delta m^2 = 10^{-5}\mathrm{eV}^2$, $E = 0.12$ GeV

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

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

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

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

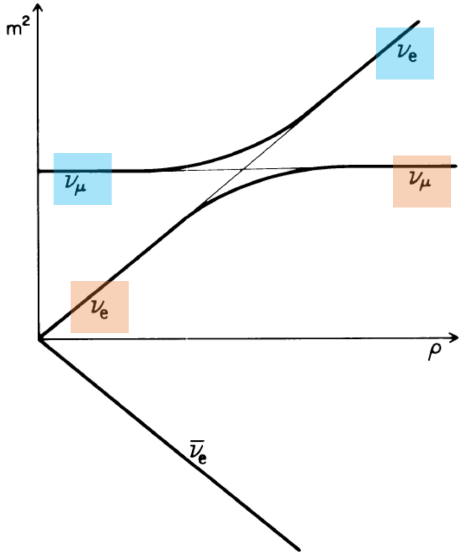
- When $A_{CC} \gg \Delta m^2$, U becomes irrelevant,

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

  (a) $\Delta m_M^2 = -A_{CC}$, $\theta_M = 0$, falling back to the previous no mixing case, or

  (b) $\Delta m_M^2 = A_{CC}$, $\theta_M = \pm\frac{\pi}{2}$, naming $\nu_1 = \nu_\mu$, $\nu_2 = \nu_e$.

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



Quiz: Is there oscillation when the mixing angle is π/2?

More on Neutrino Mass: MSW Matter Effect

Extremely relativistic kinematics

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

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

$$H = E + V_{\rm CC} \equiv E + \frac{m_{\rm M}^2}{2E}$$

   Effective mass $m_{\rm M}^2 = m^2 + A_{\rm CC}$

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

   Effective mass gap $\Delta m_{\rm M}^2 = \Delta m^2 - A_{\rm CC}$

   - When the matter potential fills up the mass gap

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

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

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

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

     For $\Delta m^2 = 10^{-5}\text{eV}^2$, $E = 0.12$ GeV
   - For $A_{\rm CC} > \Delta m^2$, $\Delta m_{\rm M}^2 < 0$
   - For $A_{\rm CC} \gg \Delta m^2$, $\Delta m_{\rm M}^2 \simeq -A_{\rm CC}$

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

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

   with effective mass gap $\Delta m_{\rm M}^2$ and mixing

$$U_{\rm M} \equiv \begin{pmatrix}\cos\theta_{\rm M} & \sin\theta_{\rm M}\\ -\sin\theta_{\rm M} & \cos\theta_{\rm M}\end{pmatrix}$$

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

$$\frac{A_{\rm CC}}{4E}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix} = \frac{\Delta m_{\rm M}^2}{4E} U_{\rm M}\begin{pmatrix}-1 & 0\\ 0 & 1\end{pmatrix} U_{\rm M}^\dagger$$

     (a) $\Delta m_{\rm M}^2 = -A_{\rm CC}$, $\theta_{\rm M} = 0$, falling back to the previous no mixing case, or

     (b) $\Delta m_{\rm M}^2 = A_{\rm CC}$, $\theta_{\rm M} = \pm\frac{\pi}{2}$, 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

$$\Delta m_{\rm M}^2 = \sqrt{\left(\Delta m^2\cos 2\theta - A_{\rm CC}\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\tan 2\theta_{\rm M} = \frac{\tan 2\theta}{1 - \dfrac{A_{\rm CC}}{\Delta m^2 \cos 2\theta}}$$

e.g. Giunti & Kim (2007)

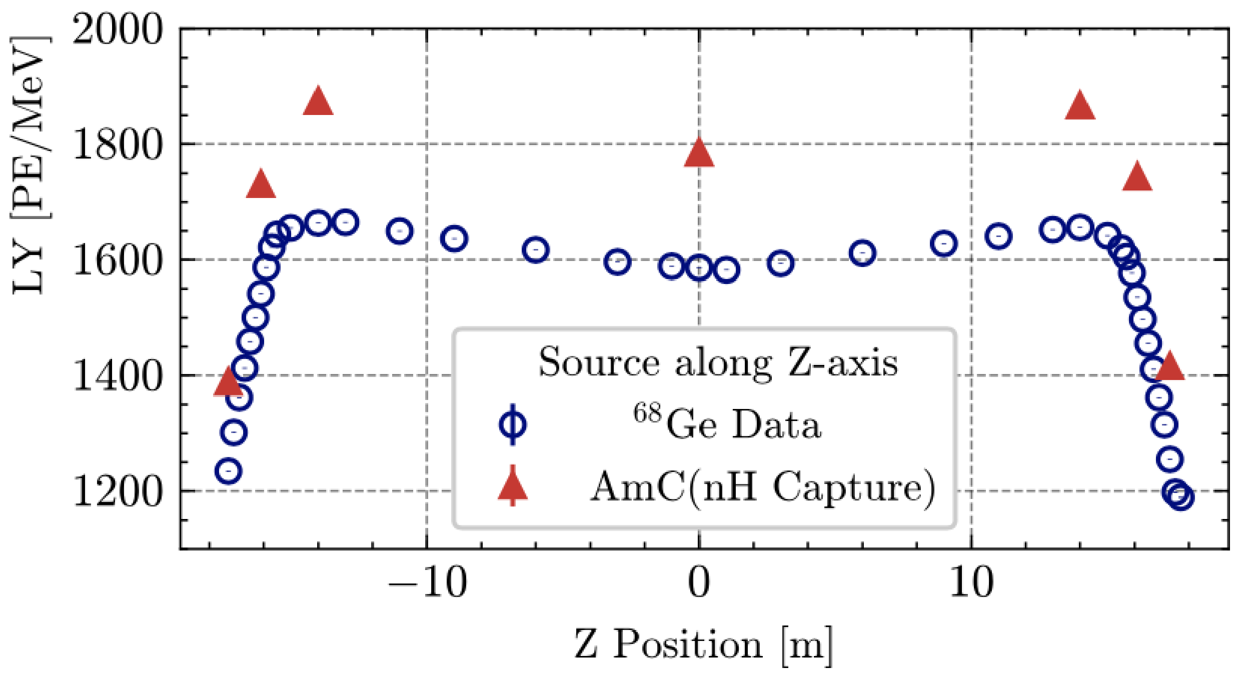
Mikheyev-Smirnov-Wolfenstein effect

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

$\theta_{\rm M}^{\rm R} = \frac{\pi}{4}$, regardless of θ

… 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	$(1.6 \pm 0.1) \times 10^{-17}$ g/g
^{232}Th	$(6.8 \pm 1.5) \times 10^{-18}$ g/g
^{210}Po	8×10^{4} 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)

Table 1
Typical CC, NC, and ES Detection Channels of the ^{8}B 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		$\nu_e + ^{12}C \rightarrow e^- + ^{12}N(1^+; gnd)$ (Fukugita et al. 1988)	16.827	$e^- + ^{12}N$ decay (β^+, $Q = 17.338$ MeV)	0.43
1	CC	$\nu_e + ^{13}C \rightarrow e^- + ^{13}N(\frac{1}{2}^-; gnd)$ (Suzuki et al. 2012)	2.2	$e^- + ^{13}N$ decay (β^+, $Q = 2.22$ MeV)	3929
2		$\nu_e + ^{13}C \rightarrow e^- + ^{13}N(\frac{3}{2}^-; 3.5\ MeV)$ (Suzuki et al. 2012)	5.7	$e^- + p$	2464
4		$\nu_x + ^{12}C \rightarrow \nu_x + ^{12}C(1^+; 15.11\ MeV)$ (Fukugita et al. 1988)	15.1	γ	4.8
3	NC	$\nu_x + ^{13}C \rightarrow \nu_x + n + ^{12}C(2^+; 4.44\ MeV)$ (Suzuki et al. 2019)	6.864	$\gamma + n$ capture	65
4		$\nu_x + ^{13}C \rightarrow \nu_x + ^{13}C(\frac{1}{2}^+; 3.089\ MeV)$ (Suzuki et al. 2012)	3.089	γ	14
5		$\nu_x + ^{13}C \rightarrow \nu_x + ^{13}C(\frac{3}{2}^-; 3.685\ MeV)$ (Suzuki et al. 2012)	3.685	γ	3032
6		$\nu_x + ^{13}C \rightarrow \nu_x + ^{13}C(\frac{5}{2}^+; 3.854\ MeV)$ (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.