Physics of Jiangmen Underground Neutrino Observatory

Runze Zhao
On behalf of JUNO collaboration
2025.08.18

Summer Institute 2025
August 17-22 Yeosu, Korea

Outline

- ◆ Neutrino Oscillation Physics at JUNO
  - 3-flavor oscillation paradigm
  - What does JUNO aim for?
  - Key features to achieve the goal

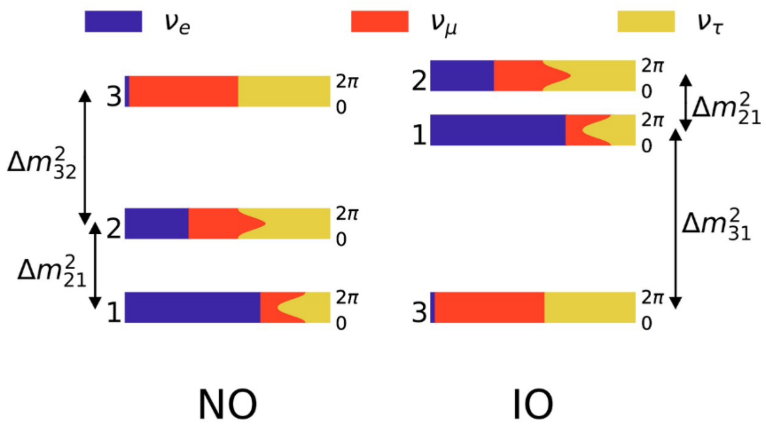
- ◆ Other physics at JUNO
  - More sources: Solar neutrino, Geo-neutrino, supernova neutrino
  - More physics (BSM): sterile neutrino, nucleon decay, dark matter, etc.

- ◆ Status of JUNO (if time allows…)

3-Flavor Neutrino Oscillation

- Neutrinos are mixed:

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



Probability of finding the α neutrino flavor in the i-th neutrino mass eigenstate. The CP-violating phase is varied (0→2π).

[P.F. de Salas et al, *arXiv: 1806.11051*]

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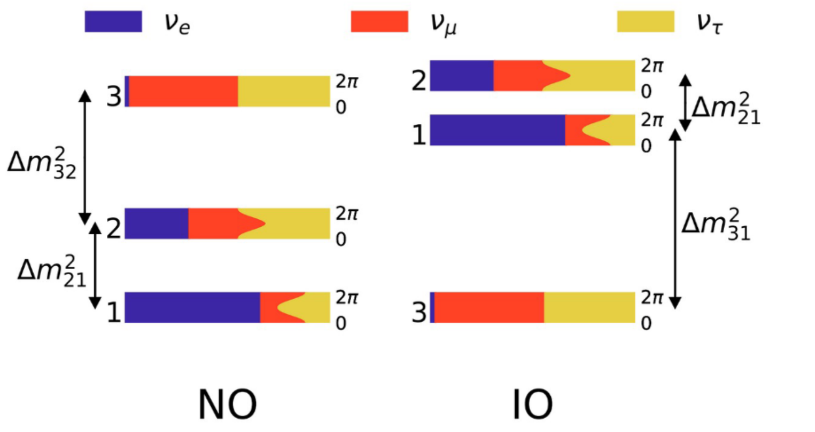

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Atmospheric **Reactor & CP phase** **Solar** **Majorana phase**

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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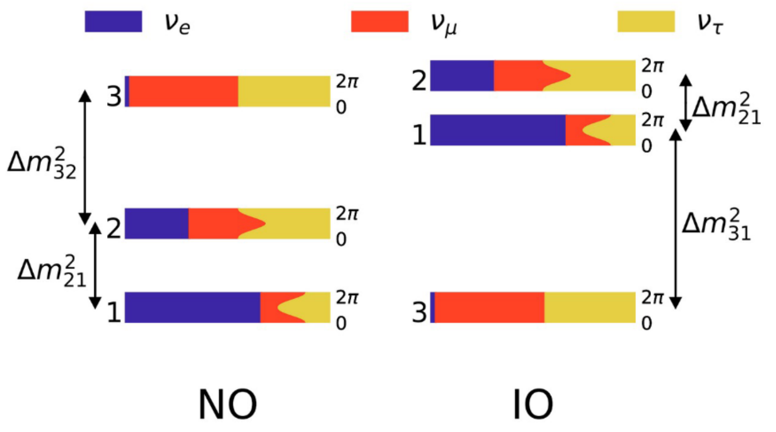

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✓ **Known**: θ_{23}, θ_{12}, θ_{13}, $|\Delta m^2_{32}|$, Δm^2_{21}

1998 Atm. ν osc. θ_{23}, $|\Delta m^2_{32}|$
2002 Solar ν osc. θ_{12}, Δm^2_{21}
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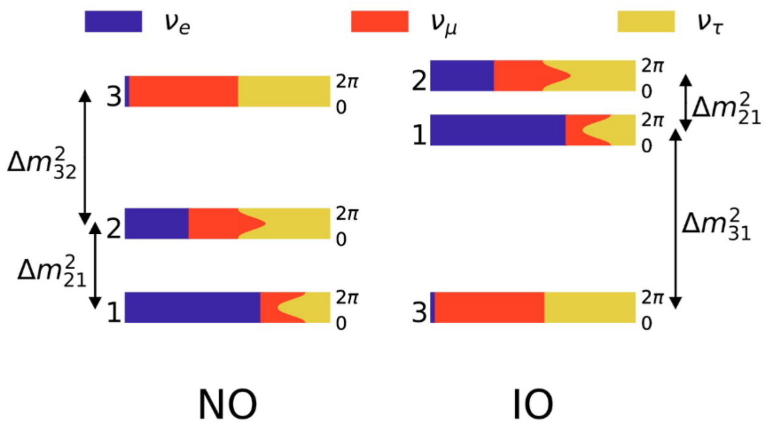

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Open Questions in Neutrino Oscillation Physics

- **Neutrino mass ordering**: Normal ordering (NO) or inverted ordering (IO)?
- **CP violation**?
- **Precision measurements** of mixing angles and mass splittings
- 3 flavors only or any **sterile** states?

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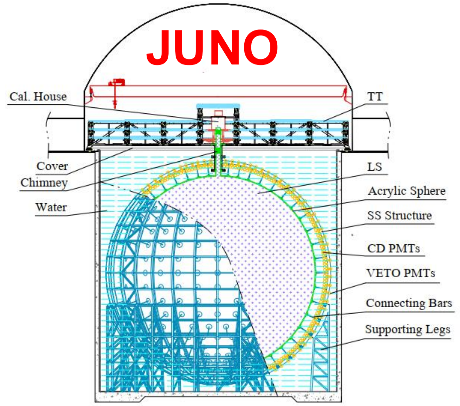

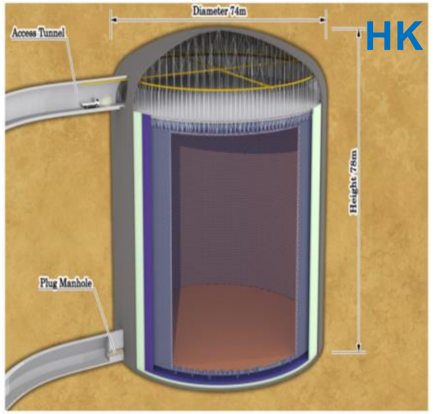

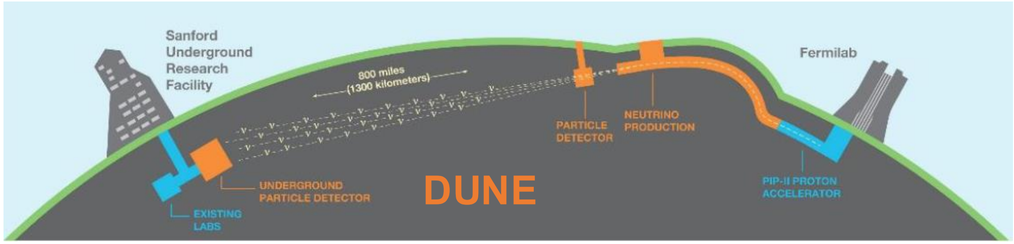

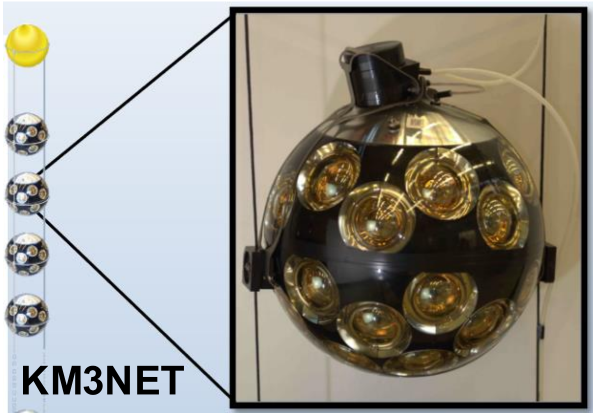

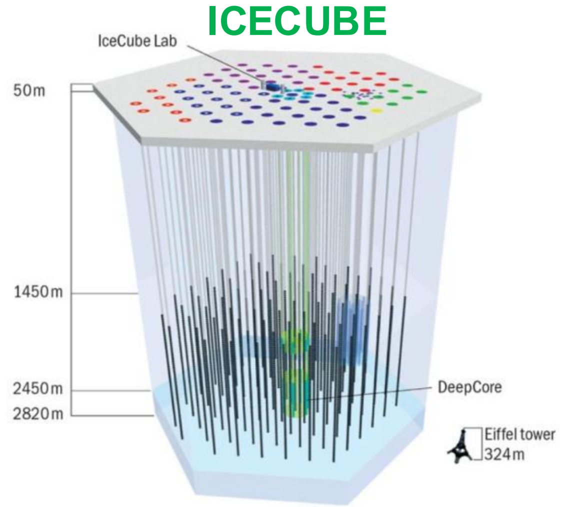

Jiangmen Underground Neutrino Observatory

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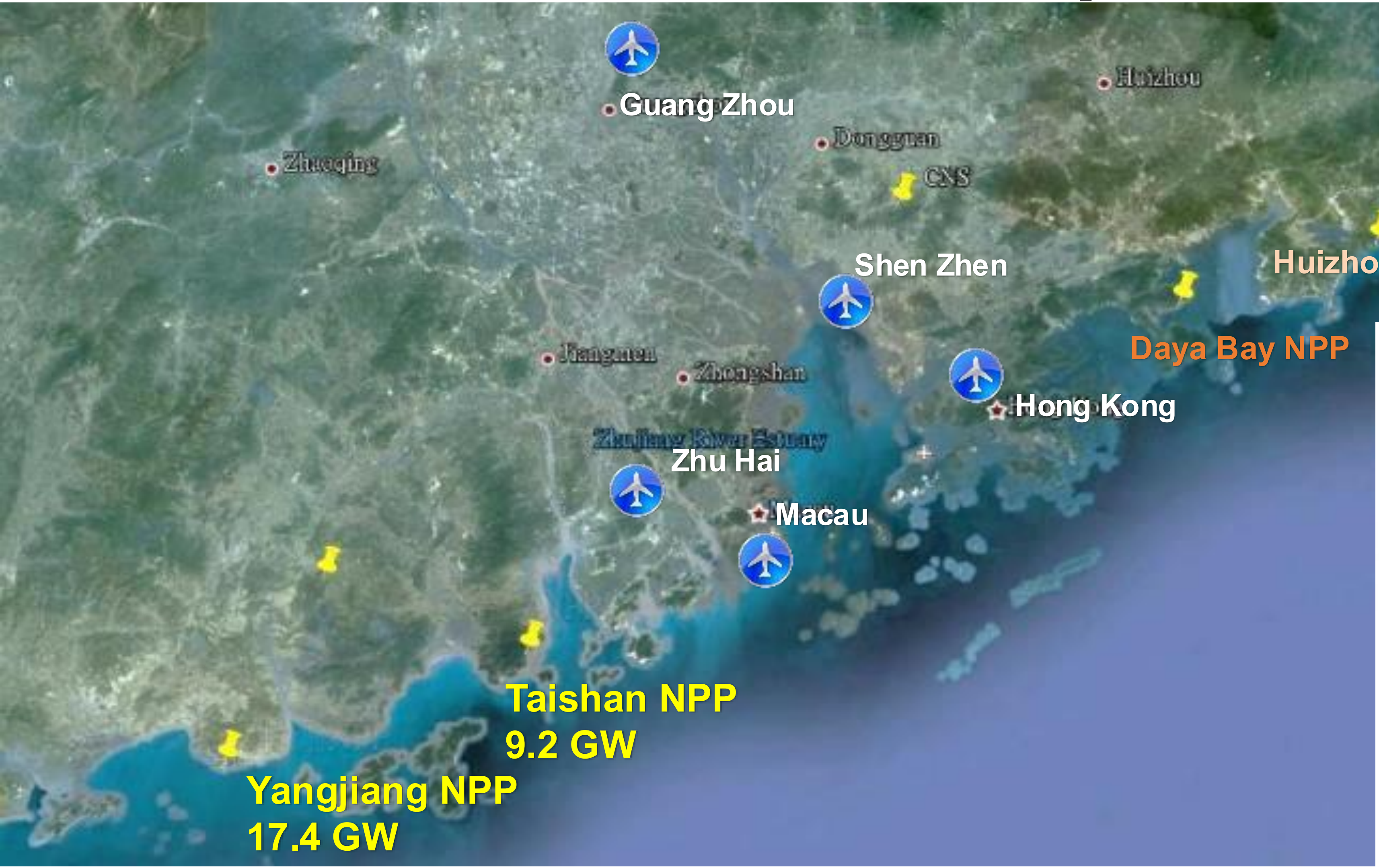
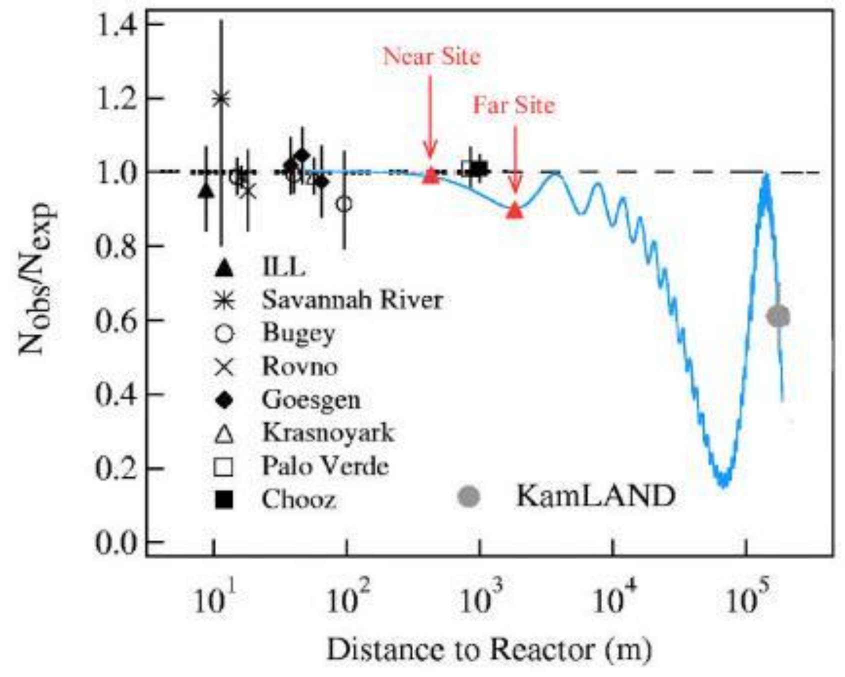
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 \frac{\overset{\text{Slow component}}{\boxed{\Delta m^2_{21}}}L}{4E} - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\frac{\boxed{\Delta m^2_{31}}L}{4E} + \overset{\text{Fast component}}{\sin^2\theta_{12}\sin^2\frac{\boxed{\Delta m^2_{32}}L}{4E}}\right]$$





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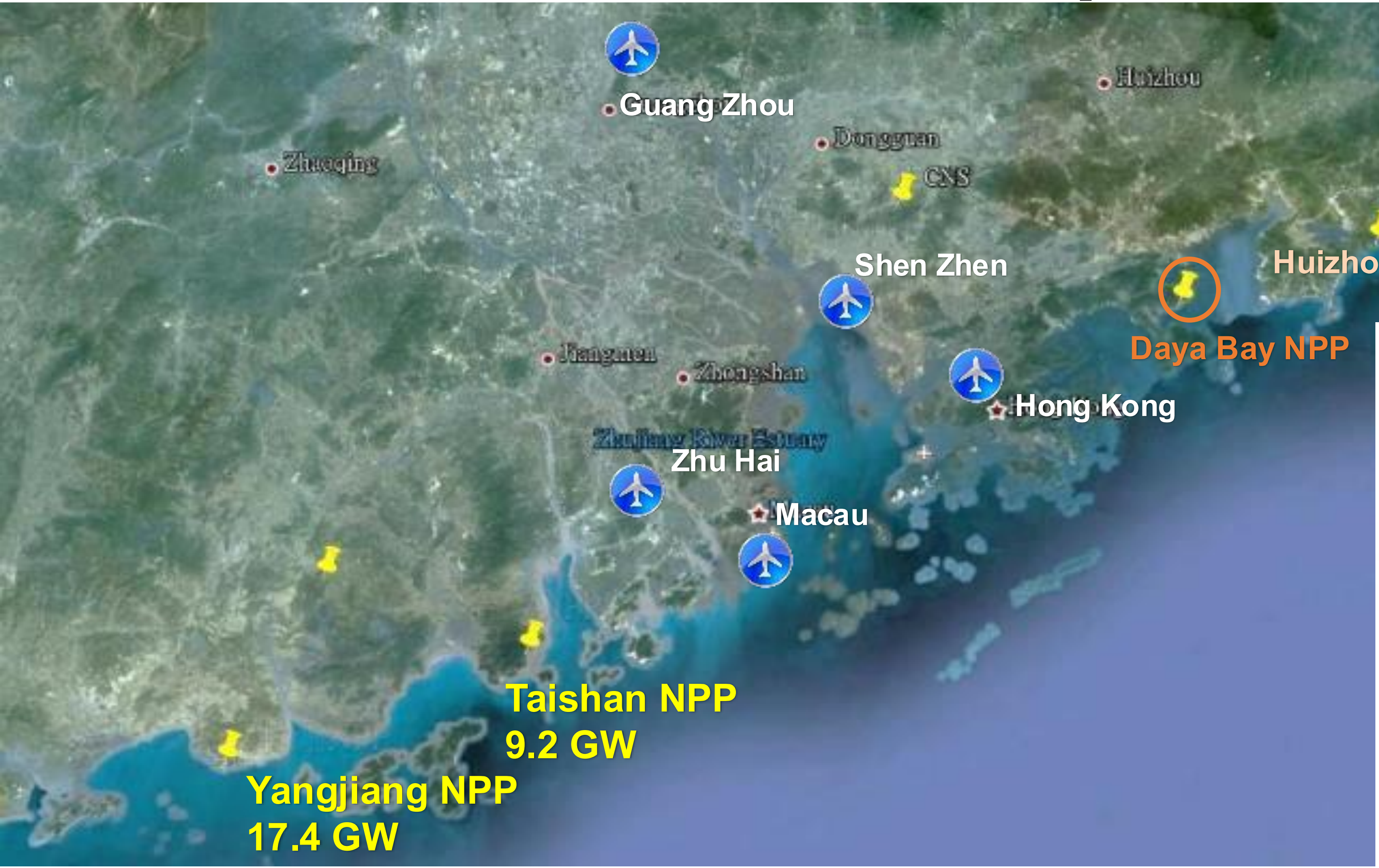

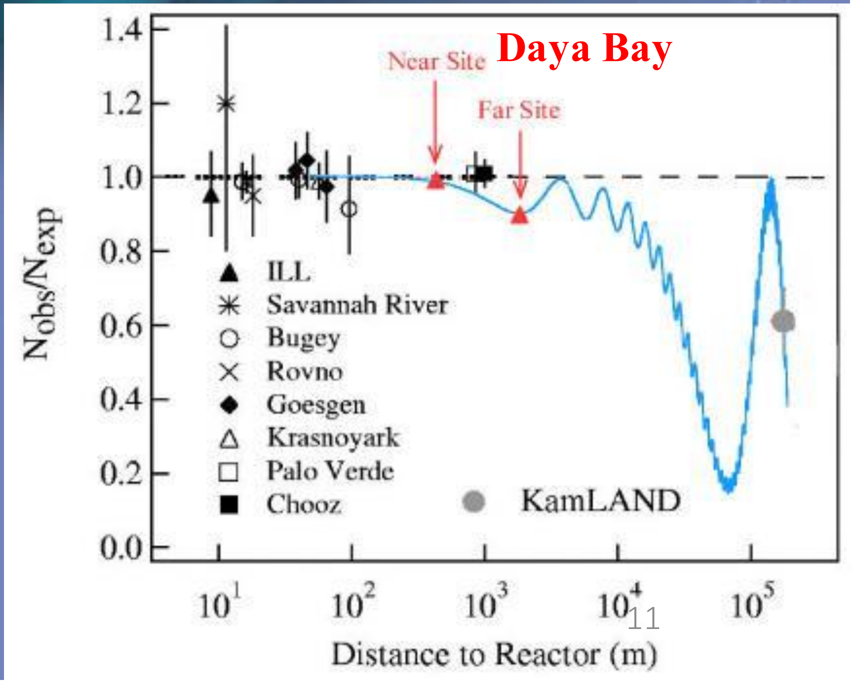

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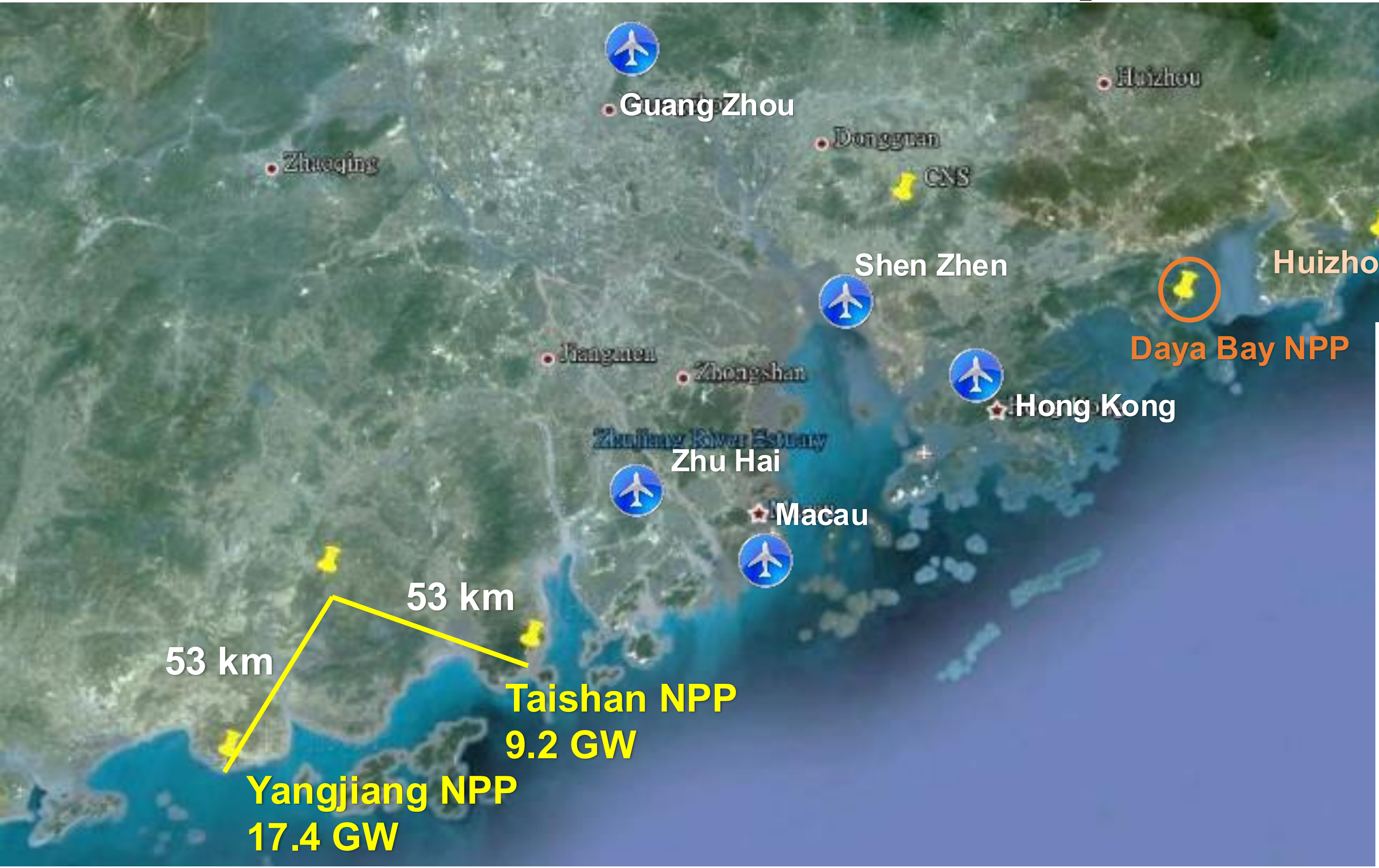

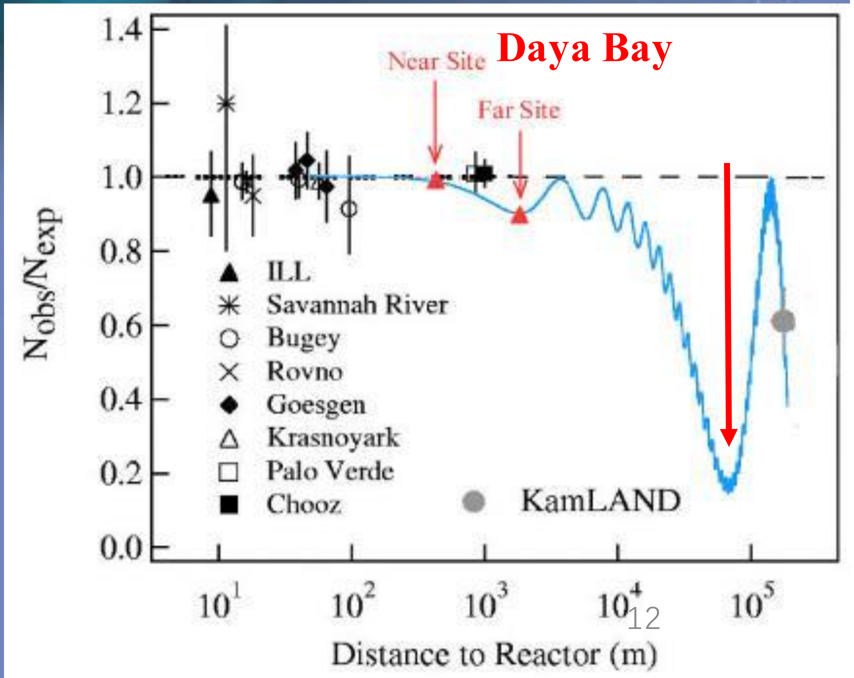

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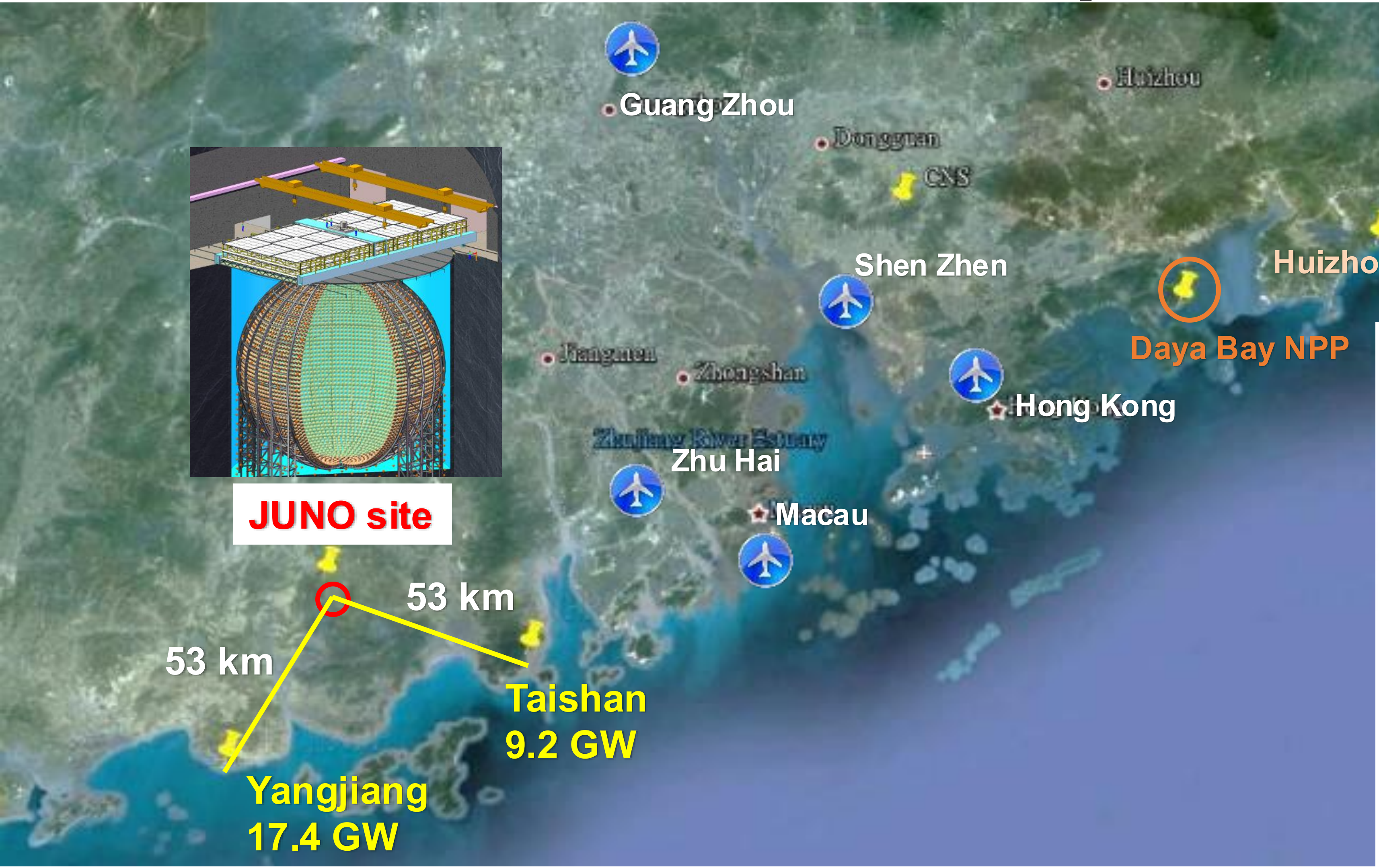

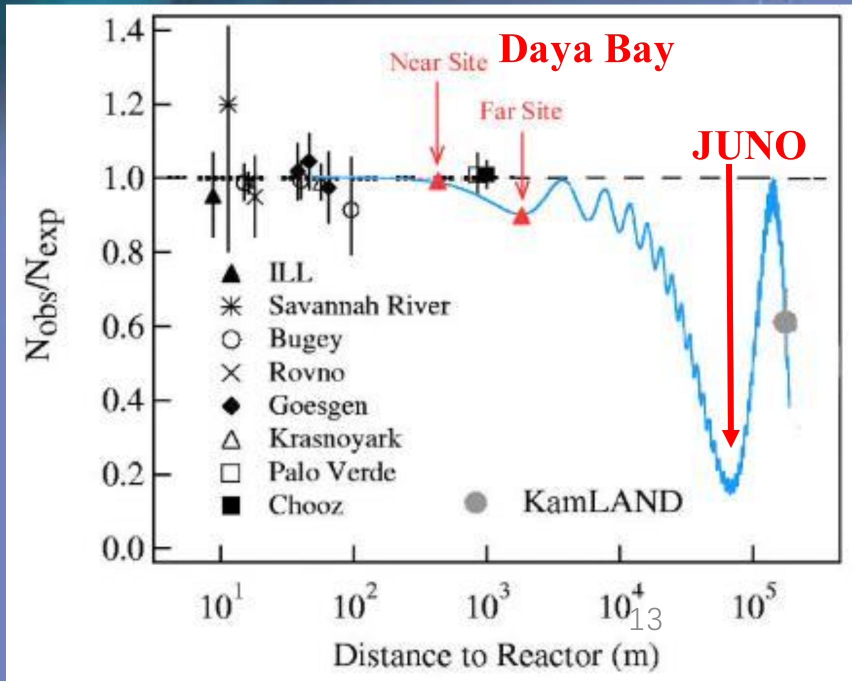

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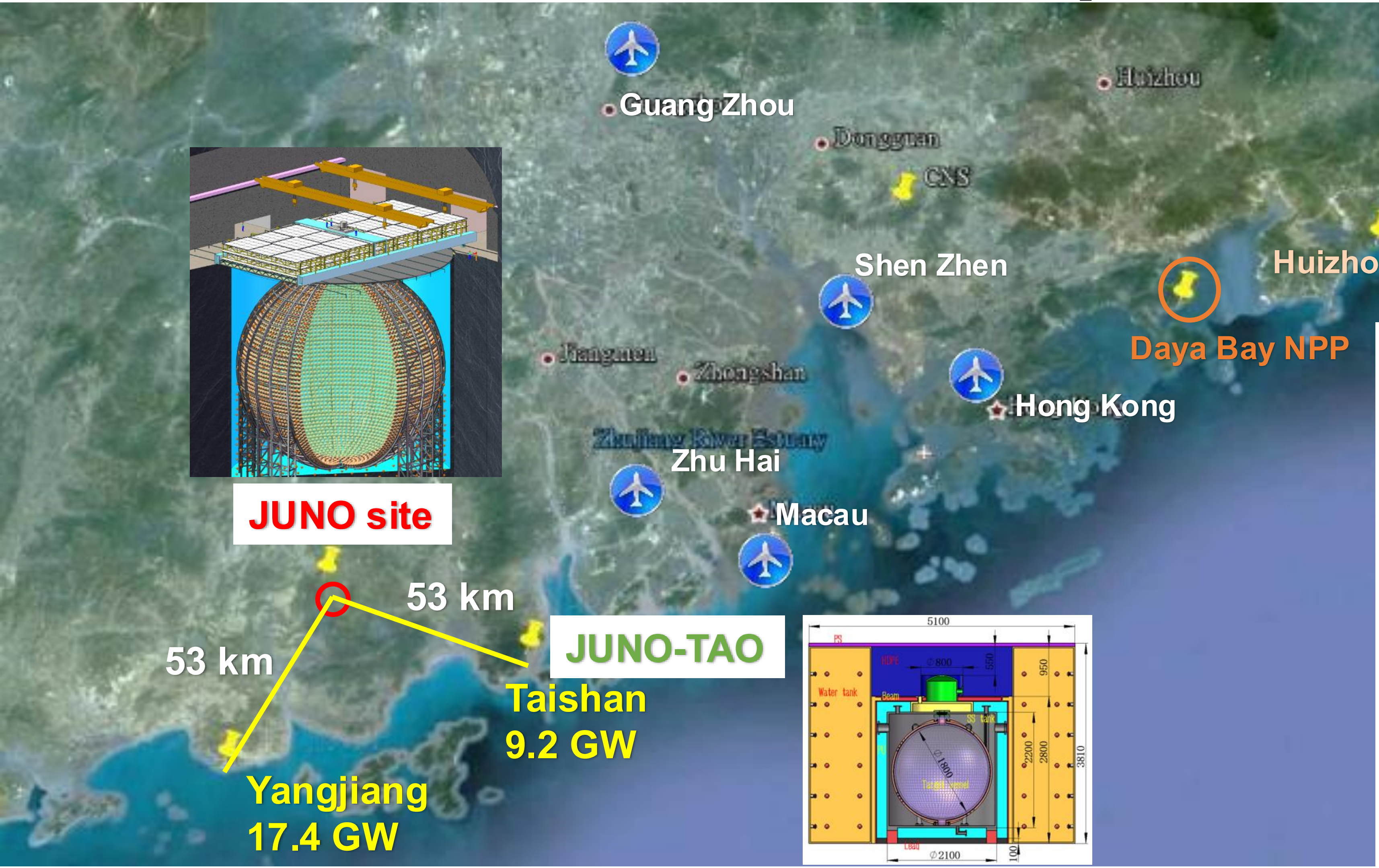

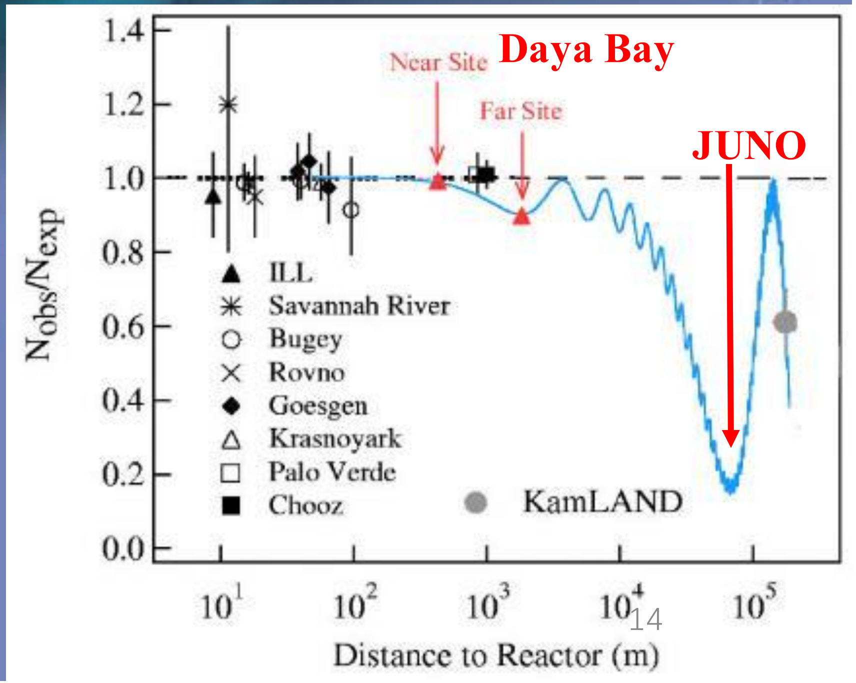

Neutrino Oscillation Physics in JUNO

Slow component

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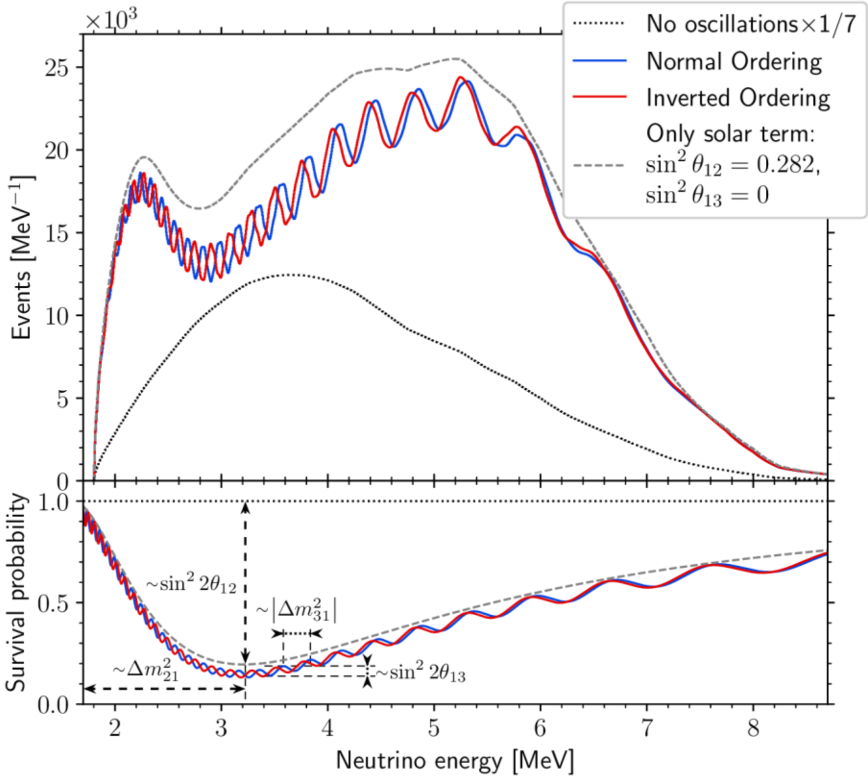
NMO sensitive



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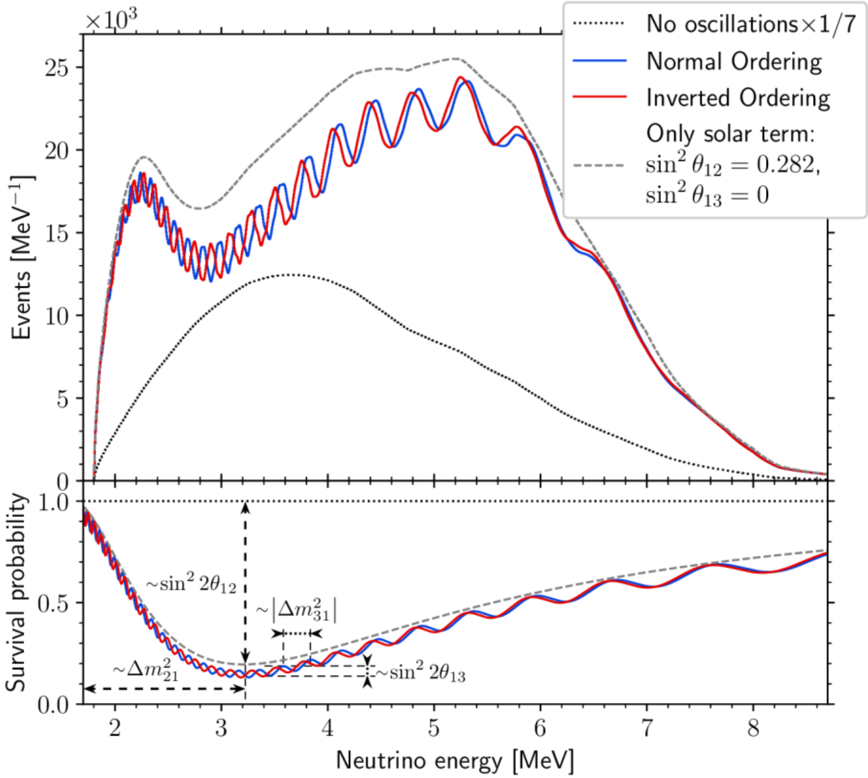

■ **In JUNO:**

- Measurement of mass ordering (sign of Δm^2_{31}) is **independent of δ_{cp}**
- Can measure $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31} to **sub-percent precision**

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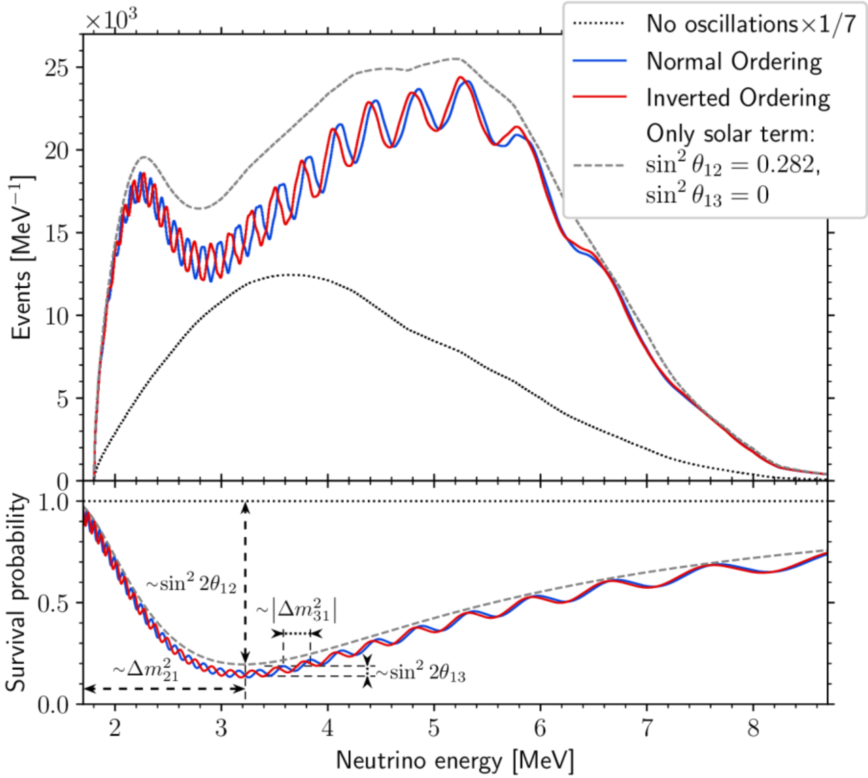

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- **Requirements**
  - Large statistics
  - High energy resolution (3%)
  - Low background
  - Precise reactor $\bar{\nu}$ spectrum as input

Key Features of JUNO

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Key Features of JUNO

[JUNO paper: *arXiv 2405.18008*]

- Requirements
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  - ✓ **Powerful nuclear reactors**
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Reactor	Power [GW_{th}]	Baseline [km]	IBD Rate [day^{-1}]
Taishan	$\boxed{9.2}$	52.71	18.4
Core 1	4.6	52.77	9.2
Core 2	4.6	52.64	9.2
Yangjiang	$\boxed{17.4}$	52.46	35.3
Core 1	2.9	52.74	5.8
Core 2	2.9	52.82	5.8
Core 3	2.9	52.41	5.9
Core 4	2.9	52.49	5.9
Core 5	2.9	52.11	6.0
Core 6	2.9	52.19	5.9
Daya Bay	17.4	215	3.65
Total IBD rate			57.4

- 2 nuclear power plants
- 8 reactor cores
- **26 GW_{th}**

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  - ✓ **20 kton liquid scintillator**
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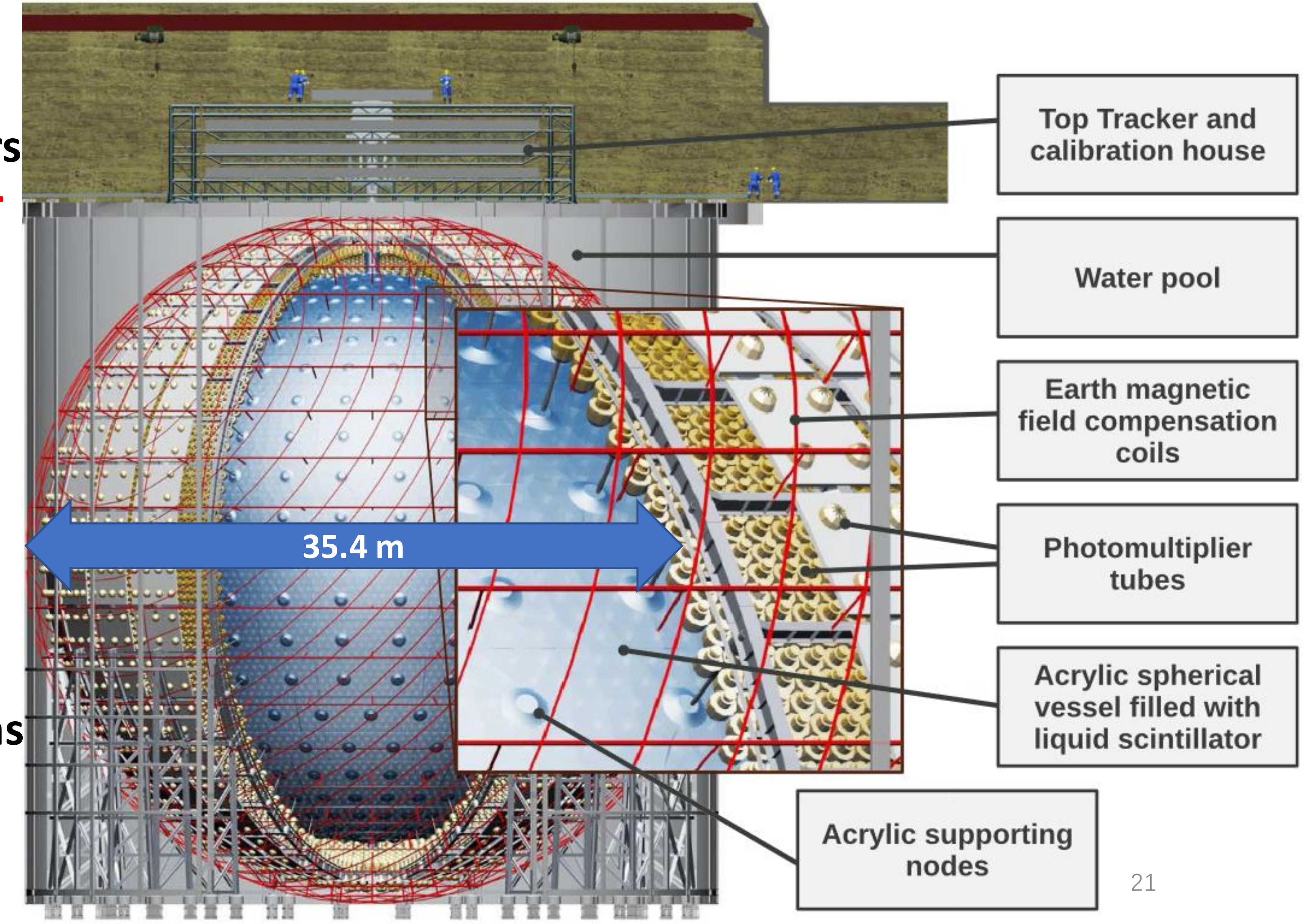

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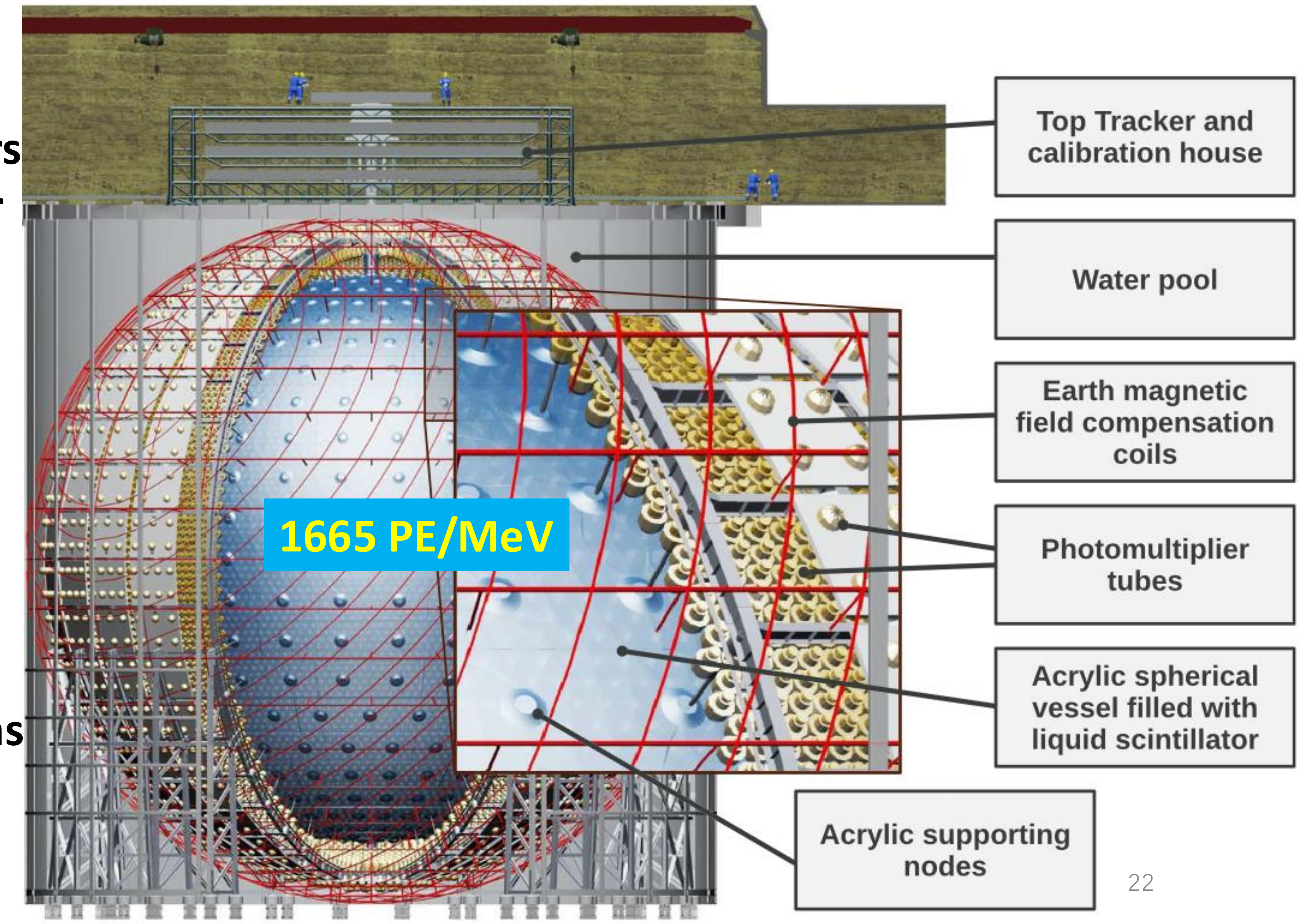

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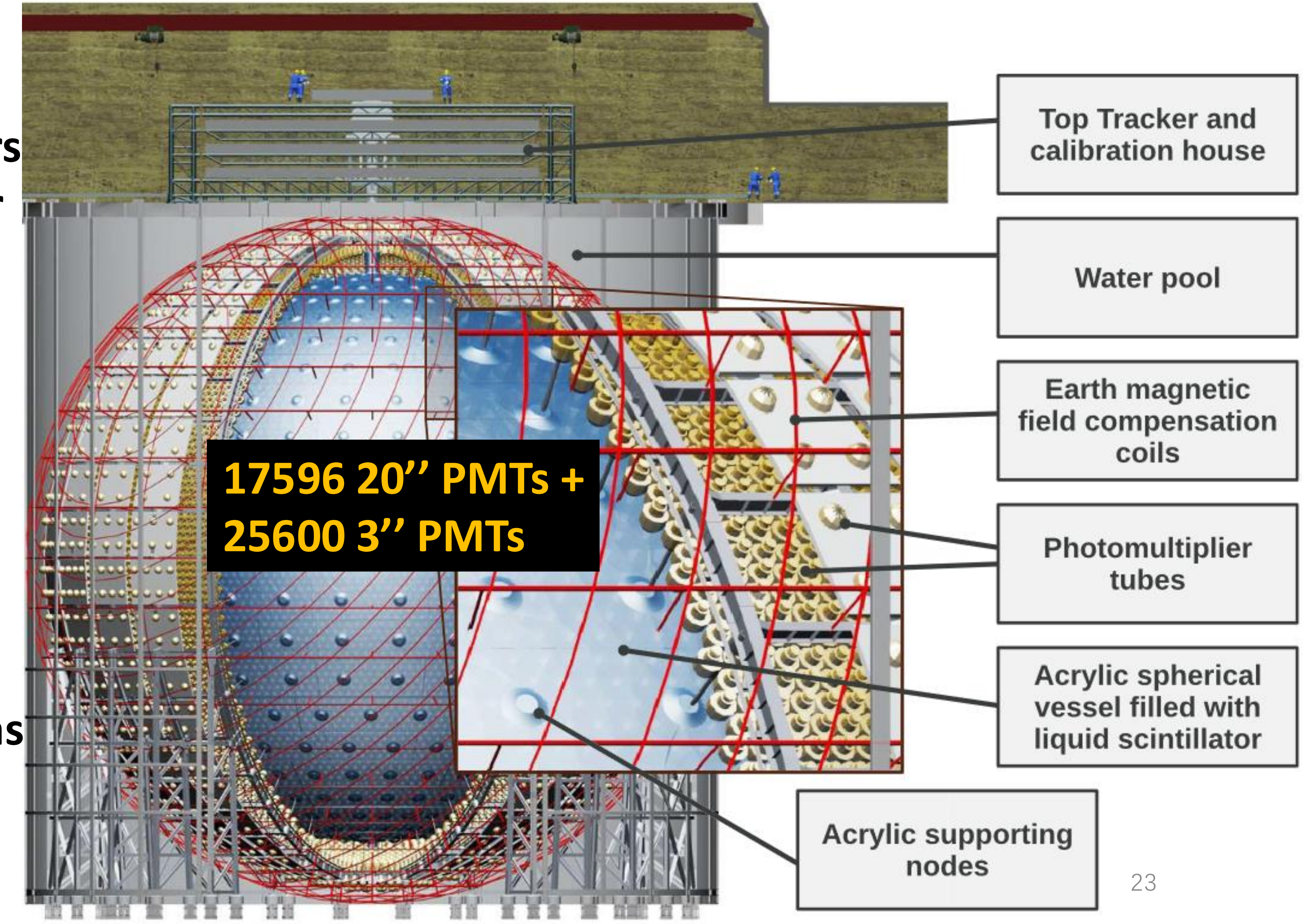

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	LPMT (20-inch)		SPMT (3-inch)
	Hamamatsu	NNVT	HZC
Quantity	5000	15012	25600
Charge Collection	Dynode	MCP	Dynode
Photon Detection Efficiency	28.5%	30.1%	25%
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

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  - ✓ **650m overburden (1800 m.w.e.)**
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- **Cosmic muon in LS: ~5 Hz**

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Veto Strategy

57 reactor $\bar{\nu}_e$ + 71 β-n decay of $^{9}Li/^{8}He$ /day

Residual: ⬇ after muon veto

92% reactor $\bar{\nu}_e$ + 4% β-n decay of $^{9}Li/^{8}He$ /day

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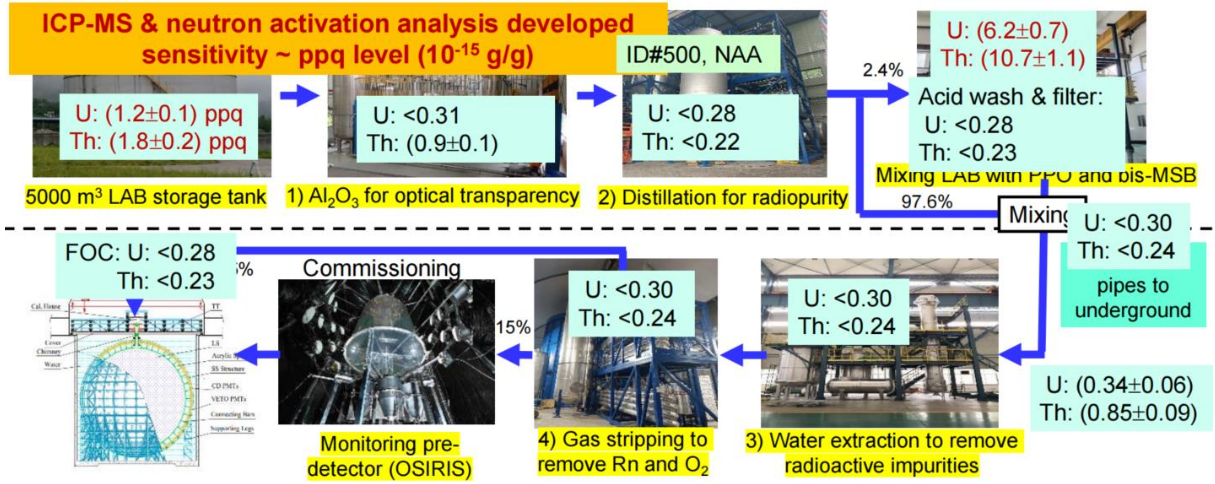
92% reactor $\bar{\nu}_e$ + 4% β-n decay of $^{9}Li/^{8}He$ /day

- **Minimum U/Th requirement for NMO < 10^{-15} g/g, aiming for 10^{-17} g/g**

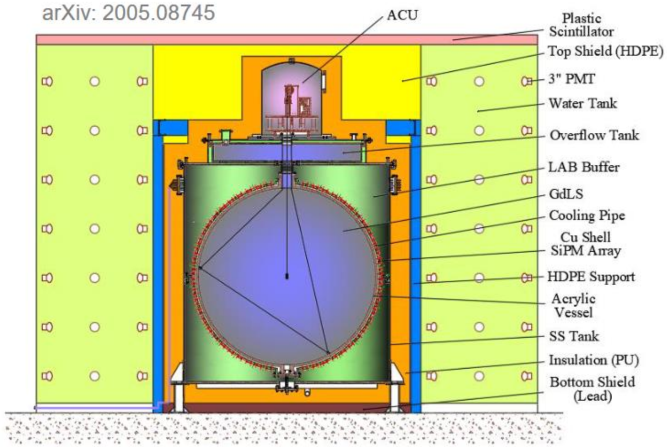


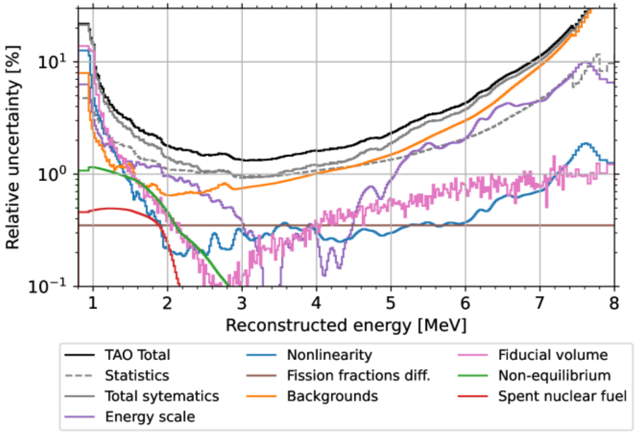
Key Features of JUNO

- ■ Requirements
- **Large statistics**
  - ✓ **Powerful nuclear reactors**
  - ✓ **20 kton liquid scintillator**
- **High energy resolution (3%)**
  - ✓ **High light yield**
  - ✓ **78% geometric-coverage**
  - ✓ **High PMT efficiency (30%)**
- **Low background**
  - ✓ **650m overburden (1800 m.w.e.)**
  - ✓ **Muon veto strategy (91.6%)**
  - ✓ **Material screening + clean environment**
- **Precise reactor $\overline{\nu}$ spectrum as input**
  - ✓ **JUNO-TAO**

JUNO-TAO

- **<2%** energy resolution at 1MeV
- **Sub-percent** shape uncertainty
- ➢ **Provide precise reactor $\overline{\nu}$ spectrum as reference for JUNO**

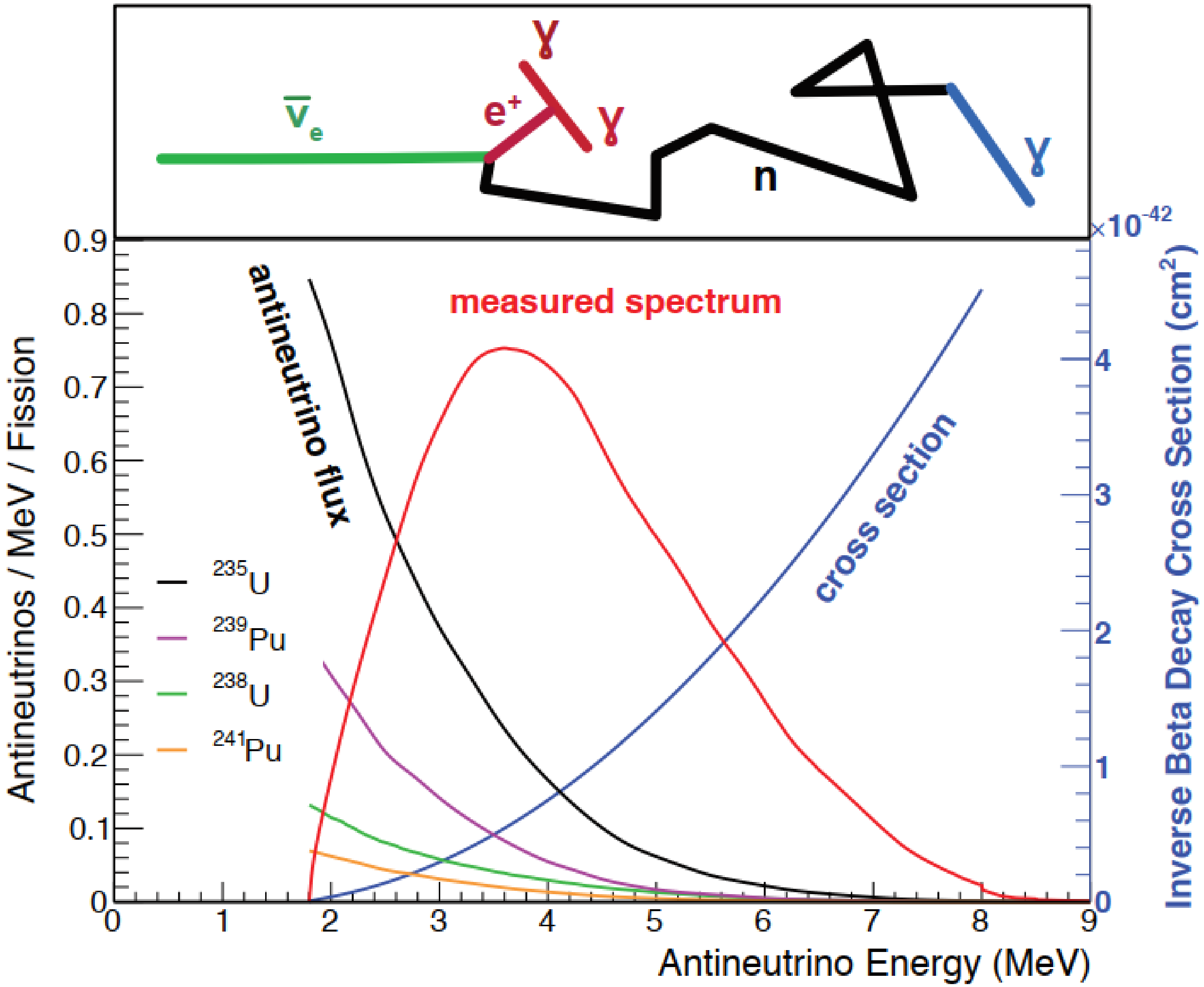




Inverse Beta Decay (IBD)

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

(interaction threshold: 1.8 MeV)



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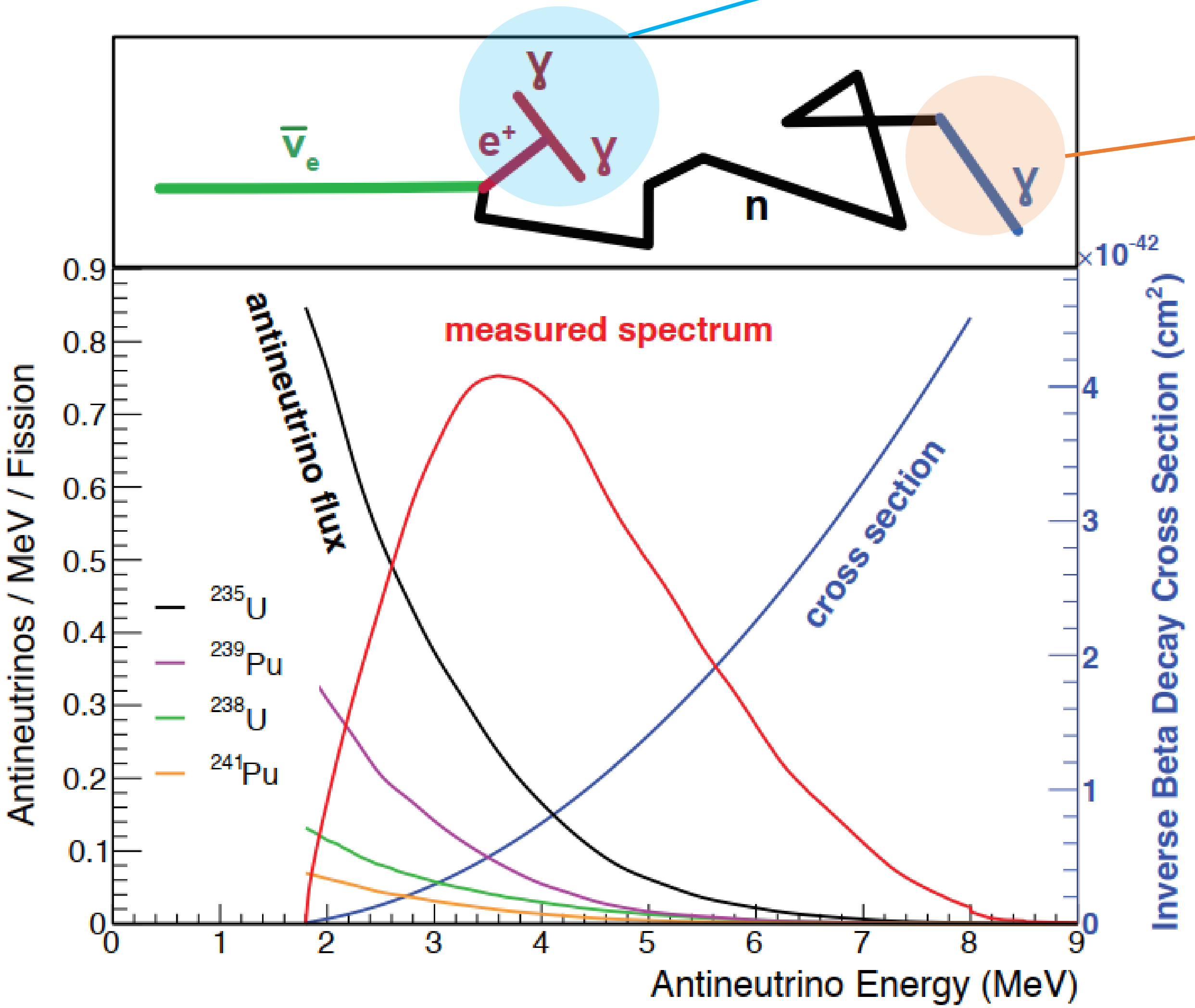

Prompt signal:
Solve for neutrino energy

$$E_\nu = E_{e^+} + \Delta m_{n-p} + T_n$$

Delayed signal:
Neutron capture at 2.2 MeV on H or at 4.9 MeV on ^{12}C within ~200 μs

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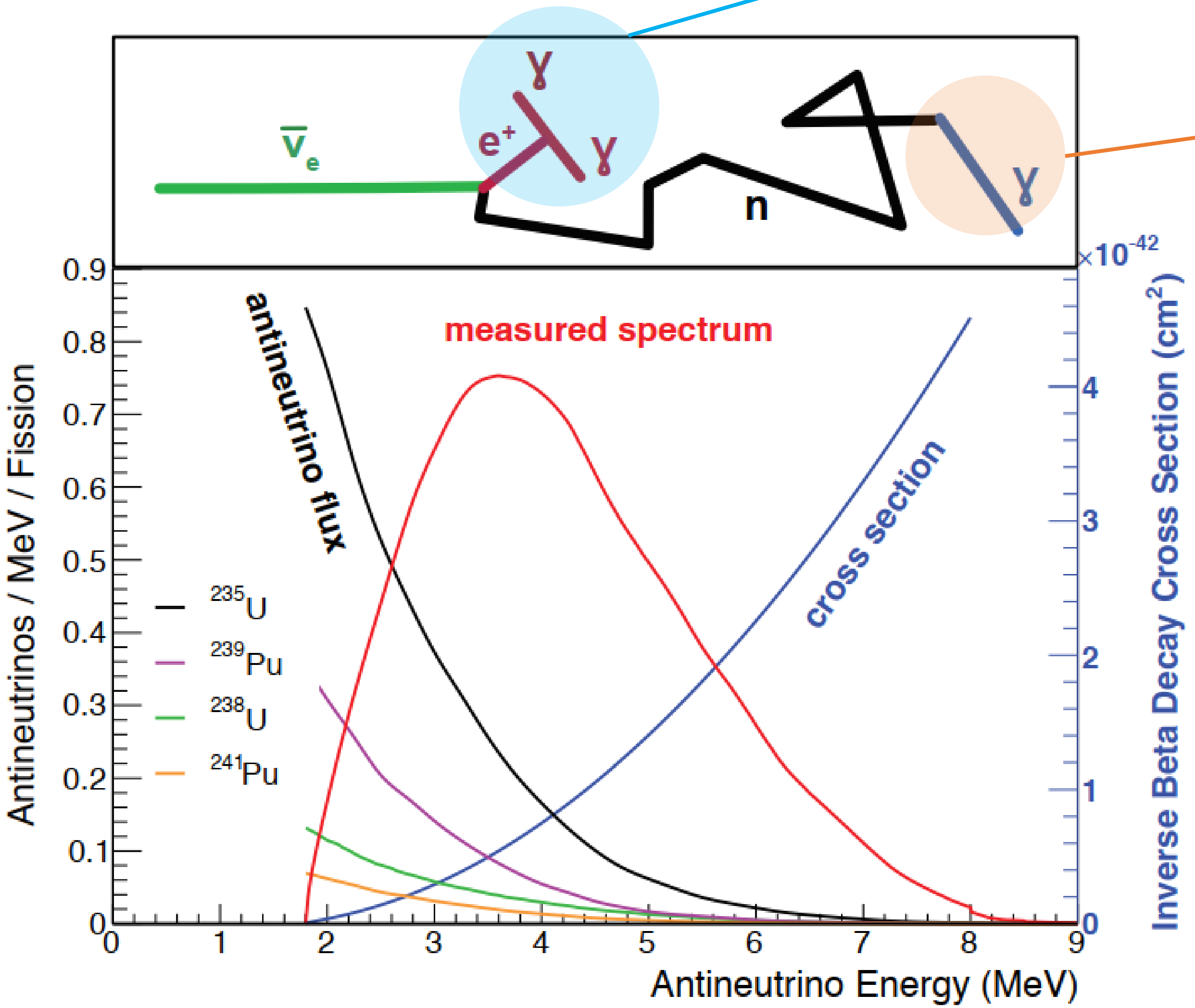

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Delayed signal:
Neutron capture at 2.2 MeV on H or at 4.9 MeV on ^{12}C within ~200 μs

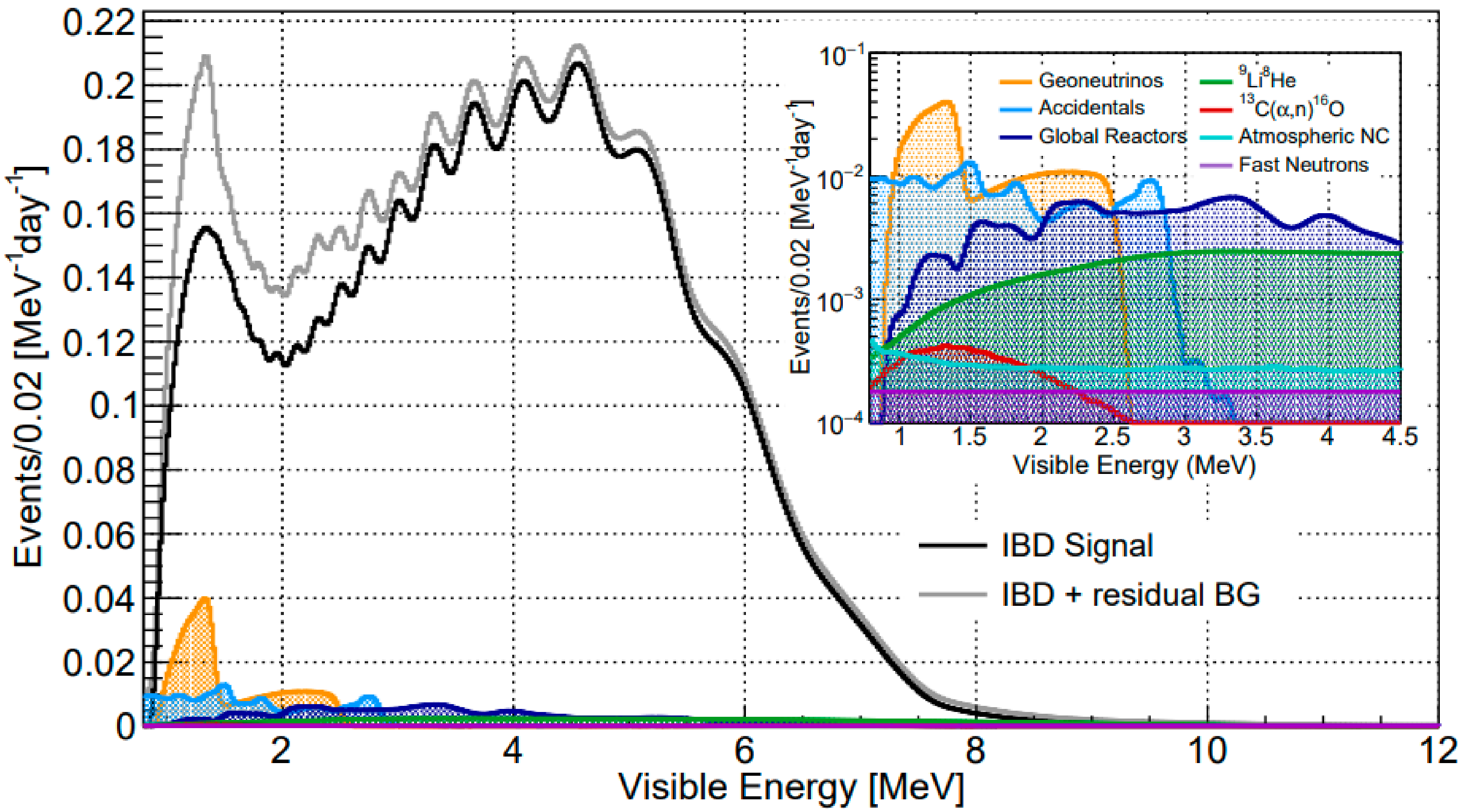
Selection of IBD candidates: (**82.2%** efficiency)

- Fiducial Volume: **r < 17.2 m** (91.5%)
- Selection cuts (98.1%)
  - E_p: **[0.8, 12.0] MeV**
  - E_d: **[1.9, 2.5] U [4.4, 5.5] MeV**
  - Time difference: **ΔT < 1.0 ms**
  - Vertex difference: **$R_{p\text{-}d}$ < 1.5 m**
- Muon Veto (91.6%)

Backgrounds for Reactor Neutrino Signal

[JUNO paper: *arXiv 2405.18008*]

- After IBD selection:



Backgrounds for Reactor Neutrino Signal

- After IBD selection:

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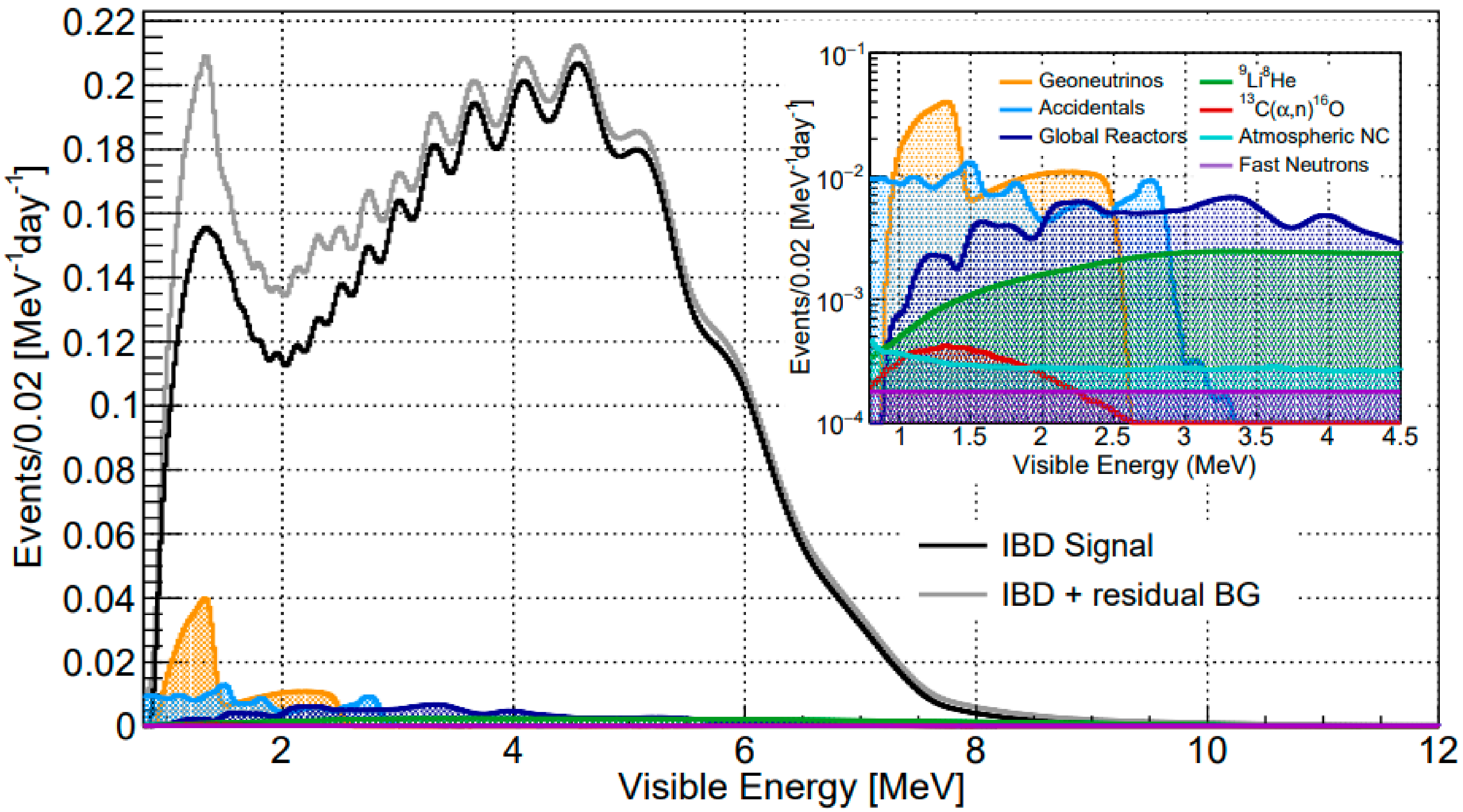


Background	Rate [day^{-1}]	Rate Unc. [%]	Shape Unc. [%]
Geoneutrinos	1.2	30	5
Global reactors	1.0	2	5
Accidentals	0.8	1	~0
^{9}Li/^{8}He	0.8	20	10
^{13}C(α,n)^{16}O	0.05	50	50
Atmospheric ν	0.16	50	50
Fast neutrons	0.1	100	20
Total	**4.11**		

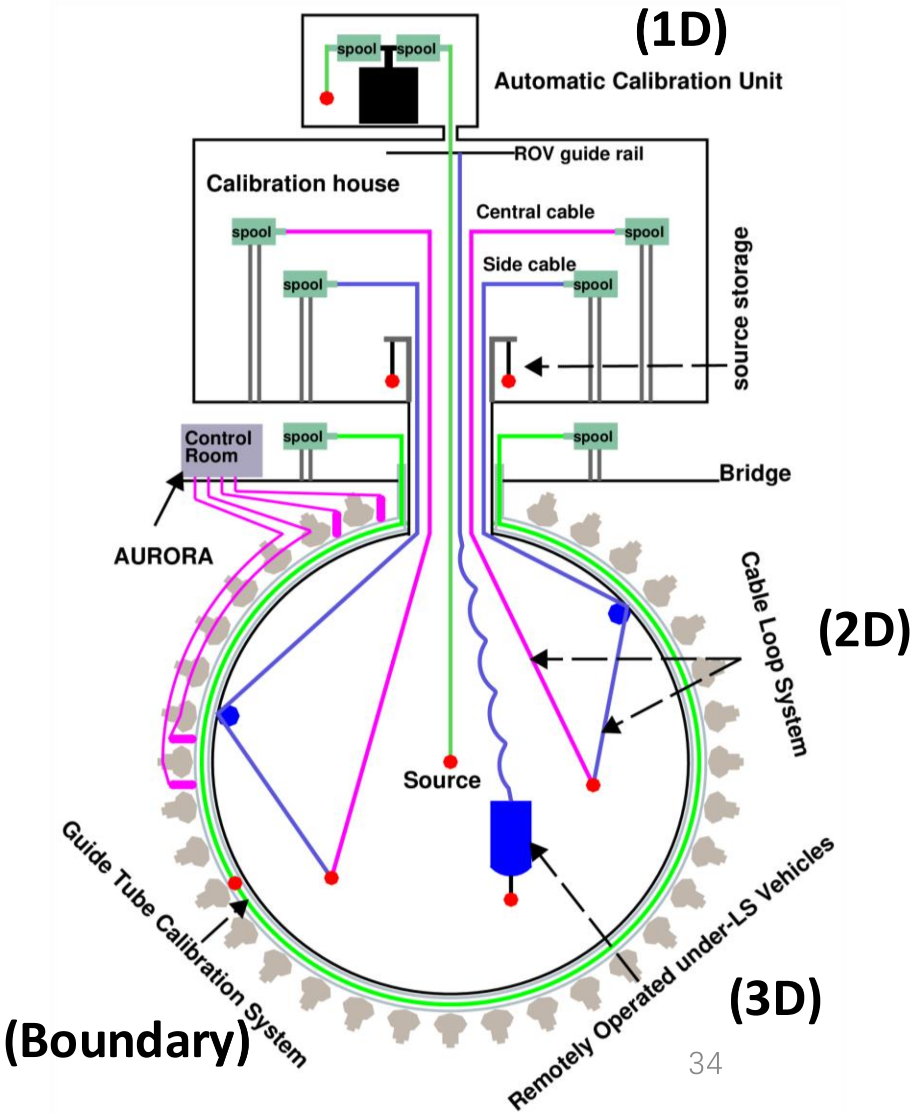
Reactor neutrino signal:
47.1 day^{-1} ± 1.5% (syst.)

Energy Resolution in JUNO

- Goal: 3% at 1 MeV for e⁺ from IBD signals

$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}.$$

Multiple calibration campaigns & sources



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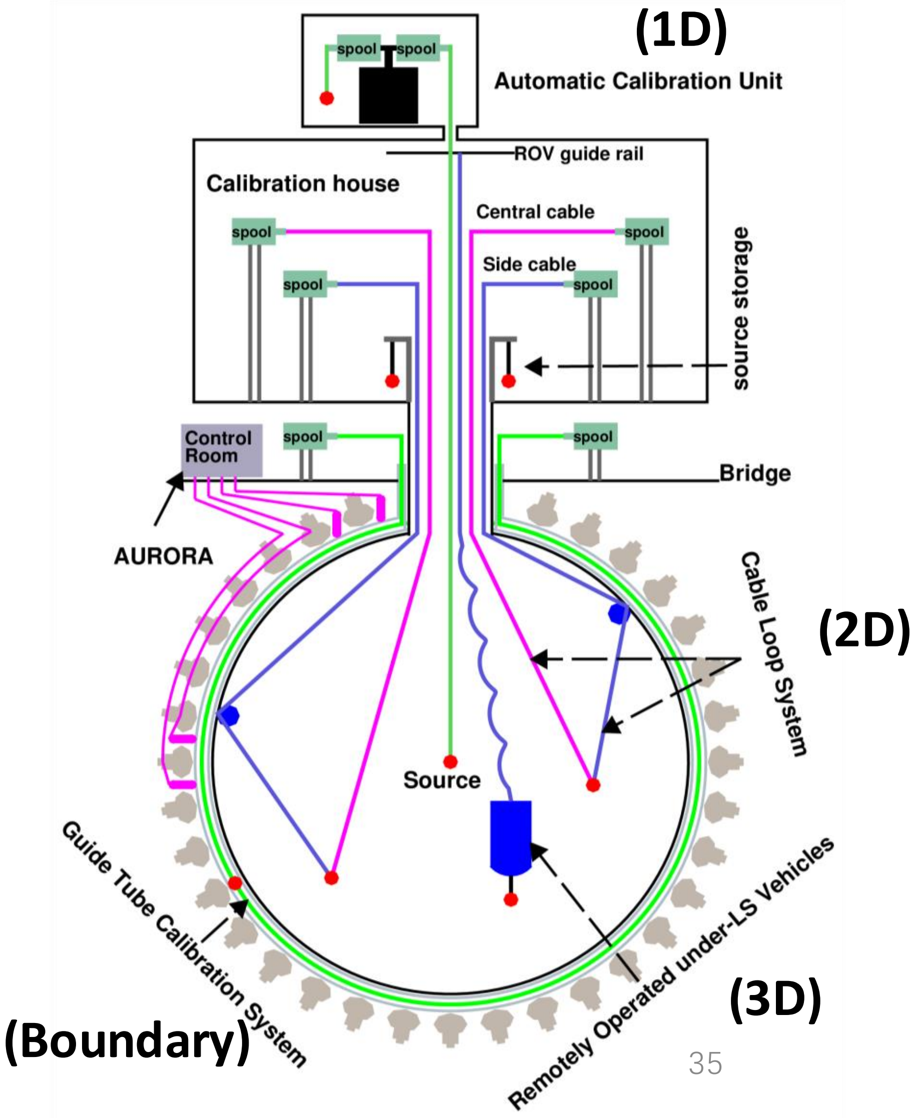
- Photon statistics

Multiple calibration campaigns & sources



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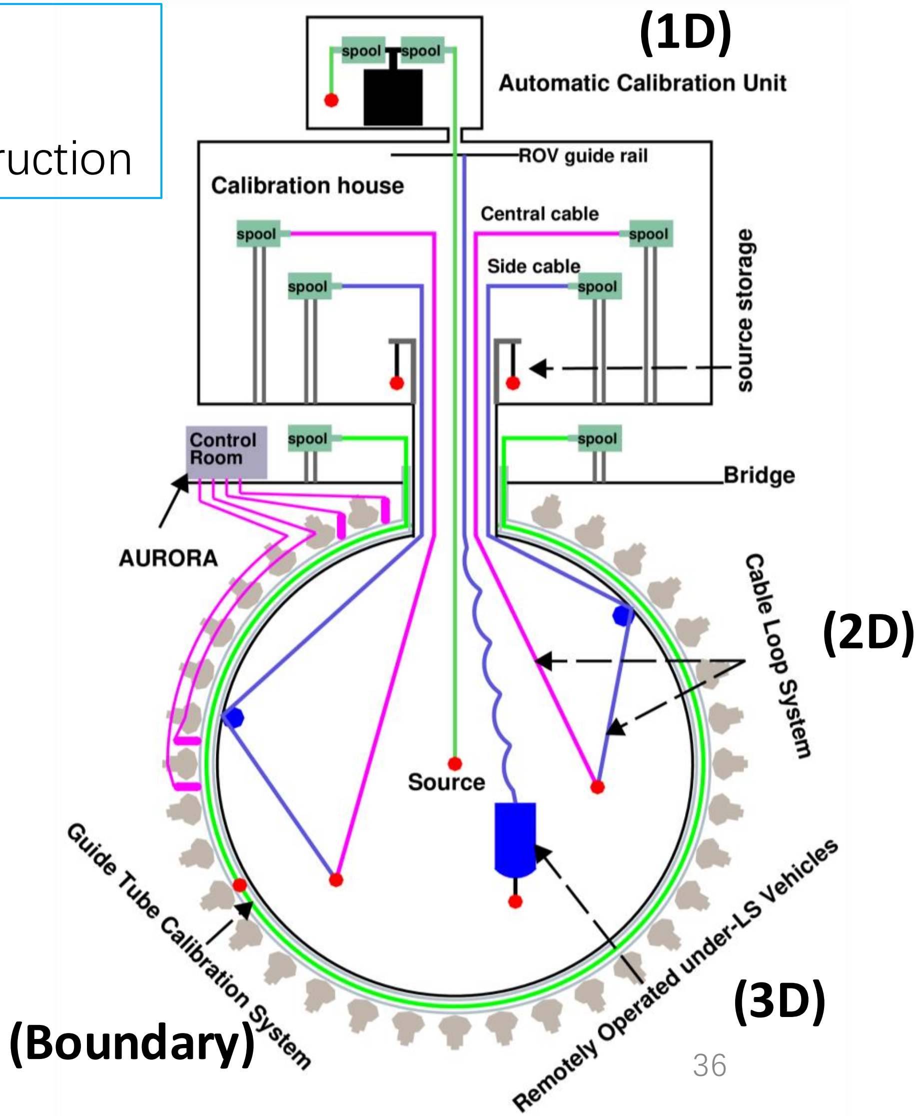
- Photon statistics

- Scintillation quenching effect
- Cherenkov radiation
- Detector uniformity and reconstruction

Multiple calibration campaigns & sources



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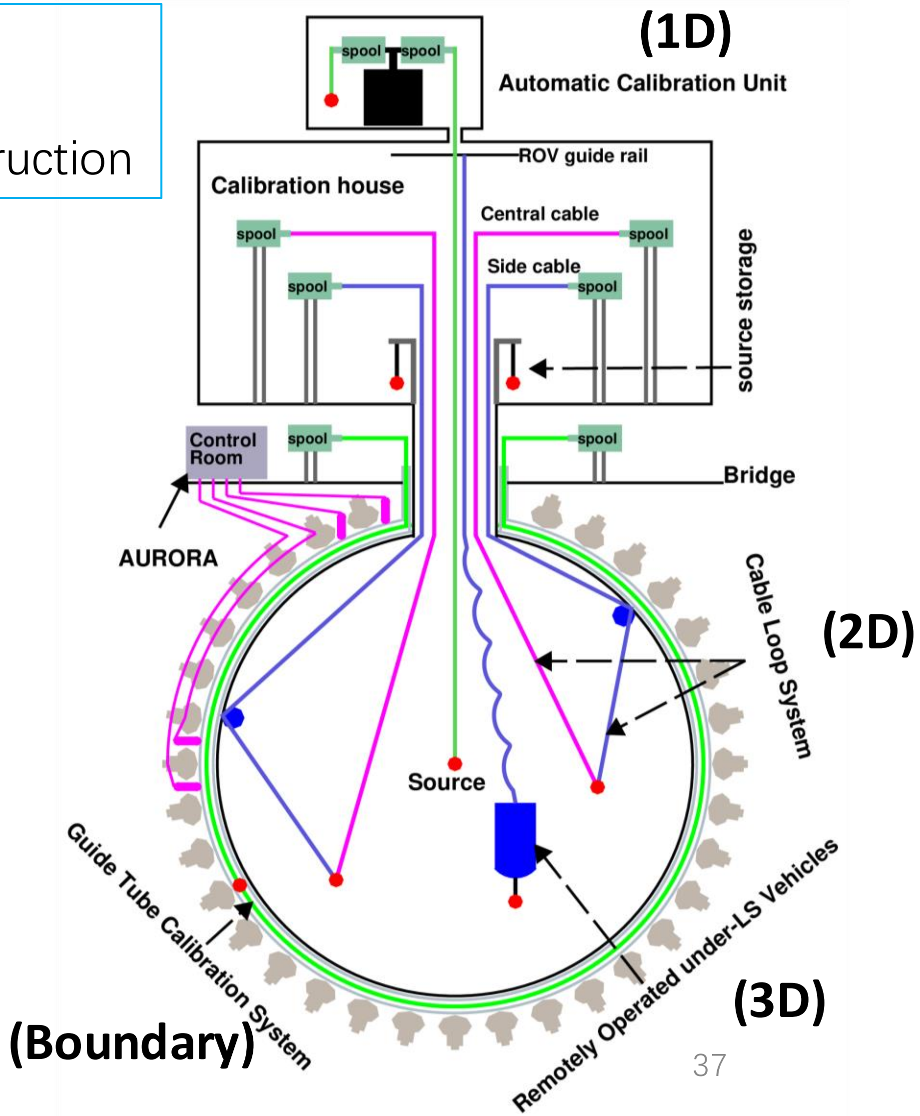
- Scintillation quenching effect
- Cherenkov radiation
- Detector uniformity and reconstruction

- Photon statistics

- Annihilation-induced γ's
- Dark noise

Multiple calibration campaigns & sources



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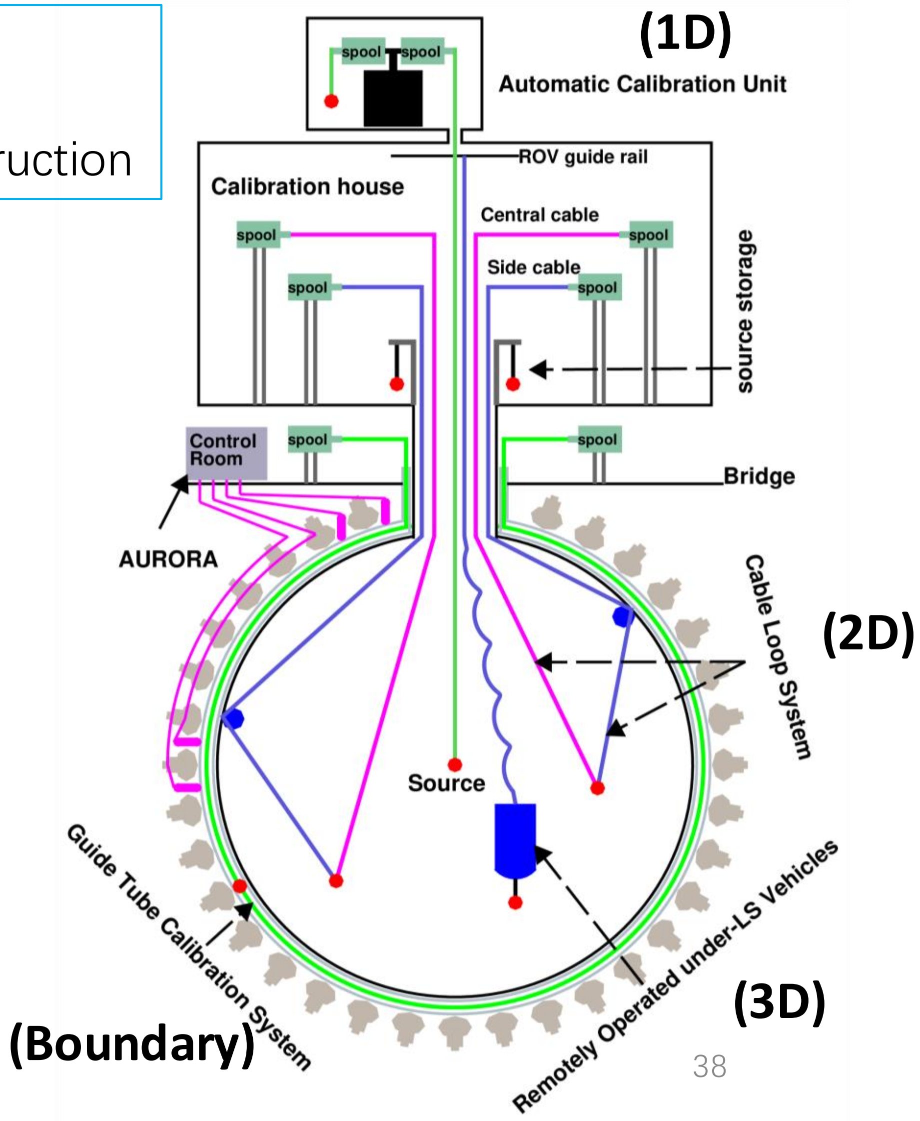
- Photon statistics

- Scintillation quenching effect
- Cherenkov radiation
- Detector uniformity and reconstruction

- Annihilation-induced γ's
- Dark noise

Change	Light yield in CD center [PE/MeV]	Energy Resolution
Previous Estimation	1345	3.0% @ 1 MeV
Photon Detection Efficiency (**27%->30%**)	**+11%↑**	
New CD Geometry	**+3%**	
New PMT Optical Model & LS Properties	**+8%**	

Multiple calibration campaigns & sources



Energy Resolution in JUNO

- Goal: 3% at 1 MeV for e^+ from IBD signals

[JUNO paper: *arXiv 2405.17860*]

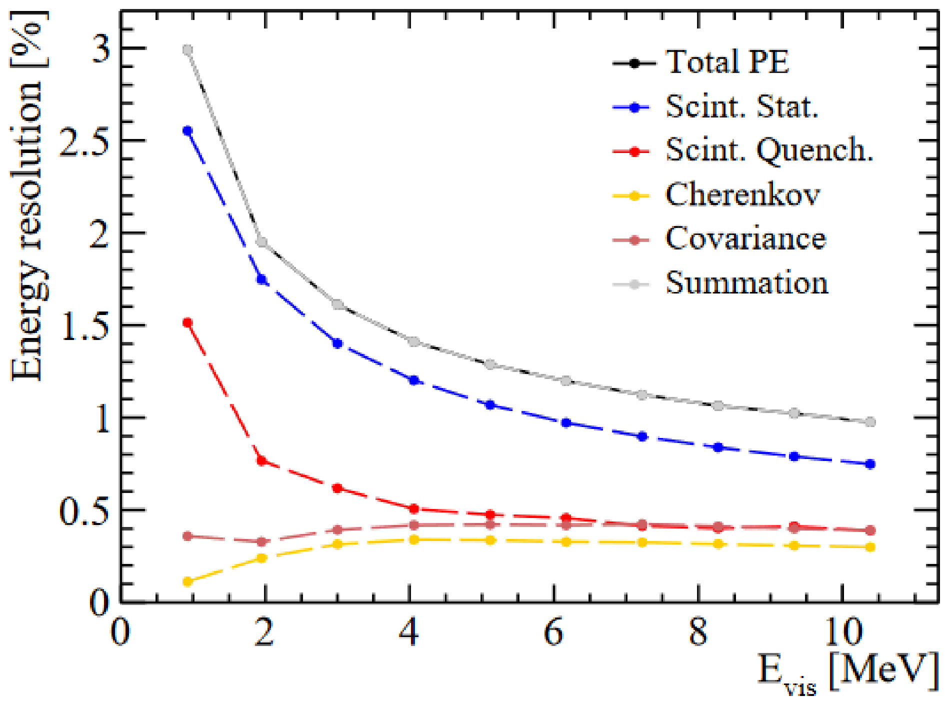
$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}.$$

- Scintillation quenching effect
- Cherenkov radiation
- Detector uniformity and reconstruction

- Photon statistics

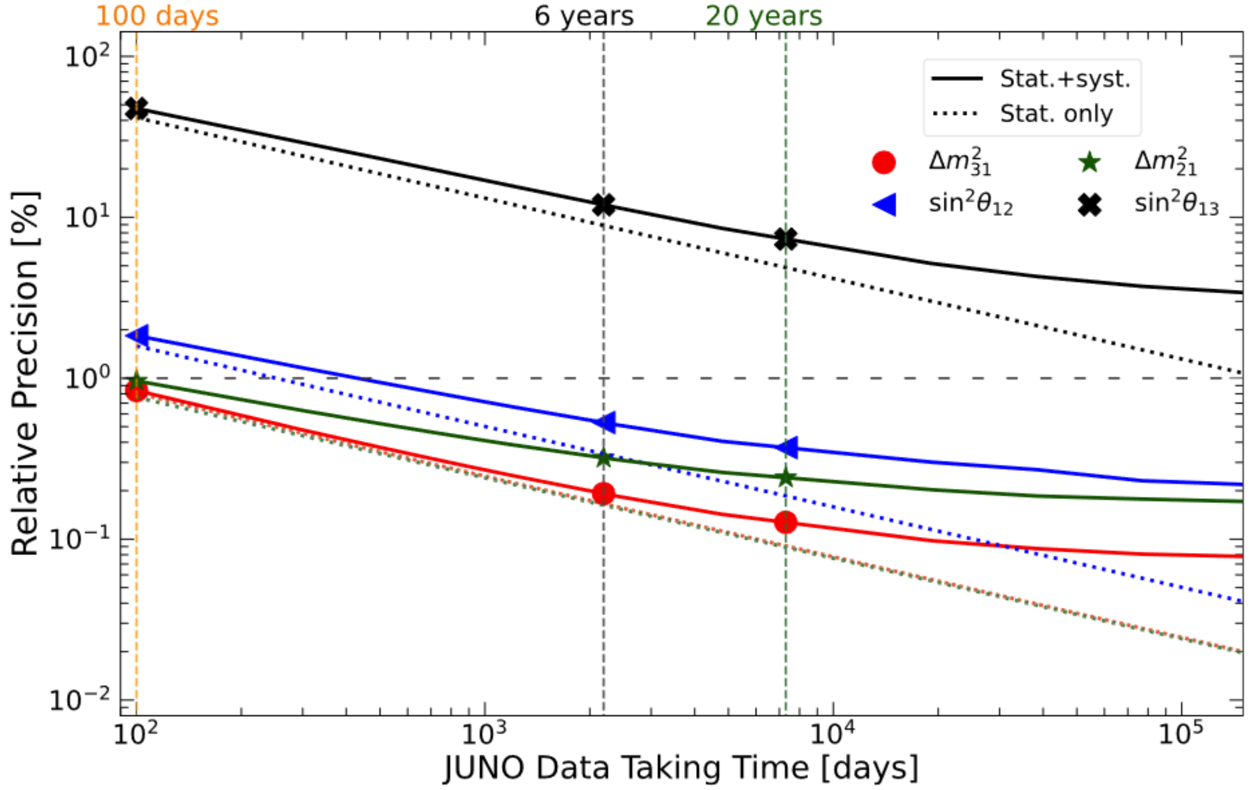
- Annihilation-induced γ's
- Dark noise

Change	Light yield in CD center [PE/MeV]	Energy Resolution
Previous Estimation	1345	3.0% @ 1 MeV
Photon Detection Efficiency (**27%->30%**)	**+11%↑**	**2.95% @ 1 MeV**
New CD Geometry	**+3%**	
New PMT Optical Model & LS Properties	**+8%**	



Precision Measurement on Oscillation Parameters

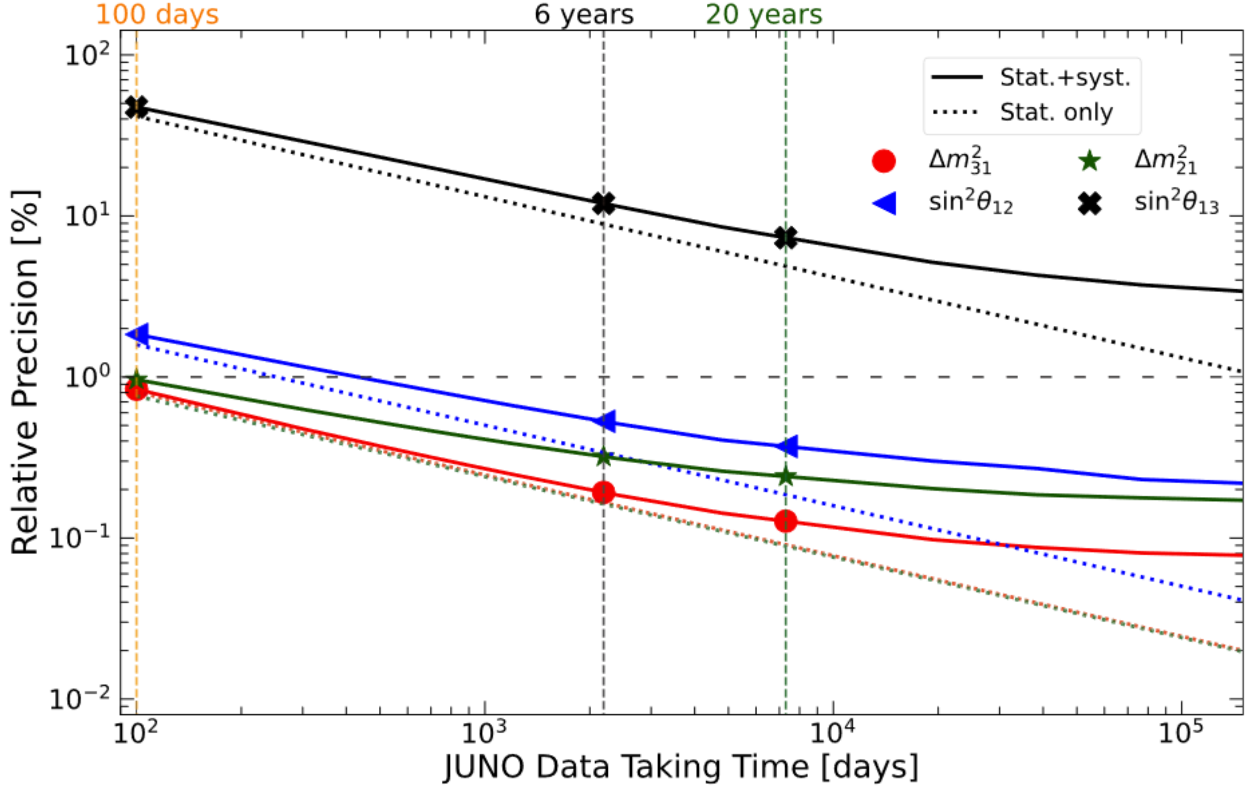
[JUNO paper: *Chin. Phys. C 46 (2022)*]



Precision Measurement on Oscillation Parameters

[JUNO paper: *Chin. Phys. C 46 (2022)*]

- **World leading** measurements on $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ in 100 days



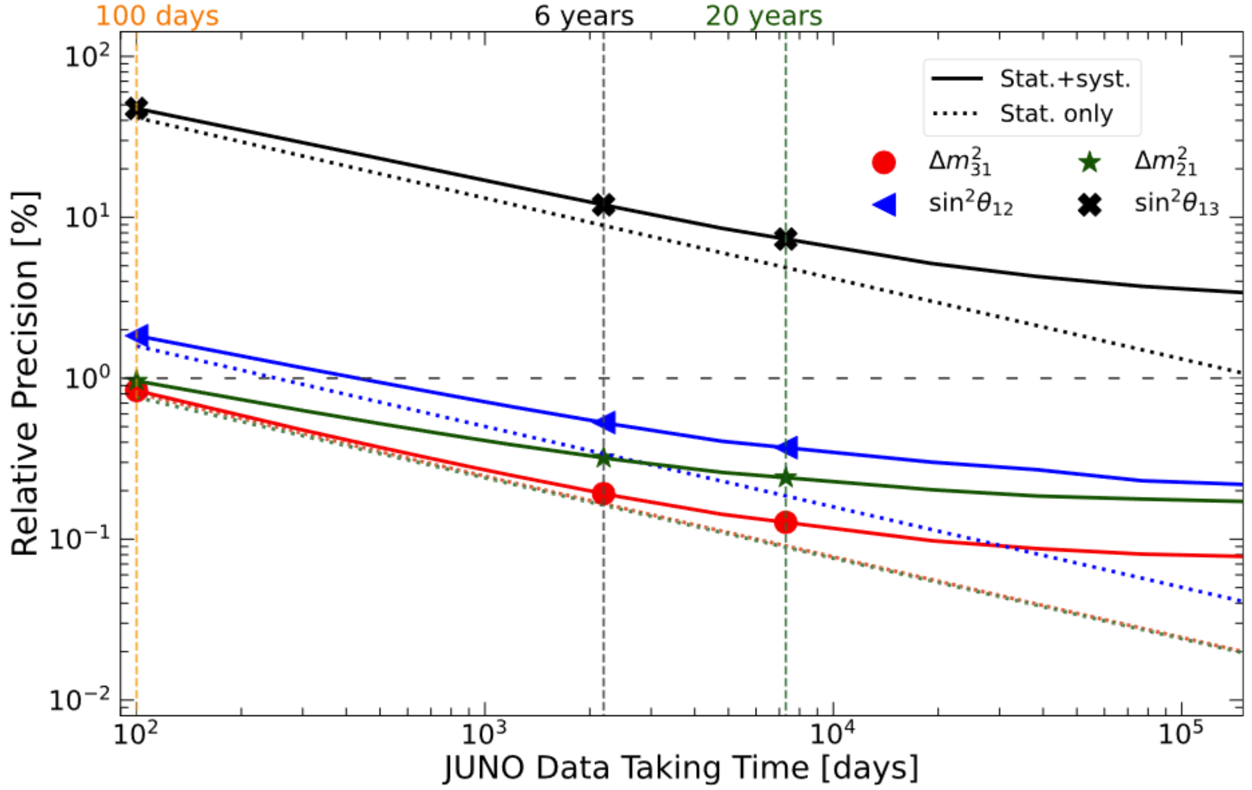
	Central Value	PDG2020	100 days
Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)
Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)

Precision Measurement on Oscillation Parameters

[JUNO paper: *Chin. Phys. C 46 (2022)*]

- **World leading** measurements on $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ in 100 days

- Precision **< 0.5%** in 6 years

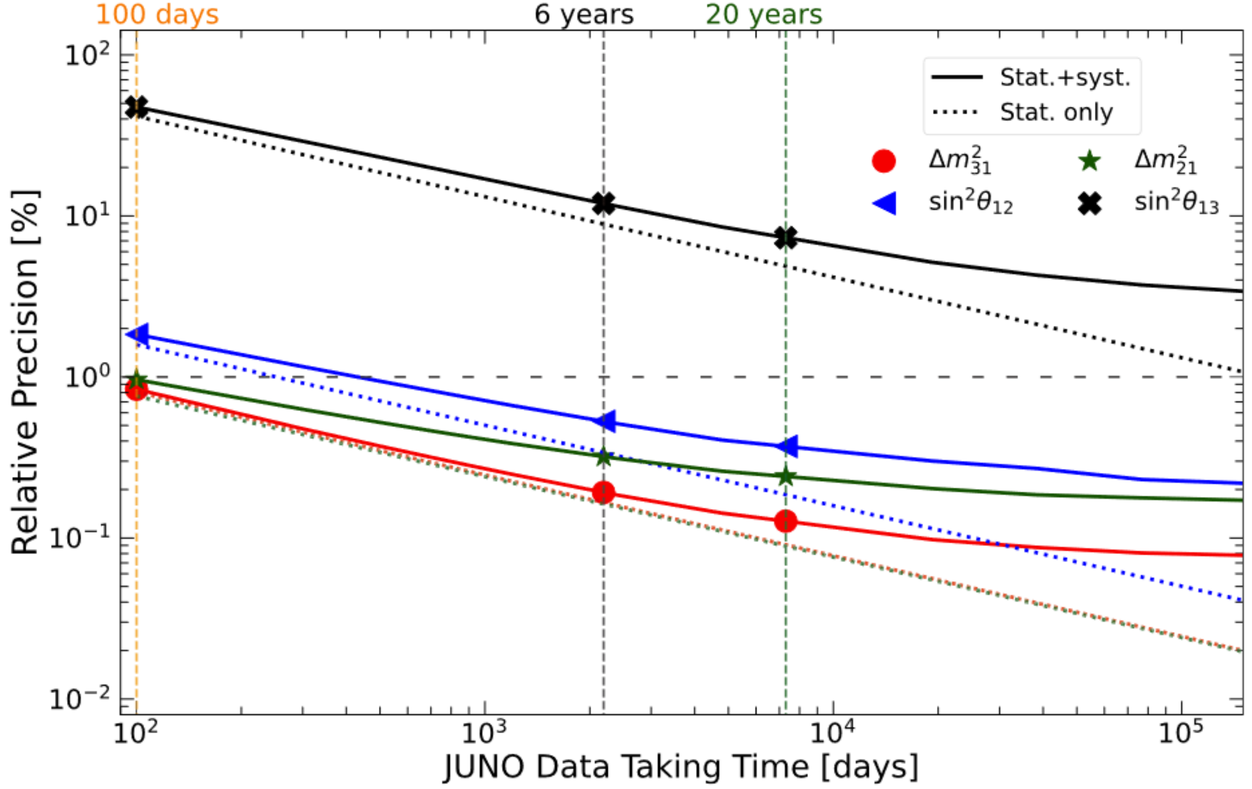


	Central Value	PDG2020	100 days	6 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)

Precision Measurement on Oscillation Parameters

[JUNO paper: *Chin. Phys. C 46 (2022)*]

- **World leading** measurements on $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ in 100 days
- Precision **< 0.5%** in 6 years
- **One order of magnitude** precision improvement with respect to current global precision

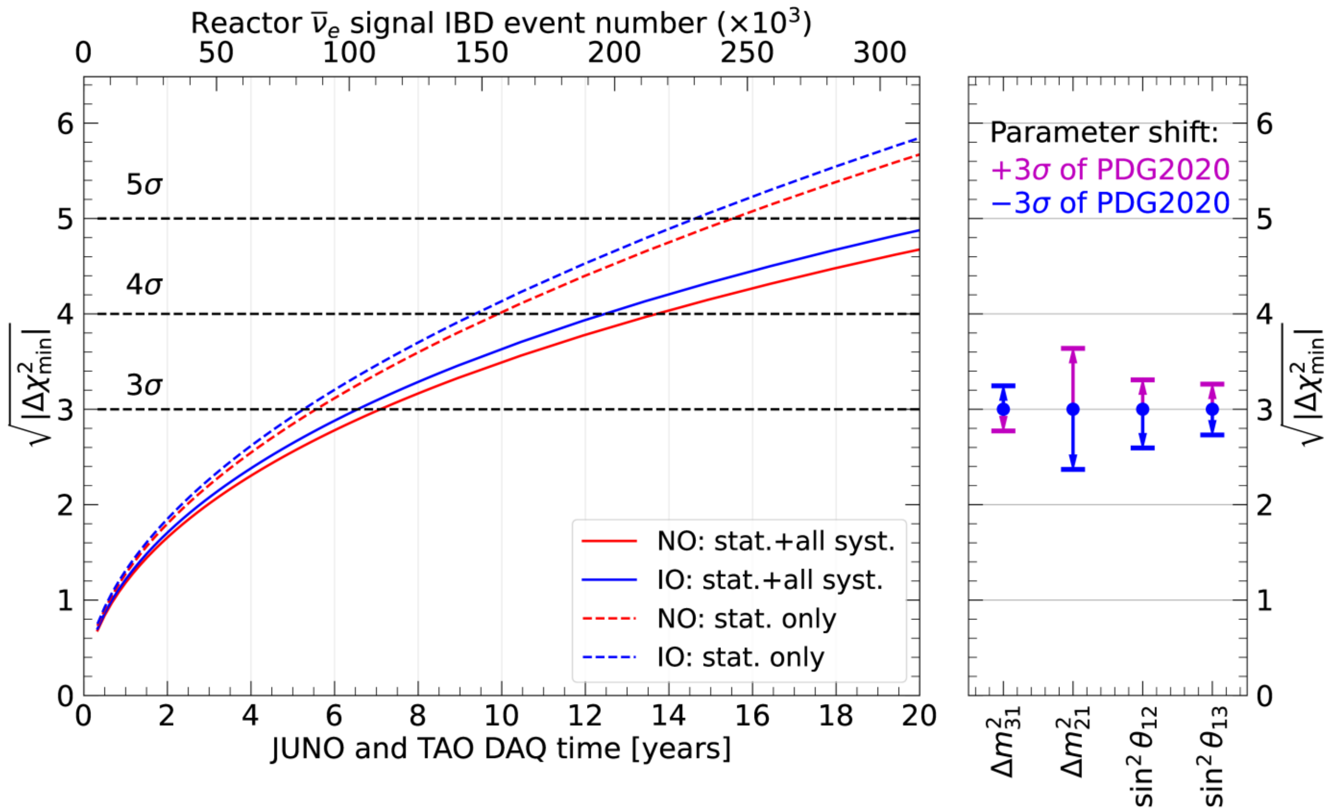


	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

Neutrino Mass Ordering (with Reactor Neutrinos)

[JUNO paper: *arXiv 2405.18008*]

- JUNO's median sensitivity to NMO
  - Reach 3σ (3.1σ)significance in 7.1 years of DAQ time when NO (IO) is true



Neutrino Mass Ordering (with Reactor Neutrinos)

- JUNO's median sensitivity to NMO
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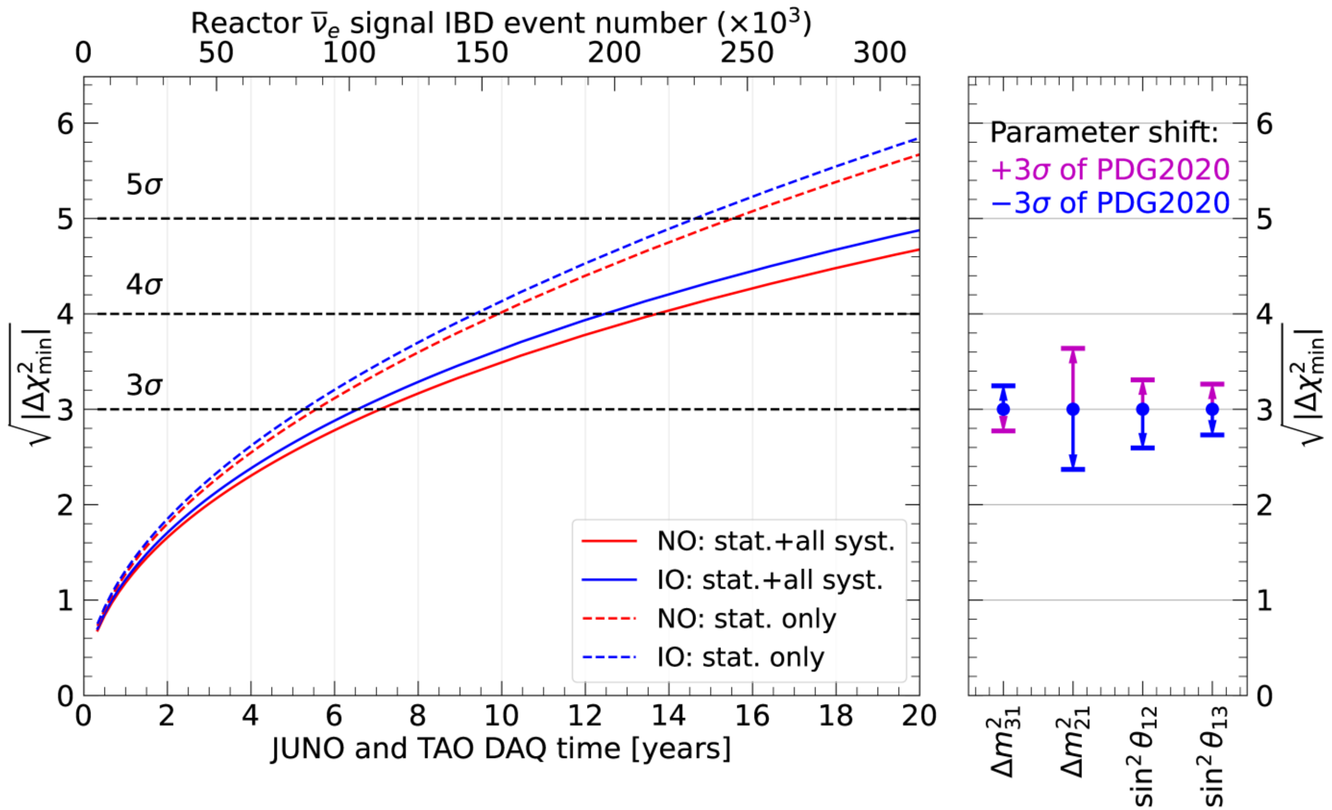
Design: [JUNO Yellow Book] *arXiv 1507.05613*
Now: [JUNO (recent) paper] *arXiv 2405.18008*

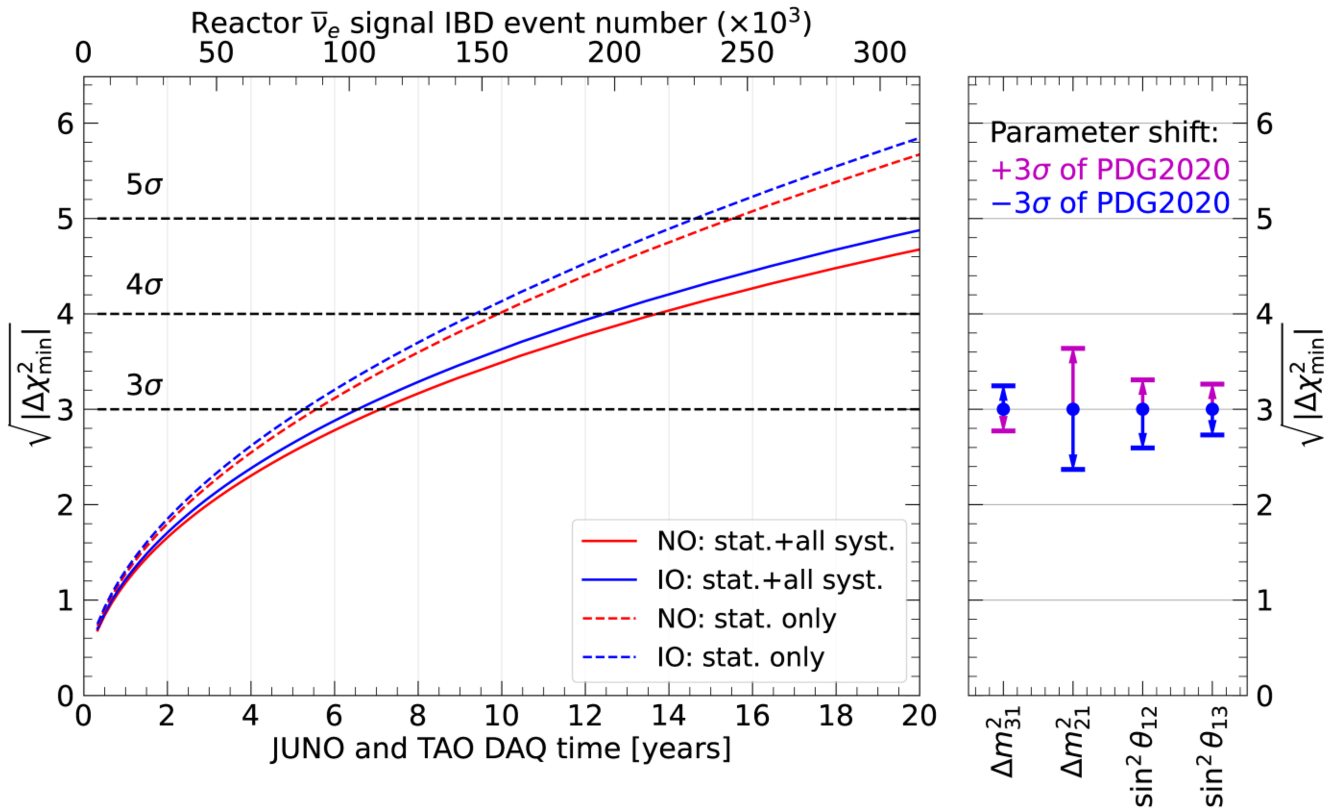


	Design *	Now *
Thermal Power	36 GW_{th}	26.6 GW_{th} (26%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Signal rate	60 /day	47.1 /day (22%↓)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3% @ 1 MeV	2.9% @ 1 MeV (3%↑)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. Exposure	**< 6 yrs X 35.8 GW_{th}**	**~ 6.5 yrs X 26.6 GW_{th}**

Neutrino Mass Ordering (with Reactor Neutrinos)

Design: [JUNO Yellow Book] *arXiv 1507.05613*
Now: [JUNO (recent) paper] *arXiv 2405.18008*

- ■ JUNO's median sensitivity to NMO
- Reach 3σ (3.1σ)significance in 7.1 years of DAQ time when NO (IO) is true
- ➢ Consider atmospheric ν can improve sensitivity



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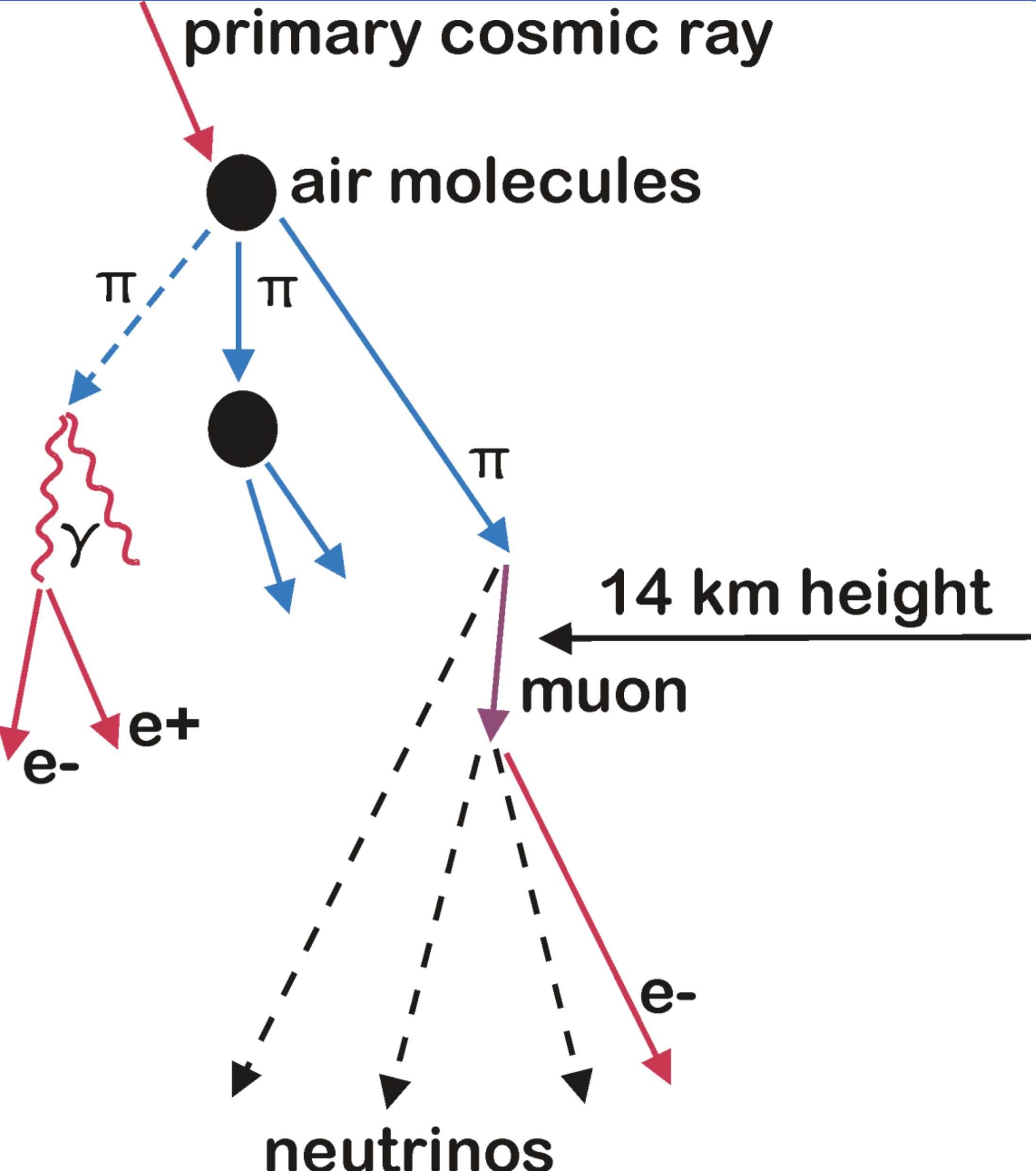
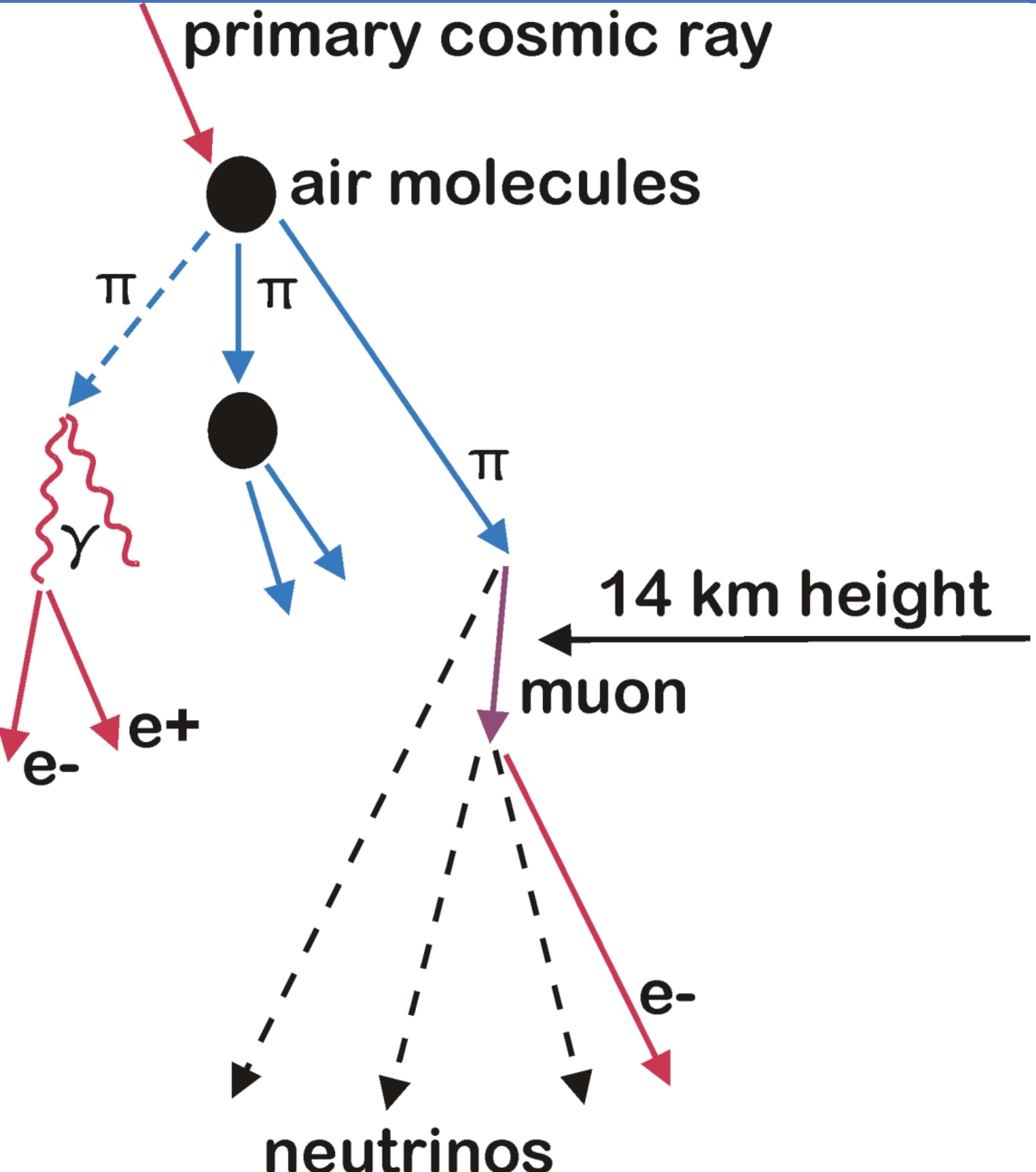
Neutrino Mass Ordering (with Atmospheric Neutrinos)

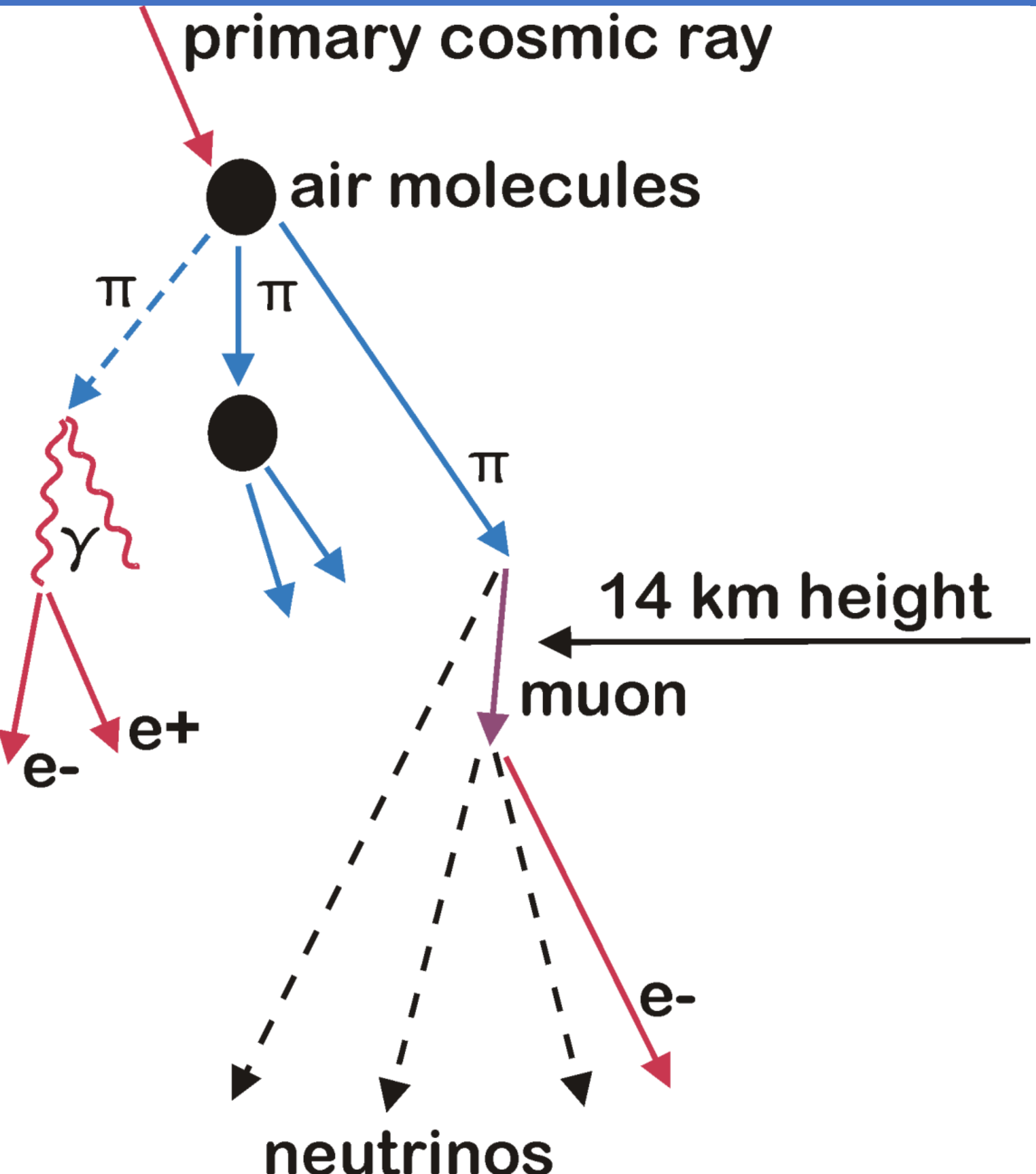


Neutrino Mass Ordering (with Atmospheric Neutrinos)



- $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$
- $\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$

Neutrino Mass Ordering (with Atmospheric Neutrinos)



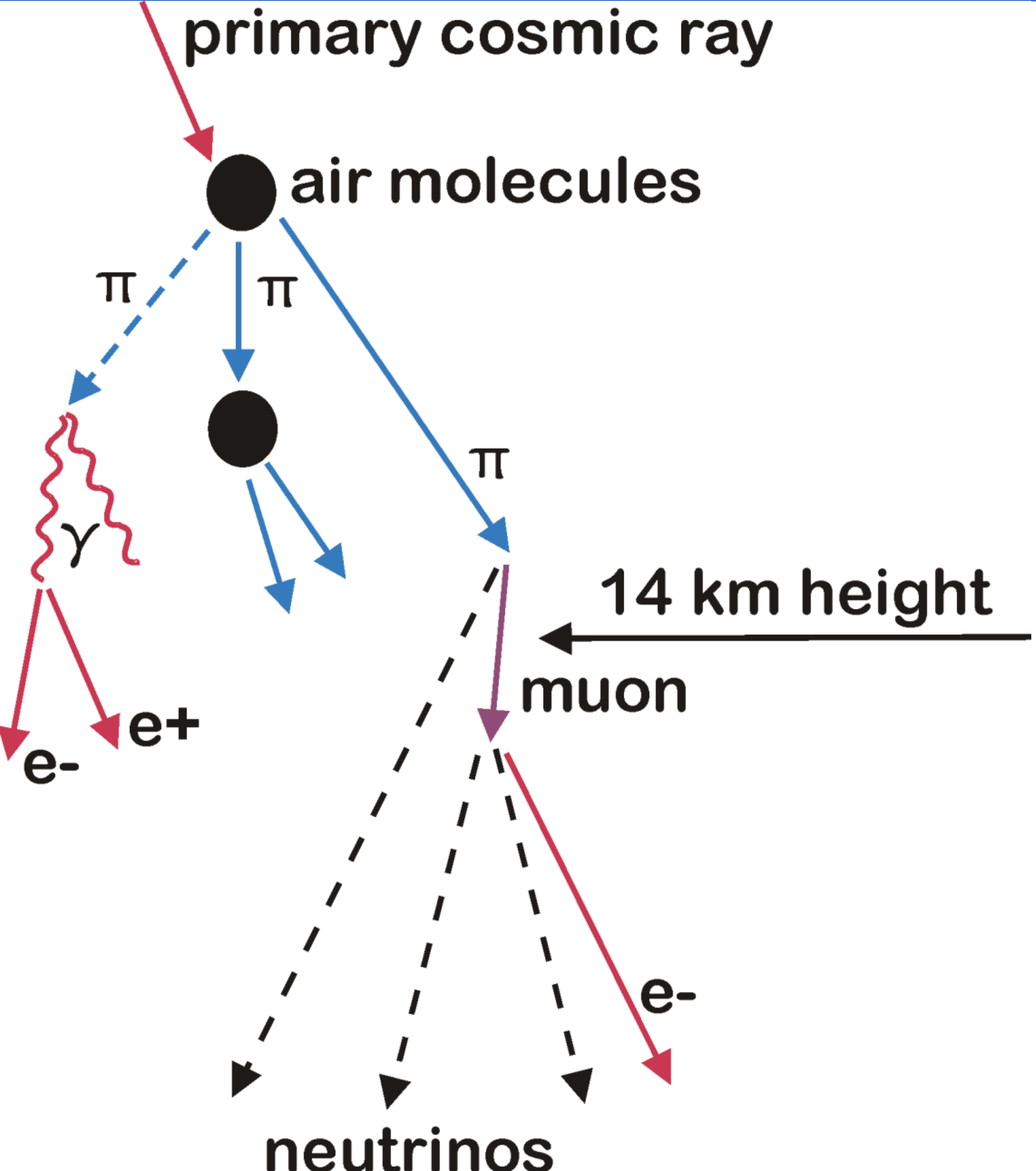
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$

  $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

  $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

Neutrino Mass Ordering (with Atmospheric Neutrinos)



- $\pi^+ \to \mu^+ + \nu_\mu$

  $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

- $\pi^- \to \mu^- + \bar{\nu}_\mu$

  $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

E ~ 0.1 GeV – 10 TeV
L ~ 15 – 13000 km

Neutrino Mass Ordering (with Atmospheric Neutrinos)

With matter effect:

ν ($\overline{\nu}$: A ➔ -A)

[JUNO Physics Book: *J. Phys. G43:030401 (2016)*]

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m^2_{31})^m \frac{L}{E_\nu}\right]$$

$$(\Delta m^2_{31})^m = \Delta m^2_{31}\sqrt{(\cos 2\theta_{13} - A/\Delta m^2_{31})^2 + \sin^2 2\theta_{13}}$$

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{(\cos 2\theta_{13} - A/\Delta m^2_{31})^2 + \sin^2 2\theta_{13}} .$$

$$A = 2\sqrt{2}G_F N_e E_\nu$$

Neutrino Mass Ordering (with Atmospheric Neutrinos)

With matter effect:

- $P_{NO}(\nu_\alpha \to \nu_\beta) = P_{IO}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

ν ($\bar{\nu}$: A ➔ -A)

[JUNO Physics Book: *J. Phys. G43:030401 (2016)*]

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m_{31}^2)^m \frac{L}{E_\nu}\right]$$

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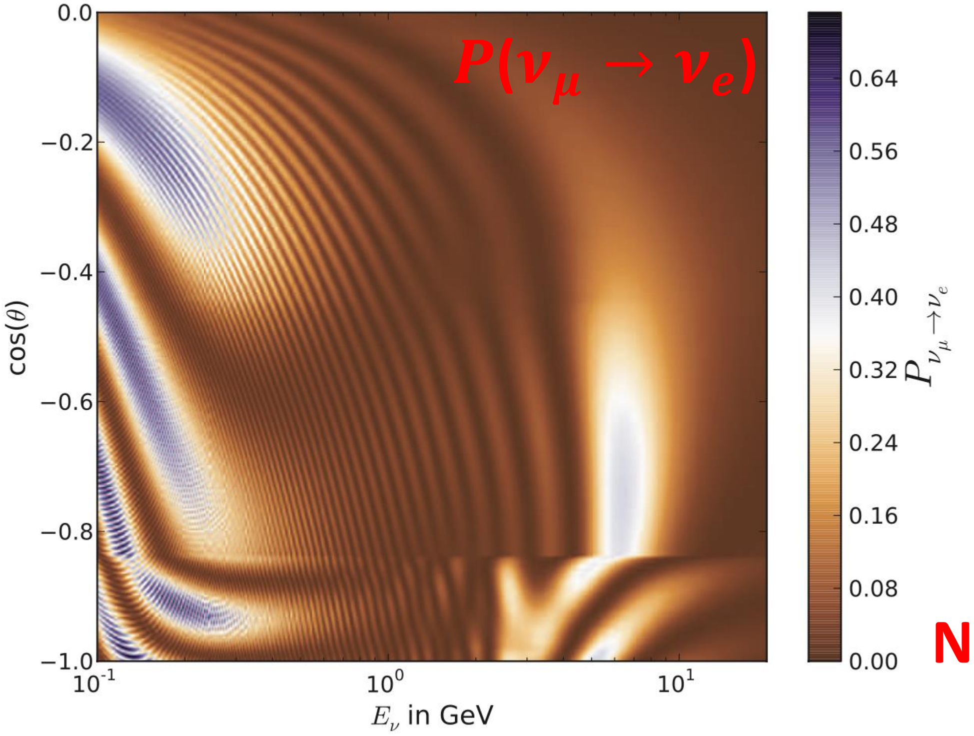
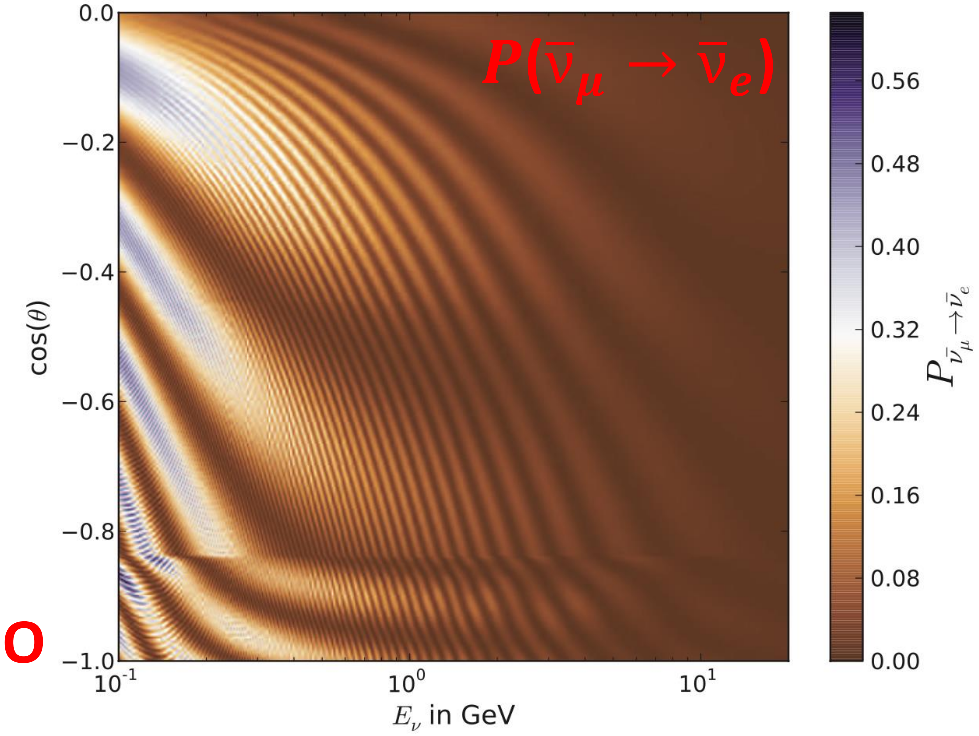


NO



Neutrino Mass Ordering (with Atmospheric Neutrinos)

With matter effect:

- $\boldsymbol{P_{NO}(\nu_\alpha \to \nu_\beta) = P_{IO}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$
- Resonance E_ν^{atm}: 3-10 GeV

ν ($\bar{\nu}$: A → -A)

[JUNO Physics Book: *J. Phys. G43:030401 (2016)*]

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m_{31}^2)^m \frac{L}{E_\nu}\right]$$

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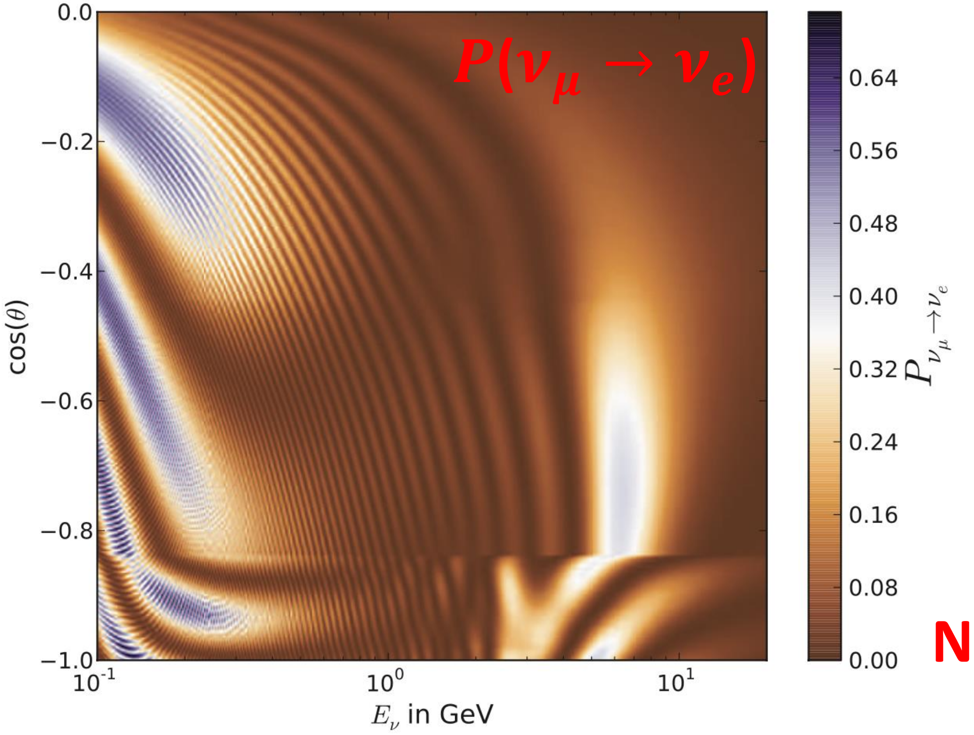

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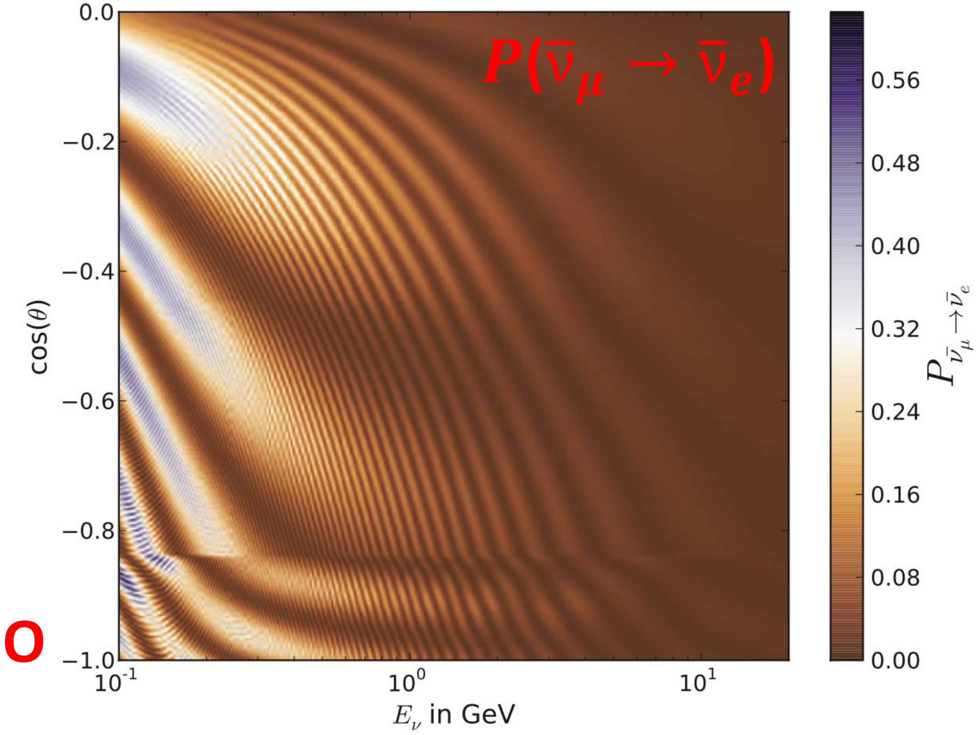

Neutrino Mass Ordering (with Atmospheric Neutrinos)

With matter effect:

- $\boldsymbol{P_{NO}(\nu_\alpha \to \nu_\beta) = P_{IO}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$
- Resonance E_ν^{atm}: 3-10 GeV
- Signal channel: **Charged Current (CC)**
- Background: Neutral Current (NC), cosmic muons

ν ($\bar{\nu}$: A ➔ -A)

[JUNO Physics Book: *J. Phys. G43:030401 (2016)*]

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m^2_{31})^m \frac{L}{E_\nu}\right]$$

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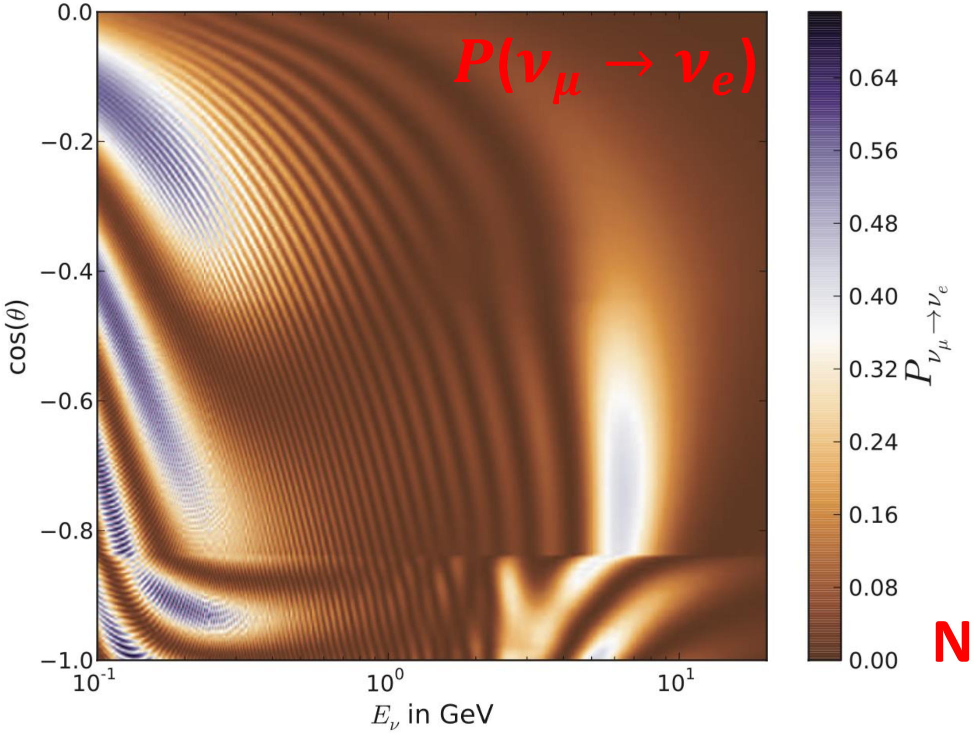
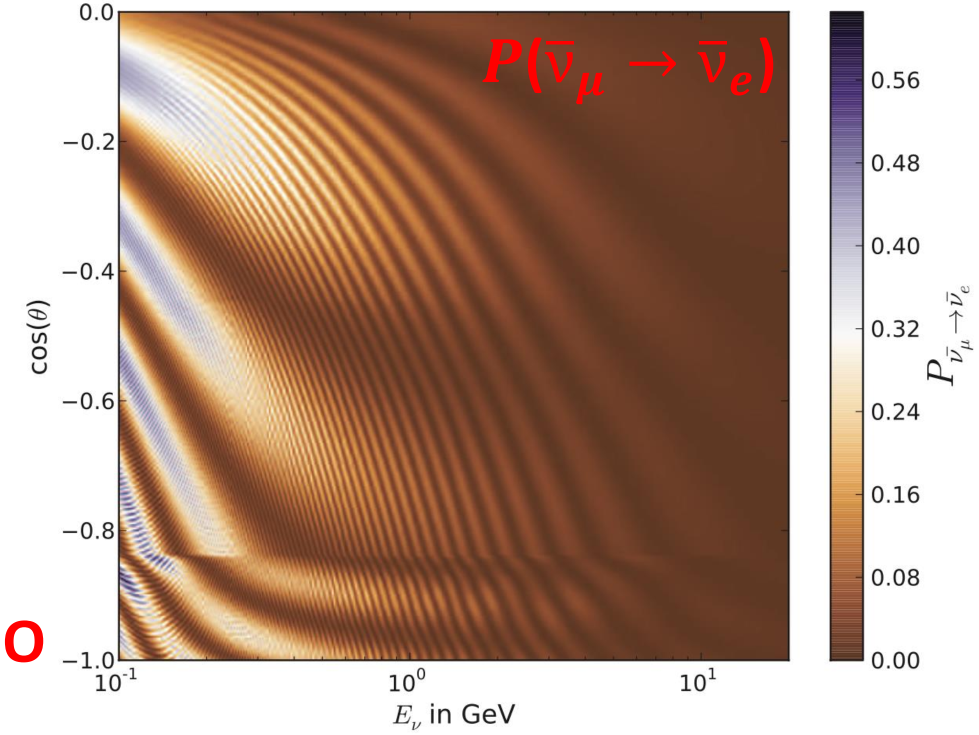


NO



Neutrino Mass Ordering (with Atmospheric Neutrinos)

- 78% geometric coverage offers great potential in **PID**, **direction** and **energy** reconstruction

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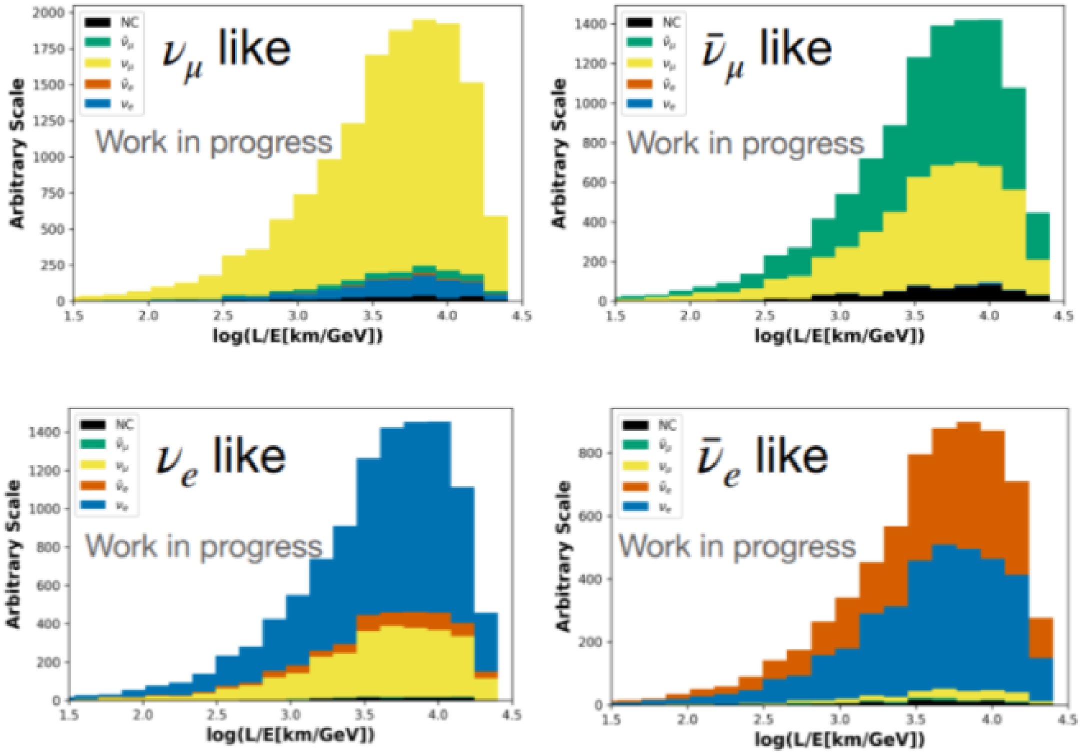

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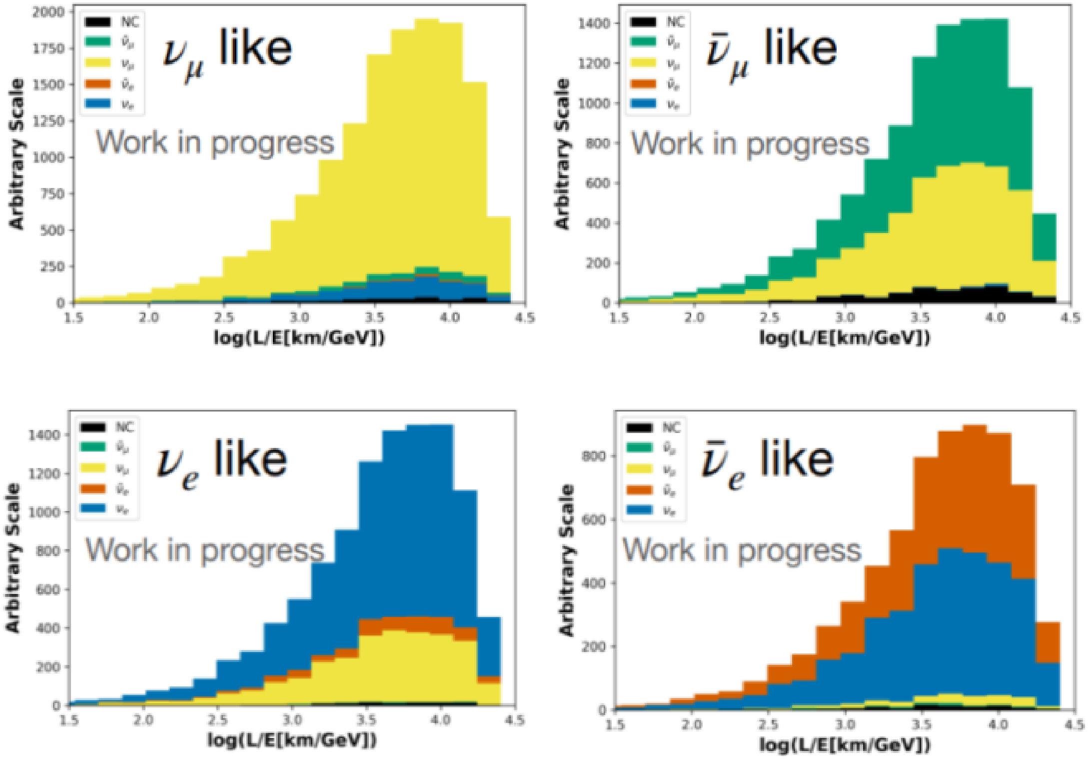

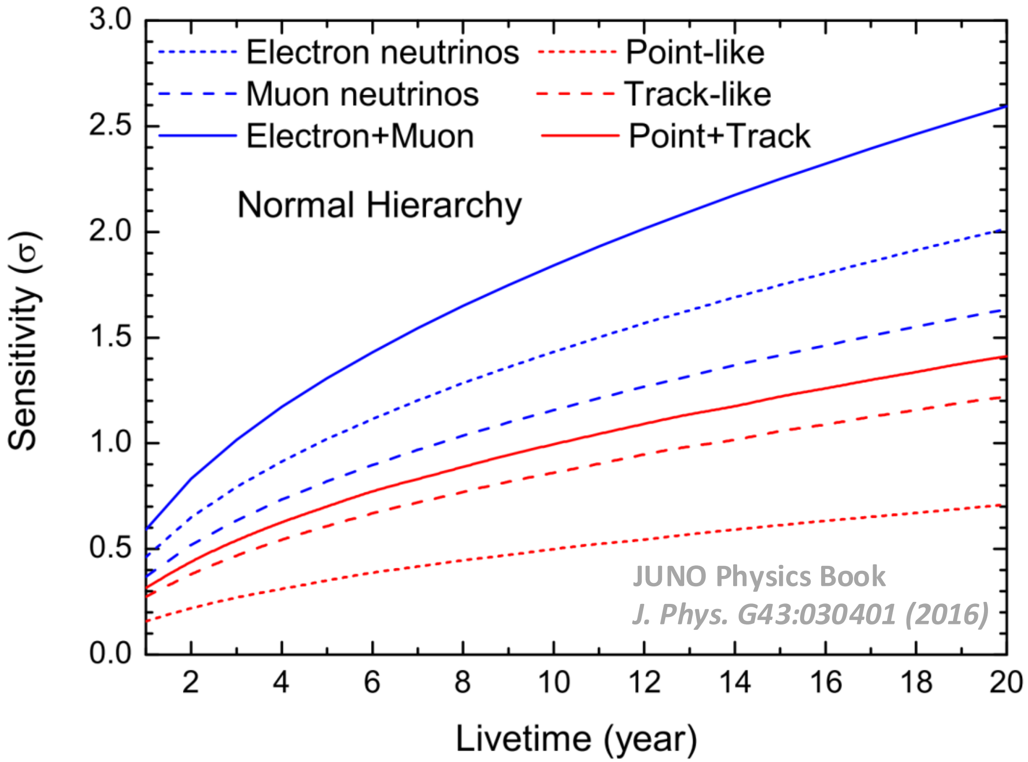

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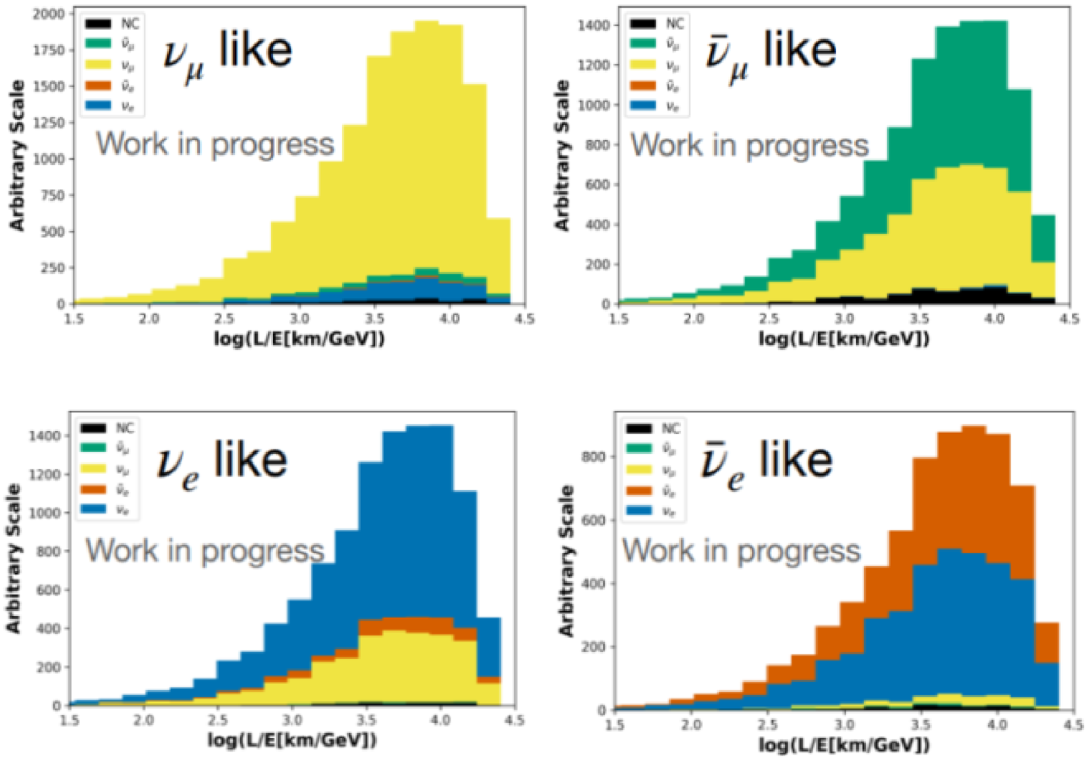
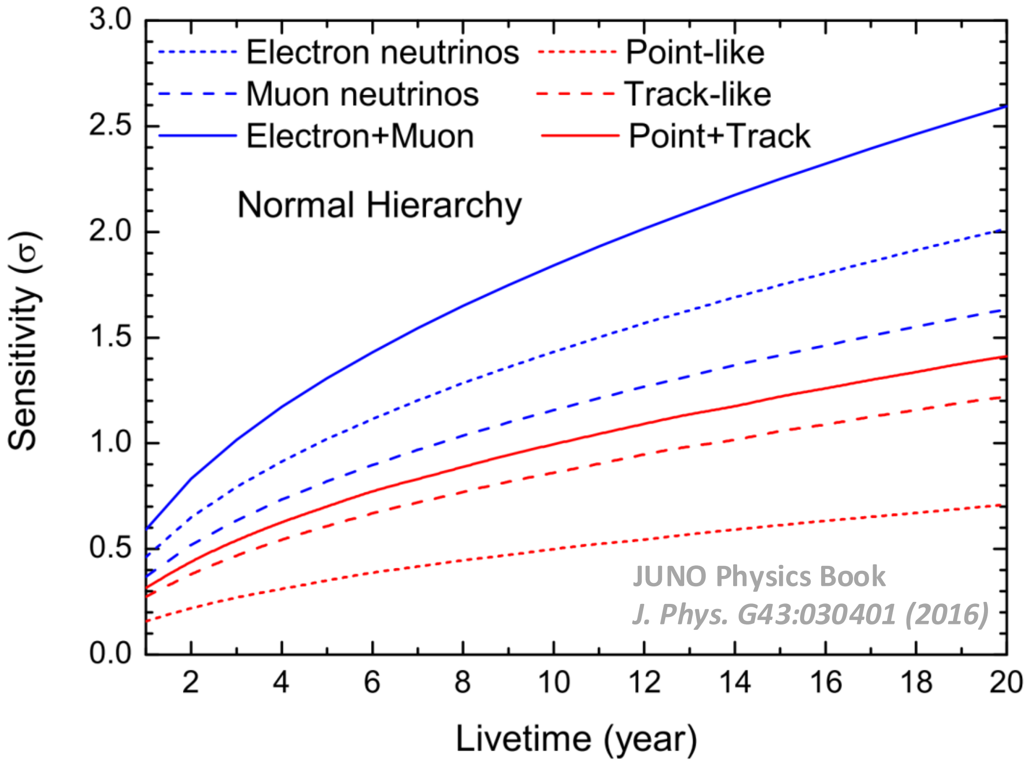


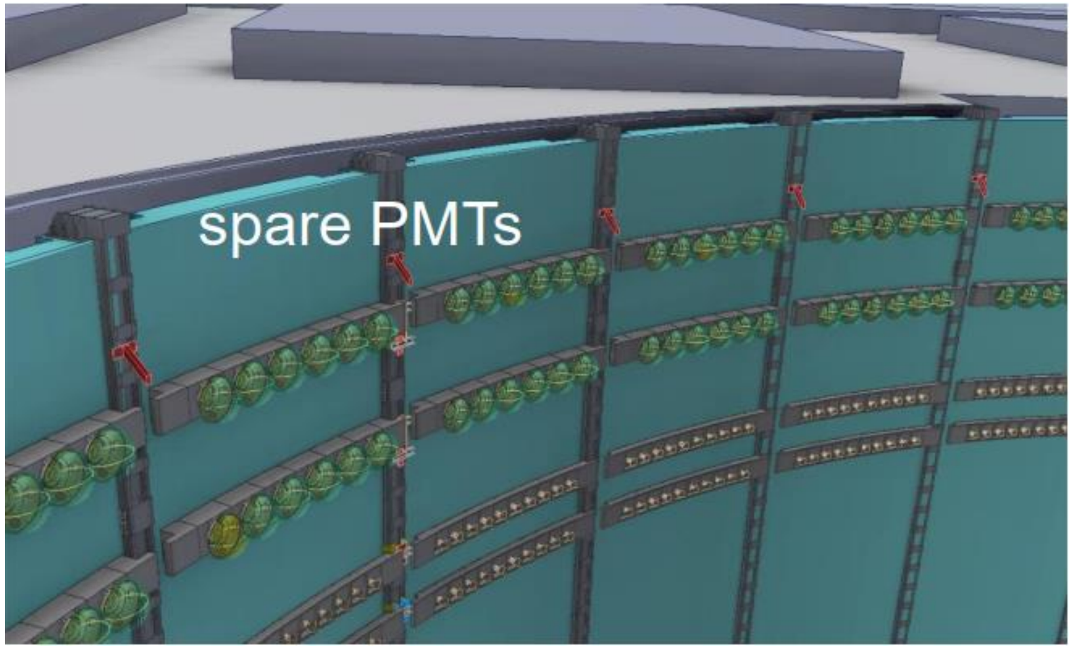


Neutrino Mass Ordering (with Atmospheric Neutrinos)

- 78% geometric coverage offers great potential in **PID**, **direction** and **energy** reconstruction

- e/μ separation
- ν/$\bar{\nu}$ separation
- ν energy
- track direction

- **0.8-1.4σ** on NMO @ 6 years with atm ν only
- Combine reactor + atmospheric ν to boost NMO sensitivity
- Install spare PMTs on top of water pool to **improve PID and direction** reconstruction



JUNO: A Multipurpose Neutrino Observatory

- Reactor neutrino
- Atmospheric neutrino

JUNO Physics Book: *J. Phys. G43:030401 (2016)*

JUNO: A Multipurpose Neutrino Observatory

- Reactor neutrino
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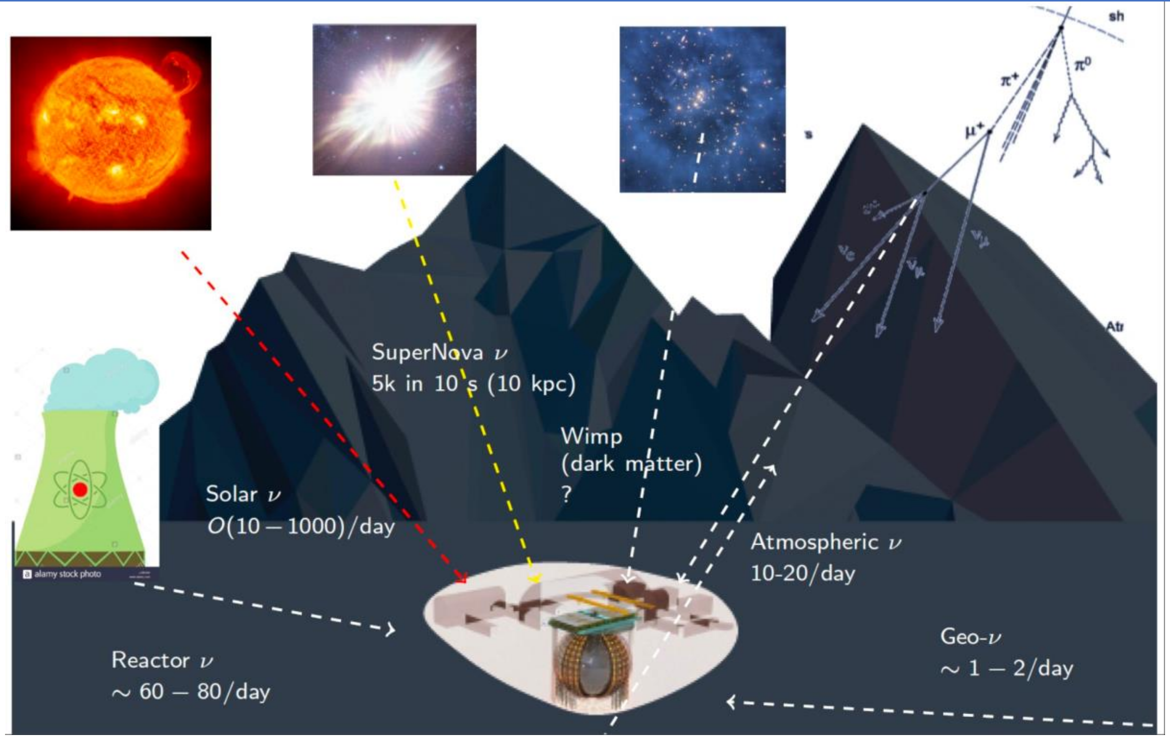
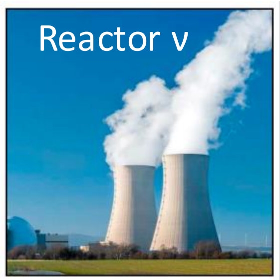
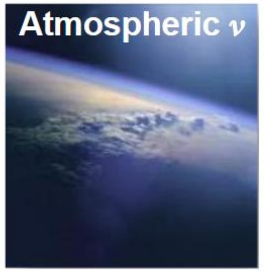
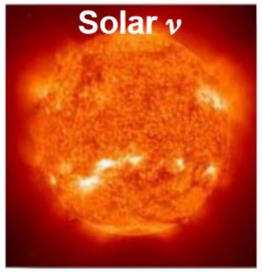
- Solar neutrino
- Geoneutrino
- Supernova neutrino





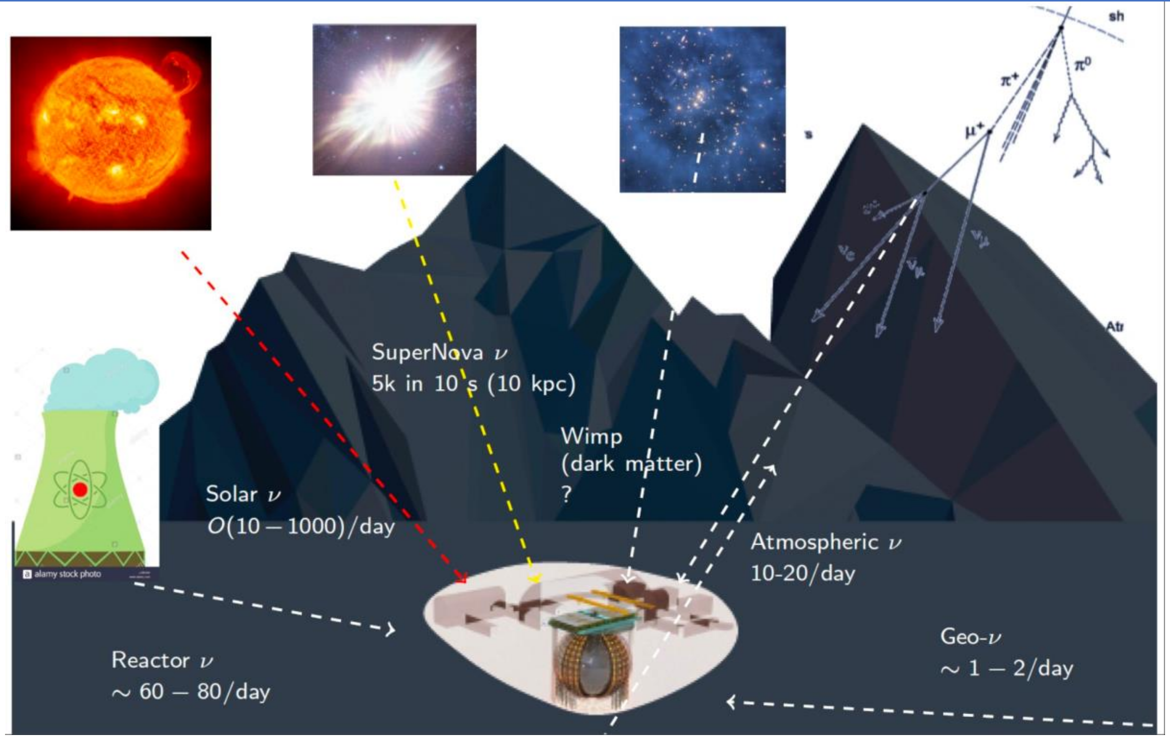


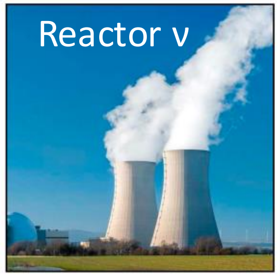


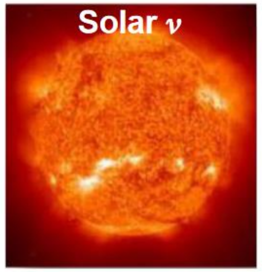
JUNO Physics Book: *J. Phys. G43:030401 (2016)*

JUNO: A Multipurpose Neutrino Observatory

- Reactor neutrino
- Atmospheric neutrino
- Solar neutrino
- Geoneutrino
- Supernova neutrino
- Sterile neutrino
- Nucleon decay
- Dark Matter
- 0νββ (in next generation)







+ **New Physics**

JUNO Physics Book: *J. Phys. G43:030401 (2016)*

High Energy Solar Neutrino (^8B)

[JUNO paper: *Astrophys. J 965, 122 (2024)*]

- ^8B ν to measure solar oscillator parameters:
  - Channel: ES (dominated) + CC + NC

ES:	$\nu_x \pm e^- \rightarrow \nu_x + e^-$
CC:	$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$
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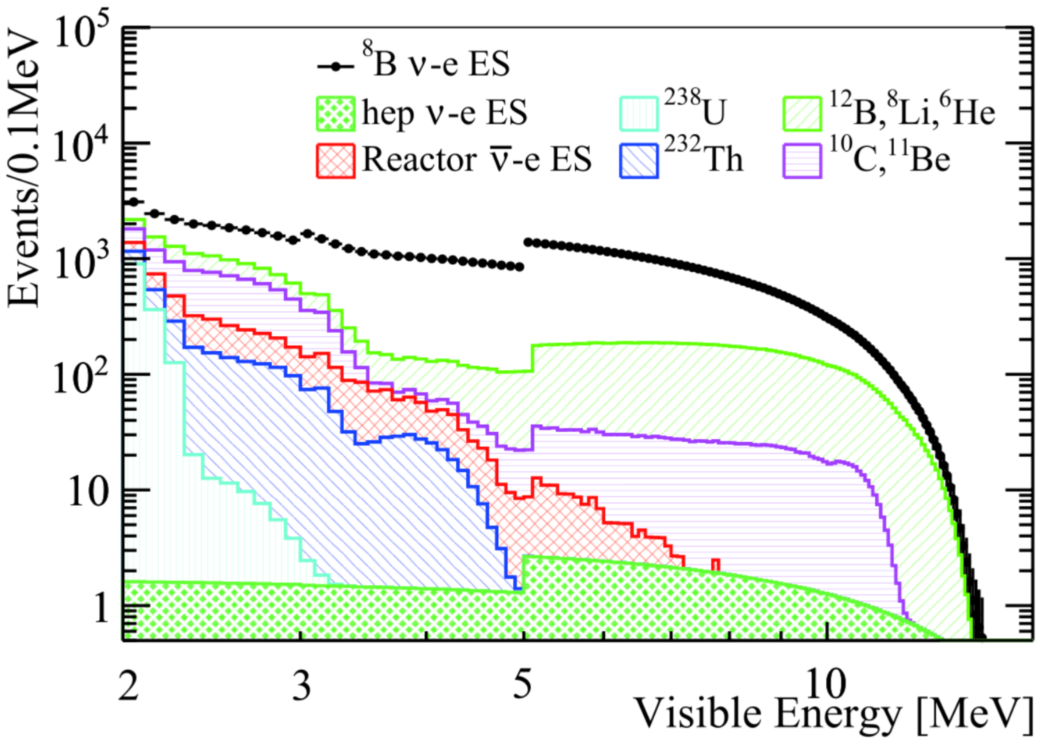

High Energy Solar Neutrino (^{8}B)

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- ^{8}B ν to measure solar oscillator parameters:
- Channel: ES (dominated) + CC + NC
- Signal / background: 60k / 30k (in 10 years)
- ^{8}B flux: 5% (3% w/ SNO) **$\sin^2\theta_{12}$: 8%** **Δm^2_{21} : 20%**
- Measure reactor and solar ν to solve the tension

ES:	$\nu_x \pm e^- \rightarrow \nu_x + e^-$
CC:	$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$
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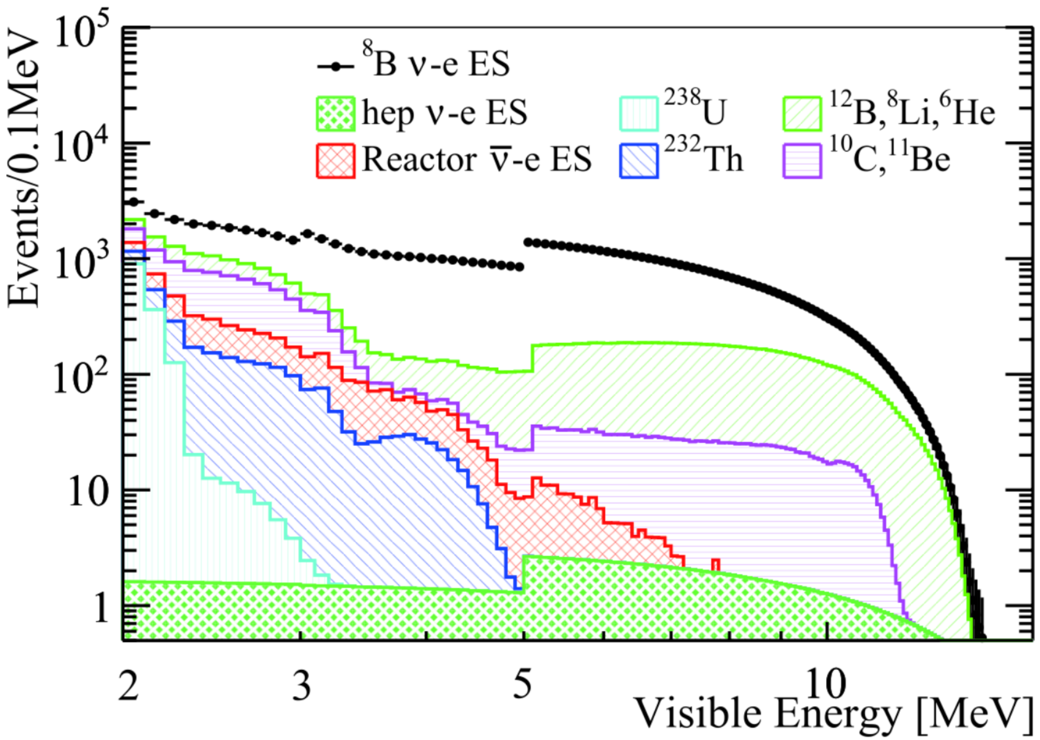
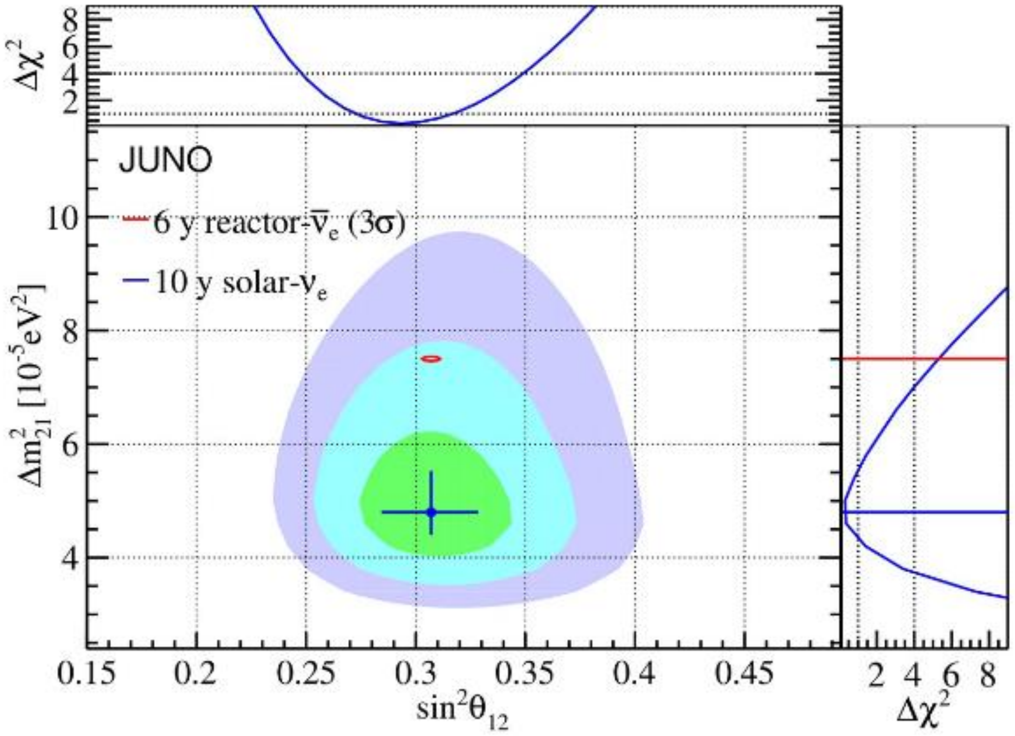
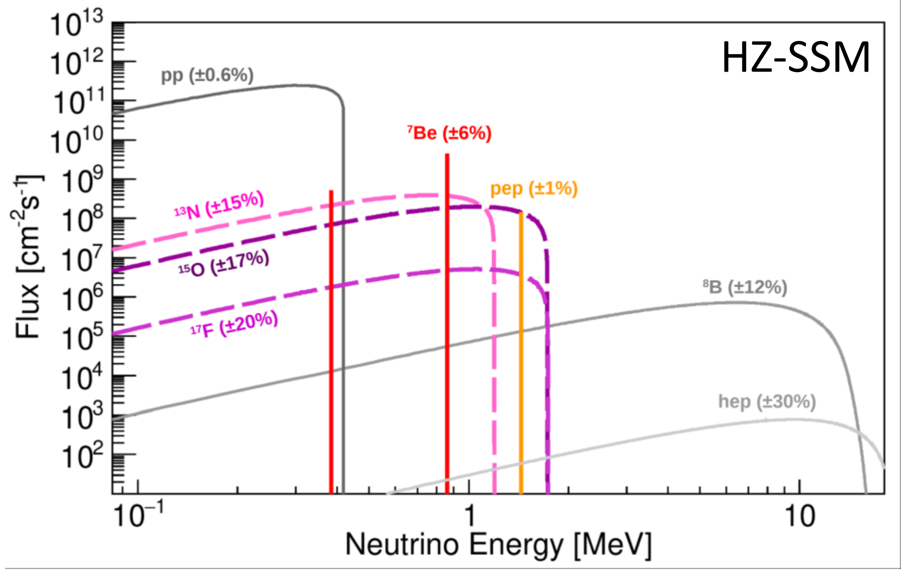




Intermediate Energy Solar Neutrino

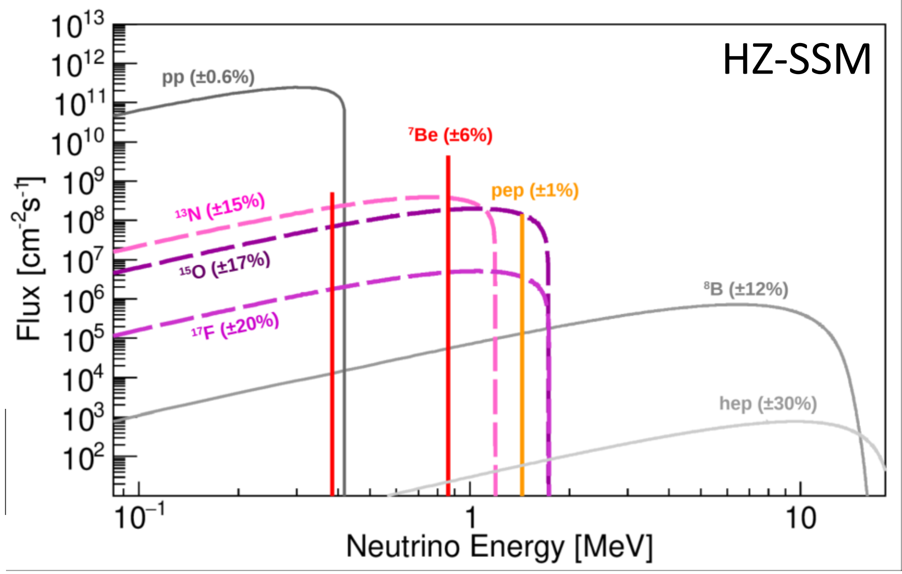
- Good sensitivity to ^{7}Be, pep and CNO neutrinos <2 MeV
  - Improve the understanding of ν-emitting solar processes



[JUNO paper: *JCAP 10(2023) 022*]

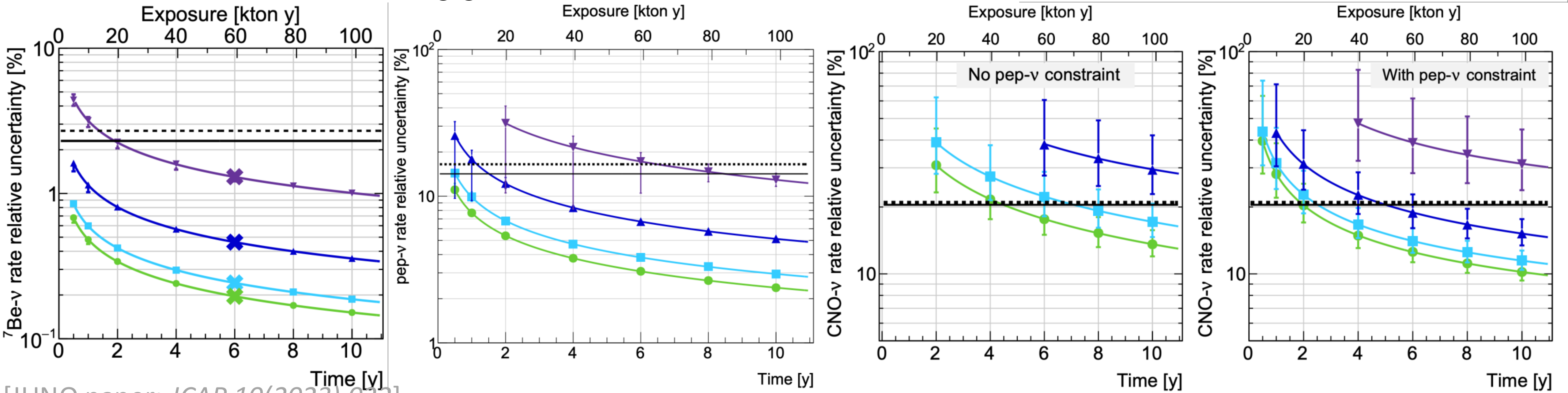
Intermediate Energy Solar Neutrino

- ■ Good sensitivity to ^{7}Be, pep and CNO neutrinos <2 MeV
- ➢ Improve the understanding of ν-emitting solar processes
- ➢ First CNO measurement without external constraints
- ➢ Improve Borexino results on ^{7}Be and pep in 1-2 years



Radiopurity scenario of ^{238}U, ^{232}Th in LS

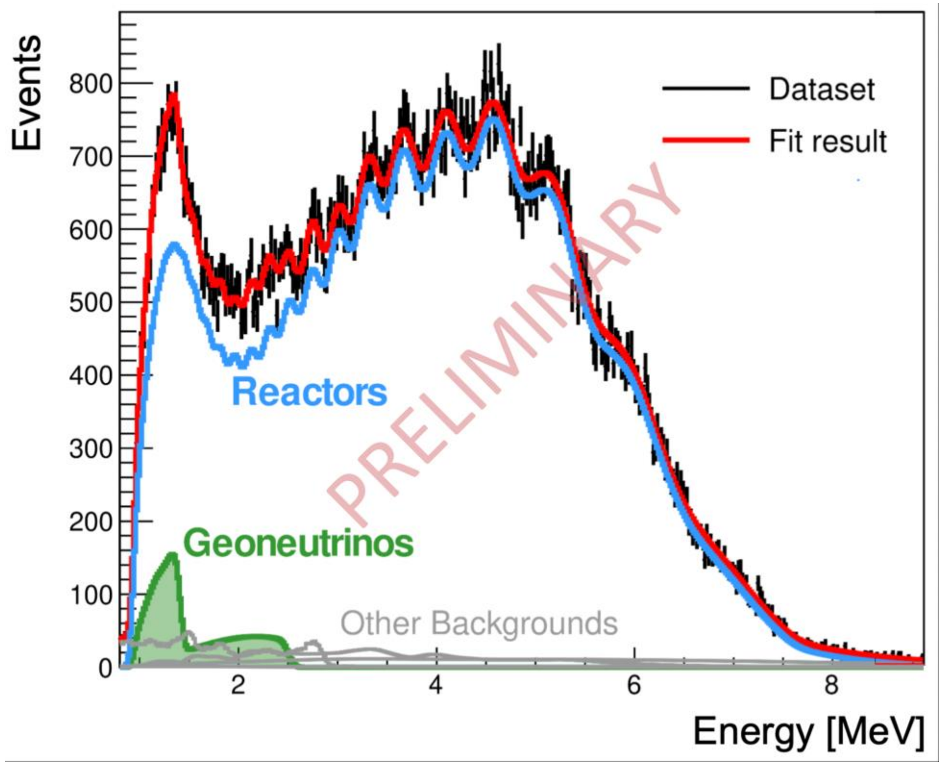
Very Low 10^{-19} g/g | Low 10^{-17} g/g | Medium 10^{-16} g/g | High 10^{-15} g/g | BX stat. | BX stat.+syst.



[JUNO paper: *JCAP 10(2023) 022*]

Geoneutrino

- Neutrinos from U/Th inside the Earth
- JUNO will collect the largest dataset of geo-ν: 1~2 events/day
- Precision of ~8% in 10 years with fixed U/Th ratio
  - In comparison: KamLAND ~15%, Borexino ~17%
- Leading precision of U and Th components



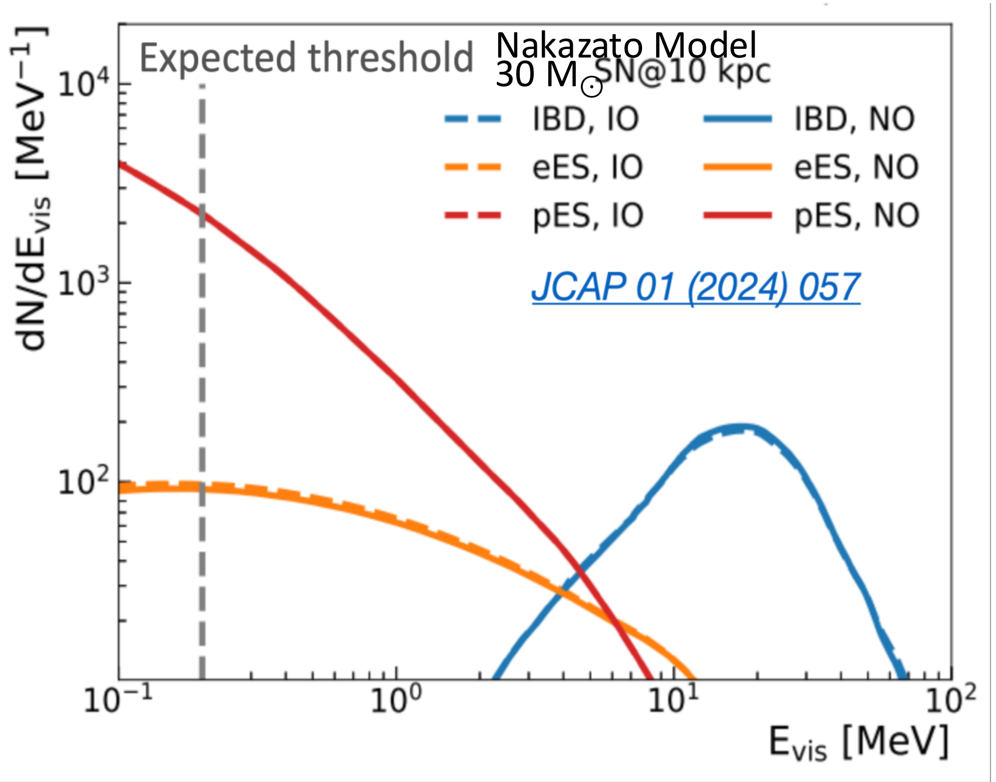
10 years, no assumption on Th/U ratio:

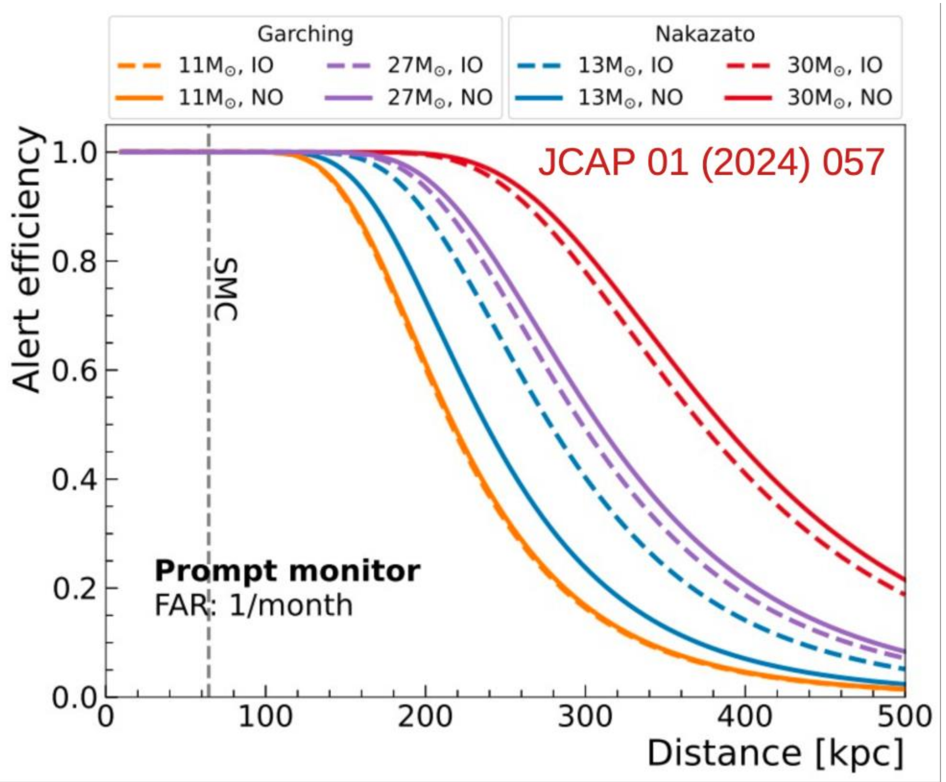
^{232}Th	~35%
^{238}U	~30%
^{232}Th+^{238}U	~15%
^{232}Th/^{238}U	~55%

PRELIMINARY

Supernovae (SN) Neutrino

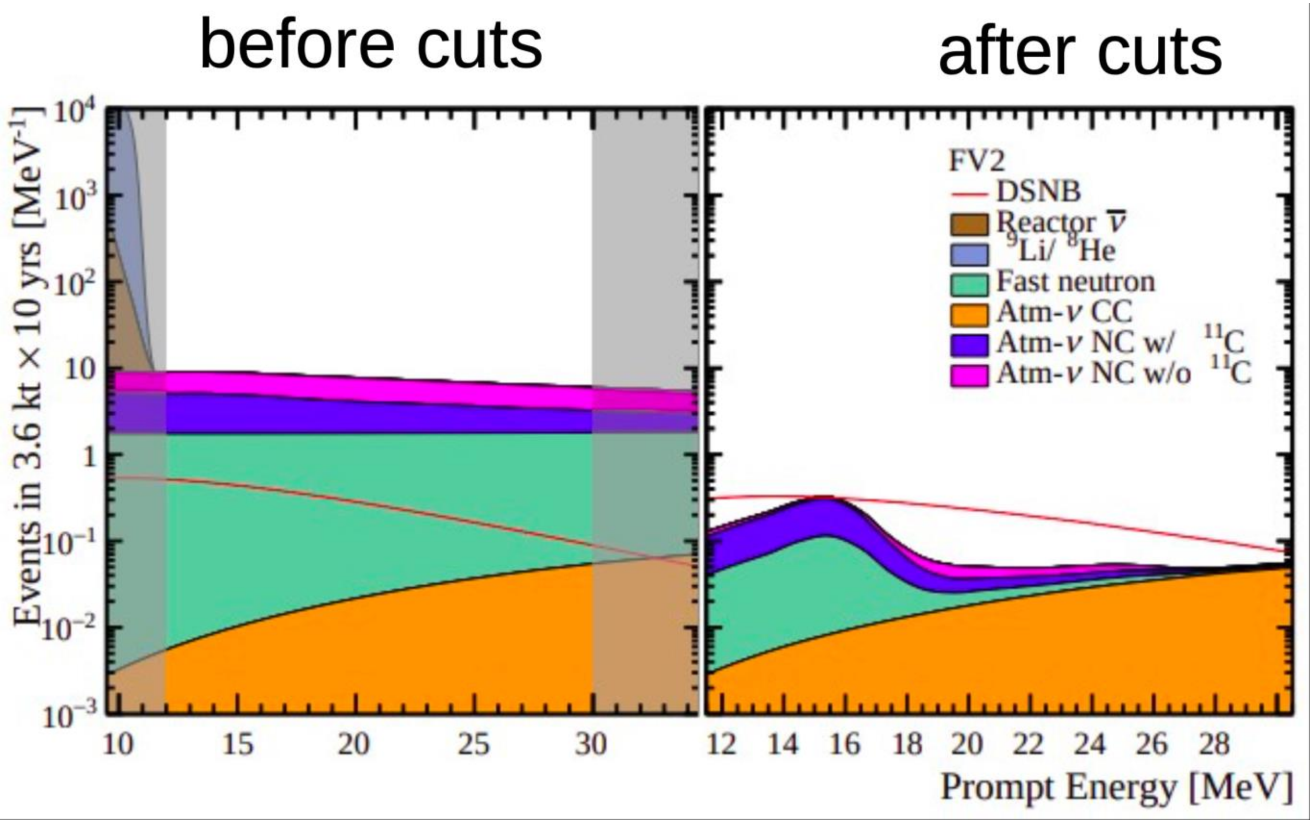
- ■ 3 detection channels sensitive to all flavors
- ➢ ~10^4 events (5k IBD) for a typical SN @ 10 kpc
  - Prompt monitor can identify signal in 10-30 ms
- ➢ Excellent capability of early warning: >90% of core-collapsed SN (CCSN) at d<200-300 kpc
- ➢ Be able to determine flavor content, energy spectrum and time evolution of SN burst ν





Diffused Supernova Neutrino Background (DSNB)

- Superposition of ν from all past SN explosions (yet to be observed)
- Selection: [12,30] MeV with fiducial volume cut & pulse shape discrimination
- ➢ S/B ratio improved from 2 to 3.5



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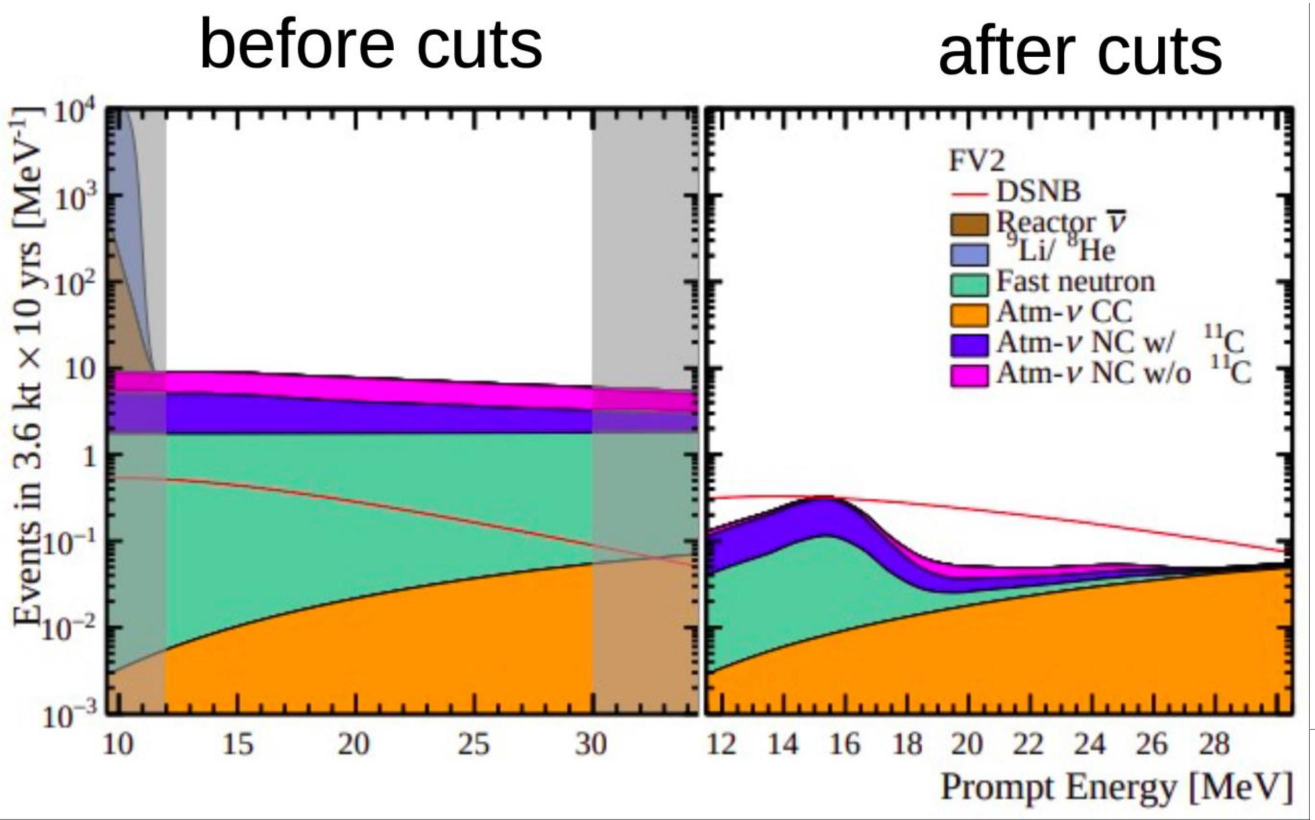
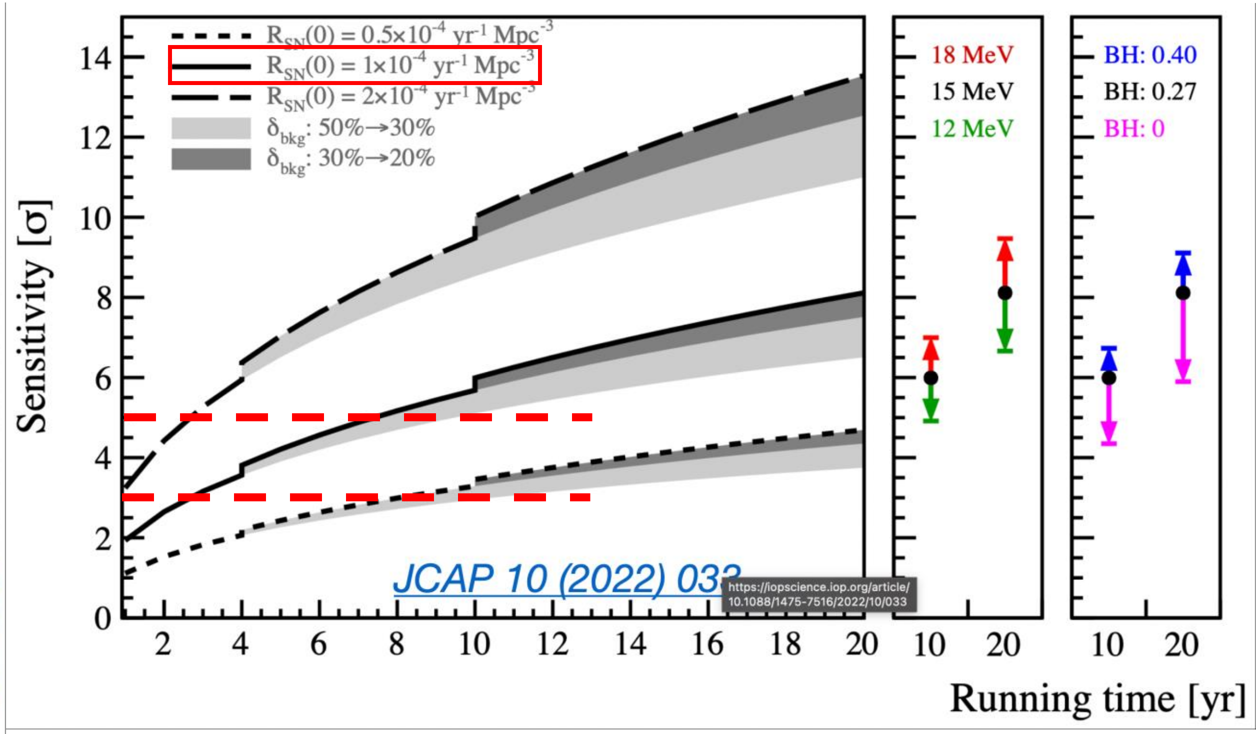
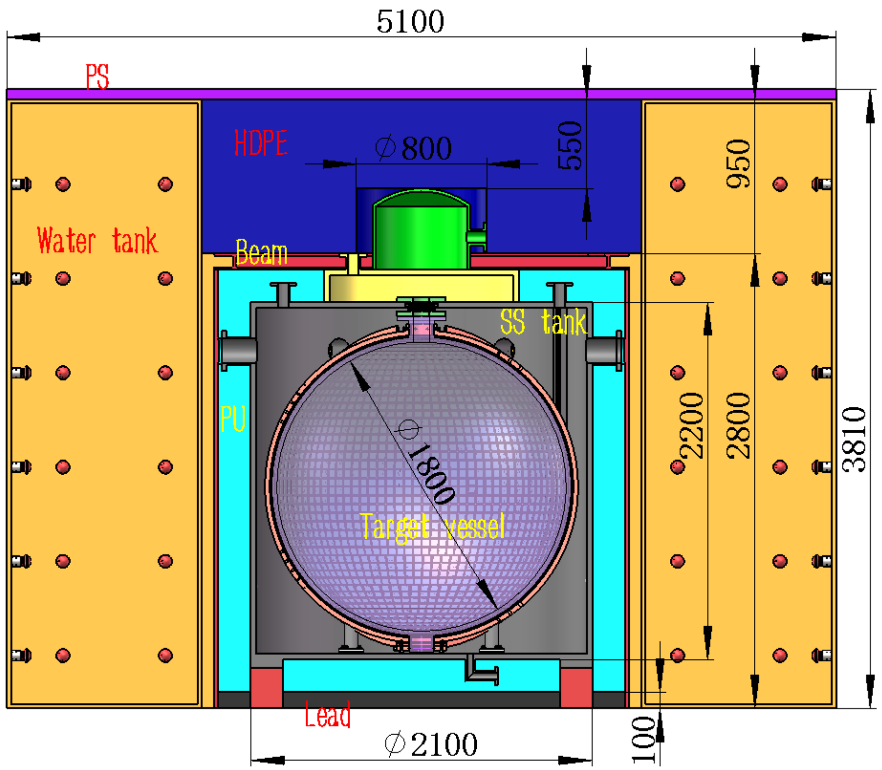
- S/B ratio improved from 2 to 3.5
- 3σ (>5σ) detection significance in 3 (10) years of data for nominal model





Sterile Neutrino (at TAO)

- **T**aishan **A**ntineutrino **O**bservatory
  - 44 m from a 4.6 GW reactor
  - 2.8 ton Gd-dopped LS
  - 94% geometric-coverage of SiPM
  - Operated at -50 °C



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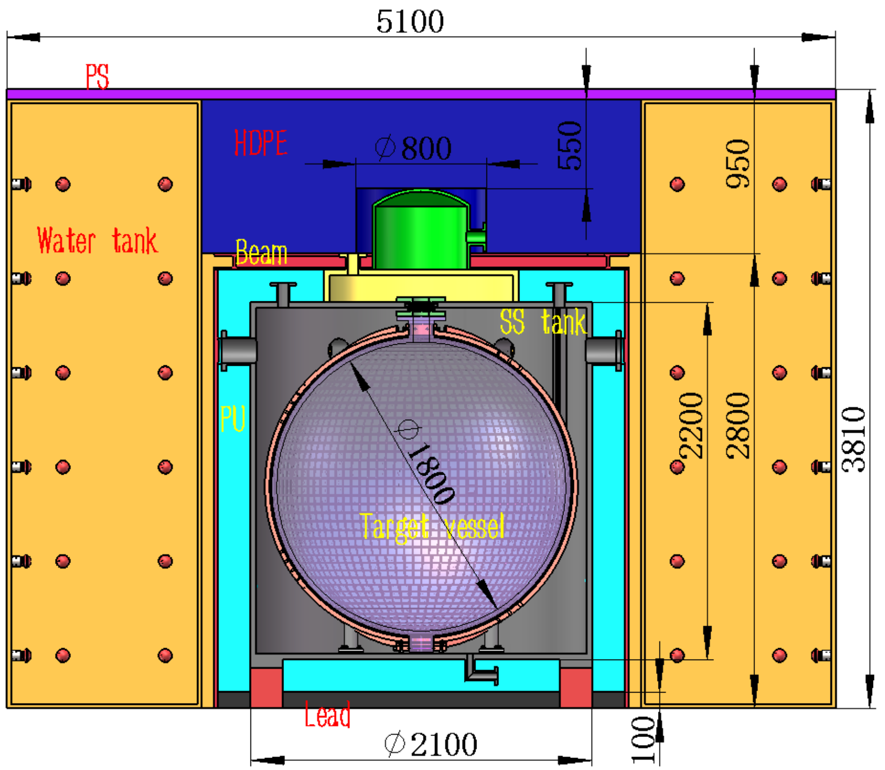
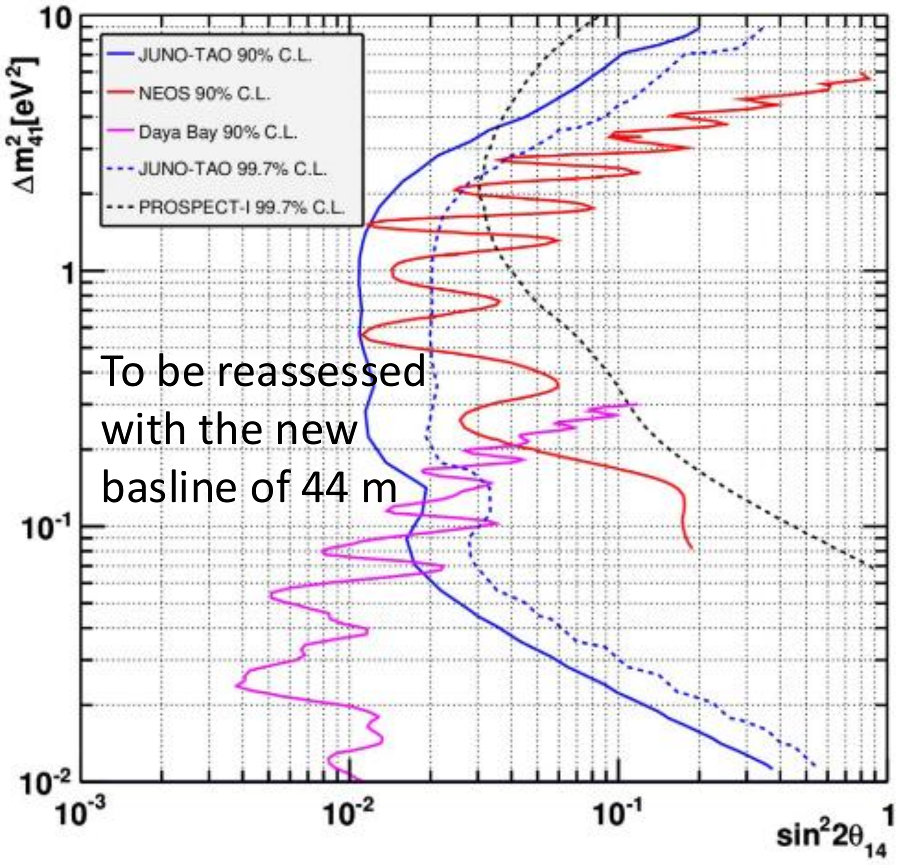


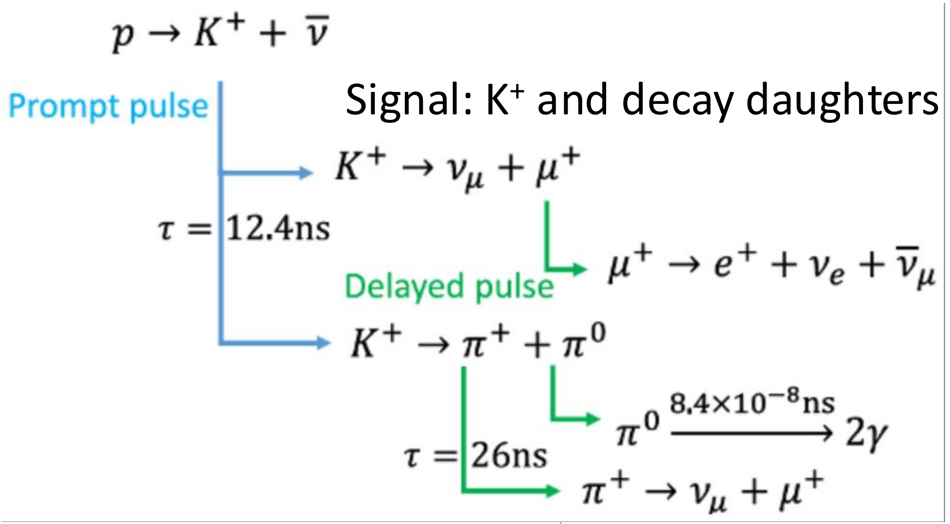
- ➢ sensitive to sterile neutrino
- ➢ Will provide new constraints in 0.1-3 eV^2 Δm^2 region



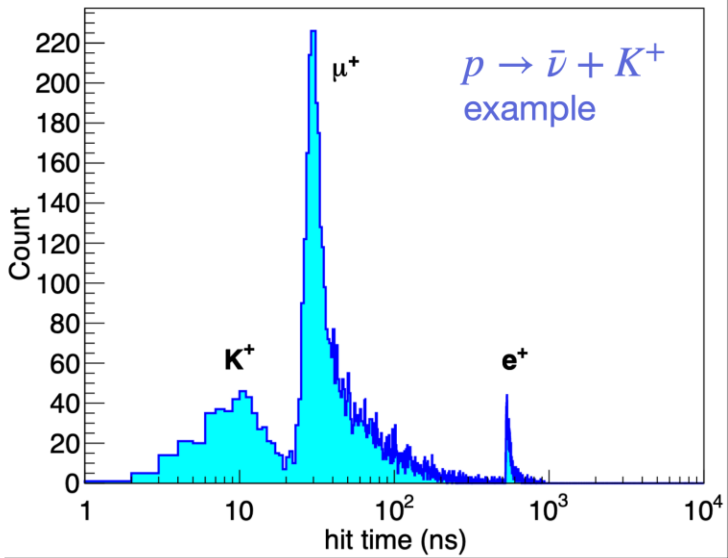
Nucleon Decay via triple coincidence

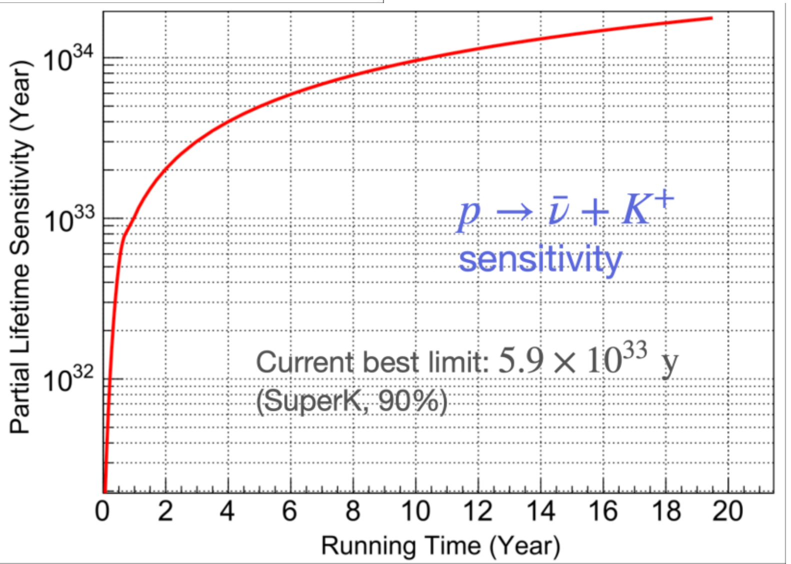
- 20 ktons of LS: 1.45 x 10^{33} free protons & 5.30 x 10^{33} bound protons/neutrons

Proton decay



CPC 47, 113002 (2023)





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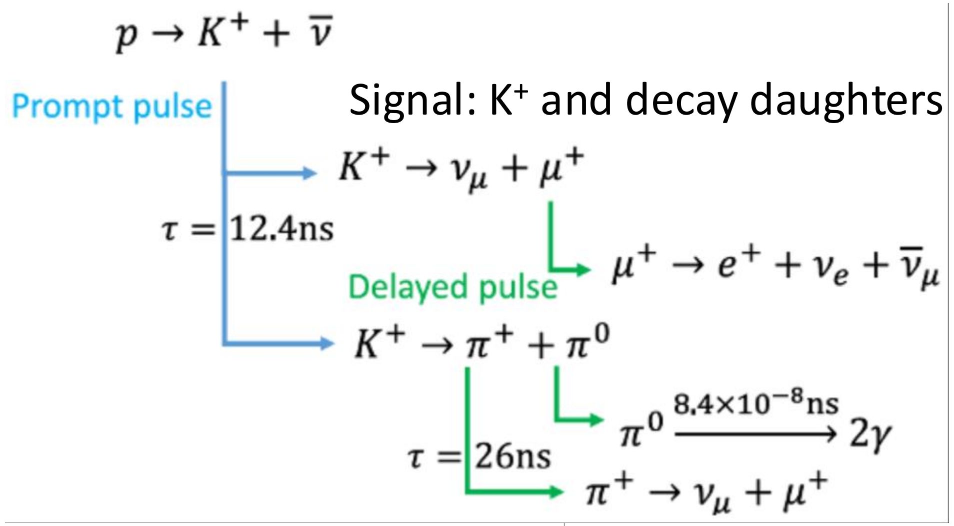
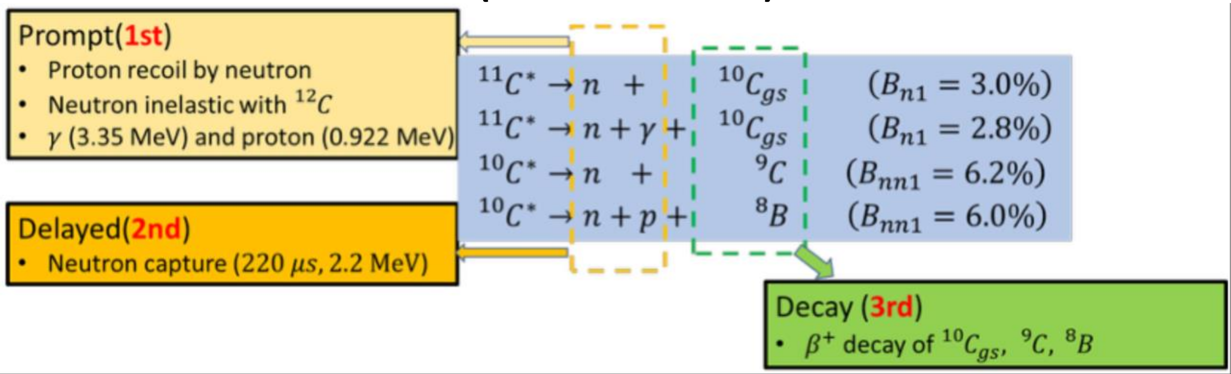


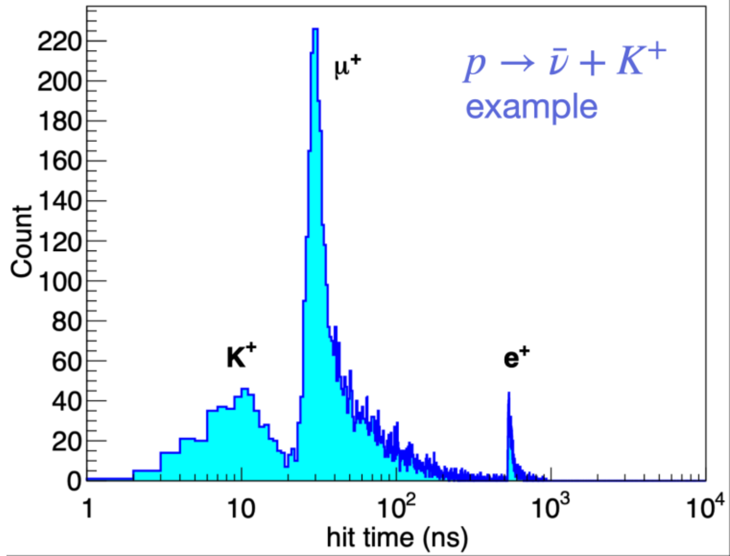
Neutron invisible decays

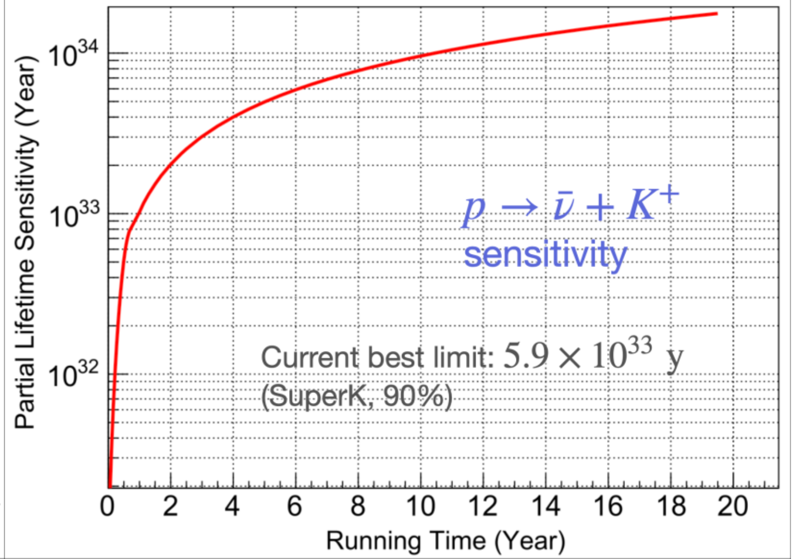
- n → *inv* (^{12}C → ^{11}C*)
- nn → *inv* (^{12}C → ^{10}C*)

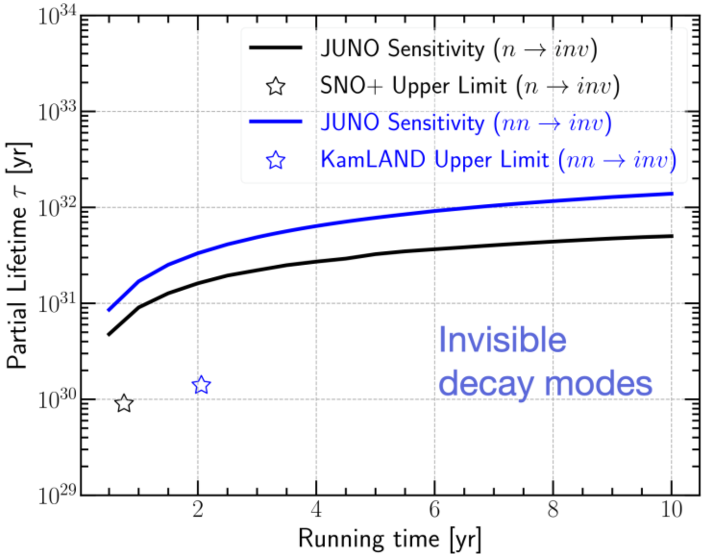
Signal: de-excitation of excited nucleus



CPC 47, 113002 (2023)



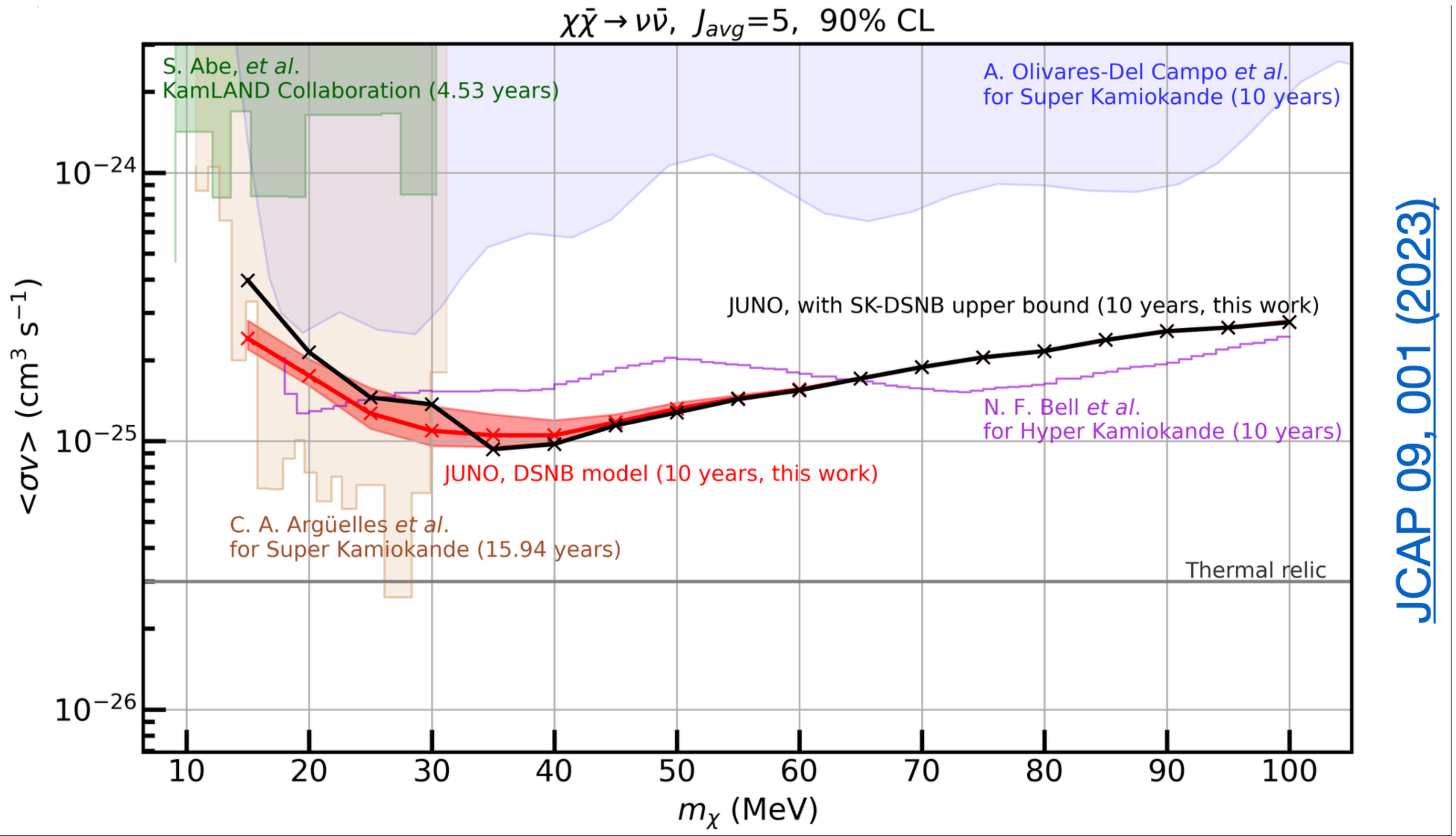




EPJC 85, 5 (2025)

Dark Matter

- Leading sensitivity to MeV dark matter annihilation in the galactic halo
- Look for monochromatic neutrinos ($E_\nu = m_\chi$) from $\chi\chi \rightarrow \nu\bar{\nu}$ decays
- Get power from energy resolution and pulse shape dicrimination

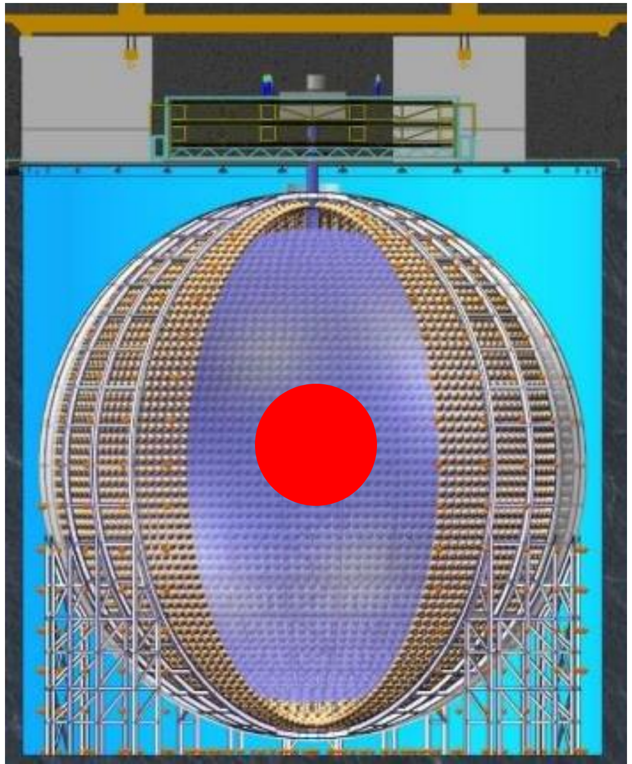


JCAP 09, 001 (2023)

0νββ in Next Generation of JUNO

- JUNO could be transformed into a 0νββ search experiment after 10 years
  - Key advantage: size, energy resolution
    - Aim for O(100 ton) scale loading of Te or Xe
  - R&D in progress
    - Goals: Te-loaded LS with high light yield, high transparency, long-term stability, low bkg

Insert a balloon filled with ^{136}Xe-loaded LS(or ^{130}Te) into the JUNO detector



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

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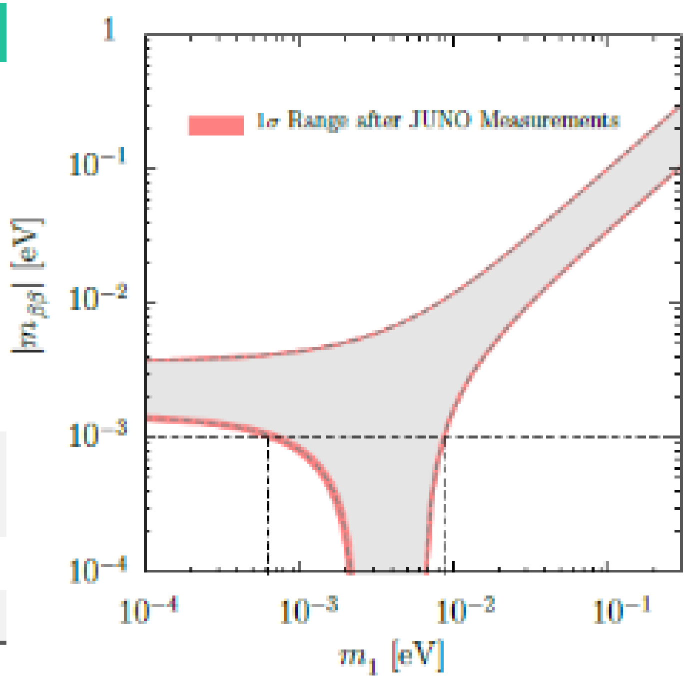
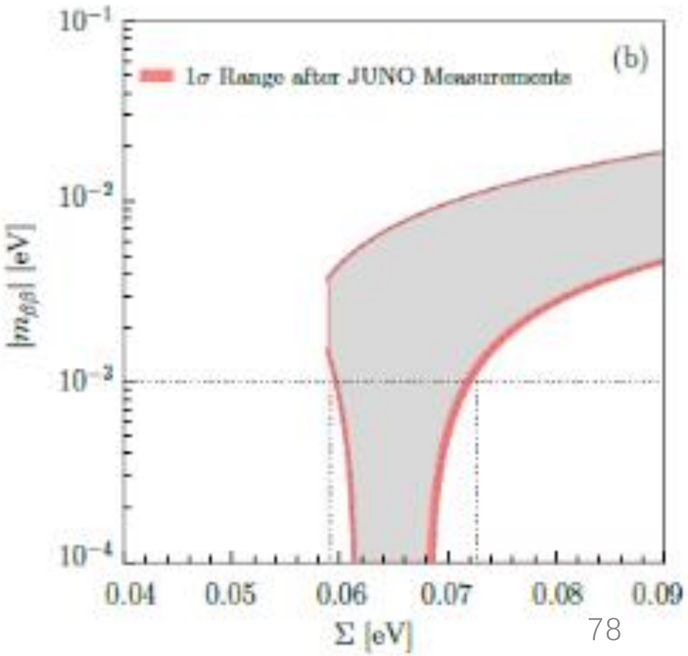
  - R&D in progress
    - Goals: Te-loaded LS with high light yield, high transparency, long-term stability, low bkg
  - Potential to explore normal mass ordering parameter space at lowest masses

	Isotope	Mass(t)	$\langle m_{\beta\beta}\rangle$,meV
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
Darwin/Panda-nT	^{136}Xe	3-5	7-22
LEGEND-1000/CDEX-1t	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO-ββ	^{136}Xe	50	4-10
	^{130}Te	100	3-14

J. Cao et al., arXiv:1908.08355





Status of JUNO

A Long Journey

Tunnel Digging

Project Start

2013

2015

Start of civil construction

A Long Journey

Tunnel Digging

Project Start

2013

2015

Start of civil construction

Beginning of detector installation

2022

2024 Dec 1

End of detector installation

Early Time of Detector Installation

A Long Journey

2013

Project Start

Tunnel Digging

2015

Start of civil construction

2022

Beginning of detector installation

Early Time of Detector Installation

2024 Dec 1

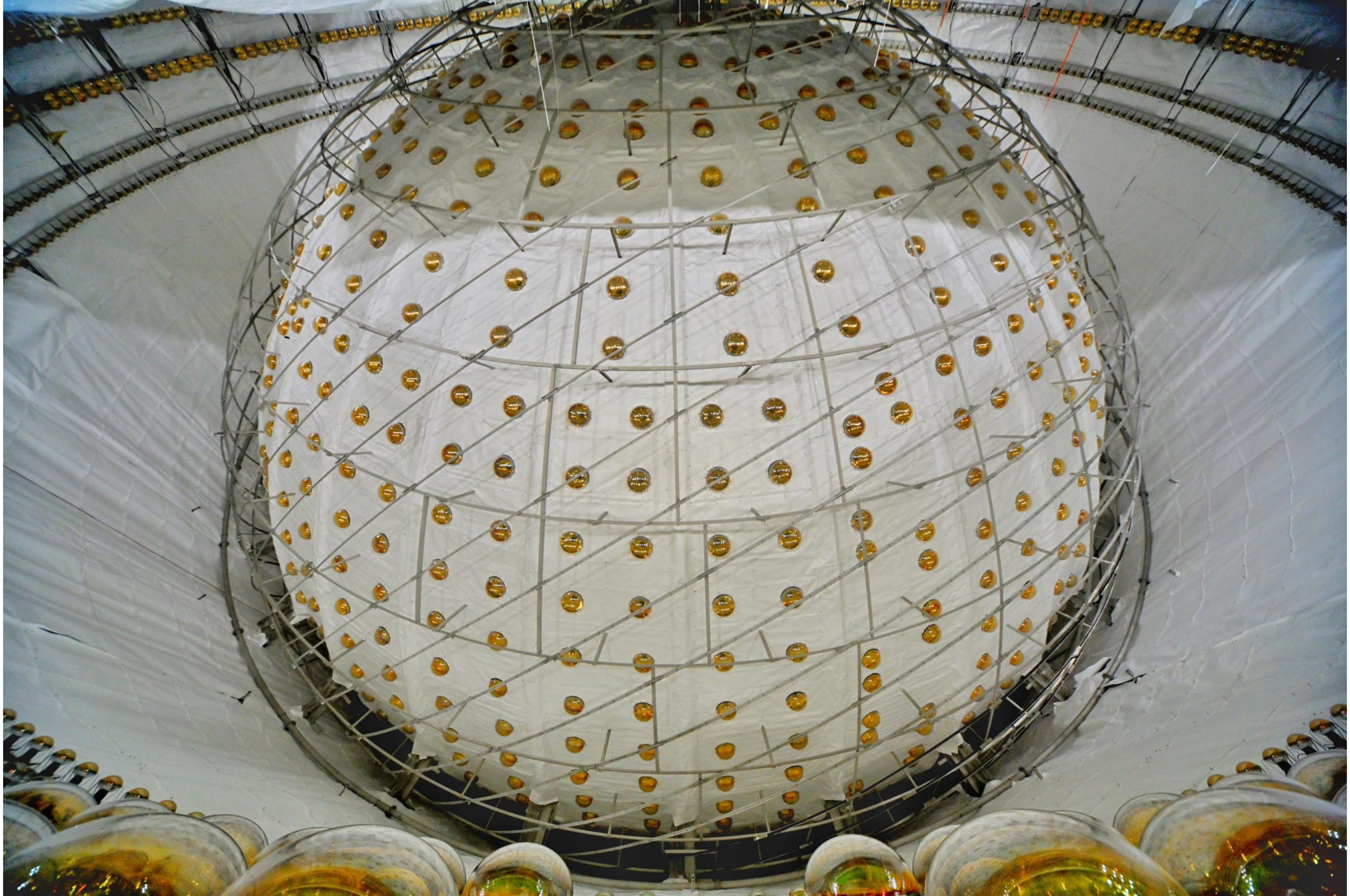
Inspection of bonding lines

End of detector installation

2024 Dec 17

Cleaning & installation of extra PMTs

Completion of acrylic vessel installation

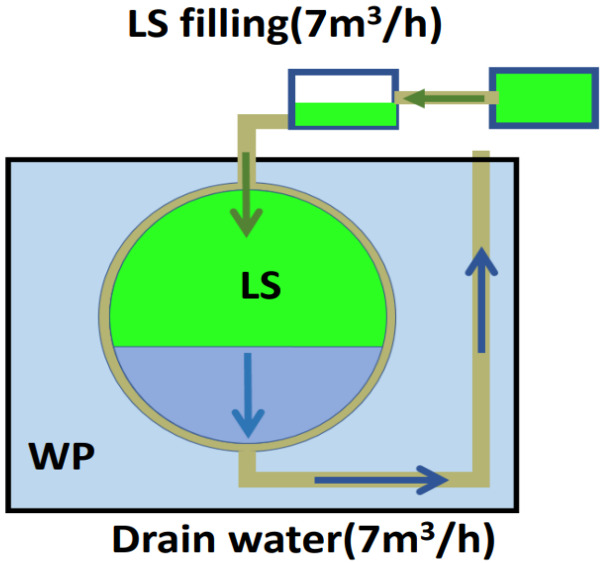


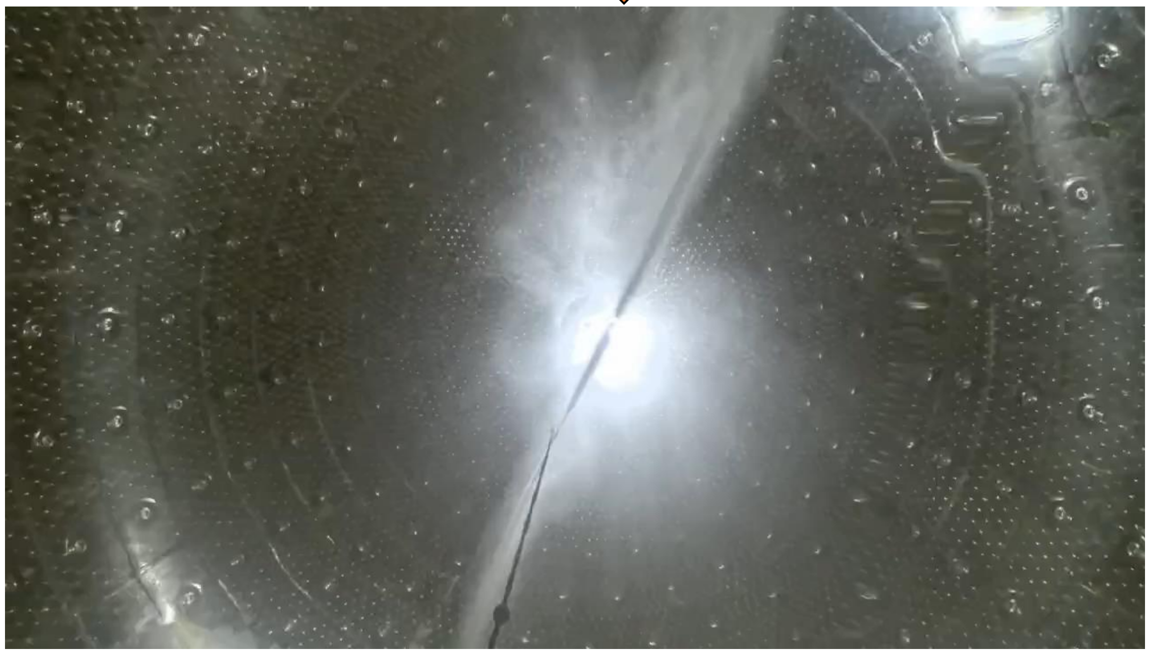
Final Cleaning & Filling Scheme

Reduce Rn, dust to class <1000

Complete CD construction → days settlement with proper moisture → Remove the protective film and wash the acrylic surface by the high pressure water spray → Fill CD and VETO by high purity water → replacing water in CD by LS

Water for CD: U/Th<10^{-15} g/g, ^{226}Ra<0.1 mBq/m^3
Water for VETO: U/Th<10^{-14} g/g





Liquid Scintillator Production

- Four purification plants designed to reach a radio-purity of **10^{-17}** g/g (U/Th) and **20 m** attenuation length at 430 nm

5000 m^3 LAB tank

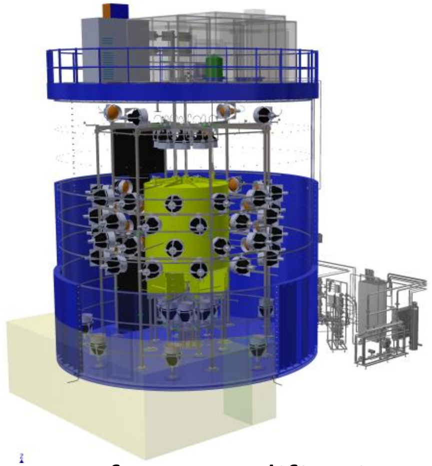
Al_2O_3 to remove particles

Distillation to remove radioactive impurities

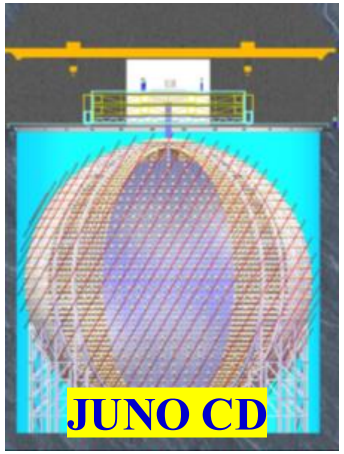
Add 2.5 g/L PPO and 3 mg/L bis-MSB

Water extraction to remove radioactive impurities

Gas stripping to remove Rn and O_2



OSIRIS for LS qualification



Water Filling Phase

Start of water filling

End of water filling

Calibration

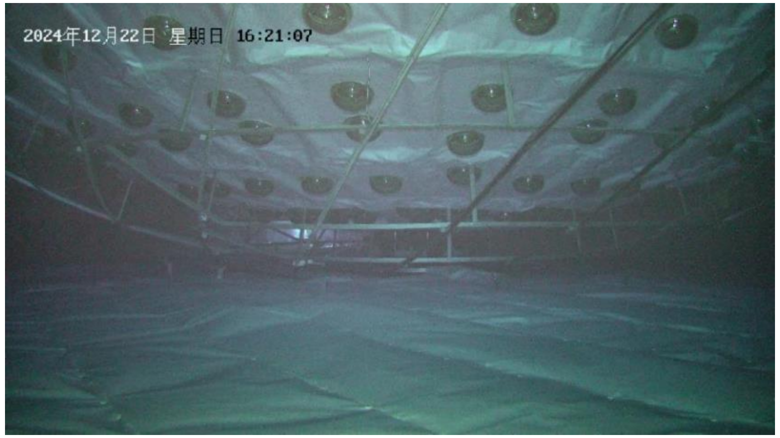
Test runs

Water Phase

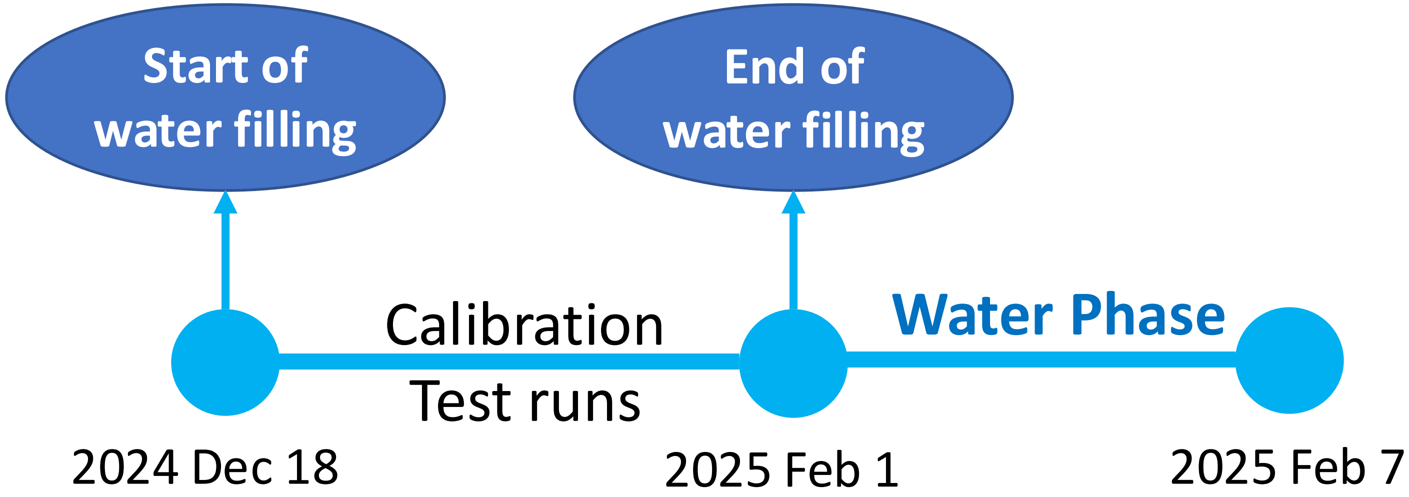
2024 Dec 18

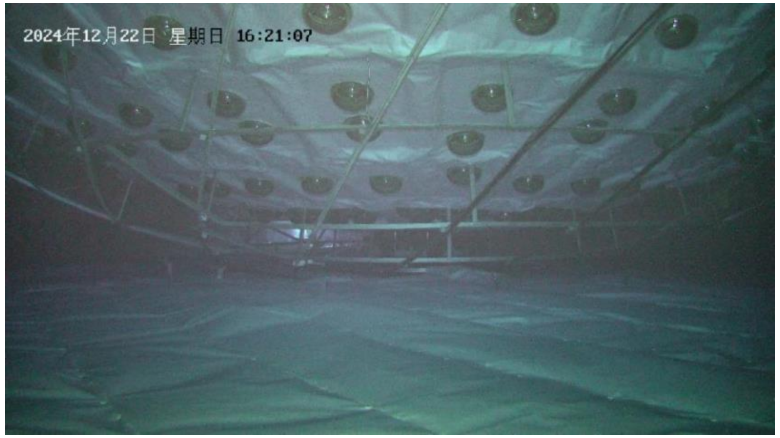
2025 Feb 1

2025 Feb 7



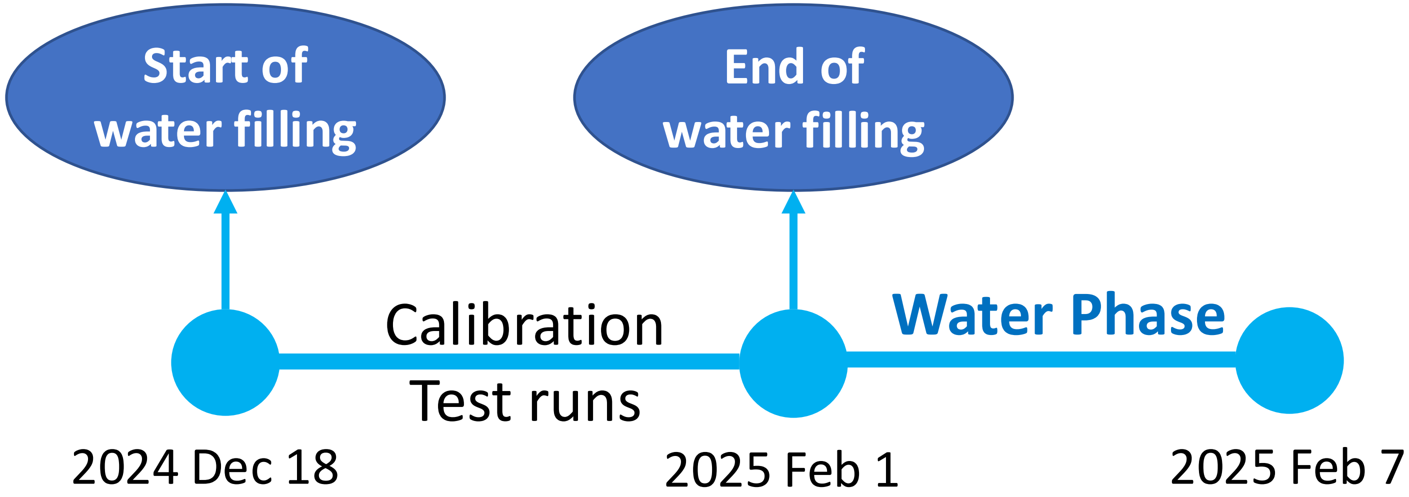
Water Filling Phase

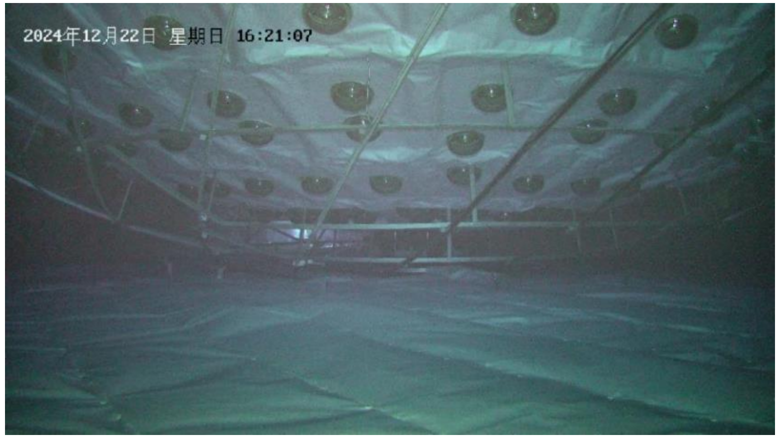


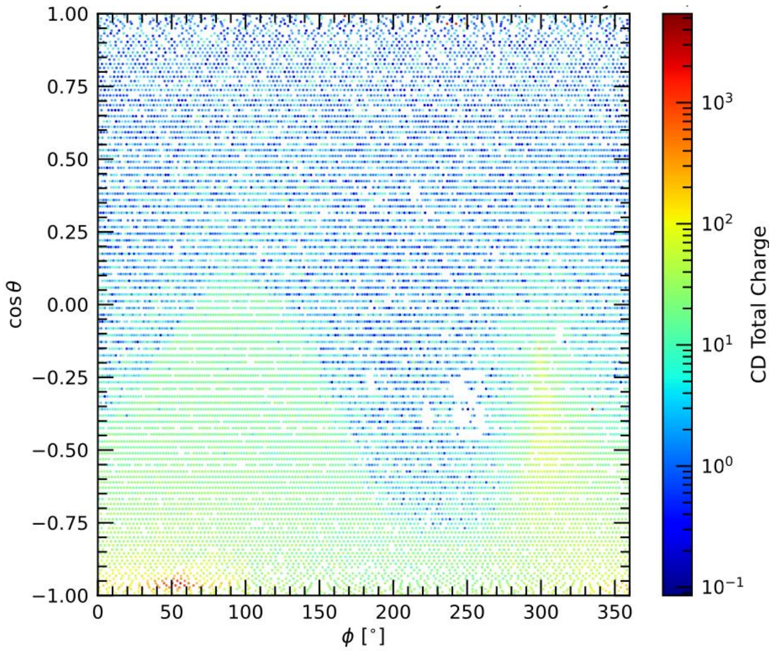


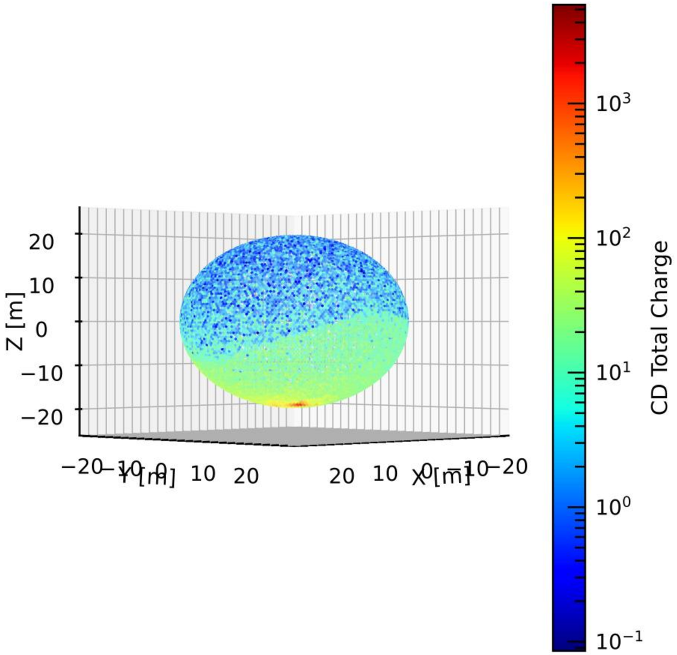
- Highlights:
  - Calibration of 20’’ PMTs (gain, time delays) with laser data
  - Small failure rate of 20’’ PMT: ~20/20k (0.1% loss during installation/due to high dark rate)
  - Calibration sources work as expected (Am-Be and Am-C) and used to probe low-energy threshold

Water Filling Phase



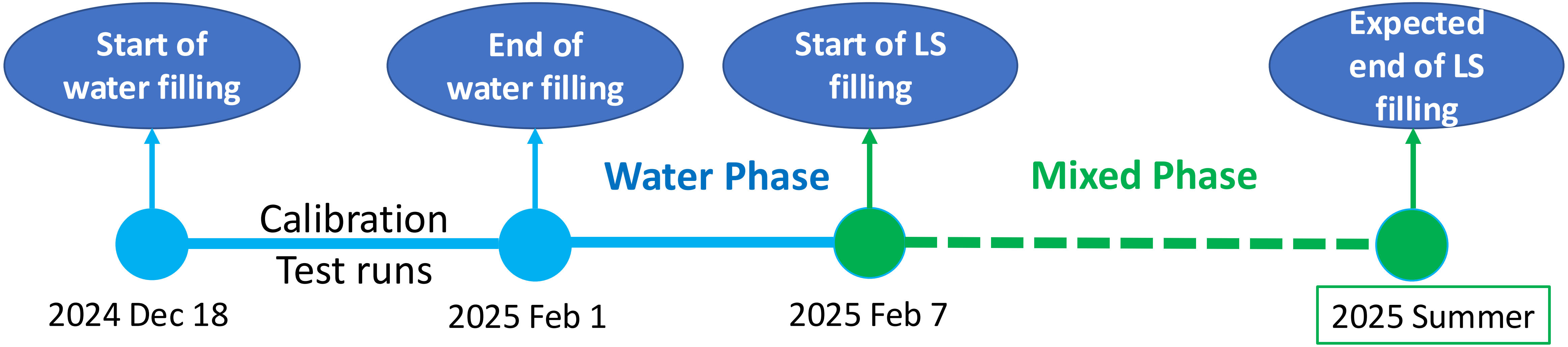






- **Highlights:**
  - Calibration of 20'' PMTs (gain, time delays) with laser data
  - Small failure rate of 20'' PMT: ~20/20k (0.1% loss during installation/due to high dark rate)
  - Calibration sources work as expected (Am-Be and Am-C) and used to probe low-energy threshold
  - Observe first muon events!

Current Phase: Liquid Scintillator Filling



Current Phase: Liquid Scintillator Filling

Start of water filling — 2024 Dec 18

Calibration

Test runs

End of water filling — 2025 Feb 1

Water Phase

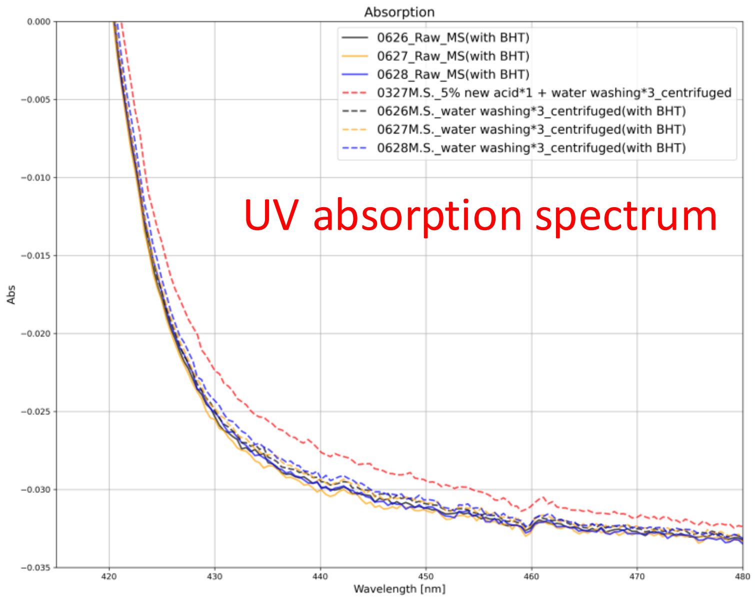
Start of LS filling — 2025 Feb 7

Mixed Phase

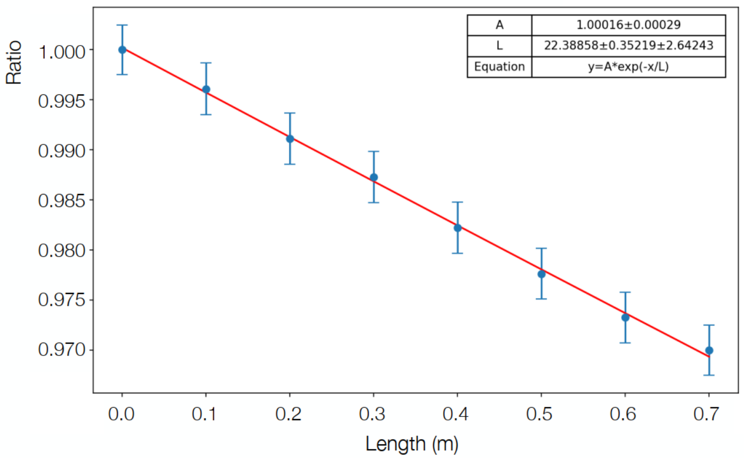
Intensive calibration

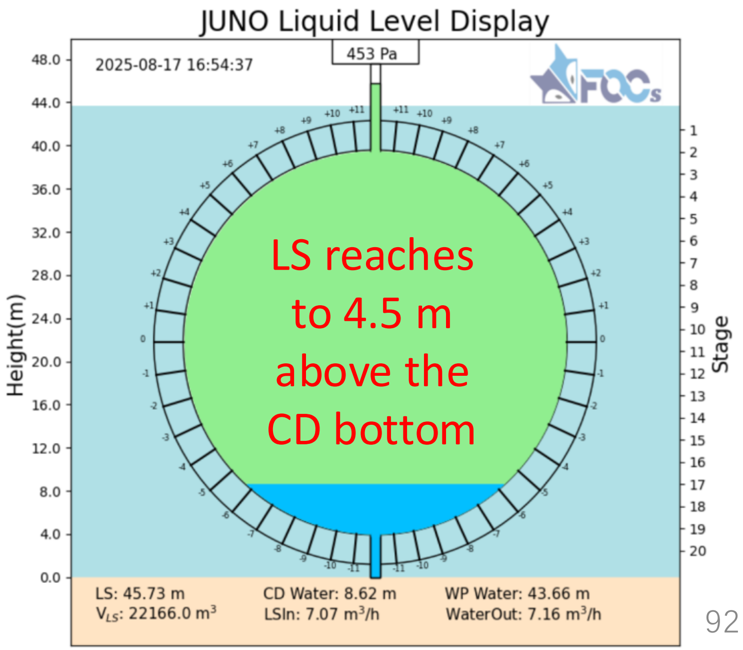
Monitoring radiopurity and LS properties

Expected end of LS filling — 2025 Summer



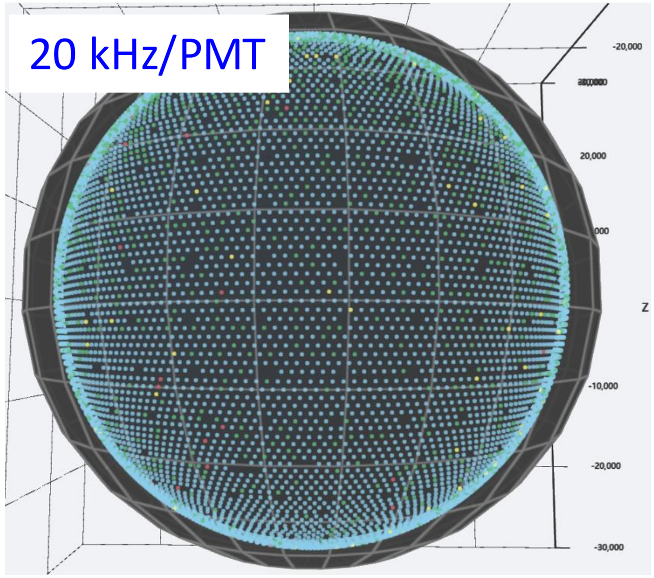
Attenuation Length ~ 22.4 m





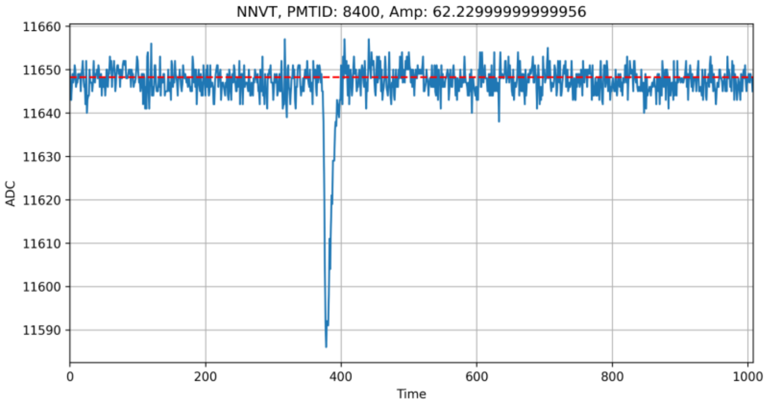
Status of Detector Performance: PMT & LS

Dark rate of 20” PMTs in CD



Total PMTs installed: 17596
Unstable or Flashing: <1%
Gain stable within 1%

Waveform of a typical PMT



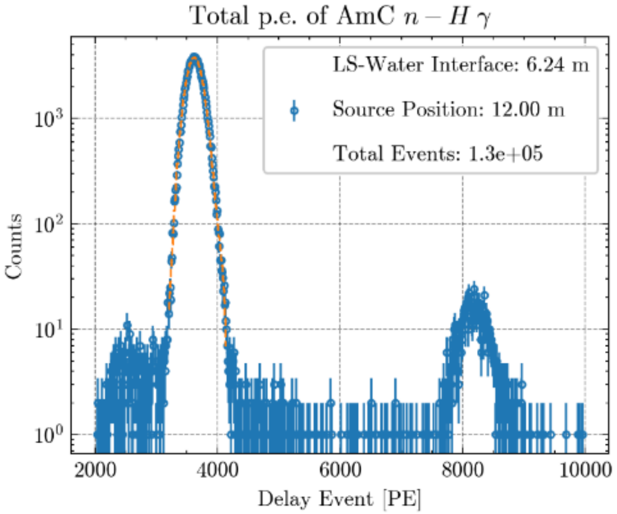
Good grounding and low noise:
RMS ~2.8 ADC ch. ➔ ~0.055 PE
Current PMT threshold: 0.2 PE/ch.
Trigger: ~ 300 PMTs/225ns
➔ ~150 keV
(Under adjustment)

Performance of LS in CD

- ^{222}Rn in fresh LS: < 1mBq/m^3
- Current Rn level: < 0.1mBq/m^3
- U/Th: <10^{-16} g/g

from AmBe calibration

- Attenuation length: ~20m
- Light yield: ~ 1600/MeV



All in agreement with the design and expectations

Summary

- JUNO will be the largest liquid scintillator experiment with rich physics program
- **Unprecedented** sensitivities in neutrino oscillation physics
- Currently under liquid scintillator filling phase
- Taking commissioning data: detector is in good performance so far ☺
- **Expect physics data-taking by end of summer 2025**

Physics	Sensitivity
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31} <0.5% in 6 years
Neutrino Mass Ordering	3σ in ~7.1 years by reactor neutrinos

Thank you!

감사합니다!

谢谢！

~700 collaborators from 74 institutions in 17 countries/regions

Backup1: Precision Measurement of Oscillation Parameters

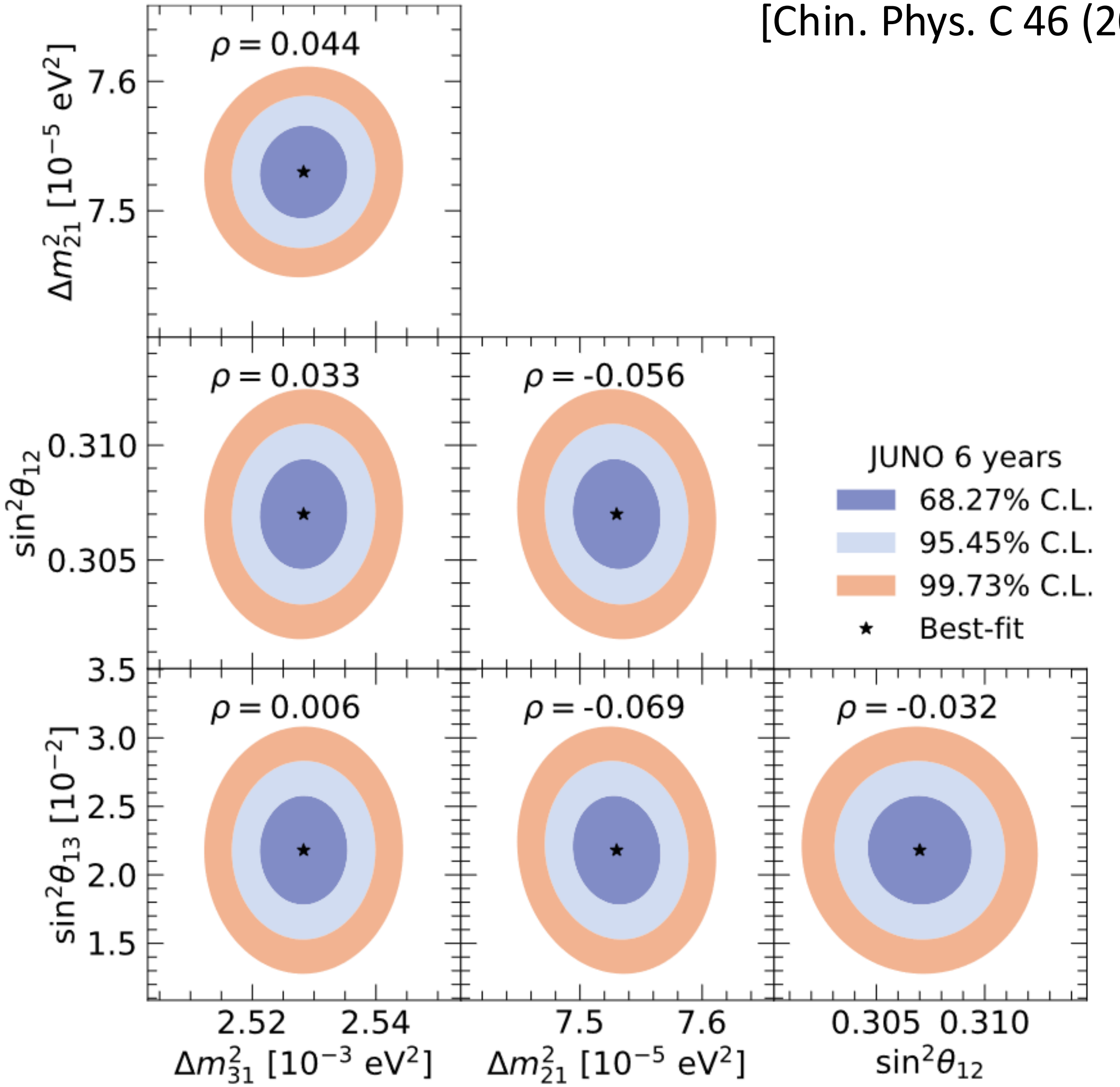
[Chin. Phys. C 46 (2022)]

Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

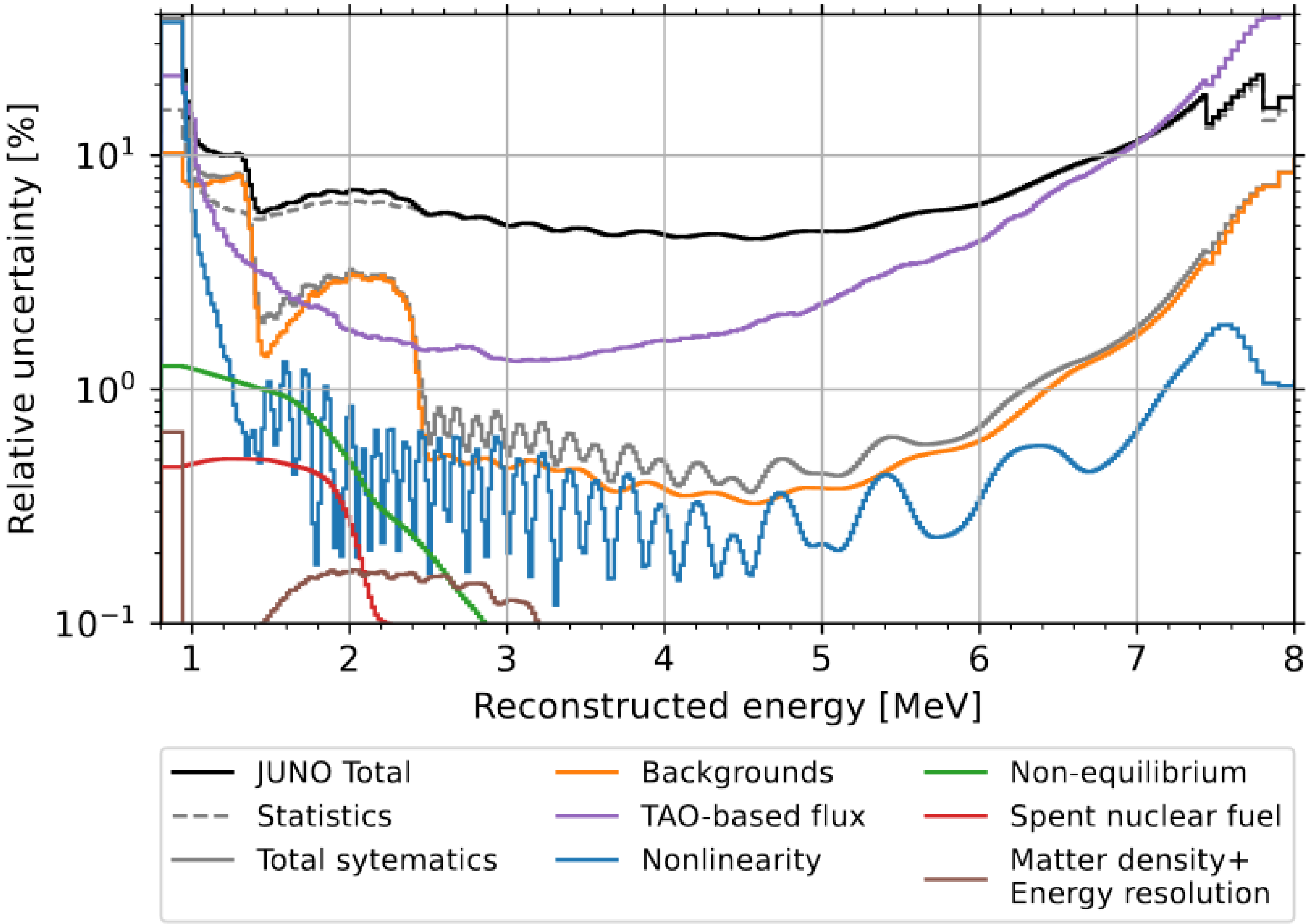
Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

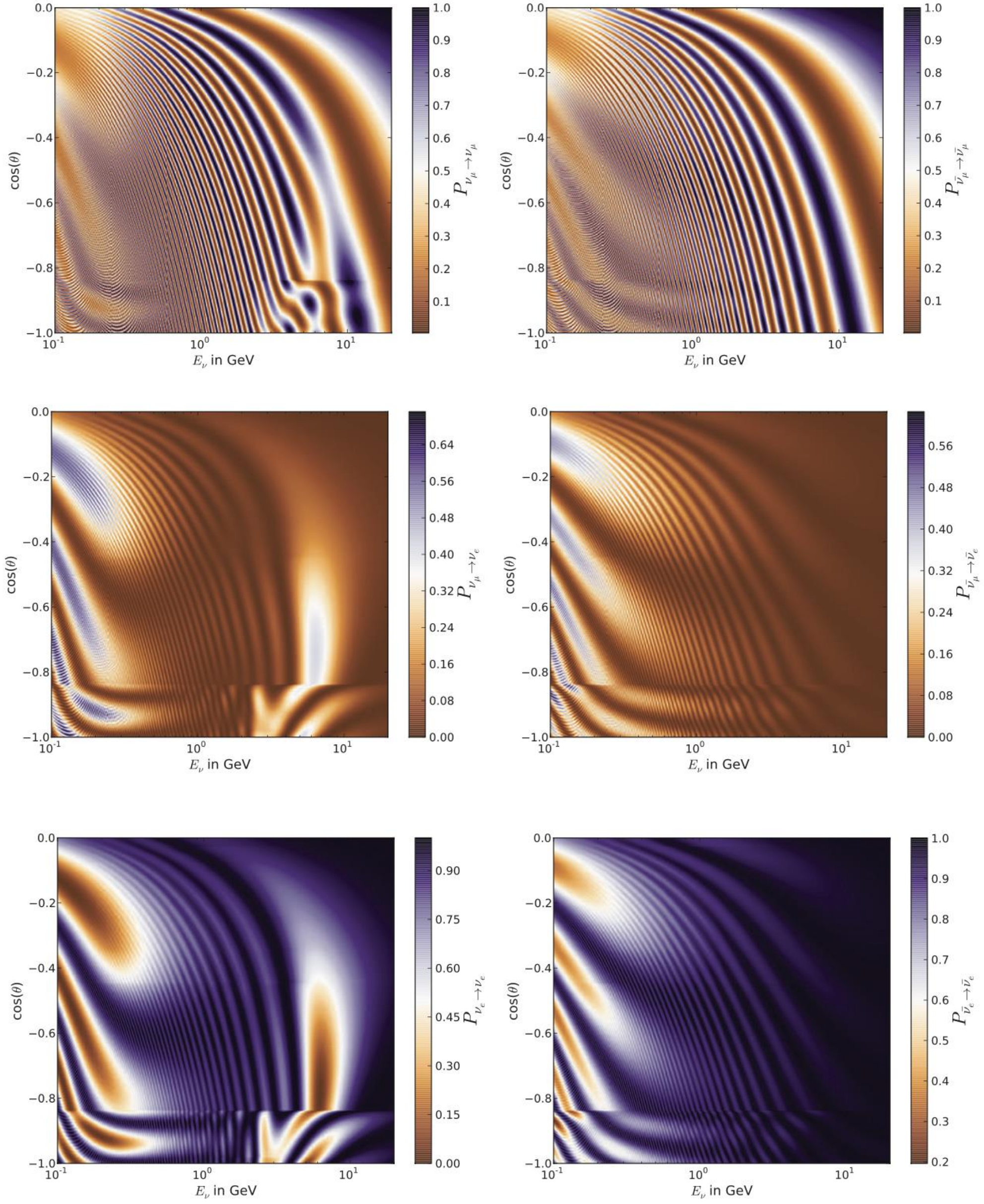
$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11



Backup2: Uncertainties of Neutrino Spectrum at JUNO



Backup3: Atmospheric Neutrino Oscillation



$$P_{\mathrm{NH}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{IH}}(\bar\nu_\alpha \to \bar\nu_\beta)\ ,\ P_{\mathrm{IH}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{NH}}(\bar\nu_\alpha \to \bar\nu_\beta)$$

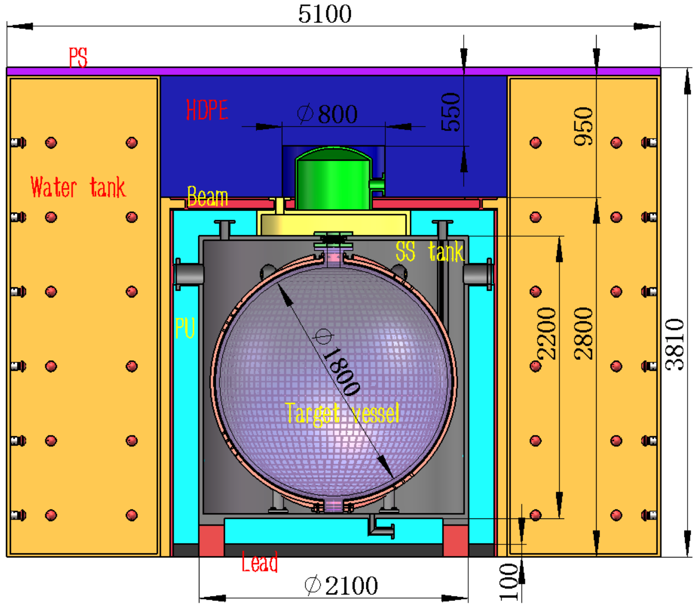
$$\begin{aligned}
P(\nu_e \to \nu_e) &\approx 1 - \sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m_{31}^2)^m \frac{L}{E_\nu}\right]; \\
P(\nu_e \to \nu_\mu) &\approx P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m_{31}^2)^m \frac{L}{E_\nu}\right]; \\
P(\nu_\mu \to \nu_\mu) &\approx 1 - \cos^2\theta_{13}^m \sin^2 2\theta_{23} \sin^2\left[1.27\frac{\Delta m_{31}^2 + A + (\Delta m_{31}^2)^m}{2}\frac{L}{E_\nu}\right] \\
&\quad - \sin^2\theta_{13}^m \sin^2 2\theta_{23} \sin^2\left[1.27\frac{\Delta m_{31}^2 + A - (\Delta m_{31}^2)^m}{2}\frac{L}{E_\nu}\right] \\
&\quad - \sin^4\theta_{23} \sin^2 2\theta_{13}^m \sin^2\left[1.27(\Delta m_{31}^2)^m \frac{L}{E_\nu}\right],
\end{aligned}$$

$$\begin{aligned}
(\Delta m_{31}^2)^m &= \Delta m_{31}^2 \sqrt{(\cos 2\theta_{13} - A/\Delta m_{31}^2)^2 + \sin^2 2\theta_{13}} \\
\sin^2 2\theta_{13}^m &= \frac{\sin^2 2\theta_{13}}{(\cos 2\theta_{13} - A/\Delta m_{31}^2)^2 + \sin^2 2\theta_{13}}.
\end{aligned}$$

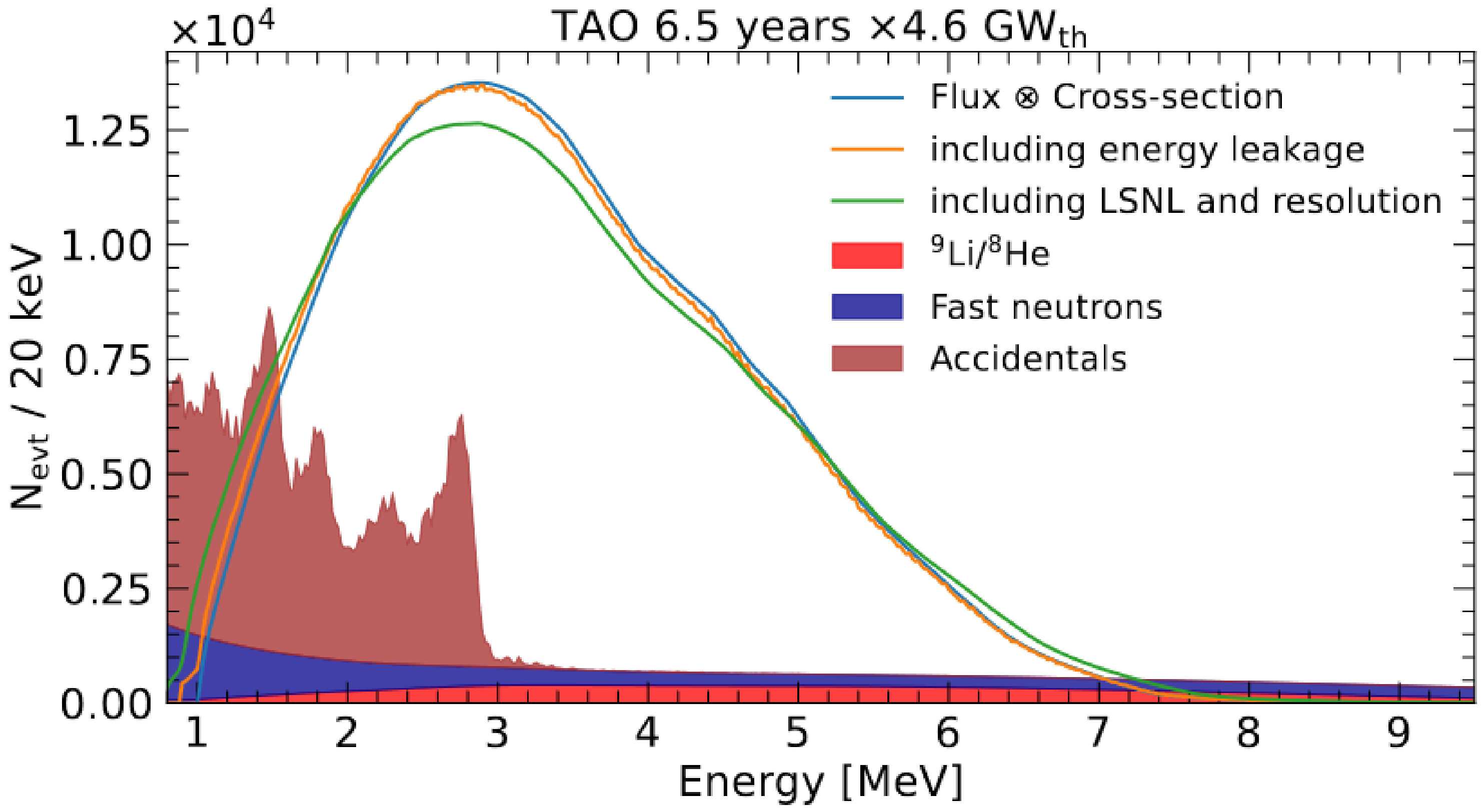
$$E_\nu = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2} G_F N_e} = 32.1\mathrm{GeV}\,\frac{g/\mathrm{cm}^3}{\rho}\,\frac{0.5}{Y_e}\,\frac{\Delta m_{31}^2}{2.43\times 10^{-3}\mathrm{eV}^2}\cos 2\theta_{13}$$

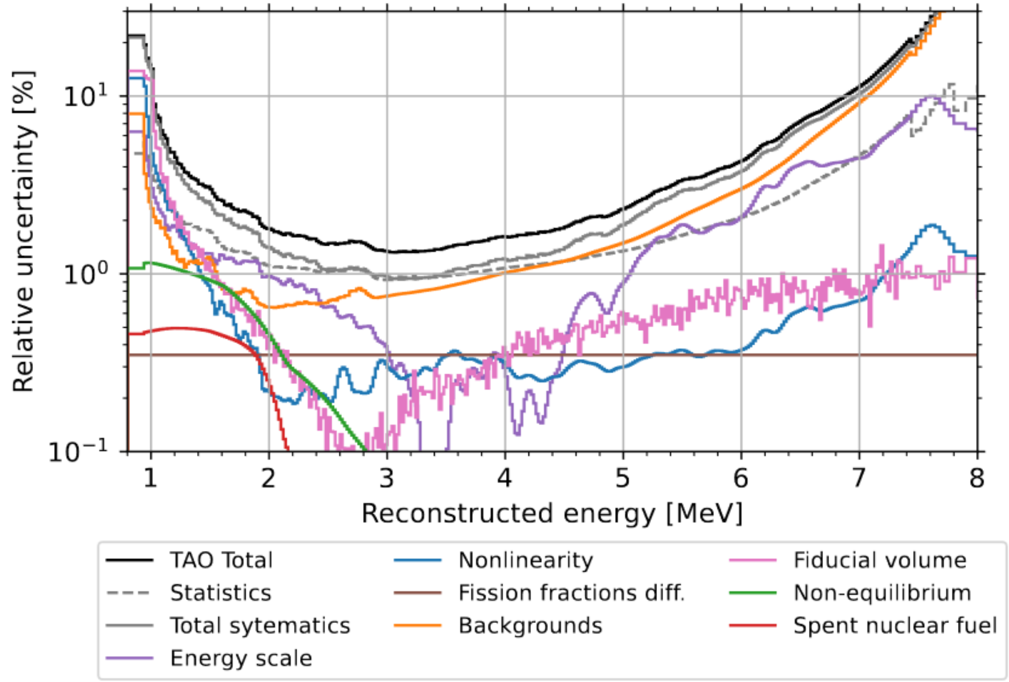
Backup4: JUNO-TAO

- Taishan Anti-neutrino Observatory (TAO)
  - A satellite detector of JUNO
  - Independent and precise measurement of reactor neutrino spectrum
  - 2.8 kton Gd-dopped LS
  - ~44 m from nuclear core
  - Resolution 1.5% at 1 MeV
  - 94% optic coverage with SiPMs
  - Gd-LS and SiPM at -50 ℃
- Status
  - Installation finished, under filling phase
  - Plan to start data-taking this summer



Backup5: Neutrino Spectrum & Uncertainties at TAO

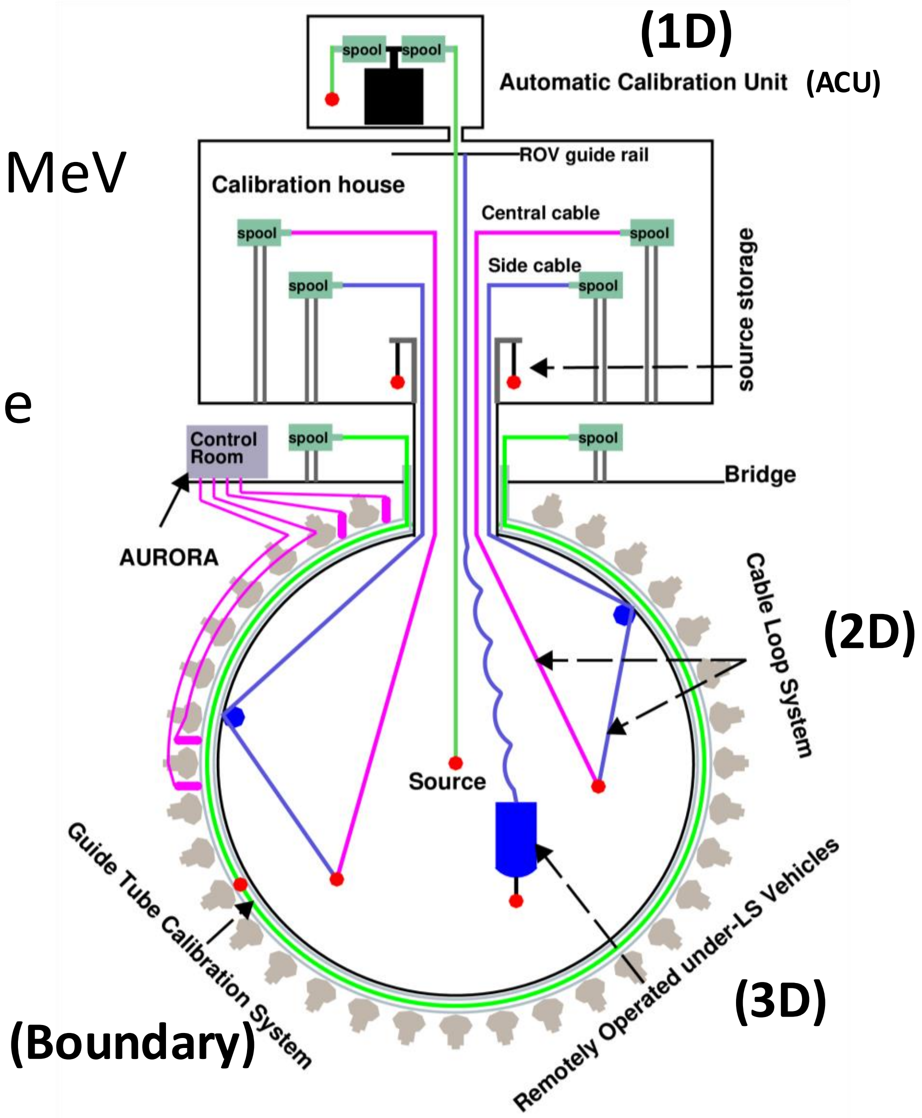




Backup7: Calibration System in JUNO

- ■ Multiple calibration campaigns →
- Determination of e^+ energy non-linearity at <1%
- Optimization of e^+ energy resolution at <3% level at 1 MeV
- ➢ ACU works well so far, in LS filling
  - ^{137}Cs, ^{54}Mn, ^{60}Co, ^{68}Ge, ^{241}Am-Be, ^{241}Am-^{13}C used
  - 4 rounds of calibration along z-axis have been done

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV



Radioactive sources + laser sources + natural radioactive isotopes