Neutrino Mass Ordering Determination and the JUNO Experiment

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On behalf of JUNO Collaboration
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Outline

- Question: Neutrino Mass Ordering
- Review of Experiment Results
- JUNO Potential and Progress
- Summary

Knowns about Neutrino

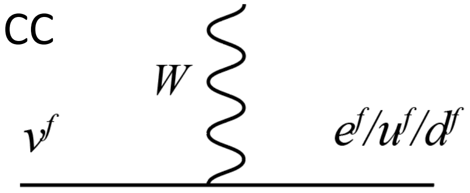
Standard Model

$$\mathcal{L}_0 = \sum_{f=1}^{3} [\bar{\nu}^f \, i\gamma^\mu \partial_\mu \nu^f + \bar{e}^f \, (i\gamma^\mu \partial_\mu - m_E^f) e^f + \bar{u}^f \, (i\gamma^\mu \partial_\mu - m_U^f) u^f + \bar{d}^f \, (i\gamma^\mu \partial_\mu - m_D^f) d^f] + \cdots$$

Found three flavor of **spinor** neutrinos

Neutrinos participate in **weak** interaction

CC



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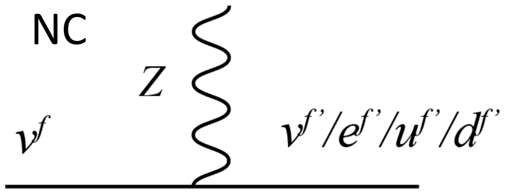

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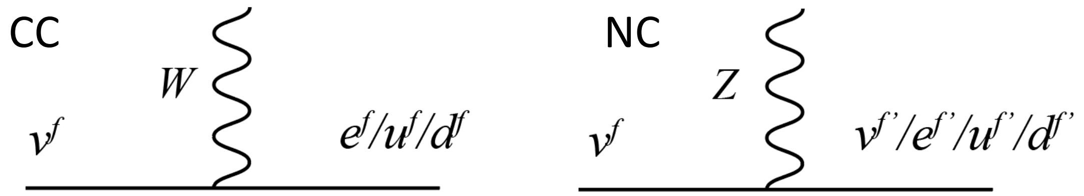

Neutrino Oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i\rangle$$

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\boxed{|\nu_\alpha(L)\rangle \approx \sum_{i=1}^{n} U^*_{\alpha i} e^{-i\frac{m_i^2 L}{2E_i}}|\nu_i(0)\rangle}$$

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

PMNS Matrix

Knowns about Neutrino

Standard Model

$$\mathcal{L}_0 = \sum_{f=1}^{3} [\bar{v}^f\, i\gamma^\mu \partial_\mu v^f + \bar{e}^f\, (i\gamma^\mu \partial_\mu - m_E^f) e^f + \bar{u}^f\, (i\gamma^\mu \partial_\mu - m_U^f) u^f + \bar{d}^f\, (i\gamma^\mu \partial_\mu - m_D^f) d^f] + \cdots$$

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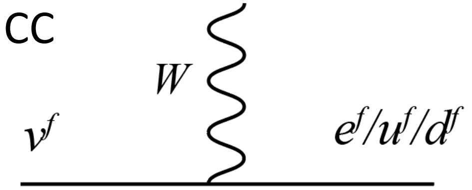
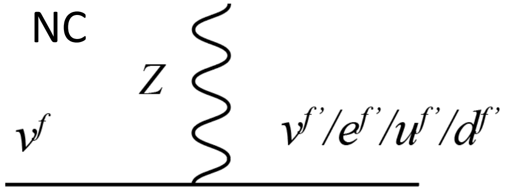




Neutrino Oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}^* |\nu_i\rangle \qquad i\frac{\partial}{\partial t}\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = H \begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} \qquad |\nu_\alpha(L)\rangle \approx \sum_{i=1}^{n} U_{\alpha i}^* e^{-i\frac{m_i^2 L}{2E_i}} |\nu_i(0)\rangle$$

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

PMNS Matrix

Oscillation probability relates to δ_{CP},

neutrino mixing angles $(\theta_{12}, \theta_{23}, \theta_{13}) \approx (34, 43, 8.6)$ degree

neutrino mass splittings $(\Delta m_{21}^2, |\Delta m_{31}^2|) \approx (7.5\mathrm{e}^{-5},\ 2.51\mathrm{e}^{-3})\ \mathrm{eV}^2$ (NuFit2024 NO)

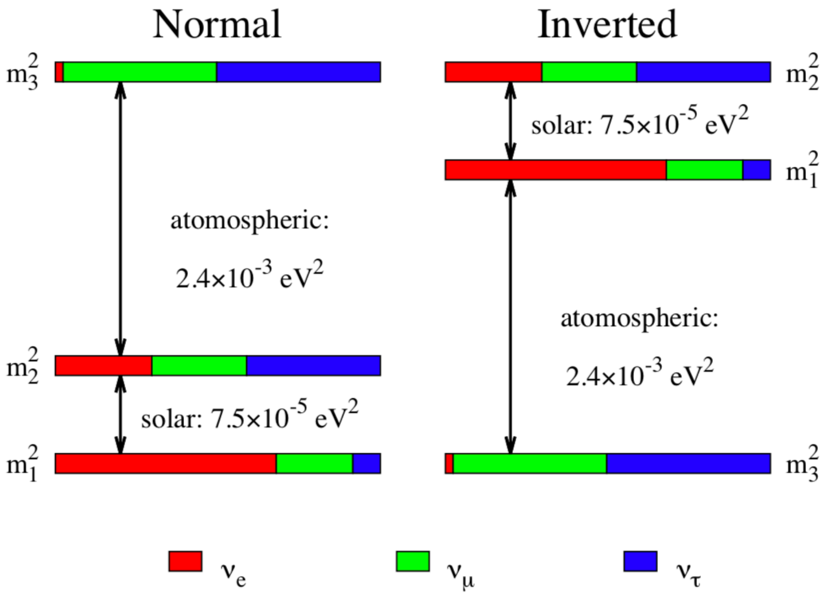
Neutrino participates in **weak/gravity** interaction

Unknown about Neutrino

Is $\sin^2\theta_{23} = 0.5$?

$|\nu_3\rangle$ contains more $|\nu_\mu\rangle$ or $|\nu_\tau\rangle$?

What is the ordering of neutrino masses?



How large is the δ_{CP}?

$P(\nu_\mu \to \nu_e)/P(\bar{\nu}_\mu \to \bar{\nu}_e) =?$

What is the smallest mass of neutrinos?

$\min(m_1, m_2, m_3) =?$

Is Neutrino Majorana or Dirac? Neutrinos are their own anti-particles ?

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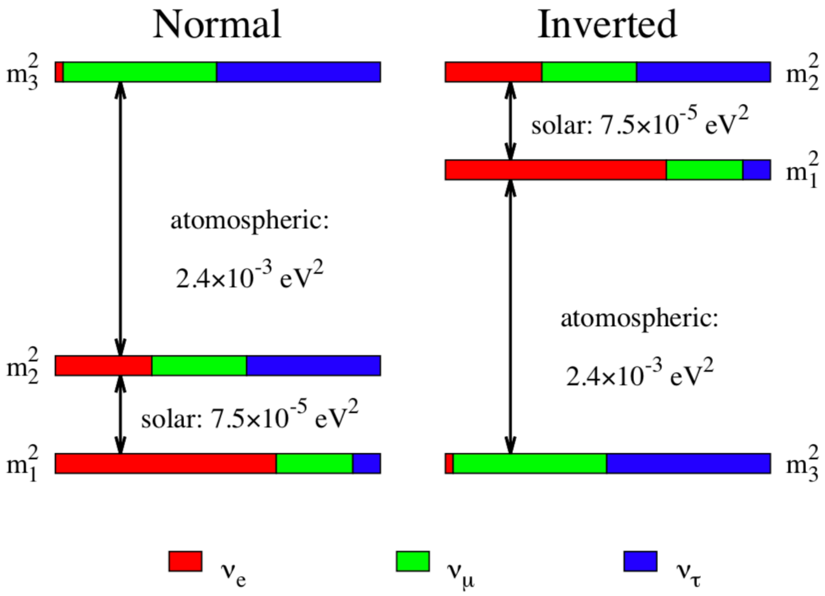


Is Neutrino Majorana or Dirac? Neutrinos are their own anti-particles ?

What is the origin of neutrino mass?

How to extend SM?

$$\mathcal{L}_{\text{mass}} = -Y^e_{ij}\bar{L}^i H e^j_R \boxed{-Y^\nu_{ij}\bar{L}^i\widetilde{H}\nu^j_R}\boxed{-iM_{ij}(\nu^i_R)^c\nu^j_R} + \text{h.c.}$$

If it is Dirac, why m_ν is so small?

Otherwise, where does M_ν come from?

Are there other types of neutrino?

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1?$$

Sterile or dark neutrinos?

Why to Measure Neutrino Mass Ordering

Is $\sin^2\theta_{23} = 0.5$?
How large is the δ_{CP}?

What is the smallest mass of neutrinos?
Is Neutrino Majorana or Dirac?

How the neutrino masses ordered?

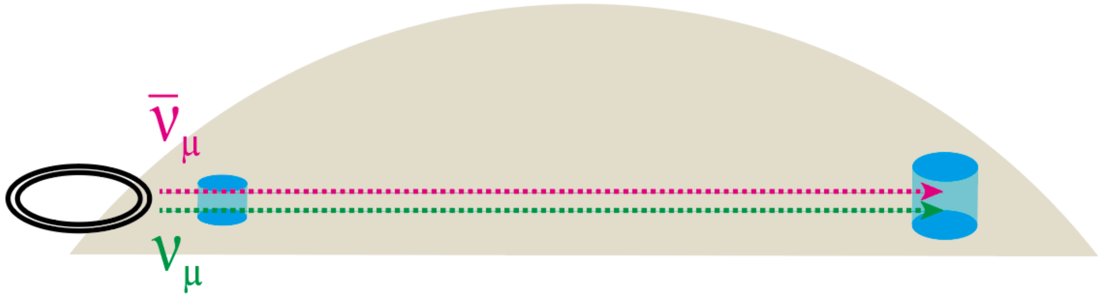
What is the origin of neutrino mass?
Are there other types of neutrinos?

What is the mechanism of Supernova burst?
How will neutrino affects the evolution of universe…

- Improve the sensitivity of δ_{CP} and $\sin^2\theta_{23}$
- Improve the constraint of life of $0\nu\beta\beta$ decay
- Improve the constraint of neutrino absolute mass
- Improve the constraint of cosmic parameters

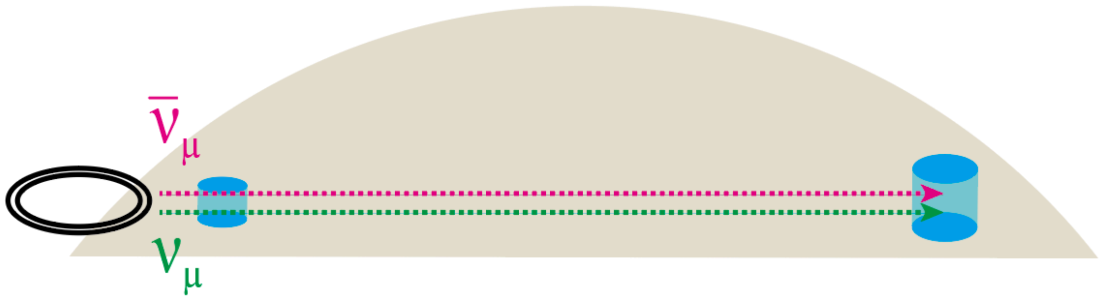
How to Measure Neutrino Mass Ordering

Accelerator Neutrino Oscillation Methods



MSW: $$H_{\text{Matter}} = H_{\text{Vacuum}} + \boxed{\mathbf{U}^\dagger \begin{pmatrix} 2\sqrt{2}G_F n_e E & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \mathbf{U}}$$

Accelerator Neutrino Oscillation Methods



$$P(\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\frac{\Delta m^2_{31}L}{4E}]$$
$$\overset{(-)}{+}\alpha\frac{J_0\sin\delta_{CP}}{A(1-A)}\sin\frac{\Delta m^2_{31}L}{4E}\sin(A\frac{\Delta m^2_{31}L}{4E})\sin[(1-A)\frac{\Delta m^2_{31}L}{4E}]$$
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\frac{\Delta m^2_{31}L}{4E}\sin(A\frac{\Delta m^2_{31}L}{4E})\sin[(1-A)\frac{\Delta m^2_{31}L}{4E}]$$
$$+\alpha\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\frac{\Delta m^2_{31}L}{4E})$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Sensitive to $\delta_{CP}, MO, \theta_{23}$

$$\boxed{A = (-)2\sqrt{2}G_F n_e E/\Delta m^2_{31}}$$
$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

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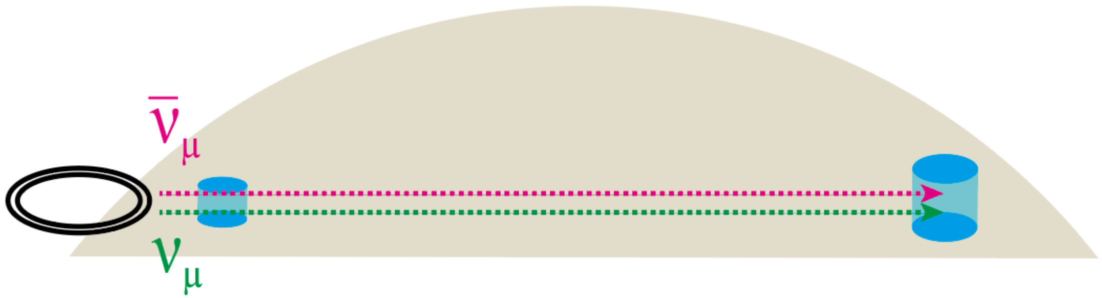

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$\boxed{A = (-)2\sqrt{2}G_F n_e E/\Delta m^2_{31}}$$

$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

Sensitive to $\delta_{CP}, MO, \theta_{23}$

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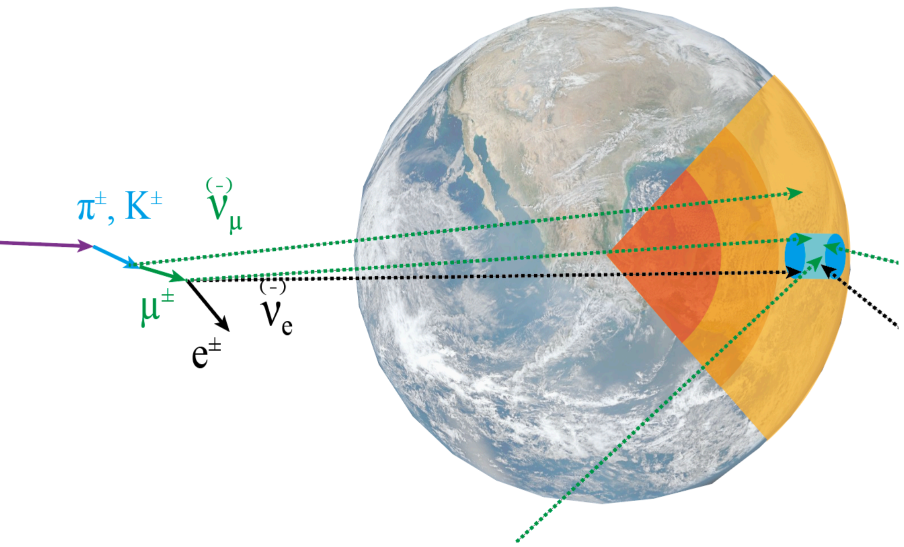
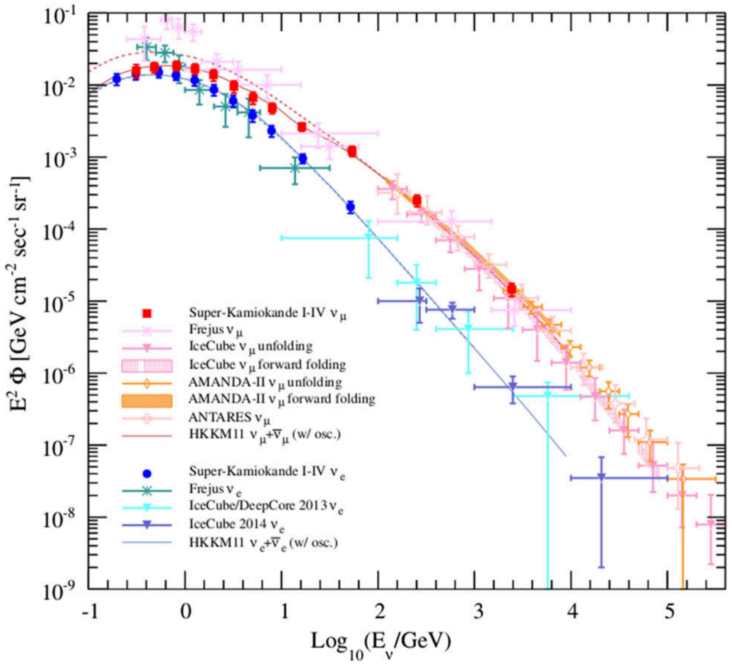
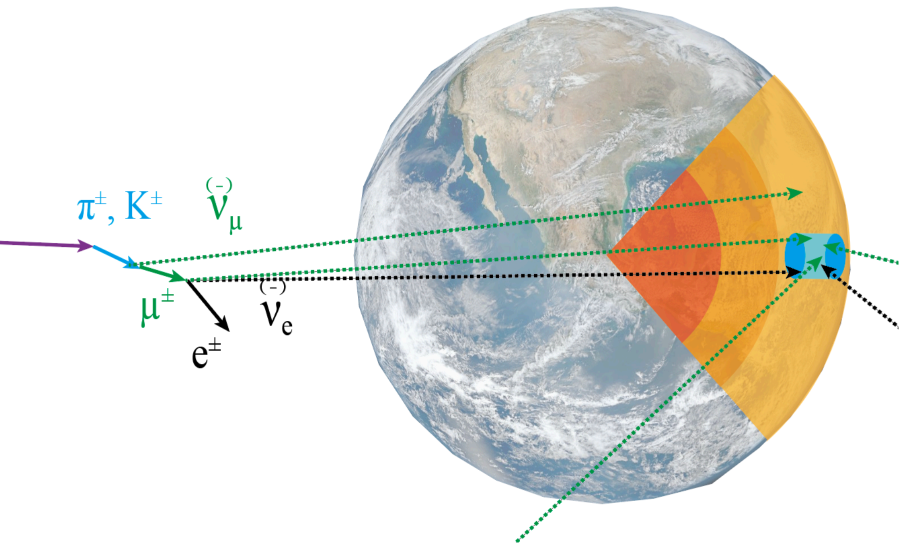
Experiments	Baseline	Energy	Dominant CC Observables	Advantages
MINOS	735 km	3/7/9 GeV	$\{\nu_e,\bar{\nu}_e\}(E),\{\nu_\mu,\bar{\nu}_\mu\}(E)$	Covers high energy region
T2K/T2HK	295 km	0.6 GeV	$\{\nu_e,\bar{\nu}_e\}(p^\mu,\theta_l),\{\nu_\mu,\bar{\nu}_\mu\}(p^\mu,\theta_l)$	Good resolution/Better
NOvA	810 km	1.8 GeV	$\{\nu_e,\bar{\nu}_e\}(E),\{\nu_\mu,\bar{\nu}_\mu\}(E)$	Separate hierarchy and δ effects; 3D tracking and calorimetry
DUNE	1300 km	2.5 GeV	$\{\nu_e,\bar{\nu}_e\}(E),\{\nu_\mu,\bar{\nu}_\mu\}(E)$	High statistics; High resolution

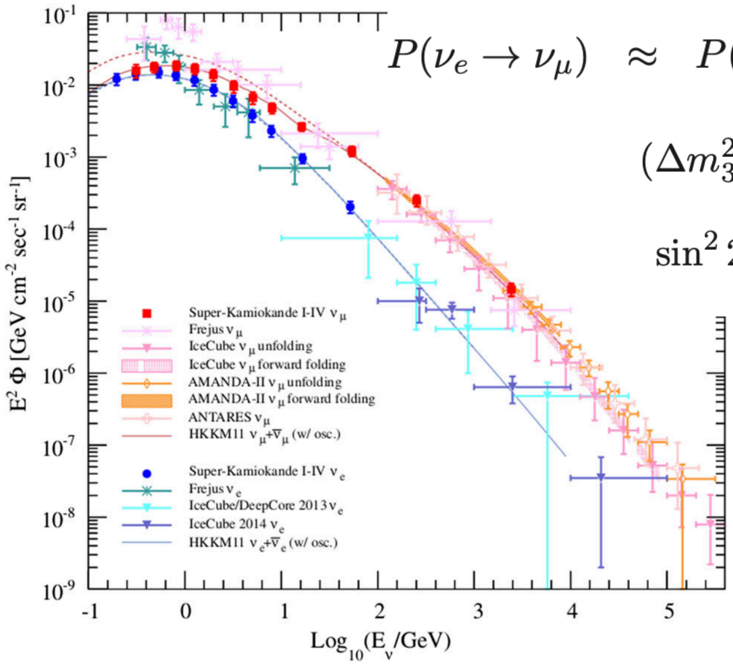
Atmospheric Neutrino Oscillation Methods





Atmospheric Neutrino Oscillation Methods





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

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

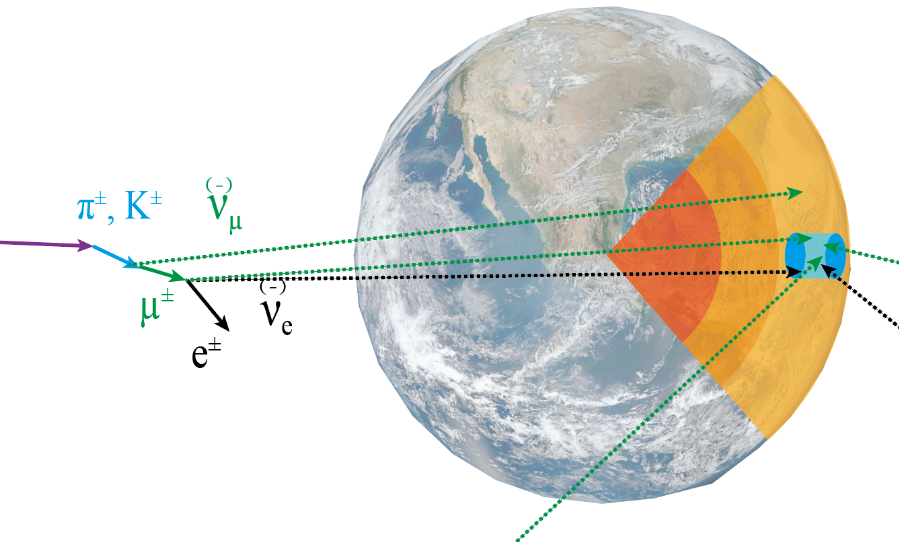
$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{(\cos 2\theta_{13} - A/\Delta m_{31}^2)^2 + \sin^2 2\theta_{13}}\,.$$

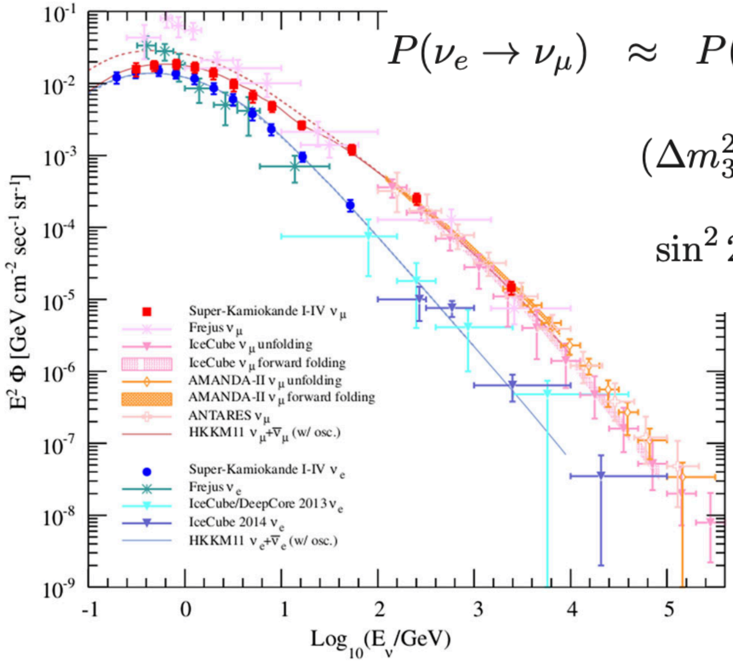
$$A = 2\sqrt{2}G_F N_e E_\nu$$

MSW Resonance $A = \Delta m_{31}^2 \cos 2\theta_{13}$

Sensitive to MO, θ_{23}

Atmospheric Neutrino Oscillation Methods





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

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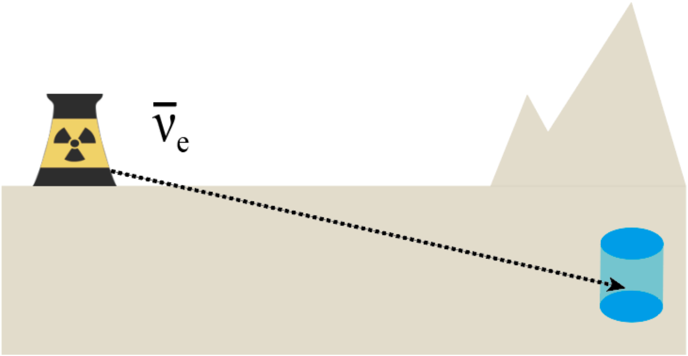
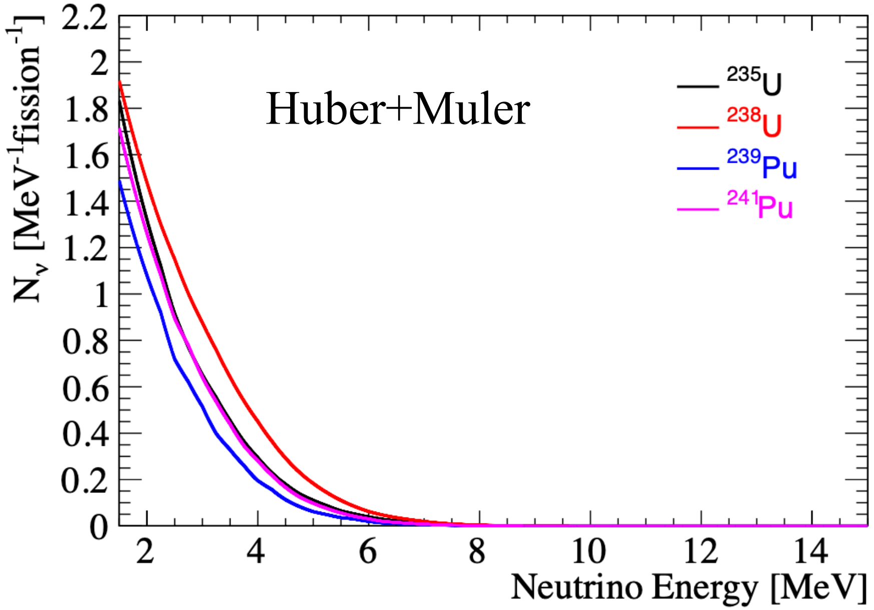
MSW Resonance $A = \Delta m_{31}^2 \cos 2\theta_{13}$

Sensitive to MO, θ_{23}

Experiments	Energy	Dominant CC Observables	Advantages
Super-K/Hyper-K	0.1-10 GeV	$\{\nu_e, \bar{\nu}_e\}(E,L), \{\nu_\mu, \bar{\nu}_\mu\}(E,L)$	High statistics; Good resolution/Better
IceCube+DeepCore	5-1000 GeV	$\{\nu_\mu + \bar{\nu}_\mu\}(E,L), \{\nu_\tau + \bar{\nu}_\tau\}(E,L)$	High energy region; ν_τ apperance
KM3Net-ORCA	1-50 GeV	$\{\nu_\mu + \bar{\nu}_\mu\}(E,L), \{\nu_\tau + \bar{\nu}_\tau\}(E,L)$	Lower energy threshold
JUNO	0.01-10 GeV	$\{\nu_e, \bar{\nu}_e\}(E,L), \{\nu_\mu, \bar{\nu}_\mu\}(E,L)$	Very Low energy threshold; Good resolution
DUNE	0.1-10 GeV	$\{\nu_e, \bar{\nu}_e\}(E,L), \{\nu_\mu, \bar{\nu}_\mu\}(E,L)$	High statistics; Good resolution

Reactor Neutrino Oscillation Methods





$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2\frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2\frac{\Delta m_{32}^2 L}{4E}\right]$$

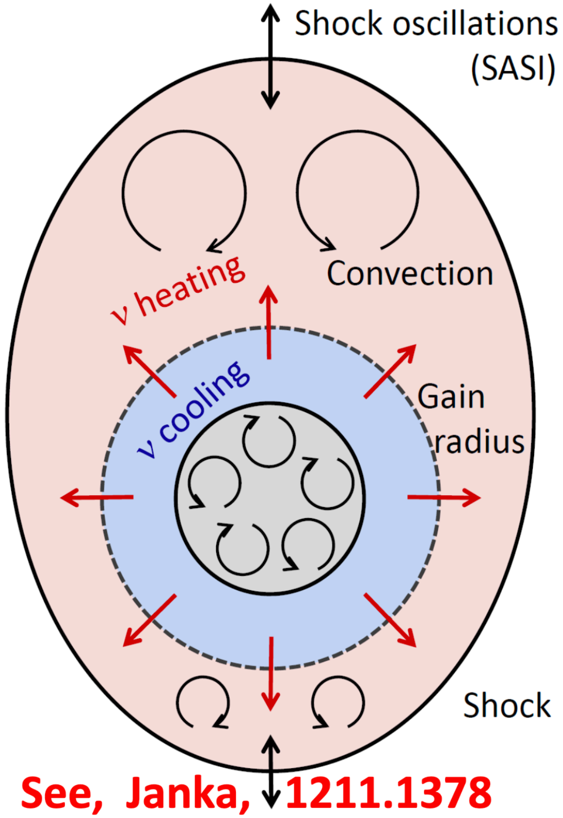
NO : $|\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2|$

IO : $|\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2|$

Sensitive to MO

Experiments	Baseline	Dominant Observables	Advantages
JUNO	53 km	$\{\bar{\nu}_e\}(\boldsymbol{E})$	Independent of θ_{23} and δ_{CP}

Supernova Neutrino Oscillation Methods



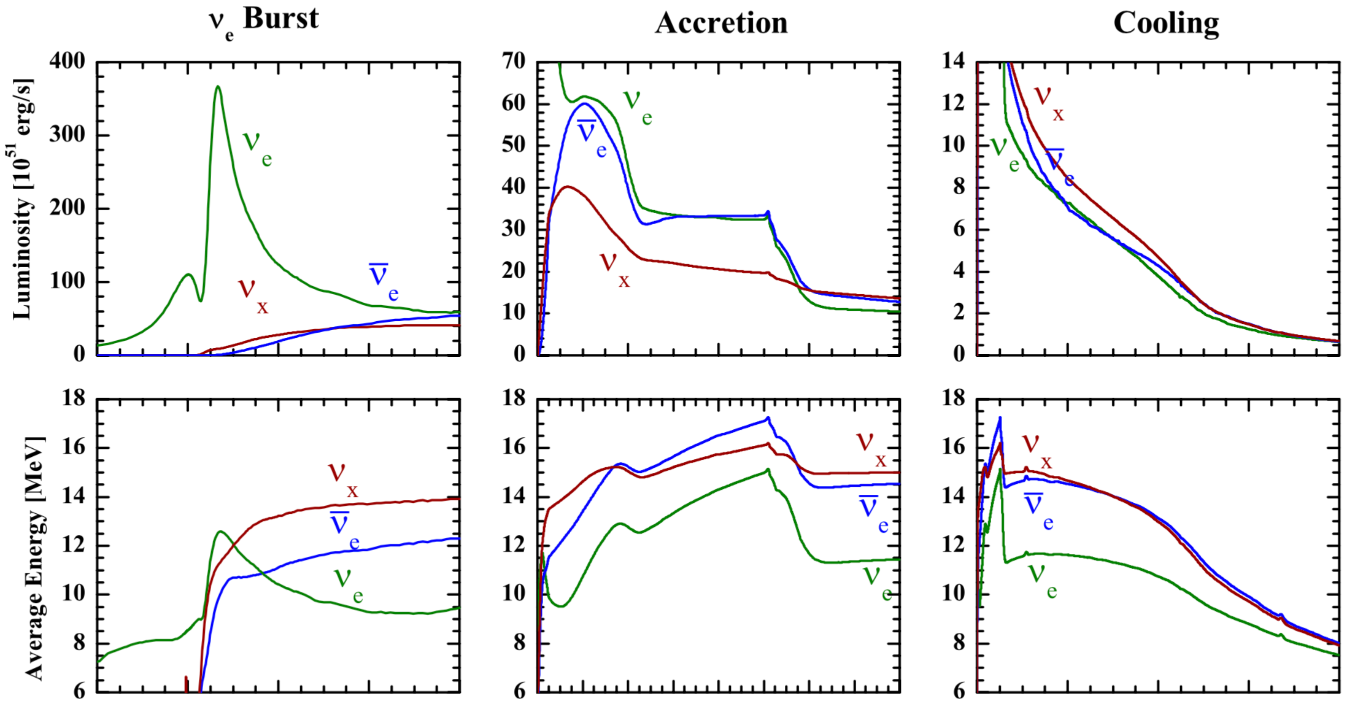
See, Janka, 1211.1378

MSW effect

$$NO: \Phi_{\bar{\nu}_e} \approx \cos^2\theta_{12}\Phi^0_{\bar{\nu}_e} + \sin^2\theta_{12}\Phi^0_{\bar{\nu}_x}$$

$$IO: \Phi_{\bar{\nu}_e} \approx \Phi^0_{\bar{\nu}_x}$$

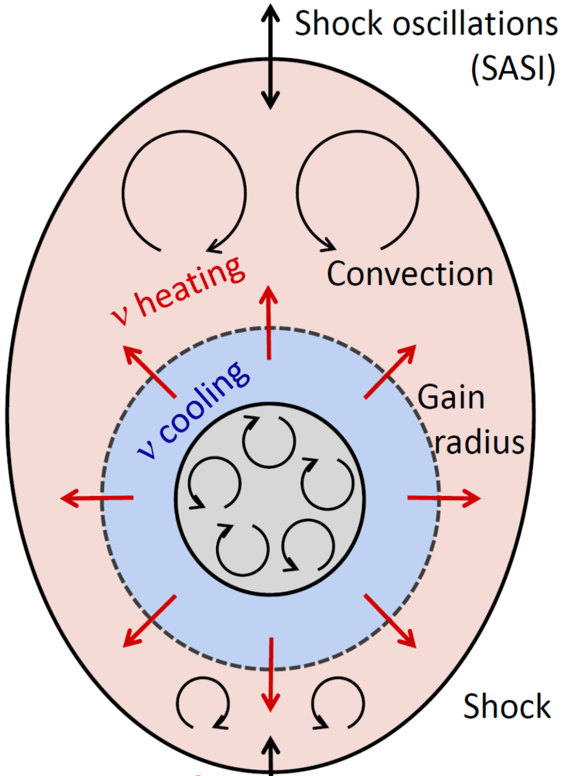
Phys.Rev. D62 (2000) 033007



J. Phys. G 43 (2016) 030401

Challenges: Collective oscillation; Model dependences

Supernova Neutrino Oscillation Methods



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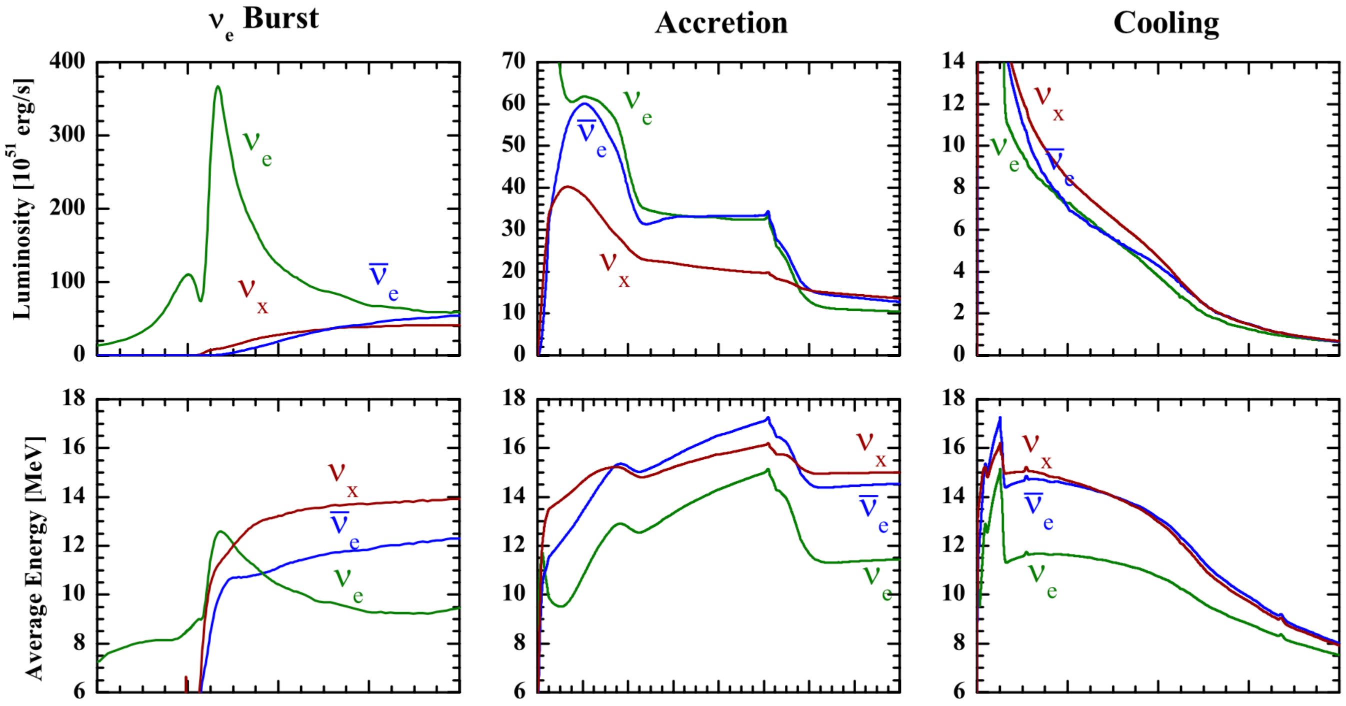


J. Phys. G 43 (2016) 030401

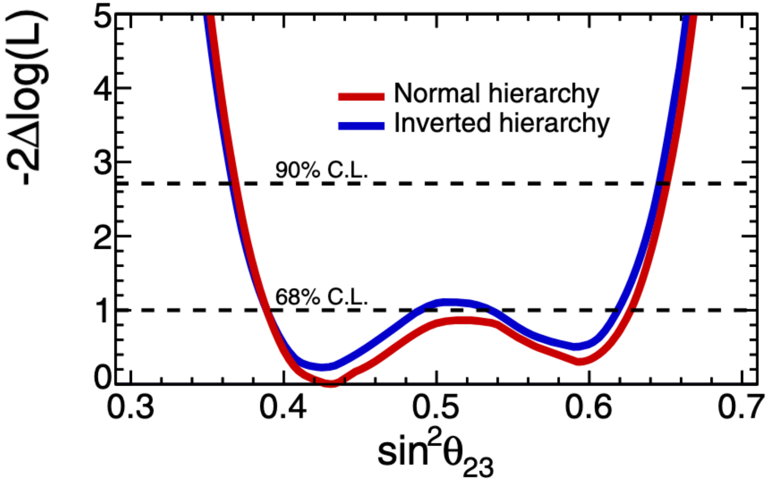
Challenges: Collective oscillation; Model dependences

Experiments	Energy	Dominant Channels and Observables	Advantages
Super-K/Hyper-K	> 5 MeV	IBD: $\bar{\nu}_e + p \to e^+(p^\mu) + n$	High statistics
JUNO	>0.1 MeV	IBD: $\bar{\nu}_e + p \to e^+(E) + n$ pES: $\nu + p \to \nu + p(E)$	Very low energy threshold; Multi-channels
DUNE	> 5 MeV	$\nu_e + {}^{40}\mathrm{Ar} \to e^-(p^\mu) + {}^{40}\mathrm{K}^*$	ν_e information

Accelerator methods: MINOS/T2K/NOvA

MINOS

P. R. L. 125, 131802



Accelerator methods: MINOS/T2K/NOvA

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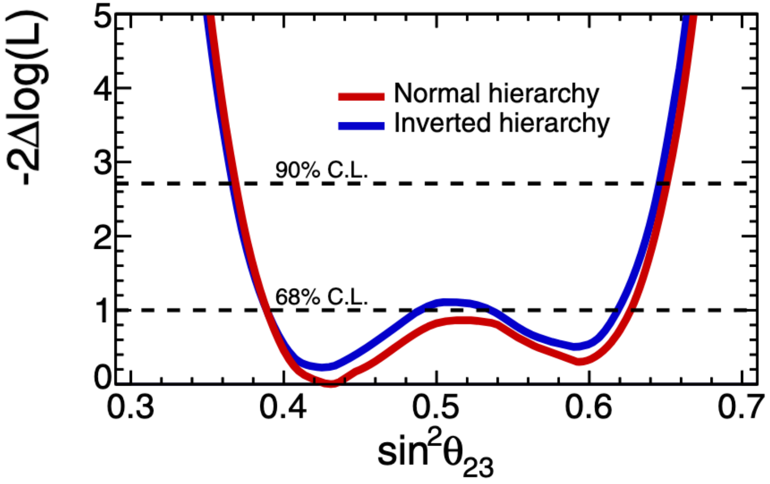
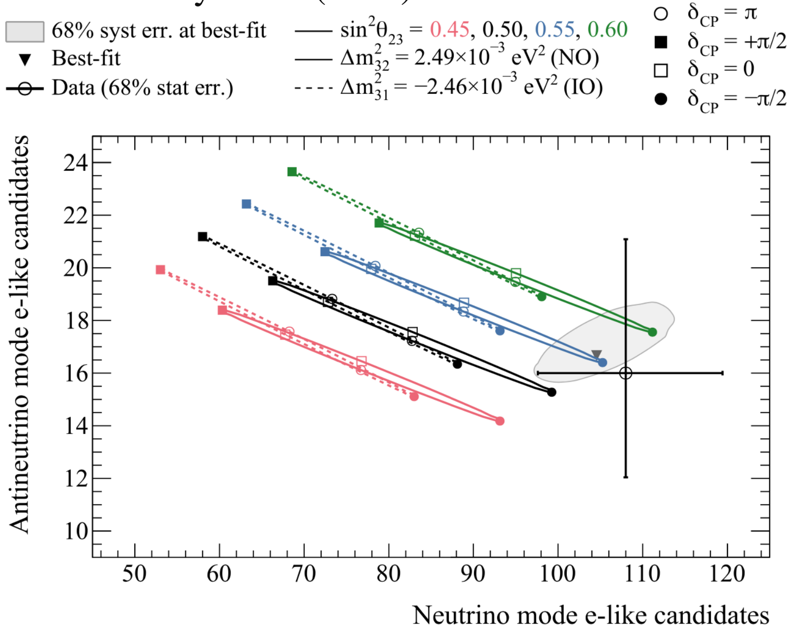
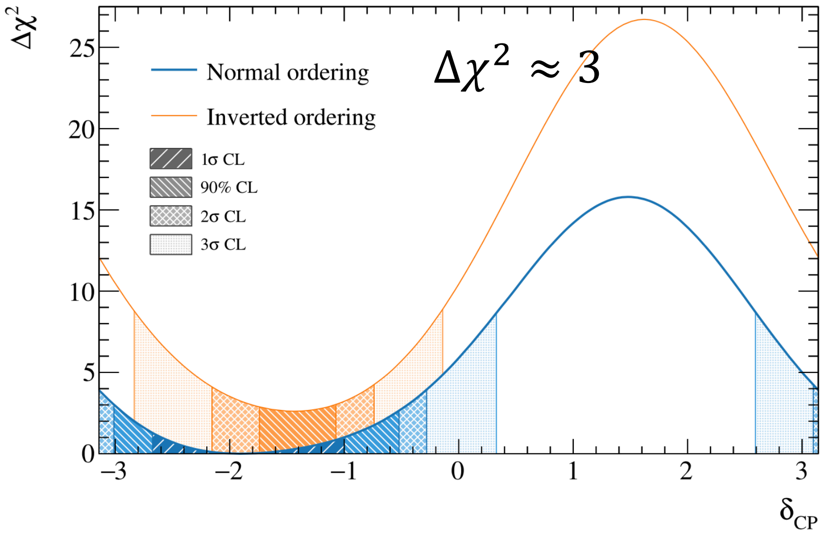
P. R. L. 125, 131802



T2K: Favors normal ordering, upper octant, and a nearly maximally CPV

Eur. Phys. J. C (2023) 83:782





Accelerator methods: MINOS/T2K/NOvA

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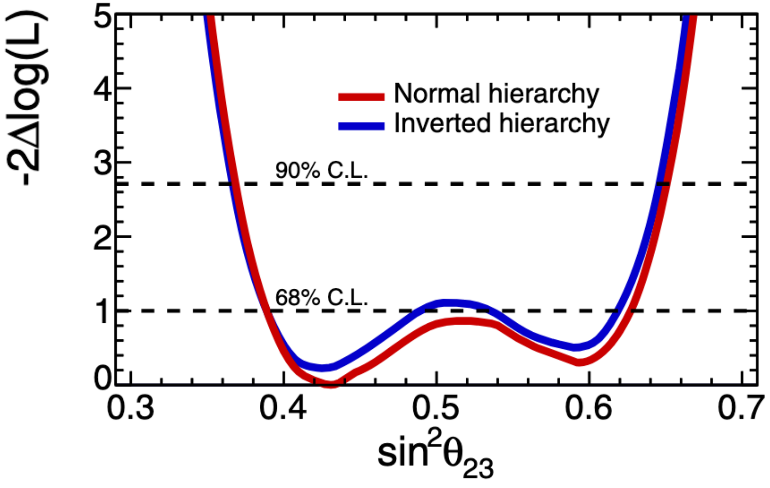
P. R. L. 125, 131802



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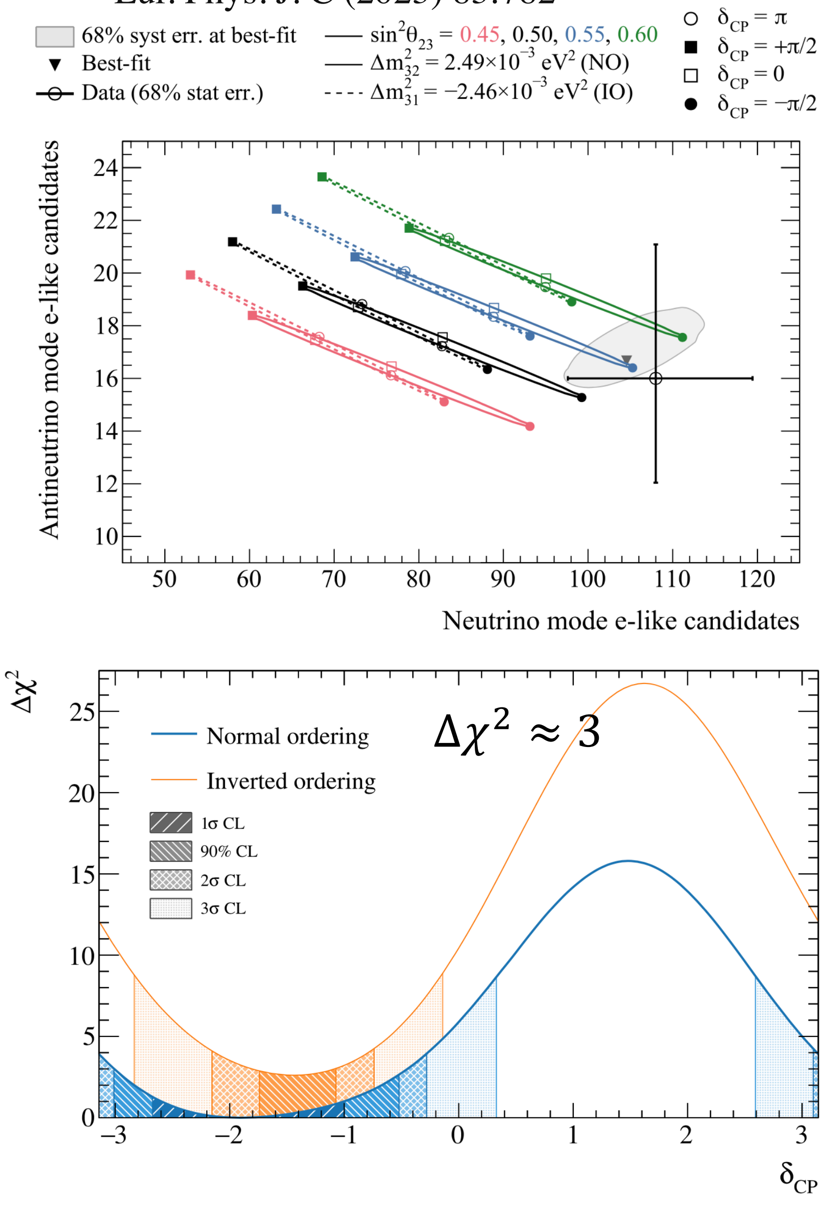
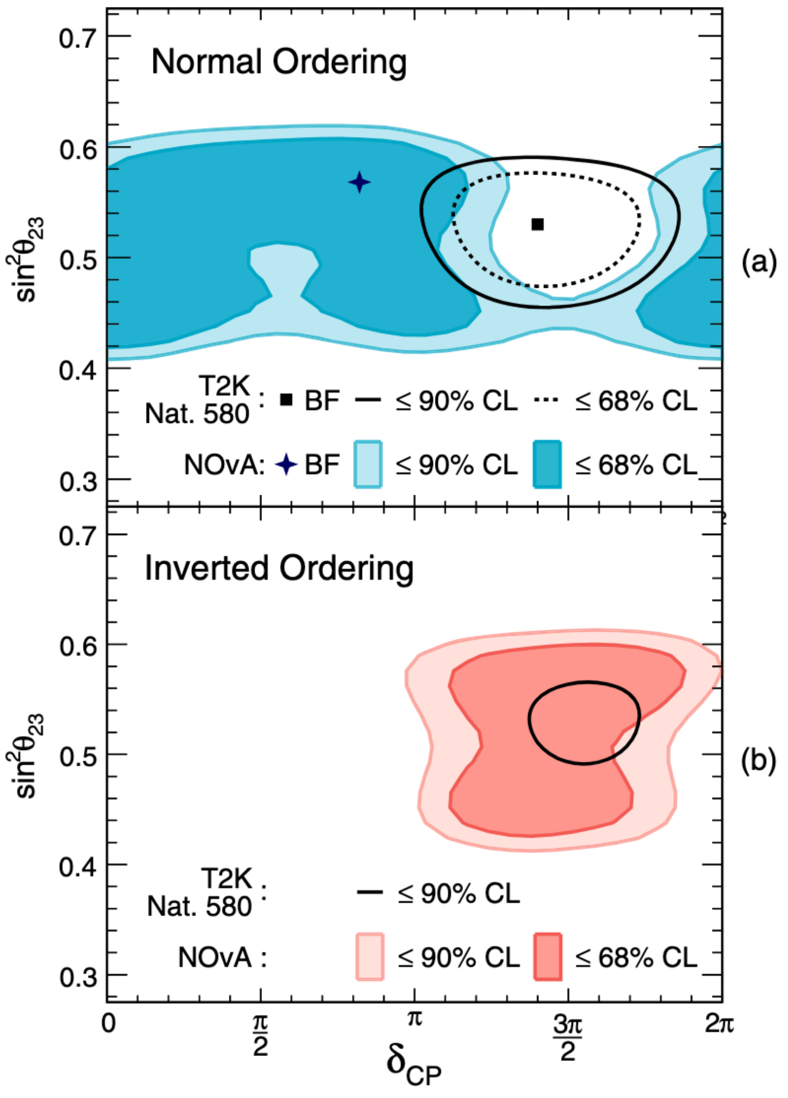


PHYS. REV. D 106, 032004 (2022)



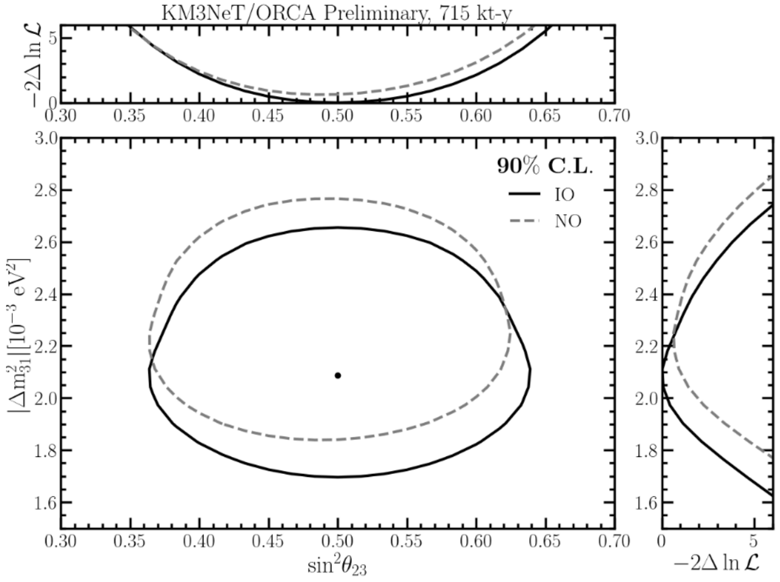
T2K: Favors normal ordering, upper octant, and a nearly maximally CPV

NOvA: Favors the normal ordering, upper octant, but a non-maximal CPV

Atmospheric methods: ORCA/SK/IceCube+DeepCore

ORCA

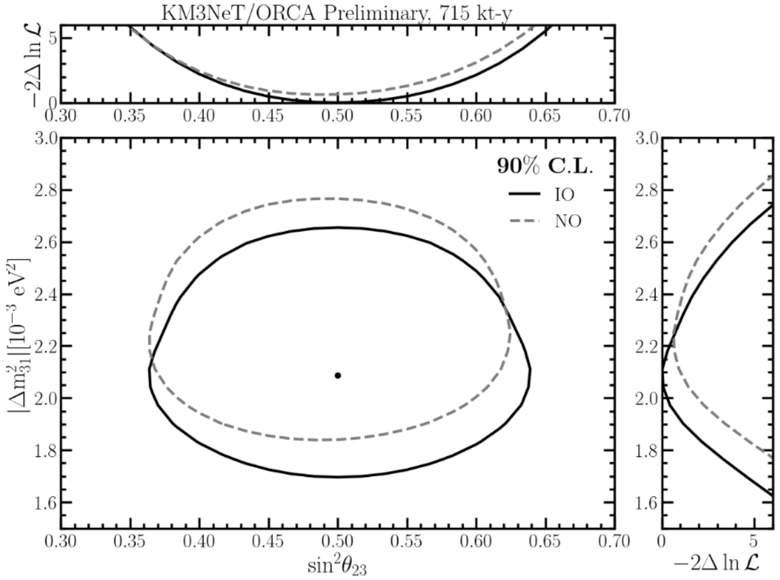
agenda.infn.it/event/37867/contributions/227962



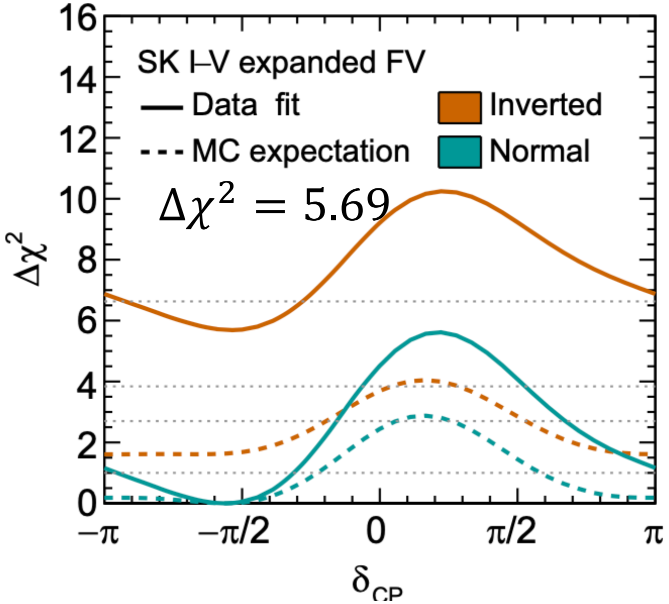
Atmospheric methods: ORCA/SK/IceCube+DeepCore

ORCA

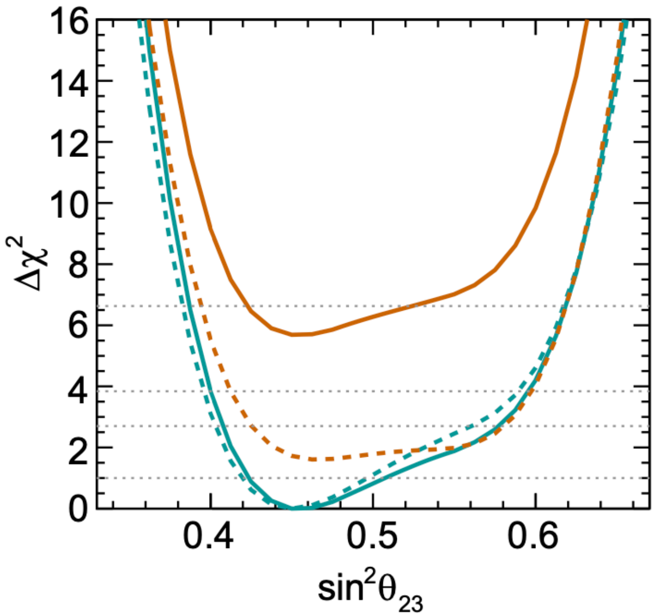
agenda.infn.it/event/37867/contributions/227962



PHYS. REV. D 109, 072014

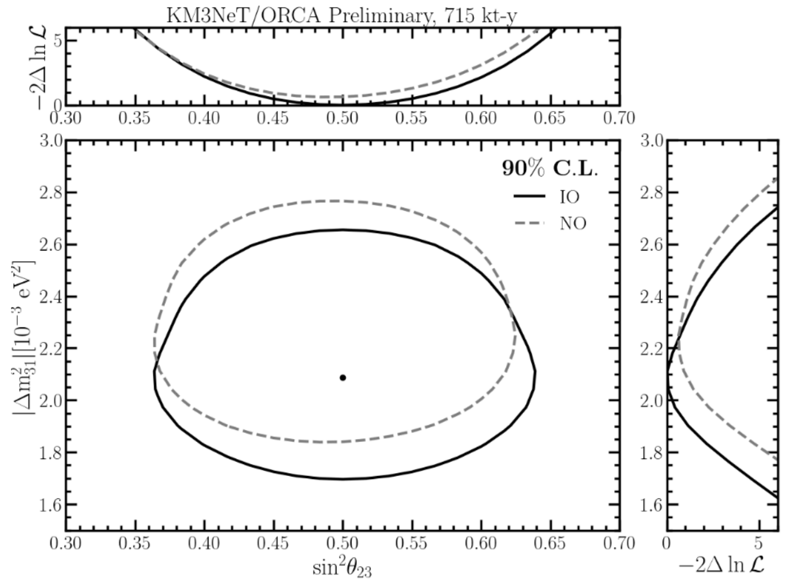


SK: Favors normal ordering, upper octant, and a nearly maximally CPV

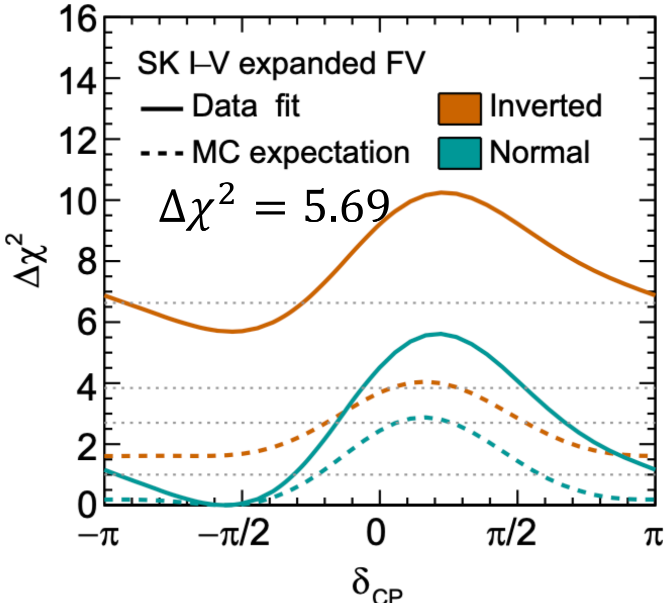


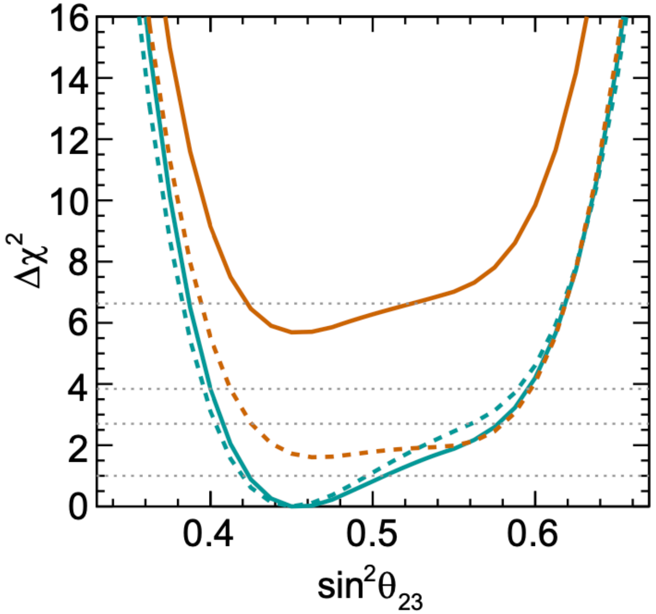
Atmospheric methods: ORCA/SK/IceCube+DeepCore

ORCA
agenda.infn.it/event/37867/contributions/227962

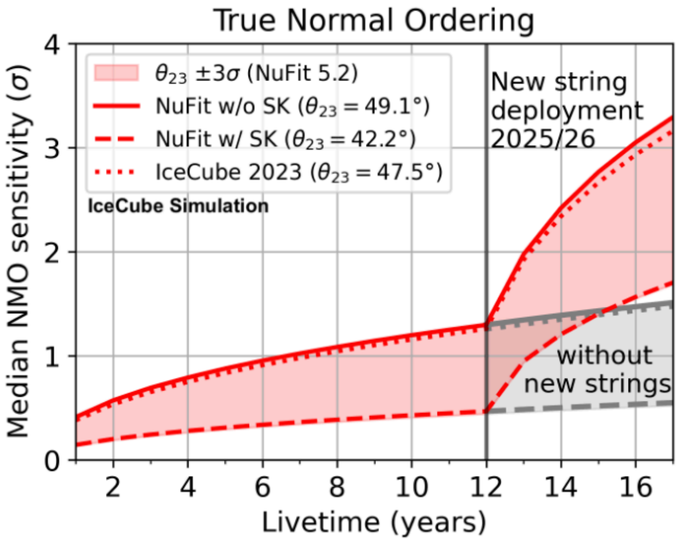


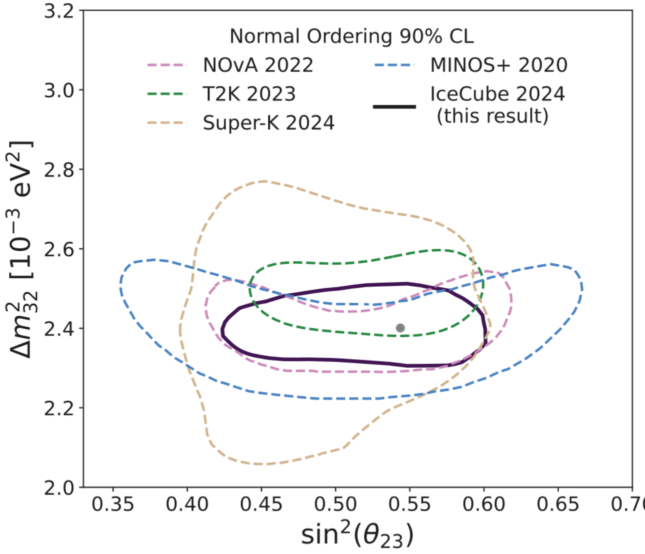
PHYS. REV. D 109, 072014





agenda.infn.it/event/37867/contributions/227906/



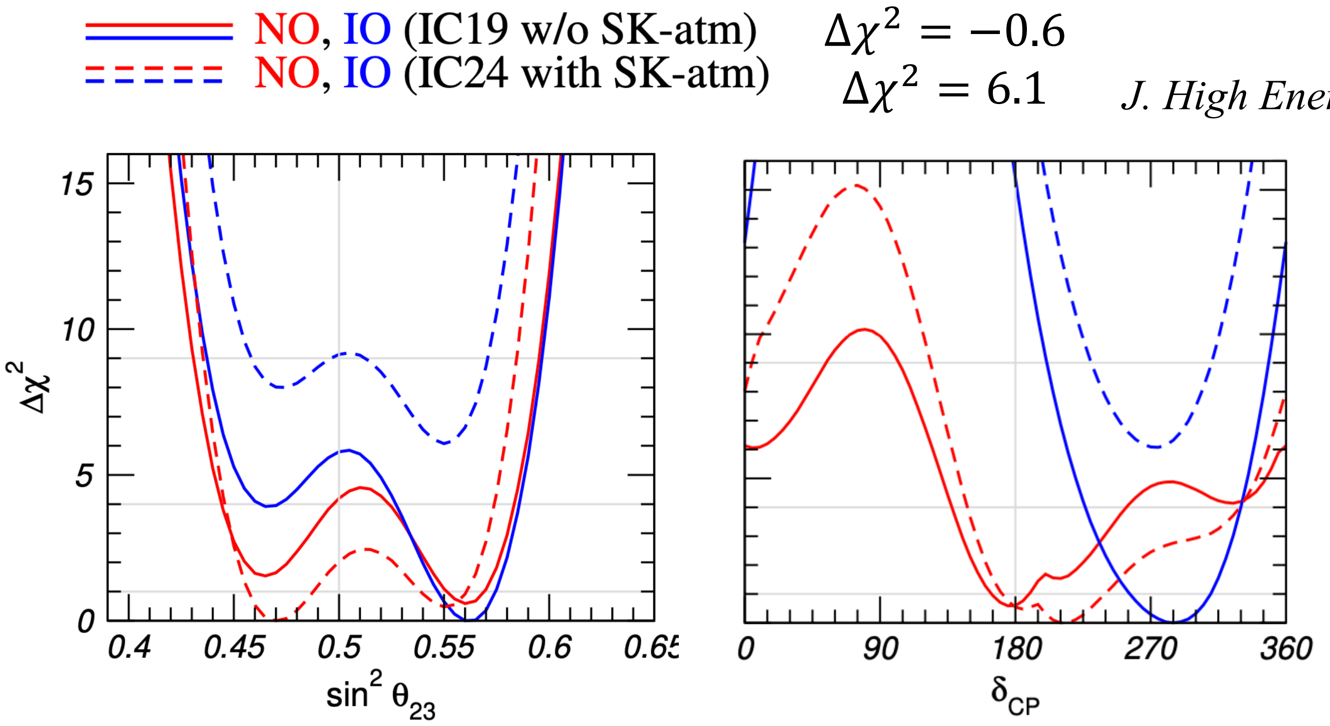


P. R. L. 134, 091801

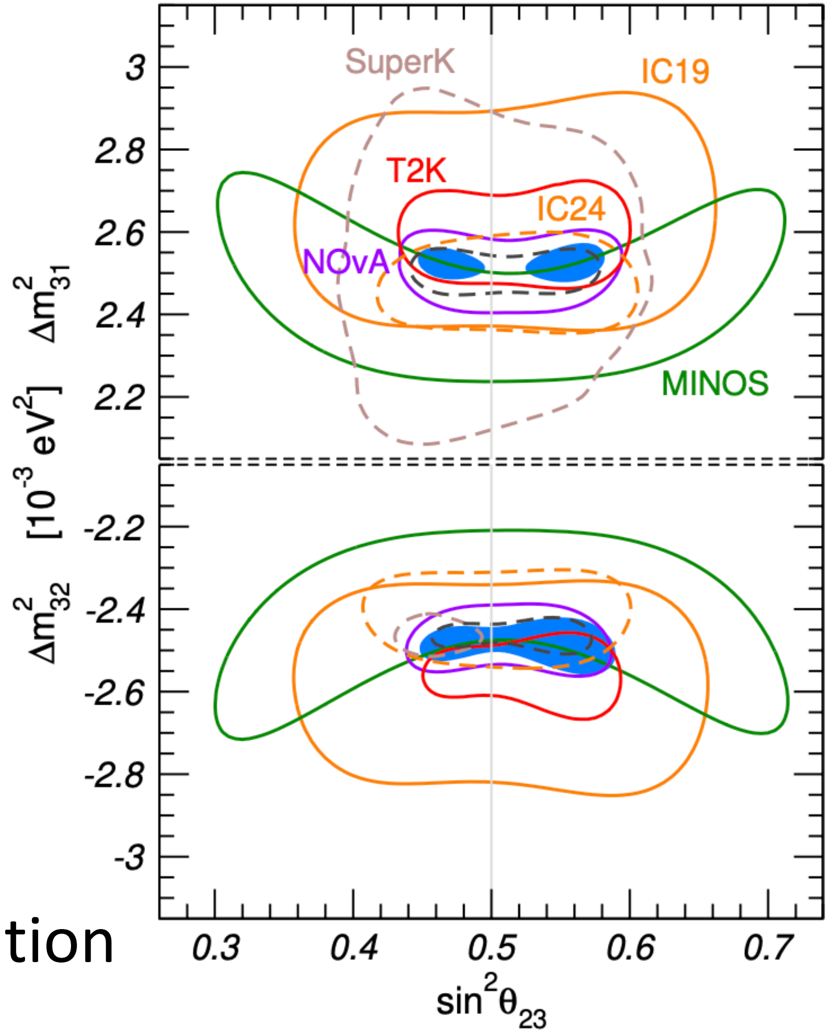
SK: Favors normal ordering, upper octant, and a nearly maximally CPV

IceCube: Slightly favors the normal ordering and upper octant

Global Fit

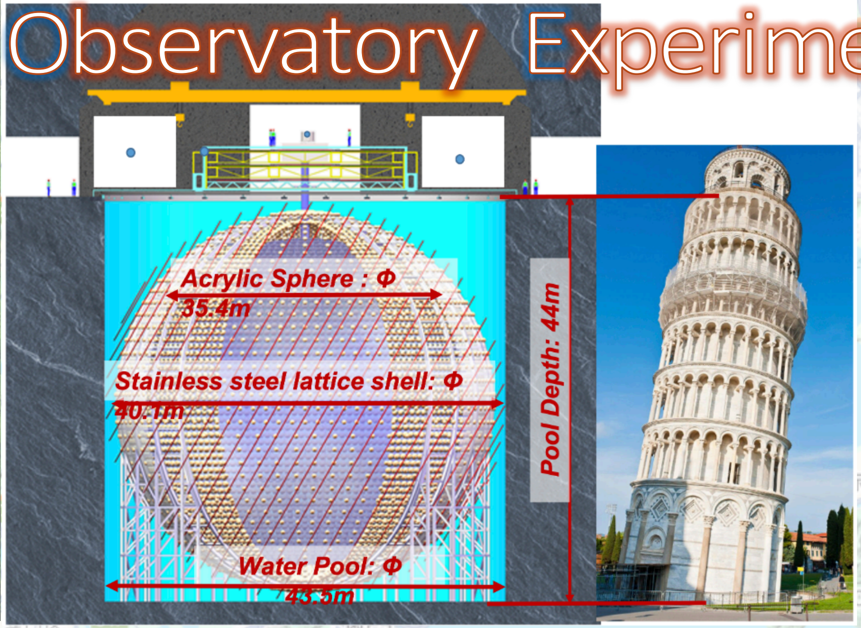


J. High Energ. Phys. **2024**, 216



- Global data prefers normal ordering
- CPV strongly depends on MO
- Octant of θ_{23} is still unknown
- Additional data is required for the determination

The Jiangmen Underground Neutrino Observatory Experiment



Physics goals: 1, NMO 2, Sub-percent measurement of $\sin^2 2\theta_{12}$, Δm^2_{21}, Δm^2_{31} 3, Solar, earth, atmospheric, supernova neutrino.

Key performances:

1, Detector scale

- 20 kton high light yield and transparency LS

2, Overall energy resolution

- 3%(<2%)@1 MeV for JUNO(TAO)

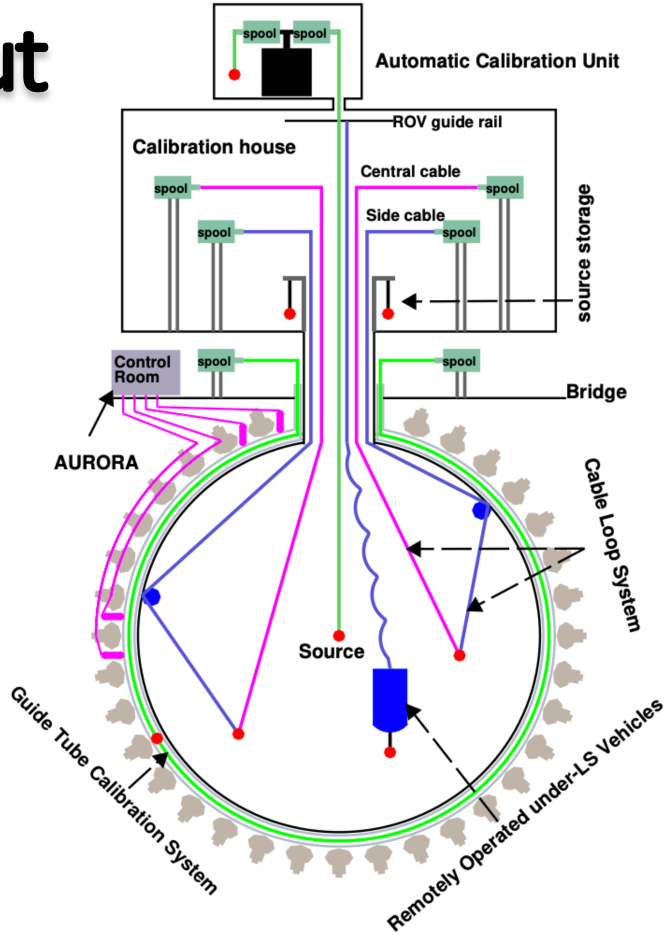
3, Detector backgrounds

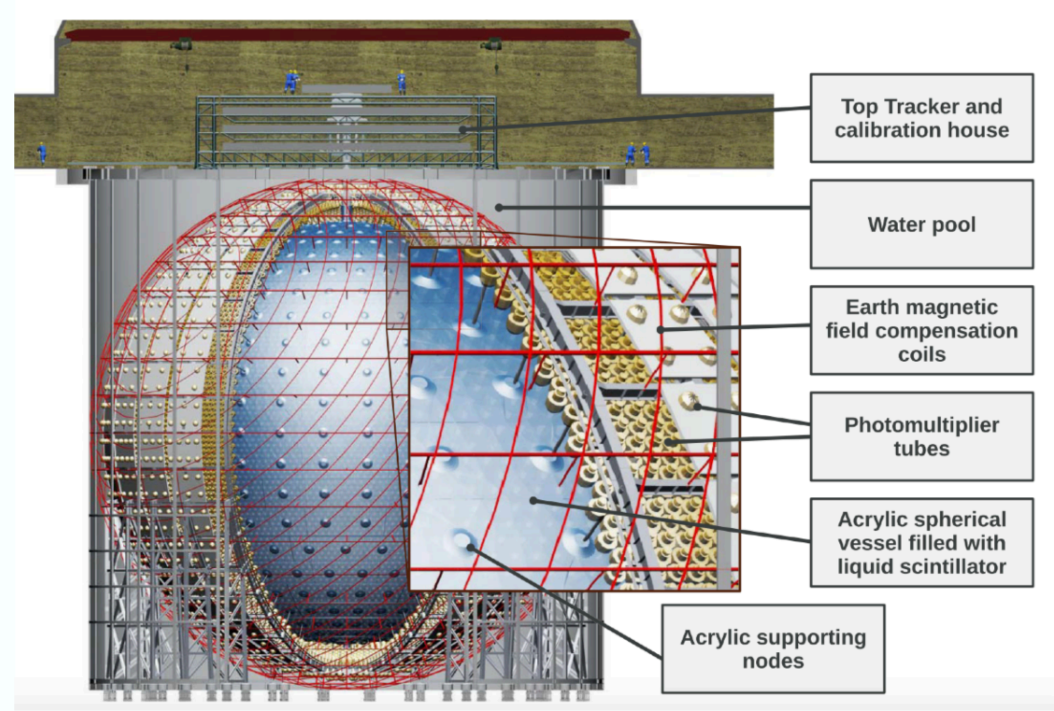
- Comparable to Borexino

Detector Layout

- Central detector (CD)
  - 20 kton LS
  - 17612 20-inch PMTs (75% coverage)
  - 25600 3-inch PMTs (3% coverage)
  - 3D calibration system

  → Precise neutrino energy calorimetry





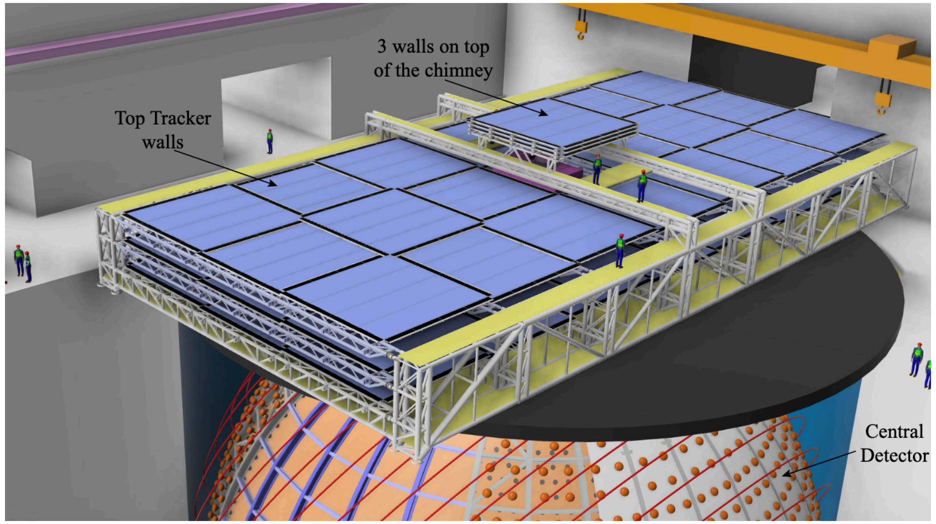
- Water Cherenkov detector (WP)
  - 35 kton pure water
  - 2400 20-inch PMTs
  - 600 8-inch PMTs

  → Muon detection and background reduction

Detector Layout

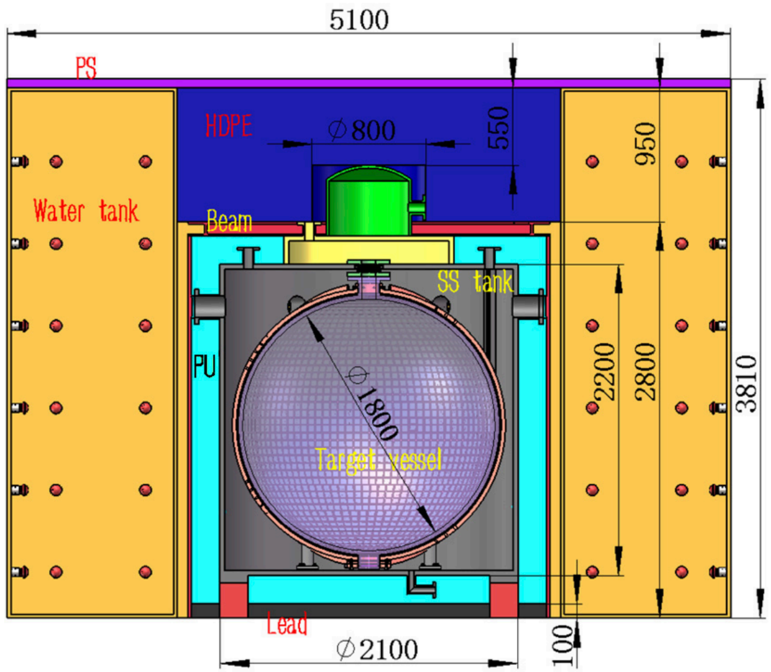
- Top Tracker (TT)
  - 3 layers plastic scintillator covering ~60% of the surface

  → Unambiguity muon directing



- Near detector (TAO)
  - 2.8 ton Gd-doped liquid scintillator
  - >94% coverage (~10 m^2) of SiPM
  - 44 m far from reactor

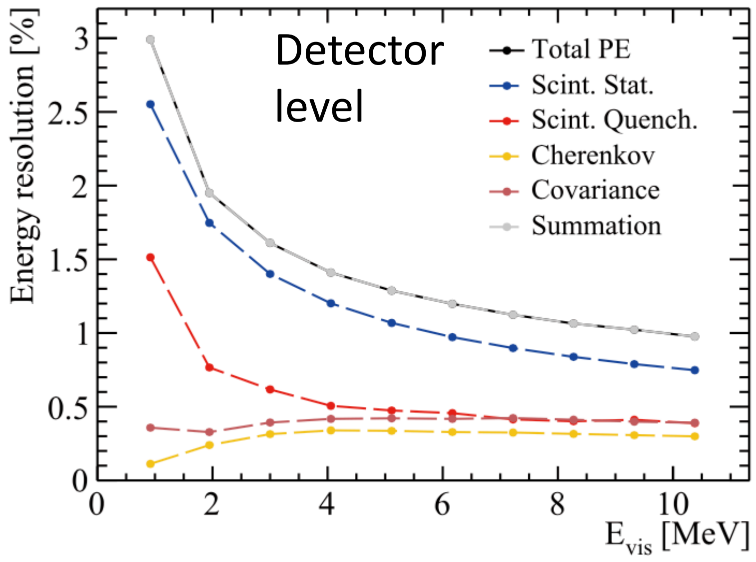
  → Precise measurement of un-oscillated energy spectrum of $\bar{\nu}_e$



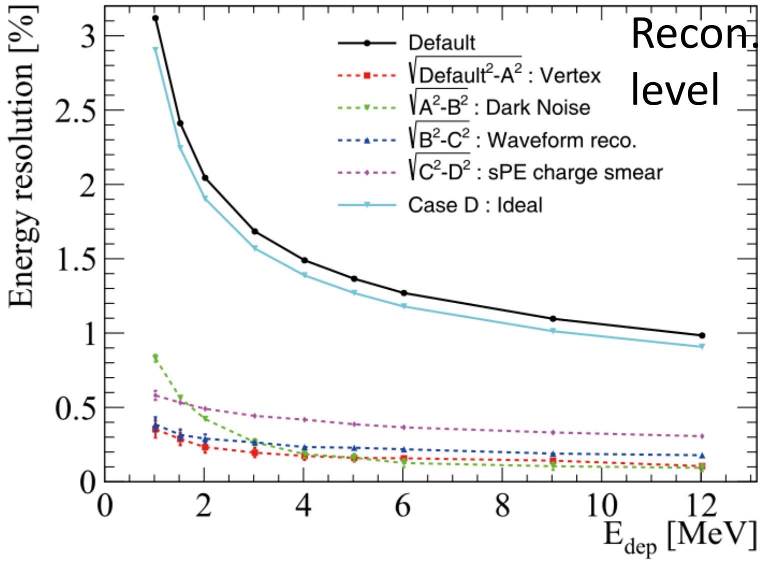
*See poster by Giovanni

Expected Detector Performance

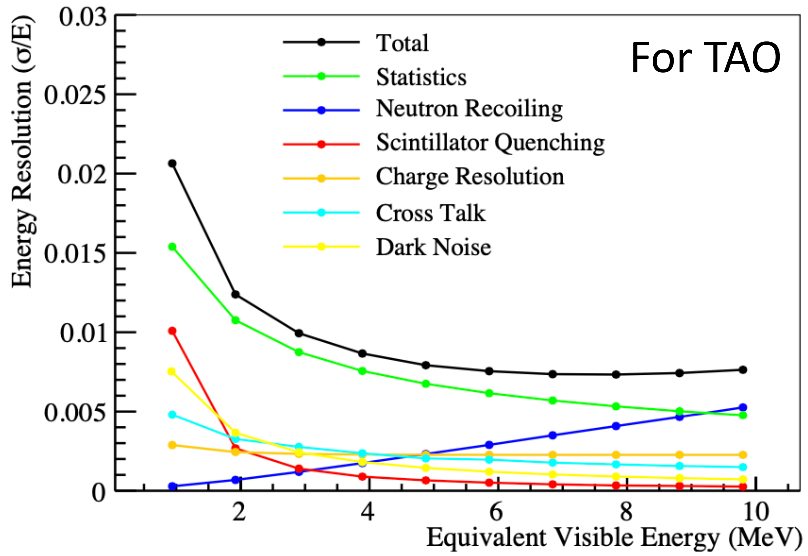
Chin. Phys. C **49**, 033104



Chin. Phys. C **49**, 033104



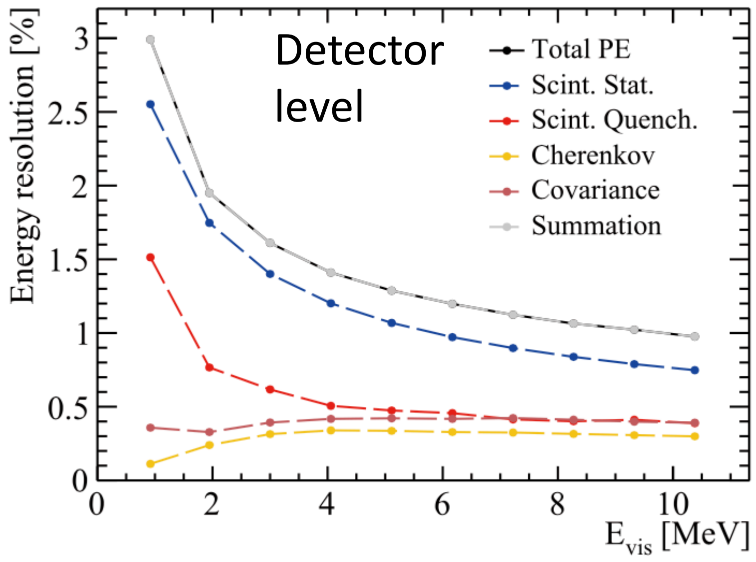
arXiv:2005.08745



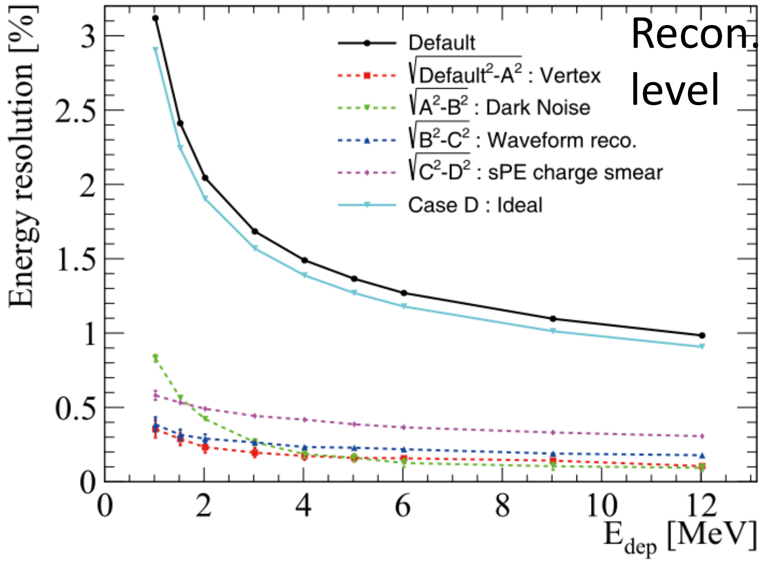
- Components of energy resolution are clear
- JUNO energy resolution is ~2.95% @1 MeV
- TAO energy resolution < 2% @1 MeV

Expected Detector Performance

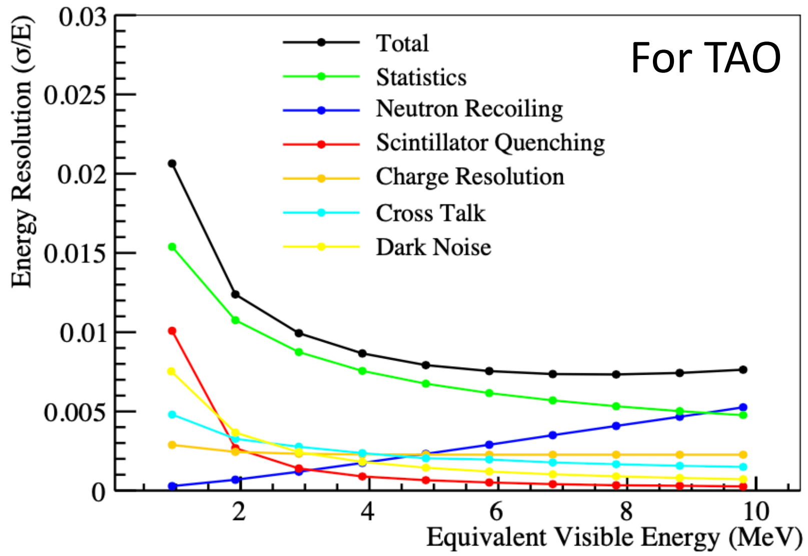
Chin. Phys. C **49**, 033104



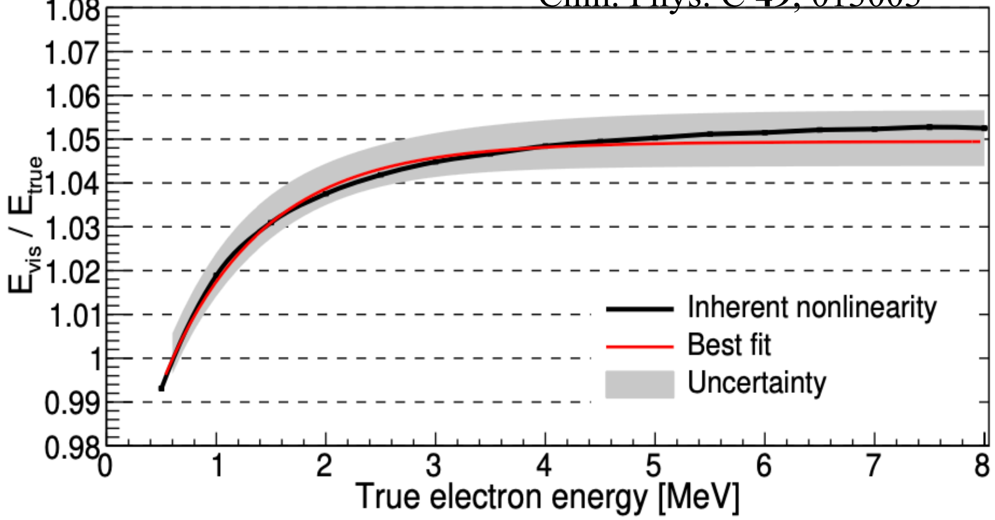
Chin. Phys. C **49**, 033104



arXiv:2005.08745



Chin. Phys. C **49**, 013003



- Components of energy resolution are clear
- JUNO energy resolution is ~2.95% @1 MeV
- TAO energy resolution < 2% @1 MeV
- Uncertainty of energy non-linearity < 1%

Measurement Principle of NMO

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E}\right]$$

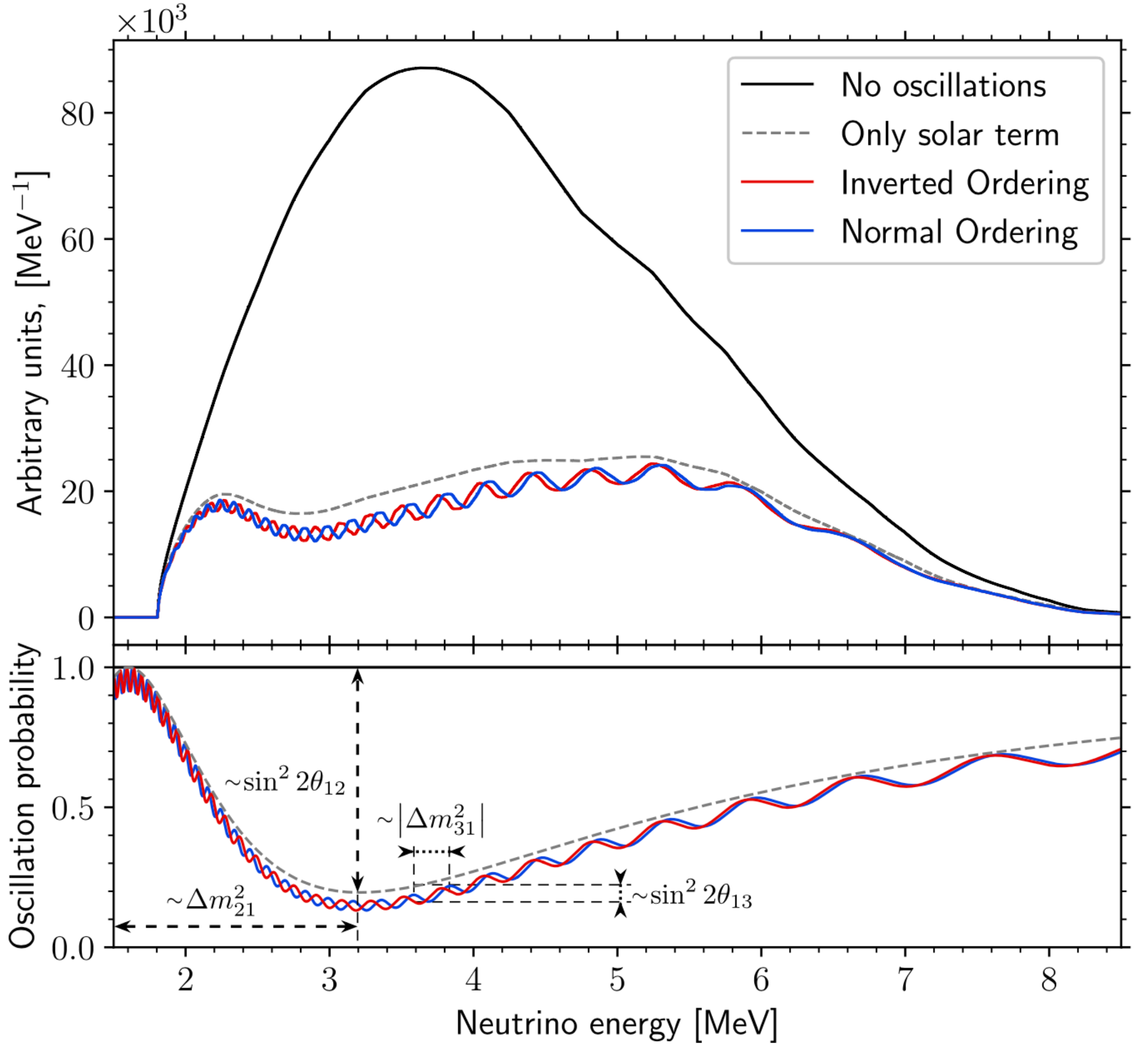
NO : $|\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2|$

IO : $|\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2|$

$$\mathcal{T}\left(\vec{\vartheta}, \sin^2\theta_{13}, \vec{\eta}, \vec{\zeta}\right) = \sum_d \left(\mu^d\left(\vec{\vartheta}, \sin^2\theta_{13}, \vec{\eta}, \vec{\zeta}\right) - D^d\right)^T \times \left(V_{\text{stat}}^d + V_{\text{b2b}}^d\right)^{-1}\left(\mu^d - D^d\right) + \chi^2_{\text{osc}}\left(\sin^2\theta_{13}\right) + \chi^2_{\text{nuis.}}(\vec{\eta}) + \chi^2_{\text{corr.nuis.}}(\vec{\zeta}),$$

$$\Delta\mathcal{T} = \min \mathcal{T}_{\text{IO}}(D) - \min \mathcal{T}_{\text{NO}}(D) \qquad \Delta\chi^2_{\min} = \overline{\Delta\mathcal{T}}$$

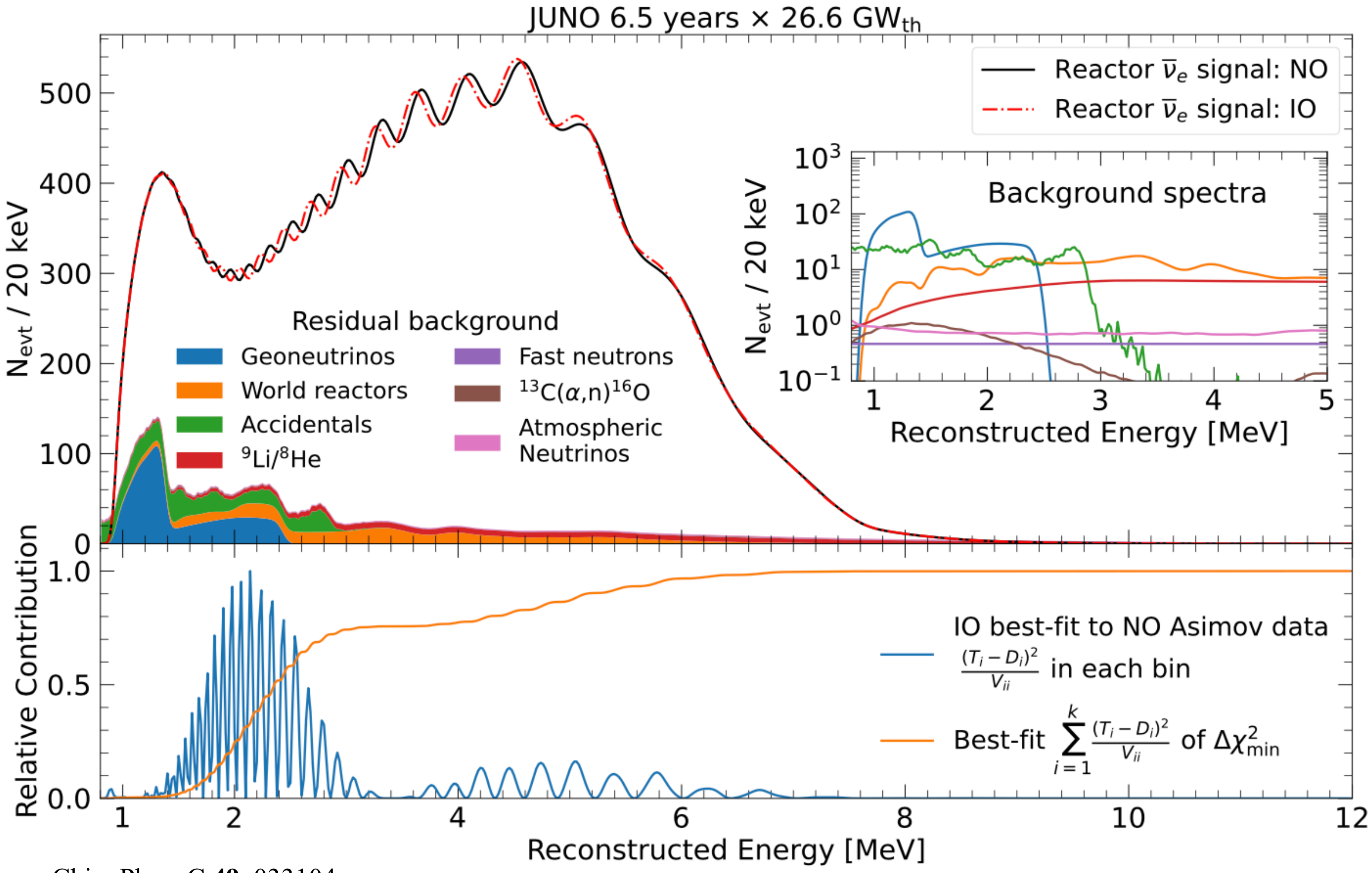
Testing statistic   Sensitivity



Chin. Phys. C **49**, 033104

NMO Sensitivity with Reactor Neutrinos

- A daily detection rate of 47.1 reactor neutrinos
- The most sensitive region is [1.5, 3] MeV

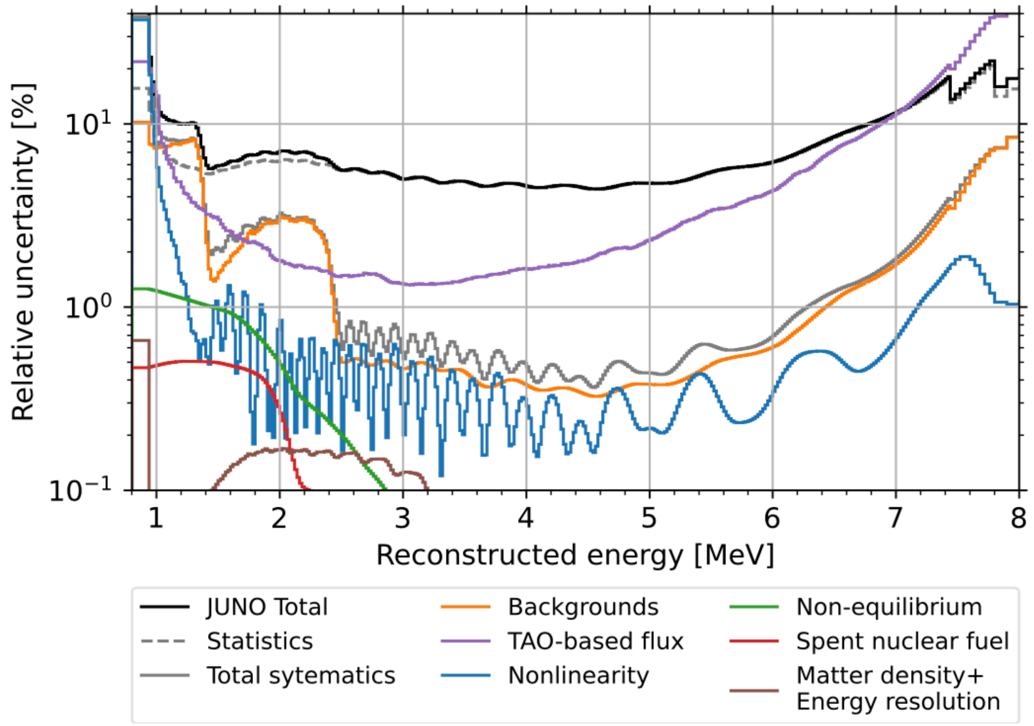


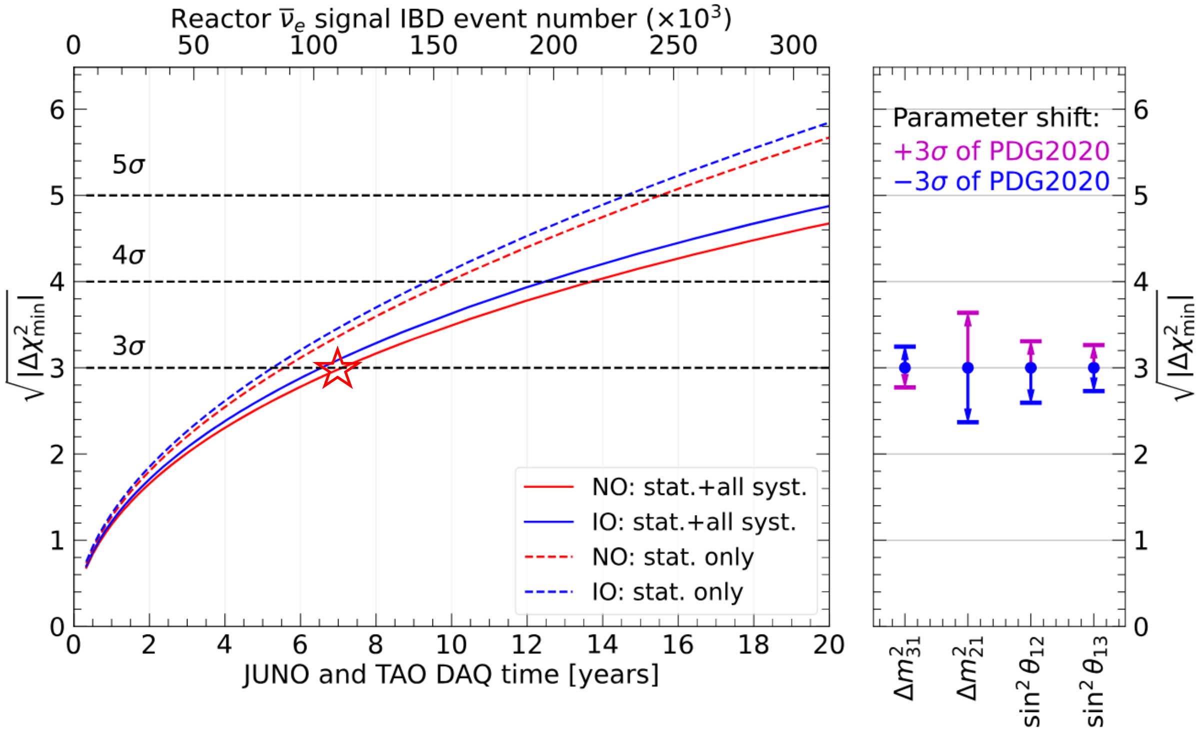
Chin. Phys. C **49**, 033104

Chin. Phys. C **49**, 033104

NMO Sensitivity with Reactor Neutrinos

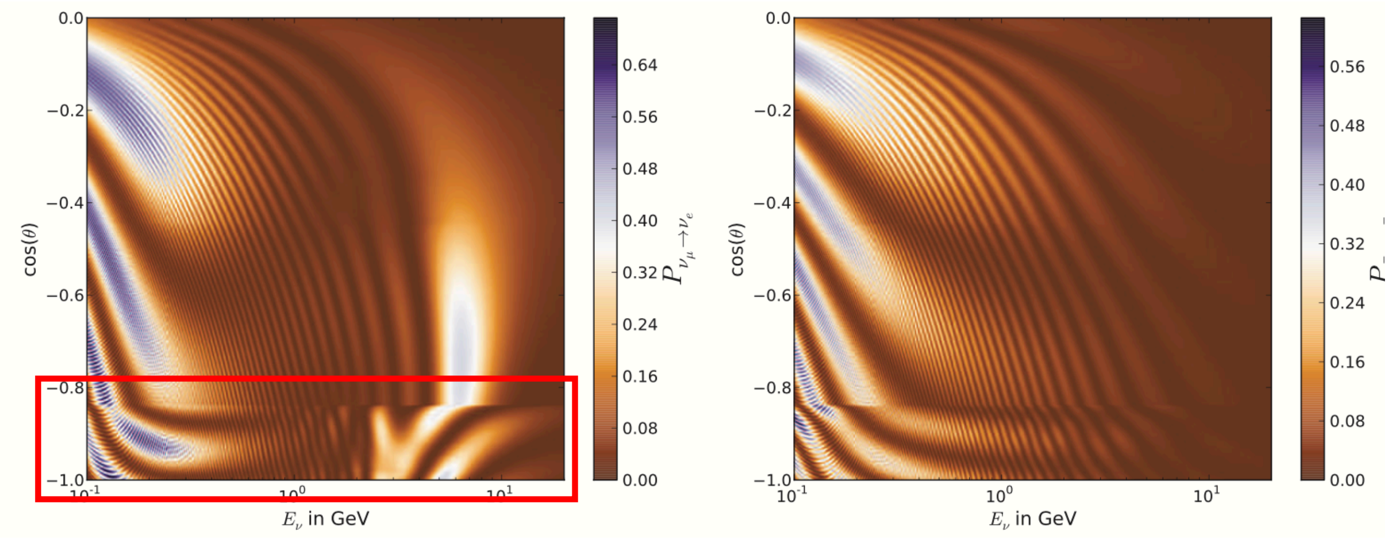
Chin. Phys. C **49**, 033104



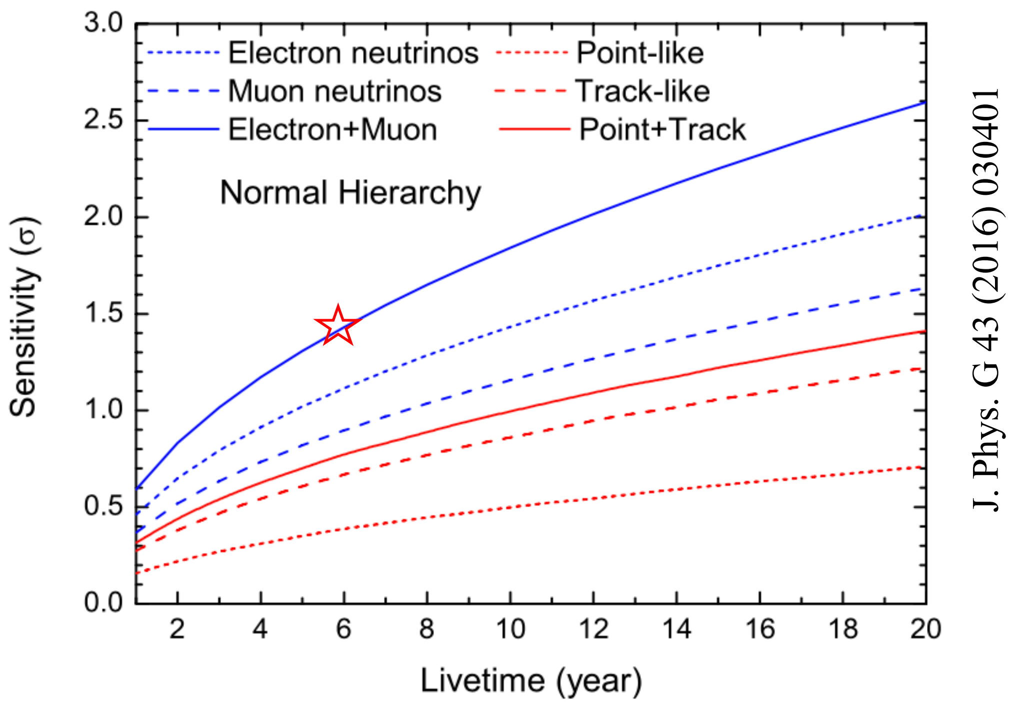


- The uncertainty of reactor neutrino flux < 2% in [1.5, 4] MeV
- With an exposure of 6.5 years, JUNO will achieve a median sensitivity of 3σ to reject the incorrect MO hypothesis

NMO Sensitivity with Atmospheric Neutrinos



these structures swap between neutrinos and antineutrinos for the IO hypothesis



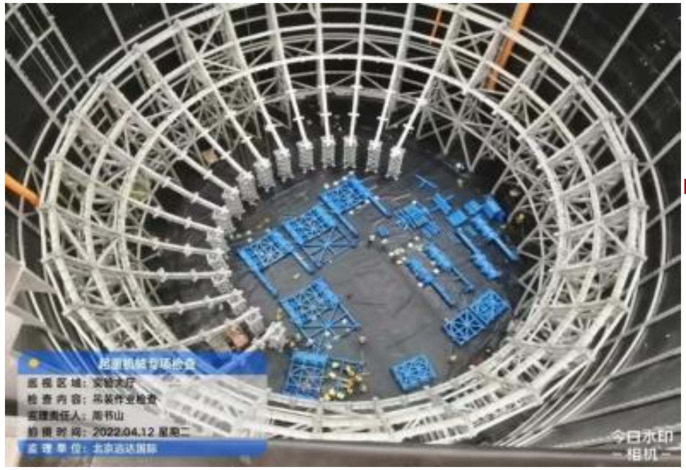
- Very low energy threshold and excellent energy resolution
- Characteristic signals from Michel electrons, neutron captures and unstable daughter nuclei are helpful for the particle recognition

*See talk for more details about solar and earth neutrino physics by Livia on June 18

JUNO STATUS

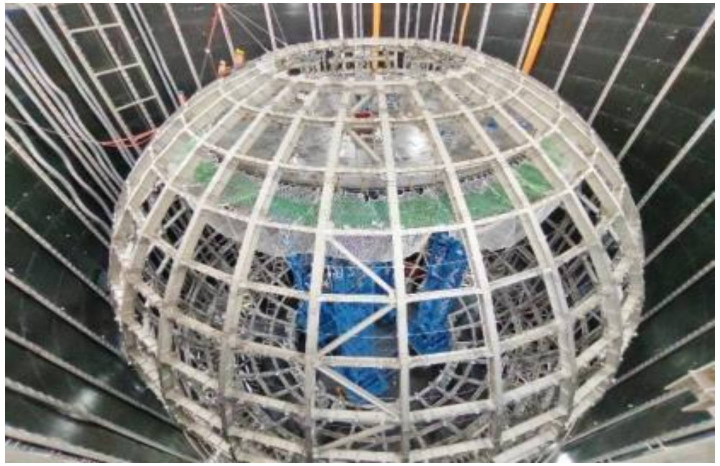
Detector Construction

The CD installation begins in spring 2022



Bottom structure

Platform for Acrylic assembly



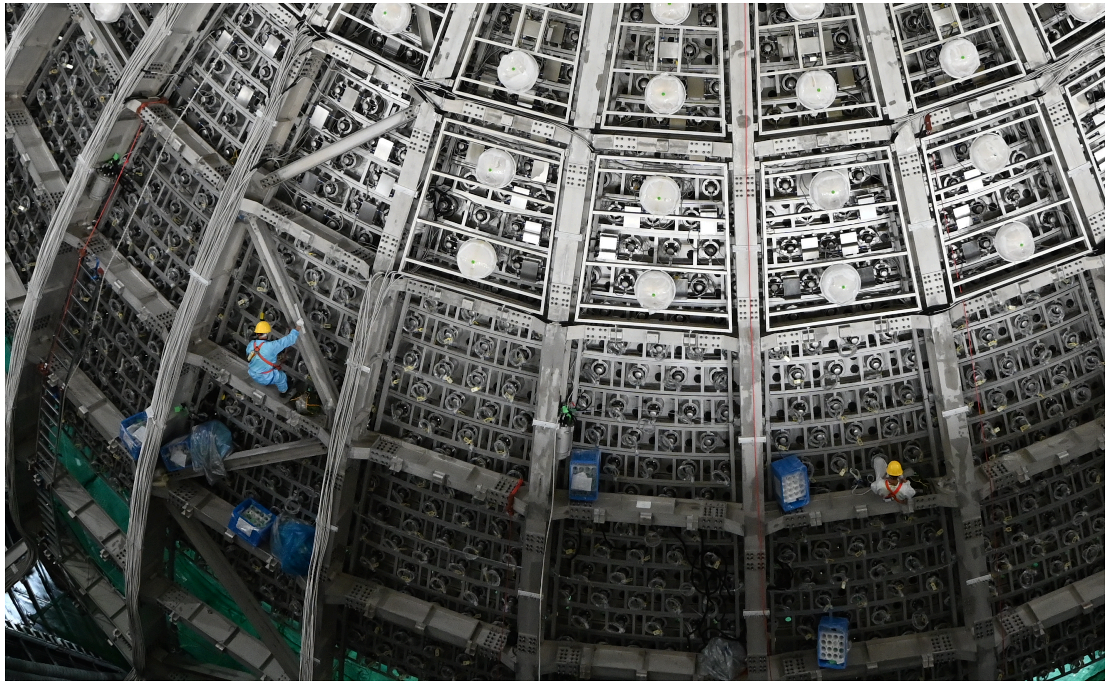
Top structure

5 layers of Acrylic

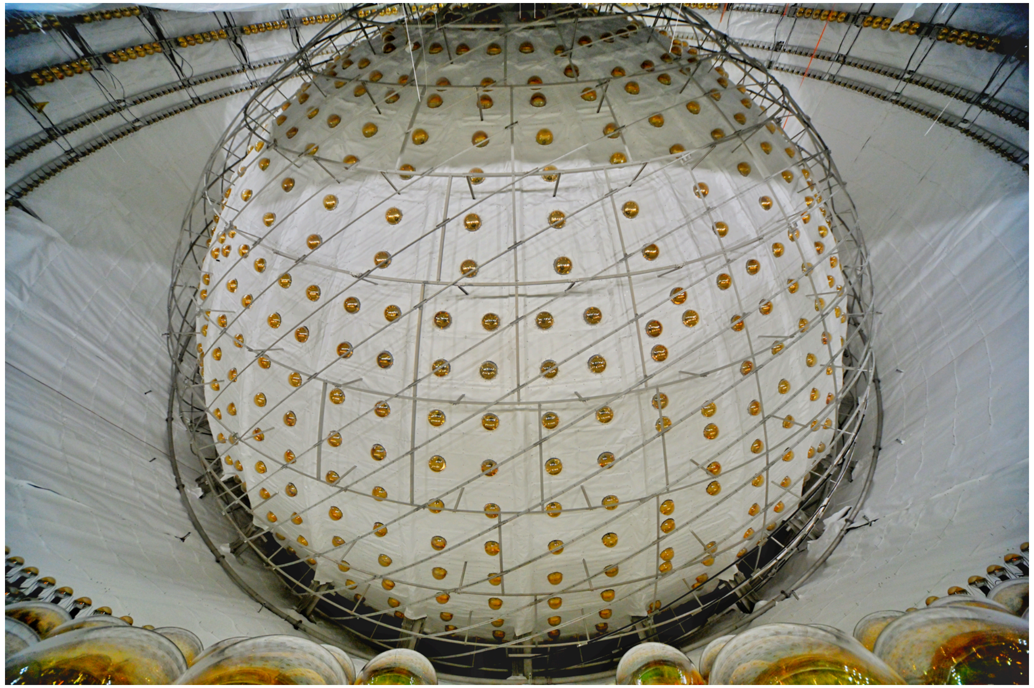
20 layers of Acrylic

23 layers of acrylic

Detector Construction



PMT and electronics installation

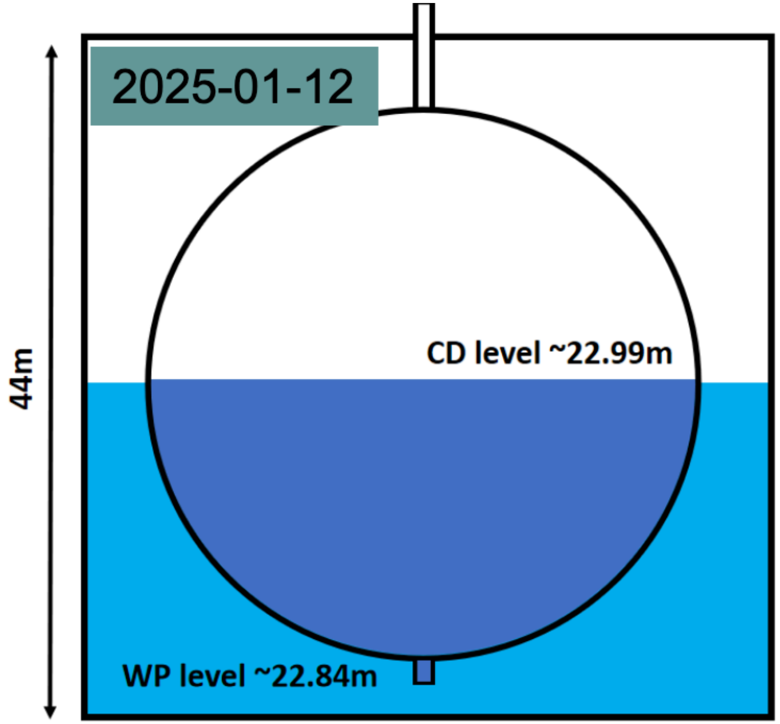


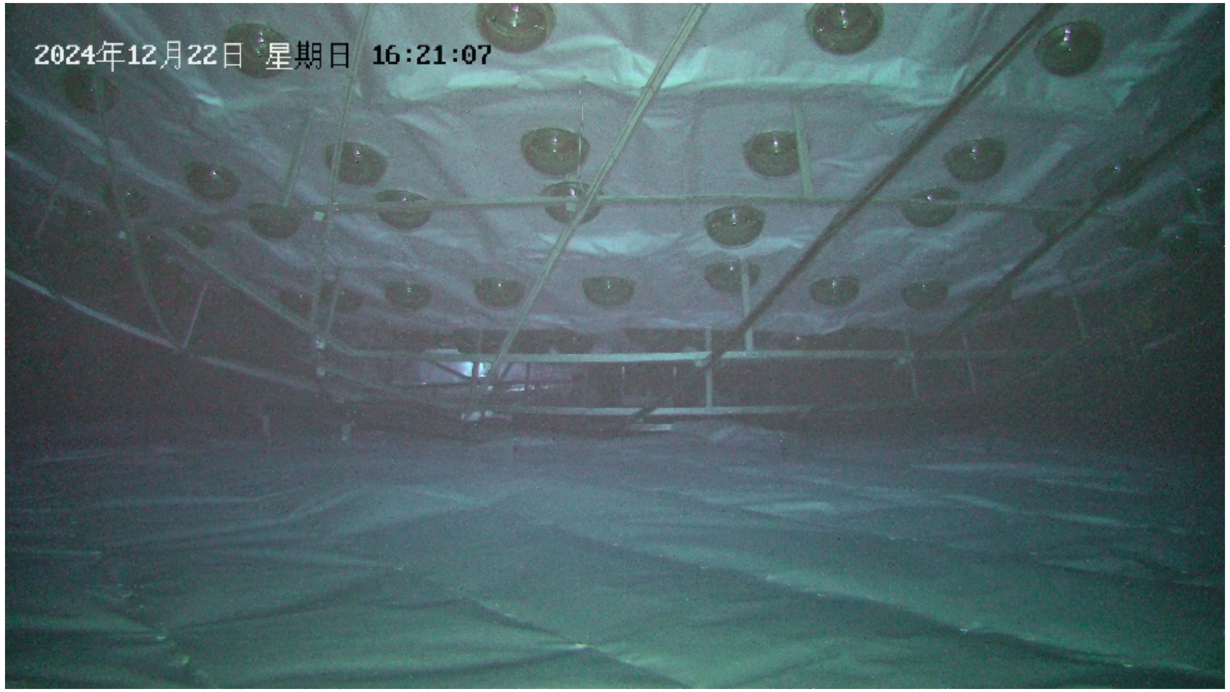
Final overview of CD

The installation of CD and WP was completed by December 2024

LS filling strategy: first fill with water, then replace the water with LS

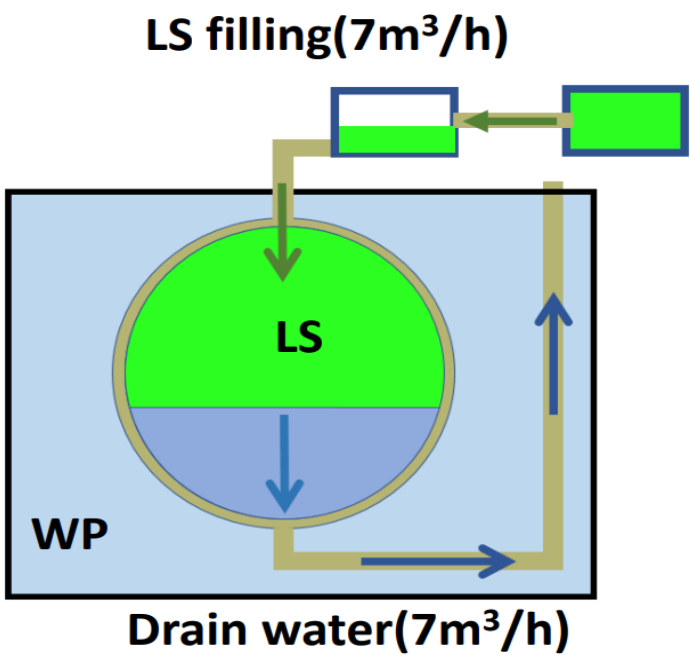
Water Filling

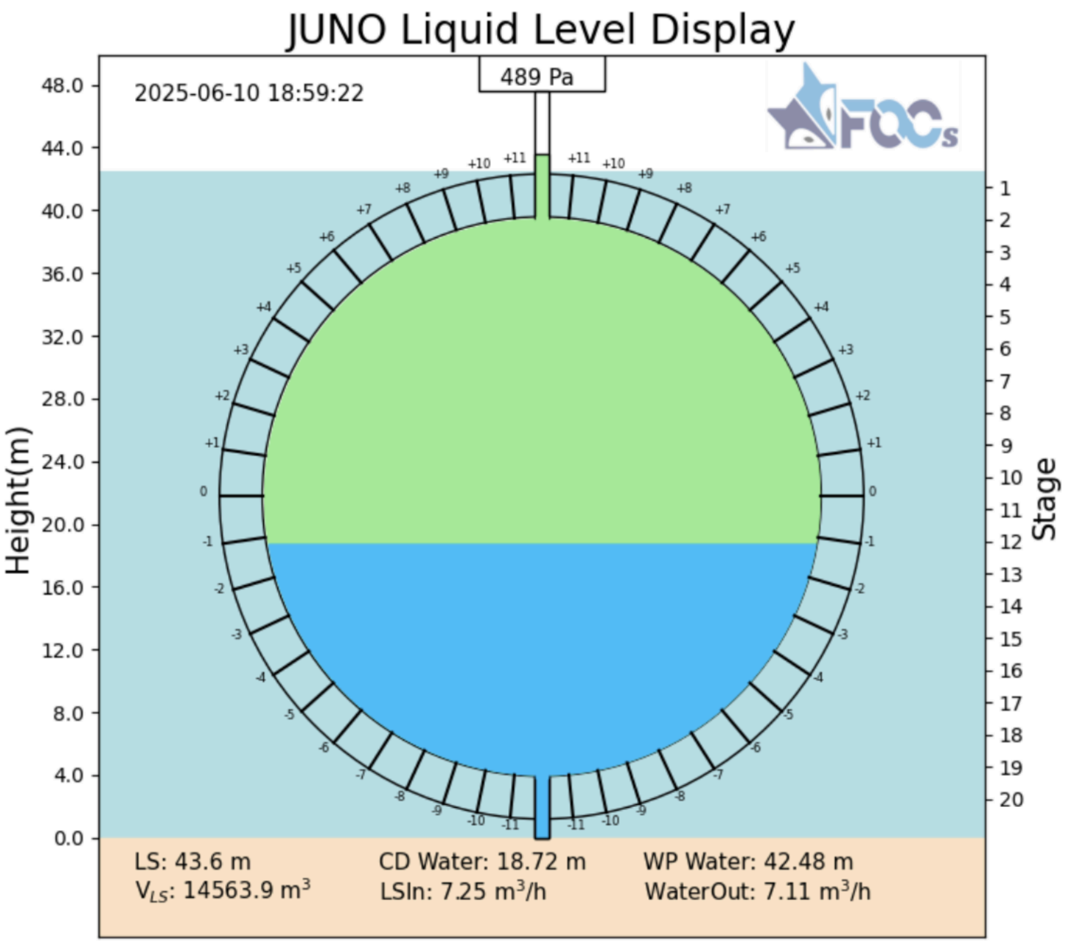




- The water filling was started in December 2024
- CD and WP were filled with water simultaneously
- The water filling was completed in February 2025

LS Filling Status

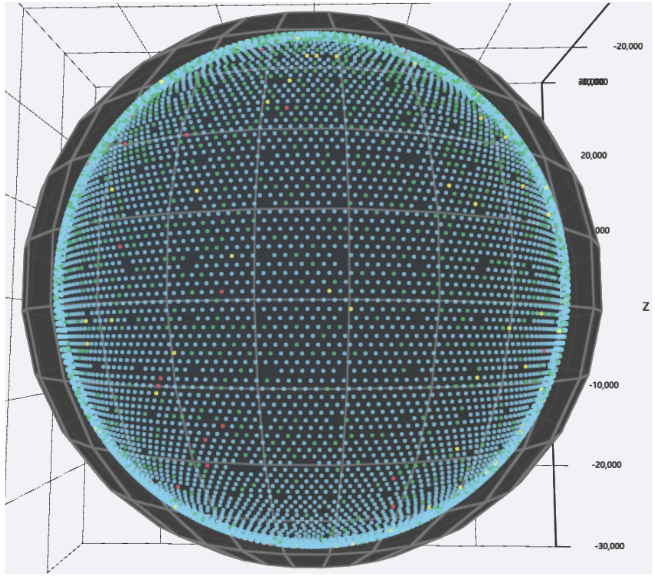




- LS filling was started on February 8, 2025
- Remove water and fill LS simultaneously
- Completion is expected by July 2025

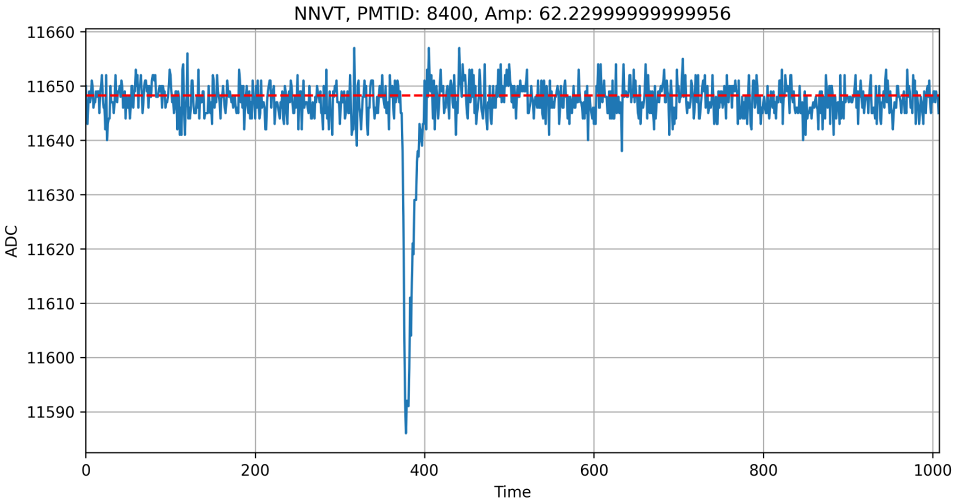
Commissioning Status

Dark rate of 20” PMTs in CD



Total PMTs installed: 17596
DNR is ~20 kHz/PMT

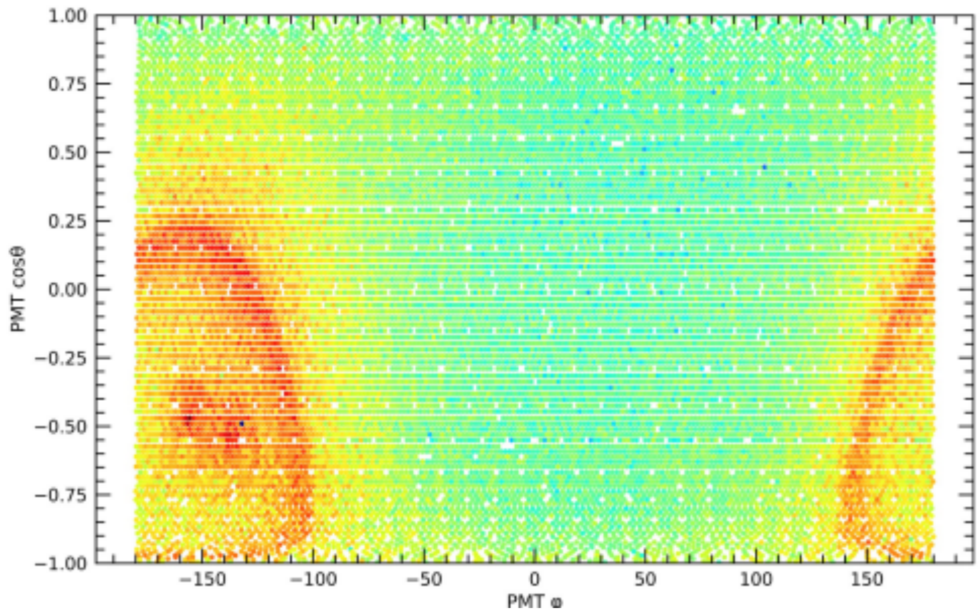
Waveform of a typical PMT

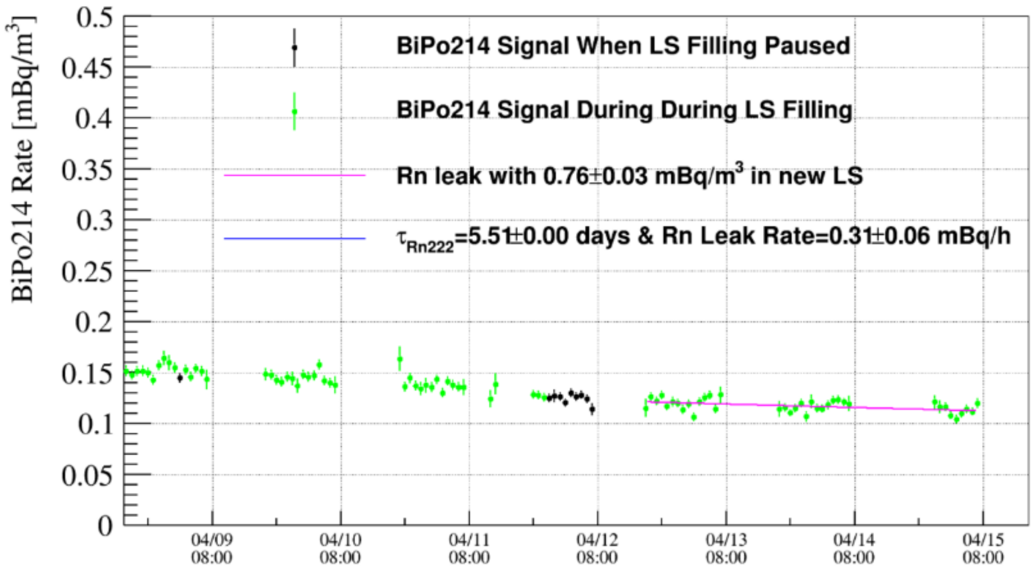


Good grounding and low noise:
RMS ~2.8 ADC ch. ➔ ~0.055 PE
PMT threshold: 0.2 PE/ch.
Trigger: ~ 300 PMTs/225ns ➔ ~150 KeV

All in agreement with the design and expectations

Commissioning Status



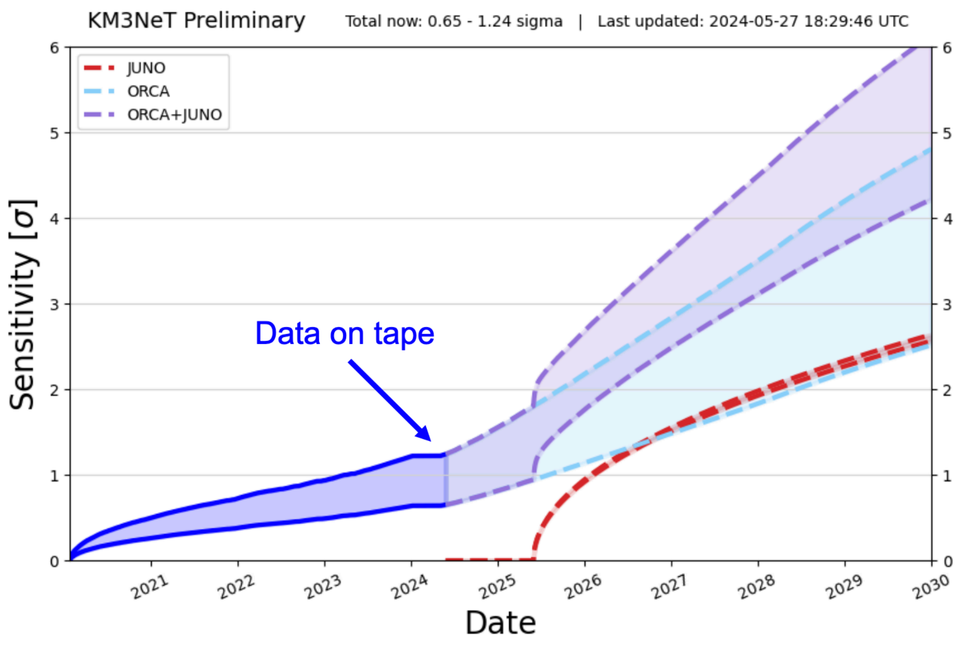


The muon events during the water phase were collected

Rn in fresh LS: < 1 mBq/m^3
U/Th <10^{-15} g/g

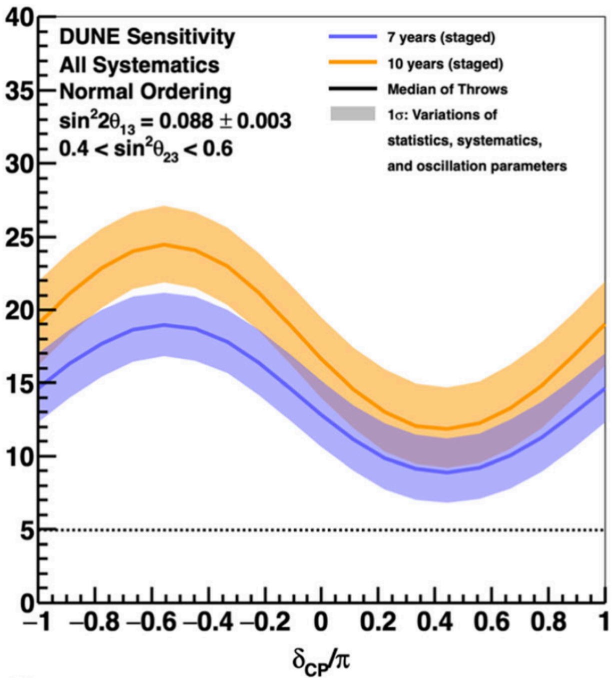
NMO Future

JUNO, ORCA



agenda.infn.it/event/37867/contributions/233917

DUNE Takes 1-3 years to reach 5σ



Eur. Phys. J. C (2020) 80:978

Hyper-K

	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	$2.2\,\sigma$ →	$3.8\,\sigma$
	0.60	$4.9\,\sigma$ →	$6.2\,\sigma$
θ_{23} octant	0.45	$2.2\,\sigma$ →	$6.2\,\sigma$
	0.55	$1.6\,\sigma$ →	$3.6\,\sigma$

10 years with 1.3MW, normal mass ordering is assumed

agenda.infn.it/event/37867/contributions/233905

The NMO is highly likely to be determined by the end of 2030 with a significance of 3σ

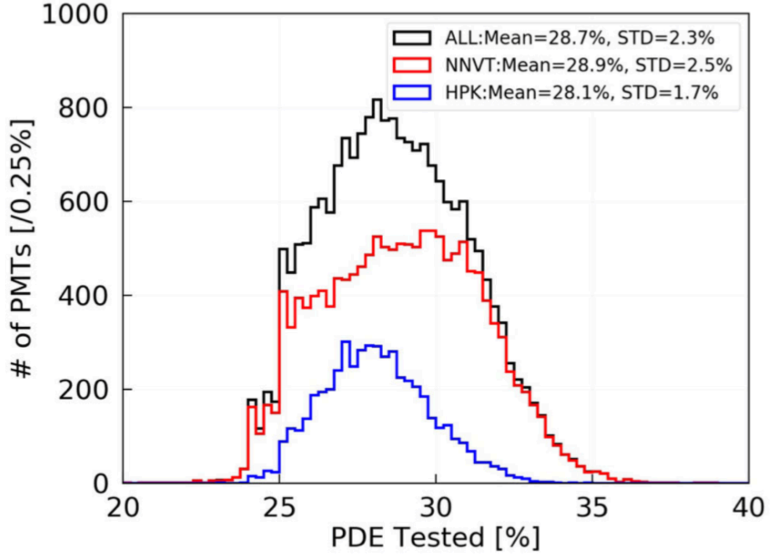
Summary

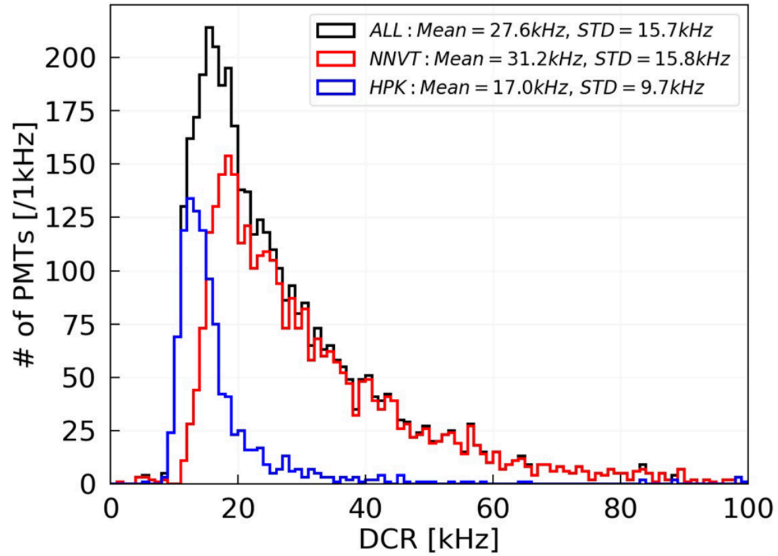
- Current experiments favor NO but show tension in θ_{23}, δ_{CP}
- JUNO is projected to be completed by summer 2025
- JUNO is expected to determine the NMO with 3σ significance around 2030
- NMO is anticipated to be determined with 5σ significance by 2035

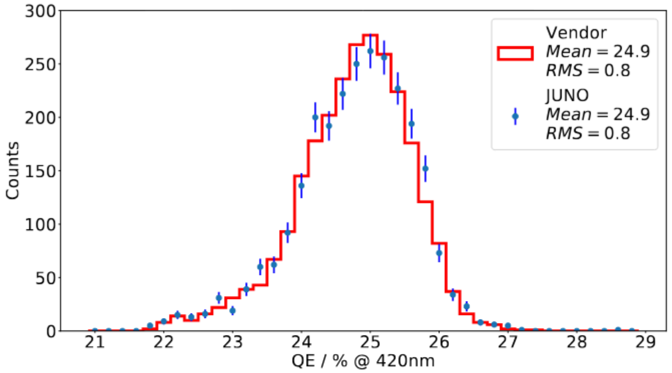
Thank you!

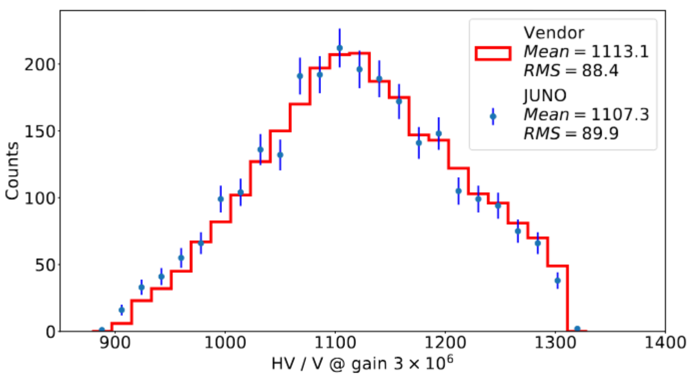
Back up

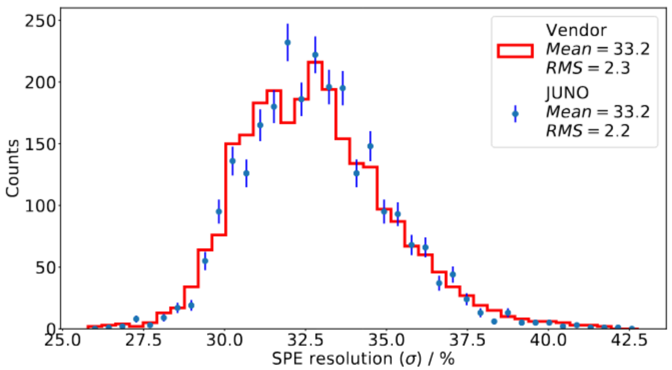
PMT testing

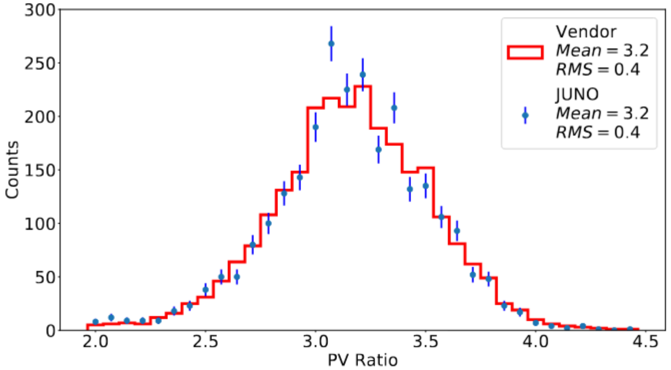

ALL:Mean=28.7%, STD=2.3%
NNVT:Mean=28.9%, STD=2.5%
HPK:Mean=28.1%, STD=1.7%
# of PMTs [/0.25%]
PDE Tested [%]

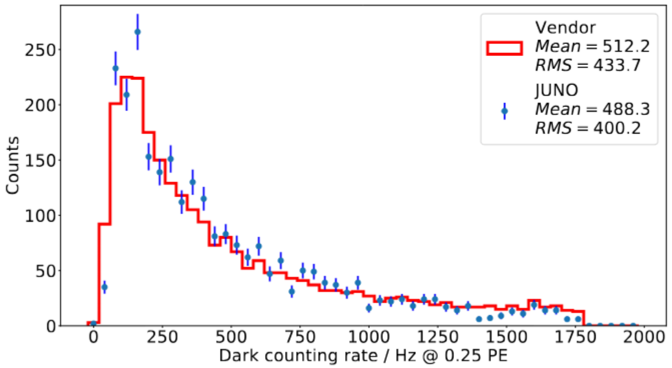

ALL : Mean = 27.6kHz, STD = 15.7kHz
NNVT : Mean = 31.2kHz, STD = 15.8kHz
HPK : Mean = 17.0kHz, STD = 9.7kHz
# of PMTs [/1kHz]
DCR [kHz]

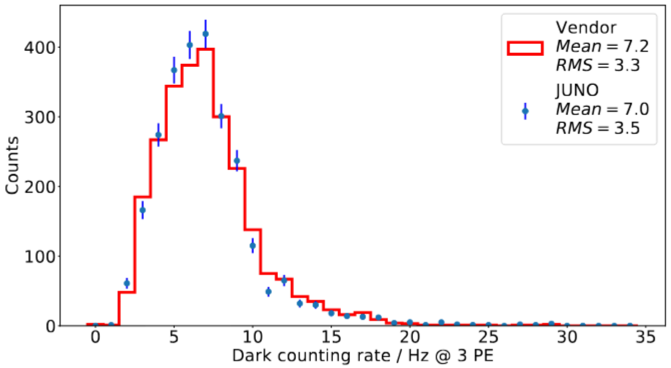

Vendor
Mean = 24.9
RMS = 0.8
JUNO
Mean = 24.9
RMS = 0.8
Counts
QE / % @ 420nm


Vendor
Mean = 1113.1
RMS = 88.4
JUNO
Mean = 1107.3
RMS = 89.9
Counts
HV / V @ gain 3 × 10^6

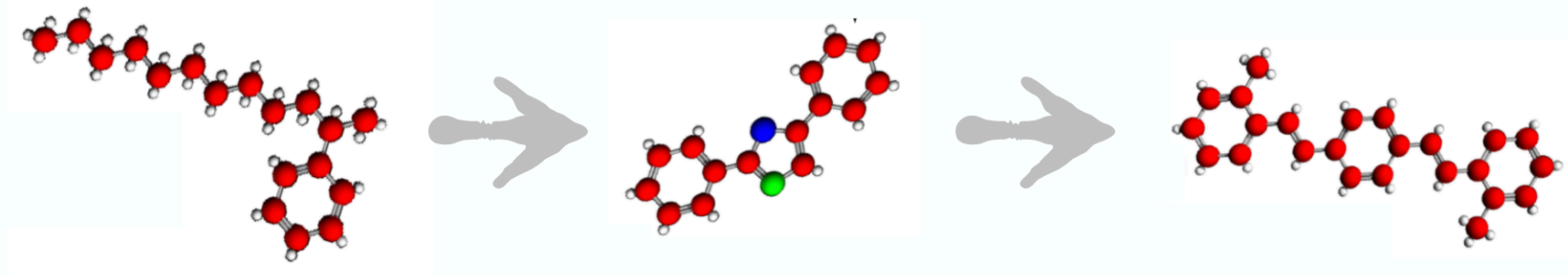

Vendor
Mean = 33.2
RMS = 2.3
JUNO
Mean = 33.2
RMS = 2.2
Counts
SPE resolution (σ) / %


Vendor
Mean = 3.2
RMS = 0.4
JUNO
Mean = 3.2
RMS = 0.4
Counts
PV Ratio


Vendor
Mean = 512.2
RMS = 433.7
JUNO
Mean = 488.3
RMS = 400.2
Counts
Dark counting rate / Hz @ 0.25 PE


Vendor
Mean = 7.2
RMS = 3.3
JUNO
Mean = 7.0
RMS = 3.5
Counts
Dark counting rate / Hz @ 3 PE

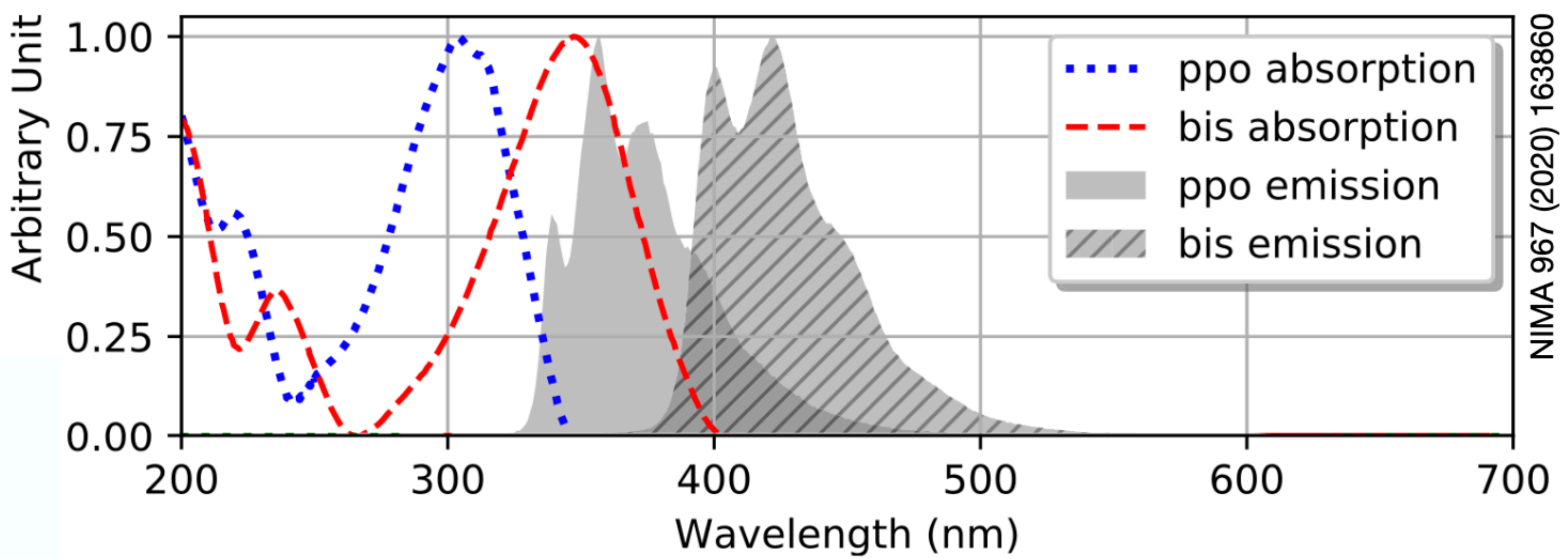
LS receipt



Solvent:
Linear Alkyl-Benzene
LAB

Fluor: 2.5 g/L PPO

Wavelength shifter:
3 mg/L bis-MSB



LS Production

Four purification plants for 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

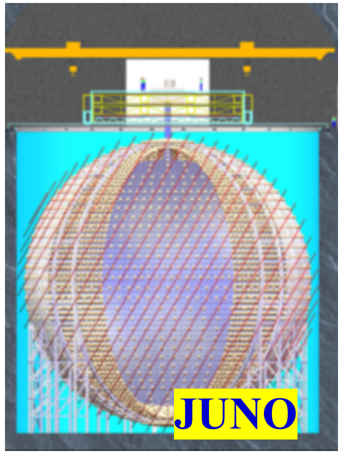
Distillation to remove radioactive impurities

Water extraction to remove radioactive impurities

Gas stripping to remove Rn and O_2

15%

OSIRIS for LS qualification



85%