Neutrino Phenomenology

Atmospheric, Long-baseline, Three-flavor effects, Earth matter effects….

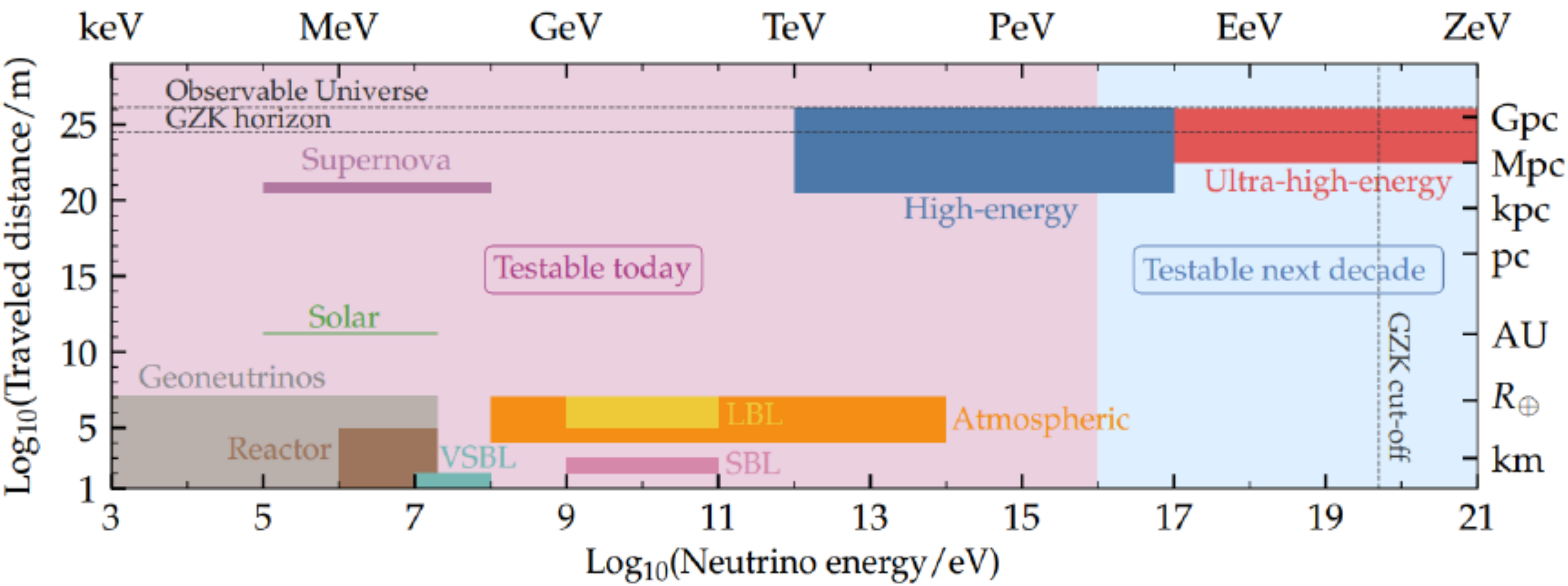
Sanjib Kumar Agarwalla

sanjib@iopb.res.in and sagarwalla@icecube.wisc.edu

Institute of Physics (IOP), Bhubaneswar, India

Department of Physics and WIPAC, UW Madison, USA

Panorama of Neutrinos: Across 18 orders in E and 25 orders in L



Remarkable progress over the last two decades

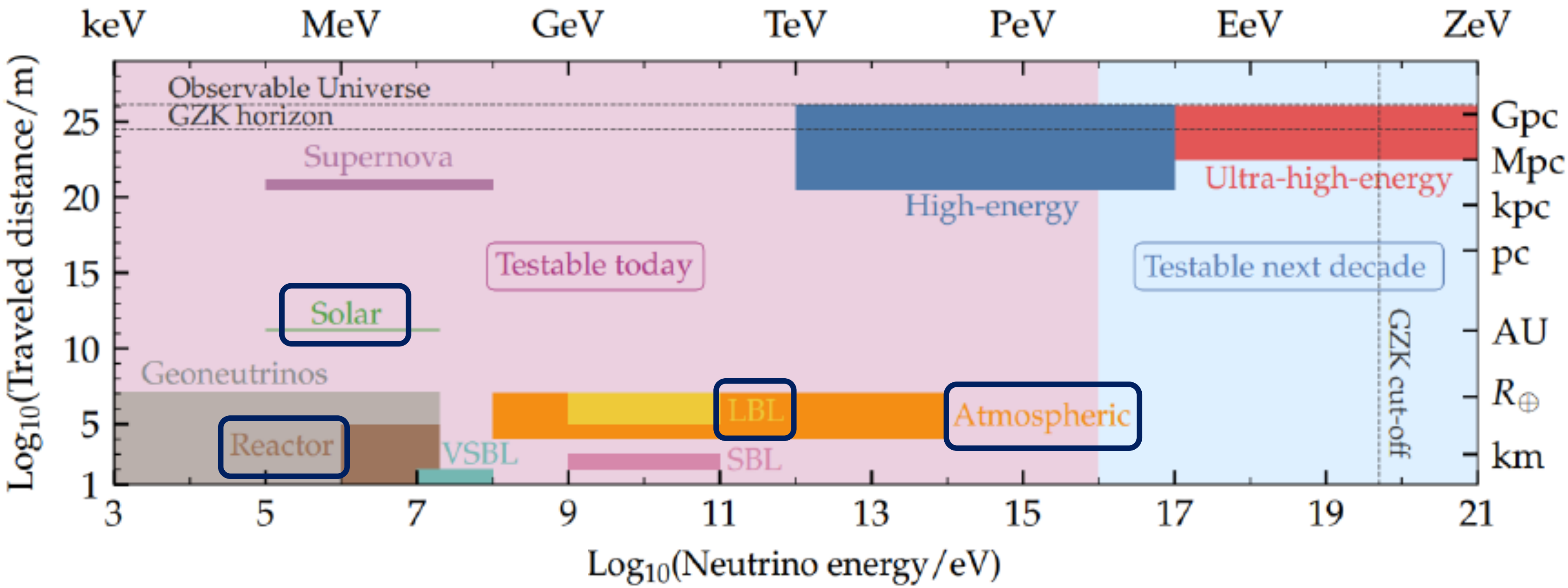
Neutrinos detected from various sources having different energy and distance scales

Detection of cosmic neutrinos opened a new window onto the Universe

Era of Neutrino Astronomy began

2002 Nobel Prize to Raymod Davis Jr. (Sun) and Masatoshi Koshiba (Supernova)

Neutrino Oscillation – A Signature for BSM Physics



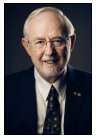
Neutrinos change their flavor as they move in space and time → Neutrinos Oscillate

Solar, Atmospheric, Reactor, and Accelerator (LBL) experiments firmly established Neutrino Flavor Oscillation → implies Neutrinos are <u>Massive</u> and <u>Mix</u> with each other

Neutrinos are <u>Massless</u> in the basic <u>Standard Model</u> (SM) of particle physics

Physics <u>beyond the Standard Model (BSM)</u> necessary to explain non-zero ν mass & mixing

2015 Nobel Prize to Takaaki Kajita (Super-K) & Arthur B. McDonald (SNO)



Probing BSM Scenarios Across 18 orders in E and 25 orders in L

Non-zero neutrino mass: first experimental proof (gateway) for BSM physics

Several BSM possibilities can be introduced in the framework of Effective Field Theory (EFT)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \cdots$$

d=5 Weinberg Operator: LLHH, Λ: New Physics Scale
S. Weinberg, PRL 43 (1979) 1566

BSM Scenarios naturally arise due to different mechanisms for generating ν masses (e.g. seesaw)

Many models of BSM physics suggest new fundamental particles and interactions, new sources of CP violation, lepton number and lepton flavor violations, possibilities of Lorentz and CPT violation

Probing BSM Scenarios Across 18 orders in E and 25 orders in L

Non-zero neutrino mass: first experimental proof (gateway) for BSM physics

Several BSM possibilities can be introduced in the framework of Effective Field Theory (EFT)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \cdots$$

d=5 Weinberg Operator: LLHH, Λ: New Physics Scale
S. Weinberg, PRL 43 (1979) 1566

BSM Scenarios naturally arise due to different mechanisms for generating ν masses (e.g. seesaw)

Many models of BSM physics suggest new fundamental particles and interactions, new sources of CP violation, lepton number and lepton flavor violations, possibilities of Lorentz and CPT violation

Probe BSM Physics at High Energies (TeV-PeV)

High-Energy (TeV-PeV) Astrophysical Neutrinos coming from cosmic distances (Mpc-Gpc)

Giant Neutrino Telescopes: IceCube@South Pole, KM3NeT@Mediterranean Sea, future IceCube-Gen2

Novel Approach --
New Physics beyond the reach of modern Colliders

Probing BSM Scenarios Across 18 orders in E and 25 orders in L

Non-zero neutrino mass: first experimental proof (gateway) for BSM physics

Several BSM possibilities can be introduced in the framework of Effective Field Theory (EFT)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \cdots$$

d=5 Weinberg Operator: LLHH, Λ: New Physics Scale
S. Weinberg, PRL 43 (1979) 1566

BSM Scenarios naturally arise due to different mechanisms for generating ν masses (e.g. seesaw)

Many models of BSM physics suggest new fundamental particles and interactions, new sources of CP violation, lepton number and lepton flavor violations, possibilities of Lorentz and CPT violation

Probe BSM Physics at High Energies (TeV-PeV)

High-Energy (TeV-PeV) Astrophysical Neutrinos coming from cosmic distances (Mpc-Gpc)

Giant Neutrino Telescopes: IceCube@South Pole, KM3NeT@Mediterranean Sea, future IceCube-Gen2

Novel Approach --
New Physics beyond the reach of modern Colliders

Probe BSM Physics at Low Energies (MeV-GeV)

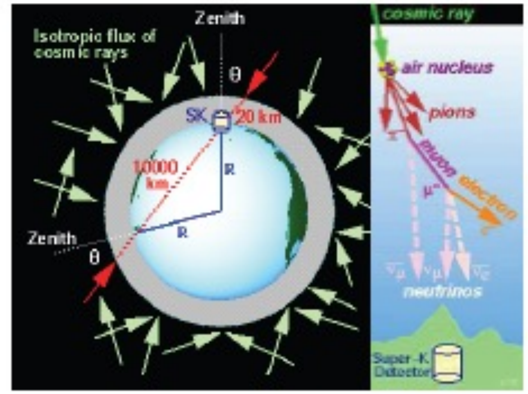
Low-Energy (MeV-GeV) Accelerator & Atmospheric νs travelling terrestrial distances (few m - 1000s of km)

Accelerator: DUNE@USA, T2HK@Japan
Atmospheric: DeepCore, DUNE, Hyper-K, INO

Expected to measure oscillation parameters with a precision around a few % -- sensitive to sub-leading BSM physics at low energies

Complement BSM search @ High-Energy Colliders

Golden Age of Neutrino Physics (1998 – 2024 & Beyond)

sun	reactors	atmosphere	accelerators
			
Homestake, SAGE, GALLEX SuperK, SNO, Borexino	KamLAND, CHOOZ Double Chooz, Daya Bay, RENO	SuperKamiokande IceCube, DeepCore	K2K, MINOS, T2K NOvA

Over the last two decades or so, marvelous data from world-class experiments

- Solar neutrinos (ν_e)
- Atmospheric neutrinos ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$)
- Reactor anti-neutrinos ($\bar{\nu}_e$)
- Accelerator neutrinos ($\nu_\mu, \bar{\nu}_\mu$)

→ *Data from various neutrino sources and vastly different energy and distance scales*

↓

Neutrinos change their flavor as they move in space and time

We have just started our journey in the mysterious world of neutrinos

Three-Flavor Neutrino Oscillation Framework: Simple & Robust

It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

$L/E = 500$ km/GeV $\quad$ $L/E = 15,000$ km/GeV

$\Delta m^2_{31} \sim 2.5 \times 10^{-3}$ eV^2 $\quad$ $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$ $\quad$ $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

Three mixing angles: $\theta_{23}, \theta_{13}, \theta_{12}$ and one CP-violating (Dirac) phase δ_{CP}

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}$$

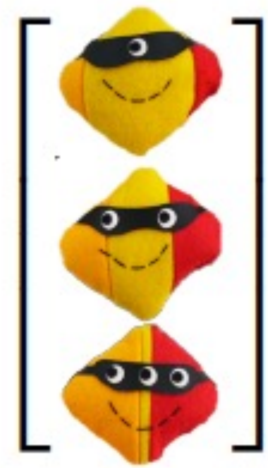
$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$

$\Delta m^2_{ij} = m^2_i - m^2_j$

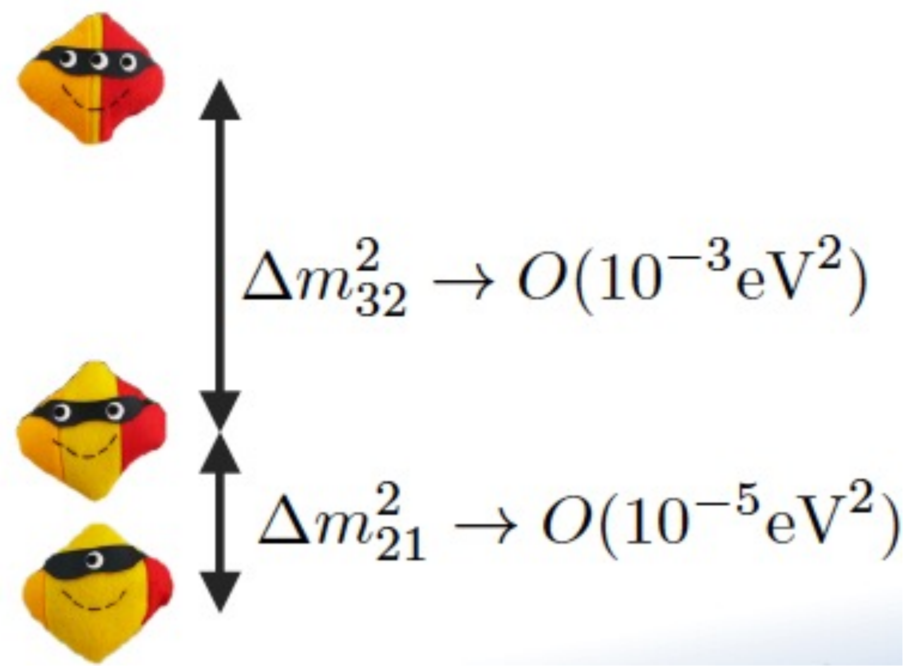
for antineutrinos replace δ_{CP} by $-\delta_{CP}$

Three-Flavor Neutrino Oscillations

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



- Oscillations among the three neutrino flavors depend on:
  - The mixing matrix
    - θ_{23}, θ_{13}, δ_{CP}, θ_{12}
  - The mass differences
    - $\Delta m^2{}_{32}$, $\Delta m^2{}_{21}$



The Pontecorvo-Maki-Nakagawa-Sakata Matrix

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

$\theta_{12} = 33.41^{\circ}{}^{+0.75^{\circ}}_{-0.72^{\circ}}$ $\theta_{23} = 49.1^{\circ}{}^{+1.0^{\circ}}_{-1.3^{\circ}}$ $\theta_{13} = 8.54^{\circ}{}^{+0.11^{\circ}}_{-0.12^{\circ}}$ $\delta_{CP} = 197^{\circ}{}^{+42^{\circ}}_{-25^{\circ}}$

w/o Super-K atmospheric neutrino data assuming normal mass ordering

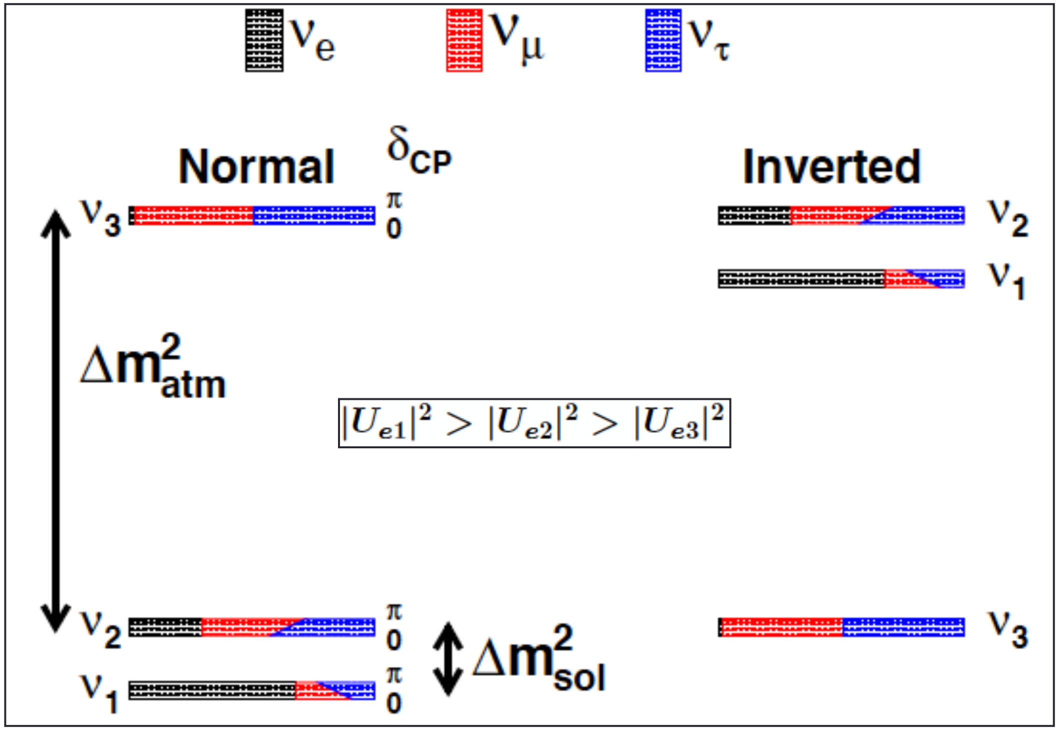
$$|U| = \begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix} = \begin{bmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.779 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{bmatrix}$$

3σ ranges (99.73% C.L.) for the magnitudes of the elements of the PMNS matrix (NuFIT.org)

- Neutrino mixings in the PMNS matrix are large as compared to the quark mixings in the CKM matrix
- In the CKM matrix, the quark mixing angles are $\theta_{12} = 13.04^{\circ} \pm 0.05^{\circ}$, $\theta_{23} = 2.38^{\circ} \pm 0.06^{\circ}$, $\theta_{13} = 0.201^{\circ} \pm 0.011^{\circ}$
- Neutrino mixings are inconsistent with TBM neutrino mixing ($\theta_{12} \approx 35.3^{\circ}$ $\theta_{23} \approx 45^{\circ}$ $\theta_{13} = 0^{\circ}$) at > 5σ

Neutrino Mass Ordering: Important Open Question

- The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known



ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

Neutrino mass spectrum can be normal or inverted ordered

We only have a lower bound on the mass of the heaviest neutrino

$$\sqrt{2.5 \cdot 10^{-3}\mathrm{eV}^2} \sim 0.05\ \mathrm{eV}$$

We currently do not know which neutrino is the heaviest

Matter effect inside the Sun played an important role to fix the ordering between m_2 & m_1

Matter effect inside the Earth will play a crucial role to fix the ordering between m_3 & m_1

Mass Ordering Discrimination : A Binary yes-or-no type question

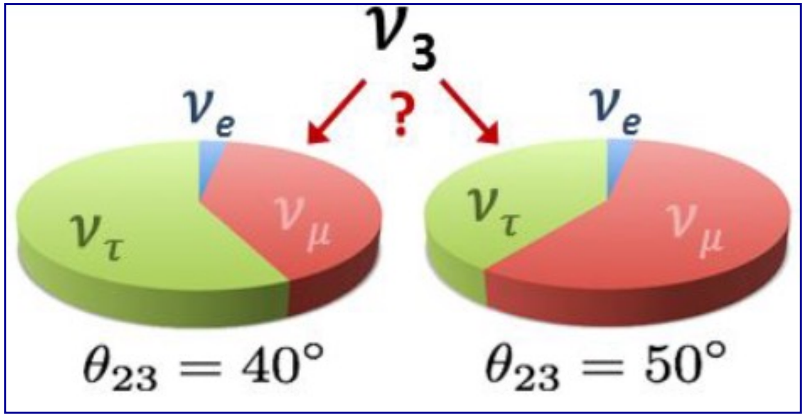
Octant of 2-3 Mixing Angle: Important Open Question

→ In ν_μ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$

→ If $\sin^2 2\theta_{23}$ differs from 1 (recent hints), we get two solutions for θ_{23}

→ One in lower octant (LO: $\theta_{23} < 45$ degree)

→ Other in higher octant (HO: $\theta_{23} > 45$ degree)



Octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

$\nu_\mu \rightarrow \nu_e$ oscillation channel can break this degeneracy

Preferred value would depend on the choice of neutrino mass ordering

Leptonic CP Violation: Important Open Question

Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in neutrino sector, provided $\delta_{CP} \neq 0^\circ$ and 180°

Need to measure the CP-odd asymmetries:

$$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \quad (\alpha \neq \beta)$$

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4 J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E} L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E} L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E} L\right)\right]$$

Jarlskog CP-odd Invariant → $J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta_{CP}$

Three-flavor effects are key for CPV, need to observe interference

Conditions for observing CPV:
1) Non-degenerate masses ✔
2) Mixing angles $\neq 0^\circ$ & 90° ✔
3) $\delta_{CP} \neq 0^\circ$ and 180° (Hints)

Quark Mixing vs. Neutrino Mixing

$$|V_{\rm CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

PDG 2022

$$|U|^{\text{with SK-atm}}_{3\sigma\ \text{PMNS}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$

NuFIT 5.1 (2021)

The goal is to achieve the CKM level precision for the PMNS
A Long Journey Ahead! But the precision is improving rapidly for PMNS

Good News: There may be large CPV in neutrino sector than quark sector

$$J_{CP} = \frac{1}{8} \cos\theta_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{23}\ \sin 2\theta_{12}\ \sin\delta_{CP}$$

$J_{\rm CKM} \sim 3 \times 10^{-5}$, whereas $J_{\rm PMNS}$ can be as large as 3×10^{-2}

CP Violation: Necessary Requirement for Matter-Antimatter Asymmetry

Five irreducible CP-Violating Phases in the ν Standard Model

In the Quark Sector:

+ The CP-odd phase in the CKM matrix – measured to be $\gamma \simeq 70^{\circ}$
 - Governs all the CP-violating phenomena observed so far

+ The strong CP-phase θ of the QCD Vacuum
 - Known to be vanishingly small $< 10^{-10}$

In the Lepton Sector:

+ The Dirac CP-odd phase δ_{CP} in the 3×3 unitary ν mixing matrix
 - Can be measured in ν oscillation experiments (hints)

+ The Majorana neutrinos can have two more CP-violating phases
 - No effect in ν oscillations, only affect LNV processes (unknown)

Remember

The CKM CP phase is not responsible for the baryon asymmetry of the Universe

The PMNS CP phase is the only hope

The discovery of non-zero CP-violating phase δ_{CP} in neutrino oscillation experiments would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry of the Universe

The determination of CP violation requires the full interplay of 3-flavor effects in neutrino oscillations

Three-Flavor Effects in $\nu_\mu \to \nu_e$ Oscillation Channel

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (0.03) and $\sin 2\theta_{13}$ (0.3),

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$\sin^2 2\theta_{13}$: 0.09 → θ_{13} driven

$\sin^2\theta_{23}$ → Resolves octant

$$- \alpha \sin 2\theta_{13} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

$\alpha \sin 2\theta_{13}$: 0.009 → CP-odd

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP-even

$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

α^2: 0.0009 → Solar Term

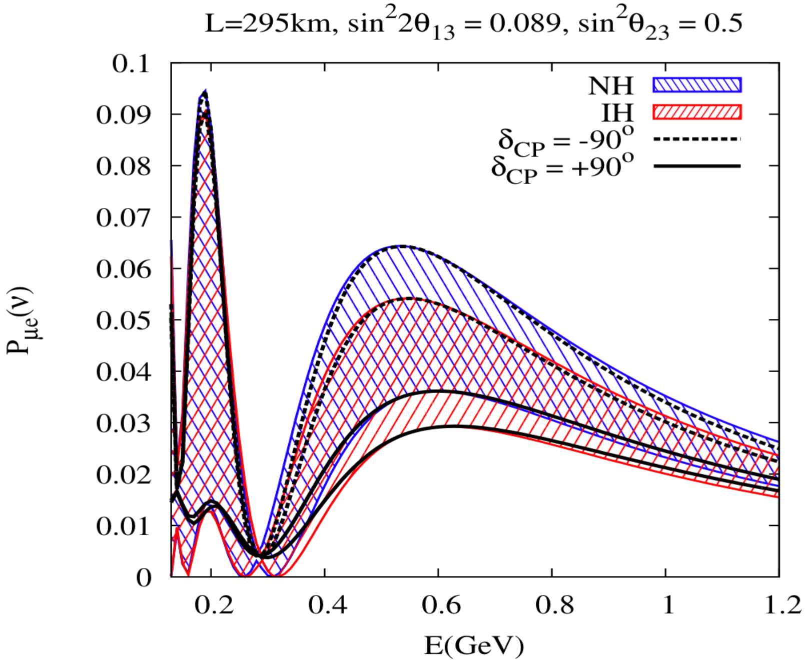
where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

- changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!
- changes sign with polarity causes fake CP asymmetry!

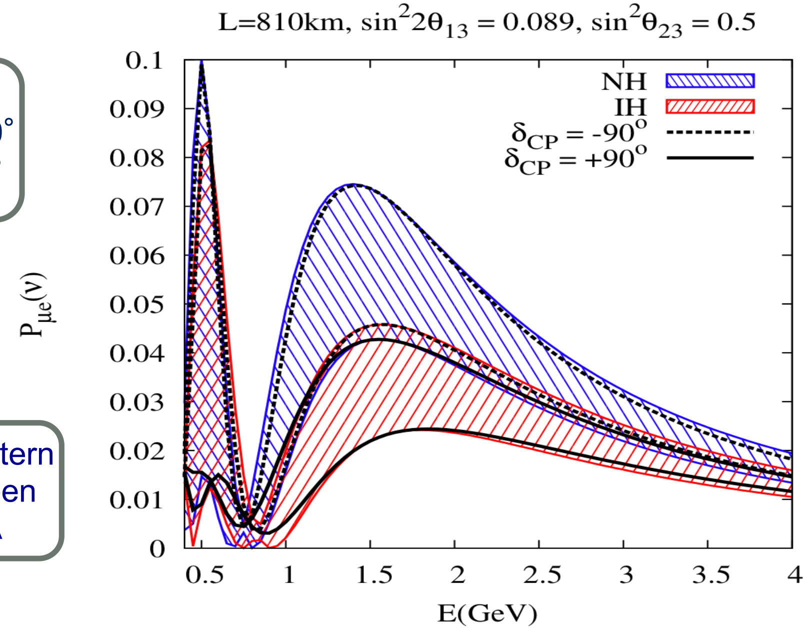
Cervera et al., hep-ph/0002108
Freund et al., hep-ph/0105071
Agarwalla et al., e-Print: 1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracies. How can we break them?

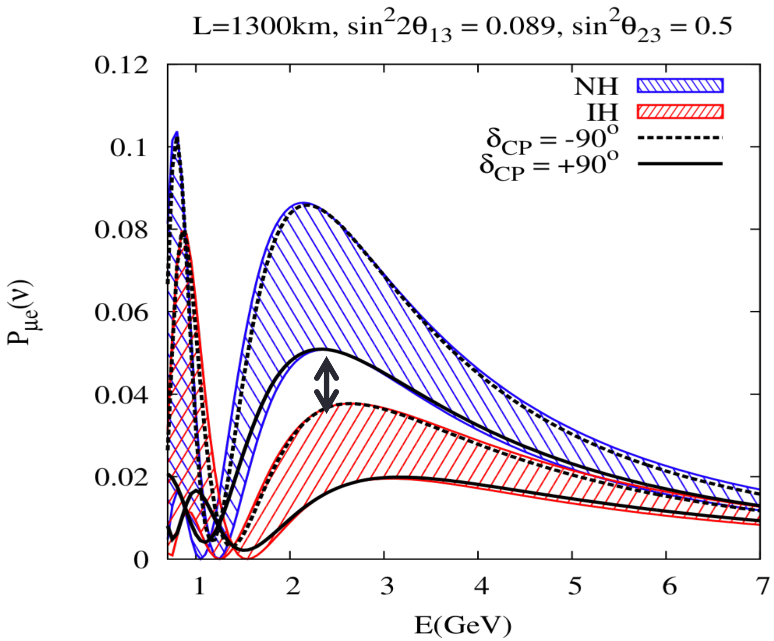
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



For ν:
Max: NH, -90°
Min: IH, 90°

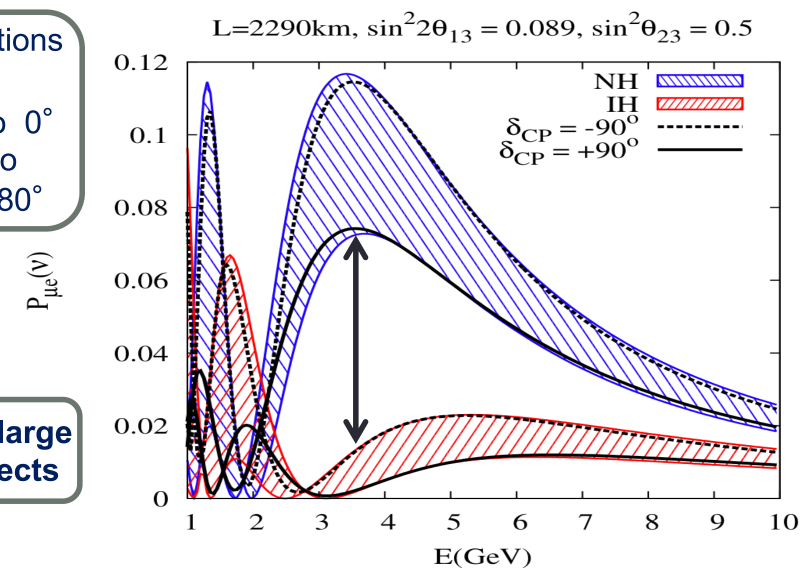


Degeneracy pattern different between T2K & NOvA



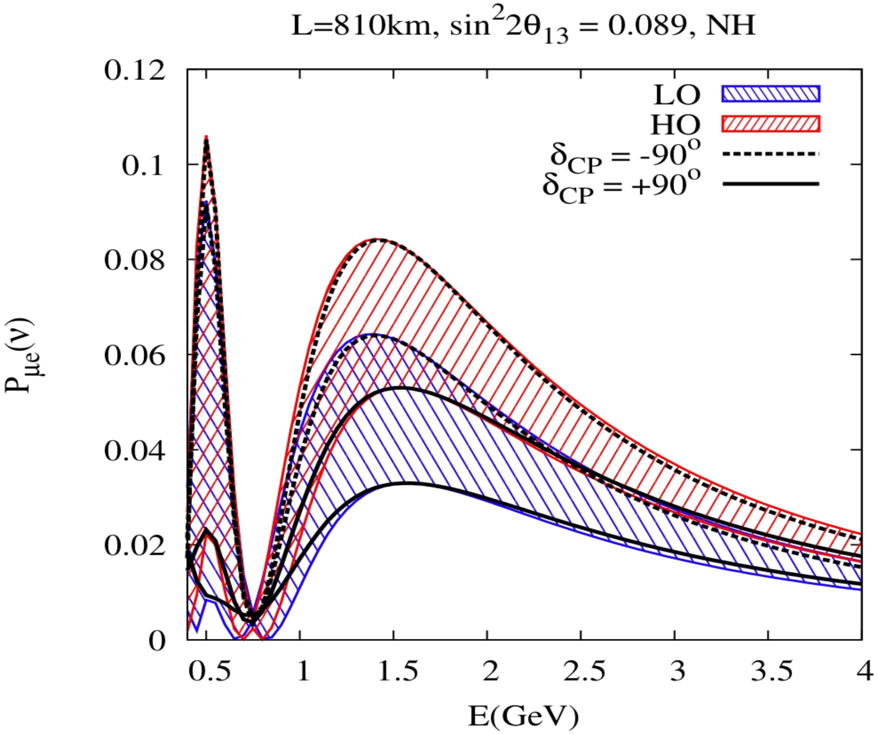
Favorable combinations
For neutrino
NH, LHP: -180° to 0°
For antineutrino
IH, UHP: 0° to 180°

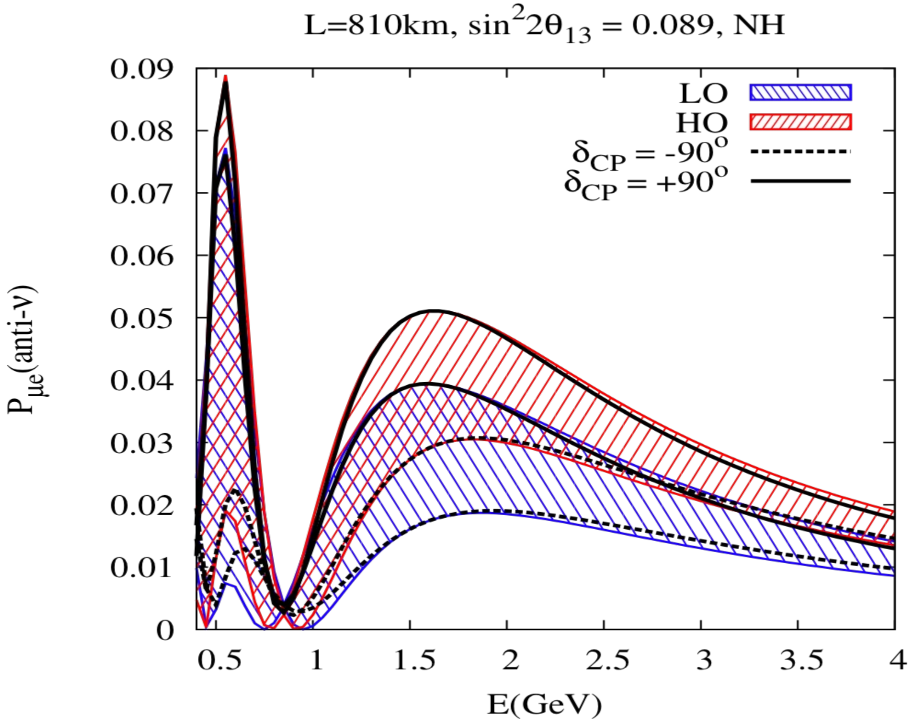
Large θ_{13} causes large Earth matter effects



Agarwalla, Prakash, Raut, Sankar, 2012-2013

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel





For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

Unfavorable CP values for neutrino are favorable for antineutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

Oscillation Probabilities with One Mass Scale Dominance

take $\Delta m^2_{21} = 0$

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

$$
\begin{aligned}
P_{\mu\mu}^{approx} = 1 &- \sin^2\theta_{13}^M \sin^2 2\theta_{23} \sin^2 \frac{[(\Delta m^2_{31} + A) - (\Delta m^2_{31})^M]L}{8E_\nu} \\
&- \cos^2\theta_{13}^M \sin^2 2\theta_{23} \sin^2 \frac{[(\Delta m^2_{31} + A) + (\Delta m^2_{31})^M]L}{8E_\nu} \\
&- \sin^2 2\theta_{13}^M \sin^4\theta_{23} \sin^2 \frac{(\Delta m^2_{31})^M L}{4E_\nu},
\end{aligned}
$$

$$
P_{e\mu}^{approx} = \sin^2 2\theta_{13}^M \sin^2\theta_{23} \sin^2 \frac{(\Delta m^2_{31})^M L}{4E_\nu}
$$

where,

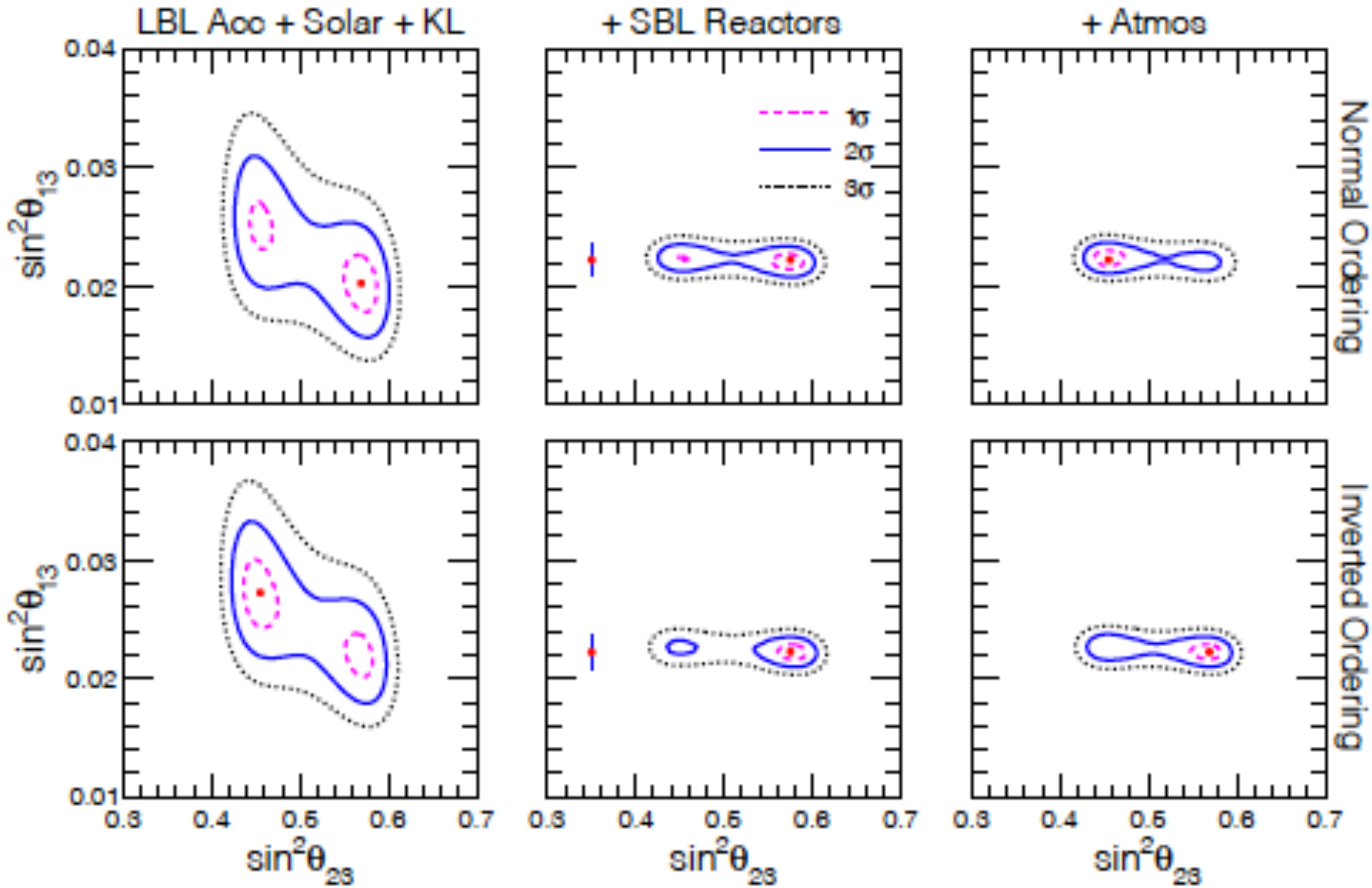
$$
(\Delta m^2_{31})^M = \left((\Delta m^2_{31} \cos 2\theta_{13} - A)^2 + \Delta m^2_{31} \sin^2 2\theta_{13} \right)^{1/2},
$$

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

Choubey, Roy, hep-ph/0509197v2

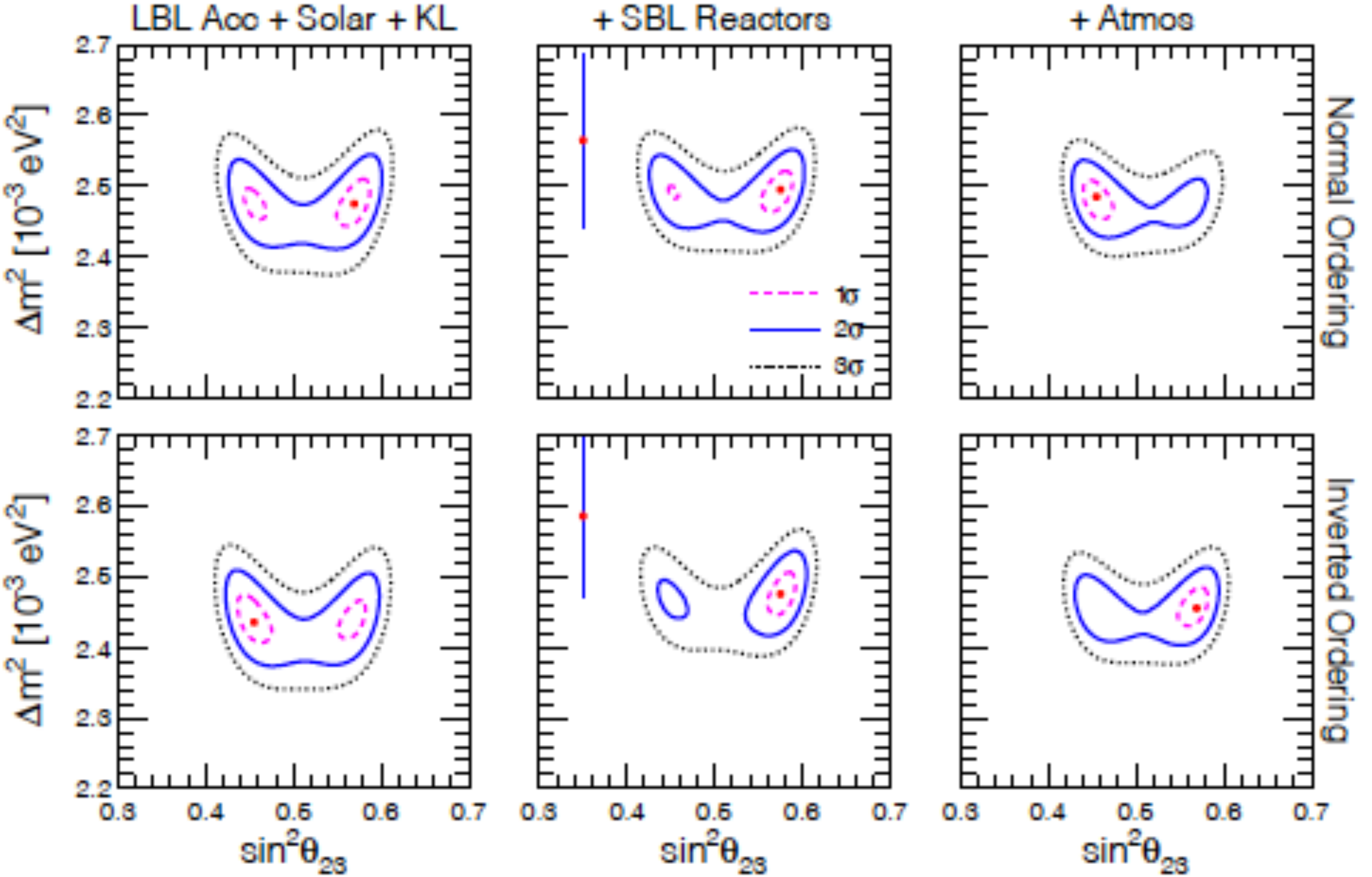
- If θ_{13} would have been zero, there is no Earth matter effect
- No discrimination between Normal Ordering and Inverted Ordering
- Large $\theta_{13} \rightarrow$ good news for Neutrino Mass Ordering

Correlations & Degeneracies between 1-3 & 2-3 Mixing Angles



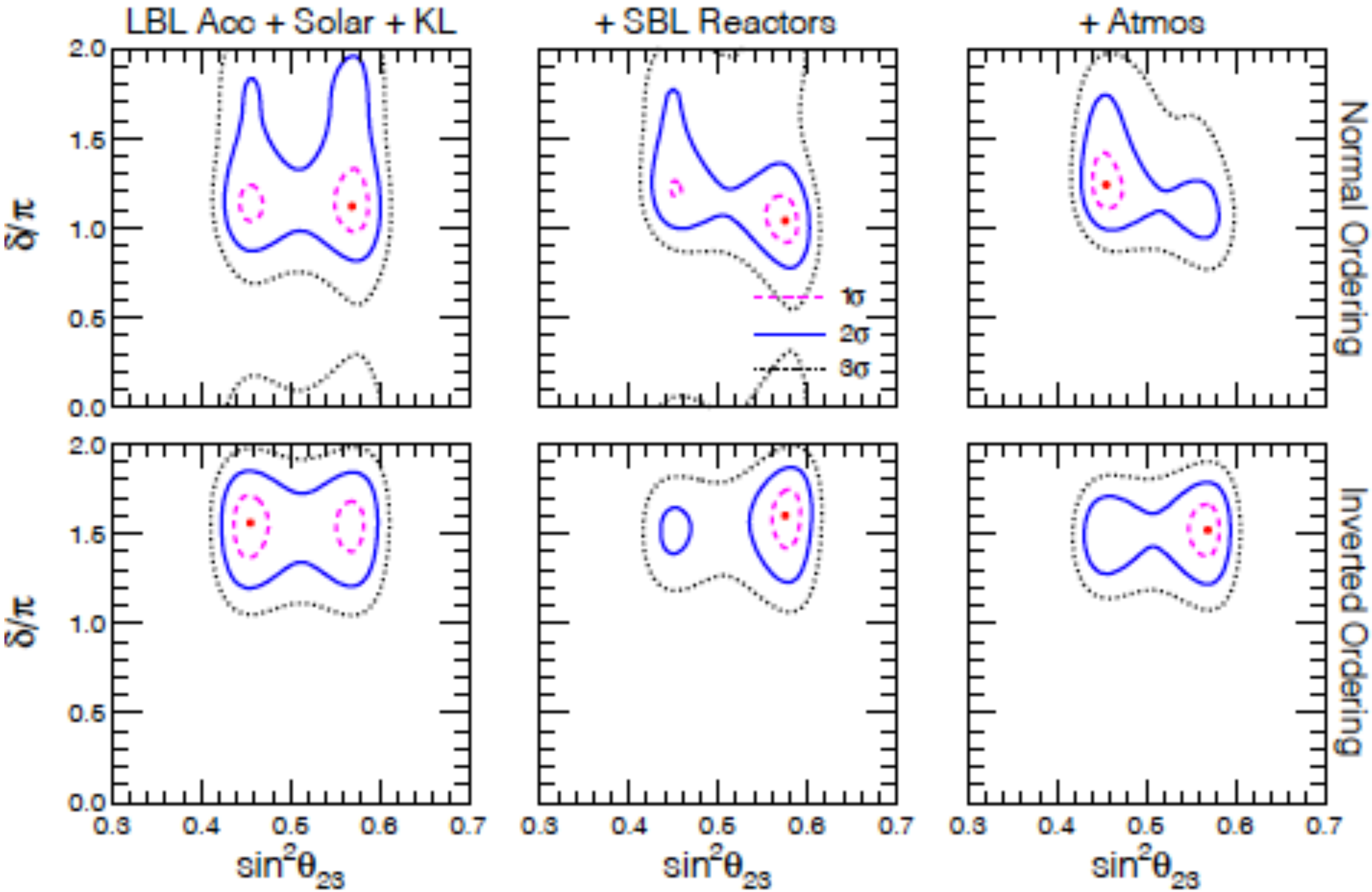
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

Correlations & Degeneracies between 2-3 Oscillation Parameters



Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

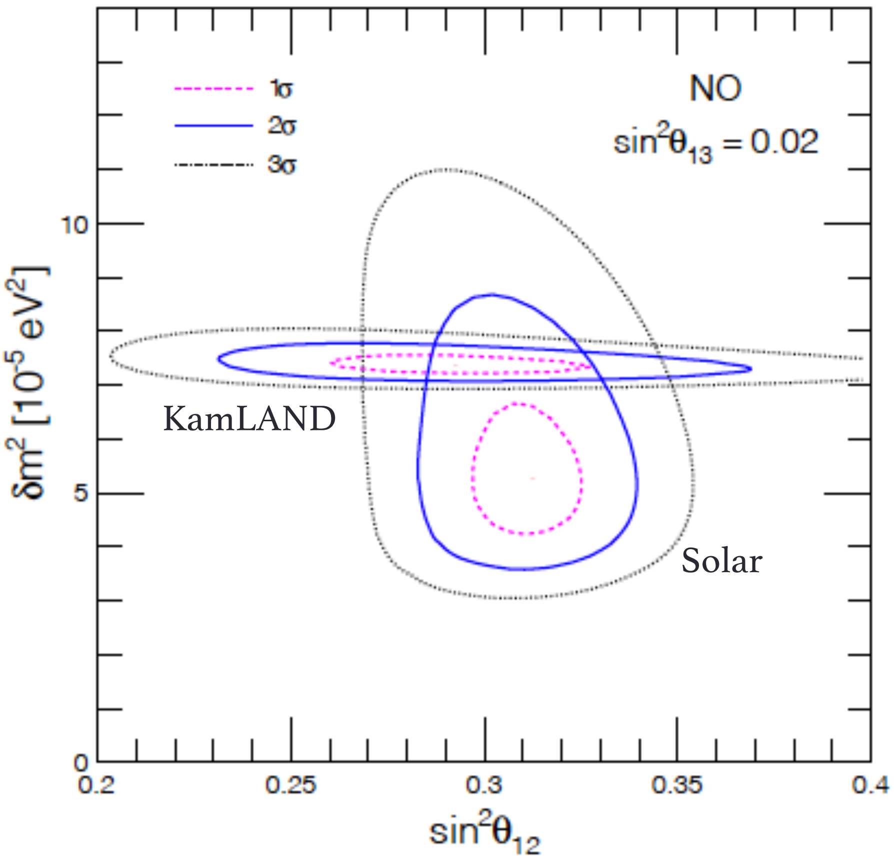
Correlations & Degeneracies between CP Phase & 2-3 Mixing Angle



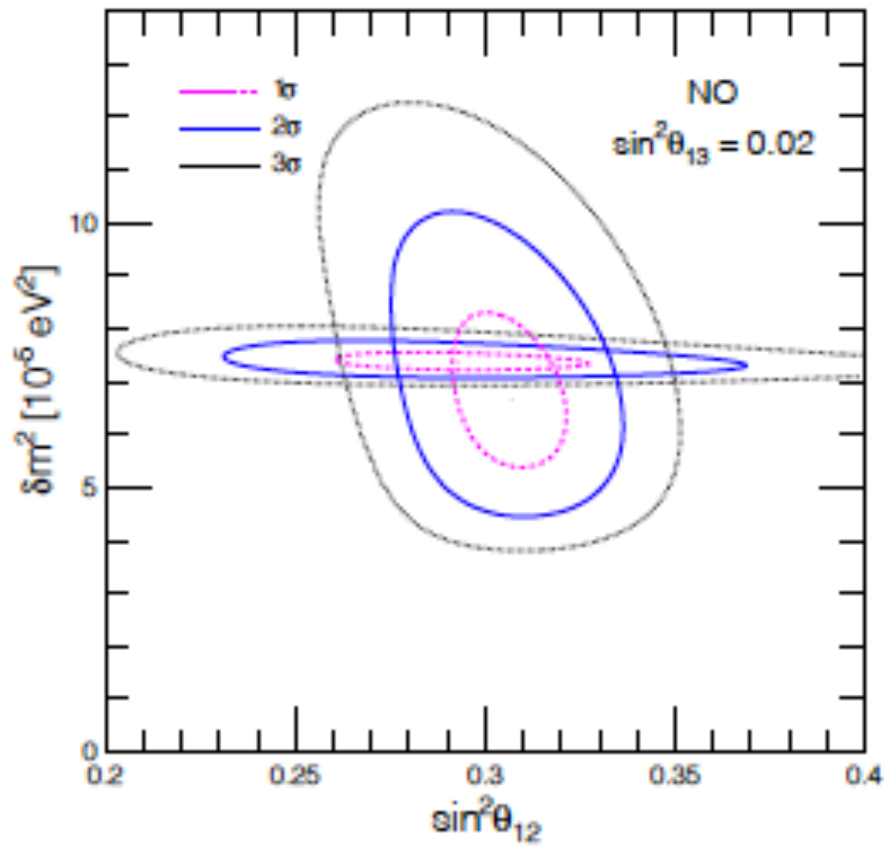
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

Tension between Solar and KamLAND data removed

In 2018



In 2021



< 2σ tension between Solar and KamLAND data

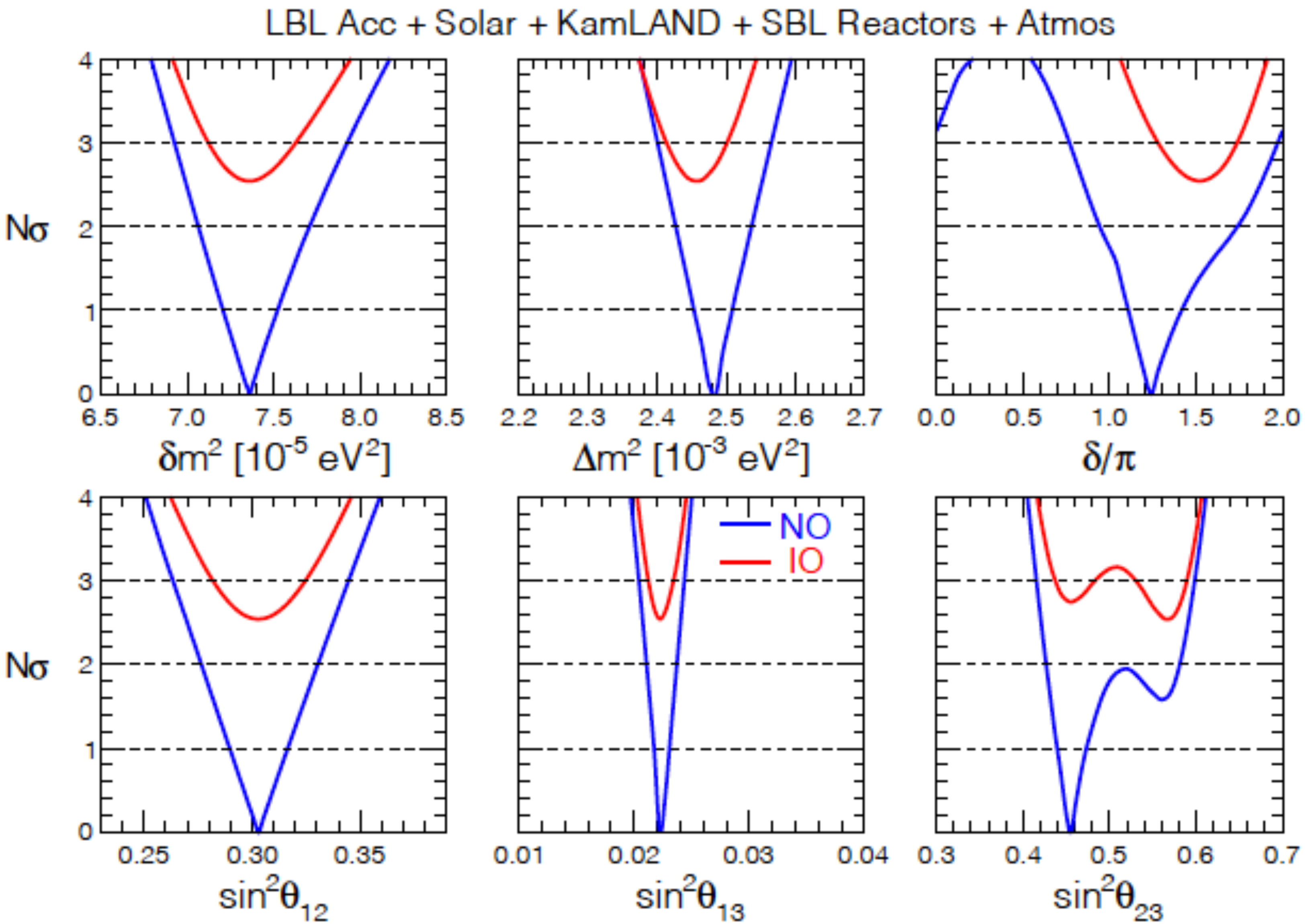
Capozzi, Lisi, Marrone, Palazzo, arXiv:1804.09678v1 [hep-ph]

The tension is removed now!
Due to a slightly smaller day-night asymmetry in SK-IV 2970-day Solar data

Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

Global Fit of Neutrino Oscillation Parameters Circa 2022

Preference for Normal Mass Ordering (~ 2.5σ), θ_{23} < 45 degree and sin$\boldsymbol{\delta}$ < 0 (both at 90% C.L.)



Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

Present Status of Neutrino Oscillation Parameters Circa 2022

Parameter	Ordering	Best fit	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.401 – 2.565	1.1
	IO	2.455	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.04 – 2.44	3.0
	IO	2.23	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.16 – 5.99	6.7
	IO	5.69	4.17 – 6.06	5.5
δ/π	NO	1.24	0.77 – 1.97	16
	IO	1.52	1.07 – 1.90	9
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+6.5		

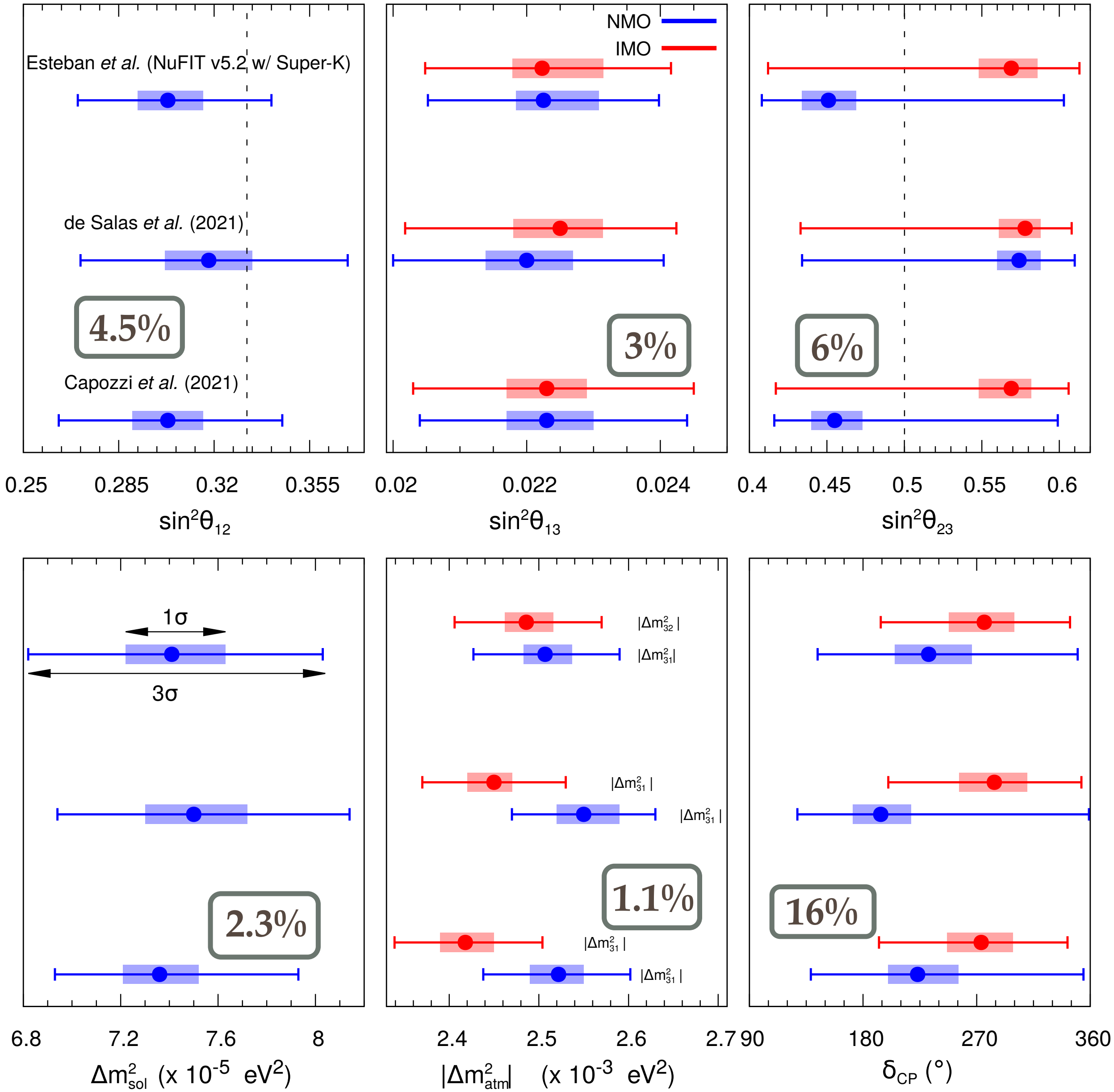
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v1 [hep-ph]

See also, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792v1 [hep-ph]

See also, de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortolla, Valle, arXiv:2006.11237v2 [hep-ph]

Remarkable Precision on Neutrino Oscillation Parameters

Robust three-flavor neutrino oscillation paradigm

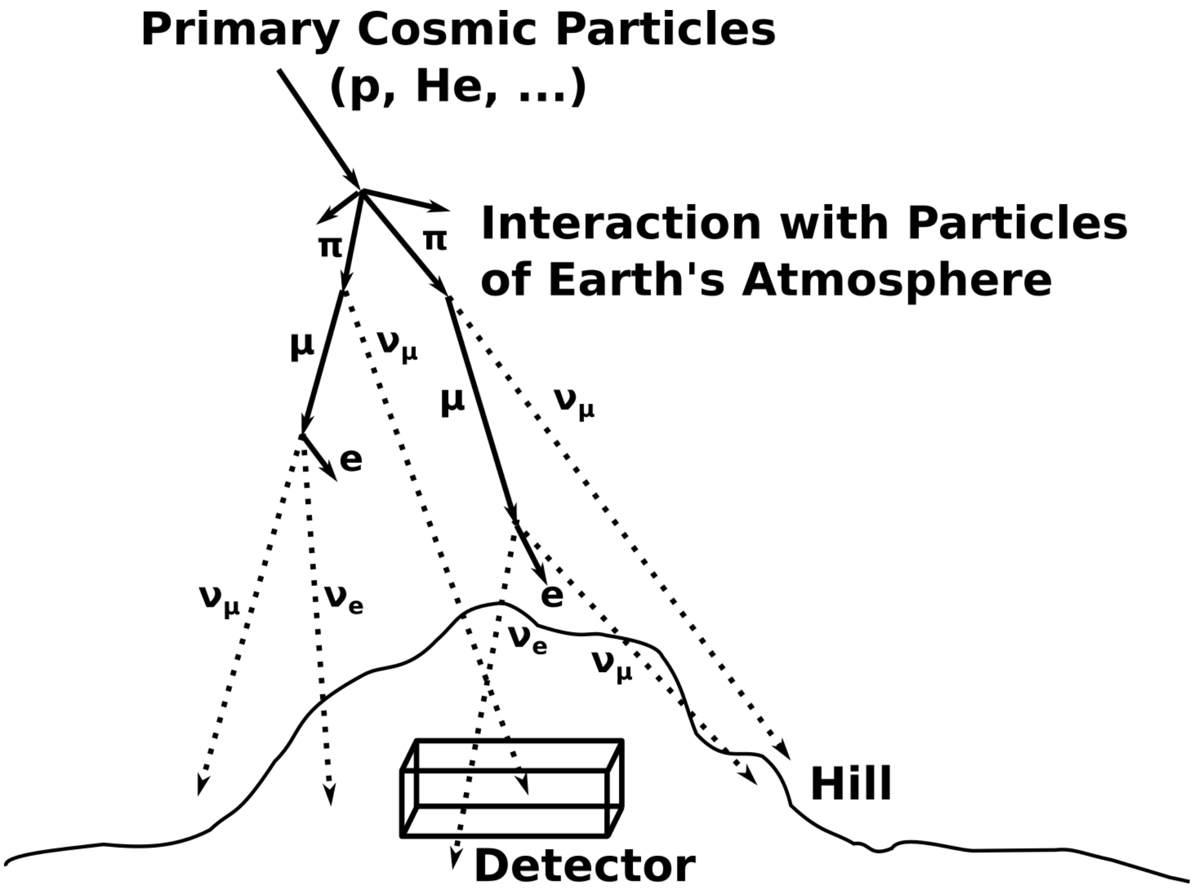


Huge boost for the discovery of NMO, CPV, and θ_{23} Octant

Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206

Atmospheric Neutrinos

Atmospheric Neutrinos



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

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

Atmospheric Flux Ratio

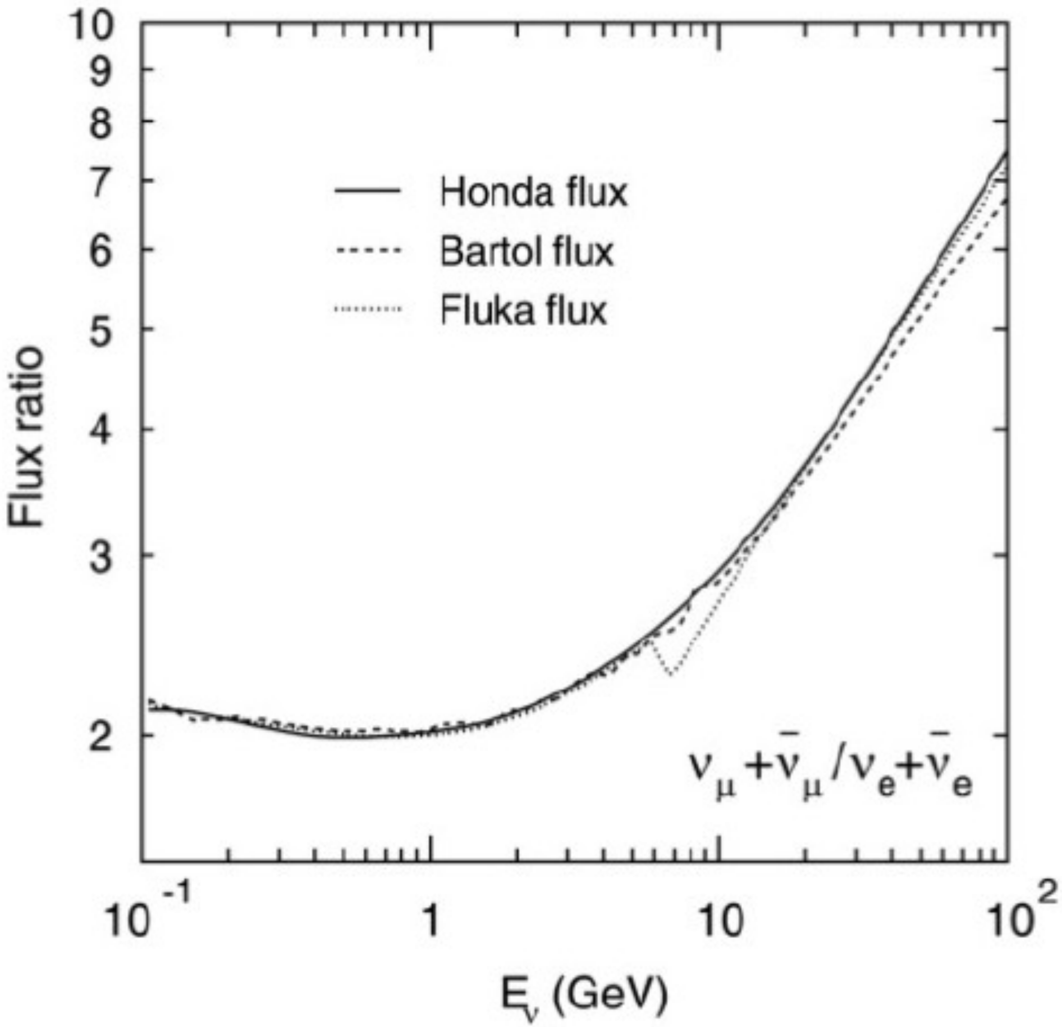
Expected ratio:

$$\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e} \sim 2$$

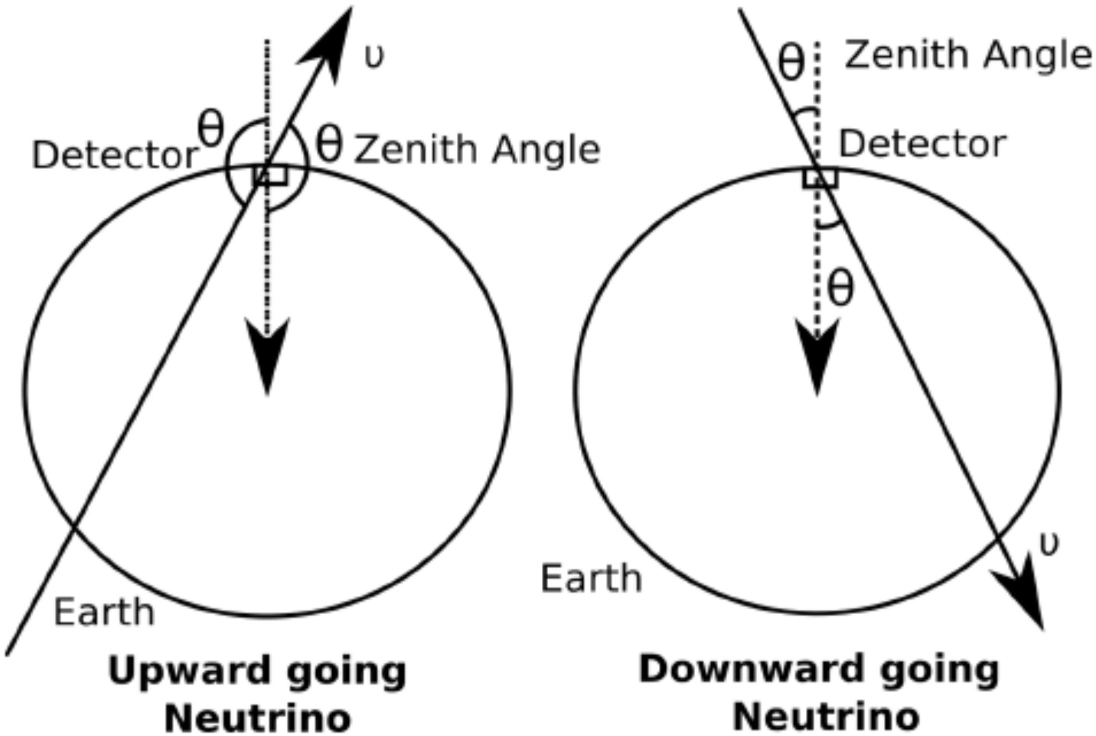
But at high energies:

$$\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e} > 2$$

Reason: at high energies, muons reach Earth's surface without decaying



Upward and Downward Directions for Atmospheric Neutrinos



Upward-going neutrinos:

$$\pi/2 < \theta < \pi$$

$$-1 < \cos\theta < 0$$

$$L_\nu \approx 2R\cos\theta_\nu$$

Downward-going neutrinos:

$$0 < \theta < \pi/2$$

$$0 < \cos\theta < 1$$

$$L_\nu \approx 0$$

$$L_\nu = \sqrt{(R+h)^2 - (R-d)^2 \sin^2\theta_\nu} - (R-d)\cos\theta_\nu$$

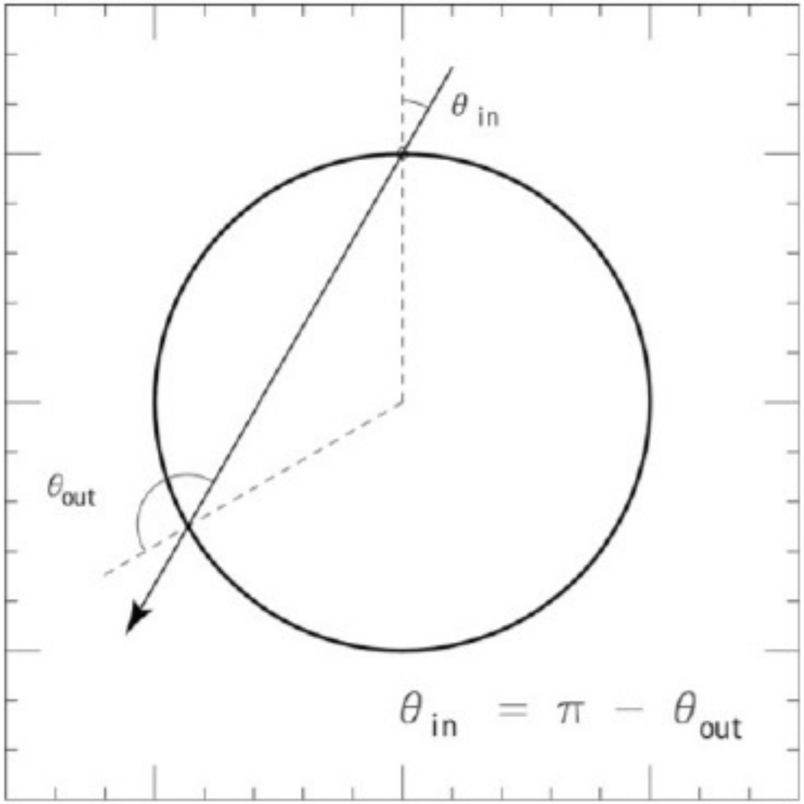
R = radius of Earth (6371 km)
h = average ν production height from surface (~ 10 to 25 km)
d = depth of the detector underground (~ 100 m to 2 km)

Upward-going neutrinos feel Earth's matter effect during oscillations inside Earth – key for neutrino oscillation tomography of Earth

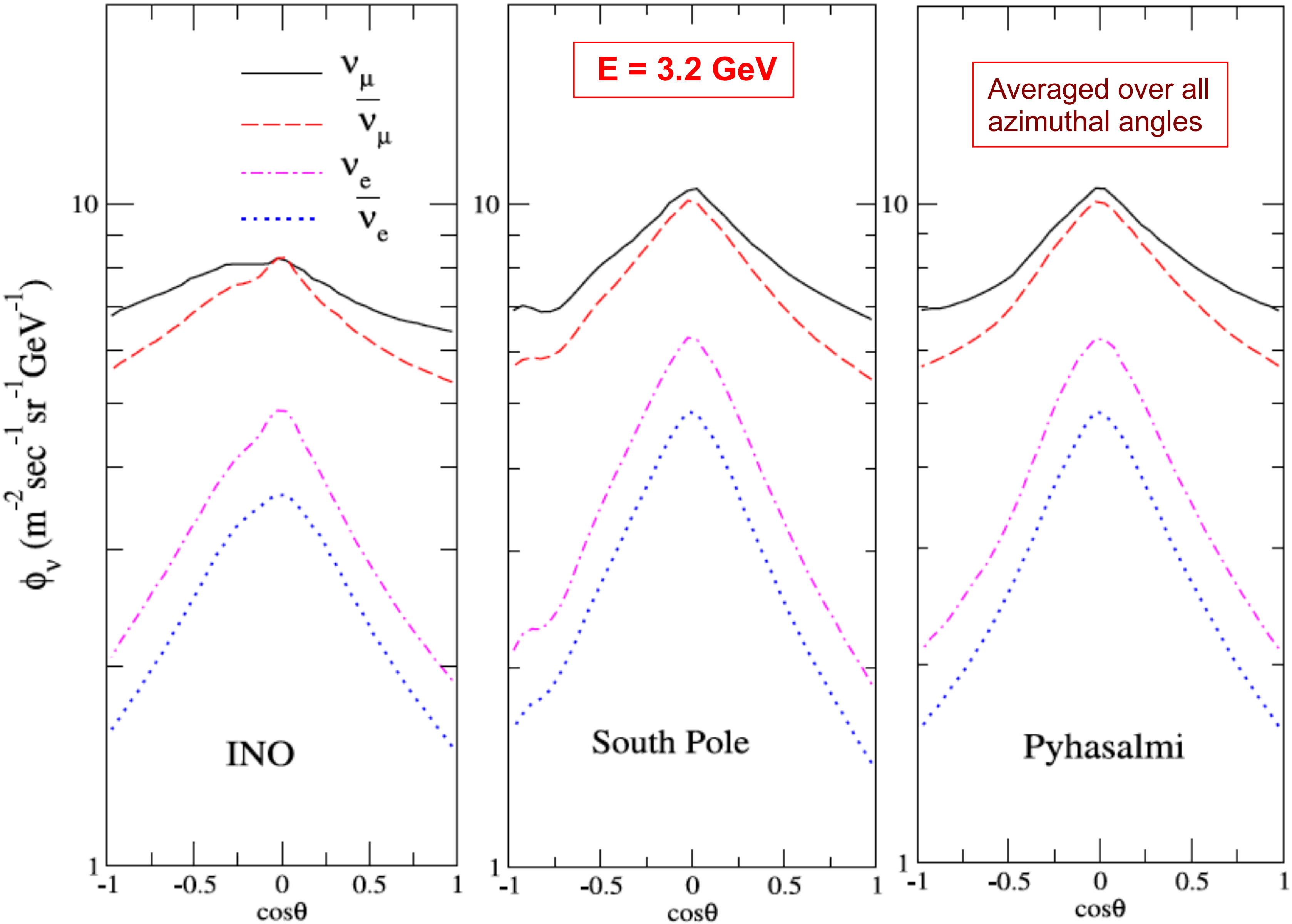
Atmospheric Flux: Up/Down Symmetry

- The cosmic ray fluxes are isotropic
- The cosmic ray flux are constant at entry and exit points
- The neutrino flux should be up-down symmetric

A neutrino trajectory that enters the Earth with a zenith angle θ_{in} will exit with a zenith angle $\theta_{out} = \pi - \theta_{in}$

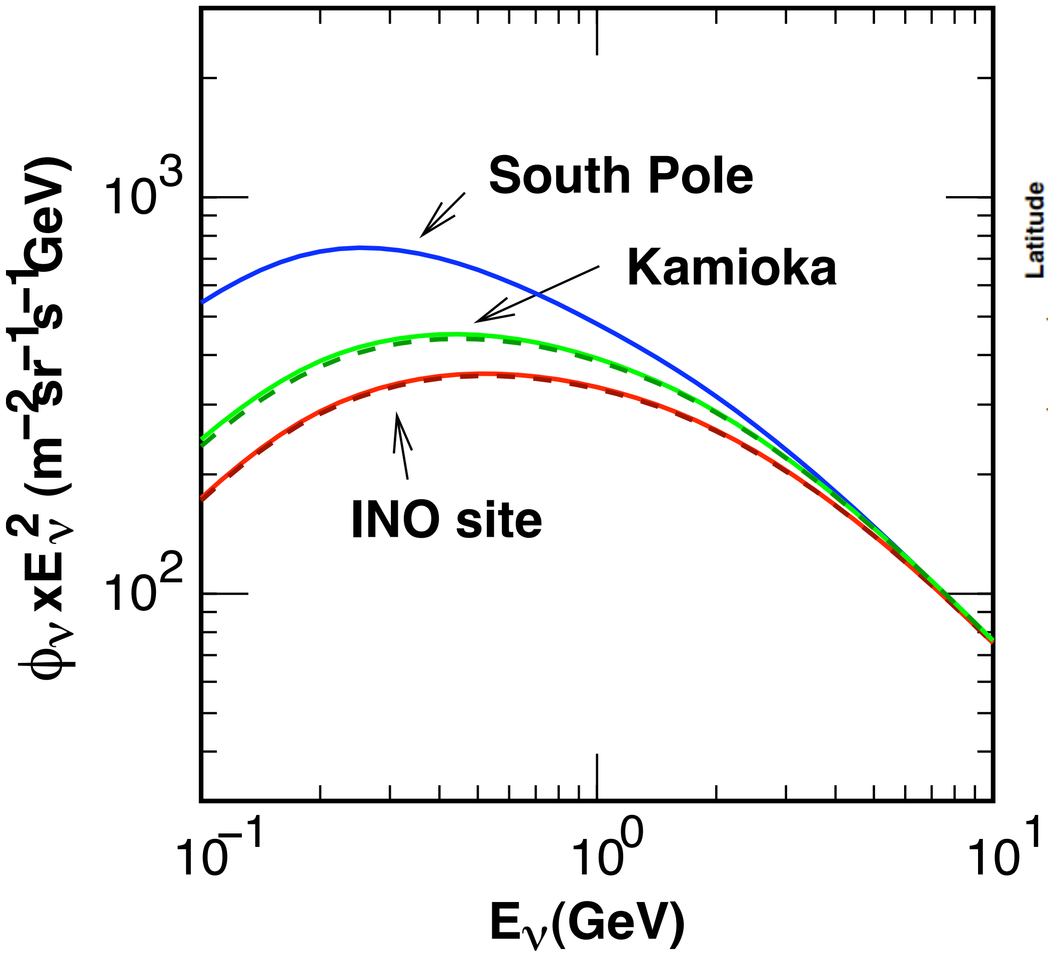


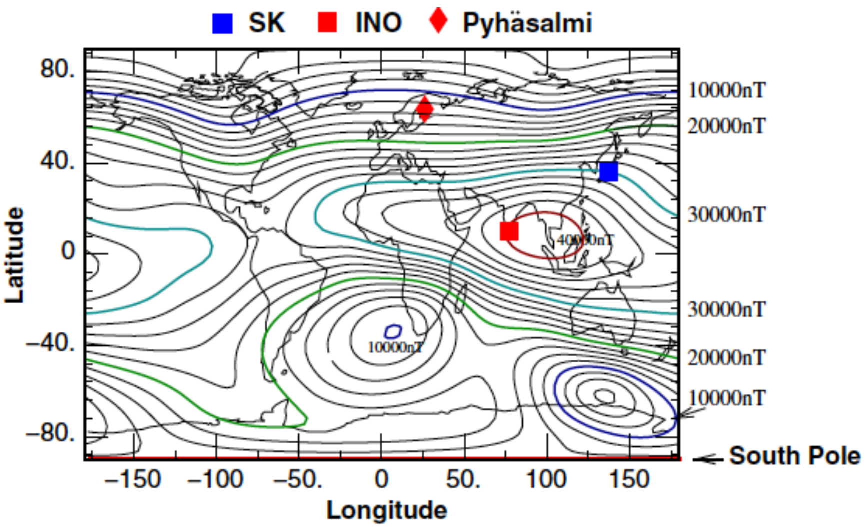
Atmospheric Neutrino Flux



Athar, Honda, Kajita, Kasahara, Midorikawa, PLB 718 (2013) 1375 - 1380

Atmospheric Neutrino Flux: Effect of Geomagnetic Field





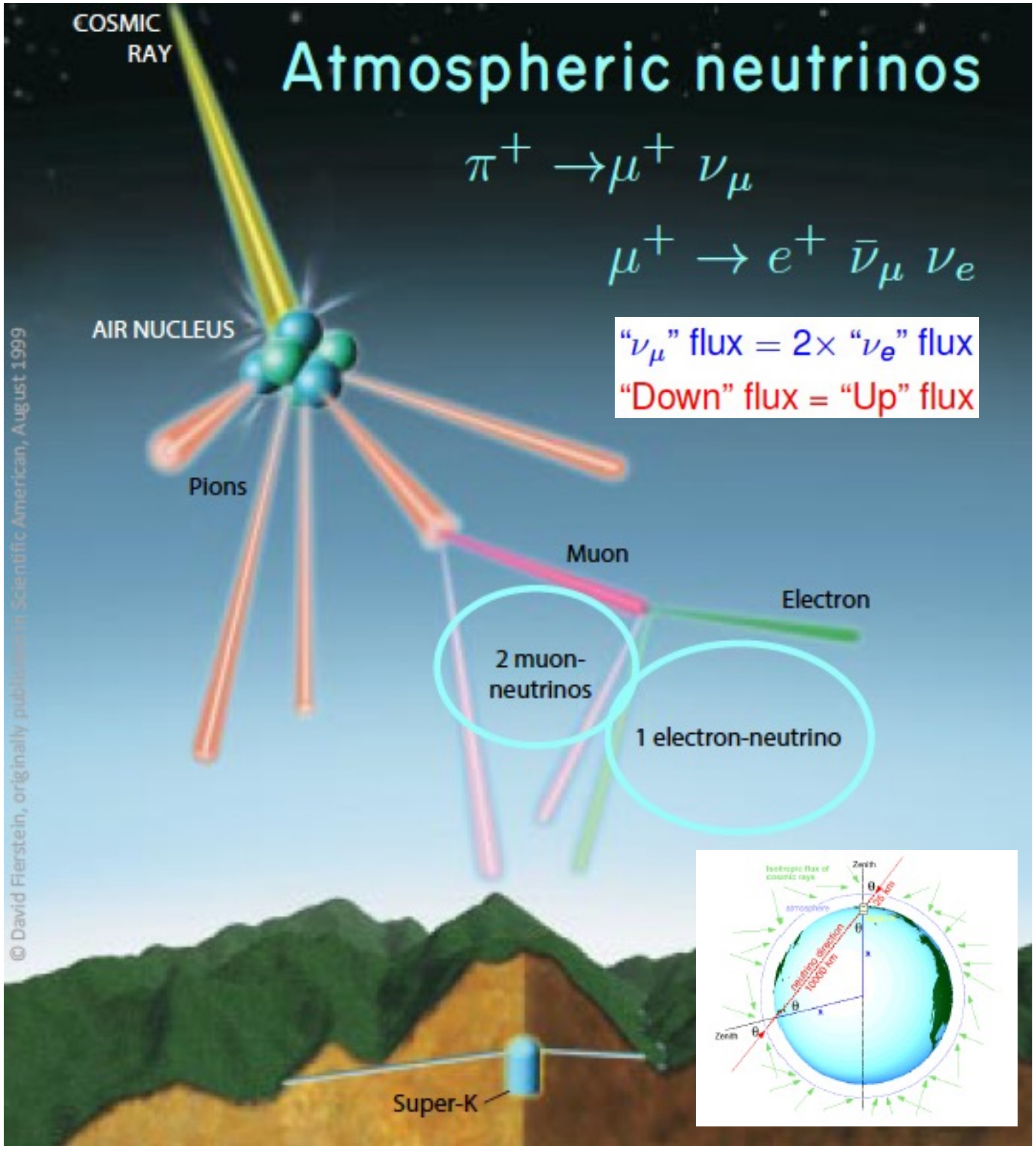
Magnitude of the horizontal component of geomagnetic field: magnitude at the Earth's surface ranges from 25 to 65 μT

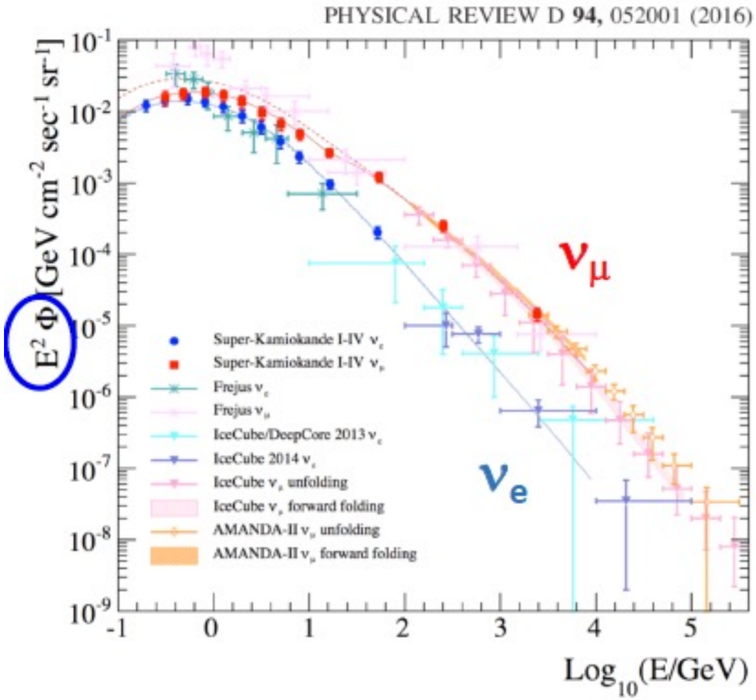
The strength is stronger near the equator (INO site) than at the South Pole (IceCube site). Therefore, the rigidity cutoff is higher for the INO site which reduces the flux at low energies

Averaged over all the directions and summed over all the flavors of neutrino and antineutrino

Athar, Honda, Kajita, Kasahara, Midorikawa, PLB 718 (2013) 1375 - 1380

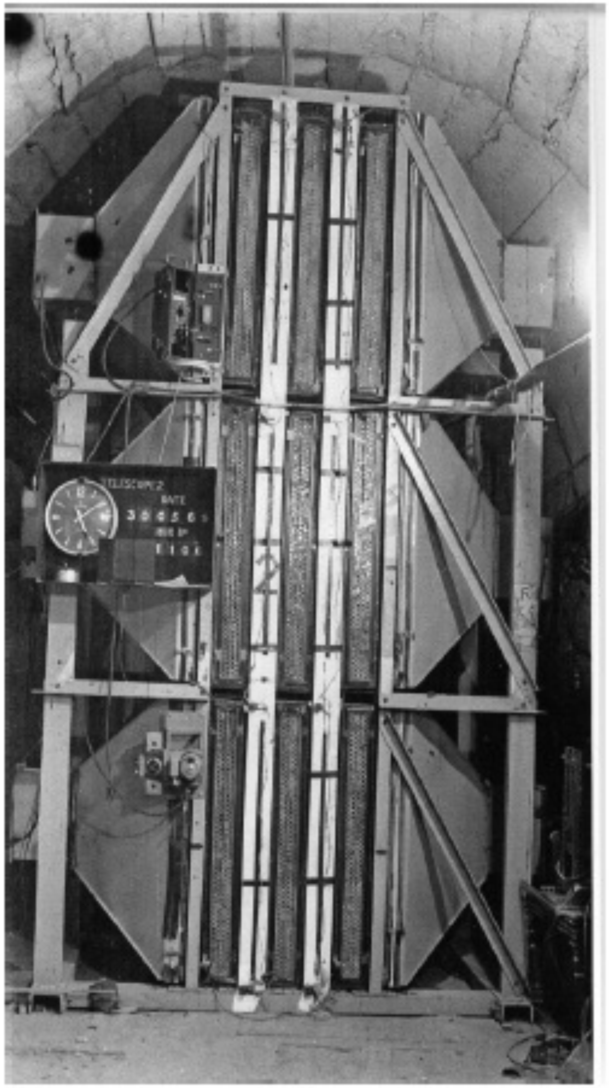
Atmospheric Neutrinos





- Almost isotropic flux up-down symmetric
- Known flavor composition (ν_e, ν_μ, and their antiparticles)
- Wide range of energies (MeV to PeV)
- Steeply falling power-law spectrum

Detection of Atmospheric Neutrinos



Detector in
Kolar Gold Fields

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

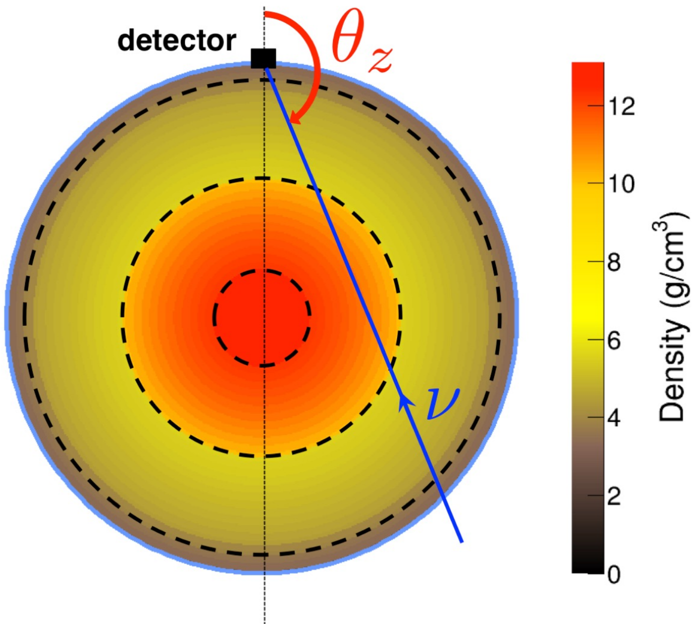
Physics Letters 18, (1965) 196
(15th Aug 1965)

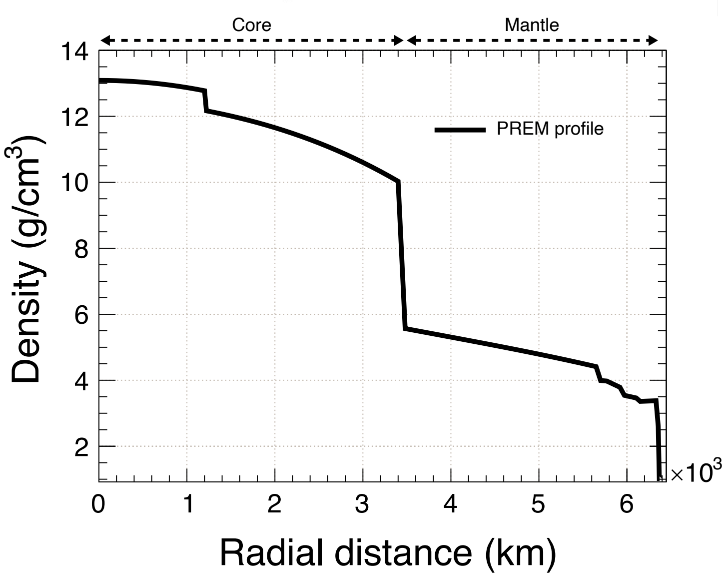
EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

PRL 15, (1965) 429
(30th Aug 1965)

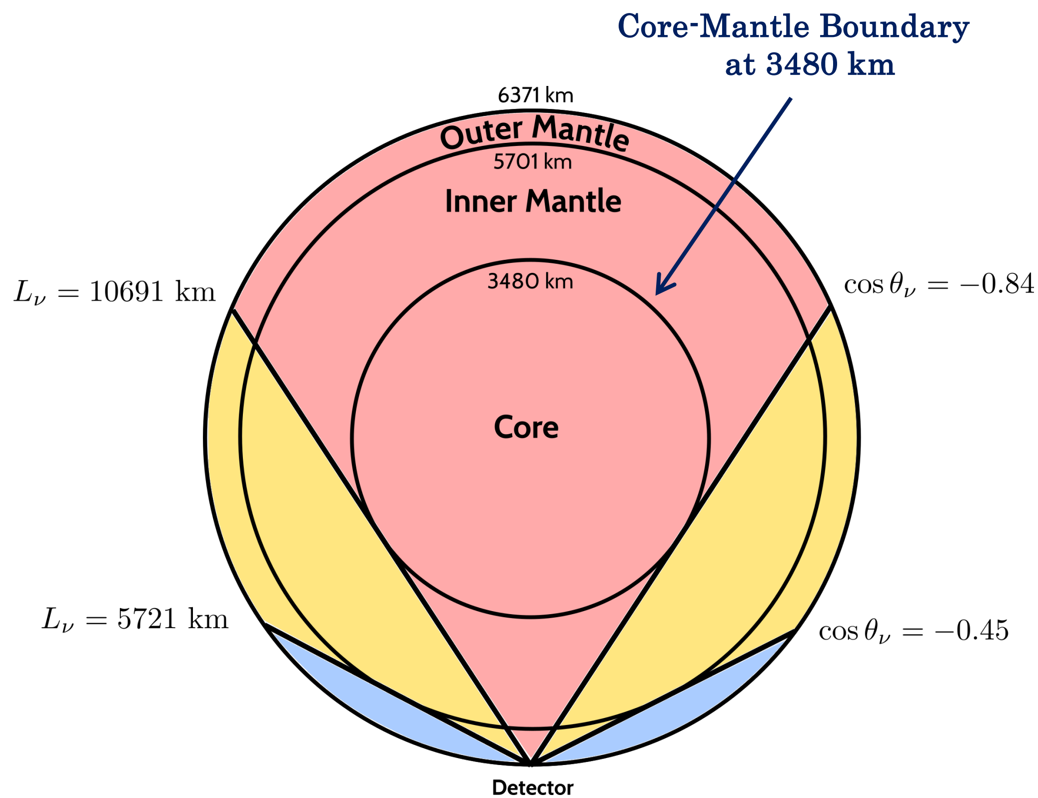
PREM and Neutrino Trajectories Deep Inside the Earth





PREM is not a measured profile!

The gravitational and seismic measurements are used to infer the radial density distribution inside Earth – known as Preliminary Reference Earth Model (PREM)



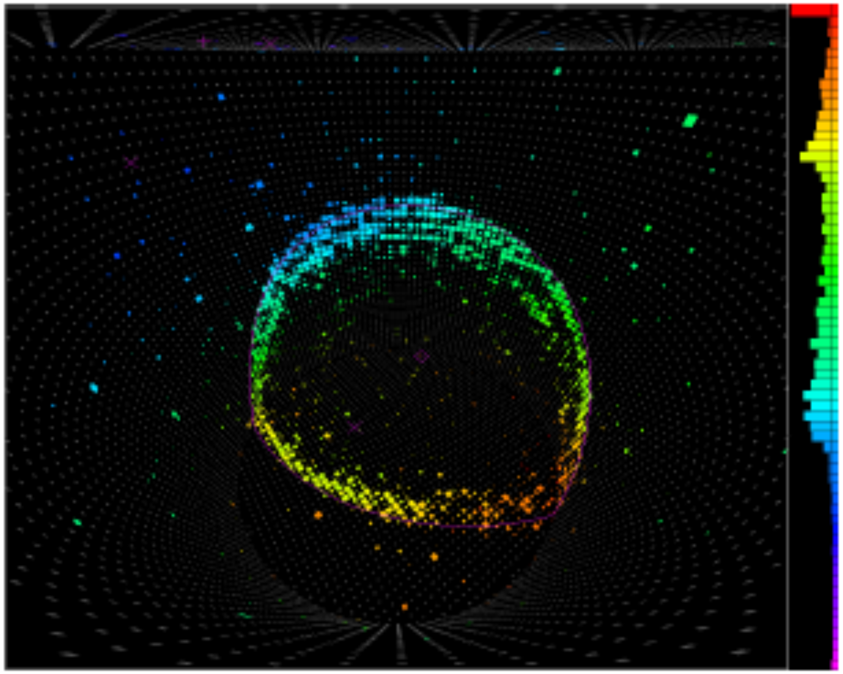
Three-Layered Model of Earth

Anil Kumar and Sanjib Kumar Agarwalla, JHEP 08 (2021) 139

Event Signatures in Super-Kamiokande

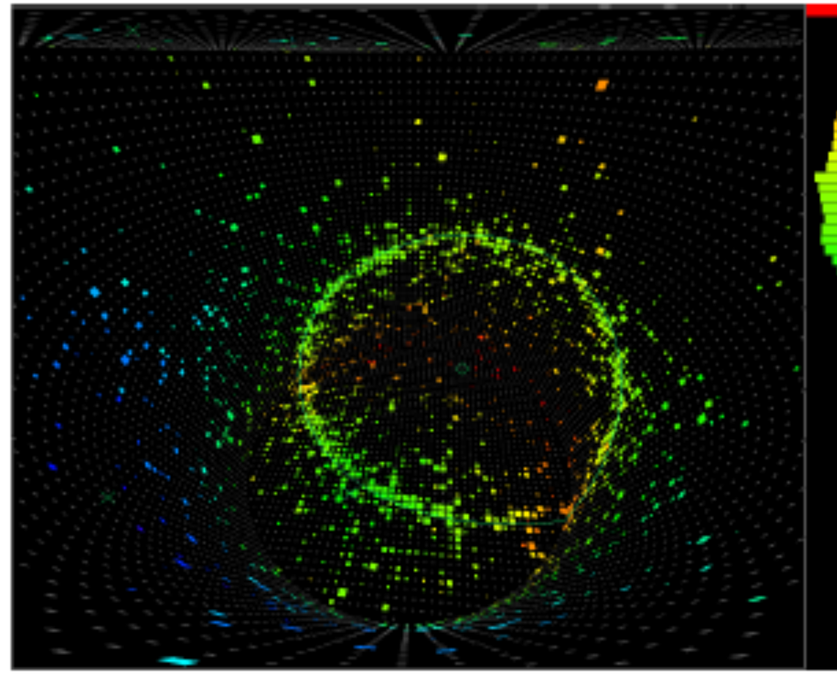
muon from ν_μ

(sharp outer edge)



electron from ν_e

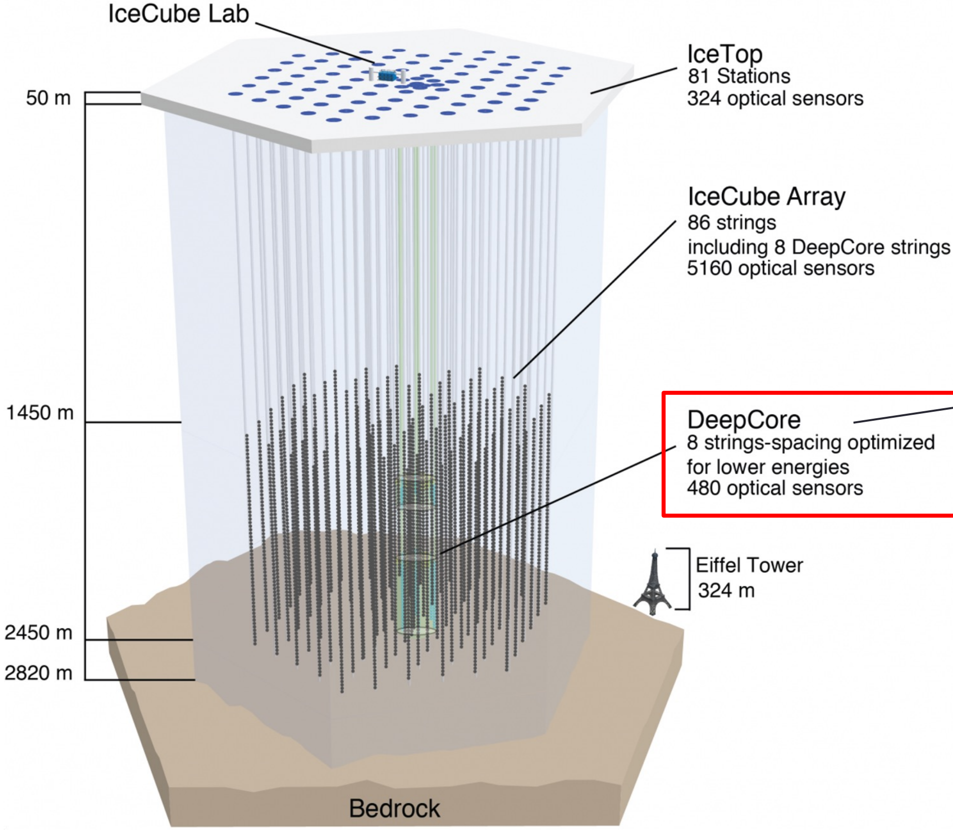
(fuzzy ring)

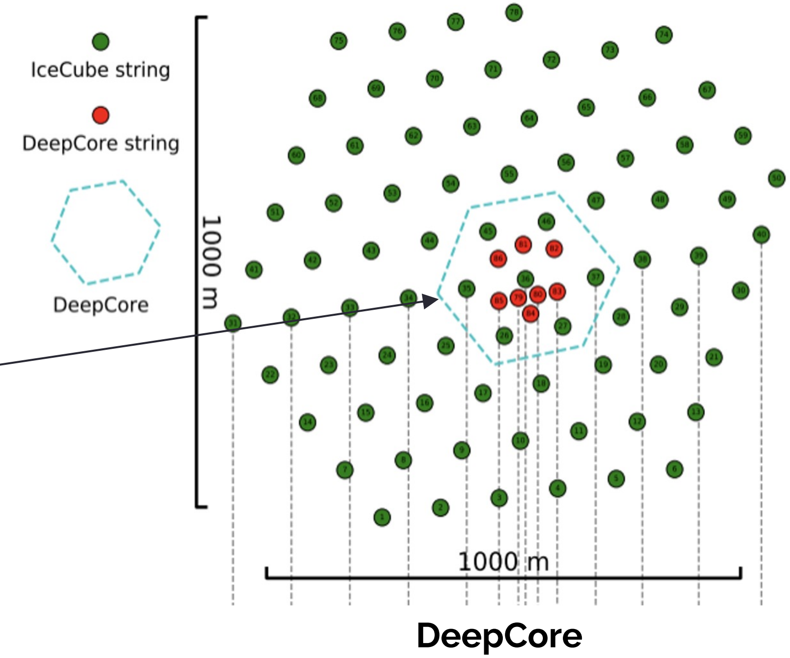


- detector responsible for discovery of atmospheric ν oscillations (1998), being used for T2K to measure $\nu_\mu \rightarrow \nu_e$ oscillations with accelerator ν's

Each dot is one phototube, and its color represents the relative amount of light it collected, in terms of the amount of electric charge produce by the phototube, during the 1.3 μs time window in which the displayed data were logged. The location and shape of the ring tell us the direction of the outgoing charged particle.

DeepCore Detector

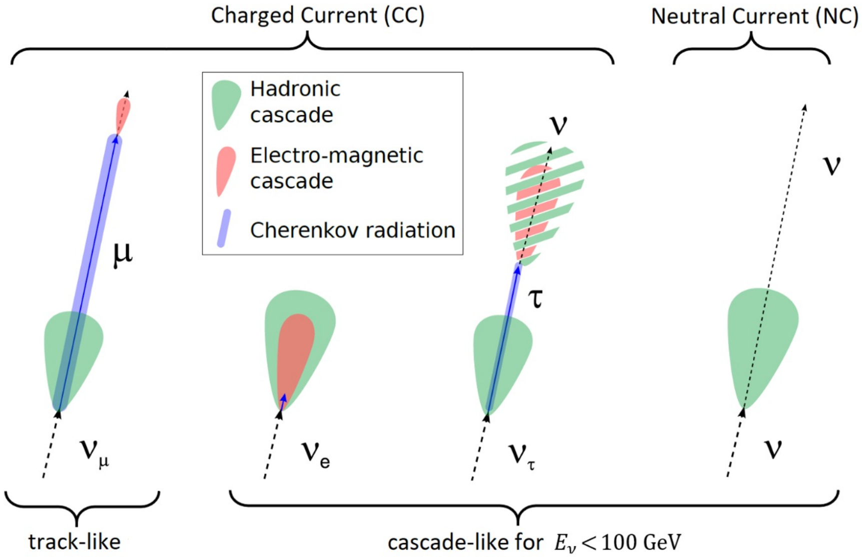




- 8 dedicated strings with denser spacing
- Optimized for GeV scale neutrinos
- Uses IceCube as VETO
- Fiducial volume ~ 10 Mton

The design and performance of IceCube DeepCore (2012): Astroparticle Physics, 35(10), 615-624 (2012)

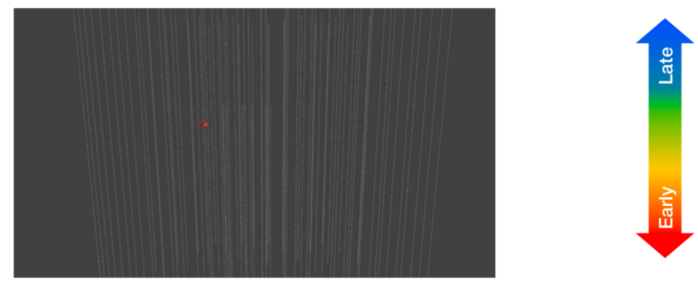
Event Signatures in IceCube



- **Signals:**
  - ν_e , ν_μ , ν_τ
  - Predominantly DIS interactions
- **Observables:**
  - Energy
  - Direction
  - Event type (PID)
- **Backgrounds:**
  - Atmospheric muons
  - Random detector noise

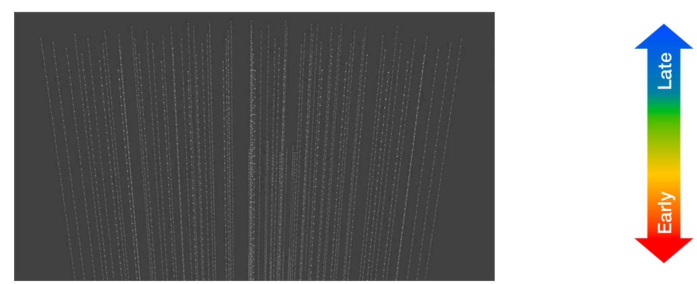
Track-like events:

- Elongated
- Source: ν_μ CC



Cascade-like events:

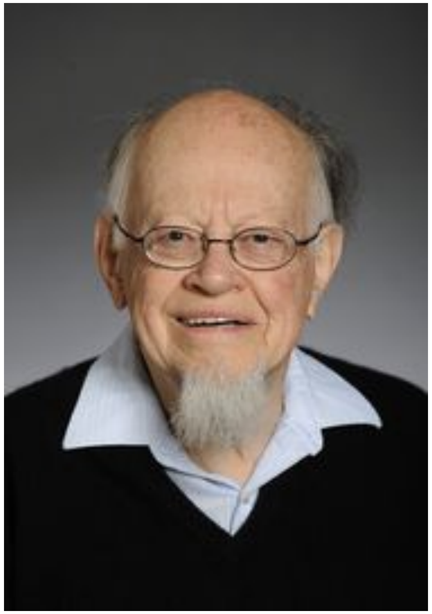
- Spherical
- Source: ν_e CC, ν_τ CC, all NC



Size of the colored sphere: amount of photon/energy observed in a DOM

Neutrino Oscillations in Matter: MSW Effect

- The MSW Effect (Wolfenstein 1978, Mikheyev and Smirnov 1985)
- Matter can change the pattern of neutrino oscillations significantly
- Resonant enhancement of oscillations and resonant flavor conversion possible
- Causes flavor conversion of solar neutrinos (LMA MSW solution established)



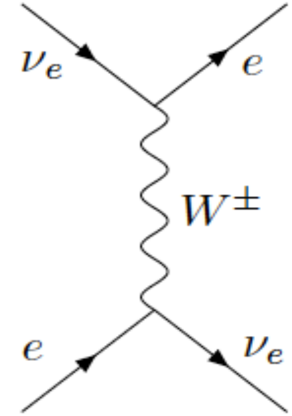
Lincoln Wolfenstein

Stanislav Mikheyev

Alexei Smirnov

Neutrino Oscillations in Matter: MSW Effect

Neutrino propagation through matter modify the oscillations significantly



Coherent forward scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e

MSW matter term: $A = \pm 2\sqrt{2} G_F N_e E$ or $A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})$

N_e = electron number density , + (-) for neutrinos (antineutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino to antineutrino

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → **even if $\delta_{CP} = 0$, causes fake CP asymmetry**

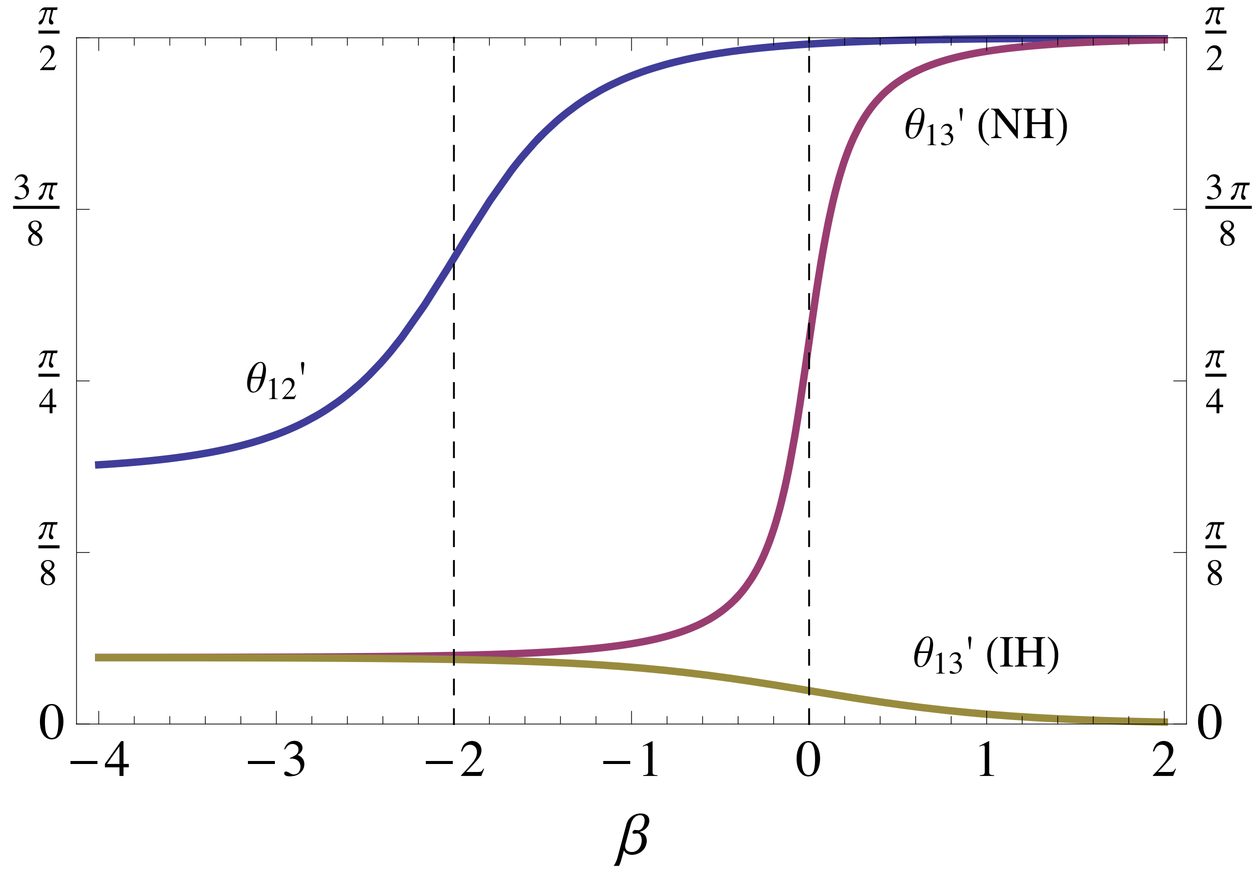
Matter term modifies oscillation probability differently depending on the sign of Δm^2

$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\rm res}^{\rm Earth} = 6 - 8\,\mathrm{GeV}$ → **Resonant conversion – Matter effect**

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ **Resonance occurs for neutrinos (antineutrinos) if Δm^2 is positive (negative)**

Effective Mixing Angles in the presence of Matter Effect



$$a = 2\sqrt{2}G_F N_e E \quad = 7.63\times10^{-5}(\text{eV}^2)\left(\frac{\rho}{\text{g/cm}^3}\right)\left(\frac{E}{\text{GeV}}\right)$$

$$\frac{a}{|\delta m_{31}^2|} = \varepsilon^{-\beta}, \qquad \varepsilon = \sqrt{\frac{\delta m_{21}^2}{|\delta m_{31}^2|}} \approx 0.17$$

$$\tan 2\theta_{12}' = \frac{(\delta m_{21}^2 / c_{13}^2)\sin 2\theta_{12}}{(\delta m_{21}^2 / c_{13}^2)\cos 2\theta_{12} - a}, \qquad \tan 2\theta_{13}' = \frac{(\delta m_{31}^2 - \delta m_{21}^2 s_{12}^2)\sin 2\theta_{13}}{(\delta m_{31}^2 - \delta m_{21}^2 s_{12}^2)\cos 2\theta_{13} - a},$$

Approximation works when $\theta_{13} = O(\varepsilon)$

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

Neutrino Oscillation Length Resonance / Parametric Resonance

- Oscillations of atmospheric neutrinos inside Earth can feel this resonance when neutrino trajectories cross the core of Earth

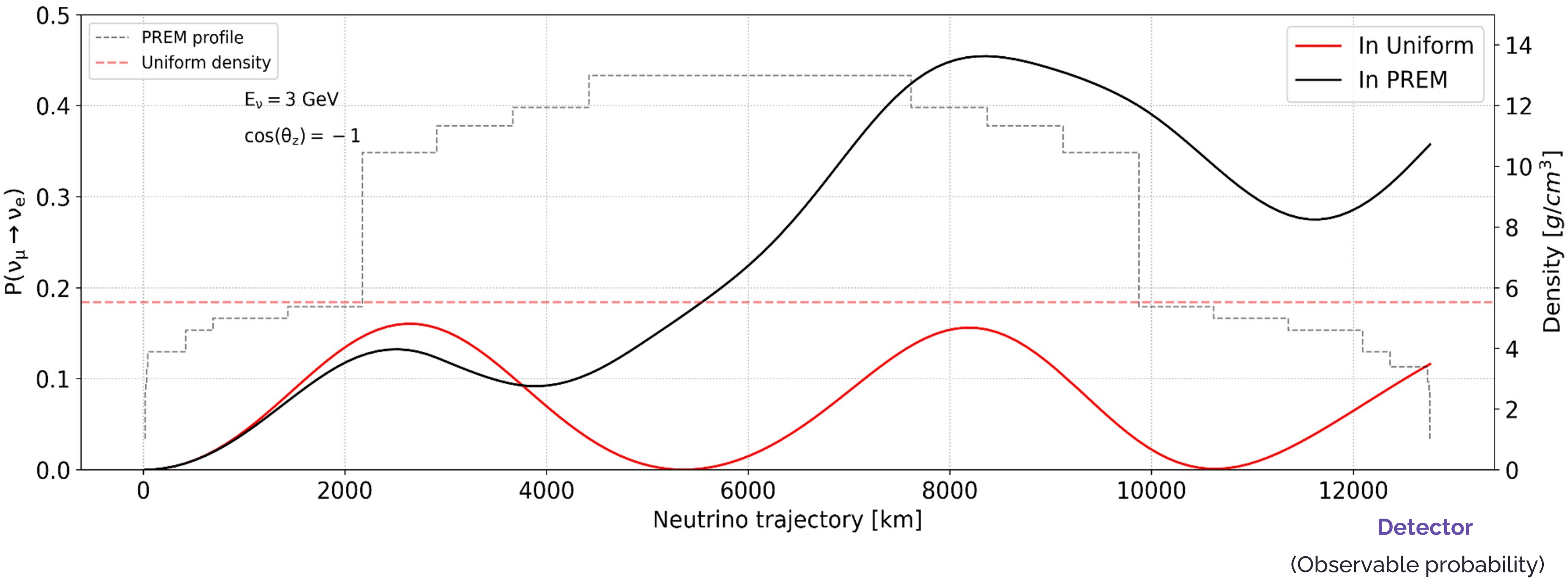
- The probabilities of neutrino flavor transitions can be strongly enhanced if the oscillation phase undergoes certain modification in matter

- This can happen if the variation in the matter density along the neutrino path is correlated in a certain way with the change in the oscillation phase

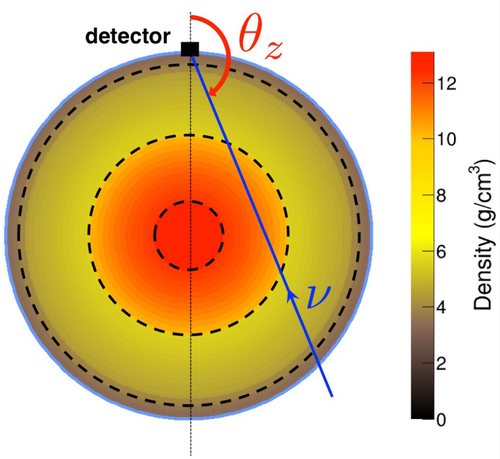
- This amplification of the neutrino oscillation probability in matter due to specific phase relationships can get accumulated if the matter density profile along the neutrino path repeats itself (periodic)

Petcov 1998, Liu and Smirnov 1998, Akhmedov 1998

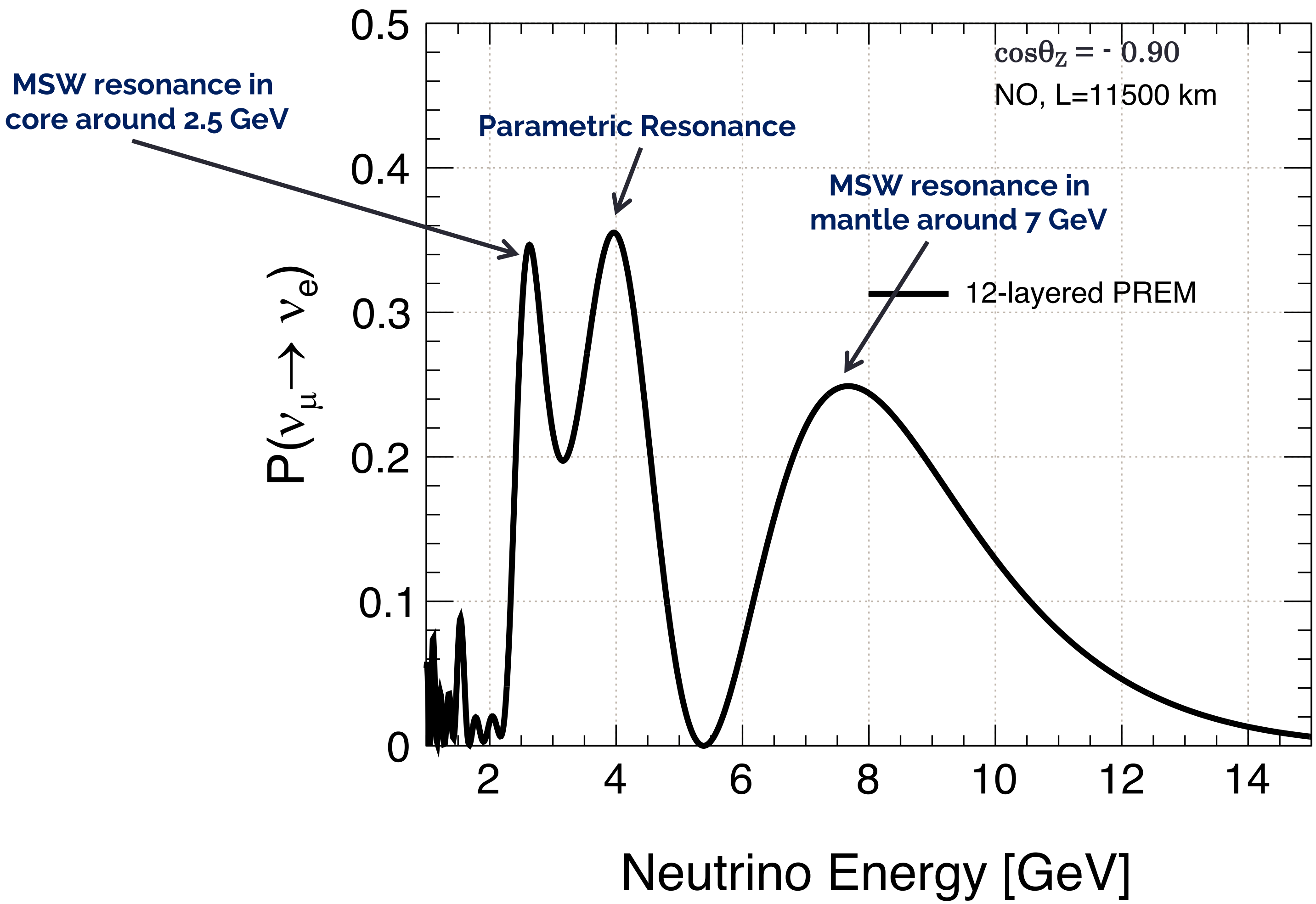
Parametric Resonance inside Earth



- Resonance occurs when frequency of density modulation matches with the frequency of oscillation
- Oscillation probability in PREM profile starts to differ from uniform density profile, once it sees the density jump in PREM at the core-mantle boundary (3480 km)
- Significant enhancement in probability in PREM is visible for core-passing trajectories due to parametric resonance

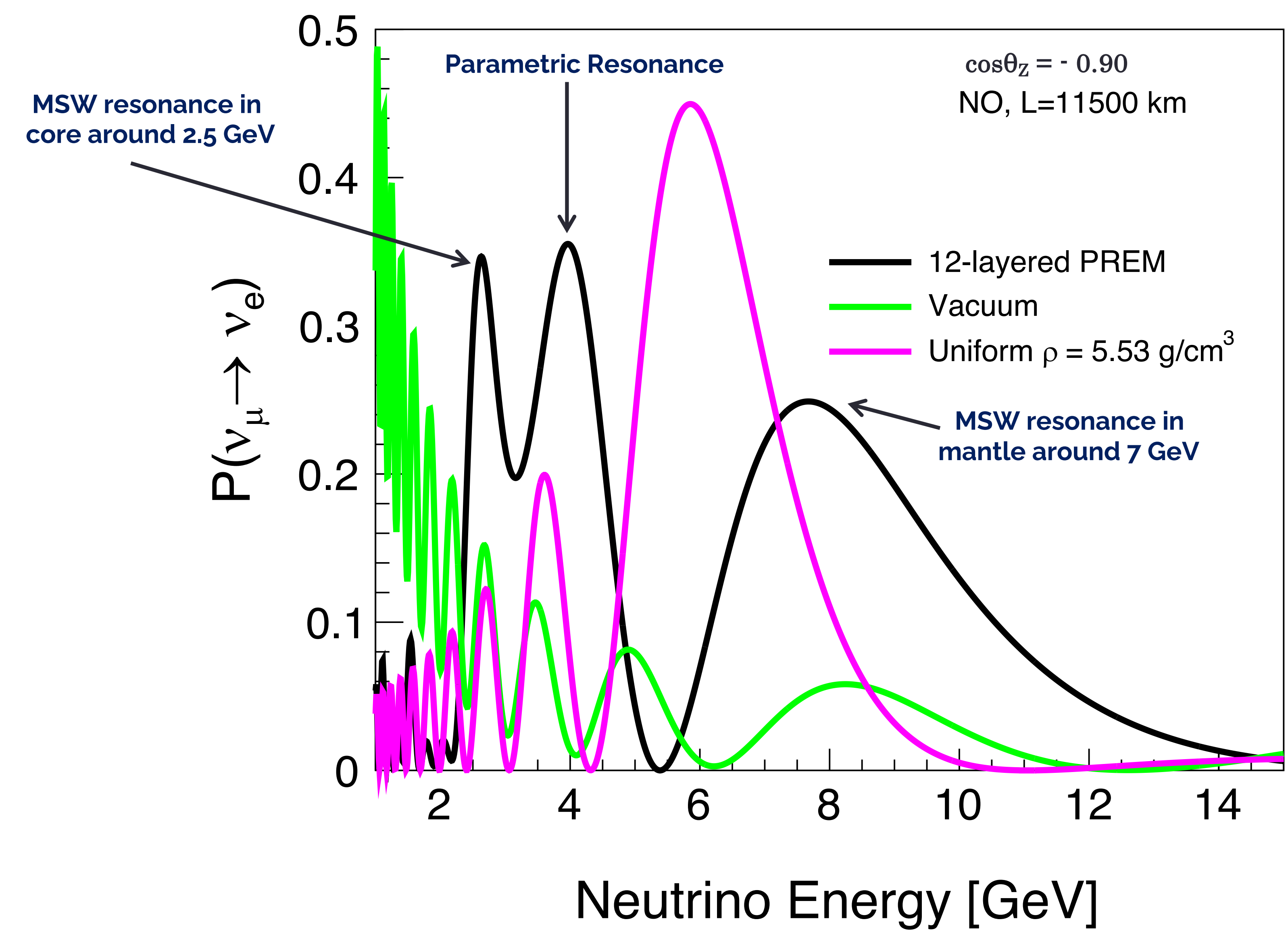


Matter Resonances inside Earth



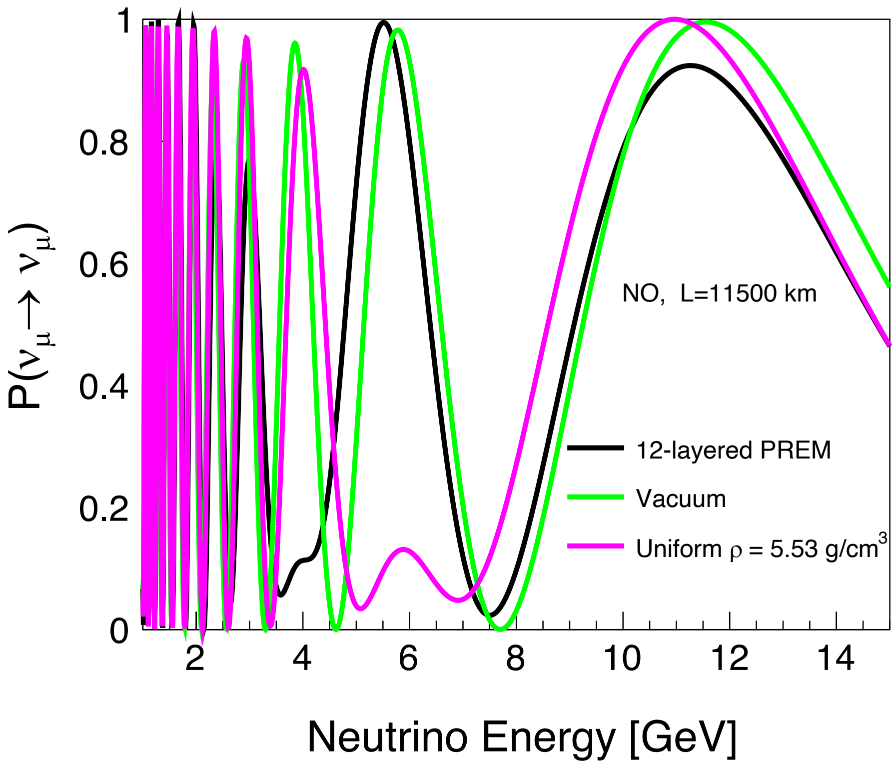
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\,{\rm eV}^2}\right)\cos 2\theta_{13}$$

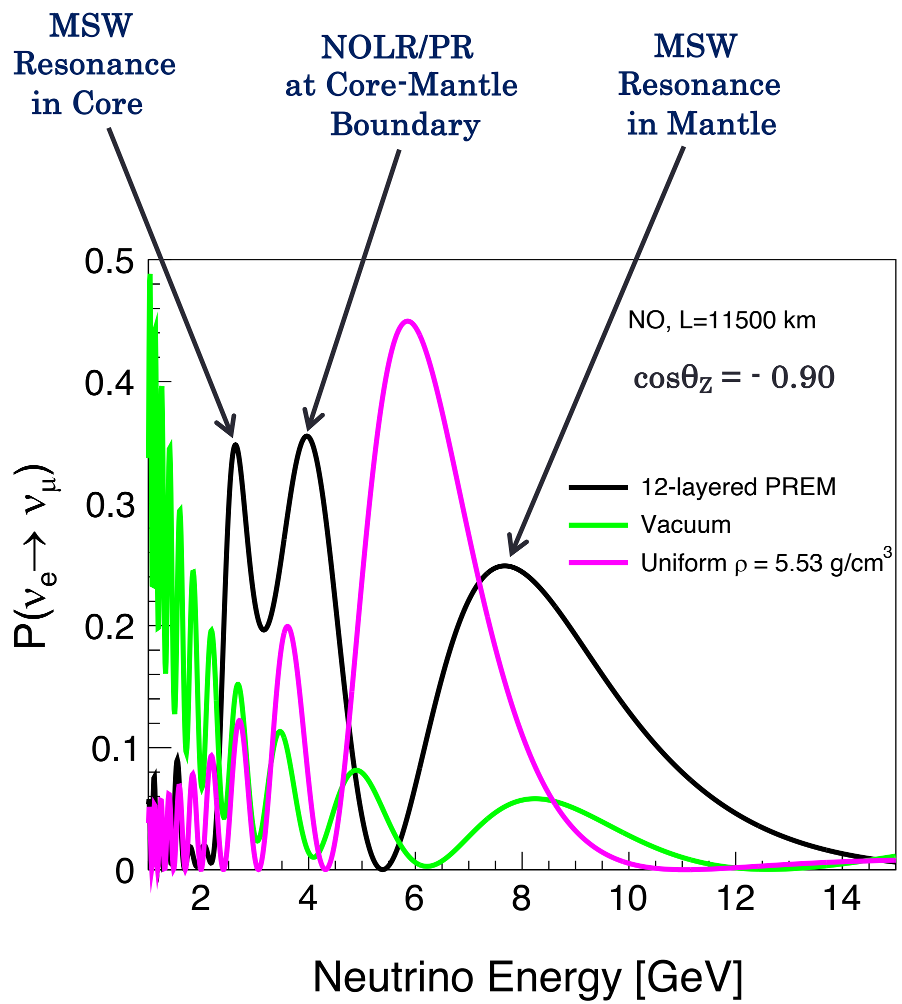
Matter Resonances inside Earth



Similar oscillation patterns for antineutrinos with inverted mass ordering

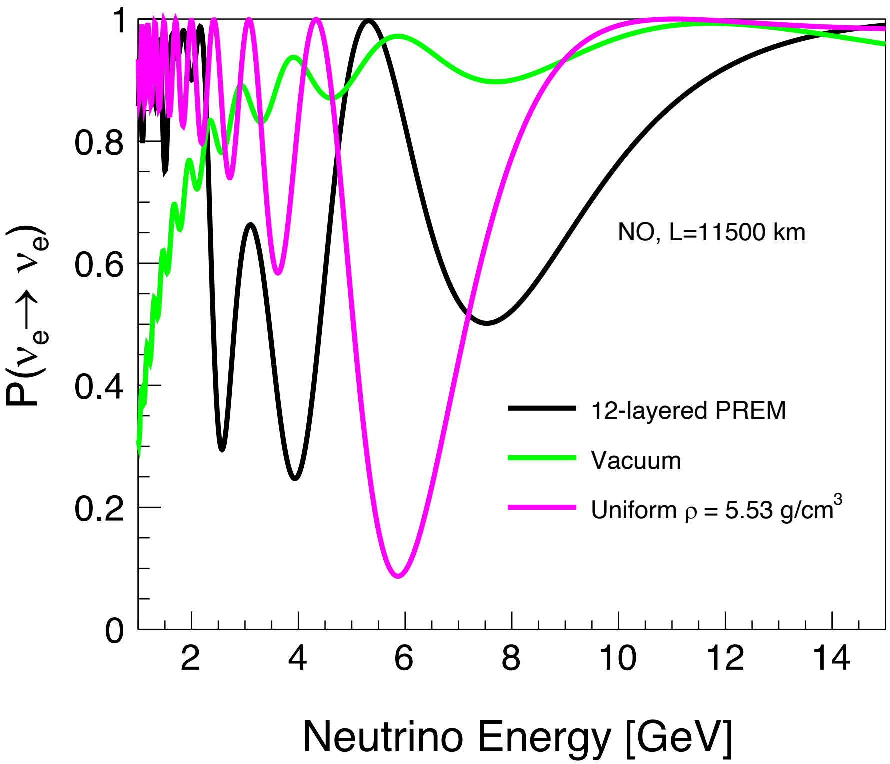
Neutrino Oscillation Probabilities for a Core-Passing Track-Like Events

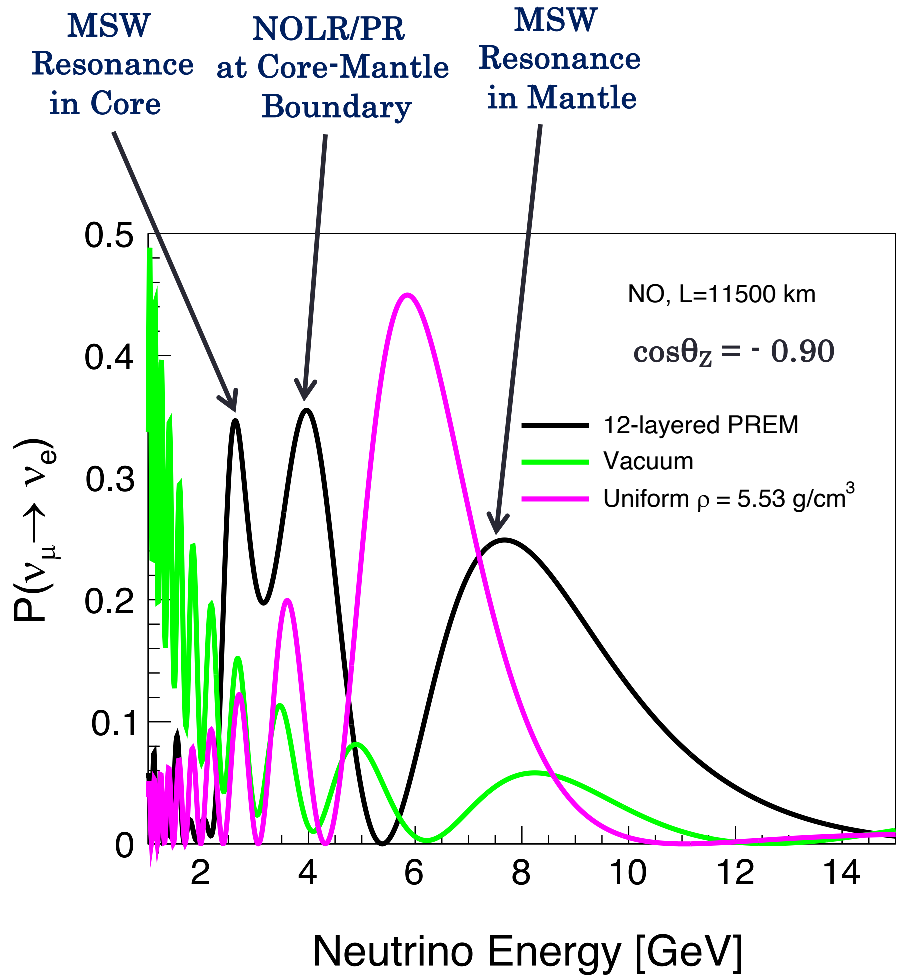




Similar oscillation patterns for antineutrinos with inverted mass ordering

Neutrino Oscillation Probabilities for a Core-Passing Cascade-Like Events

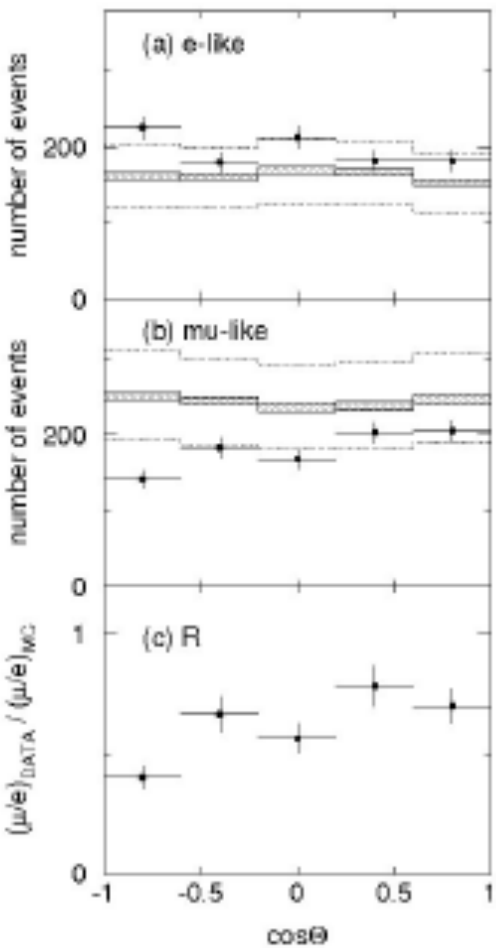


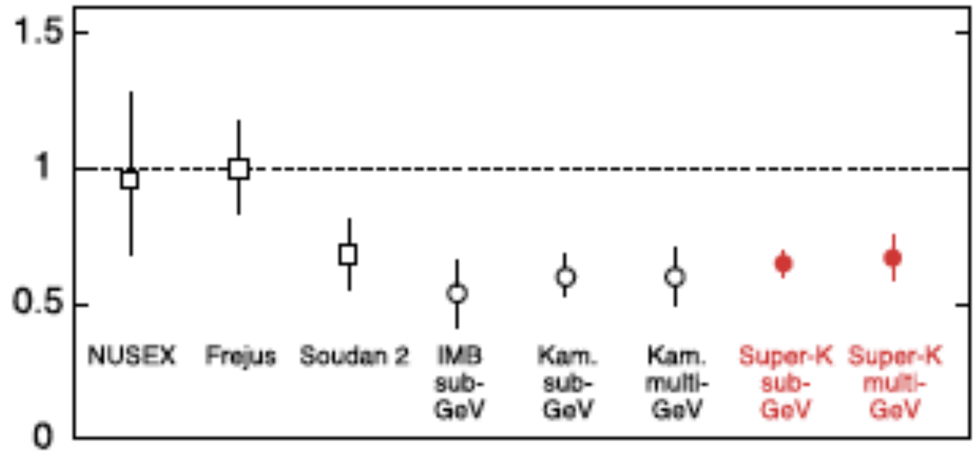


Similar oscillation patterns for antineutrinos with inverted mass ordering

Super-Kamiokande

Double ratio:





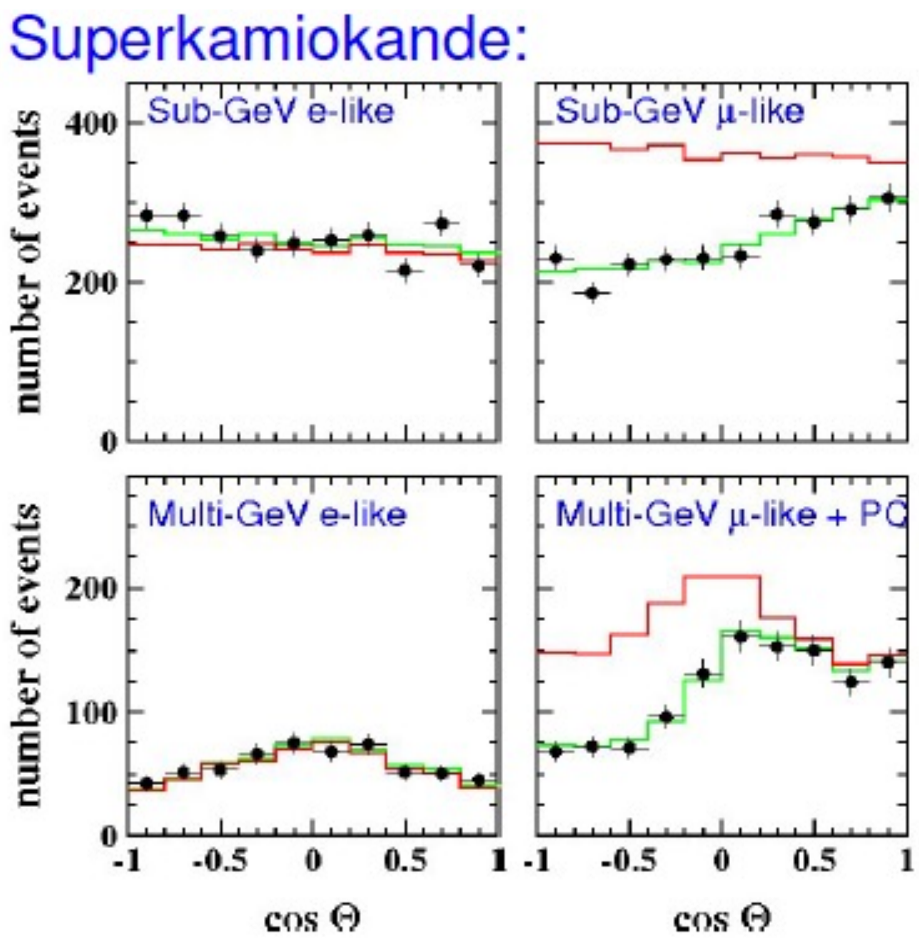
$$R = \frac{(N_\mu/N_e)_{data}}{(N_\mu/N_e)_{MC}}$$

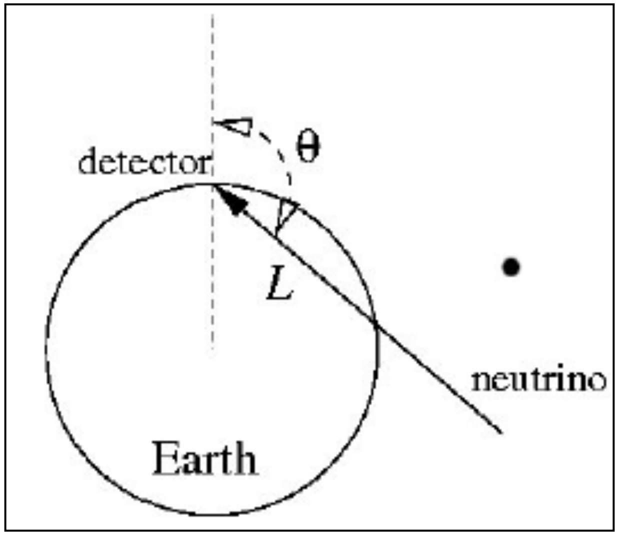
- Expected $R = 1$
- Observed $R < 1$

Year 1988:

First results from Kamiokande on atmospheric neutrino anomaly

K.S. Hirata, et al., Experimental study of the atmospheric neutrino flux, Phys. Lett. B 205 (1988) 416.





- Electron neutrinos match predictions
- High energy ν_μ from above: match predictions
- High energy ν_μ through the earth: partially lost
- Low energy ν_μ: lost even when coming from above, loss while passing through the Earth even greater

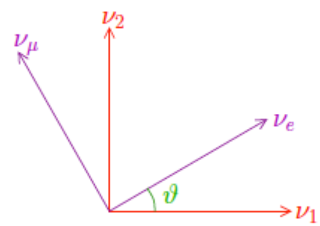
Zenith angle dependence

Neutrino Flavor Oscillations

- **Flavor States :** ν_e and ν_μ (produced in Weak Interactions)
- **Mass Eigenstates :** ν_1 and ν_2 (propagate from Source to Detector)

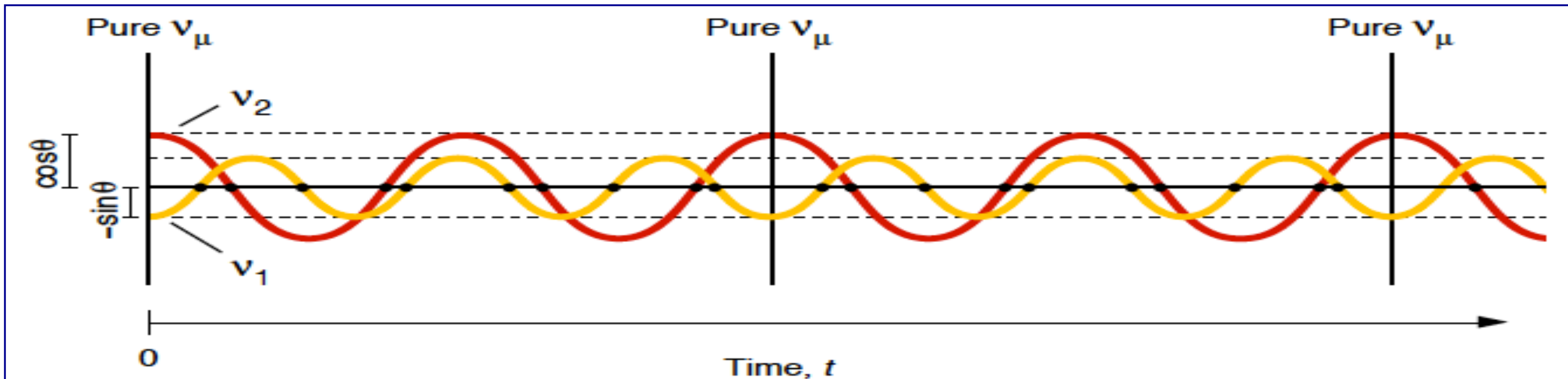
A Flavor State is a linear superposition of Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k} |\nu_k\rangle \qquad (\alpha = e, \mu)$$



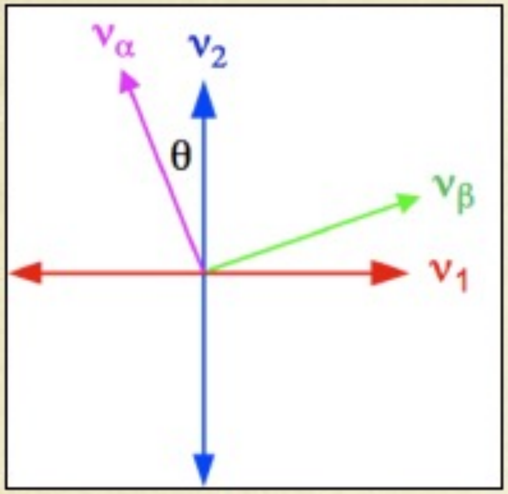
$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$|\nu_e\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle$$



If the masses of these two states are different, then they will take different times to reach the same point and there will be a phase difference and hence interference

Two Neutrino Mixing



$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

standard 2D rotation

$$\Delta m^2_{ij} \equiv m^2_j - m^2_i$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m^2_{ij}\frac{L}{E}\right)$$

t

The angle θ is the level of mixing and therefore sets the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

2 experimental quantities
E = neutrino energy
L = distance traveled

Oscillation Dip in Muon Neutrino Survival Probability

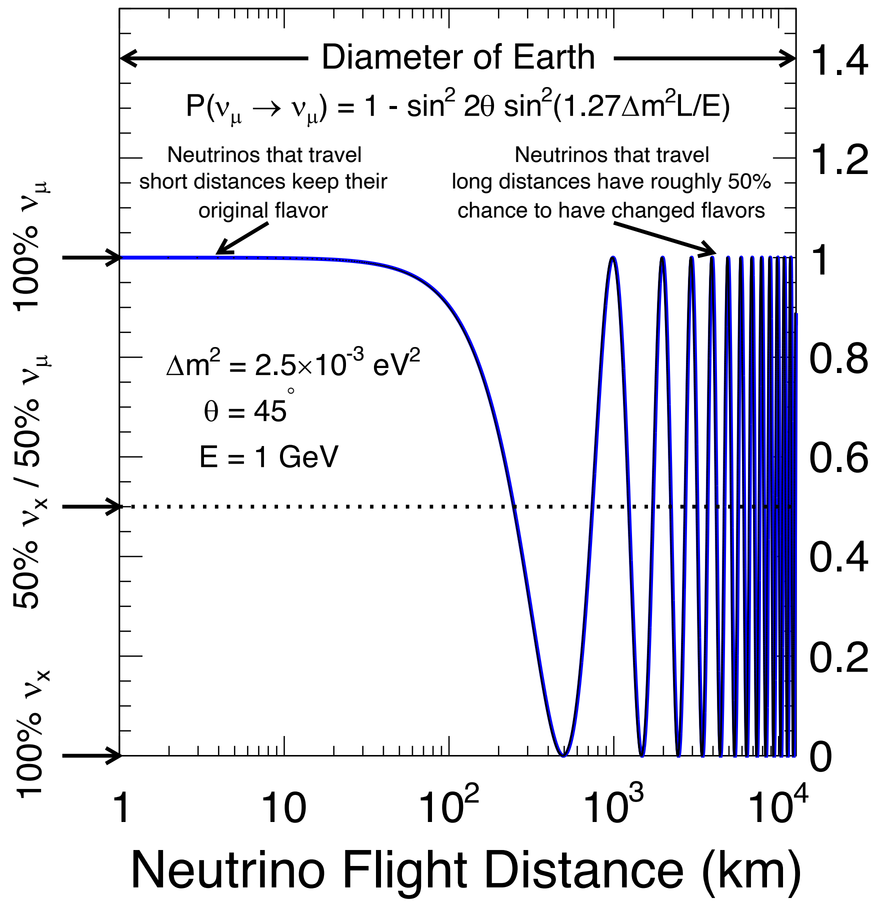
Atmospheric neutrinos have access to a wide range of baselines:

- Vertically downward-going neutrinos: 15 km
- Vertically upward-going neutrinos: 12757 km

For $E_\nu = 1$ GeV:

- At smaller baselines: neutrino oscillations are not developed
- At larger baselines: about 50% ν_μ have oscillated
- At certain baselines: about 100% ν_μ have oscillated

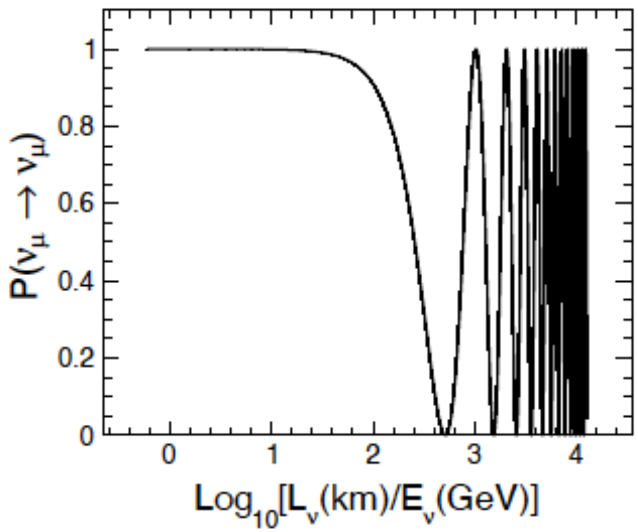
Oscillation dip feature corresponds to the case when all muon neutrinos are oscillated, i.e. $P(\nu_\mu \to \nu_\mu) = 0$.

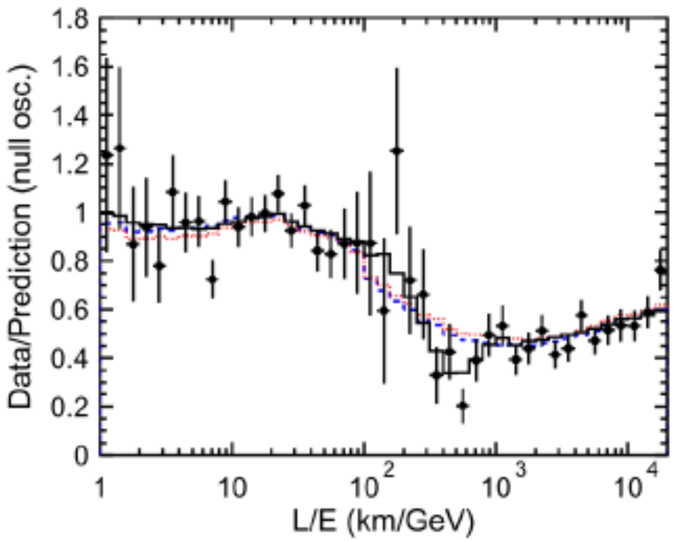


Oscillation Dip in Muon Neutrino Survival Probability

The L/E dependence of survival probability $P(\nu_\mu \to \nu_\mu)$ in two-flavor oscillation is given as:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left(1.27 \cdot |\Delta m^2_{32}| \left(\text{eV}^2\right) \cdot \frac{L_\nu\,(\text{km})}{E_\nu\,(\text{GeV})}\right)$$





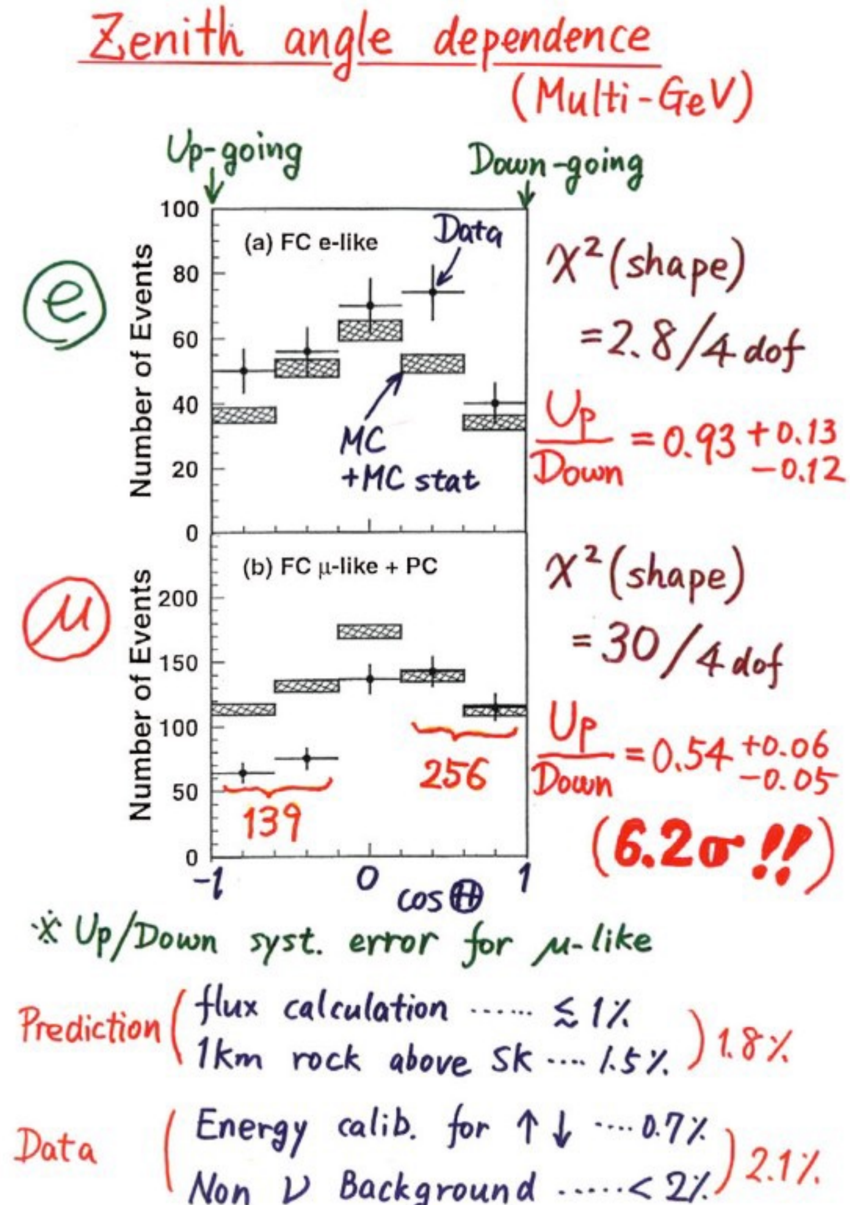
For $\theta_{23} = 45^\circ$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}\ \text{eV}^2$, $P(\nu_\mu \to \nu_\mu) = 0$ when

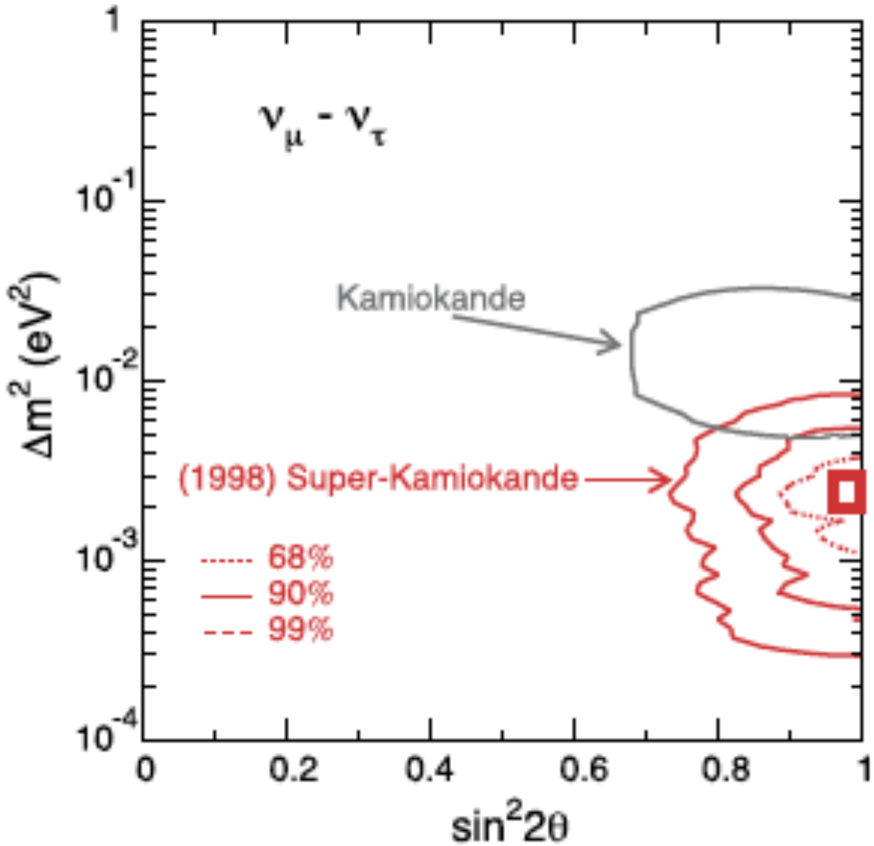
$$\frac{1.27 \Delta m^2_{32} L_\nu}{E_\nu} = \frac{\pi}{2}$$

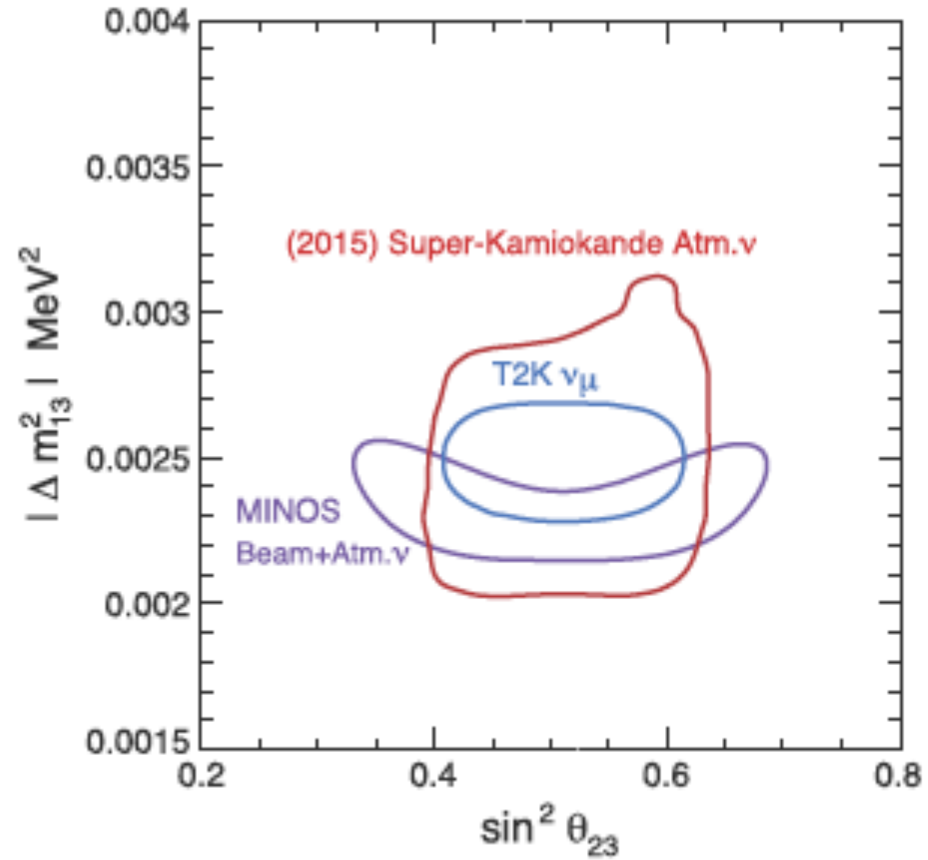
$$\frac{L_\nu}{E_\nu} = 515.35\ \text{km/GeV} \ \&\ \log_{10}\left(\frac{L_\nu}{E_\nu}\right) = 2.71$$

The Super-K experiment was the first experiment to confirm the sinusoidal L/E dependence of the ν_μ survival probability by observing a dip around L/E = 500 km/GeV. (Phys.Rev.Lett. 93 (2004) 101801)

- Indeed, more ν_μ travelling through the Earth are lost
- The zenith angle dependence fits the form of the probability expressions exactly
- Neutrino oscillation hypothesis proved!

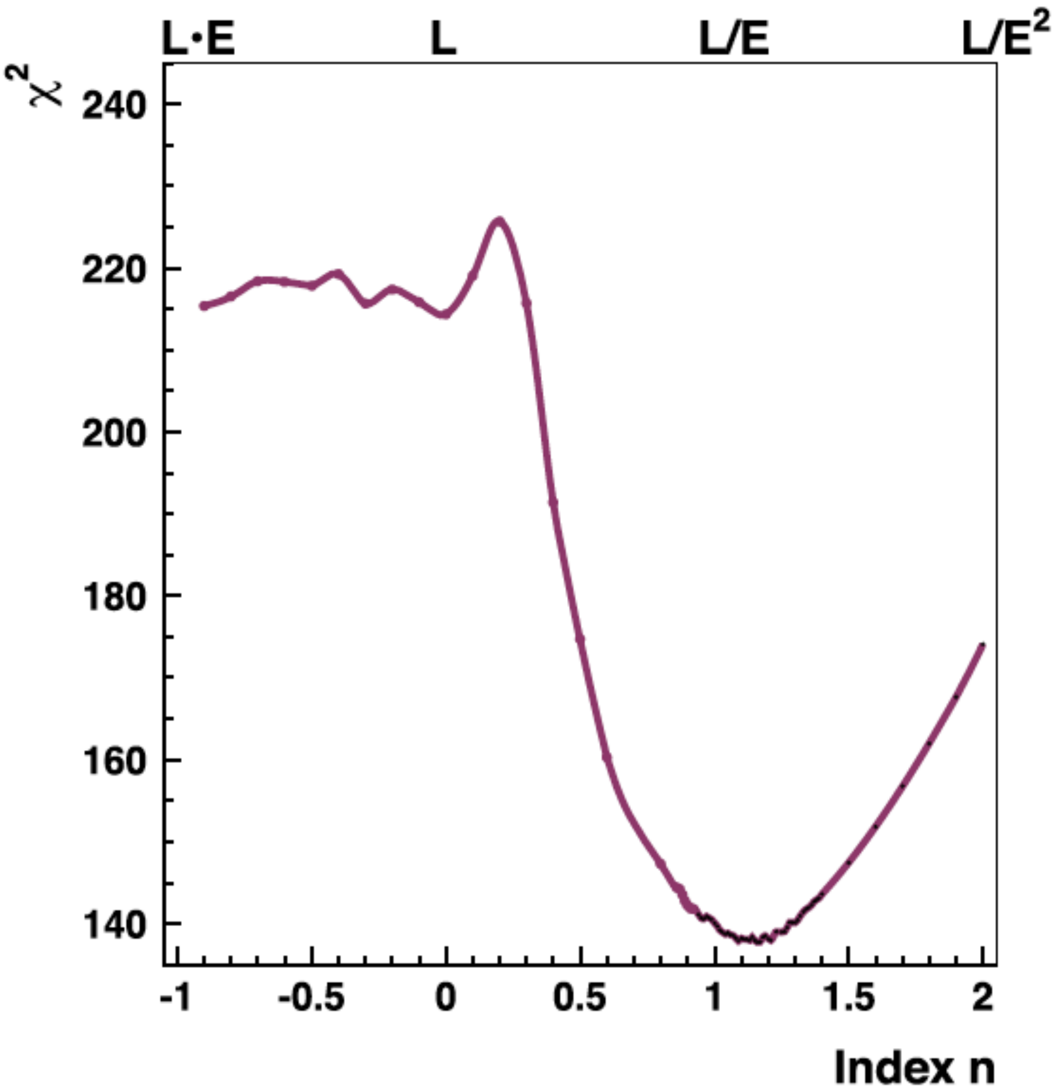






1998 to 2015:
Impressive Journey of Atmospheric Neutrinos establishing Neutrino Oscillations

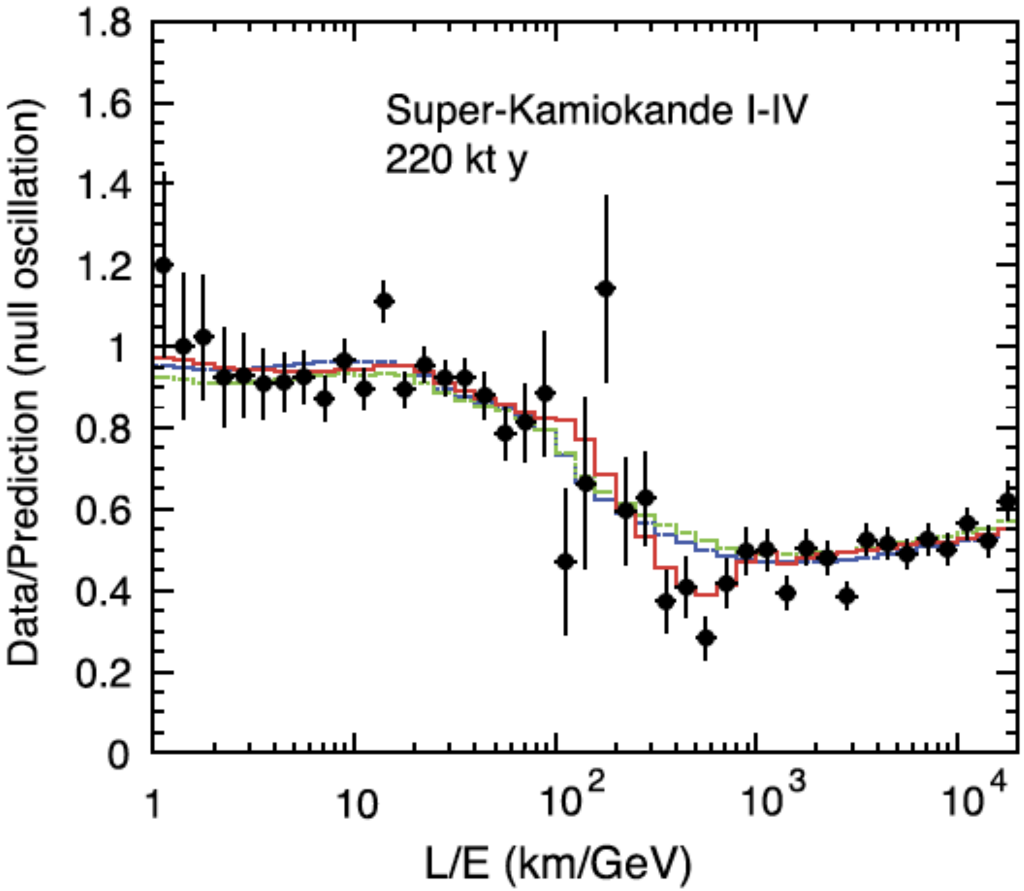
L/E Dependence of Super-K Atmospheric Neutrino Data



- A scan in $\Delta\varkappa^2$ for oscillation frequency proportional to L × E^{-n}
- The oscillation frequency due to neutrino mass has an index of n = 1, which is the index that best fits the Super-Kamiokande atmospheric neutrino data
- Alternate models of muon neutrino deficit (such as neutrino decay, decoherence, Lorentz violation) may be found that have n ≠ 1, however the Super-Kamiokande data favors L/E dependence, i.e., n = 1

T. Kajita, E. Kearns, M. Shiozawa (Super-Kamiokande Collaboration), Nuclear Physics B 908 (2016) 14-29

L/E Dependence of Super-K Atmospheric Neutrino Data



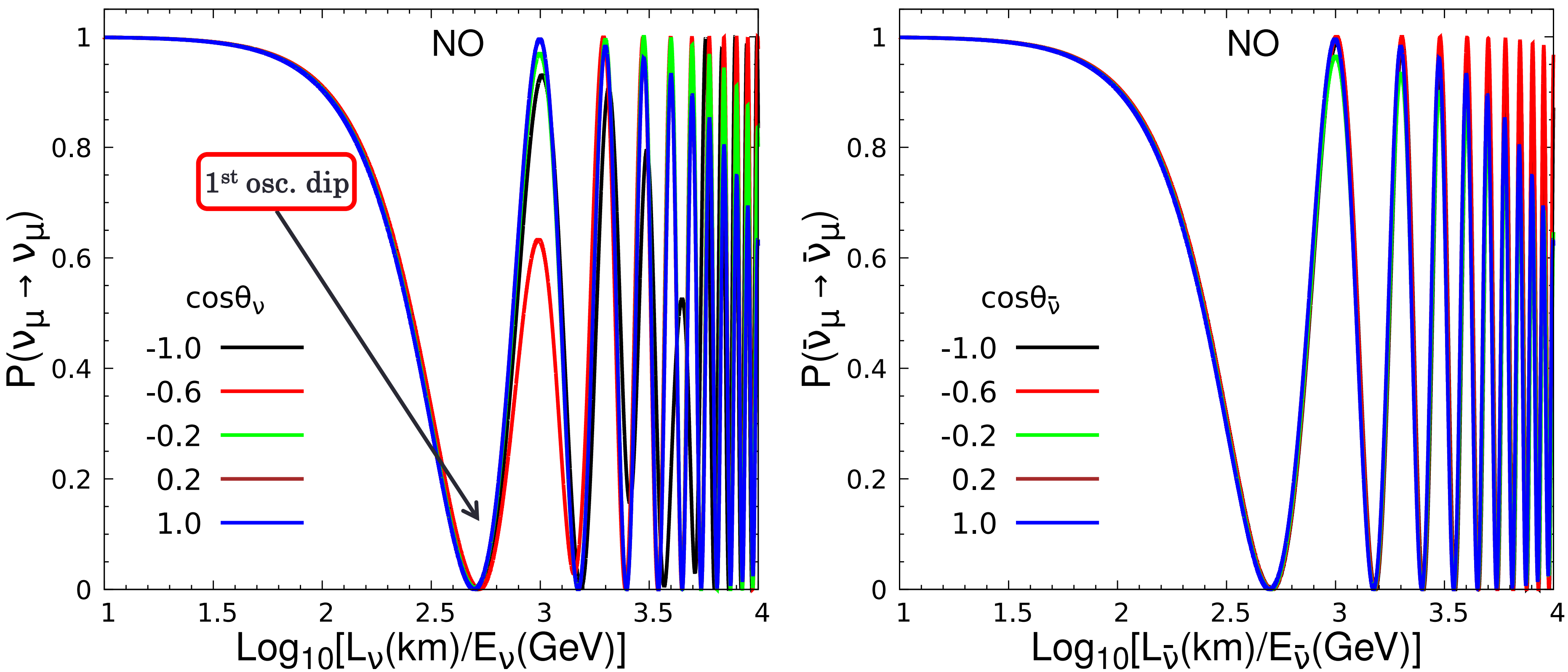
- The ratio of data to MC events (in the absence of neutrino oscillation) as a function of the reconstructed L/E
- Solid red line: the best-fit three-flavor expectation for neutrino oscillation
- The dashed blue line: the best-fit expectation for neutrino decay
- The dotted green line: the best-fit expectation for neutrino decoherence

There is more than 4σ evidence for a dip in the rate of muon neutrinos near 500 GeV/km supporting the L/E dependence of mass-induced neutrino flavor transition. The observation of this dip is crucial to reject the other hypotheses of neutrino oscillation

T. Kajita, E. Kearns, M. Shiozawa (Super-Kamiokande Collaboration), Nuclear Physics B 908 (2016) 14-29

Oscillation Dip in Muon Neutrino Survival Probability

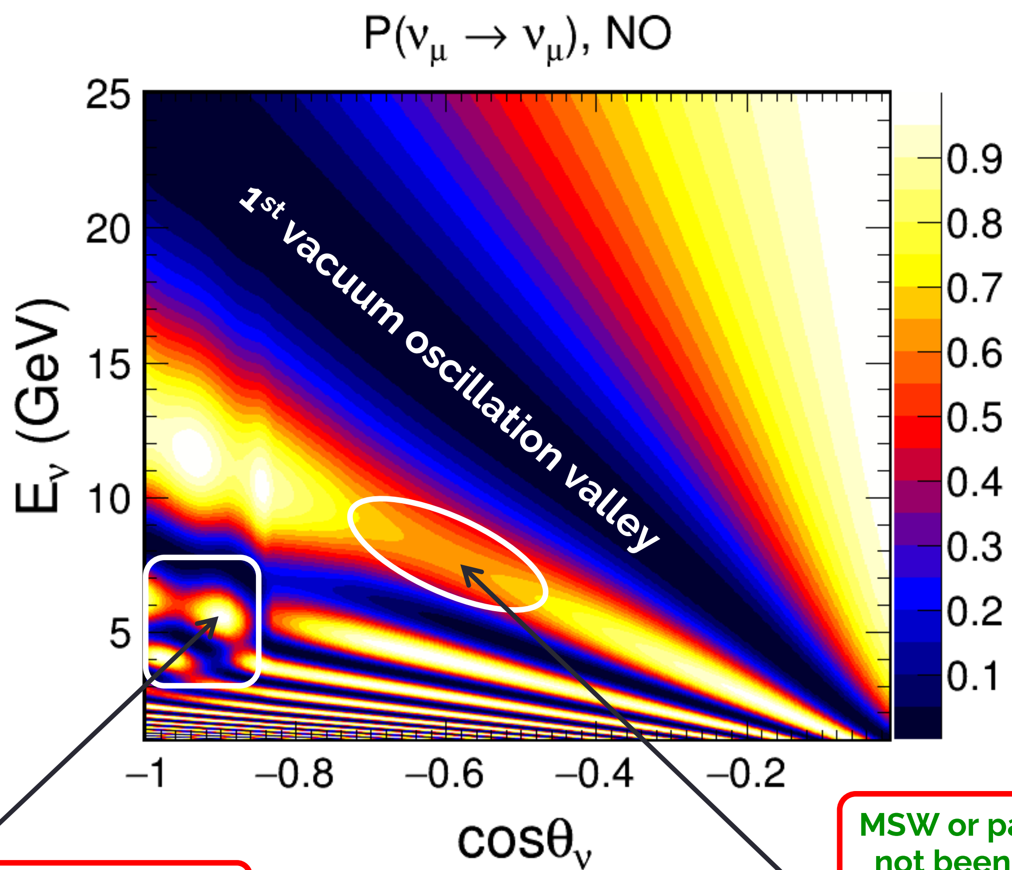
Three-flavor oscillation framework in the presence of Earth's matter (PREM profile)



Anil Kumar, Amina Khatun, Sanjib Kumar Agarwalla, Amol Dighe, EPJC 81 (2021) 2, 190, arXiv: 2006.14529

- Oscillation dip can be observed around $\log_{10}(L_\nu/E_\nu) = 2.7$
- Matter effect in $P(\nu_\mu \to \nu_\mu)$ for the case of neutrino (due to normal mass ordering) can be observed around $\log_{10}(L_\nu/E_\nu) = 3.0$

Oscillation Valley in Muon Neutrino Survival Probability



MSW or parametric resonances have not been observed yet inside Earth!

Parametric resonance region

$\cos\theta_\nu < -0.8$
3 GeV < E_ν < 6 GeV
reducing threshold helps

MSW resonance region

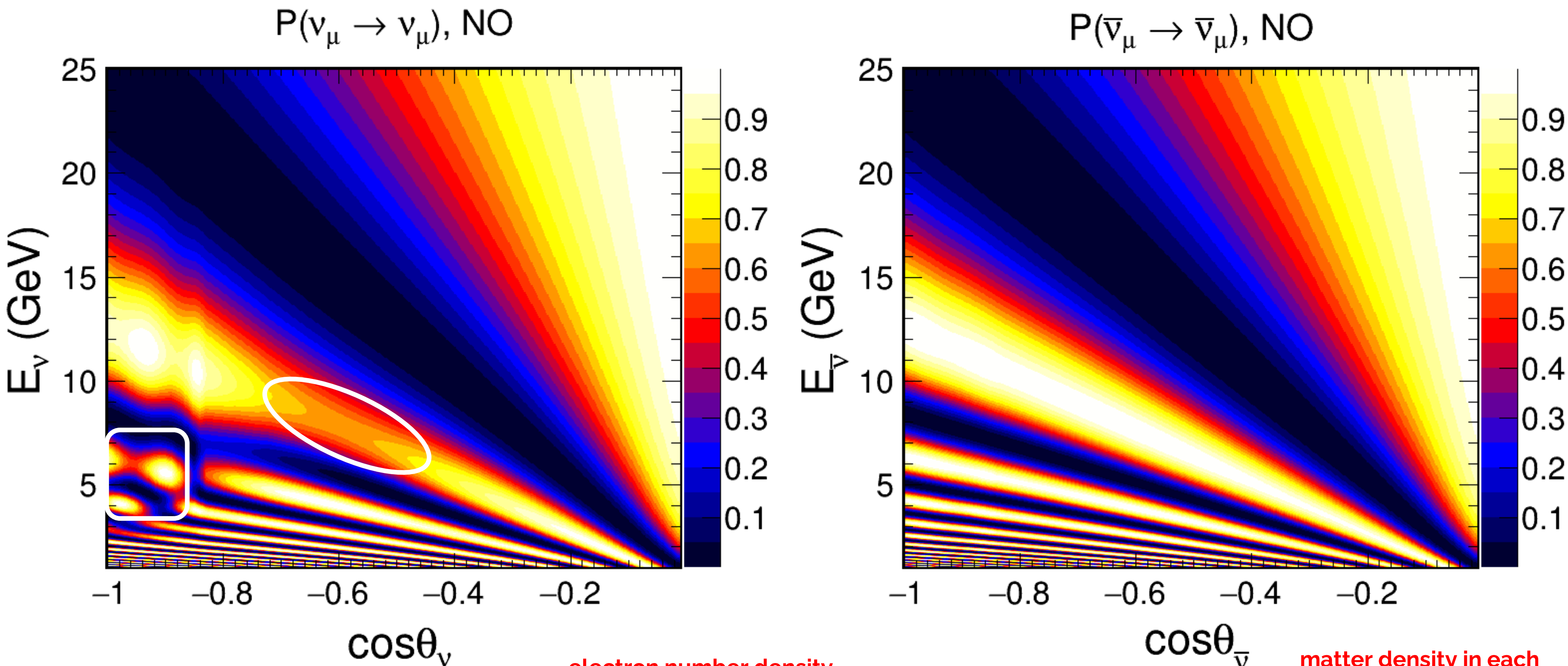
$-0.8 < \cos\theta_\nu < -0.5$
6 GeV < E_ν < 10 GeV

Kumar, Khatun, Agarwalla, Dighe, EPJC 81 (2021) 2, 190

Oscillation Valley in Muon Neutrino Survival Probability

Neutrinos (antineutrinos) feel Earth's matter effect for normal (inverted) mass ordering

normal ordering: $m_3 > m_2 > m_1$ or inverted ordering: $m_2 > m_1 > m_3$



electron number density

matter density in each layer inside Earth

$$V_{\rm CC} = \pm\sqrt{2}G_F N_e \approx \pm 7.6 \times Y_e \times 10^{-14} \left[\frac{\rho}{g/cm^3}\right] \text{eV}$$

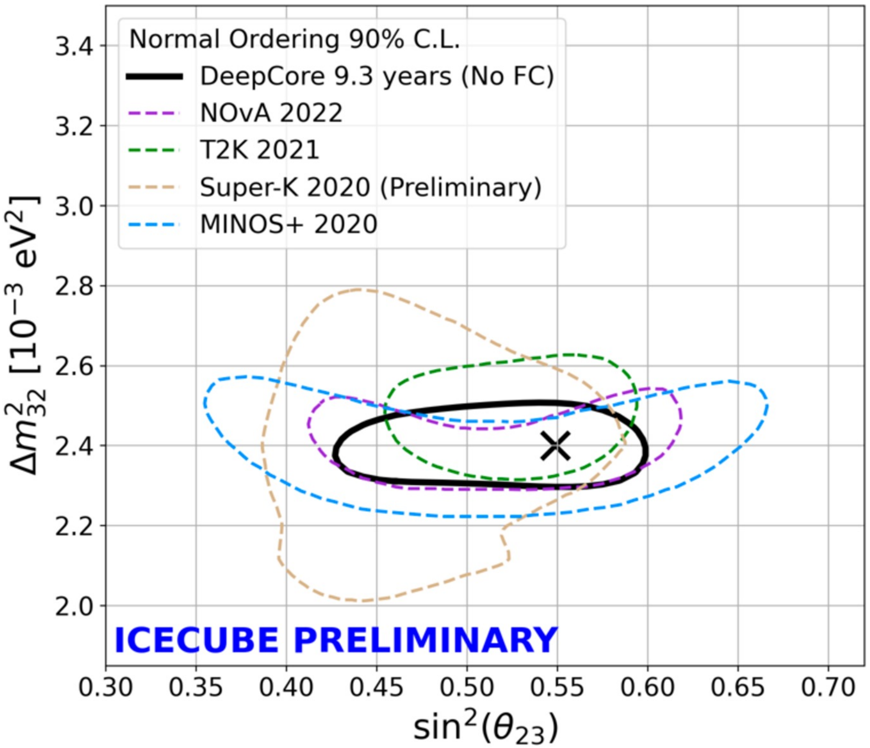
$$Y_e = N_e/(N_p + N_n)$$

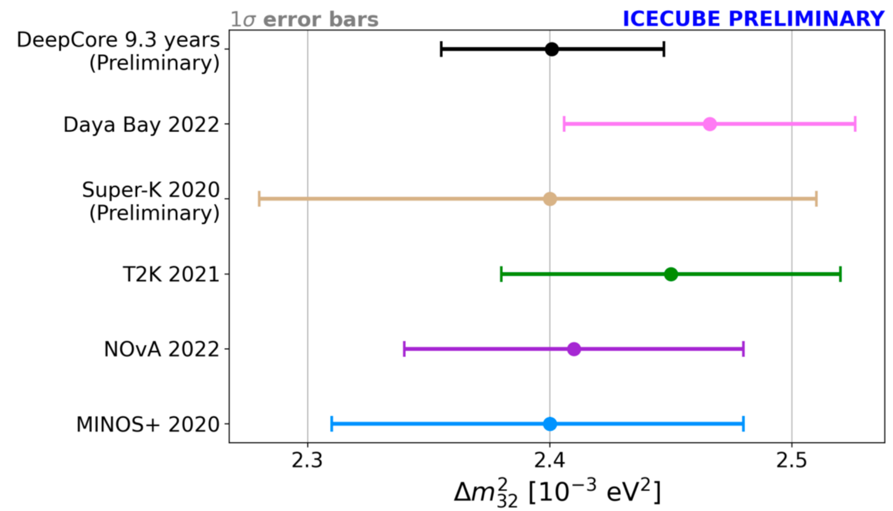
relative electron number density

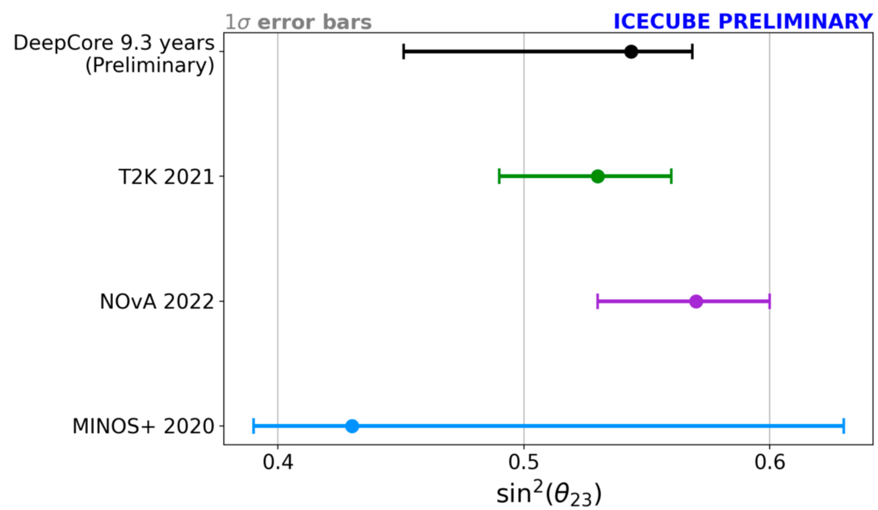
+1 (-1) for neutrino (antineutrino)

chemical composition of Earth

Latest Oscillation Results from DeepCore





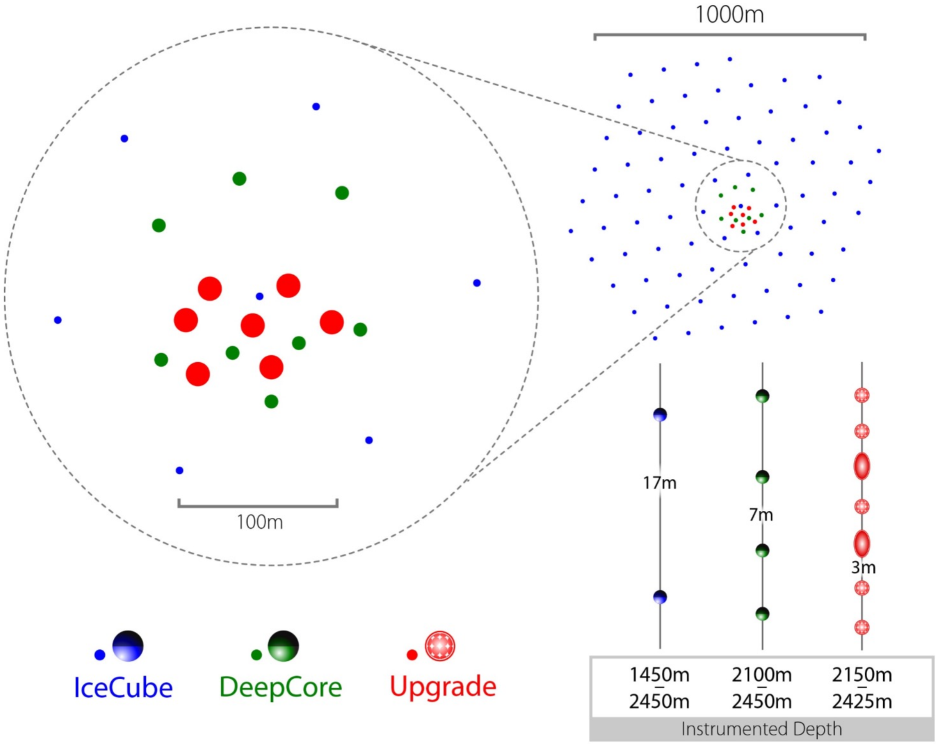


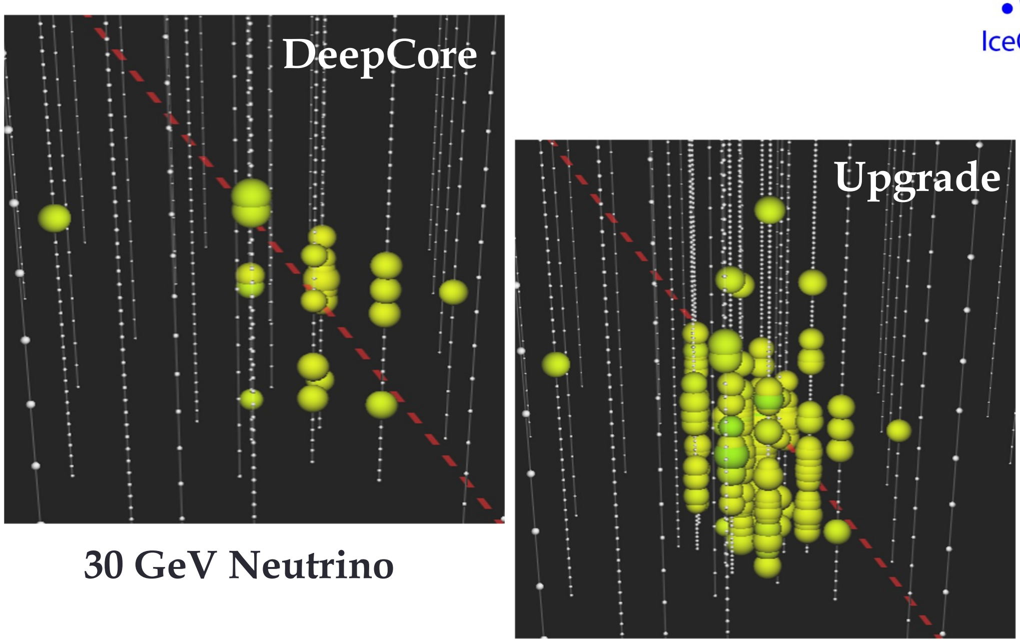
- These new result are compatible & complementary with the existing measurements
  - High-precision measurement on Δm^2_{32}
- Very high-energy sample (5 – 100 GeV) & different systematic uncertainties
  - Strong validation of the standard 3-flavor oscillation

ICRC2023 arXiv:2307.15855

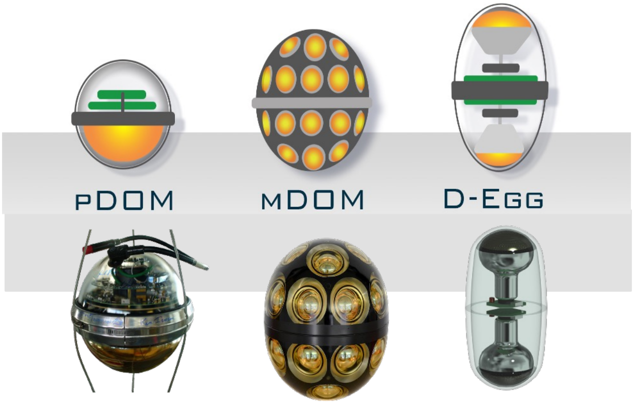
A New Extension of DeepCore: IceCube Upgrade

- **2 Mton of dense instrumentation for low-energy measurements**
- **7 new strings in the center region of detector: energy threshold ~ 1 GeV**
- **Higher event rate: 4 x DeepCore**
- **To be deployed in the Antarctic summer of 2025/26**





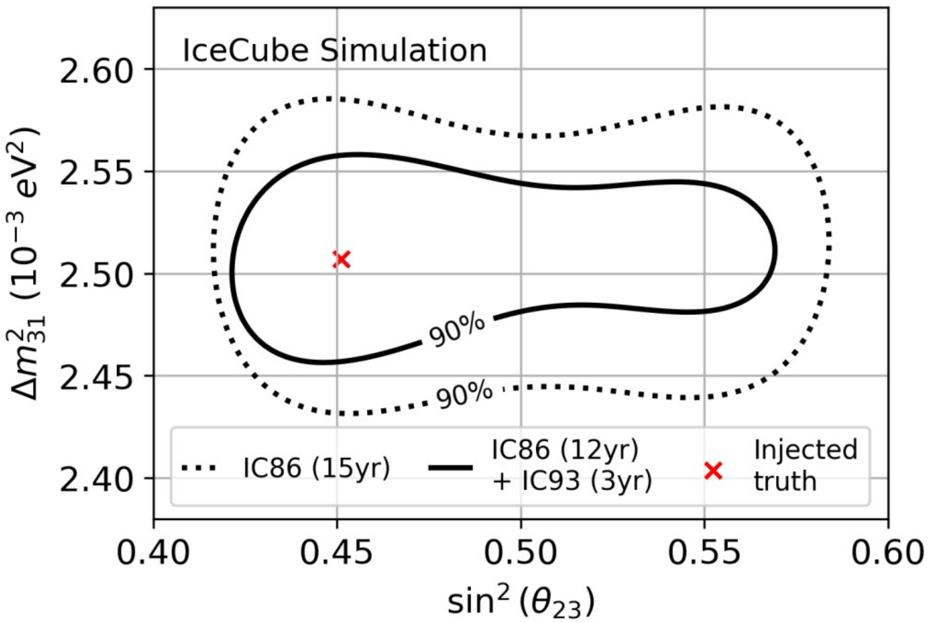
30 GeV Neutrino

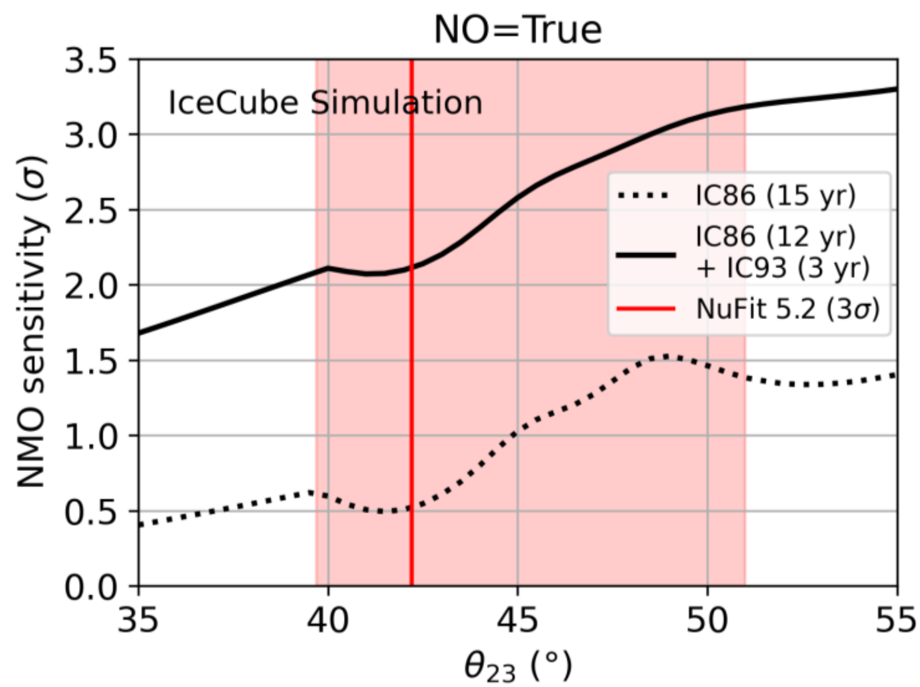


2 new types of optical modules w/ multi-PMT configurations

ICRC2019 arXiv:1908.09441 ICRC2023 arXiv:2307.15295

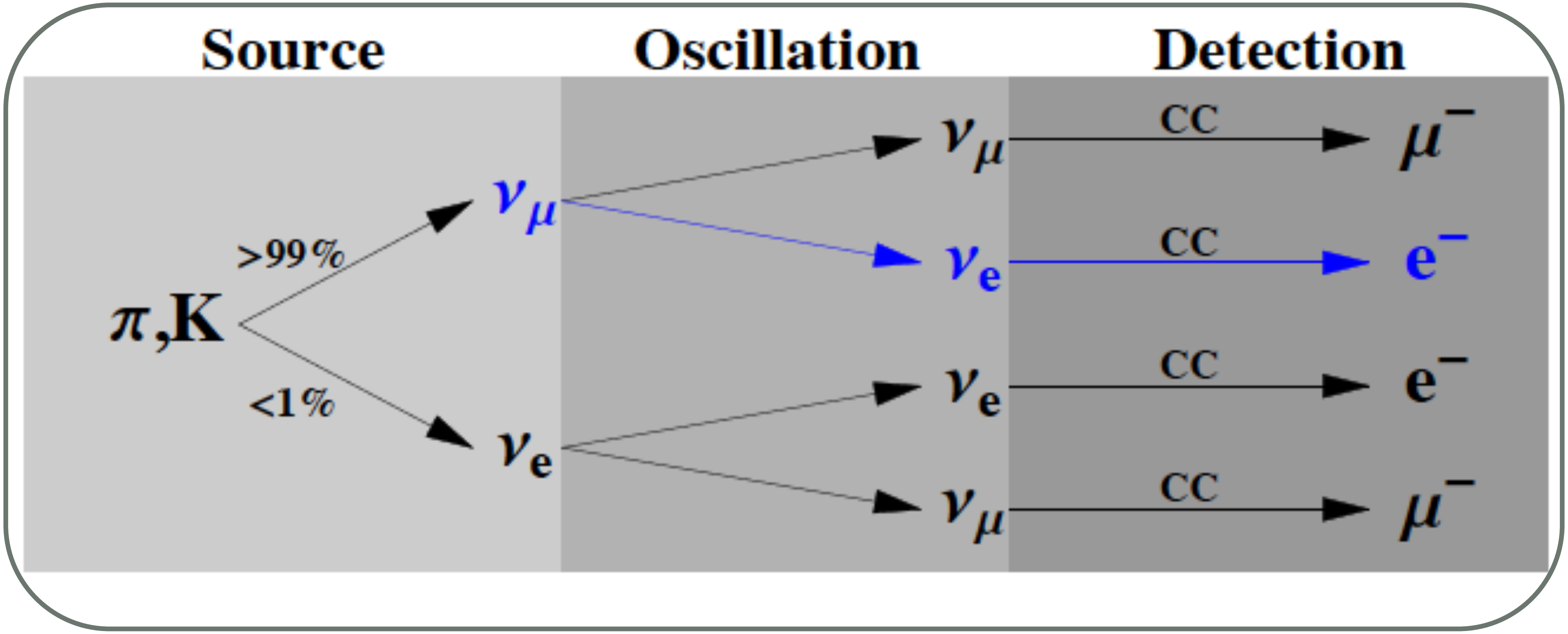
Sensitivity of IceCube Upgrade: Atmospheric Oscillation Parameters





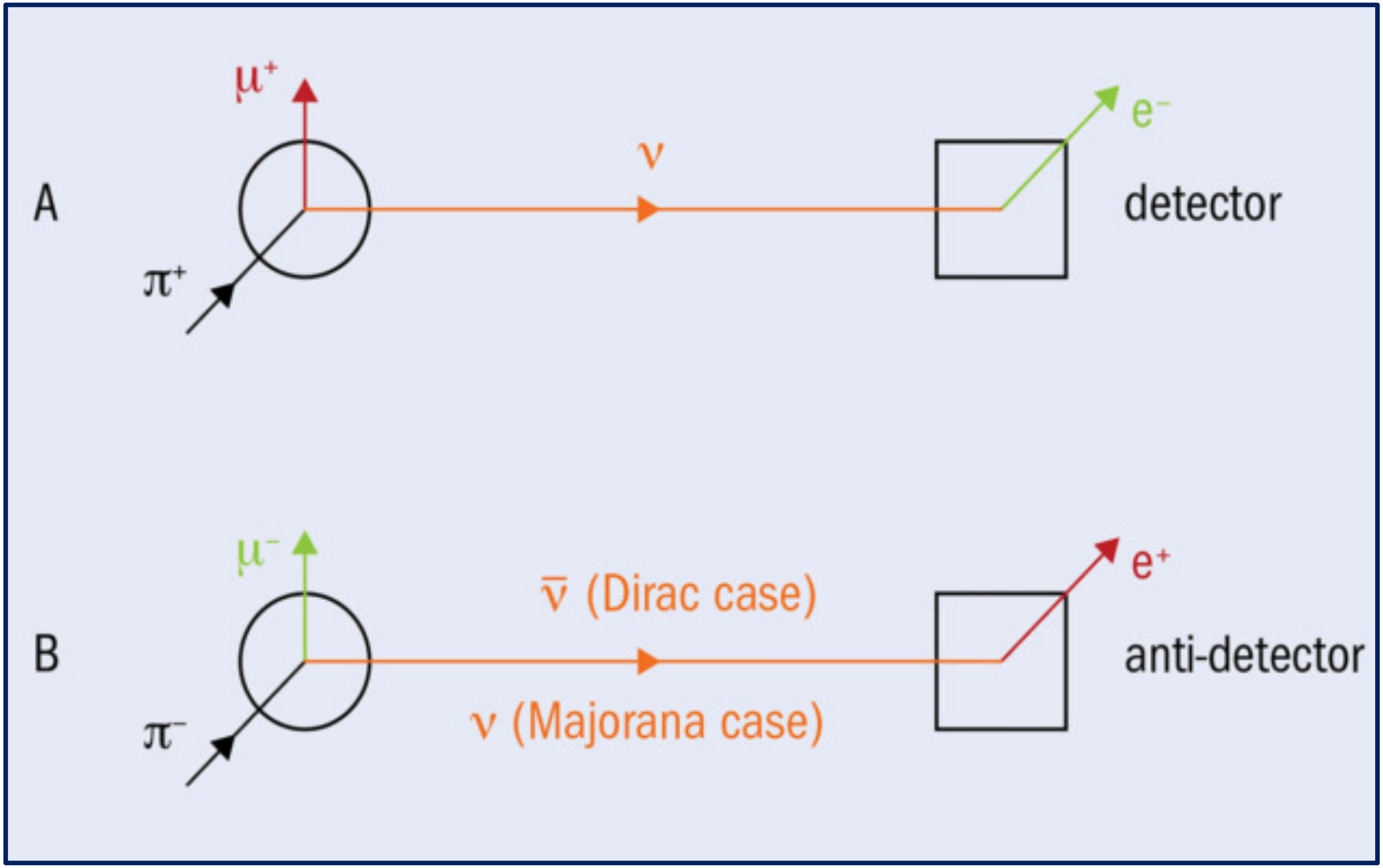
ICRC2023 arXiv:2307.15295

- 90% confidence level after 3 years with the new strings assuming NuFit 5.2 best-fit values
- With the new strings, IceCube's sensitivity to Δm^2_{31} and θ_{23} increases by about 20 to 30%
- 4 times enhancement in the sensitivity to neutrino mass ordering



Traditional approach: Neutrino beam from pion decay

The Pursuit of Leptonic CPV in LBL Experiments



The whole idea is based on comparing the rates of two CP-mirror-image processes

Above experimental approach is a perfectly valid probe of leptonic CPV regardless of whether neutrinos are Dirac or Majorana particles

Accelerator Long-Baseline Neutrino Experiments

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$: Appearance Channel

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$: Disappearance Channel

T2K (Japan) & NOvA (USA) [running, off-axis]

FD: 295 km
1st Osc. Max. ~ 0.6 GeV

FD: 810 km
1st Osc. Max. ~ 1.6 GeV

narrow-band beam

DUNE (USA) [upcoming, on-axis]

FD: 1285 km
1st Osc. Max. ~ 2.6 GeV

wide-band beam

T2HK (Japan) [upcoming, off-axis]

FD: 295 km
1st Osc. Max. ~ 0.6 GeV

narrow-band beam

Current Long-Baseline Experiments: T2K and NOvA

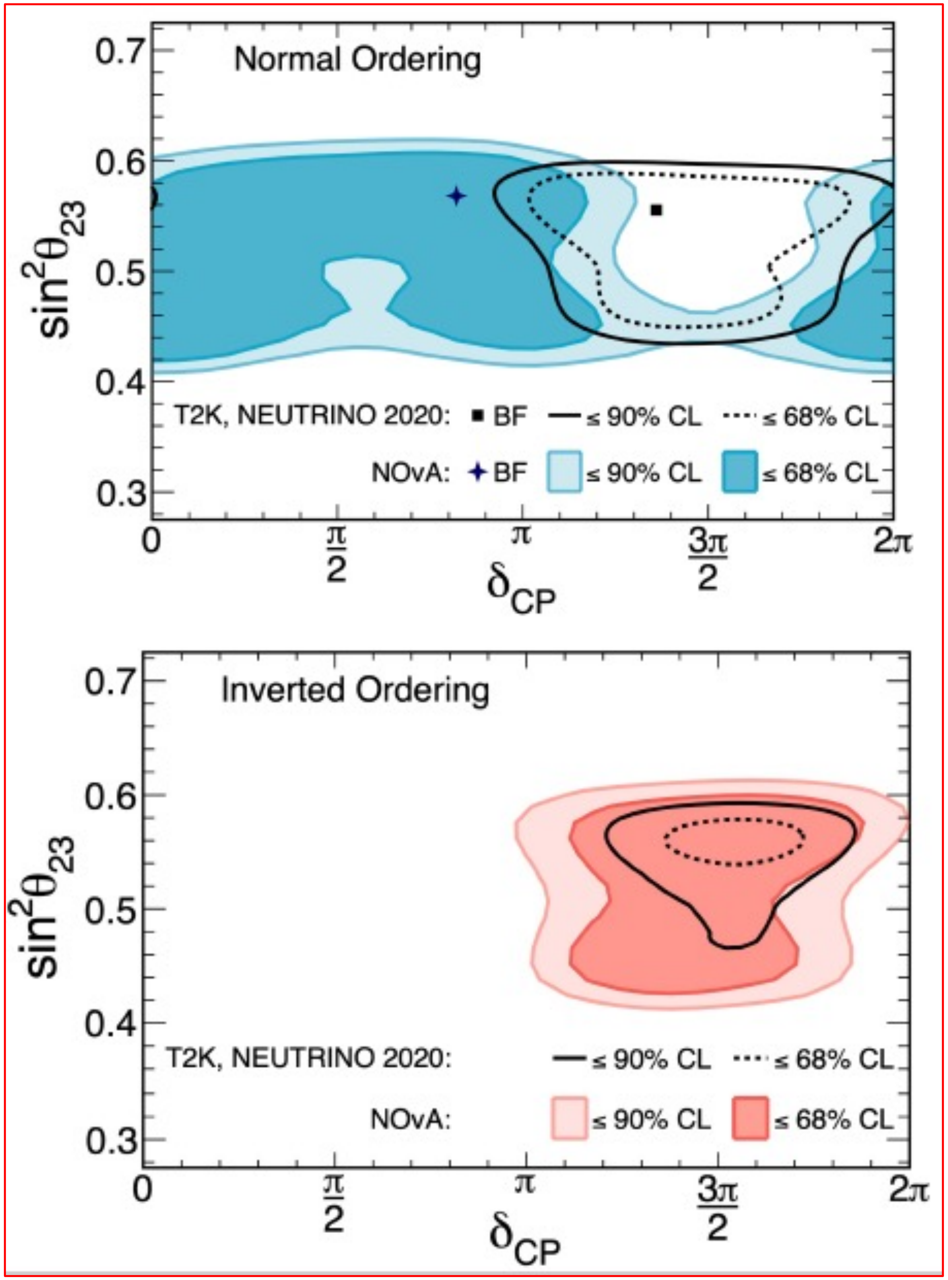
T2K and NOvA operate at different energies and baselines

Complement each other and help to remove degeneracies among various oscillation parameters

Probe multiple oscillation maxima

Compare neutrino and antineutrino oscillation probabilities

Latest CP Measurements from T2K and NOvA



Complementarity between T2K & NOvA

Both T2K & NOvA individually show a slight preference for NMO

NMO: T2K excludes large regions of the NOvA constraints at 90% C.L., & NOvA excludes parts of T2K's 90% C.L. region

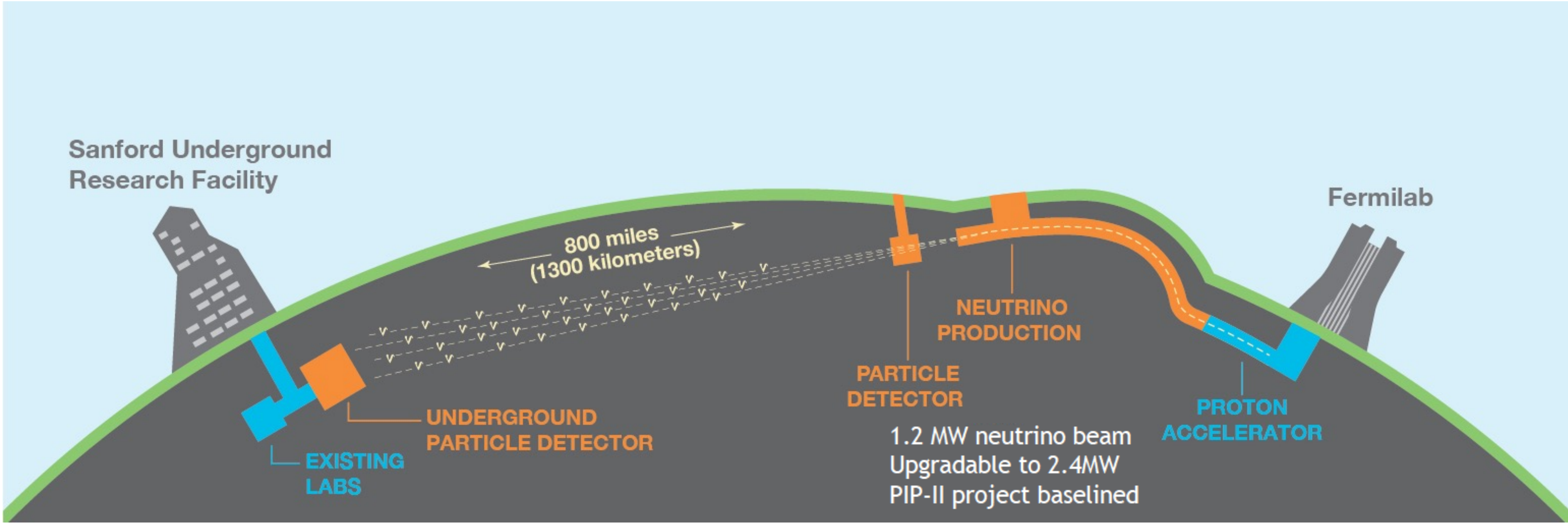
IMO: Both the experiments consistently favour the $\pi < \delta_{CP} < 2\pi$ region, with a weak preference for the upper octant

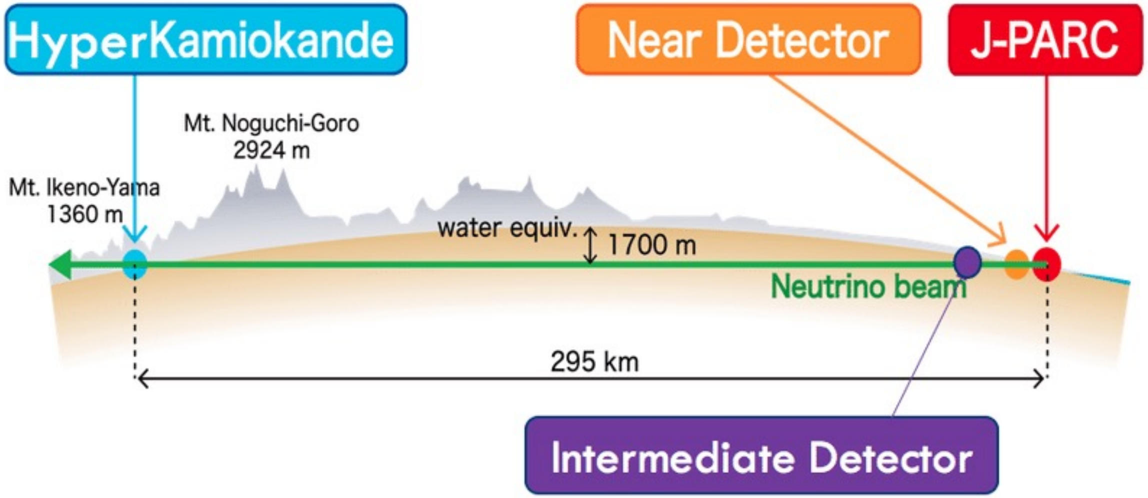
Both the experiments need more data (at present statistically limited) to have better measurements

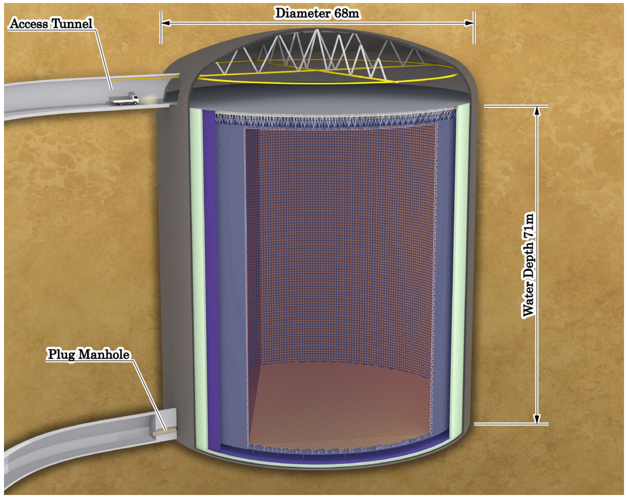
Joint oscillation analyses between T2K, Super-K, & NOvA would be very helpful

T2K: arXiv:2303.03222 [hep-ex]
NOvA: arXiv: 2108.08219 [hep-ex]

Future Long-Baseline Experiments: DUNE, T2HK, and T2HKK







Essential Features of DUNE, T2HK (JD), and T2HKK (JD+KD)

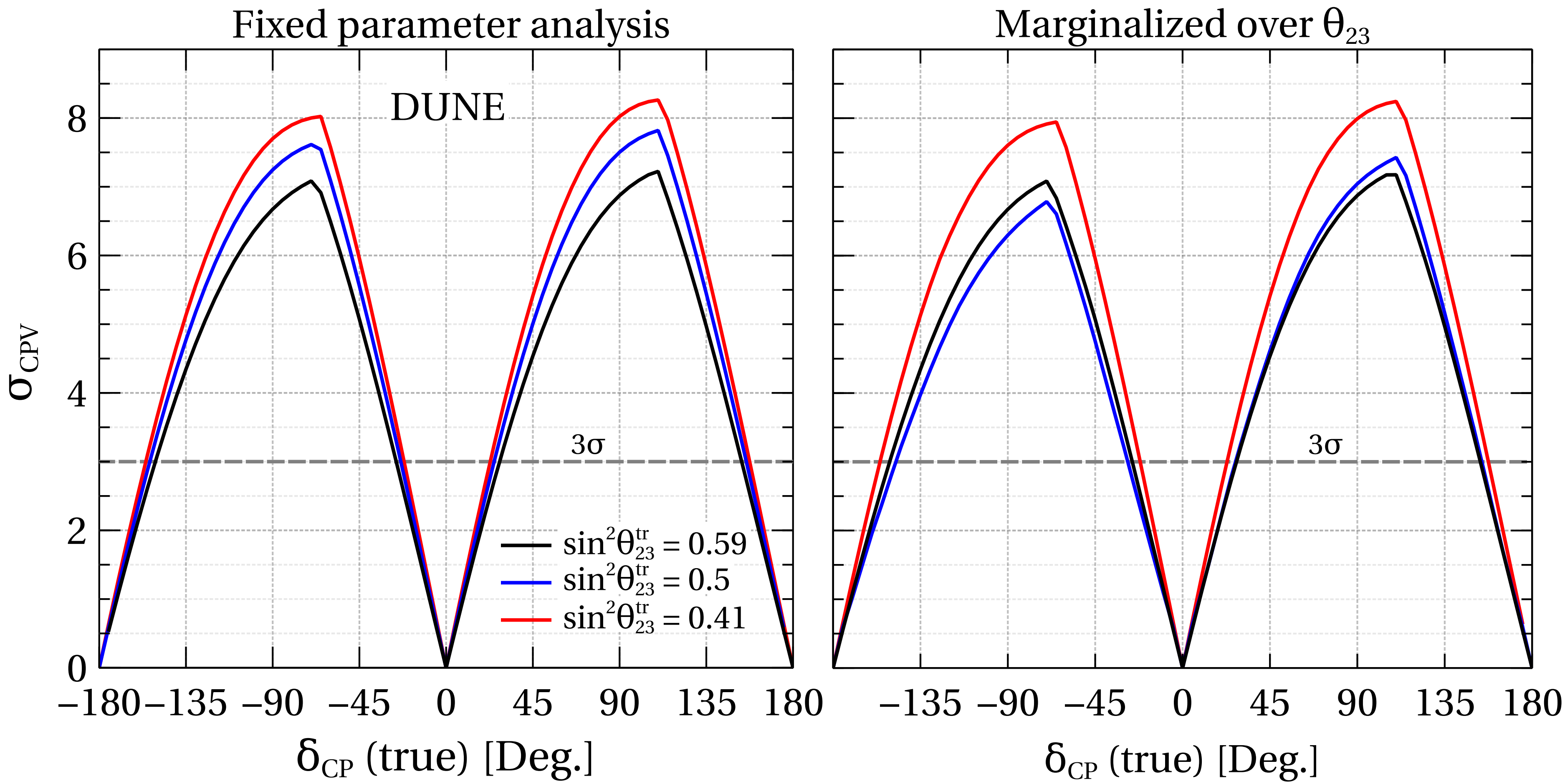
Characteristics	DUNE	JD/KD
Baseline (km)	1285	295 (1100)
ρ_{avg} (g/cm^3)	2.848	2.7 (2.8)
Beam Type	wide-band, on-axis	narrow-band, 2.5° off-axis
Beam Power	1.2 MW	1.3 MW
Proton Energy	120 GeV	30 GeV
P.O.T./year	1.1×10^{21}	2.7×10^{22}
Flux peaks at (GeV)	2.5	0.6
1st (2nd) oscillation maxima for appearance channel (GeV)	2.6 (0.87)	0.6 (0.2) / 1.8 (0.6)
Detector mass (kt)	40, LArTPC	187 each, water Cherenkov
Runtime ($\nu + \bar{\nu}$) yrs	5 + 5	2.5 + 7.5
Exposure (kt·MW·yrs)	480	2431
Signal Norm. Error (App.)	2%	5% **(2.7%)**
Signal Norm. Error (Disapp.)	5%	3.5%

DUNE Collaboration: arXiv:2103.04797 [hep-ex]

Hyper-Kamiokande Collaboration: arXiv:1611.06118 [hep-ex]

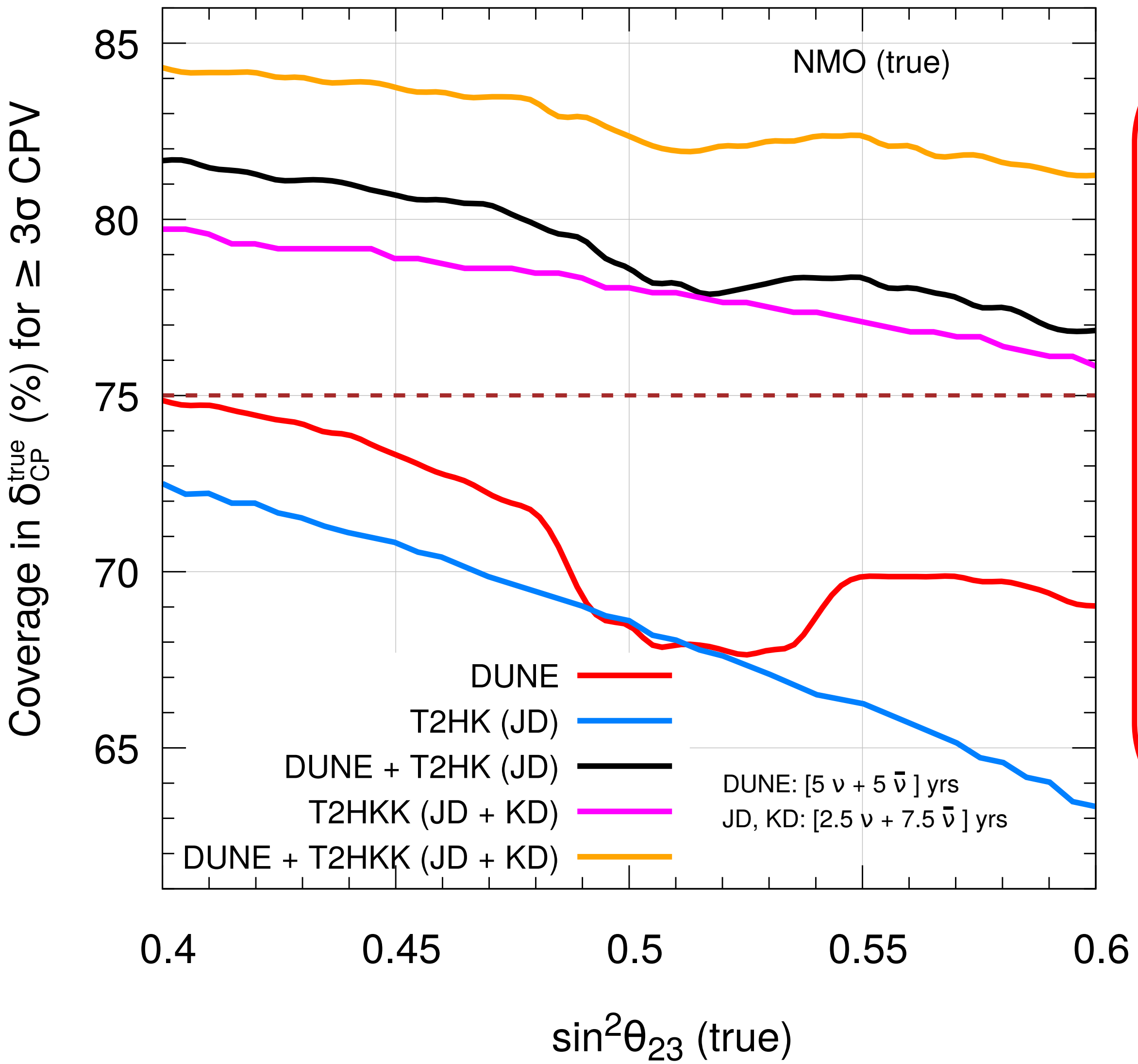
Due to upgraded ND280 & a new Intermediate Water Cherenkov Detector (IWCD) ~ at 1 km

CP Violation in DUNE for three different choices of θ_{23}



CP violation sensitivity deteriorates around maximal mixing choices of true θ_{23} while minimizing over test θ_{23} in the fit. Why?

CP Coverage for Leptonic CP Violation at ≥ 3σ as a function of θ_{23}



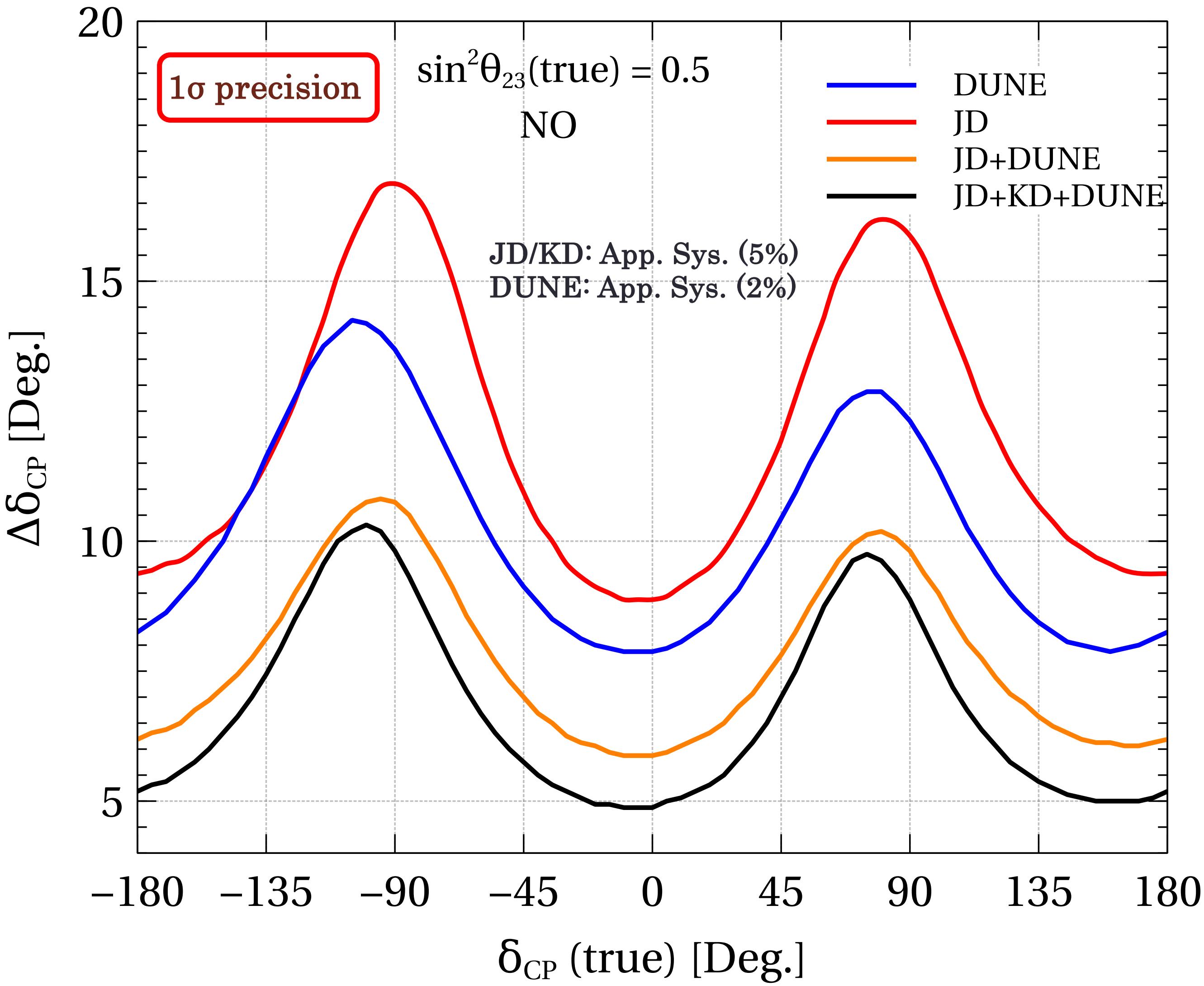
CP asymmetry decreases with increasing θ_{23} → CP coverage gets reduced as we increase θ_{23}

Around maximal mixing choices of θ_{23} → sensitivity gets deteriorated in DUNE

Combination of DUNE & T2HK is must to achieve leptonic CP violation at ≥ 3σ for at least 75% choices of δ_{CP} irrespective of θ_{23}

S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, arXiv:2211.10620 [hep-ph]

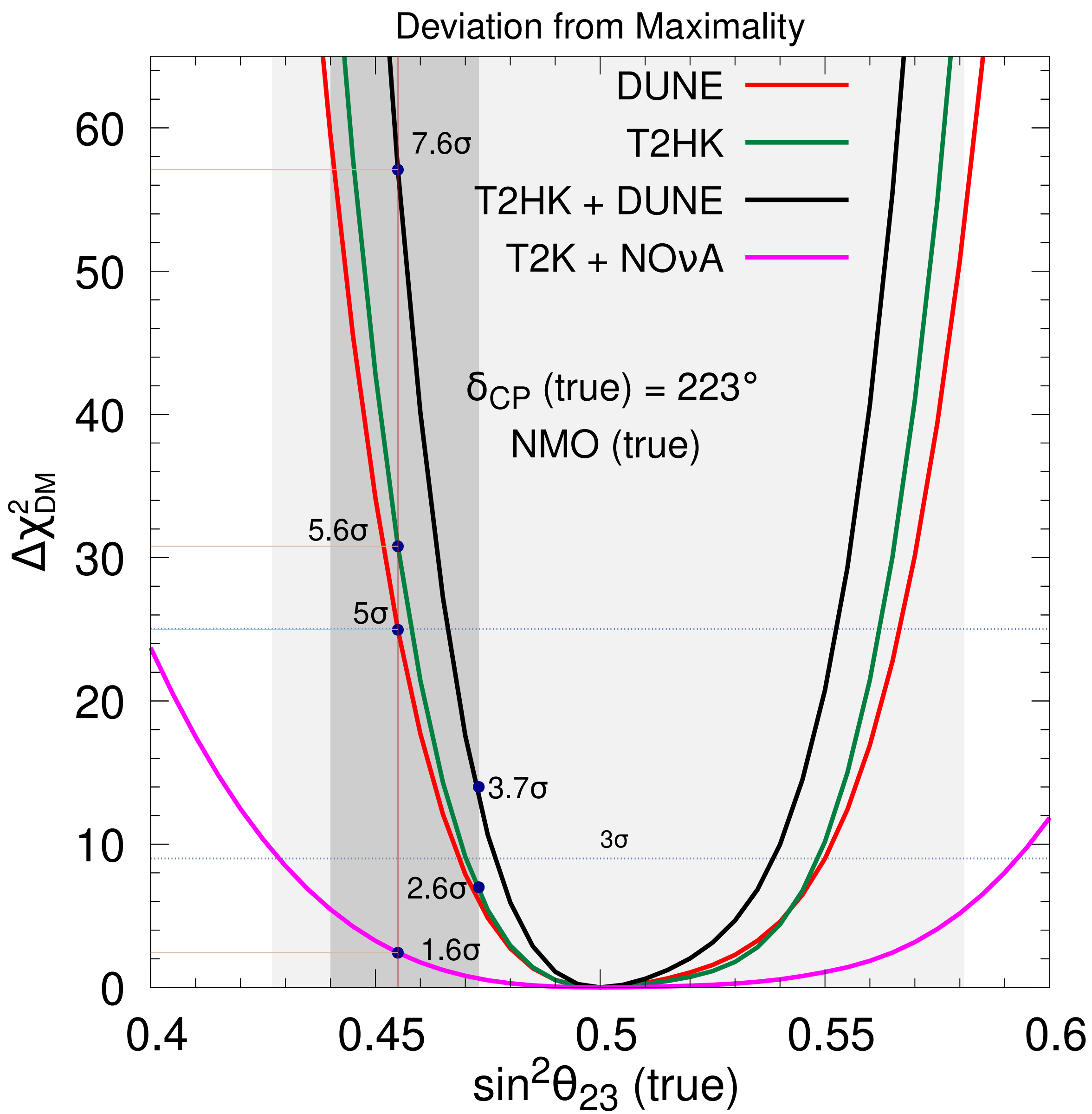
High-Precision Measurement of Dirac CP Phase



DUNE + T2HK (JD) can measure any value of δ_{CP} with a 1σ precision $\lesssim 10^\circ$

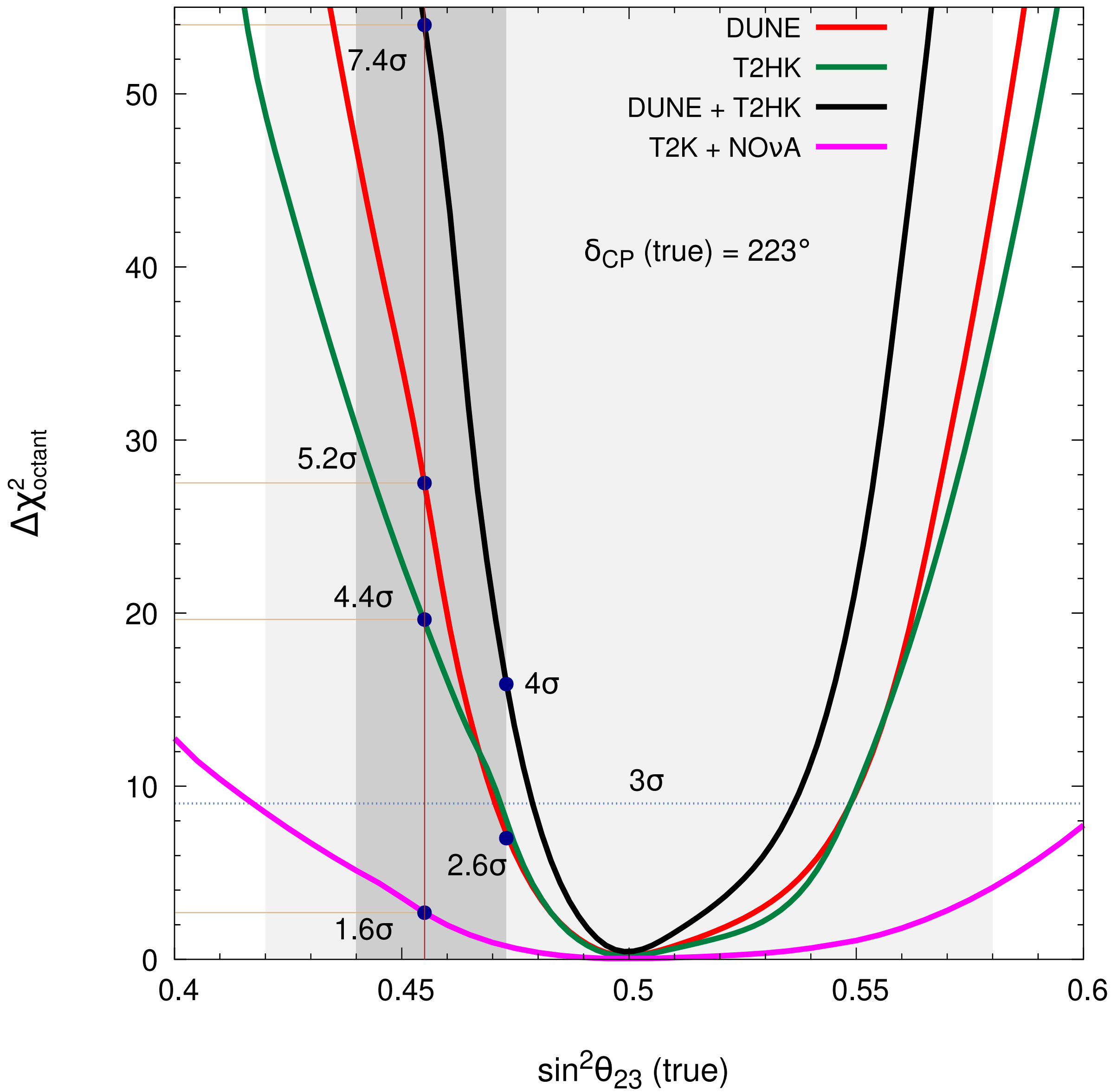
S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, in preparation

Deviation from Maximal θ_{23}



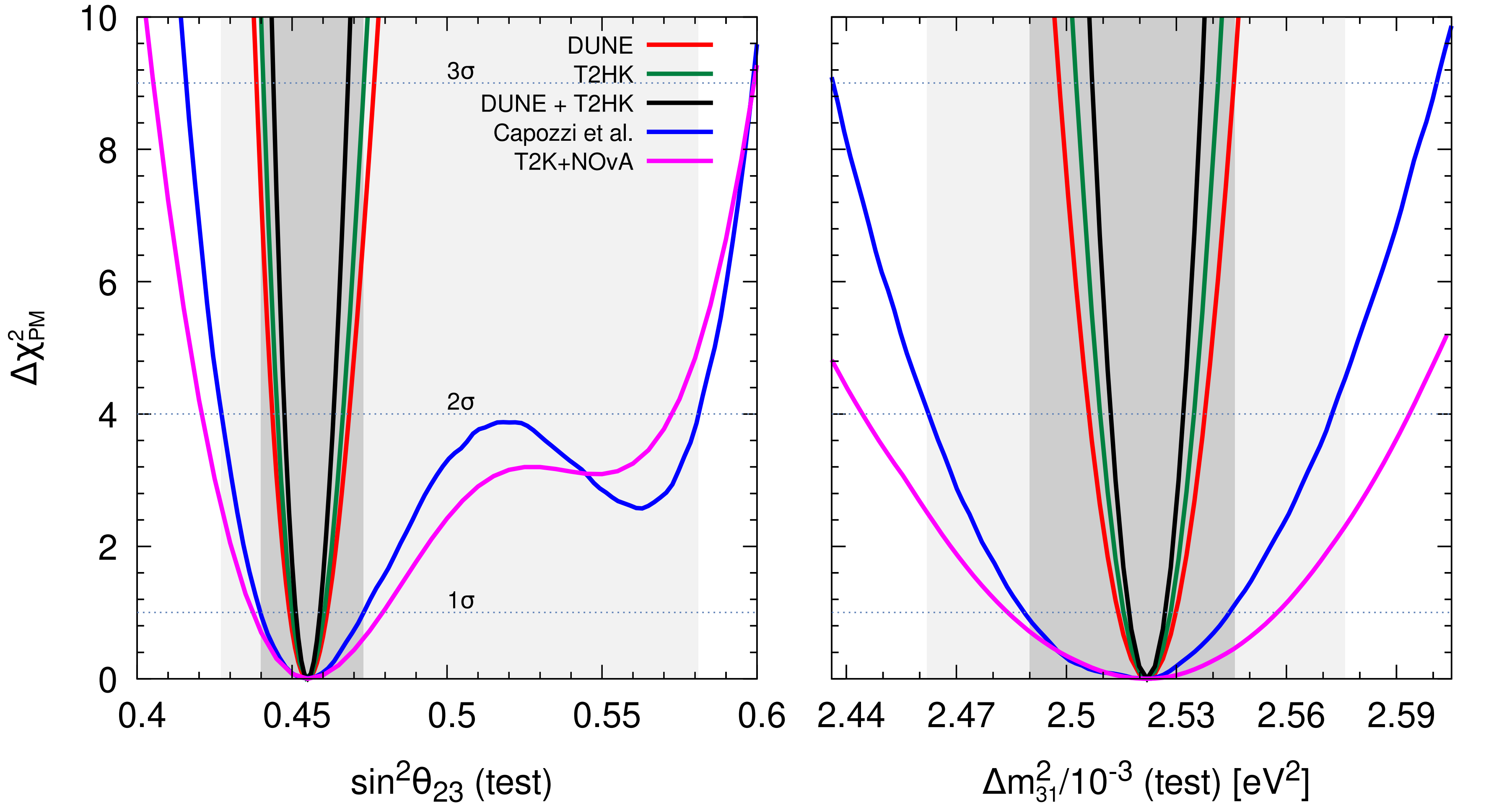
Agarwalla, Kundu, and Singh, in preparation

Discovery of θ_{23} Octant



Agarwalla, Kundu, and Singh, in preparation

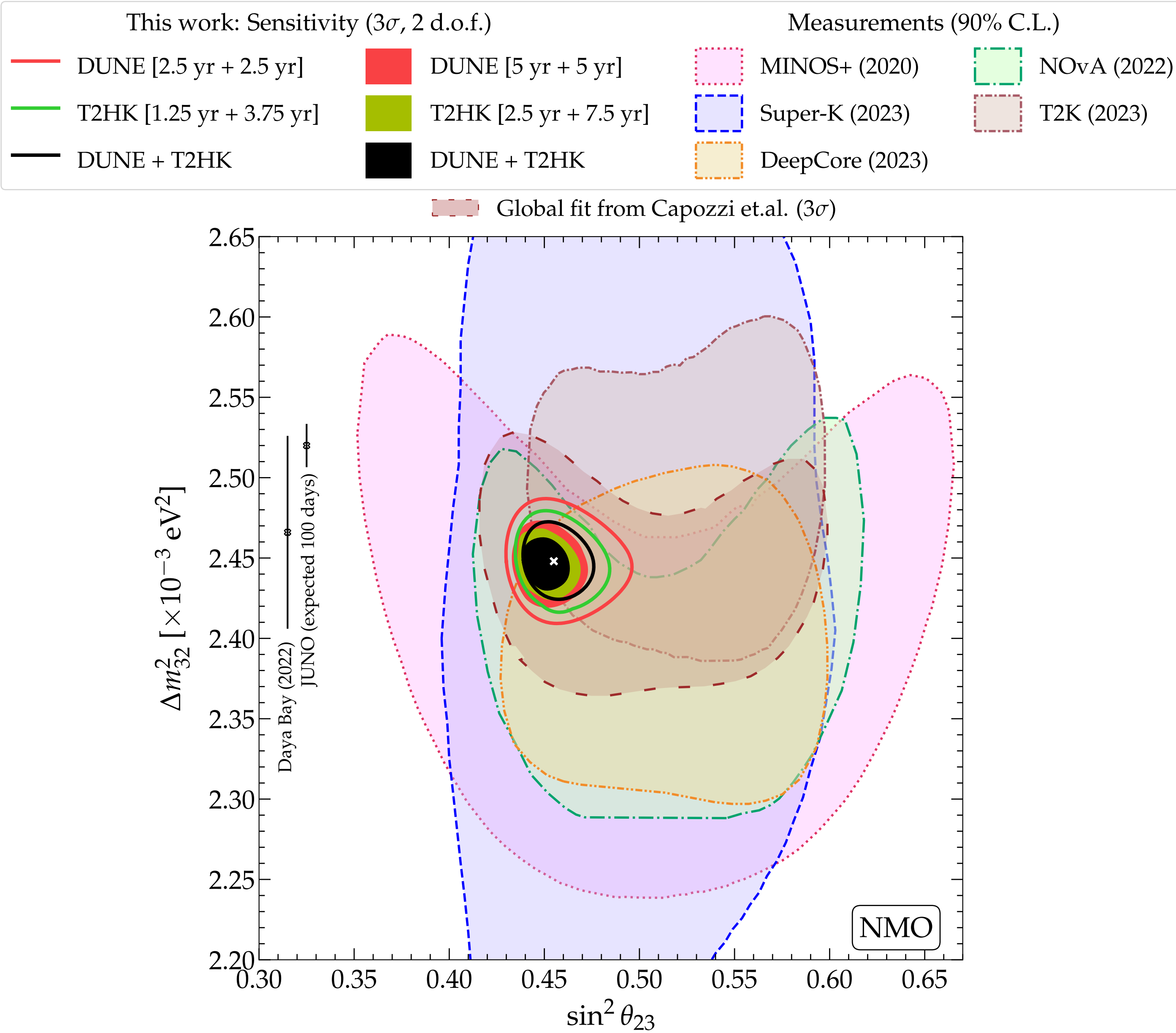
Precision Measurement of Atmospheric Oscillation Parameters



Parameter	Relative 1σ precision (%)					
	T2HK	DUNE	T2HK+DUNE	T2K+NOνA	Capozzi *et al.*	JUNO
$\sin^2\theta_{23}$	1.18	1.40	0.88	7.10	6.72	—
Δm^2_{31}	0.25	0.31	0.20	0.99	1.09	0.2

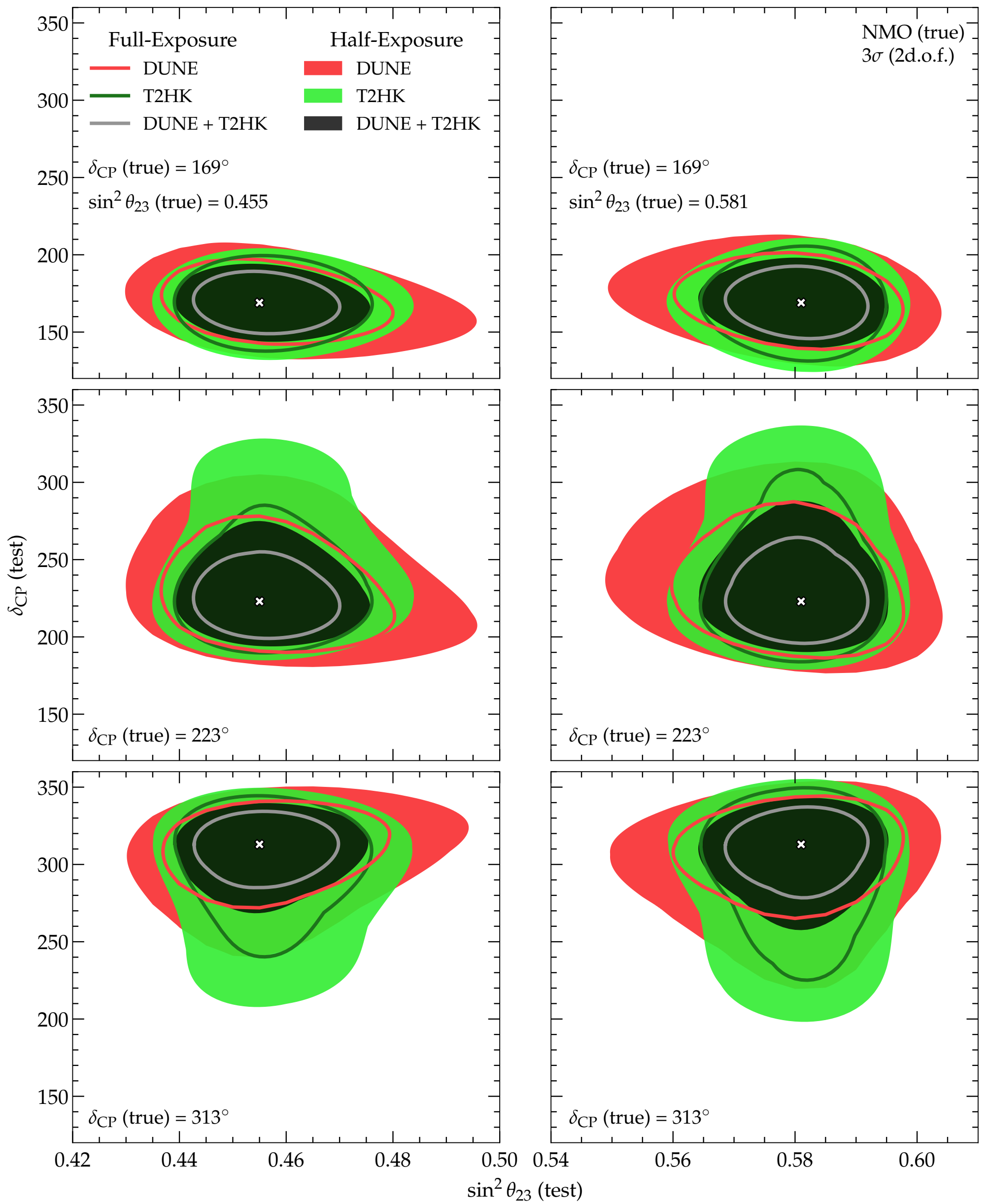
Agarwalla, Kundu, and Singh, in preparation

Precision Measurement of Atmospheric Oscillation Parameters



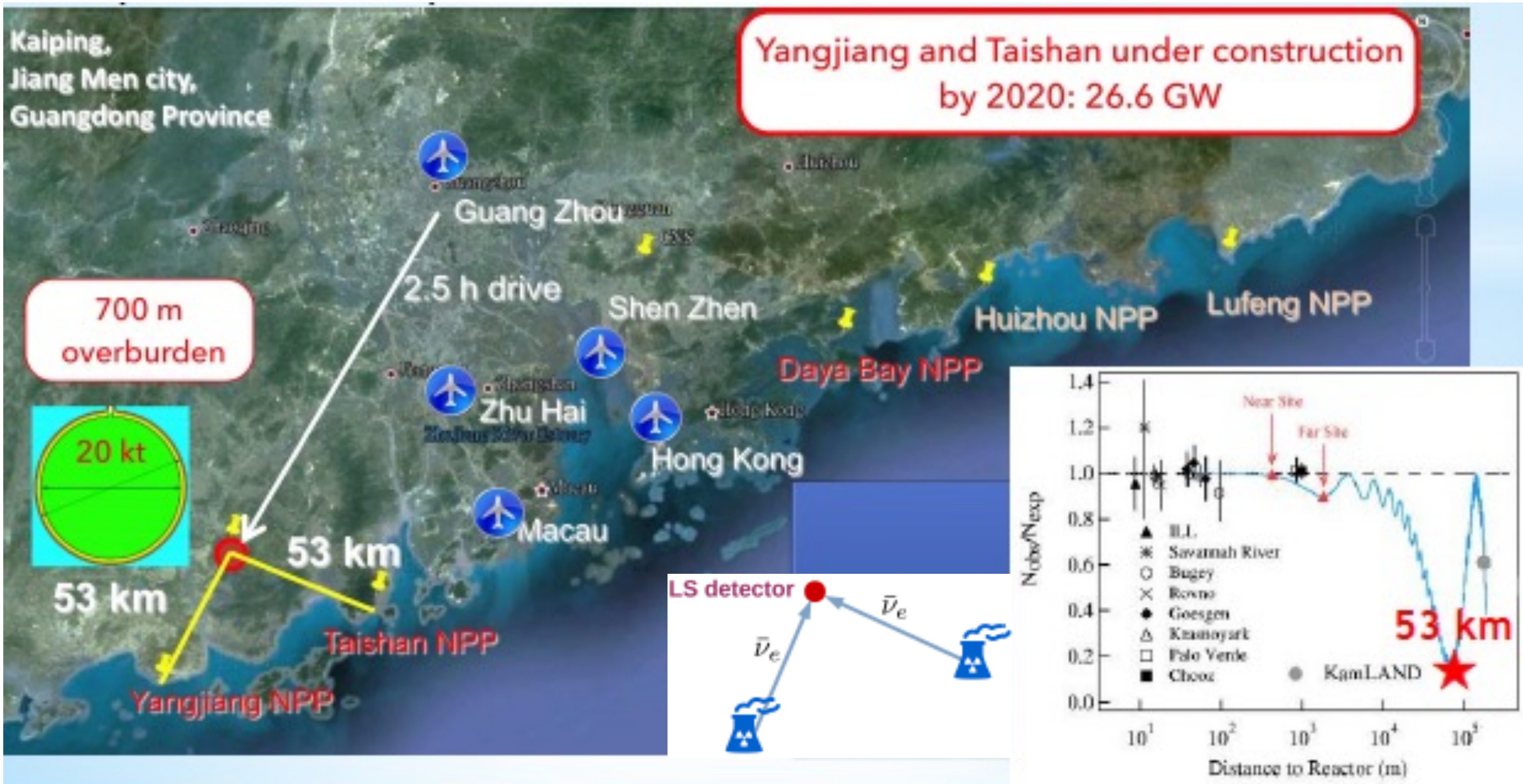
Agarwalla, Kundu, and Singh, in preparation

Allowed Regions in Plane ($\sin^2\theta_{23} - \delta_{CP}$) Plane



Agarwalla, Kundu, and Singh, in preparation

The Jiangmen Underground Neutrino Observatory (JUNO)



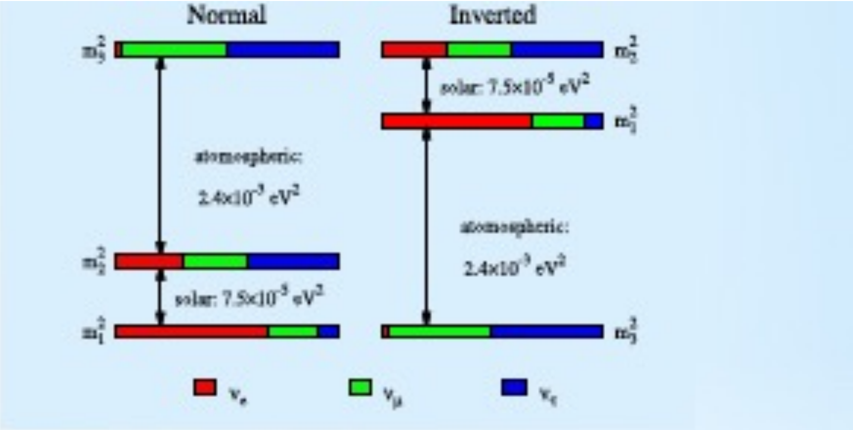
- 20 kt liquid scintillator detector with an unprecedented 3% energy resolution at 1 MeV
- Neutrino mass ordering measurement & improved precision on oscillation parameters

Interference effects in JUNO

The electron antineutrino survival probability in vacuum :

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

$$\Delta_{ij} = 1.27\Delta m^2_{ij}L/E$$



Depending on the NMH, the oscillation frequency differs :

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21}\\
\text{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \qquad \omega P_{31} > \omega P_{32}\\
\text{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \qquad \omega P_{31} < \omega P_{32}
\end{aligned}
$$

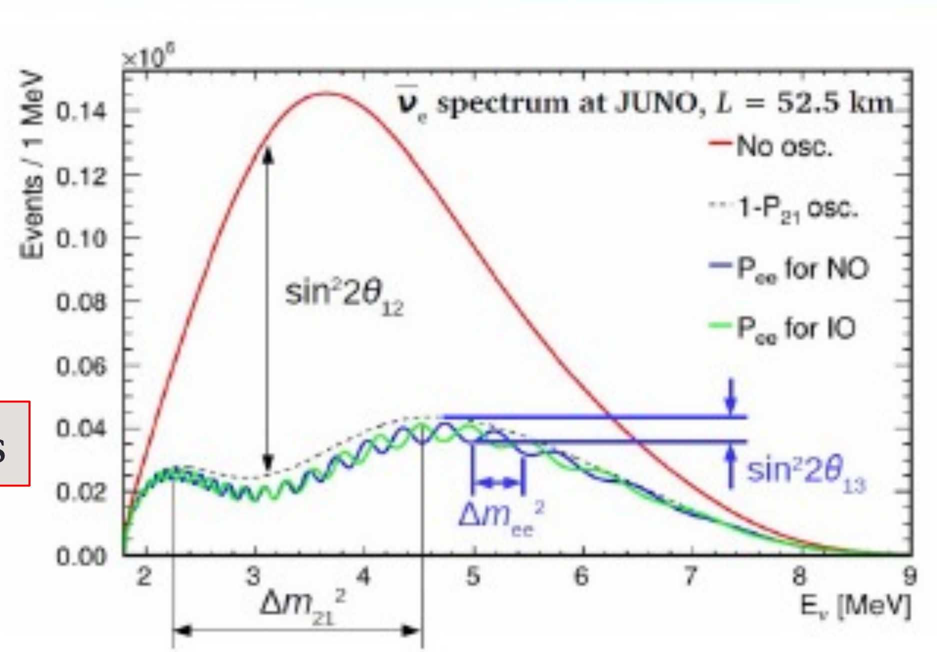
The L/E spectrum contains the NMH information

3σ mass hierarchy in 6 years

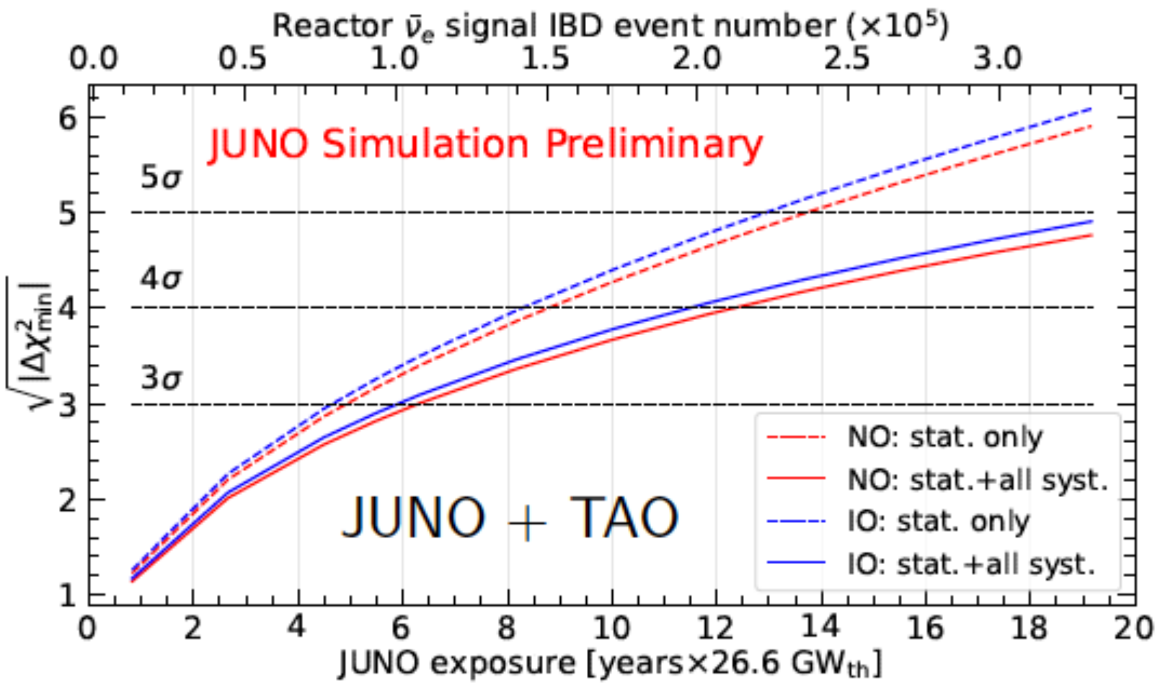
Key issues :

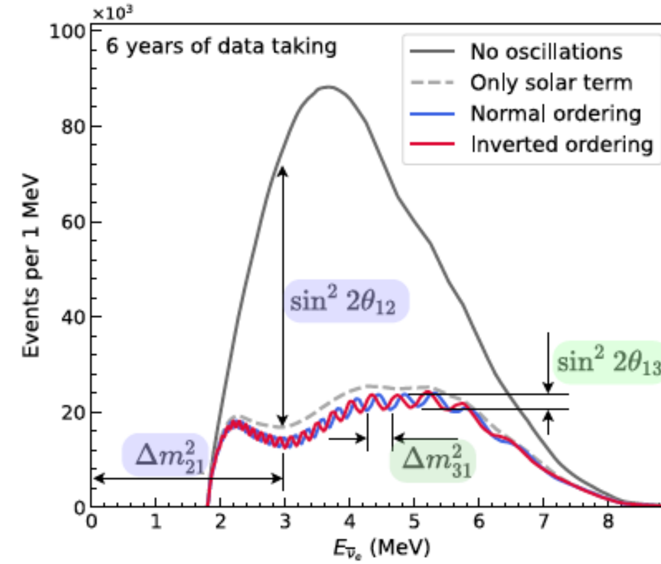
- energy resolution and energy scale
- Large statistics

JUNO antineutrino energy spectrum:



Neutrino Mass Ordering with JUNO

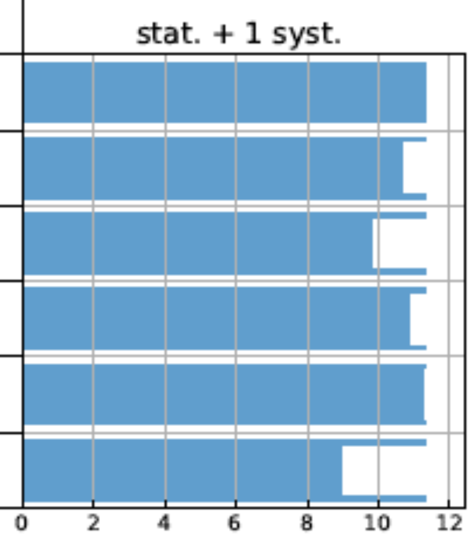




Observe two oscillation modes: slow (solar frequency) and fast (atmospheric frequency)

Neutrino mass ordering (NMO) sensitivity: $\Delta\chi^2 = |\chi^2_{\min}(\mathrm{NO}) - \chi^2_{\min}(\mathrm{IO})|$

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



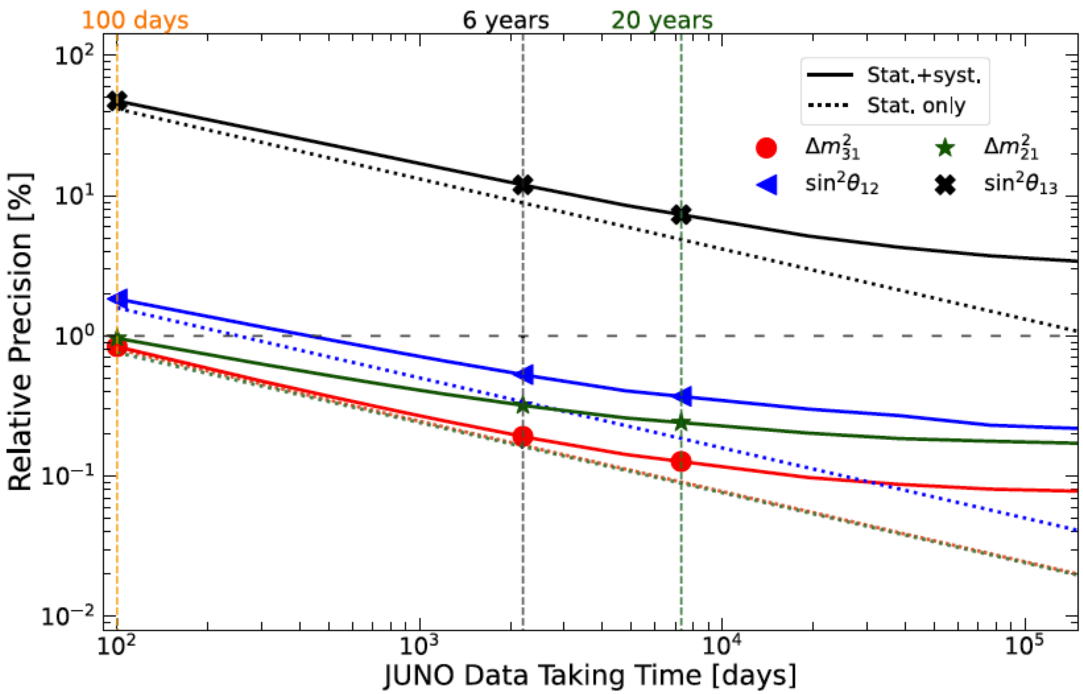
JUNO Simulation Preliminary

Median NMO sensitivity:
3**σ** in 6 years

Sensitivity does not depend on Earth matter effect, θ_{23}, and δ_{CP}

High-Precision Measurement of Oscillation Parameters with JUNO

Run time	Parameter precision (%)			
	$\lvert\Delta m^2_{31}\rvert$	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
100 days	0.8	1.0	1.9	47.9
6 years	0.2	0.3	0.5	12.1
20 years	0.1	0.2	0.3	7.3
PDG 2020	1.3	2.4	4.2	3.2

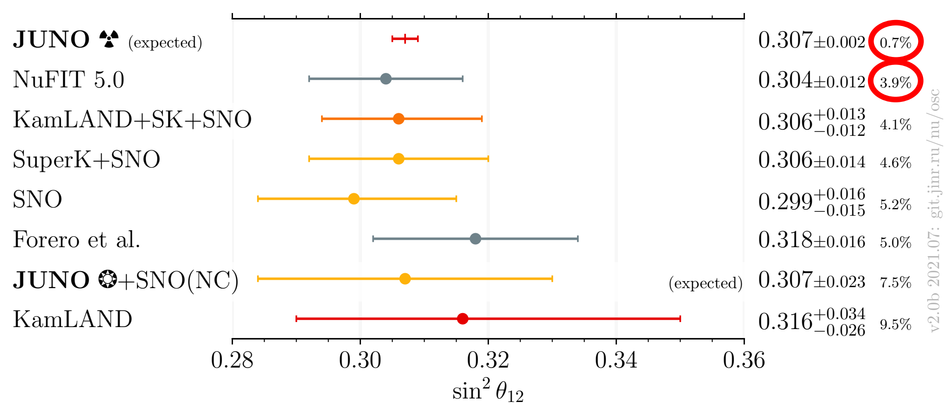


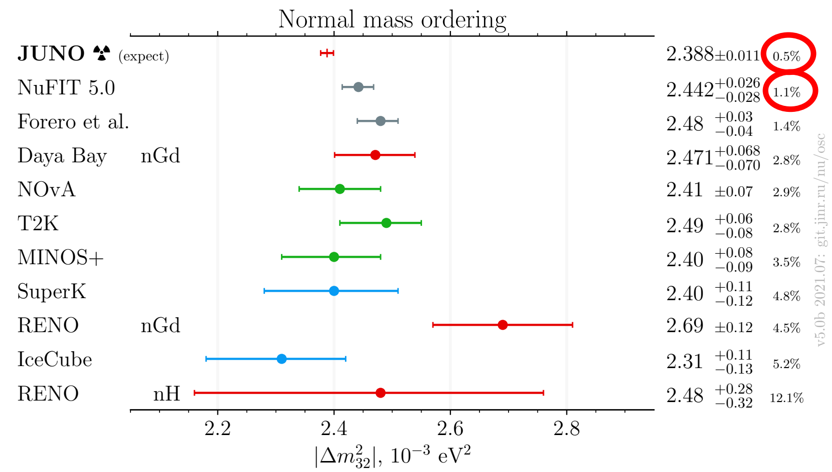
World-leading precision in 100 days!

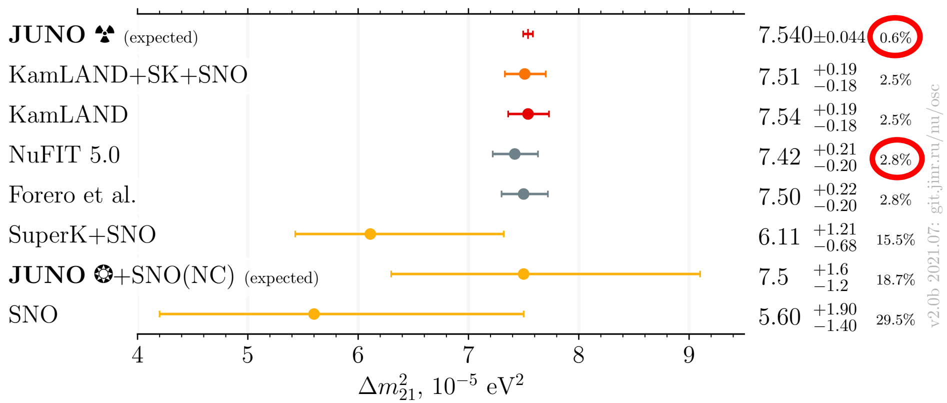
Sub-precent precision in 6 years on solar oscillation parameters & atmospheric mass-squared splitting

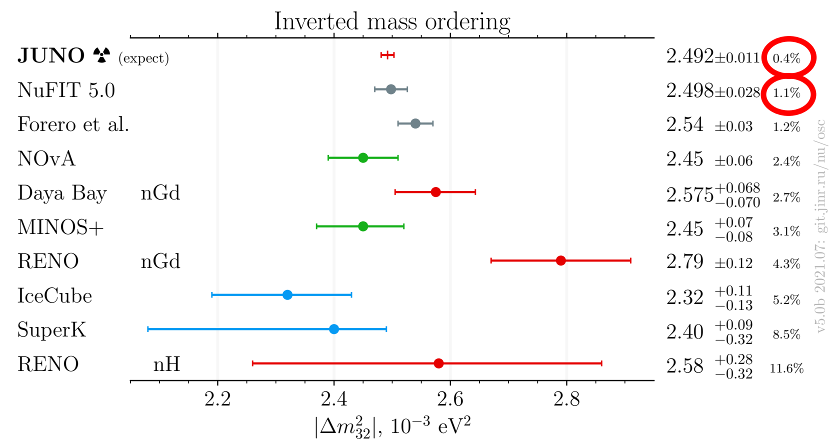
JUNO Collaboration: Chinese Phys. C 46 123001 (2022)

Very Bright Future Ahead: Triumph of JUNO





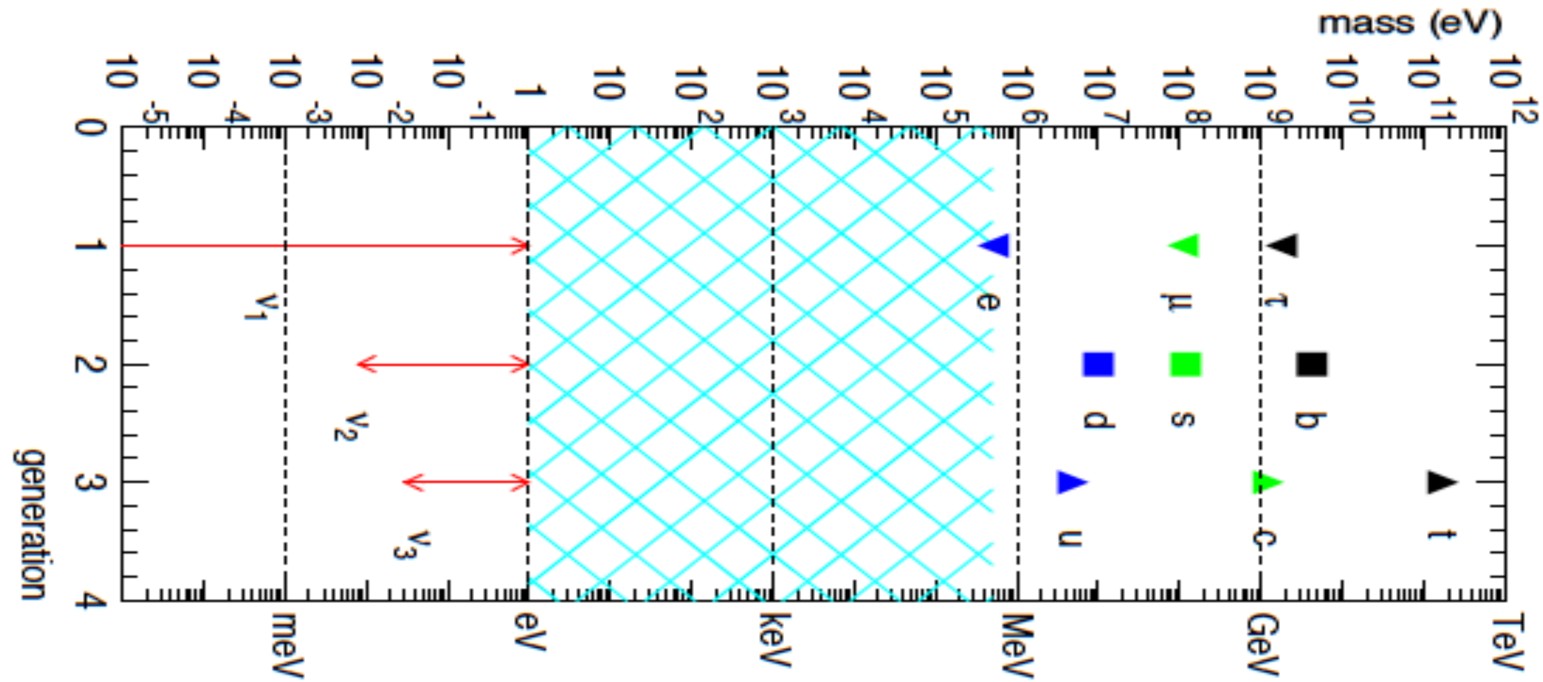




Maxim Gonchar (JUNO Collaboration) EPS-HEP 2021, July 26

JUNO will improve significantly our knowledge on neutrino oscillation parameters. These developments are crucial to probe sub-leading three-flavor effects in next-generation long-baseline experiments for the discovery of NMO, leptonic CPV, and Octant of 2-3 mixing angle

The Two Fundamental Questions



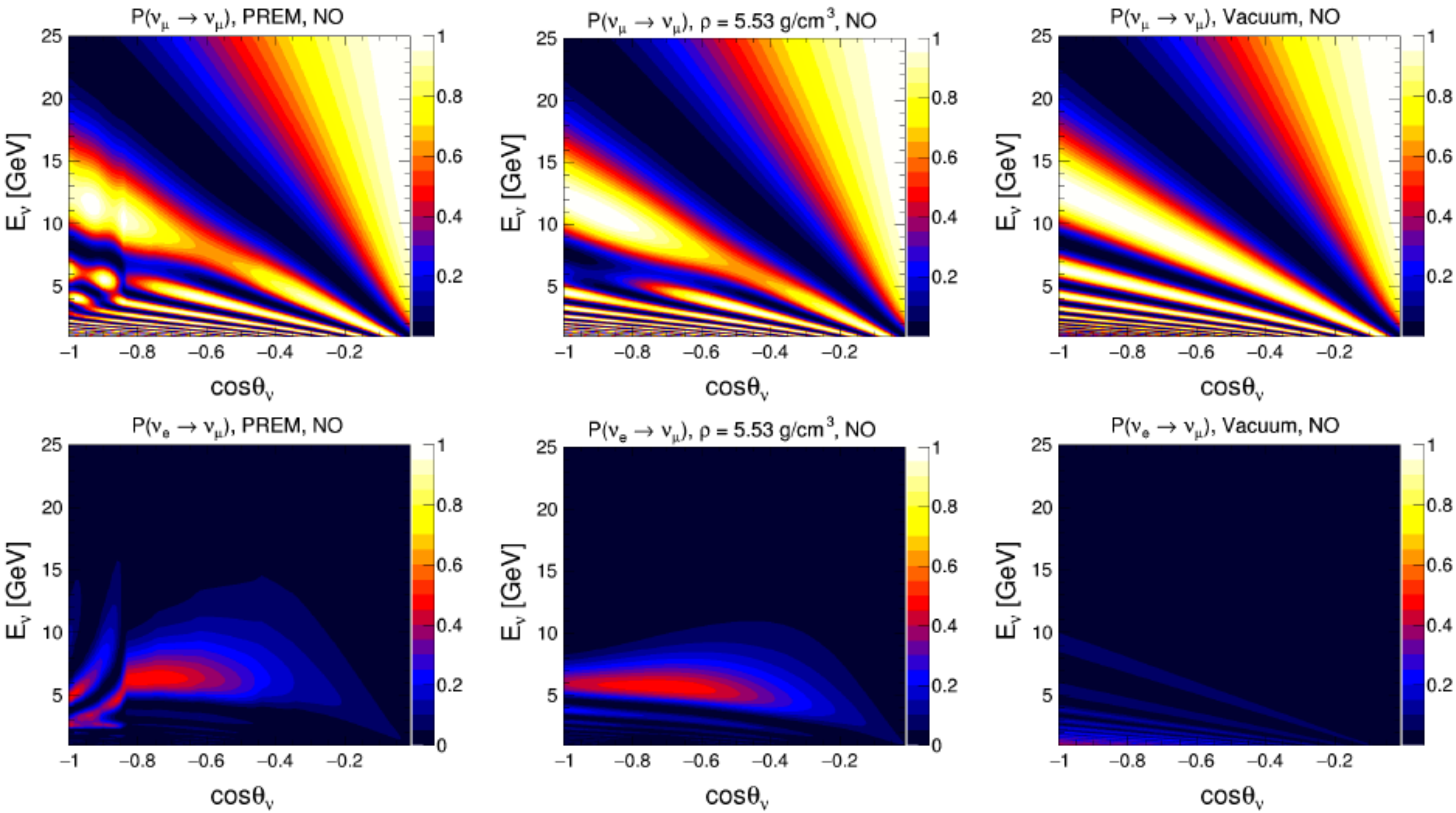
Why are neutrinos so light? The origin of Neutrino Mass!

	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45°$	$8.5°$	$34°$	?
Quarks	$2.4°$	$0.20°$	$13°$	$69°$

Why are lepton mixings so different from quark mixings?

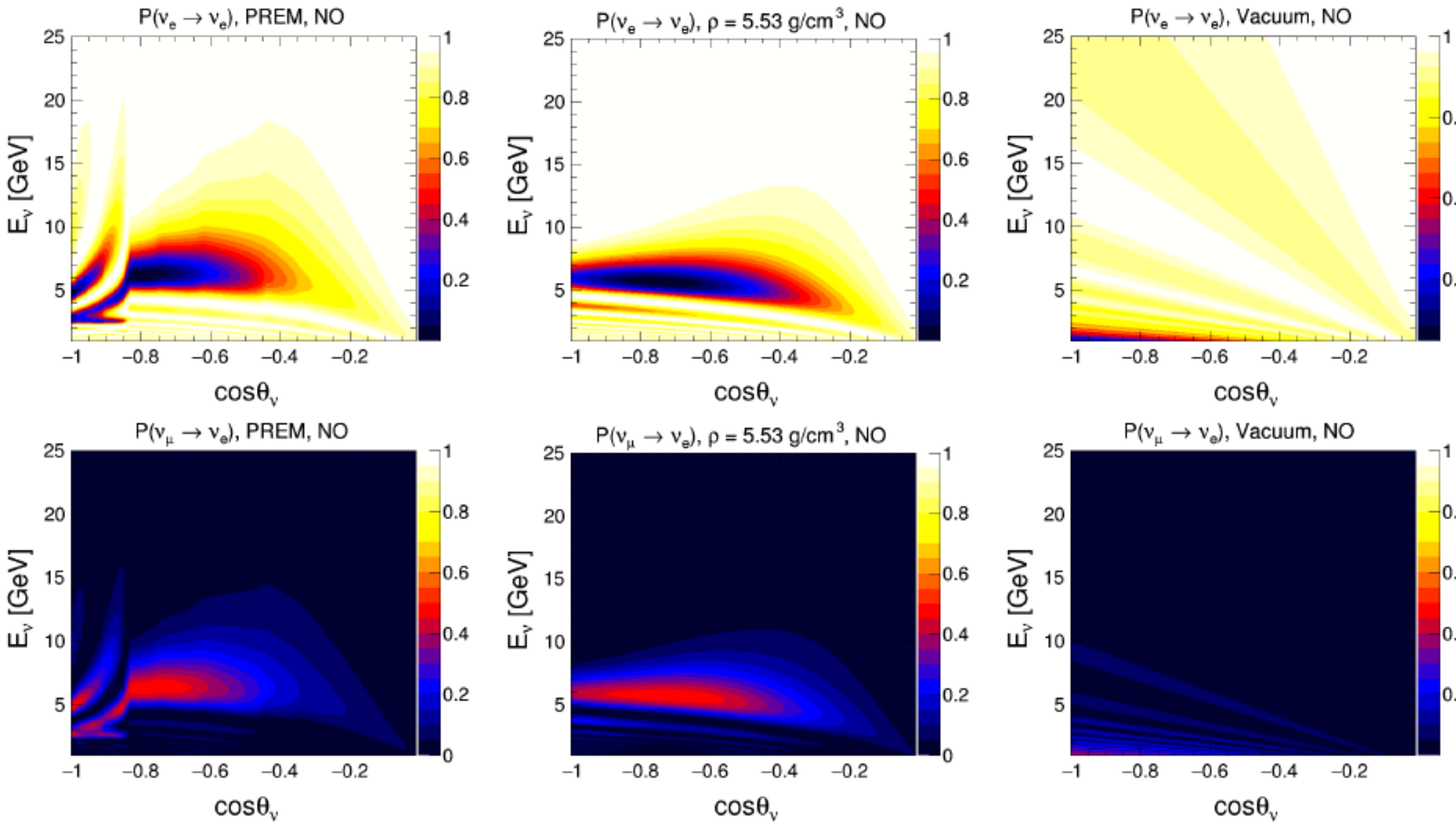
The Flavor Puzzle!

Neutrino Oscillograms for a Core-Passing Track-Like Events



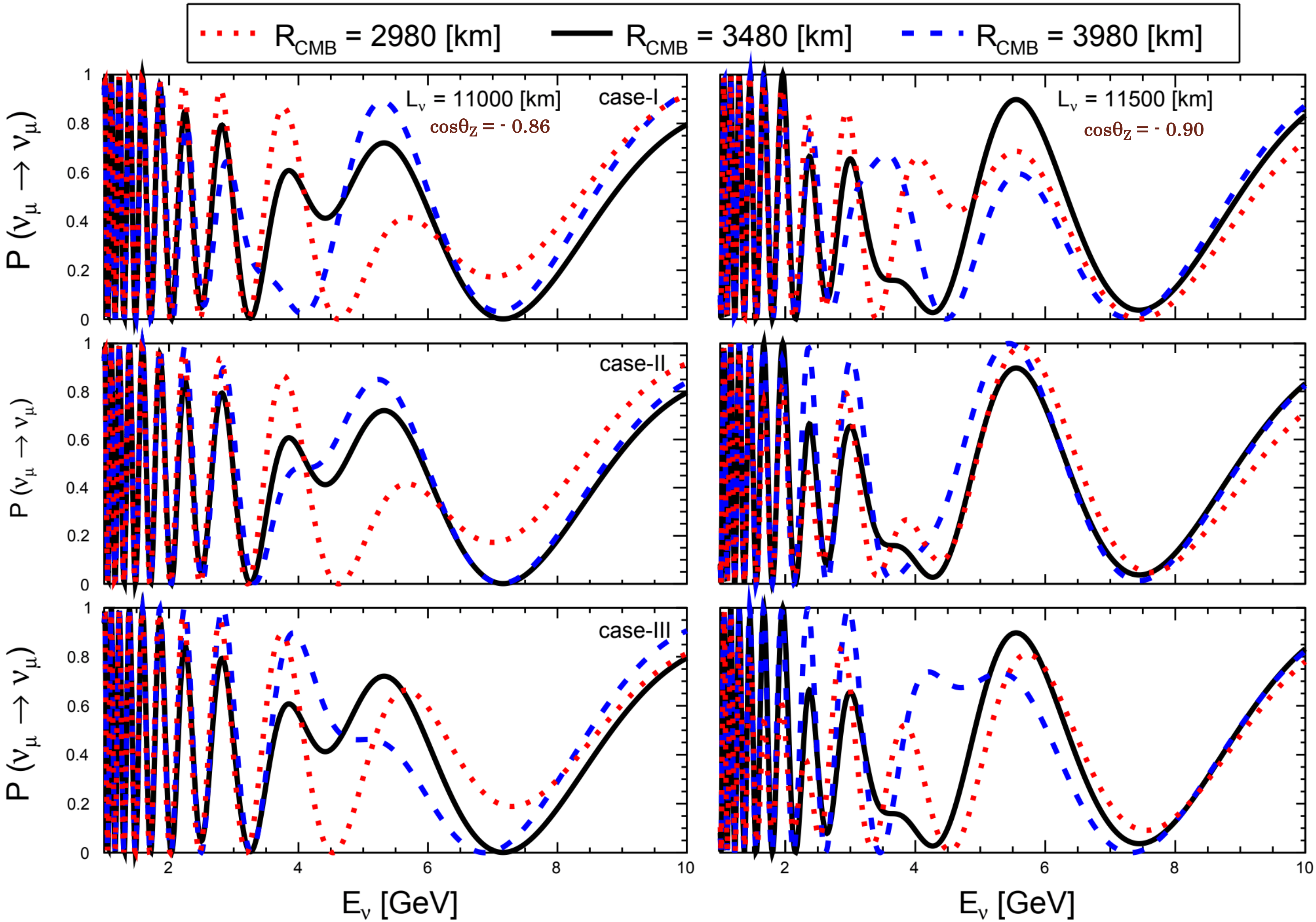
We get similar oscillograms for antineutrinos with inverted mass ordering

Neutrino Oscillograms for a Core-Passing Cascade-Like Events

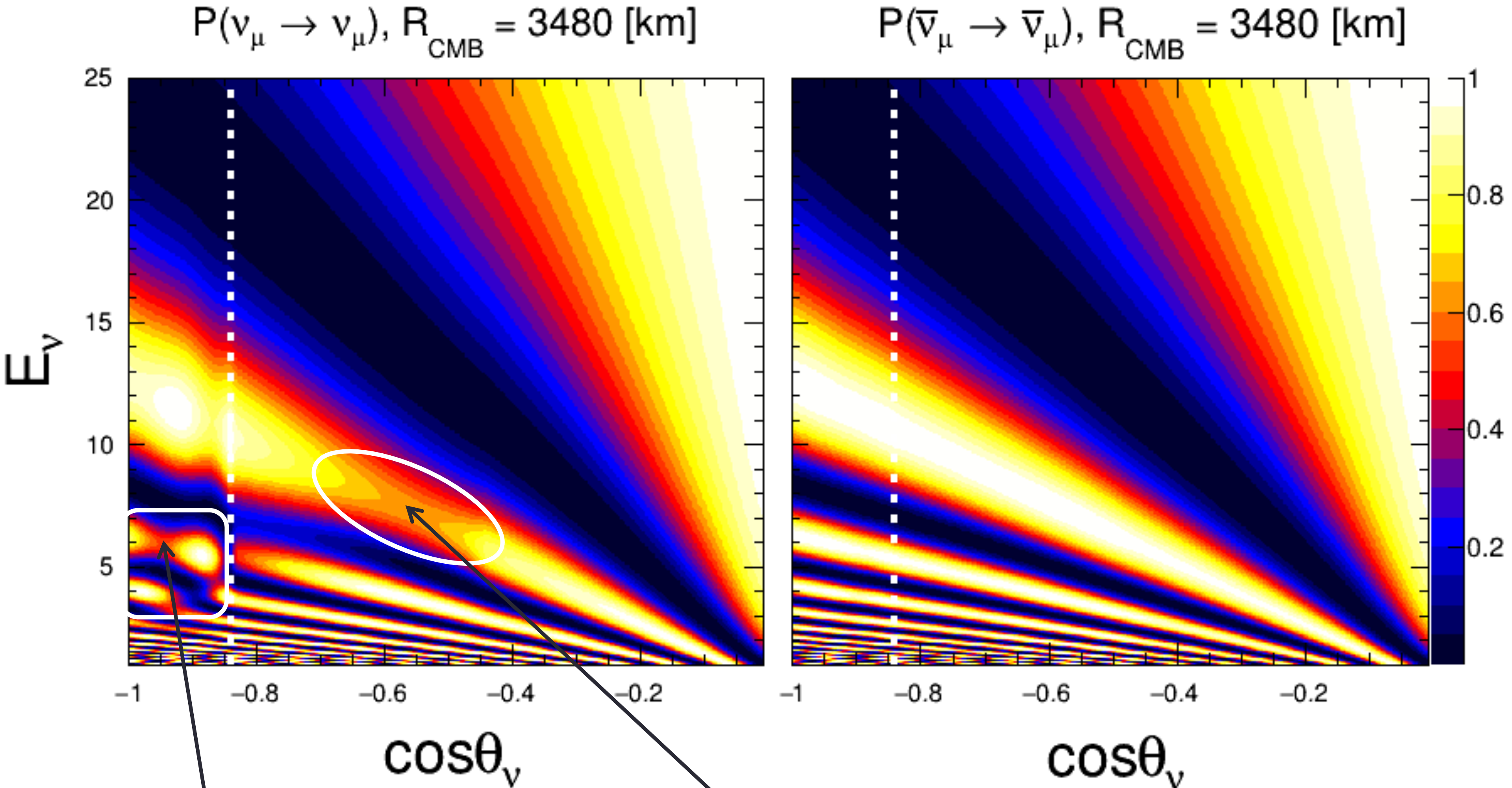


We get similar oscillograms for antineutrinos with inverted mass ordering

Muon Neutrino Survival Probabilities with Varying CMB



Muon Neutrino Survival Oscillograms with Standard CMB



Non-Adiabatic Neutrino Oscillation Length Resonance (NOLR) or Parametric Resonance (PR) Region

$\cos\theta_\nu < -0.8$
$3 \text{ GeV} < E_\nu < 6 \text{ GeV}$

Adiabatic MSW Resonance Region

$-0.8 < \cos\theta_\nu < -0.5$
$6 \text{ GeV} < E_\nu < 10 \text{ GeV}$

Neutrinos experience matter effect for NO

Antineutrinos experience matter effect for IO

The Role of the CP-Violating CKM Phase

- If the SM extensions do not violate *CP* (this would be rather unnatural), **could the CKM phase generate the observed baryogenesis ?**

- KM *CP*-violating asymmetries, d_{CP}, must be proportional to the Jarlskog invariant *J* :

$$d_{CP} = J \cdot \tilde{F}_U \cdot \tilde{F}_D$$

where: $J = \mathrm{Im}\left(V_{ud}V_{cs}V_{us}^{*}V_{cd}^{*}\right) \simeq A^2\lambda^6\eta = (3.1 \pm 0.2)\times 10^{-5}$, and: $\tilde{F}_U = \left(m_t^2 - m_c^2\right)\cdot\left(m_t^2 - m_u^2\right)\cdot\left(m_c^2 - m_u^2\right)$

$$\tilde{F}_D = \left(m_b^2 - m_s^2\right)\cdot\left(m_b^2 - m_d^2\right)\cdot\left(m_s^2 - m_d^2\right)$$

- Since (some) non-zero quark masses are required, *CP* symmetry can only be broken where the Higgs field has already condensed to $v_T \neq 0$ (i.e., electroweak symmetry is broken)

- To make d_{CP} dimensionless, we divide by dimensioned parameter $D = T_c$ at the EW scale ($T_c = T_{EW} \sim 100$ GeV), with $[D] = \mathrm{GeV}^{12}$

$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \approx 10^{-19} \ll \eta \approx O\left(10^{-10}\right)$$

→ KM *CP* violation seems to be *irrelevant* for baryogenesis !