Probing the Earth's Core using Atmospheric Neutrinos at INO

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Validating the Earth's Core using Atmospheric Neutrinos with ICAL at INO

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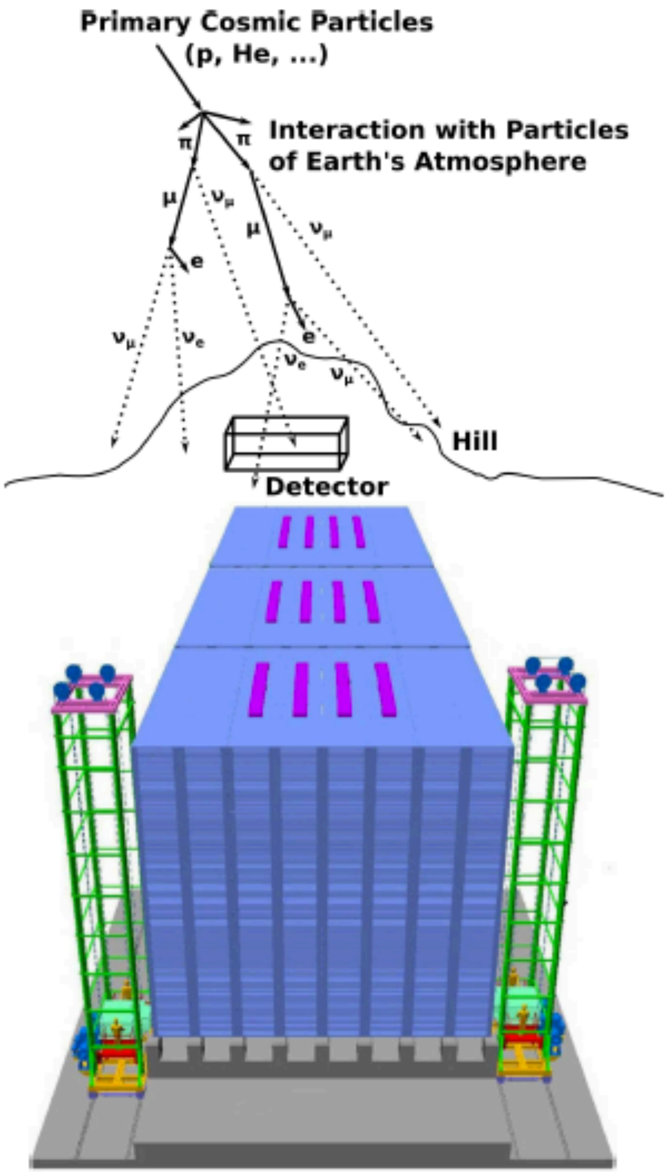
Magnetized Iron Calorimeter Detector (ICAL) at INO

- **ICAL@INO:** 50 kton magnetized iron calorimeter detector at the proposed India-based Neutrino Observatory (INO)
- **Location:** Bodi West Hills, Theni District, Tamil Nadu, India
- **Aim:** To determine mass ordering and precision measurement of atmospheric oscillation parameters.
- **Source:** Atmospheric neutrinos and antineutrinos in the multi-GeV range of energies over a wide range of baselines.
- **Uniqueness:** Charge identification capability helps to distinguish μ^- and μ^+ and hence, ν_μ and $\bar{\nu}_\mu$
- **Muon energy range:** $1 - 25$ GeV, **Muon energy resolution:** $\sim 10\%$
- **Baselines:** $15 - 12000$ km, **Muon zenith angle resolution:** $\sim 1^\circ$



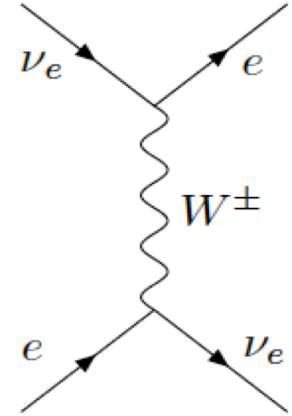
Pramana - J Phys (2017) 88 : 79, arXiv:1505.07380

Neutrino Oscillations in Matter: MSW Effect

Neutrino propagation through matter modify the oscillations significantly

Coherent forward elastic 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 (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to antineutrino mode

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

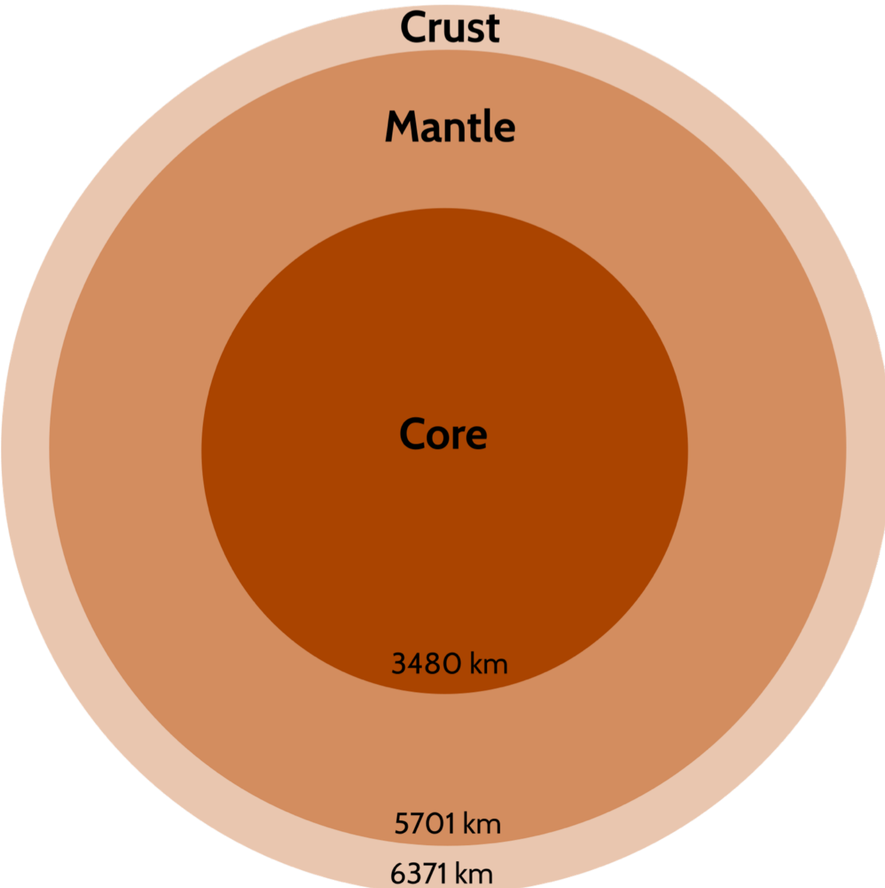
Matter term modifies oscillation probability differently depending on the sign of Δm^2

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

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

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

Internal Structure of Earth



Three-layered model of Earth

Crust: solid, rocks, brittle, lowest density

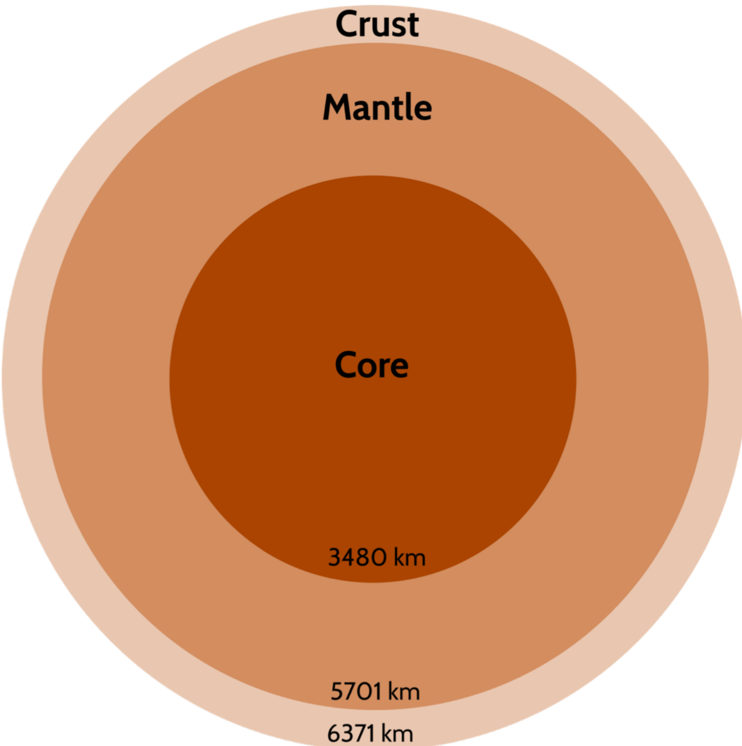
Mantle: hot, solid upper mantle, viscous plastic lower mantle

Core: solid inner core, liquid outer core, iron and nickel

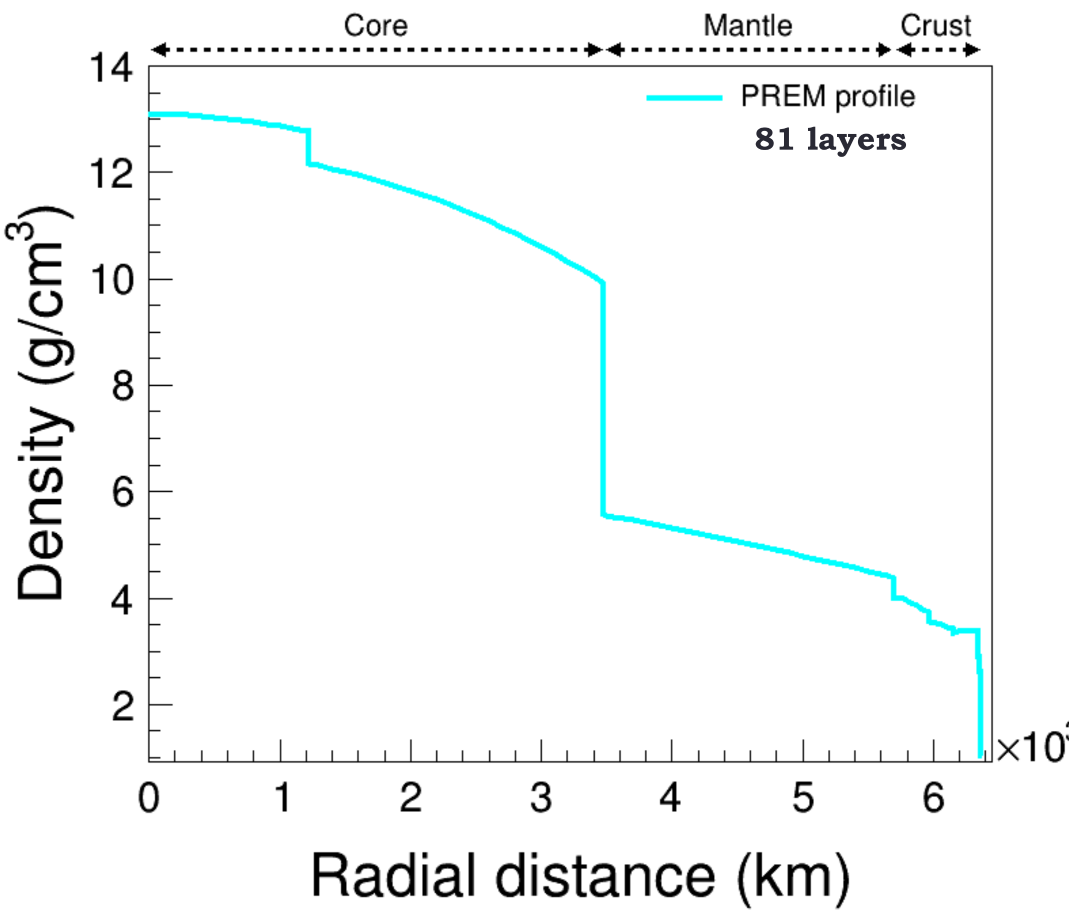
Region	R_{min} (km)	R_{max} (km)	Density (g/cm^3)
Core	0	3480	11.37
Mantle	3480	5701	5
Crust	5701	6371	3.3

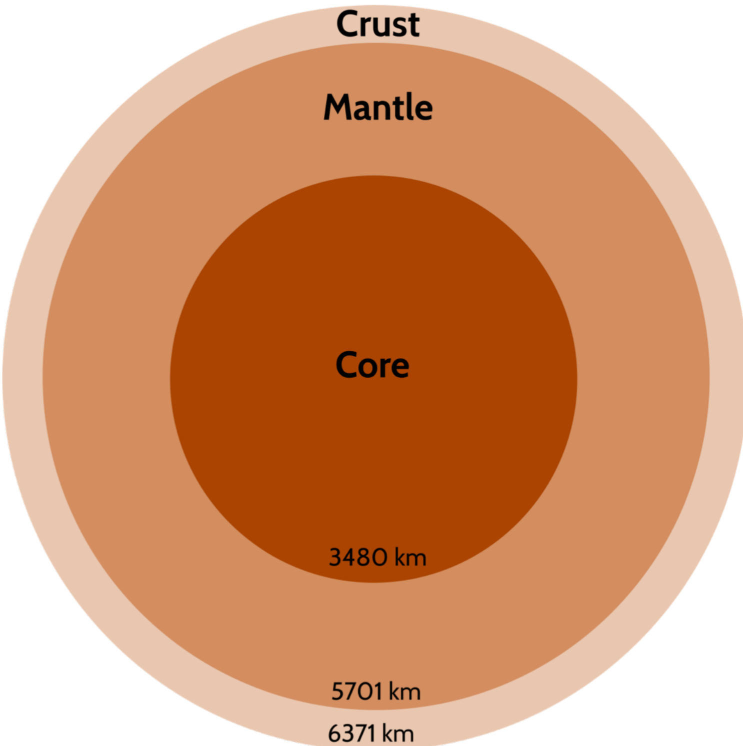
E. C. Robertson, The interior of the Earth, an elementary description, 1966.
D. E. Loper and T. Lay, The core-mantle boundary region, Journal of Geophysical Research: Solid Earth 100 (1995), no. B4 6397–6420.
D. Alfè, M. J. Gillan, and G. D. Price, Temperature and composition of the earth's core, Contemporary Physics 48 (2007), no. 2 63–80.

Internal Structure of Earth

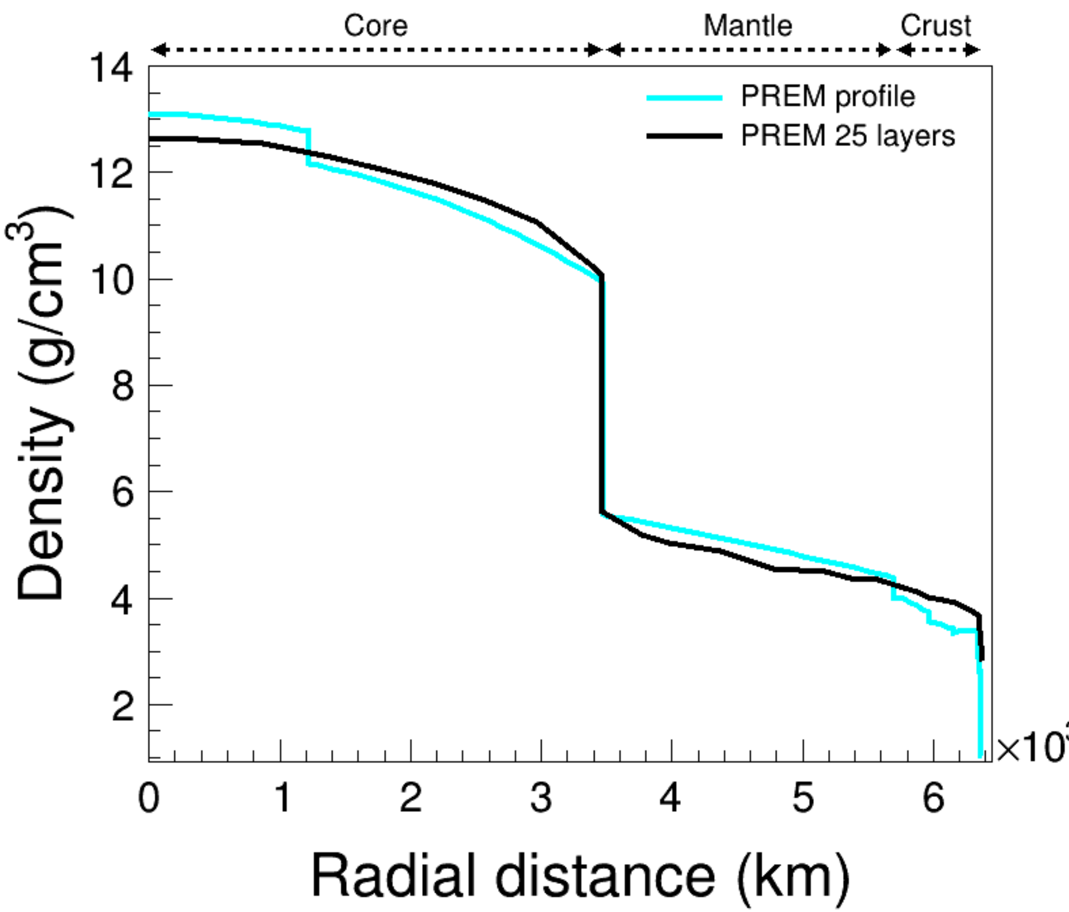


Three-layered model of Earth



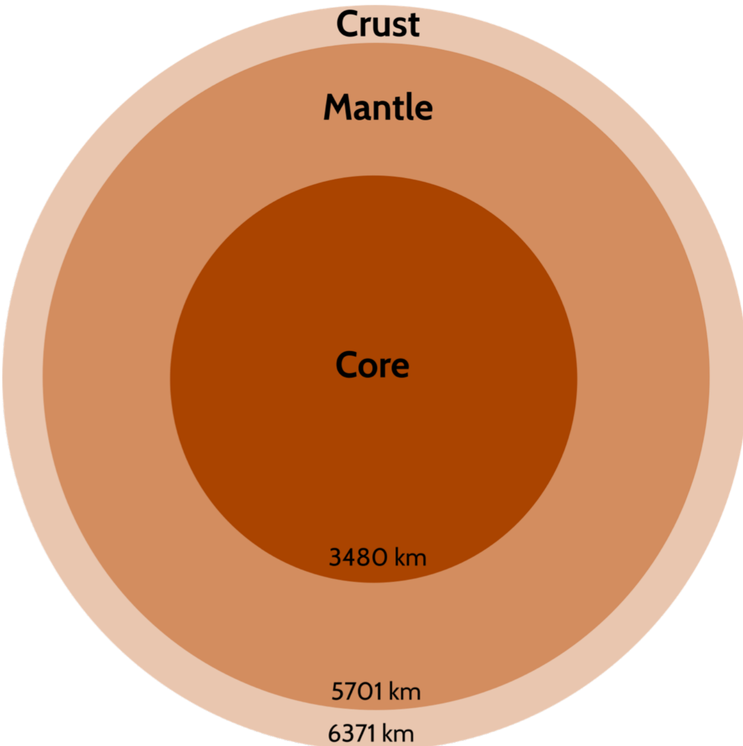


Three-layered model of Earth

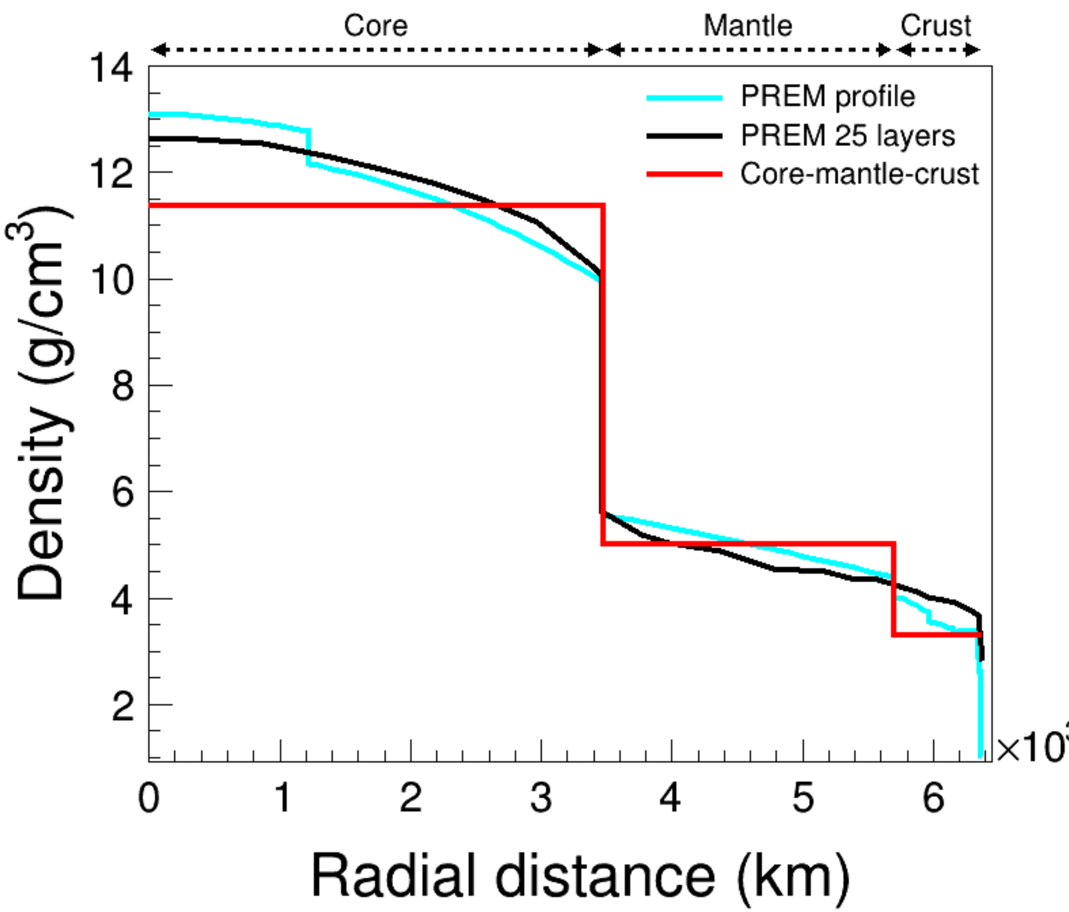


ICAL cannot distinguish between profiles having 81 and 25 layers

Internal Structure of Earth

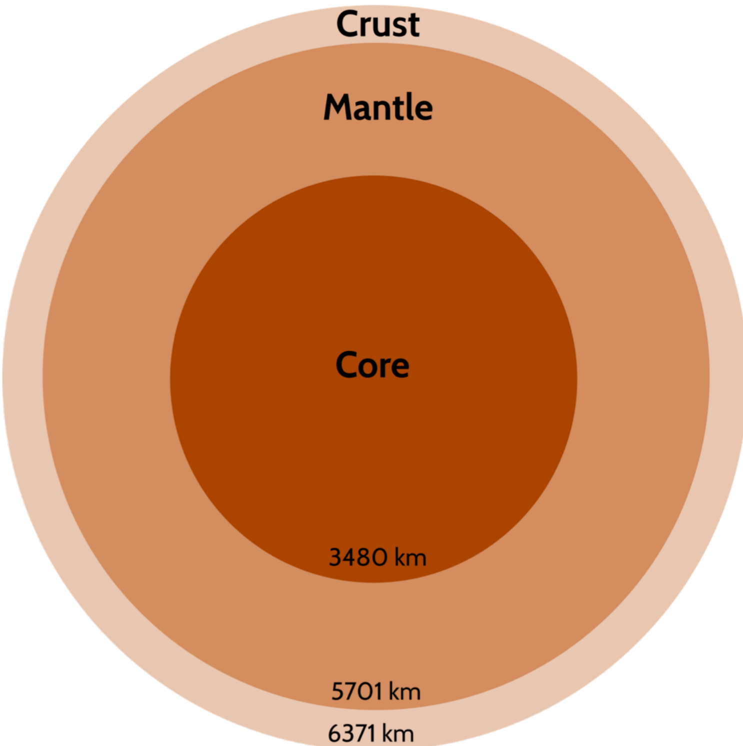


Three-layered model of Earth

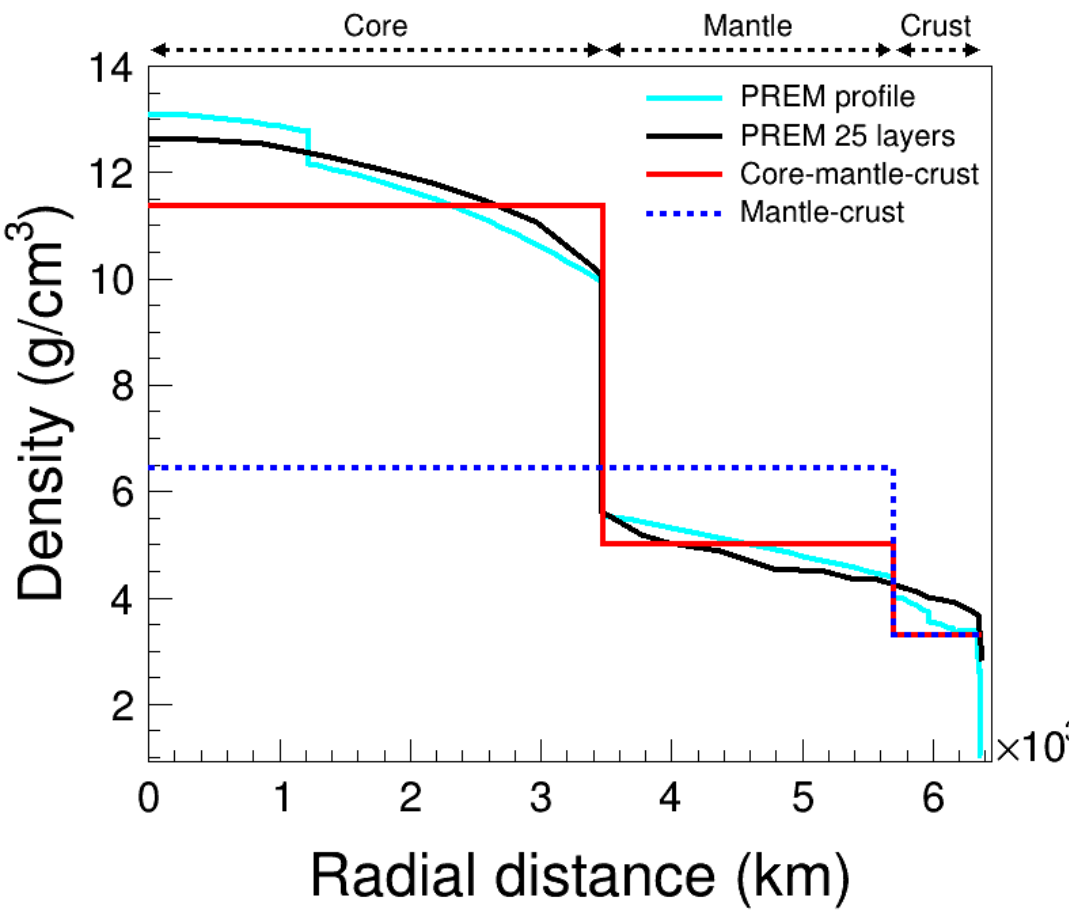


Profiles	Layer boundaries (km)	Layer densities (g/cm^3)
Core-mantle-crust	(0, 3480, 5701, 6371)	(11.37, 5, 3.3)

Internal Structure of Earth

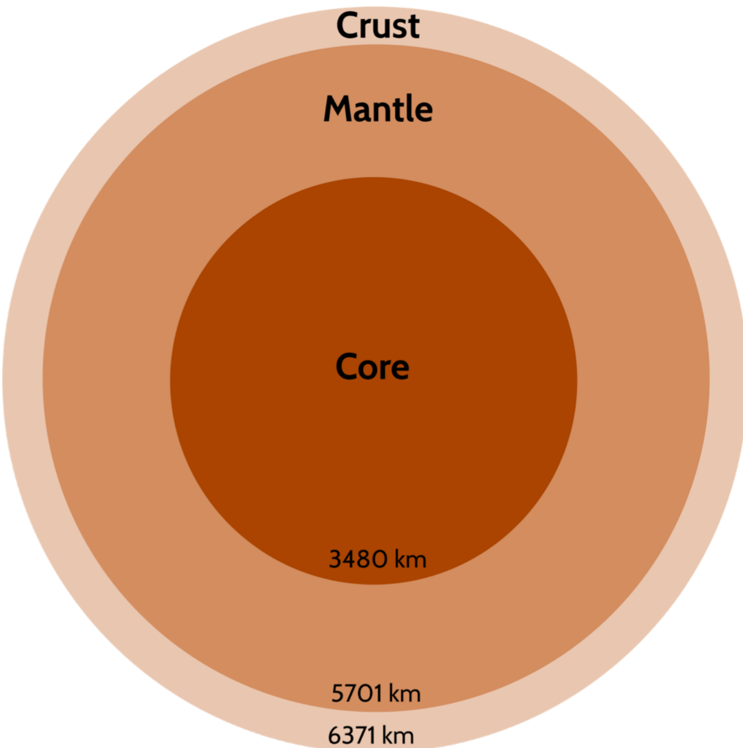


Three-layered model of Earth

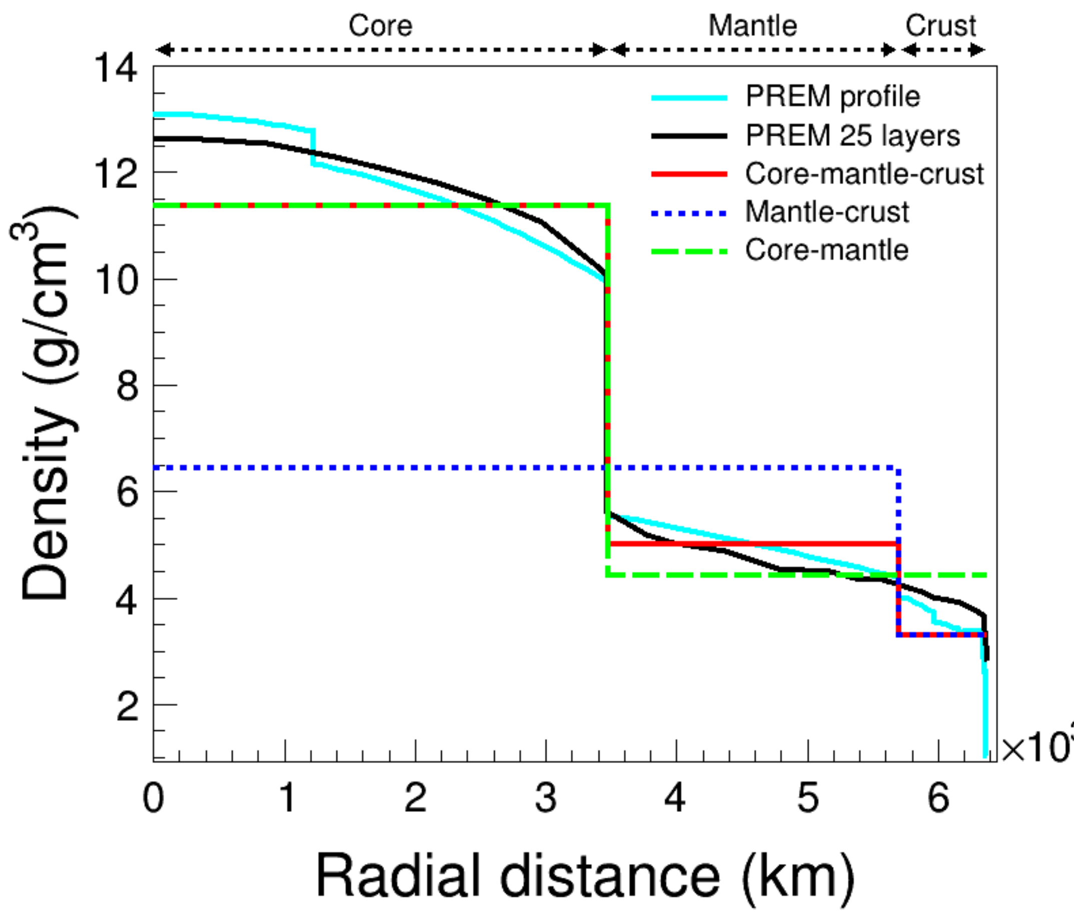


Profiles	Layer boundaries (km)	Layer densities (g/cm^3)
Mantle-crust	(0, 5701, 6371)	(6.45, 3.3)

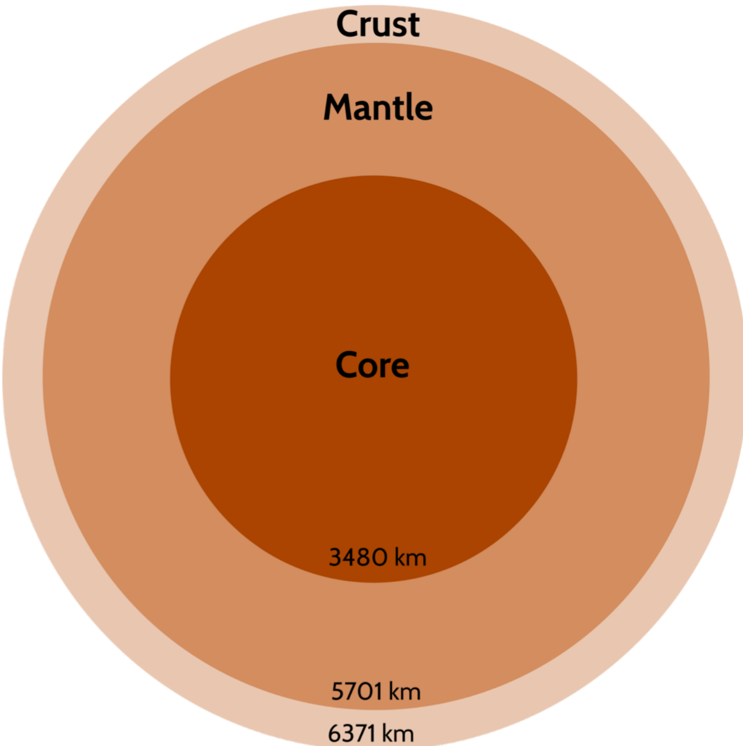
Internal Structure of Earth



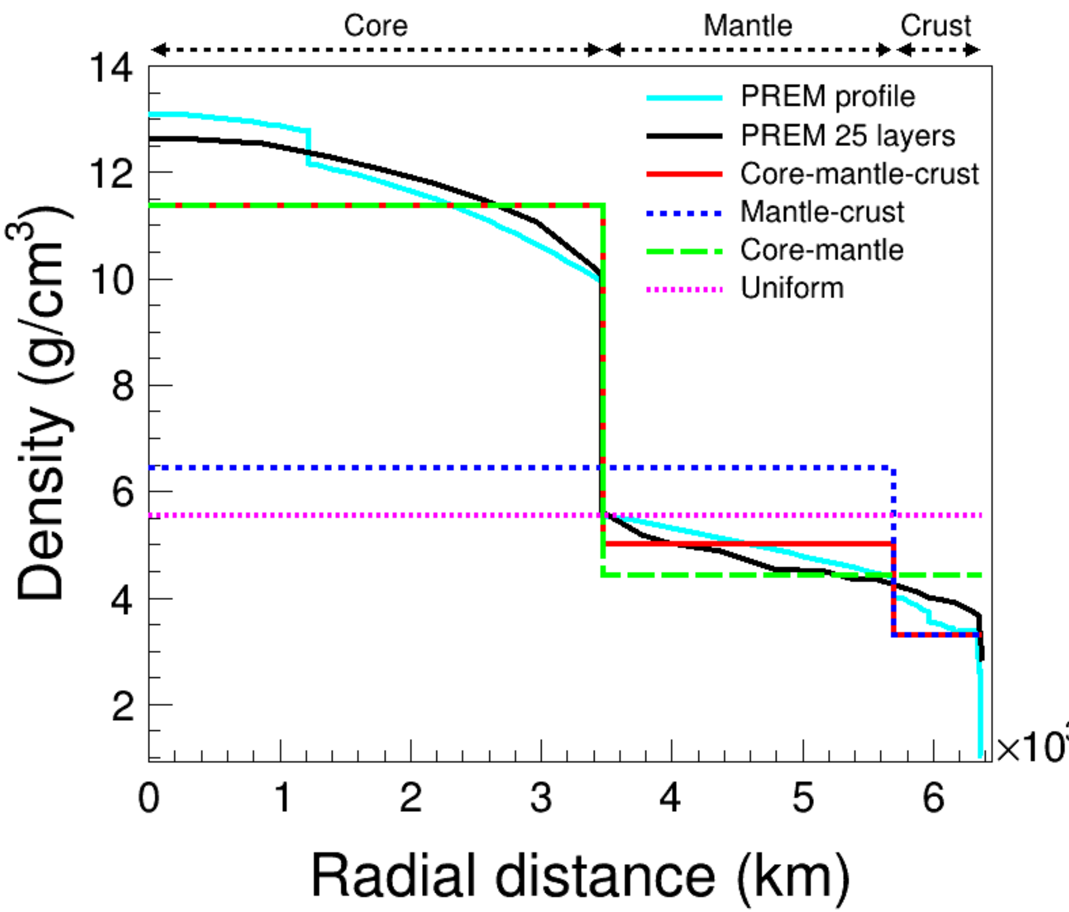
Three-layered model of Earth



Profiles	Layer boundaries (km)	Layer densities (g/cm^3)
Core-mantle	(0, 3480, 6371)	(11.37, 4.42)



Three-layered model of Earth



Profiles	Layer boundaries (km)	Layer densities (g/cm^3)
Uniform	(0, 6371)	(5.55)

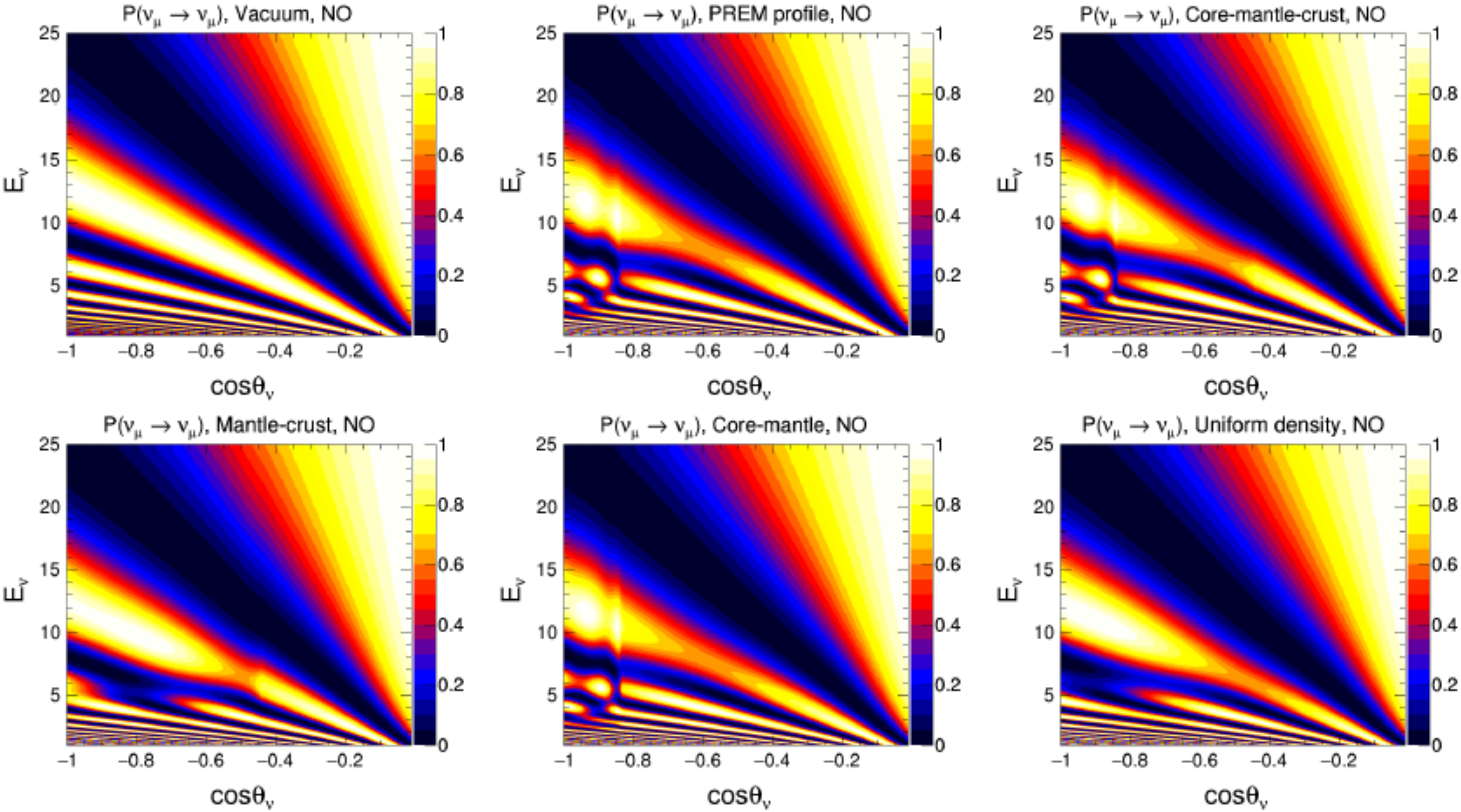
Various Models of Earth

Profiles	Layer boundaries (km)	Layer densities (g/cm^3)
PREM	25 layers	25 densities
Core-mantle-crust	(0, 3480, 5701, 6371)	(11.37, 5, 3.3)
Mantle-crust	(0, 5701, 6371)	(6.45, 3.3)
Core-mantle	(0, 3480, 6371)	(11.37, 4.42)
Uniform	(0, 6371)	(5.55)

While constructing alternative profiles of Earth, the radius and mass of Earth remain invariant

Effect of Various Density Profiles on Muon ν Survival Probability

$\sin^2 2\theta_{12}$	$\sin^2 \theta_{23}$	$\sin^2 2\theta_{13}$	$\Delta m^2_{\rm eff}$ (eV^2)	Δm^2_{21} (eV^2)	$\delta_{\rm CP}$	Mass Ordering
0.855	0.5	0.0875	2.49×10^{-3}	7.4×10^{-5}	0	Normal (NO)

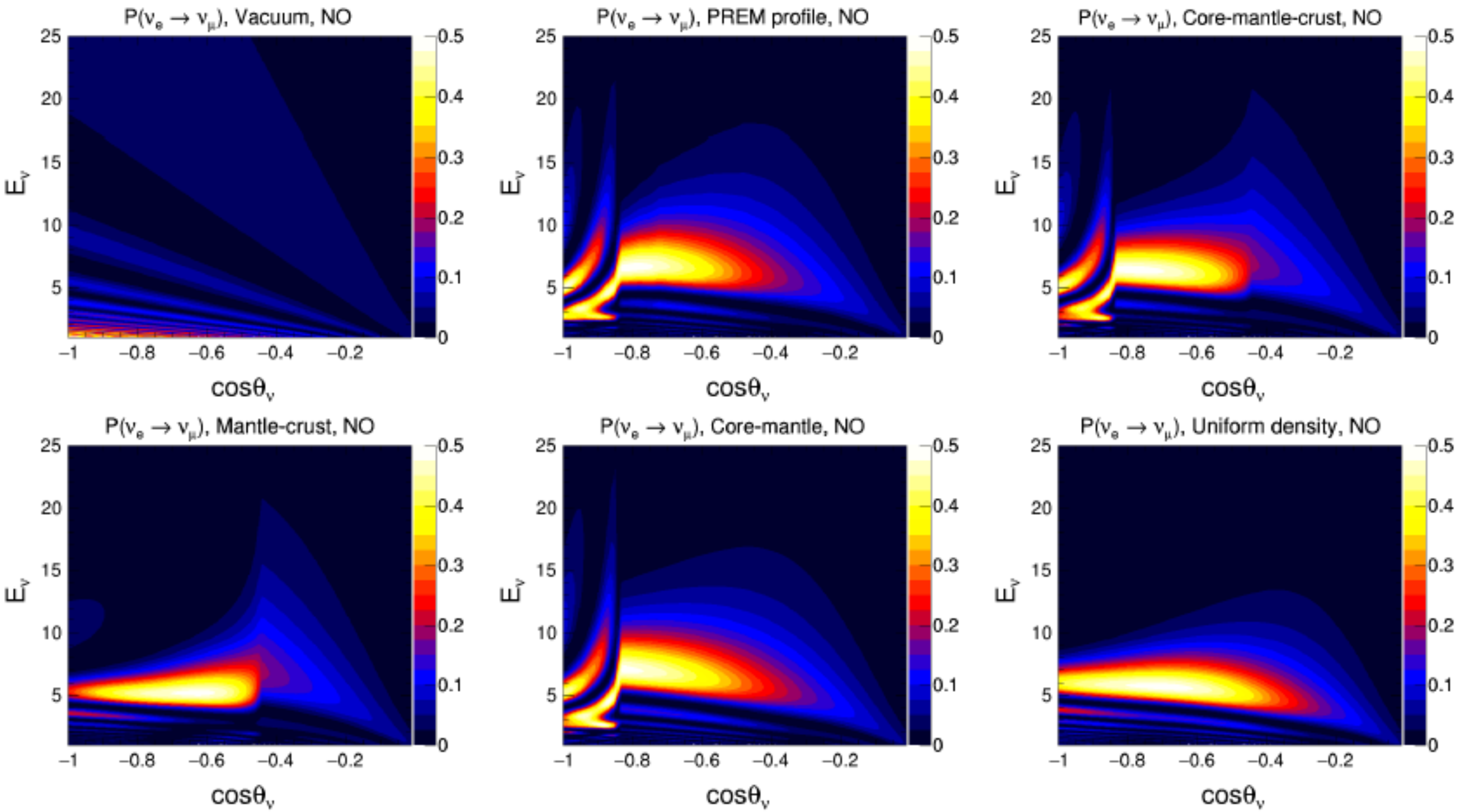


MSW resonance: red yellow patch (- 0.8 < cosθ < - 0.5 and 6 GeV < E_ν < 10 GeV)

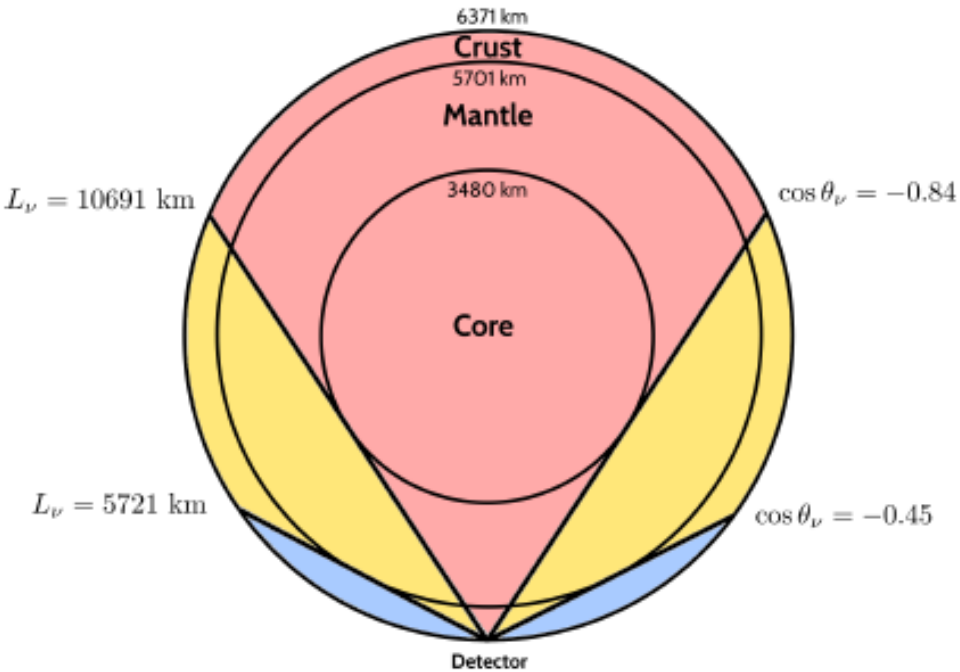
Neutrino Oscillation Length/Parametric resonance: red and yellow patches (cosθ < - 0.8 and 3 GeV < E_ν < 6 GeV

Effect of Various Density Profiles on Muon ν Appearance Probability

$\sin^2 2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	$\Delta m^2_{\rm eff}$ (eV^2)	Δm^2_{21} (eV^2)	$\delta_{\rm CP}$	Mass Ordering
0.855	0.5	0.0875	2.49×10^{-3}	7.4×10^{-5}	0	Normal (NO)



Reconstructed Muon Events Passing Through Different Layers of Earth



Neutrino flux (Honda) at INO location

500 kt•yr ICAL (magnetized) exposure

NUANCE event generator

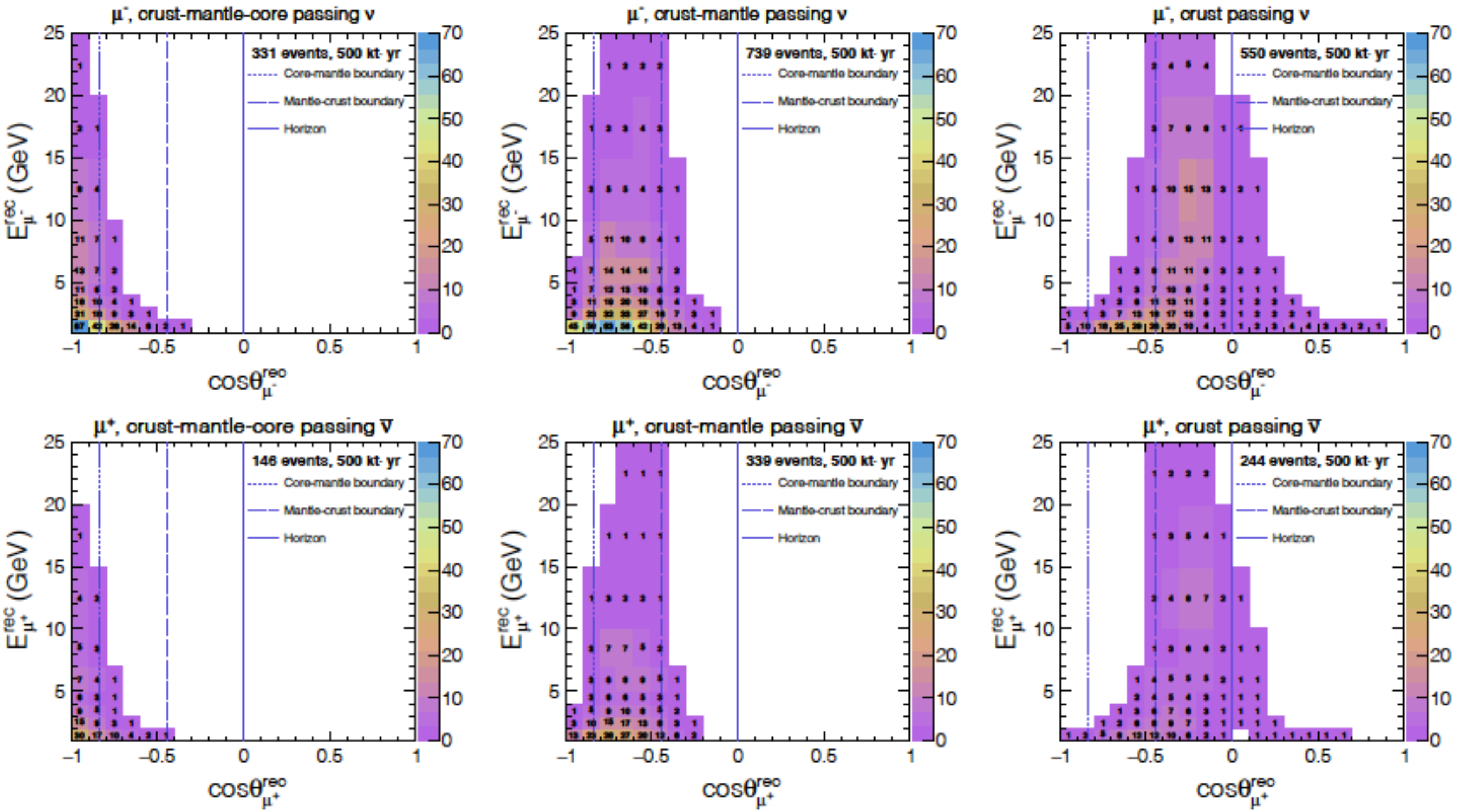
Migration matrices using GEANT4

3-flavor ν oscillations in matter with PREM profile

Reconstructed muon events

Regions	$\cos\theta_\nu$	L_ν (km)	μ^- Events	μ^+ Events
Crust-mantle-core	(-1.00, -0.84)	(10691, 12757)	331	146
Crust-mantle	(-0.84, -0.45)	(5721, 10691)	739	339
Crust	(-0.45, 0.00)	(437, 5721)	550	244
Downward	(0.00, 1.00)	(15, 437)	2994	1324
Total	(-1.00, 1.00)	(15, 12757)	4614	2053

Reconstructed Muon Event Distributions Through Various Earth Layers



Reconstructed muon event distributions at ICAL for 500 kt•yr exposure for neutrinos passing through various regions in the Earth

Binning Scheme and Systematic Uncertainties

Observable	Range	Bin width	Number of bins	
$E_\mu^{\rm rec}$ (GeV)	[1, 4]	0.5	6	12
	[4, 7]	1	3	
	[7, 11]	4	1	
	[11, 21]	5	2	
$\cos\theta_\mu^{\rm rec}$	[-1.0, -0.4]	0.05	12	21
	[-0.4, 0.0]	0.1	4	
	[0.0, 1.0]	0.2	5	
$E'^{\rm rec}_{\rm had}$ (GeV)	[0, 2]	1	2	4
	[2, 4]	2	1	
	[4, 25]	21	1	

- **20% flux normalization error**
- **10% cross section error**
- **5% energy dependent tilt error in flux**
- **5% error in zenith angle dependence of flux**
- **5% overall systematics**

Statistical Analysis

In this analysis, the χ^2 statistics is expected to give median sensitivity of the experiment in the frequentist approach.

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'^{\rm rec}_{\rm had}}} \sum_{j=1}^{N_{E^{\rm rec}_\mu}} \sum_{k=1}^{N_{\cos\theta^{\rm rec}_\mu}} \left[2(N^{\rm theory}_{ijk} - N^{\rm data}_{ijk}) - 2N^{\rm data}_{ijk} \ln\left(\frac{N^{\rm theory}_{ijk}}{N^{\rm data}_{ijk}}\right)\right] + \sum_{l=1}^{5} \xi_l^2$$

where,

$$N^{\rm theory}_{ijk} = N^0_{ijk}\left(1 + \sum_{l=1}^{5} \pi^l_{ijk}\xi_l\right)$$

Similarly, χ^2_+ is defined for μ^+

$$\chi^2_{\rm ICAL} = \chi^2_- + \chi^2_+$$

$$\Delta\chi^2_{\text{ICAL-profile}} = \chi^2_{\rm ICAL}\ (\text{Mantle-Crust}) - \chi^2_{\rm ICAL}\ (\text{Core-Mantle-Crust})$$

- Marginalization over systematic uncertainties and $\sin^2\theta_{23}$: (0.36, 0.66), $\Delta m^2_{\rm eff}$: (2.1, 2.6) $\times 10^{-3}$ eV^2, and mass ordering: (NO, IO)

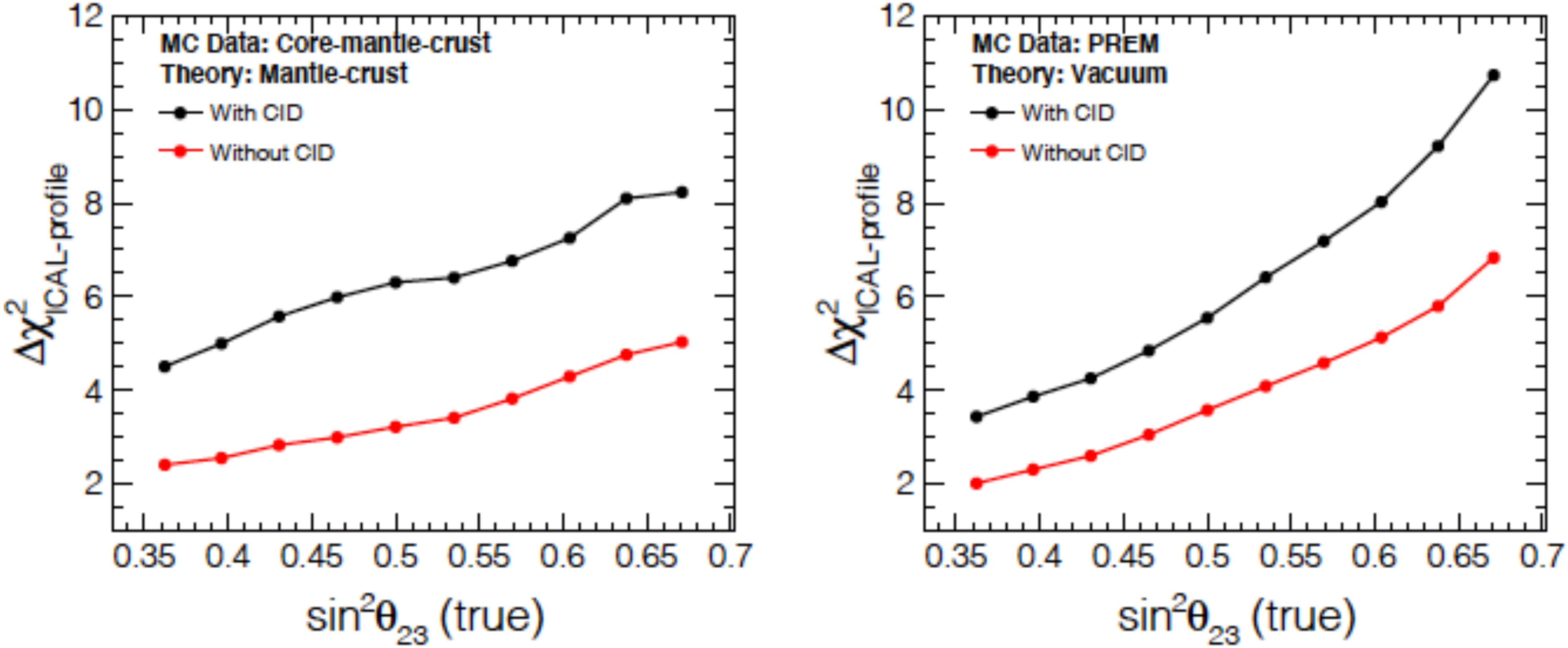
Sensitivity to Validate Earth's Core with and without CID

MC Data	Theory	$\Delta\chi^2_{\text{ICAL-profile}}$			
		NO(true)		IO(true)	
		with CID	w/o CID	with CID	w/o CID
Core-mantle-crust	Vacuum	4.65	2.96	3.53	1.43
Core-mantle-crust	Mantle-crust	6.31	3.19	3.92	1.29
Core-mantle-crust	Core-mantle	0.73	0.47	0.59	0.21
Core-mantle-crust	Uniform	4.81	2.38	3.12	0.91
PREM profile	Core-mantle-crust	0.36	0.24	0.30	0.11
PREM profile	Vacuum	5.52	3.52	4.09	1.67
PREM profile	Mantle-crust	7.45	3.76	4.83	1.59
PREM profile	Core-mantle	0.27	0.18	0.21	0.07
PREM profile	Uniform	6.10	3.08	3.92	1.18

Impact of Marginalization Over Various Oscillation Parameters

MC Data	Theory	$\Delta\chi^2_{\text{ICAL-profile}}$				
		Fixed parameter	Marginalization over			
			$\sin^2\theta_{23}$	$\lvert\Delta m^2_{\text{eff}}\rvert$	$\pm\lvert\Delta m^2_{\text{eff}}\rvert$	All
Core-mantle-crust	Mantle-crust	6.90	6.36	6.84	6.84	6.31
Core-mantle-crust	Vacuum	6.80	6.44	5.16	4.94	4.65
PREM	Mantle-crust	7.88	7.47	7.81	7.81	7.45
PREM	Vacuum	7.71	7.28	6.10	5.89	5.52

Impact of Different True Choices of $\sin^2 \theta_{23}$



Concluding Remarks

We explore the possibility of utilizing neutrino oscillations in the presence of matter to extract information about the internal structure of Earth complementary to seismic studies

Using good directional resolution, ICAL observe 331 μ^- and 146 μ^+ core-passing events with 500 kt•yr exposure

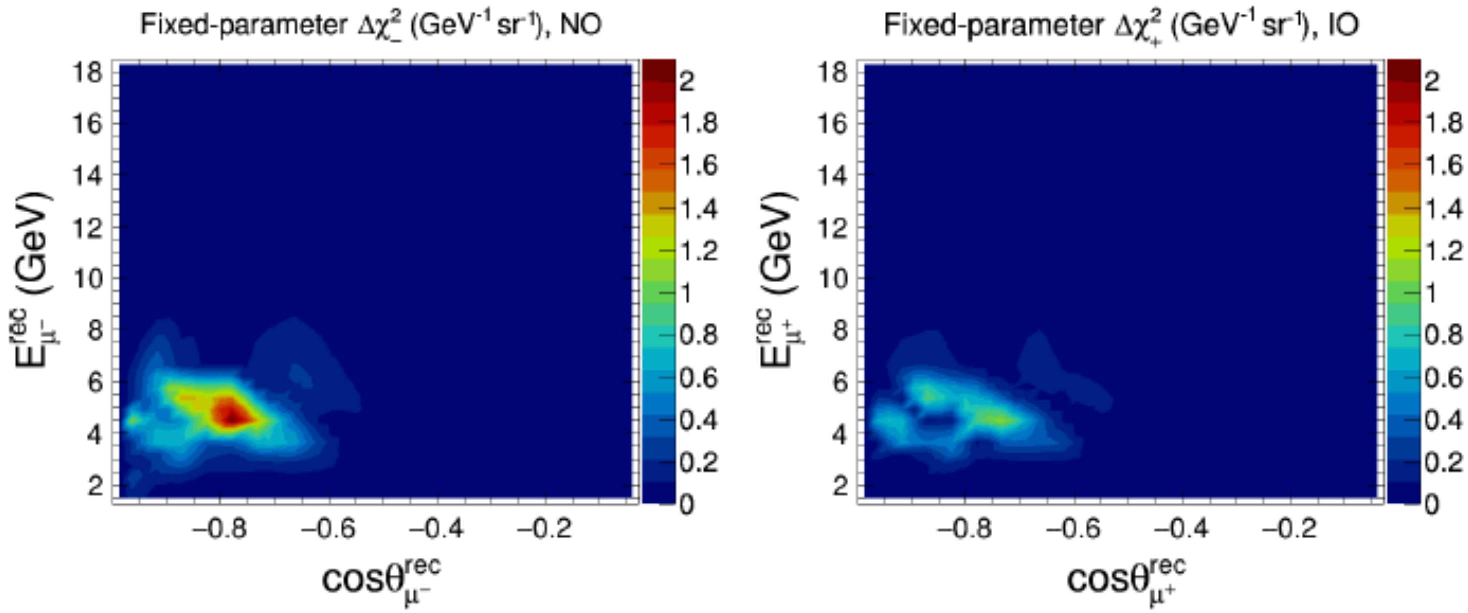
The presence of Earth's core can be independently confirmed at ICAL with a median $\Delta\chi^2$ of 7.45 (4.83) assuming normal (inverted) mass ordering

Thank you!

Backup Slides

Effective Regions in $(E_\mu^{\rm rec}, \cos\theta_\mu^{\rm rec})$ Plane to Validate Earth's Core

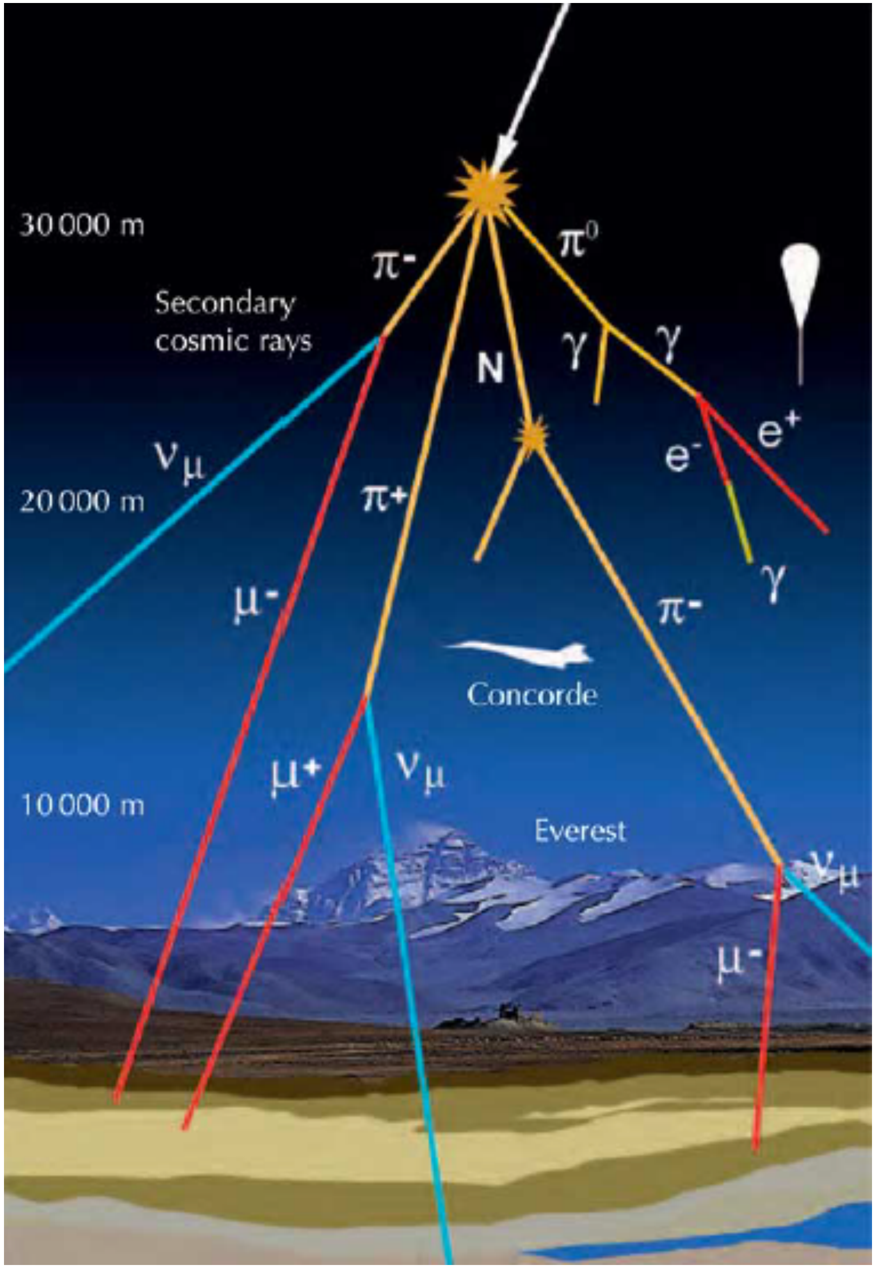
• MC Data: Core-mantle-crust • Theory: Mantle-crust • 500 kt·yr exposure at ICAL • Systematic uncertainties are marginalized whereas oscillation parameters are kept fixed in theory



	Fixed-parameter $\Delta\chi^2$	
	NO	IO
Contribution from μ^-	6.85	0.02
Contribution from μ^+	0.05	4.08
Total	6.90	4.10

Note: $\Delta\chi^2_-$ and $\Delta\chi^2_+$ are calculated without pull penalty $\sum_{l=1}^{5}\xi_l^2$ to explore contributions from each bin in $(E_\mu^{\rm rec},\ \cos\theta_\mu^{\rm rec})$ plane for μ^- and μ^+ events, respectively.

Atmospheric Neutrinos: Neutrinos from Cosmic Rays

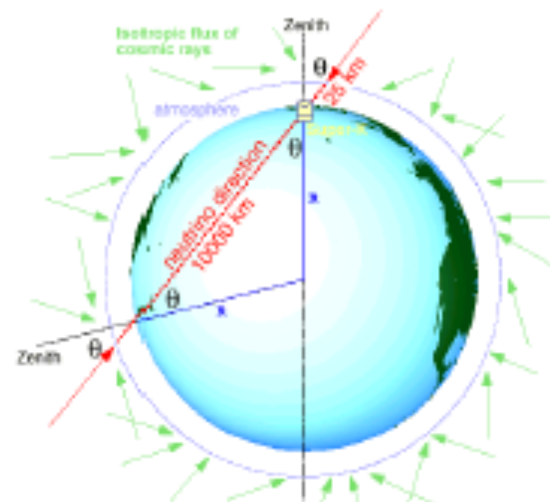


$$\pi^+ \to \mu^+ + \nu_\mu$$

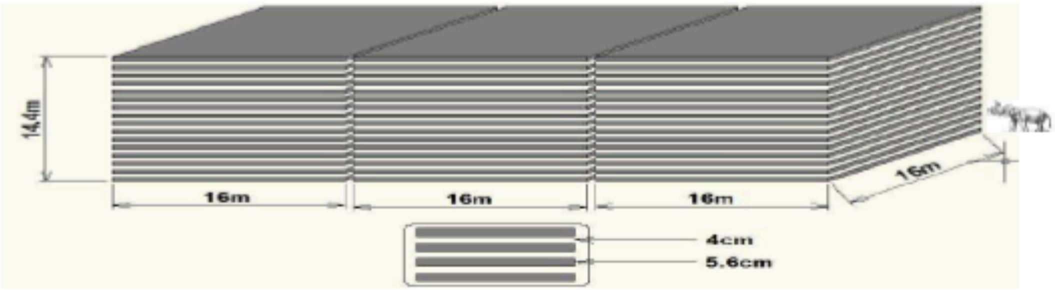
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

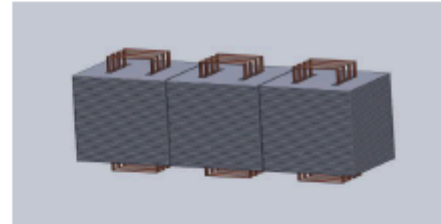
"ν_μ" flux = 2× "ν_e" flux

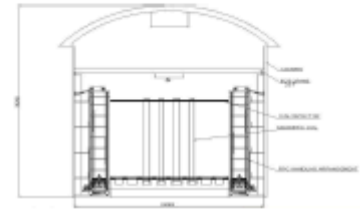
"Down" flux = "Up" flux



Schematic of Iron Calorimeter (ICAL) Detector at INO

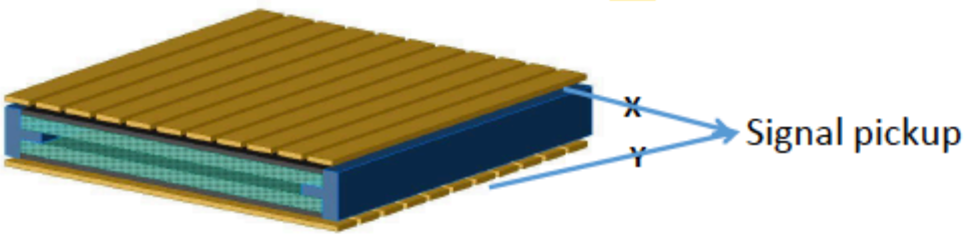




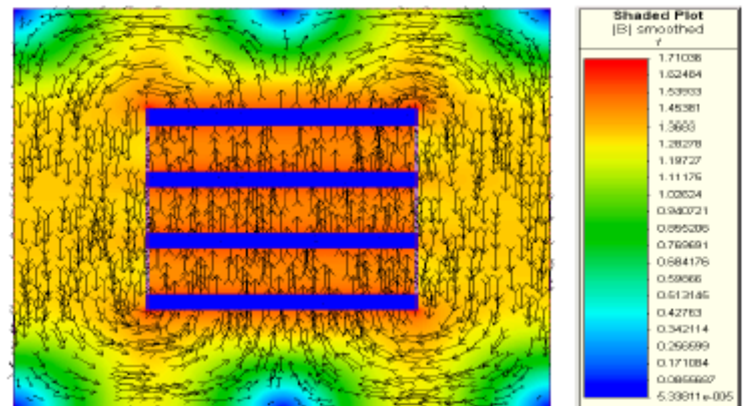


51 kt world's largest electromagnet

3 modules × 17 kton
Each with 150 layers Fe+RPC
B-field > 1 Tesla (90%)



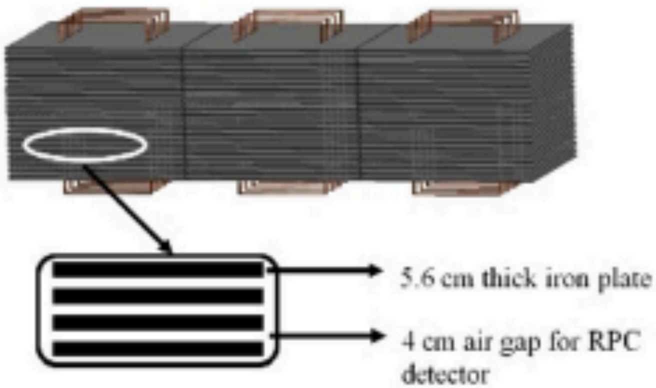
Glass RPC for detecting charged particles
~30,000 RPCs required, ~ 3.8 M channels



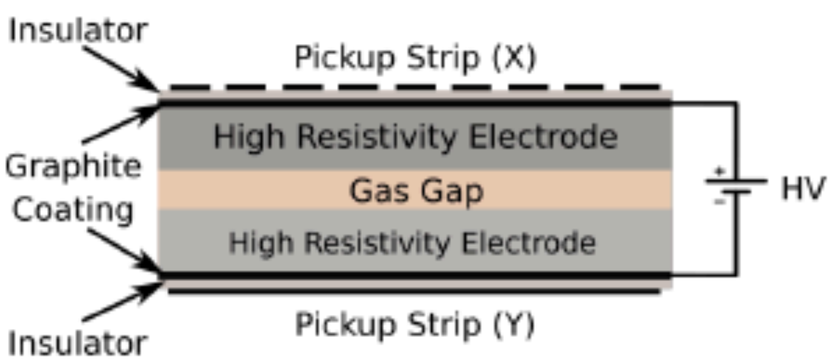
B-field for 60 kA-turns, typical low C steel

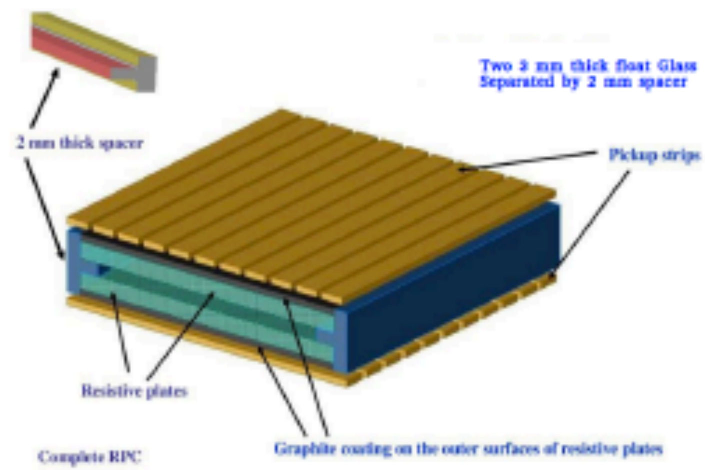
Observe atmospheric neutrinos and antineutrinos separately over a wide range of energies & baselines using 50 kt magnetized Iron Calorimeter (ICAL) detector

ICAL Design and Specfications



ICAL	
No. of modules	3
Module dimension	16 m × 16 m × 14.5 m
Detector dimension	48 m × 16 m × 14.5 m
No. of layers	151
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	2 m × 2 m
Readout strip width	3 cm
No. of RPC units/Layer/Module	64
Total no. of RPC units	∼ 30,000
No. of electronic readout channels	3.9×10^6



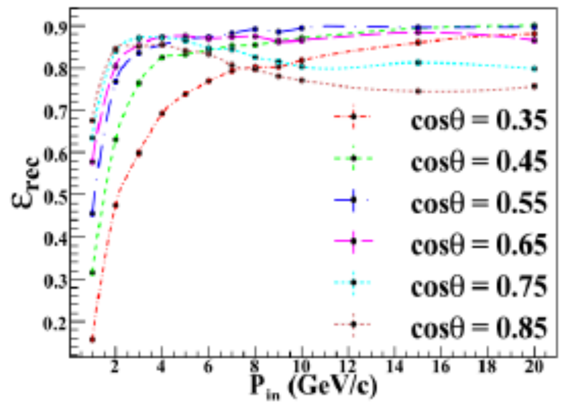


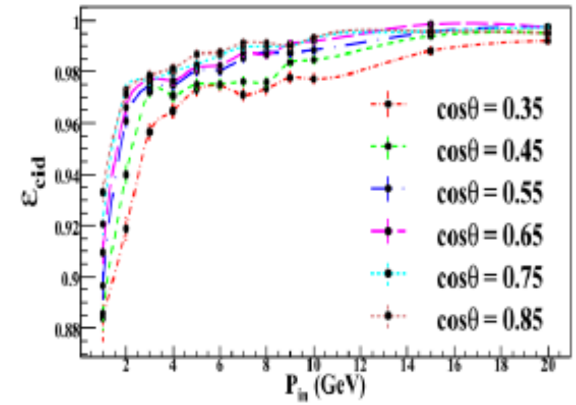
Resistive plate chamber (RPC) (active element) sandwiched between iron plates (passive element)

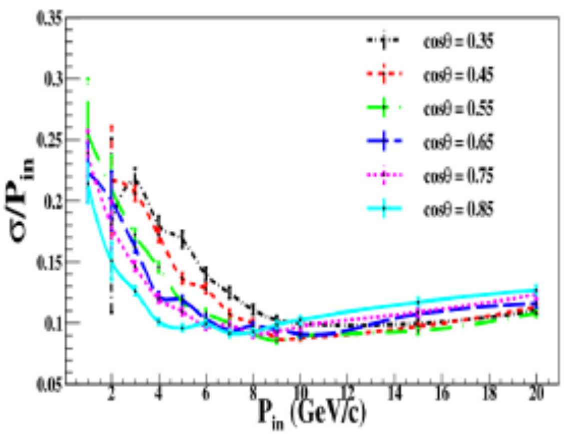
Detector Response of ICAL

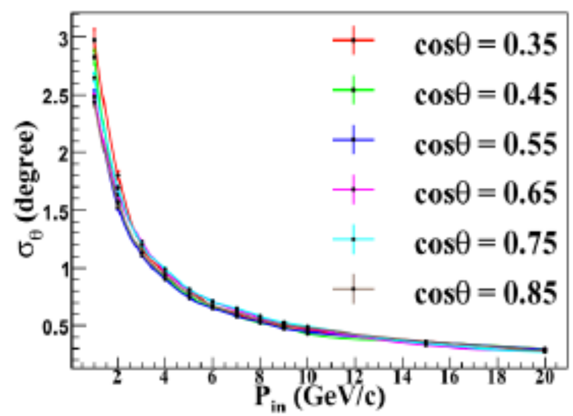
In CC events at ICAL:

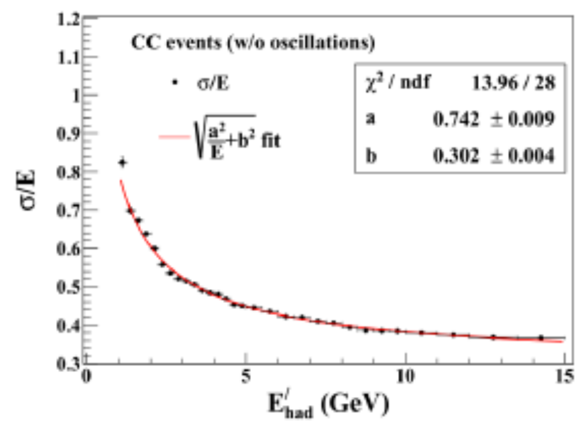
- Muon → track
- Hadron → shower











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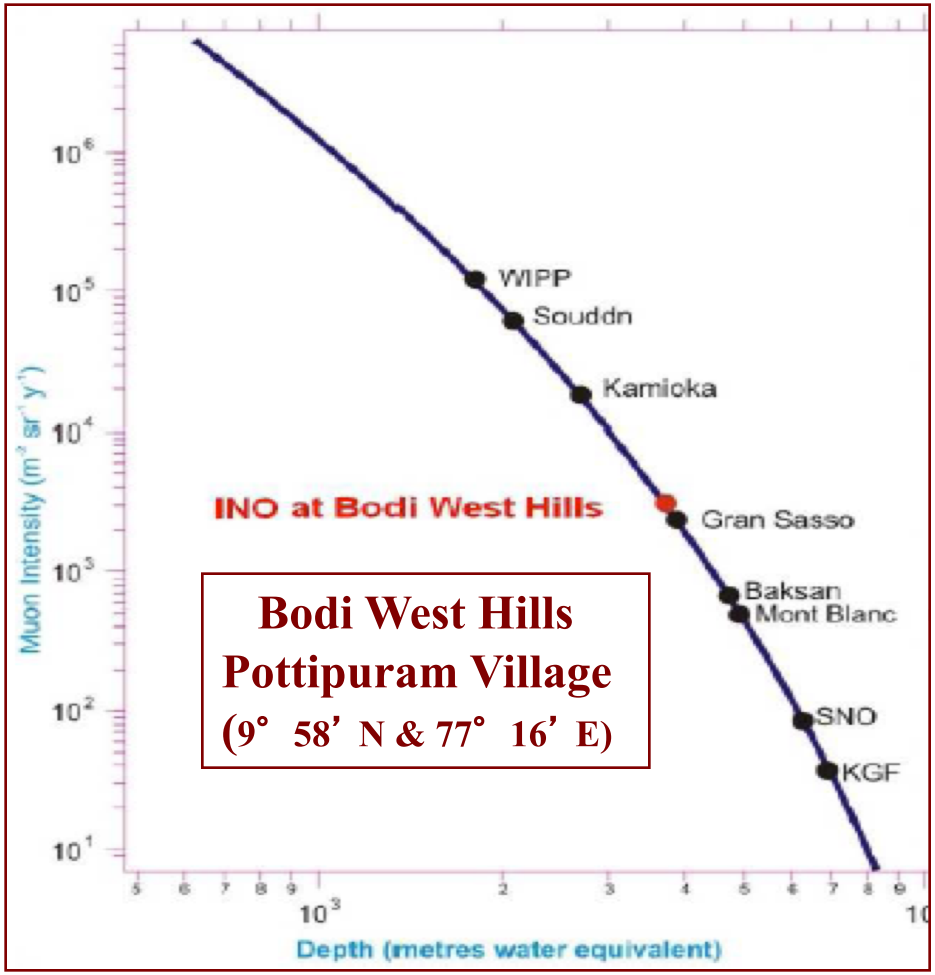
Coordinates of INO



Located 115 km west of the Madurai city in the Theni district of Tamil Nadu

Come up with an underground lab, surface facilities, & build massive 50 kton magnetized Iron Calorimeter (ICAL) detector to study atmospheric neutrinos

Three Neutrino Mixing

Three neutrino mixing firmly established...

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

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

Atmospheric & Long-baseline accelerator neutrinos

Quasi 2-neutrino mixing

Solar & Long-baseline reactor neutrinos

$L/E = 500 \text{ km/GeV}$

$L/E = 15,000 \text{ km/GeV}$

$\Delta m^2_{31} \sim 2.5 \times 10^{-3} \text{ eV}^2$

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

$\Delta m^2_{21} \sim 7.6 \times 10^{-5} \text{ eV}^2$

Some Things We Know and Don't Know

Three neutrino mixing firmly established…

$$\theta_{12} \approx 34^\circ$$

$$\theta_{23} \approx 45^\circ$$

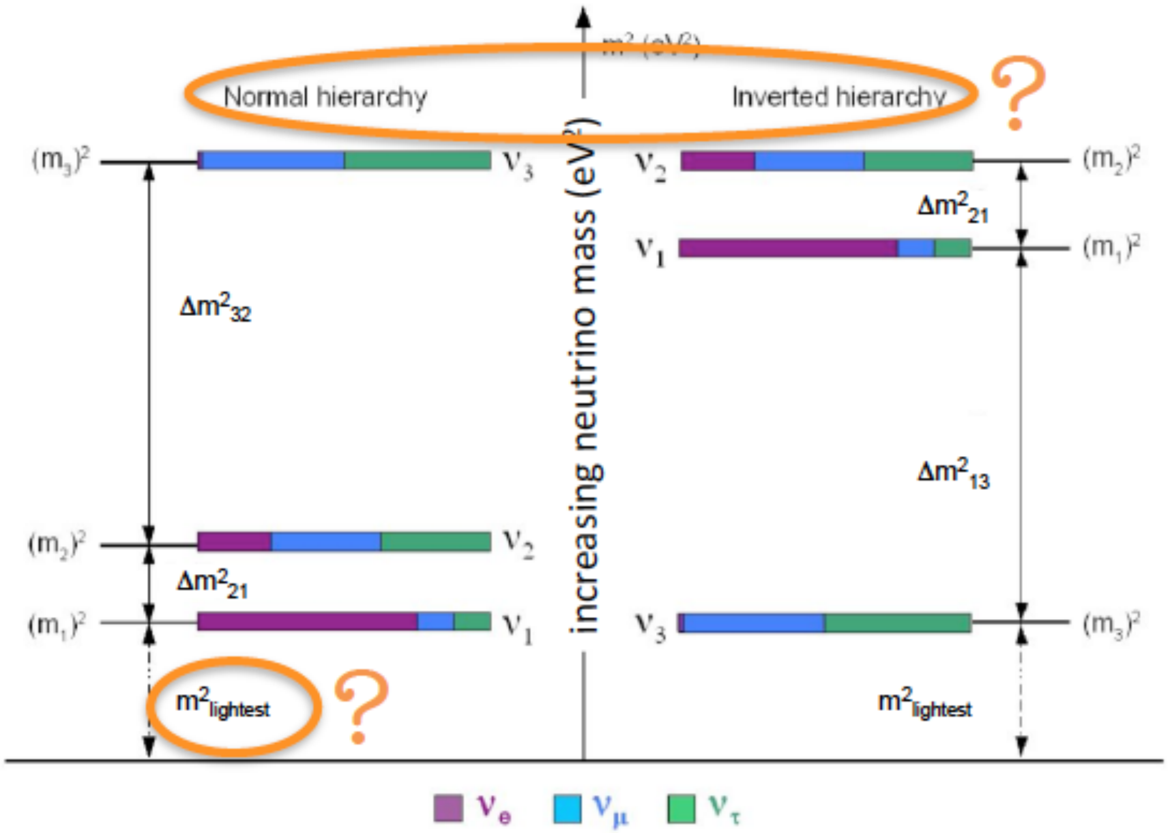
$$\theta_{13} \approx 9^\circ$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$$

$$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$$

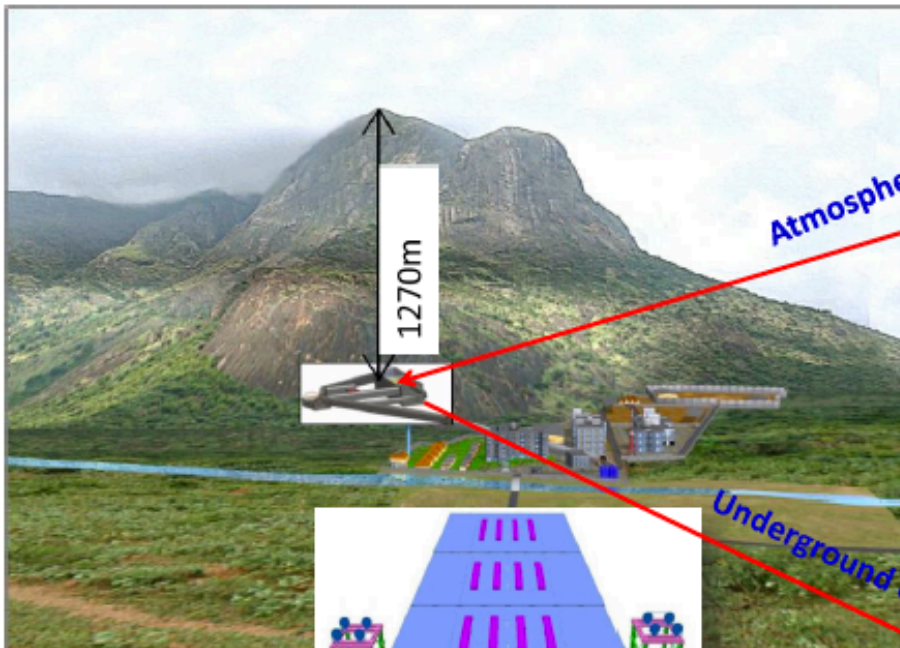
$$\delta_{CP} = \ ?$$

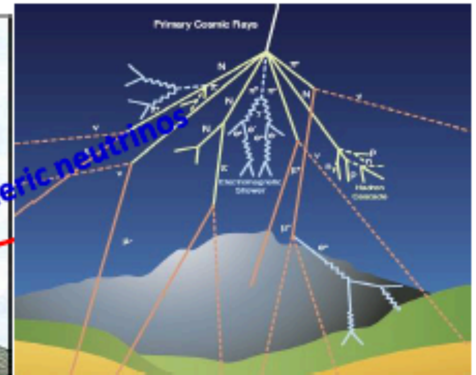
?



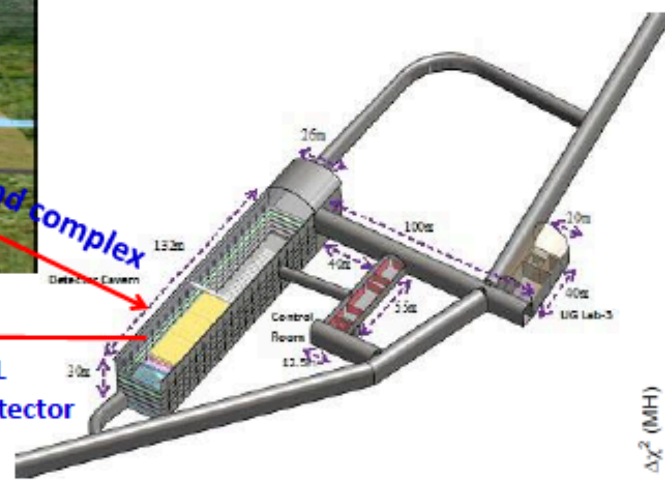
flavor content of the mass eigenstates determined by mixing matrix elements (mixing angles) that are measured experimentally

India based Neutrino Observatory at Pottipuram (Theni)

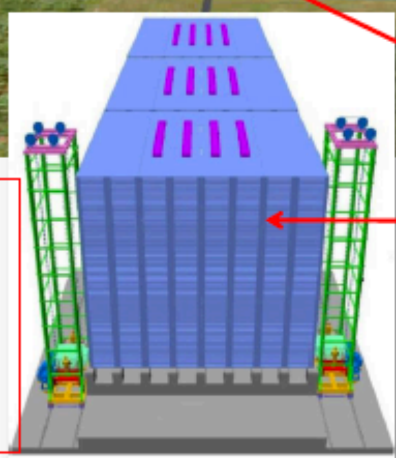




Collaboration of ~28 institutions (research centres, Universities, IITs)

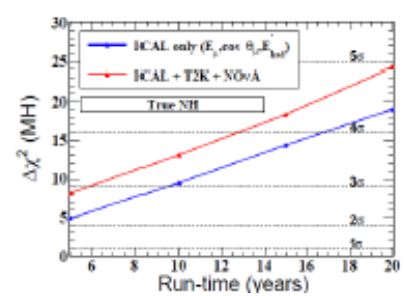


51 kton ICAL neutrino detector

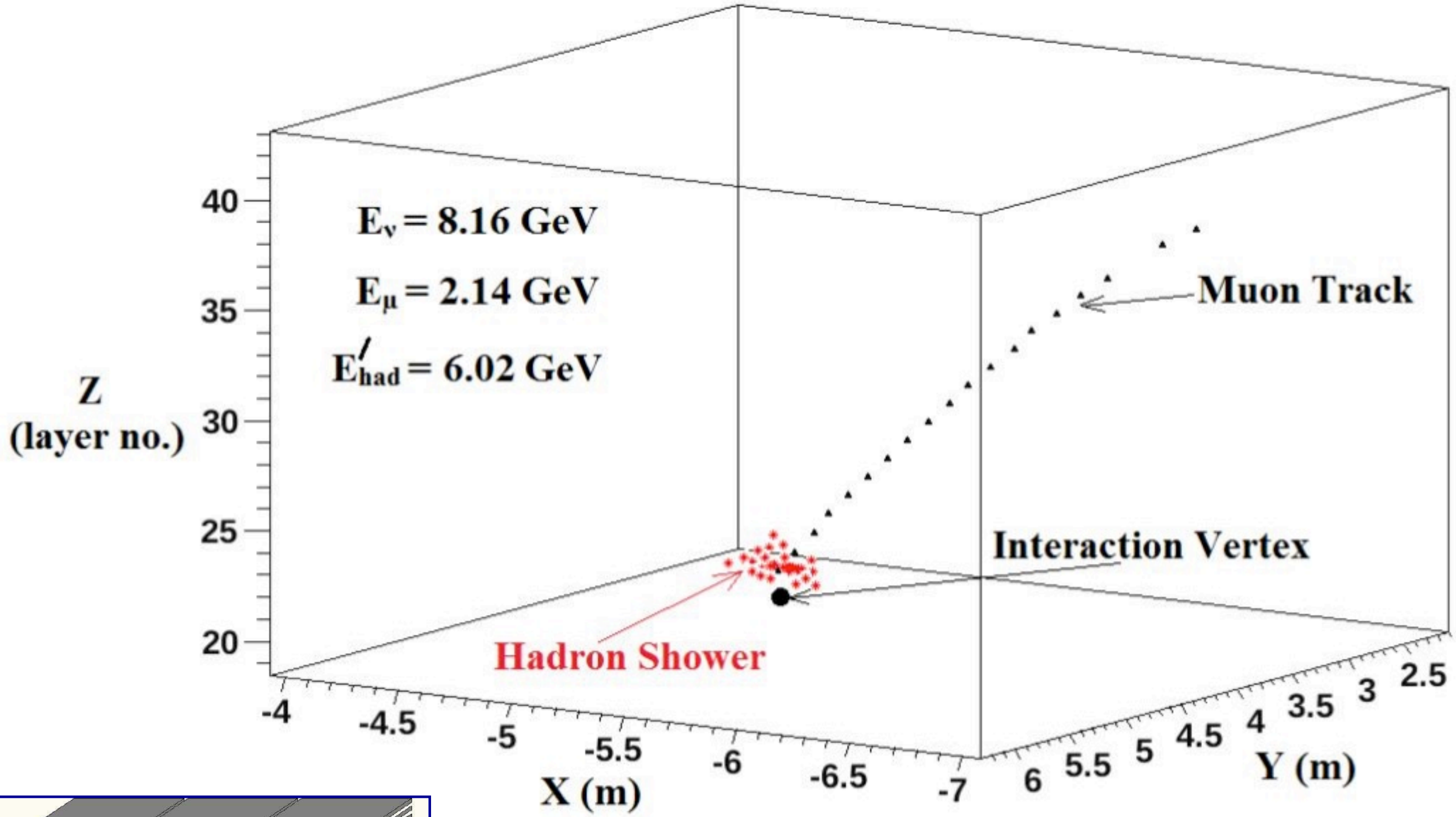


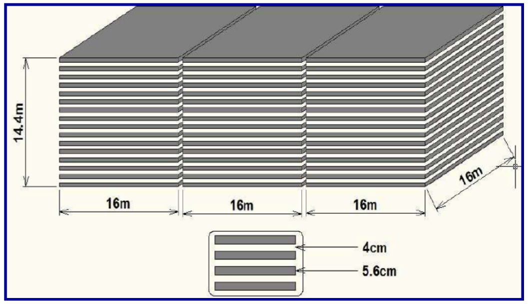
Will be largest electromagnet in the world – 51,000 tons. ~30000 glass RPCs (×3 world total)

Mass ordering of ν



Event Display Inside the ICAL Detector

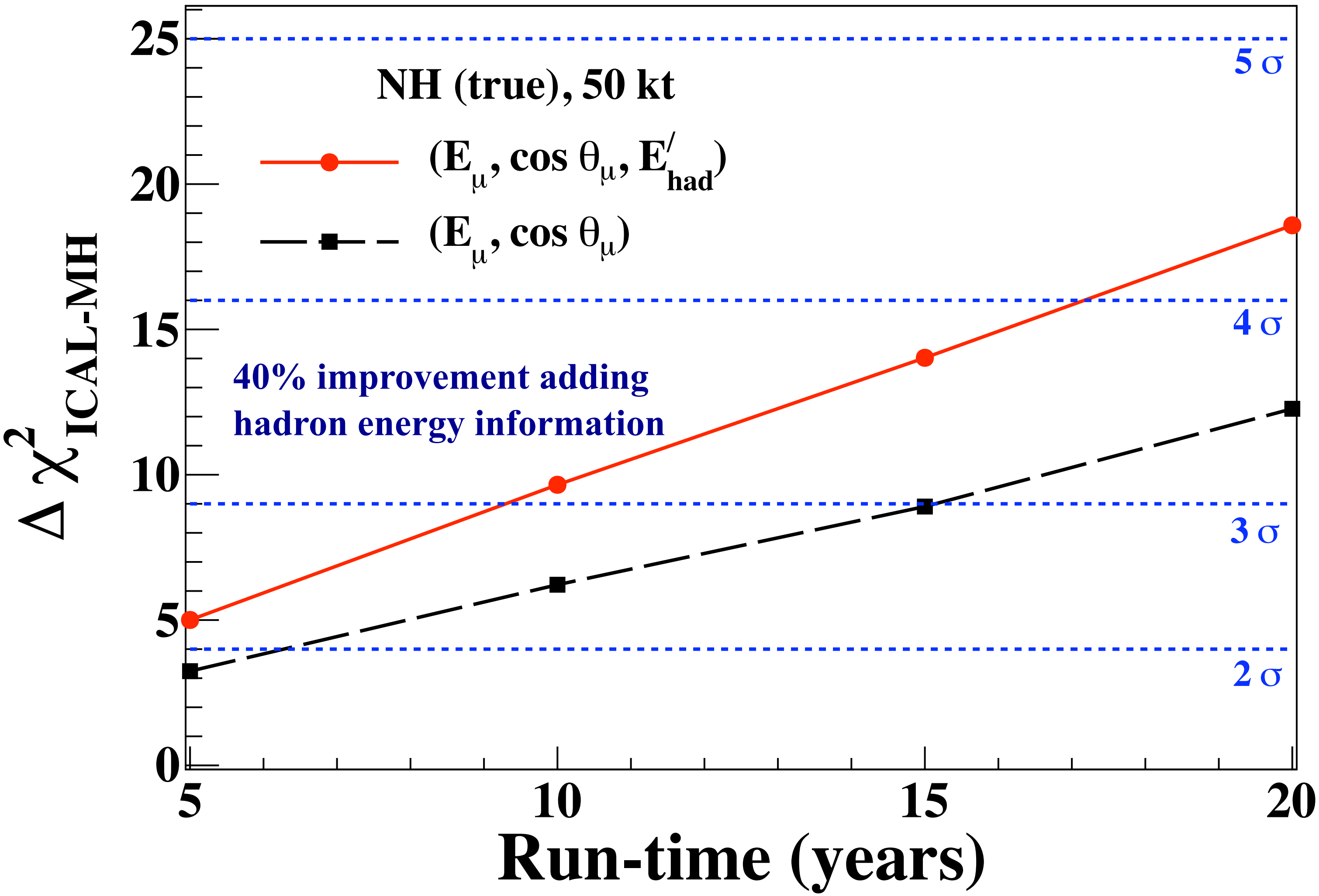




Using GEANT4 simulation

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph]

Identifying Neutrino Mass Hierarchy with ICAL



Median Sensitivity

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

50 kt ICAL can rule out the wrong hierarchy with $\Delta\chi^2 \approx 9.5$ in 10 years