Neutrino Oscillation Tomography of Earth with a Magnetized Detector having Charge-identification Capability

Anil Kumar

Postdoc (Visitor), DESY Zeuthen, Germany

IOPB Bhubaneswar, SINP Kolkata, HBNI Mumbai, India

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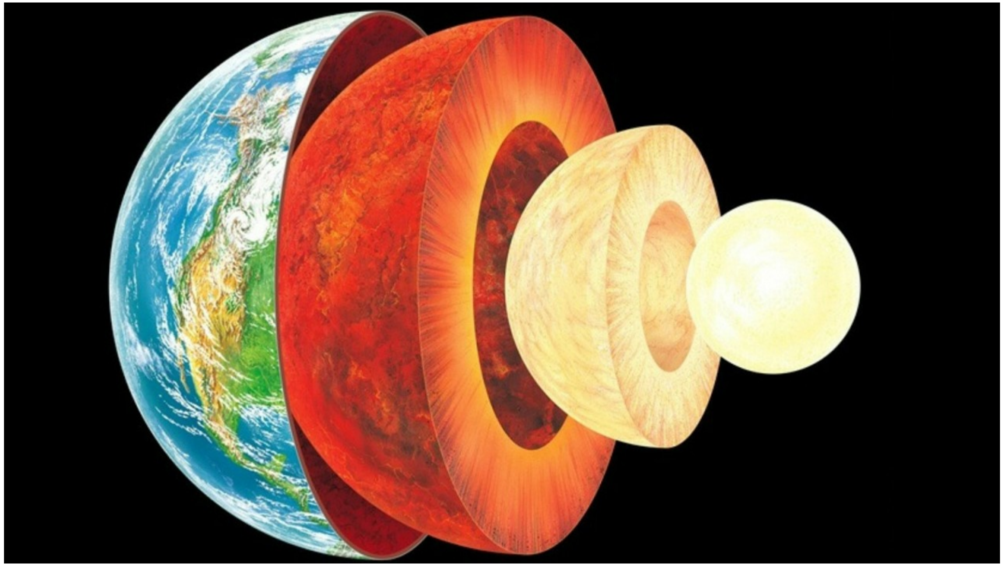
Collaborators: Sanjib Kumar Agarwalla, Anuj Kumar Upadhyay, Amol Dighe

The Interior of Earth

- What lies in the interior of Earth has been a long-standing puzzle and active research is being carried out in this direction.
- The regions deep below the Earth's surface are inaccessible due to large temperatures, pressures, and extreme environments.
- The information about the interior of Earth is obtained indirectly using:
  - Gravitational measurements
  - Seismic studies



Gravitational Measurements

Gravitational measurements exploits the gravitational interactions of matter inside Earth.

Average density

- For given mass[1] (~5.97×10^{24} kg) and radius of Earth (~6400 km), average density of Earth ~5.5 g/cm^3
- Density of ordinary rock ~2.8 g/cm^3, therefore, the density near the centre of Earth is higher than 5.5g/cm^3

Moment of intertia

- For uniform sphere, $I = 2/5MR^2 \Rightarrow I/MR^2 = 0.4$
- Measured[2] $I/MR^2 \sim 0.33$, [3]$I \sim 8.017 \times 10^{37}$ kg m^2
- Since $I_{measured} < I_{expected}$, more matter is concentrated near the axis of rotation

[1]B. Luzum et al., Celest. Mech. Dyn. Astron. 110, 293 (2011).

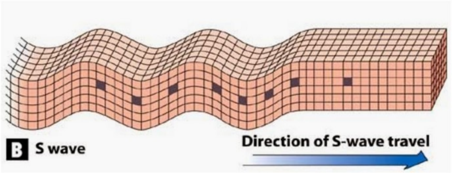
[2]Williams, James G. The Astronomical Journal. 108: 711 (1994)

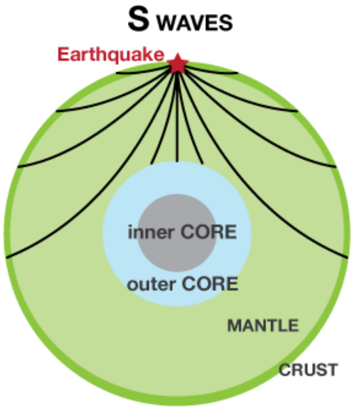
[3]W. Chen, J. Ray, W. B. Shen, and C. L. Huang, J. Geod. 89, 179 (2015).

Seismic Studies

Seismic measurements exploits the electromagnetic interactions of matter inside Earth.

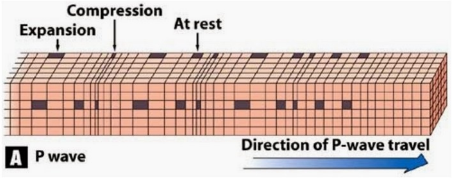
Body waves consisting of transverse vibrations are known as **S-waves**:

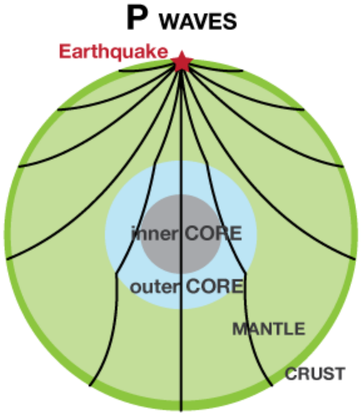




$$V_S = \sqrt{\frac{\mu}{\rho}}$$

Body waves consisting of longitudinal vibrations are known as **P-waves**:





$$V_P = \sqrt{\frac{\mu + \frac{4}{3}\mu}{\rho}}$$

Velocities of seismic waves depend upon the elastic constants of the material, such as density (ρ), bulk modulus (κ), shear modulus (μ).

E. C. Robertson, The interior of the Earth, an elementary description, 1966.

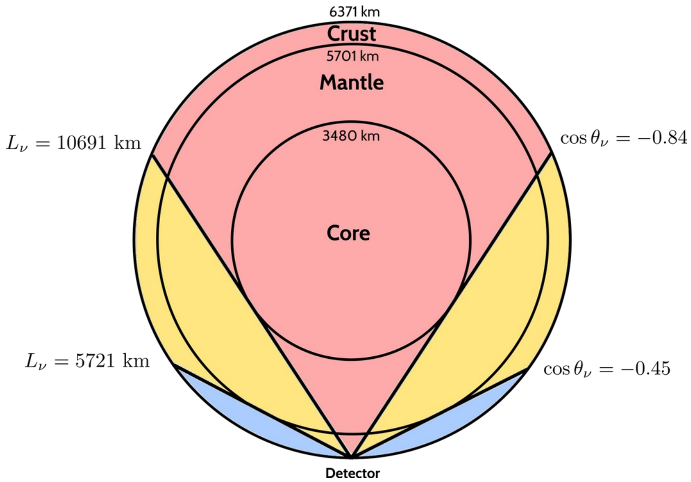
Image source: https://thinkgeogeek.blogspot.com/2014/01/seismic-waves.html

A Brief Review of the Internal Structure of Earth

The gravitational and seismic measurements are used to infer the density distribution inside Earth which is known as **Preliminary Reference Earth Model (PREM)**.

- **Crust:** solid, rocks, brittle, lowest density
- **Mantle:** hot, solid outer mantle, viscous plastic inner mantle
- **Core:** solid inner core, liquid outer core, iron and nickel

Note that PREM is not a measured profile.



References:

- A.M. Dziewonski, and D.L. Anderson, Preliminary reference earth model, Phys.Earth Planet.Interiors 25 (1981) 297-356
- 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.

Anil Kumar, Sanjib Kumar Agarwalla, JHEP 08 (2021) 139, arXiv: 2104.11740

Multi-messenger Tomography of Earth

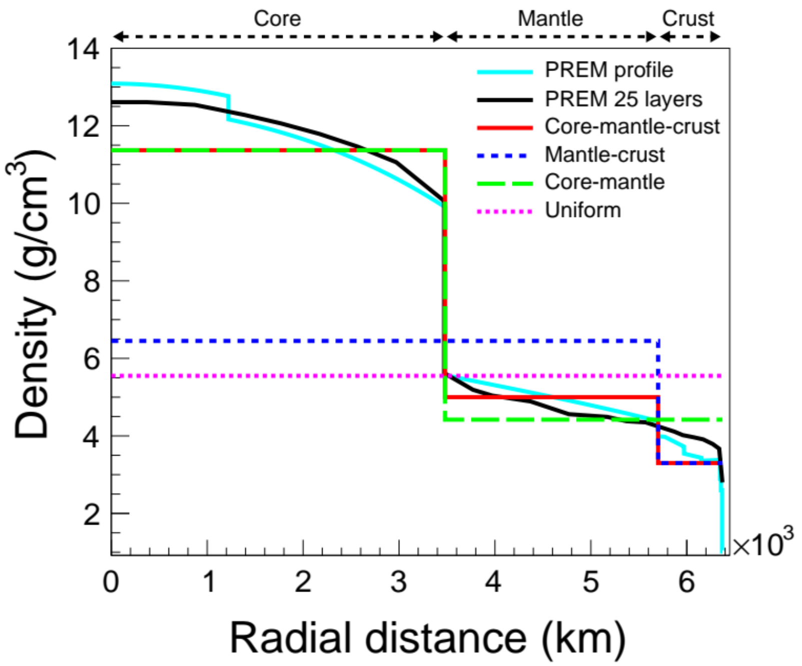
- **Neutrino absorption tomography:** Neutrino attenuation at energies greater than a few TeV. (• Placci, Alfredo and Zavattini, Emilio, 1973, https://cds.cern.ch/record/2258764 • L. Volkova and G. Zatsepin, Izvestiya Akademii Nauk SSSR, Seriya Fizicheskaya 38 (1974), no. 5 1060–1063. • Andrea Donini et. al. Nature Physics volume 15, pages 37–40 (2019))
- **Neutrino oscillation tomography:** While passing through Earth, neutrinos undergo charged-current coherent forward elastic scattering with ambient electrons and this results in the modification of neutrino oscillation patterns. These density-dependent matter effects can be used to reveal the internal structure of Earth. (L. Wolfenstein, Phys. Rev. D17 (1978) 2369)
- **Neutrino diffraction tomography:** The possibility of Earth tomography using the study of diffraction pattern produced by coherent neutrino scattering in crystalline matter inside Earth is technologically not feasible. (A. D. Fortes et. al. Using neutrino diffraction to study the Earth's core, Astronomy and Geophysics 47 (2006), no. 5 5.31–5.33.)

Since neutrinos interact via weak interactions, probing Earth through neutrino absorption and oscillations is complimentary to seismic studies (electromagnetic interactions) and gravitational measurement (gravitational interactions). This is the beginning of a new era of **Multi-messenger tomography of Earth**.

The proposed work is based on neutrino oscillation tomography using ICAL detector at INO.

Density Distributions for Various Profiles of Earth

Profiles	Layer boundaries (km)	Layer densities (g/cm³)
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



Note that while considering alternative profiles of Earth, we assume the radius and the mass of Earth to be invariant.

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Earth's Matter Effects

Neutrinos feel a charged-current potential V_{CC} during coherent elastic and forward scattering with electrons inside Earth

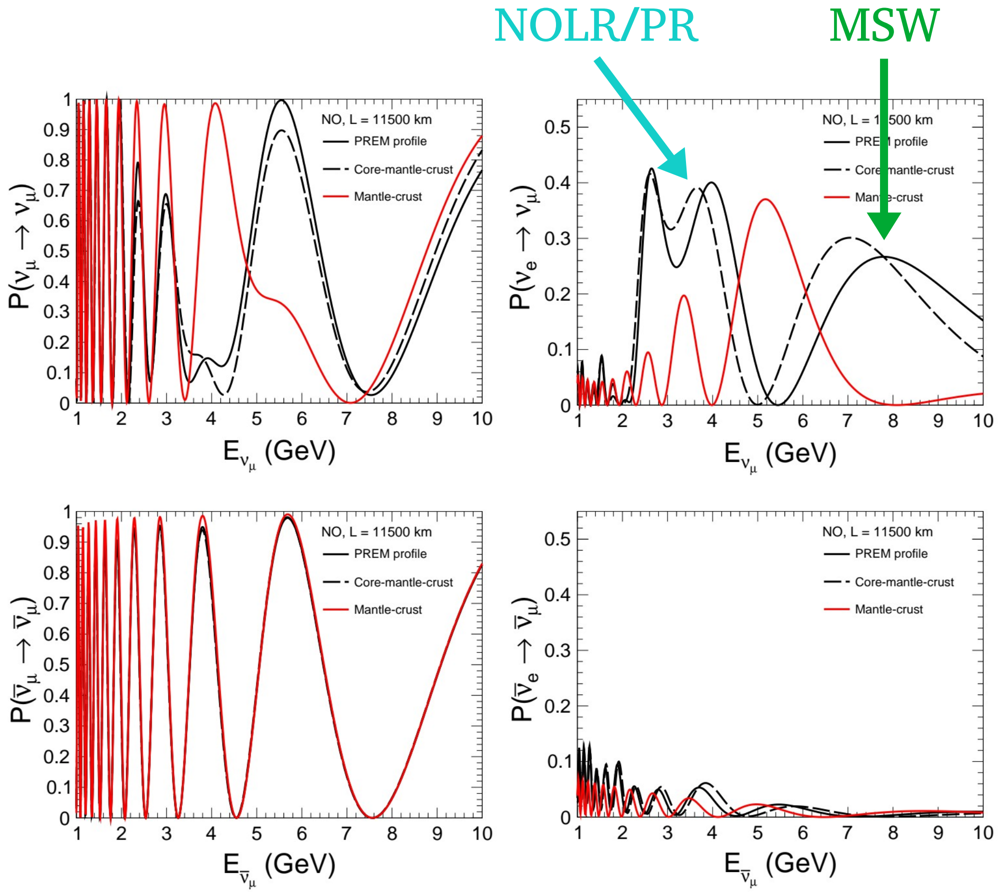
$$V_{CC} = \pm\sqrt{2}G_F N_e$$
$$\approx \pm 7.6 \times Y_e \times 10^{-14} \left[\frac{\rho}{\mathrm{g/cm^3}}\right] \ \mathrm{eV}$$

where, $Y_e = N_e/(N_p + N_n)$, corresponds to the relative electron number density inside the matter and ρ denotes the matter density.

The matter effects occur for neutrino (antineutrino) if NO (IO) is true

Mikheyev–Smirnov–Wolfenstein (MSW) resonance (L. Wolfenstein, Phys. Rev. D17 (1978) 2369): 6 GeV < E_ν < 10 GeV0

Neutrino oscillation length resonance (NOLR) (Petcov, Phys. Lett. B 434 (1998) 321)/**parametric resonance resonance (PR)** (Akhmedov, Nucl. Phys. B538 (1999) 25): 2 GeV < E_ν < 5 GeV



Effect of diff. Density Profiles on $P(\nu_\mu \rightarrow \nu_\mu)$ Oscillograms

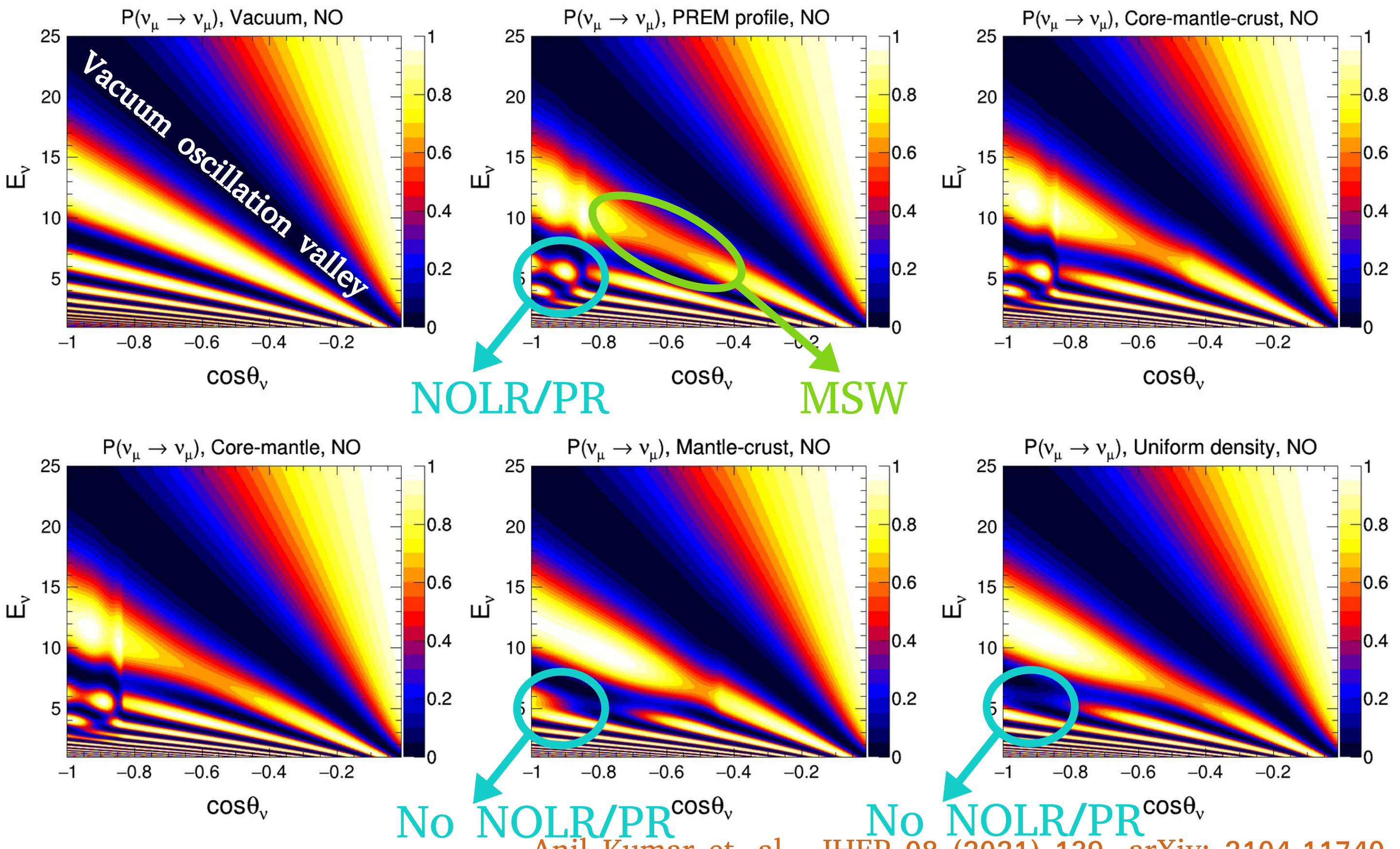
MSW resonance: red patch around $-0.8 < \cos\theta_\nu < -0.5$ and 6 GeV $< E_\nu < 10$ GeV

NOLR/PR: yellow patches around $\cos\theta_\nu < -0.8$ and 2 GeV $< E_\nu < 6$ GeV

No Core → No NOLR/PR

Note:

- Reducing energy threshold helps
- MSW and NOLR/PR have not been observed in any experiment till now



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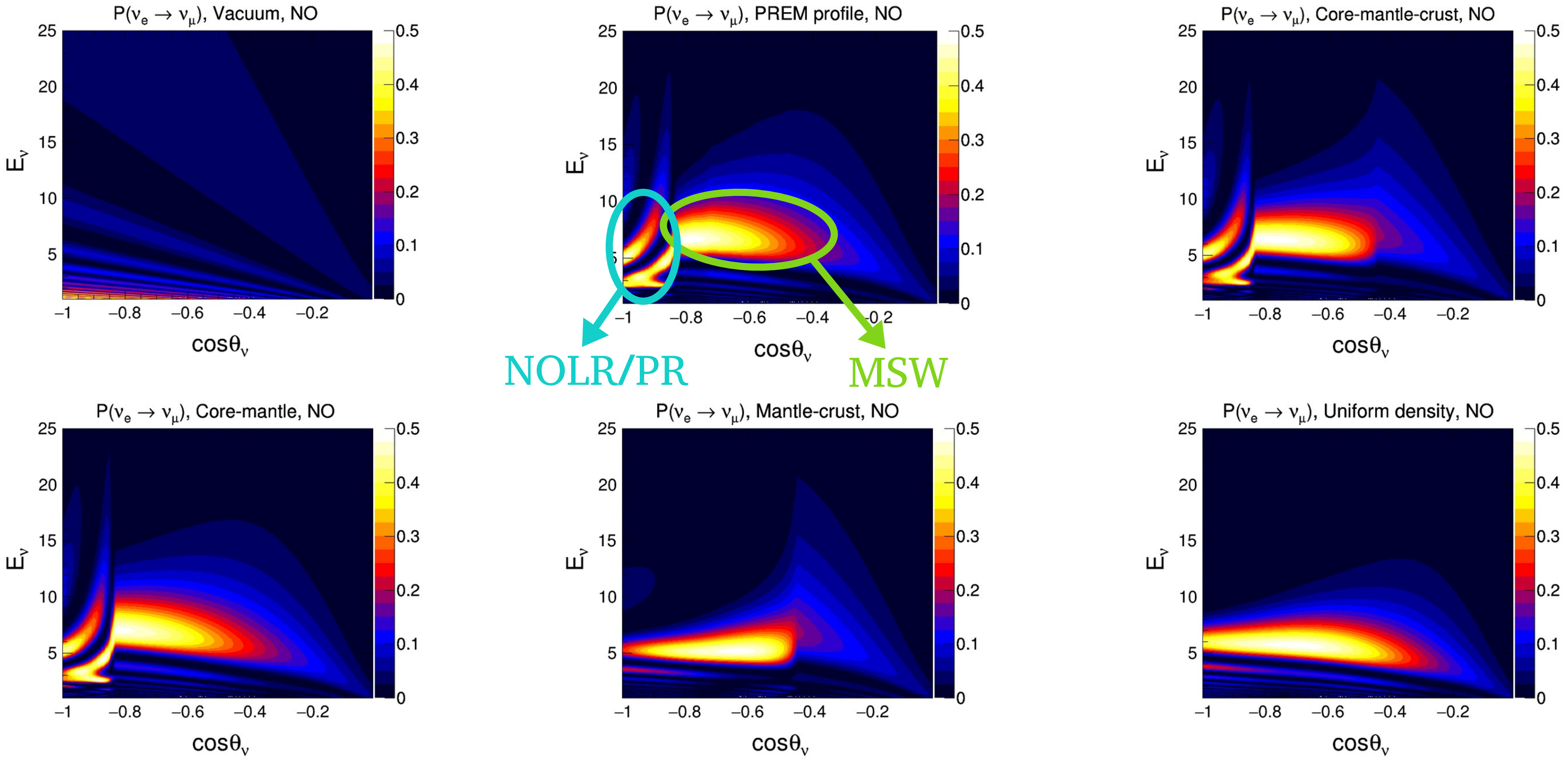
Effect of diff. Density Profiles on $P(\nu_e \to \nu_\mu)$ Oscillograms



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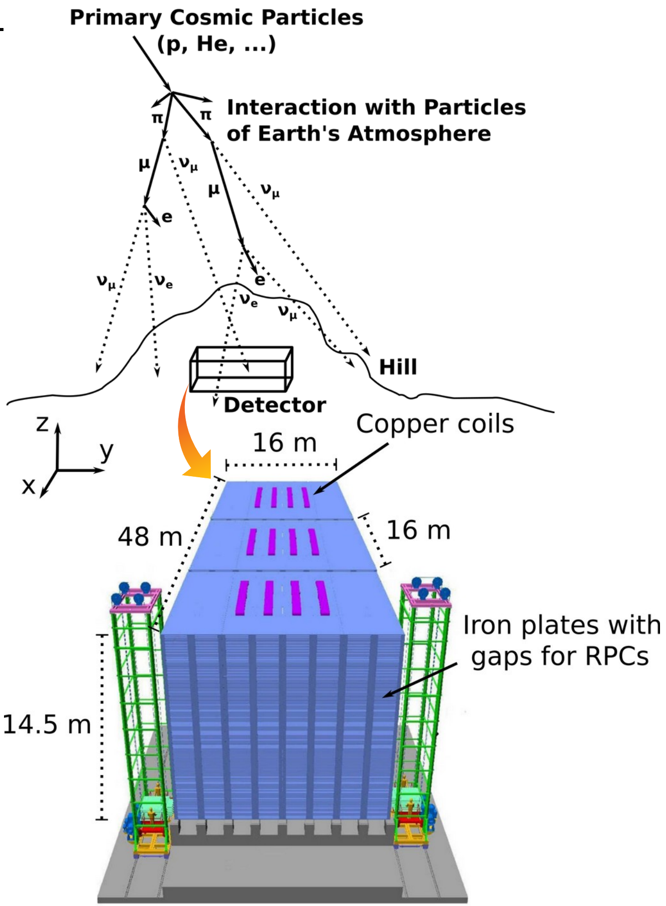
Iron Calorimeter Detector (ICAL) at INO

- **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 neutrino mass ordering and precision measurement of atmospheric neutrino 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:** ~ 10%
- **Baselines:** 15 – 12000 km
- **Muon zenith angle resolution:** ~ 1°



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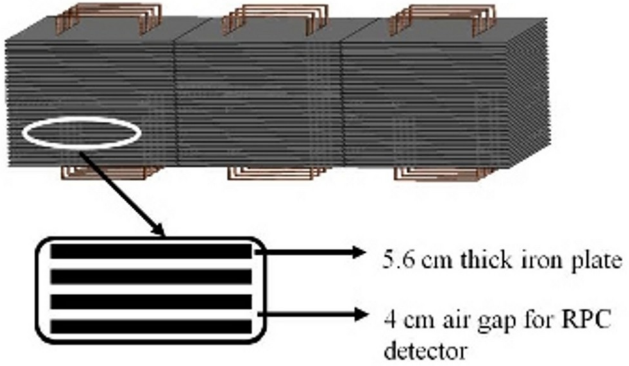
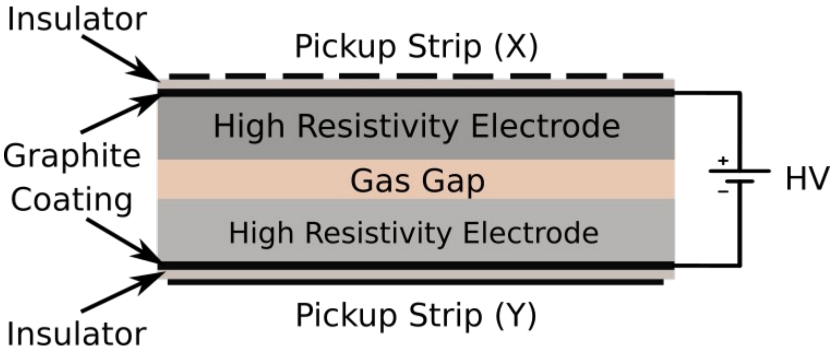
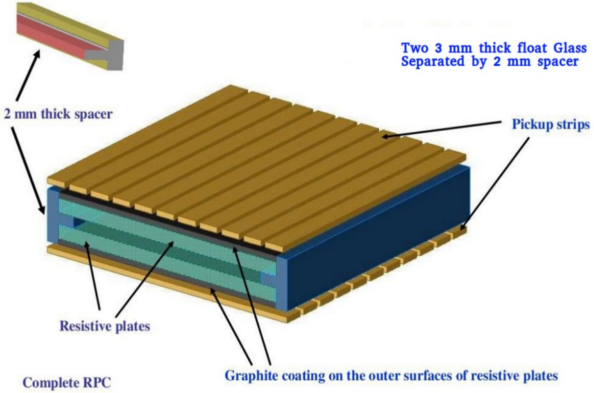
ICAL Design an Specifications



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	$\sim$ 30,000
No. of electronic readout channels	3.9×10^6





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

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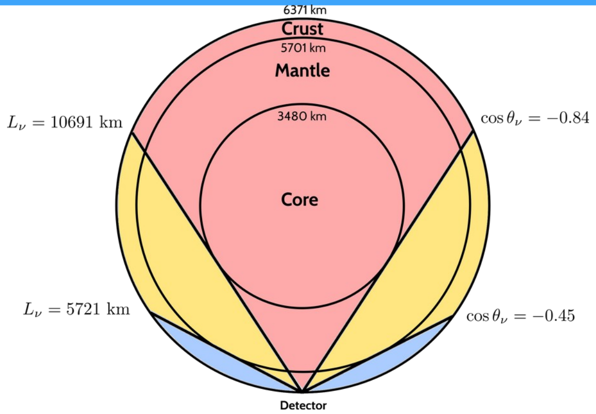
Identifying Events for Neutrinos Passing through Different Layers of Earth

- Neutrino flux (Honda) at INO site
- 500 kt·yr exposure at ICAL
- Three-flavor neutrino oscillations in the presence of matter with the 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

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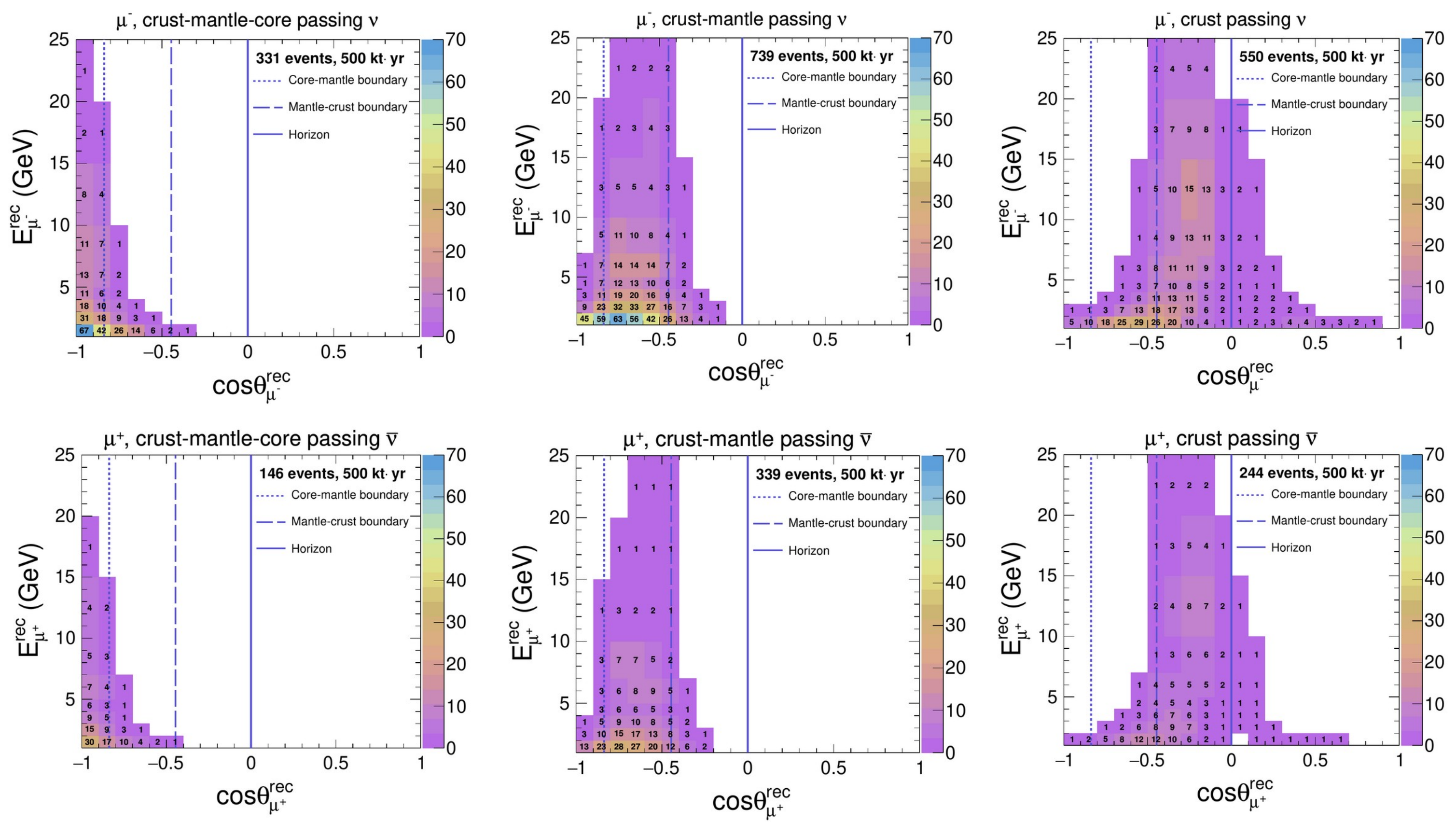
Distribution of Events for Neutrinos Passing through Different Layers of Earth

- Neutrino flux at INO site
- 500 kt·yr exposure at ICAL
- Three-flavor neutrino oscillations in the presence of matter with the PREM profile.



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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,

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

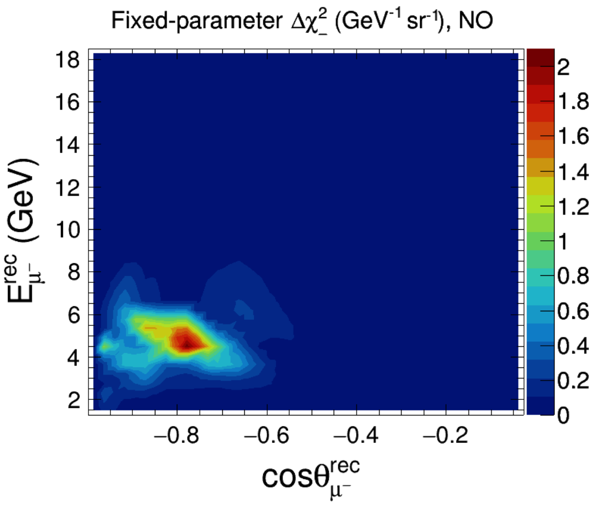
Similarly, χ^2_+ is defined for μ^+

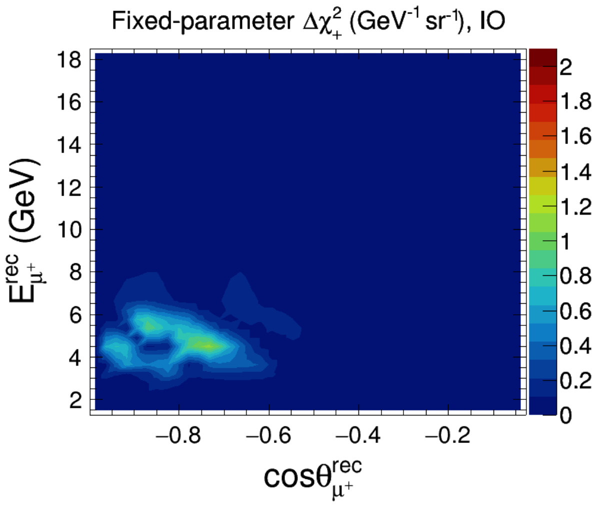
$$\chi^2_{\rm ICAL} = \chi^2_- + \chi^2_+$$

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

Effective Regions in (E_μ^{rec}, $\cos\theta_\mu^{rec}$) 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 to explore contributions from each bin in (E_μ^{rec}, $\cos\theta_\mu^{rec}$) plane for μ^- and μ^+ events, respectively.

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Sensitivity to Validate Earth's Core with and without CID

- 500 kt·yr exposure at ICAL
- Marginalization over:
  - systematic uncertainties
  - Oscillation parameter:
    - $\sin^2\theta_{23}$: (0.36, 0.66)
    - Δm^2_{eff}: (2.1, 2.6) $\times 10^{-3}$ eV^2
    - mass ordering: (NO, IO)

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

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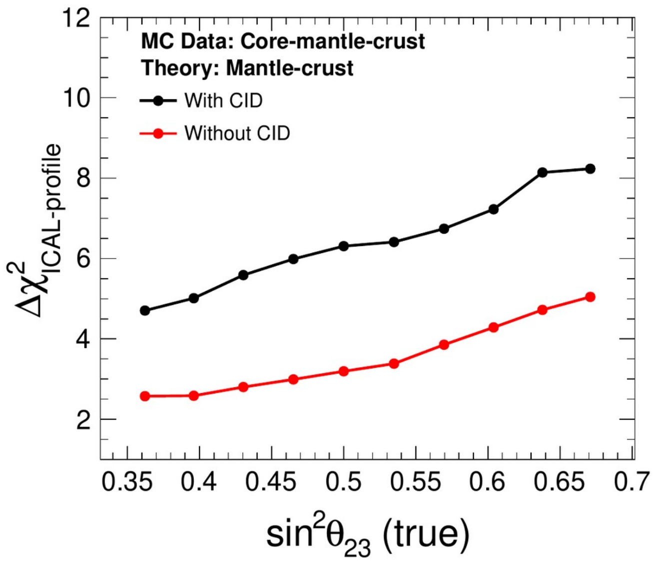
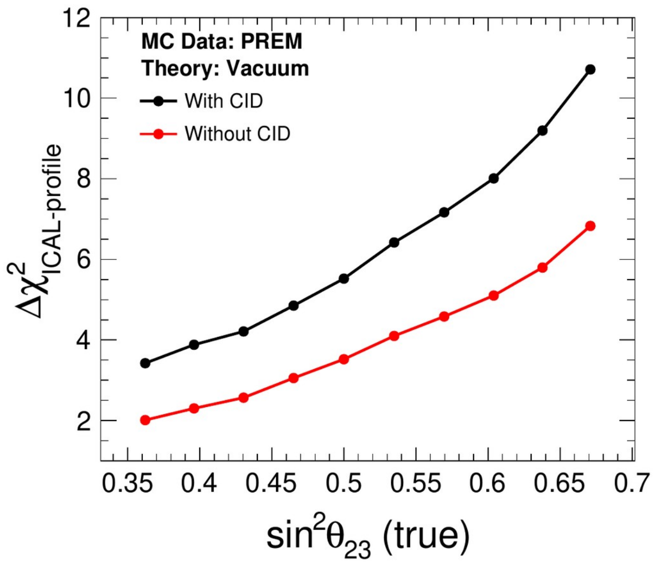
Impact of Different True Choices of $\sin^2\theta_{23}$

- 500 kt·yr exposure at ICAL
- Marginalization over:
  - systematic uncertainties
  - Oscillation parameter:
    - $\sin^2\theta_{23}$: (0.36, 0.66)
    - Δm^2_{eff}: (2.1, 2.6) $\times 10^{-3}$ eV^2
    - mass ordering: (NO, IO)





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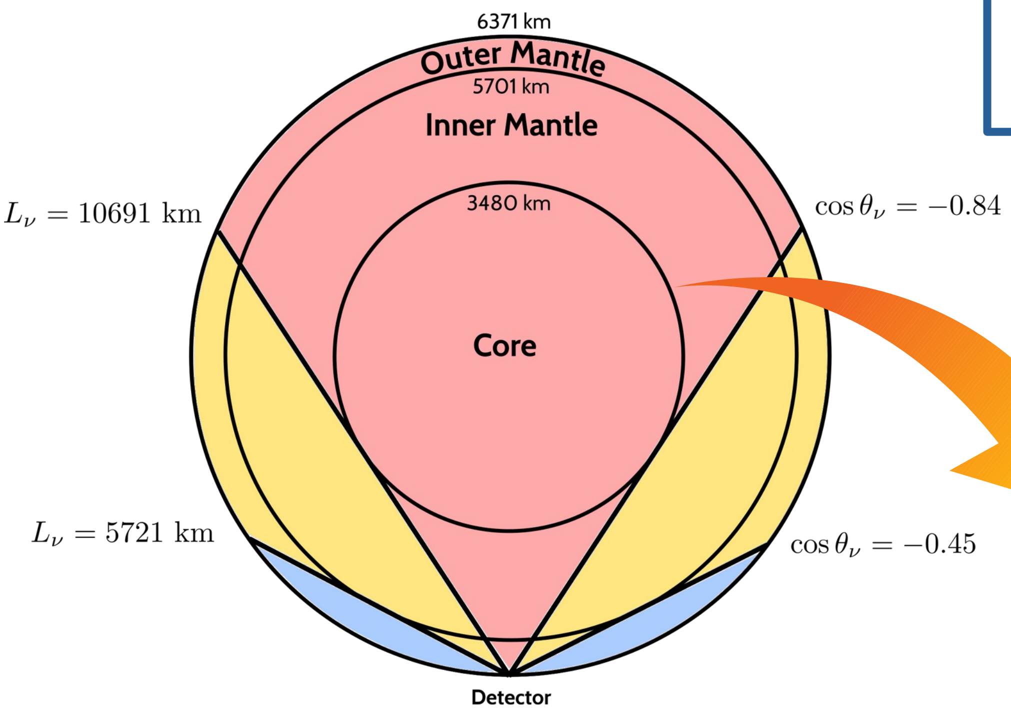
Probing Location of Core-Mantle Boundary



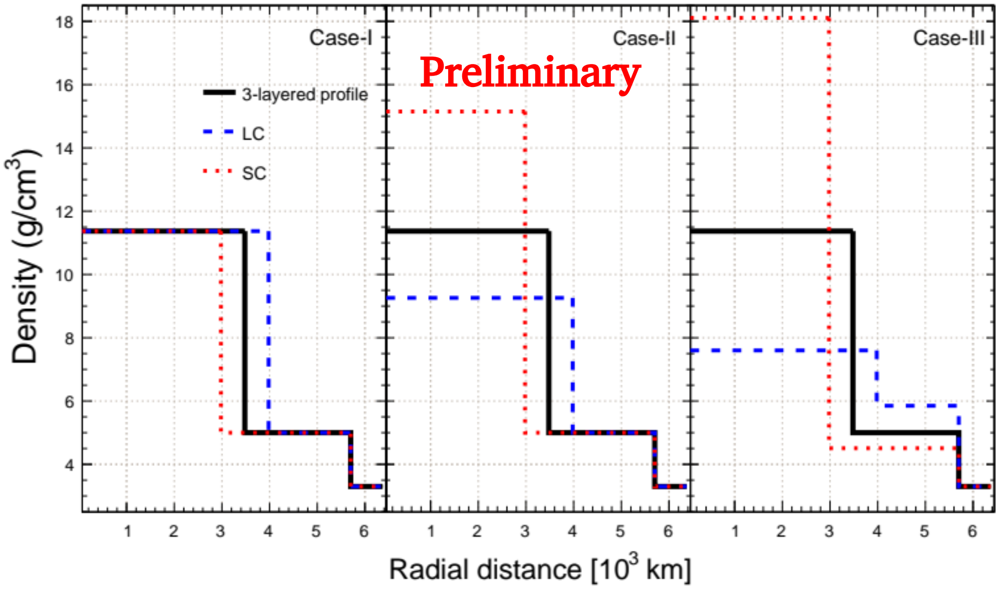
Till now, we talked about the sensitivity to establish the presence of high-density core.

The next important task is to probe the location of Core-mantle boundary (CMB)

Varying CMB in Different Ways

We consider three density models while varying CMB:

- **Case-I**: density of each layer is kept fixed. The total mass of Earth is not constant.
- **Case-II**: density of core modifies such that the total mass of Earth remain constant.
- **Case-III**: densities of core and inner mantle modify such that the individual masses of core and inner-mantle remain constant. The total mass of the Earth is also constant.



- Nominal Core: 3480 km
- Larger Core (LC): 3480 + 500 km
- Smaller Core (SC): 3480 − 500 km

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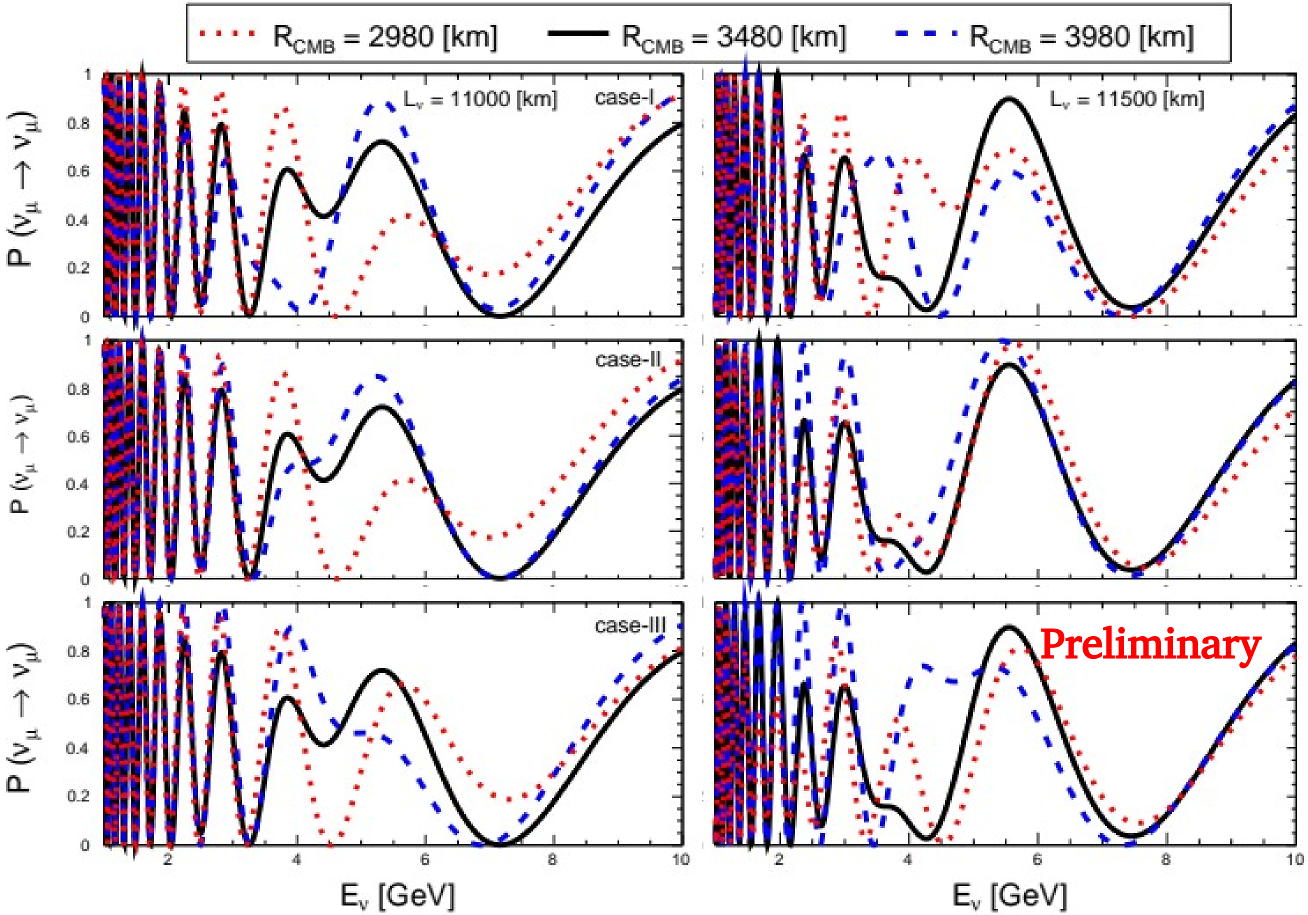
Effect of CMB Variation on Oscillation Probability

Observations:

- CMB variation significantly affects oscillation probability $P(\nu_\mu \rightarrow \nu_\mu)$ at low energy of 2 to 5 GeV (NOLR/PR)
- Effect of CMB variation depends on the baseline.



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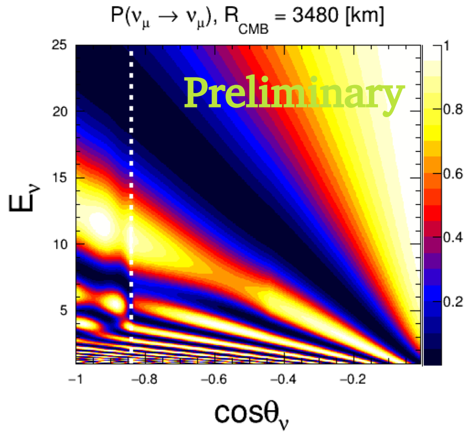
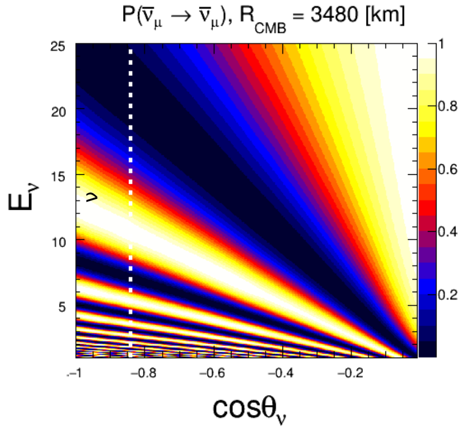
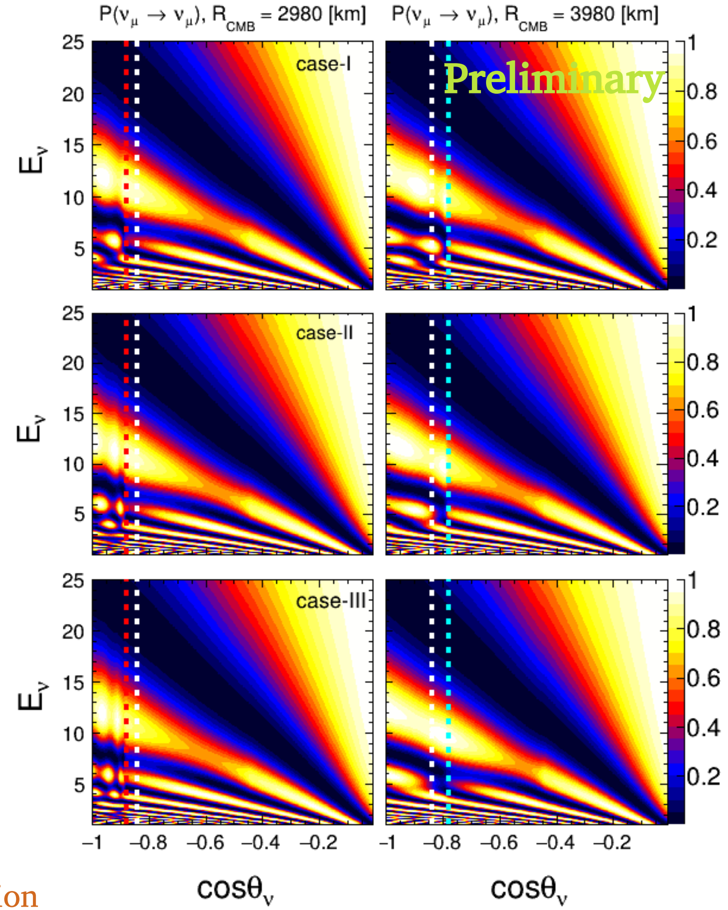
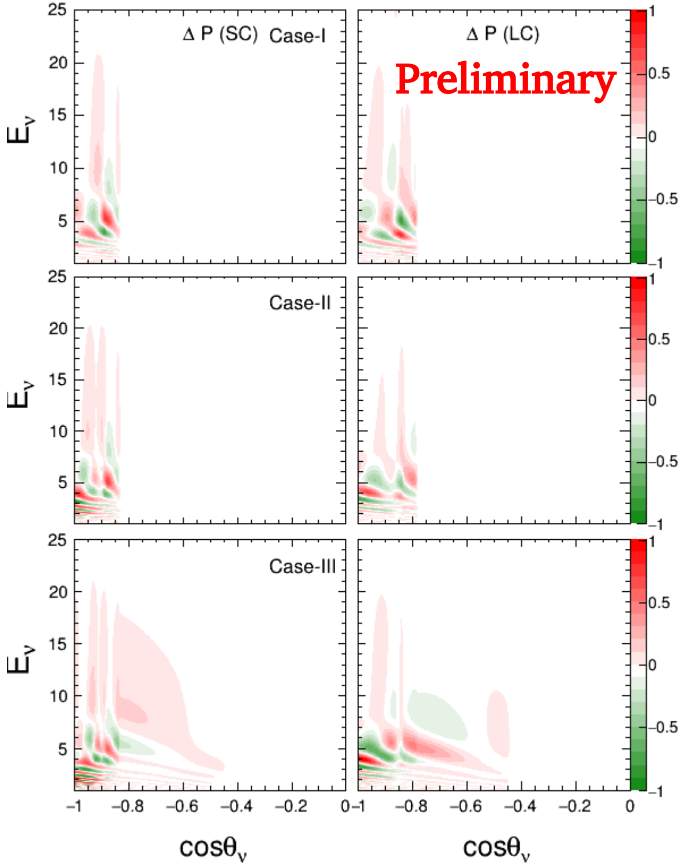
Effect of CMB Variation on Oscillograms









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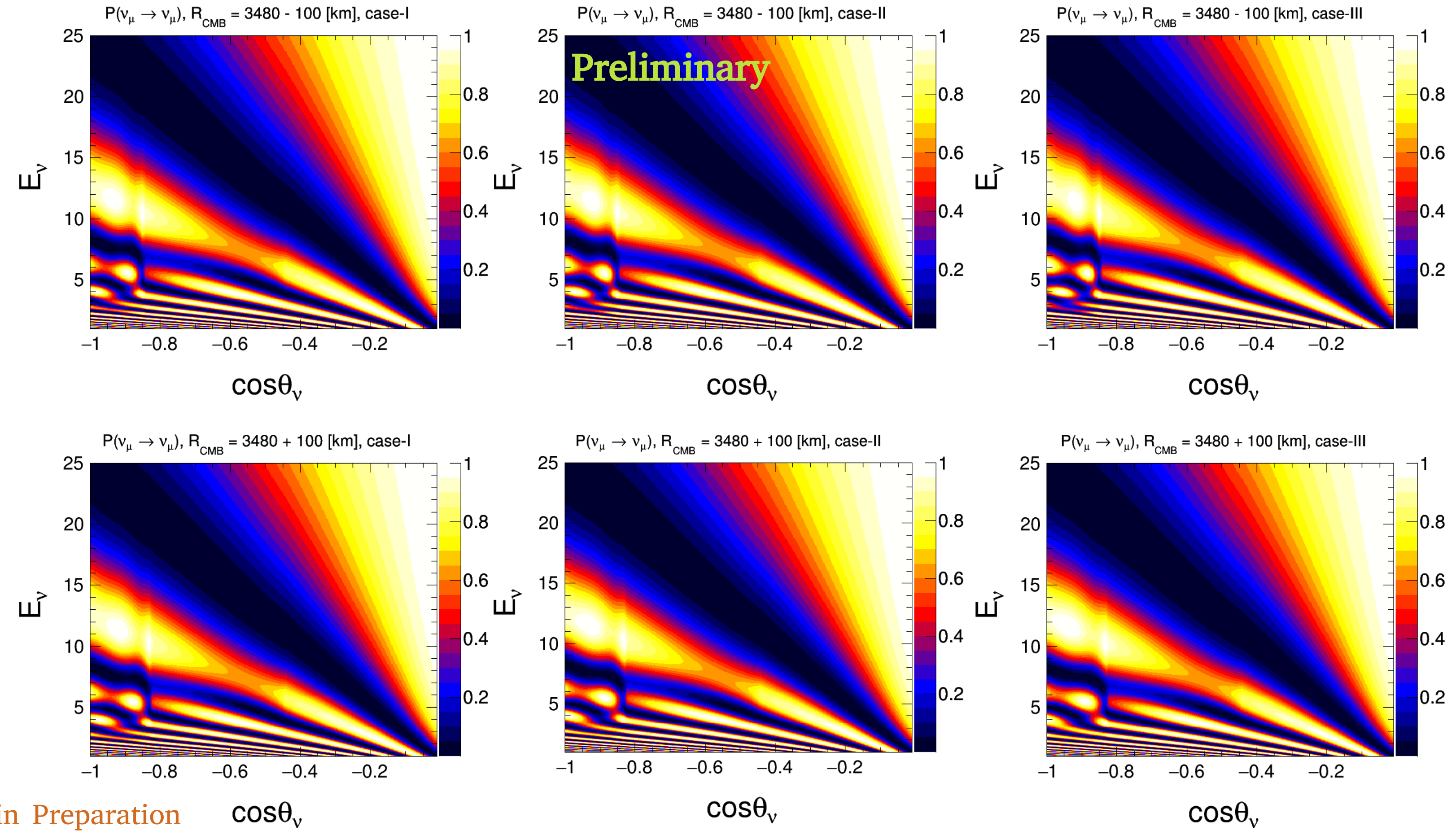
Effect of CMB Variation on Oscillograms



Observations:

- For smaller core, the NOLR/PR shfits to left and patterns shrink
- For larger core, the NOLR/PR shifts to right and patterns broaden

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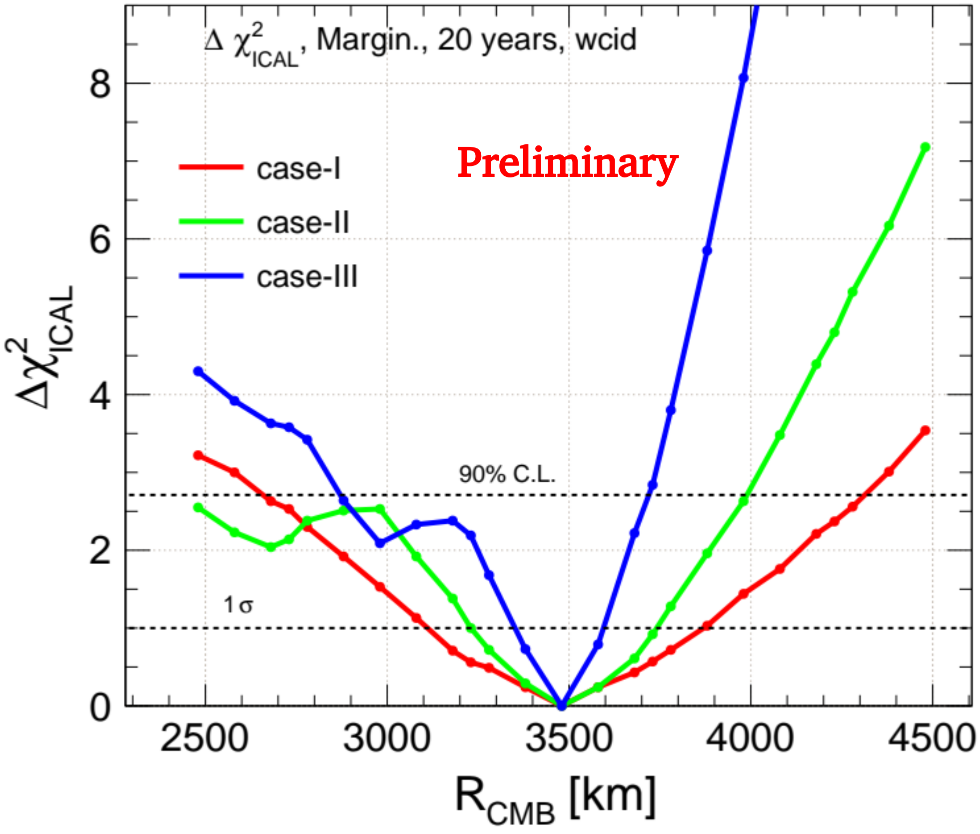
Sensitivity for Locating Core-Mantle Boundary



		$\Delta\chi^2_{ICAL\text{-}profile}$ (1 Mt.yr)	
		w CID	w/o CID
Case-I	R_{CMB} = 2980 km	1.53	1.01
	R_{CMB} = 3980 km	1.44	0.95
Case-II	R_{CMB} = 2980 km	2.53	1.66
	R_{CMB} = 3980 km	2.63	1.67
Case-III	R_{CMB} = 2980 km	2.09	1.33
	R_{CMB} = 3980 km	8.07	5.23

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Summary

- In combination with gravitational and seismic studies, neutrino oscillations and absorption based measurements would pave the way for **“multi-messenger tomography of Earth”**.
- Atmospheric neutrinos have energies in the multi-GeV range where the Earth matter effects are significant, hence they would serve as probes of the internal structure of Earth.
- ICAL can detect 331 μ^- and 146 μ^+ core passing events in 10 years.
- 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.
- The location of Core-mantle boundary can be probed using the atmospheric neutrinos at ICAL.

We acknowledge the financial support from the Department of Atomic Energy (DAE), Department of Science and Technology (DST), Govt. of India, Science and Engineering Research Board (SERB), and the Indian National Science Academy (INSA).

Thank you

Backup: Impact of Marginalization over Various Oscillation Parameters

- 500 kt·yr exposure at ICAL
- Marginalization over systematic uncertainties.
- Marginalization range for $\sin^2\theta_{23}$: (0.36, 0.66), $|\Delta m^2_{\text{eff}}|$: (2.1, 2.6) $\times 10^{-3}$ eV^2, and mass ordering: (NO, IO)

MC Data	Theory	$\Delta\chi^2_{\text{ICAL-profile}}$				
		Fixed parameter	Marginalization over			
			$\sin^2\theta_{23}$	$\|\Delta m^2_{\text{eff}}\|$	$\pm\|\Delta m^2_{\text{eff}}\|$	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