Neutrino tomography of Earth using INO@ICAL

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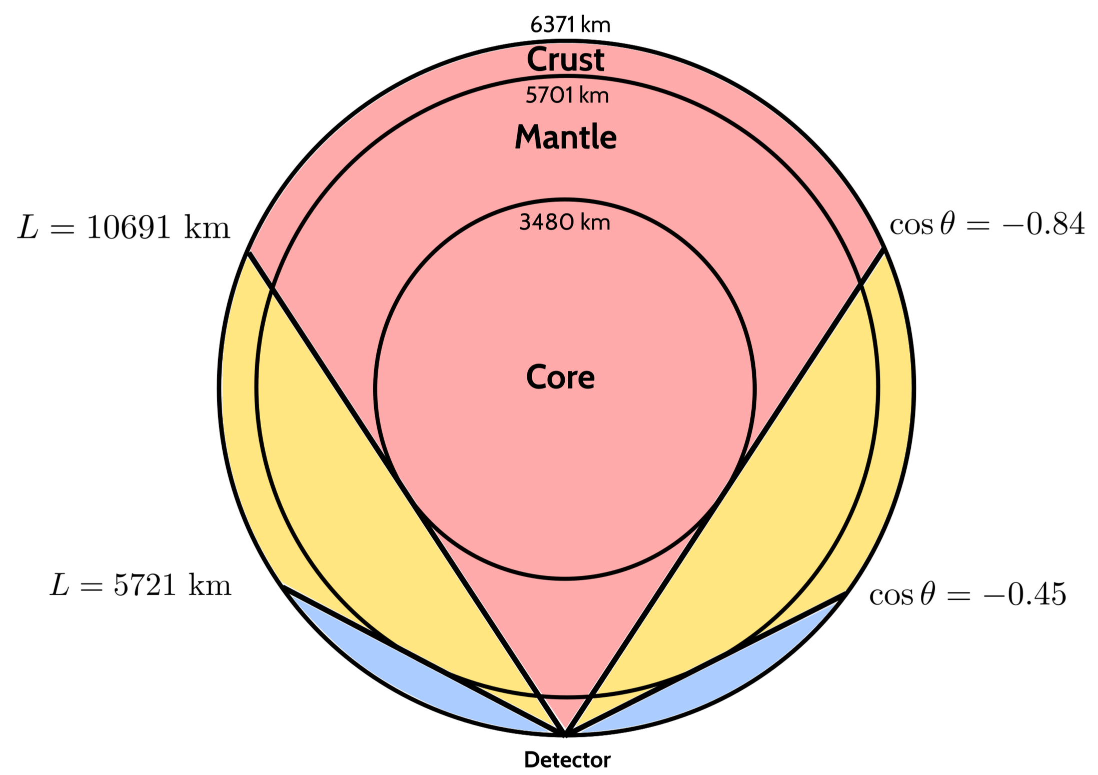
Iron Calorimeter (ICAL) detector at INO [1] can play an important role to reveal the existence of Earth's core since it can reconstruct core passing ν_μ and $\bar{\nu}_\mu$ separately with high resolution in the multi-GeV range of energy.

- **ICAL@INO:** 50 kton magnetized iron detector
- **Uniqueness:** CID for muons, distinguishes 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°

Internal Structure of Earth



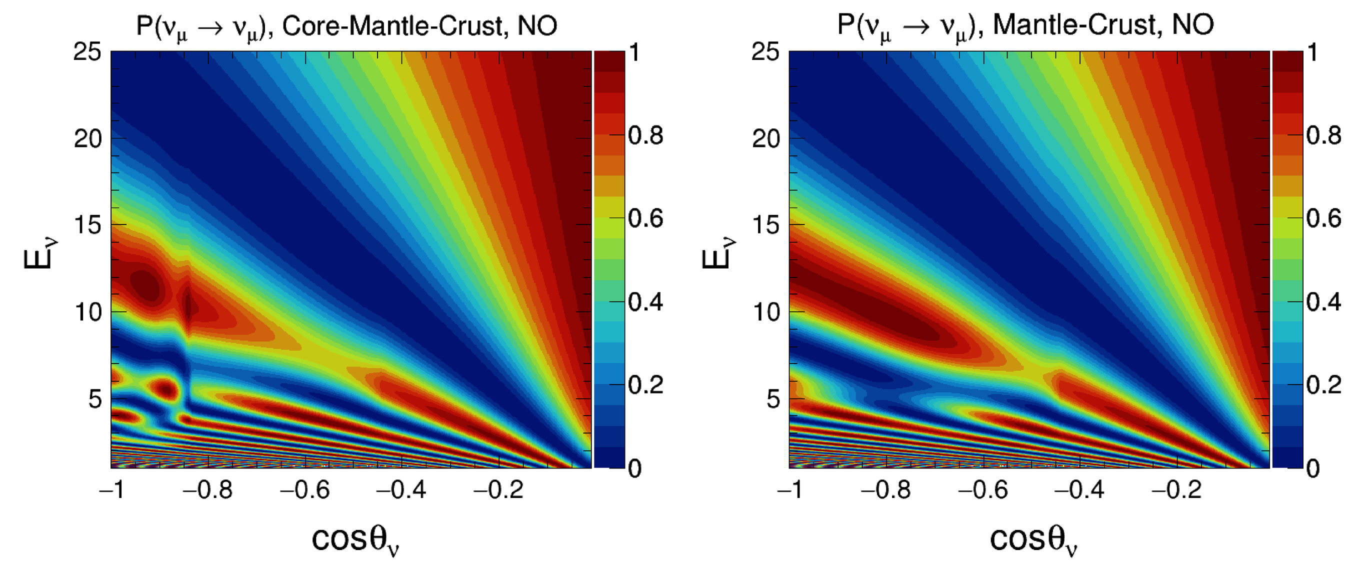
Three layer profile of Earth

Profiles	Boundaries (km)	Densities (g/cm^3)
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)

Neutrino Oscillations in Matter

- The atmospheric neutrinos undergo coherent elastic forward scattering with electrons inside the Earth which leads to the modification of neutrino oscillations[2].
- Neutrinos passing through the mantle feel the Mikheyev-Smirnov-Wolfenstein (MSW) resonance.
- The core passing neutrinos experience parametric resonance.

Probability Oscillograms



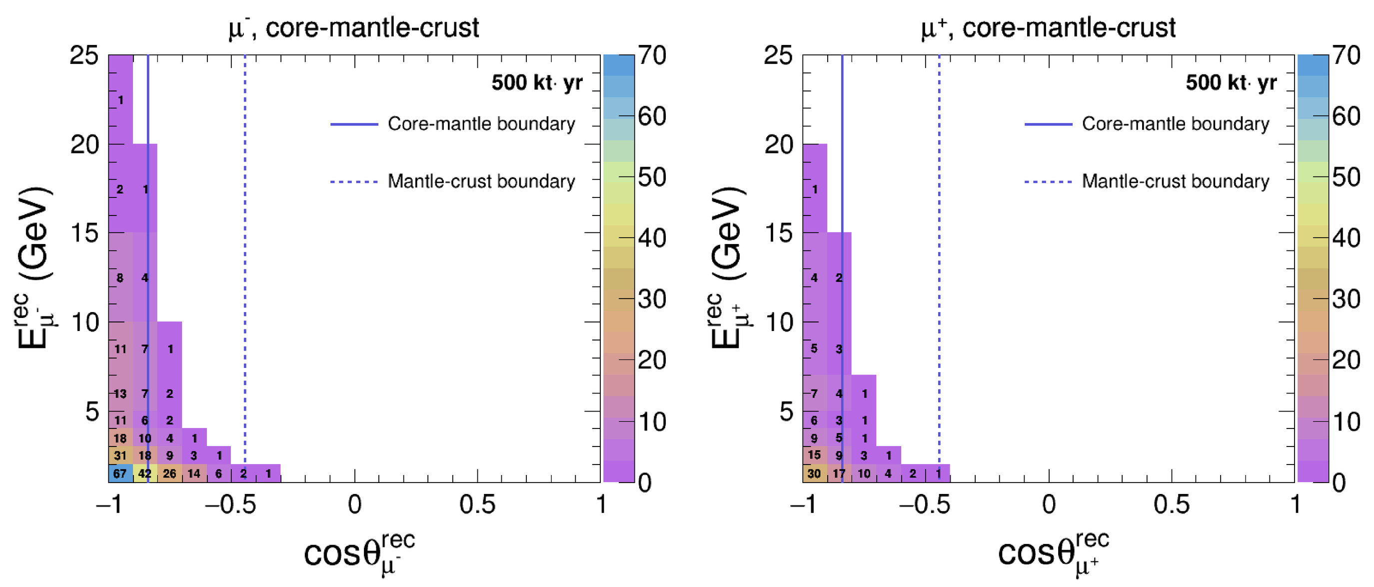
Core -> Parametric resonance

Methodology

- Three flavor neutrino oscillations in the presence of matter by considering various profiles of Earth based on PREM profile[3].
- Neutrino events are generated for flux at Theni site using NUANCE.
- The detector properties are incorporated using a migration matrix obtained from GEANT simulations by ICAL collaboration.
- Systematics and uncertainty on oscillation parameters are taken into account while performing statistical analysis.

Core Passing Neutrino Events

Regions	$\cos\theta_\nu$	Baseline (km)	μ^- Events	μ^+ Events
Core-mantle-crust	(-1.00, -0.84)	(10691, 12757)	331	146
Mantle-crust	(-0.84, -0.45)	(5721, 10691)	739	339
Crust	(-0.45, 0.00)	(437, 5721)	550	244



Statistical Analysis and Results

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

where,

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

Similarly, χ^2_+ is defined for μ^+

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

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

• Neutrino Flux: Theni • Exposure: 500 kt·yr • Marginalization over $\sin^2\theta_{23}$: (0.36, 0.66), Δm^2_{eff}: (2.1, 2.6) $\times 10^{-3}$ eV^2, and mass ordering: (NO, IO)

Data	Theory	$\Delta\chi^2_{\text{ICAL-profile}}$			
		NO(true)		IO(true)	
		CID	No CID	CID	No 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

Summary and Conclusion

- Using atmospheric neutrinos at ICAL in 10 years, the presence of Earth's core can be established at $\Delta\chi^2$ of 6.31 for normal ordering and 3.92 for inverted ordering
- Charge identification capability of ICAL plays a crucial role in establishing the presence of core.

References

[1] A. Kumar et al. "Invited review: Physics potential of the ICAL detector at the India-based Neutrino Observatory (INO)". In: *Pramana* 88.5 (2017), p. 79. ISSN: 0973-7111.

[2] L. Wolfenstein. "Neutrino oscillations in matter". In: *Phys. Rev. D* 17 (9 1978), pp. 2369–2374.

[3] Adam M. Dziewonski and Don L. Anderson. "Preliminary reference Earth model". In: *Physics of the Earth and Planetary Interiors* 25.4 (1981), pp. 297 –356. ISSN: 0031-9201.

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