

Neutrino Oscillation Analysis with Atmospheric Neutrinos

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Dec 15, 2025

WHEPP 2025

IIT Hyderabad

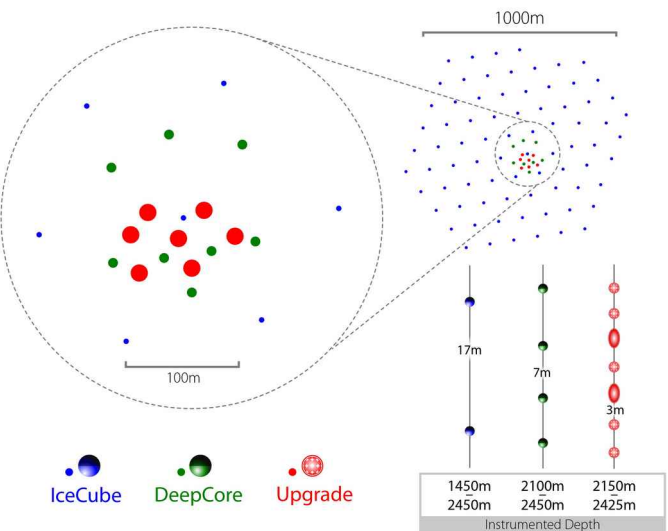
HELMHOLTZ



ICECUBE
NEUTRINO OBSERVATORY



IceCube DeepCore



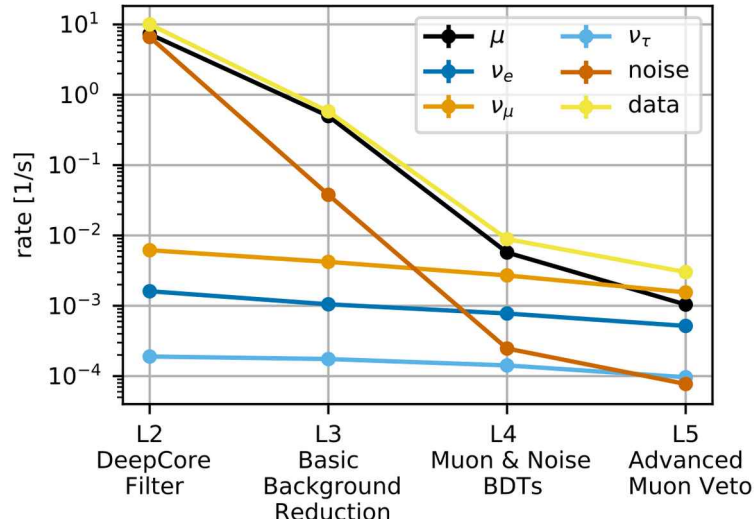
Signals:

- ν_μ, ν_e, ν_τ
- Predominantly DIS interactions

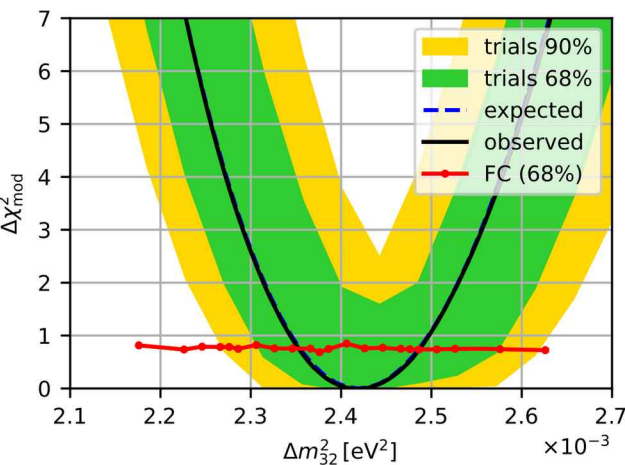
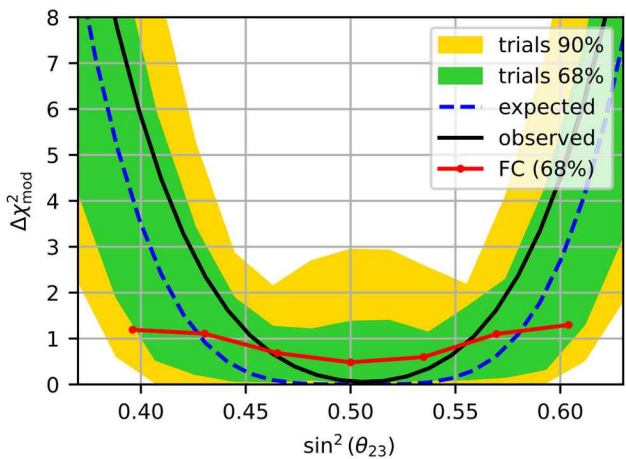
Backgrounds:

- Atmospheric muons
- Random detector noise

Systematics: DAEMON flux, cross-section, detector response, neutrino and muon normalizations.



Filters at various levels reduce backgrounds such as **noise** and **atmospheric muons** below 1% of signal.



7.5-yr Golden Event Sample

I performed the computationally expensive calculations of the Feldmann Cousins confidence intervals for θ_{23} and Δm^2_{32} measurements.

PRD 108, 012014 (2023)

Invisible Neutrino Decay Analysis

Chikashige, Mohapatra, Peccei, PLB 98 (1981) 265
 Gelmini, Roncadelli, PLB 99 (1981) 411
 Gelmini, Valle, PLB 142 (1984) 181

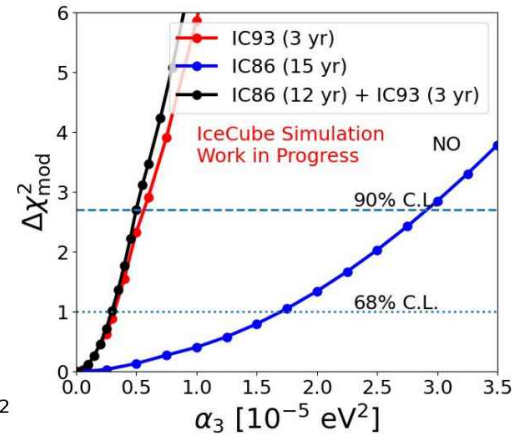
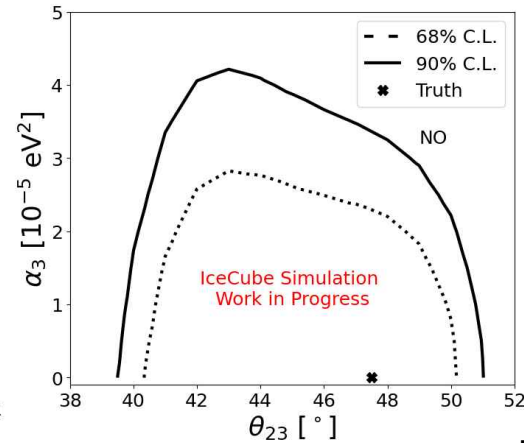
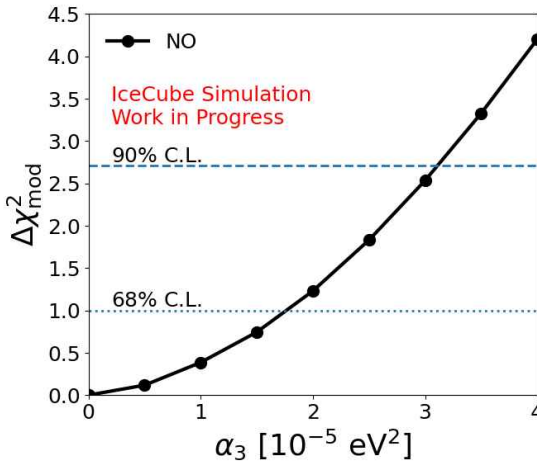
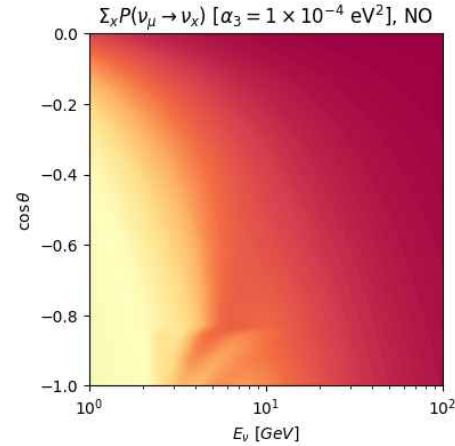
- Modified Hamiltonian in flavor basis for decay of ν_3 :

$$D = e^{-\frac{t}{\gamma\tau_i}} = e^{-\frac{m_i t}{\tau_i E}} = e^{-\frac{\alpha_i L}{E}}$$

$$H = \frac{1}{2E} U \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix} \right] U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where, $\alpha_i = \frac{m_i}{\tau_i}$

9.28-yr CNN reconstructed sample at DeepCore

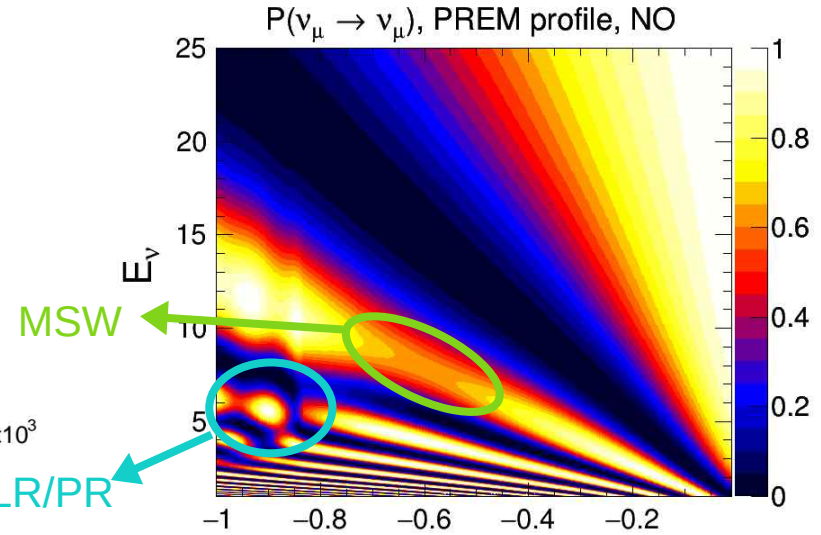
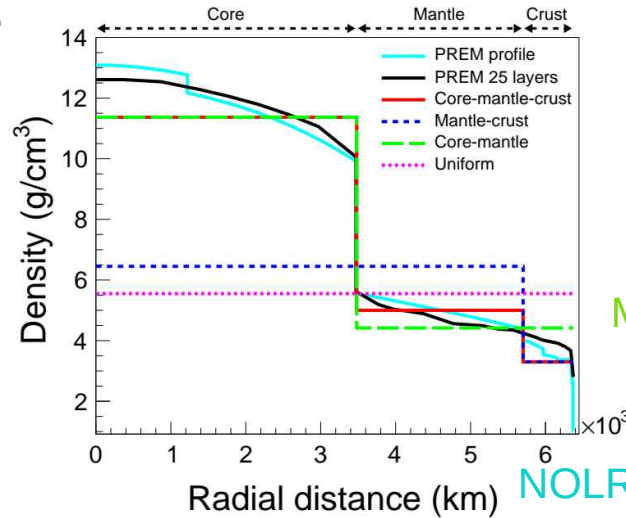
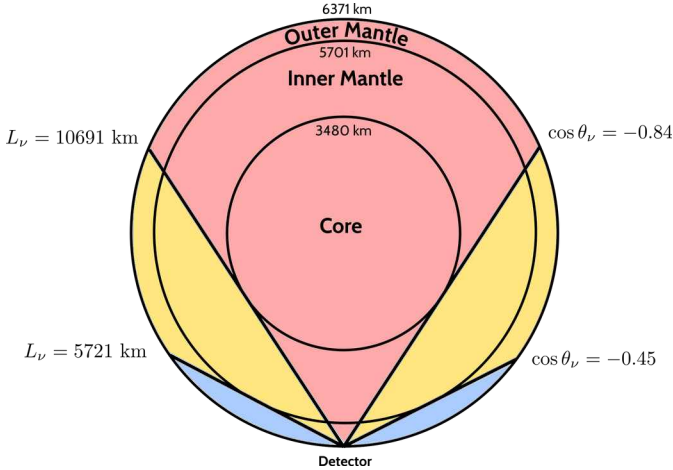


Currently, this analysis is being unblinded

α_3 sensitivity increases significantly with IceCube Upgrade.

Neutrino Oscillation Tomography of Earth

The matter effects experienced by atmospheric neutrinos passing through Earth can be used to probe the interiors of Earth.



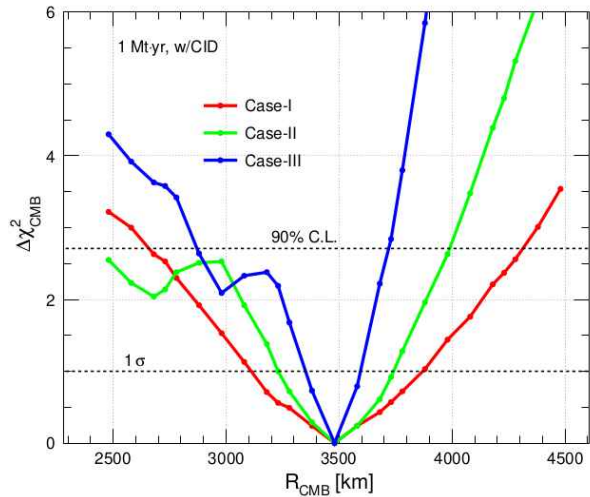
Mikheyev–Smirnov–Wolfenstein (MSW) resonance (L. Wolfenstein, *Phys. Rev. D* 17 (1978) 2369): $6 \text{ GeV} < E_\nu < 10 \text{ GeV}$
Neutrino oscillation length resonance (NOLR) (Petcov, *Phys. Lett. B* 434 (1998) 321)/**parametric resonance resonance (PR)** (Akhmedov, *Nucl. Phys. B* 538 (1999) 25): $2 \text{ GeV} < E_\nu < 5 \text{ GeV}$

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

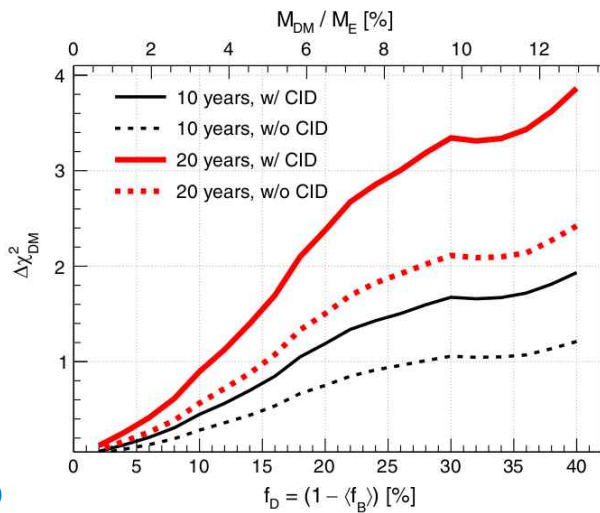
Sensitivity with INO-ICAL $\cos \theta_\nu$

MC Data	Theory	$\Delta \chi^2_{\text{ICAL-profile}}$	
		with CID	w/o CID
PREM Profile	Vacuum	5.52	3.52
PREM Profile	Mantle-crust	7.45	3.76
PREM Profile	Uniform	6.10	3.08

Location of the core

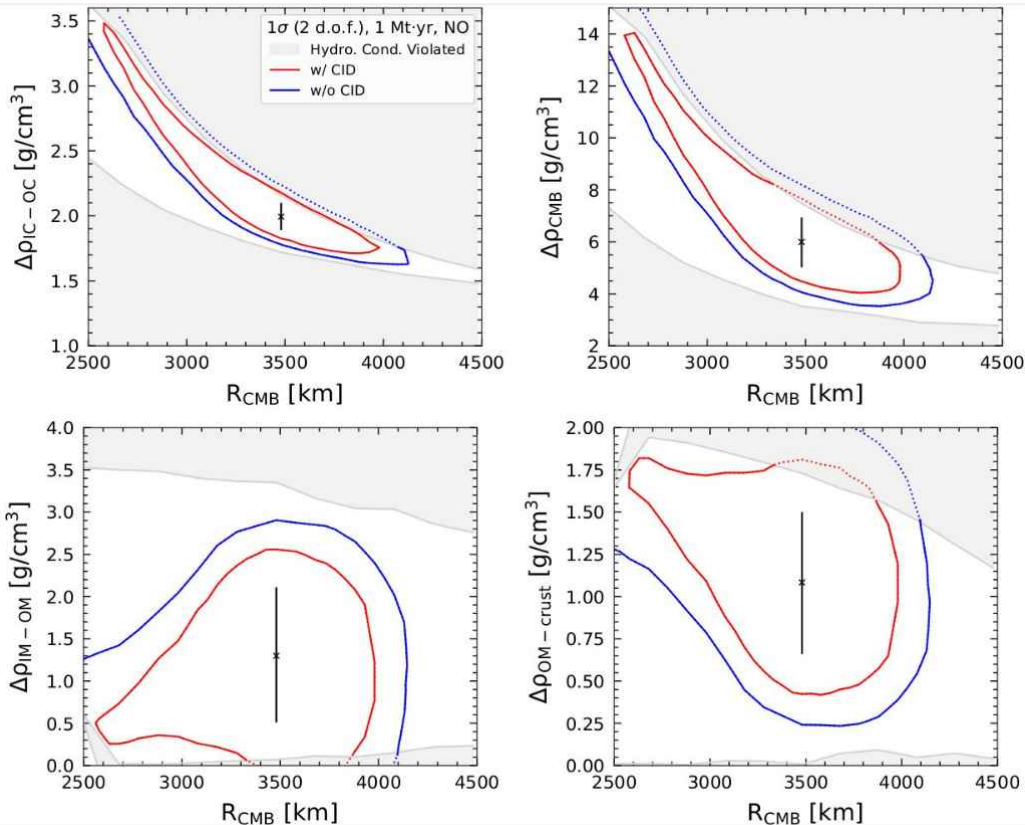


Dark matter inside Earth



Sensitivity study with INO-ICAL

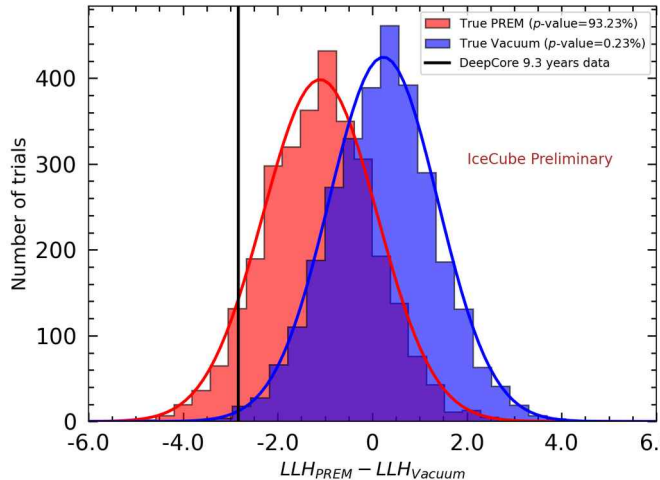
Correlated measurement of the density jump and location of core



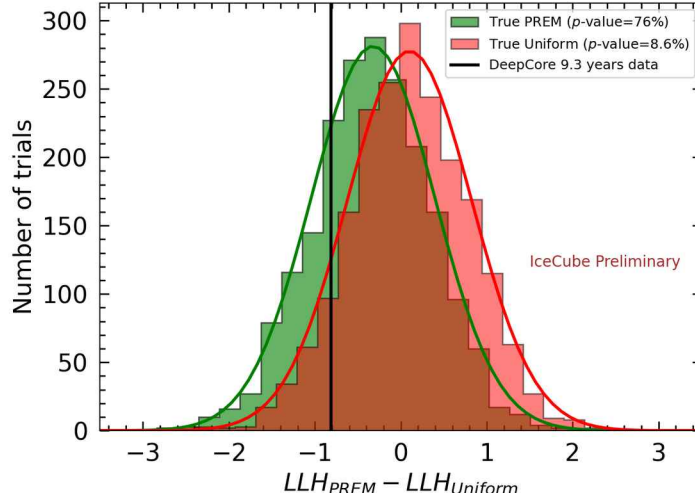
Anuj, Anil, Amol, Sanjib, JHEP 04 (2023) 068, PRD 107 (2023) 11, 115030, arXiv:2405.04986

Neutrino tomography with IceCube DeepCore

DeepCore: Earth's Matter Effects



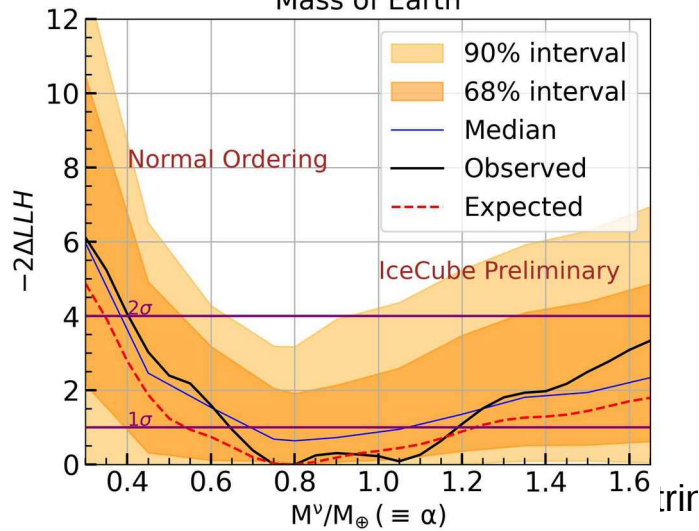
DeepCore: Layered Structure Inside Earth



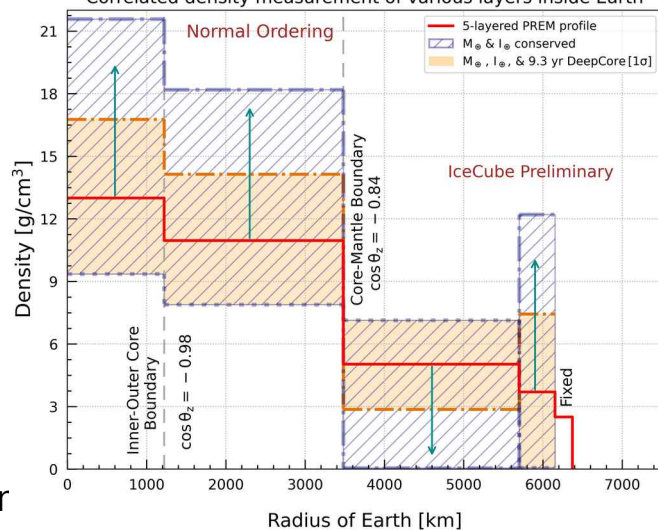
Significance to reject vacuum hypothesis: 1.82σ

Significance to reject uniform hypothesis: 0.36σ

Mass of Earth



Correlated density measurement of various layers inside Earth



Mass of Earth:

$$M_\nu/M_\oplus = 0.775^{+0.414}_{-0.129} \pm 0.2$$

Anuj, Krishnamoorthi, Sharmistha, Anil, Sanjib (IceCube Collaboration). EPJ-ST 234,5055–5064 (2025)

Thank You