Exploring constraints on the core radius and density jumps inside Earth using atmospheric neutrino oscillations

Based on arXiv:2405.04986

Anuj Kumar Upadhyay

(anuju@iopb.res.in)

Aligarh Muslim University, Aligarh & Institute of Physics, Bhubaneswar, India

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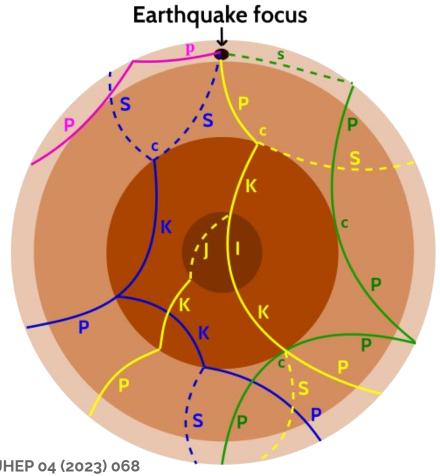
Collaborators: Anil Kumar, Sanjib Kumar Agarwalla, Amol Dighe

Outline

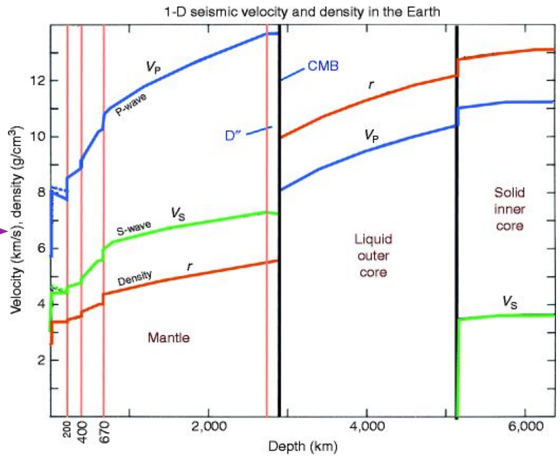
- Information About Earth's interior
- Atmospheric Neutrinos
- Earth's Matter Effects: Key to Probe Internal Structure of Earth
- Neutrinos for constraining the correlated density jumps and location of core-mantle boundary
  - ICAL@INO
  - Sensitivity Results

The Interior of Earth

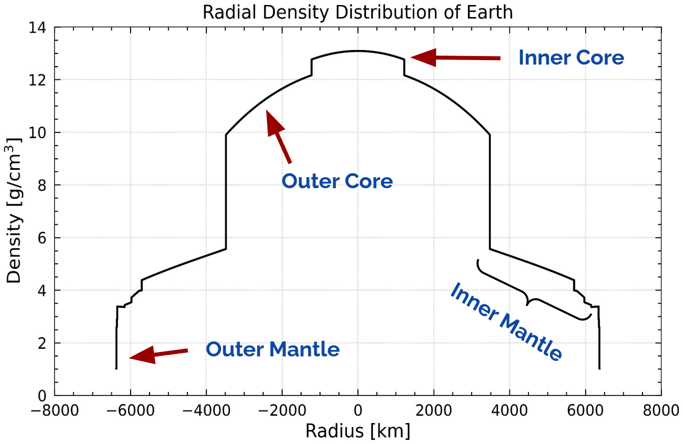
- Information about the interior of Earth is obtained from indirect probes used in traditional **seismic** and **gravitational** studies → **Preliminary Reference Earth Model (PREM)**



JHEP 04 (2023) 068



"PREM" Dziewonski and Anderson (1981)



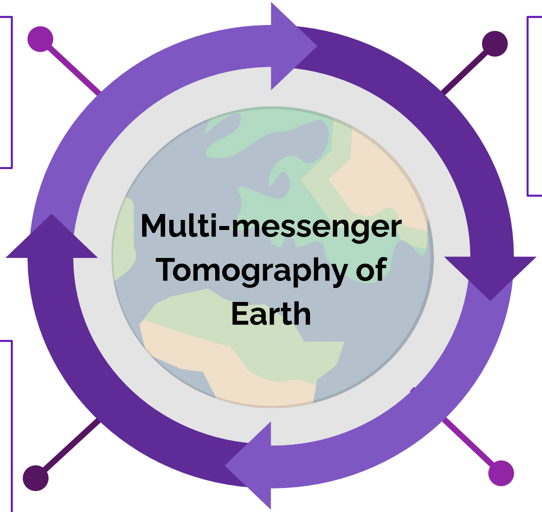
- Broadly classified: two concentric shell - the outer one is mantle, and the inner one with a much higher density is core
- Mantle consists of hot rocks of silicate and core is composed of metals like iron and nickel
- Outer core is expected be liquid (absence of S-waves and decrease in the velocity of P-waves)
- **Core-Mantle Boundary (CMB): the largest compositional discontinuity within the Earth at a depth of 2891 km**
- **The large density contrast across the CMB**

Multi-messenger Tomography of Earth

Neutrinos can penetrate deep inside Earth and may shed light on internal structure and composition

Gravitational Measurement
- Gravitational interactions
- Total mass & moment of inertia

Seismic Studies
- Uses seismic waves from earthquakes
- Electromagnetic interactions



Neutrino Absorption Tomography
- Weak interactions
- Absorption of high-energy (TeV-PeV) neutrinos

Neutrino Oscillation Tomography
- Weak interactions
- Coherent forward scattering of low-energy (MeV-GeV) neutrinos with electrons

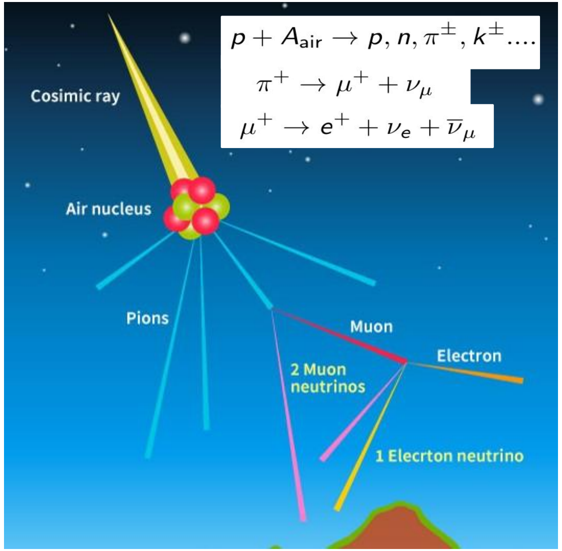
Geoneutrinos
- Brings crucial information about the mantle
- Radiogenic contribution to Earth's heat budget

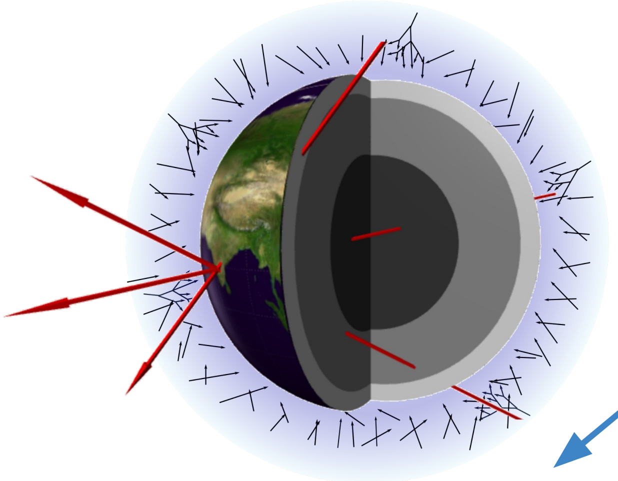
Present study is based on neutrino oscillation tomography

Atmospheric Neutrinos

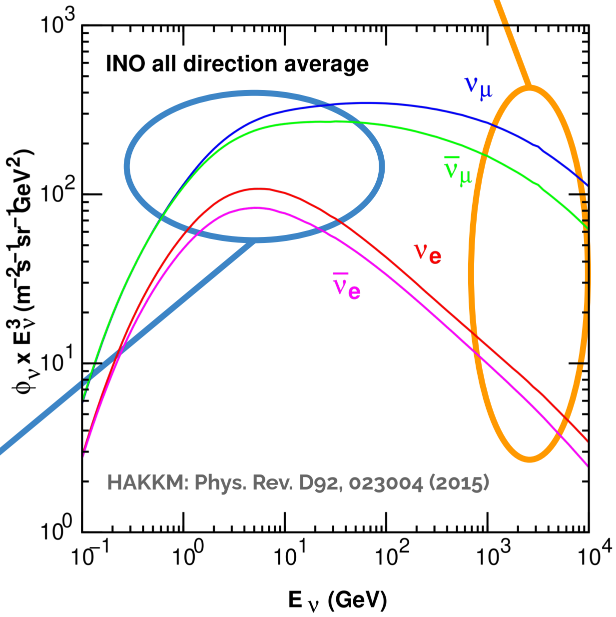
At high (TeV-PeV) energies: Neutrino absorption tomography

- Atmospheric neutrinos are the ideally suited source of neutrinos to probe the internal structure of Earth





At low (MeV-GeV) energies: Neutrino oscillation tomography

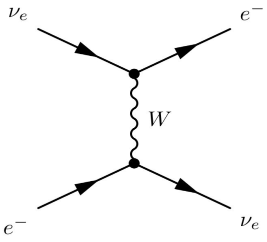


- **Baseline:** ~20 km to 12760 km
- **Wide energy range:** few MeV to more than TeV

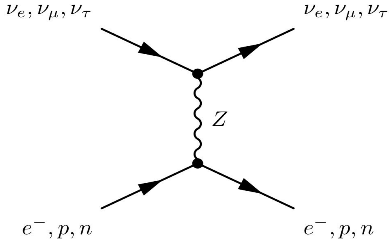
Earth's Matter Effect in Neutrino Oscillations

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

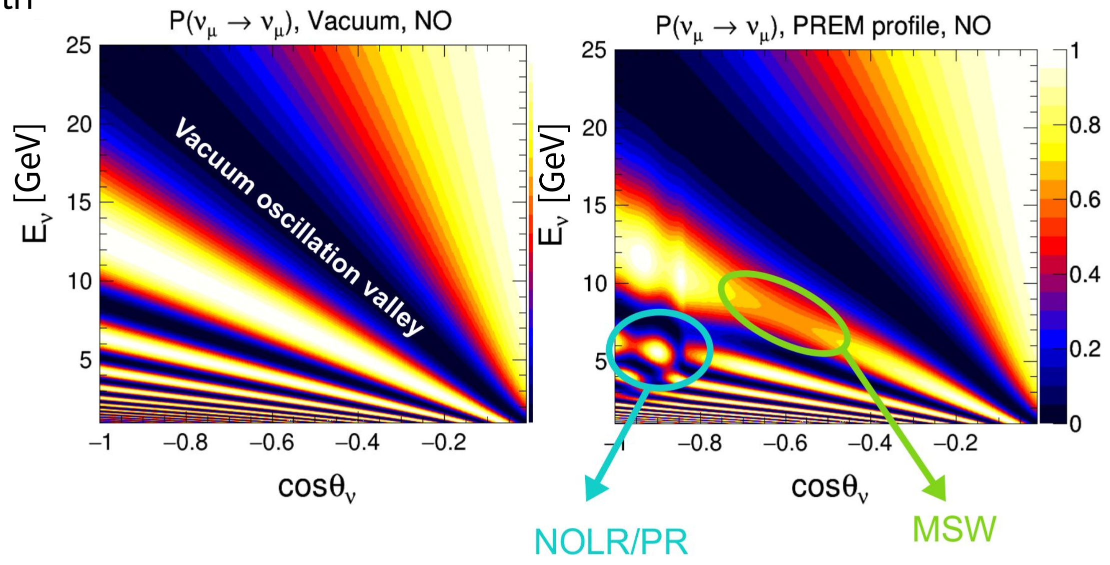
CC interaction



NC interaction



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



Mikheyev–Smirnov–Wolfenstein (MSW) resonance (L. Wolfenstein, PRD 17 (1978) 2369): 6 GeV < E_ν < 10 GeV

Neutrino oscillation length resonance (NOLR) (Petcov, PLB 434 (1998) 321)/**parametric resonance resonance (PR)** (Akhmedov, NPB 538 (1999) 25): 2 GeV < E_ν < 6 GeV

Earth's Matter Effects: key to Probe Internal Structure of Earth

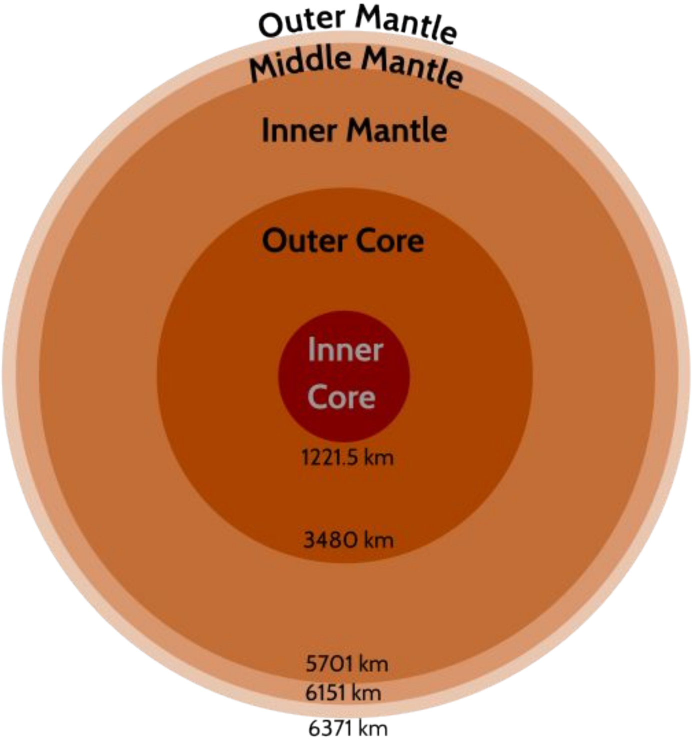
- Earth's matter effect driven neutrino oscillation measurements provide a complementary and independent information about internal structure of Earth

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

- ρ: matter density → **Density of each layer inside Earth**
- $Y_e = N_e/(N_p + N_n)$: relative electron number density → **Chemical composition of Earth**

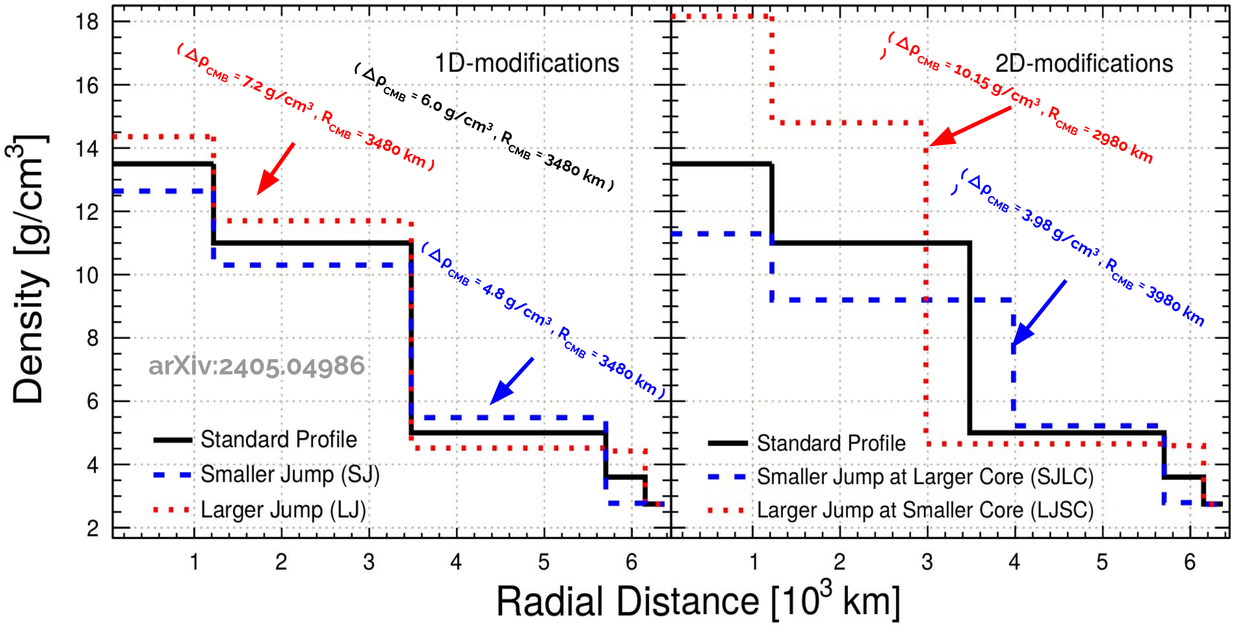
- Recent sensitivity studies using atmospheric neutrino oscillations to probe the internal structure of Earth →
  - **Presence of Earth's core:** JHEP 08 (2021) 139 (ICAL)
  - **Location of core-mantle boundary:** PRD 104 (2021) 11, 113007 (DUNE), JHEP 04 (2023) 068 (ICAL)
  - **Density distribution:** Nucl.Phys.B 908 (2016) 250-267 (PINGU & ORCA), JHEP 05 (2022) 187 (DUNE), Eur.Phys.J.C 82 (2022) 5, 461 (ORCA)
  - **Chemical composition:** Sci.Rep. 5 (2015) 15225, Eur.Phys.J.C 82 (2022) 7, 614 (ORCA), Front.Earth Sci. 11 (2023) 1008396

Toy Density Model of Earth



- Consider a five-layered density profile of Earth, guided by the PREM profile
- **Five layers:**
  - Inner Core (IC),
  - Outer Core (OC),
  - Inner Mantle (IM),
  - Middle Mantle (MM),
  - Outer Mantle (OM)
- **Four significant density jumps:**
  - IC-OC ($\triangle\rho_{IC\text{-}OC}$)
  - CMB ($\triangle\rho_{CMB}$)
  - IM-MM ($\triangle\rho_{IM\text{-}MM}$)
  - MM-OM ($\triangle\rho_{MM\text{-}OM}$)

Toy Density Models of Earth with Modifying Density Jumps & R_{CMB}

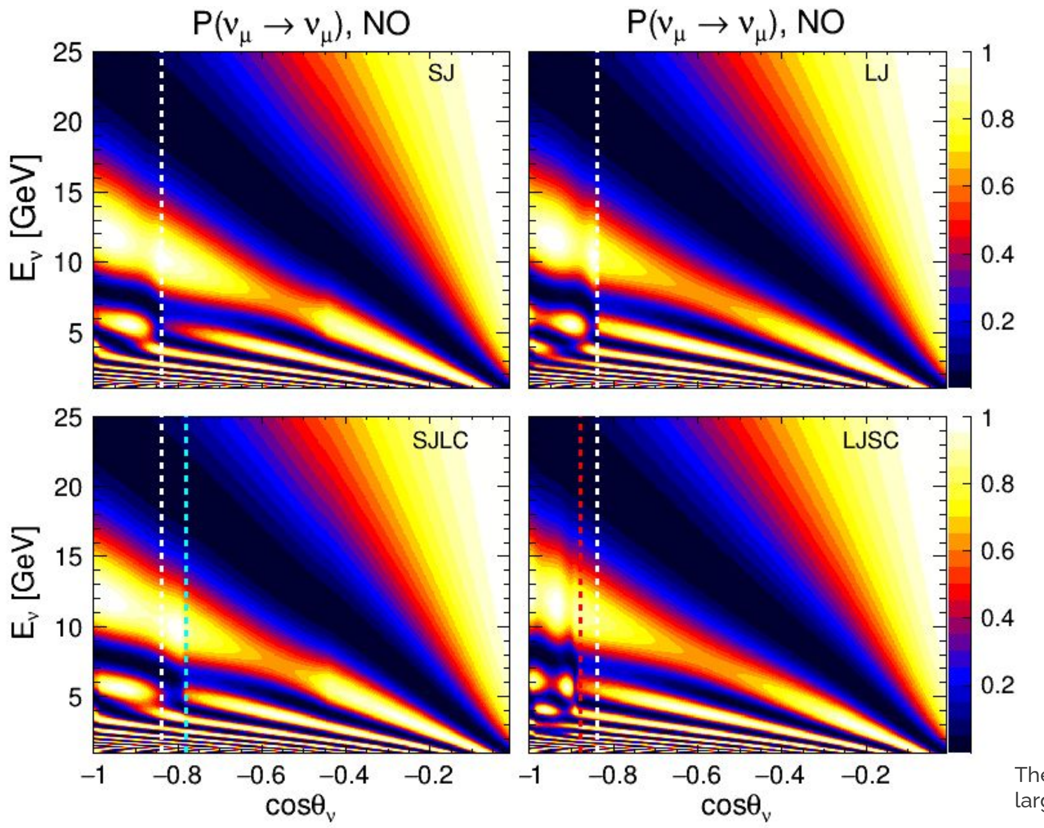


- **Constraints:**
  - Mass and Moment of inertia of Earth are fixed
  - Density of outer mantle is fixed
  - Density ratio between inner core and outer core (ρ_{IC} / ρ_{OC}) is fixed
  - Hydrodynamic condition ($\rho_{inner\ layer} > \rho_{outer\ layer}$) is satisfied

1D-modifications: R_{CMB} is fixed at 3480 km and only $\Delta\rho_{CMB}$ is varied

2D-modifications: R_{CMB} is varied simultaneously with $\Delta\rho_{CMB}$

Effect of Density Jump ($\Delta\rho_{CMB}$) & R_{CMB} Variation on Oscillograms



Observations:

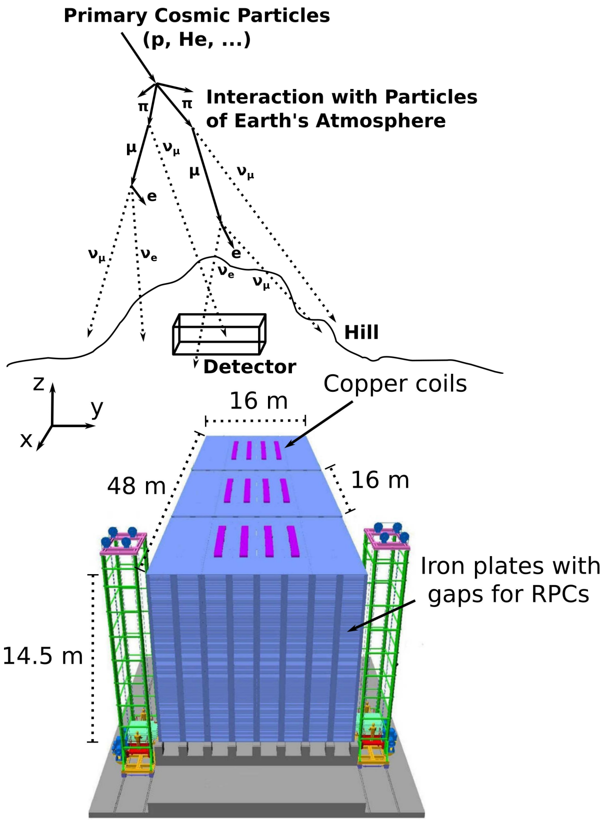
- **For SJ**:
  - NOLR/PR shift to left
  - MSW resonance region shrinks
- **For LJ**:
  - NOLR/PR shift to right
  - MSW resonance region stretches
- **For LJSC**:
  - NOLR/PR shifts to right and patterns shrink
  - MSW resonance region stretch
- **For SJLC**:
  - NOLR/PR shifts to left and patterns become wider
  - MSW resonance region shrink

The white, red, and cyan vertical dotted lines represent the standard, smaller, and larger R_{CMB} values, respectively.

Opposite modification in MSW and NOLR/PR region for SJ and LJ, and LJSC and SJLC scenarios

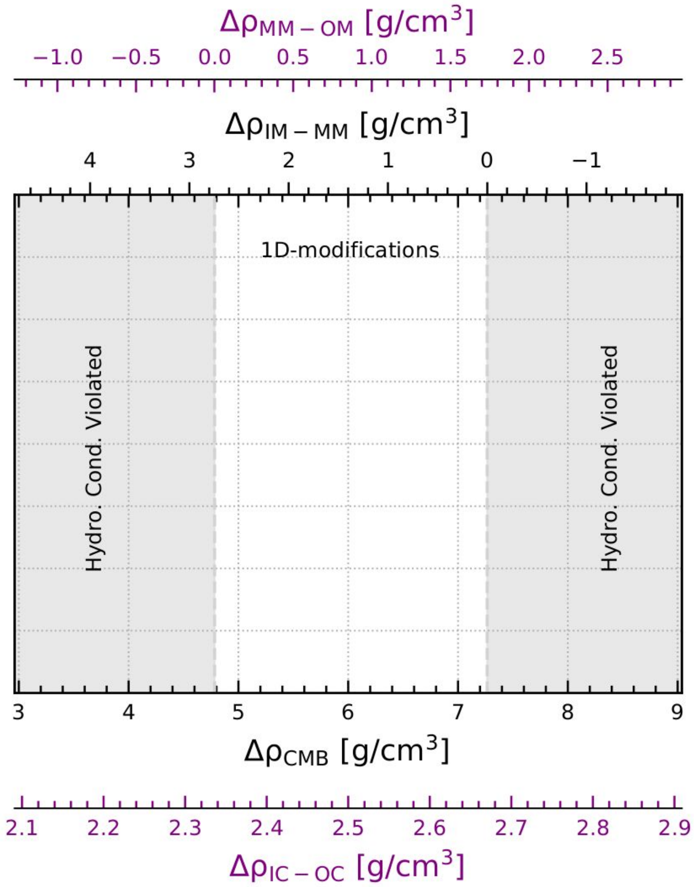
Iron Calorimeter Detector (ICAL) at INO

- **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°



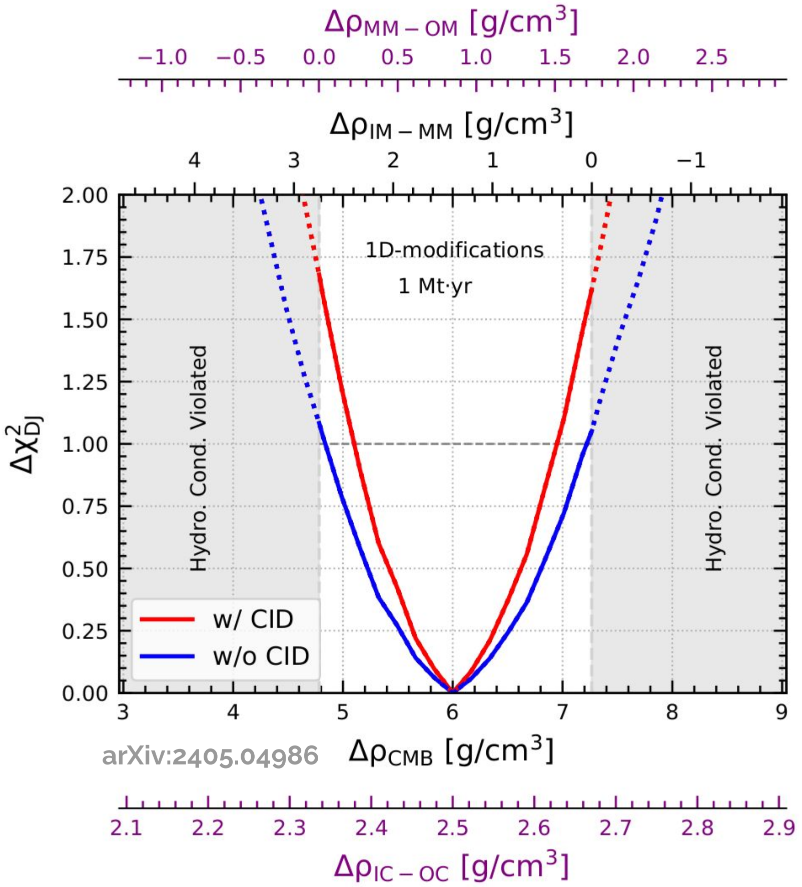
Pramana 88 (2017) 5, 79, arXiv:1505.07380

Sensitivity for Constraining Correlated Density Jumps at Standard R_{CMB}



- The gray area: unphysical region where the hydrostatic equilibrium condition is violated
- White region: allowed by the gravitational measurements and hydrostatic equilibrium condition

Sensitivity for Constraining Correlated Density Jumps at Standard R_{CMB}



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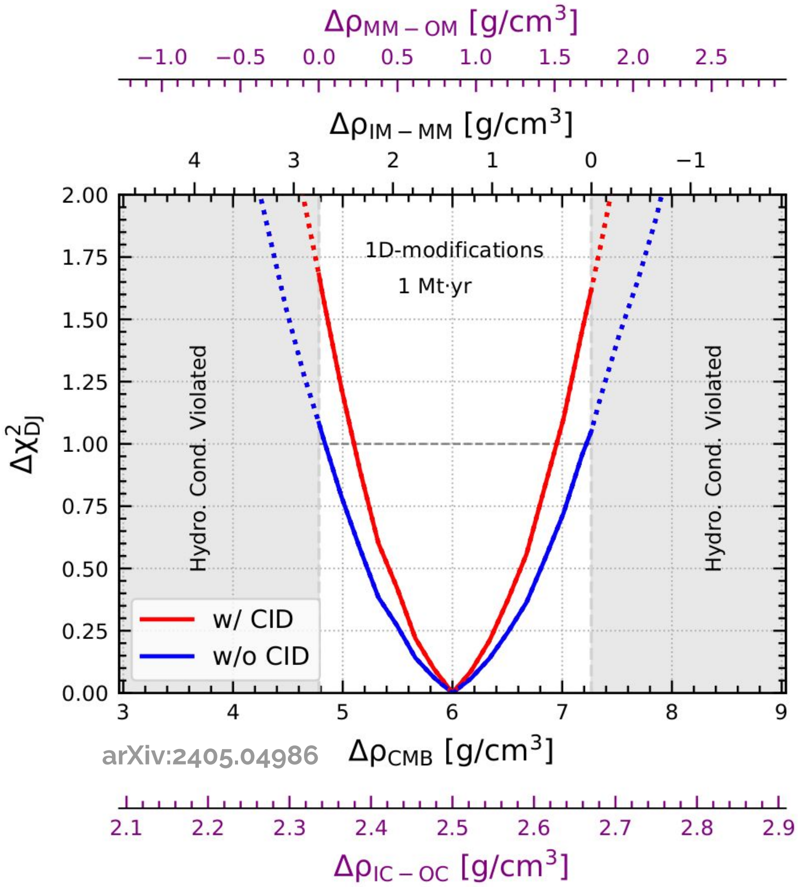
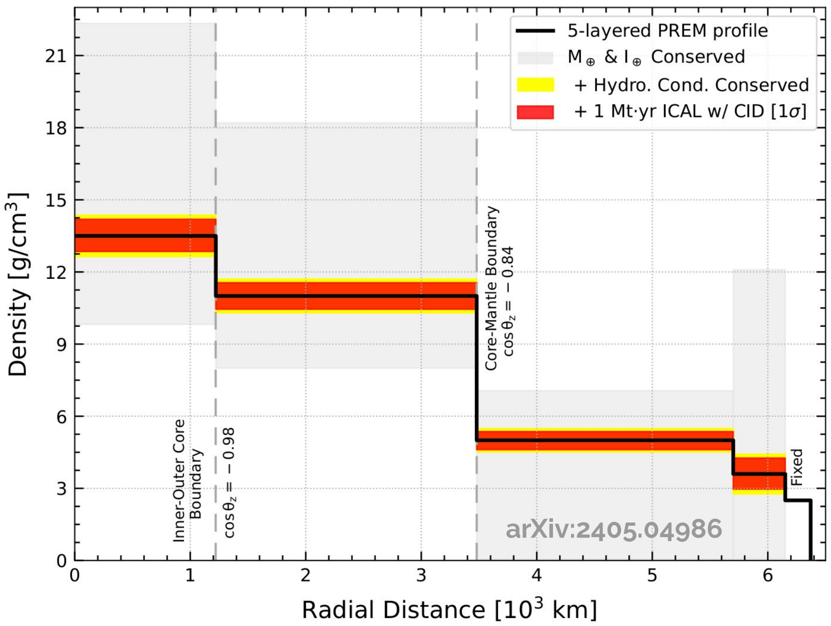
$$\Delta\chi^2_{\text{1D-DJ}} = \chi^2(\text{modified } \Delta\rho) - \chi^2(\text{standard } \Delta\rho)$$

- The gray area: unphysical region where the hydrostatic equilibrium condition is violated
- White region: allowed by the gravitational measurements and hydrostatic equilibrium condition
- **Added neutrino oscillation data on these external constraints**
  - **Further constrain the allowed region**
- Neutrino data at ICAL would be able to measure $\Delta\rho_{CMB}$ as [5.1, 7.0] g/cm^3 at 1σ with a relative precision of about 15%
- In the absence of CID, the sensitivity deteriorate to [4.8, 7.2] g/cm^3 at 1σ with a relative precision of about 20%

Sensitivity for Constraining Correlated Density Jumps at Standard R_{CMB}

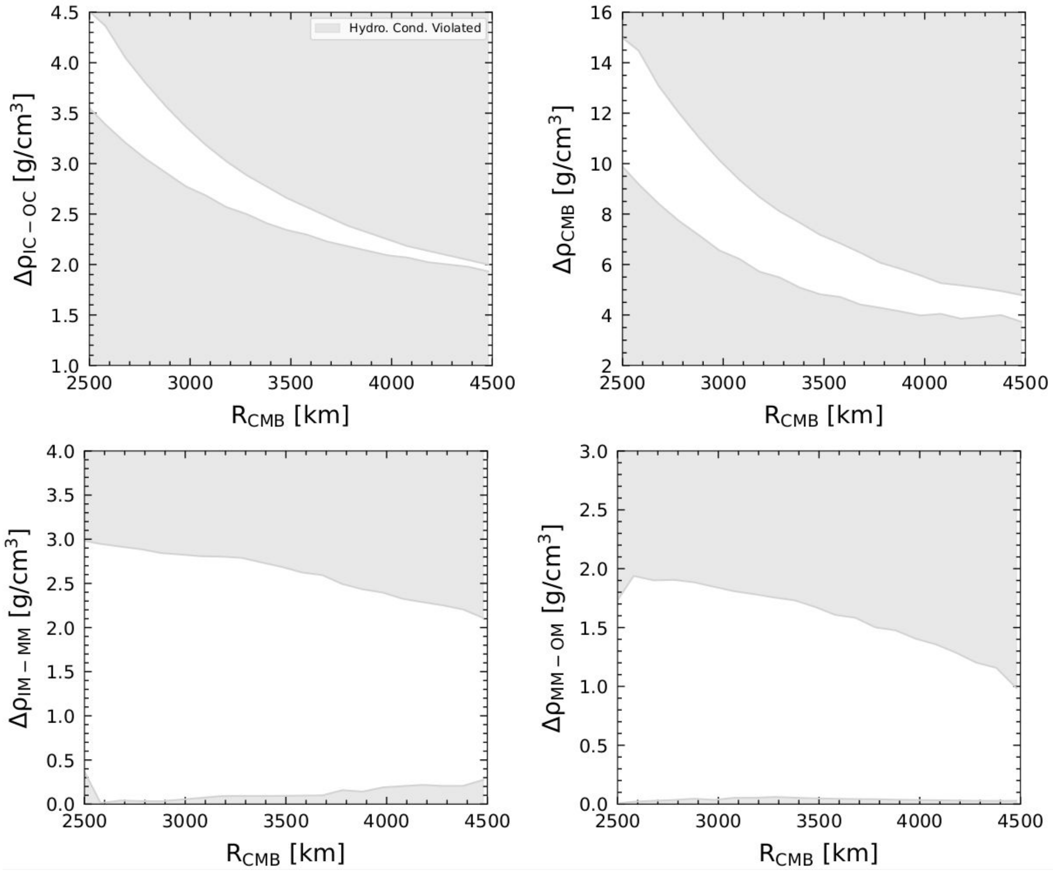


$$\Delta\chi^2_{\text{1D-DJ}} = \chi^2(\text{modified } \Delta\rho) - \chi^2(\text{standard } \Delta\rho)$$



- Neutrino data improve the constraints on the densities of layers of Earth placed by Earth's mass and moment of inertia

Sensitivity for Constraining Correlated Density Jumps and Location of R_{CMB}



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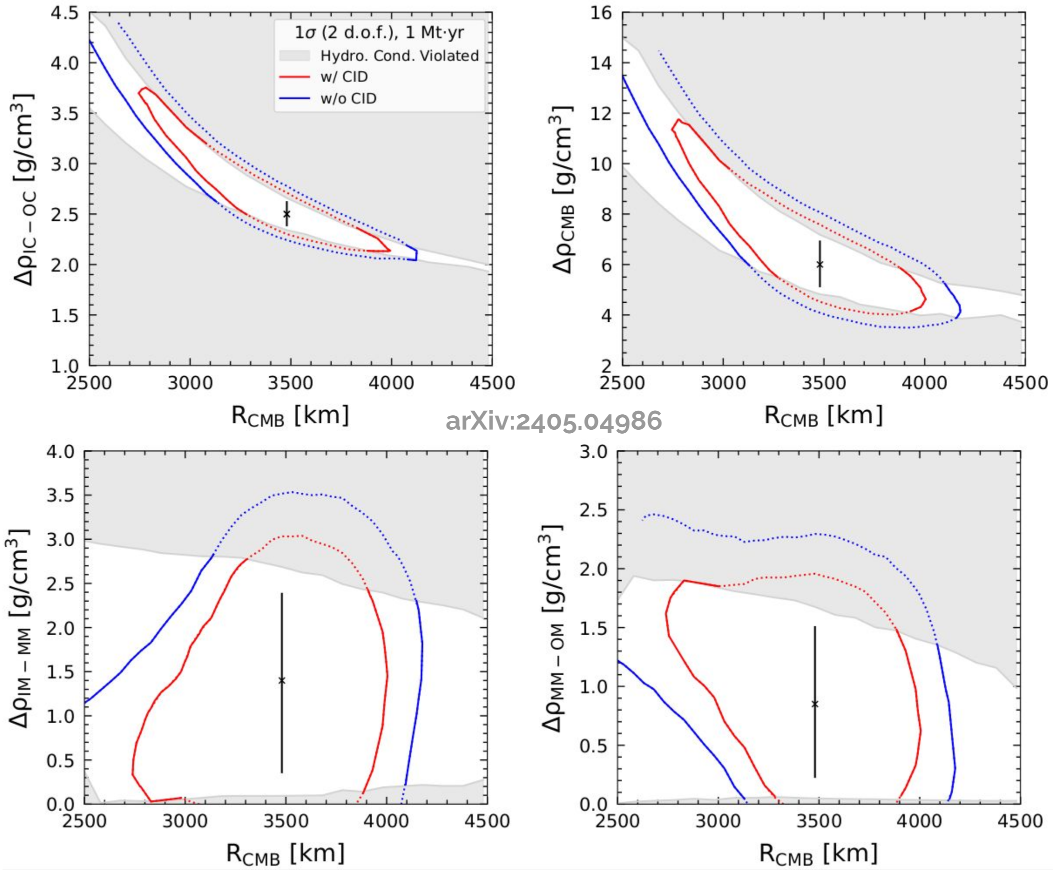
Sensitivity for Constraining Correlated Density Jumps and Location of R_{CMB}



$$\Delta\chi^2_{\text{DJ-CMB}} = \chi^2(\text{modified } \Delta\rho \ \& \ R_{\text{CMB}}) - \chi^2(\text{standard } \Delta\rho \ \& \ R_{\text{CMB}})$$

- The gray area: unphysical region where the hydrostatic equilibrium condition is violated
- White region: allowed by the gravitational measurements and hydrostatic equilibrium condition
- **Neutrino oscillation data can help us to further constrain the allowed region**
- **An example of the complementarity to the existing measurements**

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
- Neutrino data improve the constraints on the densities of Earth's layers placed by Earth's mass and moment of inertia
- ICAL detector with 1 Mt·yr exposure would be able to measure the density jump at CMB ($\Delta\rho_{CMB}$) at the standard R_{CMB} = 3480 km with a relative precision of about **15%** at the 1σ C.L
- ICAL would be able to further constrain the allowed region by existing measurements

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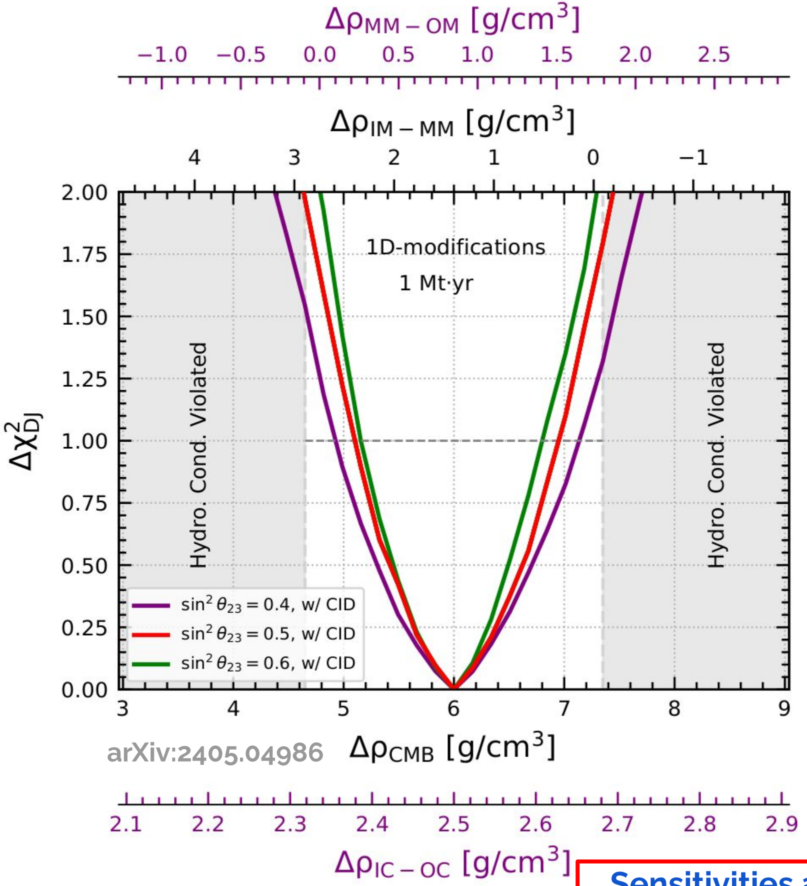
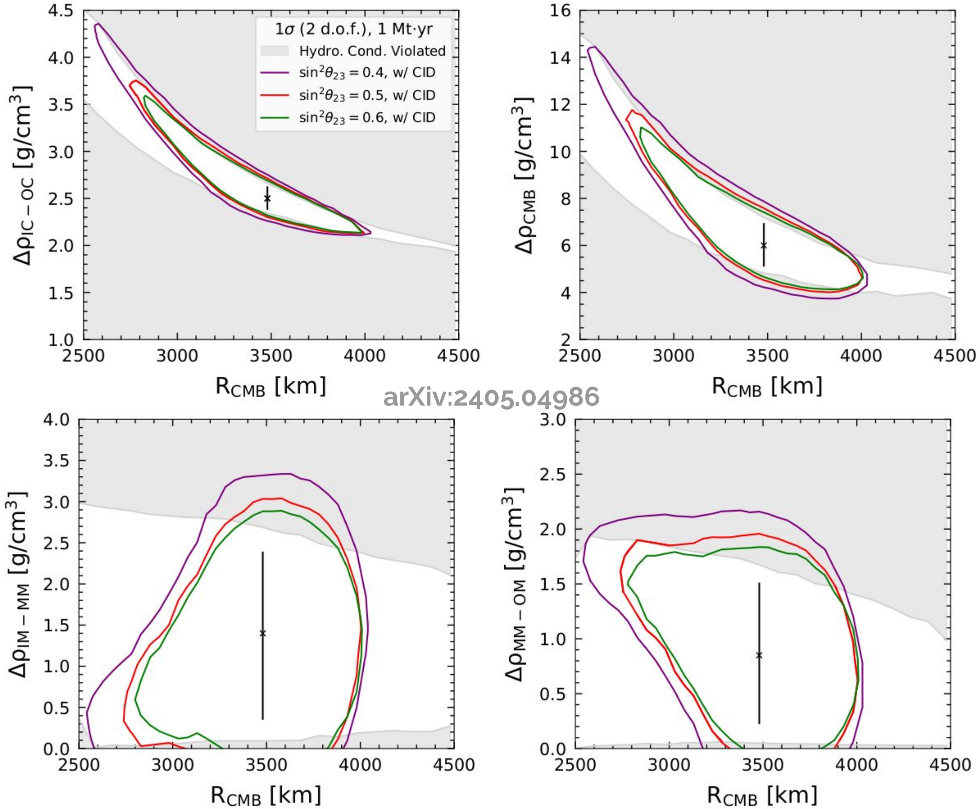
(DST/INSPIRE Fellowship/2019/IF190755)

Thank you!

Backup

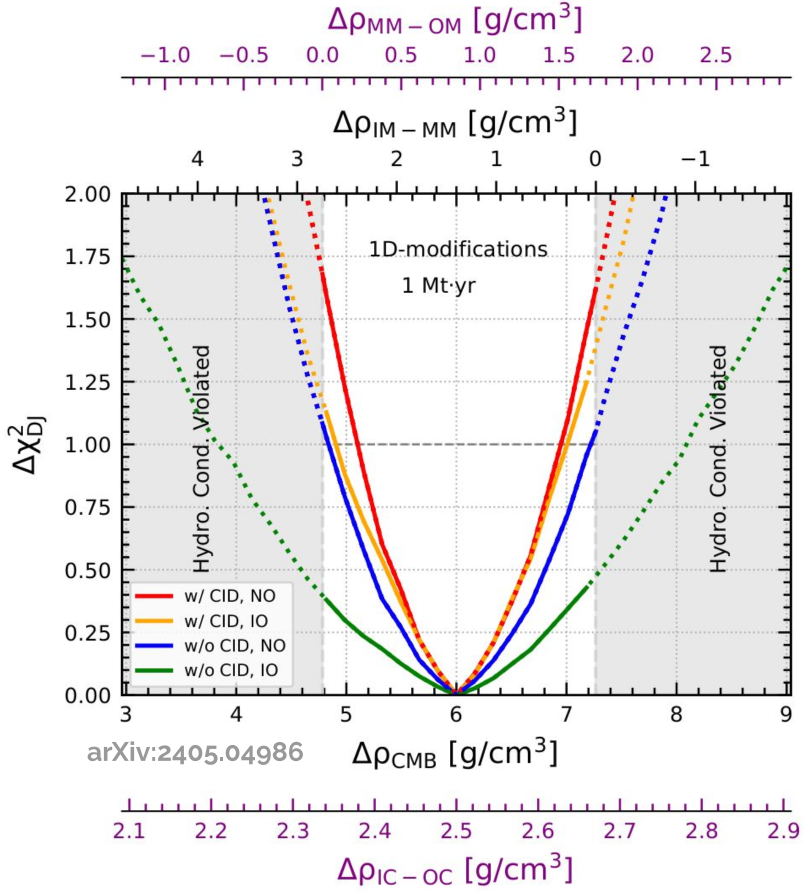
Impact of Different True Choices of $\sin^2\theta_{23}$ on Sensitivity





Sensitivities are larger (smaller) for higher (lower) octant

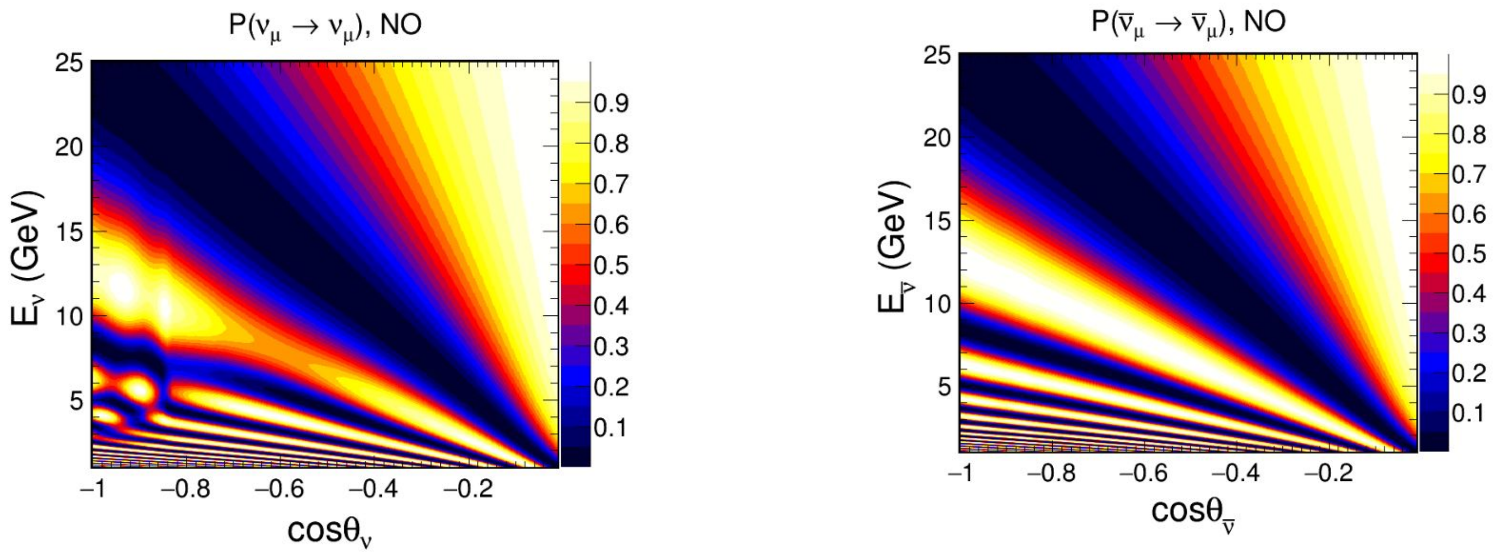
Impact of Inverted Mass Ordering on Sensitivity



arXiv:2405.04986

- The orange (green) curve corresponds to the expected sensitivity for the IO scenario with (without) the CID capability of the ICAL detector
- Density constraints for IO are similar to NO 1σ with CID capability of ICAL
- No constraints without CID capability of ICAL

Oscillations in Neutrinos and Antineutrinos

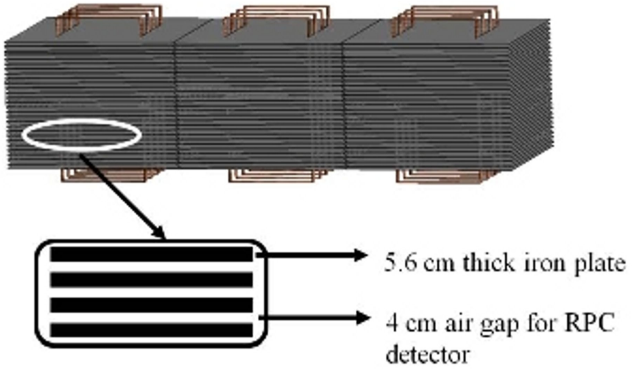


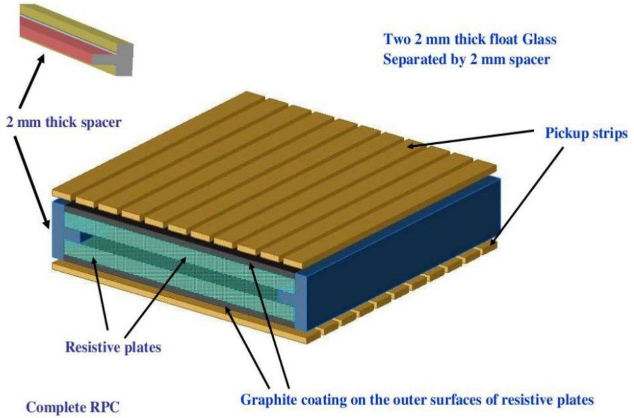
- For NO, matter effects occur mainly in neutrino channel
- But for IO, matter effects occur mainly in antineutrino channel

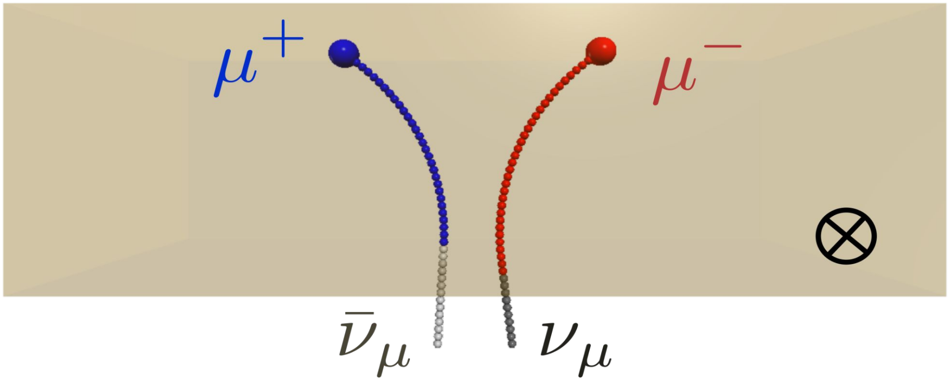
It is important to detect neutrinos and antineutrinos separately to preserve the matter effects

Design of ICAL Detector

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







- μ^- and μ^+ bend in the opposite direction in the presence of magnetic field
- Therefore, neutrinos and antineutrinos can be detected separately

Pramana 88 (2017) 5, 79, arXiv:1505.07380

Statistical Analysis

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

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

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^+

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

Five-layered profile

- Five layers: Inner Core (IC), Outer Core (OC), Inner Mantle (IM), Middle Mantle (MM), Outer mantle (OM)

Layers	Radius (km)	Depth (km)	Density (g/cm^3)
Inner Core	0 - 1221.5	5149.5 - 6371	13.5
Outer Core	1221.5 - 3480	2891 - 5149.5	11.0
Inner Mantle	3480 - 5701	670 - 2891	5.0
Middle Mantle	5701 - 6151	220 - 670	3.6
Outer Mantle	6151 - 6371	0 - 220	2.75

- M_E (PREM) = 5.9723×10^{24} kg
- MI_E (PREM) = 8.01724×10^{37} kg m^2
- M_E (Grav.) = 5.9722×10^{24} kg
- MI_E (Grav.) = 8.01736×10^{37} kg m^2

The Interior of Earth

Properties	Value (±)	Units
Earth's Mass	$(5.9722 \pm 0.006) \times 10^{24}$	kg
Mean moment of inertia	$(8.01736 \pm 0.00097) \times 10^{37}$	kg m^2
Earth's mean radius	6371.23 (0.01)	km
Core-mantle boundary	3483 ± 5	km
Inner-outer core boundary	1220 ± 10	km

- W.F. McDonough, Elsevier (2003), p. 547
- W. Chen et. al. Journal of Geodesy 89,179–188 (2015)
- B. Luzum et.al. Celestial Mechanics and Dynamical Astronomy 110, 293–304 (2011)