Earth tomography with oscillating neutrinos at ICAL

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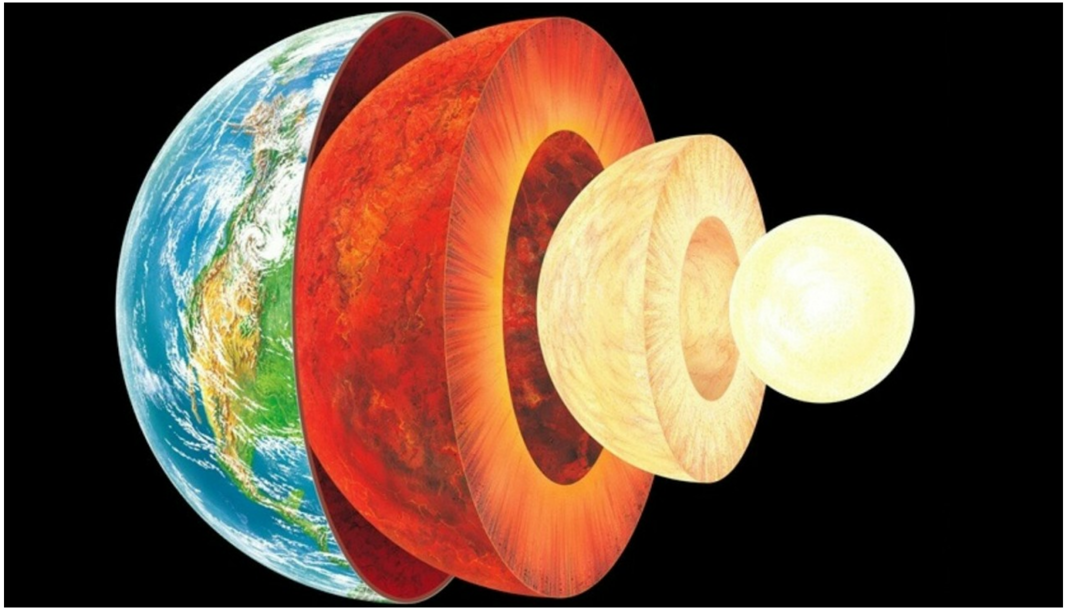
Outline

- Information about Earth’s interior
- Matter effects: key to probe Earth tomography
- Neutrinos for Earth tomography
  - Validating Earth’s Core
  - Locating Core-Mantle Boundary
  - Probing dark matter inside Earth’s core

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**

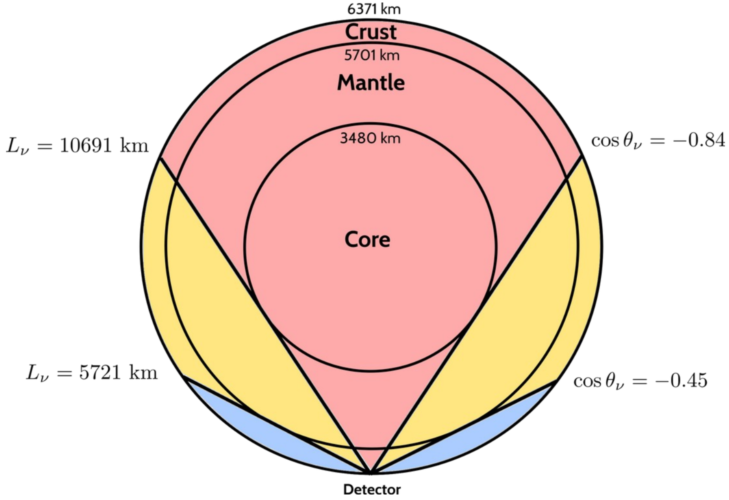


A Brief Review of the Internal Structure of Earth

- 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.



Anil Kumar et. al., JHEP 08 (2021) 139, arXiv: 2104.11740

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- 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.
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Neutrino Oscillations & Atmospheric Neutrinos

Example: two-flavor case

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\,\nu_j(L)\,\rangle = e^{-i\left(\frac{m_j^2\,L}{2\,E}\right)}\,|\,\nu_j(0)\,\rangle$$

$$P_{\nu_\mu\rightarrow\nu_e} = |\,\langle\nu_e(L)\,|\,\nu_\mu\rangle\,|^2$$

$$P\,(\nu_\mu \rightarrow \nu_e) \;=\; \sin^2 2\theta\;\sin^2\left(\frac{\Delta m^2}{4}\,\frac{L}{E_\nu}\right)$$

Oscillation probabilities are functions of the mixing angles and differences in mass squared

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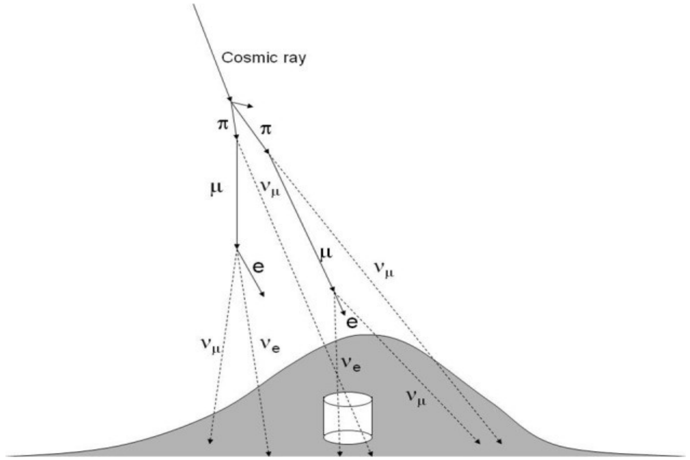
Oscillation probabilities are functions of the mixing angles and differences in mass squared



$$p + A_{air} \to p, n, \pi^\pm, k^\pm \ldots.$$

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

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

The energy range for atmospheric neutrinos is between **0.1 GeV and 10 TeV** and baseline between **15 km to 13000 km**.

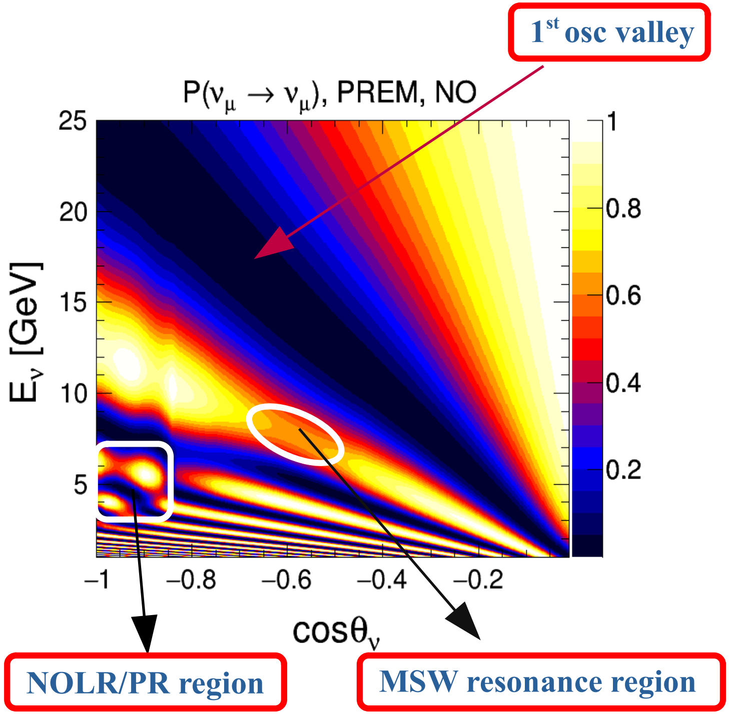
Matter effects: key to probe Earth tomography

- The atmospheric neutrinos undergo coherent elastic forward scattering with ambient electrons inside the Earth which leads to the modification of neutrino oscillations.

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

$$Y_e = N_e/(N_p + N_n)$$

ρ denotes the matter density
+1 (-1) for neutrino (antineutrino)



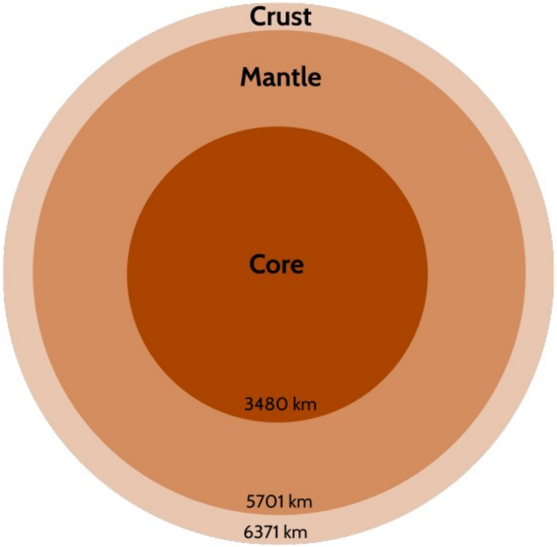
- **MSW resonance** (L. Wolfenstein, PRD 17 (1978) 2369): red patch around

$-0.8 < \cos\theta_\nu < -0.5$ and $6 \text{ GeV} < E_\nu < 10 \text{ GeV}$

- **Neutrino oscillation length resonance (NOLR)** (Petcov, PLB 434 (1998) 321)/**parametric resonance (PR)** (Akhmedov, NPB 538 (1999) 25): yellow patches around $\cos\theta_\nu < -0.8$ and

$3 \text{ GeV} < E_\nu < 6 \text{ GeV}$

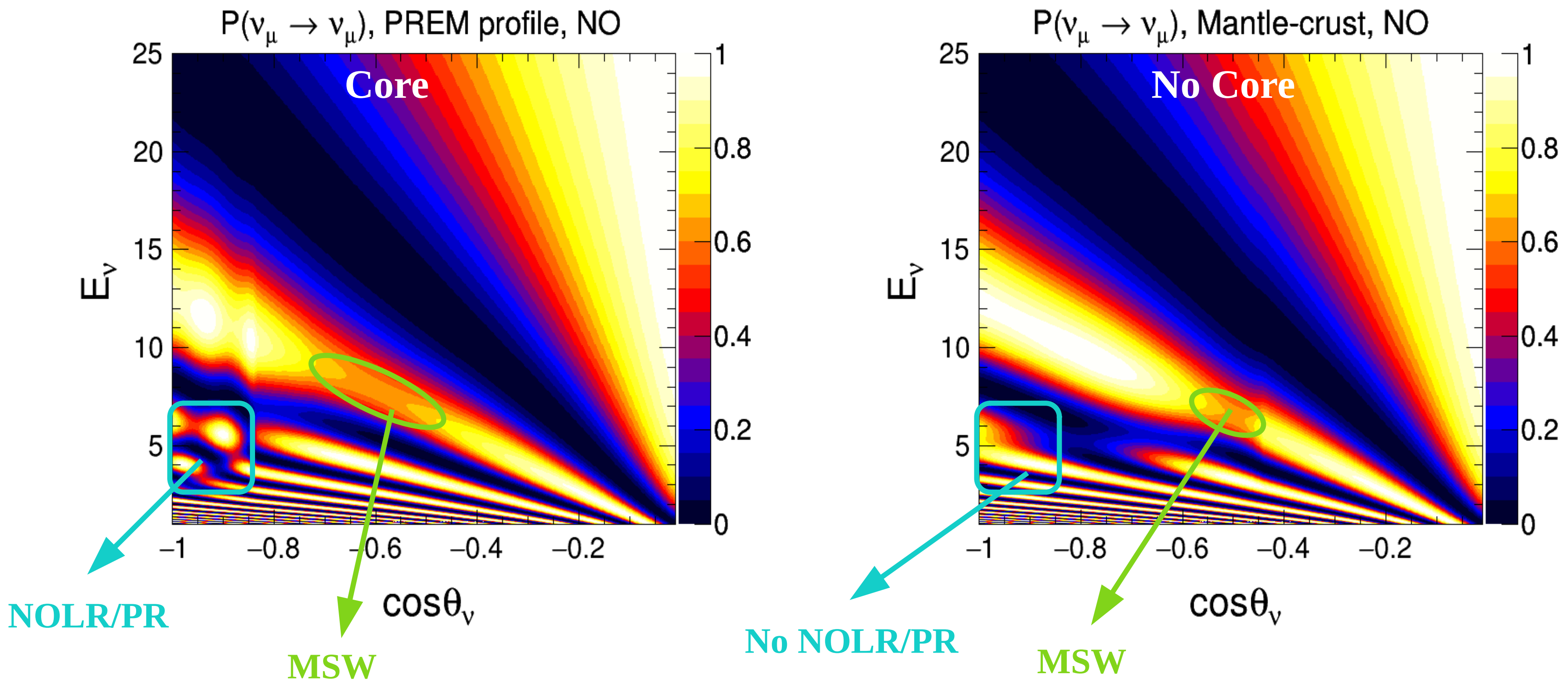
Validating the Earth's core using Atmospheric Neutrinos



Three-Layered Model of Earth

Based on: Anil Kumar et. al., JHEP 08 (2021) 139

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



Anil Kumar et. al., JHEP 08 (2021) 139

Sensitivity to Validate Earth's Core with and without CID

$$\Delta\chi^2_{\text{ICAL-profile}} = \chi^2_{\text{ICAL}}\ (\text{mantle-crust}) - \chi^2_{\text{ICAL}}\ (\text{core-mantle-crust})$$

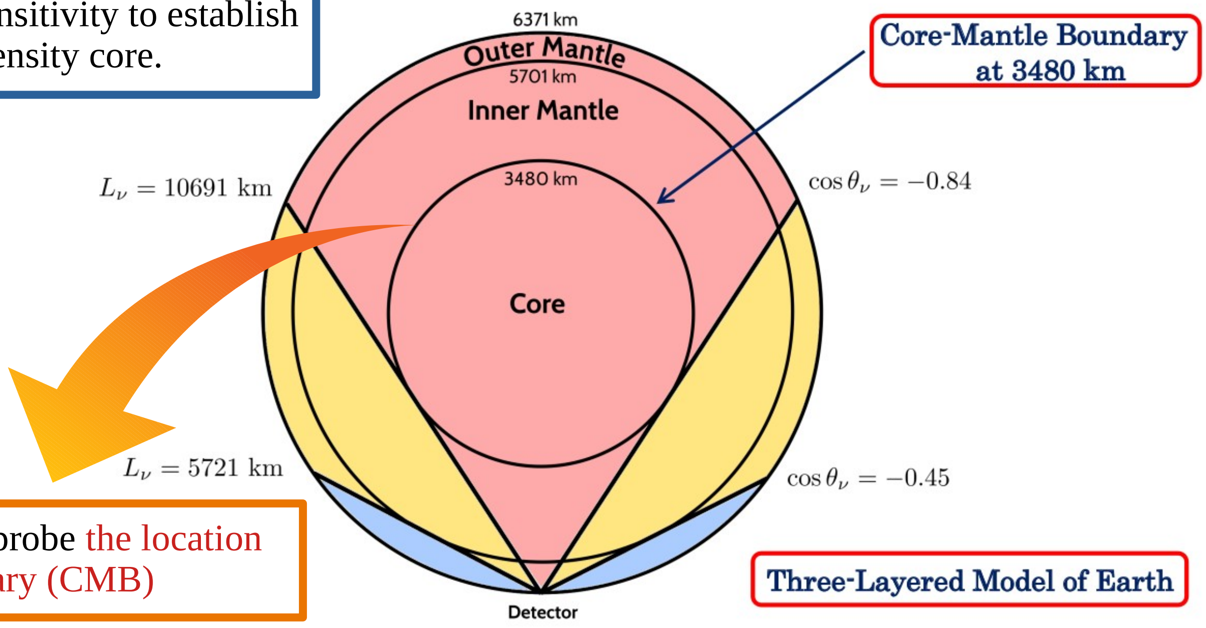
- 500 kt·yr exposure at ICAL
- Marginalization over:
  - systematic uncertainties
  - Oscillation parameter:
    - $\sin^2\theta_{23}$: (0.36, 0.66)
    - Δm^2_{eff}: (2.1, 2.6) $\times 10^{-3}$ eV^2
    - mass ordering: (NO, IO)

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

Anil Kumar et. al., JHEP 08 (2021) 139

Locating Core-Mantle Boundary (CMB) using Atmospheric Neutrinos

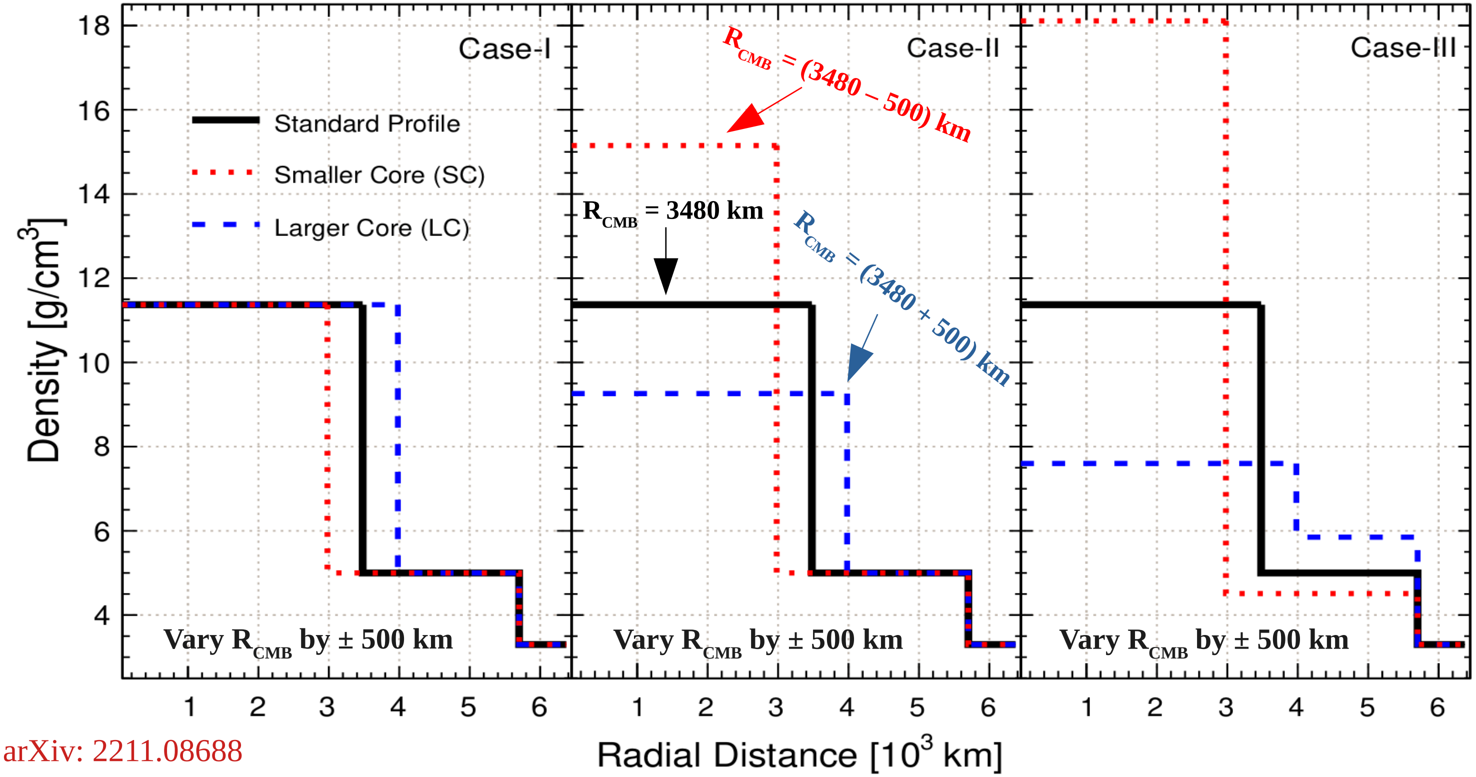
Till now, we talked about the sensitivity to establish the presence of high-density core.



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

Based on: A K Upadhyay et. al., arXiv: 2211.08688

A Few Toy Models of Earth with Varying CMB



A K Upadhyay et. al., arXiv: 2211.08688

Case-I: Densities of all layers fixed and $M_\oplus$ is not invariant

Case-II: Densities of inner & outer mantle fixed. Core density varies to keep $M_\oplus$ invariant

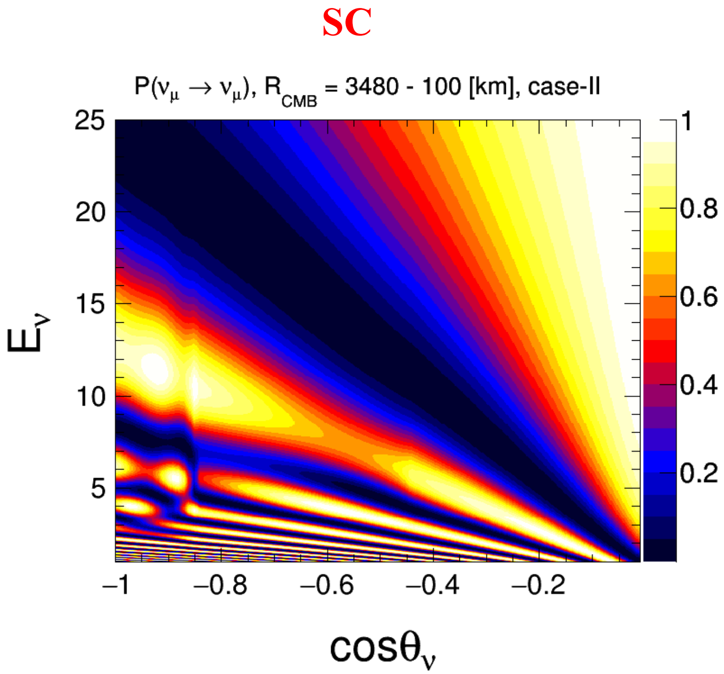
Case-III: Core & inner mantle densities vary to keep their masses fixed. Outer mantle density fixed & $M_\oplus$ invariant

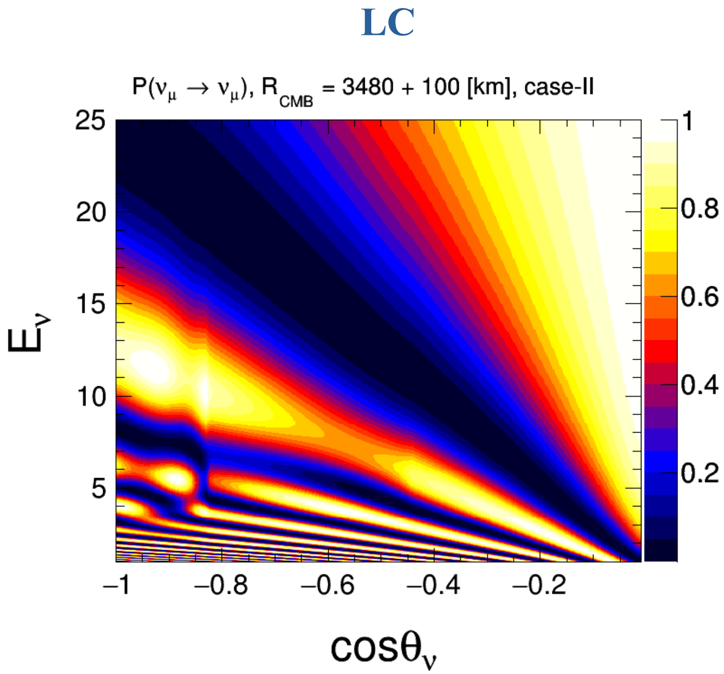
Effect of CMB Variation on Oscillograms

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

Case-II





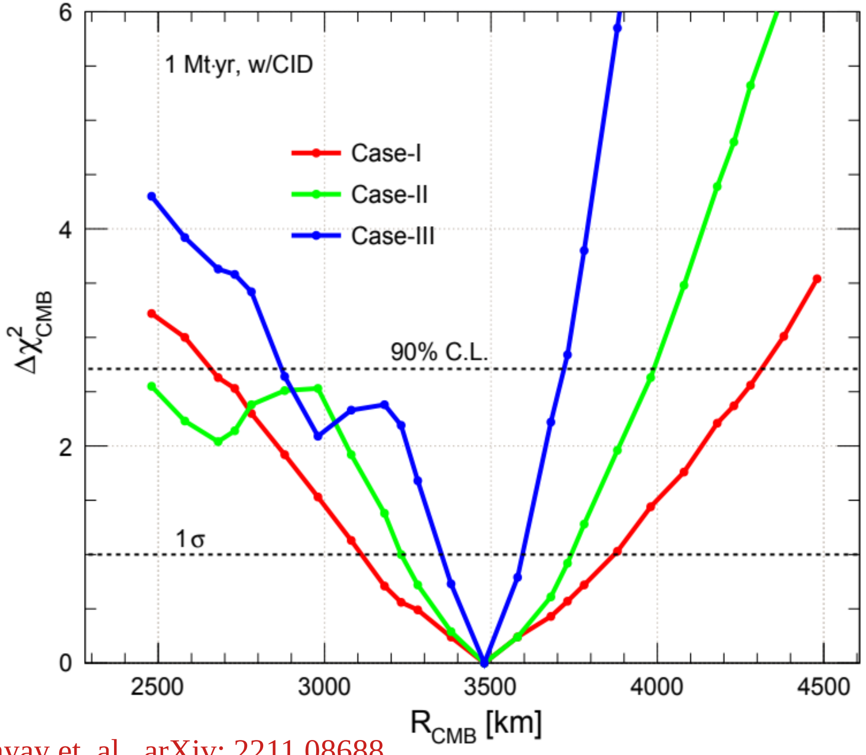
A K Upadhyay et. al., arXiv: 2211.08688

Sensitivity for Locating Core-Mantle Boundary

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

- 1 Mt·yr exposure at ICAL
- Marginalization over: (1) systematic uncertainties, (2) Oscillation parameter: (2a) $\sin^2\theta_{23}$: (0.36, 0.66), (2b) $\Delta m^2_{\rm eff}$: (2.1, 2.6) $\times 10^{-3}$ eV^2 (2c), mass ordering: (NO, IO)

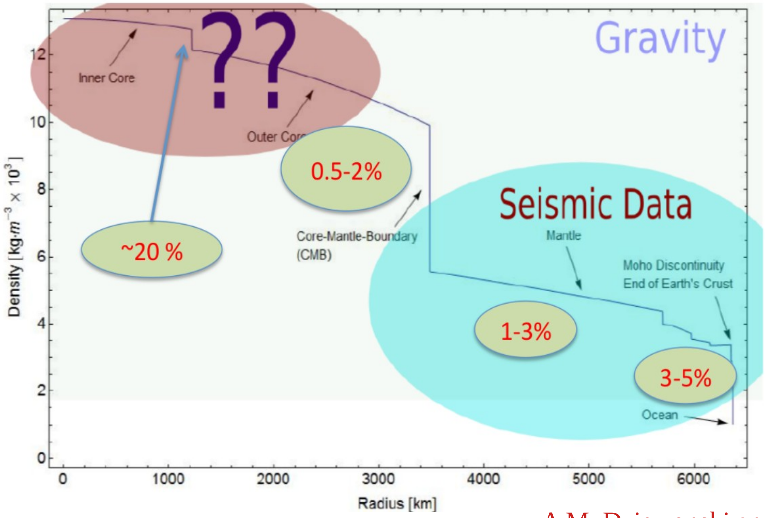
		$\Delta\chi^2_{\text{ICAL-profile}}$ (1 Mt.yr)	
		w CID	w/o CID
Case-I	R_{CMB} = 2980 km	1.53	1.01
	R_{CMB} = 3980 km	1.44	0.95
Case-II	R_{CMB} = 2980 km	2.53	1.66
	R_{CMB} = 3980 km	2.63	1.67
Case-III	R_{CMB} = 2980 km	2.09	1.33
	R_{CMB} = 3980 km	8.07	5.23



- 1σ precision of about ± 380 km, **± 250 km**, and ± 120 km for Case-I, **Case-II**, and Case-III, respectively.

A K Upadhyay et. al., arXiv: 2211.08688

Probing dark matter inside the Earth's core using Atmospheric Neutrinos



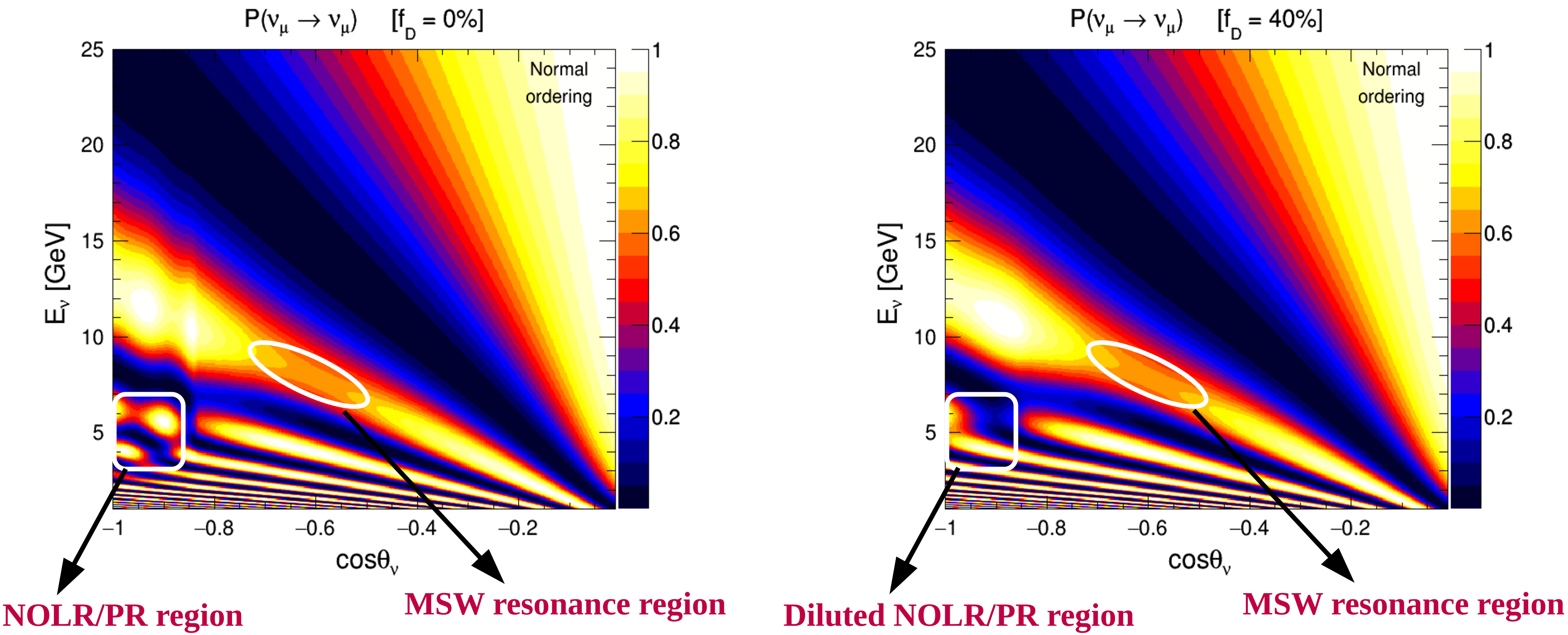
From the talk given by Prof. Andrea Donini at MMTE Workshop 2022

A M. Dziewonski and D L. Anderson, Phys. Earth Planet. Interiors 25 (1981) 297

- Atmospheric neutrinos can be used to measure the amount of baryonic matter present inside Earth core.
- **If the baryonic matter observed by neutrinos is found to be less than the expected mass from gravitational measurement, we can attribute the difference to the presence of dark matter inside the core.**

Based on: A K Upadhyay et. al., arXiv: 2112.14201

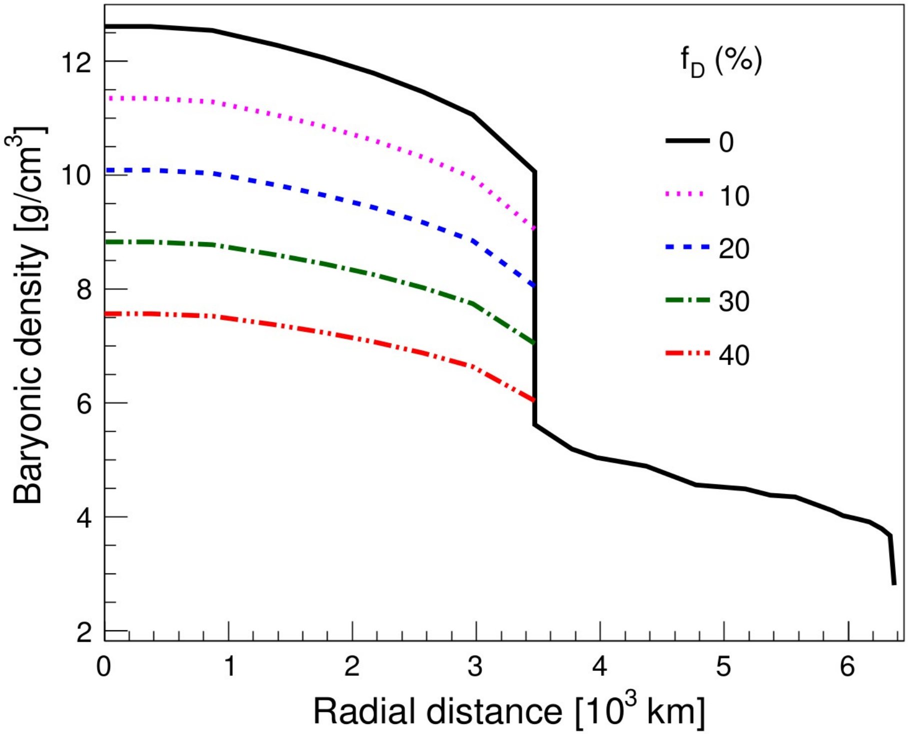
Modified Probability Oscillograms in presence of DM

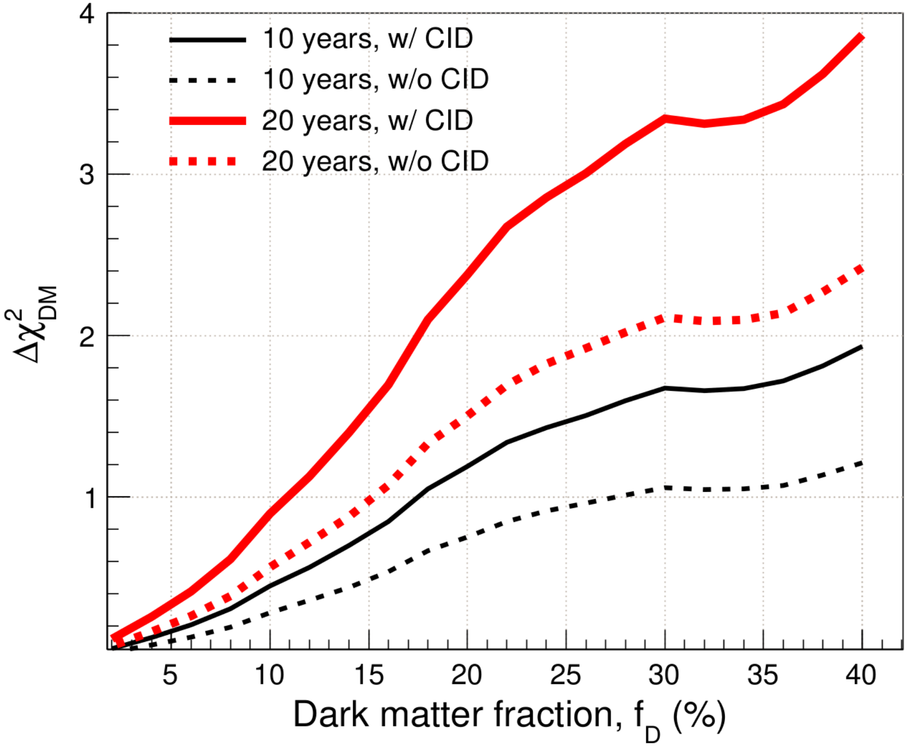


NOLR/PR is highly diluted in presence of DM

Sensitivity to rule out dark matter fraction

$$\Delta\chi^2_{\rm DM} = \chi^2_{\rm ICAL}\ (\textbf{Dark matter}) - \chi^2_{\rm ICAL}\ (\textbf{No dark matter})$$





Sensitivity with which ICAL can rule out f_D

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.
- ICAL detector with 1000 kt·yr exposure would be able to locate the CMB with a precision of about ±250 km at 1σ confidence level.
- If dark matter constitutes 40% of the mass inside the core, a detector like ICAL at INO with muon charge identification capability can be sensitive to it at around 2σ confidence level with 1000 kt·yr exposure.

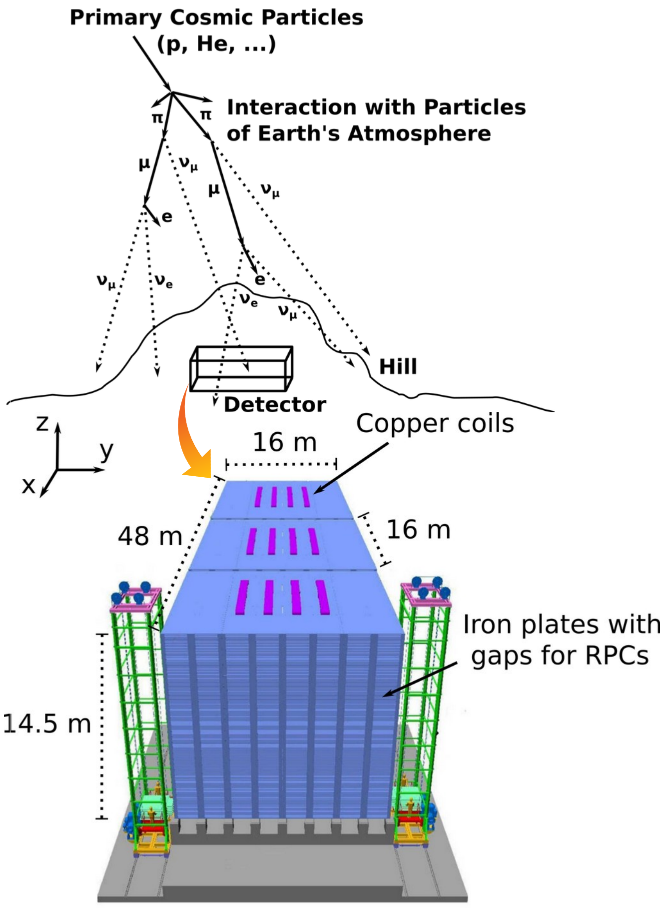
We acknowledge the financial support from the Department of Atomic Energy (DAE), Department of Science and Technology (DST), Govt. of India, Science and Engineering Research Board (SERB), and the Indian National Science Academy (INSA).

Thank you

Backup

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 - J Phys (2017) 88 : 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,

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

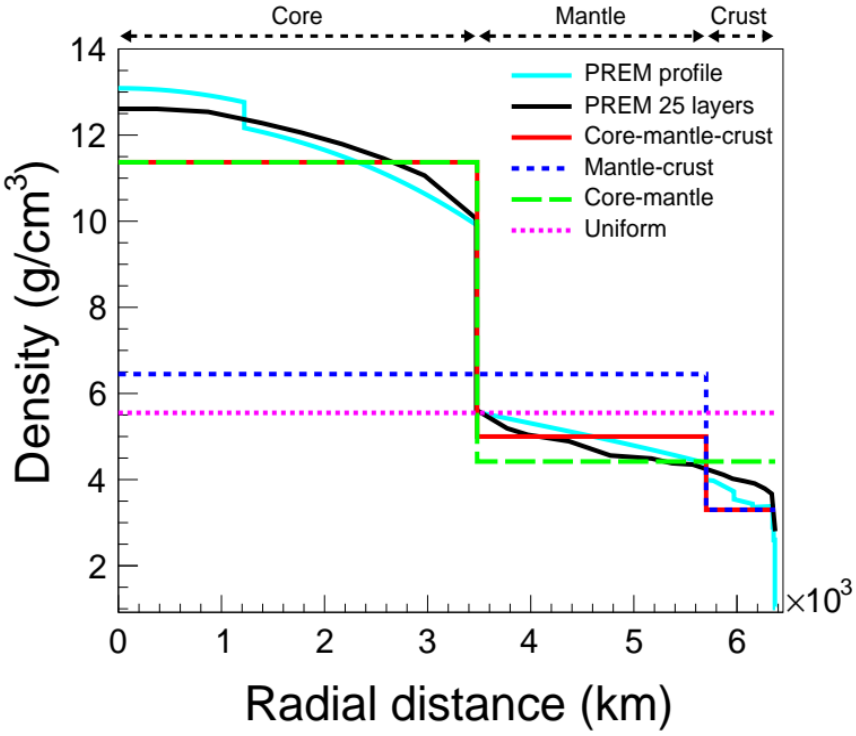
Similarly, χ^2_{+} is defined for μ^+

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

Density Distributions for Various Profiles 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)

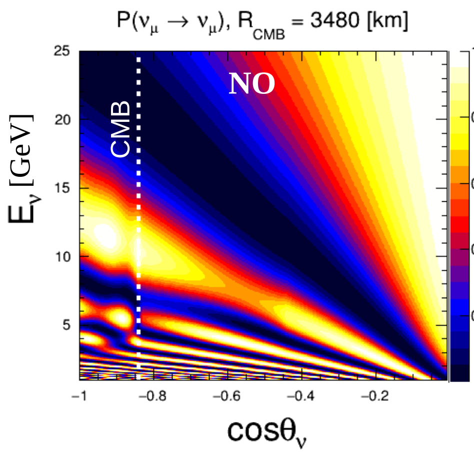
Anil Kumar et. al., JHEP 08 (2021) 139

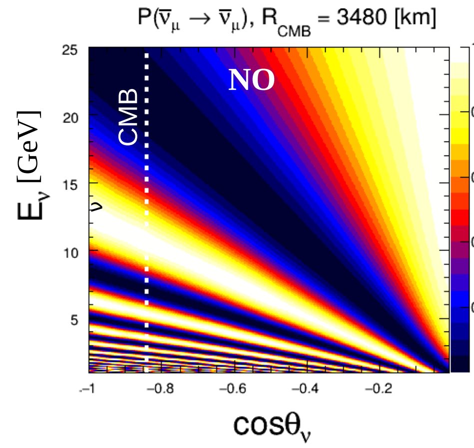


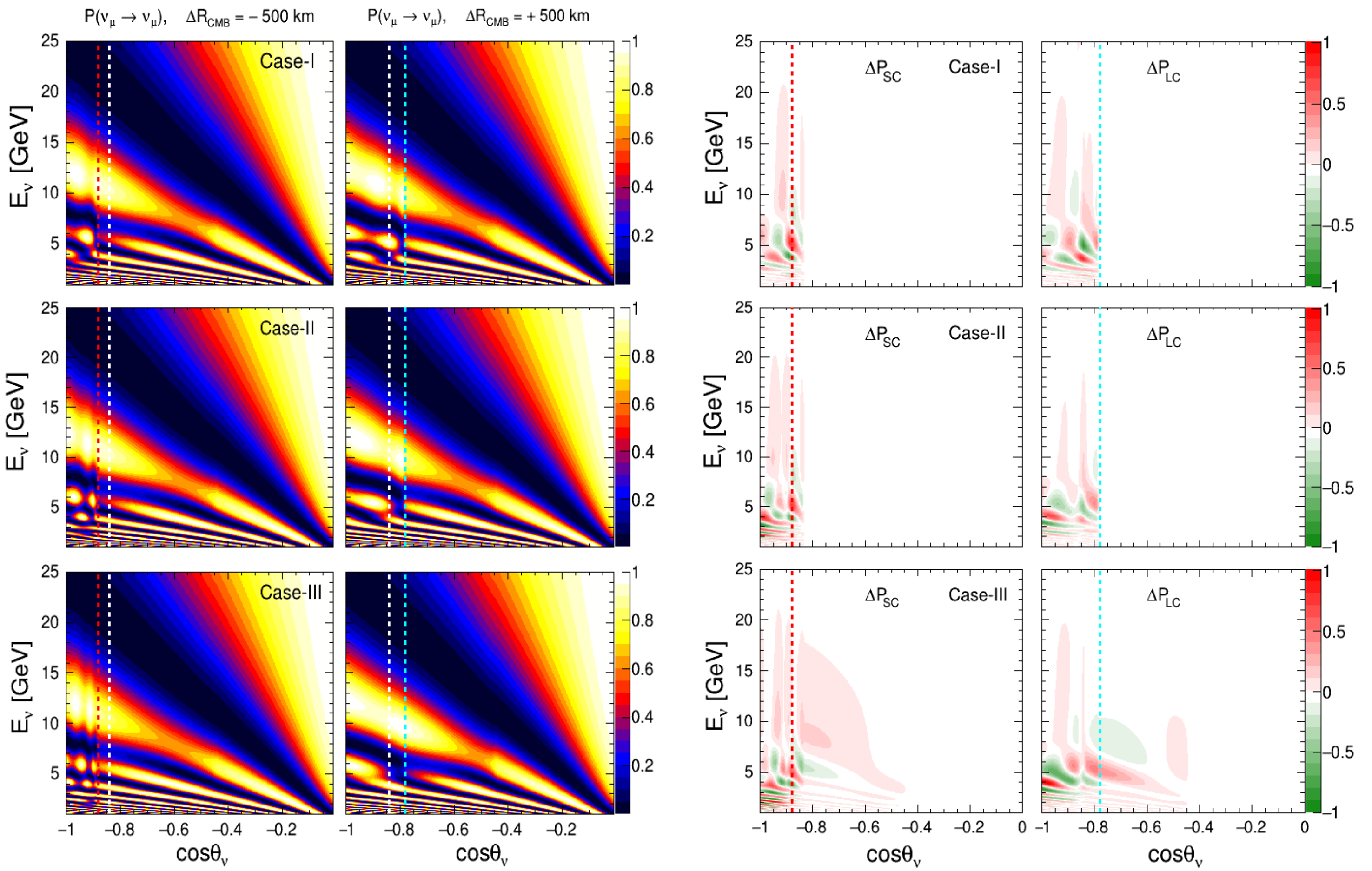
While constructing alternative profiles of Earth, the radius & mass of Earth remain invariant

Atmospheric neutrino experiments can distinguish between these alternative profiles of Earth utilizing neutrino oscillations in the presence of Earth's matter in multi-GeV energy range

Effect of CMB Variation on Oscillograms







A K Upadhyay et. al., arXiv: 2211.08688

Dark matter inside Earth core

- Dark matter (DM) fraction of core, f_{D}, defined as:

$$f_{\text{D}} \cdot M_{\text{core}} = \int_0^{R_{\text{CMB}}} 4\pi r^2 \left(\rho_{\text{PREM}}(r) - \rho_{\text{B}}(r)\right) dr \tag{1}$$

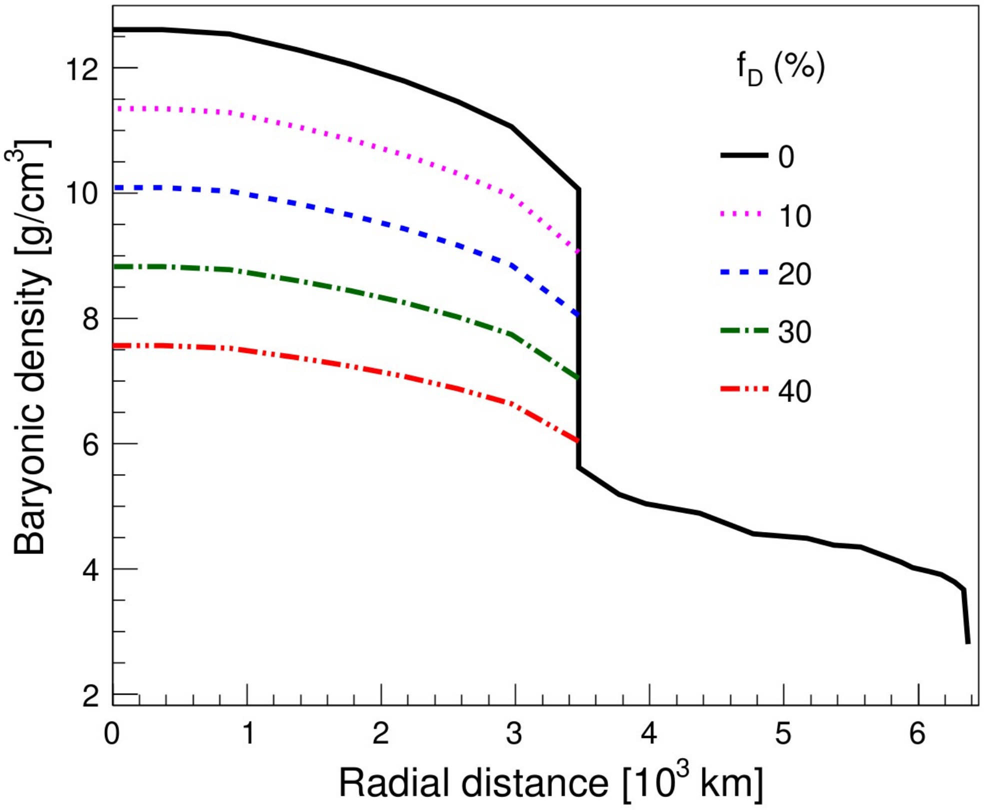
- Baryonic mass fraction, f_{B}, defined as:

$$\rho_{\text{B}}(r) = f_{\text{B}}(r)\, \rho_{\text{PREM}}(r) \tag{2}$$

- We choose a toy model with uniform $f_{\text{B}}(r) = 1 - f_{\text{D}}$

The mass of the DM is compensated by decreasing the density of core by a uniform fraction f_{D}.

Baryonic profiles in presence of dark matter



Decreasing density of core by f_D

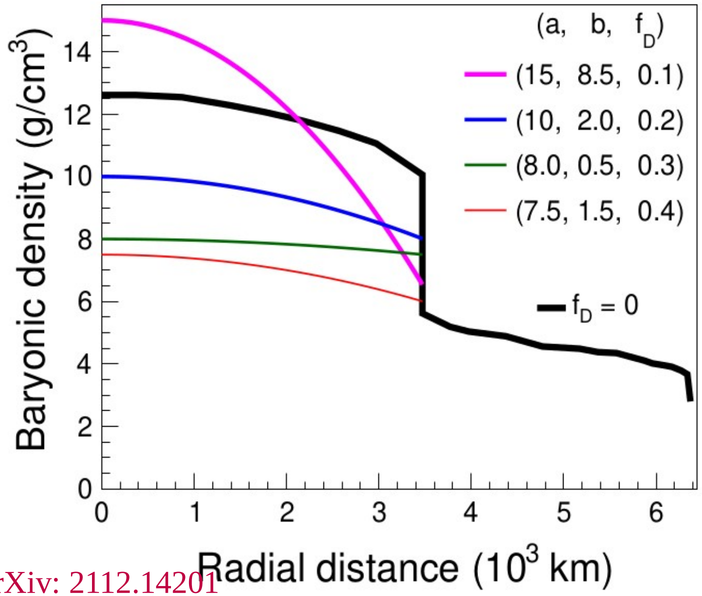
A K Upadhyay et. al., arXiv: 2112.14201

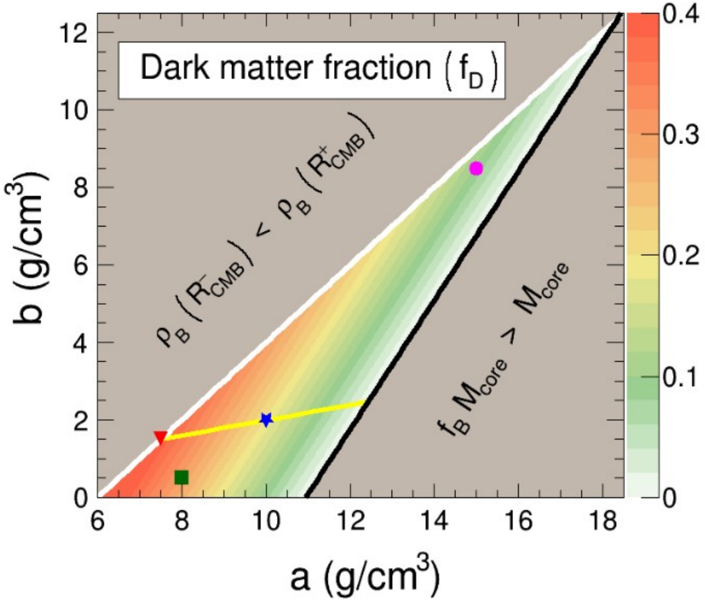
Constrains on baryonic profiles inside core

- Parameterize the baryonic matter density profile inside the core as,

$$\rho_B(r) = a - b.(r/R_{CMB})^2$$

  where a and b are positive constants with the units of density.
- Density decreases monotonically.
- The gray regions are unphysical.
- Colored dots (right plot) corresponds to the colored density profiles (left plot).
- Each point inside the triangular region corresponds to an allowed baryonic profile.

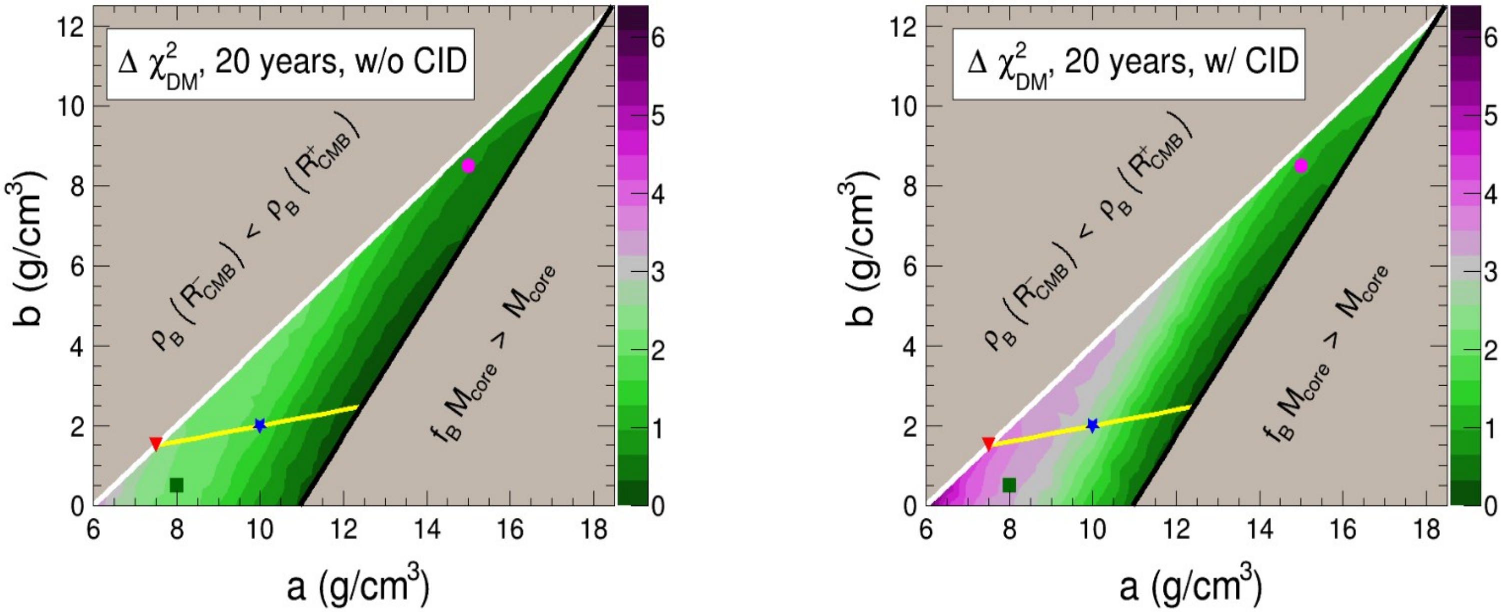




A K Upadhyay et. al., arXiv: 2112.14201

Constrains on baryonic profiles inside core

- The points along the black line corresponds to the profiles without DM, i.e. $f_D = 0$.
- Each point on yellow line (having a form $b = \gamma a$) represent the core density profile with constant drop in density by f_D. (like the plot on slide 12)
- $\Delta\chi^2_{\rm DM}$ for $f_D = 0.2$ and $f_D = 0.4$ are 2.65 (1.68) and 4.03 (2.51) for with (without) CID capability, respectively.



Sensitivity to some representative baryonic density profiles

A K Upadhyay et. al., arXiv: 2112.14201