Probing Interiors of Earth using Magnetized Neutrino Detector

Iron Calorimeter (ICAL) Detector at India-based Neutrino Observatory (INO)

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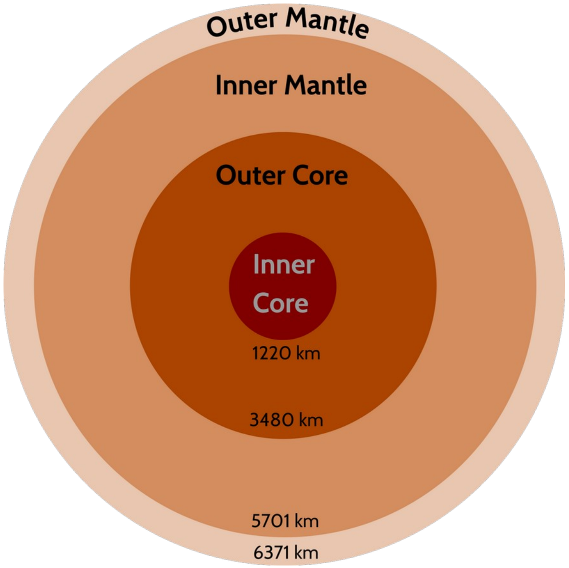
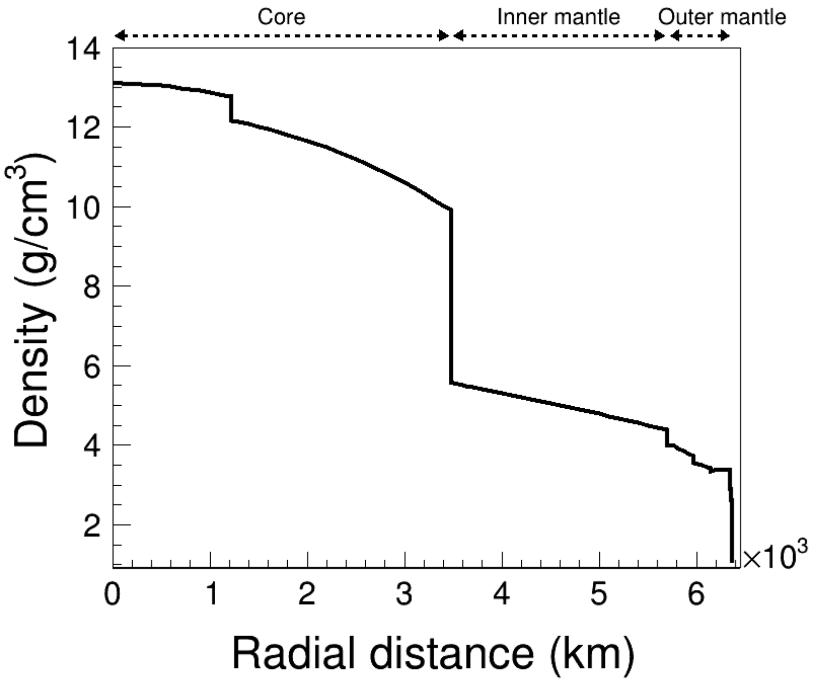
- Introduction
- Matter effects in neutrino oscillations
- Magnetized ICAL detector at INO
- Analyses:
  - Presence of core inside Earth
  - Location of core-mantle boundary
  - Dark matter inside Earth

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 **<u>Preliminary Reference Earth Model (PREM)</u>**.





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

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:** The density-dependent matter effects due to interactions of neutrinos with ambient electrons inside Earth can be used to reveal the internal structure of Earth.
  - **Atmospheric neutrinos** (L. Wolfenstein, Phys. Rev. D17 (1978) 2369)
  - **Supernova neutrinos** (A. S. Dighe, M. T. Keil, G. G. Raffelt, arXiv:hep-ph/0303210)
  - **Solar neutrinos** (P. Bakhti, A.Y. Smirnov, Phys. Rev. D 101 (2020) 123031)

- **Geoneutrinos:** The decay of radioactive elements inside Earth results in geoneutrinos which can help us understand the heat budget of Earth. (W.F. McDonough and H. Watanabe, arXiv:2209.13746)

Since neutrinos interact via **weak interactions**, probing Earth through **neutrino** 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**.

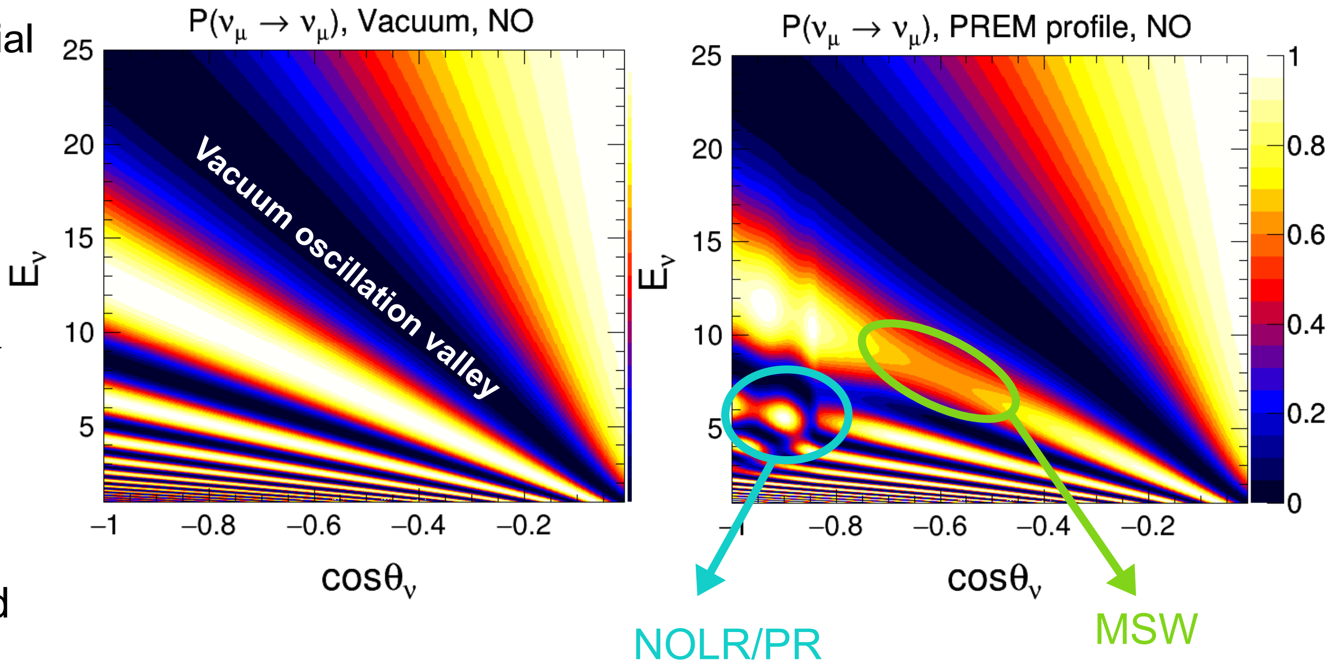
The analyses presented in this talk are based on **neutrino oscillation tomography** using ICAL detector at INO.

Earth's Matter Effects in Neutrino Oscillations

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

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

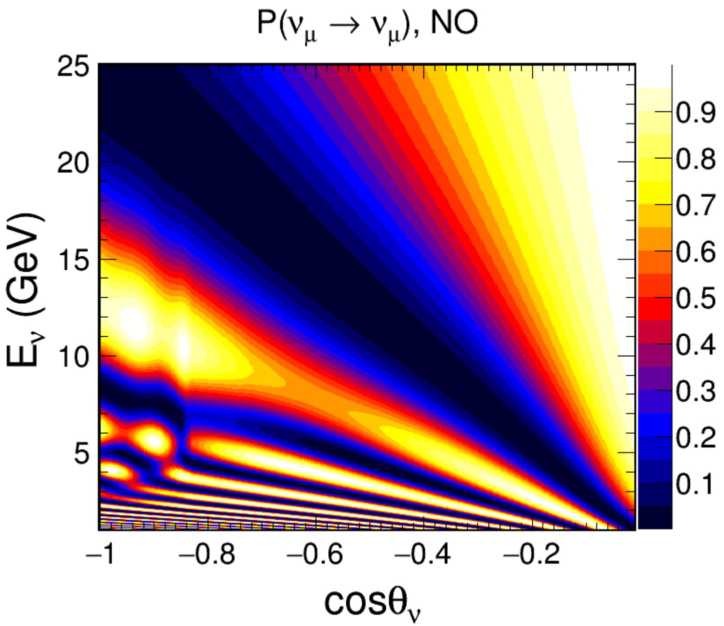
where, $Y_e = N_e/(N_p + N_n)$, corresponds to the relative electron number density inside the matter and ρ denotes the matter density.

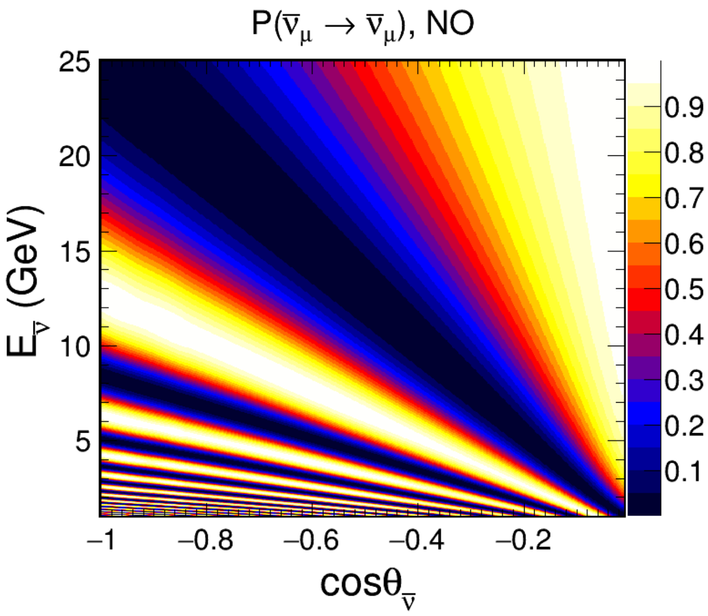


<u>Mikheyev–Smirnov–Wolfenstein (MSW) resonance</u> (L. Wolfenstein, Phys. Rev. D17 (1978) 2369): 6 GeV < E_ν < 10 GeV

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

Oscillations in Neutrinos and Antineutrinos



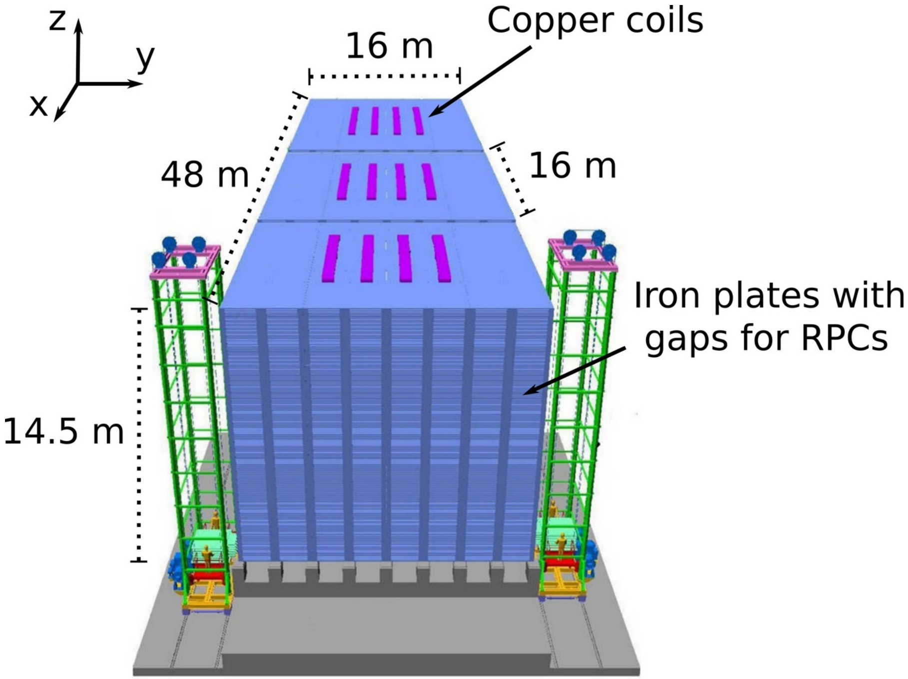


- For NO, matter effects occur mainly in neutrino channel.
- But for IO, matter effects occur mainly in antineutrino channel.

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

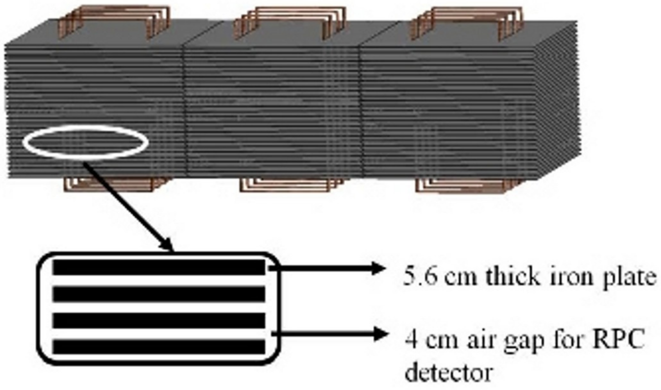
Iron Calorimeter Detector (ICAL) at INO

- **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°

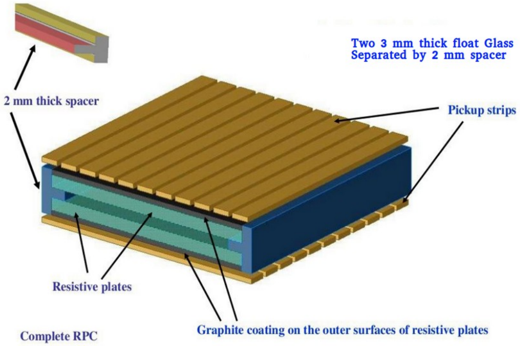


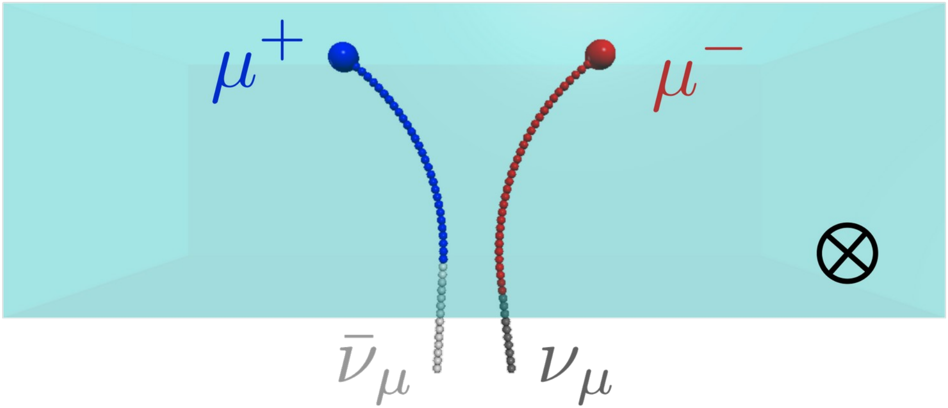
Pramana - J Phys (2017) 88 : 79, arXiv:1505.07380

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.

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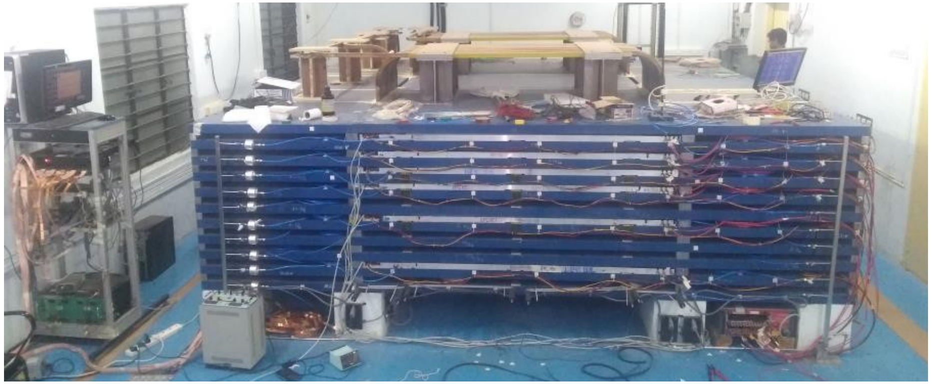
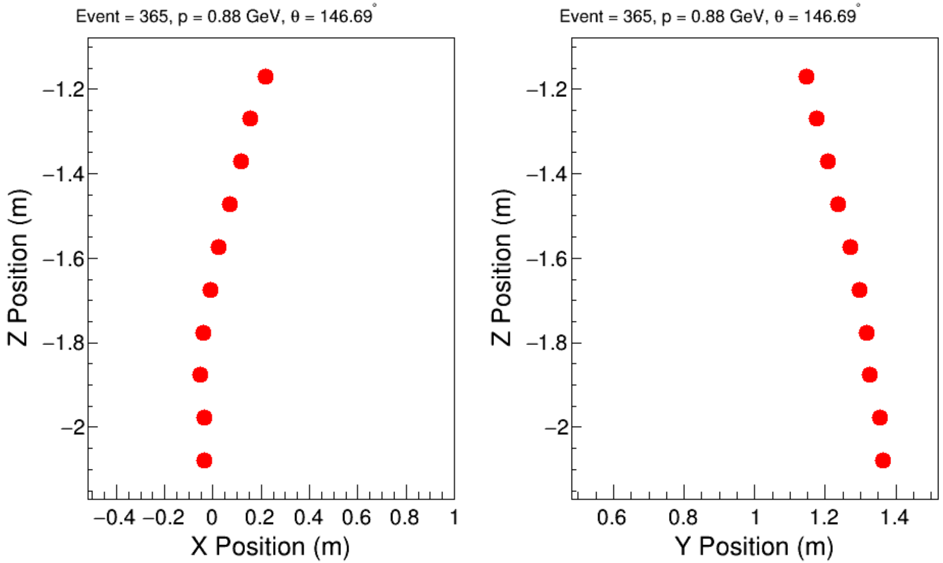
Bending of Muons in Magnetic Field



Mini-ICAL detector module at Madurai

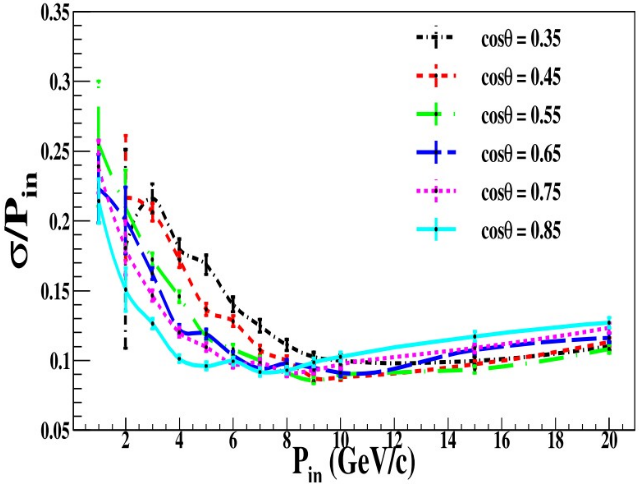


Experimentally observed opposite bending of cosmic μ^- and μ^+ at mini-ICAL

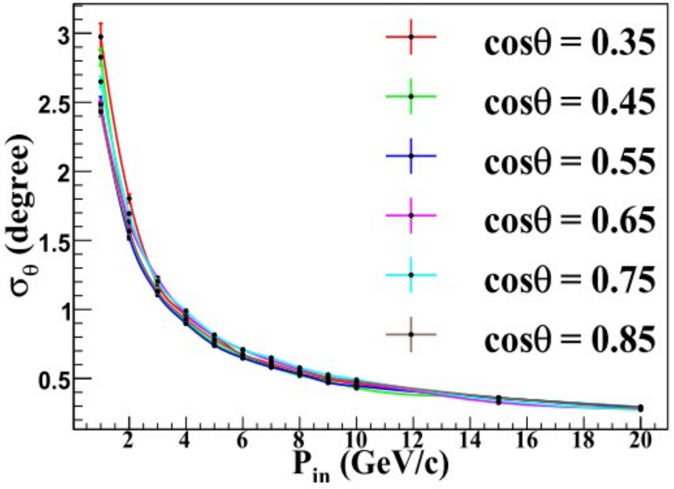
Detector Response of ICAL

Charged-current interaction of ν_μ at ICAL results in

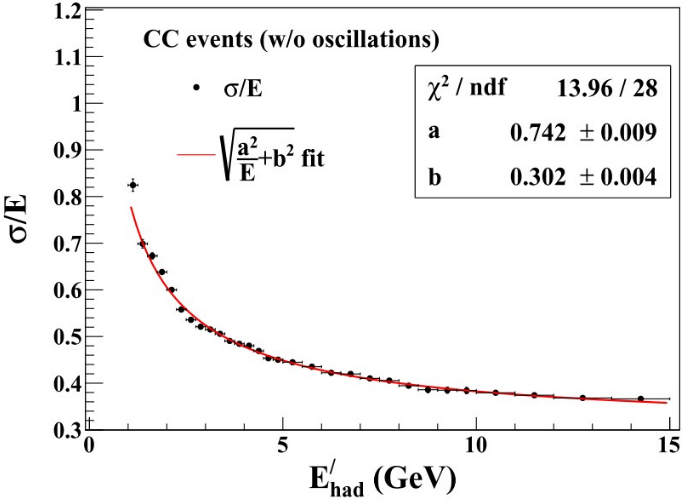
- Muons -> Tracks
- Hadrons -> Shower



Muon energy resolution



Muon direction resolution

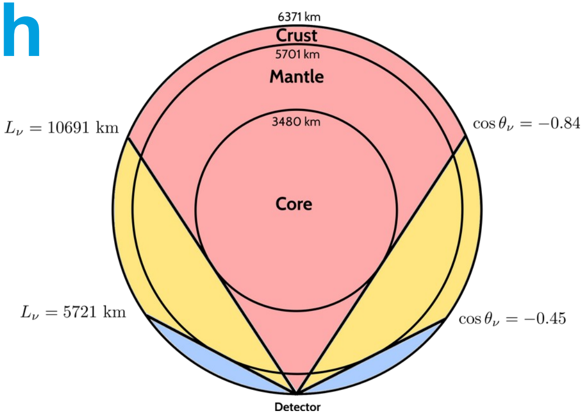


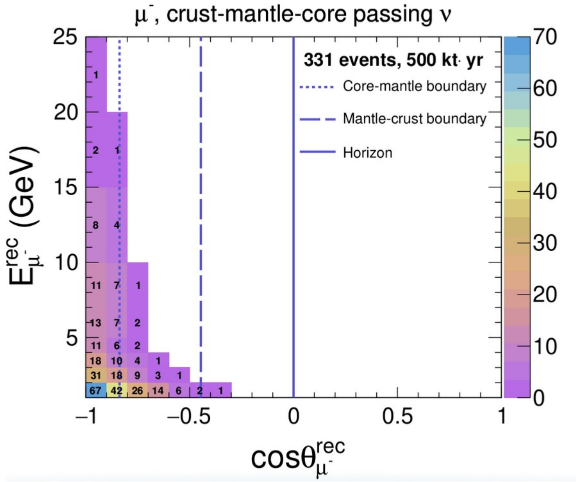
Hadron energy resolution

Pramana - J Phys (2017) 88 : 79, arXiv:1505.07380

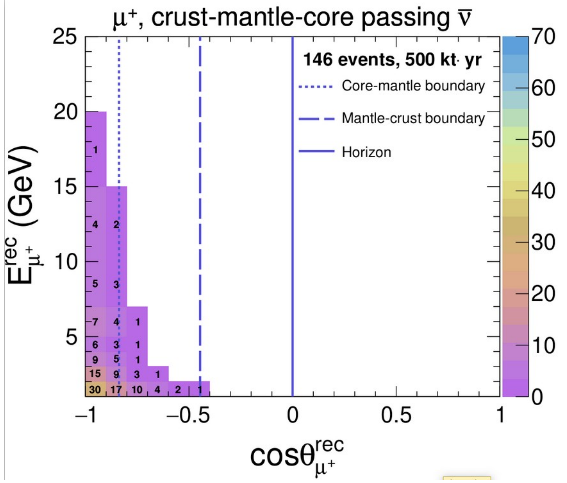
Identifying Events for Neutrinos Passing through Different Layers of Earth

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





	$\cos\theta_\nu$	L_ν (km)	μ^-	μ^+
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	2054

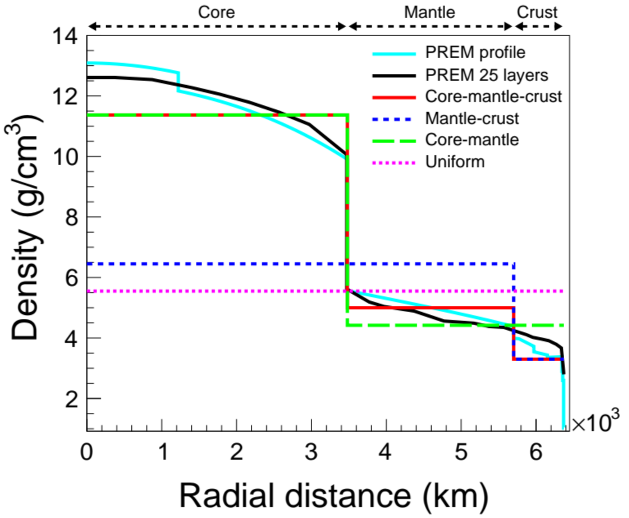


Direction resolution of ICAL is sufficient to preserve the information of core-passing neutrinos.

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

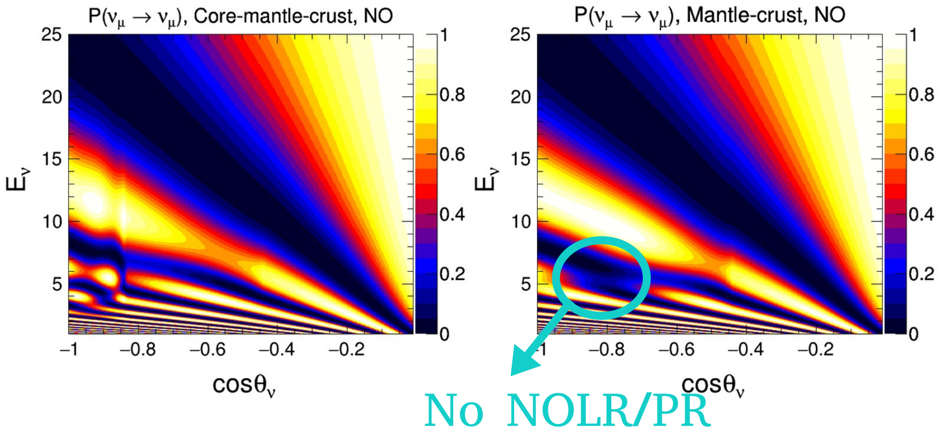
Validating the Presence of the Core of Earth

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.

No Core → No NOLR/PR



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

Sensitivity to Validate Earth's Core with and without CID

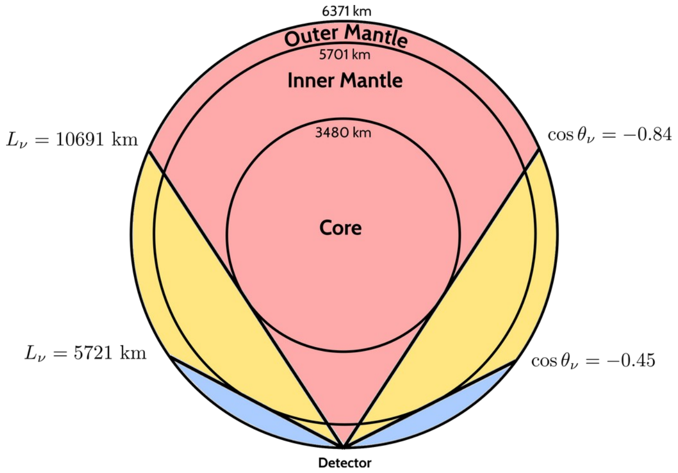
- 500 kt·yr exposure at ICAL
- Marginalization over:
  - systematic uncertainties
  - Oscillation parameter:
    - $\sin^2\theta_{23}$: (0.36, 0.66)
    - Δm^2_{eff}: (2.1, 2.6) ×10^{-3} eV^2
    - mass ordering: (NO, IO)

MC Data	Theory	$\Delta\chi^2_{ICAL\text{-}profile}$			
		NO (true)		IO (true)	
		with CID	w/o CID	with CID	w/o CID
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

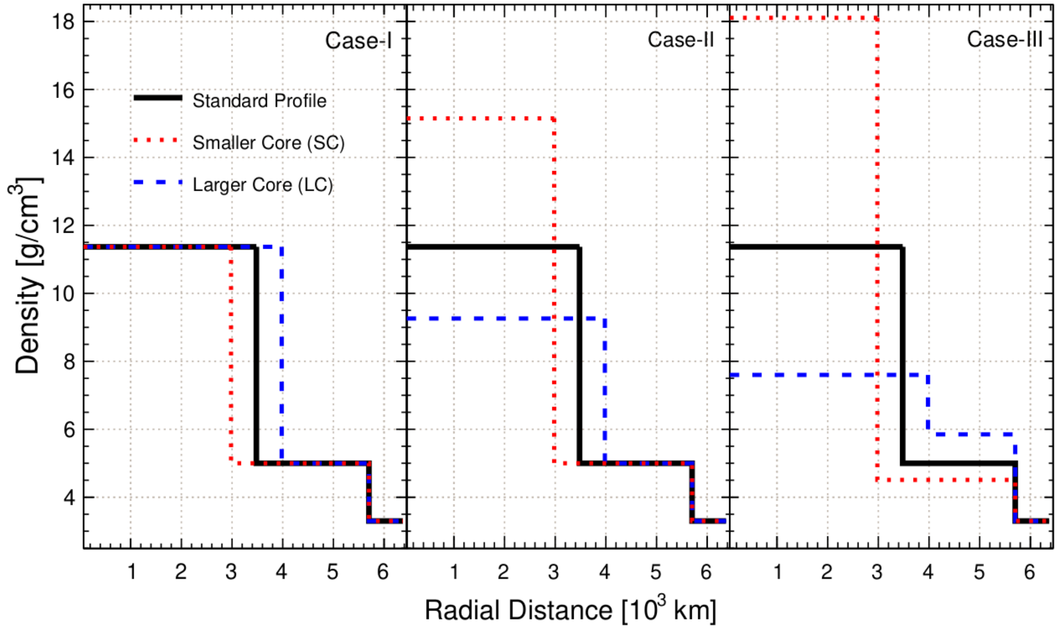
The presence of CID enhances ICAL sensitivity for validating the presence of Earth's core.

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

Measuring the Location of Core-mantle Boundary (CMB)



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



We consider three density models for modified 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.

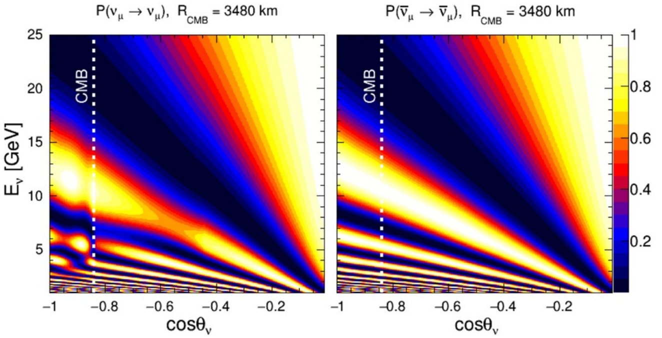
Refer to talk by Anuj Kumar Upadhyay

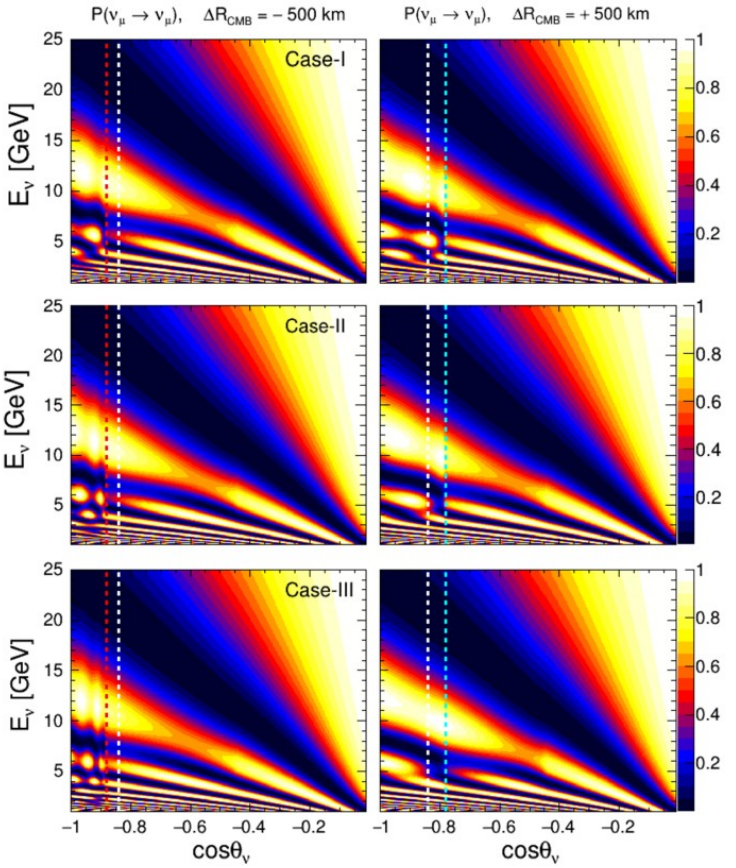
Anuj Kumar Upadhyay et. al., JHEP 04 (2023) 068, arXiv: 2211.08688

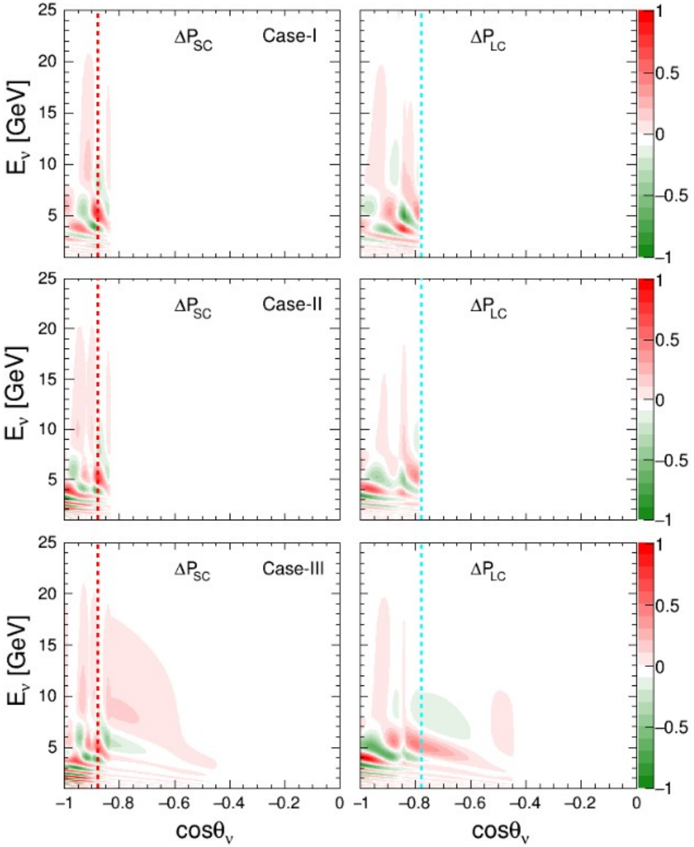
Effect of CMB Variation on Oscillograms

Observations:

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

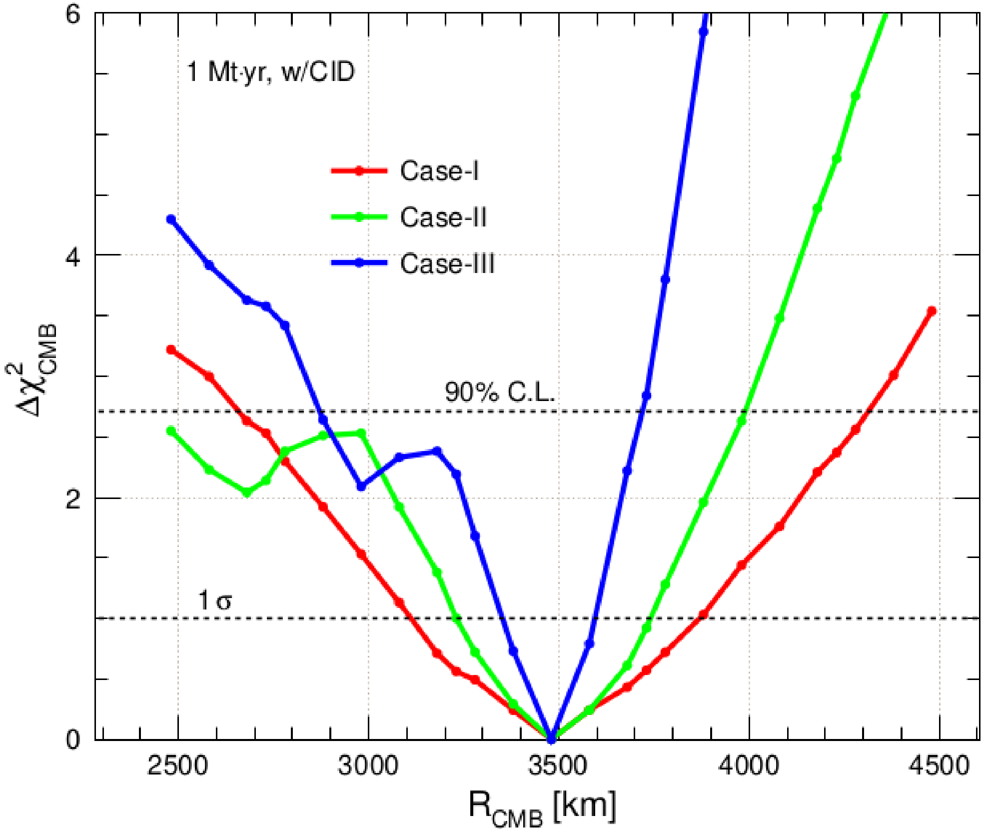






Anuj Kumar Upadhyay et. al., JHEP 04 (2023) 068, arXiv: 2211.08688

Sensitivity for Locating Core-Mantle Boundary



Location of CMB at 1σ with CID

- Case-I: ± 380 km
- Case-II: ± 250 km
- Case-III: ± 120 km

Location of CMB at 1σ without CID

- Case-II: ± 330 km

Therefore, the presence of CID enhances the ICAL sensitivity for the location of CMB.

Anuj Kumar Upadhyay et. al., JHEP 04 (2023) 068, arXiv: 2211.08688

Probing the Possible Presence of Dark Matter inside Earth

- The Gravitational measurements depend upon the total mass of Earth (baryonic matter + possible dark matter).
- We assume that the interaction of neutrino with dark matter (DM) particle is minimum.
- Therefore, DM can’t affect neutrino oscillation patterns directly.
- However, the matter effects in neutrino oscillations depends upon the electron density inside Earth, and hence, on baryonic matter density.
- Any deficit in the total amount of baryonic matter seen by matter effects in neutrino oscillations may indicate the possible presence of DM inside Earth.
- Therefore, matter effects in neutrino oscillations can place an independent upper bound on DM inside Earth.

Anuj Kumar Upadhyay et. al., PRD 107 (2023) 11, 115030, arXiv: 2112.14201

Modified Baryonic Density in Core to accomodate DM inside Earth

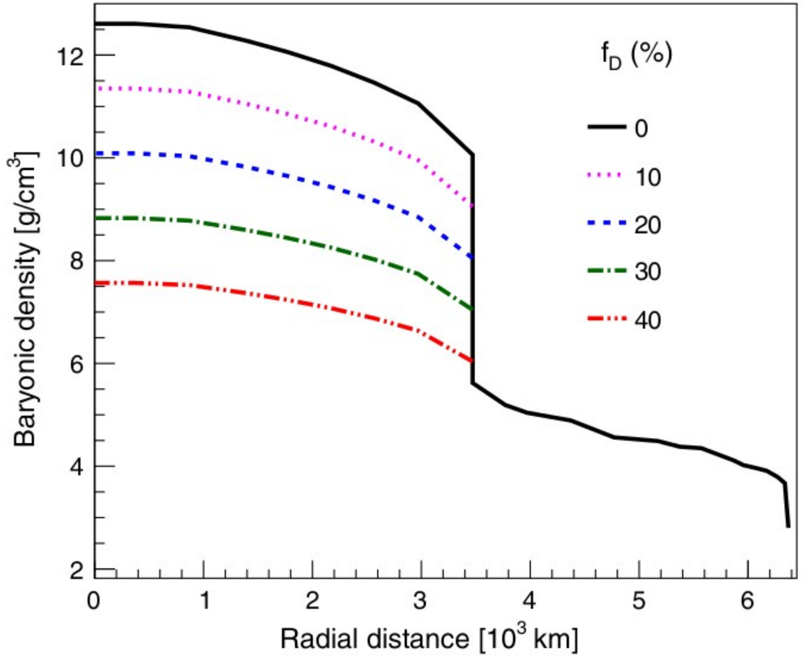
- We assume that the density of mantle is more precisely known.
- We incorporate the presence of DM inside the Earth by modifying the density of core.
- However, DM can spill outside core also.

$$\rho_{\rm B}(r) = f_{\rm B}(r)\,\rho_{\rm PREM}(r)$$

$$\langle f_{\rm B}\rangle \cdot M_{\rm core} = \int_0^{R_{\rm CMB}} 4\pi r^2 \rho_{\rm B}(r) dr$$

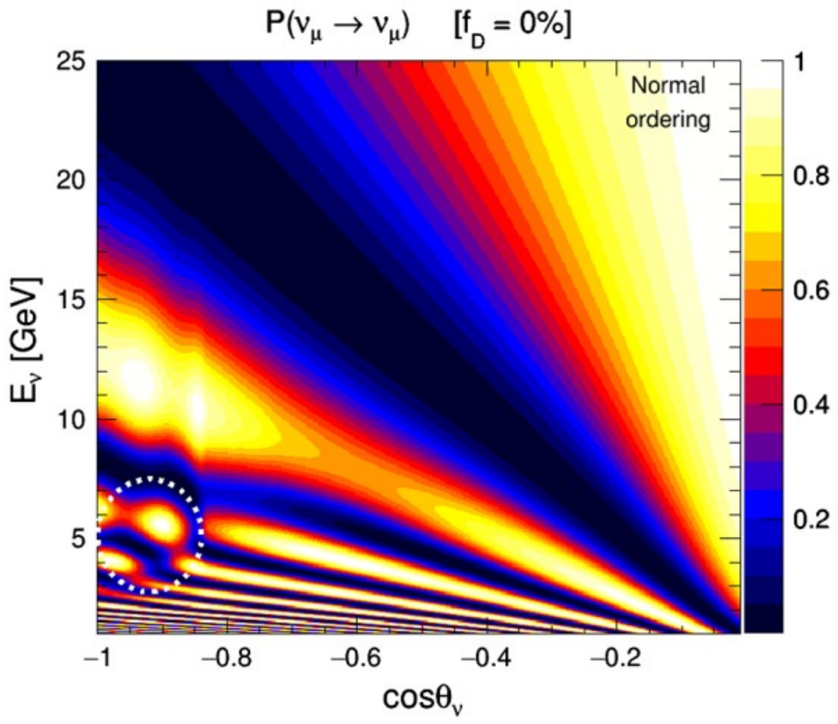
$$f_{\rm D} \equiv 1 - \langle f_{\rm B}\rangle$$

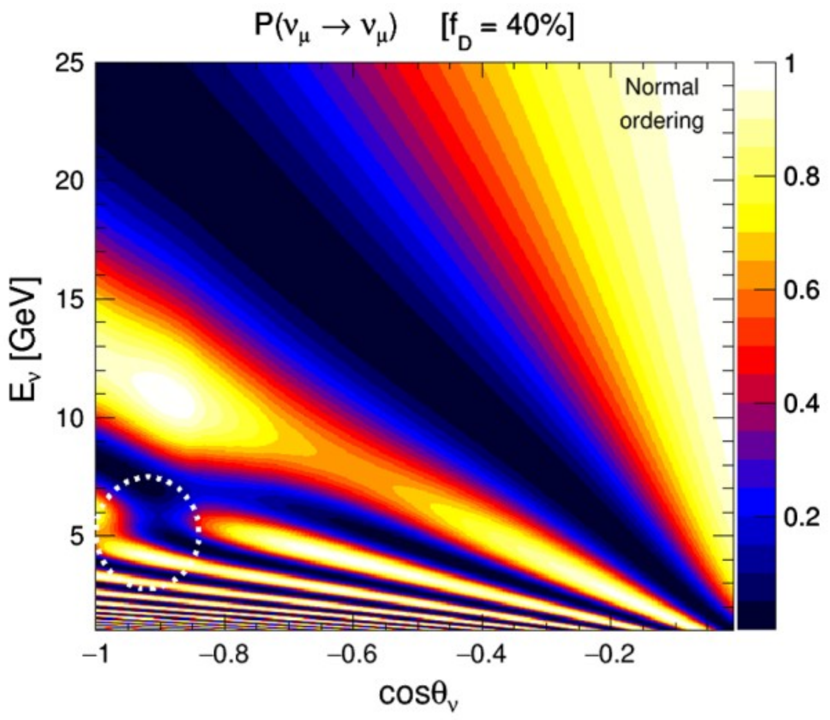
f_B (%)	f_D (%)	M_{DM} / M_E (%)
100	0	0
90	10	3.2
80	20	6.5
70	30	9.7
60	40	13.0



Anuj Kumar Upadhyay et. al., PRD 107 (2023) 11, 115030, arXiv: 2112.14201

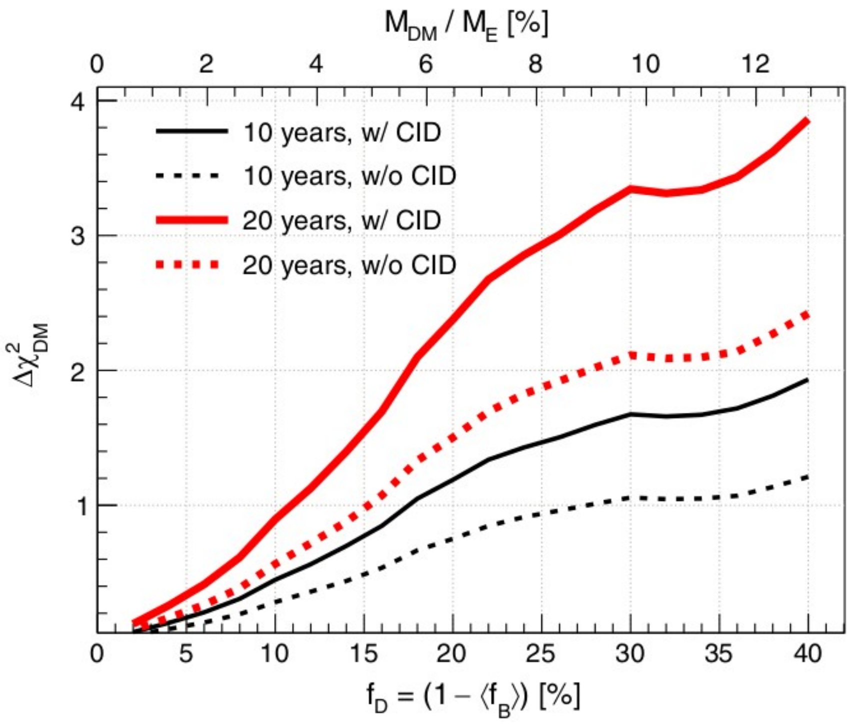
Effect of DM inside Earth on Neutrino Oscillograms





The presence of DM inside core affects the NOLR/PR region.

ICAL Sensitivity for the Presence of Dark Matter



ICAL sensitivity to DM in term of the total mass of Earth (M_{DM}/ M_E) at 1σ level:

- 10 years: ~5.5%
- 20 years: ~3.5%

This can also be interpreted in terms of the ICAL sensitivity towards the measurement of the mass of Earth.

The presence of CID enhances the ICAL sensitivity for the possible presence of dark matter inside Earth.

Anuj Kumar Upadhyay et. al., PRD 107 (2023) 11, 115030, arXiv: 2112.14201

ICAL Sensitivity for Profile of Earth

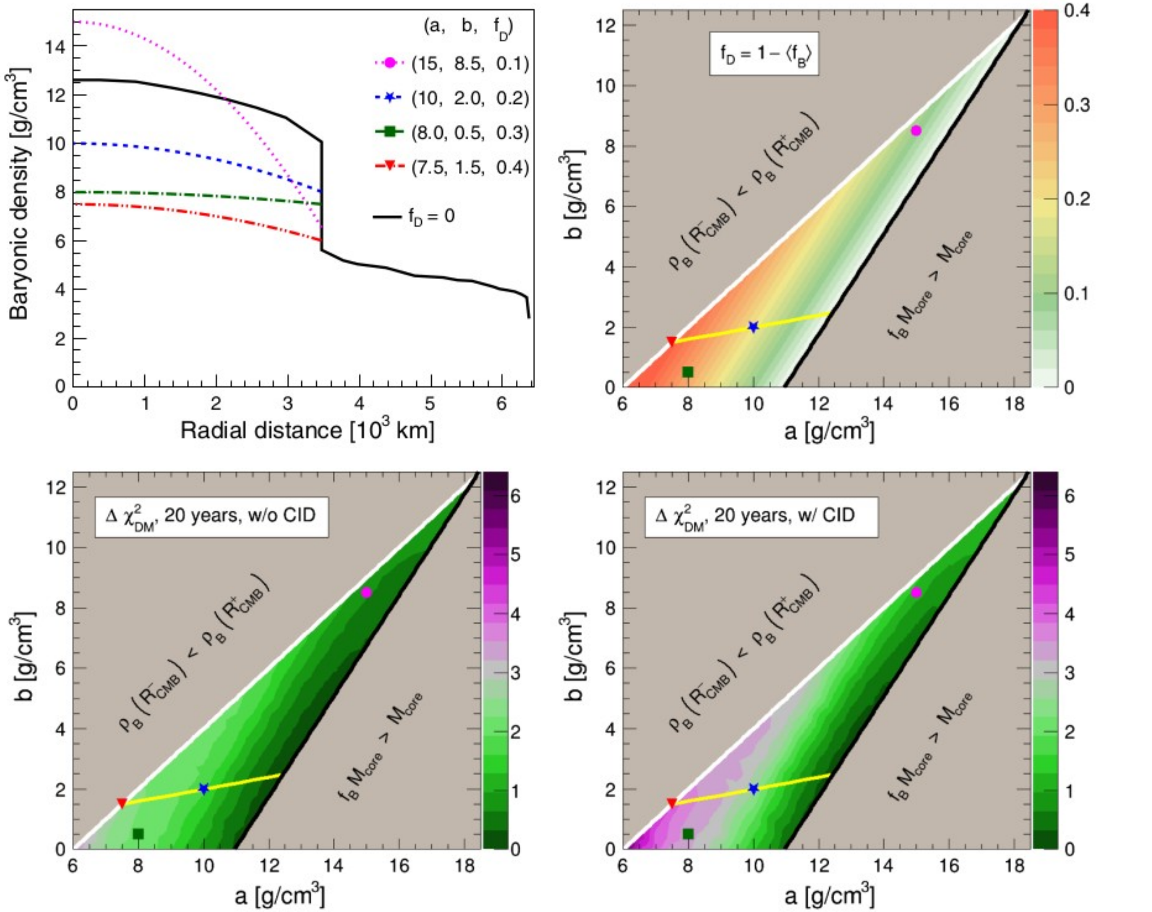
Consider, the density profile inside core

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

$$\int_0^{R_{\mathrm{CMB}}} 4\pi r^2 \rho_B(r) dr \leq M_{\mathrm{core}}$$

where, parameters *a* and *b* control the shape of the distribution.

- CID improves sensitivity
- Even for the same f_D, ICAL has some sensitivity to parameters *a* and *b*, and hence to density profile.



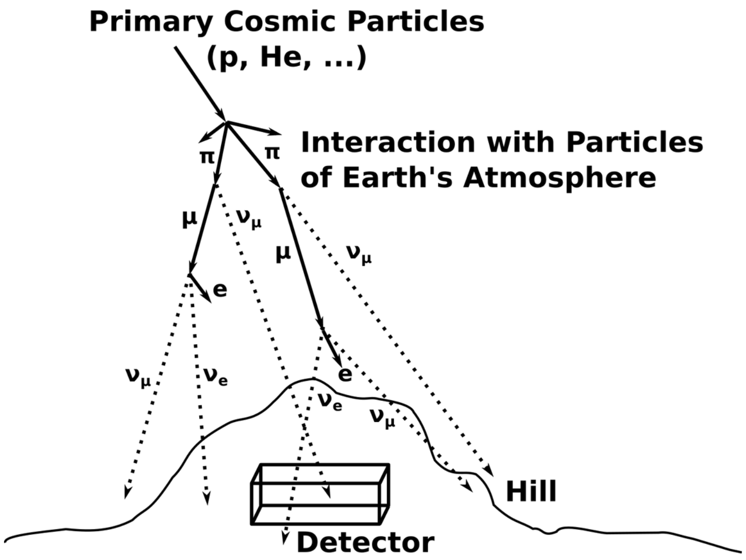
Anuj Kumar Upadhyay et. al., PRD 107 (2023) 11, 115030, arXiv: 2112.14201

Summary

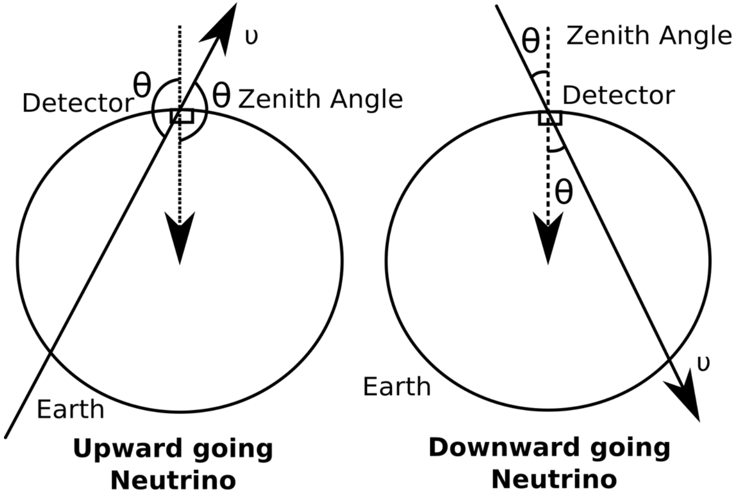
- The weak interactions of neutrinos provide an indepedent way to probe the interior of Earth which is complementary to seismic studies and gravitational measurements.
- The upward-going atmospheric neutrinos interact with ambient electrons and experience Earth's matter effects which are different for neutrinos and antineutrinos.
- The presence of charge identification capability due to magnetic field at ICAL helps in preserving the different matter effects felt by neutrinos and antineutrinos.
- ICAL can validate the presence of Earth's core with $\Delta\chi^2$ of 7.45 (4.83) for NO (IO) with 500 kt.yr exposure.
- ICAL sensitvity to measure the location of CMB at 1σ is about ± 250 km with 1000 kt.yr exposure.
- ICAL sensitivity to the presence of possible DM is about 5.5% of the total mass of Earth using 1000 kt.yr exposure.
- ICAL can also have some sensitivity to the shape of density distribution inside core.

Backup

Atmospheric Neutrinos



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$



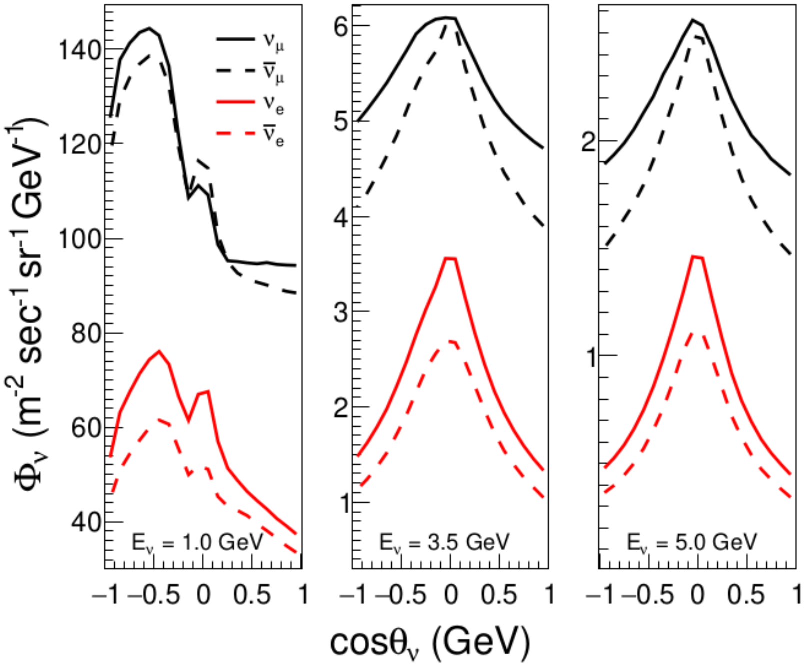
$90° \leq \theta \leq 180°$
$-1 \leq \cos\theta \leq 0$

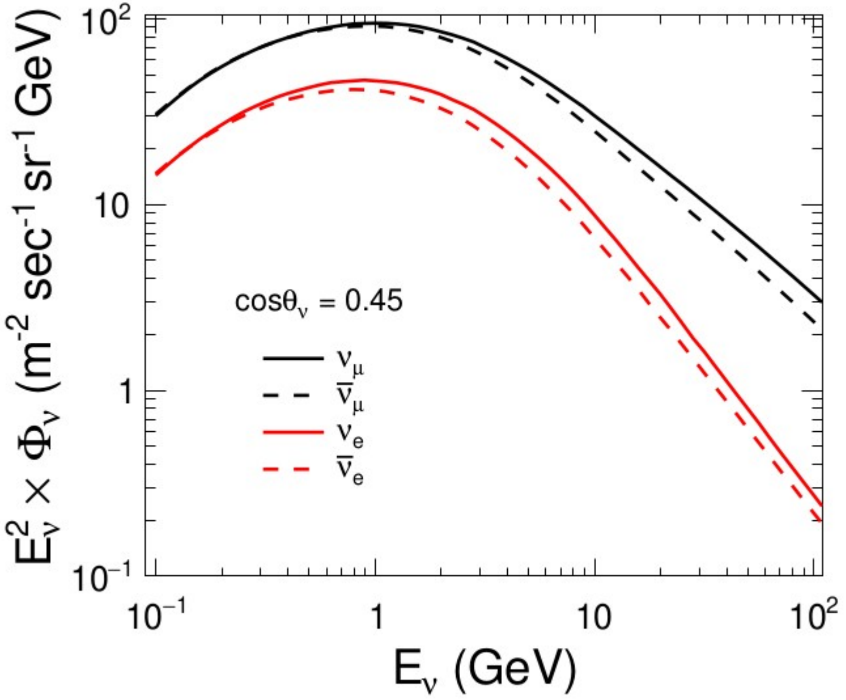
$0° \leq \theta \leq 90°$
$0 \leq \cos\theta \leq 1$

Expectation: $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$

but at high energies $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} > 2$

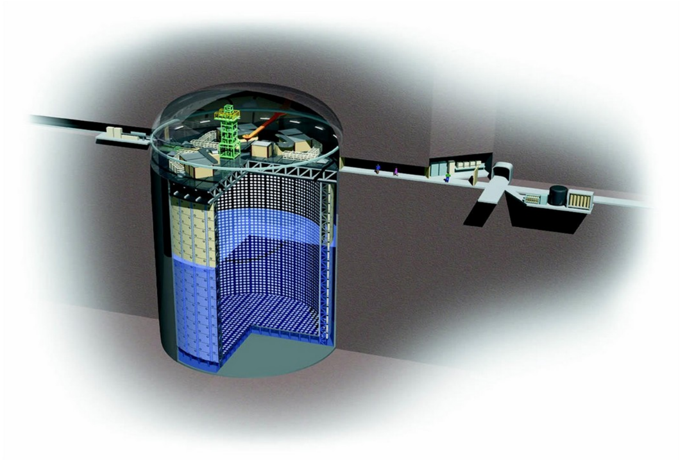
Flux of Atmospheric Neutrinos





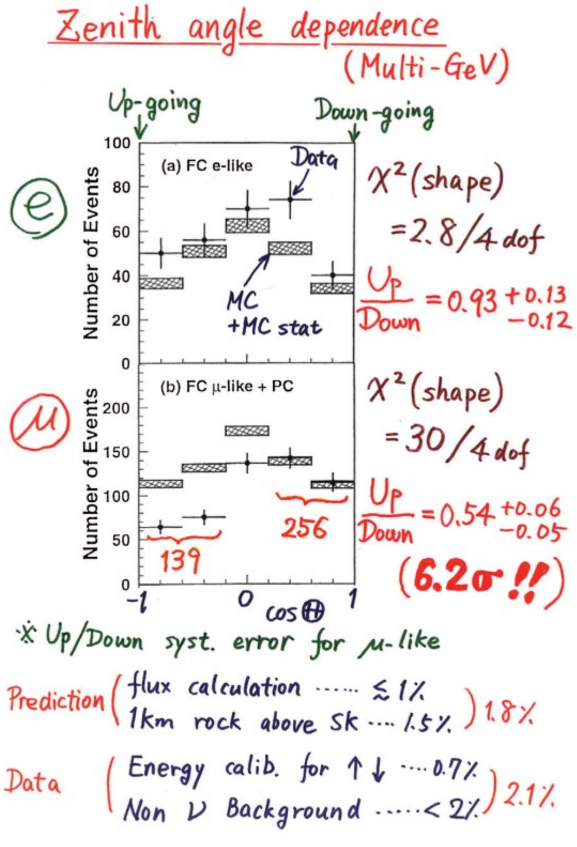
- Flux of atmospheric neutrinos is up-down symmetric for energy above ~5 GeV
- Flux of atmospheric neutrinos decrease with energy following a power-law ($\sim E^{-2.7}$)

Observed Asymmetry in Atmospheric Neutrinos

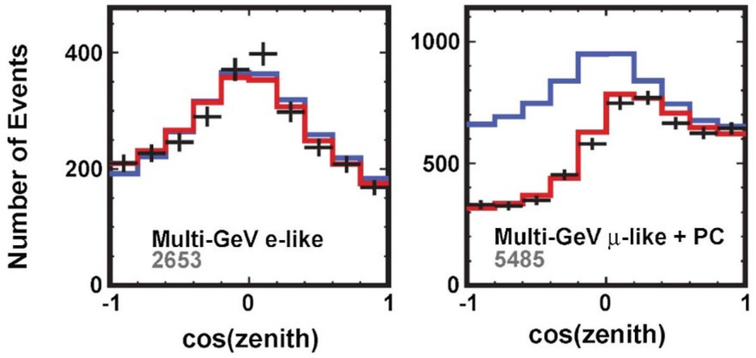


Super-Kamiokande Detector

- In 1998, Super-Kamiokande experiment observed a deficit in the upward-going multi-GeV muon neutrinos.
- Observed electron neutrinos were same as expected.



Neutrino 1998 conference, Super-K collaboration



T. Kajita, Reviews of Modern Physics, Vol 88, Jul-Sep 2016

Atmospheric neutrino events observed at Super-K (2015)

- MC without neutrino oscillations (blue)
- MC with neutrino oscillations (red)

Atmospheric neutrino data at Super-K agrees with hypothesis of neutrino oscillations

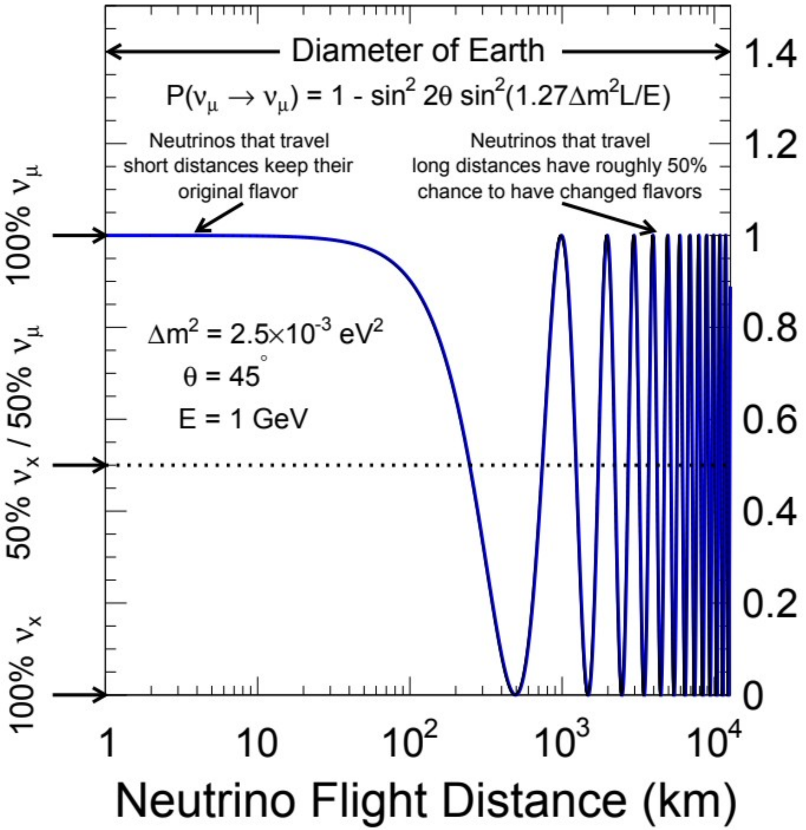
Neutrino Oscillations

Atmospheric neutrinos have access to a wide range of baselines:

- Vertically downward-going neutrinos: 15 km
- Vertically upward-going neutrinos: 12757 km

For E_ν = 1 GeV:

- At smaller baselines: neutrino oscillations are not developed
- At larger baselines: about 50% ν_μ have oscillated
- At certain baselines: about 100% ν_μ have oscillated



Three-flavor Neutrino Oscillations

Representing flavor states as mass eigenstates:

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i$$

$$\text{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where, $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

Probability of oscillation of flavor α to β:

$$P(\nu_\alpha \to \nu_\beta) = \left| U_{\beta 1}U^*_{\alpha 1} + U_{\beta 2}U^*_{\alpha 2}e^{-i2\alpha\Delta} + U_{\beta 3}U^*_{\alpha 3}e^{-i2\Delta} \right|^2$$

$$\text{where,} \quad \Delta = \frac{\Delta m^2_{31} L_\nu}{4E_\nu}, \quad \Delta m^2_{ij} = m^2_i - m^2_j, \quad \text{and} \quad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

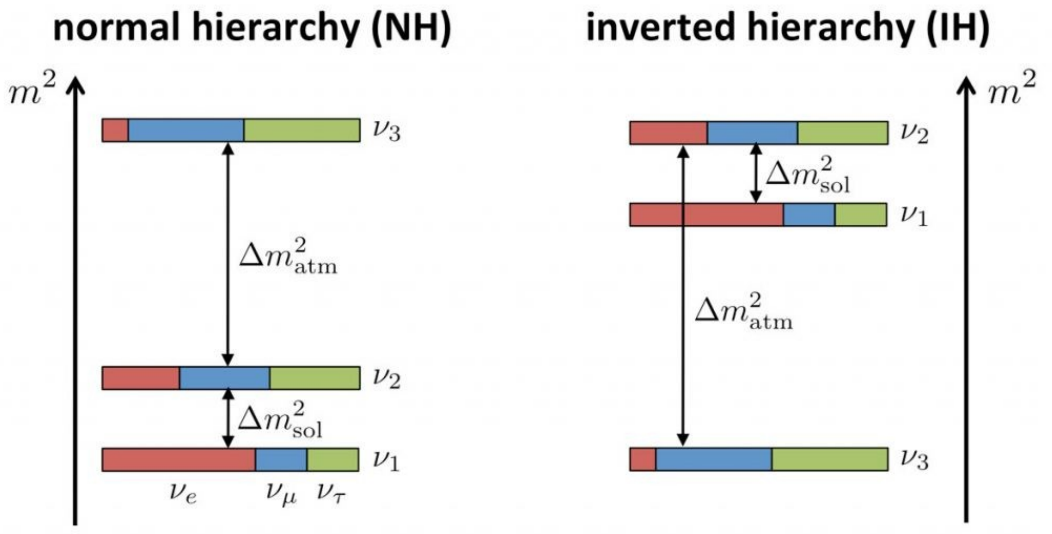
Benchmark value of Neutrino Oscillation Parameters

$\sin^2 2\theta_{12}$	$\sin^2 \theta_{23}$	$\sin^2 2\theta_{13}$	Δm^2_{eff} (eV^2)	Δm^2_{21} (eV^2)	δ_{CP}	Mass Ordering
0.855	0.5	0.0875	2.49×10^{-3}	7.4×10^{-5}	0	Normal (NO)

$$\Delta m^2_{\text{atm}} = m_3^2 - m_2^2$$

$$\Delta m^2_{\text{sol}} = m_2^2 - m_1^2$$

- Normal Ordering (NO): $(m_3 > m_2 > m_1)$
- Inverted Ordering (IO): $(m_2 > m_1 > m_3)$



Statistical Analysis

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

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

where,

$$N_{ijk}^{\rm theory} = N_{ijk}^{0}\left(1 + \sum_{l=1}^{5} \pi_{ijk}^{l}\xi_l\right)$$

Similarly, χ^2_+ is defined for μ^+

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

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

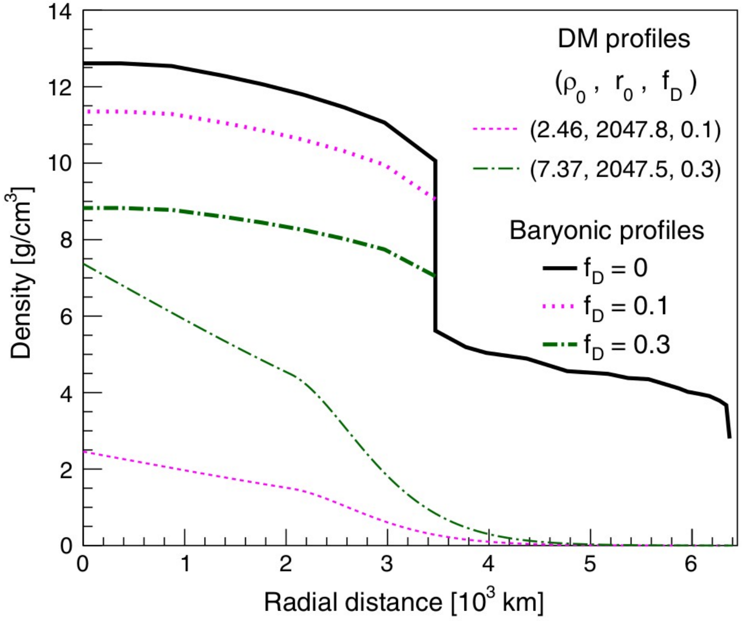
Sensitivity to Validate Earth's Core with and without CID

- 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	$\Delta\chi^2_{ICAL\text{-}profile}$			
		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, arXiv: 2104.11740

Accommodating a Realistic DM Profile



DM profile as "modified Burkert" form

A. Burkert and J. Silk, arXiv:astro-ph/9904159.

$$\rho_{\rm DM}(r) = \begin{cases} \rho_0\left[\left(1+\frac{r}{R_s}\right)\left(1+\frac{r^2}{R_s^2}\right)\right]^{-1} & \text{if } r \le r_0, \\ \rho_{\rm DM}(r_0)\left(\frac{r}{r_0}\right)^{\alpha}\exp\left[-\frac{(r-r_0)}{r_{\rm decay}}\right] & \text{if } r > r_0. \end{cases}$$

$$\alpha = \frac{r_0}{r_{\rm decay}} - \frac{2c^2}{(1+c^2)} - \frac{c}{(1+c)}, \quad \text{with} \quad c \equiv \frac{r_0}{R_s},$$

$$\int_0^{R_{\rm Earth}} 4\pi r^2 \rho_{\rm DM}(r) dr = (1 - \langle f_{\rm B}\rangle)\cdot M_{\rm core}.$$

Four parameters: ρ_0 , R_s , r_0 , and r_{decay}

- Since the values of M_E and I_E provide two constraints, it would typically always be possible to satisfy these by choosing appropriate values of the above four parameters.
- For illustration, we choose R_s = 5000 km and R_{decay} = 0.05 R_s

Anuj Kumar Upadhyay et. al., PRD 107 (2023) 11, 115030, arXiv: 2112.14201