Neutrino oscillations in Earth: a unique tool to probe dark matter inside the Core

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NuFact 2022: The 23rd International Workshop on Neutrinos from Accelerators

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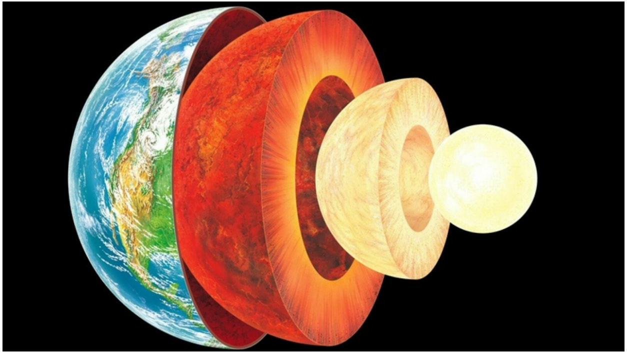
The Interior of Earth

- 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



Gravitational Measurements

Gravitational measurements exploits the gravitational interactions of matter inside Earth.

Average density

- For given mass[1] ($\sim 5.97 \times 10^{24}$ kg) and radius of Earth (~ 6400 km), average density of Earth $\sim 5.5\ \mathrm{g/cm^3}$
- Density of ordinary rock $\sim 2.8\ \mathrm{g/cm^3}$, therefore, the density near the centre of Earth is higher than $5.5\ \mathrm{g/cm^3}$

Moment of inertia

- For uniform sphere, $I = \frac{2}{5} MR^2 \Rightarrow \frac{I}{MR^2} = 0.4$
- Measured[2], $\frac{I}{MR^2} \sim 0.33$, [3] $I_{\oplus} \sim 8.017 \times 10^{37}$ kg m^2.
- Since $I_{\text{measured}} < I_{\text{expected}}$, more matter is concentrated near the axis of rotation

[1]B. Luzum et al., Celest. Mech. Dyn. Astron. 110, 293 (2011).

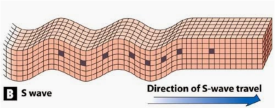
[2]Williams, James G. The Astronomical Journal. 108: 711 (1994)

[3]W. Chen, J. Ray, W. B. Shen, and C. L. Huang, J. Geod. 89, 179 (2015).

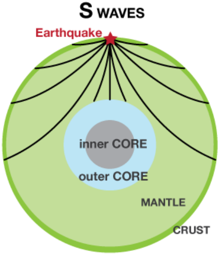
Seismic Studies

Seismic measurements exploits the electromagnetic interactions of matter inside Earth.

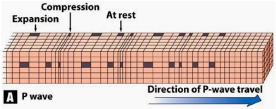
Body waves consisting of transverse vibrations are known as **S-waves**:



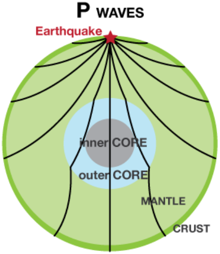
$$V_S = \sqrt{\frac{\mu}{\rho}}$$



Body waves consisting of longitudinal vibrations are known as **P-waves**:



$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$



Velocities of seismic waves depend upon the elastic constants of the material, such as density (ρ), bulk modulus (κ), shear modulus (μ)

E. C. Robertson, The interior of the Earth, an elementary description, 1966.

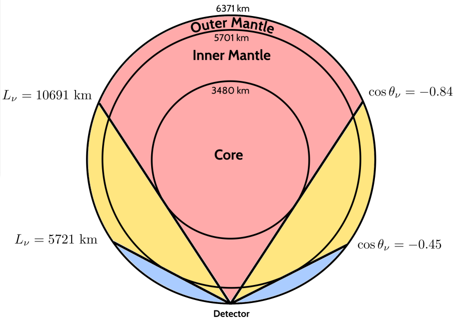
Image source: https://thinkgeogeek.blogspot.com/2014/01/seismic-waves.html

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).

Note that PREM is not a measured profile.

- **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



Three-layered model of Earth

References:

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

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.

D. Alfè, M. J. Gillan, and G. D. Price, Temperature and composition of the earth's core, Contemporary Physics 48 (2007), no. 2 63–80.

Anil Kumar, Sanjib Kumar Agarwalla, JHEP 08 (2021) 139, arXiv: 2104.11740

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:** While passing through Earth, neutrinos undergo charged-current coherent forward elastic scattering with ambient electrons and this results in the modification of neutrino oscillation patterns. These density-dependent matter effects can be used to reveal the internal structure of Earth. (L. Wolfenstein, Phys. Rev. D17 (1978) 2369)
- **Neutrino diffraction tomography:** The possibility of Earth tomography using the study of diffraction pattern produced by coherent neutrino scattering in crystalline matter inside Earth is technologically not feasible. (A. D. Fortes et. al. Using neutrino diffraction to study the Earth's core, Astronomy and Geophysics 47 (2006), no. 5 5.31–5.33.)

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

This work is based on neutrino oscillation tomography.

Motivation

- Neutrinos may provide an independent and complementary tool to probe the deep inside Earth via weak interactions.
- 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.**
- We illustrate with the Iron Calorimeter (ICAL) detector at India-based Neutrino Observatory (INO*) as the concrete example of an atmospheric neutrino experiment.

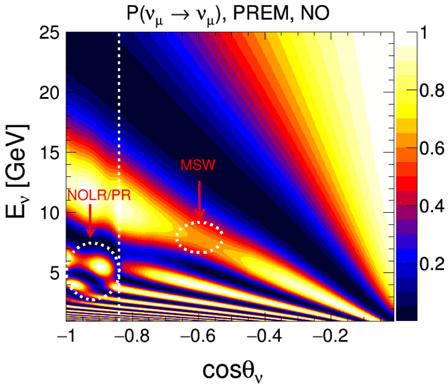
*Pramana - J Phys (2017) 88 : 79, arXiv:1505.07380

Matter Effects on Neutrino Oscillograms

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

- **MSW resonance (L. Wolfenstein, PRD 17 (1978) 2369):** red patch around $-0.8 < \cos\theta_\nu < -0.5$ and 6 GeV $< E_\nu <$ 10 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 GeV $< E_\nu <$ 6 GeV



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

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.

Note: $\bar{\nu}$ with IO shows the similar matter effects

Dark matter inside Earth core

- Dark matter (DM) mass fraction of core, f_D, defined as:

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

  where, $\rho_\mathrm{PREM}(r)$ and $\rho_\mathrm{B}(r)$ are the density distributions for PREM and baryonic profiles.

- Baryonic mass fraction, f_B, defined as:

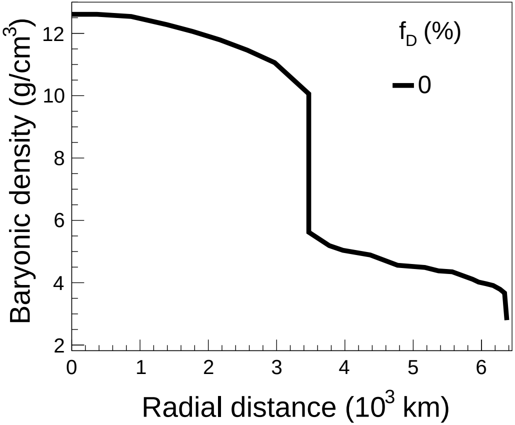
$$\rho_\mathrm{B}(r) = f_\mathrm{B}(r)\, \rho_\mathrm{PREM}(r) \tag{2}$$

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

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

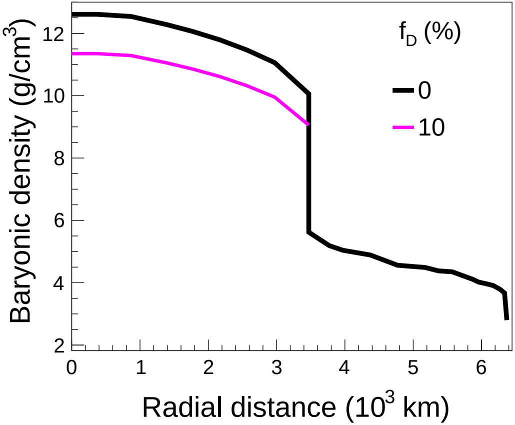
- Standard PREM density profile of Earth with no DM fraction, i.e. $f_D = 0$.



PREM profile

Baryonic profiles in presence of dark matter

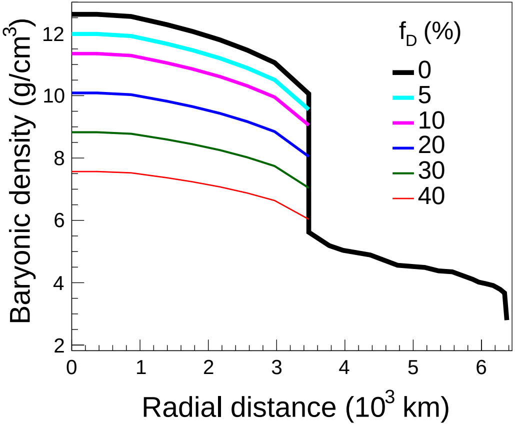
- Baryonic density profile of Earth, obtained by decreasing the density of the core by DM fraction f_D=10%.



Decreasing density of core by f_D

Baryonic profiles in presence of dark matter

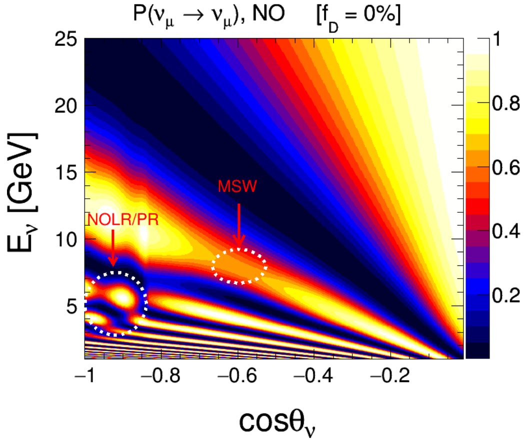
- Baryonic density profiles of Earth, obtained by decreasing the density of the core by DM fraction f_D.

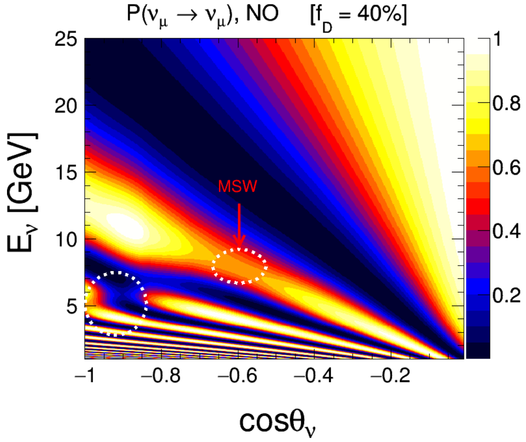


Decreasing density of core by f_D

Modified Probability Oscillograms in presence of DM

- Difference in the oscillation probabilities is apparent, especially in the NOLR/parametric resonance region.

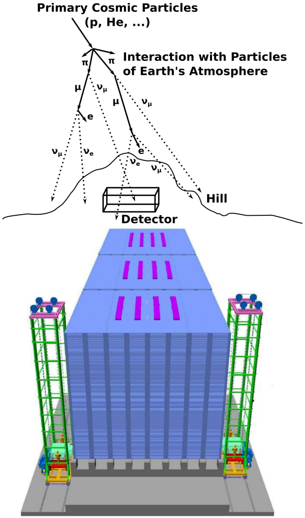




NOLR/PR is highly diluted in presence of DM

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 mass ordering and precision measurement of atmospheric 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:** $\sim 10\%$
- **Baselines:** 15 – 12000 km, **Muon zenith angle resolution:** $\sim 1^\circ$



*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.

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

where,

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

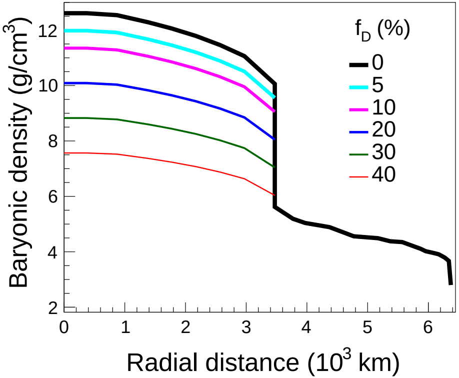
Similarly, χ^2_+ is defined for μ^+

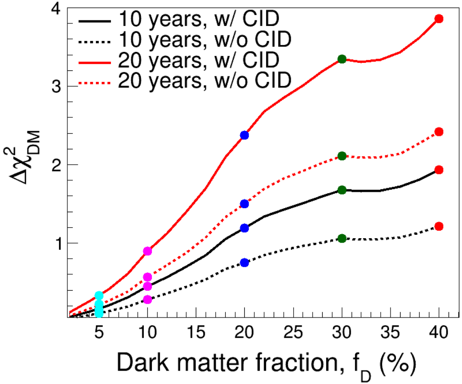
$$\chi^2_{\rm ICAL} = \chi^2_- + \chi^2_+$$

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

Sensitivity to rule out dark matter fraction

- Colored dots (right plot) represents the density profiles with the corresponding colored curves (left plot).
- The sensitivity to DM increases with f_D, reaching $\Delta\chi^2_{\mathrm{DM}} \approx 4$ (2σ) for an exposure of 20 years, utilizing the CID capability of ICAL.
- **Note:** The sensitivity for DM would be lower by almost 40% without this CID capability.





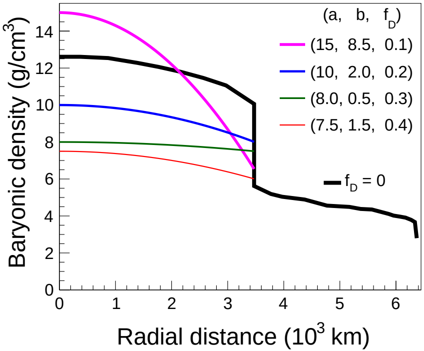
Sensitivity with which ICAL can rule out f_D

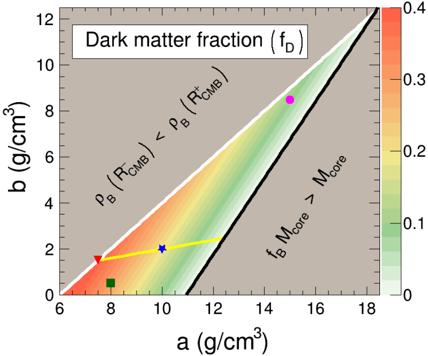
Constrains on baryonic profiles inside core

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

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

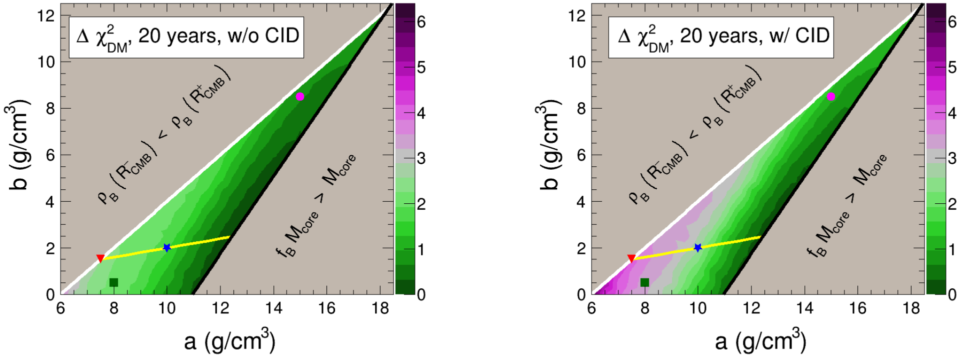
where a and b are positive constants with the units of density.
- Density decreases monotonically.
- The gray regions are unphysical.
- Colored dots (right plot) corresponds to the colored density profiles (left plot).
- Each point inside the triangular region corresponds to an allowed baryonic profile.





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

Summary and Conclusion

- 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.
- 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.

Scan me for more details

Acknowledgement

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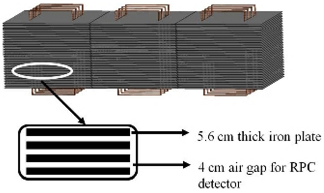
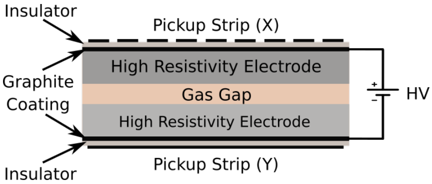
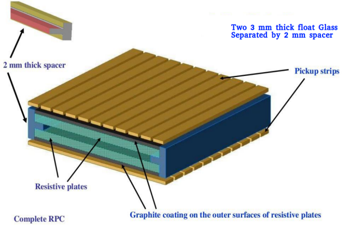
ICAL Design and Specifications



ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 14.5 m
Detector dimension	48 m $\times$ 16 m $\times$ 14.5 m
No. of layers	151
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC units/Layer/Module	64
Total no. of RPC units	$\sim$ 30,000
No. of electronic readout channels	3.9×10^6





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

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