Study of the internal structure of the Earth using neutrino oscillations at IceCube DeepCore

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Outline of talk

- Motivation
- Atmospheric neutrinos & matter effects in Earth
- IceCube detector
- Analysis methodology
- Asimov sensitivity with DeepCore
- Upgrade
- Summary

Motivation

Analysis motivation

Knowledge about Earth's interior based on :

- Gravitational measurements
  - Mass of the Earth[1]
  - Moment of Inertia of the Earth[2]
- Seismic studies
  - Distribution of matter, their physical and chemical properties

Gravitational + Seismic measurements → Preliminary Reference Earth Model (PREM)

Now we can also use weak interaction of neutrinos to study the Earth !

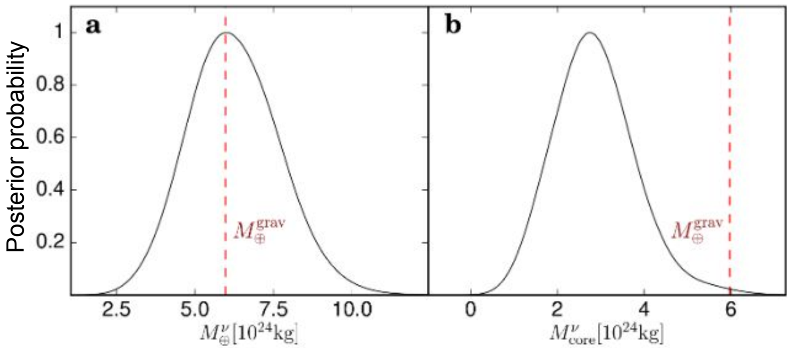
- Neutrino oscillation tomography
- Neutrino absorption tomography

- Neutrinos will act as an independent and complementary tool to gravitational and seismic studies in probing the Earth
- These methods do not intend to compete with existing studies, but rather tries to explore the potential of neutrino in a new way

[1]B. Luzum et al., Celest. Mech. Dyn. Astron. 110, 293 (2011)
[2]W. Chen, J. Ray, W. B. Shen, and C. L. Huang, J. Geod. 89, 179 (2015)

Contemporary studies

Neutrino absorption tomography (with IC86)



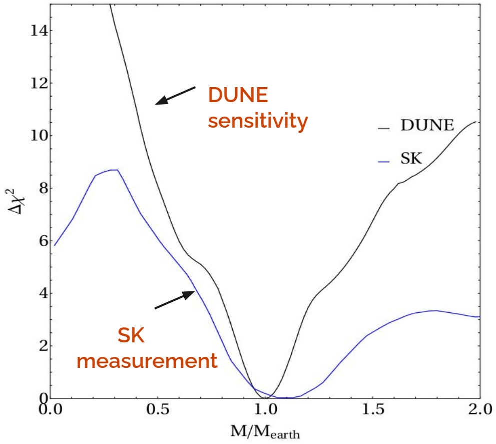
Neutrino tomography of the Earth (Nature Physics, 2019)

$$M_\oplus^\nu = (6.0^{+1.6}_{-1.3}) \times 10^{24} \quad \text{kg}$$

$$M_{core}^\nu = (2.72^{+0.97}_{-0.89}) \times 10^{24} \quad \text{kg}$$

- Mass of Earth (Relative 1σ precision → ~25%)
- Mass of Core (Relative 1σ precision → ~34%)

Neutrino oscillation tomography



Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV (Phys. Rev. D, 2018)
DUNE atmospheric neutrinos: Earth tomography (JHEP, 2022)

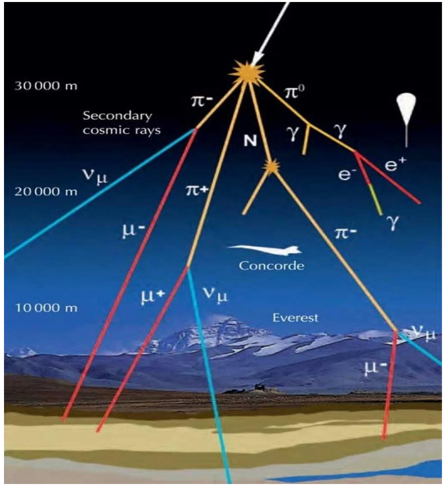
- Super-K measurement (NO) : Relative 1σ precision ΔM ~ 21% (328 kton-years)
- DUNE sensitivity (NO) : Relative 1σ precision ΔM ~ 9.48% (400 kton-years)

Image source: Neutrino Earth tomography in DUNE (see talk in MMTE 2022 by Ivan Martinez-Soler)

Can DeepCore measure the mass of Earth and the densities of different layers of Earth using neutrino oscillation of atmospheric neutrinos ?

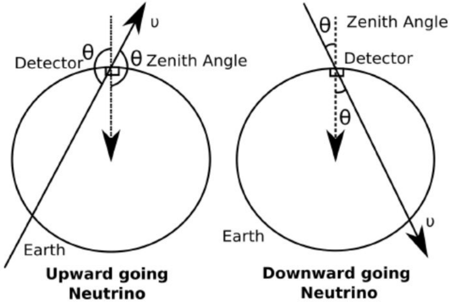
Atmospheric neutrinos

- Produced by interaction of cosmic rays in the Earth's atmosphere.
- Advantages:
  - Wide range of baselines (15 km to 12757 km)
  - Energy (0.1 GeV to ~TeV).

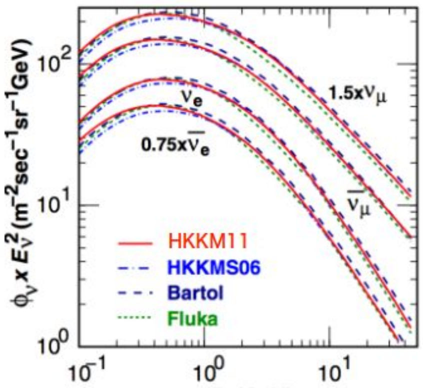


Upward going neutrino:
$\pi/2 < \theta < \pi$; $-1 < \cos\theta < 0$

Downward going neutrino:
$0 < \theta < \pi/2$; $0 < \cos\theta < 1$

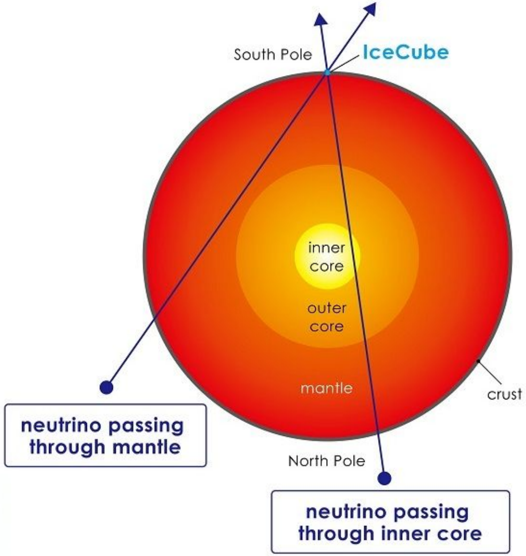


PRD 83, 123001 (2011)



Matter effects in Earth

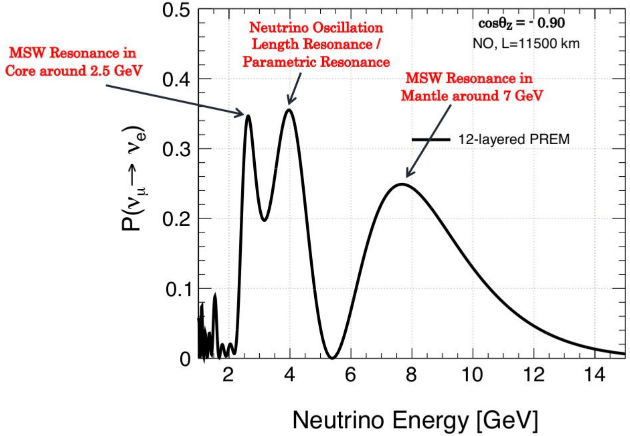
- Upward-going atmospheric neutrinos travel through Earth to experience matter effect.

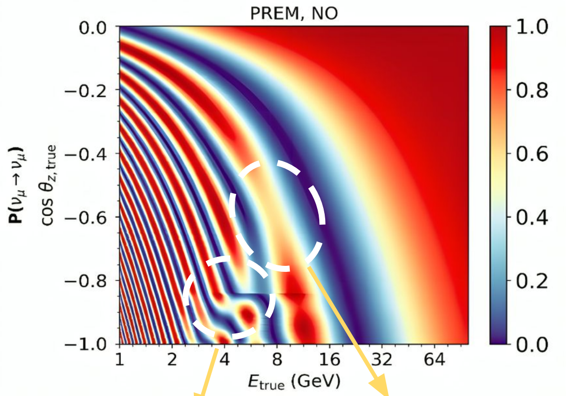


Matter effect in Earth

Mikheyev–Smirnov–Wolfenstein (MSW) effect
($-0.8 < \cos\theta_\nu < -0.5$, 6 GeV < E_ν < 10 GeV)

Parametric Resonance (PR)
($\cos\theta_\nu < -0.8$, 3 GeV < E_ν < 6 GeV)





Parametric Resonance
$\cos\theta_\nu < -0.8$
3 GeV < E_ν < 6 GeV

MSW resonance
$-0.8 < \cos\theta_\nu < -0.5$
6 GeV < E_ν < 10 GeV

$$E_{\mathrm{MSW}} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_{\mathrm{F}} N_A Y_e \rho}$$

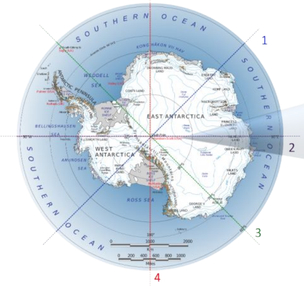
Electron no. density

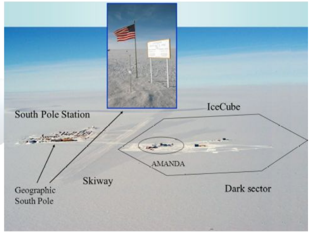
Density inside Earth

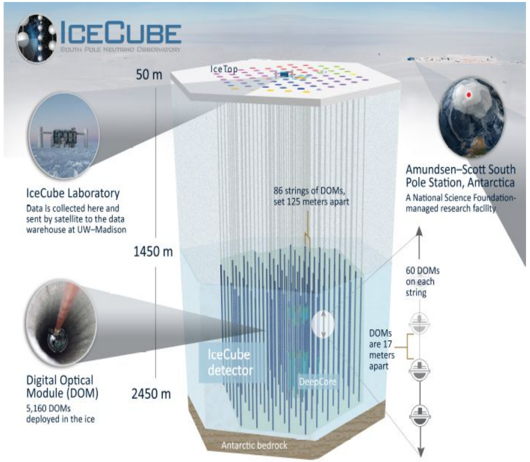
Image source (top right) : Link

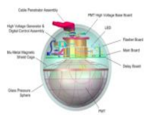
IceCube detector

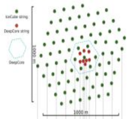
- $1\ km^3$ neutrino detector at South Pole
- Cherenkov detector
- 5160 DOMs - deployed between 1450 m and 2450 m below the surface of the ice on 86 vertical strings
- DeepCore DOMs placed deeper than 1750 m
  - 8 closely spaced strings
  - 7 IceCube strings
- 8 DeepCore strings
  - Bottom 50 DOMS - spacing of 7 m (depth 2100 m - 2450 m)
  - Top 10 DOMs - spacing of 10 m (depth < 2000 m), form a veto cap
- Icecube has ability to detect neutrinos in PeV scale
- DeepCore designed for low energy neutrinos, having energies in GeV



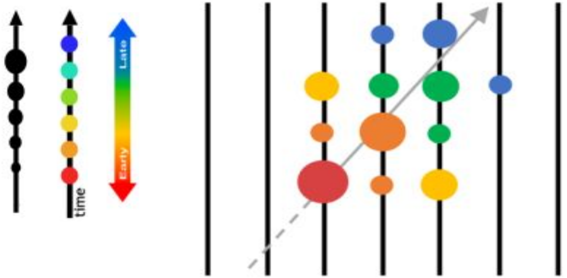


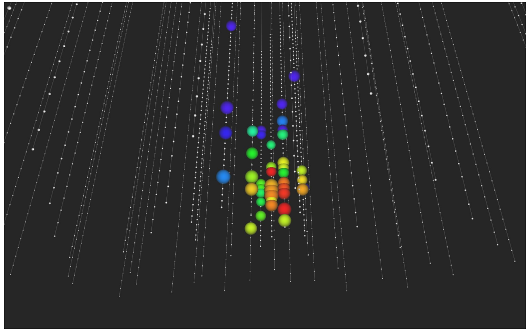






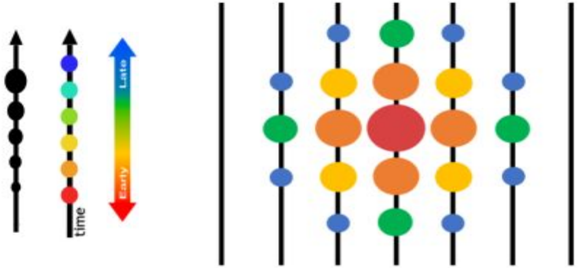
Different categories of event

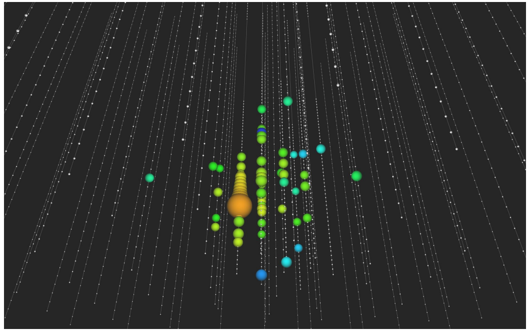




Track-like events:

- Elongated
- Source: ν_μ CC





Cascade-like events:

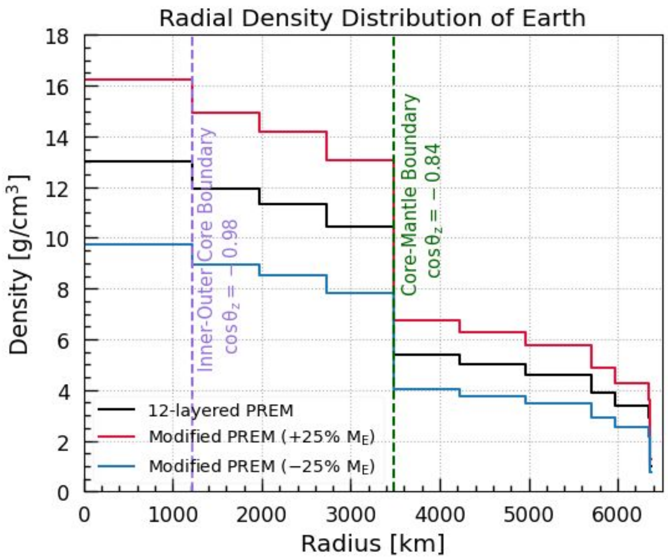
- Spherical
- Source: ν_e CC, ν_τ CC, all NC

Analysis methodology

Analysis I : Mass of the Earth

True profile: 12-layered PREM profile

- Radius of Earth = 6371 km
- Earth has been considered neutral ($N_p = N_e$)
- Electron number density ratio: $Y_e = N_e / (N_p + N_n)$:
  - Y_e (Inner Core) = 0.4656
  - Y_e (Outer Core) = 0.4656
  - Y_e (Mantle) = 0.4957
- Density is a free variable here - density in all layers scaled by the same scaling factor
- Hydrostatic equilibrium condition preserved : $\rho_{\text{inner layer}} > \rho_{\text{outer layer}}$

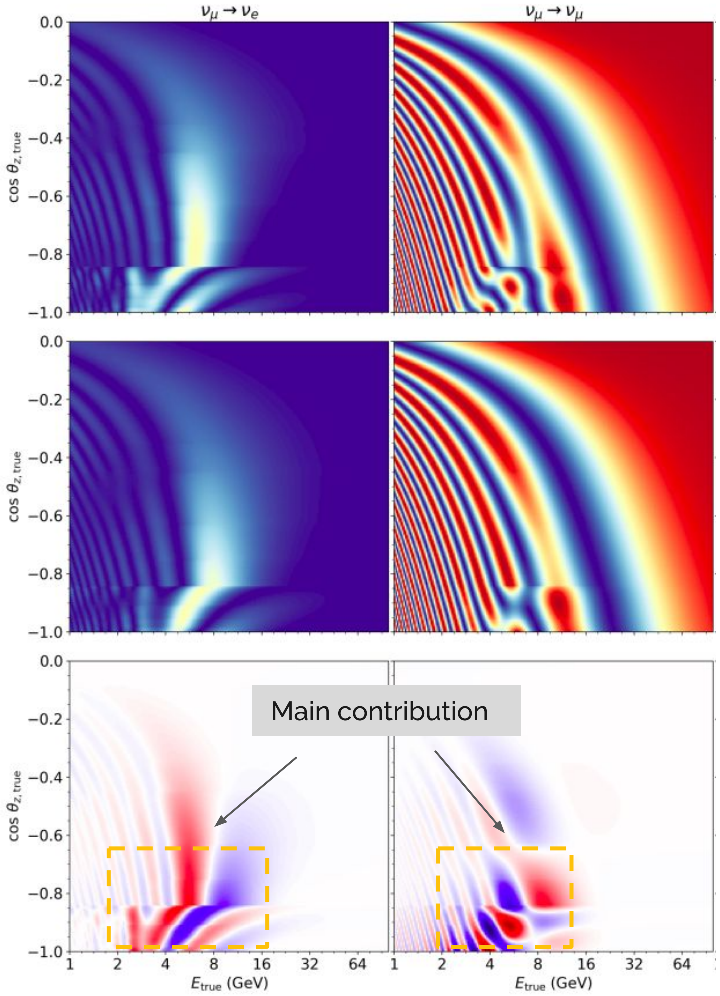


Test Statistic : Log Likelihood (LLH)

Probabilities and their differences

- Oscillograms shown for μ → e and μ → μ
  - Row 1 → PREM profile
  - Row 2 → Earth profile with density decreased by 30% in all layers
  - Row 3 → probability difference

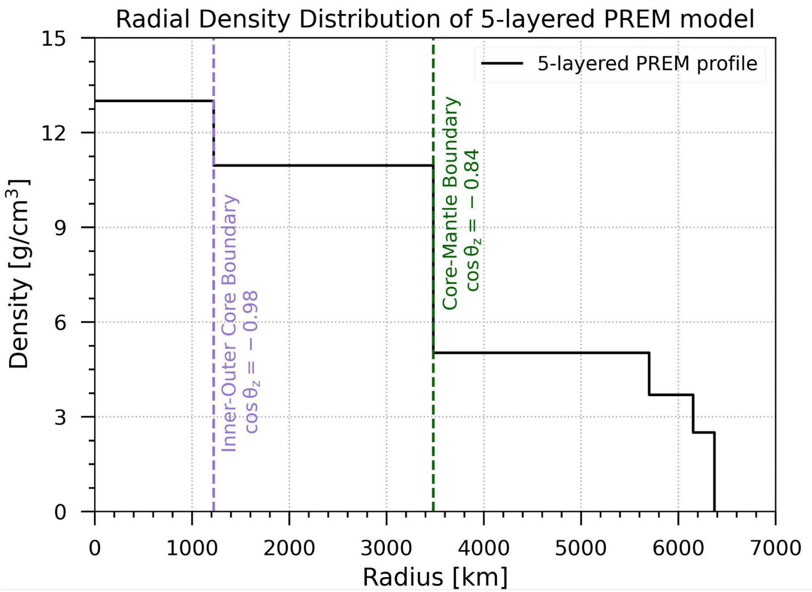
- Main contribution to our signal from lower energy and higher baselines



Analysis II : Correlated density measurement of various layers inside Earth

True profile: 5-layered PREM profile

- Radius of Earth = 6371 km
- Earth has been considered neutral ($N_p = N_e$)
- Electron number density ratio: $Y_e = N_e / (N_p + N_n)$:
  YeI = 0.4656 , YeO = 0.4656 , YeM = 0.4957
- Densities in the true profile:
  - Inner core : 13.0 g/cm^3
  - Outer core : 10.96 g/cm^3
  - Inner mantle : 5.03 g/cm^3
  - Middle mantle : 3.7 g/cm^3
  - Outer mantle : 2.5 g/cm^3
- External constraints used:
  - Total mass of the Earth
  - Moment of Inertia of the Earth



Test Statistic : Log Likelihood (LLH)

Analysis II : Correlated density measurement of various layers inside Earth

- External constraints :
  - Total mass of the Earth
  - Moment of Inertia of the Earth

$$M = \frac{4\pi}{3}[\rho_{\rm IC}R_{\rm IC}^3 + \rho_{\rm OC}(R_{\rm OC}^3 - R_{\rm IC}^3) + \rho_{\rm IM}(R_{\rm IM}^3 - R_{\rm OC}^3) + \rho_{\rm MM}(R_{\rm MM}^3 - R_{\rm IM}^3) + \rho_{\rm OM}(R_{\oplus}^3 - R_{\rm MM}^3)]$$

$$I = \frac{8\pi}{15}[\rho_{\rm IC}R_{\rm IC}^5 + \rho_{\rm OC}(R_{\rm OC}^5 - R_{\rm IC}^5) + \rho_{\rm IM}(R_{\rm IM}^5 - R_{\rm OC}^5) + \rho_{\rm MM}(R_{\rm MM}^5 - R_{\rm IM}^5) + \rho_{\rm OM}(R_{\oplus}^5 - R_{\rm MM}^5)]$$

- Inner core and outer core scaled by same scaling factor (say α) (by our choice)
- Inner mantle and middle mantle scaled by separate scaling factors (say β and γ respectively)
- Outer mantle not scaled (as it is assumed to be known)
- Radial boundaries kept fixed

Analysis II : Correlated density measurement of various layers inside Earth

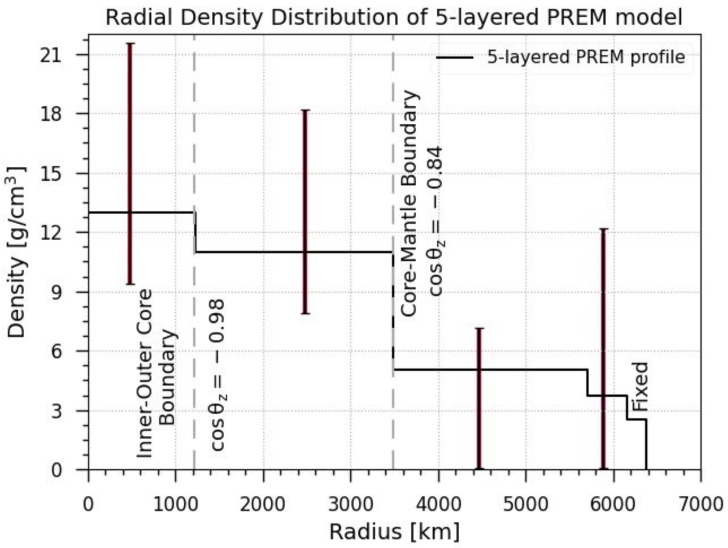
- External constraints :
  - Total mass of the Earth
  - Moment of Inertia of the Earth

$$M = \frac{4\pi}{3}[\alpha(\rho_{\mathrm{IC}} R_{\mathrm{IC}}^3 + \rho_{\mathrm{OC}}(R_{\mathrm{OC}}^3 - R_{\mathrm{IC}}^3)) + \beta(\rho_{\mathrm{IM}}(R_{\mathrm{IM}}^3 - R_{\mathrm{OC}}^3)) + \gamma(\rho_{\mathrm{MM}}(R_{\mathrm{MM}}^3 - R_{\mathrm{IM}}^3)) + \rho_{\mathrm{OM}}(R_{\oplus}^3 - R_{\mathrm{MM}}^3)]$$

$$I = \frac{8\pi}{15}[\alpha(\rho_{\mathrm{IC}} R_{\mathrm{IC}}^5 + \rho_{\mathrm{OC}}(R_{\mathrm{OC}}^5 - R_{\mathrm{IC}}^5)) + \beta(\rho_{\mathrm{IM}}(R_{\mathrm{IM}}^5 - R_{\mathrm{OC}}^5)) + \gamma(\rho_{\mathrm{MM}}(R_{\mathrm{MM}}^5 - R_{\mathrm{IM}}^5)) + \rho_{\mathrm{OM}}(R_{\oplus}^5 - R_{\mathrm{MM}}^5)]$$

- Scaling factor for core - `core_density_scale` (α) is given as an independent input (this is our choice)
- The equations are then solved for β and γ in terms of α
- For every value of `core_density_scale` (α), there will be a unique value of β and γ

Analysis II : Correlated density measurement of various layers inside Earth



Earth layer	Inner core (0-1221.5) km	Outer core (1221.5 - 3480) km	Inner mantle (3480 - 5701) km	Middle mantle (5701 - 6151) km	Outer mantle (6151 - 6371) km
Density in true profile (g/cm^3)	13.0	10.96	5.03	3.7	2.5
Density range (g/cm^3)	[9.36, 21.58]	[7.89, 18.19]	[0.05, 7.14]	[0.07, 12.21]	2.5

Asimov sensitivity with DeepCore

Analysis setup

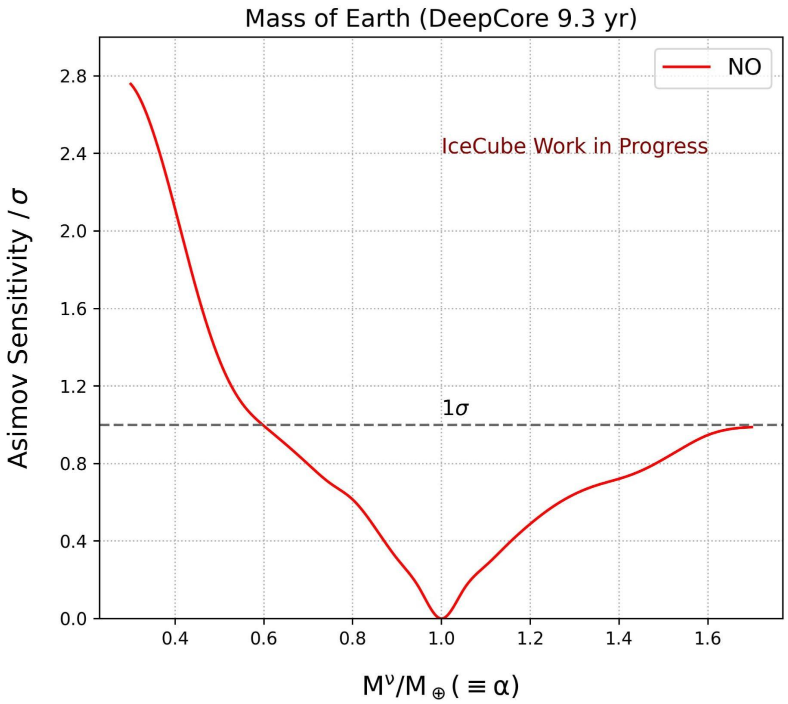
- Used 9.3 years of event sample
- Since, matter effect significant at lower energies and higher baselines, optimized binning
- Introduced finner binning in energy and zenith

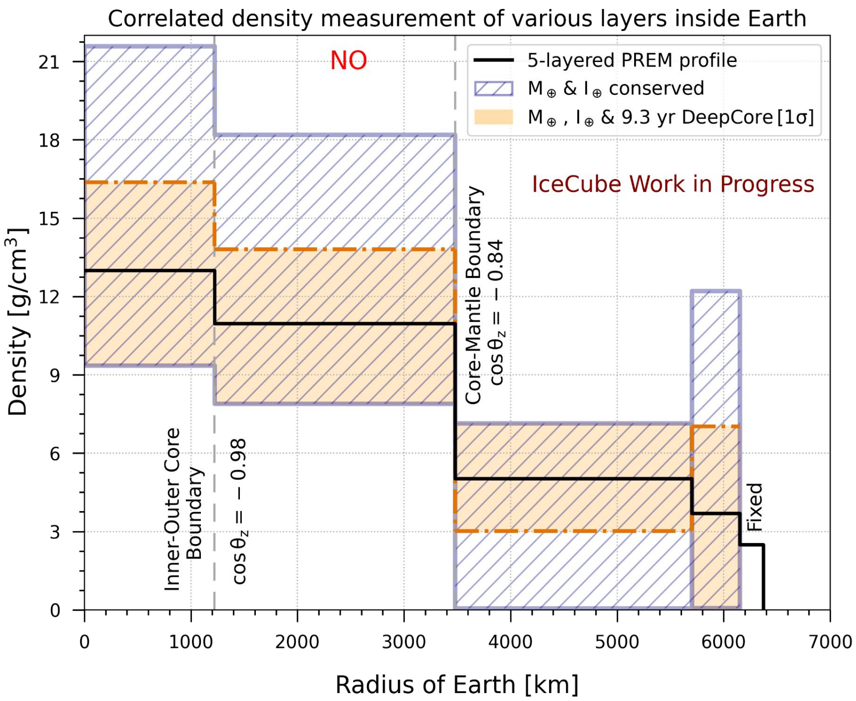
Observables	Number of Bins	Range	Step
Energy	17	[5, 100] GeV	log
cos(zenith)	20	[-1, 0]	linear
PID	3	[0, 0.33, 0.39, 1] [Cascade, Mixed, Track]	linear

Oscillation parameters:

Mass ordering	θ_{12} (deg.)	θ_{13} (deg.)	θ_{23} (deg.)	Δm^2_{21} (eV^2)	Δm^2_{31} (eV^2)	δ_{CP} (deg.)
NO (IO)	33.41	8.54	47.5	7.41×10^{-5}	2.47 $(-2.47) \times 10^{-3}$	0

Asimov sensitivity with DeepCore



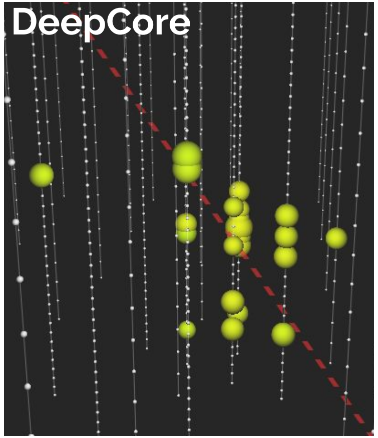


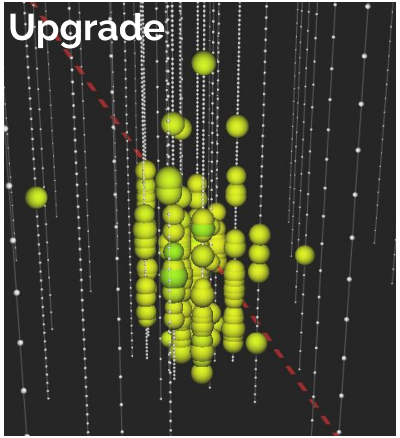
- Sensitivity has been obtained after marginalizing over θ_{23} and Δm^2_{31}
- 1σ precision expected to be ~40% to the left for mass of Earth
- For correlated density measurement, we expect a nearly 42% reduction in the allowed band (from ext. constraints of mass and moment of inertia) when neutrino data is added.

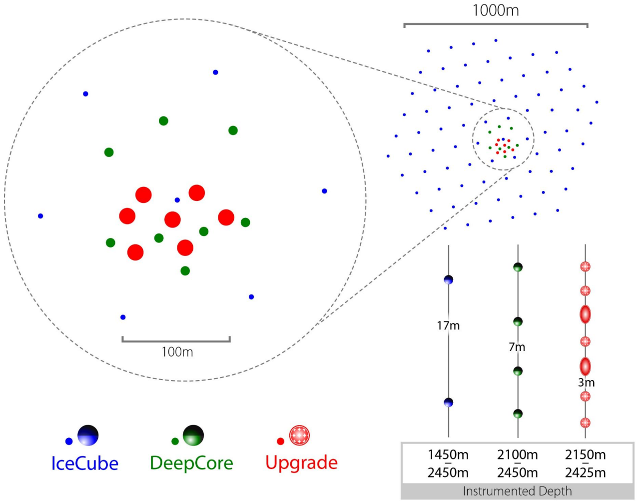
How much improvement can we get with Upgrade?

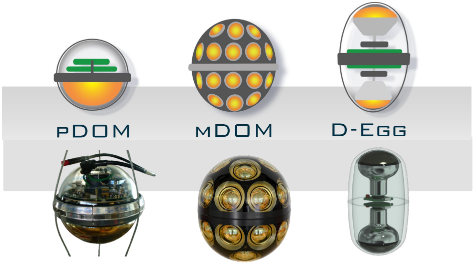
Upgrade

- Increased density of strings in center region of detector
- 7 new strings (Fiducial volume ~ 2 Mton)
- Energy threshold ~ 1 GeV









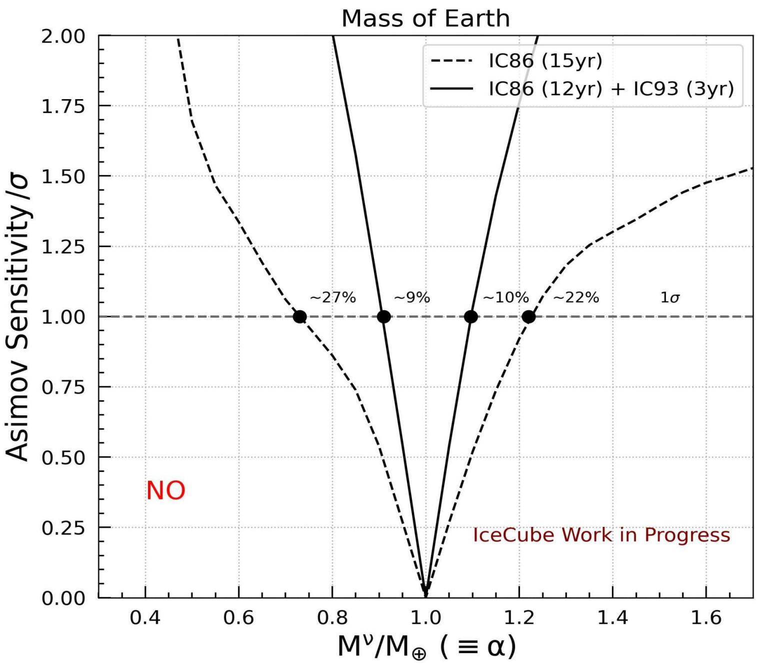
ICRC2019 arXiv:1908.09441 ICRC2023 arXiv:2307.15295

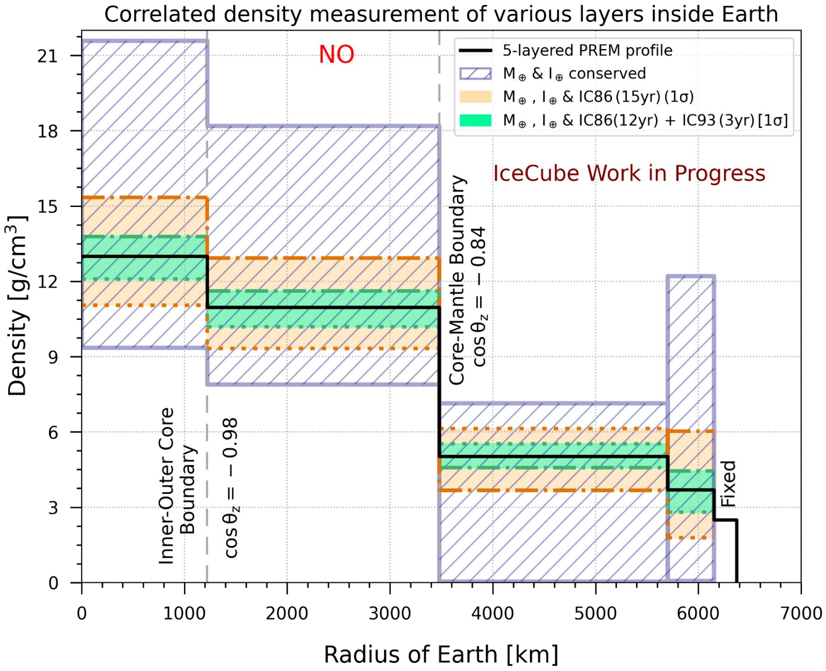
Analysis setup

- Similar systematic parameters as DeepCore
  - Upgrade have one separate uncertainty parameter for new optical modules
- We will be comparing the Asimov sensitivities for two configuration
  - DeepCore (15 years)
  - IceCube Upgrade (3 years) + DeepCore (12 years)
- Binning scheme

Detector	Energy	cos(zenith)	PID
DeepCore	[5, 300], 12 log bins	[-1, 0.3], 10 linear bins	[0., 0.5, 0.85, 1.]
IceCube Upgrade	[3, 300], 12 log bins	[-1, 0.0], 10 linear bins	[0, 0.5, 0.9, 1]

Asimov sensitivity with Upgrade





- Relative 1σ precision for mass of Earth expected to improve around 2.5 times
- For correlated density measurement, expected 1σ density band given by neutrino data + ext. constraints (mass and moment of inertia) reduces by 60% when we add 3 years of Upgrade to the DeepCore projections

Summary

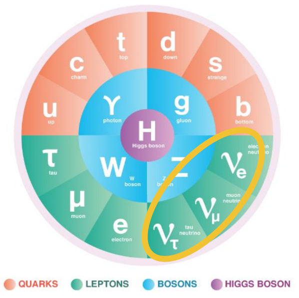
- Neutrinos serve as an independent and complementary tool in understanding Earth
- Huge baseline and energy range of atmospheric neutrinos gives a big advantage
- Using 9.28 years of DeepCore sample for the study of correlated density measurement, we expect a nearly 42% reduction in the allowed band (from ext. constraints of mass and moment of inertia) when neutrino data is added to it.
- Further, we see that Upgrade gives significant improvement in sensitivity for both the analyses on mass of Earth and correlated density measurement

Thank You

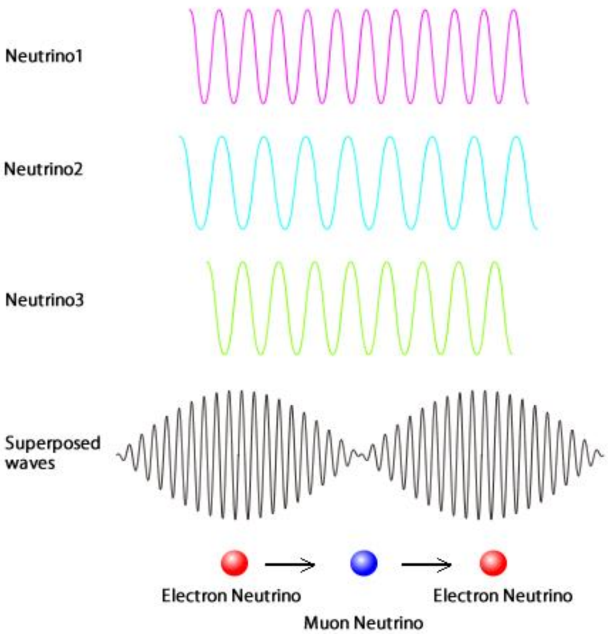
Backup

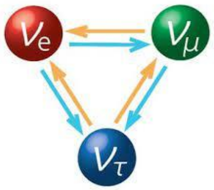
Neutrino oscillation

Neutrino oscillation



- Neutrinos are fermions. They are neutral particles with a spin of ½. They interact only through mainly through weak interaction.
- They are assumed to be massless in the Standard Model.
- Neutrinos come in three flavors : electron neutrino, muon neutrino and tau neutrino
- When neutrinos travel from one point to another in space , they oscillate from one flavor to another.
- This is a quantum mechanical effect
- Neutrino oscillations are possible only if neutrinos have mass.





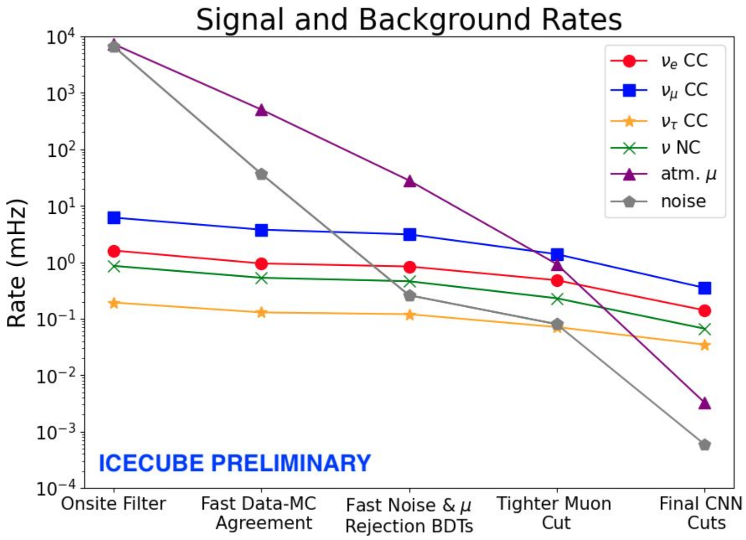
Systematic uncertainties

- Flux uncertainties:
  - Cosmic ray spectrum
  - Pion & Kaon production uncertainties (Barr parameters) Barr et al., Phys. Rev. D 74, 094009
- Cross section uncertainties: (Detailed study of cross section parameters)
  - Axial mass uncertainty for resonance and quasielastic events
  - GENIE - CSMS transition for DIS (Internal note)
- Detector and Ice properties:
  - Optical efficiency of the photo sensor (DOM efficiency)
  - Bulk Ice scattering and absorption The Cryosphere 14, 2537 (2020)
  - Hole ice
  - Birefringence (BFR) (double refraction of light due to anisotropy of ice) Cryosphere Discuss. 2022, 1 (2022)
  - Muon Light Yield (photon propagation in the ice from muons)
- Atmospheric muon scale Gaisser et al.+ Sibyll2.1
- Normalization of neutrino event counts

Event sample used for DeepCore

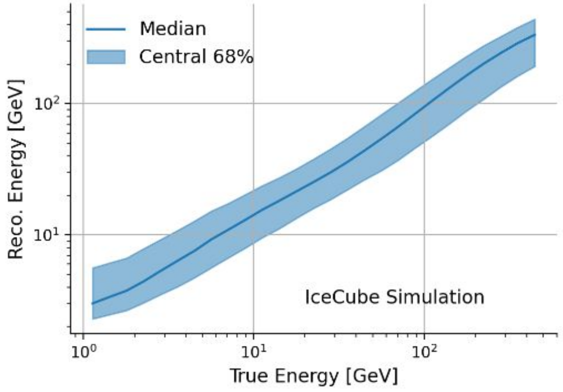
9.3 year Deepcore sample

- High statistics (~192k events)
- Used Convolutional Neural Network (CNN) for reconstruction of neutrino energy, zenith and particle identification (PoS-ICRC2023-1143)

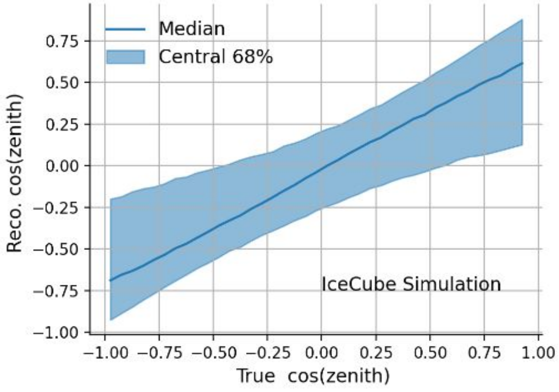


Selection	Expected MC Events (9.3 yr)	% of Sample
$\nu_e + \bar{\nu}_e$ CC	48616	25.2
$\nu_\mu + \bar{\nu}_\mu$ CC	110656	57.5
$\nu_\tau + \bar{\nu}_\tau$ CC	10938	5.7
$\nu_{\text{all}} + \bar{\nu}_{\text{all}}$ NC	21412	11.1
μ_{atm}	973	0.5
All MC	192597	–

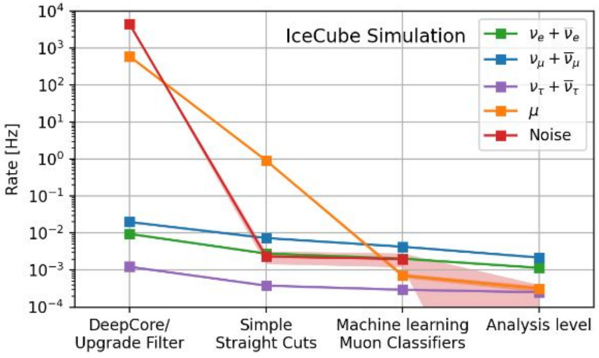
Upgrade reconstruction



(a) Energy



(b) Zenith Angle



Event rates as a function of selection step, from filter level up to the analysis level.

Performance for the reconstruction of neutrino energy (left) and zenith angle (right). Shown are the median and central 68% region of the reconstructed quantity as a function of the simulated truth. The bending of the angle towards the edges is due the quantity being bound ∈ [−1, 1].

arXiv:2307.15295