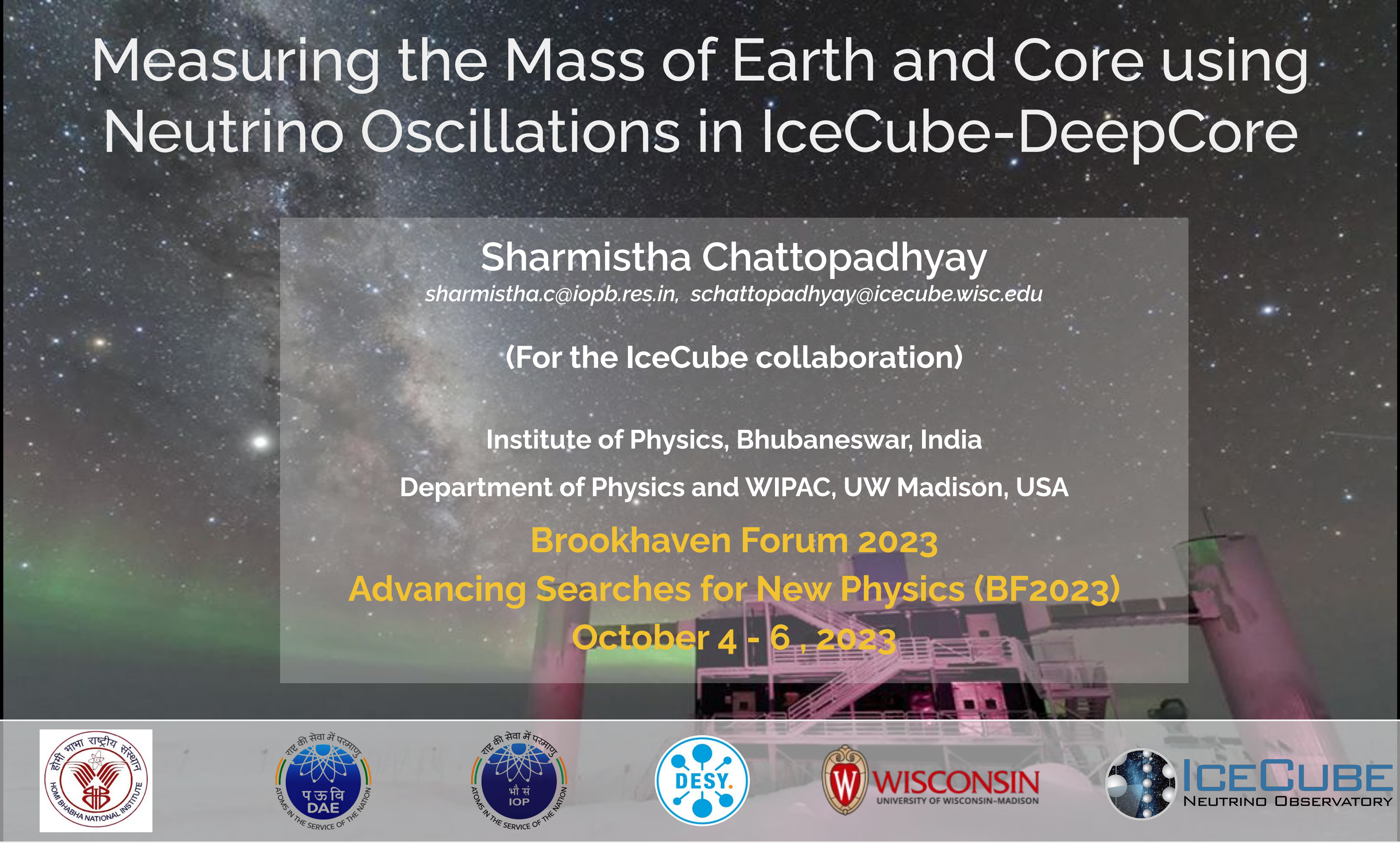

Measuring the Mass of Earth and Core using Neutrino Oscillations in IceCube-DeepCore

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Advancing Searches for New Physics (BF2023)
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Using Neutrinos to Understand Earth's Interior

Current Knowledge about Earth

Knowledge about Earth's interior based on :

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

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

Current Knowledge about Earth

Knowledge about Earth's interior based on :

- Gravitational measurements
  - Mass of the Earth
  - Moment of Inertia of the Earth
- 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 !

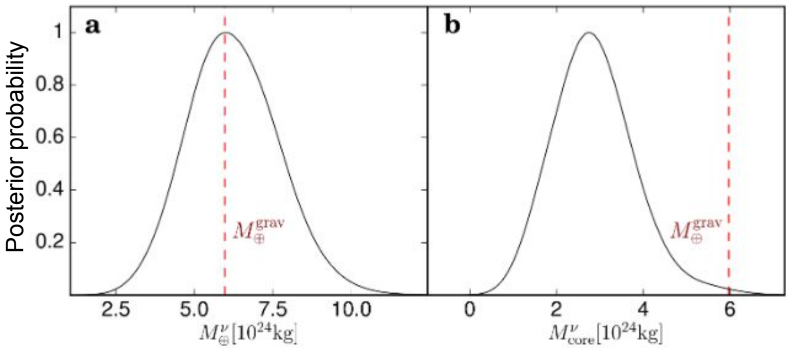
- Neutrino oscillation tomography
- Neutrino absorption tomography

Neutrinos will act as an independent and complementary tool to gravitational and seismic studies in probing the Earth

Neutrino Absorption & Oscillation Tomography

Contemporary studies on measurement of the mass of Earth & Earth's core using neutrinos

Neutrino absorption tomography (with IC86)



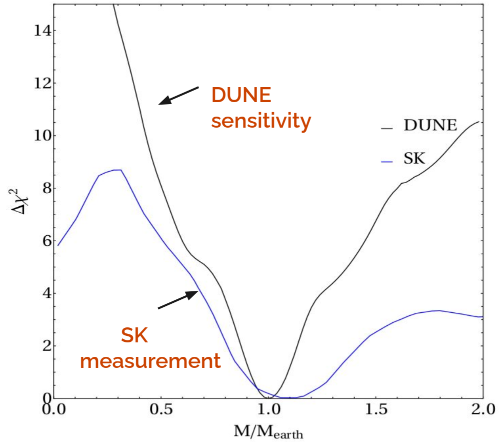
Neutrino tomography of the Earth (Nature Physics, 2018)

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

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

- 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)

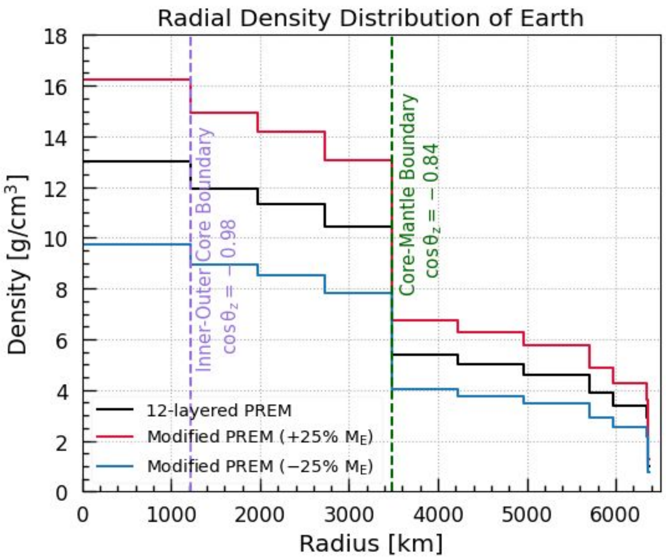
Analysis

Analysis I : Measuring the Mass of Earth

Can we measure the Mass of Earth using Matter Effects in Neutrino Oscillations in DeepCore?

True profile: 12-layered PREM profile

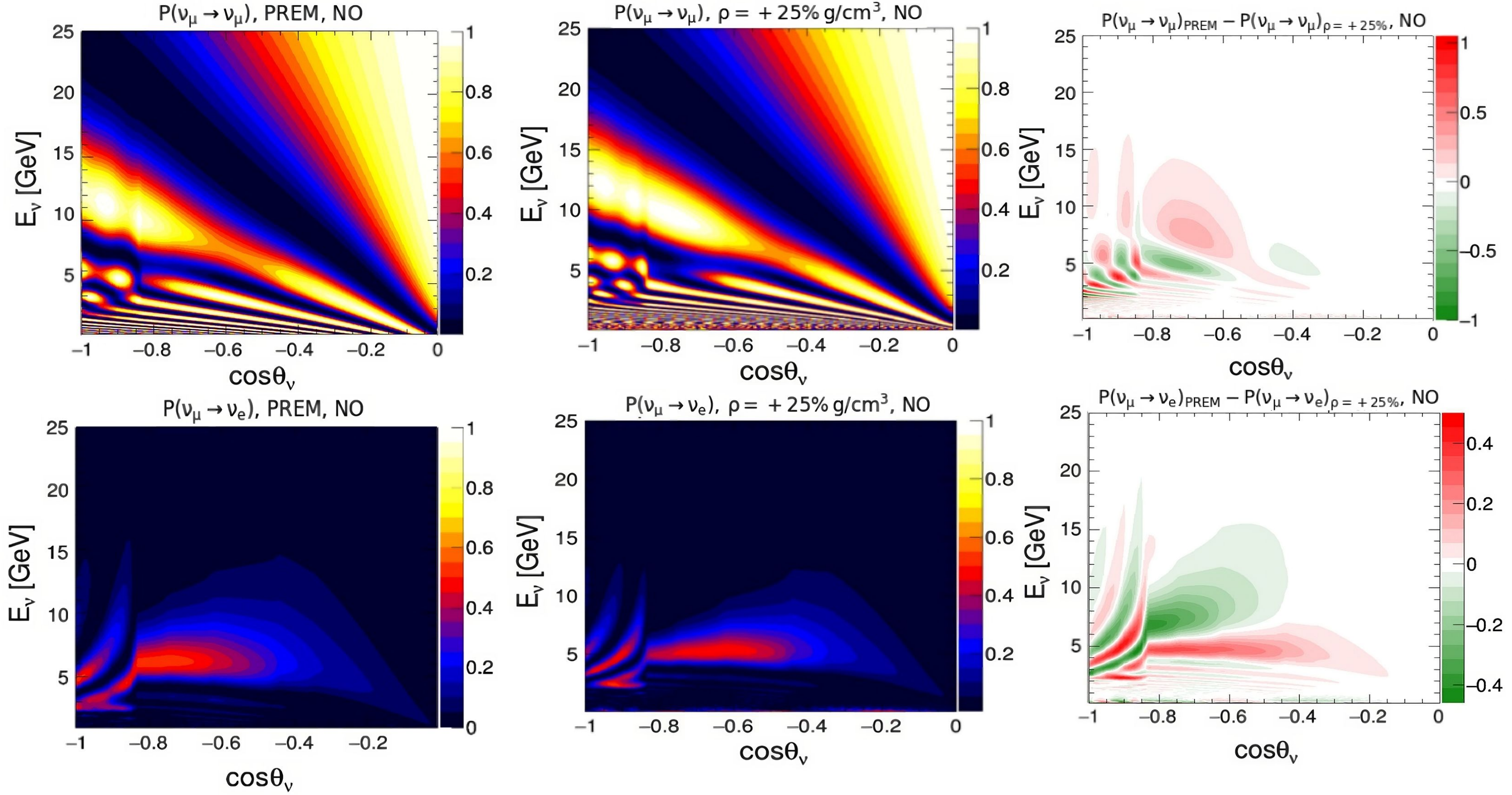
- Radius of Earth = 6371 km
- Earth has been considered neutral ($N_p = N_e$)
- Electron number density ratio: $Y_e = N_e / (N_p + N_n)$:
  - Y_e (Inner Core) = 0.4656
  - Y_e (Outer Core) = 0.4656
  - Y_e (Mantle) = 0.4957
- All layers scaled by the same scaling factor
- Hydrostatic equilibrium condition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



Using same binning as other two matter effect analyses

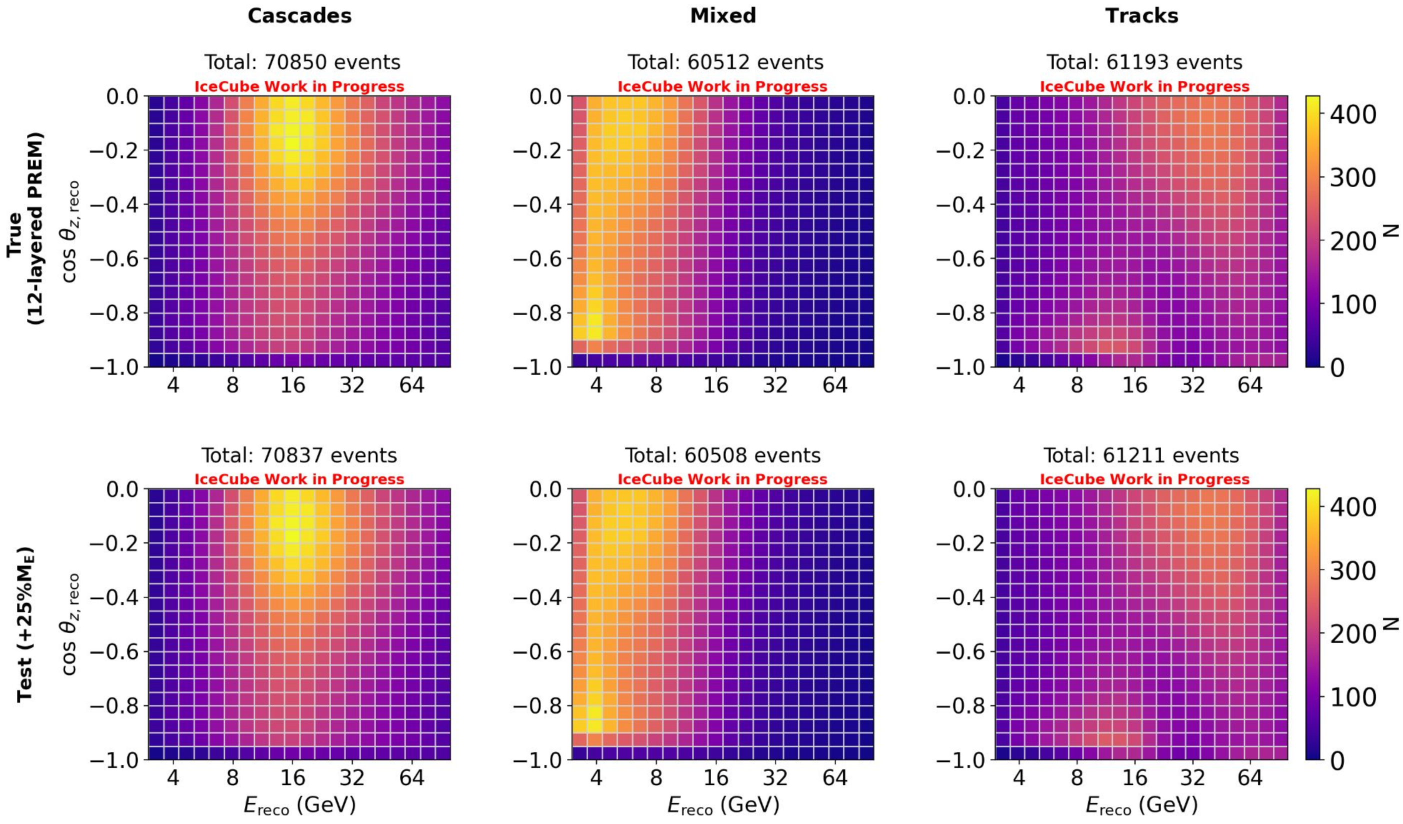
Test Statistic : Log Likelihood (LLH) - Used Wilks theorem to determine the test statistic value that corresponds to 1σ or 68% C.L.

Probabilities & Their Differences [PREM vs. Modified profile], NO



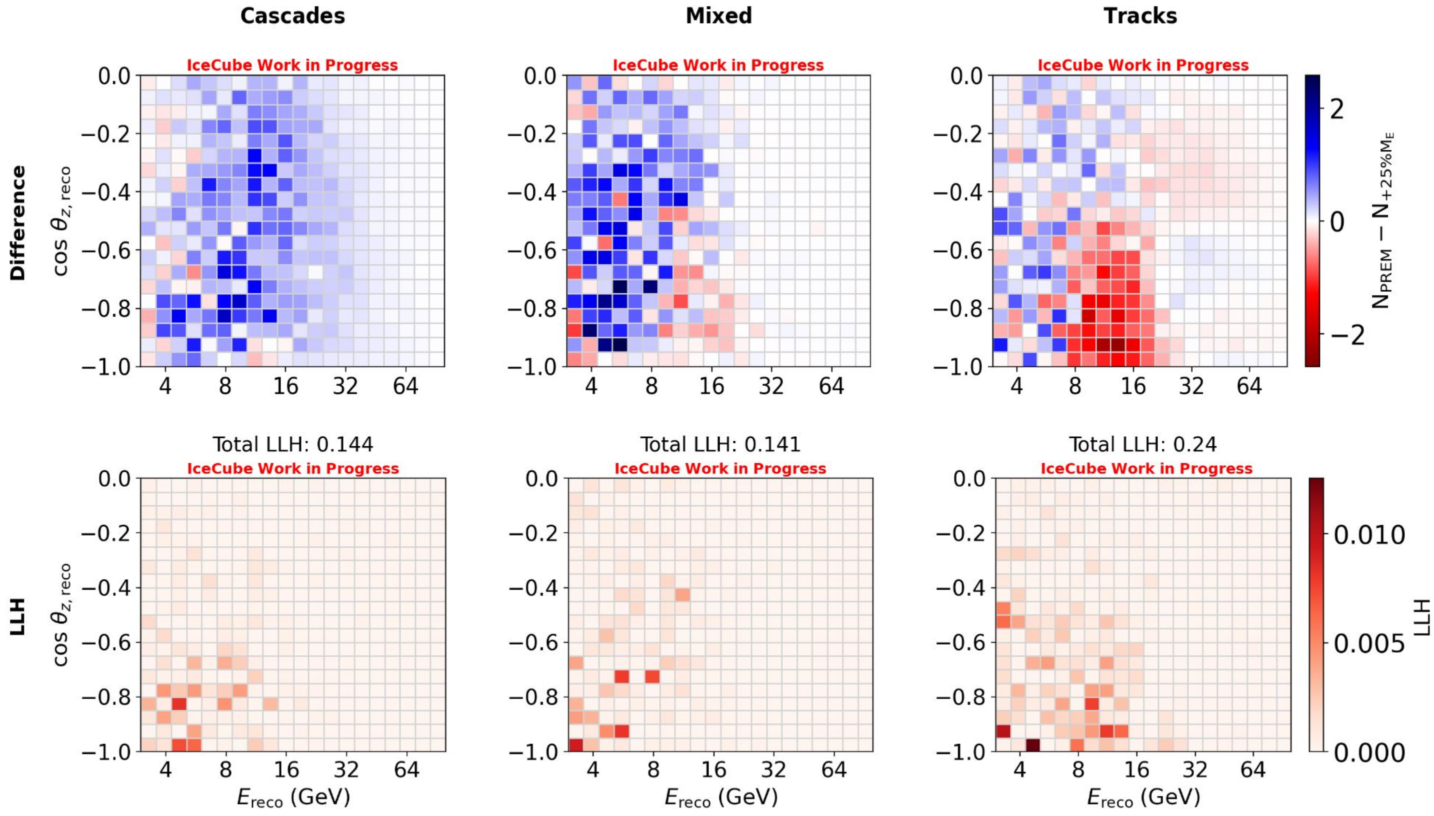
- Main contribution to our signal from lower energy and higher baselines

Expected Event Distributions,NO



- PREM & Test hypo.: For true values of all oscillation and systematic parameters

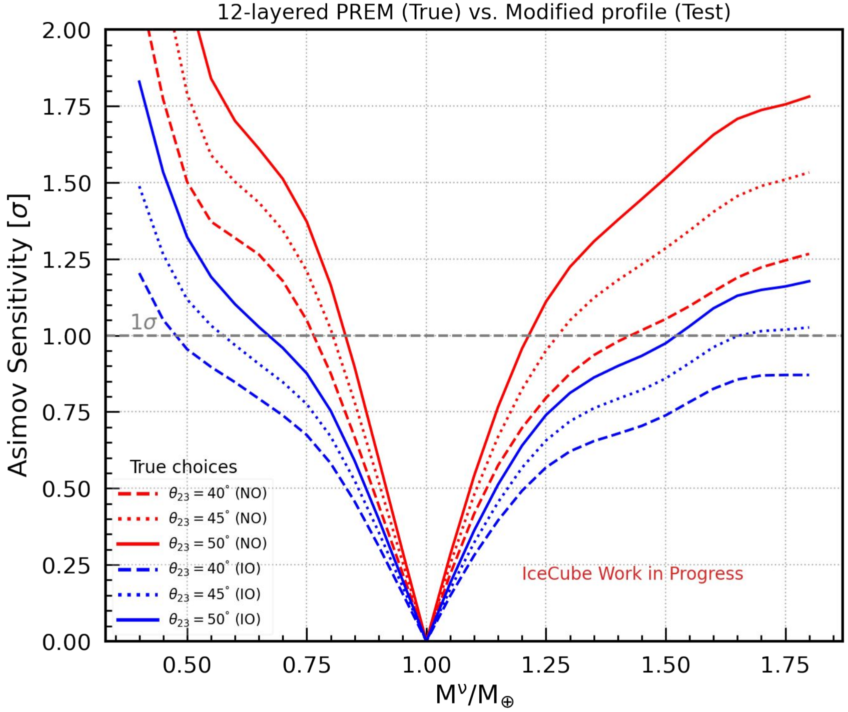
Distributions of Simulated Event Differences & LLH, NO



- Distribution of event difference plotted for true values of osc. and sys. parameters.
- Most of the LLH contribution comes from tracks

Asimov Sensitivity for the Mass of Earth with IceCube-DeepCore

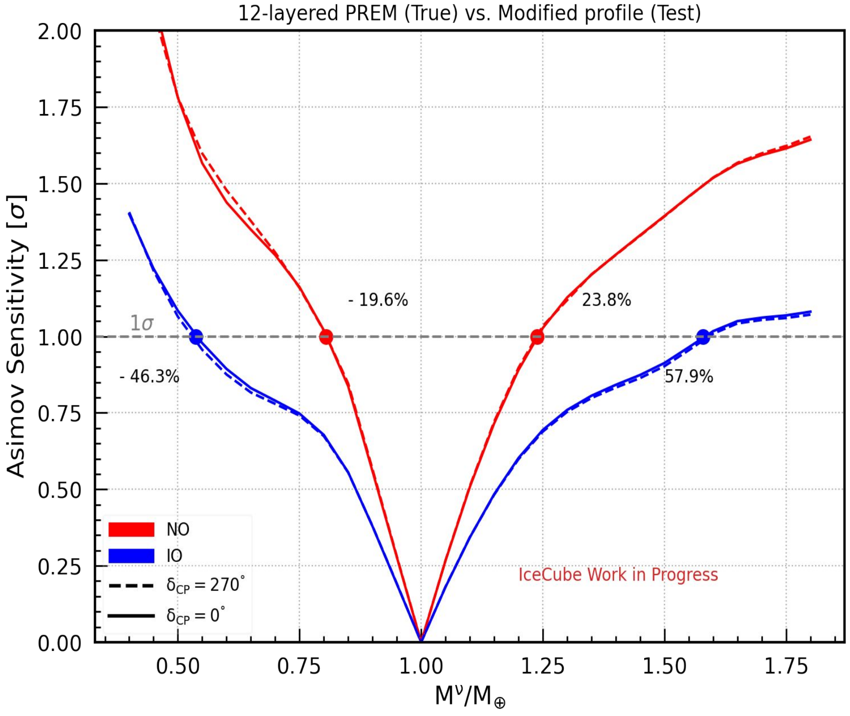
Effect of θ_{23}



- Minimized over relevant oscillation and systematic parameters
- Sensitivity depends on neutrino mass ordering
- Sensitivity for NO is higher than IO due to the lower cross section and flux rate of antineutrino
- **Relative 1σ precision for NO for $\theta_{23} = 45^{\circ}$ & $\delta_{CP} = 0^{\circ}$: ~ 24%**
- Relative 1σ precision improves with θ_{23}

Asimov Sensitivity for the Mass of Earth with IceCube-DeepCore

Effect of δ_{CP}



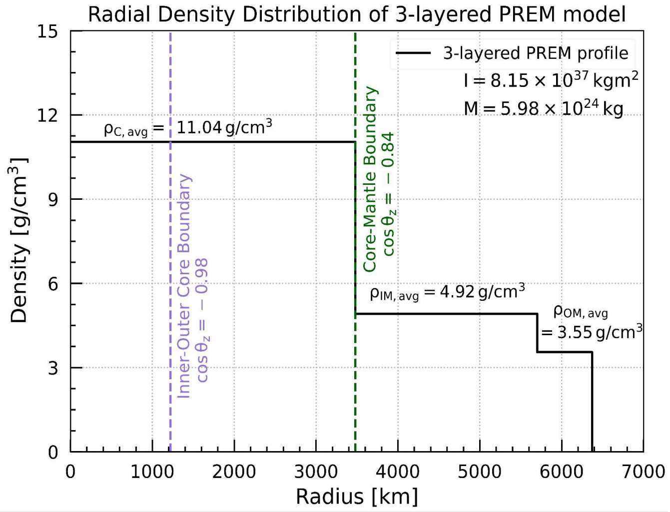
- Minimized over relevant oscillation and systematic parameters
- Minimal effect of δ_{CP}
- Relative 1σ precision for NO for $\theta_{23} = 47.5^{\circ}$ & $\delta_{CP} = 0^{\circ}$: ~ 22%
- **Comparable to relative 1σ precision of Super-K (~ 21%)** (PhysRevD.97.072001)

Analysis II : Measuring the Mass of Earth's Core

Can we measure the Mass of Earth's Core using Matter Effects in Neutrino Oscillations in DeepCore?

True profile: 3-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
- External constraints used:
  - Total mass of the Earth
  - Moment of Inertia of the Earth
  - Hydrostatic equilibrium condition
- Avg. densities for the true profile have been obtained from the 12-layered PREM model



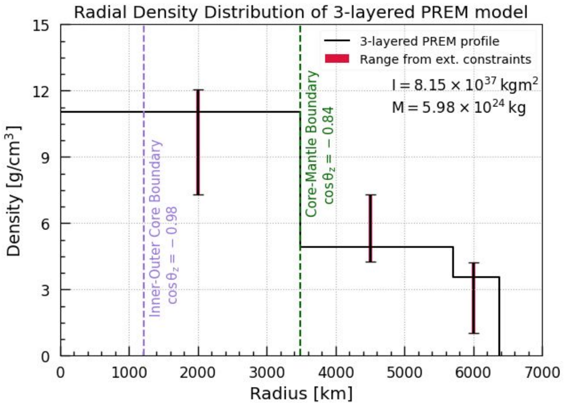
Using same binning as other two matter effect analyses

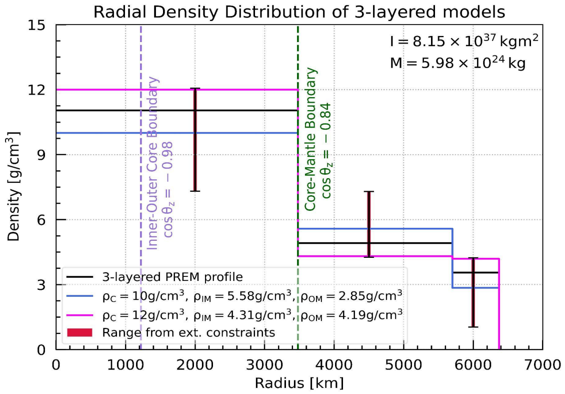
Test Statistic : Log Likelihood (LLH) - Used Wilks theorem to determine the test statistic value that corresponds to 1σ or 68% C.L.

Measuring the Mass of Earth's Core using 3-layered Profile (w/ ext. constraints)

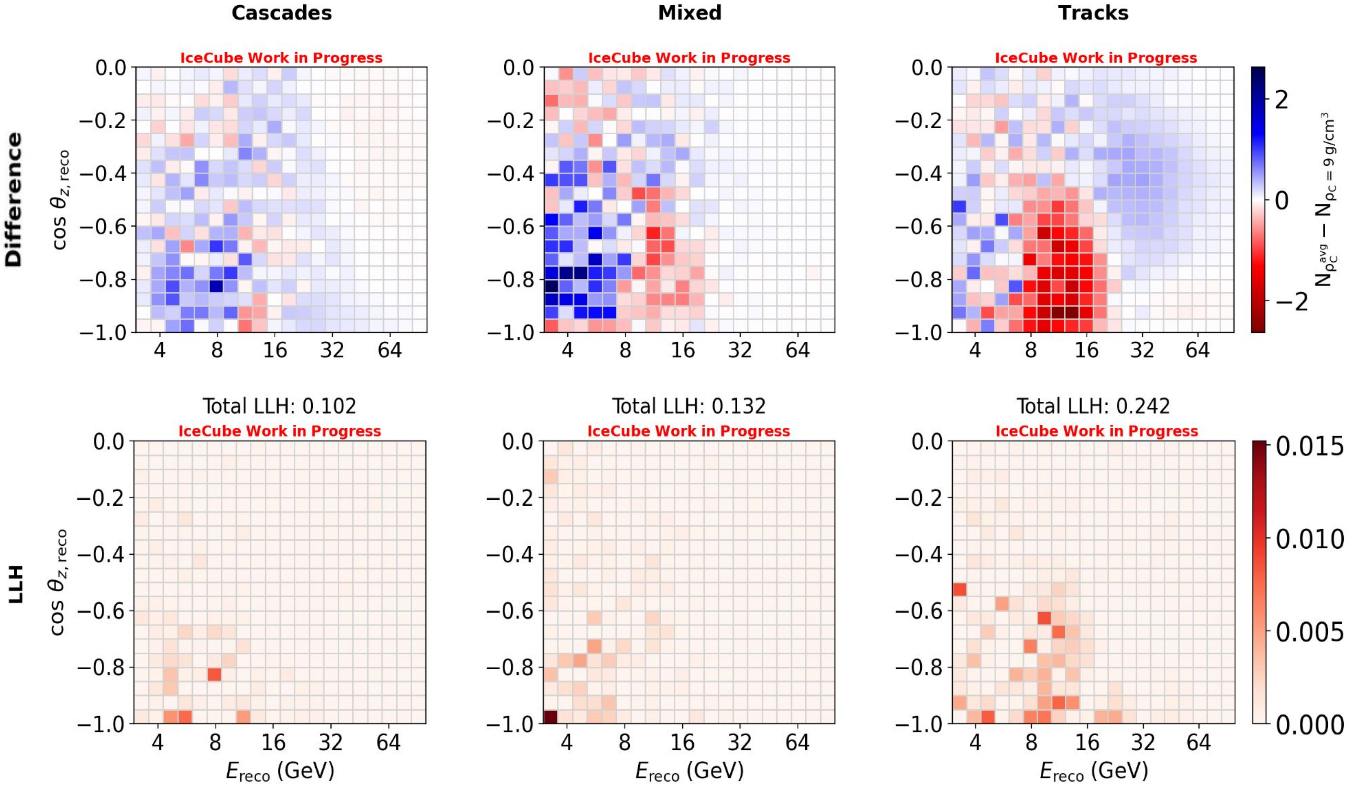
- True profile: 3-layered PREM profile
  - → Core : 0 - 3480 km : $\rho_{C,\,avg}$ = 11.04 g/cm^3
  - → Inner mantle : 3480 - 5701 km : $\rho_{IM,\,avg}$ = 4.92 g/cm^3
  - → Outer mantle : 5701 - 6371 km : $\rho_{OM,\,avg}$ = 3.55 g/cm^3

- Density ranges in theory:
  - → Core : 0 - 3480 km : ρ_C = [7.31 - 12.08] g/cm^3
  - → Inner mantle : 3480 - 5701 km : ρ_{IM} = [4.25 - 7.31] g/cm^3
  - → Outer mantle : 5701 - 6371 km : ρ_{OM} = [1.04 - 4.25] g/cm^3





Distributions of Simulated Event Differences & LLH, NO



True Profile:

$\rho_{C,avg}$ = 11.04 g/cm^3

$\rho_{IM,avg}$ = 4.92 g/cm^3

$\rho_{OM,avg}$ = 3.55 g/cm^3

Test Profile:

ρ_C = 9 g/cm^3

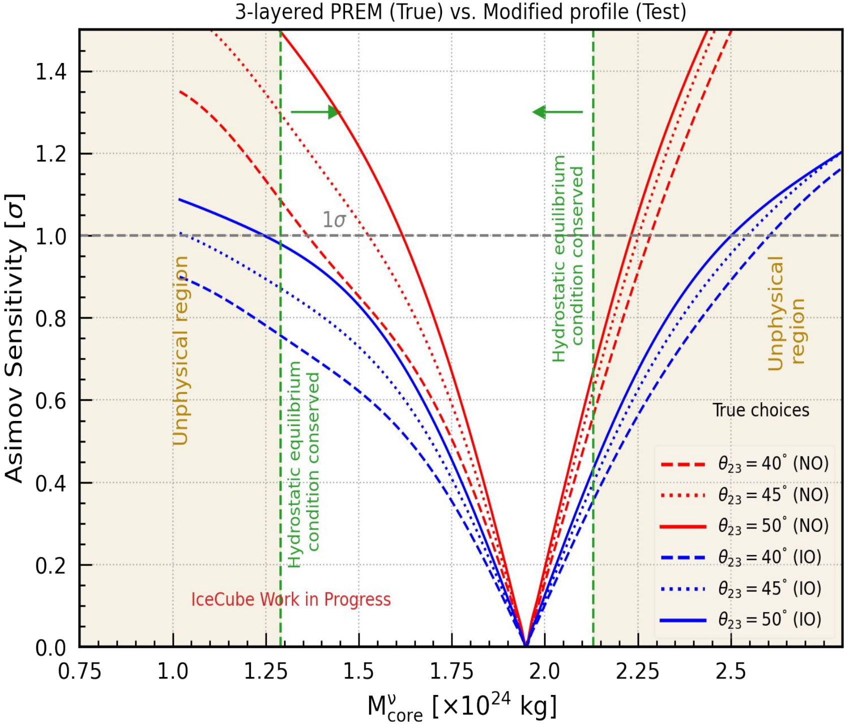
ρ_{IM} = 6.22 g/cm^3

ρ_{OM} = 2.18 g/cm^3

- Distribution of event difference plotted for true values of osc. and sys. parameters.
- Most of the LLH contribution comes from tracks

Asimov Sensitivity for Mass of Earth's Core using IceCube-DeepCore

Effect of θ_{23}

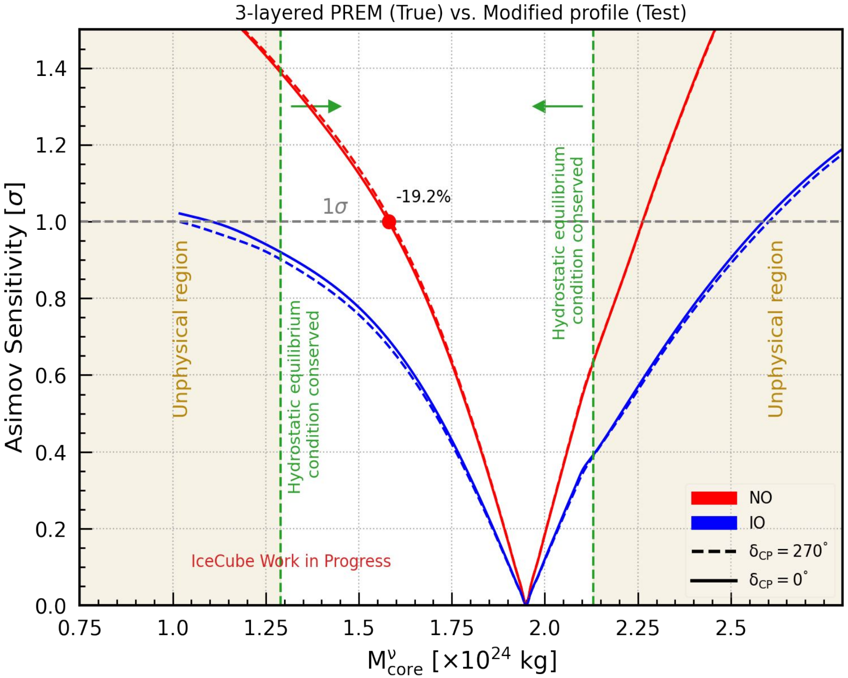


The shaded region in the plot signifies the range of core masses which do not adhere to the condition of hydrostatic equilibrium

- Minimized over relevant oscillation and systematic parameters
- Lower bound on Core mass from ext. const. : 1.29×10^{24} kg
- Upper bound on Core mass from ext. const. : 2.13×10^{24} kg
- Lower bound at 1σ for NO for $\theta_{23} = 45^\circ$ & $\delta_{CP} = 0^\circ$: 1.52×10^{24} kg (~ 22%)
- Upper bound at 1σ for NO for $\theta_{23} = 45^\circ$ & $\delta_{CP} = 0^\circ$: 2.25×10^{24} kg (~ 16%)
- For comparison : Relative 1σ precision for NO from neutrino absorption tomography : ~ 34% (Nature Phys. 15 (2019))
- Lower bound at 1σ improves with θ_{23}

Asimov Sensitivity for Mass of Earth's Core using IceCube-DeepCore

Effect of δ_{CP}



The shaded region in the plot signifies the range of core masses which do not adhere to the condition of hydrostatic equilibrium

- Minimized over relevant oscillation and systematic parameters
- Minimal effect of $\boldsymbol{\delta}_{CP}$
- **Lower bound at 1σ for NO for θ_{23} = 47.5047° & δ_{CP} = 0° : 1.57 x 10^{24} kg (~ 19%)**
- **Upper bound at 1σ for NO for θ_{23} = 47.5047° & δ_{CP} = 0° : 2.26 x 10^{24} kg (~ 16%)**
- For comparison : Relative 1σ precision for NO from neutrino absorption tomography : ~ 34% (Nature Phys. 15 (2019))

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, we expect to obtain a precision of ~22% for mass of Earth and ~18% for mass of Earth’s core, for normal ordering, with our choice of oscillation and systematic parameters

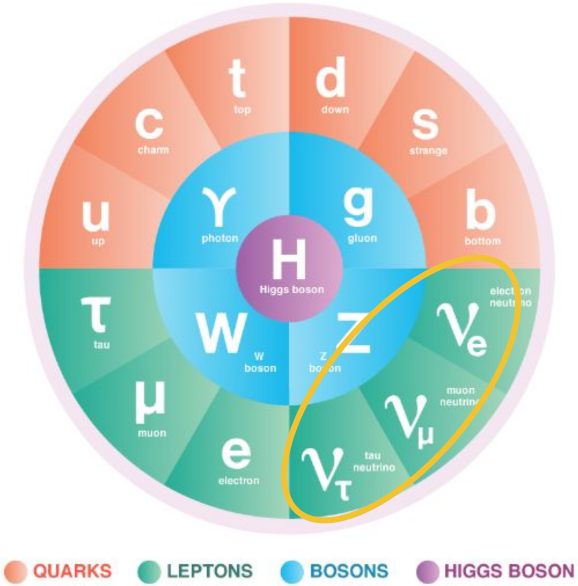
Thank You

Backup

Neutrino Oscillations and Matter Effects

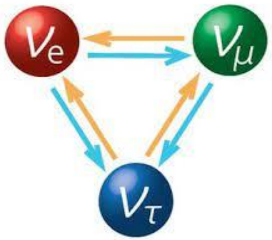
Neutrino

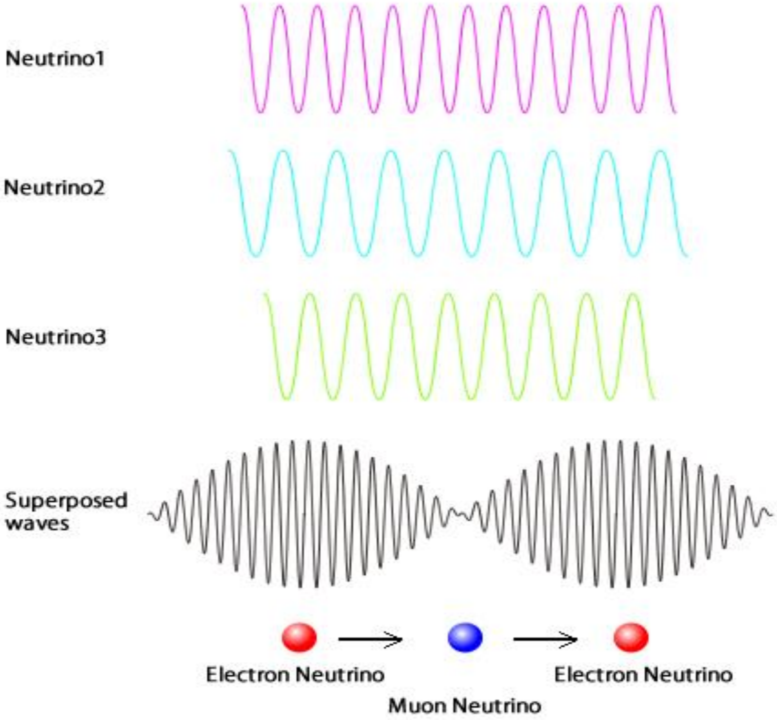
- Neutrinos are fermions. They are neutral particles with a spin of ½. They interact only through mainly through weak interaction.
- They are assumed to be massless in the Standard Model.
- Neutrinos come in three flavors : electron neutrino, muon neutrino and tau neutrino



Neutrino Oscillations

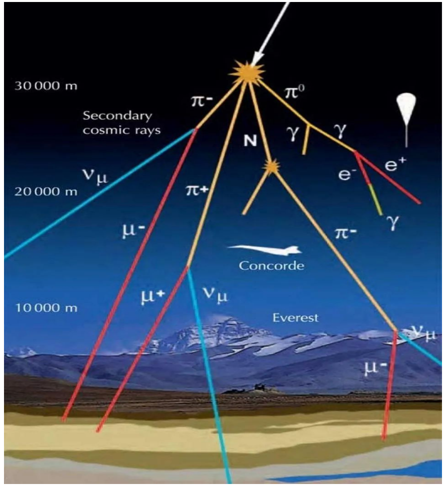
- When neutrinos travel from one point to another in space , they oscillate from one flavor to another.
- This is a quantum mechanical effect
- Neutrino oscillations are possible only if neutrinos have mass.





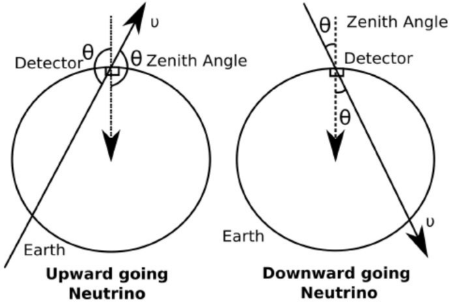
Atmospheric Neutrinos

- 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).

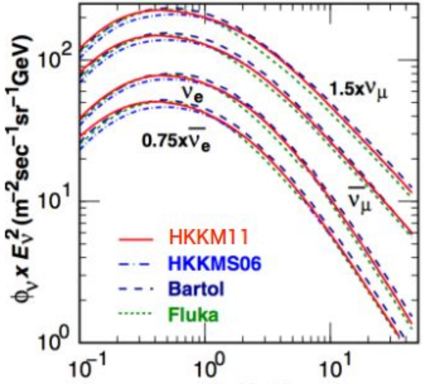


Upward going neutrino:
$\pi/2 < \theta < \pi$; $-1 < \cos\theta < 0$

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



PRD 83, 123001 (2011)



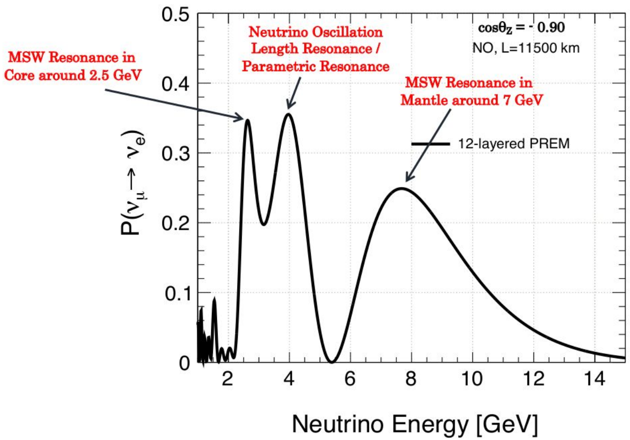
Matter Effects in Earth

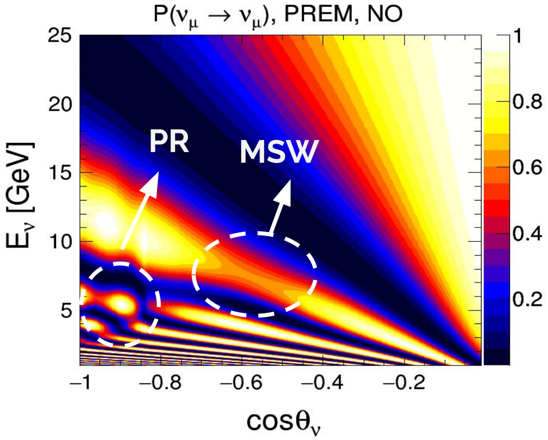
- Upward-going atmospheric neutrinos travel through Earth to experience matter effect.

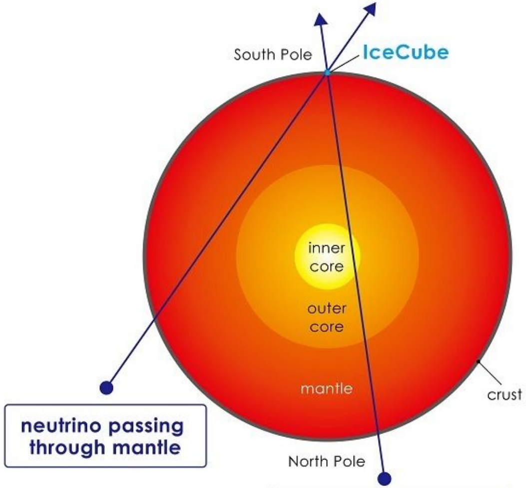
Matter effect in Earth

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

Parametric Resonance (PR)
$(\cos\theta_\nu < -0.8,\ 3\text{ GeV} < E_\nu < 6\text{ GeV})$







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

Electron no. density

Density inside Earth

Image source (top right) : Link

Statistical Method

Following Poissonian LLH

$$\text{Test Statistics (TS)} = \text{LLH} + \text{Prior pull} = \sum_{\mathrm{i}\in\mathrm{bins}} [-\lambda_\mathrm{i} + \mathrm{x_i}\ln(\lambda_\mathrm{i}) - \ln(\mathrm{x_i}!)] + \frac{1}{2}\sum_{\mathrm{j}\in\mathrm{sys}} \frac{(\mathrm{p_j} - \hat{\mathrm{p}}_\mathrm{j})^2}{\sigma_\mathrm{j}^2}$$

$\mathrm{x_i}$ - Observed value of i^{th} bin

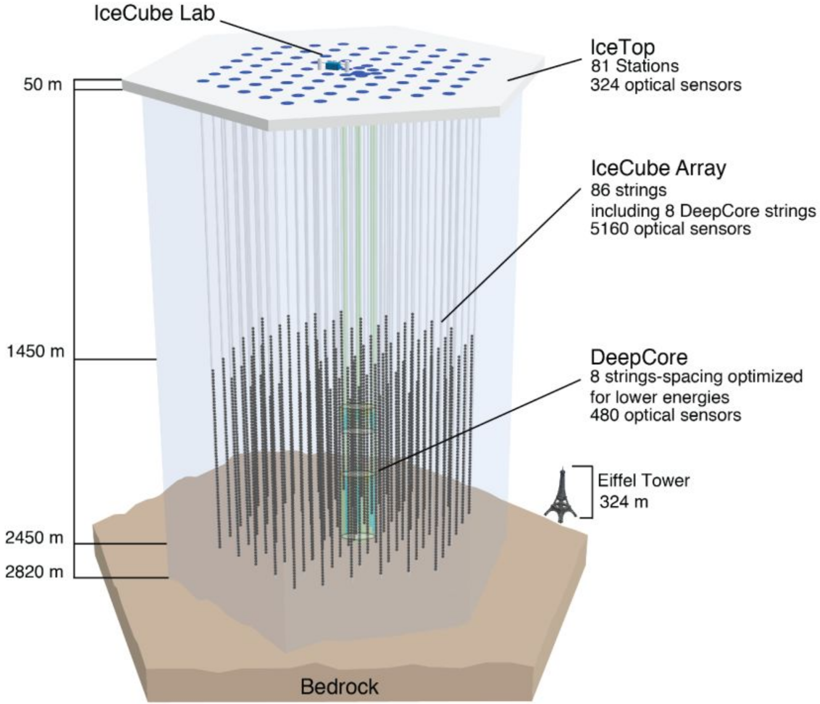
λ_i - Expected value of i^{th} bin

$\mathrm{p_j}$, $\hat{\mathrm{p}}_\mathrm{j}$, and σ_j^2 are the nominal, best-fit, and Gaussian prior of j^{th} systematics, respectively

The IceCube Detector

IceCube-DeepCore

- 1 km^3 neutrino detector at South Pole.
- 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.



Binning and Test Statistic

- Signals for matter effect related studies predominantly come from lower energy (3 < E < 8 GeV) and cos (zenith) < -0.6.
- Binning optimized to have fine binning.

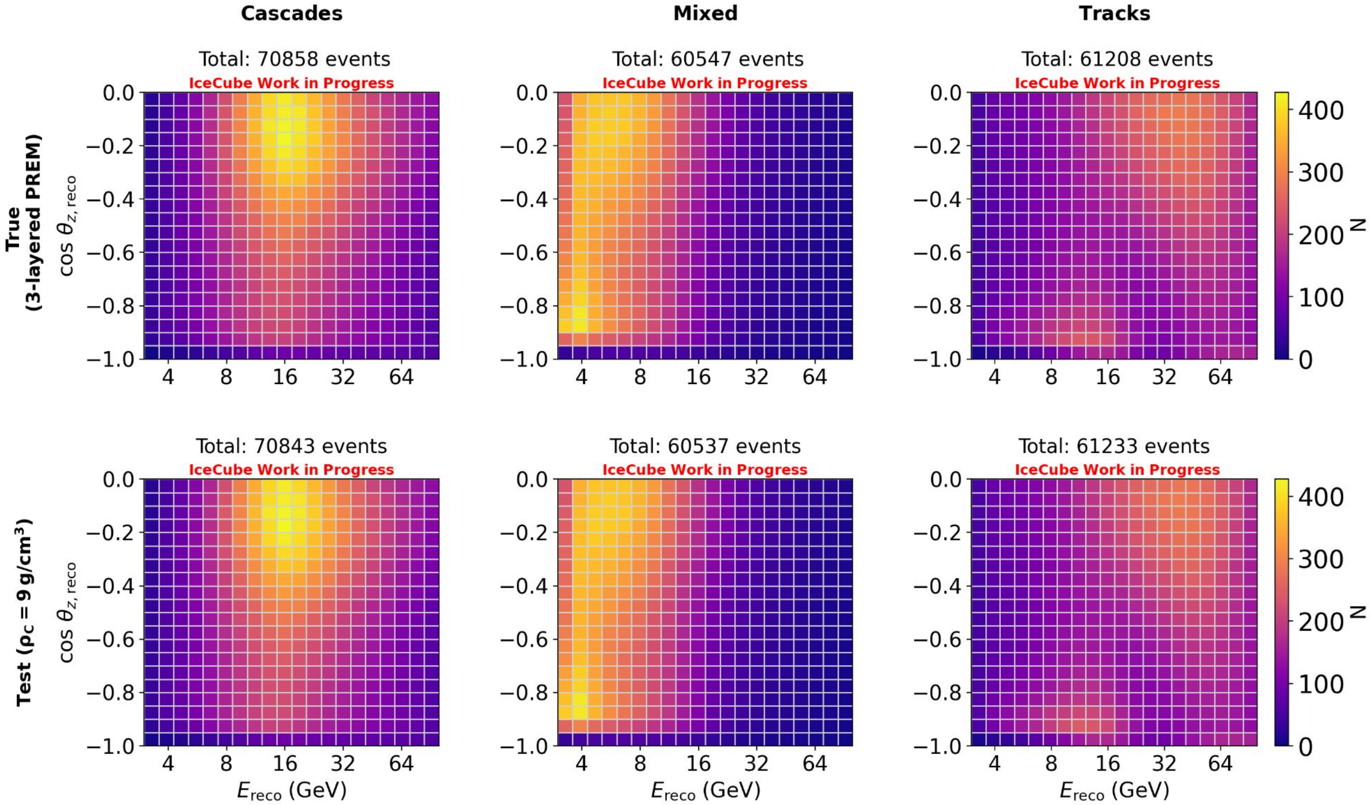
Optimized binning

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

Test Statistic used : Log Likelihood (LLH)

Used Wilks theorem to determine the test statistic value that corresponds to 1σ or 68% C.L.

Mass of Core : Expected Event Distributions,NO



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Test Profile:

ρ_C = 9 g/cm^3

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- PREM & Test hypo.: For true values of all oscillation and systematic parameters