Probing the Interior of Earth using Atmospheric Neutrino Oscillations at IceCube DeepCore

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Jan 29, 2026
Free Meson Seminar,
TIFR Mumbai

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- Sharmistha Chattopadhyay

The analyses presented here are performed for the IceCube Collaboration.

HELMHOLTZ

The Interior of Earth

- What lies in the interior of Earth has been a long-standing puzzle and an 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.

Credit: scitechdaily

The Kola Superdeep Borehole is the deepest human-made hole on Earth with vertical depth of 12.262 km.

Hence, indirect methods are used to probe the interior of Earth!

Credit: mossandfog.com

Multi-messenger Tomography of Earth

Gravitational Measurements
- Gravitational interactions
- Information on the Earth's total mass and moment of inertia

Seismic Studies
- Use seismic waves from earthquakes
- Mechanical waves of acoustic energy
- Reveal the internal structures and identify large-scale variations in matter density and properties

Neutrino Absorption Tomography
- Weak interactions
- Absorption of high-energy (TeV-PeV) neutrinos

Neutrino Oscillation Tomography
- Weak interactions
- Coherent forward scattering of low-energy (MeV-GeV) electron neutrinos with ambient electrons
- Modify neutrino oscillation patterns

Geoneutrinos
- Brings crucial information about the mantle
- Improve understanding of the radiogenic contribution to Earth's heat budget

Recent workshops:
- MMTE 2022 (Salt Lake City, Utah),
- MMTE 2023 (APC, Paris)
- Neutrino Geoscience 2025 (Kingston, Canada)

Gravitational Measurements

Gravitational measurements exploits the gravitational interactions of matter inside Earth to provide information on mass and moment of inertia.

Average density

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

Moment of inertia

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

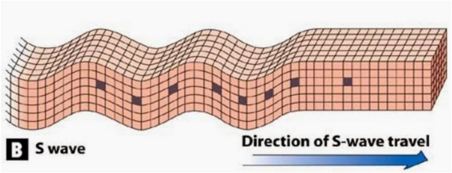
Internal regions are more denser than the surface!

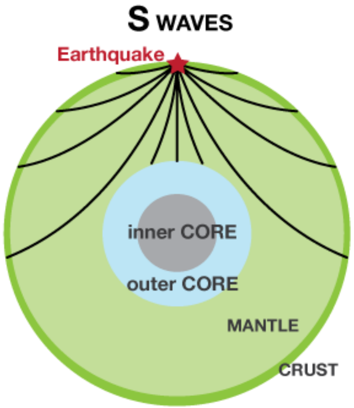
[1]B. Luzum et al., Celest. Mech. Dyn. Astron. 110, 293 (2011).
[2]Williams, James G. The Astronomical Journal. 108: 711 (1994)
[3]W. Chen, J. Ray, W. B. Shen, and C. L. Huang, J. Geod. 89, 179 (2015).

Seismic Measurements

Seismic measurements exploit the electromagnetic interactions of matter inside Earth.

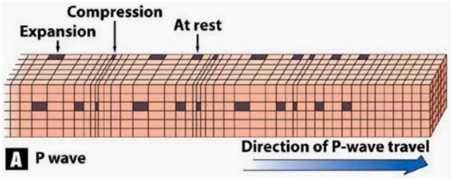
Body waves consisting of transverse vibrations are known as **S-waves**:

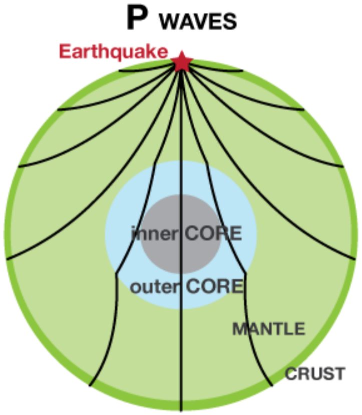




$$V_S = \sqrt{\frac{\mu}{\rho}}$$

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





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

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

S-wave cannot propagate through the liquid outer core!

Preliminary Reference Earth Model (PREM)

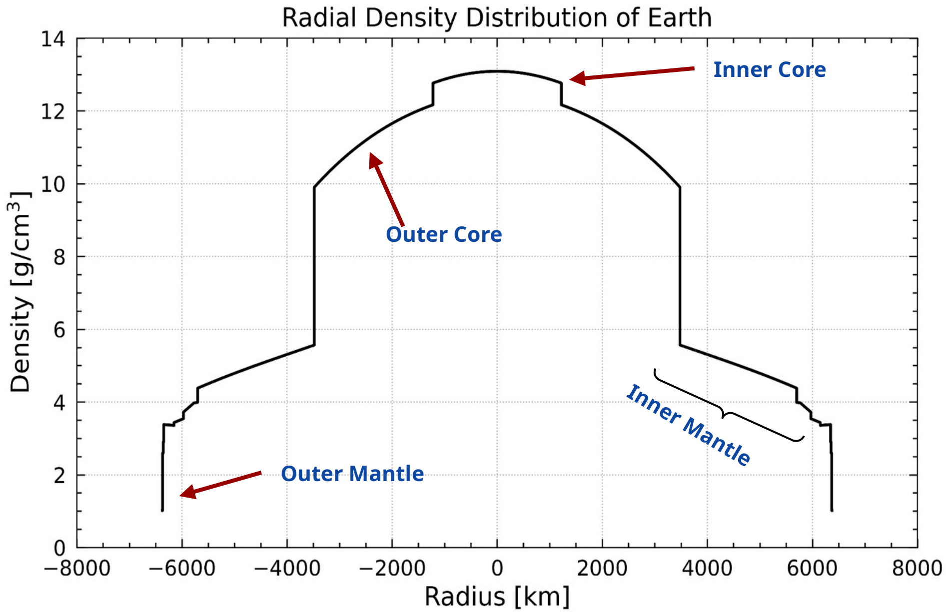
Inversion of seismic wave data + gravitational constraints on Earth's total mass and moment of inertial

↓

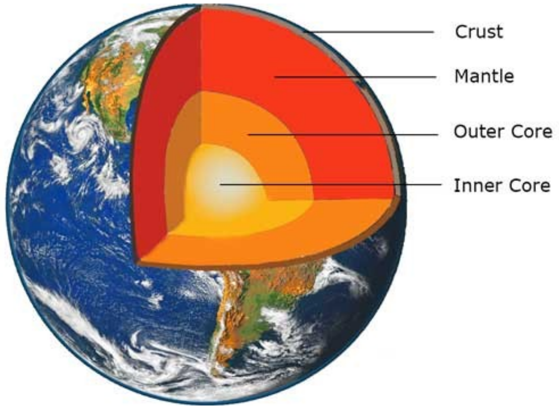
Radial profile of Earth's matter density

↓

Preliminary Reference Earth Model (PREM)

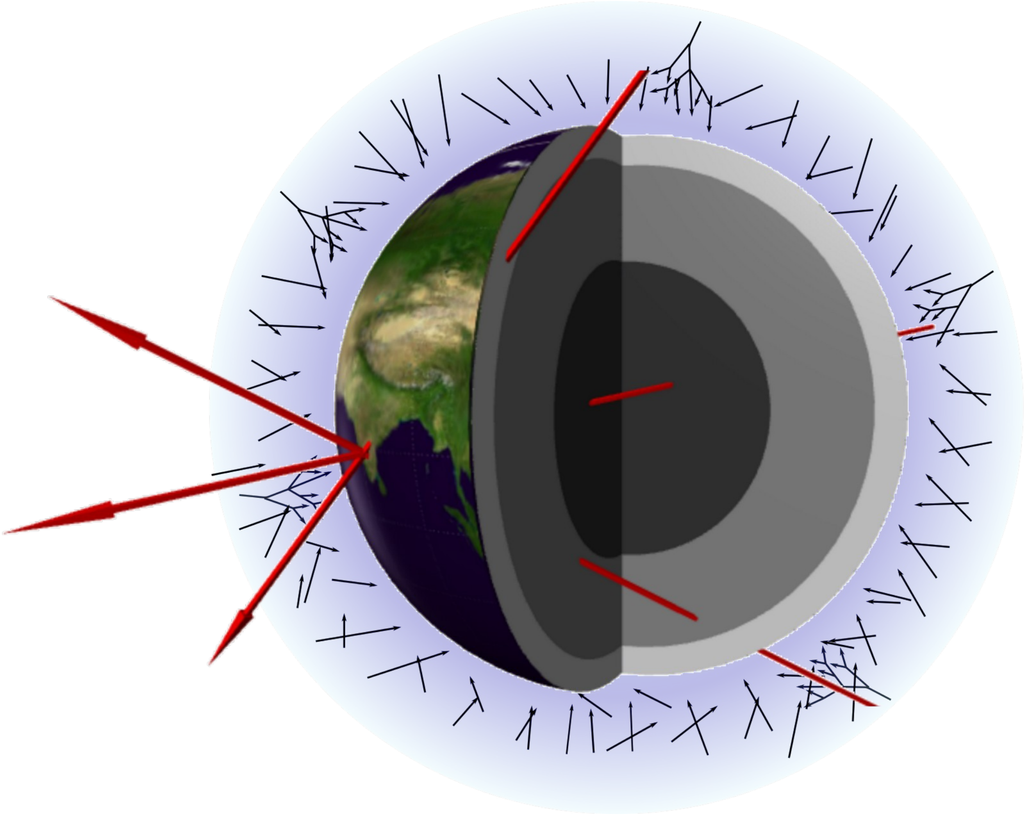


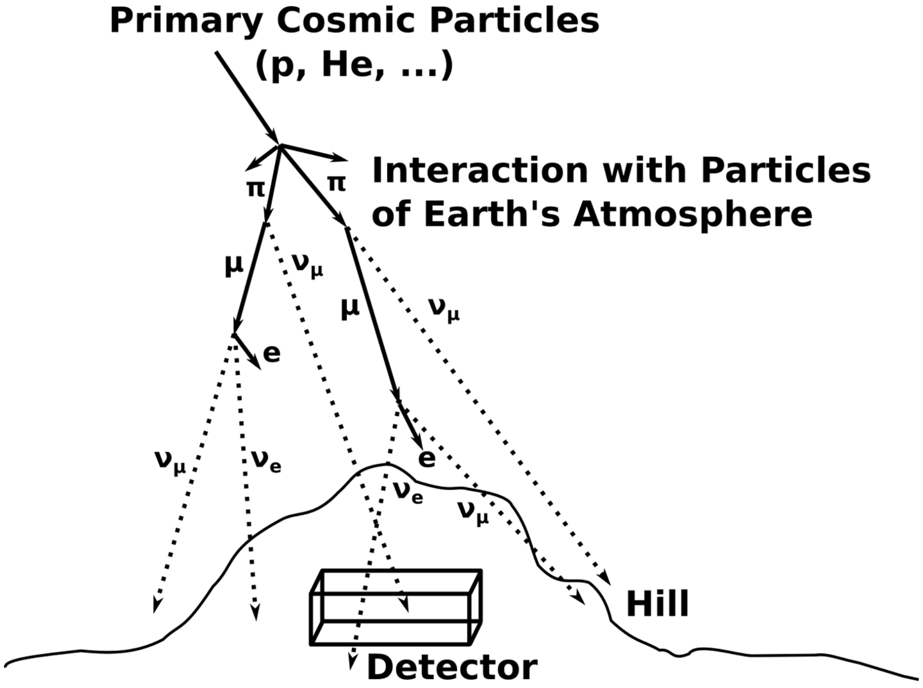
- **Crust:** solid, rocks, brittle, lowest density
- **Mantle:** hot, solid outer mantle, viscous plastic inner mantle
- **Core:** iron and nickel
  - Inner core: solid
  - Outer core: liquid



Dziewonski and Anderson, PREM, Phys.Earth Planet.Interiors 25 (1981) 297-356

Atmospheric Neutrinos

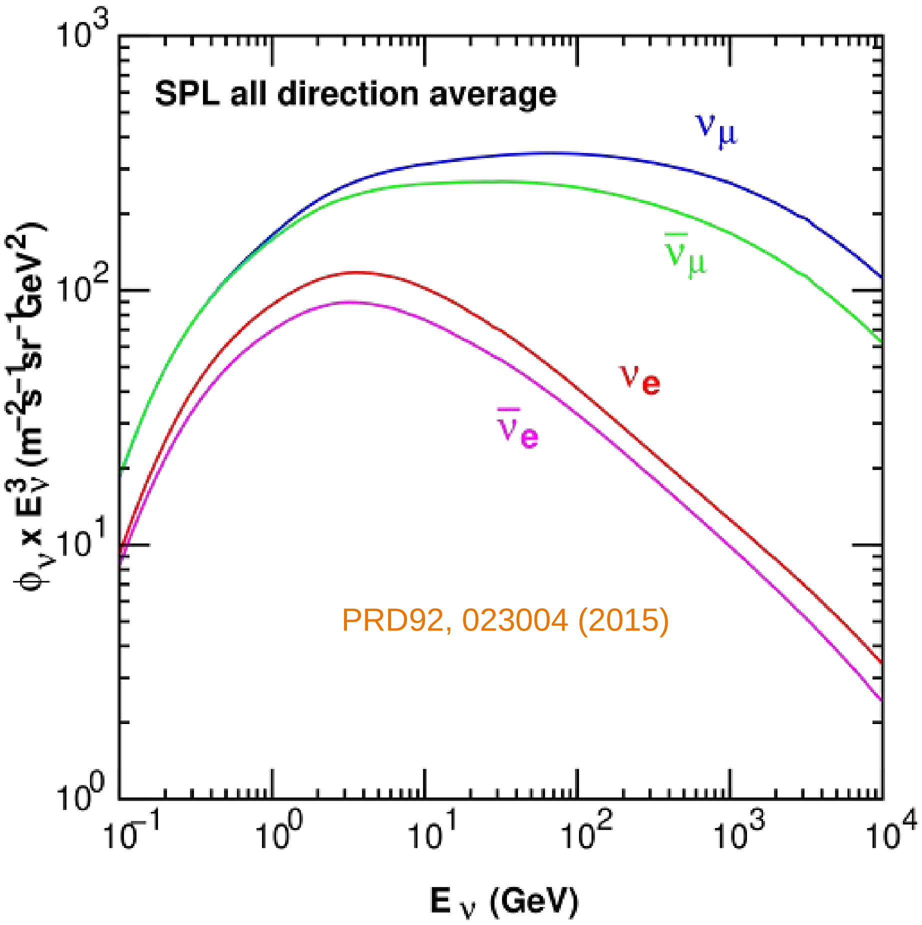


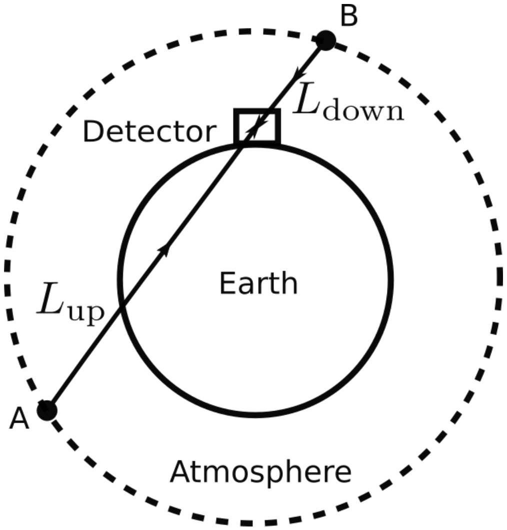


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- Baselines: ~ 20 km to 12700 km
- Wide energy range: few MeV to more than TeV

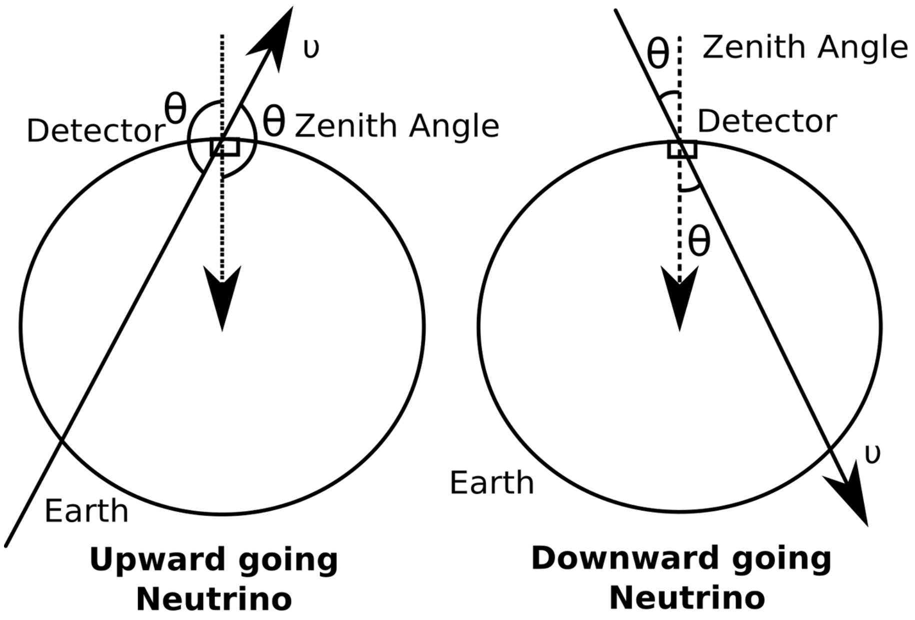
Atmospheric Neutrinos



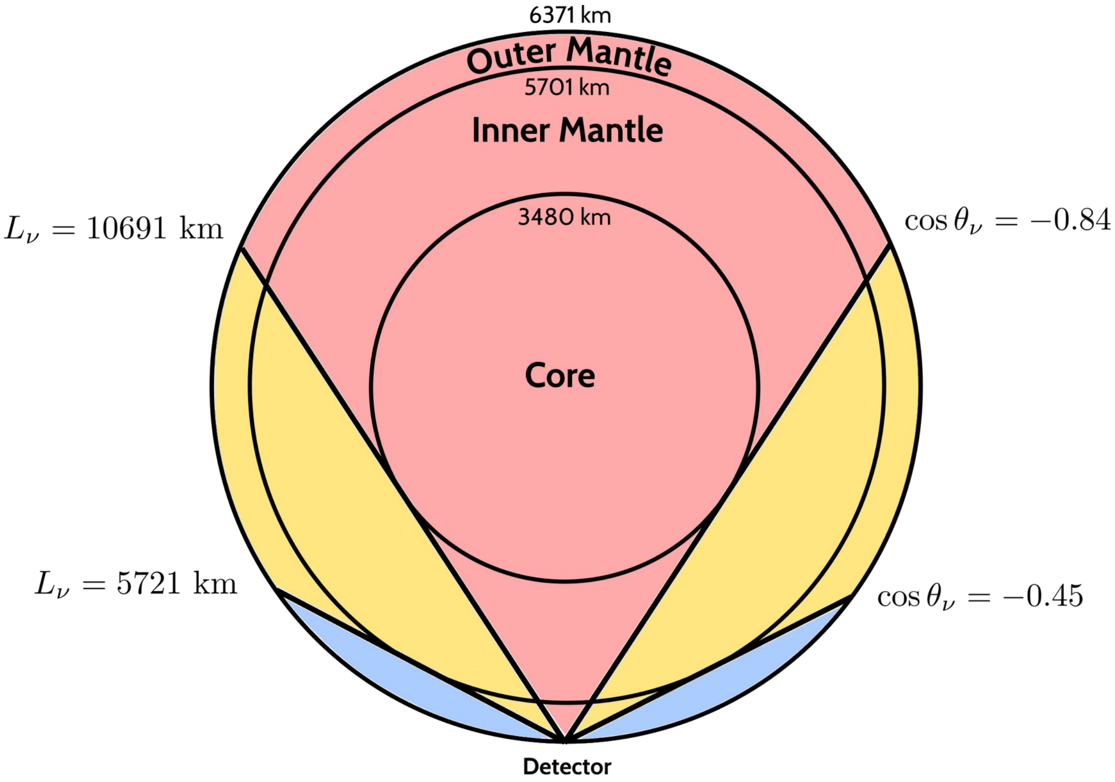


- In the GeV range, initial atmospheric neutrino flux is almost isotropic (up-down symmetric)
- Steeply falling power-law spectra ($\sim E^{-2.7}$) in the GeV range

Atmospheric Neutrinos Passing through Earth

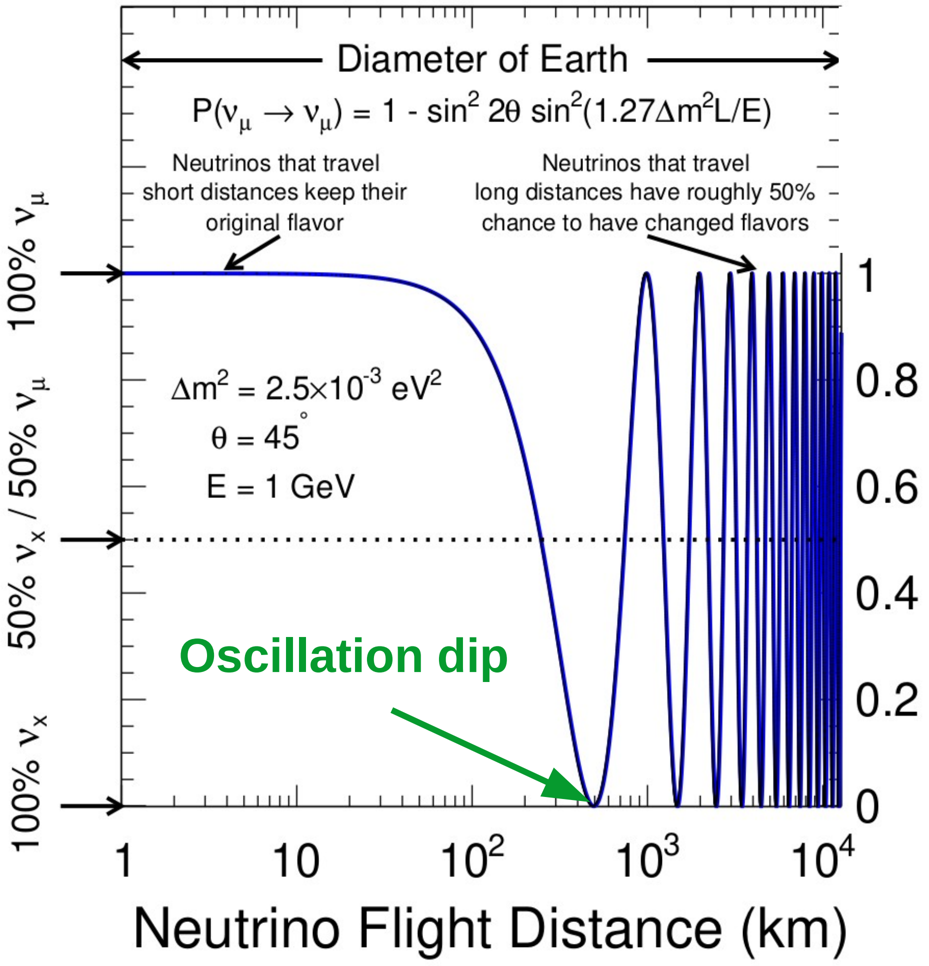


-1 < cos θ < 0   0 < cos θ < 1



Upward-going neutrinos with large baselines pass through multiple layers inside Earth.

Atmospheric Neutrino Oscillations



Location of oscillation dip → θ

Depth of oscillation dip → Δm^2

Atmospheric neutrino oscillation experiments:

- **Currently running:** IceCube DeepCore, Super-K
- **Under deployment:** IceCube Upgrade, ORCA at Km3NET
- **Upcoming:** Hyper-K, DUNE

Three-Flavor Neutrino Oscillations

Neutrino flavor eigenstates ν_α as superposition of mass eigenstates ν_i

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

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

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

Probability of oscillation of flavor α to β:

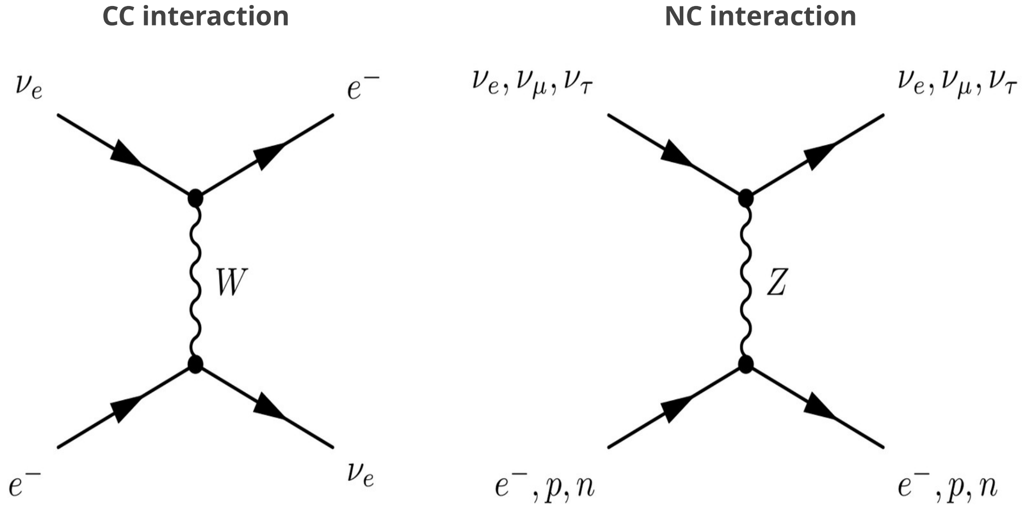
$$P(\nu_\alpha \to \nu_\beta) = \left| U_{\beta 1}U^*_{\alpha 1} + U_{\beta 2}U^*_{\alpha 2}e^{-i2\alpha\Delta} + U_{\beta 3}U^*_{\alpha 3}e^{-i2\Delta} \right|^2$$

where, $\Delta = \frac{\Delta m^2_{31} L_\nu}{4E_\nu}$, $\Delta m^2_{ij} = m_i^2 - m_j^2$, and $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$

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

Interaction of Neutrinos inside Earth

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



Electron number density

Matter density in each layer inside Earth

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

$$Y_e = \frac{N_e}{N_p + N_n}$$

Chemical composition of a layer inside Earth

Relative electron number density

+ve : neutrinos
-ve: antineutrinos

Wolfenstein, PRD 17 (1978) 2369

Matter Resonances inside Earth

Neutrino Oscillation Length Resonance (NOLR)

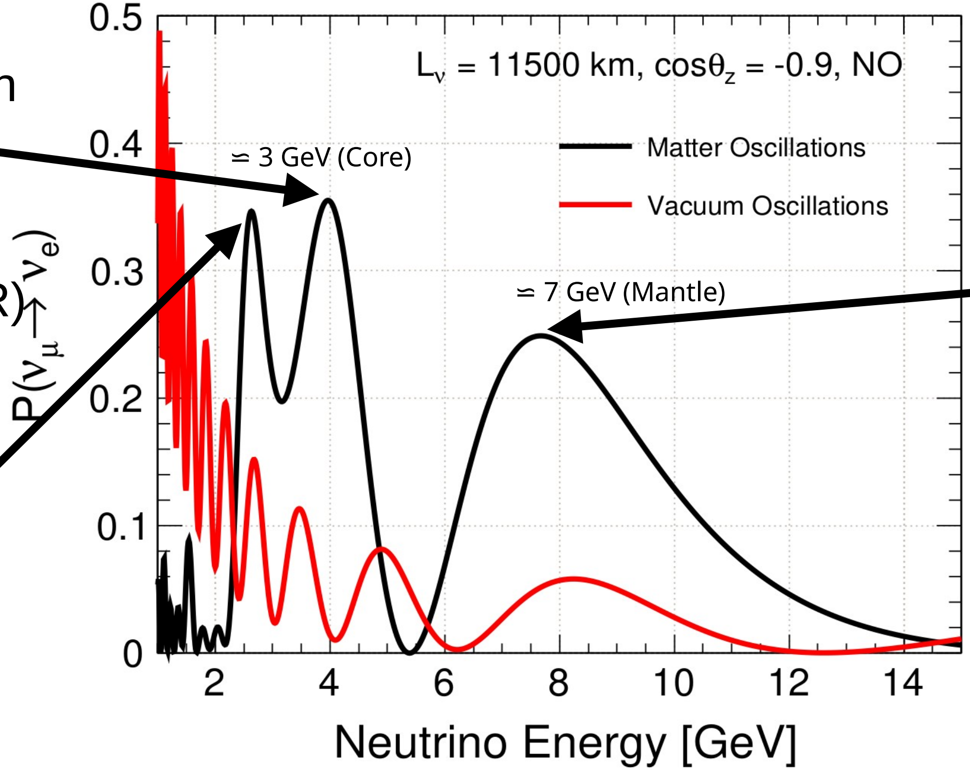
Petcov, PLB 434 (1998) 321

or

Parametric resonance (PR)

Akhmedov, NPB 538 (1999) 25

MSW resonance in core around 2.5 GeV



Mikheyev-Smirnov-Wolfenstein (MSW) resonance in mantle around 7 GeV

Wolfenstein, PRD 17 (1978) 2369
Mikheyev, and Smirnov, Sov.J.Nucl.Phys. 42 (1985) 913-917

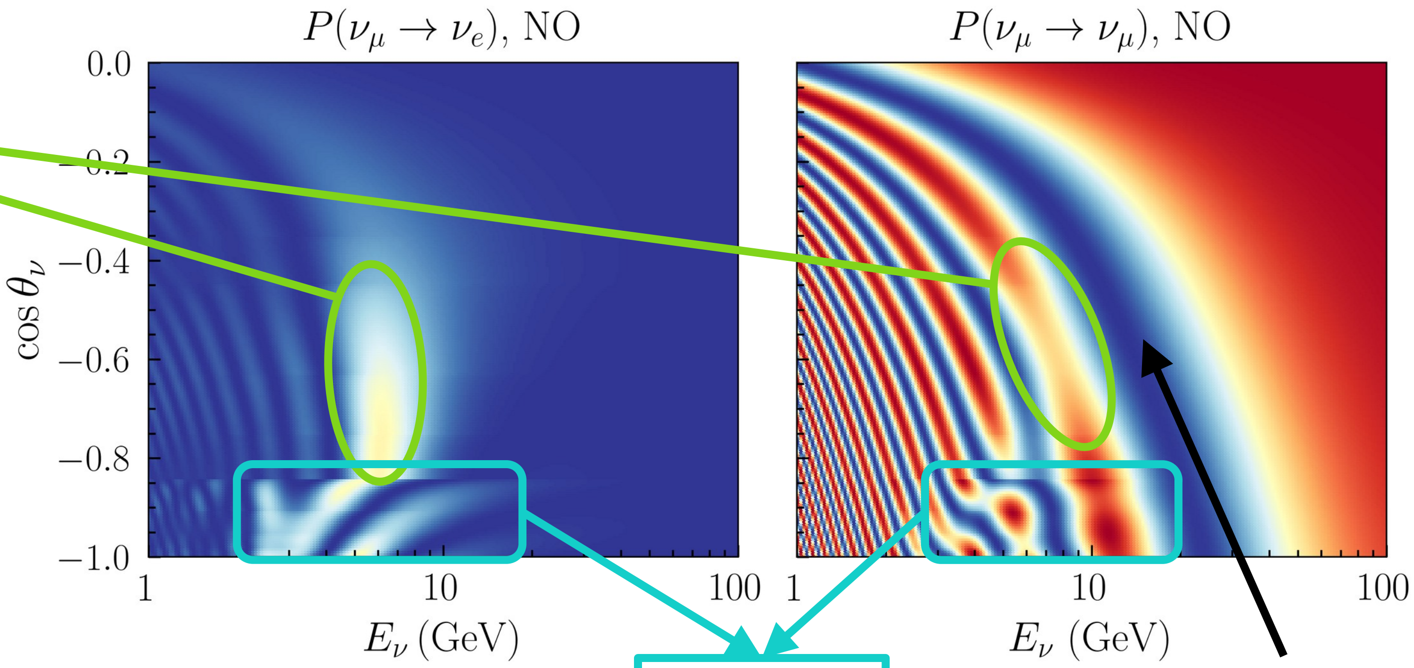
$$E_{\rm res} = \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7~\text{GeV}\left(\frac{4.5\,\text{g/cm}^3}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}~\text{eV}^2}\right)\cos 2\theta_{13}$$

Neutrinos (antineutrinos) feel Earth's matter effects for normal (inverted) mass ordering.

Matter Resonances in Probability Oscillograms

MSW

-0.8 < cos θ_ν < - 0.5
6 GeV < E_ν < 10 GeV



Useful to probe
Earth's matter effects

NOLR/PR

Vacuum
oscillation
valley

MSW or parametric resonances have not been observed yet inside Earth!

cos θ_ν < - 0.8
3 GeV < E_ν < 6 GeV
Lower threshold helps

Recent Tomography Sensitivity Studies

Recent sensitivity studies using atmospheric neutrino oscillations to probe the internal structure of Earth

- Presence of Earth's core: JHEP 08 (2021) 139 (ICAL)
- Location of core-mantle boundary: PRD 104 (2021) 11, 113007 (DUNE), JHEP 04 (2023) 068 (ICAL)
- Density jump at core and its location: arXiv: 2405.04986 (ICAL)
- Density distribution: Nucl.Phys.B 908 (2016) 250-267 (PINGU & ORCA), JHEP 05 (2022) 187 (DUNE), Eur.Phys.J.C 82 (2022) 5, 461 (ORCA)
- Chemical composition: Sci.Rep. 5 (2015) 15225, Eur.Phys.J.C 82 (2022) 7, 614 (ORCA), Front.Earth Sci. 11 (2023) 1008396

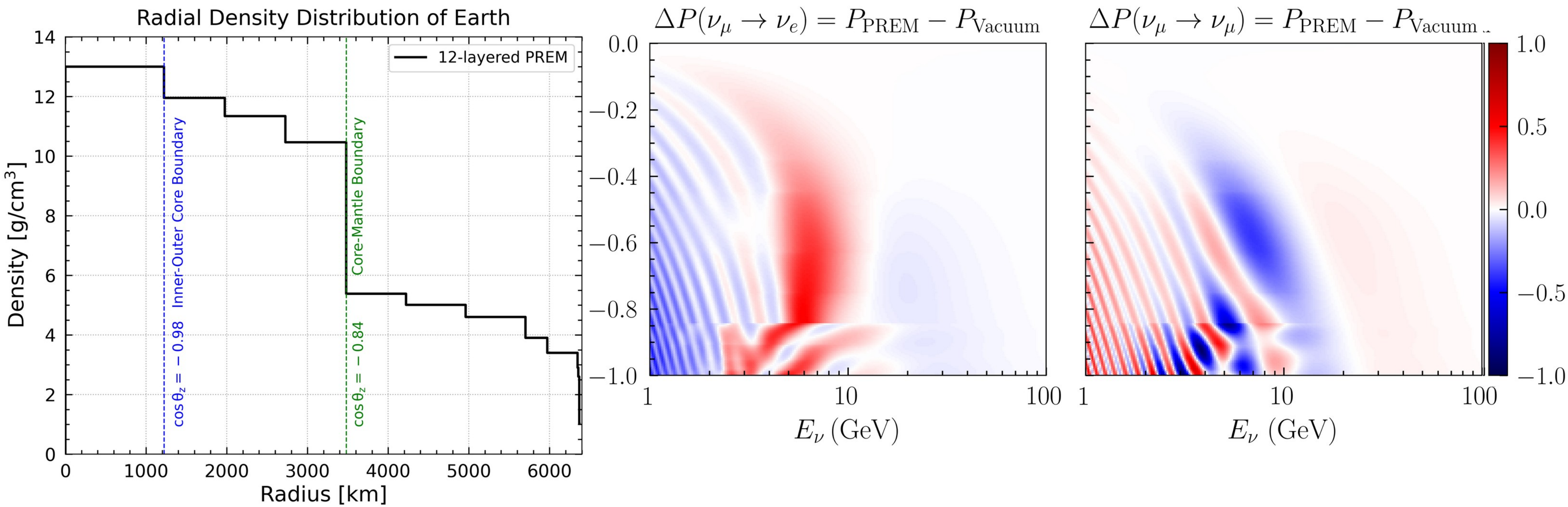
Analyses with IceCube DeepCore

- Establishing Earth's matter effects by ruling out **vacuum** profile with respect to PREM (Anuj Kumar Upadhyay)
- Validating layered structure inside Earth by ruling out **uniform** profile (Krishnamoorthi J)
- Measuring **mass of Earth** (Sharmistha Chattopadhyay)
- Measuring **correlated densities** of layers (Sharmistha Chattopadhyay)

EPJST 234 (2025) 16, 5055-5064,
Springer Proc.Phys. 322 (2026) 463-466,

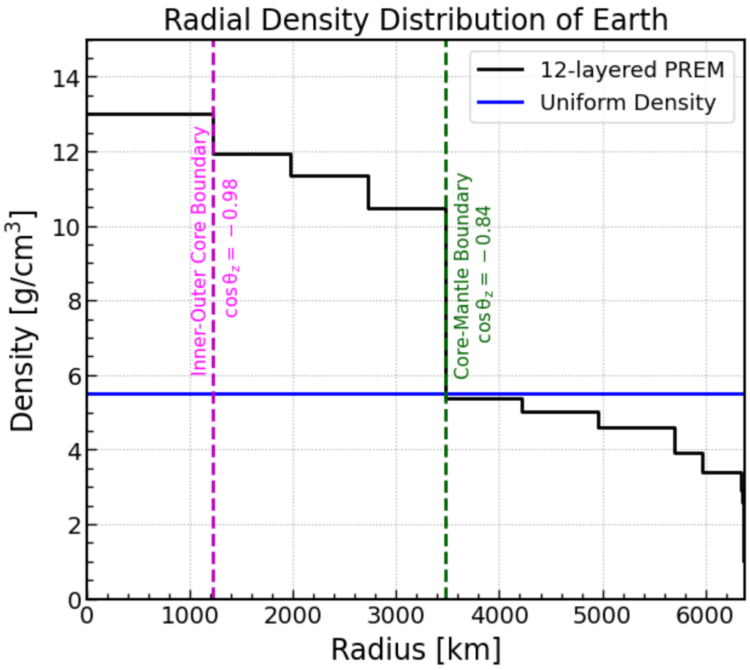
Springer Proc.Phys. 322 (2026) 447-450,
Springer Proc.Phys. 322 (2026) 417-421

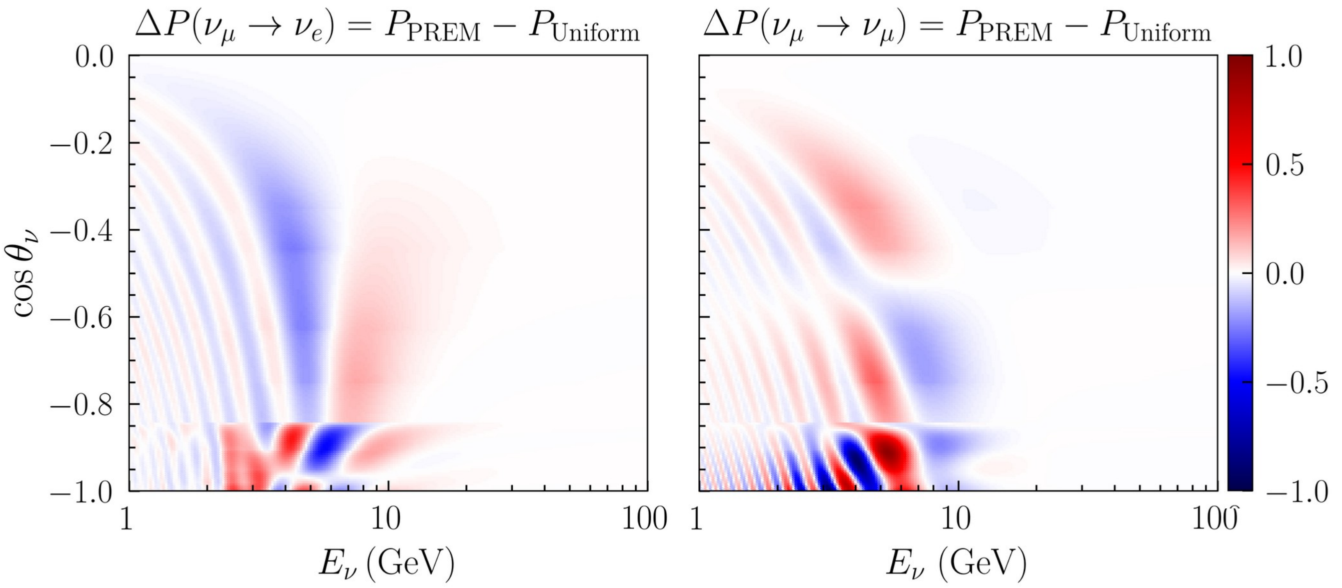
Establishing Earth's Matter Effects



The presence of matter modifies oscillograms in the lower energies over a wide range of baselines.

Validating Layered Structure inside Earth

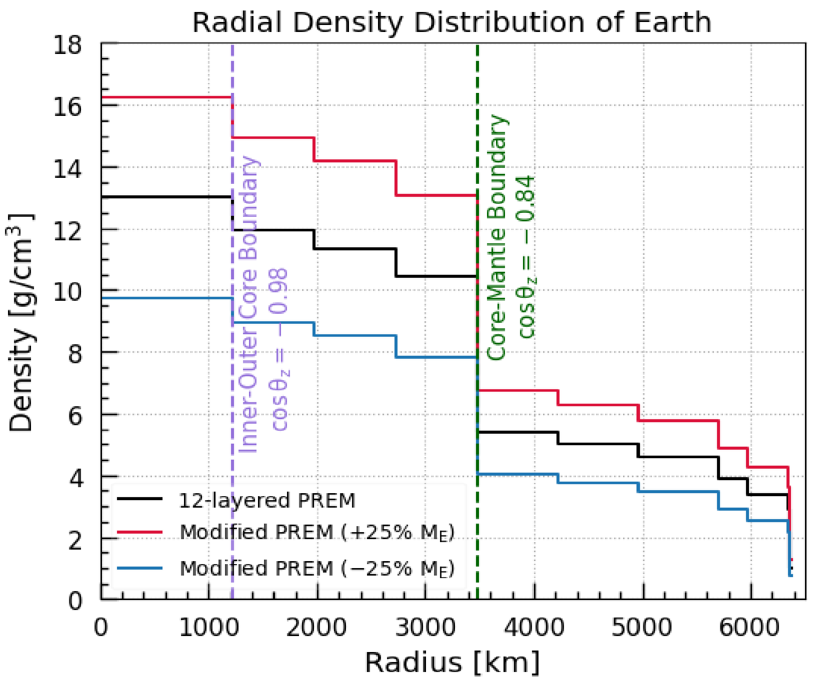


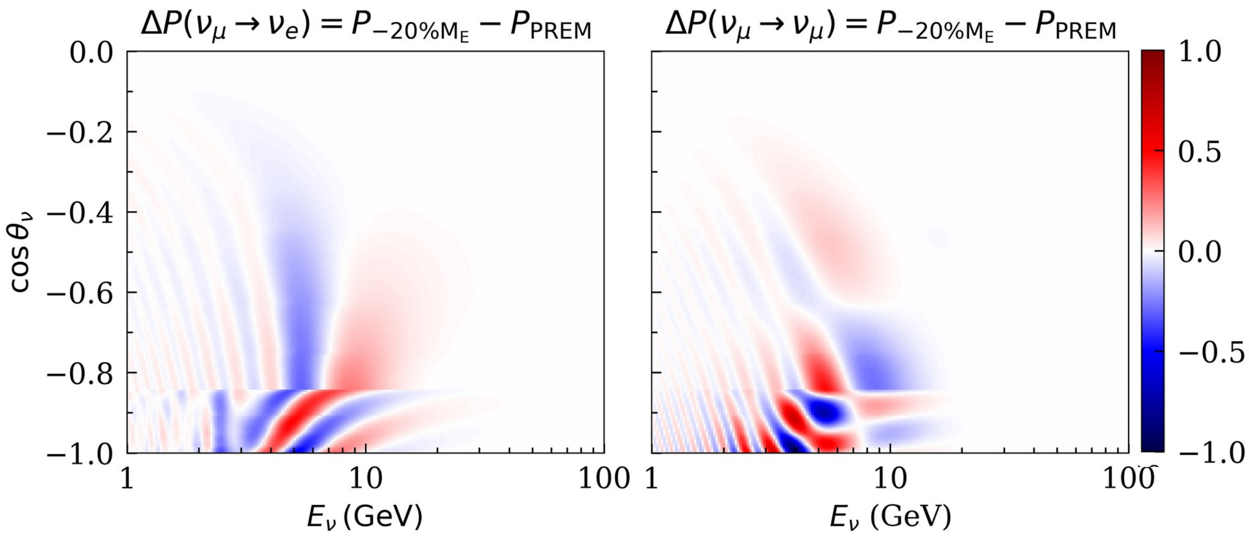


Effects are more prominent at lower energies and larger baselines around NOLR/PR regions.

Measurement of the Mass of Earth

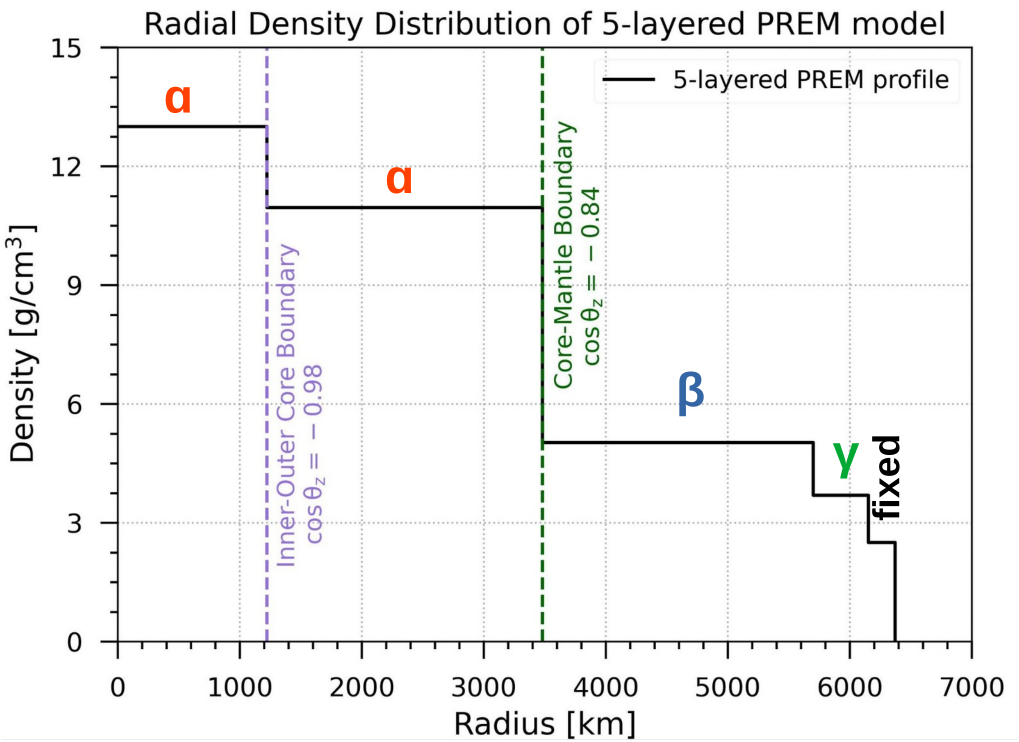
Densities of all layers are scaled by the same scaling factor





Effects can be seen at lower energies over a wide range of baselines.

Correlated Density Measurement



External Constraints:

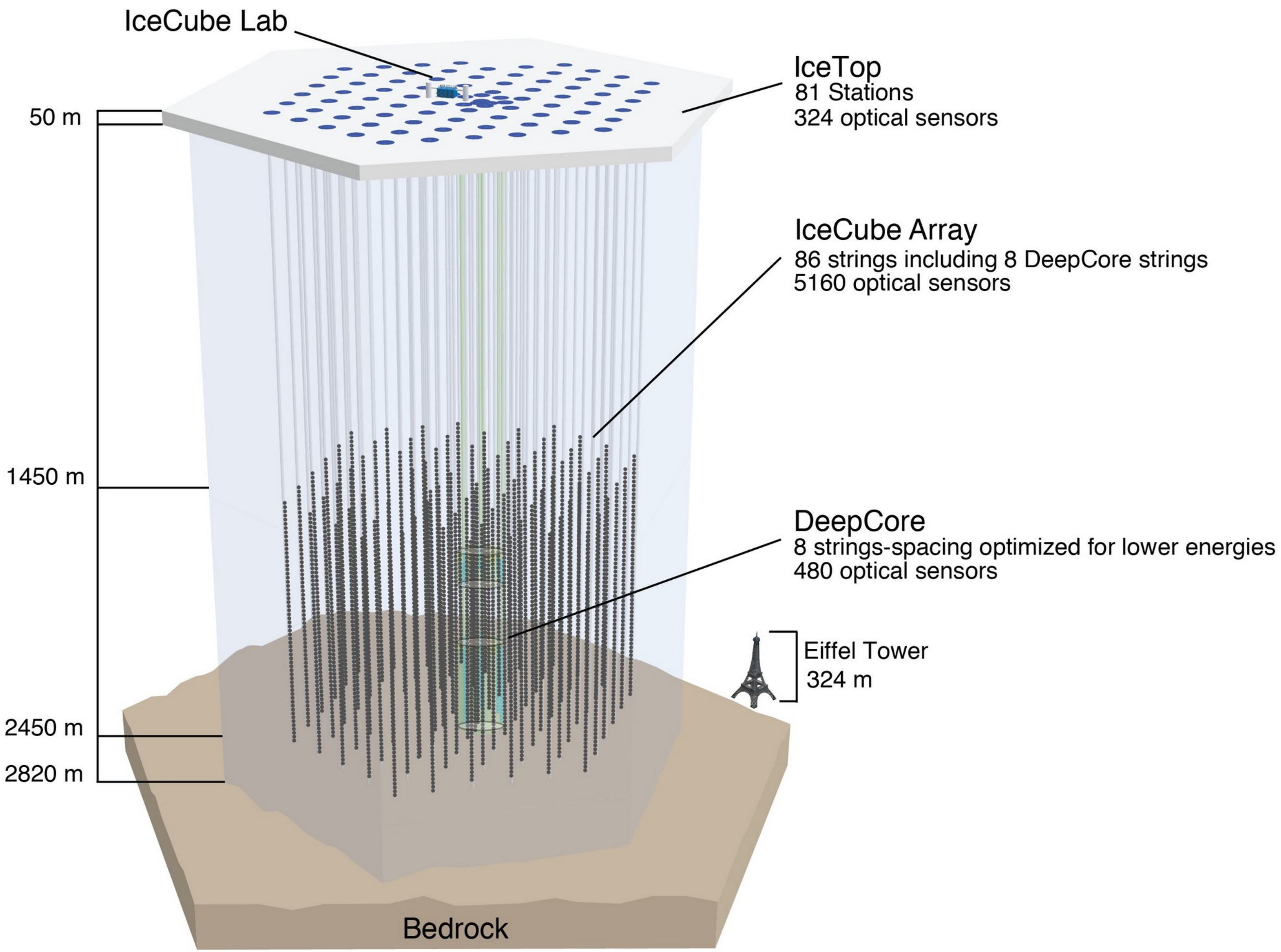
- Mass of Earth
- Moment of Inertia of Earth
- Hydrostatic equilibrium condition

Scaling factors:

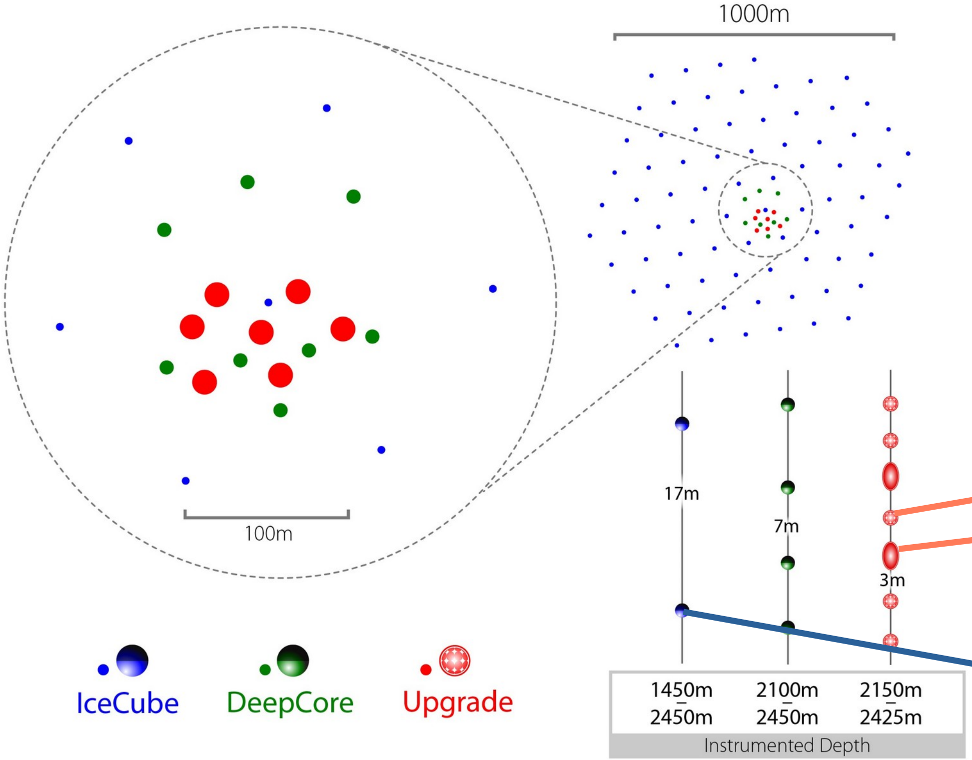
- Inner Core: α
- Outer Core: α
- Inner mantle: β
- Middle mantle: γ
- Outer mantle: fixed

After incorporating all external constraints, only α remains as the independent free scaling factor. Others can be determined in terms of it.

IceCube Neutrino Observatory



IceCube DeepCore



mDOM

D-Egg

DOM

- **IceCube**: up to **PeV energies**
- **DeepCore: GeV-scale**
- IceCube **Upgrade:** Energy threshold of a few GeV

Events at DeepCore

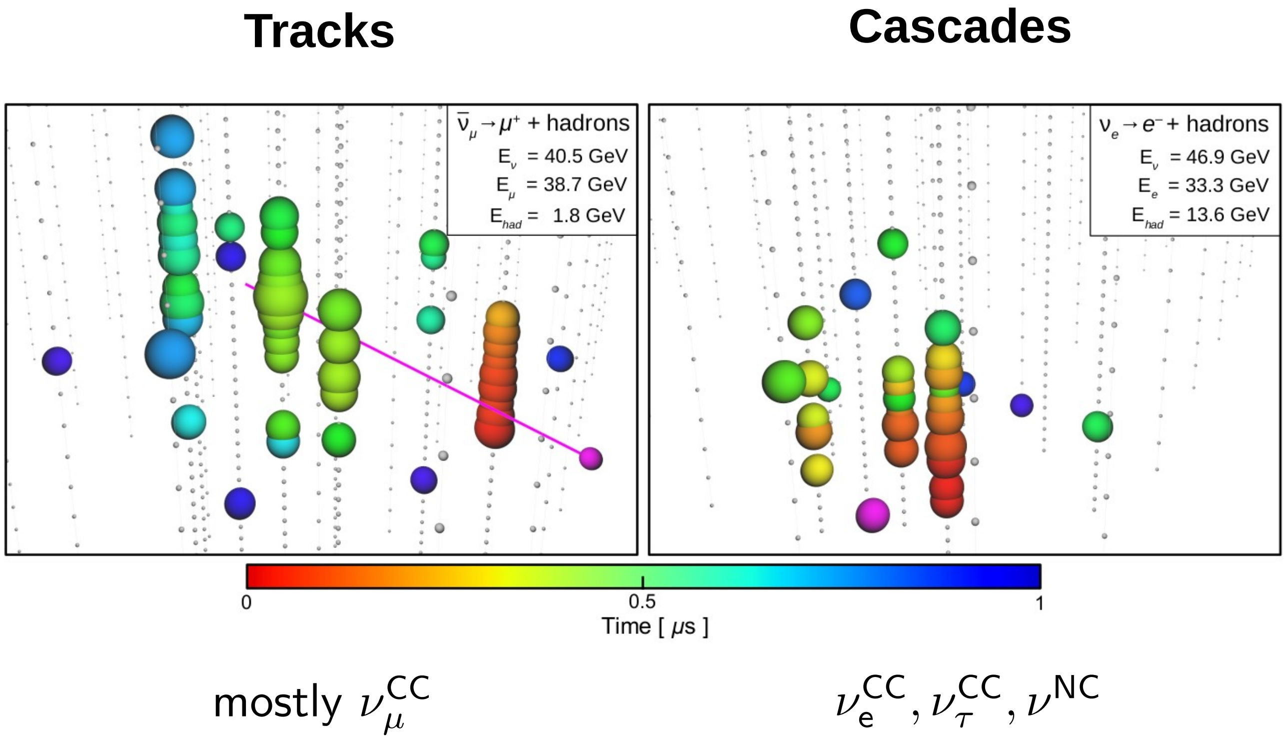
Red = Early Hits
Blue = Late Hits

Signals:

- ν_μ, ν_e, ν_τ
- Predominantly DIS interactions
- Operate above τ production threshold of 3.5 GeV

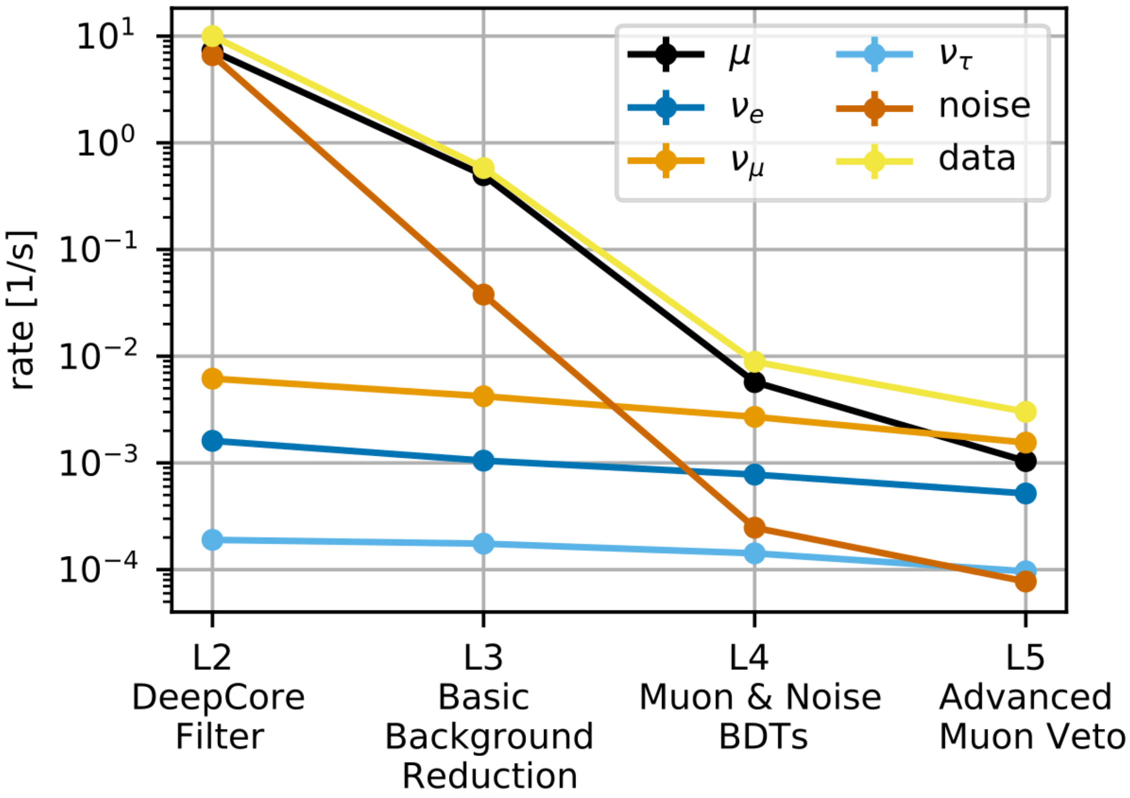
Backgrounds:

- Atmospheric muons
- Random detector noise



A. Terliuk, Ph.D. thesis (2018)

Event Selection



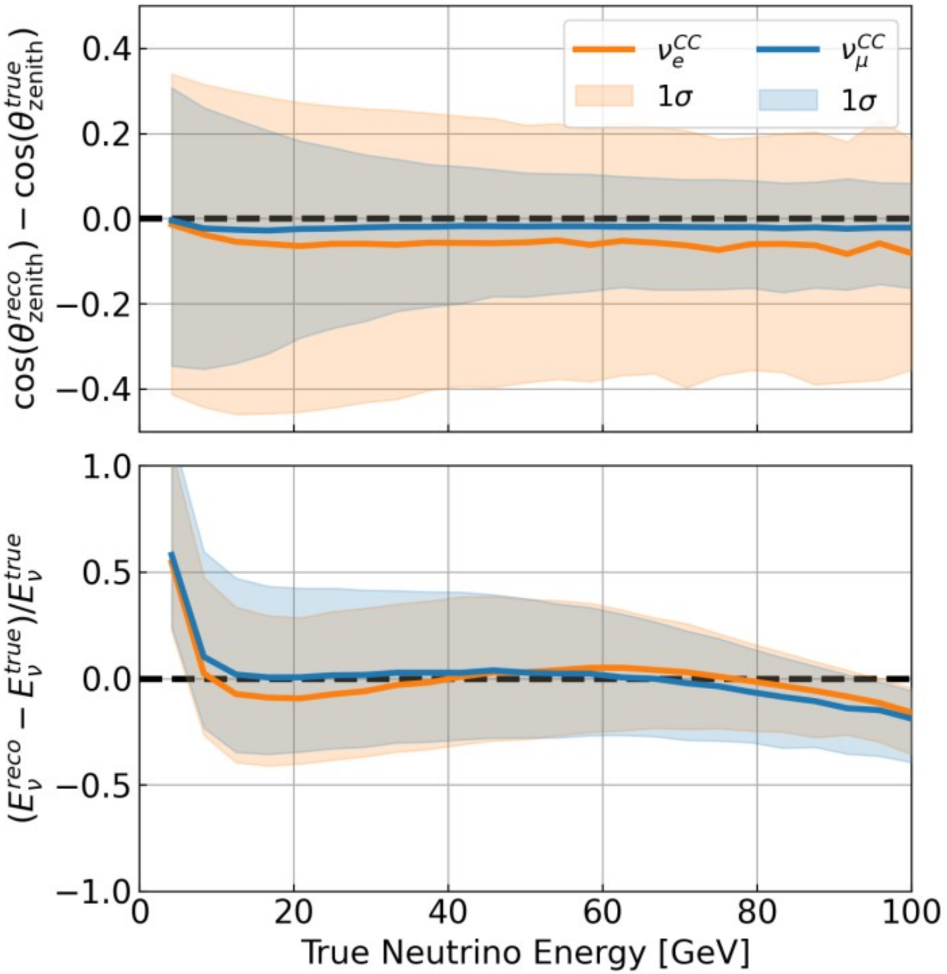
Filters at various levels reduce backgrounds such as noise and atmospheric muons below 1% of signal.

PRD 108, 012014 (2023)

Sample with CNN-based Reconstruction

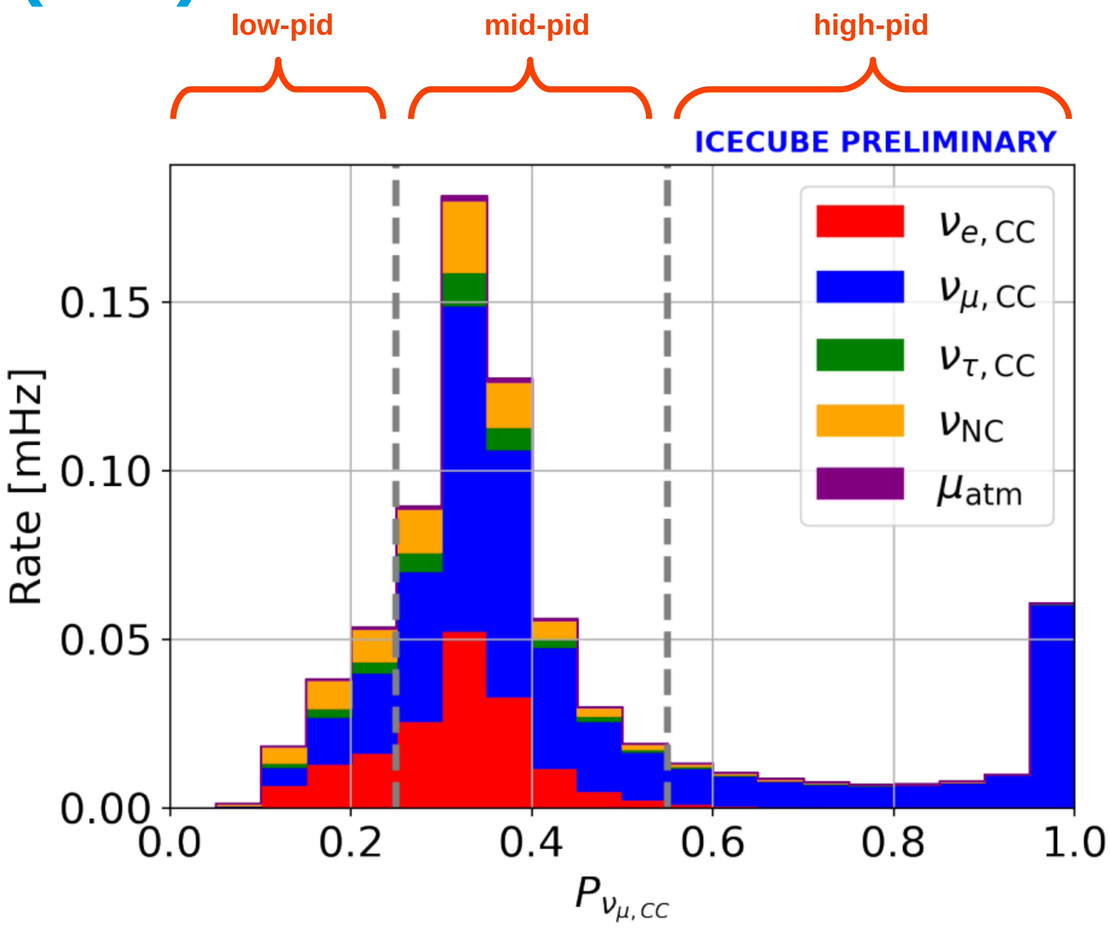
IceCube Collaboration
PRL 134, 091801 (2025),
arXiv:2505.16777

- Livetime: 9.3 years (2012-2021)
- Total events: ~150K
- High signal (ν_μ CC)
- Low background (noise and atm. Muon) rate (~0.6 %)
- CNNs trained for neutrino energy, arrival direction, interaction vertex, particle identification (PID), atmospheric muon classification.



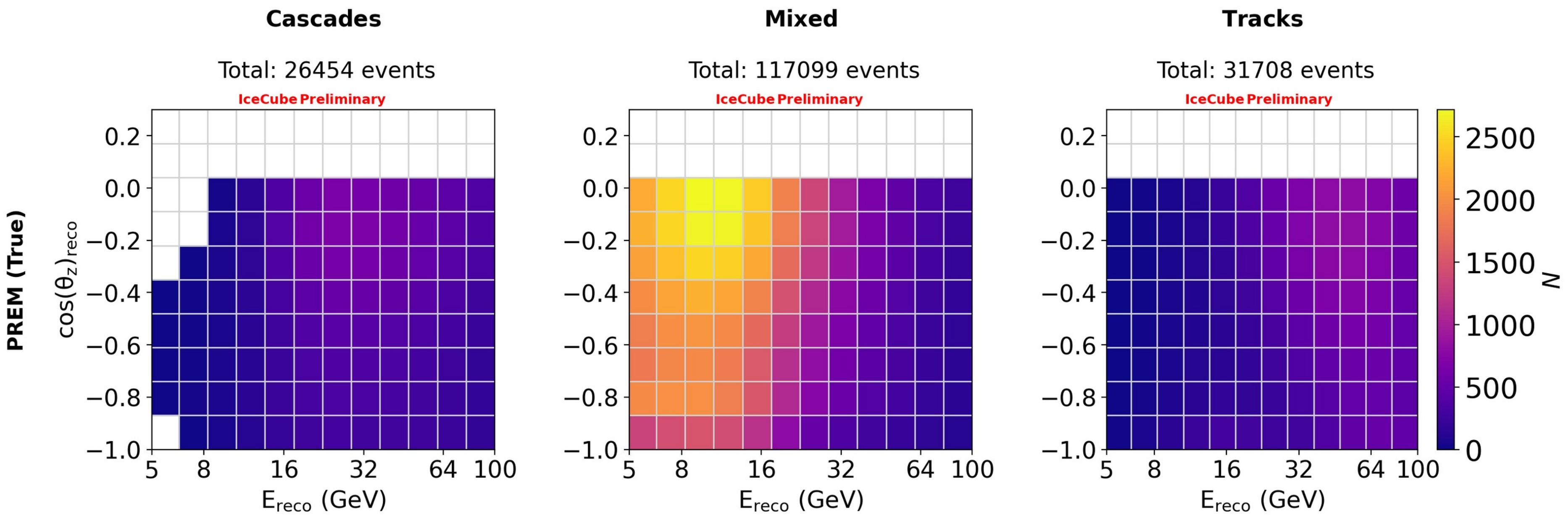
Particle Identification (PID)

- PID score: Probability of an event being track-like
- Both track-like and cascade-like topologies are included in the analysis



PRL 134, 091801 (2025)

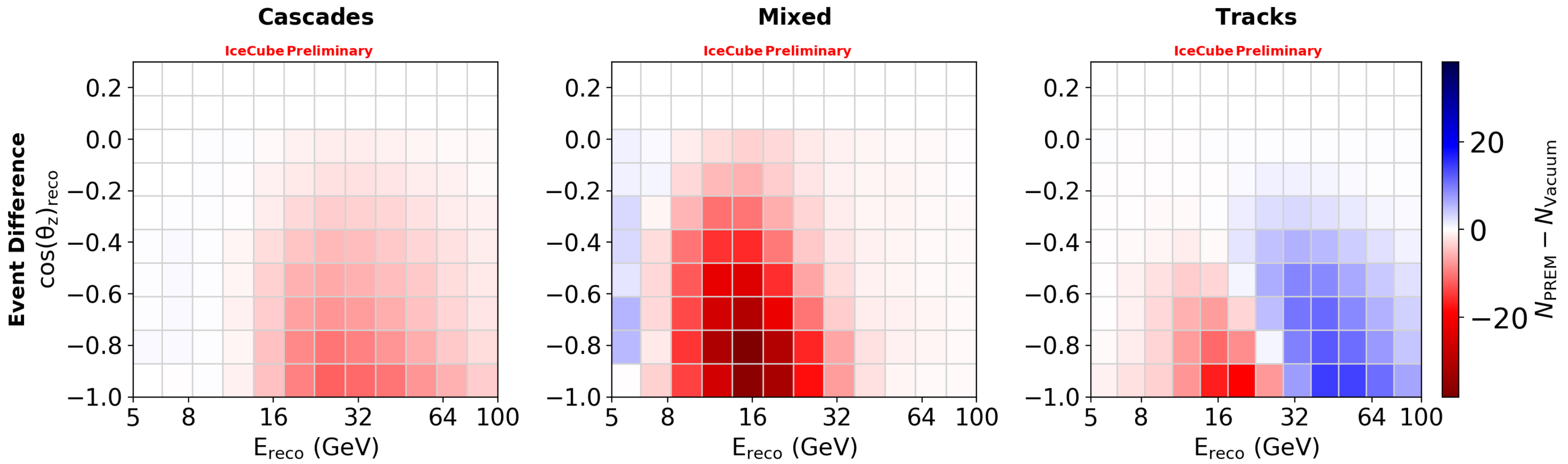
Expected Events at DeepCore



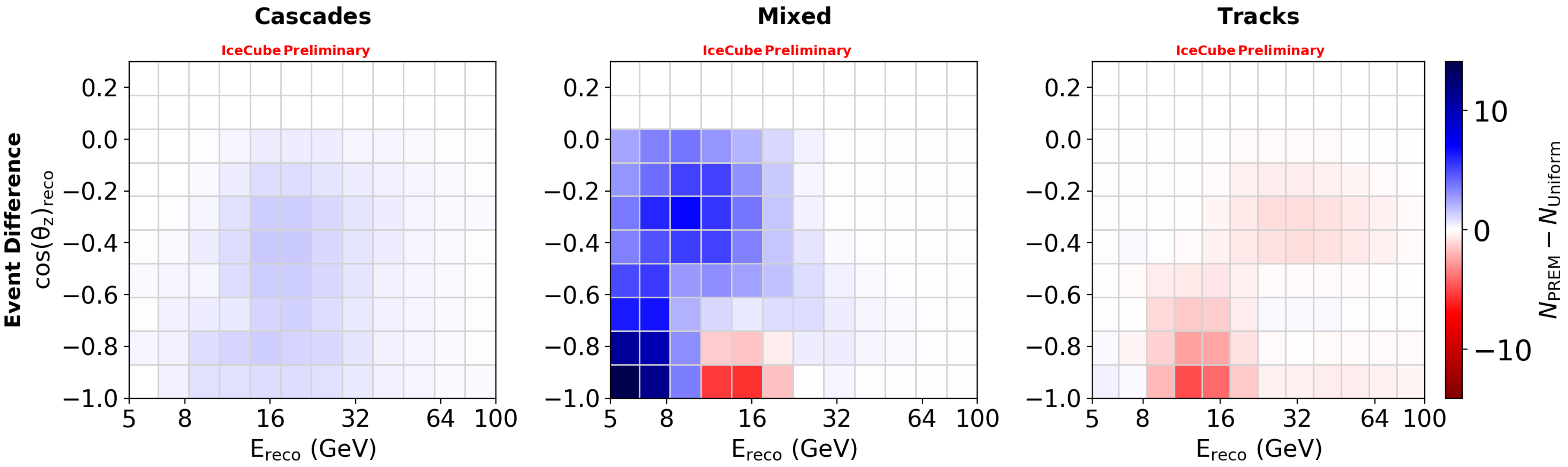
Binning Scheme:

- Energy: [5, 100] GeV, 12 log bins;
- cosθ: [-1, 0.04], 8 linear bins;
- PID: [0, 0.25, 0.55, 1]

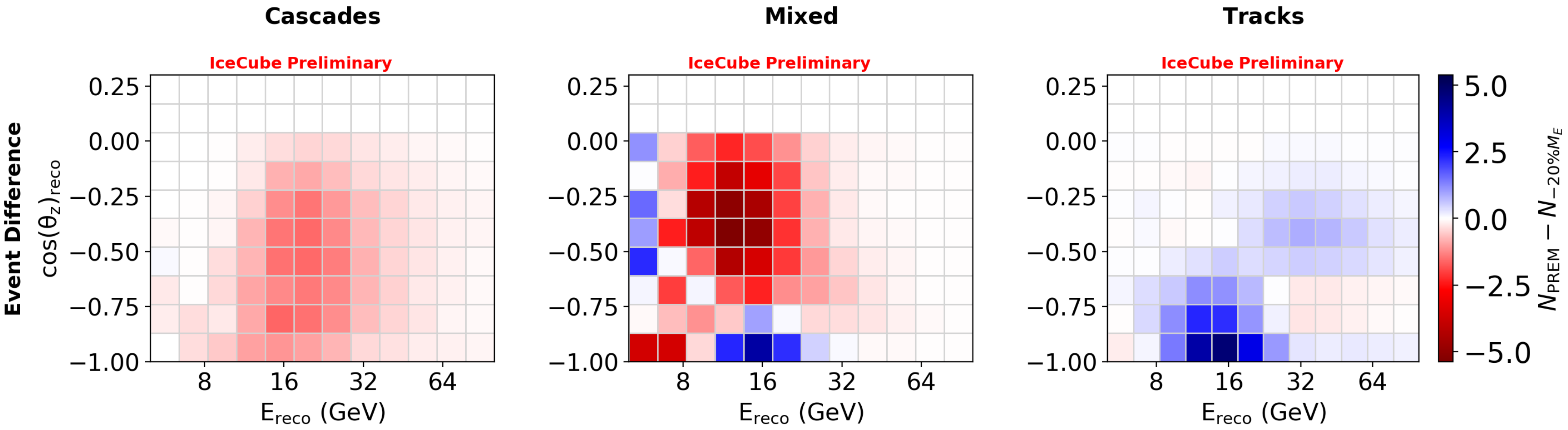
Event Difference due to Earth's Matter Effects



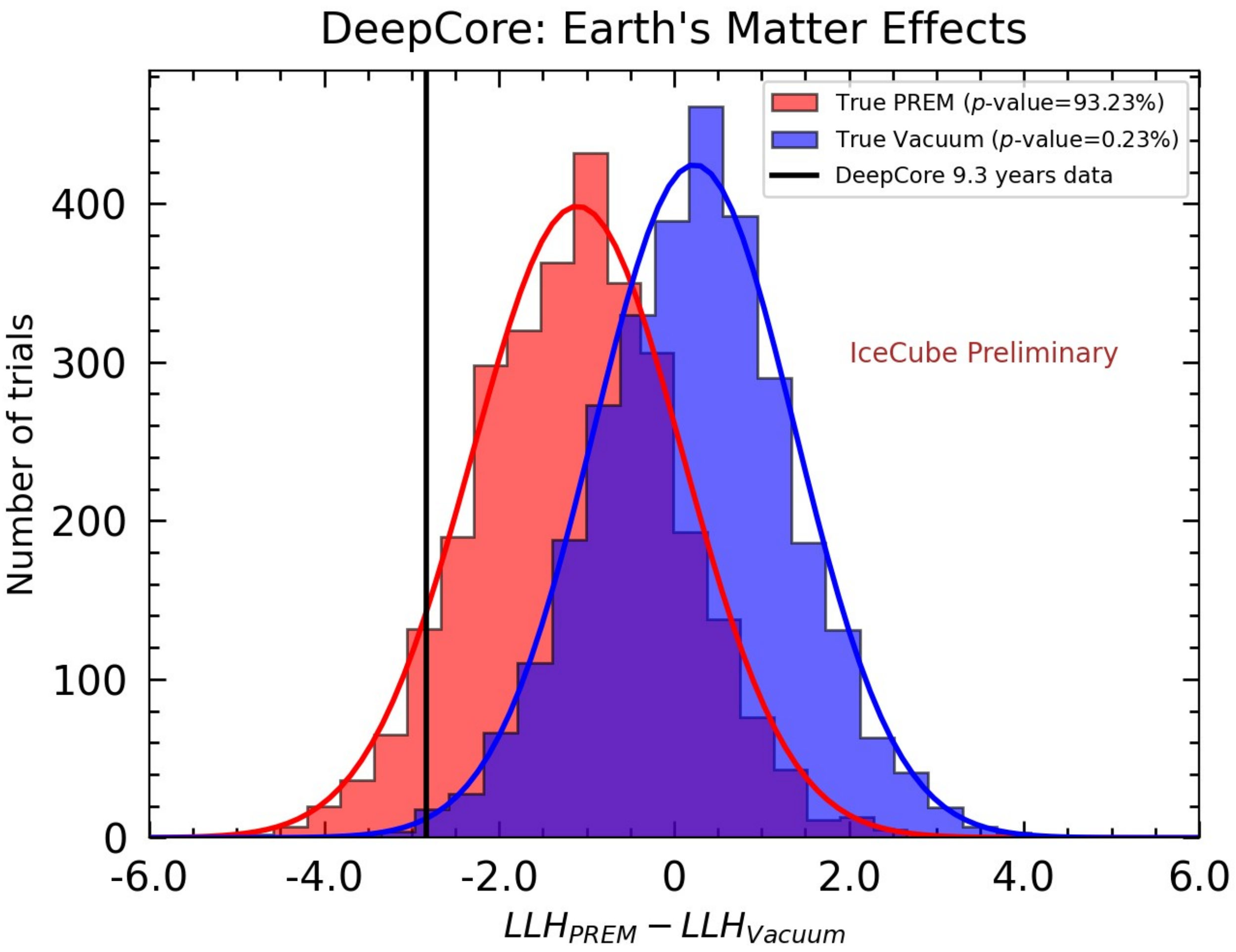
Effect of Uniform Density Profile on Events



Effect of Modified Mass of Earth on Events

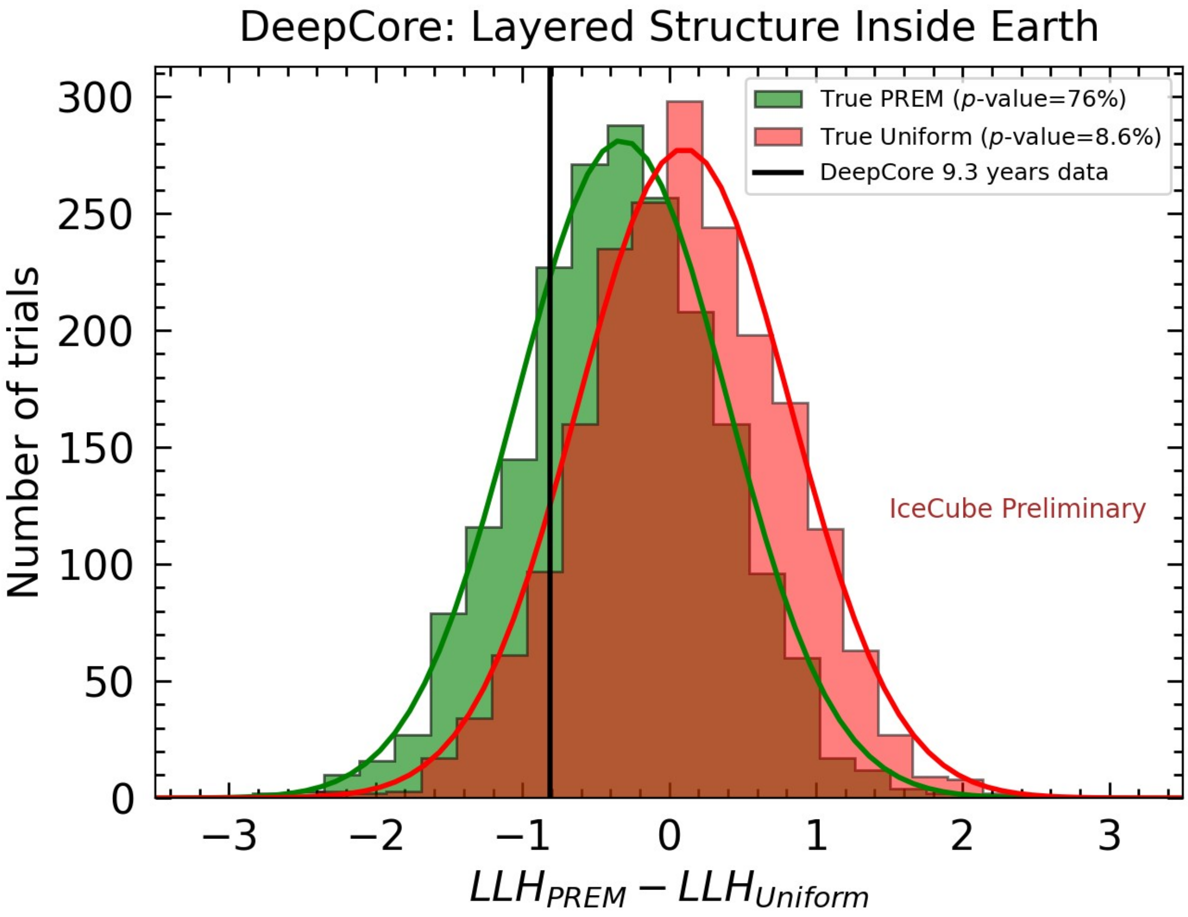


Results: Establishing Earth's Matter Effects



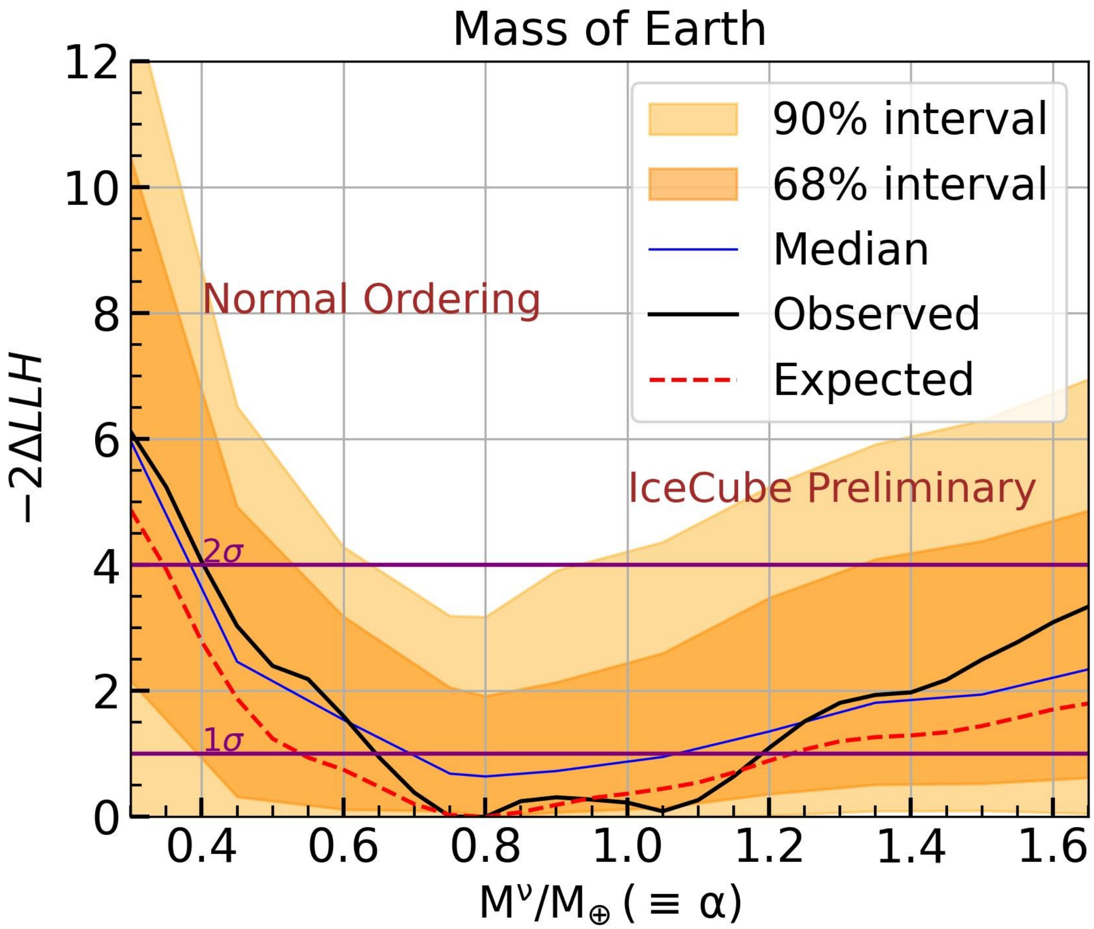
Significance to rule out vacuum hypothesis w.r.t. PREM: 1.82σ

Result: Validating Layered Structure inside Earth



Significance to rule out uniform hypothesis w.r.t. PREM: 0.36σ

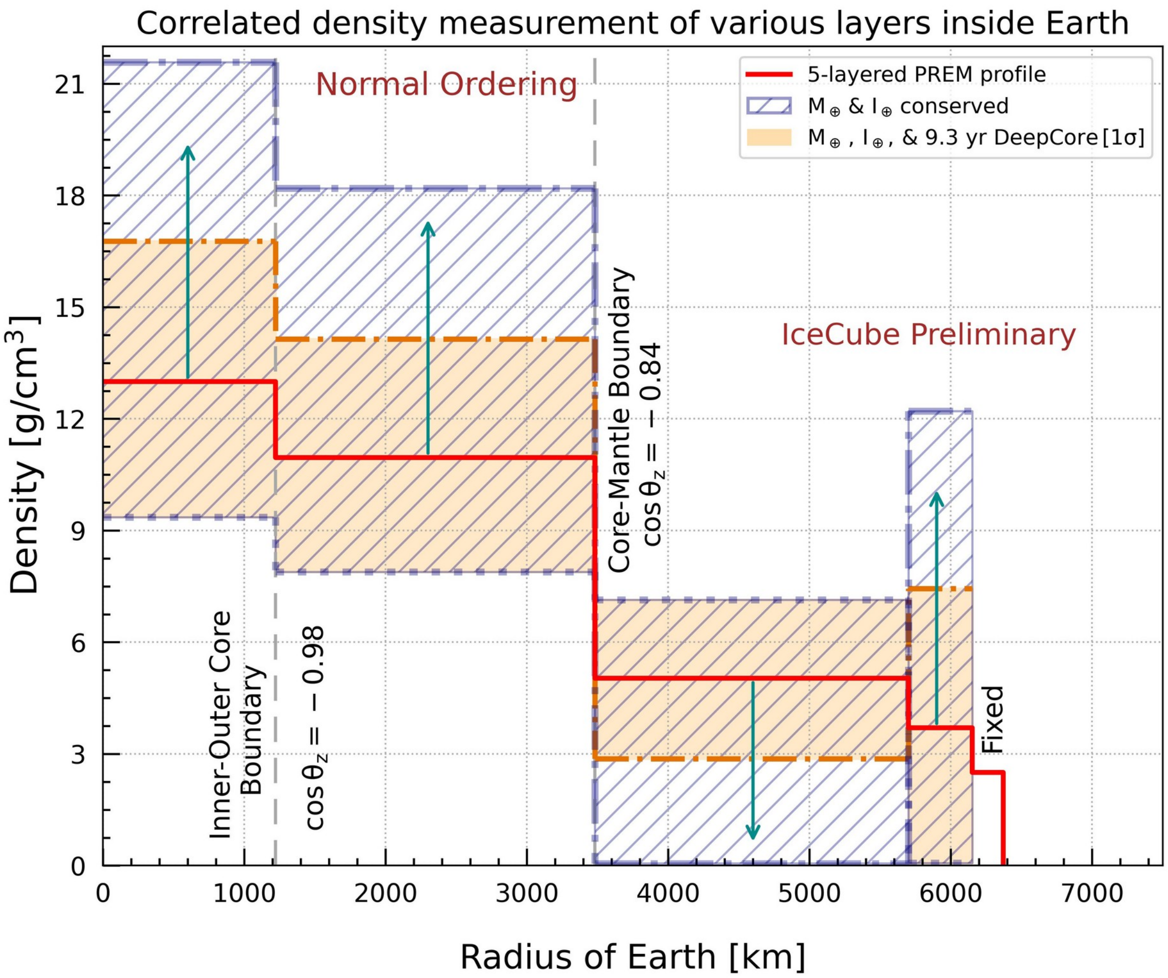
Result: Measurement of Mass of Earth



Mass of Earth:

$$\mathrm{M}_{\nu}/\mathrm{M}_{\oplus} = 0.775^{+0.414}_{-0.129} \pm 0.2$$

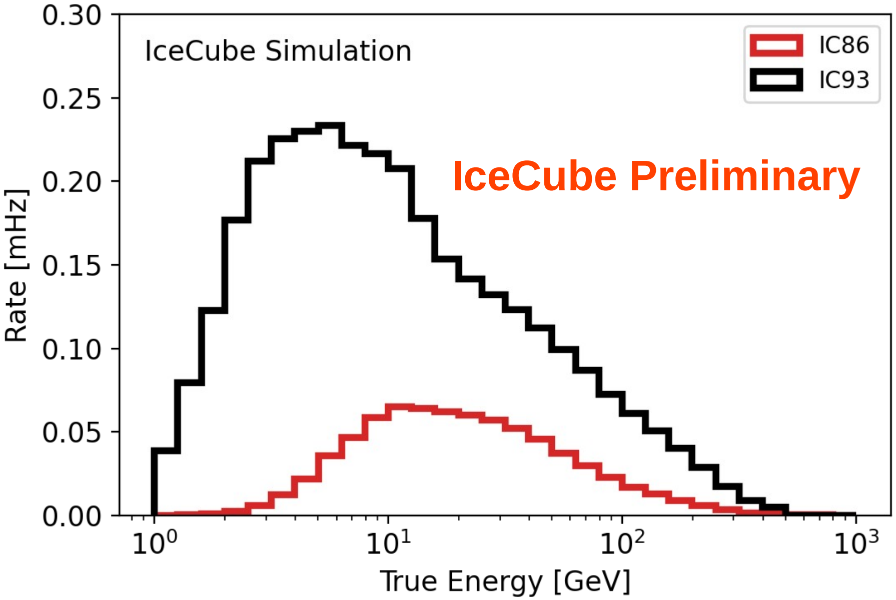
Sensitivity: Measurement of Correlated Densities



IceCube Upgrade

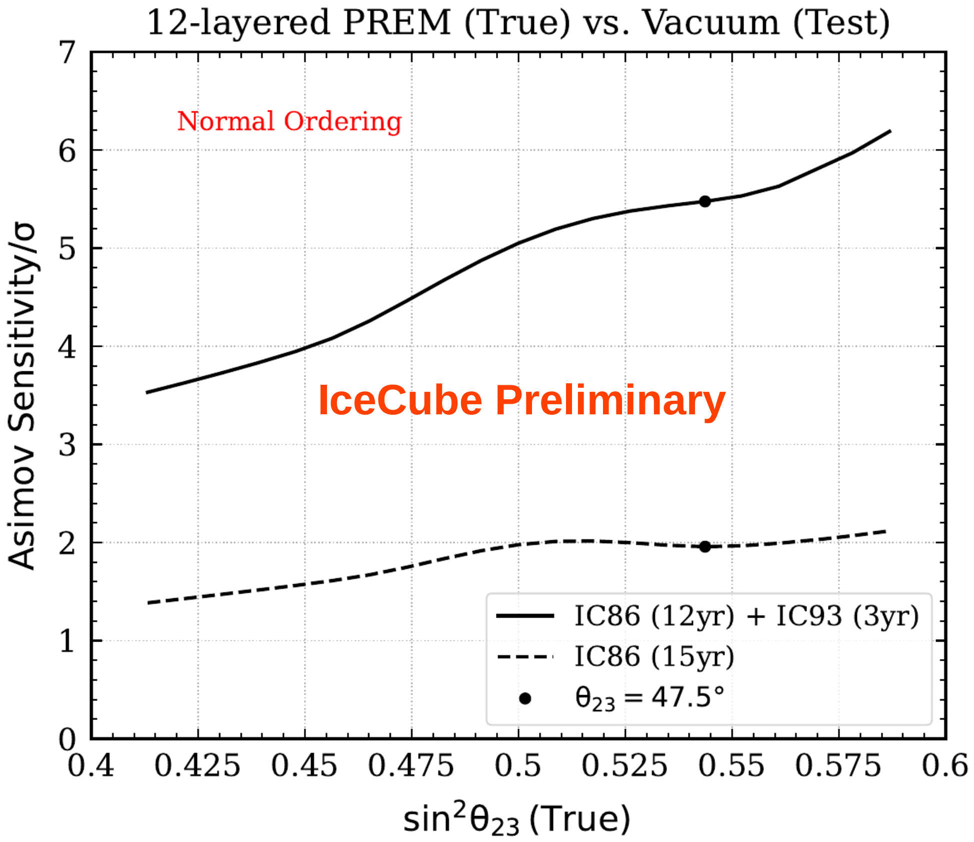
- New modules
  - D-Egg
  - mDOM
- Calibration devices
- R&D modules

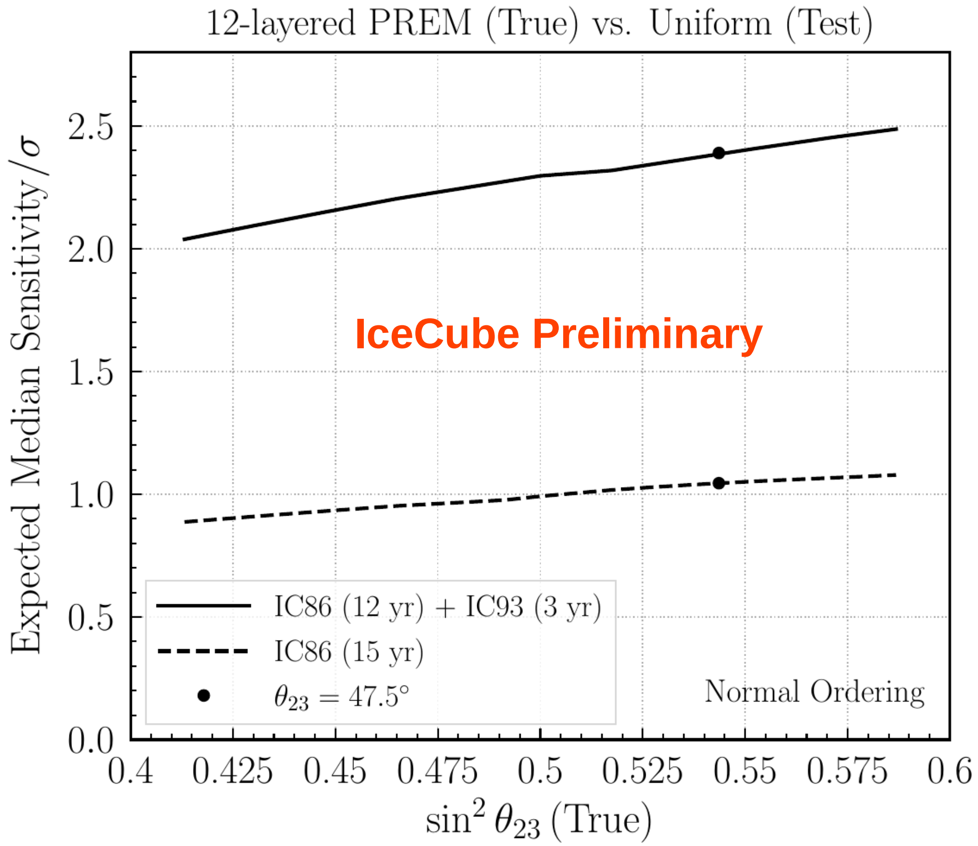
- More strings in central region
- More photons/event
- Lower threshold
- Improved statistics
- Improved reconstruction



ICRC2019 arXiv:1908.09441
ICRC2023 arXiv:2307.15295

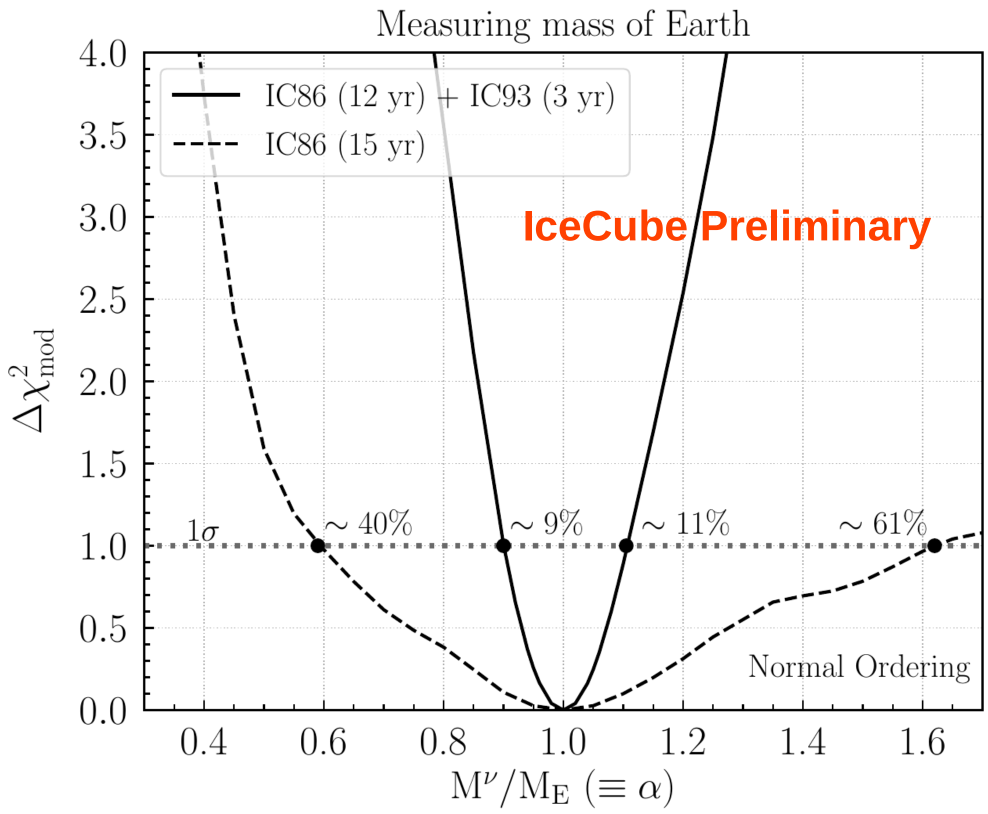
Sensitivity for IceCube Upgrade

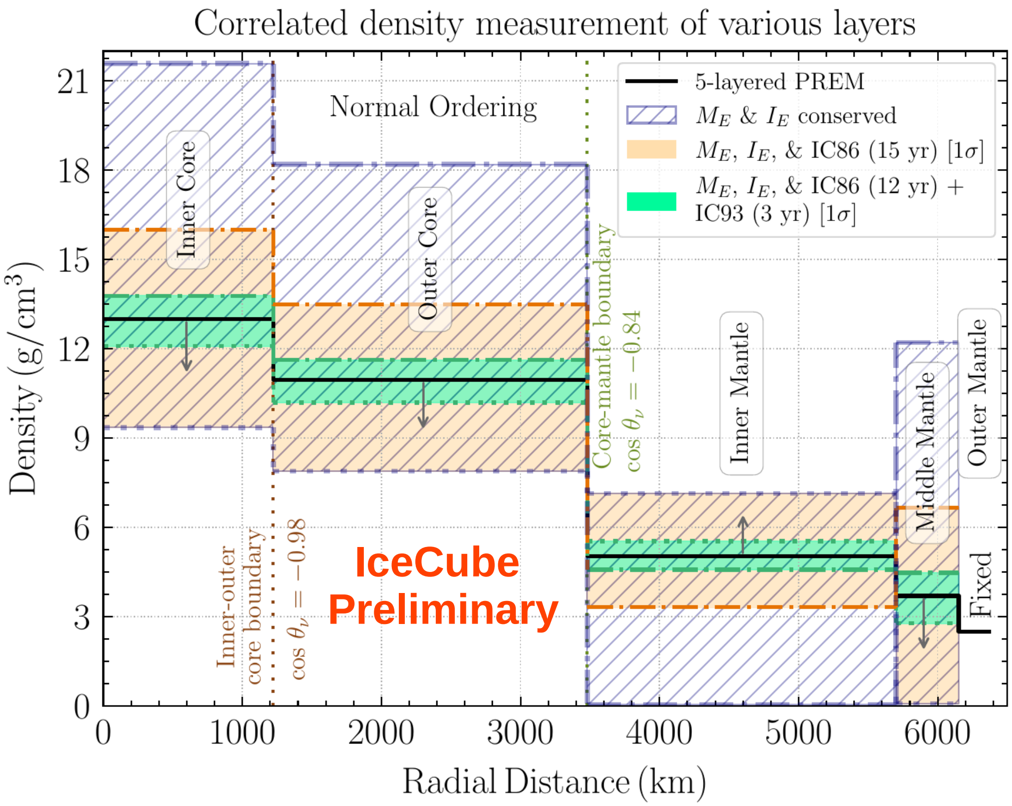




Sensitivity increases significantly with IceCube Upgrade.

Sensitivity for IceCube Upgrade



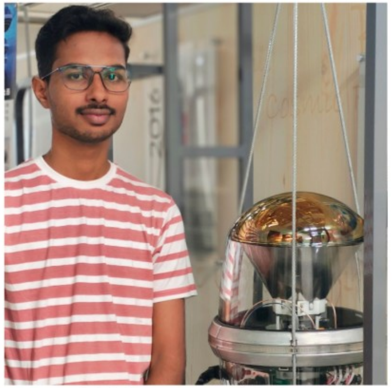


Sensitivity increases significantly with IceCube Upgrade.

The Earth Tomography Team

Sanjib Kumar Agarwalla, IOP

Anil Kumar, Postdoc, DESY
Zeuthen Germany & IOP



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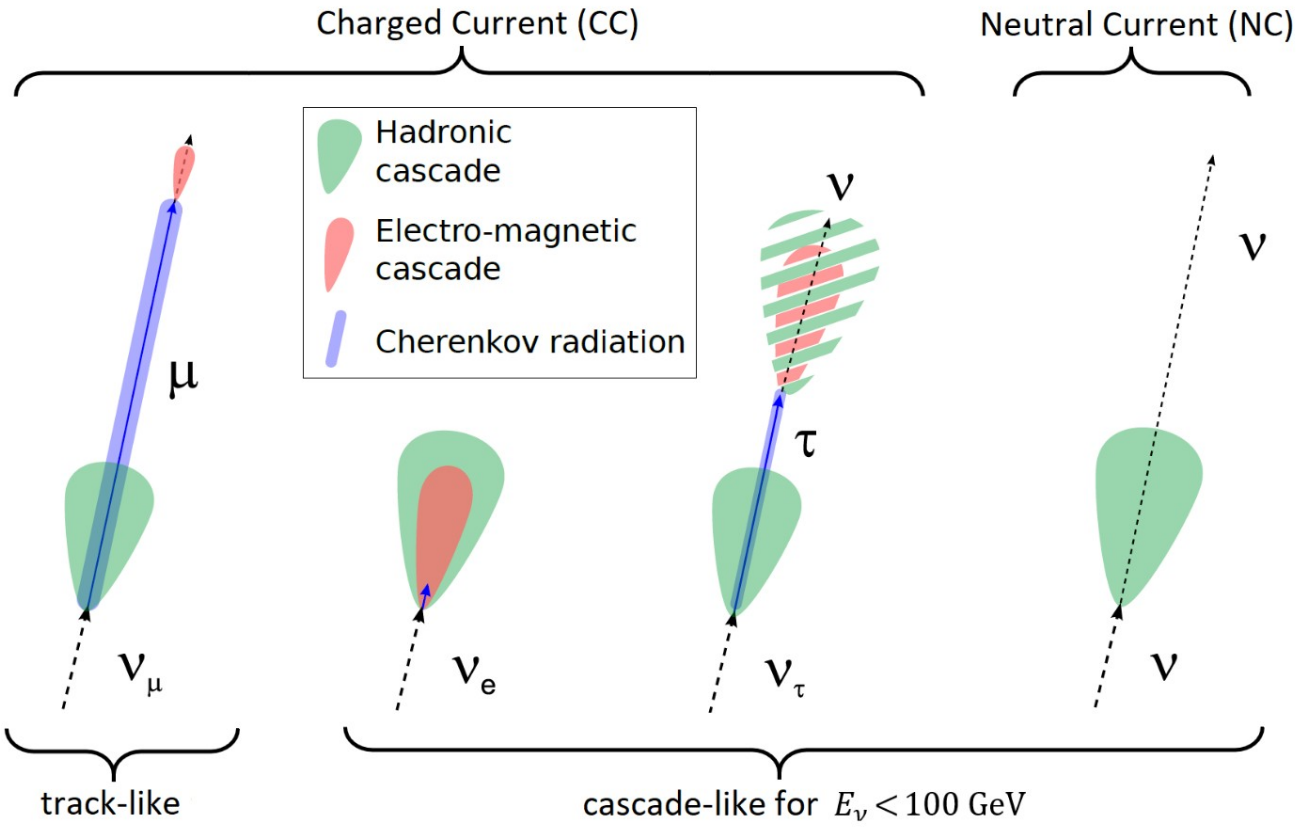
Summary and Conclusion

- Neutrino tomography of the Earth is a fascinating and largely unexplored area of neutrino physics.
- It comprises two methods: neutrino absorption tomography and neutrino oscillation tomography.
- Currently, neutrino oscillation tomography using the atmospheric neutrinos is the most feasible option, given ongoing experiments.
- Our analyses with IceCube DeepCore data show that neutrino oscillations can be used to probe interior of Earth.
- Upcoming atmospheric neutrino experiments like IceCube Upgrade can have much better sensitivity for Earth tomography.
- Multi-messenger tomography of Earth is an interdisciplinary field involving collaboration between geophysicists, geochemists, and particle physicists.

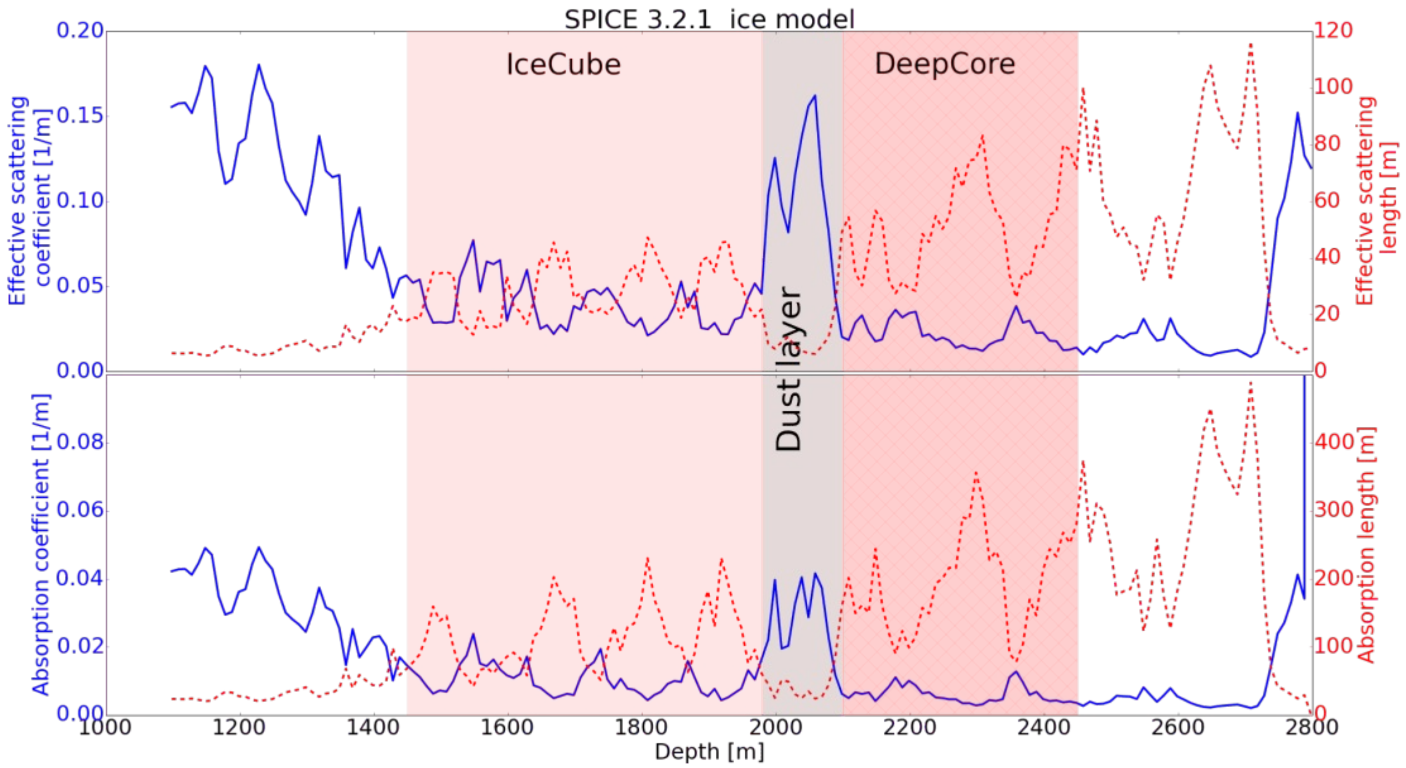
Thank You

Backup

Events at IceCube



Ice Properties



Benchmark Values of Oscillation Parameters

θ_{12}	θ_{13}	θ_{23}	Δm^2_{21}	Δm^2_{31}	δ_{CP}
33.44°	8.54°	47.5047°	$7.41 \times 10^{-5} eV^2$	$2.47467 \times 10^{-3} eV^2$	0°

NuFIT 5.2 (2022)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

Correlated Density Measurements

Incorporating mass and moment of inertia of Earth

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

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

- Y_e (Inner Core) = 0.4656
- Y_e (Outer Core) = 0.4656
- Y_e (Mantle) = 0.4957

Systematics

Flux uncertainties

Cosmic ray spectrum

Pion & Kaon production uncertainties Barr et al., Phys. Rev. D 74, 094009

Cross section

Axial mass uncertainty for resonance and quasielastic events

GENIE - CSMS transition for DIS JHEP 08, 042 (2011)

Detector and Ice properties

Optical efficiency of the photo sensor

Ice scattering and absorption

Birefringence (double refraction of light due to anisotropy of ice)

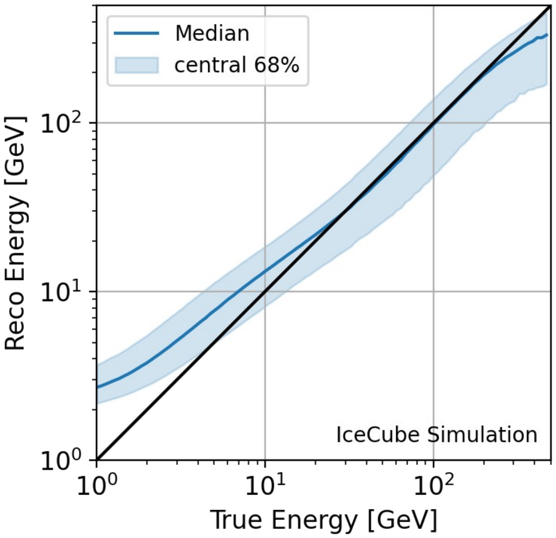
Muon Light Yield (photon propagation in the ice from muons)

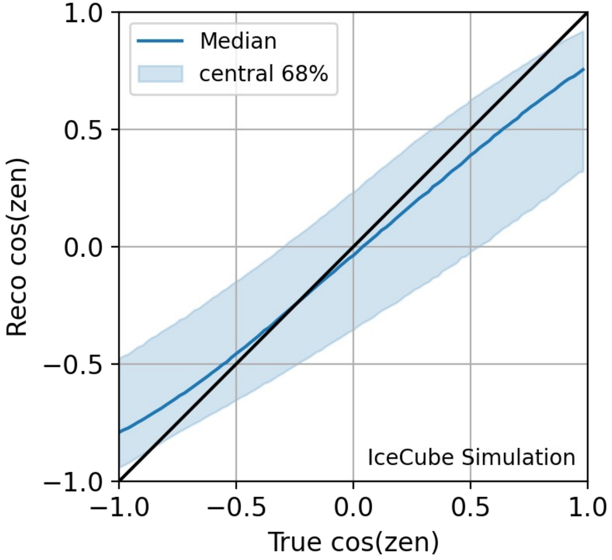
Atmospheric muon scale Gaisser et al.+ Sibyll2.1

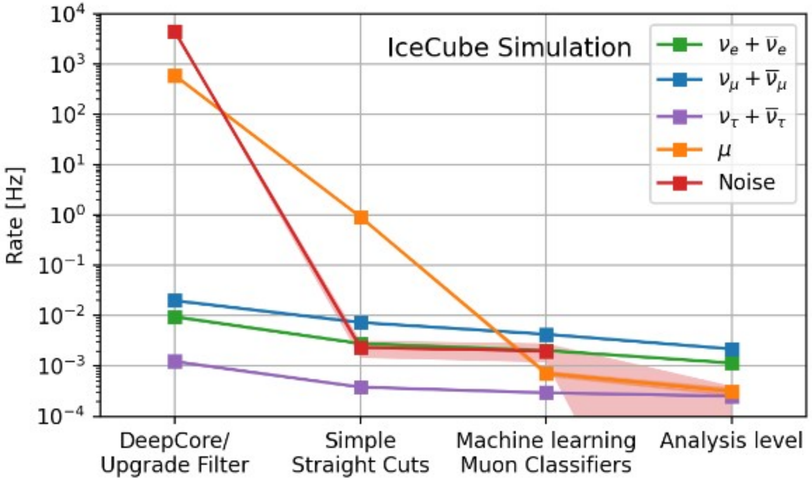
Normalization of neutrino event counts

PRD 108 (2023) 1, 012014

Reconstruction and Event Selection for Upgrade







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

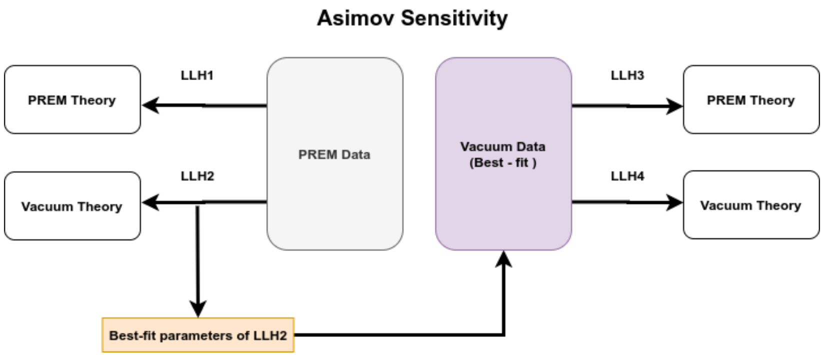
Statistical Methods

- **Following Poissonian LLH**

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

x_i - Observed value of i^{th} bin
λ_i - Expected value of i^{th} bin
p_j, $\hat{p}_j$, and σ_j^2 are the nominal, best-fit, and Gaussian prior of j^{th} systematics, respectively

- **Asimov Sensitivity to reject vacuum hypothesis**



(For the assumption of true PREM)

$$\eta_\sigma = \frac{(LLH_3 - LLH_4) - (LLH_1 - LLH_2)}{\sqrt{(2 \times (LLH_3 - LLH_4)}}$$

$$\Delta LLH = \quad N(\pm\overline{\Delta LLH}, 2\sqrt{\overline{\Delta LLH}})$$

See: Mattias Blennow et al., (JHEP 03 (2014) 028) , X Qian et al., (PRD 86 113011 (2012)), and Emilio Ciuffoli et al., (JHEP 01 (2014) 095)

Upgrade 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]