

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

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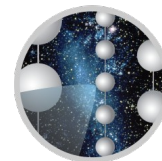
DENSITY 2026

IISER Pune

Collaborators:

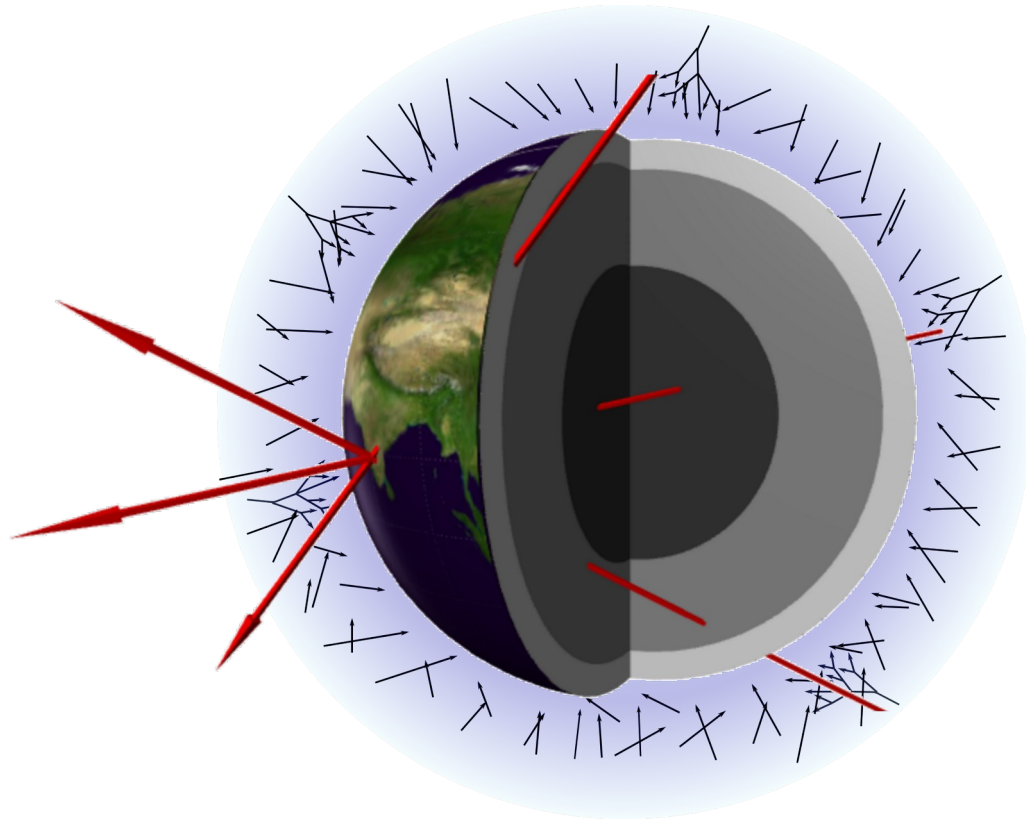
- Sanjib Kumar Agarwalla
- Anuj Kumar Upadhyay
- Krishnamoorthi J
- Sharmistha Chattopadhyay

The analyses presented here are performed
for the IceCube Collaboration.

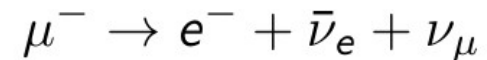
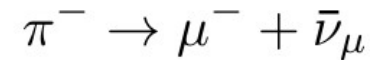
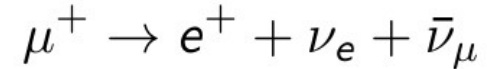
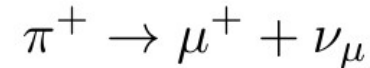
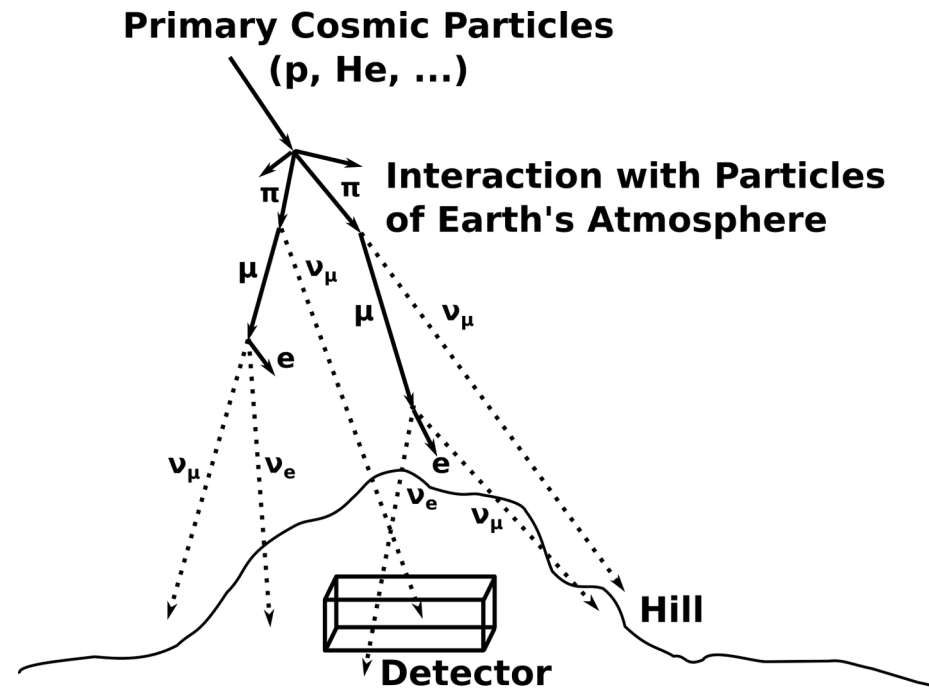


ICECUBE
NEUTRINO OBSERVATORY

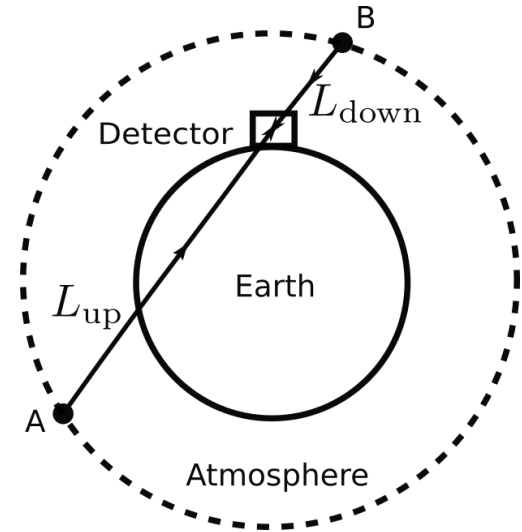
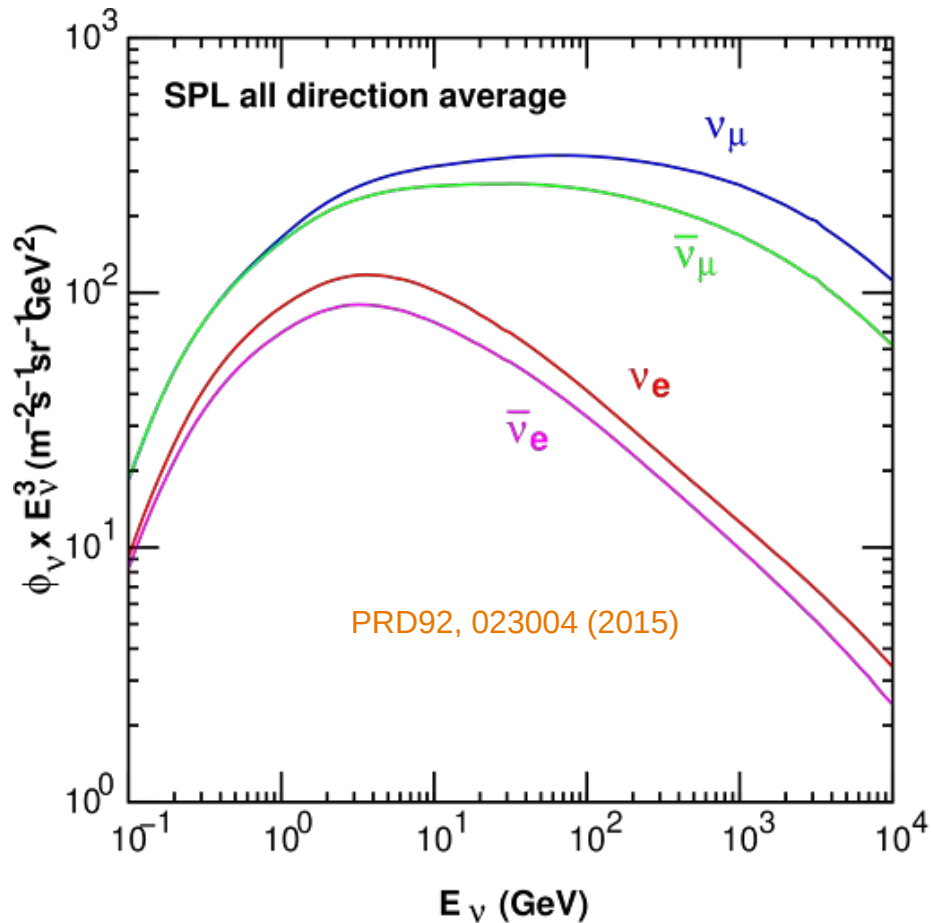
Atmospheric Neutrinos



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

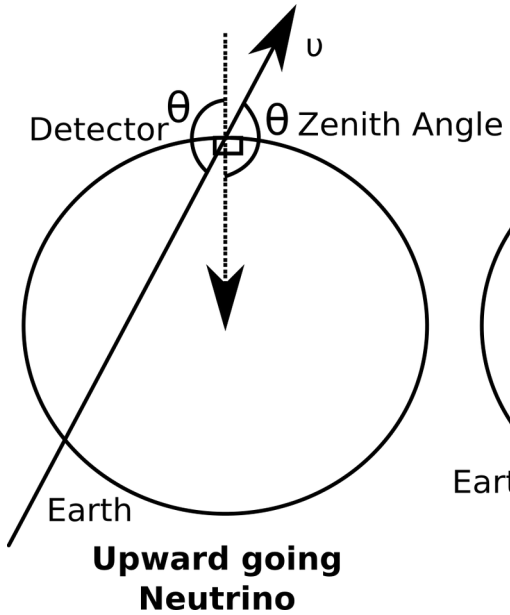


Atmospheric Neutrinos

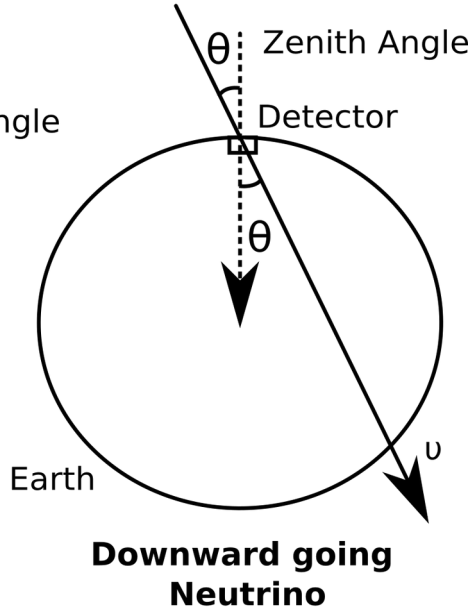


- In the GeV range, initial atmospheric neutrino flux is almost isotropic (up-down symmetric)
- Steeply falling power-law spectra ($\sim E^{-2.7}$) in the GeV range

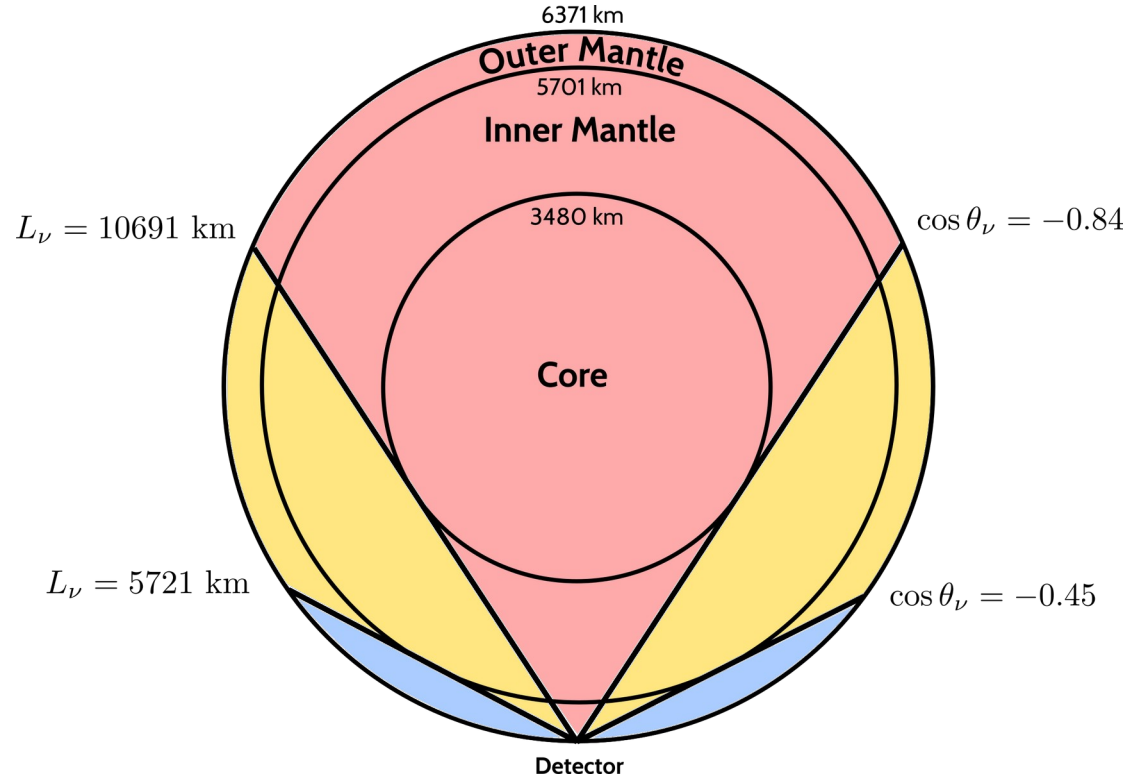
Atmospheric Neutrinos Passing through Earth



$$-1 < \cos \theta < 0$$

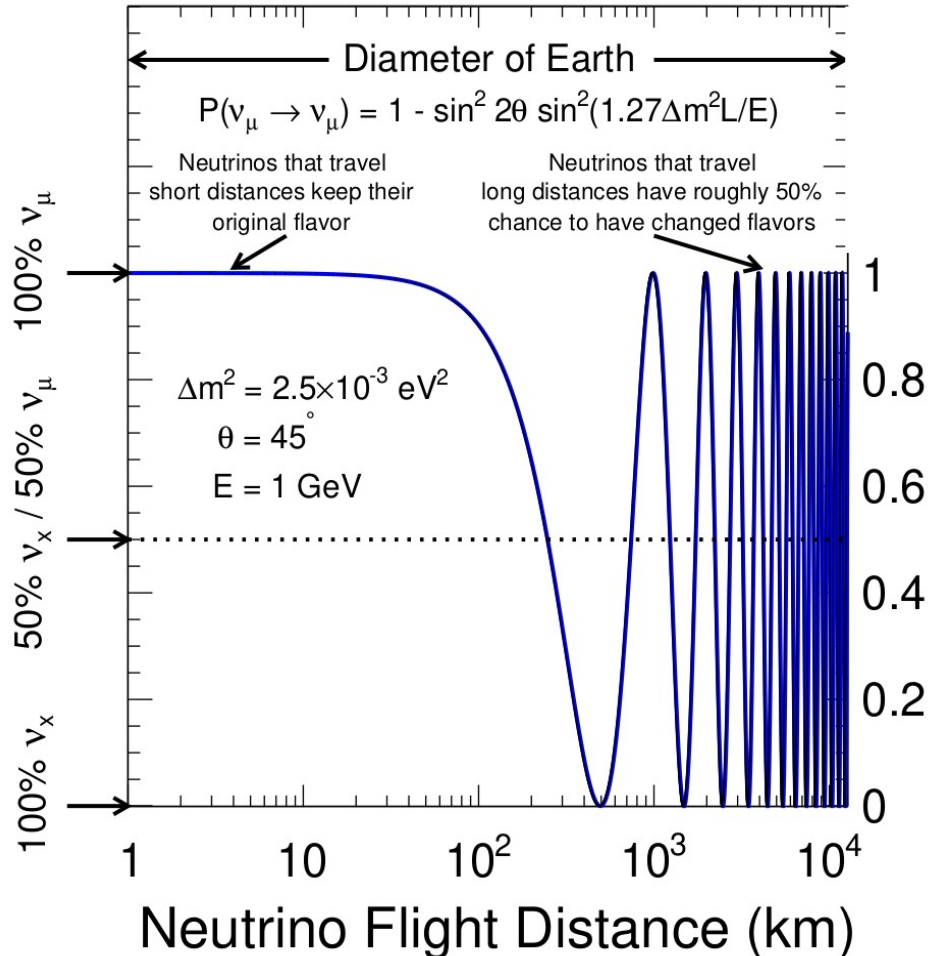


$$0 < \cos \theta < 1$$



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

Atmospheric Neutrino Oscillations



Atmospheric neutrino oscillation experiments:

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

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

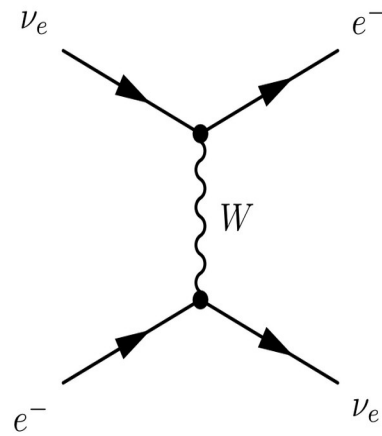
Matter density in each layer inside Earth

$$V_{CC} = \pm \sqrt{2} G_F N_e$$

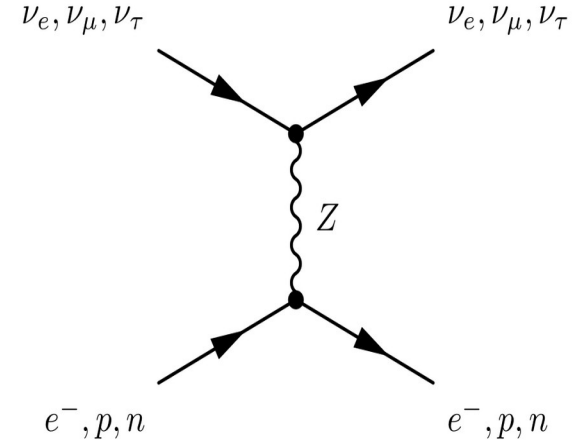
$$\approx \pm 7.6 \times Y_e \times 10^{-14} \left[\frac{\rho}{\text{g/cm}^3} \right] \text{ eV}$$

+ve : neutrinos
-ve: antineutrinos

CC interaction



NC interaction



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

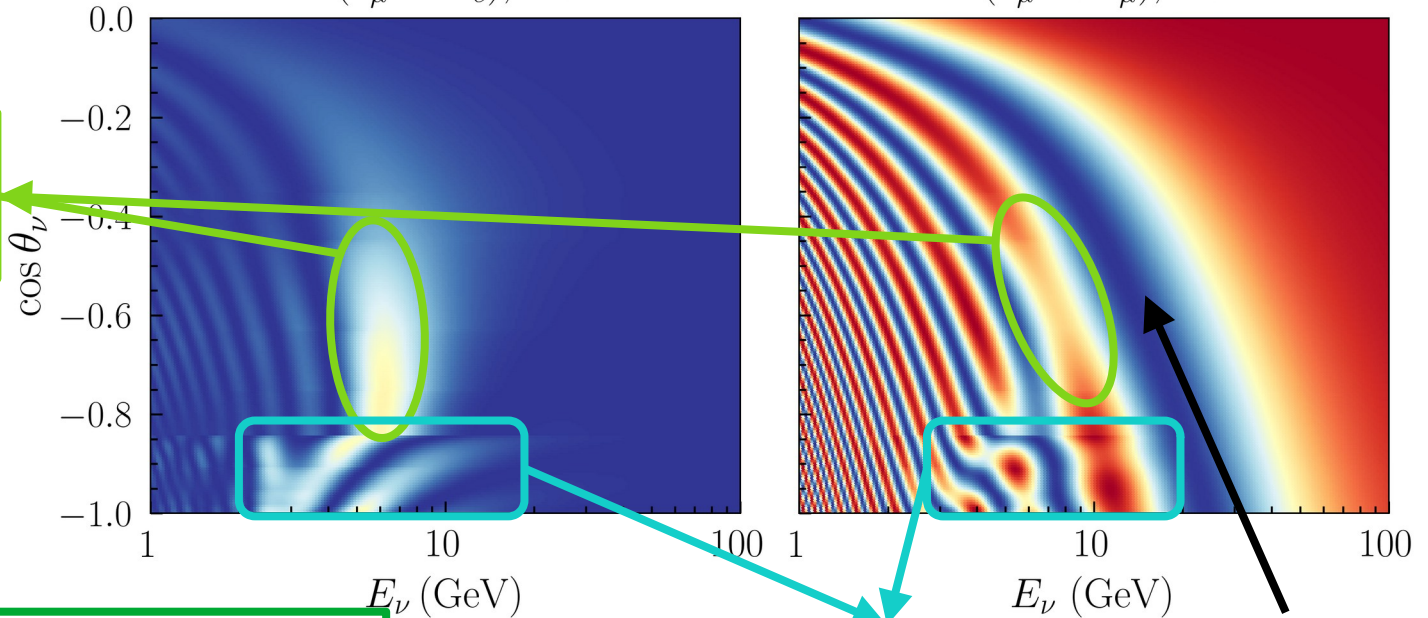
Chemical composition of a layer inside Earth

Relative electron number density

Matter Resonances in Probability Oscillograms

$P(\nu_\mu \rightarrow \nu_e), \text{NO}$

$P(\nu_\mu \rightarrow \nu_\mu), \text{NO}$



Mikheyev-Smirnov-Wolfenstein (MSW) Resonance

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

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

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

Neutrino Oscillation Length Resonance (NOLR) / Parametric resonance (PR)

Vacuum oscillation valley

Petcov, PLB 434 (1998) 321,
Akhmedov, NPB 538 (1999) 25

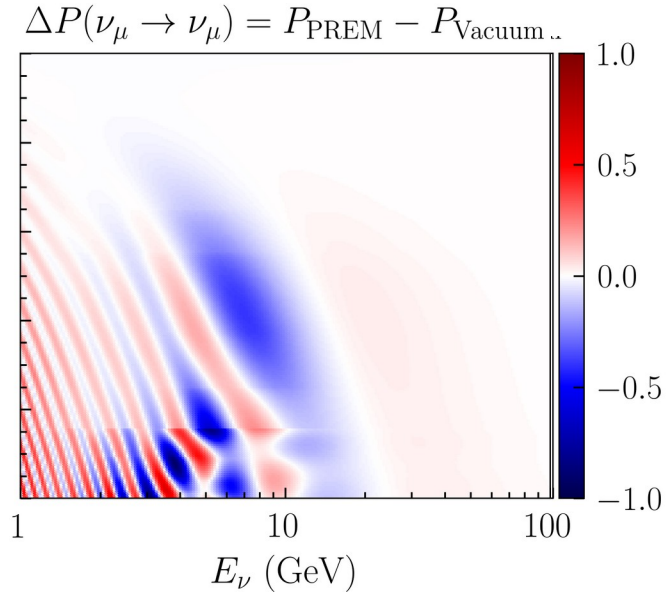
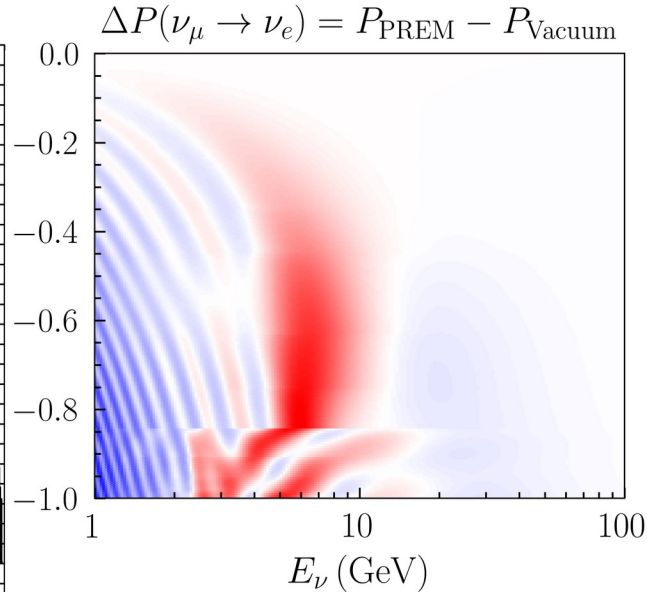
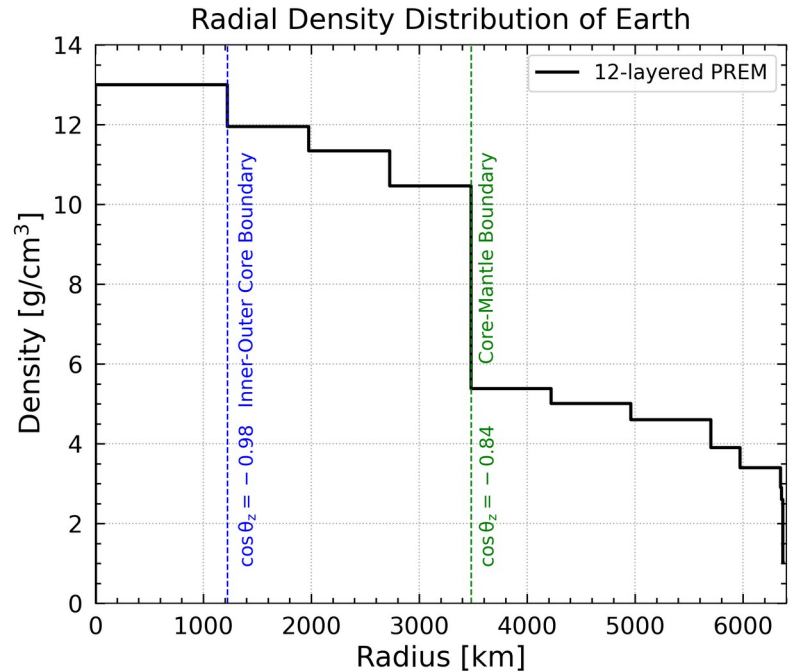
Analyses with IceCube DeepCore

- 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,

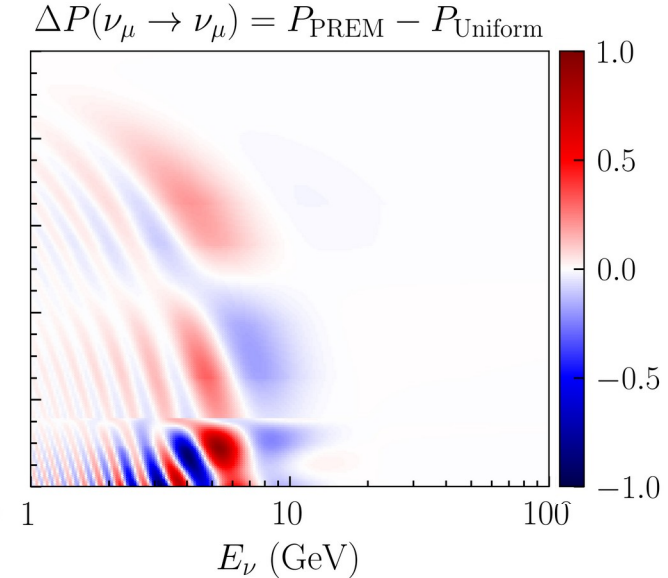
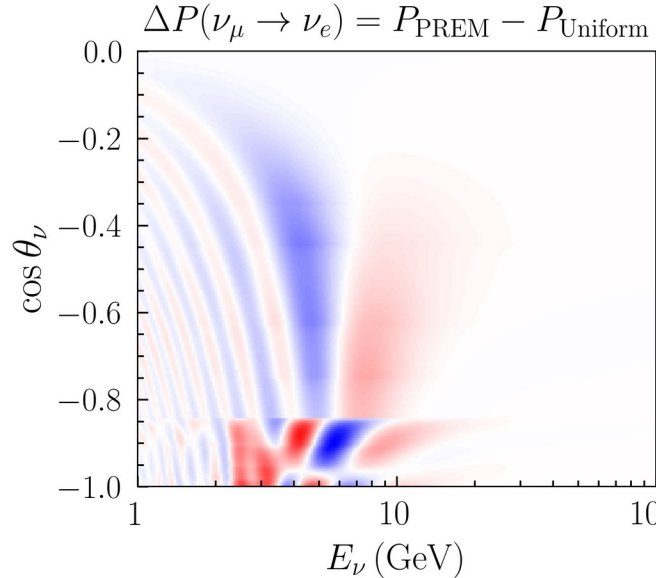
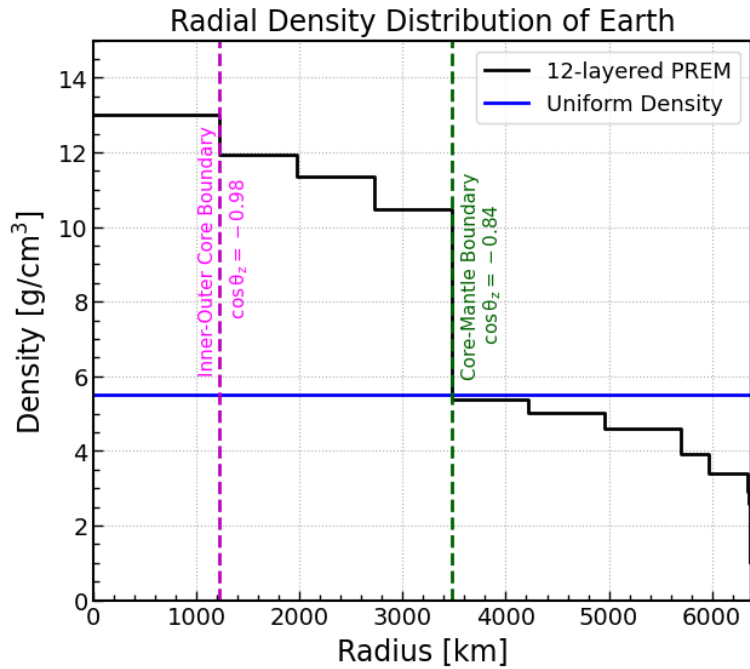
Springer Proc.Phys. 322 (2026) 447-450,
Springer Proc.Phys. 322 (2026) 417-421

Establishing Earth's Matter Effects



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

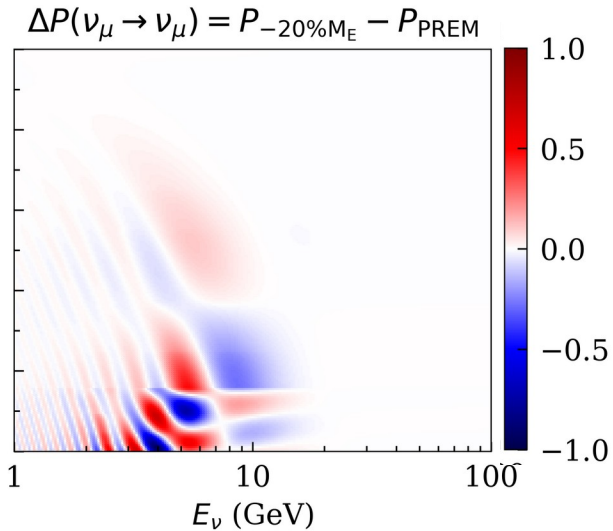
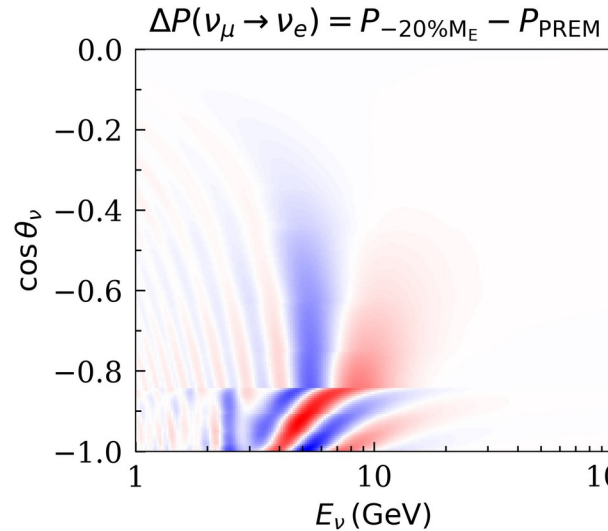
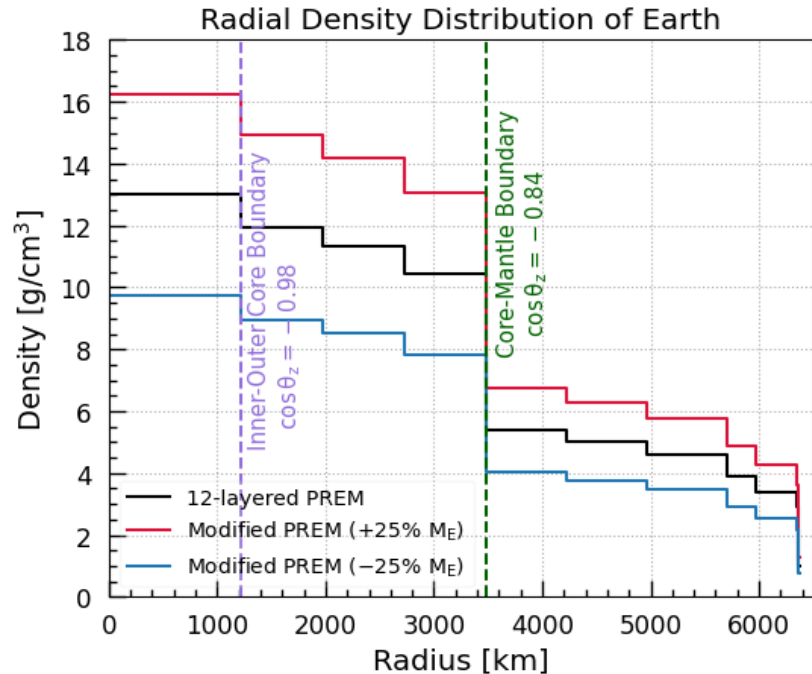
Validating Layered Structure inside Earth



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

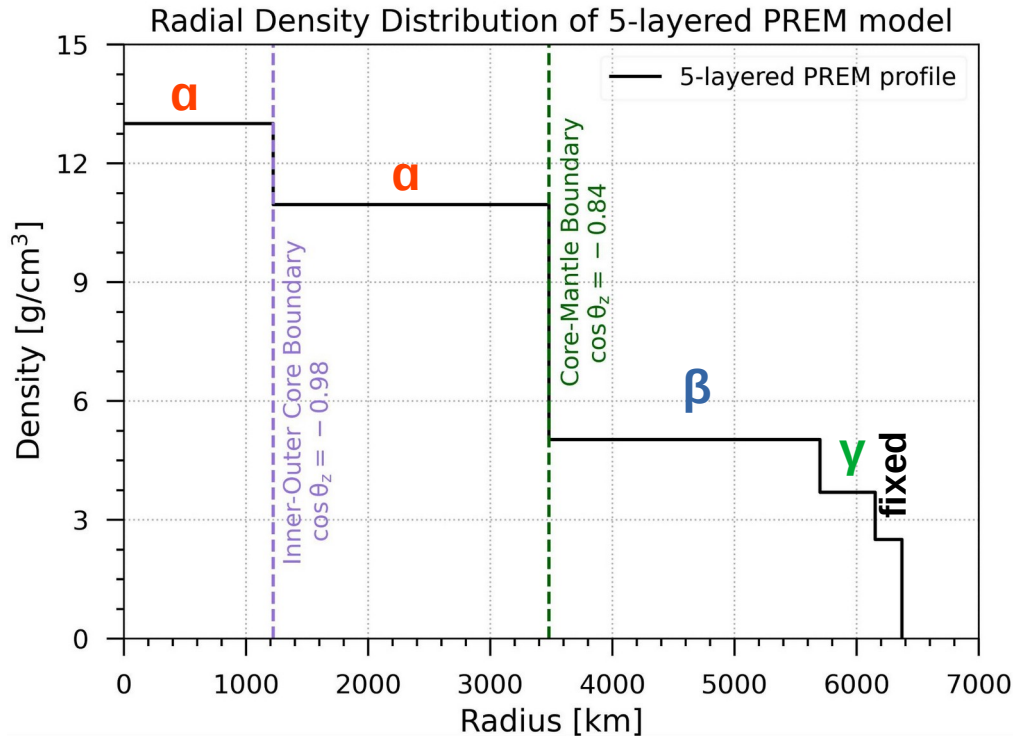
Measurement of the Mass of Earth

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:

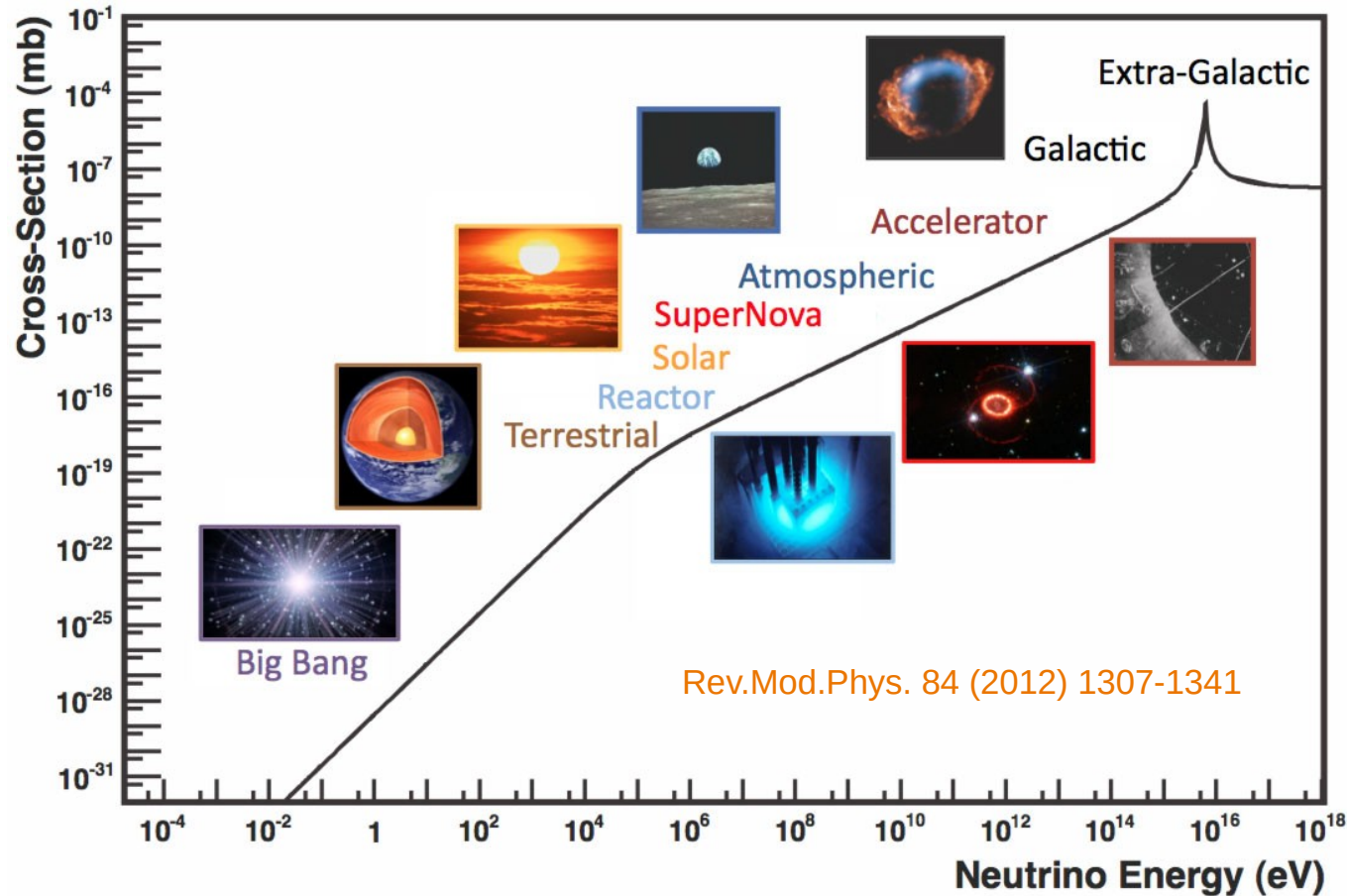
- Mass of Earth
- Moment of Inertia of Earth
- Hydrostatic equilibrium condition

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.

Neutrino Interaction Cross Section



- Neutrinos interact only via weak interactions
- Extremely small interaction cross section
- Very difficult to detect
- Observe secondary particles produced during neutrino interactions

To compensate small cross section, huge detectors are needed and data is taken for long time!

Charged-Current Interactions of Neutrinos

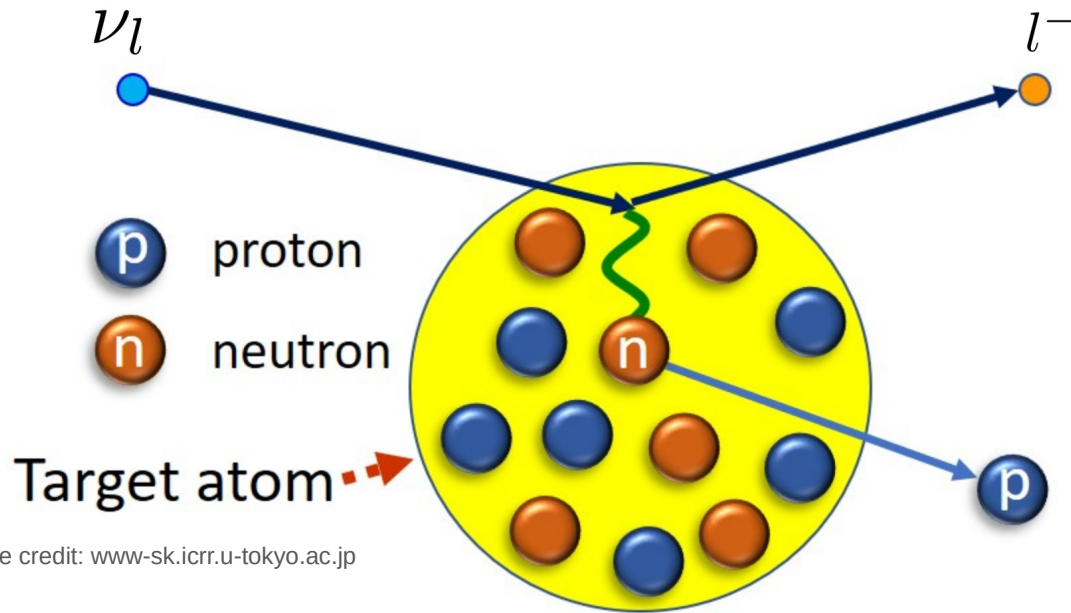
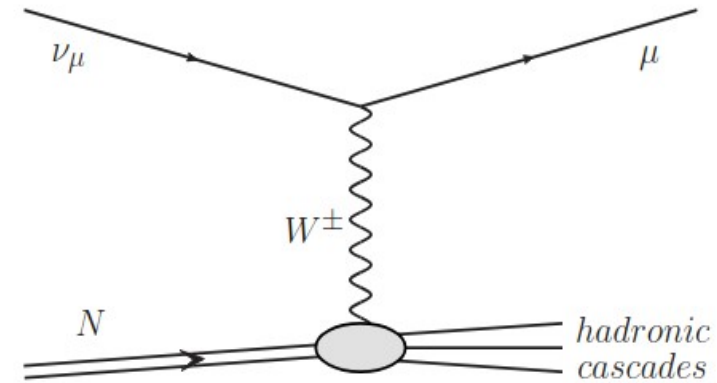
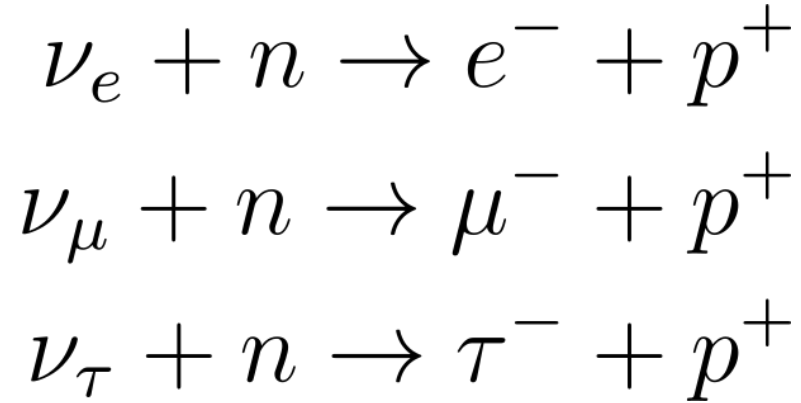
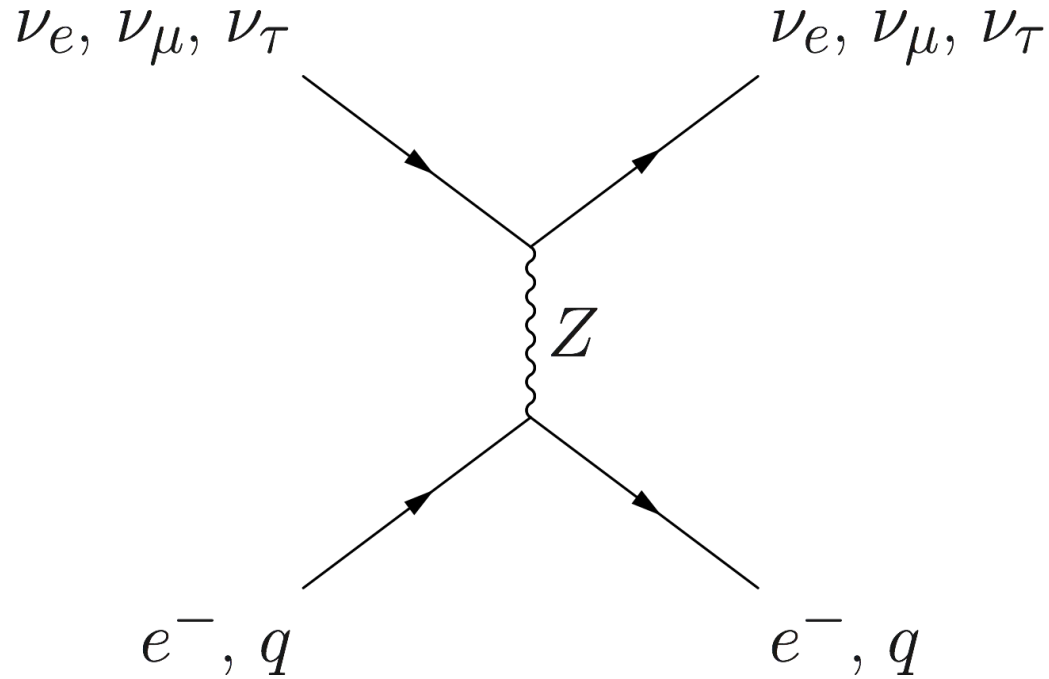


Image credit: www-sk.icrr.u-tokyo.ac.jp

During a charged-current (CC) interaction, a neutrino produces a charged lepton of the same flavor.



Neutral-Current Interactions of Neutrinos



During a neutral-current (NC) interaction, a neutrino scatters off by transferring energy to the target particle.

Energy Deposit Patterns for Charged Particles

Muons



Long tracks

Electrons



Electromagnetic cascade

Tau lepton

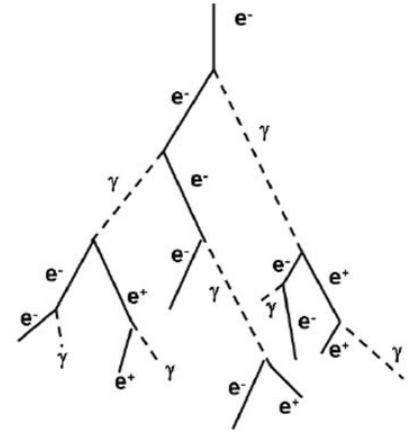


Long tracks or
electromagnetic cascade

Hadrons

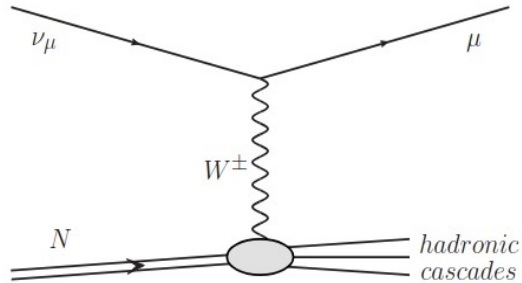


Hadronic cascade

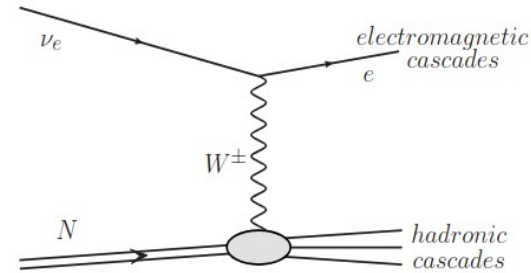


Event Topologies in Neutrino Interactions

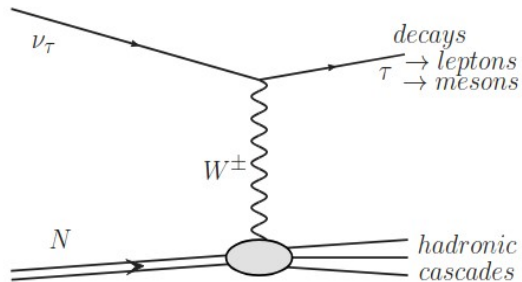
● **CC: $\nu_\mu + N \rightarrow \mu + \text{hadrons}$ (tracks)**



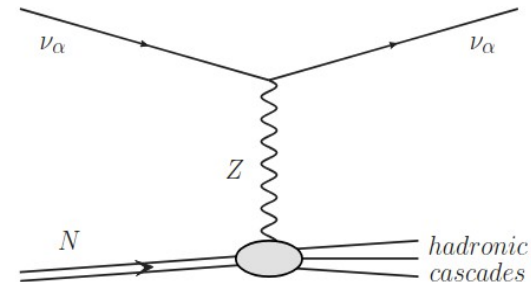
● **CC: $\nu_e + N \rightarrow e + \text{hadrons}$ (cascades)**



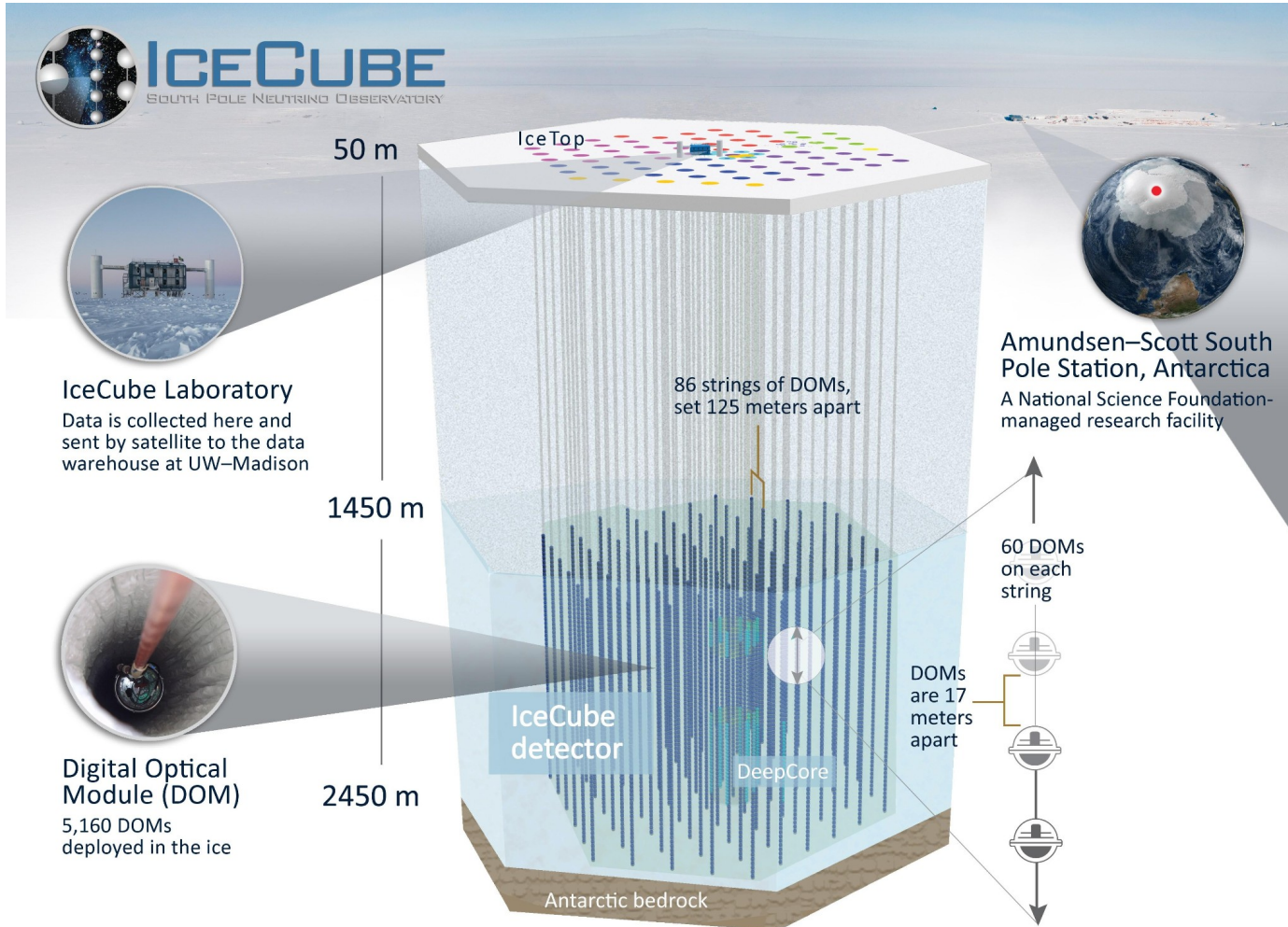
● **CC: $\nu_\tau + N \rightarrow \tau + \text{hadrons}$ (double cascades)**



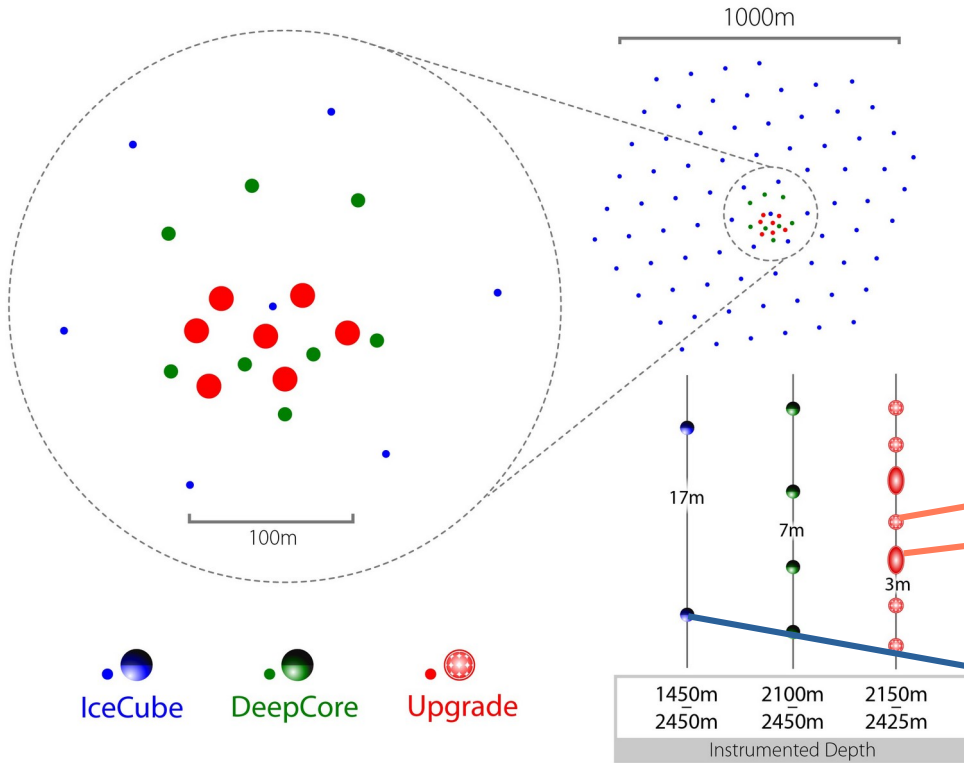
● **NC: $\nu_\alpha + N \rightarrow \nu_\alpha + \text{hadrons}$ (cascades)**



IceCube Neutrino Observatory



IceCube DeepCore



mDOM

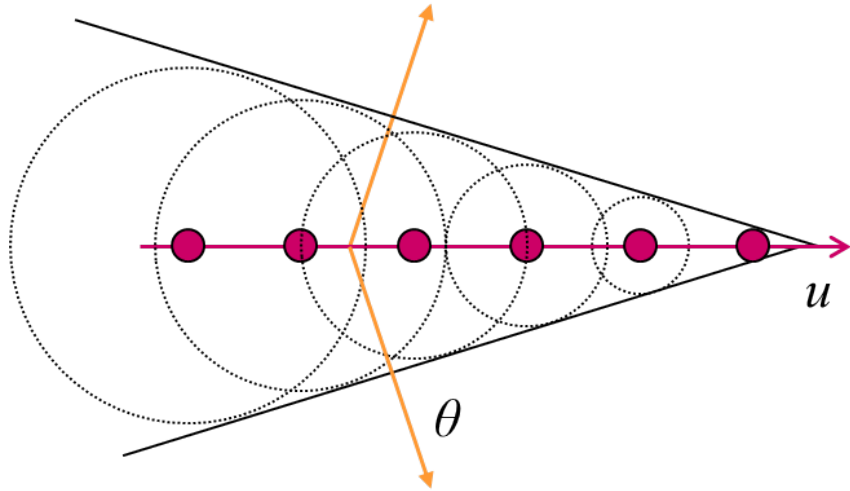
D-Egg



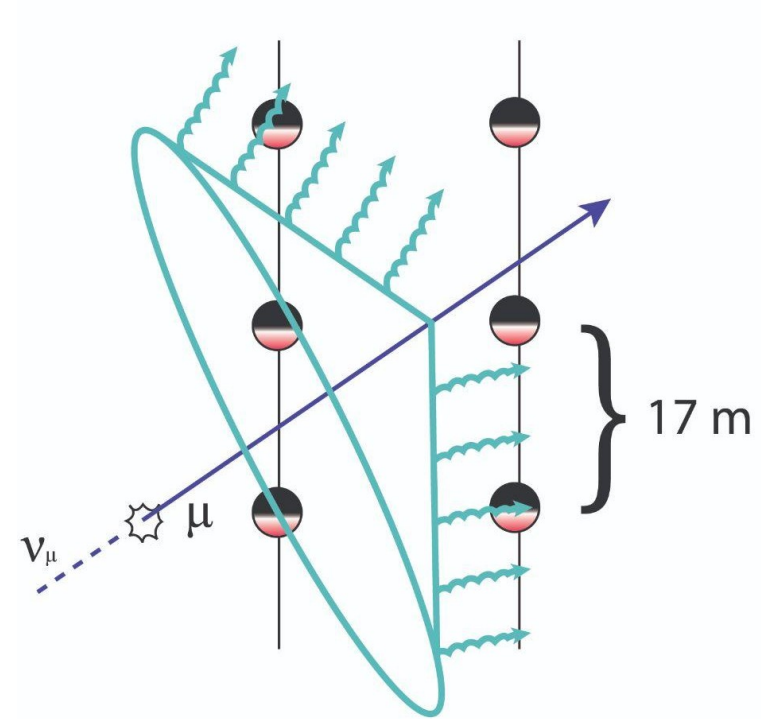
DOM

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

Neutrino Detection at IceCube



When a charged particle travels faster than light in a medium, it emits a light known as Cherenkov light.



DOMs at IceCube detect Cherenkov photons produced during neutrino interactions in Ice.

Events at IceCube DeepCore

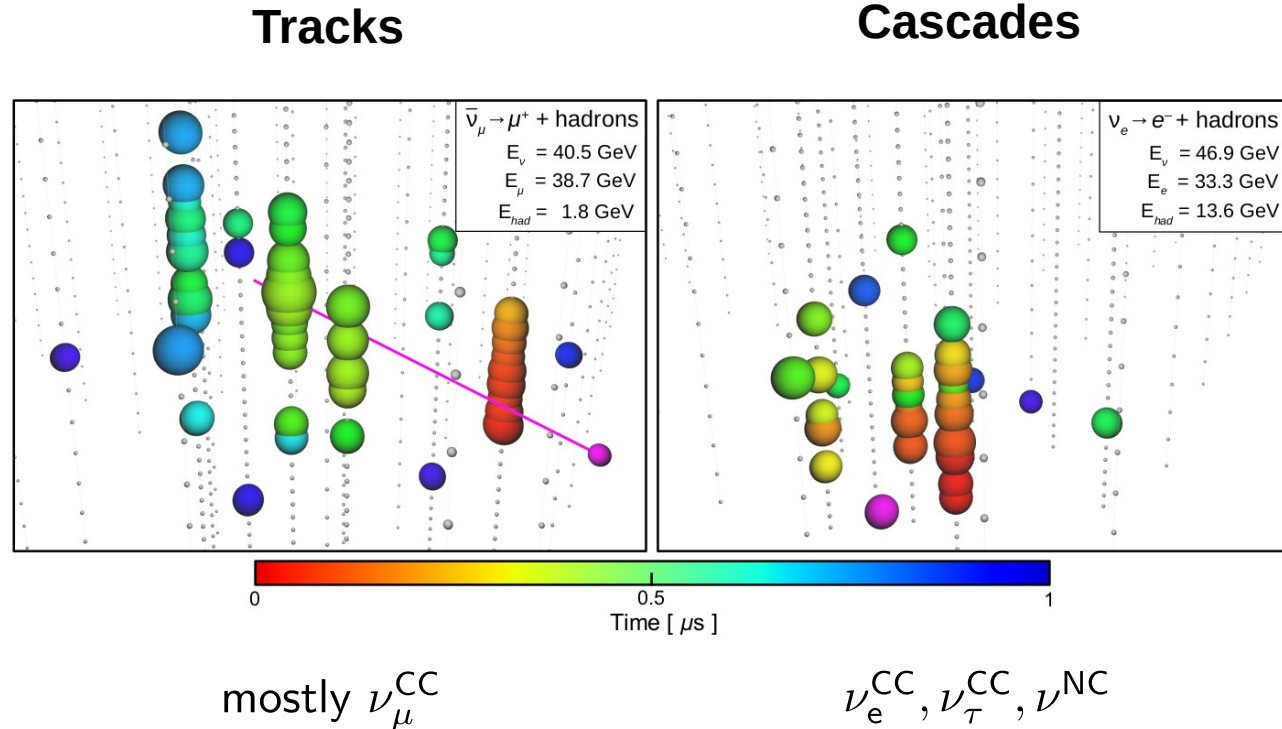
Red = Early Hits
Blue = Late Hits

Signals:

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

Backgrounds:

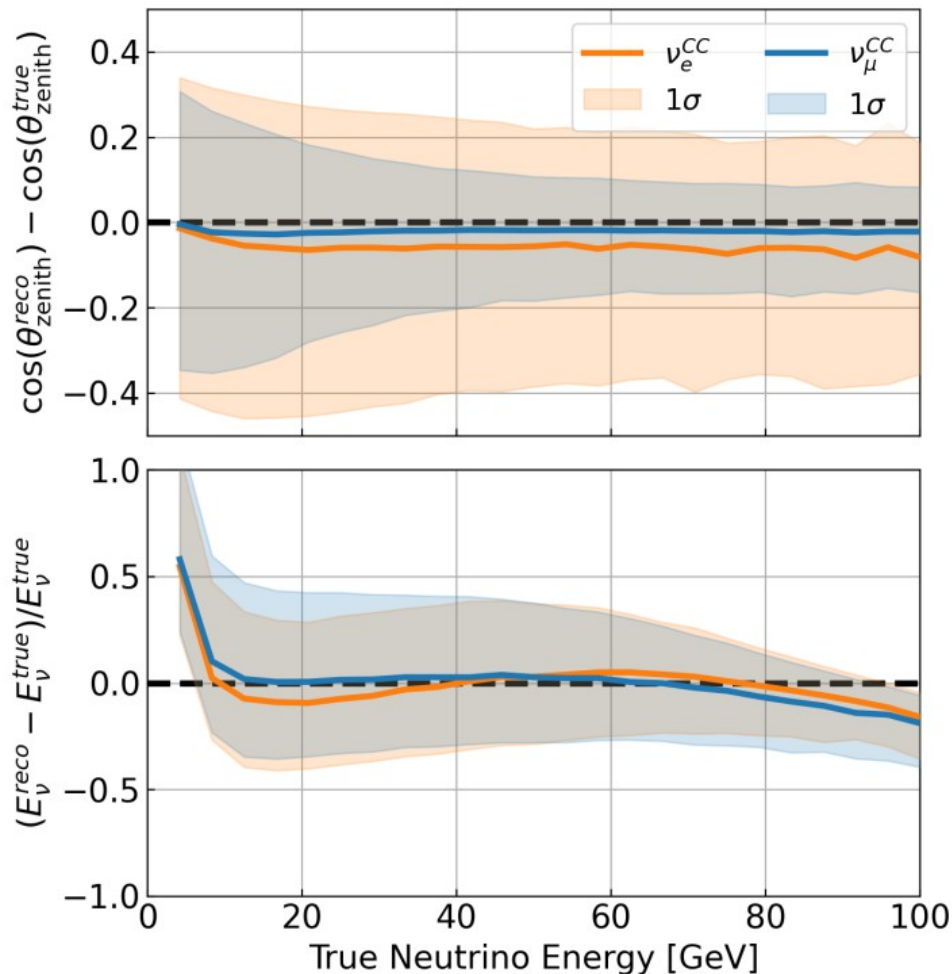
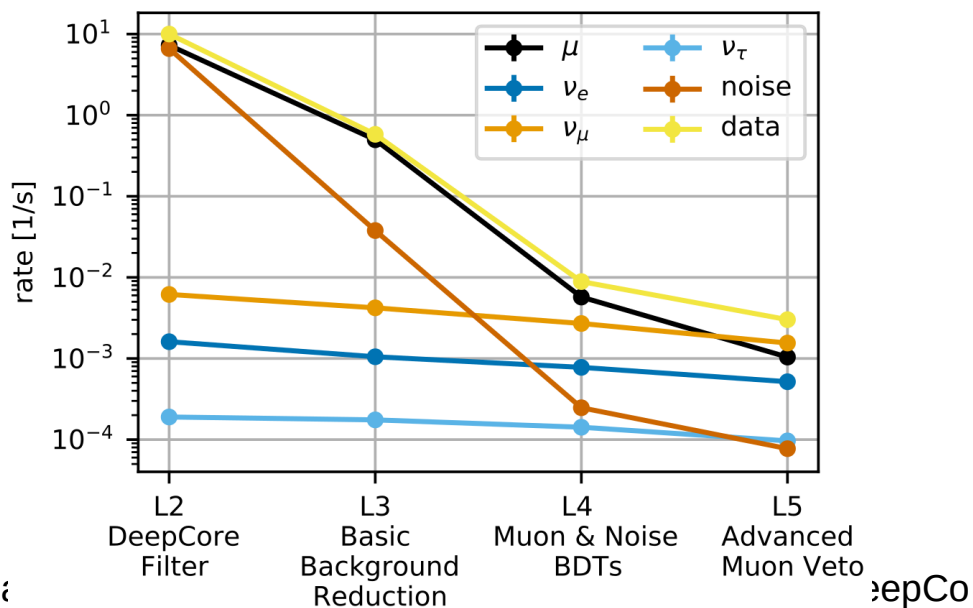
- Atmospheric muons
- Random detector noise



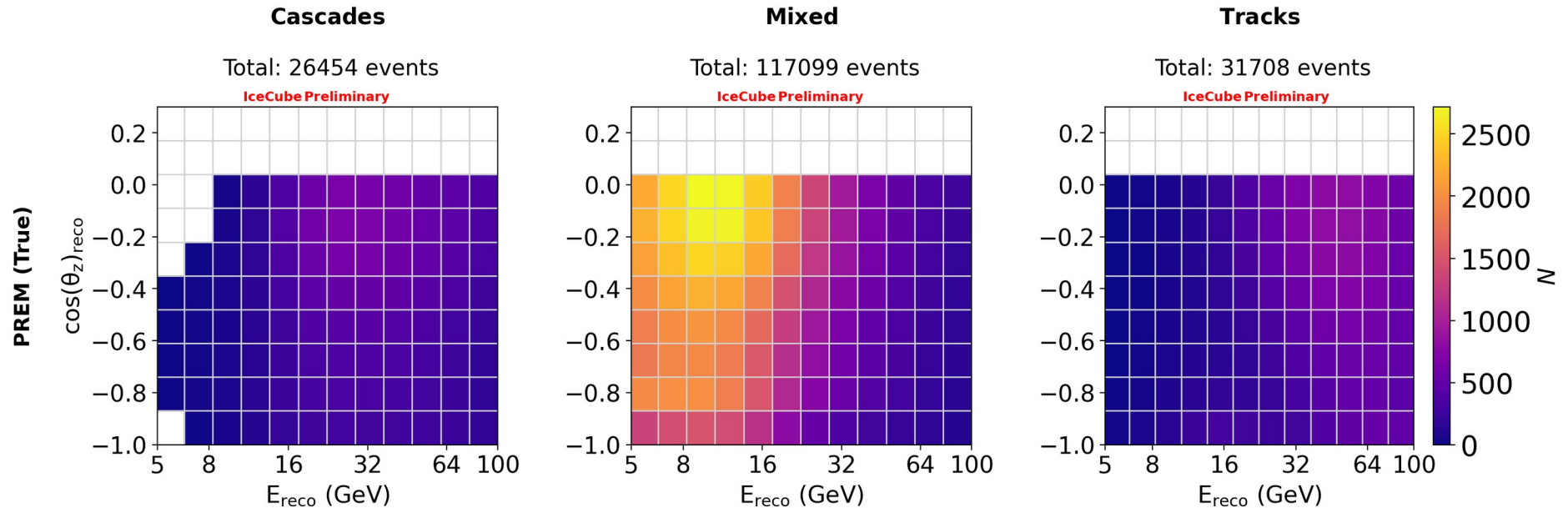
A. Terliuk, Ph.D. thesis (2018)

Sample with CNN-based Reconstruction

- 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.



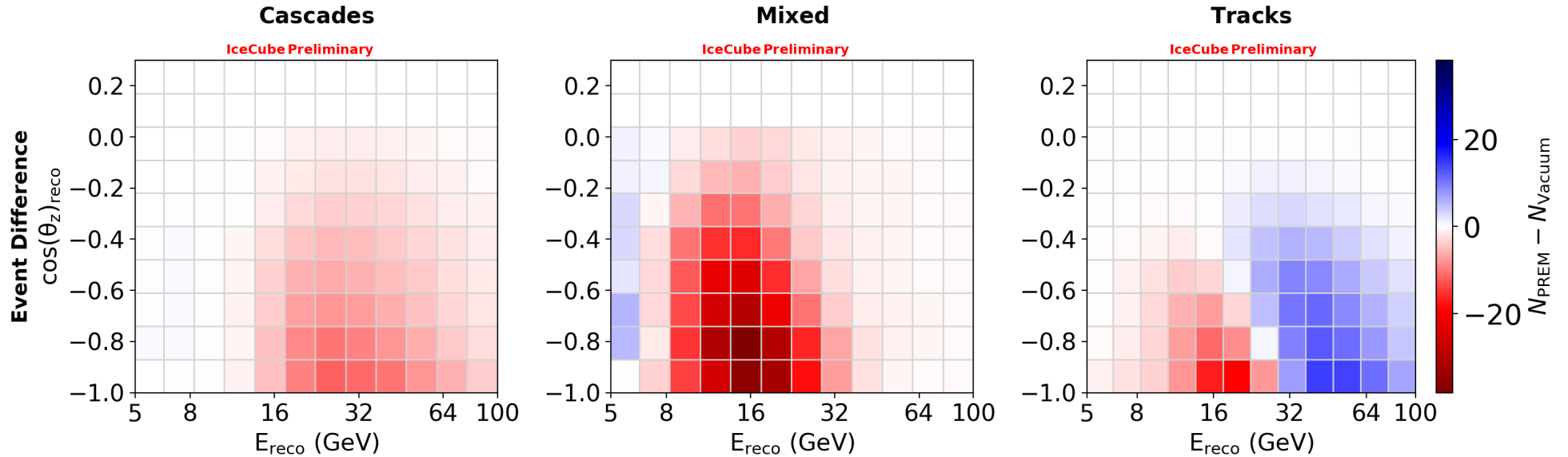
Expected Nominal Events at DeepCore



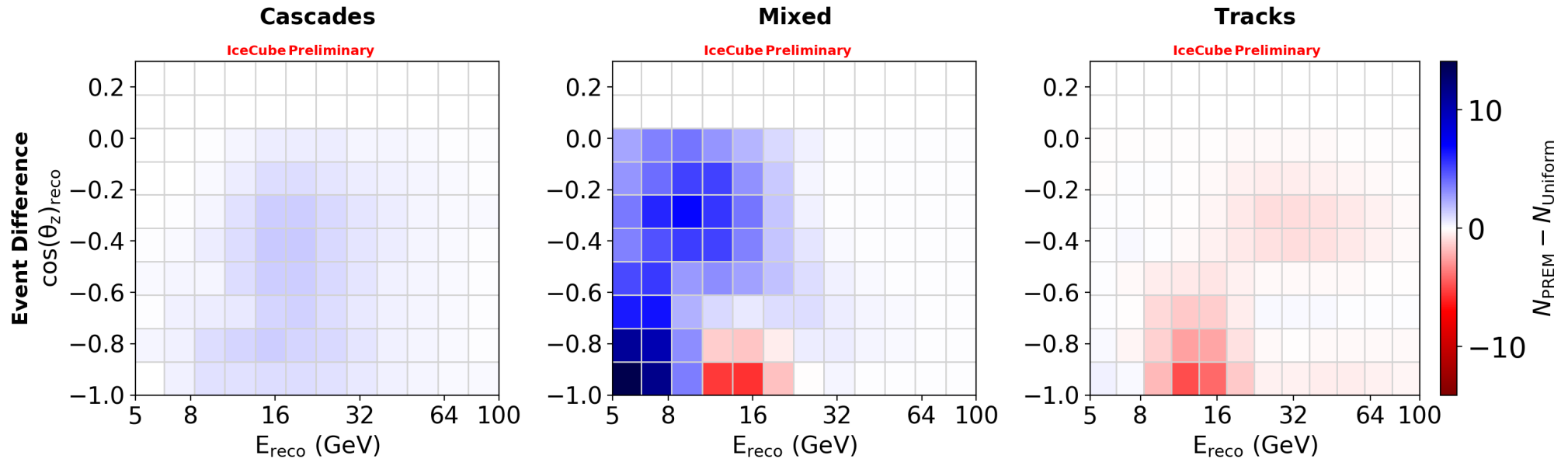
Binning Scheme:

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

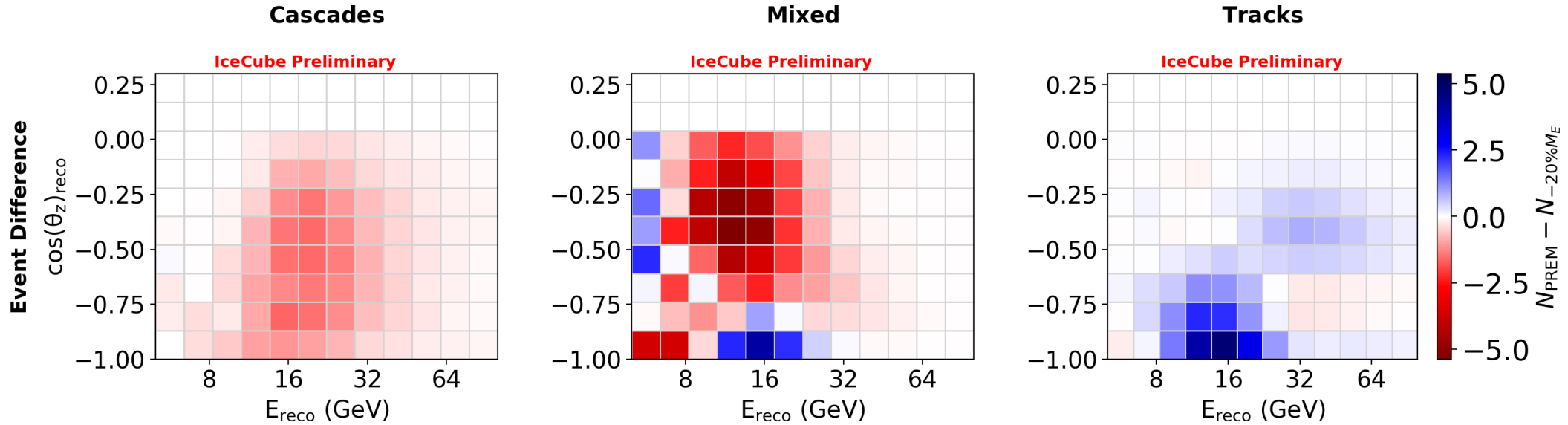
Event Difference due to Earth's Matter Effects



Effect of Uniform Density Profile on Events

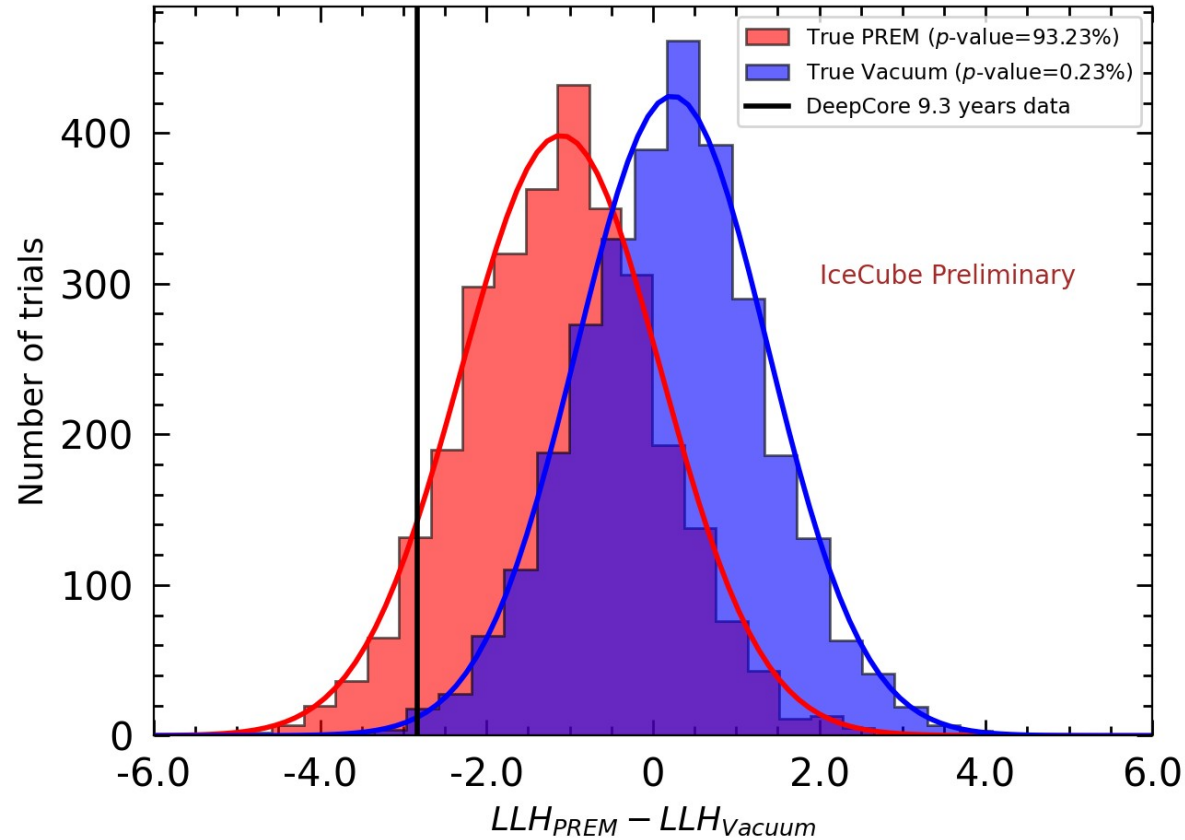


Effect of Modified Mass of Earth on Events



Results: Establishing Earth's Matter Effects

DeepCore: Earth's Matter Effects



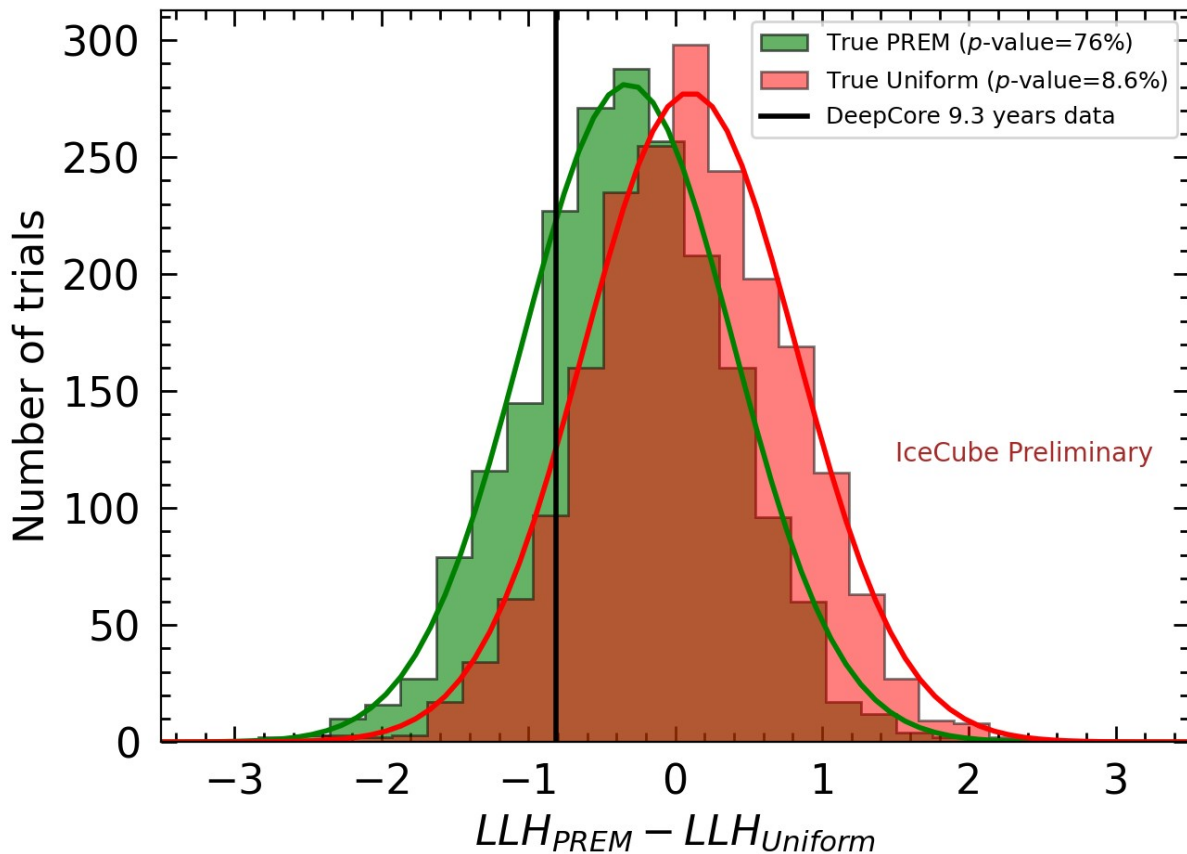
Significance to rule out vacuum hypothesis w.r.t. PREM: 1.82σ

Poissonian Log-likelihood (LLH)

$$LLH = \sum_{i \in \text{bins}} \log \left(\frac{n_i^{n_o} e^{-n_i}}{n_o!} \right) - \frac{1}{2} \sum_{j \in \text{syst}} \frac{(\hat{s}_j - s_j)^2}{\sigma_j^2}$$

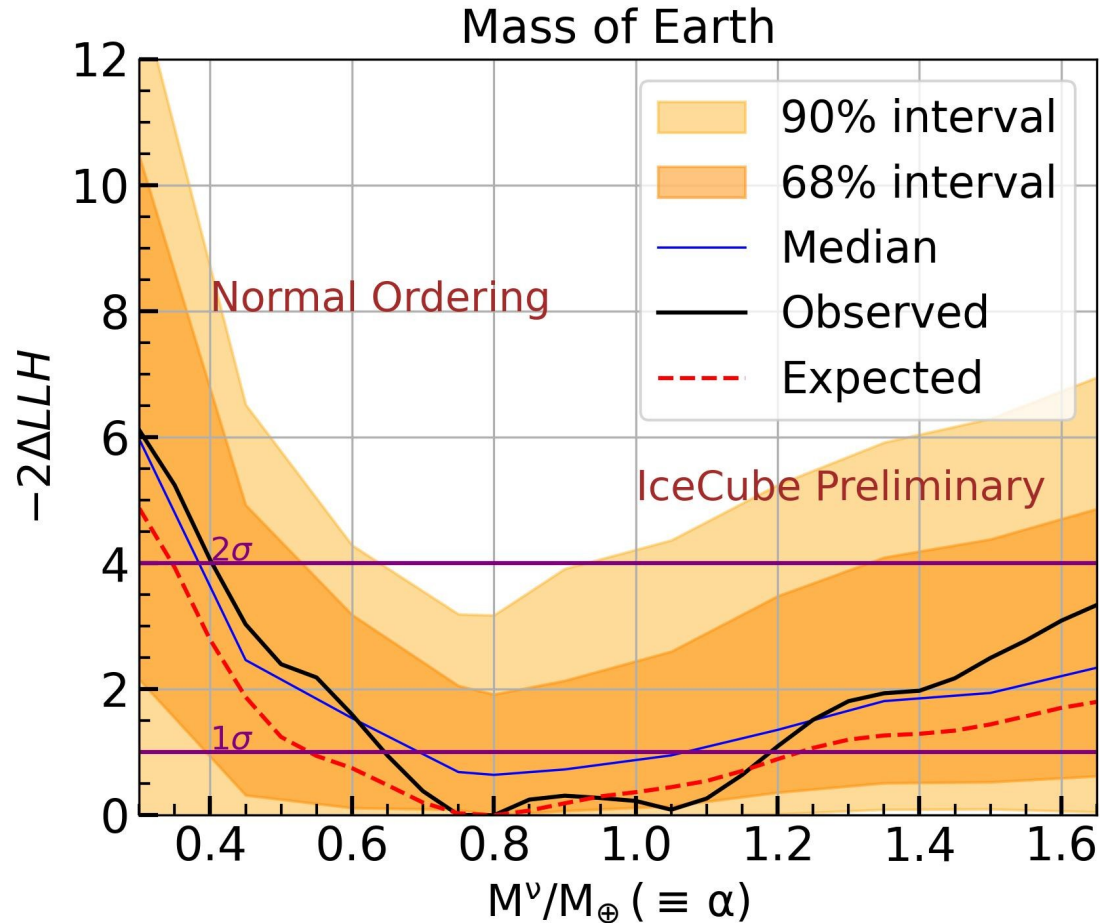
Result: Validating Layered Structure inside Earth

DeepCore: Layered Structure Inside Earth



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

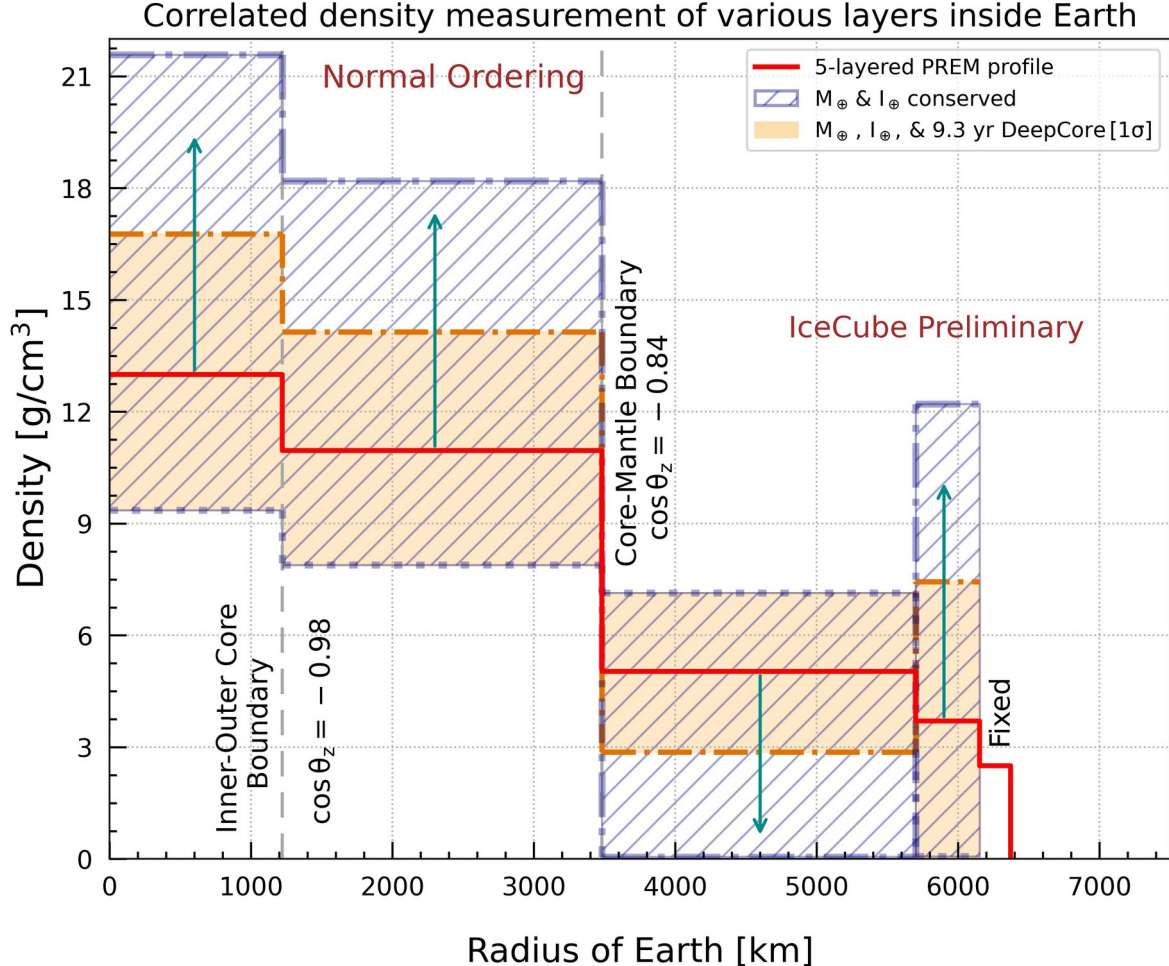
Result: Measurement of Mass of Earth



Mass of Earth:

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

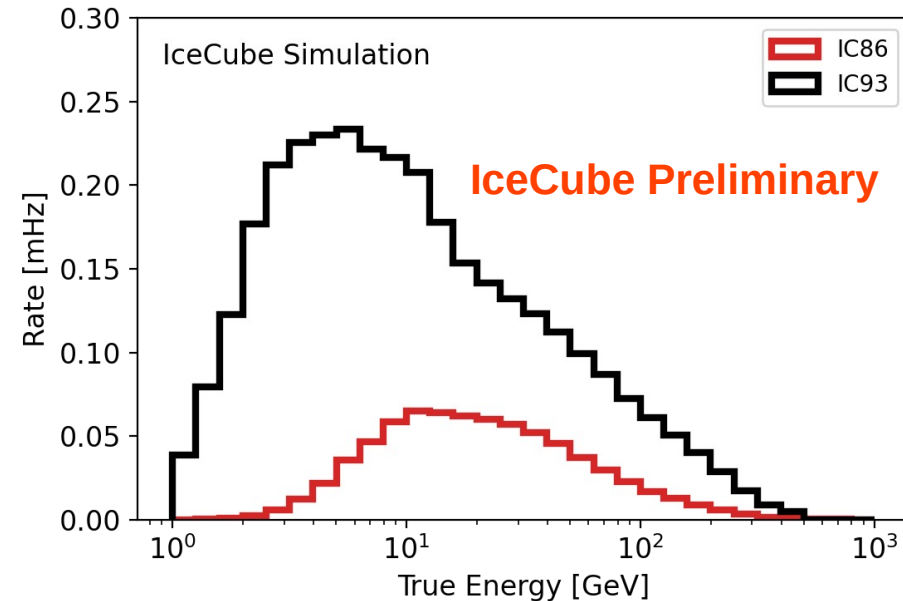
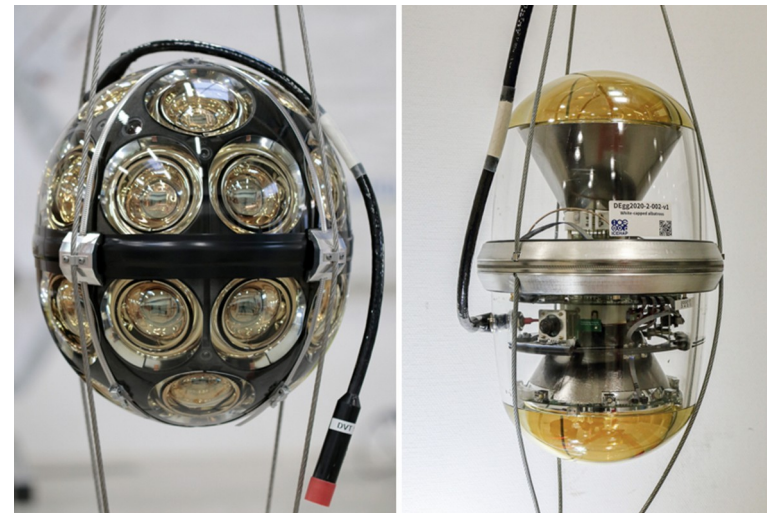
Sensitivity: Measurement of Correlated Densities



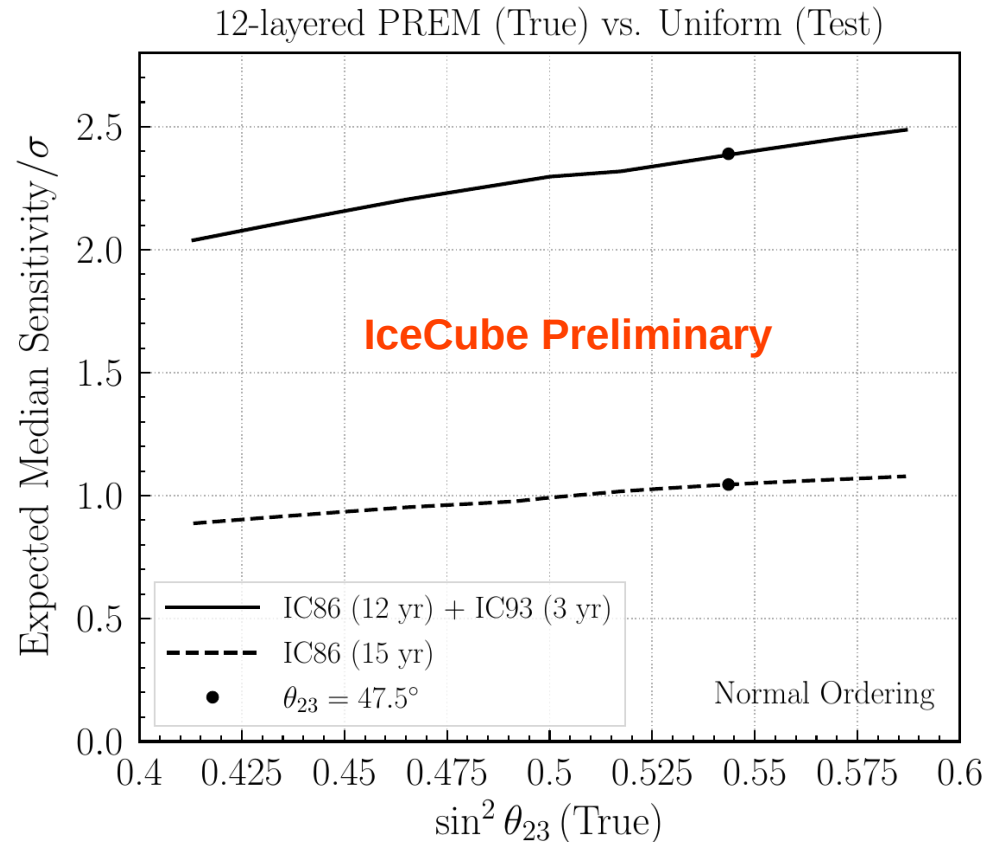
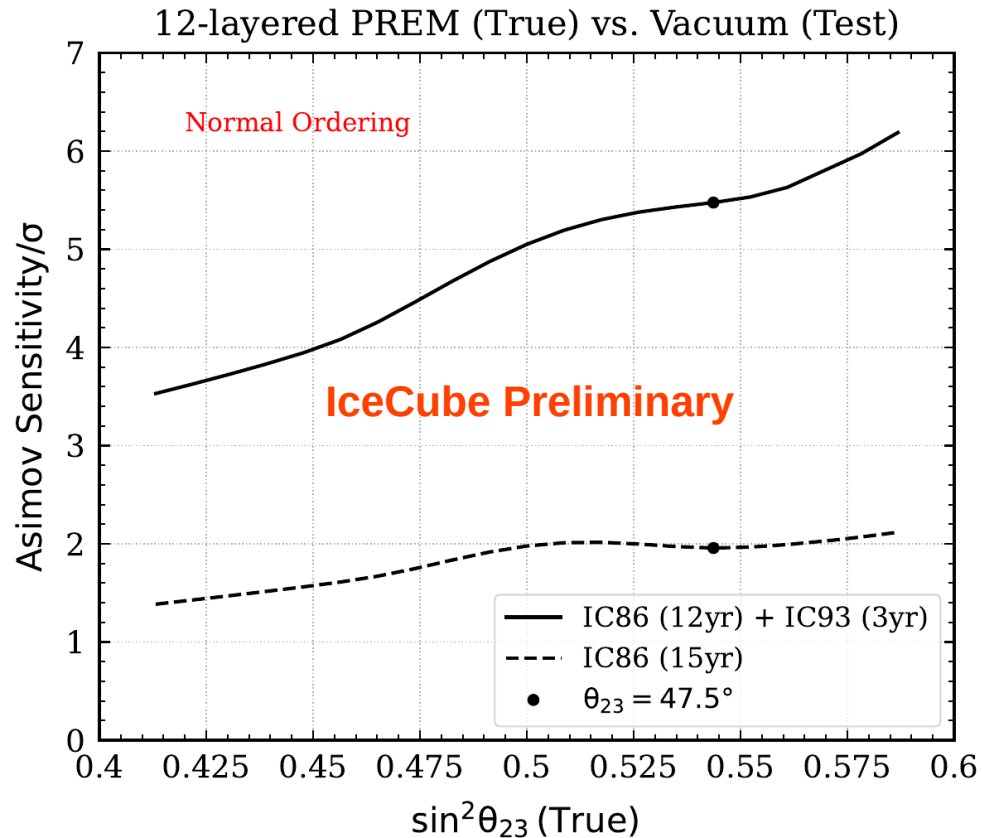
IceCube Upgrade

- 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](https://arxiv.org/abs/1908.09441)
ICRC2023 [arXiv:2307.15295](https://arxiv.org/abs/2307.15295)



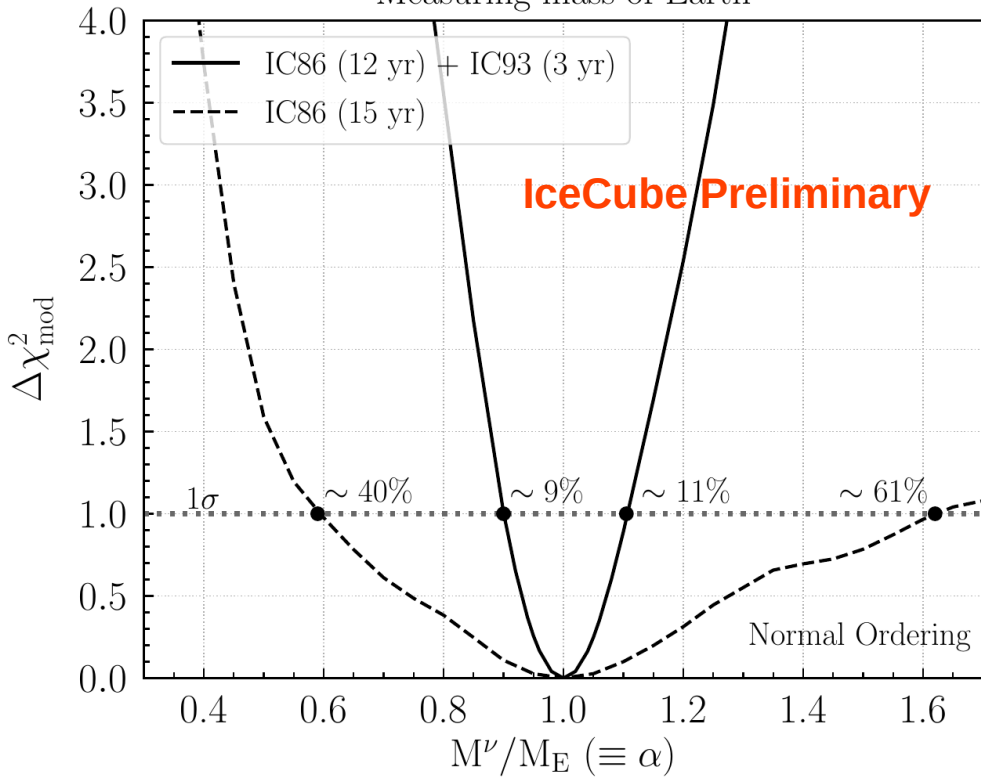
Sensitivity for IceCube Upgrade



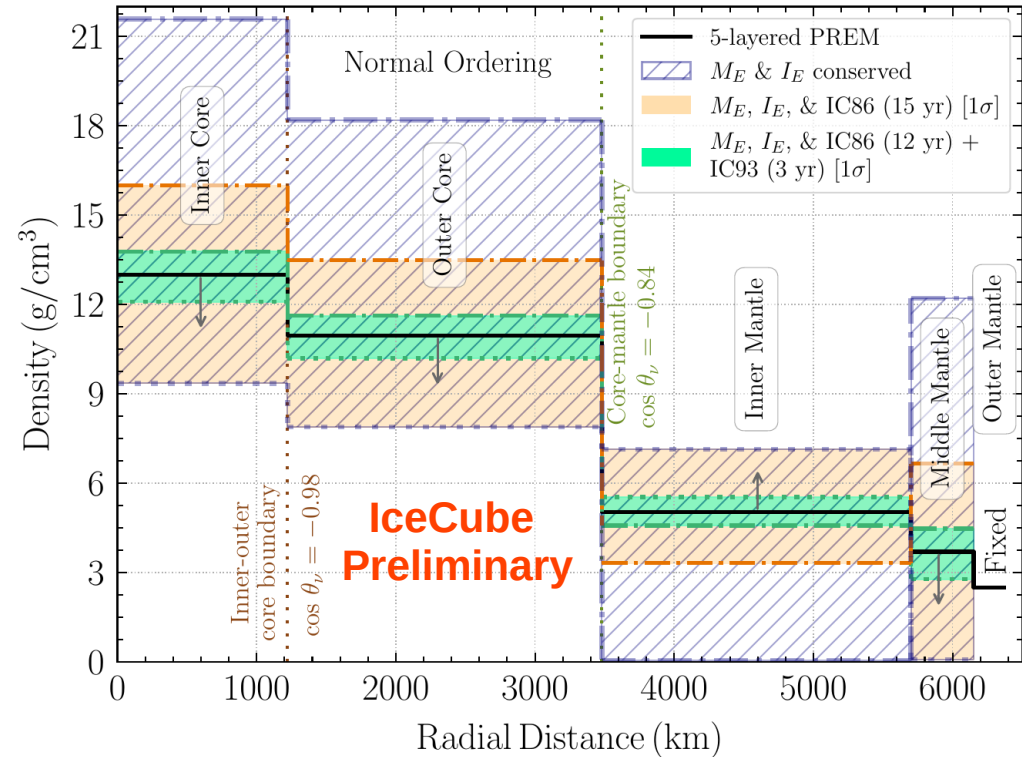
Sensitivity increases significantly with IceCube Upgrade.

Sensitivity for IceCube Upgrade

Measuring mass of Earth



Correlated density measurement of various layers



Sensitivity increases significantly with IceCube Upgrade.

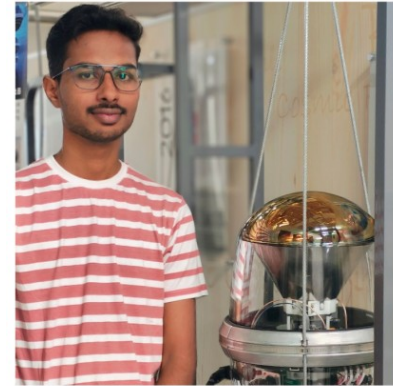
The Earth Tomography Team



Sanjib Kumar Agarwalla, IOP



Anil Kumar, Postdoc, DESY
Zeuthen Germany & IOP



Krishnamoorthi J
Ph.D. Student, IOP



Anuj Kumar Upadhyay
Ph.D. Student, IOP



Sharmistha Chattopadhyay
Ph.D. Student, IOP

Summary and Conclusion

- Neutrino oscillation tomography using atmospheric neutrinos is feasible, given ongoing experiments.
- Our analyses with IceCube DeepCore data show that atmospheric 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.

Thank You

Backup

Three-Flavor Neutrino Oscillations

Neutrino flavor eigenstates ν_α as superposition of mass eigenstates ν_i

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

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

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

Probability of oscillation of flavor α to β :

$$P(\nu_\alpha \rightarrow \nu_\beta) = |U_{\beta 1}U_{\alpha 1}^* + U_{\beta 2}U_{\alpha 2}^*e^{-i2\alpha\Delta} + U_{\beta 3}U_{\alpha 3}^*e^{-i2\Delta}|^2$$

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

• Normal Ordering (NO): ($m_3 > m_2 > m_1$)

• Inverted Ordering (IO): ($m_2 > m_1 > m_3$)

Recent Neutrino Tomography Sensitivity Studies

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

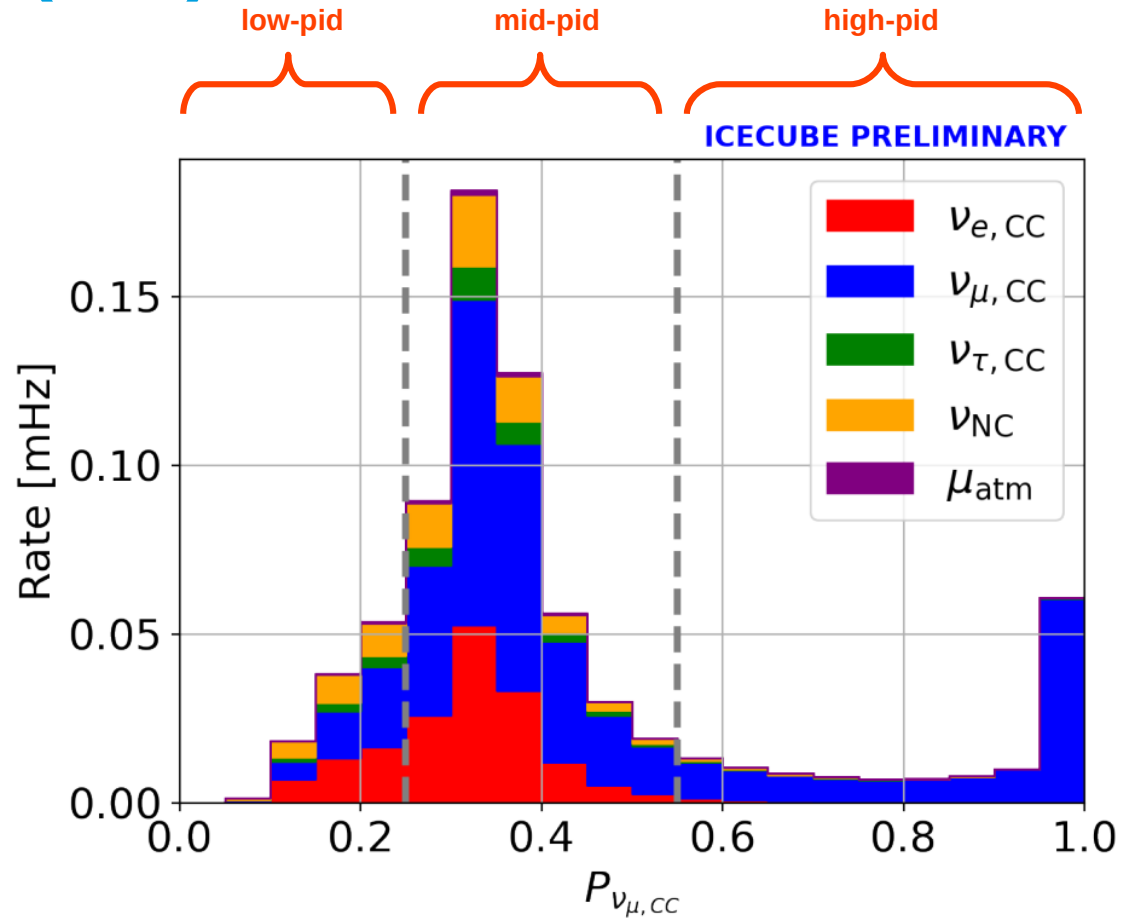
- Presence of Earth's core: JHEP 08 (2021) 139 (ICAL)
- Location of core-mantle boundary: PRD 104 (2021) 11, 113007 (DUNE), JHEP 04 (2023) 068 (ICAL)
- Density jump at core and its location: arXiv: 2405.04986 (ICAL)
- Density distribution: Nucl.Phys.B 908 (2016) 250-267 (PINGU & ORCA), JHEP 05 (2022) 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

MSW Resonance Energy

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

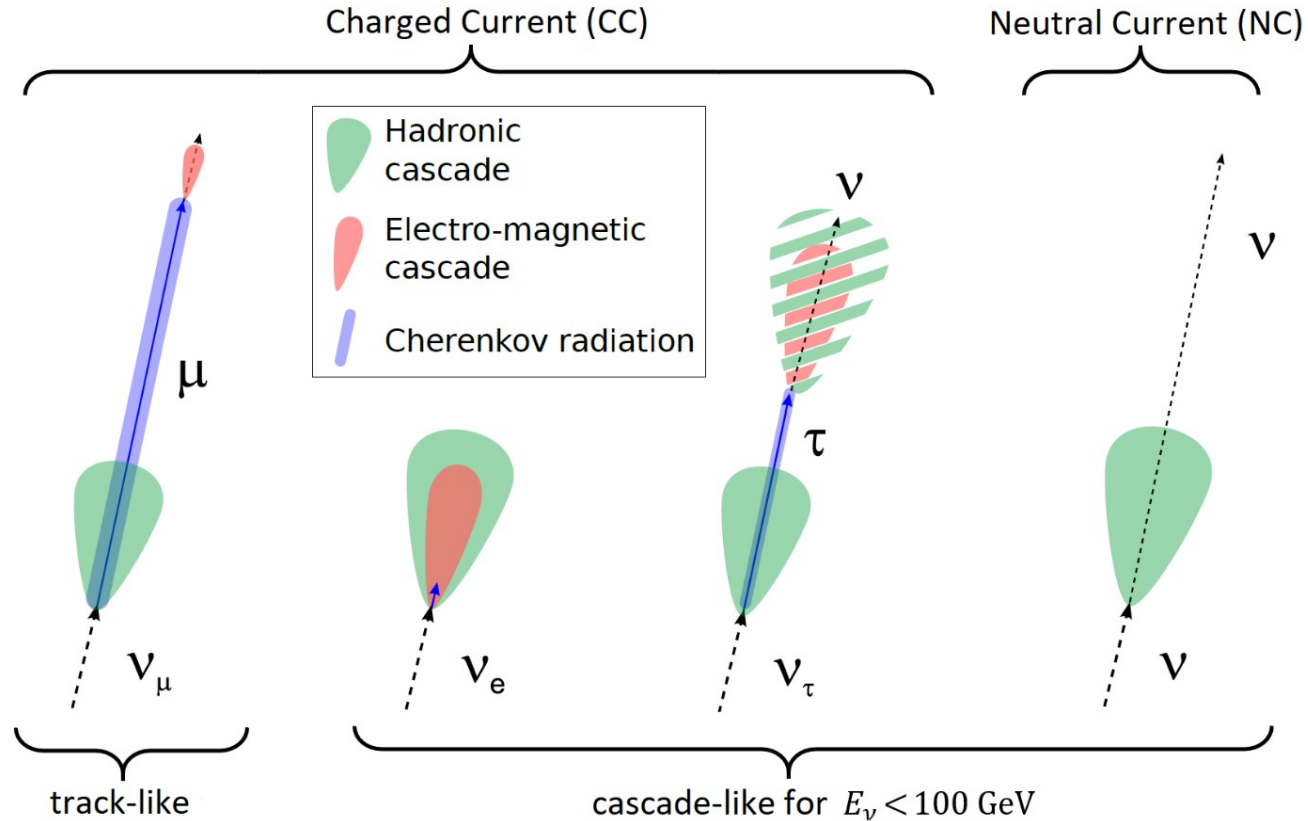
Particle Identification (PID)

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

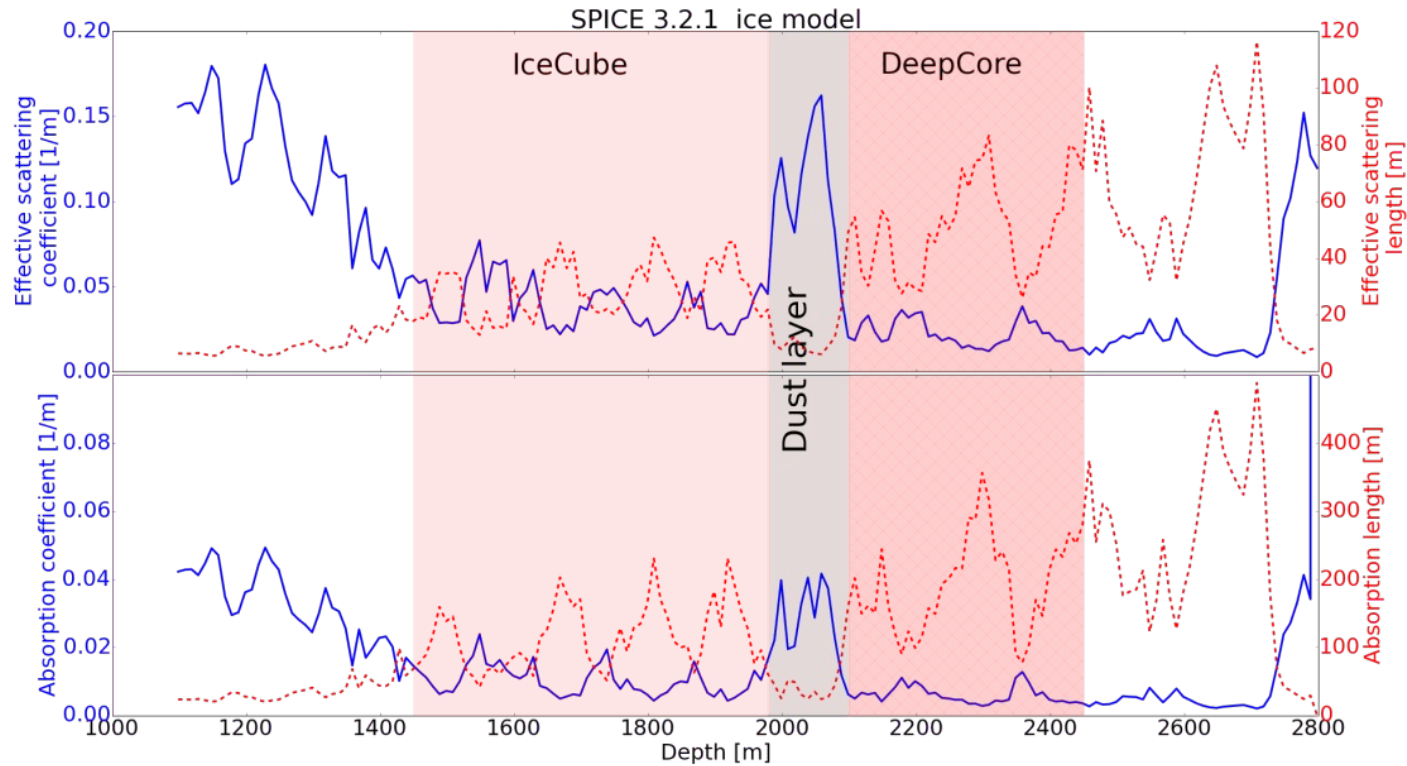


PRL 134, 091801 (2025)

Events at IceCube



Ice Properties



Benchmark Values of Oscillation Parameters

θ_{12}	θ_{13}	θ_{23}	Δm_{21}^2	Δm_{31}^2	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)					
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
		without SK atmospheric data	$\sin^2 \theta_{12}$	$0.303^{+0.012}_{-0.011}$	0.270 \rightarrow 0.341
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	31.31 \rightarrow 35.74	$33.41^{+0.75}_{-0.72}$	31.31 \rightarrow 35.74
	$\sin^2 \theta_{23}$	$0.572^{+0.018}_{-0.023}$	0.406 \rightarrow 0.620	$0.578^{+0.016}_{-0.021}$	0.412 \rightarrow 0.623
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	39.6 \rightarrow 51.9	$49.5^{+0.9}_{-1.2}$	39.9 \rightarrow 52.1
	$\sin^2 \theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	0.02029 \rightarrow 0.02391	$0.02219^{+0.00060}_{-0.00057}$	0.02047 \rightarrow 0.02396
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	8.19 \rightarrow 8.89	$8.57^{+0.12}_{-0.11}$	8.23 \rightarrow 8.90
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	108 \rightarrow 404	286^{+27}_{-32}	192 \rightarrow 360
	$\frac{\Delta m_{21}^2}{10^{-5} eV^2}$	$7.41^{+0.21}_{-0.20}$	6.82 \rightarrow 8.03	$7.41^{+0.21}_{-0.20}$	6.82 \rightarrow 8.03
	$\frac{\Delta m_{3\ell}^2}{10^{-3} eV^2}$	$+2.511^{+0.028}_{-0.027}$	+2.428 \rightarrow +2.597	$-2.498^{+0.032}_{-0.025}$	-2.581 \rightarrow -2.408

Correlated Density Measurements

Incorporating mass and moment of inertia of Earth

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

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

- 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)

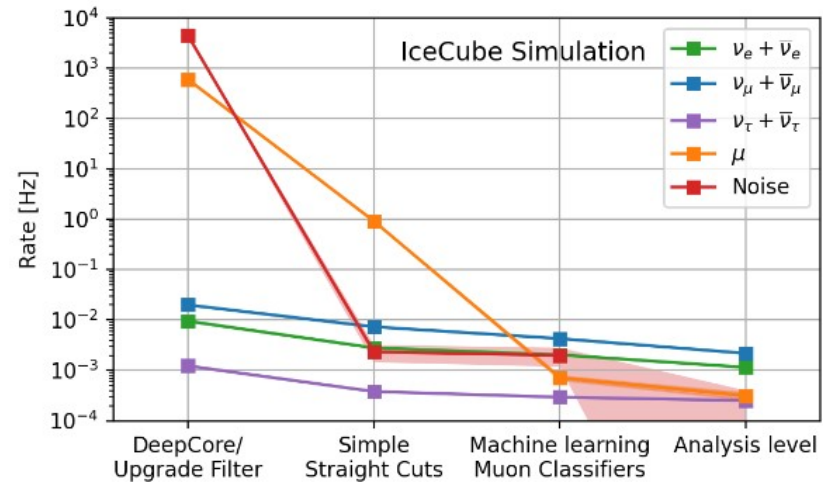
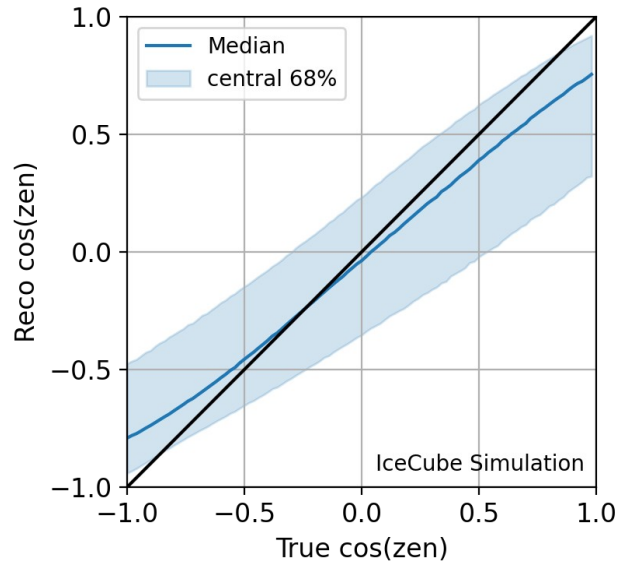
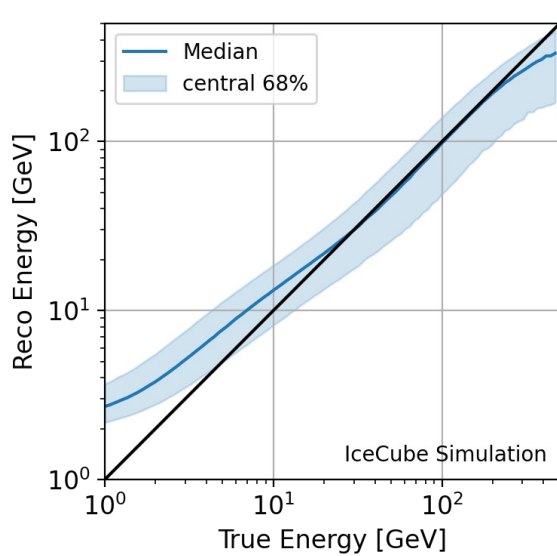
Muon Light Yield (photon propagation in the ice from muons)

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**

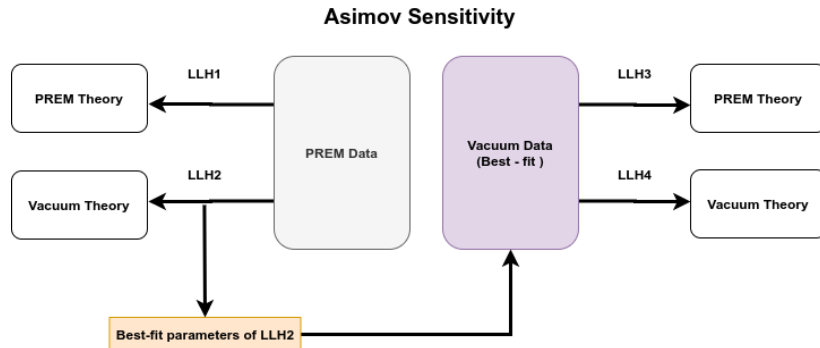
$$\text{Test Statistics (TS)} = \text{LLH} + \text{Prior pull} = \sum_{i \in \text{bins}} [-\lambda_i + x_i \ln(\lambda_i) - \ln(x_i!)] + \frac{1}{2} \sum_{j \in \text{sys}} \frac{(p_j - \hat{p}_j)^2}{\sigma_j^2}$$

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)

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

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

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]