Establishing Layered Structure Inside Earth Using Neutrino Oscillations at IceCube - DeepCore

Krishnamoorthi J

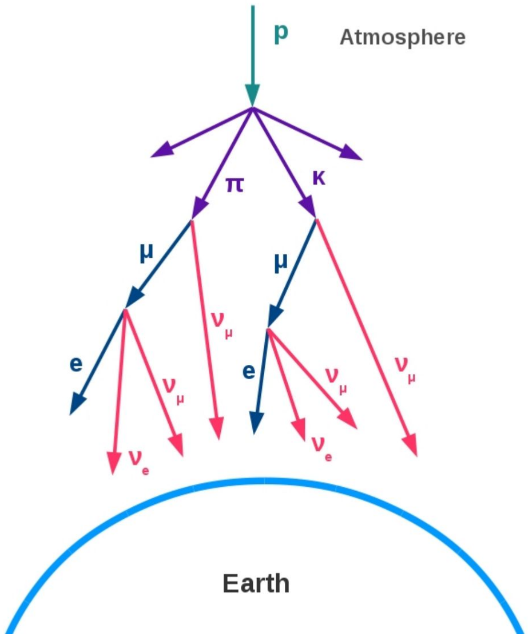
krishnamoorthi.j@iopb.res.in & kjayakumar@icecube.wisc.edu

(For the IceCube collaboration)

Aligarh Muslim University, Aligarh, India & Institute of Physics, Bhubaneswar, India
Department of Physics and WIPAC, UW Madison, USA

Brookhaven Forum 2023
Advancing Searches for New Physics (BF2023)
October 4 - 6 , 2023

Atmospheric Neutrinos : Production



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

- Primary cosmic ray (mostly proton) interacts with nuclei in Earth atmosphere and produces charged particles like pions and kaons
- Short lived pions decay into muons and neutrinos where the muons further decay into lighter lepton and neutrinos

Atmospheric Neutrinos : Advantages

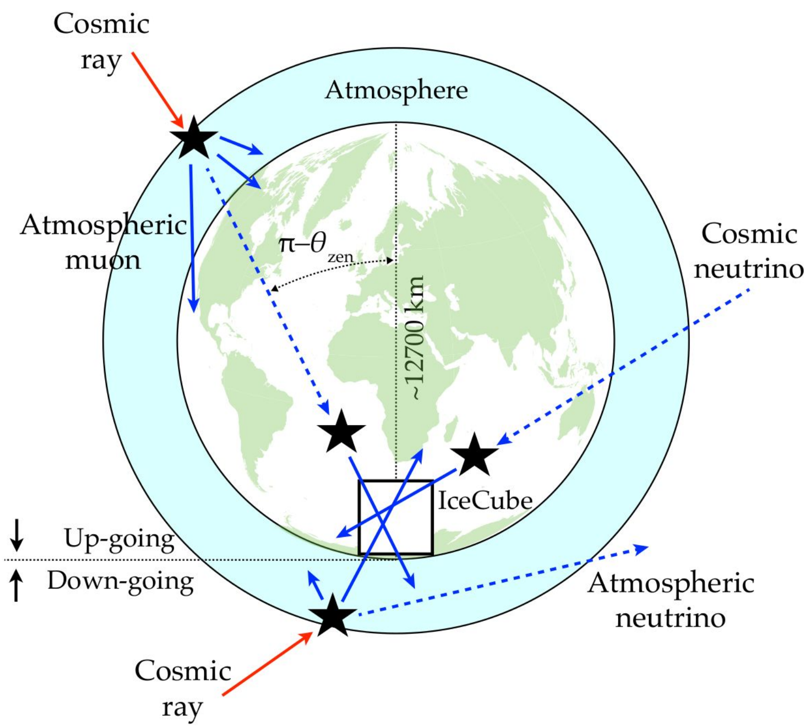
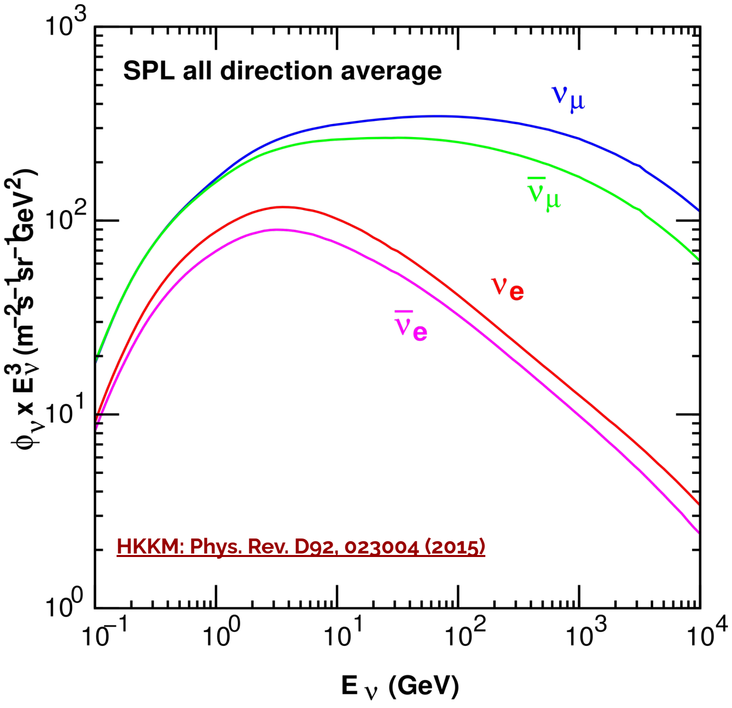


Image source : Probing particle physics with IceCube. Eur. Phys. J. C 78, 924 (2018)

$$^* L_\nu = \sqrt{(R+h)^2 - (R-d)^2 \sin^2\theta_\nu} - (R-d)\cos\theta_\nu$$

- Primary cosmic ray (mostly proton) interacts with nuclei in Earth atmosphere and produces charged particles like pions and kaons
- Short lived pions decay into muons and neutrinos where the muons further decay into lighter lepton and neutrinos
- Advantage
  - Baseline* : ~15 km to ~12757 km

Atmospheric Neutrinos : Advantages



- Primary cosmic ray (mostly proton) interacts with nuclei in Earth atmosphere and produces charged particles like pions and kaons
- Short lived pions decay into muons and neutrinos where the muons further decay into lighter lepton and neutrinos
- Advantage
  - Baseline : ~15 km to ~12757 km
  - Energy range: ~0.1 GeV to ~TeV

Atmospheric Neutrinos : Oscillations

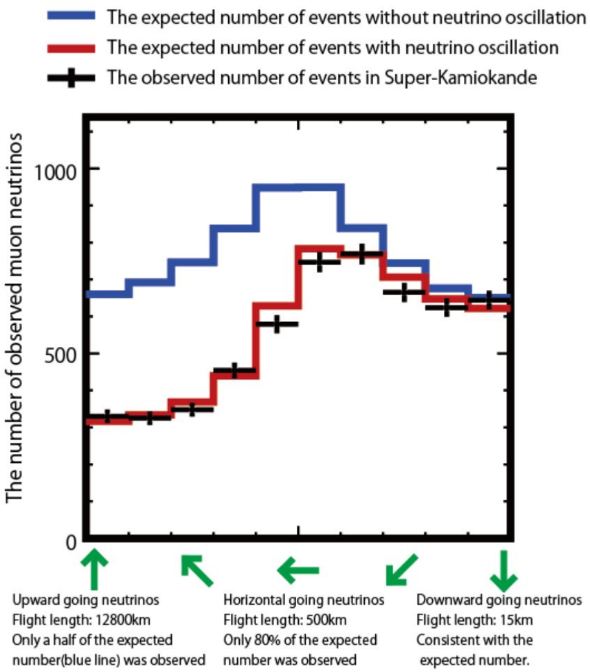


Image source: Super-Kamiokande

Y. Fukuda et al. (Super-Kamiokande), Phys. Rev. Lett. 81, 1562 (1998).

- Primary cosmic ray (mostly proton) interacts with nuclei in Earth atmosphere and produces charged particles like pions and kaons
- Short lived pions decay into muons and neutrinos where the muons further decay into lighter lepton and neutrinos
- Advantage
  - Baseline : ~15 km to ~12757 km
  - Energy range: ~0.1 GeV to ~TeV
- Neutrinos are oscillating

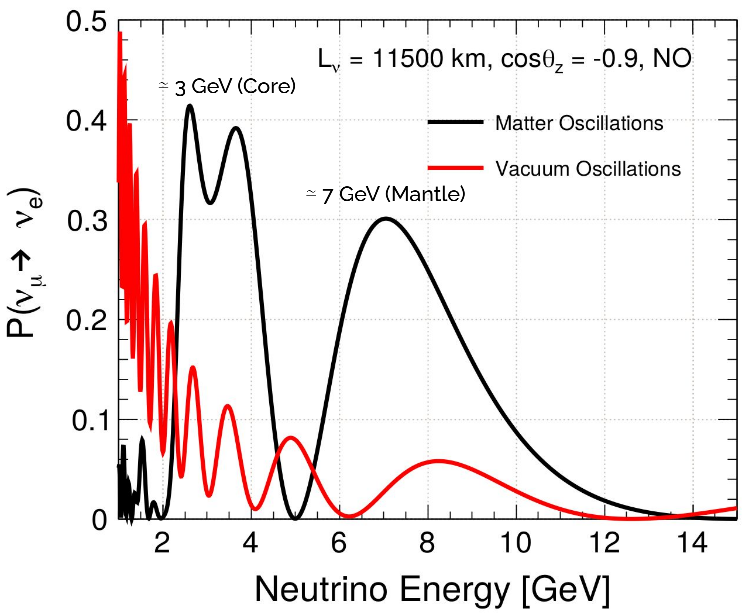
Neutrino Oscillation in Matter

- Neutrino propagation through matter modify the oscillations significantly
- Coherent forward scattering of neutrinos with matter particles
- Charged current interaction of neutrino with electrons creates an extra potential for neutrino

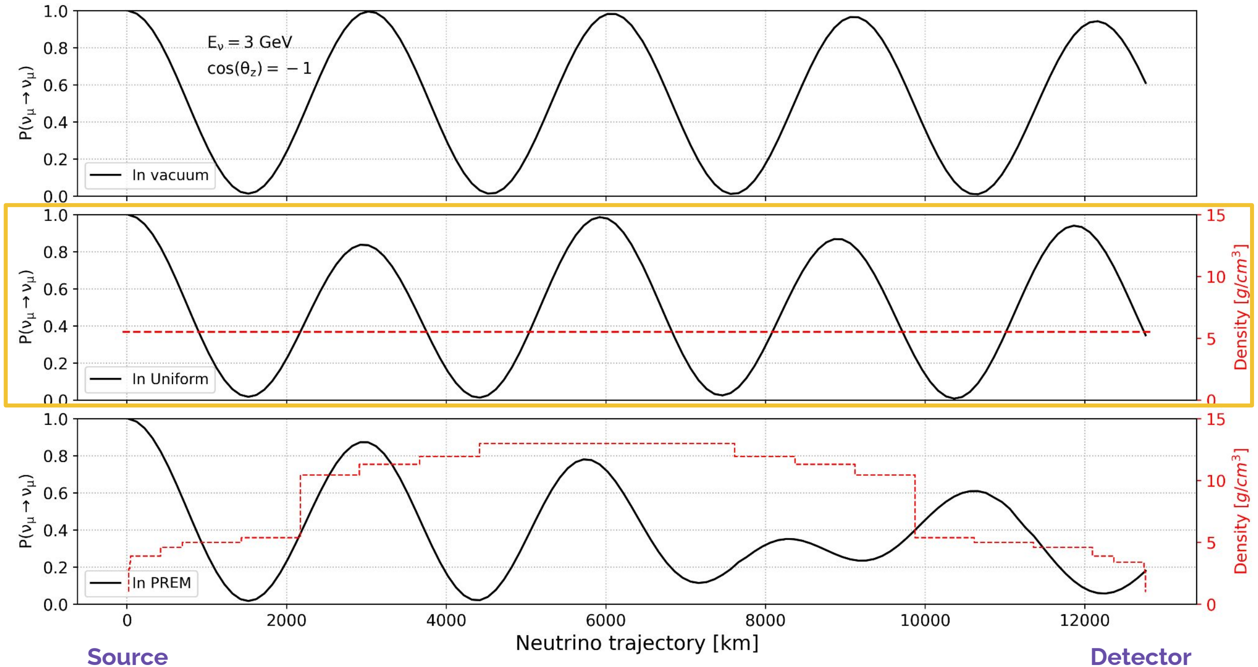
$$V_{CC} = \pm\sqrt{2}G_F N_e \approx \pm 7.6 \times Y_e \times 10^{-14} \left[\frac{\rho}{g/cm^3}\right] \text{eV}$$

$$Y_e = N_e/(N_p + N_n)$$

ρ denotes the matter density
+1 (-1) for neutrino (antineutrino)



Layered Structure of Earth: In the Eyes of Neutrinos



Source

Detector
(Observable probability)

In Uniform

- Interaction of neutrino with matter modifies the neutrino oscillation parameters
- Maximal mixing angle
- Maximum transition

$$\sin 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m_M^2}$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}$$

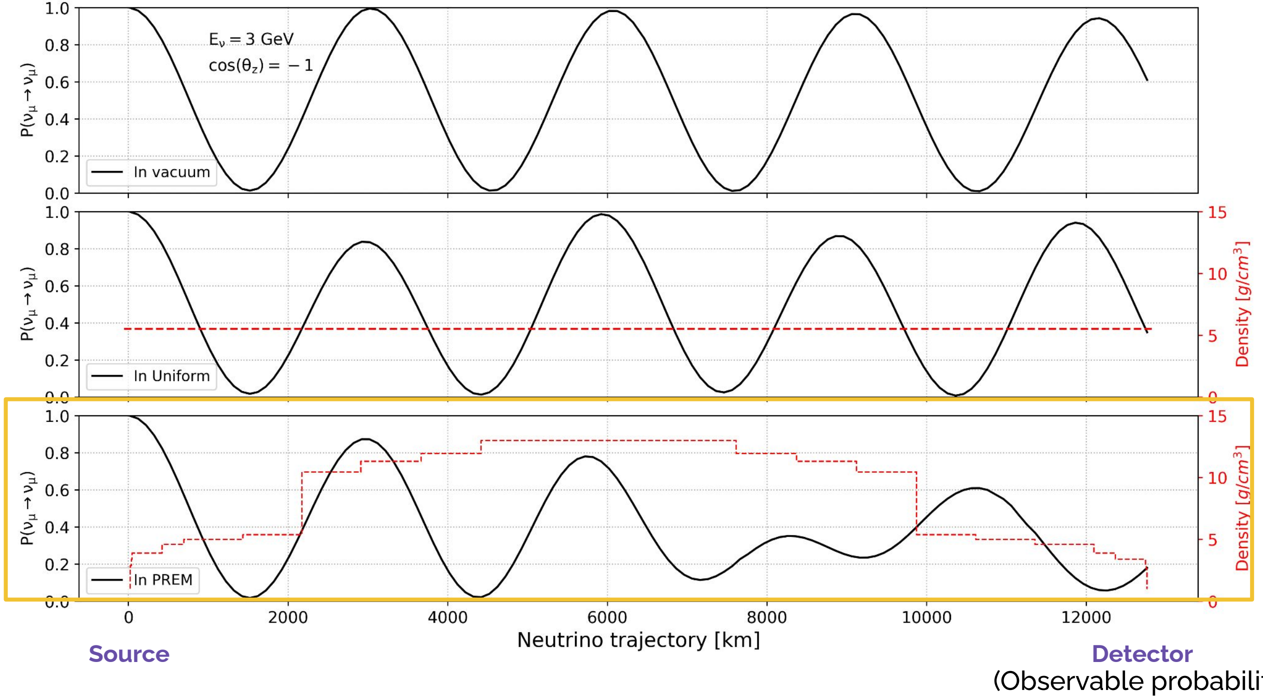
$$A_{CC} = 2\sqrt{2} G_F E \rho N_A Y_e$$

- MSW resonance (L. Wolfenstein, PRD 17 (1978) 2369)

MSW Resonance

$$E_{\text{res}} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

Layered Structure of Earth: In the Eyes of Neutrinos



In PREM

- Periodic modulation of density (n)

$$n(x) = \bar{n} + n_1 \cos \omega_d x$$

- If frequency of density modulation equals to the frequency of oscillation, resonance occurs

$$k\omega_d = \Delta_m(\bar{n}), \;\; k = 1, 2..$$

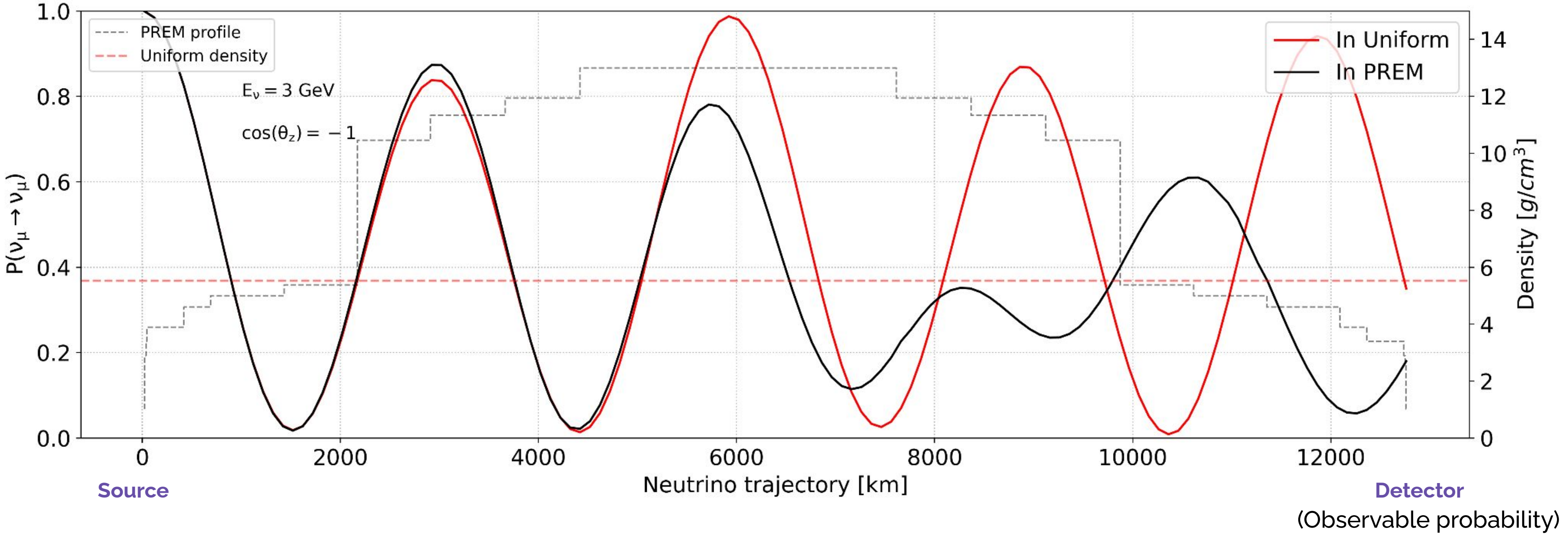
$$\Delta_m(\bar{n}) = \frac{\Delta m^2}{2E}[(\cos 2\theta - \frac{2VE}{\Delta m^2})^2 + \sin^2 2\theta]^{1/2}$$

(Neutrino oscillation frequency in average density)
(V - matter potential term)

- Neutrino Oscillation Length Resonance (NOLR) (Petcov, PLB 434 (1998) 321) or Parametric Resonance (PR) (Akhmedov, NPB 538 (1999) 25)
- Parametric effects in neutrino oscillations, Physics Letters B, Volume 226, Issues 3–4, (1989)

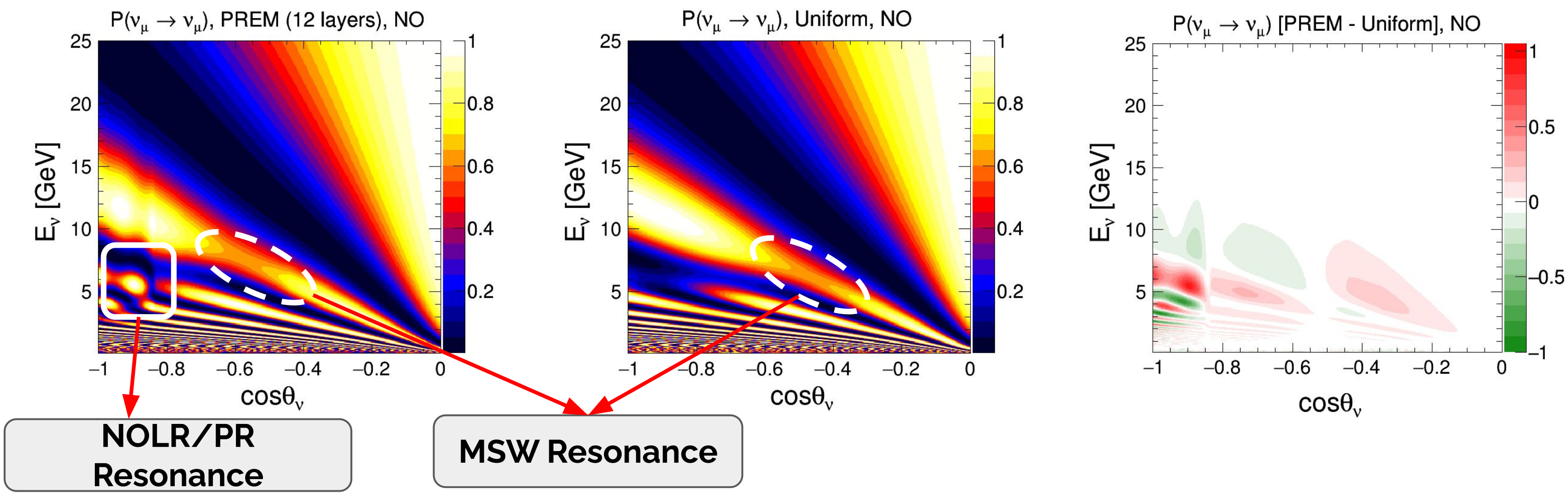
NOLR/PR Resonance

Layered Structure of Earth: In the Eyes of Neutrinos



- Probability in PREM profile start to differ from uniform density profile, once it sees the density jump in PREM (Outer core)
- Further deviation of probability in PREM is visible due to NOLR/PR resonance

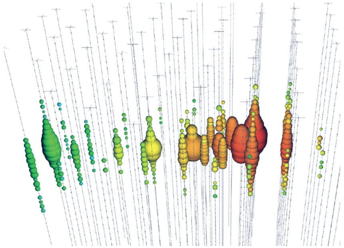
Neutrino Oscillogram: PREM and Uniform Density



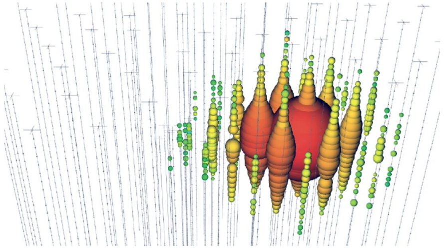
- MSW resonance is visible in both the Earth profiles
- NOLR/PR resonance only present in the PREM profile
- Difference in the oscillation pattern occurs at lower energy and higher baseline
- **Is it possible to infer information about the layered structure of Earth ?**

IceCube - DeepCore

- 1 km^3 deep under antarctic ice
- 5160 Digital Optical Modules (DOMs) detect Cherenkov photons
- Can see upto **PeV - scale**



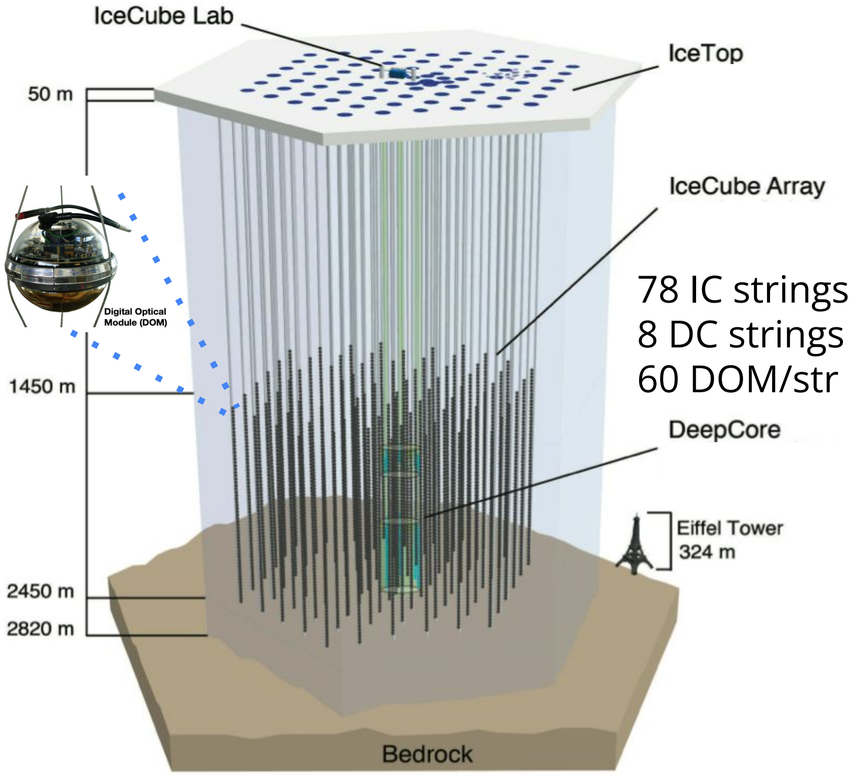
Track-like events:
- Source: ν_μ CC



Cascade-like events:
- Source: ν_e CC, ν_τ CC, all NC

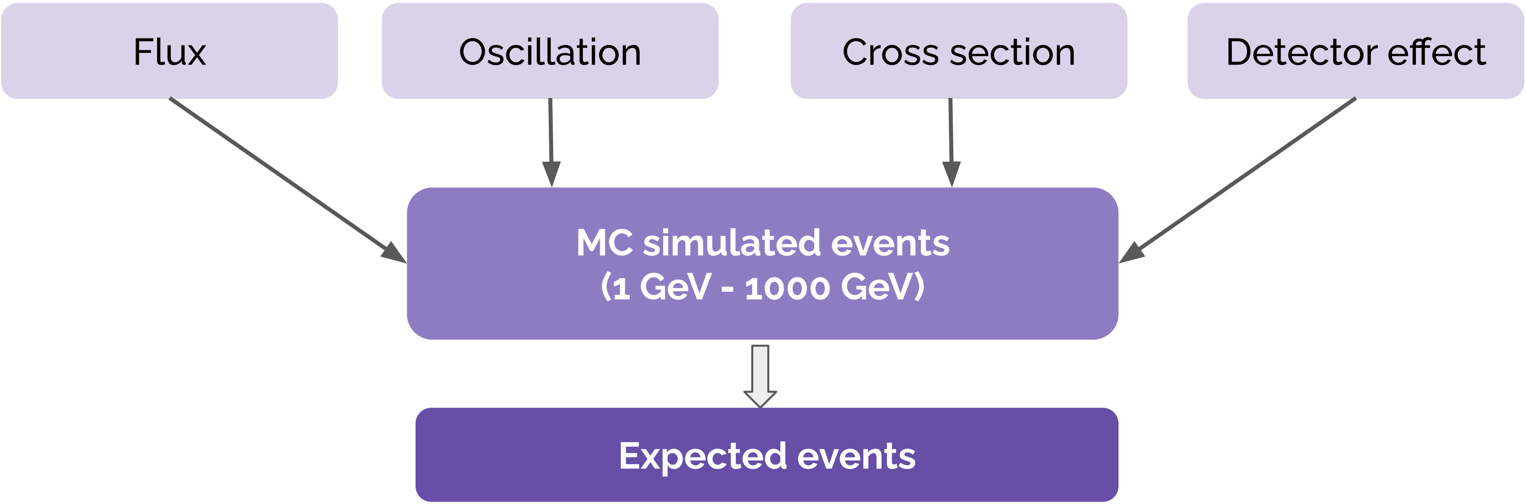
DeepCore

- 8 dedicated strings with denser spacing
- Optimized for **GeV - scale neutrinos**
- Uses IceCube as VETO for the atmospheric muons



78 IC strings
8 DC strings
60 DOM/str

Simulated Neutrino Events



- Convolutional Neural Networks (CNN) based reconstruction
- MC sample exposure: 9.3 years (2012 - 2021)
- Filters are applied to eliminate primary backgrounds: random coincidence triggers and muon contamination is < 1%
- Total no. of events ~ 192 k

Refer slide 23 for the considered uncertainties

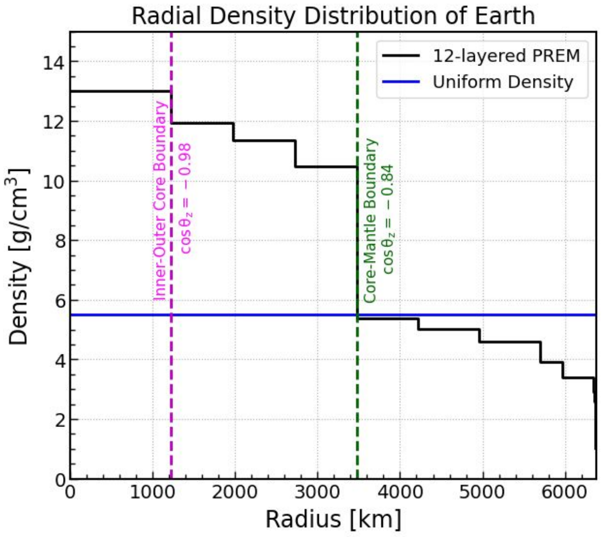
PREM Profile vs. Uniform Density Profile

Can DeepCore rule out the hypothesis of homogeneous matter inside Earth?

(Motivated by M.C. Gonzalez-Garcia et.al. *Radiography of Earth's Core and Mantle with Atmospheric Neutrinos*, PRL 100 (2008) 061802)

- In both density profiles, Earth mass and radius are kept constant
- Earth has been considered as neutral ($N_e = N_p$) and isoscalar ($N_p = N_n$)
  - Therefore electron number density ratio : $Y_e = N_e/(N_p+N_n) = 0.5$ (only for Uniform density profile)

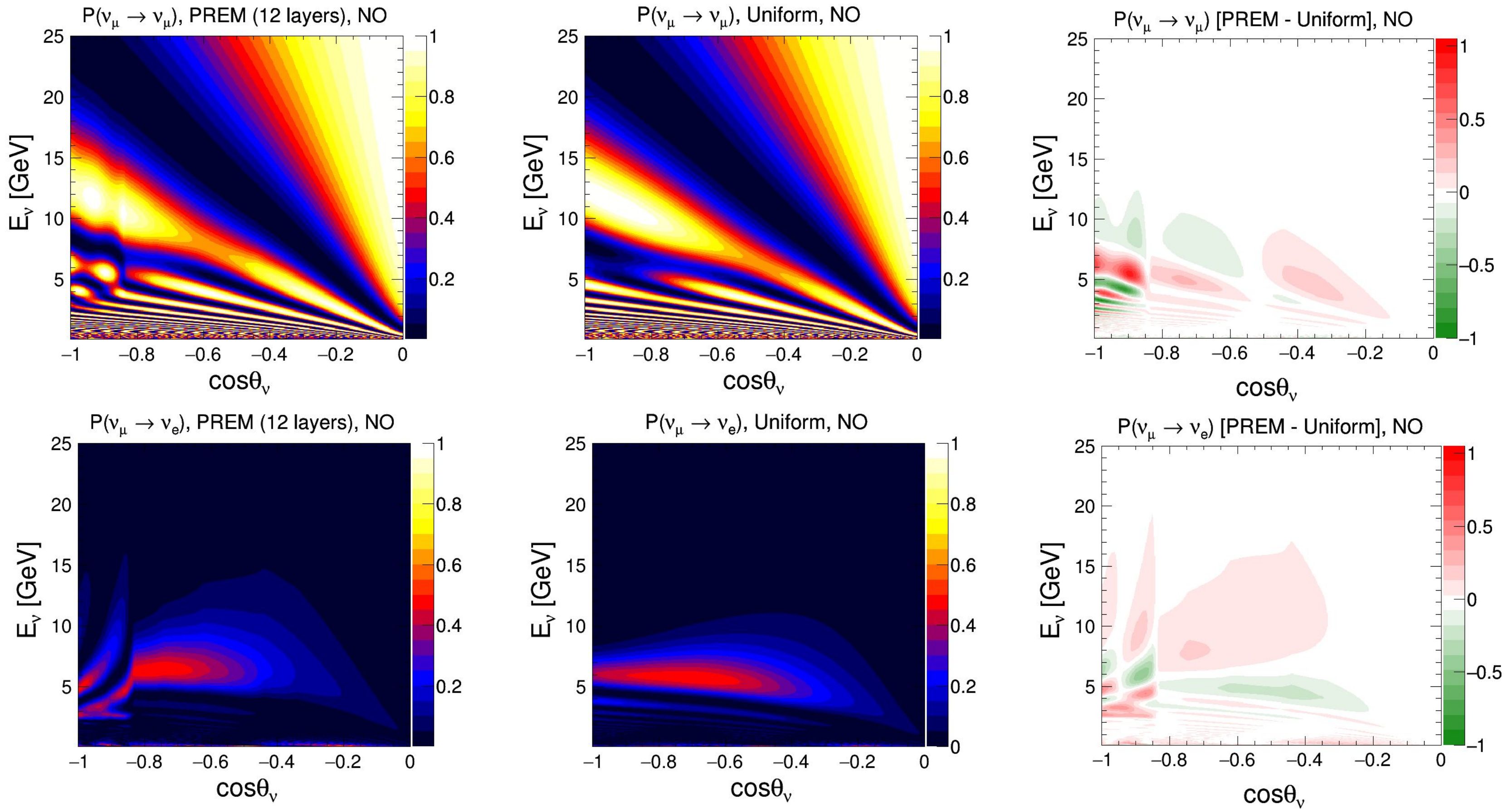
Earth Density Profile	Layer Boundaries	Layer Density [g/cm³]	Electron Number Density Y_e
PREM	12 Layers	12 Densities	YeI (0.4656), YeO (0.4656), YeM (0.4957)
Uniform density	1 Layer	5.53	Y_e (0.5)



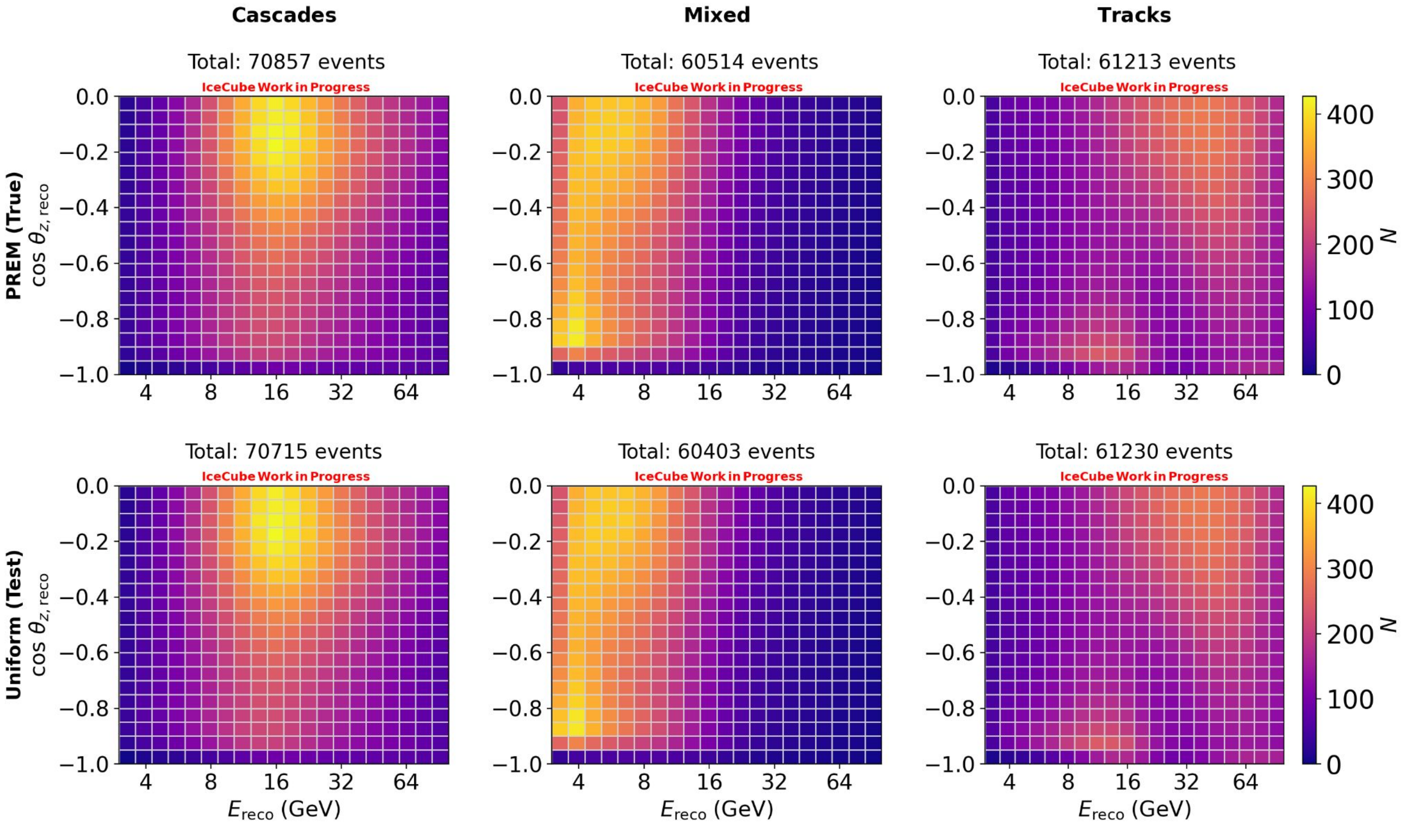
Probabilities & Their Differences [PREM vs. Uniform], NO

Track-like

Cascade-like

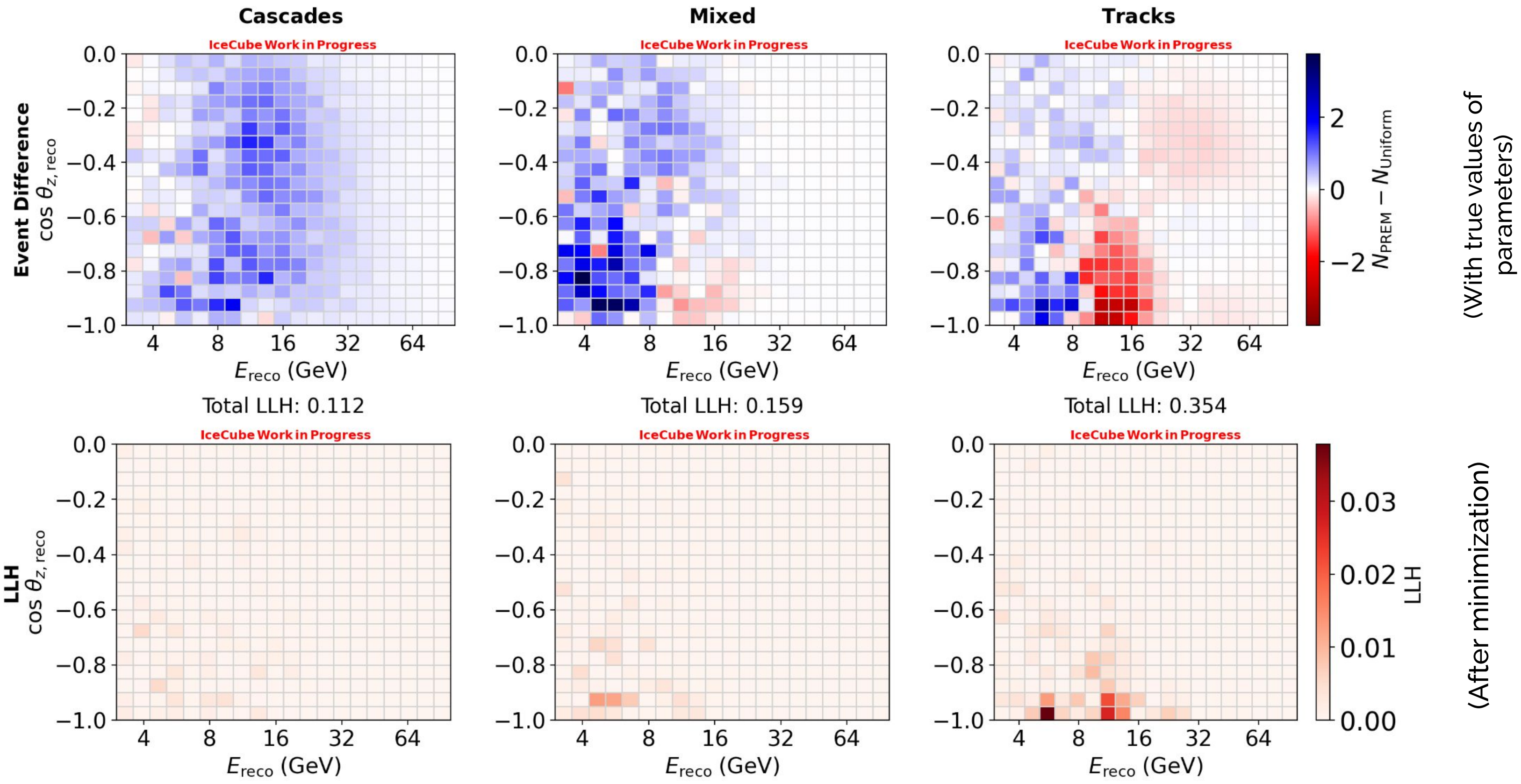


Expected Event Distributions [PREM vs. Uniform], NO



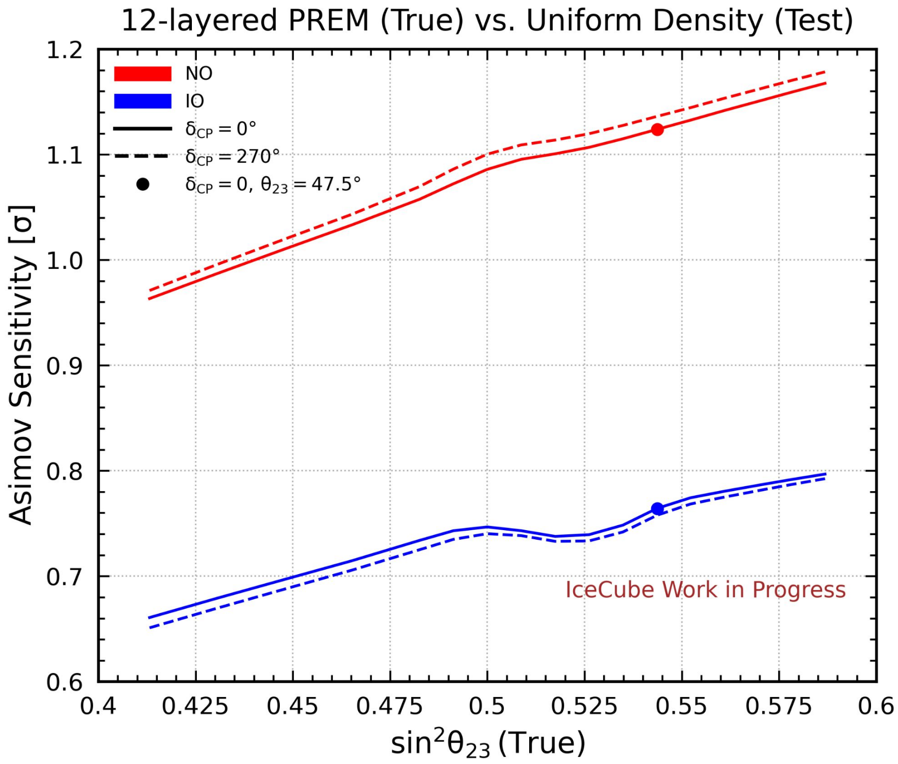
- **PREM & Uniform:** For true values of all oscillation and systematic parameters

Distribution of Simulated Event Differences & LLH, NO



- Most of the LLH contribution comes from lower energy and higher baselines (core-passing neutrinos)

Asimov Sensitivity to Reject Uniform Hypo. with IceCube-DeepCore



- **True hypo.**: 12-layered PREM
- **Test hypo.**: Uniform density
- 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
- Sensitivity is increasing with θ_{23}

- **For NO: θ_{23} = 47.5° & δ_{CP} = 0°**
  - **Sensitivity = 1.12 σ**
- **For IO: θ_{23} = 47.5° & δ_{CP} = 0°**
  - **Sensitivity = 0.76 σ**

Conclusion

IceCube

- Neutrino uses weak interaction
- Atmospheric neutrinos have a wide range of energies and baselines
- By exploiting the neutrino matter effect, one can infer the information about the interior of Earth
- Using 9.3 years of atmospheric neutrino MC sample, the expected Asimov sensitivity to reject uniform density hypothesis is **1σ** for the assumption of NO

Thank You

Backup

Binning Scheme & Benchmark Values of Oscillation Parameters

- Matter effect significant at lower energies and higher baselines
- Binning optimization is necessary
- Reduced the energy threshold down to 3 GeV

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

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

- Using Log LikeliHood (LLH) as a metric

Statistical Methods

- **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

- **Sensitivity (to reject Uniform hypothesis)**

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

(For the assumption of true PREM)

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

LLH1: PREM (Data) → PREM (Theory)
LLH2: PREM (Data) → Uniform (Theory)

LLH3: Uniform (Data)* → PREM (Theory)
LLH4: Uniform (Data)* → Uniform (Theory)

* Uniform (Data) is generated with the best fit values from LLH2 fit

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)

Systematic Treatment

- **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
- **Detector and Ice properties**
  - Optical efficiency of the photo sensor
  - Ice scattering and absorption
  - Birefringence (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**

➔ In total, about 40 systematics are tested individually; around **20 high-impact** parameters are included as nuisance parameters and kept free in the analysis

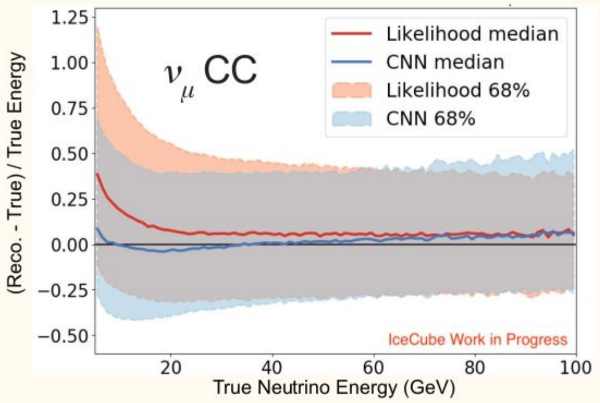
For more details, see: **Phys.Rev.D 108 (2023) 1, 012014**

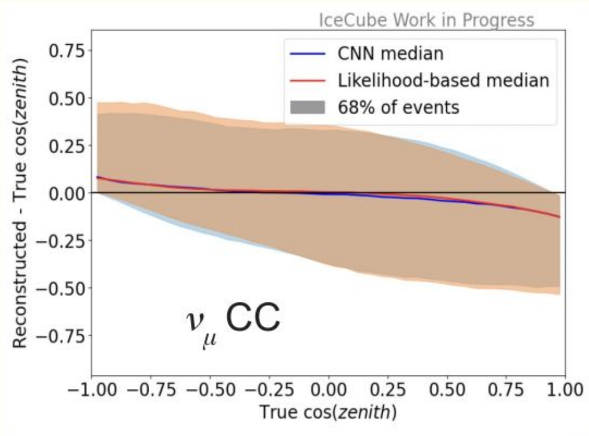
Reconstruction performance

Shiqi Yu, DIS2023

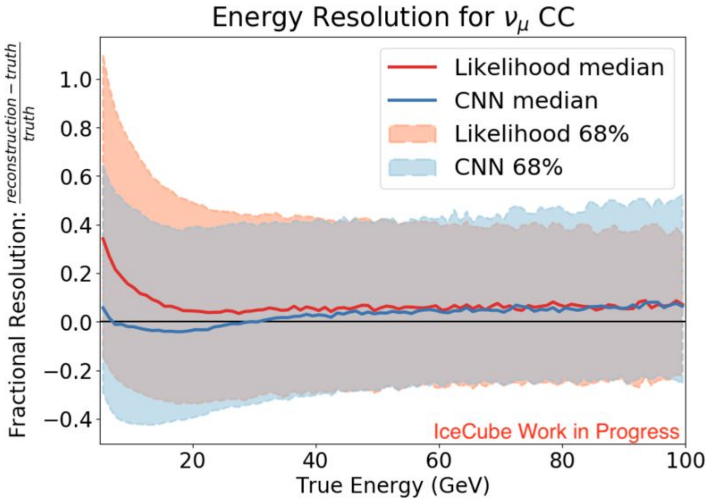
Reconstruction Performance

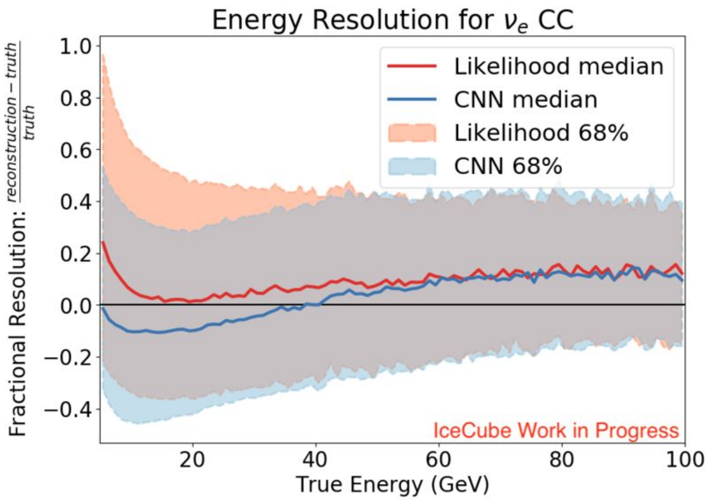
- Flat median against true neutrino energy and zenith;
- CNN has comparable resolution to current method, and better at low energy (majority of sample)





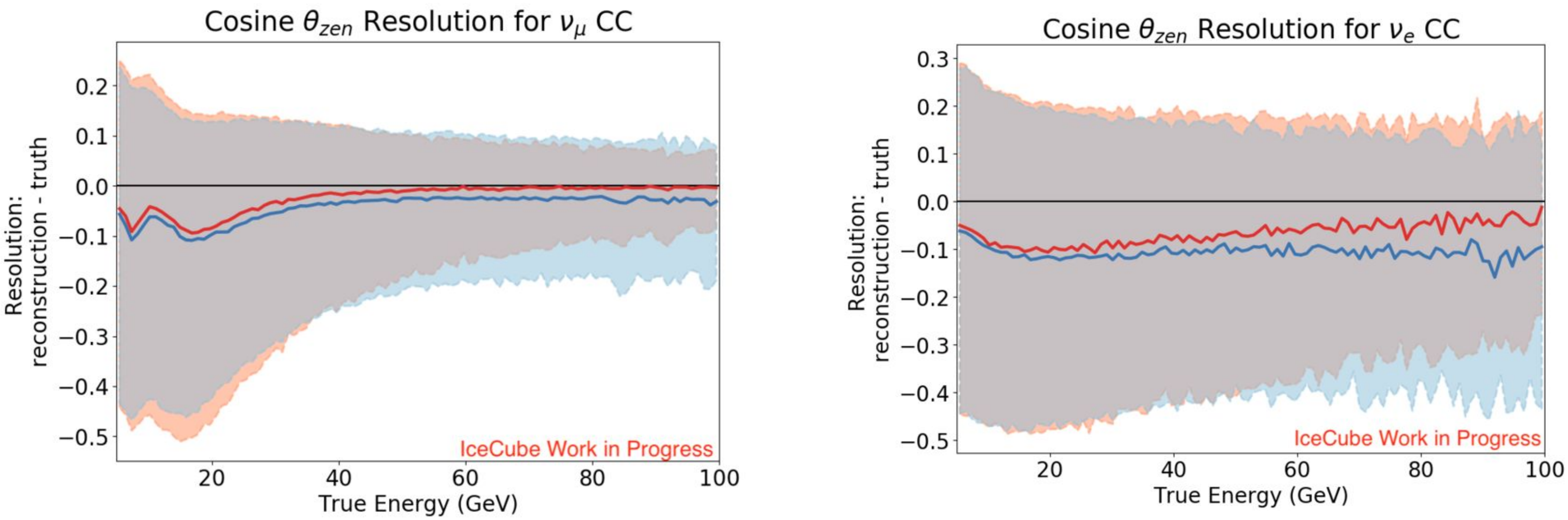
Energy Resolution





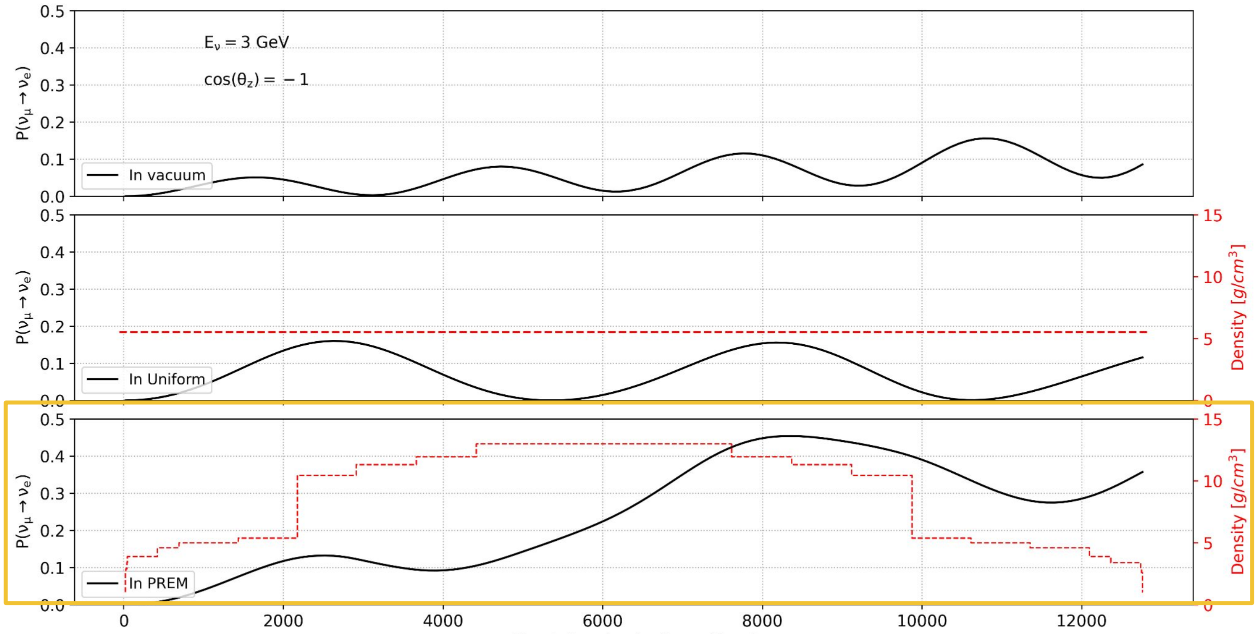
Resolution of energy reconstruction as a function of true neutrino energy

Zenith Resolution



Resolution of zenith reconstruction as a function of true neutrino energy

Layered Structure of Earth: In the Eyes of Neutrinos



Source

Detector
(Observable probability)

In PREM

- Periodic modulation of density

$$n(x) = \bar{n} + n_1 \cos \omega_d x$$

- If frequency of density modulation equals to the frequency of oscillation, resonance occurs

$$k\omega_d = \Delta_m(\bar{n}), \ \ k = 1, 2..$$

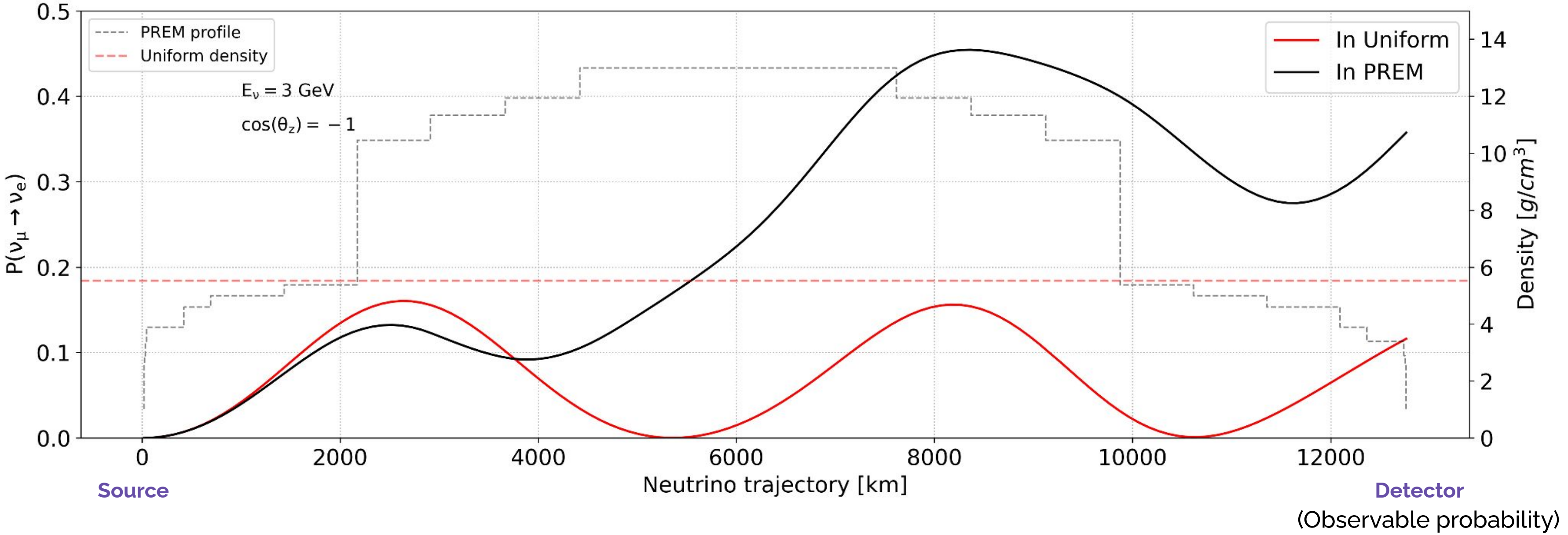
$$\Delta_m(\bar{n}) = \frac{\Delta m^2}{2E}[(\cos 2\theta - \frac{2VE}{\Delta m^2})^2 + \sin^2 2\theta]^{1/2}$$

(Neutrino oscillation frequency in average density)

- Neutrino Oscillation Length Resonance (NOLR) (Petcov, PLB 434 (1998) 321) or Parametric Resonance (PR) (Akhmedov, NPB 538 (1999) 25)
- Parametric effects in neutrino oscillations, Physics Letters B, Volume 226, Issues 3–4, (1989)

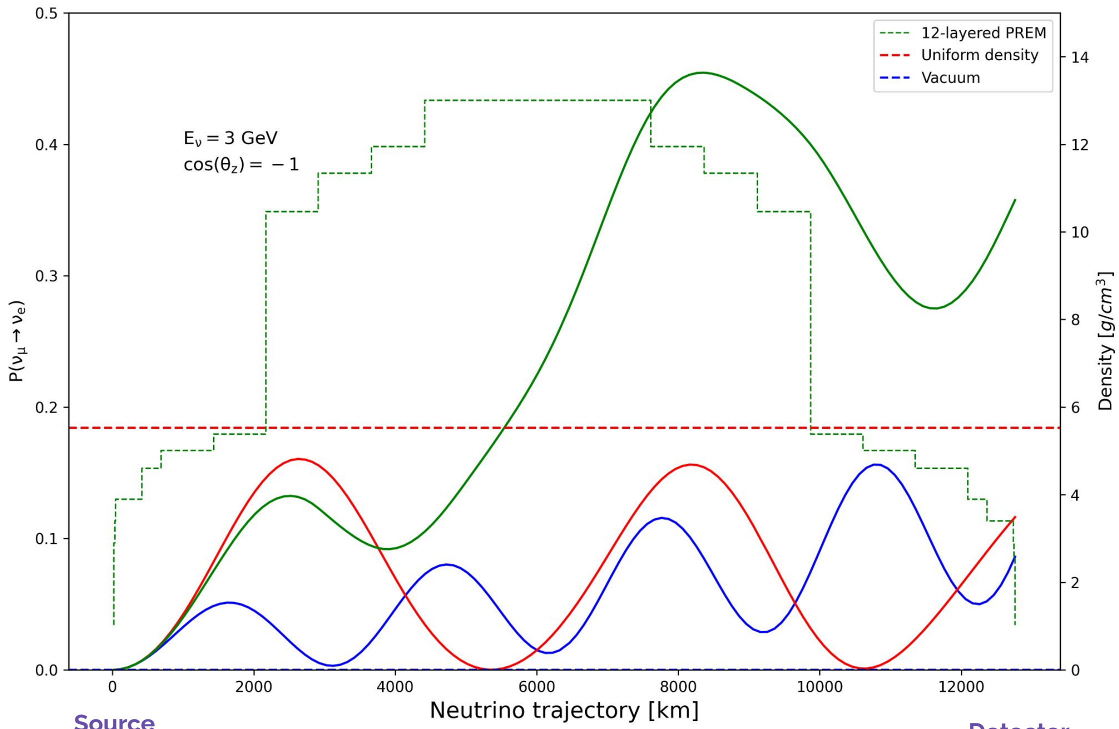
NOLR/PR Resonance

Layered Structure of Earth: In the Eyes of Neutrinos



- Probability in PREM profile start to differ from uniform density profile, once it sees the density jump in PREM (Outer core)
- Further deviation of probability in PREM is visible due to NOLR/PR resonance

Layered Structure of Earth: In the Eyes of Neutrinos



Source

Detector

(Observable probability)