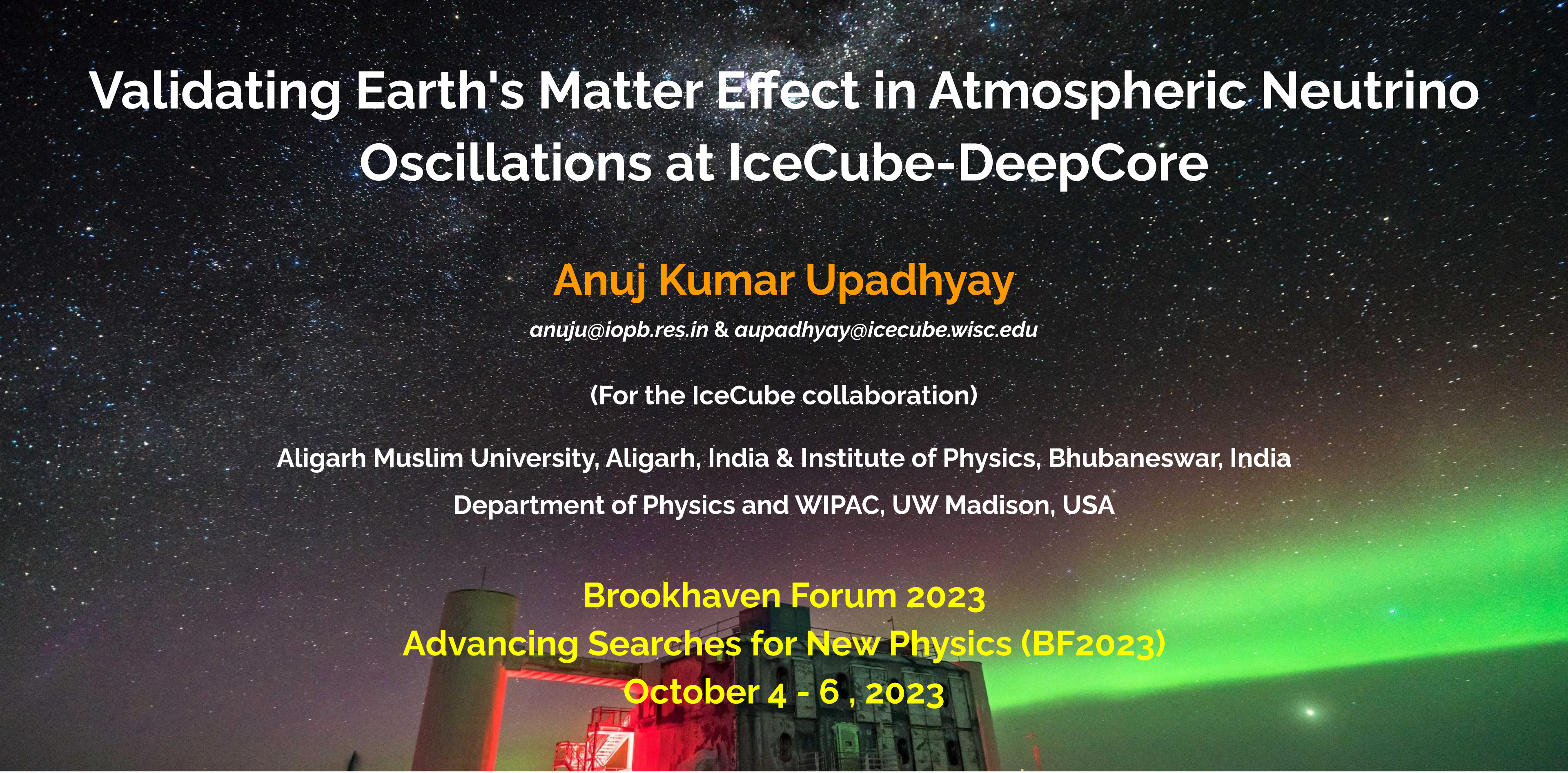

Validating Earth's Matter Effect in Atmospheric Neutrino Oscillations at IceCube-DeepCore

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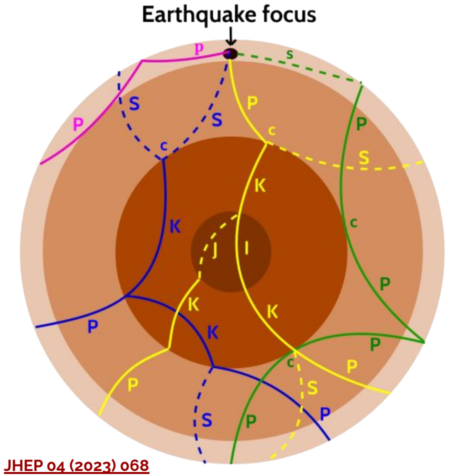
Brookhaven Forum 2023
Advancing Searches for New Physics (BF2023)
October 4 - 6 , 2023

Outline

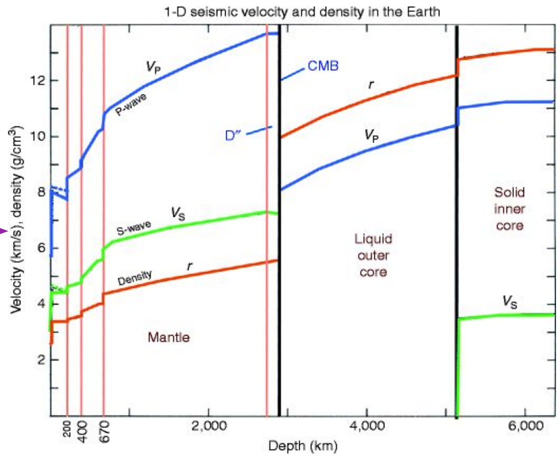
- Interior of Earth
- Atmospheric Neutrinos
- Earth's Matter Effect in Neutrino Oscillations
- Validating Earth's Matter Effect at IceCube-DeepCore
    - IceCube-DeepCore Detector
    - Expected Sensitivity

The Interior of Earth

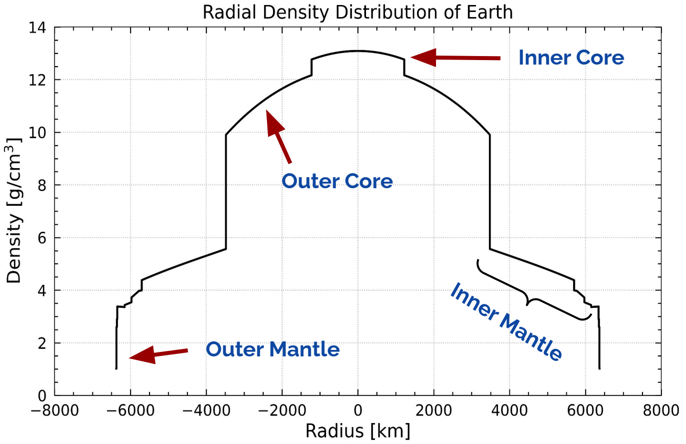
- Information about the interior of Earth is obtained from indirect probes using traditional **seismic** and **gravitational** studies → **Preliminary Reference Earth Model (PREM)**



JHEP 04 (2023) 068



"PREM" Dziewonski and Anderson (1981)

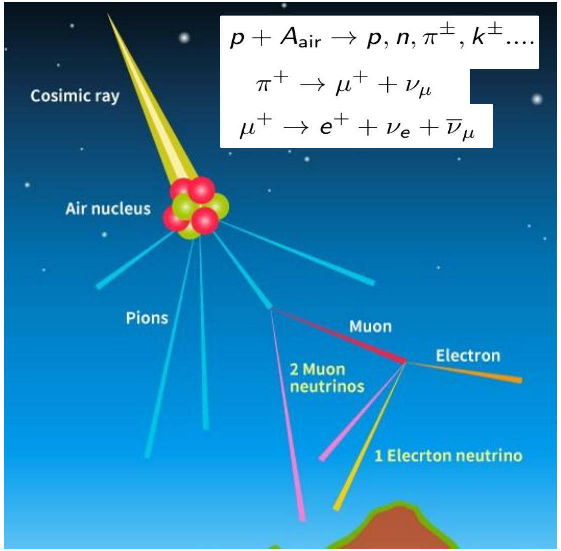


- Broadly classified: two concentric shell - the outer one is mantle, and the inner one with a much higher density is core
- Mantle consists of hot rocks of silicate and core is composed of metals like iron and nickel
- Outer core is expected to be liquid (absence of S-waves and decrease in the velocity of P-waves)
- Core-Mantle Boundary (CMB): the largest chemical compositional and density discontinuity within the Earth

Atmospheric Neutrinos

At high (TeV-PeV) energies: Neutrino absorption tomography

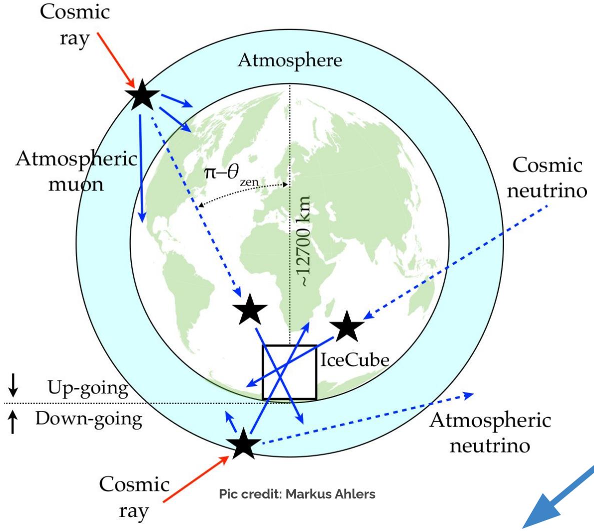
- Produced a few km above the Earth's surface by primary cosmic ray interactions



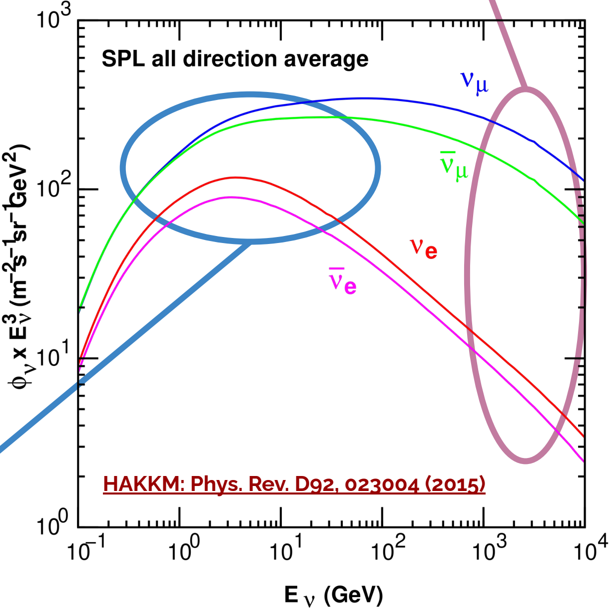
$$p + A_{\mathrm{air}} \rightarrow p, n, \pi^{\pm}, k^{\pm} \ldots$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$



Pic credit: Markus Ahlers

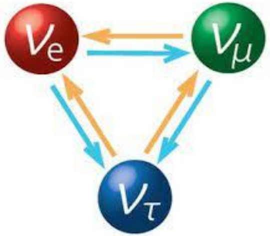


HAKKM: Phys. Rev. D92, 023004 (2015)

At low (MeV-GeV) energies: Neutrino oscillation tomography

- **Baseline:** ~20 km to 12760 km
- **Wide energy range:** few MeV to more than TeV

Neutrino Oscillations



- Neutrino changes its flavor while propagating
- Quantum mechanical phenomenon
- Mixing described by PMNS matrix (U)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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, $\Delta = \frac{\Delta m^2_{31} L_\nu}{4E_\nu}, \quad \Delta m^2_{ij} = m^2_i - m^2_j, \quad \text{and} \quad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$

In the two-flavor approximations:

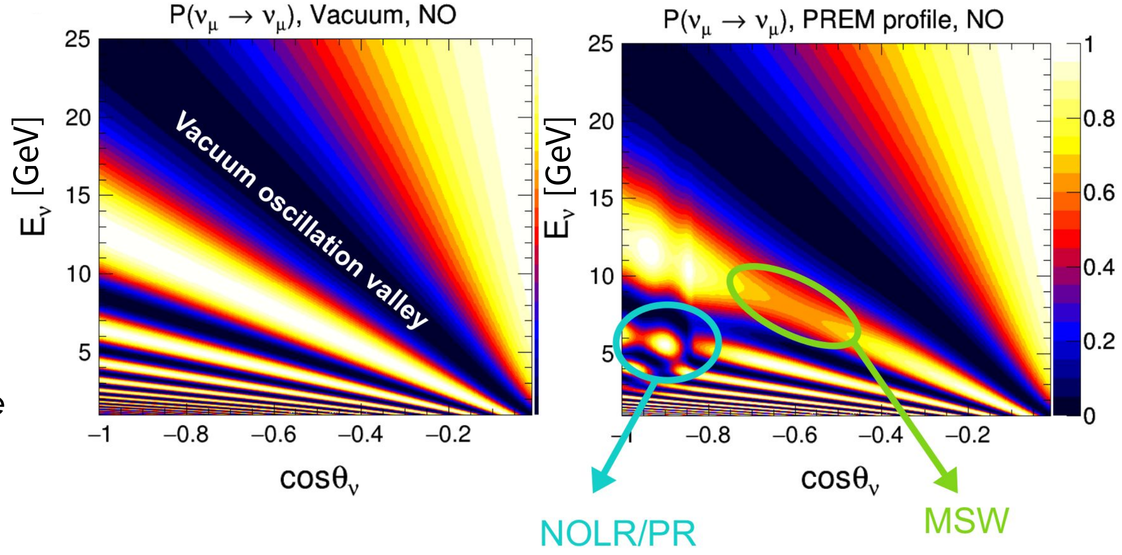
$$\boxed{P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2_{32} L}{E}\right)}$$

Earth's Matter Effect in Neutrino Oscillations

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

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

where, $Y_e = N_e/(N_p + N_n)$, corresponds to the relative electron number density inside the matter and ρ denotes the matter density



Mikheyev–Smirnov–Wolfenstein (MSW) resonance
(L. Wolfenstein, PRD 17 (1978) 2369): 6 GeV < E_ν < 10 GeV

Neutrino oscillation length resonance (NOLR) (Petcov, PLB 434 (1998) 321)/**parametric resonance resonance (PR)** (Akhmedov, NPB 538 (1999) 25): 2 GeV < E_ν < 6 GeV

Earth's Matter Effects: key to Probe Internal Structure of Earth

- Earth's matter effect driven neutrino oscillation measurements provide a complementary and independent information about internal structure of Earth

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

- ρ: matter density ⟶ Density of each layer inside Earth
- $Y_e = N_e/(N_p + N_n)$: relative electron number density ⟶ Chemical composition of Earth

Neutrino oscillations help us to:

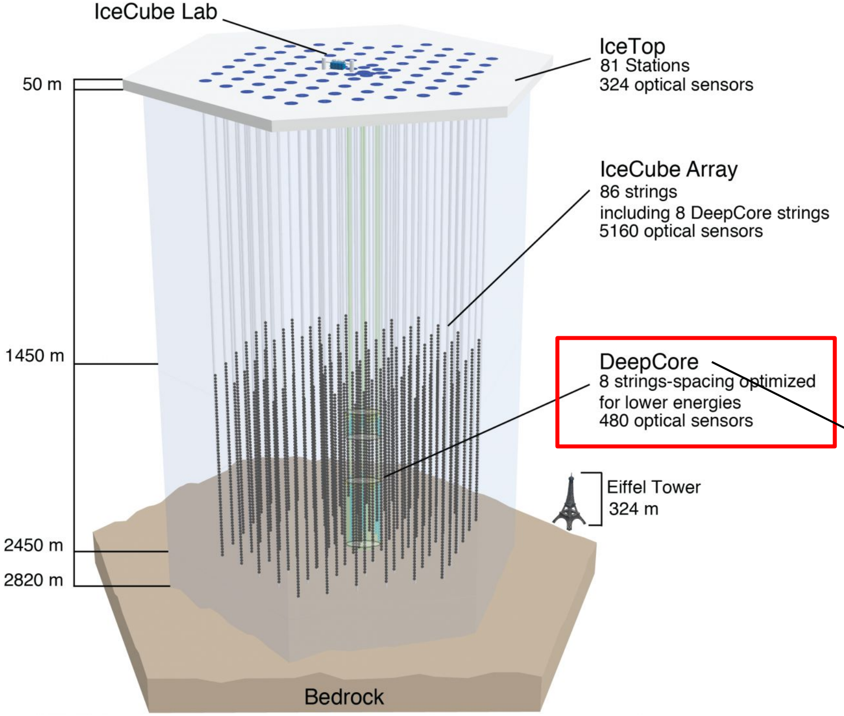
- Establish layered structure inside Earth
- Measure the mass of Earth and core

Next talk by Krishnamoorthi J

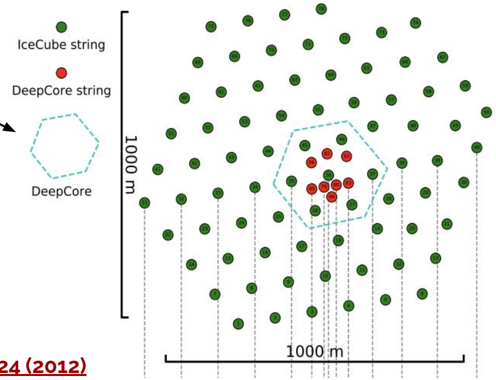
Next talk by S. Chattopadhyay

- **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 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

IceCube-DeepCore Neutrino Telescope



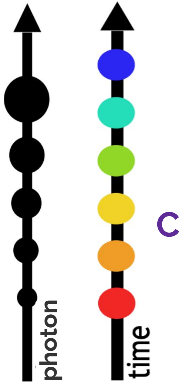
- 1 km^3 neutrino detector deep under ice at South Pole
- Three components: IceTop, IceCube and DeepCore
- Neutrino interactions inside ice produce secondary charged particles
- Secondary charged particles emit Cherenkov photons
- 5160 digital optical modules (DOMs) detect Cherenkov photons
- IceCube can detect neutrinos up to **PeV energies**
- **DeepCore:** Denser sub-array in the bottom central region can observe low-energy neutrinos at **GeV-scale**

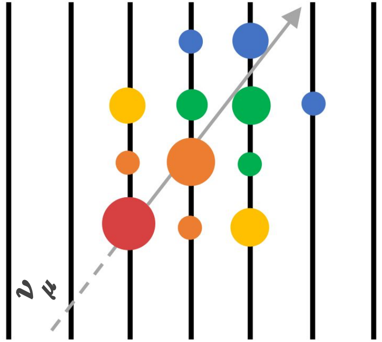


Ref. : The design and performance of IceCube DeepCore: Astroparticle Physics, 35(10), 615-624 (2012)

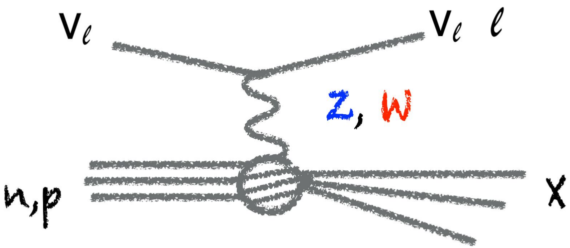
Event Signatures in IceCube-DeepCore

Track-like events:

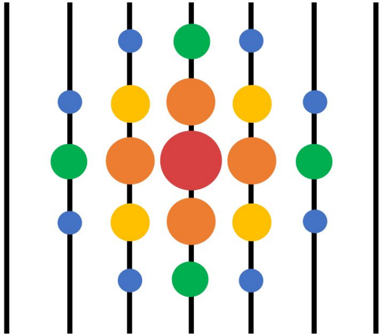




- Elongated
- Source: ν_μ CC



Cascade-like events:



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

Signals:

- ν_e , ν_μ , ν_τ
- Predominantly DIS interactions

Backgrounds:

- Atmospheric muons
- Random detector noise

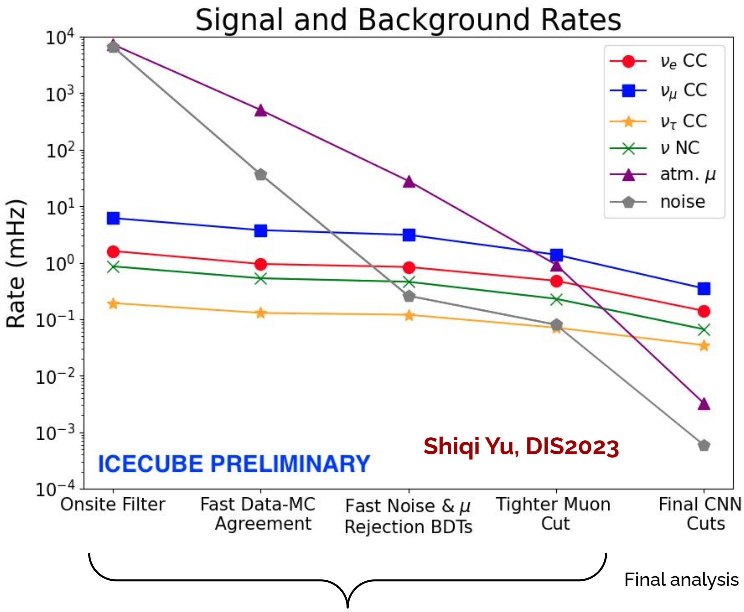
Observables:

- Energy
- Direction
- Event type (PID)

Simulated Neutrino Event Sample

- Convolutional Neural Networks (CNN) based reconstruction
- Monte Carlo (MC) sample exposure: 9.3 years (2012 - 2021)
- Large number of statistics (~192k events)
- Neutrinos comprise 99.5% of sample
- High statistics (ν_μ CC)
- Filters are applied to eliminate primary backgrounds: noise and atm. muon contamination (~0.5%)

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	–



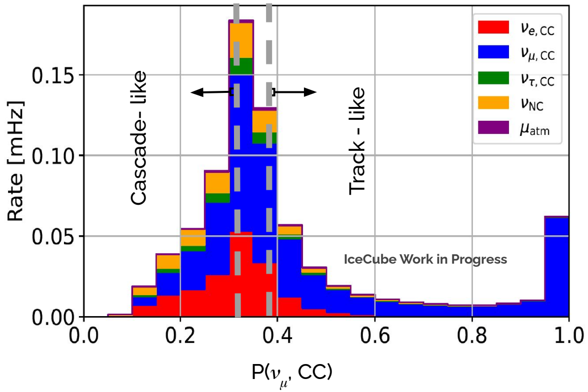
Final analysis cut

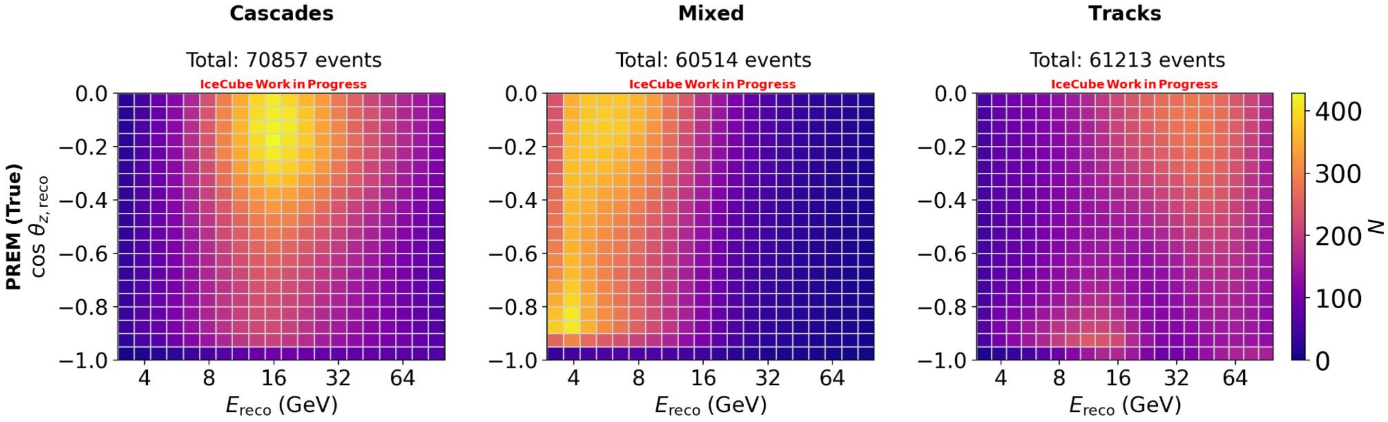
Event processing level (Filter)

3D Binning Scheme

- 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





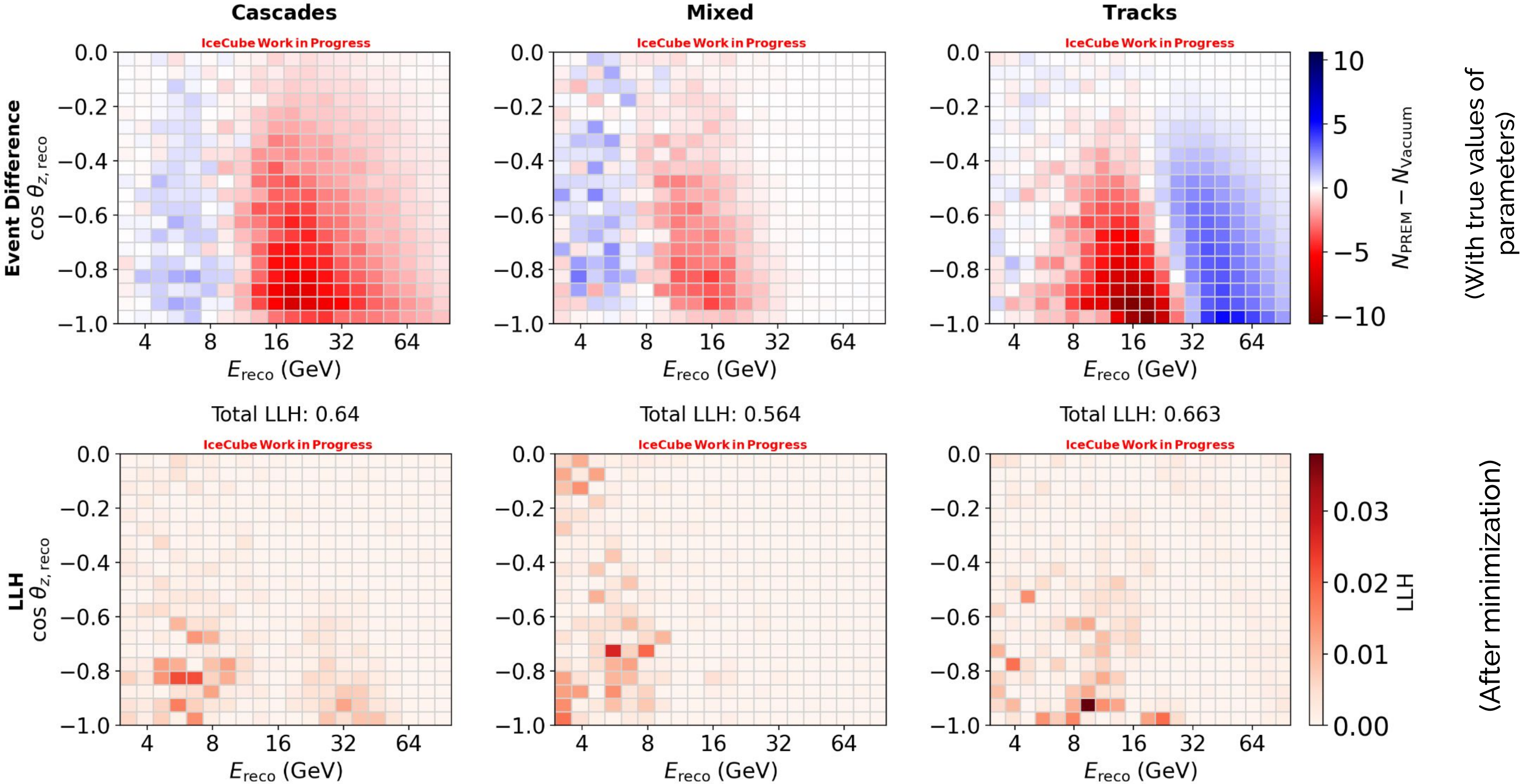
Systematic Uncertainties Considered

- **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 The Cryosphere 14, 2537 (2020)
    - 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

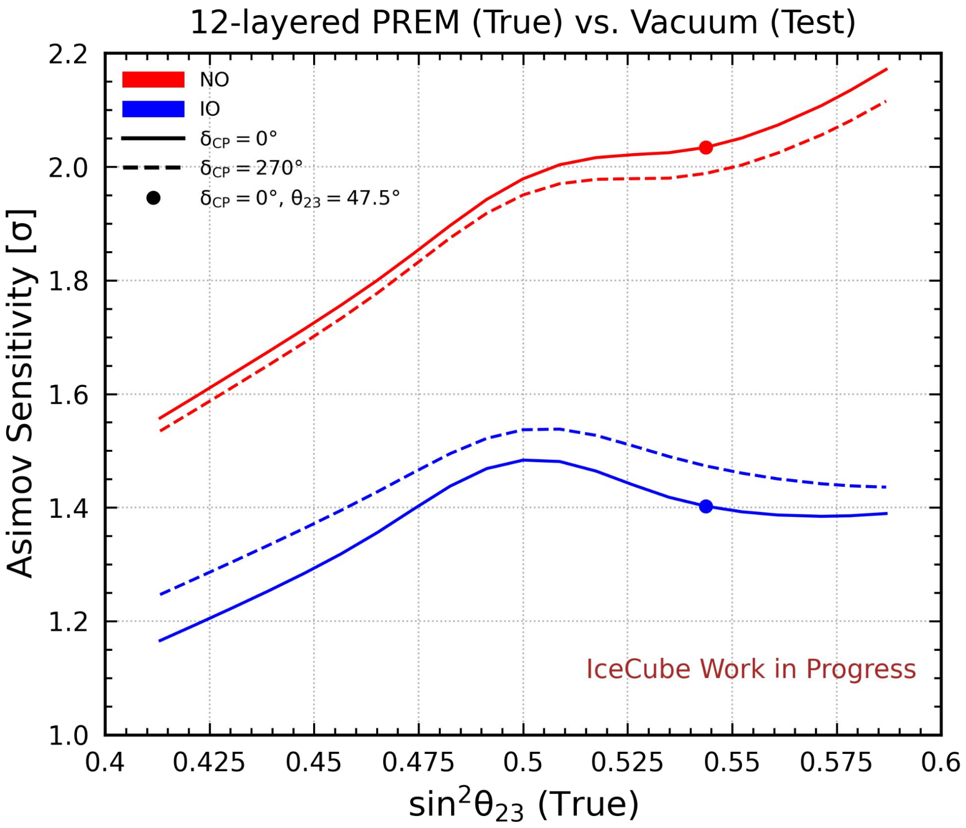
For more details, see: Phys.Rev.D 108 (2023) 1, 012014

Distributions of Simulated Event Differences & LLH, NO



- Most of the LLH contribution comes from lower energy and higher baselines

Asimov Sensitivity to Reject Vacuum Hypo. with IceCube-DeepCore

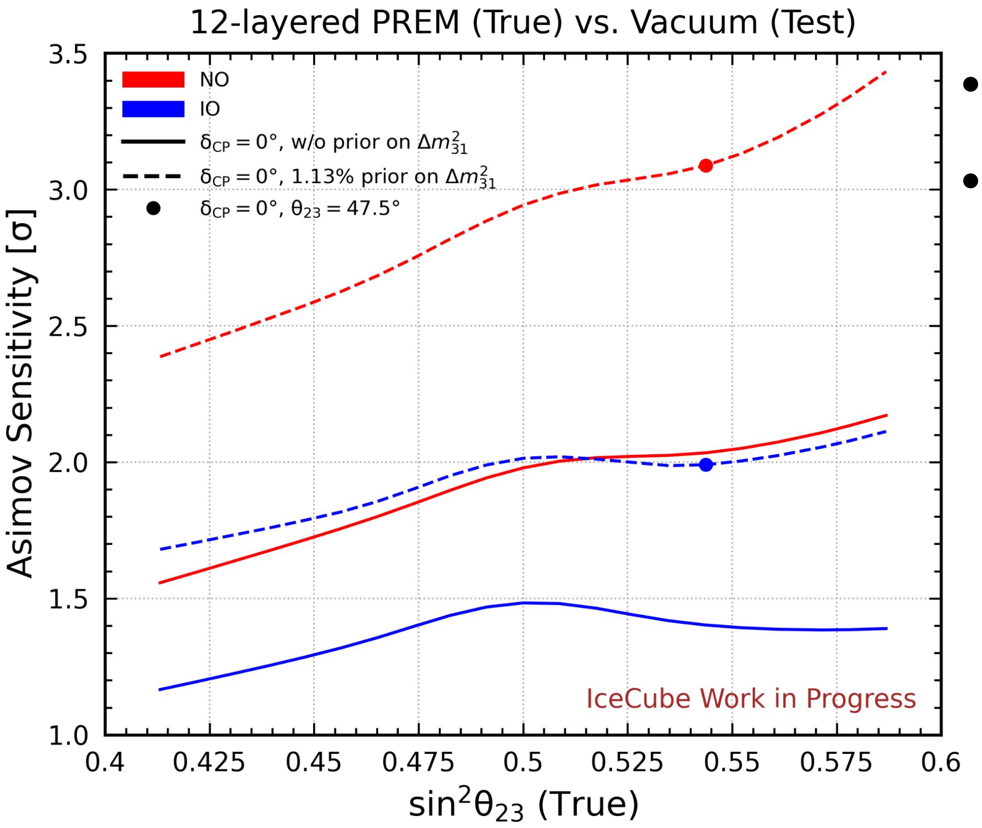


- **True hypo.:** 12-layered PREM
- **Test hypo.:** Vacuum
- Minimized over relevant oscillation and systematic parameters
- Sensitivity for NO is higher than IO due to the lower cross section and flux rate of antineutrino

- **For NO: θ_{23} = 47.5° & δ_{CP} = 0°**
  - **Sensitivity = 2.0 σ**
- **For IO: θ_{23} = 47.5° & δ_{CP} = 0°**
  - **Sensitivity = 1.4 σ**

- Super-K excludes the vacuum oscillations at 1.6σ
PRD 97, 072001 (2018)

Impact of prior on Δm^2_{31}



- Measurement of Δm^2_{31} and the matter effects have degeneracy
- Freely varying Δm^2_{31} will dilute the sensitivity of matter effect measurements
- Degeneracy effect can be reduced using some external information as a prior on Δm^2_{31}

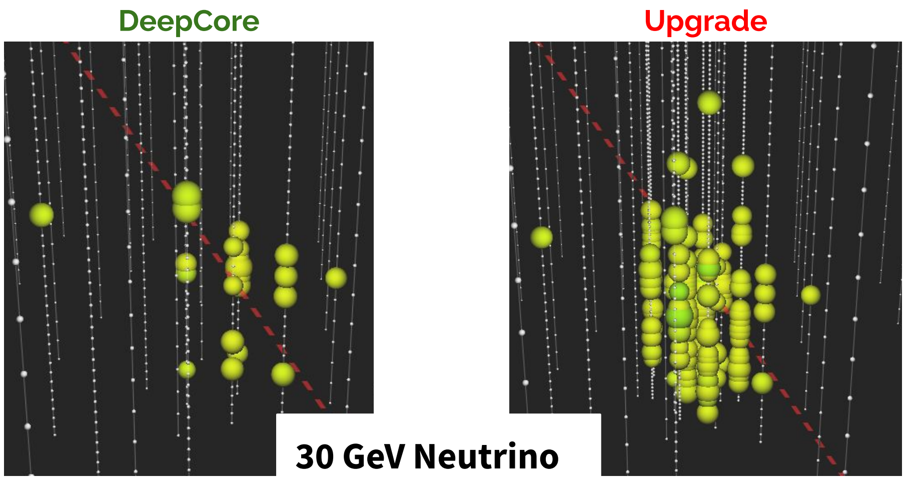
1.13% Gaussian prior on Δm^2_{31} around 0.00247 eV²
σ = ± 0.000028 eV²

True Mass Ordering	Asimov Sensitivity [σ]	
	w/o prior	w prior
NO	2.0	**3.1**
IO	1.4	**2.0**

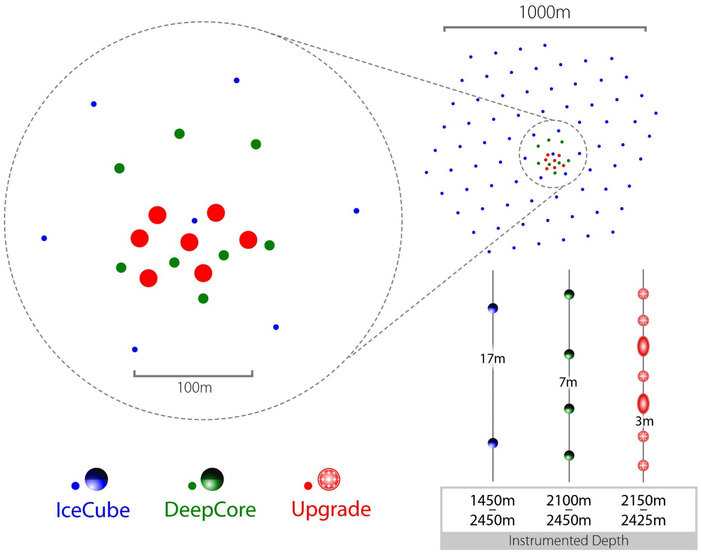
- External information as a prior on Δm^2_{31} enhance the significance by 50%

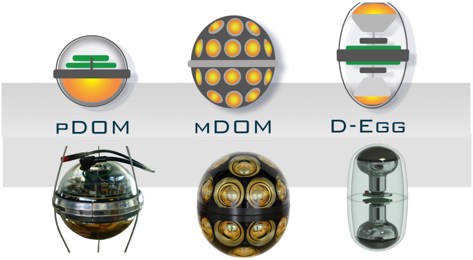
What Next: The IceCube Upgrade

- Increased density of strings in center region of detector
- 7 new strings (Fiducial volume ~ 2 Mton)
- Energy threshold ~ 1 GeV
- Target deploying 2025/26



30 GeV Neutrino





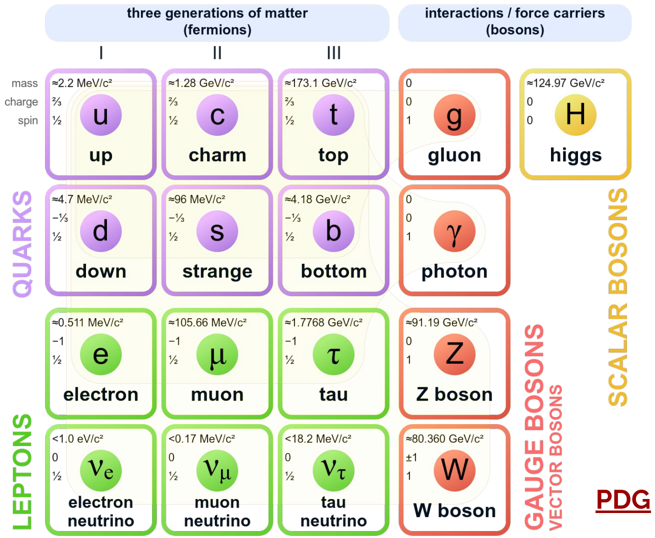
ICRC2019 arXiv:1908.09441 ICRC2023 arXiv:2307.15295

Summary

- Atmospheric neutrinos have energies in the multi-GeV range where the Earth matter effects are significant
- Matter effects would serve as probes of various standard and beyond standard scenarios
- In combination with gravitational and seismic studies, neutrino oscillations and absorption based measurements would pave the way for **“Multi-Messenger Tomography of Earth”**
- Using high statistics (~ 192 k events in 9.3 yr of data), low-energy threshold (~ 3 to 5 GeV), access to multiple baselines, optimized binning scheme in reconstructed energy and zenith, efficient PID, we expect that **IceCube-DeepCore can validate the presence of Earth’s matter effect with ~ 2.0σ C.L for NO**

Backup

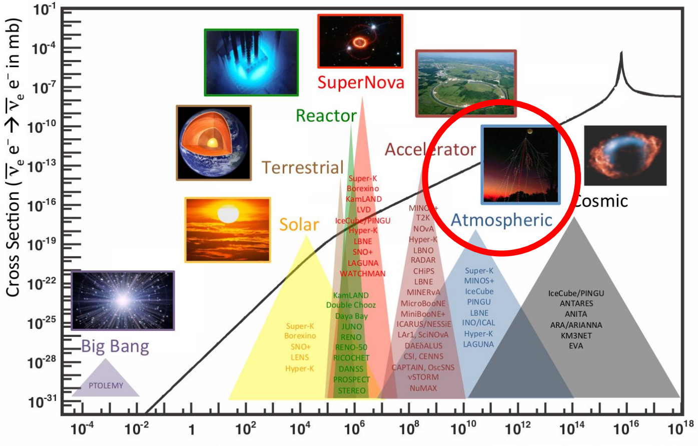
Neutrinos in the Standard Model (SM)



PDG

- Three active neutrinos: ν_e , ν_μ , and ν_τ
- Zero charge (neutral)
- Fermion (spin 1/2)
- Only couple via weak force (and gravity)
- Neutrinos are massless in the basic SM

Sources of neutrinos

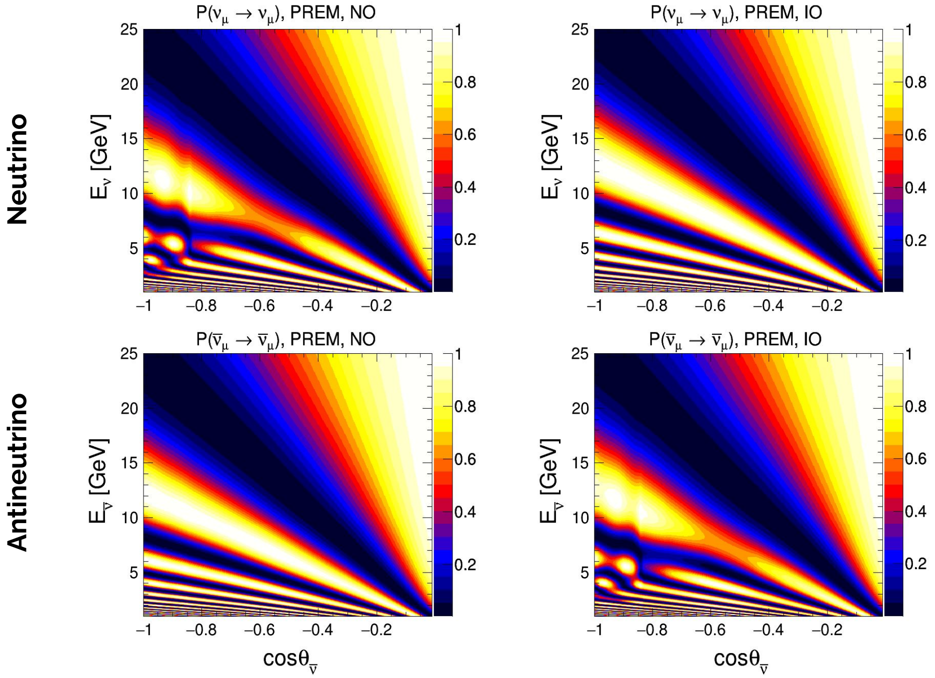


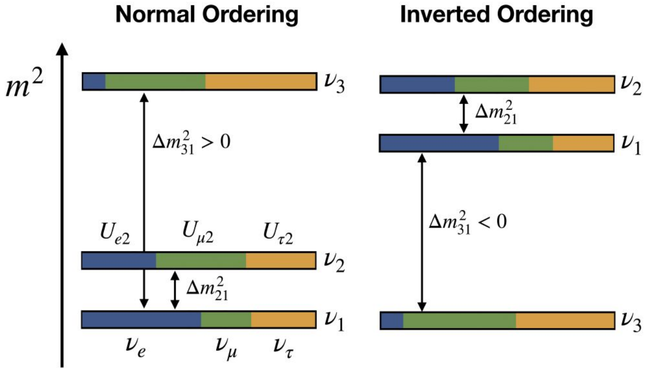
arXiv:1310.4340v1

- Almost massless: at least a million times lighter than electron
- Non-zero neutrino mass: first experimental proof (gateway) for BSM physics

Earth's Matter Effects: key to Probe Neutrino Mass ordering

- **Neutrino Mass Ordering (NMO):** sign of Δm^2_{31} is unknown
  - Normal (NO): $m_3 > m_2 > m_1$ or Inverted (IO): $m_2 > m_1 > m_3$?





NuFACT 2022, Phys. Sci. Forum 2023, 8(1), 7

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

True NO: $+\Delta m^2_{31}$ **True IO:** $-\Delta m^2_{31}$

Resonance occurs for neutrinos if NO is true or antineutrinos if IO is true

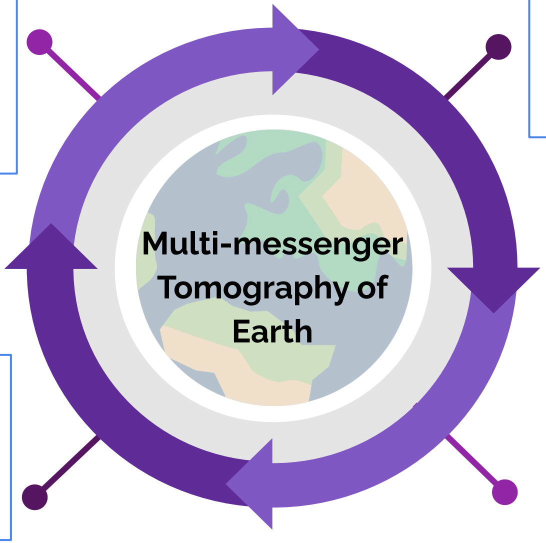
Multi-messenger Tomography of Earth

Seismic Studies

- Uses seismic waves from earthquakes
- Electromagnetic interactions

Gravitational Measurement

- Gravitational interactions
- Total mass & moment of inertia



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) neutrinos with electrons

Geoneutrinos

- Brings crucial information about the mantle
- Radiogenic contribution to Earth's heat budget

Present study is based on Earth's matter effects in atmospheric neutrino oscillations at IceCube-DeepCore

PREM Profile vs. Vacuum

By rejecting the vacuum hypothesis with respect to the PREM hypothesis, we aim to distinguish which hypothesis is favoured by atmospheric neutrino data

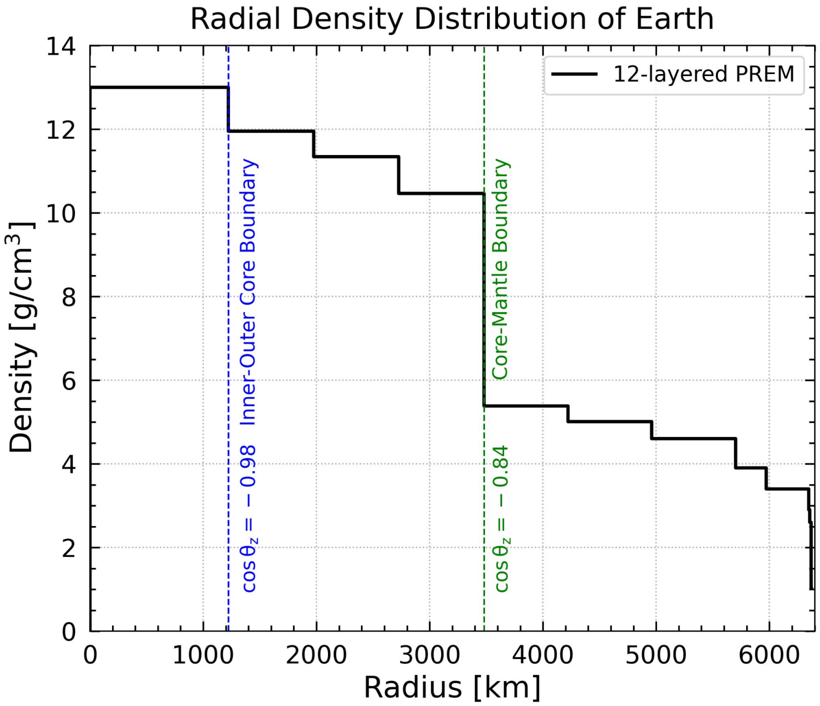
- 12-layered PREM profile
- For PREM profile, electron number density ratio:

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

Y_e (Inner Core) = 0.4656 (1 layer)

Y_e (Outer Core) = 0.4656 (3 layers)

Y_e (Mantle) = 0.4957 (8 layers)



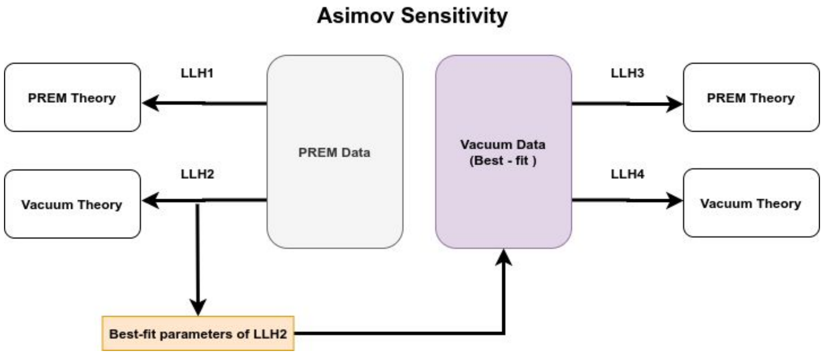
Statistical Methods

- **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

- **Asimov Sensitivity to reject vacuum hypothesis**



(For the assumption of true PREM)

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

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

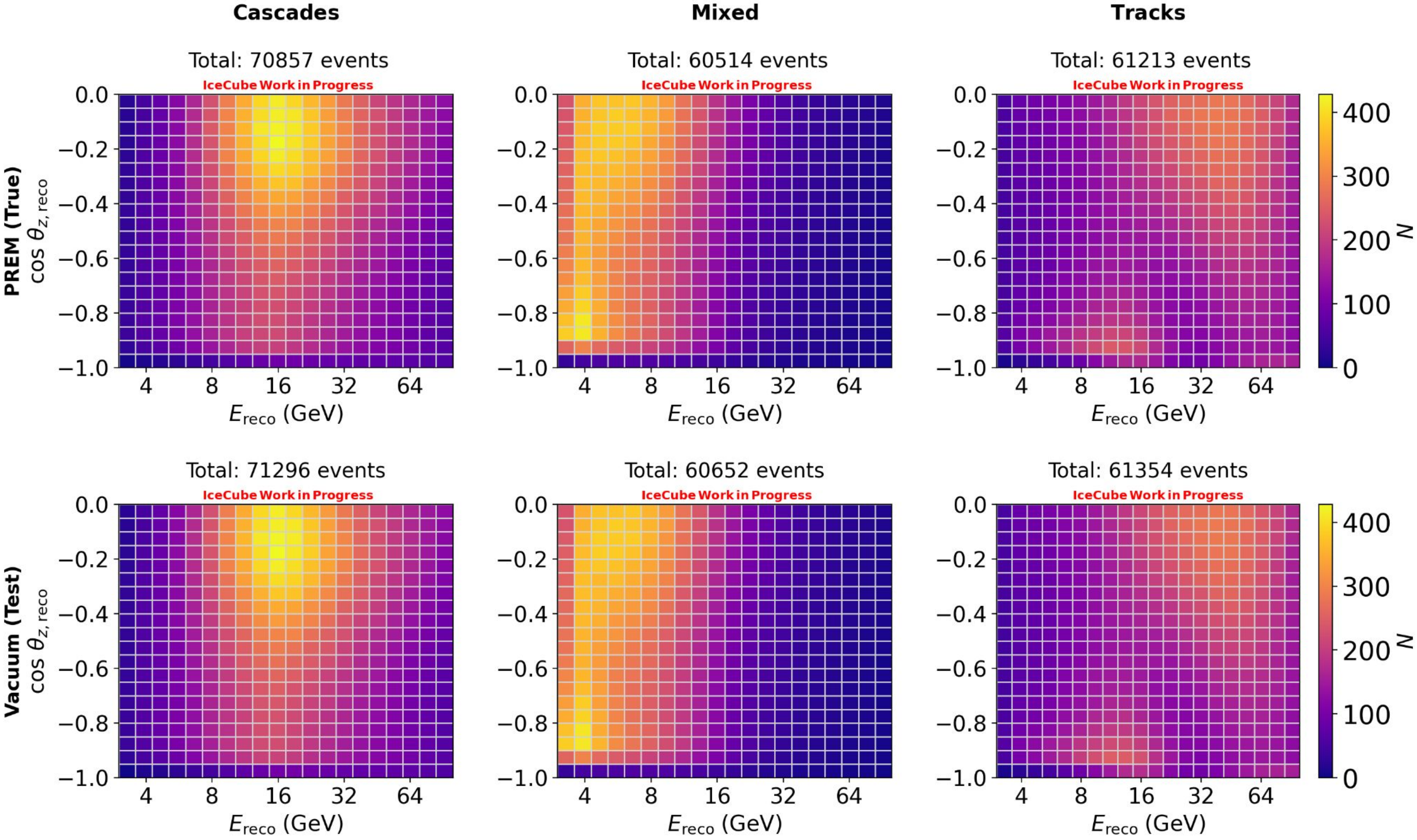
See: Mattias Blennow et al., (JHEP 03 (2014) 028) , X Qian et al., (PRD 86 113011 (2012)), and Emilio Ciuffoli et al., (JHEP 01 (2014) 095)

Systematic Treatment

	Param	Nominal	Range	Fixed/Free
Flux (19)	**Delta_index ($\Delta\gamma_\nu$)**	0 ± 0.1	[-0.5, 0.5]	Free
	pion_ratio	0	[-0.25, 0.25]	Fixed
	barr_a_Pi	0	[-0.5, 0.5]	Fixed
	barr_b_Pi	0	[-1.5, 1.5]	Fixed
	barr_c_Pi	0	[-0.5, 0.5]	Fixed
	barr_d_Pi	0	[-1.5, 1.5]	Fixed
	barr_e_Pi	0	[-0.25, 0.25]	Fixed
	barr_f_Pi	0	[-0.5, 0.5]	Fixed
	barr_g_Pi	0 ± 0.3	[-1.5, 1.5]	Free
	barr_h_Pi	0 ± 0.15	[-0.75, 0.75]	Free
	barr_i_Pi	0 ± 0.61	[-3.05, 3.05]	Free
	barr_w_K	0 ± 0.4	[-2.0, 2]	Free
	barr_x_K	0	[-0.5, 0.5]	Fixed
	barr_y_K	0 ± 0.3	[-1.5, 1.5]	Free
	barr_z_K	0	[-3.05, 3.05]	Fixed
	barr_w_antiK	0	[-2.0, 2]	Fixed
	barr_x_antiK	0	[-0.5, 0.5]	Fixed
	barr_y_antiK	0	[-1.5, 1.5]	Fixed
	barr_z_antiK	0	[-0.61, 0.61]	Fixed

	Param	Nominal	Range	Fixed/Free
Oscillations (6)	**θ_{12}**	33.41	[31.31, 35.74]	Fixed
	θ_{13}	8.54	[8.19, 8.89]	Fixed
	θ_{23}	47.5	[38, 52]	Free
	δ_{CP}	0	[0, 360]	Fixed
	Δm^2_{21}	7.41e-05	[6.82e-05,8.03e-05]	Fixed
	Δm^2_{31}	2.47e-03	[0.001, 0.004]	Free
Cross section (3)	**M_A(QE) (0.99 GeV)**	0 ± 1	[-2.0, 2.0]	Free
	M_A(RES) (1.12 GeV)	0 ± 1	[-2.0, 2.0]	Free
	dis_csms	0 ± 1	[-3.0, 3.0]	Free
Neutrino weight (1)	**N_ν (Neutrino scale)**	1	[0.1, 2.0]	Free
Detector (7)	**Dom_eff**	1 ± 0.1	[0.8, 1.2]	Free
	hole_ice_p0	0.101569	[-0.6, 0.5]	Free
	hole_ice_p1	-0.049344	[-0.2, 0.2]	Free
	bulk_ice_abs	1 ± 0.05	[0.9, 1.1]	Free
	bulk_ice_scatter	1.05 ± 0.1	[0.85, 1.25]	Free
	bfr_eff	0	[0, 1]	Free
	muon light yield	0.0	[0, 1]	Free
Atm. muon (2)	**$\Delta\gamma_\mu$ (atm. muon index)**	0	[-3.0, 3.0]	Fixed
	N_μ (atm. muon scale)	1 ± 0.4	[0.0999, 3.0]	Free

Simulated Event Distributions, NO



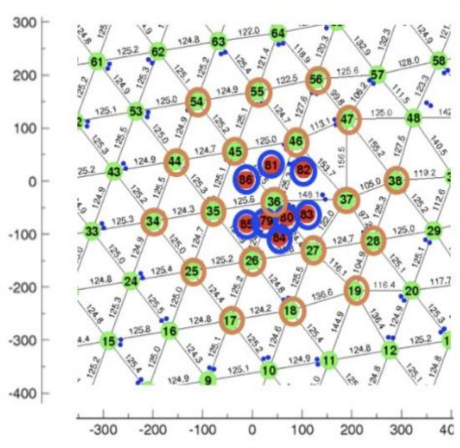
- **PREM & Vacuum:** For true values of all oscillation and systematic parameters

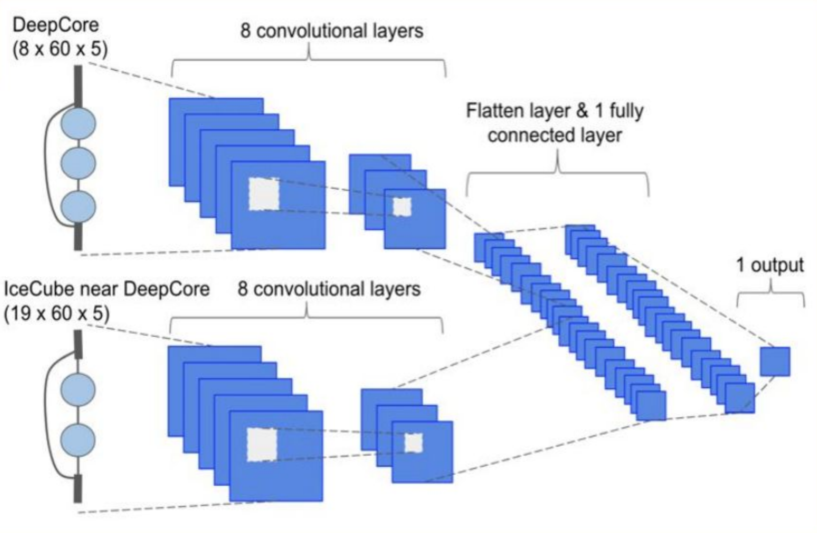
Convolutional Neural Networks (CNNs)

DOI: 10.22323/1.395.1053

- Only use DeepCore & nearby IceCube strings;
- Five CNNs trained on balanced MC samples: optimized for different variables.

Shiqi Yu, DIS2023

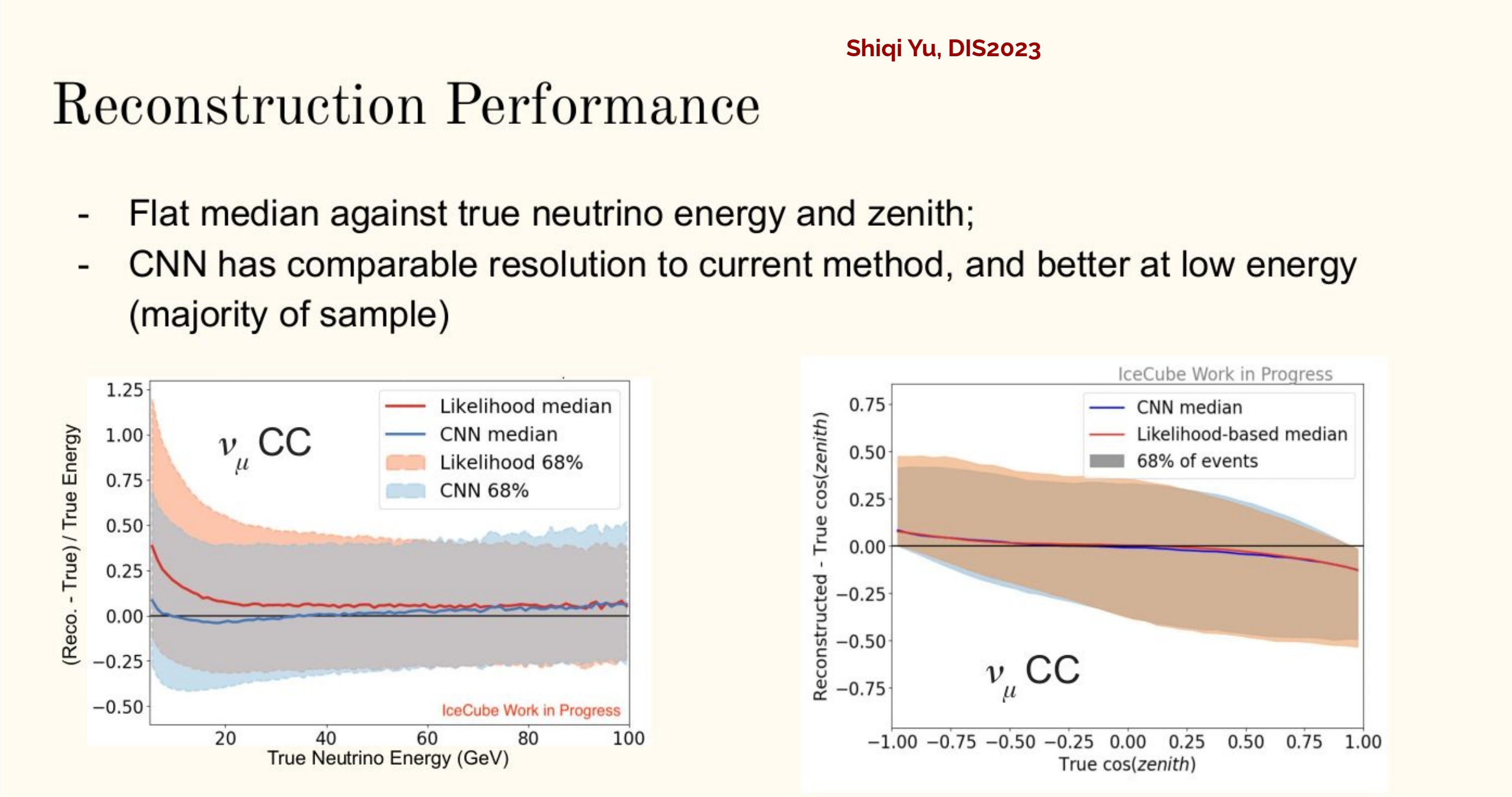




5 summarized variables per DOM:

- sum of charges
- time of first (last) pulse
- charge weighted mean (std.) of times of pulses

Reconstruction Performance



Shiqi Yu, DIS2023

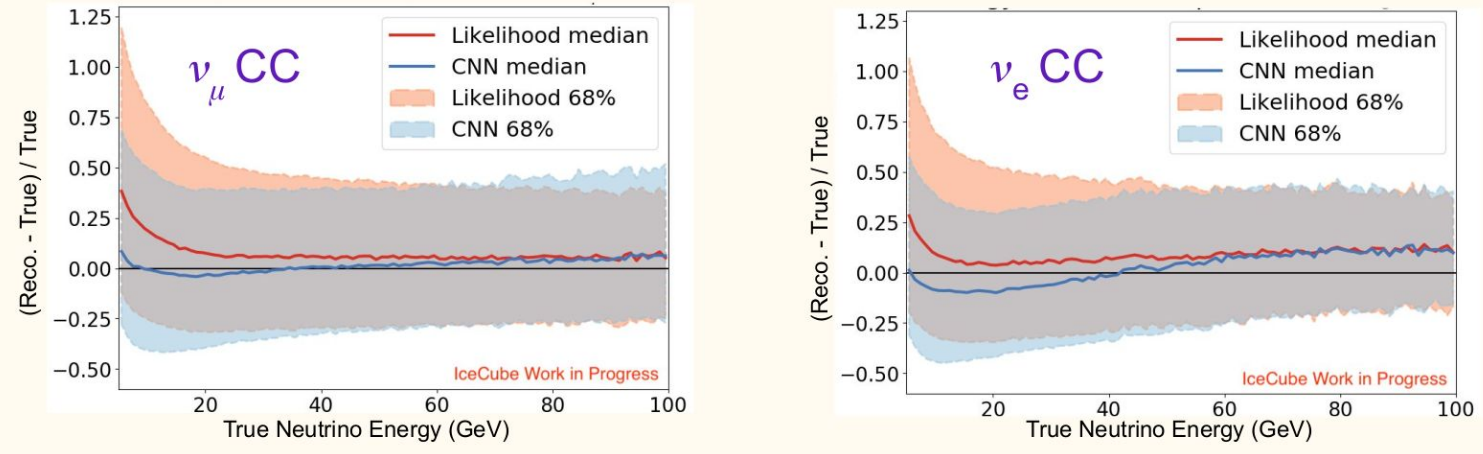
Reconstruction Performance

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

Final Level Resolution: Energy

J. Micallef, et al. ICRC 2021 proceeding

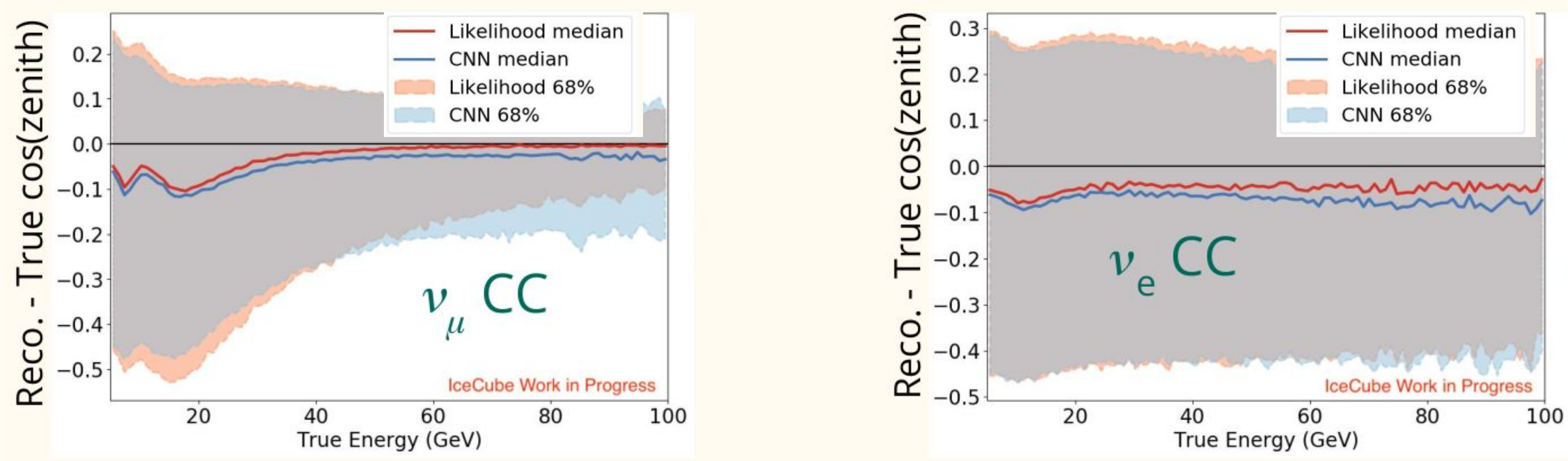
- Flat median against true neutrino energy:
  - CNN has better resolution at low energy (majority of sample)



Resolution of energy reconstruction as a function of true neutrino energy

Final Level Resolution: Zenith

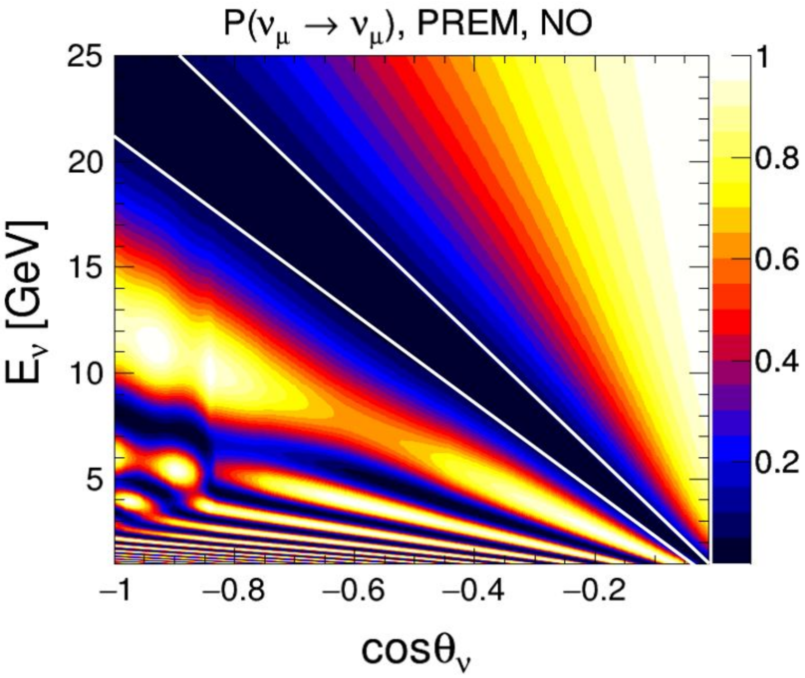
- Direction bias flat against true energy
- Better resolution for ν_μ CC (signal)



Resolution of zenith reconstruction as a function of true neutrino energy

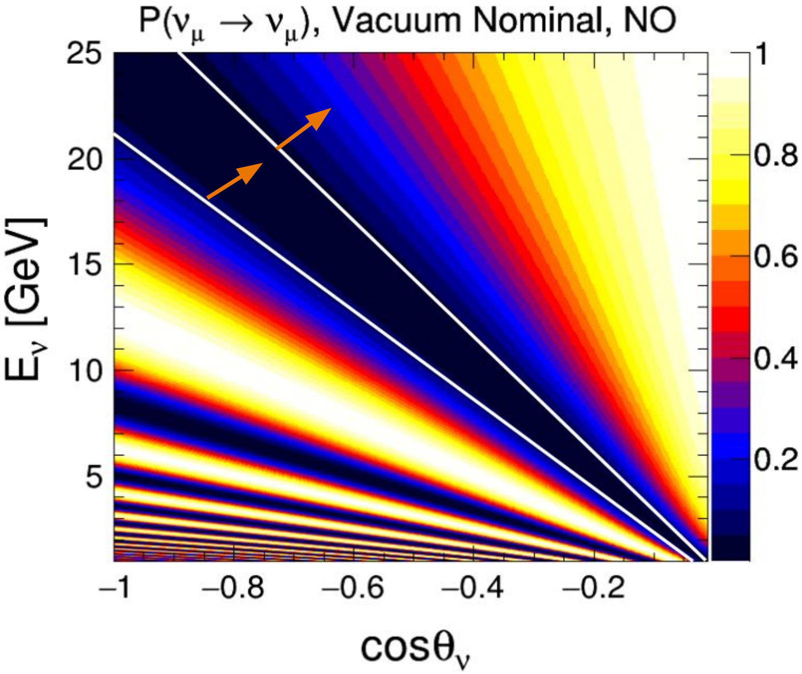
Impact of free Δm^2_{31}

- $P(\nu_\mu \rightarrow \nu_\mu)$ probability oscillogram for **PREM profile at nominal value** of Δm^2_{31} and θ_{23}
  - $\Delta m^2_{31} = 2.48\times10^{-3}$ eV^2 (Nominal) and $\theta_{23} = 45^\circ$



Impact of free Δm^2_{31}

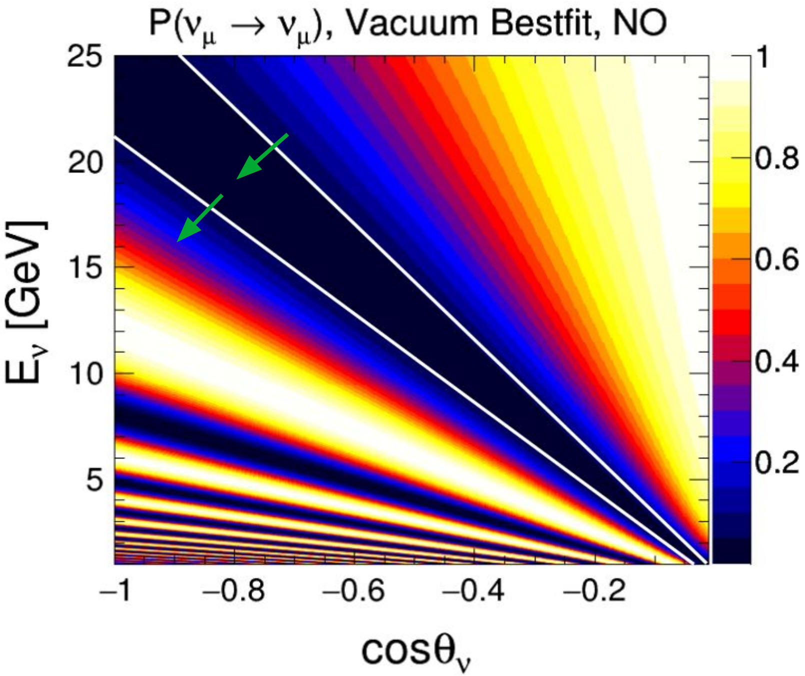
- $P(\nu_\mu \rightarrow \nu_\mu)$ probability oscillogram for **vacuum profile at nominal value** of Δm^2_{31} and θ_{23}
  - $\Delta m^2_{31} = 2.48\times10^{-3}$ eV^2 (Nominal) and $\theta_{23} = 45^\circ$



- From matter to nominal vacuum, valley shifted upwards

Impact of free Δm^2_{31}

- $P(\nu_\mu \rightarrow \nu_\mu)$ probability oscillogram for **vacuum profile at best-fit value** of Δm^2_{31} and θ_{23}
  - $\Delta m^2_{31} = \boxed{2.39\times10^{-3}\ \text{eV}^2}$ (Best-fit) and $\theta_{23} = 45^\circ$



- From nominal vacuum to best-fit vacuum, the valley shifts downwards.