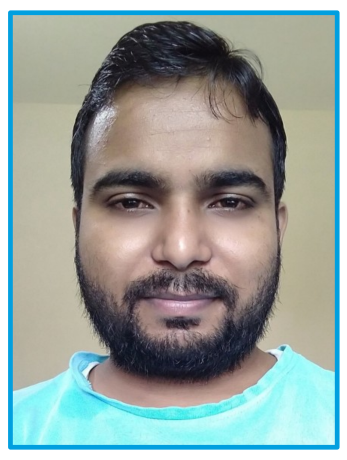
Probing Invisible Neutrino Decay using Oscillations of Atmospheric Neutrinos at IceCube DeepCore

ID #381



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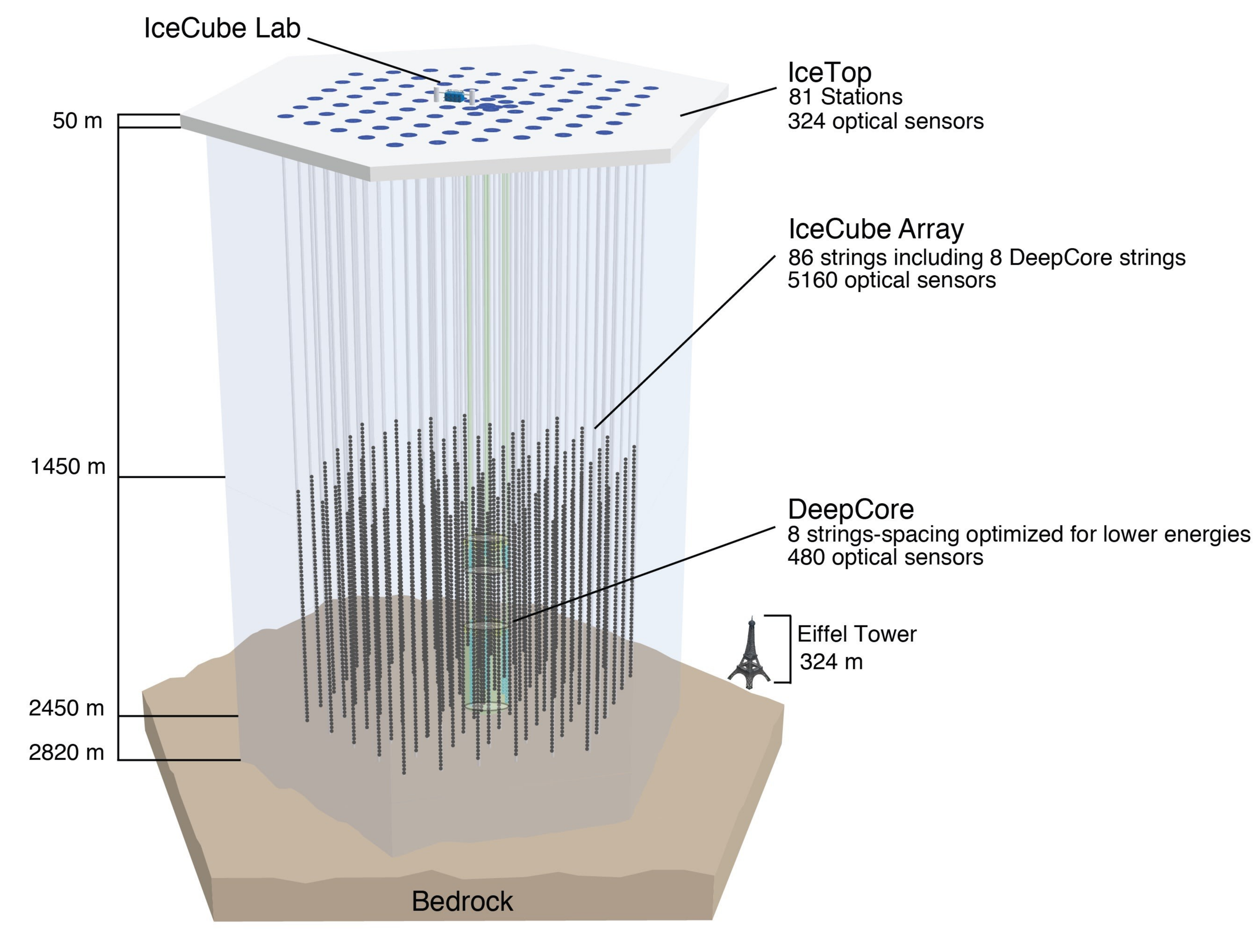
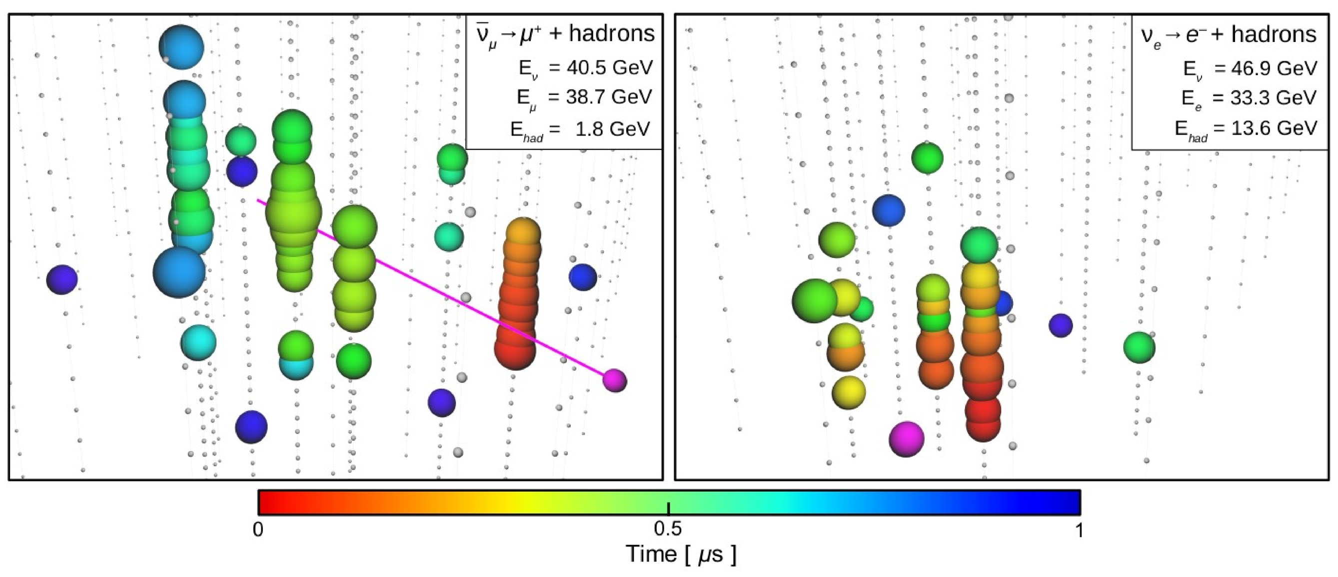
1. IceCube Neutrino Observatory



- Neutrino interactions inside ice produce secondary charged particles, which emit Cherenkov photons.
- Cherenkov photons are detected by the digital optical modules (DOMs).
- **DeepCore** is the bottom central region of IceCube having closely spaced DOMs with sensitivity to low-energy neutrinos at the **GeV scale.**
- DeepCore observes atmospheric neutrinos having
  - Baselines: ~ 20 km to 12750 km
  - Wide energy range: a few GeV to more than TeV
- In this analysis, we use DAEMON flux for atmospheric neutrinos [1].

2. Events at IceCube DeepCore



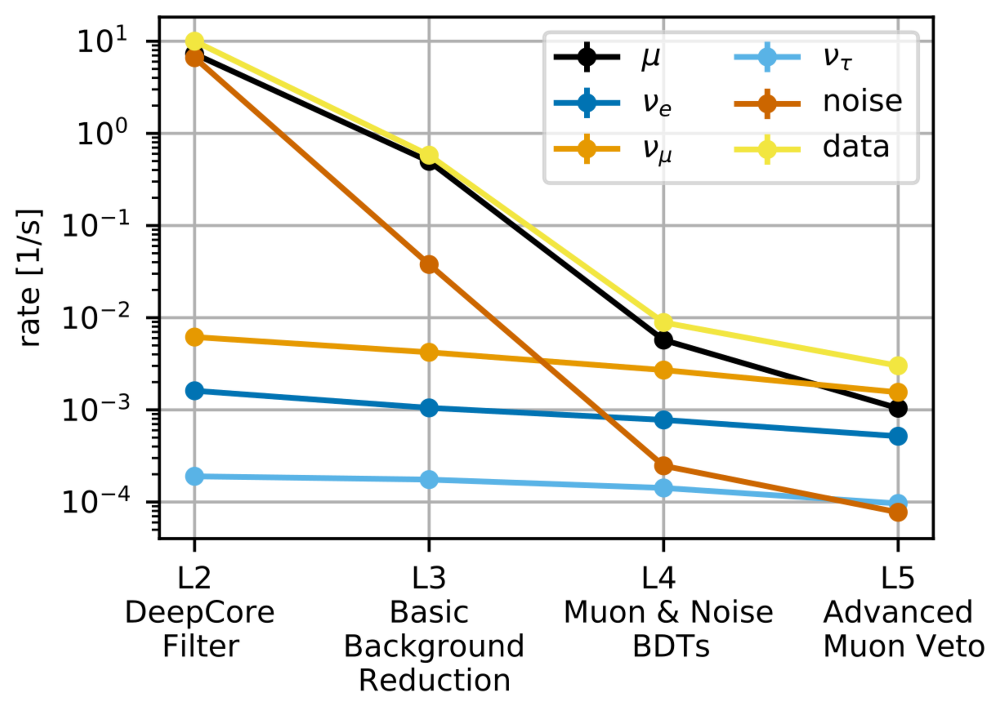
Track-like (ν_μ CC, Left) and cascade-like (ν_e CC, Right) events at DeepCore [2].

Signals:

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

Backgrounds:

- Atmospheric muons
- Random detector noise



Events rates after application of each filter [3].

Event Selection

- Filters at various levels reduce backgrounds such as noise and atmospheric muons by more than 6 orders of magnitude.
- Signal reduces by only 1 order of magnitude.
- The same filters are applied to data as well as simulated Monte Carlo (MC).

Reconstruction based on Convolutional Neural Network (CNN) [4]

- Trained for neutrino energy, arrival direction, interaction vertex, particle identification (PID), and atmospheric muon classification
- High statistics (~150k)
- Analysis using:
  - cascade-like, mixed & track-like events corresponding to PID bins: [0, 0.33, 0.39, 1]
  - E_{reco}: 20 log bins in [5, 100] GeV, $\cos\theta_{reco}$: 20 linear bins in [-1, 0]

3. Invisible Neutrino Decay

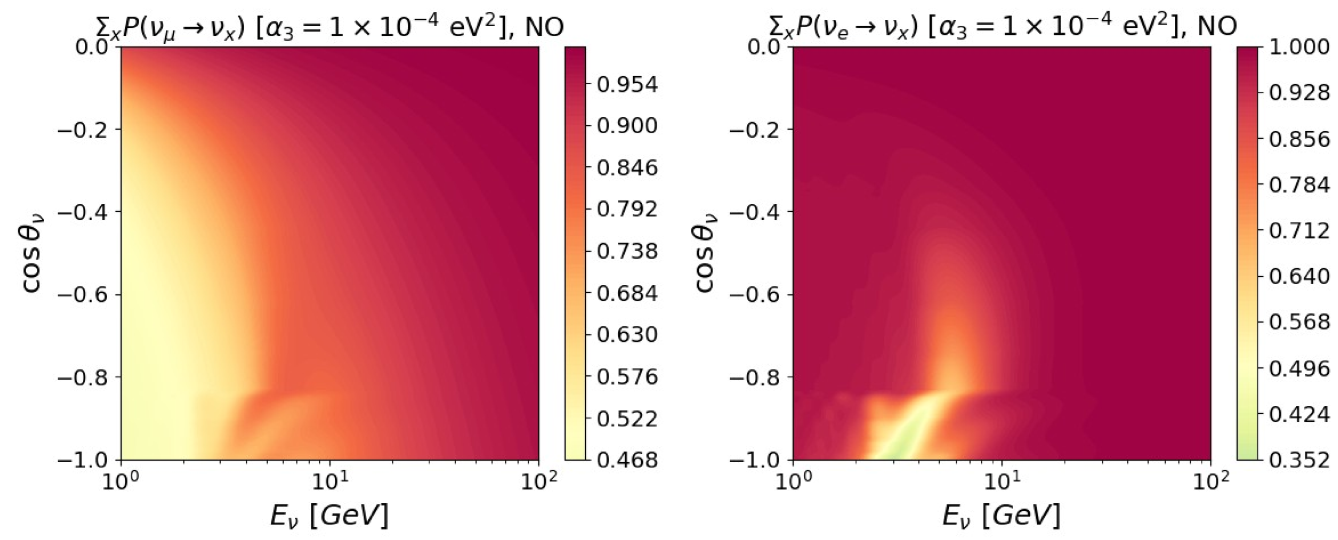
- Neutrinos could decay via invisible mode where either the decay products are sterile neutrinos or have sufficiently low energy to avoid detection [5 – 9].
- The heaviest mass eigenstate ν_3 (normal ordering) decays to a fourth sterile neutrino ν_4 with a lifetime of τ_3 in the rest frame

$$\nu_3 \rightarrow \nu_4 + J$$

  where J is a pseudo-scalar singlet, or Majoron.
- We assume that there is no mixing between the three active neutrinos and the sterile neutrino, so it cannot oscillate back into an active state.
- Modified Hamiltonian in the flavor basis:

$$H_{\text{Total}} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + U\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -i\alpha_3\end{pmatrix}U^\dagger\right] + \begin{pmatrix}V & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix},$$

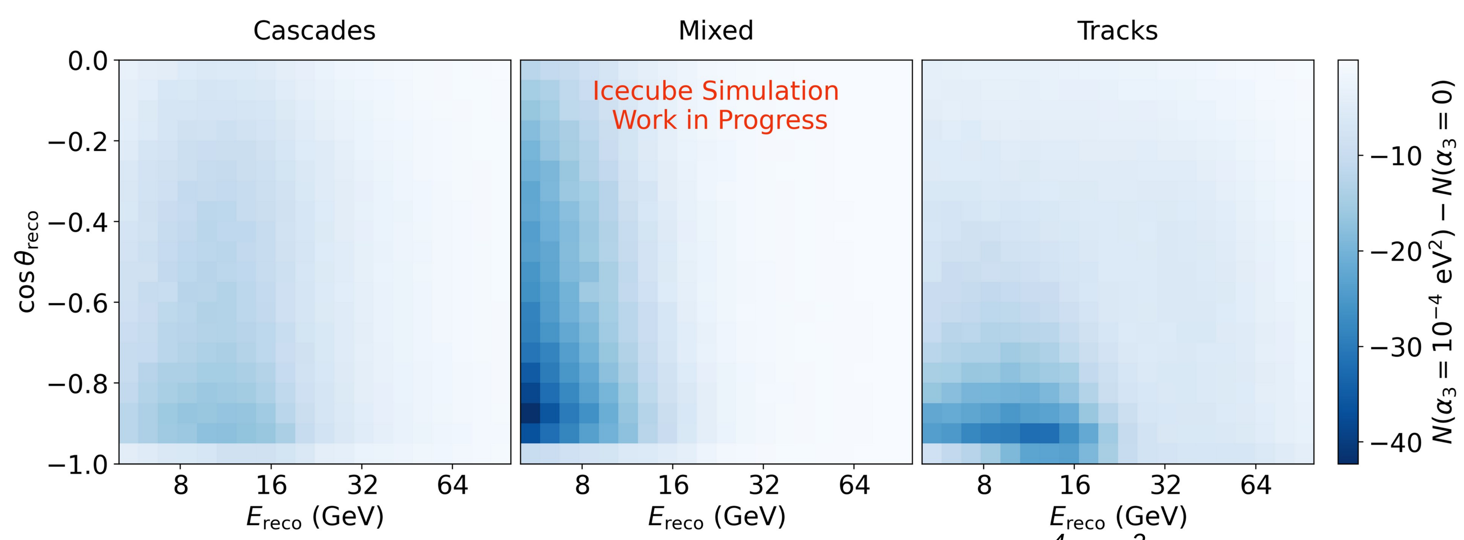
$$V = \pm\sqrt{2}N_e G_F \qquad \alpha_3 = m_3/\tau_3$$



Probabilities of ν_μ (left) and ν_e (right) to oscillate into active flavors.

- For demonstration purpose, the value of α_3 is taken to be larger than our sensitivity.
- The yellow regions appear due to the decay of ν_3 to the sterile state ν_4.

4. Analysis



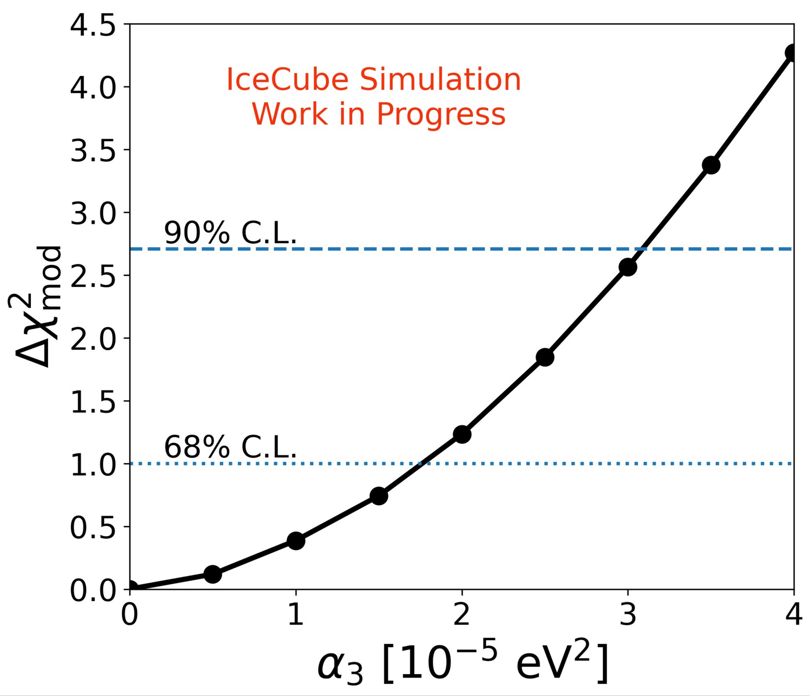
Difference of simulated events with decay ($\alpha_3 = 1 \times 10^{-4}$ eV^2) and without decay ($\alpha_3 = 0$) for the nominal choices of oscillation and systematic parameters.

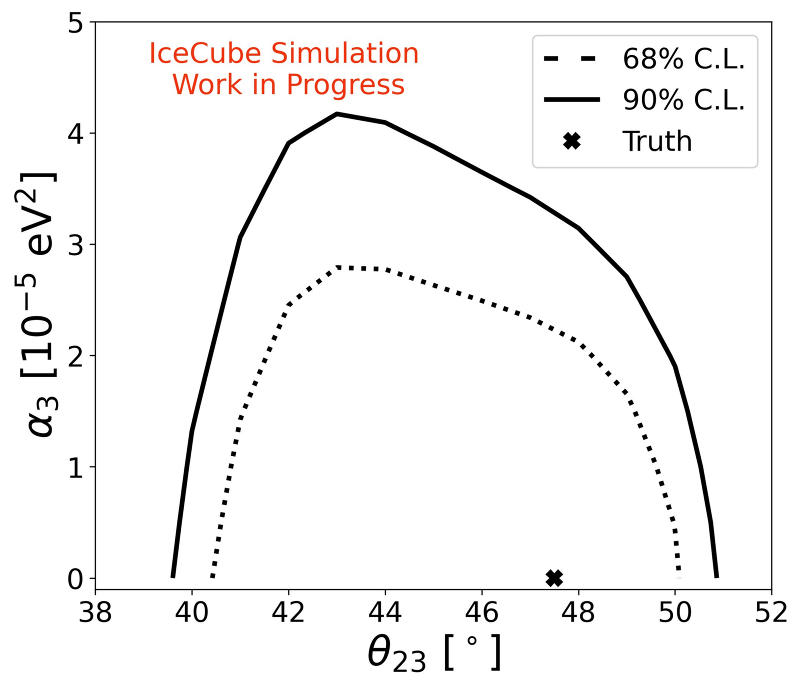
	Expected Events (9.28 yr)
Cascades	58663
Mixed	36853
Tracks	50729
Total	146245

Fit is performed over uncertainties of:

- Systematic parameters: DAEMON flux, cross section, detector response, neutrino normalization, and cosmic muon background normalization
- Oscillation parameters: θ_{23} and Δm^2_{31}

Sensitivity using Simulated Data at IceCube DeepCore





	DeepCore (this analysis)	T2K, NOνA [8]	T2K, MINOS [7]	T2K, NOνA, MINOS /MINOS+ [9]	K2K, MINOS, SK I + II [6]
α_3 (90% C.L.) [10^{-5} eV^2]	3.1	29	24	2.7	0.23

References

[1] Yañez, Fedynitch, PRD 107 (2023) 12, 123037
[2] Terliuk, Ph.D. Thesis, (2018), DOI: 10.18452/19304
[3] IceCube Collaboration, PRD 108 (2023) 1, 012014
[4] IceCube Collaboration, arXiv:2405.02163
[5] PLB 98 (1981) 265, PLB 99 (1981) 411, PLB 142 (1984) 181
[6] Gonzalez-Garcia et al., PLB 663 (2008) 405
[7] Gomes et al., PLB 740 (2015) 345
[8] Choubey et al., JHEP 08 (2018) 141
[9] Ternes et al., PRD 109 (2024) 7, L071701

The XXXI International Conference on Neutrino Physics and Astrophysics (Neutrino 2024), June 16-22, 2024, Milan, Italy