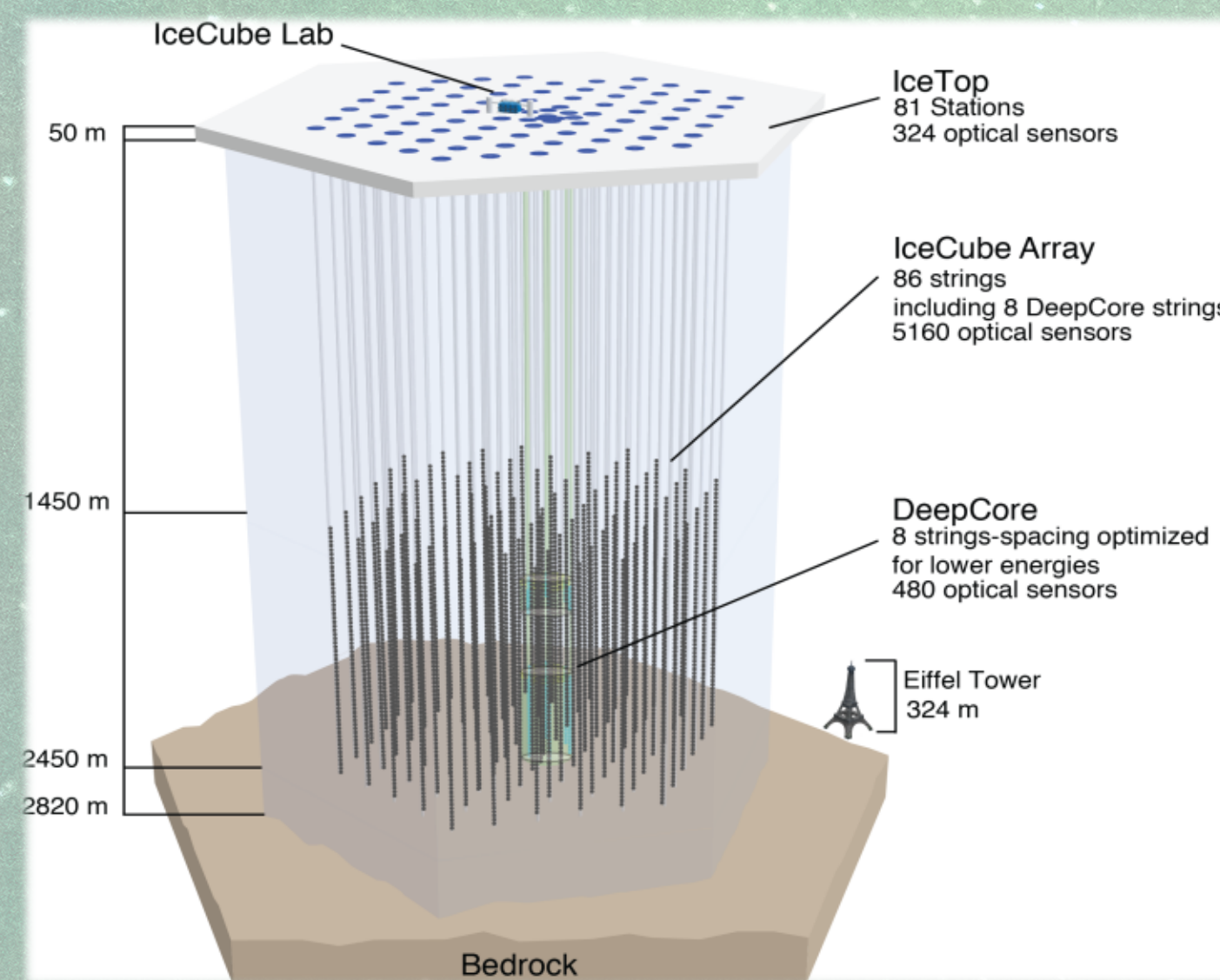


Measuring the Energy Spectrum and Flavor Composition of Diffuse Astrophysical Neutrinos with Starting Events in IceCube

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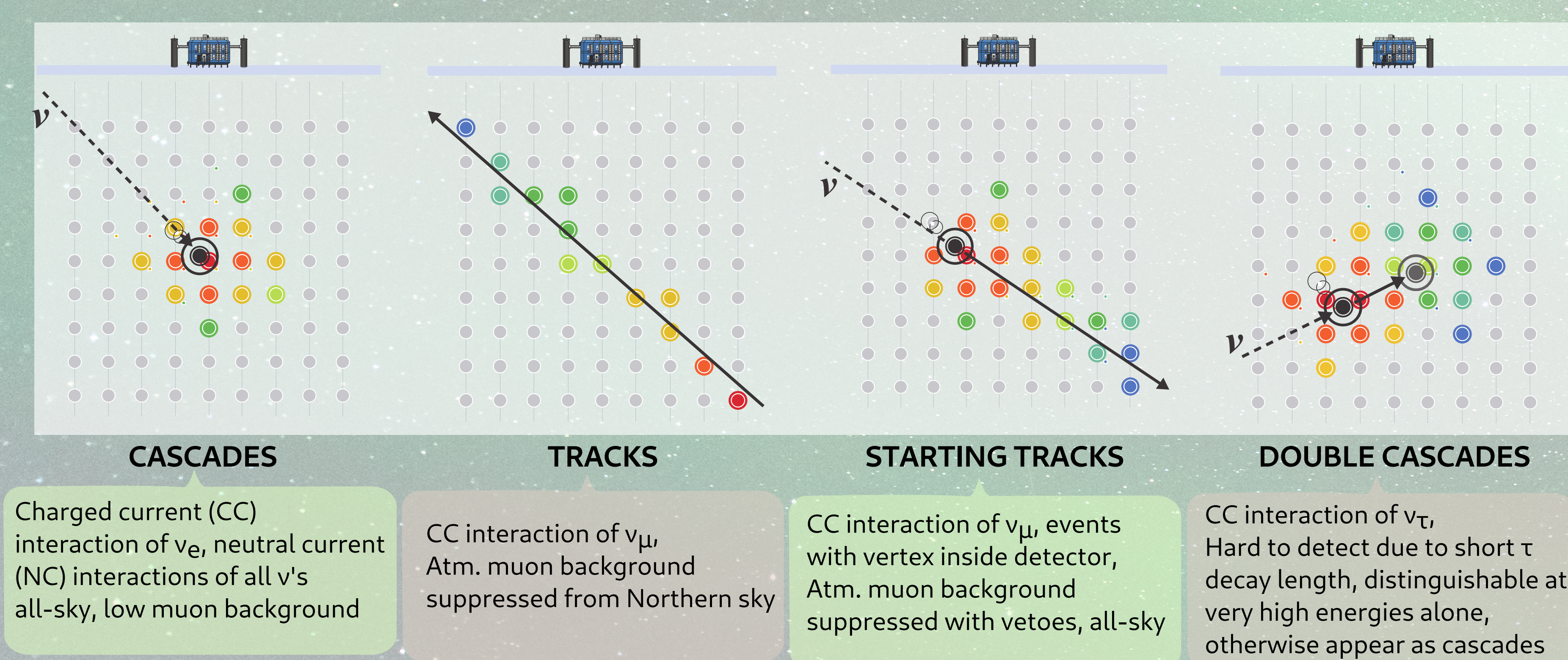
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The IceCube Detector



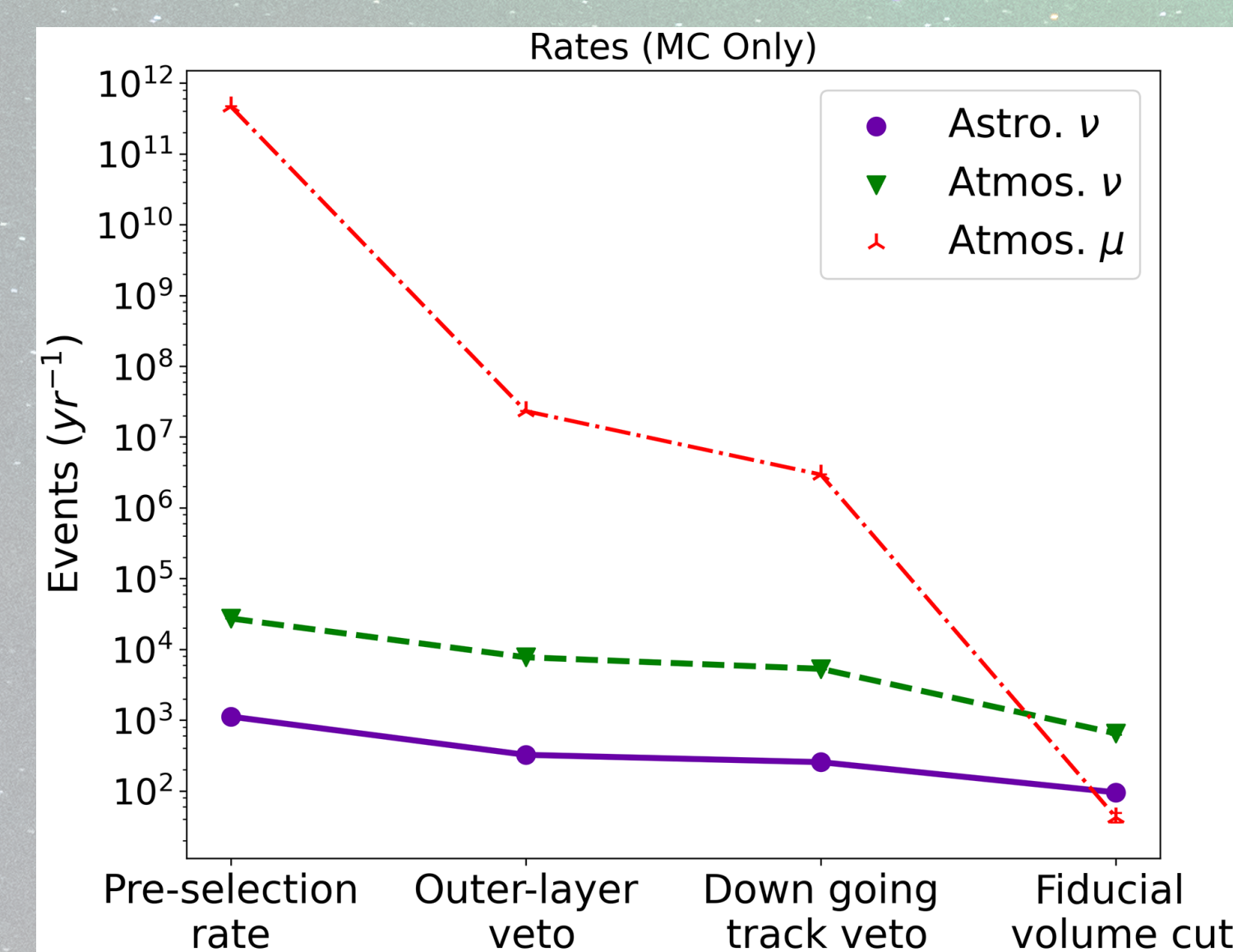
- The IceCube Neutrino Observatory at the South Pole observes neutrinos with energy > hundreds of GeV.
- Neutrino interaction with ice produces charged daughter particles that emit Cherenkov light; detected with Digital Optical Modules (DOMs)
- Flux of cosmic neutrinos measured since ~2013^[1], flavor composition since ~2015^[2].
- Early measurements restricted to highest energy neutrinos (> 60 TeV)^{[3][4]}

IceCube Event Morphologies



Medium Energy Starting Events (MESE)

- Event selection based on a series of vetoes applied to reduce the atmospheric muons in the sample
- Starting tracks and cascades with $E > 1$ TeV are kept in the sample
- Cascades and tracks discriminated with the help of a DNN
- Additional classification of double cascade events (used only for flavor measurement) using a likelihood-based method



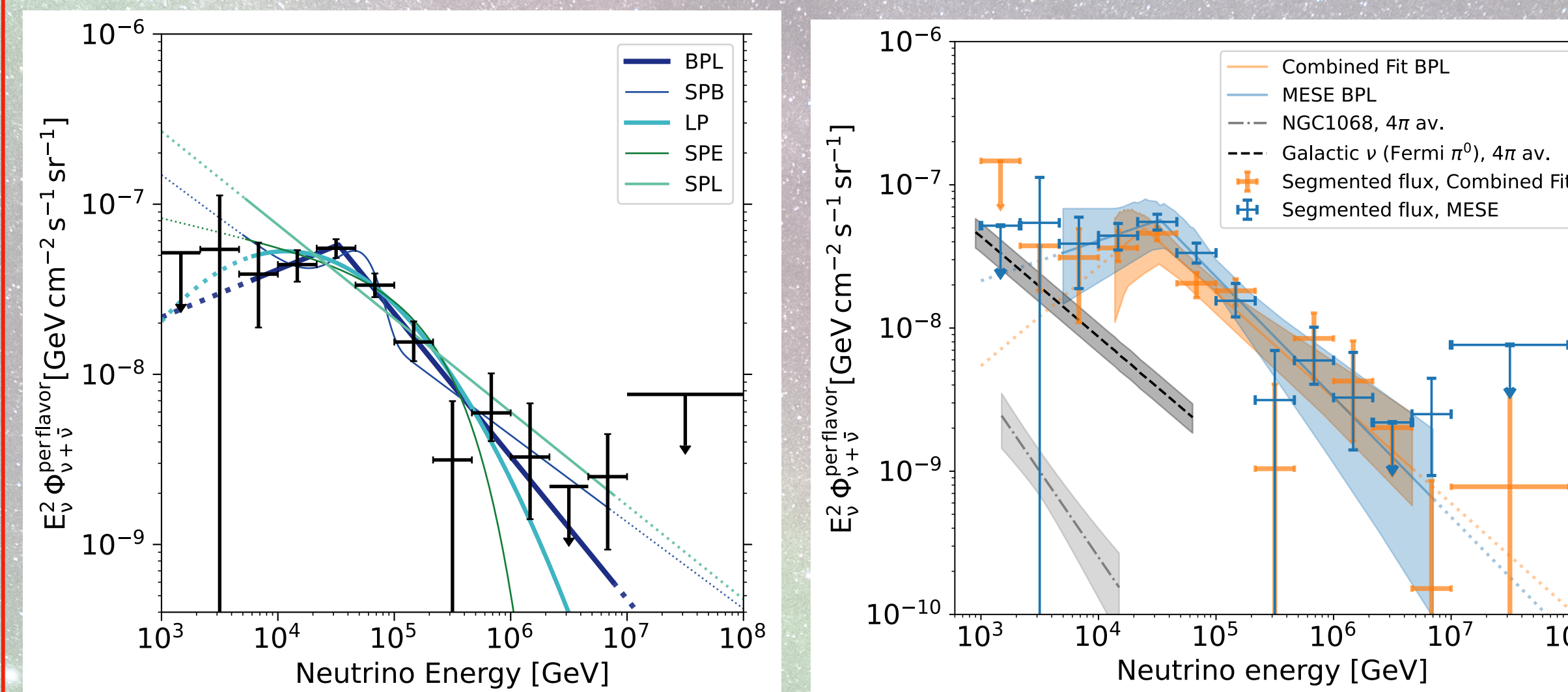
Expected rates of astrophysical neutrinos and background atmospheric neutrinos and muons derived from MC after each stage of the event selection^[5]

Analysis Methodology

- Two measurements: spectral shape of cosmic neutrinos, flavor composition of cosmic neutrinos
- Binned maximum likelihood analysis with parameters of interest:
 - Astrophysical neutrino spectral parameters (index, normalization)
 - Fraction of ν_e and ν_τ in the total astrophysical neutrino flux (with the constraint $f_e + f_\mu + f_\tau = 1$)
- 2D binning in energy, cosine zenith for cascades and starting tracks
- 3D binning in energy, cosine zenith, tau length for double cascades (only for flavor measurement)
- Atmospheric neutrino flux, atmospheric muon flux, and detector systematics treated as nuisance parameters
- Detector systematics treated via 'SnowStorm' method^[5], where gradients are derived along each parameter, from an ensemble of simulations

Results

Cosmic Neutrino Spectrum



Models tested for the astrophysical neutrino spectrum with the MESE sample: broken power law (BPL), single power law with bump (SPB), log parabola (LP), single power law with exponential cutoff (SPE), single power law (SPL). Legend is displayed in the increasing order of likelihoods^[6].

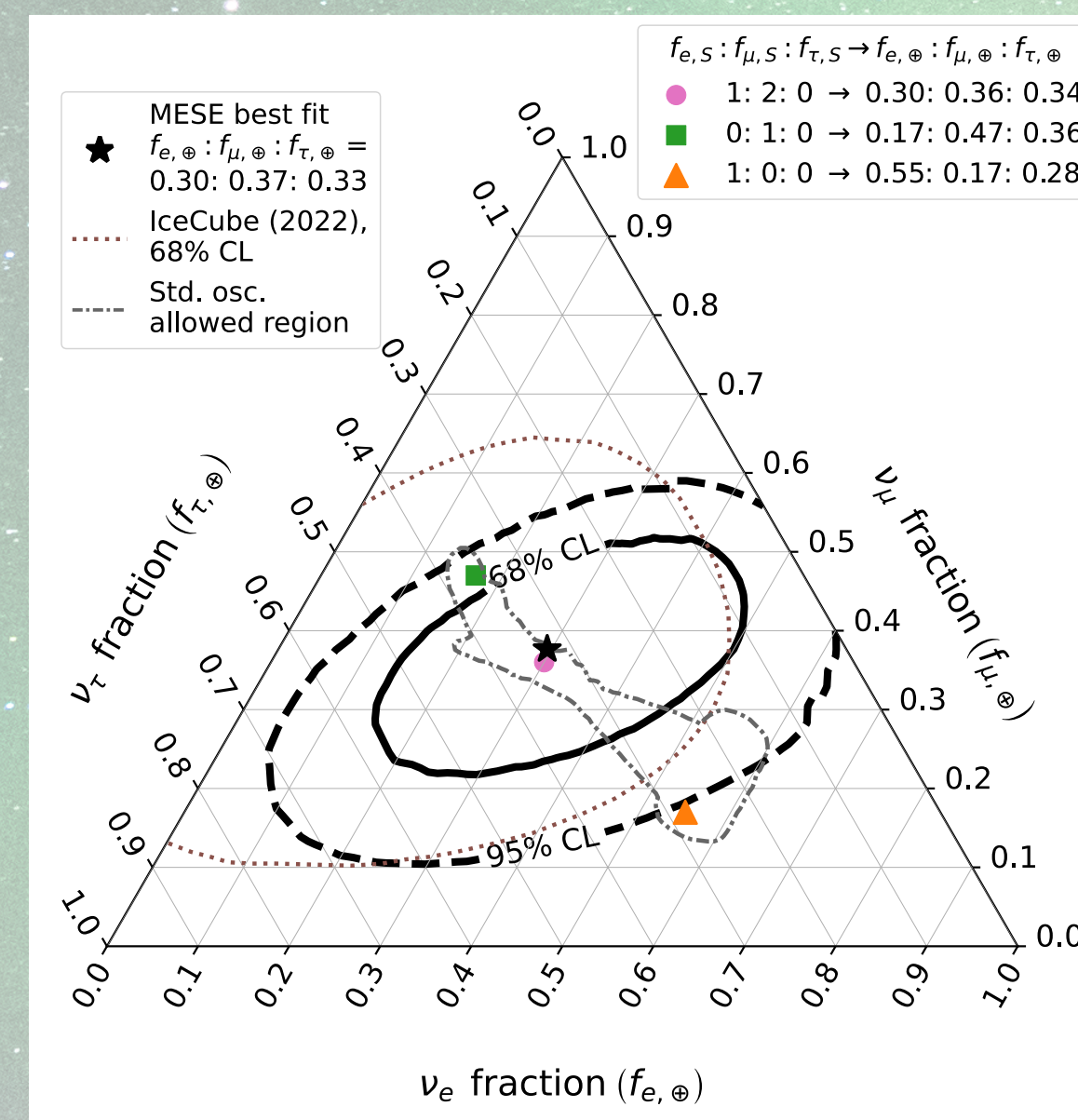
Broken power law identified as the best fit in two analyses: MESE and Combined Fit (where a joint fit is done with existing cascades and tracks samples)^[7].

- Broken Power Law fits the best to data, among the tested models^[6]
- Break energy ~ 30 TeV, steep high energy spectral index and hard low energy spectral index
- Consistent results between two IceCube analyses^[7]
- Previously, all IceCube measurements were consistent with a Single Power Law

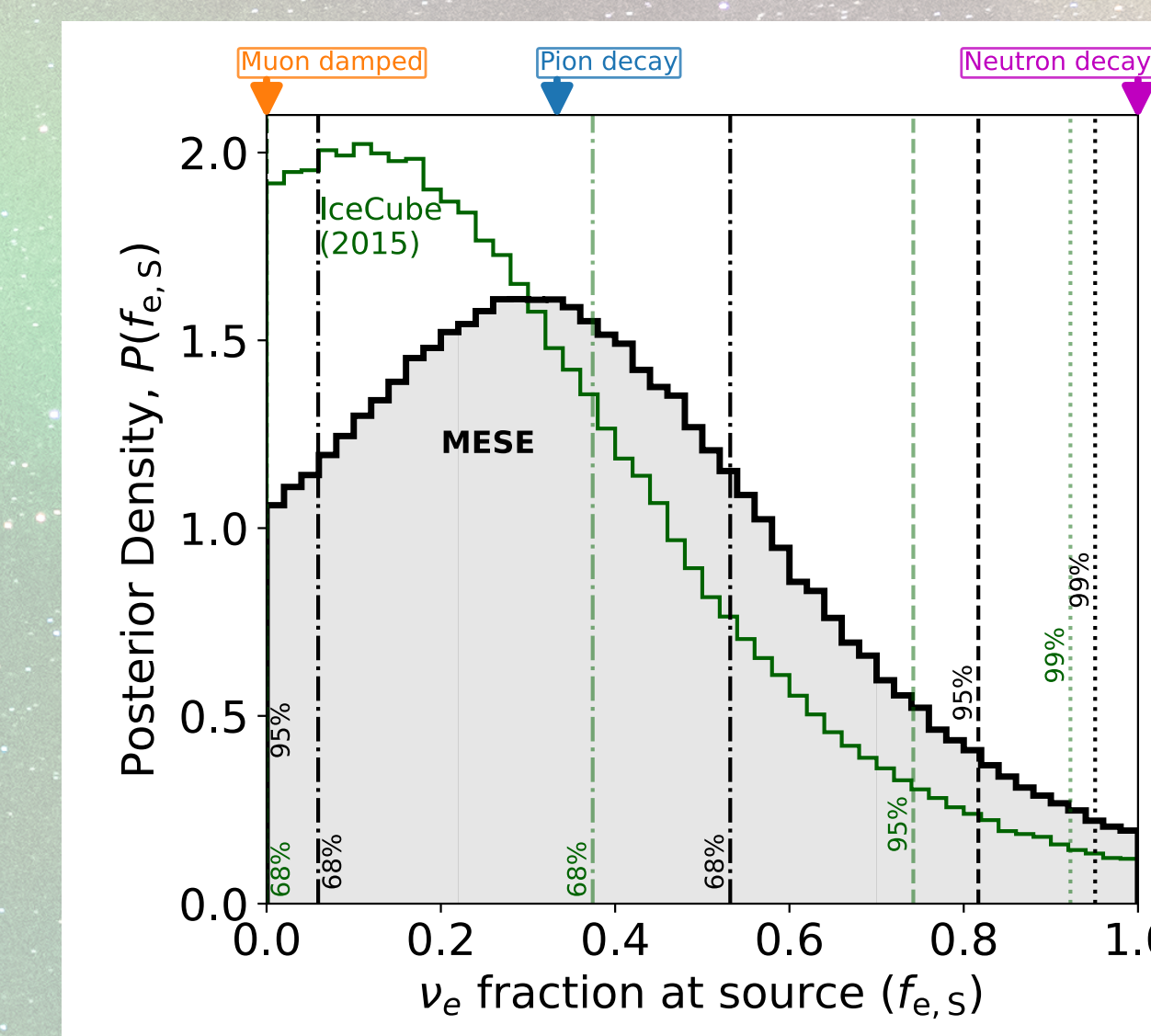
Astrophysical Model

SPL	BPL	SPE	SPB	LP
$\phi_0 = 2.13^{+0.18}_{-0.17}$	$\phi_0 = 2.28^{+0.22}_{-0.20}$	$\phi_0 = 3.9^{+1.2}_{-1.2}$	$\phi_0 = 1.42^{+0.31}_{-0.30}$	$\phi_0 = 2.58^{+0.36}_{-0.26}$
$\gamma = 2.548^{+0.039}_{-0.041}$	$\gamma_1 = 1.72^{+0.26}_{-0.35}$ $\gamma_2 = 2.839^{+0.11}_{-0.091}$	$\gamma = 2.16^{+0.11}_{-0.16}$	$\gamma = 2.51^{+0.059}_{-0.067}$	$\gamma = 2.668^{+0.12}_{-0.061}$
	$\log_{10}(E_{\text{break}}/\text{GeV}) = 4.524^{+0.097}_{-0.087}$	$\log_{10}(E_{\text{cutoff}}/\text{GeV}) = 5.52^{+0.39}_{-0.35}$	$\log_{10}(E_{\text{bump}}/\text{GeV}) = 4.3$	$\log_{10}(E_{\text{bump}}/\text{GeV}) = 4.52^{+0.097}_{-0.087}$
	$-2\Delta\ln\mathcal{L} = 27.3$ $p = 1.2 \times 10^{-6} (4.7\sigma)$	$-2\Delta\ln\mathcal{L} = 1.8$ $p = 0.18 (0.9\sigma)$	$\Phi_{\text{bump}} = 24.4^{+0.4}_{-0.4}$ $-2\Delta\ln\mathcal{L} = 22.3$ $p = 1.2 \times 10^{-5} (3.9\sigma)$	$\beta_{\text{LP}} = 0.359^{+0.11}_{-0.082}$ $-2\Delta\ln\mathcal{L} = 18.84$ $p = 1.42 \times 10^{-4} (4.2\sigma)$

Cosmic Neutrino Flavor Composition



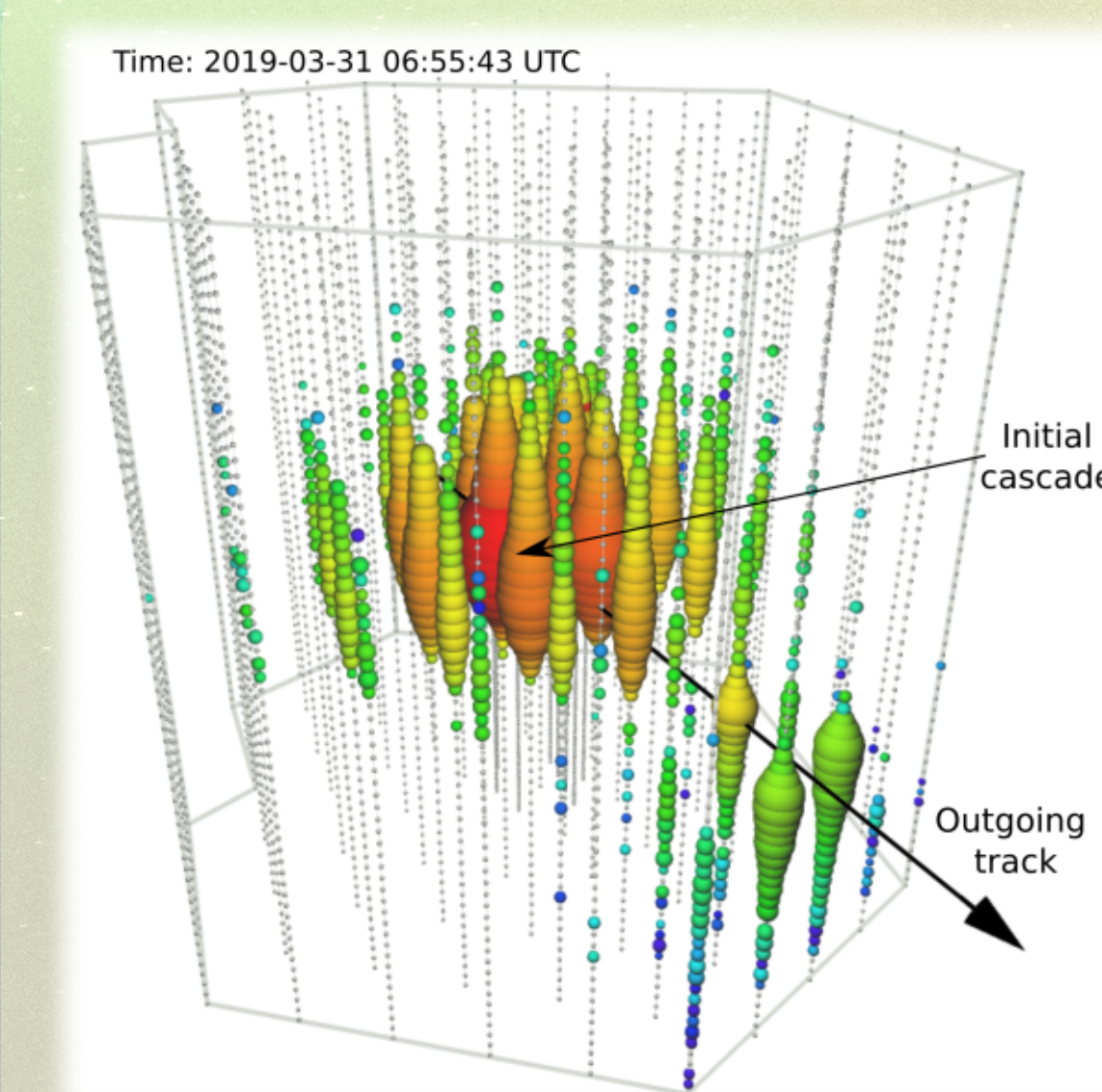
Measured flavor composition at Earth. Expected composition at Earth for benchmark production mechanisms (pion decay: circle, muon damping: square, neutron decay: triangle) are shown. The dotted line shows the 68% CL contour from IceCube's last measurement^[8].



Posterior distribution of flavor composition at source, assuming no ν_τ at source and global best-fit mixing parameters, and the likelihood profile obtained with the fit to the MESE dataset. The same with the likelihood profile from the IceCube (2015) analysis is shown^[8].

- Best fit consistent with standard theory of oscillations; fit performed under BPL assumption
- Event sample contains cascades: 4960 (4953.6 ± 154.6), tracks: 4919 (4876.2 ± 136.1), double cascades: 9 (7.0 ± 0.9); 11.4 years of data (simulations)
- First confirmation that cosmic neutrinos of all three flavors exits with > 90% CL^[8]
- Bayesian inference of flavor composition at source: neutron decay is well disfavoured, distribution consistent with pion decay

IceCube's Highest Energy Event



Event seen in MESE, and several high energy data selections (HESE, EHE)

With a mean energy of 11.4 PeV, IceCube's highest energy neutrino event is a starting track from the Southern sky^[6]



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Outlook

- Structures in the cosmic neutrino spectrum can indicate changing dominant populations, changes in production mechanism, or even dark matter excess, according to theoretical predictions^{[9][10][11]}
- Ongoing studies of the spectrum to further discern additional structures, using joint fit with multiple IceCube datasets
- Flavor composition performed here under the assumption of the same composition from TeV-PeV. Energy dependent composition^[12] measurements need additional ν_τ identification to increase the statistics
- Future inclusion of ν_τ tracks using their inelasticity signatures for identification, neural-network based identification^[13]

References

- [1] IceCube collab., PRL 111, 021103 (2013)
- [2] IceCube collab., PRL 114, 171102 (2015)
- [3] IceCube collab., PRD 104, 022002 (2021)
- [4] IceCube collab., EPJC 82, 1031 (2022)
- [5] IceCube collab., JCAP 10 (2019) 048
- [6] IceCube collab., PRD 113, 062002 (2026)
- [7] IceCube collab., PRL 136, 121002 (2026)
- [8] IceCube collab., arXiv:2510.24957
- [9] K. Murase et al., PRL 116, 071101 (2016)
- [10] K. Fang et al., ApJ. 933, 190 (2022)
- [11] C. A. Argüelles et al., Rev. Mod. Phys. 93, 035007 (2021)
- [12] T. Kashfi et al., PRL 95, 181101 (2005)
- [13] IceCube collab., PRL 132 (2024) 15, 151001