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Energy-dependent Flavor Ratio of High-energy Astrophysical Neutrinos

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Measuring the flavor composition of the TeV-PeV astrophysical neutrinos, i.e., the ratio of the flux of neutrinos of each flavor to the total flux sheds light on their production mechanisms and on the action of flavor transitions during propagation. So far, measurements of the flavor composition, based on IceCube data, have of necessity assumed that it is independent of neutrino energy, on account of the limited size of the data sample. However, the natural expectation is for the flavor composition to vary with neutrino energy, due to the presence of different neutrino production mechanisms at different energies, or to flavor-changing new physics. Therefore, we look for signs of the energy dependence of the flavor composition in recent IceCube public data and show forecasts for next-generation neutrino telescopes: Baikal-GVD, IceCube-Gen2, KM3NeT, P-ONE, TAMBO, and TRIDENT. We find that combing the data samples of telescopes in the future is critical to pin down changes in the flavor composition with energy.

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1. Introduction

Neutrinos are not deflected and rarely scatter during propagation from their faraway sources to Earth. They are thus ideal messengers for us to investigate physics in extreme environments with baselines of cosmological distances in cosmos. The discovery of high-energy astrophysical neutrinos at TeV-PeV by IceCube in 2013 [1] opens a new window to study high-energy astrophysical phenomena and significant strides have been achieved in the past decade. Alongside with the progress in the diffuse astrophysical neutrino flux observation, compelling evidence has heralded the origin of these neutrinos [2–4]. However, a full understanding of the sources and mechanisms of high-energy astrophysical neutrino production remains elusive.

Compared to other astronomical messengers, neutrinos carry three flavors, which introduces another dimension that we can measure. The flavor composition at the source depends on the production mechanism. Neutrinos undergo flavor oscillations during the journey from the source to the detector and end up with another flavor composition at Earth. Because of the structure of the neutrino mixing matrix, the composition at Earth retains some information about the original flavor ratios. Therefore, the flavor composition of detected neutrinos thus carries crucial information about their production mechanisms, propagation effects, and potential new physics.

Currently, the measurements of flavors face challenges of limited statistics and difficulty of identifying the flavor of individual neutrino events. The interpretation of flavor measurements also suffers from uncertainties in neutrino production and propagation. So far, studies of the neutrino flavor composition have focused on the averaged ratio over a broad energy range assuming a single power-law flux. However, the natural expectation for the flavor composition can vary with neutrino energy, due to the presence of different dominating neutrino production mechanisms at different energies, or to new physics effects which modify flavor or mass eigenstates as a function of energy.

A plethora of next-generation neutrino telescopes have been proposed or are under construction. These include Baikal-GVD, IceCube-Gen2, KM3NeT, P-ONE, TAMBO, and TRIDENT [5–10]. These telescopes will expand the cumulateive effective volume of neutrino telescopes by over an order of magitude. With the larger event rate and improved event identification ability in the future, the time is ripe to examine the potential of flavor studies including full energy dependence.

2. Astrophysical Scenarios

In standard astrophysical scenarios, neutrinos are primarily produced in the decay of pions via the chain processes $\pi^- \to \mu^- + \bar{\nu}_\mu$ followed by $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$, and their charge-reversed processes. As high-energy neutrinos telescopes are blind to neutrinos and antineutrinos (but see e.g. [11]), we do not distinguish them in the following discussion and denote the flavor ratio as $(f_e : f_\mu : f_\tau)$. This leads to an expected neutrino flavor ratio $(1 : 2 : 0)$ at the source. This prediction is modified if the source is affected by strong magnetic fields, which cool the intermediate muons via synchrotron losses so fast that they do not contribute to the high-energy neutrino production. In this so-called muon-damped scenario the flavor composition at the source is $(0 : 1 : 0)$. Other scenarios include e.g. neutron decay, which contribute at relatively low energies with a ratio $(1 : 0 : 0)$. Due to the neutrino flavor oscillation, the flavor at source and at Earth can

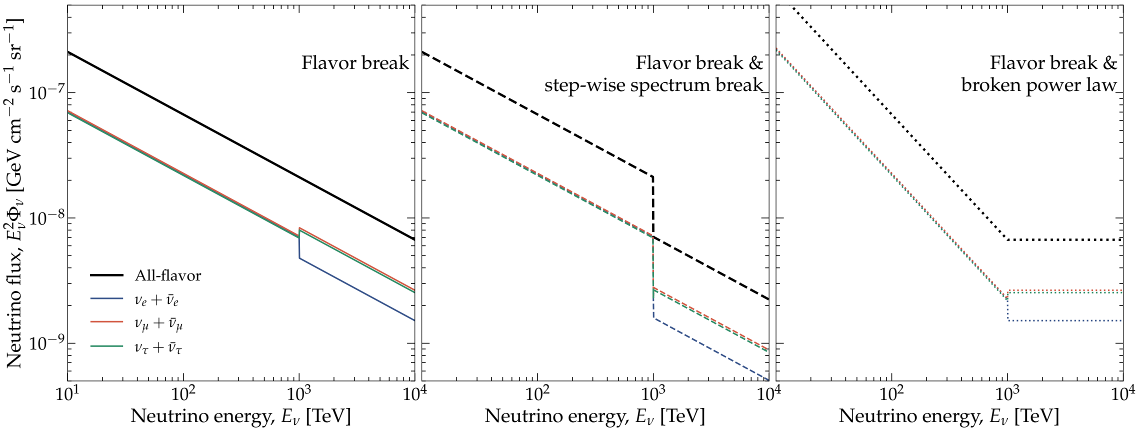

Figure 1: Benchmark fluxes used to simulate a flavor transition; the different line styles denote different model fluxes, and the different colors denote the fluxes separated per flavor at Earth. left: `PL`, middle: `Step` and right: `BPL`.

be related by

$$f_{\alpha,\oplus} = \sum_{\beta,i} f_{\beta,s} |U_{\alpha i}|^2 |U_{\beta i}|^2, \tag{1}$$

where $U_{\alpha i}$ are the components of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

The goal of this work is to investigate the sensitivity of neutrino telescopes to probe the existence of a transition between two flavor compositions at low energies (LE) and high energies (HE). The transition could occur at the source, or could be the result of combined source populations leading to different flavor compositions, and spectral shapes, dominating in different energy ranges. We thus examine three spectrum assumptions. 1) a single power law (`PL`) where the total flux follows a single power law while the flavor ratio changes above an energy threshold, 2) both fluxes follow the same power law, but the flavor change is accompanied by a step change (`Step`) in the flux normalization, and 3) a broken power law (`BPL`) where both the spectral index and flavor ratio change at the transition energy. These scenarios are illustrated in Fig. 1.

3. Method

We conduct our study in a Bayesian framework with IceCube 7.5yr high-energy starting events (HESE) and project the future sensitivities including the two event selections: HESE and through-going muons (TGM). We allow all parameters characterizing the astrophysical spectrum and flavor composition to vary freely. In addition to 4 parameters determining the two sets of flavor composition and the transition energy, which are common to all scenarios, the `PL` needs spectral index and flux normalization while `Step` requires two flux normalization with one spectral index, and `BPL` needs two spectral indices and one flux normalization.

We use the IceCube data release of HESE [12], which is accompanied by a full Monte Carlo (MC) sample of simulated events. We apply the effective likelihood used in the HESE analysis with the parameters characterizing the spectrum and flavor composition of the astrophysical flux. Parameters governing detector systematics, together with those describing atmospheric muons and neutrinos, are fixed to the best-fit values listed in Table VI.1 of [12].

For the projection of the sensitivities with combined telescopes, we assume that Baikal-GVD and KM3Net will start taking data in 2025 and IceCube-Gen2, P-ONE and TRIDENT will be turned on in 2030. When considering the starting events of other telescopes, we scale the exposure with the volumes of detectors and follow the same procedure. In order to maximize the power of the measurements in the future, we extend our study with inclusion of TGM in addition to contained neutrino events when projecting the future sensitivity. This selection includes track events induced by charged-current interactions of ν_μ outside the detector. These vastly increase the statistics of track events and thus helps the measurement of ν_μ fraction. To estimate the combined measurements, we add another Poisson likelihood specifically for TGM events to the likelihood. For the ν_μ effective areas of telescopes, we follow the framework of `PLEνM` [13], which estimates the effective area of a projected instrument as a function of declination by rotating the IceCube effective area and scaling the size. Because most of the atmospheric muons are suppressed for up-going events, the background for TGM is dominated by atmospheric neutrinos which we fix to the flux given by the MCEq simulation [14, 15]. We generate the Asimov data with parameters matching ones presented in Fig. 1 where we set the flavor composition to have the expectation of pion decay transiting to muon damped for all scenarios with a transition energy at 1 PeV. For `PL` and `Step` spectra, we assume 2.5 as the spectral index and $6.7 \times 10^{-18}\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ as the flux normalization at 100 TeV [16]. The `Step` flux has a drop by a factor of 1/3 from LE to HE, corresponding to the transition from pion decay to muon damped. The `BPL` flux has the same normalization while having spectral indices 3 and 2 for LE and HE respectively.

Additionally, with the current HESE data and generated Asimov data, we examine the power of inferring the flavor composition at the source from a flavor measurement. This has been studied in [17, 18] with a Bayesian approach assuming neutrinos are only produced as ν_e and ν_μ. For the energy-dependent case, we introduce $f_{e,S;l}$ and $f_{e,S;h}$, the ν_e fractions at LE and HE, to describe the flavor composition at source, i.e. before oscillation.We use the `NuFIT5.1` [19] oscillation parameters to model the current HESE data. For future predictions, we use the projected uncertainties reported in [18] which are expected to be significantly smaller thanks to the next generation of neutrino oscillation epxeriments including DUNE, JUNO, and HyperK.

4. Results

The posterior distributions of the flavor parameters are presented in the form of flavor triangles in Fig. 2. To quantify the power to differentiatethe existence of flavor transition from the assumption where there is no flavor transition, we compute the Bayes factor by comparing the evidence of each model by integrating the likelihood over the parameter space, i.e. $\mathcal{Z} = \int d\Theta \mathcal{L}(N_{obs}, \Theta)$, using UltraNest [20]. The Bayes factor is then defined as $\mathcal{B} = \mathcal{Z}_1/\mathcal{Z}_2$ for the two statistical models. We compare the evidence computed from the true model for each assumption which is $\mathcal{Z}_{FT}$ with the evidence assuming a single power-law spectrum with no flavor transition which is $\mathcal{Z}_{NT,\,PL}$ to obtain $\mathcal{B}_{FT,\,PL}$. Since this measure takes into account the change of the spectrum at the same time in addition to the flavor transition, we also compute $\mathcal{B}_{FT,\,Spectr.}$ by comparing the evidence matching the true model with the evidence assuming the same spectrum but without flavor transition which is $\mathcal{Z}_{NT,\,Spectr.}$.

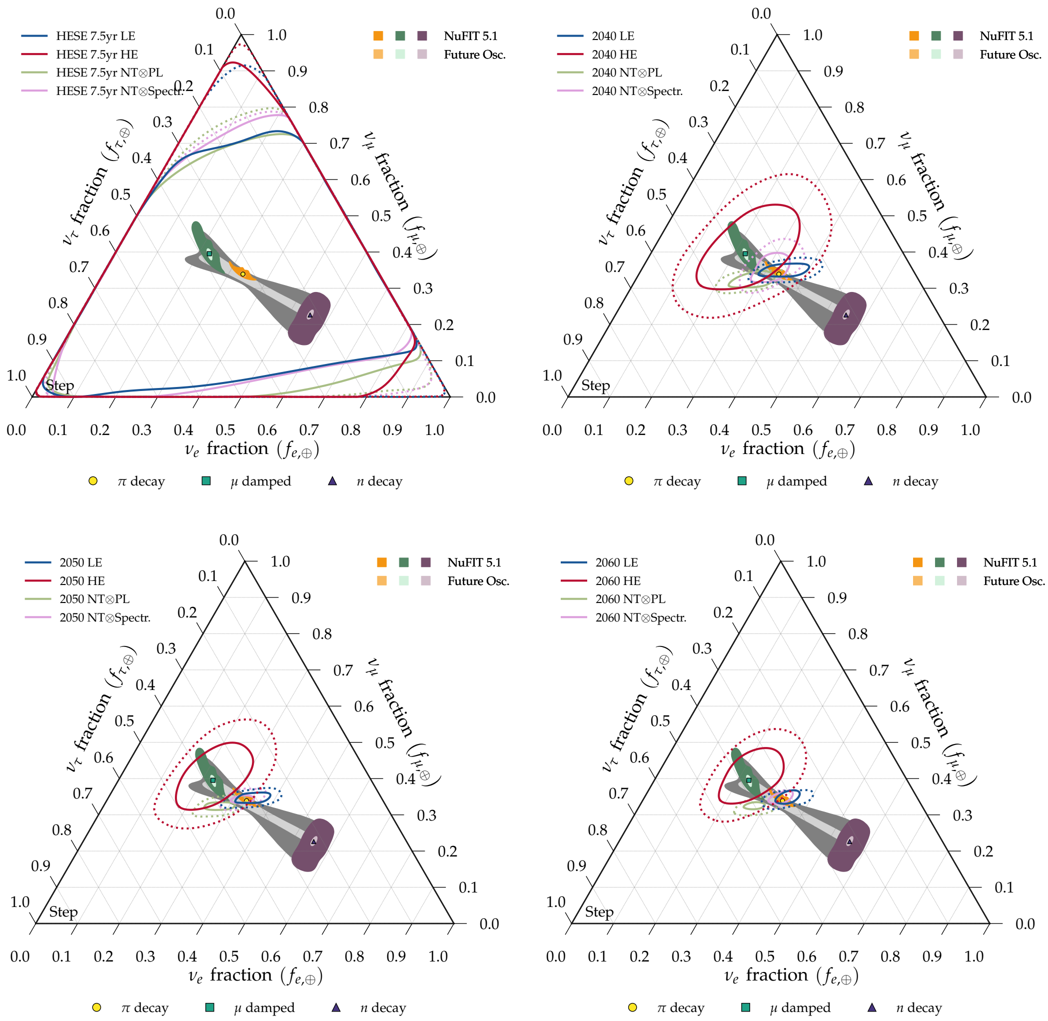

Figure 2: Flavor ratio contours of 68% (solid) and 95% (dotted) with HESE 7.5yr data and projected sensitivities with combined telescopes including HESE and TGM events for year 2040, 2050 and 2060. The model presented here is the `Step` spectrum. The blue and red contours show the LE and HE flavor compositions assuming the `Step` spectrum and existence of a flavor transition. The pink contours show the flavor ratio assuming the `Step` spectrum without a flavor transition while green contours show the flavor ratio with the general approach, i.e. assuming `Step` spectrum without a flavor transition. The shaded regions in the middle show the oscillation allowed regions for the π decay (orange), μ damped (green) and n decay (purple) scenarios and the gray regions show the standard oscillation allowed regions. Darker regions corresponds to `NuFIT5.1` and lighter regions are derived from future projections.

With the HESE 7.5yr data, as can be seen in Fig. 3, there is no preference for either model. This is expected from the limited statistics. We show the expected Bayes factor as a function of time for each of our scenarios. With an assumed 1 PeV transition energy, we can see that when comparing to the assumption of a single power law with no flavor transition, `Step` and `BPL` spectra we can be found with very strong evidence before 2040. When the spectra are assumed to be the same for comparison, it will take more exposure to reach the same significance which is challenging. As

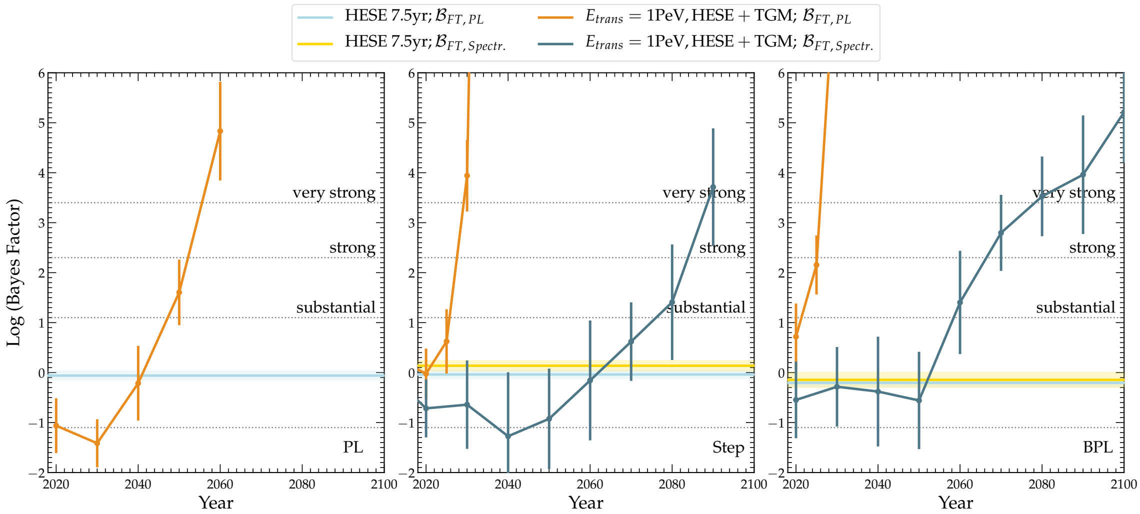

Figure 3: Bayes factors for the three scenarios shown in Fig. 1. The projections with HESE and TGM of combined telescopes are shown as a function of year. The blue and yellow lines show the results with HESE 7.5yr data while orange and turquoise lines show the forecast results. $\mathcal{B}_{FT,\,PL}$ and $\mathcal{B}_{FT,\,Spectr.}$ account for comparison with no flavor transition assuming PL and same spectrum shapes respectively. The uncertainty here is from the evidence computation from nested sampling.

can be noticed the Bayes factor can drop over time first, this is because a flavor transition splits the data into 2 sets which brings in a penalty of having less statistics in each part comparing to fitting all data for only one composition. The results depend on the real spectrum and transition energy which determine not only the total statistics but also statistics of each portion. When the transition energy is at a medium value within the energy range, optimal sensitivities would be expected.

The results of inferring the source composition are shown in Fig 4. Current HESE data result in rather flat posterior distributions of ν_e fractions where no preferred model can be found. With the future projection, we expect better sensitivities where the two production mechanism can be differentiated with great significance.

5. Conclusion

The flavor composition of high energy astrophysical neutrinos plays an essential role in revealing the production mechanisms at the source and new physics. Although previous studies are dedicated to the inference of an unvarying source flavor composition across TeV-PeV, such behavior is not guaranteed and various possibilities regarding neutrino production at source and propagation lead to energy-dependent features in the flavor composition measured at Earth. In this contribution, we have presented a study of three general scenarios without relying on specific source or new physics model. We have used current IceCube data and simulated data as a projection of the sensitivity of next-generation neutrino telescopes. As expected, current HESE 7.5yr data does not constrain the flavor composition. However, more statistical power will be gained over the next 20 years thanks to the deployment of a myriad of voluminous neutrino telescopes currently planned or in construction. Assuming a transition energy of 1 PeV, when combining the selection of HESE and TGM, the HE

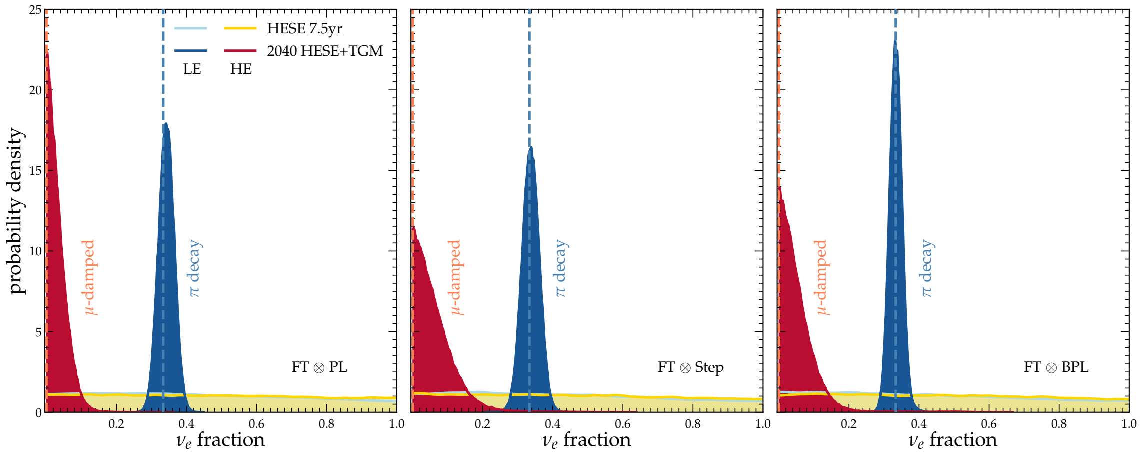

Figure 4: Posterior distributions ν_e fractions at source with the three spectrum assumptions for HESE 7.5yr data and Asimov data including HESE and TGM in 2040, corresponding to a 10yr exposure of combined telescopes, assuming a transition from pion decay to muon damped.

flavor composition can be marginally distinguished from the LE composition at 68% credible level around 2040 and at 95% after 2050. With the computation of Bayes factors, when taking into account of the spectrum change, the preference for a flavor transition can be very strong in 2030s. However, the preference is degraded markedly if we compare whether there is a flavor transition while keeping the spectrum modeling the same and a strong preference is expected beyond 2050. It is worth noting that the conclusion relies significantly on the assumption of the spectrum and transition energy.

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