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Probing Neutrino Decay Using the First Steady-State Source of High-Energy Astrophysical Neutrinos, NGC 1068

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We use the recent discovery of the first steady-state source of high-energy astrophysical neutrinos by IceCube, NGC 1068, to probe the lifetime of neutrinos. We look in the neutrino energy spectrum for characteristic features expected from the decay of neutrinos on their way to Earth. We find that present event rates, together with uncertainties in the predicted neutrino flux from NGC 1068, hinder our capacity to discern novel physics signatures in the data and place significant bounds on the neutrino lifetime. However, longer exposures and joint observations from upcoming neutrino telescopes and multi-messenger observations of NGC 1068 will improve the situation and reach significant sensitivities, enhancing our capability to probe neutrino decay, in particular, and novel physics signatures, in general.

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1. Introduction

The discovery of neutrino oscillations confirmed the existence of neutrino masses and the need for an extension of the Standard Model. In the minimal extension, neutrino lifetimes are predicted to be much longer than the age of the Universe [1–3]. However, other theoretical extensions allow for faster neutrino decay.

Probing neutrino decay is challenging. As most neutrinos are born ultrarelativistic, time dilation limits the sensitivity. Quantitatively, for a source at a distance L producing neutrinos with energy E_ν, a sizable fraction of the neutrinos will decay if their lifetime τ_ν is short enough, such that

$$\frac{L}{\tau_\nu}\frac{m_\nu}{E_\nu} \gtrsim 1\,, \tag{1}$$

where m_ν is the neutrino mass, and the factor m_ν/E_ν accounts for relativistic time dilation. Laboratory experiments, solar neutrinos, and atmospheric neutrinos have been studied in this context. Cosmology bounds were recently reexamined too [4].

The detection of astrophysical neutrinos by IceCube opens up a new opportunity for studying neutrino decay. As these sources are at cosmological distances, they provide sensitivity to shorter neutrino lifetimes compared to laboratory experiments. The flavor composition of neutrinos can be significantly altered if only some mass eigenstates are unstable, making astrophysical neutrinos particularly sensitive to decay [5, 6]. However, uncertainties in the neutrino spectrum and source distances hinder progress in this area.

The recent discovery of an excess of neutrinos in the direction of the active galactic nucleus (AGN) NGC 1068 by the IceCube Collaboration [7] is significant. NGC 1068 is a bright X-ray emitter, suggesting the presence of a hot corona suitable for neutrino emission [8]. It is the first discovered steady-state neutrino source, potentially offering better prospects for studying neutrino decay compared to the diffuse flux. Neutrinos from NGC 1068 have been detected at energies of hundreds of GeV, making relativistic time dilation less influential and allowing for probing longer lifetimes. However, currently, only muon and a small contamination of tau neutrinos have been correlated with the source, limiting available flavor information.

The main objective of this study is to investigate the feasibility of testing neutrino decay with high-energy astrophysical neutrinos, both from the diffuse flux and from a specific point source like NGC 1068 [9]. Bounds on neutrino decay from the statistical analysis of High-Energy Starting Events (HESE) [10] are provided for the diffuse flux. The statistical tools provided in the IceCube data release are utilized to obtain these bounds. For the point source, it is found that the current statistics are insufficient to reject neutrino decay based on spectral distortions. However, longer exposures and larger effective volumes offered by upcoming neutrino telescopes could improve the situation. A global network of neutrino telescopes, such as PLEνM [11], could probe uncharted regions of the parameter space and potentially establish the strongest bounds on neutrino lifetime. The assumptions made about the spectral shape of neutrinos emitted by the source are motivated by current theoretical models of neutrino emission in hot AGN coronae. The study also highlights the impact of assumptions about source behavior on the strength of bounds and emphasizes the importance of avoiding excessive assumptions when deriving bounds on beyond the Standard Model physics.

2. Neutrino propagation with invisible neutrino decay

If neutrinos are unstable, a portion of the neutrino flux originating from astrophysical sources may undergo decay before reaching Earth. In this study, we specifically consider the scenario of "invisible decay", where neutrinos decay into non-standard final states involving invisible particles such as Majorons and sterile neutrinos. Previous investigations have placed stringent constraints on this decay mechanism based on the total energy released during the explosion of SN 1987A, which was estimated from observations of electron antineutrinos at that time. However, it is important to note that these constraints are applicable only when considering the electron-flavored neutrinos. This limitation arises due to the fact that the bounds do not hold if the lightest mass eigenstate, assuming normal ordering, is stable, as it exhibits the highest electron-flavor component. Hence, in the subsequent analysis, our focus is specifically directed towards this particular scenario.

A fraction of the flux may not reach the surface of the Earth, as it may decay before that. We may easily obtain the surviving flux for the neutrino flavor β ($\beta = e,\ \mu,\ \tau$) reaching the Earth from a source at distance $r \ll H_0^{-1}$, with H_0 being the Hubble constant, as

$$\Phi_\beta(E) = \sum_{\alpha,i} |U_{\alpha i}|^2 |U_{\beta i}|^2 \frac{1}{4\pi r^2} \frac{dN_\alpha}{dE_\nu dt} \exp\left[-\frac{Lm_i}{E_\nu \tau_i}\right]. \tag{2}$$

Here, we denote by $U_{\alpha i}$ the PMNS matrix, i the mass eigenstates, and τ_i and m_i are the assumed lifetime and mass for each mass eigenstate; $dN_\alpha/dE_\nu dt$ is the neutrinos emission rate in the flavor α at the source.

The decay of low-energy neutrinos occurs at a faster rate compared to their highly boosted counterparts. Consequently, the effects of neutrino decay on the energy spectrum become apparent through two distinct mechanisms. Firstly, it results in a reduction in the overall number of neutrinos with energies below approximately $r \times \max_i(m_i/\tau_i)$, where m_i/τ_i represents the ratio of mass to lifetime for each mass eigenstate. Notably, if there exist differences in m_i/τ_i among the various mass eigenstates, one might anticipate observing distinct discontinuities in the neutrino normalization at different energy ranges. However, due to the inherent energy width of the discontinuity being of the same order of magnitude as the energy itself, this characteristic tends to be significantly smoothed out, resulting in a less pronounced feature. Secondly, neutrino decay also induces alterations in the anticipated flavor composition within the energy range affected by the decrease in flux. This arises from the partial or complete decay of specific mass eigenstates, leading to modifications in the flavor mixture. As an illustration, in a hypothetical scenario where the decay exclusively affects the second and third mass eigenstates, the flavor composition below the discontinuity would correspond solely to the first mass eigenstate.

Figure 1 shows the effect of neutrino decay on the neutrino flux spectrum at the Earth in the scenario where the lightest neutrino mass eigenstate (ν_1 in normal ordering) is stable and the two heaviest mass eigenstates (ν_2 and ν_3 in normal ordering) decay. The shaded area and the red line corresponds to the current measurement, 68% coverage band and best fit value respectively, of the neutrino spectrum from NGC 1068 by the IceCube collaboration. While the position of the discontinuity is determined by $\Gamma_i = m_i/\tau_i$, the ratio between the decayed flux at low energies and non-decayed flux at high energies is determined only by the initial flavor composition at the source. In Fig. 1 we observe how for the case $\Gamma_2 = \Gamma_3 \neq 0$ we have a single large discontinuity, while for

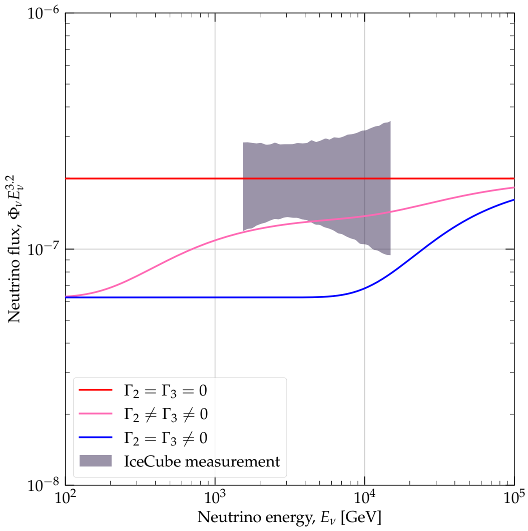

Figure 1: Effect of neutrino decay on the neutrino flux spectrum. The shaded area and the red line correspond to the current measurement and best fit reported by the IceCube Collaboration in Ref. [7]. We show two scenarios corresponding to equal and different decay ratios in neutrino mass units for the two heaviest neutrino eigenstates in normal ordering.

$\Gamma_2 \neq \Gamma_3 \neq 0$ we obtain two different discontinuities, individually less prominent than the former case. In both cases, the resulting spectral spectrum is distorted and not compatible with the current observation. Nevertheless, the effect shown in Fig. 1 assumes a fixed choice of spectral index, γ, and flux normalization, Φ_0, in the single power law model. In reality this parameters are not known and they must be inferred from the data. When they are free parameters of model, the sensitivity is lost and the neutrino flux with a decay features can be reconciled with current observations. We discuss this in detail later in Sec. 4.

We also consider the impact of neutrino decay on the full population of sources, namely the diffuse neutrino flux. In this case, we have to account for the correct redshift dependence in the suppression factors due to the decay, so that the expression for the diffuse flux becomes

$$\begin{aligned}\Phi_\beta(E)^{\text{diff}} = \quad & \sum_{\alpha,i} |U_{\alpha i}|^2 |U_{\beta i}|^2 \int_0^{+\infty} \frac{dz}{H(z)} \rho(z) \frac{dN_\alpha}{dE_\nu dt} \left[E_\nu(1+z)\right] \\ & \times \exp\left[-\frac{m_i}{\tau_i E_\nu} \int_0^z \frac{dz'}{H(z')(1+z')^2}\right]. \end{aligned} \tag{3}$$

Here, $H(z)$ is the redshift-dependent Hubble parameter, and $\rho(z)$ is the comoving number density of the sources. As in the case of the single-source flux, the diffuse flux in the presence of neutrino decay may exhibit similar signatures in the spectrum and the flavor composition.

3. Methods

We use the event list and analysis tools provided in Ref. [7] and adopt a frequentist approach to obtain the sensitivity to neutrino decay from currently available data. We used a Poisson likelihood binned in energy and angular distance measured from the position of NGC 1068. We found that current statistics are not sufficient to reject the neutrino decay hypothesis for any value of τ_i/m_i, neither for $\Gamma_2 = \Gamma_3$ nor for $\Gamma_2 \neq \Gamma_3$.

Since NGC 1068 is a steady source, we expect it to continue to emit neutrinos at a similar rate in the next years. Therefore, the number of observed events, and therefore the statistical potential, will increase with the exposure time. Moreover, in the next years we expect more neutrino telescopes to come online and add value to the overall statistics, making it possible to probe the neutrino decay with point sources. See Ref. [12] for a graphical timeline of future neutrino telescopes.

In this study with use the open-source library PLEnuM to compute the expected number of events observed from an NGC 1068-like source in the next decades. This allows us to make a prediction of the total number of neutrinos from NGC 1068 detected by a global network of neutrino telescopes. We can therefore forecast the sensitivity to neutrino decay from astrophysical sources in the upcoming high-statistics era of high-energy neutrino astronomy. As with current data, we used a Poisson likelihood, $\mathcal{L}$, binned in energy and angular distance. We adopt a frequentist approach and use the test statistics $\mathrm{TS} = -2\log\Lambda$, where $\Lambda = \mathcal{L}/\max\{\mathcal{L}\}$ to quantify and explore the significance of the points in the parameter space.

We model the neutrino flux at the Earth as in Eq. 2, where the neutrino emission rate at the source is modeled following a single power law for all neutrino flavors α. The model parameter are the power law spectral index, γ, the power law normalization, Φ_0, the neutrino lifetimes, τ_i/m_i, and the flavor composition at the source. Based on the currently known astrophysical neutrino production mechanisms, we set the fraction the ν_τ equal to zero at the source.

The total neutrino fluence emitted by NGC 1068 is currently inferred from data. In the future, a better understanding of this astrophysical source may provide us with some information about the source dynamics, allowing us to place some limits on the total energy released in the form of neutrinos. To represent this possibility, we consider the case where the a prior on the integrated flux is available. This prior is included as a penalization to the likelihood function.

4. Results

The left panel of Fig. 2 shows the χ^2 (approximated as the TS) for the case where $\tau_2/m_2 = \tau_3/m_3 = \tau/m$ and ν_1 is stable. The red and green lines corresponds to the 90% and 95% exclusion limits. At very large values of τ/m neutrinos are stable given the energy and distance scales involved, therefore not enough neutrinos decay and spectral features are not present in the neutrino flux arriving at the Earth. At low values of τ/m all ν_2 and ν_1 have decayed, and the flux arriving at the Earth is solely composed of ν_1. Since muon tracks are sensitive to mostly ν_μ, the ν_1-only neutrino flux at Earth can be reconciled with the observed data by rescale the single power law normalization, a free parameter in our model, in order to fit the correct arriving muon-neutrino flux at the Earth. If a prior on the total neutrino energy is used, then the model would be penalize for rescaling the normalization parameter of the power law, and the low τ/m allowed regime in the left panel of Fig. 2 would not be allowed anymore, making our results a lower limit on the neutrino lifetime, rather than an excluded band.

In the left panel of Fig. 3 we show the results for the case where $\tau_2/m_2 \neq \tau_3/m_3$ and ν_1 is stable. We also show how adding a prior on the total neutrino energy allows us to exclude a larger

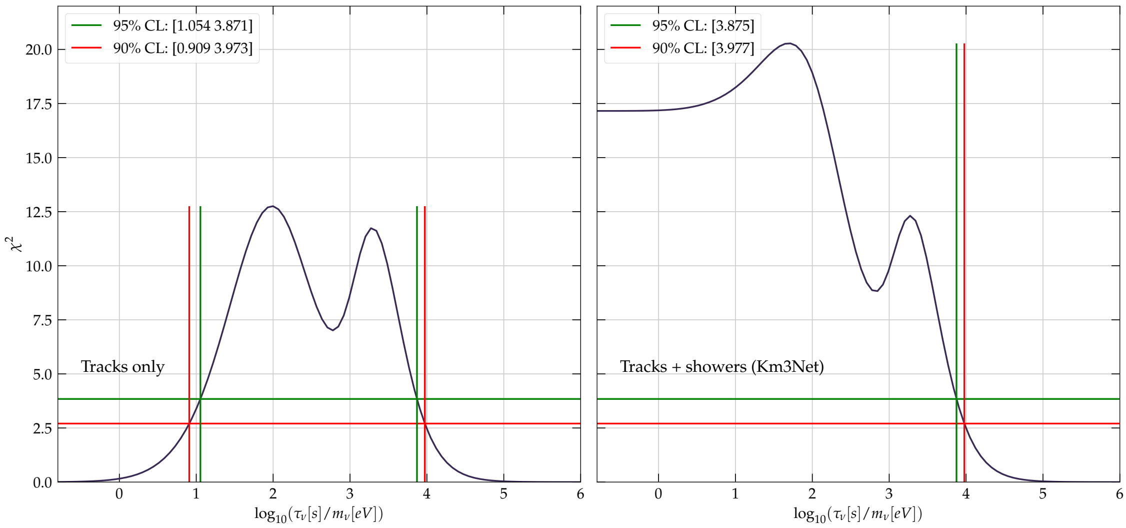

Figure 2: Caption

area of the parameter space. The asymmetry of the excluded regions for ν_2 and ν_3 arises from the difference in the ν_μ content in each mass eigenstate.

In the right panel of Fig. 3 we show how our results are impacted by the use of a different neutrino flux spectral shape model. The current mesurement by the IceCube collaboration is consistent witha simple power law in the region of interest. However, stat-of-the-art models of neutrino production mechanism in a source like NGC 1068 suggest a flux more compatible with a log-parabola or a powerlaw with an exponential cutoff. In the right panel of Fig. 3 we see how a large part of the sensitivity is loss if we model the neutrino emission rate in Eq. 2 using a powe law with an exponential cutoff instead. Since the high energy region of the flux falls rapidly, the discontinuity spectral feature imprinted by the neutrino decay effect shown in Fig. 1 will be less prominent, reducing the statistical power.

In both panels of Fig. 3 we show the results obtained using the diffuse flux of high-energy neutrinos in the HESE data set. We model the effect of neutrino decay using Eq. 3 and the available data and analysis tools for the HESE data set. Since in Eq. 3 we have to integrate the source contribution as a function of redshift, the sensitivity will depend on the evolution of the number of high-energy neutrino sources with redshift. A population model with a large number of sources at low redshift will result in a less powerful probe of neutrino decay than a population model with a large number of sources at high redshift. This is because the further the source is, the longer the distance traveled by neutrinos, the smaller the lifetime that could leave a signature in the neutrino flux detected at Earth.

5. Using neutrino flavor to probe neutrino decay

As spectral features may not be enough to probe neutrino decay with current or even future observations, we may get some insights from the flux flavor composition. In Fig. 4 we show how the different flavor components of the neutrino flux at the Earth vary depending on the initial

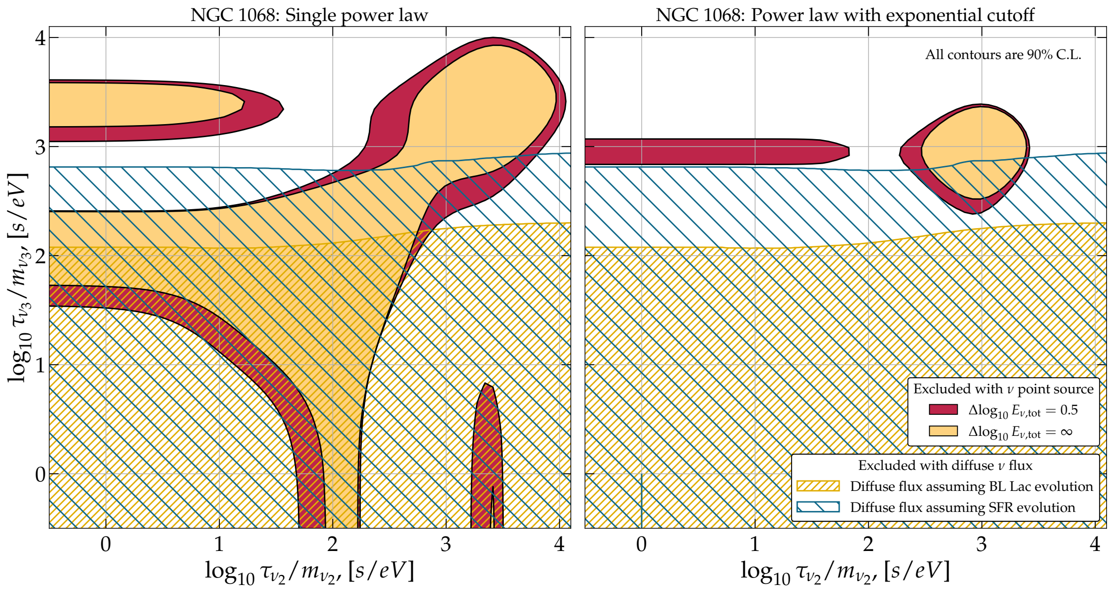

Figure 3: Caption

flavor composition at the source. We note, for example, that for the flavor split at the source $f_\alpha^S = (0.33 : 0.67 : 0)$, the ratio between the high-energy and low-energy regime separated by the neutrino decay discontinuity is the largest for muon neutrinos, which make up the most of the muon-track data set. If we do not fix the flavor composition at the source to this value but instead allow it vary freely and infer it from data, a flavor composition like $f_\alpha^S = (1 : 0 : 0)$ may be preferred, since it contains the smallest ratio for the muon neutrino flux, and therefore results easier to reconcile a neutrino flux including decay features with the observed data.

To avoid this problem we would need to gather information about the flavor composition of the neutrino flux at the Earth, which is currently not possible since the muon-track data set consists mainly of ν_μ events. This is because the muon topology provides a much better angular resolution compared to shower topologies, which are triggered by other neutrino flavors. Therefore, for discovering an astrophysical point source, the muon track data set is more convenient due to its lower background content in the angular window of interest. Nevertheless, future neutrino telescopes, such as KM3NeT, will have a better angular resolution for shower events as compared to the current resolution of IceCube. This is because KM3NeT uses water instead of ice as its detection volume, which has a milder impact on the propagation of optical signals. Although current studies regarding the performance of in-water neutrino telescopes to reconstruct the arrival direction are limited, we consider in our work a benchmark scenario of $\sigma_\Omega = 10°$.

We simulate the number of observed neutrino shower events by KM3NeT after 10 years of operation, as well as the atmospheric background content. We add this information to the total likelihood as a signal-to-background penalization term in order to join the information of tracks and showers. In Fig. 2 we show the results of this. A few shower events are significant enough to reject the low neutrino lifetime regime of the hypothesis. This regime was originally allowed because a pure ν_1 flux could be consistent with the data as long as we properly rescale the $\nu_\mu flux$. Once we

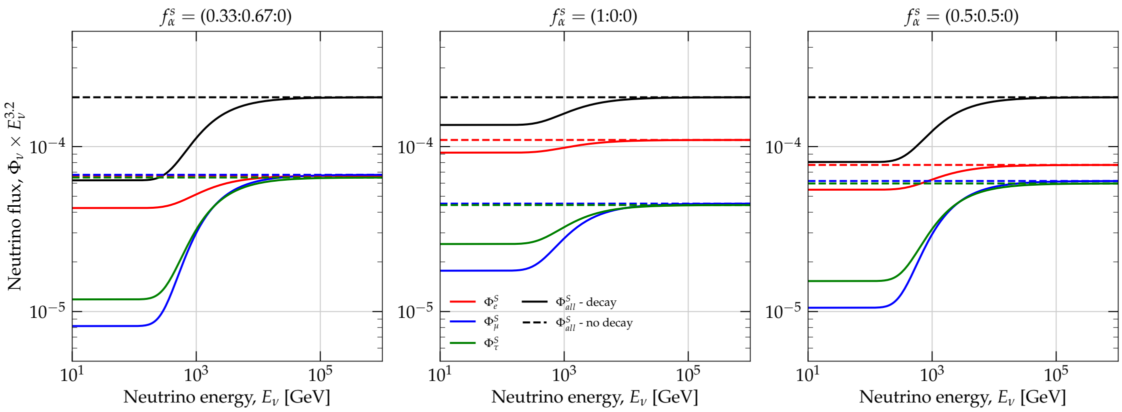

Figure 4: Neutrino flavor composition at Earth with and without neutrino decay for three different cases of initial flavor composition at the source.

include information of showers, made up of all ν flavor, it is not possible to simultaneously rescale the flux to be consistent with the tracks observation, make of ν_μ, and the shower observation, make of all ν, at the same time.

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