Determining the neutrino lifetime from cosmology

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We explore the cosmological signals of theories in which the neutrinos decay into invisible dark radiation after becoming nonrelativistic. We show that, in this scenario, near-future large-scale structure measurements from the Euclid satellite, when combined with cosmic microwave background data from Planck, may allow an independent determination of both the lifetime of the neutrinos and the sum of their masses. These parameters can be independently determined, because the Euclid data will cover a range of redshifts, allowing the growth of structure over time to be tracked. If neutrinos are stable on cosmological timescales, these observations can improve the lower limit on the neutrino lifetime by 7 orders of magnitude, from $\mathcal{O}(10)$ to 2×10^8 yr (95% C.L.), without significantly affecting the measurement of neutrino mass. On the other hand, if neutrinos decay after becoming nonrelativistic but on timescales less than $\mathcal{O}(100)$ million years, these observations may allow not just the first measurement of the sum of neutrino masses, but also the determination of the neutrino lifetime from cosmology.

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I. INTRODUCTION

Neutrino decay is a characteristic feature of models in which neutrinos have masses. Even in the minimal extension of the Standard Model (SM) that incorporates Majorana neutrino masses through the nonrenormalizable Weinberg operator, the heavier neutrinos are unstable and undergo decay at one loop into a lighter neutrino and a photon. The same is true of the minimal extension of the SM that incorporates Dirac neutrino masses through the inclusion of right-handed singlet neutrinos. In both cases, the lifetime of the heavier neutrino is of the order of $\tau_\nu \sim 10^{50}\ \mathrm{s}(0.05\ \mathrm{eV}/m_\nu)^5$, in the limit that the daughter neutrino mass is neglected [1–5]. This is much longer than the age of the Universe, and so these minimal neutrino mass models do not give rise to observable signals of neutrino decay. However, in general, the neutrino lifetime can be much shorter. For example, in theories where the generation of neutrino masses is associated with the breaking of global symmetries [6–10] (see also [11,12]), a heavier neutrino can decay into a lighter neutrino and a Goldstone boson on timescales that can be much shorter than the age of the Universe.

Until the turn of the century, the decaying neutrino scenario attracted considerable attention as a possible solution to the solar and atmospheric neutrino problems [13–16]. However, this explanation is now disfavored by the data [17–19]. More recently, radiative neutrino decays have been put forward as a possible explanation of the anomalous 21 cm signal observed by the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) experiment [20].

There is a strong lower limit on the neutrino lifetime in the case of radiative decays. In this scenario, the limits on spectral distortions in the cosmic microwave background (CMB) can be translated into bounds on radiative neutrino decays, $\tau_\nu \gtrsim 10^{19}$ s for the larger mass splitting and $\tau_\nu \gtrsim 4 \times 10^{21}$ s for the smaller one [21], greater than the age of the Universe. There are also very strong laboratory and astrophysical bounds on the neutrino dipole moment operators that induce radiative neutrino decays [22–26].

In contrast, the decay of neutrinos into invisible dark radiation is only weakly constrained by current data. At present, the most stringent bounds on invisible neutrino decays are from cosmological observations. Although limits can also be placed on neutrino decay based on data from supernovae [27,28], solar neutrinos [19,29–33], atmospheric neutrinos, and long baseline experiments [34–36], these constraints are, in general, much weaker. Cosmological measurements are sensitive to the neutrino lifetime through the gravitational effects of the relic neutrinos left over from the big bang and their decay products. If the neutrino lifetime is less than the timescale of recombination, then neutrino decay and inverse decay processes are active during the CMB epoch. These processes prevent the neutrinos from free streaming, leading to observable effects on the heights and locations of the CMB peaks [37–39]. Current limits require that the neutrinos be free streaming from redshifts $z \gtrsim 8000$ until recombination, $z \approx 1100$ [40–43] (see also [44]). This can be translated into a lower bound on the neutrino lifetime, $\tau_\nu \geq 4 \times 10^8\ \mathrm{s}(m_\nu/0.05\ \mathrm{eV})^3$ [43], which is much less than the age of the Universe. This corresponds to an upper bound on the width of the neutrino, $\Gamma_\nu \equiv \tau_\nu^{-1} \leq 8 \times 10^{10}(0.05\ \mathrm{eV}/m_\nu)^3$ km/s/Mpc. Comparing this to the Hubble expansion rate, $H_0 \approx 70$ km/s/Mpc, we see that at present there is no evidence that neutrinos are stable on cosmological timescales, and the lifetime of the neutrino remains an open question.

Knowledge of the neutrino lifetime is of particular importance for the determination of neutrino masses from cosmology. At present, the strongest upper limit on the sum of neutrino masses, $\sum m_\nu \lesssim 0.12$ eV [45], is from cosmological observations. However, this bound assumes that the neutrino number density and energy distribution have evolved in accordance with the standard big bang cosmology until the present time. If the neutrinos have decayed [46,47] or annihilated away [48,49], this bound is not valid and must be reconsidered. In particular, in the case of neutrinos that decay on cosmological timescales, values of the neutrino masses as large as $\sum m_\nu \sim 0.90$ eV are currently allowed by the data [50].

In the coming decade, major improvements are expected in the precision of cosmological observations, which would lead to great advances in neutrino physics. The Euclid satellite, scheduled to be launched in 2022, is expected to measure both the Galaxy and the cosmic shear power spectra with unprecedented precision, achieving up to subpercent accuracy over the redshift range from $z \sim 0.5$ to 2 [51]. In the more distant future, the CMB-S4 experiment [52] will lead to major advances over current CMB observations. This includes improvements in the measurement of CMB lensing, which is very sensitive to the neutrino masses. Under the assumption that neutrinos are stable, these new measurements will allow us to probe values of the neutrino masses smaller than the observed neutrino mass splittings and thereby determine $\sum m_\nu$ [53,54]. However, if the neutrinos are unstable on cosmological timescales, the question of whether $\sum m_\nu$ can, in fact, be determined remains unanswered.

In this paper, we address this question. We consider theories in which the neutrinos decay into invisible dark radiation after becoming nonrelativistic. This corresponds to the width $\Gamma_\nu \lesssim 1 \times 10^5 (m_\nu/0.1\ \mathrm{eV})^{3/2}$ km/s/Mpc for each neutrino. We show that, in this class of models, near-future large-scale structure measurements from Euclid, in combination with Planck data, may allow an independent determination of both the lifetime of the neutrinos and the sum of their masses. The reason these parameters can be independently determined is because Euclid takes measurements at multiple redshifts, which allows us to track the growth of structure over time. In the case of stable neutrinos, we find that these observations will be able to extend the lower bound on the lifetime by at least 7 orders of magnitude, from $\mathcal{O}(10)$ yr to $\mathcal{O}(0.1\text{–}10)$ Gyr depending on the neutrino mass, without significantly affecting the measurement of the sum of neutrino masses. Furthermore, we show that if the neutrinos decay after becoming nonrelativistic but with a lifetime less than $\mathcal{O}(10^8)$ yr, these observations may allow the first determination of not just the neutrino masses, but also the neutrino lifetime.

II. BREAKING THE DEGENERACY BETWEEN NEUTRINO MASS AND LIFETIME

The sensitivity of cosmological observables to the neutrino masses arises from the fact that, after the neutrinos become nonrelativistic, their contribution to the energy density redshifts like matter and is, therefore, greater than that of a relativistic species of the same abundance. This leads to a faster Hubble expansion, reducing the time available for structure formation. The net result is an overall suppression of large-scale structure [55,56] (for reviews, see [57–60]). A larger neutrino mass gives rise to greater suppression, since heavier neutrinos become nonrelativistic at earlier times, and also contribute more to the total energy density after becoming nonrelativistic. In the case of neutrinos that decay, the extent of the suppression now also depends on the neutrino lifetime. The key idea, first discussed in Refs. [46,47], is that if the neutrinos decay into massless species after becoming nonrelativistic, the suppression in power is reduced. Depending on how late the decay kicks in after the neutrinos have become nonrelativistic, the magnitude of the suppression will vary.

These features are illustrated in Fig. 1, where we show the evolution of the overdensity of cold dark matter and baryons, $\delta_{cb} \equiv \delta\rho_{cb}/\bar{\rho}_{cb}$, for three cases, based on the analysis in Ref. [50] and briefly described in the next section. The results are expressed in terms of the ratio of $(\delta_{cb})^2$ for each case to its value in the scenario with massless neutrinos. The black line corresponds to stable neutrinos with $\sum m_\nu = 0.25$ eV, while the blue line corresponds to unstable neutrinos of the same mass. To simplify the discussion, in this plot we have taken the lifetimes Γ_ν of all the three neutrinos to be the same. We see that, as compared to the stable neutrino scenario, unstable neutrinos of the same mass lead to a smaller suppression of δ_{cb} at $z = 0$. The red line corresponds to unstable neutrinos with $\sum m_\nu = 0.30$ eV, and their lifetime has been chosen to obtain the same result for the overdensity at $z = 0$ as for stable neutrinos with $\sum m_\nu = 0.25$ eV. We see from the black and red curves in Fig. 1 that the effects of a stable neutrino on the matter density perturbations cannot be easily distinguished from those of a heavier neutrino that is shorter lived based only on measurements performed at $z \lesssim 0.3$. This is because the growth of δ_{cb} is almost frozen in the region where the cosmological constant dominates ($z \lesssim 0.3$). Therefore, there is a degeneracy between $\sum m_\nu$ and τ_ν that cannot be resolved based only on measurements

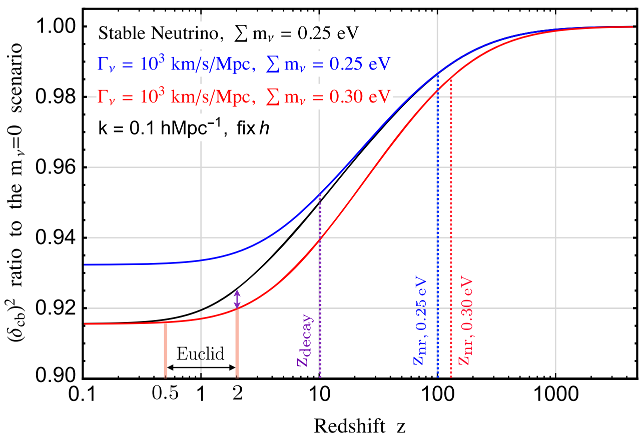

FIG. 1. Evolution of the ratio of the CDM + baryon density perturbations with respect to the case of massless neutrinos. The blue (black) curve corresponds to the case of stable (unstable) massive neutrinos with $\sum m_\nu = 0.25$ eV. Here $z_{\rm decay}$, defined as the redshift at which the neutrino width Γ_ν becomes equal to the Hubble constant, corresponds to the redshift at the time of neutrino decay. Similarly, $z_{\rm nr}$ denotes the redshift at which 80% of the neutrinos have become nonrelativistic. Unstable heavier neutrinos with $\sum m_\nu = 0.3$ eV (red) can give the same density perturbation at low redshift as stable neutrinos of mass $\sum m_\nu = 0.25$ eV. However, at $z = 2$, the perturbation in the heavier neutrino scenario deviates at the $\mathcal{O}(0.1)$% level from the stable neutrino scenario (purple arrow).

of the matter power spectrum at low redshifts. However, it is clear from Fig. 1 that the evolution of the power suppression at earlier times is different in the two cases. Consequently, the shapes of the power spectra as a function of z are distinct. This would allow these two cases to be distinguished if measurements are made at more than one redshift with subpercent precision (e.g., black vs red at $z = 0.5$ and $z = 2$ in Fig. 1). As mentioned above, the Euclid experiment is expected to take measurements at multiple redshifts between $z \approx 0.5$ and $z \approx 2$ at this level of precision. Hence, the combined Euclid and Planck data has the potential to break the degeneracy between neutrino mass and lifetime.

III. ANALYSIS

In order to calculate the effects of neutrino decay on cosmological observables, we implement the Boltzmann equations corresponding to the decay of neutrinos into dark radiation that were derived in Ref. [50] into the code CLASS [61]. We work under the assumption that, after becoming nonrelativistic, each SM neutrino decays with width Γ_{ν_i} into two massless particles. Here the indices i label the neutrino mass eigenstates. For concreteness, we assume that the decay widths of the three neutrinos satisfy the relation $\Gamma_{\nu_i} \propto m_{\nu_i}^3$. This assumption is motivated by models in which the generation of neutrino masses is associated with the breaking of global symmetries. Since Goldstone bosons are derivatively coupled, in these theories the matrix element for neutrino decay typically scales as m_ν/f, where f corresponds to the scale at which the global symmetry is broken. Then, after accounting for phase space, we typically have $\Gamma_{\nu_i} \sim m_{\nu_i}^3$. Given the observed mass splittings, this leaves only two remaining independent parameters. We choose to present the results of our analysis in terms of the parameters $(\sum m_\nu, \Gamma_\nu)$, where Γ_ν is the decay width of the heaviest neutrino. With this definition, $\Gamma_\nu \equiv \Gamma_{\nu_3}$ for the normal ordering and $\Gamma_\nu \equiv \Gamma_{\nu_2}$ for the inverted ordering. For the same values of $\sum m_\nu$ and Γ_ν, the results for the normal and inverted ordering are different. This is because the individual neutrino masses are different in the two cases. Therefore, the neutrinos become nonrelativistic at different times and have different lifetimes. These differences become increasingly small for values of $\sum m_\nu$ above 0.2 eV, since in this regime the neutrinos are quasidegenerate.

We wish to determine the extent to which a combination of Planck data and future Euclid data can help break the degeneracy between the neutrino mass and lifetime. To that end, we make use of the mock likelihoods available publicly in MontePython v3.1 and described in Refs. [62,63]. We include Euclid galaxy and cosmic shear power spectra in the "realistic" configuration; i.e., we include nonlinear scales and employ a loose (redshift-independent) nonlinear cut at comoving $k_{\rm NL} = 2\ h/{\rm Mpc}$ in the galaxy power spectrum and $k_{\rm NL} = 10\ h/{\rm Mpc}$ in the cosmic shear power spectrum, together with a nonlinear correction based on HaloFit [64,65] and a theoretical error on the nonlinear modeling (as described in Refs. [62,63]). For a few cases, we employed an alternative "conservative" prescription where we cut the data at comoving $k_{\rm NL} = 0.2h/{\rm Mpc}$ in the galaxy power spectrum and $k_{\rm NL} = 0.5\ h/{\rm Mpc}$ in the cosmic shear power spectrum and verified that this leads to very similar results. This gives us confidence in the robustness of our conclusions. In order to include Planck data in our forecast, we generate a mock dataset with the fake likelihood fake_planck_realistic available in MontePython v3.1. We analyze chains using the Python package GetDist [66].

We first forecast the lower bound on the neutrino lifetime that can be reached in the near future. We begin by generating mock datasets for the case of stable neutrinos, i.e., $\Gamma_\nu = 0$. Specifically, we generate a mock dataset for the following values of $\sum m_\nu/{\rm eV}$: [0.06, 0.12, 0.18, 0.24, 0.30] for the case of normal ordering and [0.10,0.15,0.20,0.25,0.30] for inverted ordering. This range covers the minimum $\sum m_\nu$ allowed by the normal and inverted mass spectra and also the maximum $\sum m_\nu$ consistent with the current bound derived in Ref. [50]. We then run one Markov chain Monte Carlo scan per mock dataset varying the ΛCDM parameters $\{\omega_b, \omega_{\rm cdm}, 100\theta_s, A_s, n_s, \tau_{\rm reio}\}$ together with $\{\sum m_\nu/{\rm eV}, {\rm Log}_{10}[\Gamma_\nu/({\rm km/s/Mpc})]\}$. As mentioned earlier, here Γ_ν refers to the width of the heaviest neutrino. As our modifications to CLASS have the effect of making the code much slower, we are forced to run a large number of chains (∼100) to acquire enough points to obtain robust

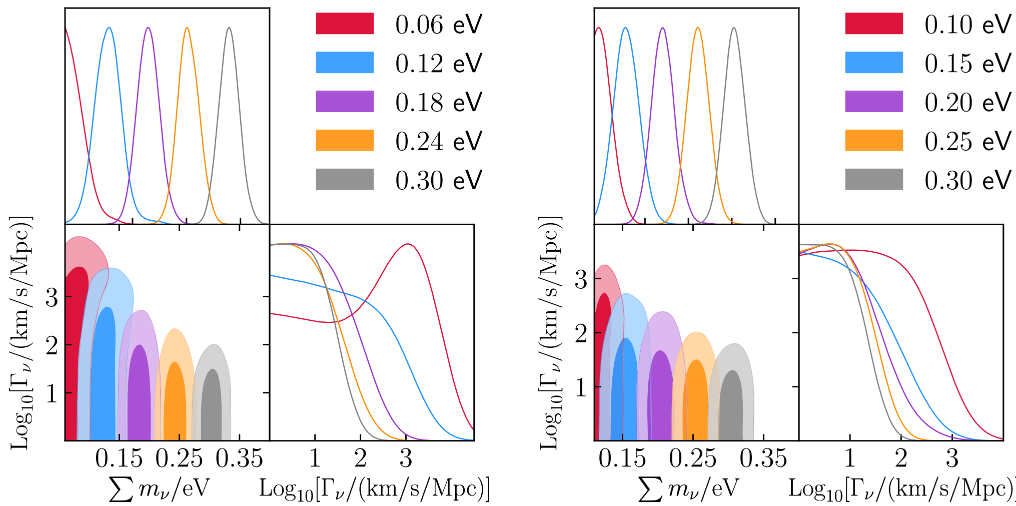

FIG. 2. Forecast of the 2D posterior of the sum of neutrino masses (at 68% C.L.) and decay width of the heaviest neutrino (at 95% C.L.) reconstructed from a combination of Planck + Euclid $P(k)$ + Euclid lensing. The fiducial model assumes that neutrinos are stable and that they follow the normal ordering (left panel) or inverted ordering (right panel).

results. This penalizes the use of the Gelman-Rubin criterion [67] as a convergence test. Nevertheless, all runs satisfy the Gelman-Rubin criterion except for the cases with fiducial $\sum m_\nu/\mathrm{eV} = 0.06$, $\sum m_\nu/\mathrm{eV} = 0.10$, and $\sum m_\nu/\mathrm{eV} = 0.12$. For these runs, we have at most $(R-1) \approx 0.3$, $(R-1) \approx 0.22$, and $(R-1) \approx 0.25$, respectively. Therefore, we primarily rely on visual inspections, and on comparison between various chunks of chains, to assess convergence. As a check, we have verified that, for all scenarios, our constraints vary by less than 10% when adapting the fraction of points removed with GetDist from 0.1 to 0.5.

Our results are displayed in Fig. 2 for the normal- (left) and inverted- (right) mass ordering cases, where we show the bounds on the decay rate Γ_ν of the heaviest neutrino as a function of $\sum m_\nu$. We summarize the bounds on the neutrino masses and lifetime for both hierarchies in Table I. Of utmost importance, we find that the combination of Planck and Euclid can break the degeneracy between $(\sum m_\nu, \Gamma_\nu)$ and set an upper bound on the neutrino lifetime, $\mathrm{Log}_{10}[\Gamma_\nu/(\mathrm{km/s/Mpc})] \leq 3.7$ (2σ), even for the lowest possible neutrino mass. Moreover, we find that the sensitivity to $\sum m_\nu$ is not significantly degraded by the additional free parameter $\log_{10}\Gamma_\nu$. As can be seen from Table I, the bounds on Γ_ν in the normal and inverted ordering cases become increasingly close above $\sum m_\nu \gtrsim 0.2$ eV. This is because in this limit the neutrinos are becoming quasidegenerate. Nevertheless, even for $\sum m_\nu = 0.3$ eV, the values of the two largest neutrino masses differ at the level of a few percent between the normal and inverted hierarchies. Since $\Gamma_\nu \propto m_\nu^3$, this accounts for the $\sim$10% difference between the bounds on Γ_ν in the two cases. Finally, we mention that we do not find any strong correlation between the decay rate and the other cosmological parameters. Therefore, for brevity we do not explicitly report the reconstructed ΛCDM parameters.

Given these constraints on $\mathrm{Log}_{10}[\Gamma_\nu/(\mathrm{km/s/Mpc})]$, we anticipate that future cosmological data will be able to determine that neutrinos are decaying if the width exceeds this limit. To demonstrate this, we turn our attention to a scenario with unstable neutrinos and generate two sets of mock data corresponding to $(\mathrm{Log}_{10}[\Gamma_\nu/(\mathrm{km/s/Mpc})], \sum m_\nu/\mathrm{eV}) = (3.7, 0.16)$ and (3,0.25) with a normal

TABLE I. Forecast constraints on the sum of neutrino masses (at 68% C.L.) and decay width of the heaviest neutrino (at 95% C.L.) from Fig. 2.

Normal ordering					
Fiducial $\sum m_\nu/\mathrm{eV}$	0.06	0.12	0.18	0.24	0.30
$\sum m_\nu/\mathrm{eV}$	<0.085	$0.125^{+0.020}_{-0.020}$	$0.183^{+0.017}_{-0.017}$	$0.243^{+0.016}_{-0.016}$	$0.303^{+0.015}_{-0.015}$
$\mathrm{Log}_{10}[\frac{\Gamma_\nu}{\mathrm{km/s/Mpc}}]$	<3.7	<3.2	<2.1	<1.7	<1.5
Inverted ordering					
Fiducial $\sum m_\nu/\mathrm{eV}$	0.10	0.15	0.20	0.25	0.30
$\sum m_\nu/\mathrm{eV}$	<0.13	$0.154^{+0.017}_{-0.017}$	$0.205^{+0.015}_{-0.017}$	$0.253^{+0.016}_{-0.016}$	$0.304^{+0.015}_{-0.015}$
$\mathrm{Log}_{10}[\frac{\Gamma_\nu}{\mathrm{km/s/Mpc}}]$	<2.7	<2.2	<1.8	<1.5	<1.3

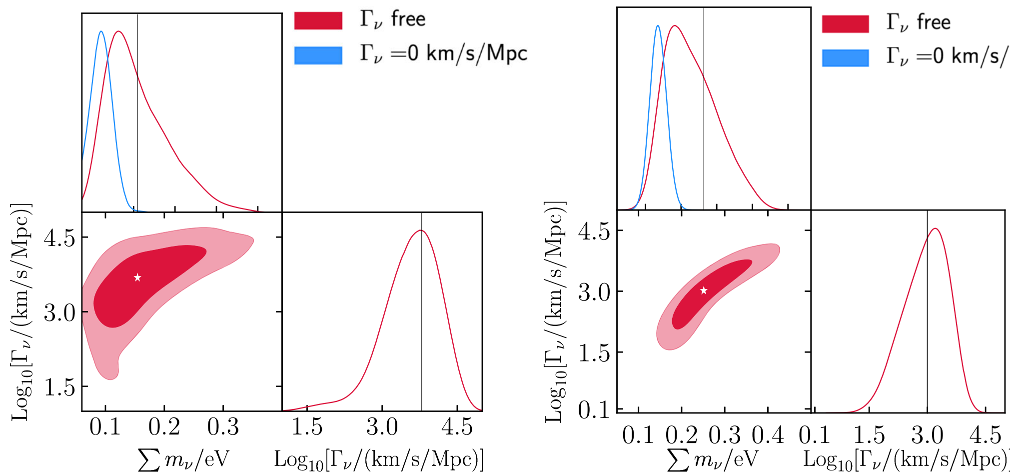

FIG. 3. The same as Fig. 2, but the fiducial model now assumes decaying neutrinos with $(\text{Log}_{10}[\Gamma_\nu/(\text{km/s/Mpc})], \sum m_\nu/\text{eV}) = (3.7, 0.16)$ (left panel) and (3,0.25) (right panel) in the normal ordering. The stars and dashed lines indicate the fiducial values of the corresponding parameters.

ordering. For each mock dataset and fiducial model, we run two cases, one in which we leave Γ_ν free to vary and another in which we enforce the constraint $\Gamma_\nu = 0$. The purpose of the latter case is to allow us to estimate the typical bias that would be introduced if this scenario was actually realized in nature and neutrino decays were not accounted for. The results of both these runs satisfy the Gelman-Rubin criterion.

Our results are shown in Fig. 3 and summarized in Table II. We find, as expected, that for both cases the combination of Planck and Euclid sets an upper limit on the neutrino lifetime, so that the decaying neutrino scenario can be distinguished from the stable case at better than 3σ. Remarkably, in both cases we also obtain a lower limit on the neutrino lifetime at 3σ, opening the door to the possibility of determining the neutrino lifetime from cosmology.

Based on our limits, one might expect that the neutrino lifetime can be determined at better than 2σ provided $\text{Log}_{10}[\Gamma_\nu/(\text{km/s/Mpc})] > 3.7$ for $\sum m_\nu/\text{eV} > 0.06$. However, recall that the regime $\text{Log}_{10}[\Gamma_\nu/(\text{km/s/Mpc})] \gtrsim 5$ is not treated in our formalism, since neutrinos would be decaying while still relativistic. We defer a detailed study of the parameter space for which next-generation experiments can determine the neutrino lifetime to future work.

Interestingly, we find that, in both the cases considered, the precision at which $\sum m_\nu$ can be detected is strongly degraded compared to the contours in Fig. 2. Indeed, in these cases the uncertainty on $\sum m_\nu$ is multiplied by ~ 5 when Γ is left free to vary and ~ 1.5 when $\Gamma_\nu = 0$ is enforced. This is of great importance for next-generation experiments which claim that a combination of datasets will be able to detect the sum of neutrino masses "at 5σ" even in the minimal mass case. Perhaps even more important, we find that, when $\Gamma_\nu = 0$ is enforced, a strong bias in the reconstructed neutrino mass away from the true value can appear. For the specific cases studied here, we find a bias of roughly −0.06 eV, i.e., a $\sim 3\sigma$ shift away from the "true" value.

TABLE II. Forecast constraints at 68% C.L. on the sum of neutrino masses and decay width of the heaviest neutrino from Fig 3.

Fiducial $(\text{Log}_{10}[\frac{\Gamma_\nu}{\text{km/s/Mpc}}], \sum m_\nu/\text{eV})$	(3.7,0.16)	(3,0.25)
$\sum m_\nu/\text{eV}$	$0.167^{+0.035}_{-0.076}$	$0.261^{+0.042}_{-0.069}$
$\text{Log}_{10}[\frac{\Gamma_\nu}{\text{km/s/Mpc}}]$	$3.59^{+0.65}_{-0.45}$	$2.96^{+0.64}_{-0.46}$
$\sum m_\nu/\text{eV}$ (stable)	$0.10^{+0.02}_{-0.02}$	$0.19^{+0.02}_{-0.02}$

IV. CONCLUSIONS

In summary, we have considered the cosmological signatures of theories in which the neutrinos decay into invisible radiation on cosmological timescales. We have shown that, in this scenario, observations of large-scale structure made at multiple redshifts may allow two fundamental parameters, the sum of neutrino masses and the neutrino lifetime, to be determined independently. We find that near-future measurements by the Euclid satellite can improve the lower limit on the neutrino lifetime in this scenario from $\mathcal{O}(10)$ to 200 million years. In the case of neutrinos that decay on shorter timescales, these measurements may allow the neutrino lifetime to be determined from cosmology.

In our analysis, we have focused on the decay of neutrinos to dark radiation, which is easier to distinguish from the case of stable neutrinos than the decay of heavier neutrinos to lighter ones. However, we expect that our results also give a good approximation to the latter scenario in the limit that the lightest neutrino is massless. This applies to both the normal and inverted hierarchies and shows that future observations will have some level of sensitivity to this interesting class of theories.

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