Constraints on inflation with an extended neutrino sector

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Constraints on inflationary models typically assume only the standard models of cosmology and particle physics. By extending the neutrino sector to include a new interaction with a light scalar mediator ($m_\phi \sim$ MeV), it is possible to relax these constraints, in particular via opening up regions of the parameter space of the spectral index n_s. These new interactions can be probed at IceCube via interactions of astrophysical neutrinos with the cosmic neutrino background for nearly all of the relevant parameter space.

I. INTRODUCTION

The success of the big bang theory is evident due to the incredible agreement between the model and the anisotropies in the cosmic microwave background (CMB). In order to explain certain questions such as the homogeneity of the universe on large scales, the flatness of the universe, and the lack of magnetic monopoles, some model of inflation is usually assumed. Since directly probing the details of inflation is difficult, a plethora of models exist on the market. Due to recent precision measurements from Planck [1] many of these models have become ruled out due in large part to constraints of the spectral index n_s and the tensor-to-scalar ratio r. It has since been shown that some regions of n_s parameter space can be allowed by including new neutrino interactions [2–4].[1]

In this paper we explore the neutrino phenomenology involved in opening up the parameter space to models of inflation previously thought to be ruled out. In particular, this new interaction will cause high energy ($\sim$TeV – PeV) neutrinos traveling astrophysical distances to resonantly scatter and lose energy off the cosmic neutrino background (CνB). By looking for dips in the spectrum, experiments like IceCube and KM3NeT can discover or constrain these models.

In Sec. II we discuss the nature of the new neutrino interaction. We then look at how cosmology is modified by such a new interaction in Sec. III and derive the allowed region in parameter space by performing a Markov Chain Monte Carlo (MCMC) analysis. In Sec. IV we discuss how different inflation models are affected. Finally, in Sec. V we

present an overview of how the new interaction could be directly probed, and we conclude in Sec. VI.

II. NONSTANDARD NEUTRINO INTERACTIONS

The Standard Model (SM) of particle physics assumes neutrinos to be exactly massless. The discovery of neutrino oscillations [6,7] has therefore been a clear hint to the existence of physics beyond the SM. Almost every attempt to account for neutrino masses necessitates the existence of yet unobserved particles or yet unobserved interactions in the neutrino sector.

The simple extension of the SM by right handed Dirac neutrinos however imposes a hierarchy problem, as there is no reason why neutrinos should be more than six orders of magnitude lighter than the charged leptons. If neutrinos are Majorana particles and $U(1)_{B-L}$ is broken, the seesaw mechanism [8] provides an easy way out: Since the mass of the right-handed sterile state is not induced by the Higgs mechanism, the right-handed neutrinos could be much heavier than their left-handed active partners. After diagonalizing the mass matrix the active neutrino states would naturally acquire small masses.

This being said, there is also the possibility that $U(1)_{B-L}$ is spontaneously broken. In that case, we expect the existence of a new Goldstone particle—the Majoron—that couples to neutrinos via Yukawa coupling,

$$\mathcal{L} = g_{\alpha\beta}\bar{\nu}_\alpha\nu_\beta\phi, \qquad (1)$$

where α and β stand for flavour or mass eigenstates, while ϕ is flavour blind.

Therefore, we expect the appearance of nonstandard neutrino interactions in those models. However, in general this kind of interaction is by no means limited to the existence of a Majoron. The parameterization above remains

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[1]Note that another way to enhance the allowed region in the $n_s - r$ plane is to add $N_{\rm eff}$ as a free parameter [5].

agnostic about the precise nature of the scalar particle, which could be linked to dark sectors or dark matter.

In the following, we restrict our discussion to diagonal couplings, i.e., $g_{\alpha\beta} \equiv g\mathbb{1}_3$ and therefore g has the same form in both flavor and mass basis. The coupling g can be constrained in three kinematic regimes: when the scalar mass m_ϕ is (i) much smaller, (ii) comparable or (iii) much larger than the center of mass energy $\sqrt{s}$. A comprehensive overview over the constraints as well as their ranges of validity in the (g, m_ϕ)-plane can be found in [9]. Those constraints on g are obtained from different observations: super novae neutrinos [10,11], big bang nucleosynthesis (BBN) [12] and the decay of the Z boson [13,14] help to constrain interactions of the form (1). A relatively large parameter range of (g, m_ϕ) is however still allowed. Measurements of the cosmic microwave background (CMB) can tighten the bounds, but interestingly also point out a parameter range of (g, m_ϕ) that is in agreement with all observations given neutrinos that self-interact according to Eq. (1).

III. A HINT FROM COSMOLOGY

Cosmological observations have proven to be a powerful tool in order to constrain physics beyond the standard model at energies that are out of reach in laboratory experiments. One of the most famous examples thereof is the constraint on the sum of neutrino masses from measurements of the CMB in combinations with baryonic acoustic oscillations (BAO), $\sum m_\nu < 0.12$ eV (95% CL) [15,16]. This bound depends on the assumed cosmological model [17] and in partcular can be relaxed if the average momentum of the CMB neutrinos is larger than that of a perfectly thermal distribution [18]. Additionally, it has been demonstrated in [2–4,19,20] that the CMB can also constrain models of nonstandard neutrino interactions, like the Majoron models described in the previous section.

A. Impact of nonstandard neutrino interactions on cosmological observables

Let us explain the impact of nonstandard interactions on the CMB in a bit more detail in the following. According to the SM neutrinos decouple from the cosmic plasma at around $T \approx 1$ MeV. Therefore, at the time of recombination, i.e., $T \approx 0.3$ eV, neutrinos are usually assumed to be entirely free-streaming. Any form of nonstandard interactions in the neutrino sector is expected to change the free-streaming behavior of neutrinos. For the model (1) and depending on the Majoron mass m_ϕ, this can happen according to two very different thermal histories: If $m_\phi > \sqrt{s}$ at all relevant time scales, the population of the Majoron itself would be thermally suppressed such that the Lagrangian (1) only introduces nonstandard neutrino self-interactions. In such a scenario neutrinos would decouple from the cosmic plasma at the standard weak

decoupling time, but remain coupled to each other until eventually much later times, when the Hubble rate $(\sim T^2/m_{\rm Pl})$ where $m_{\rm Pl}$ is the Planck mass, overtakes the neutrino self-interaction rate $(\sim g^4 T_\nu^5/m_\phi^4)$. By contrast, if the Majoron is effectively massless at the relevant time scales $(m_\phi < \sqrt{s})$, neutrinos would decouple at the standard weak decoupling time, free-stream for some time and *recouple* at later times when the Hubble rate overtakes the neutrino interaction $(\sim g^4 T)$ rate. The time of recoupling would also mark the time when the Majoron gets produced. We focus on the first scenario (the delayed decoupling scenario) in the rest of this work. This restricts the validity of our constraints to scalar masses larger than a few hundred keV, in order to ensure that the scalars are nonrelativistic at all time scales relevant for the CMB.

We can understand the cosmological impact of such neutrino self-interactions in the following way: Neutrino free-streaming leads to a suppression of the neutrino energy contrast as it transfers power to the anisotropic stress (and to higher multipole moments in the neutrino Boltzmann hierarchy). Therefore, any nonstandard neutrino interactions which are effective after the weak decoupling temperature suppress free-streaming and enhance the neutrino energy contrast.

The formalism that allows to include neutrino self-interactions in CMB calculations has been derived in [21]. In a subsequent paper [2], it has been shown that neutrino self-interactions mediated by a massive Majoron (1) lead to a scale-dependent enhancement of the anisotropy spectrum of the CMB.

As shown in [4], the impact on the matter power spectrum is mainly due to an increased amplitude of the gravitational potential at horizon entry. This results in a suppression of the matter power spectrum at small wavelengths and to a boost at wavelengths entering the horizon at the time of neutrino decoupling.

B. MCMC analysis

Since the impact of neutrino self-interactions on the CMB is degenerate in the coupling g and the Majoron mass m_ϕ, it is convenient to introduce an effective four-point coupling (in analogy to the Fermi coupling)

$$G_{\rm eff} = \frac{g^2}{m_\phi^2}. \tag{2}$$

Measurements of the CMB temperature and polarization anisotropy spectra can be used in order to constrain this effective neutrino coupling $G_{\rm eff}$ (2). Such analyses have been performed in [2–4] with Planck 2015 data [22] and in [19,20] with Planck 2013 data [23]. Interestingly, the analyses reveal a bimodal posterior distribution in the effective coupling. As expected, the major mode demands neutrinos to behave not too different from the standard assumption, i.e., to be almost free-streaming. Note that

even this mode actually only demands neutrino to start free-streaming at about $T_\nu \approx 20$ eV. We however refer to this mode as the ΛCDM mode in the following, as the posterior distributions of all cosmological parameters mainly reflect those of the standard ΛCDM limit with $G_{\text{eff}} = 0$. More remarkably, due to a degeneracy of G_{eff} and some other cosmological parameters (mainly the sound horizon θ_s at last scattering and the spectral index n_s) there exists another allowed region in the cosmological parameter space which allows neutrinos to have very strong interactions in the ballpark of $G_{\text{eff}} \approx 3 \times 10^{-2}$ MeV^{-2}. An interesting consequence of the interacting neutrino mode is a higher value of the Hubble constant H_0. This is an appealing feature, as the CMB provides a 2–3.5σ [15] lower value of the Hubble constant than local measurements do [24]. In a 1-parameter extension of ΛCDM by G_{eff} this tension is only weakened but not resolved. Adding also N_{eff} and $\sum m_\nu$ as free parameters to the analysis fully alleviates the Hubble parameter tension, and could be related to light sterile neutrino hints [4]. We however follow a minimalistic approach and only extend the neutrino sector by one additional parameter, i.e., the neutrino self-coupling G_{eff} (assuming thereby $N_{\text{eff}} = 3.046$ and $m_\nu = 0$ eV).

A further remarkable feature of the self-interacting neutrino mode is the fact that it is accompanied by a lower value of the spectral index n_s, namely in the region $n_s \approx 0.94$. As we will discuss in detail in the next section, this can have important consequences on the selection of inflationary models. Since inflationary model selection is usually performed in the posterior plane of the spectral index n_s and the tensor-to-scalar ratio r (see e.g., [1]), we extended the work of [2,3] by adding r as an additional parameter to the analysis. Therefore, we have two extra parameters in addition to the six cosmological base parameters, i.e.,

$$\{\omega_b, \omega_{\text{cdm}}, 100\theta_s, \ln(10^{10} A_s), n_s, z_{\text{reio}}\} + \log_{10}(G_{\text{eff}}) + r. \tag{3}$$

We modified the numerical Einstein-Boltzmann solver CLASS [25] in order to take into account the effect of neutrino self-interactions in the neutrino Boltzmann hierarchy. Neutrino interactions also change the propagation of gravitational waves by a suppression of the anisotropic stress [26]. This also requires a modification of the equations for tensor perturbations in CLASS. Since tensor perturbations only contribute to scales entering the horizon after recombination, this effect however turns out to be negligible.

Using the Markov Chain Monte Carlo (MCMC) engine Monte Python [27,28], we explore the cosmological parameter space studying the following combination of datasets:

TT + lowP + lensing Temperature anisotropy spectrum and low-ℓ polarization plus lensing reconstruction from Planck 2015 [22].

This combination of data sets is considered to be a conservative choice according to the Planck collaboration [22], since high-ℓ polarization data may still be subject to systematic errors.

We adopt the Gelman-Rubin convergence criterion $R < 0.01$ and apply flat parameters on all cosmological parameters (3), restricting the prior range of $\log_{10}(G_{\text{eff}}[\text{MeV}^{-2}])$ to $[-4.5, -0.1]$. This choice is justified by the fact that $\log_{10}(G_{\text{eff}}[\text{MeV}^{-2}]) < -4$ results in changes in the CMB temperature and polarization spectra below the percent level. For values $\log_{10}(G_{\text{eff}}[\text{MeV}^{-2}]) \gtrsim -0.1$ the neutrino Boltzmann hierarchy becomes so stiff that the implicit ODE-solver of CLASS fails to solve it. Neglecting larger values turns out to be a safe assumption as they are still far off the upper limit of the interacting neutrino mode.

We present our results for the 2D posteriors of the cosmological parameters most affected by the interacting neutrino mode in Fig. 1. As expected we recover the bimodal posterior distribution for G_{eff} which has been reported in [2–4,19]. We turn our discussion to the posterior in the (n_s, r) plane to Sec. IV.

In order to obtain the confidence limits of the two individual modes, we ran two more MCMC analyses: one for the self-interacting mode (which we define by the prior range $\log_{10}(G_{\text{eff}}[\text{MeV}^{-2}]) = [-2.5, -0.1]$) and one for the ΛCDM mode (defined by the prior range $\log_{10}(G_{\text{eff}}[\text{MeV}^{-2}]) = [-4.5, -2.5]$). The results of these separate runs can be found in Table I. Since the two modes are still slightly connected at 95% confidence limit, we quote the 68% confidence lower limit in case of the self-interacting mode.

As in previous works [2–4], we find that the ΛCDM mode is statistically favored over the self-interacting mode, with a difference in the best fit χ^2 values of $\Delta\chi^2 = 3.4$. Adding polarization or external data such as BAO or direct H_0 measurements of course has an impact on the significance of the self-interacting neutrino mode. Based on the extended analysis of [2–4] we however do not expect a qualitative change of the bimodal posterior distribution of $\log_{10}(G_{\text{eff}})$ when using different combinations of datasets.

Figure 2 shows how the self-interacting neutrino mode translates into the plane of the coupling g and the scalar mass m_ϕ. For $m_\phi \lesssim 0.2$ and $g \gtrsim 10^{-4}$ the scalar particle gets produced before neutrino decoupling and enhances the relativistic energy density that is usually parametrized by N_{eff} and constrained by CMB measurements [12,29].[2] Couplings larger than $g \sim 0.6$ are excluded by measurements of the decay of the Z boson [9,14,30]. Therefore, realistic values for the scalar mass of the interacting neutrino mode therefore fall into the relatively narrow range of $m_\phi \sim [0.2 \text{ MeV}, 5 \text{ MeV}]$. As we discuss in Sec. V,

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[2]The CMB constraints on N_{eff} were shown to be almost unaffected when G_{eff} is allowed to vary [2], while they change when additionally $\sum m_\nu$ is added as a free parameter [4].
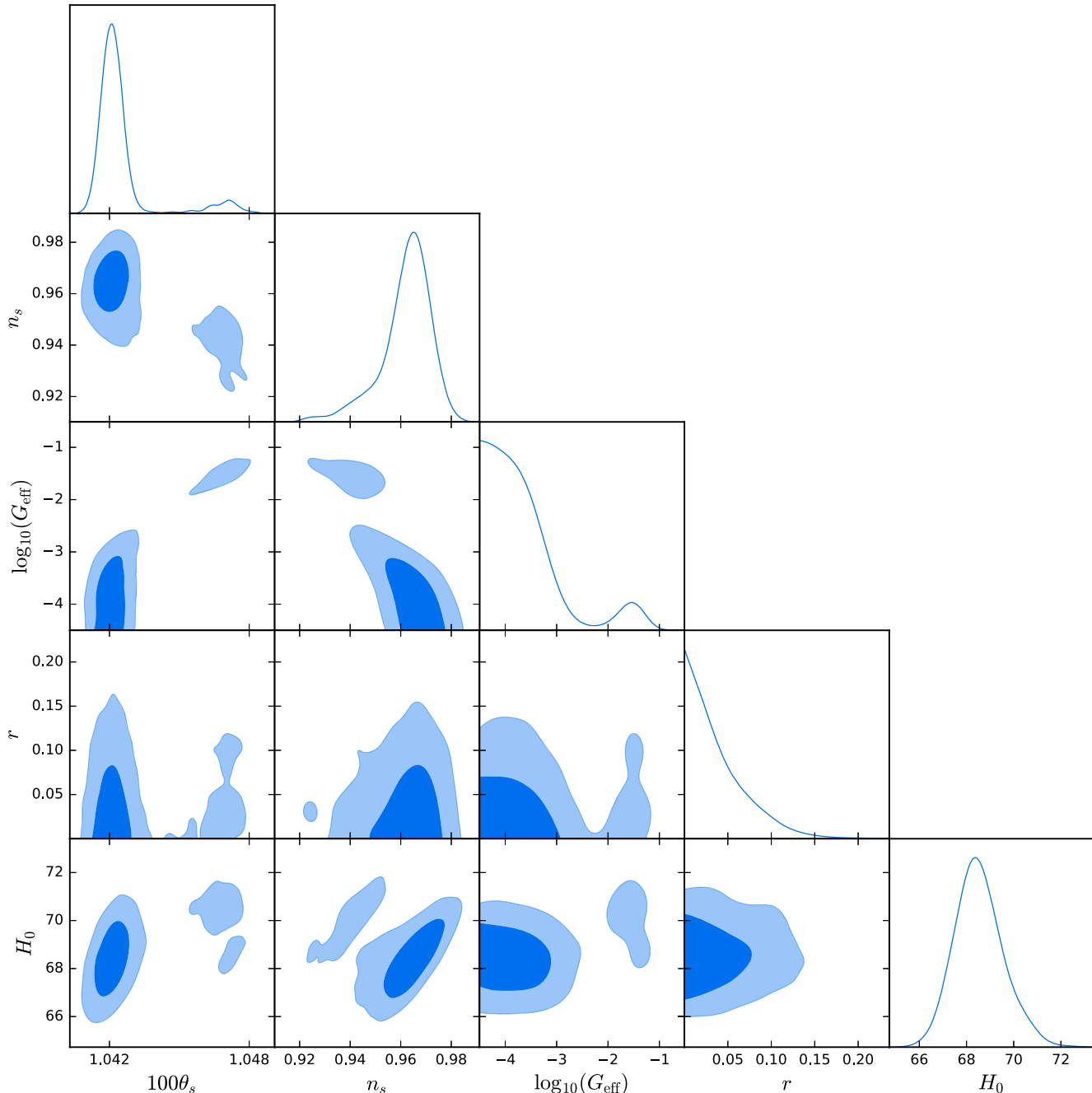
FIG. 1.   2d posterior distributions of the parameters most affected by the effective neutrino coupling G_{eff}. G_{eff} is given in units of MeV^{-2} and H_0 in km/s/Mpc.

this mass range falls by coincidence exactly into the energy window which is testable by IceCube. Let us however first focus on the impact of the self-interacting neutrino mode on constraints of inflationary models.

IV. CONSEQUENCES FOR INFLATION

Despite their indisputable success, the hot big bang model and general relativity do have some inconsistencies

that can be solved only by a period of accelerated expansion known as inflation. Inflation is the key to explain the homogeneity, the isotropy, and the flatness of the Universe, as well as the absence of monopoles.

However, inflation is not a model but a framework. There are a multitude of inflationary models in the literature [31]. And although every inflationary model produces an approximately homogeneous Universe, each does so in somewhat unique ways. Each model of inflation predicts its

TABLE I. Mean values and limits of the most affected cosmological parameters within the self-interacting neutrino mode and the ΛCDM mode. Quoted limits are at 95% confidence limits, except the one marked with a $*$ which is at 68%.

	Self-interacting mode	ΛCDM mode
$100\theta_s$	$1.0463^{+0.0018}_{-0.0028}$	$1.0421^{+0.0009}_{-0.0009}$
n_s	$0.941^{+0.016}_{-0.017}$	$0.964^{+0.015}_{-0.016}$
$\log_{10}(G_{\text{eff}}[\text{MeV}^{-2}])$	$-1.68^{+0.43}_{-0.13*}$	<-3.04
r	<0.11	<0.11
$H_0[\text{km/s/Mpc}]$	$70.06^{+2.21}_{-2.31}$	$68.35^{+1.94}_{-1.84}$

own small inhomogeneities that essentially behave as a particular models smoking gun. Therefore the experimental observation of inhomogeneities via CMB anisotropies and structure formation provides a test of the different inflation models.

Inflation models mainly predict two types of perturbations, scalar and tensor, which turn into density (matter) and gravitational wave fluctuations. Each of them is generally described by a fluctuation amplitude and a dependence on the scale of such an amplitude. In the case of scalar perturbations the amplitude is called A_S and the spectral index n_s while for gravity waves they are A_T and n_T, respectively, with the former generally given in terms of the ratio $r \propto A_T/A_S$.

These four quantities are not independent, only two of them are. As a consequence theoretical predictions for the different inflation models as well as data are presented in the $n_s - r$ plane, where one depicts the two independent quantities that are usually adopted to study the constraints
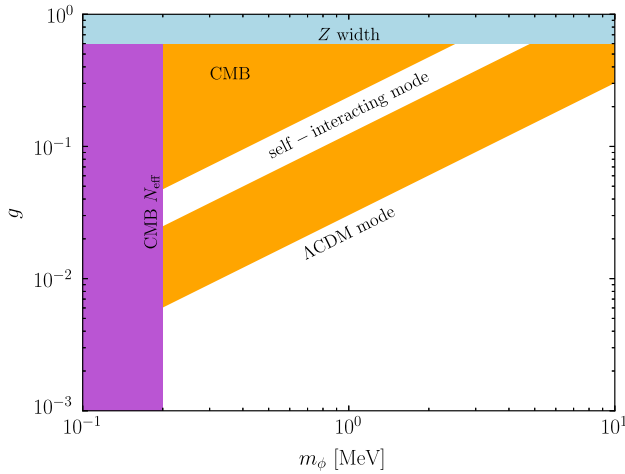

FIG. 2. Allowed parameter range for G_{eff} in the (g, m_ϕ)-plane. The white region is allowed while the various shaded regions are excluded. The two disjoint white regions correspond to the two solutions allowed by CMB data: the smaller compact one is that with a new neutrino interaction and the larger one corresponds to the ΛCDM mode.

on the various inflationary models. Establishing which region of this plane is allowed by data is essentially establishing which models of inflation survive the experimental scrutiny.

As we have already seen the inclusion of a new neutrino interaction, completely consistent with all experimental evidence so far, significantly enlarges the allowed region in the $n_s - r$ plane and therefore gives a new life to models that would be excluded or under great pressure in the absence of such an interaction. In the following we will not only show two examples of such models but also discuss how the interactions capable of giving this second chance to inflationary models can be tested in neutrino experiments in the near future.

A. Inflation observables

Specializing the Lagrangian of the form

$$\mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi), \quad (4)$$

to the case of a Friedmann-Robertson-Walker metric,

$$g_{\mu\nu} = \text{diag}\{1, -a^2(t), -a^2(t), -a^2(t)\}, \quad (5)$$

results in the equation of motion of the form

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0, \quad (6)$$

where $H = (\dot{a}/a)$ is the Hubble parameter and the prime denotes derivative with respect to φ. The amplitudes of scalar and tensor perturbations then, are given by

$$A_S^2 = \frac{512\pi}{75m_{\text{Pl}}^6}\frac{V^3}{V'^2}\bigg|_{k=aH}; \quad A_T^2 = \frac{4}{25\pi}\frac{H^2}{m_{\text{Pl}}^2}\bigg|_{k=aH}, \quad (7)$$

where the above expressions are evaluated at Hubble radius crossing, $k = aH$ with k the comoving wave number and the tensor to scalar ratio is given by

$$r \equiv 16\frac{A_T^2}{A_S^2}. \quad (8)$$

Defining the spectral indices of scalar and tensor perturbations by

$$n_s - 1 \equiv \frac{d\ln A_S^2}{d\ln k}\bigg|_{k=aH}; \quad n_T \equiv \frac{d\ln A_T^2}{d\ln k}\bigg|_{k=aH}, \quad (9)$$

and imposing the slow-roll regime, i.e., $\ddot{\varphi} \ll 3H\dot{\varphi}$ results in

$$n_s - 1 = -6\epsilon + 2\eta; \quad n_T = -2\epsilon, \quad (10)$$

where the slow roll parameters are defined as

$$\epsilon \equiv \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2; \qquad \eta \equiv \frac{m_{\rm Pl}^2}{8\pi}\frac{V''}{V}. \tag{11}$$

Inflation ends when the field φ reaches a value such that $\epsilon(\varphi_e) = 1$ and the amount of inflation generated is quantified by the number of e-folds,

$$N \simeq -\frac{8\pi}{m_{\rm Pl}^2}\int_{\varphi}^{\varphi_e}\frac{V}{V'}. \tag{12}$$

The perturbations we observe today were generated 45-60 e-folds before the end of inflation and at this value of the field we have to evaluate the spectral and scalar indices.

It is clear then, that given an inflaton potential, it is straightforward to analyze its phenomenological imprints on the CMB. Thus, considering the absolute freedom in the potential selection, simple and well-motivated potentials are especially welcomed. Among these, two potentials are especially appealing from the particle physics point of view: natural inflation (NI) and (small field) Coleman Weinberg (CW) inflation. Amazingly enough both happen to be either in tension (NI) or ruled out (CW) if we do not include the possibility of neutrino interactions.

B. Inflationary model selection

Natural inflation is a technically natural answer to the required flatness of the inflaton potential. In the original proposal the inflaton was the pseudo–Nambu Goldstone boson of a broken symmetry, shift symmetry [32,33]. The symmetry that precisely explained why the potential was "nearly" flat. Since then many types of candidates have been explored, including hybrid models and multifield models. From the purposes of this study the precise nature of the inflaton and how it is embedded in a complete particle physics model is not crucial and therefore we will focus on the original version of the model, in which there is a unique field rolling down a potential of the form

$$V(\varphi) = \Lambda^4(1 + \cos(\varphi/f)), \tag{13}$$

where f is the scale of inflation and the slow-roll parameters take the form

$$\epsilon(\varphi) \simeq \frac{m_{\rm Pl}^2}{16\pi f^2}\left[\frac{\sin(\varphi/f)}{1 + \cos(\varphi/f)}\right], \tag{14}$$

$$\eta(\varphi) \simeq -\frac{m_{\rm Pl}^2}{16\pi f^2}, \tag{15}$$

while inflation ends when the field takes a value φ_e such that

$$\cos(\varphi_e/f) = \frac{1 - 16\pi(f/m_{\rm Pl})^2}{1 + 16\pi(f/m_{\rm Pl})^2}. \tag{16}$$
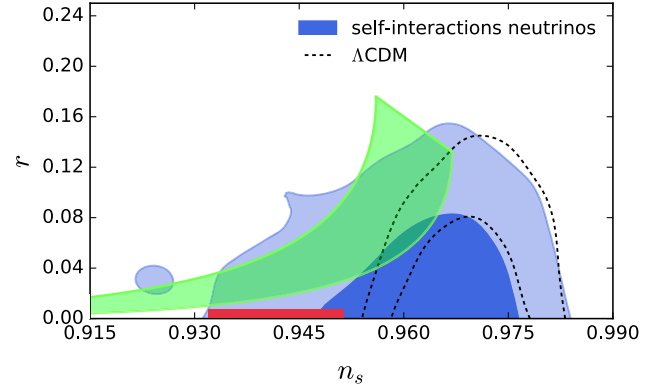

FIG. 3. Comparison of the predictions of natural inflation (green) and Coleman Weinberg inflation (red) with the 68% (dark blue) and 95% (light blue) confidence regions for the interacting neutrino mode (same data set as Fig. 1). Dashed lines mark the confidence regions obtained within the standard ΛCDM framework assuming free-streaming neutrinos ($G_{\rm eff} = 0$).

It can be easily seen that for $f < m_{\rm Pl}$, n_s is essentially independent of the number of e-folds while for $f > m_{\rm Pl}$, n_s has no dependence of f. The predictions of natural inflation can be seen in Fig. 3 for $45 < N < 60$ (green). We show the posterior distribution in the (n_s, r) plane when neutrinos are allowed to have self-interactions, i.e., a zoom-in of the (n_s, r) plot in Fig. 1. As a comparison we also show the posterior contours of the standard case when $G_{\rm eff} = 0$ (dashed) which are consistent with the Planck 2015 results. Natural inflation is not currently ruled out for the $G_{\rm eff} = 0$ case, but its predictions are out of the Planck 2015 one-sigma favored region [34] and expected to be completely excluded if tensor modes are not found at the few % level with respect to the scalar modes. Neutrino interactions keep the model afloat.

Unlike natural inflation, Coleman Weinberg potentials do not arise naturally but are unavoidable once loop corrections are included in the theory and therefore have been studied extensively [35,36] (and ruled out some time ago [37]). A general CW potential evaluated at a renormalization scale f takes the form

$$V(\varphi) = A\varphi^4\left[\ln\left(\frac{\varphi}{f}\right) - \frac{1}{4}\right] + \frac{Af^4}{4}, \tag{17}$$

which gives

$$\epsilon(\varphi) = \frac{16m_{\rm Pl}^2}{\pi f^2}\left(\frac{\varphi}{f}\right)^6\ln^2\left(\frac{\varphi}{f}\right),$$

$$\eta(\varphi) = \frac{m_{\rm Pl}^2}{2\pi f^2}\left(\frac{\varphi}{f}\right)^2\left[\ln\left(\frac{\varphi}{f}\right) + 1\right],$$

$$N(\varphi) = \frac{2\pi f^2}{m_{\rm Pl}^2}\left({\rm Ei}\left[-2\ln\left(\frac{\varphi}{f}\right)\right] - {\rm Ei}\left[-2\ln\left(\frac{\varphi_e}{f}\right)\right]\right). \tag{18}$$

From these equations it can be seen that in the small field inflation regime, i.e., $\varphi/f \ll 1$, $|\epsilon| \ll \eta$ and therefore in CW inflation

$$N \simeq \frac{3}{1 - n_s}, \tag{19}$$

while $r \propto (f/m_{\mathrm{Pl}})^4 \sim 0$. The predictions of (small field) CW inflation are shown in Fig. 3 for $45 < N < 60$. Clearly this model can only survive (and thrive) once neutrino interactions are included.

The cases presented above are just two examples but convey an important message. Neutrinos are so far the only evidence of physics beyond the Standard Model we have observed. We do know already that the possibility of a Majorana mass terms for neutrinos may introduce new scales and interactions not shared by the other fermions. Right-handed neutrinos are singlets under the Standard Model group and therefore could provide a connection to dark matter and the dark sector in a way other fermions cannot. By ignoring the possibility of neutrino interactions we are missing important regions of cosmological parameter space. We speculate that many potentially appealing and interesting inflation models were not even considered because they appeared to predict spectral indices that were ruled out in the absence of new neutrino interactions.

Even more, in the following we will show that the existence of these neutrino interactions can be experimentally tested and searched for in astrophysical experiments that are running now. Thus maybe in the near future astrophysical experiments can shed a new light on the way we analyze inflation.

V. ASTROPHYSICAL NEUTRINO FLUX

IceCube has detected for the first time the high energy astrophysical neutrino flux [38] which is now understood to be extragalactic [39,40]. This provides us with a new window to the universe and an opportunity to probe new physics models coupling to neutrinos. Consistent with our understanding of extreme nonthermal astrophysical phenomenon, the data is largely consistent with a single power law $dN/dE \propto E^{-\gamma}$ with a spectral index $-2.9 \lesssim \gamma \lesssim -2.3$. The astrophysical flux has been measured up to $\mathcal{O}(\mathrm{few})$ PeV and down to $\mathcal{O}(\mathrm{few})$ TeV. With the proposed upgrade to IceCube-Gen2 [41] it is likely that the Glashow resonance [42] at $E_\nu = 6.3$ PeV would be observed and the flux could be measured up to ~ 10 PeV depending on whether or not there is a cutoff in the flux and what the true spectrum is. The Glashow resonance occurs at $E_\nu = 6.3$ PeV when a high energy $\bar{\nu}_e$ hits an at rest e^- and creates a W^- on-shell leading to a considerably increased cross section. Detecting point sources will be easier with IceCube-Gen2 not only because of the increased statistics, but also because the angular resolution of tracks will improve. Once point sources are found, it may be possible
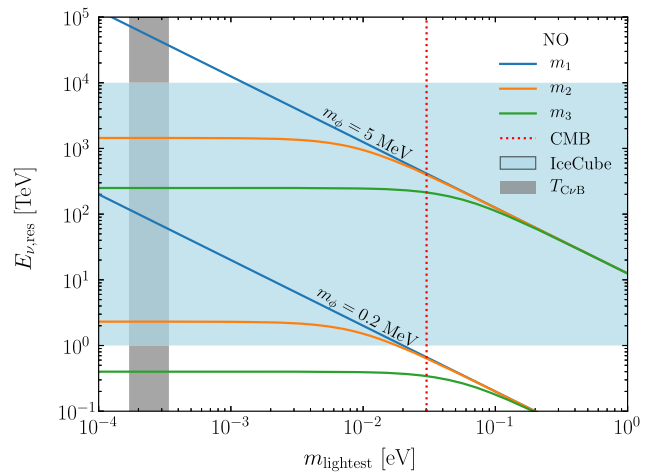

FIG. 4.   The resonant energy of each of the three CνB mass eigenstates as a function of the lightest neutrino mass in the normal mass ordering. The upper three curves are for $m_\phi = 5$ MeV and the lower three for $m_\phi = 0.2$ MeV. These curves are for the NO, the IO is generally the same without the middle, orange, m_2 curve. The blue band is the broadest range of energies that IceCube could possibly measure the astrophysical neutrino flux. The gray band indicates the temperature of the CνB over $z \in [0, 1]$; for m_{lightest} below $T_{C\nu B}$, the resonant energy for m_1 levels off as it is relativistic. The red dashed line indicates the limit from cosmology at $\sum m_\nu < 0.12$ eV [15,16].

to extend the measurement of the astrophysical flux down to lower energies, possibly ~ 1 TeV or lower by using the known locations of the sources to cut through the atmospheric background.

The presence of such a new mediator ϕ given in (1) would lead to a resonant absorption of high energy neutrinos off the cosmic neutrino background (CνB) [9,30,43–46]. The resonant energy is

$$E_{\nu_i}^{\mathrm{res}} = \frac{m_\phi^2 - m_{\nu_i}^2}{2m_{\nu_i}} \approx \frac{m_\phi^2}{2m_{\nu_i}}, \tag{20}$$

for nonrelativistic CνB neutrinos. Such an absorption would lead to a dramatic signal in IceCube that would be very hard to reproduce with standard astrophysics. As identified in [43], the redshift dependence of the unknown source population will smear out the signal somewhat, but the result is generally independent of the redshift evolution. While the resonant energy is a function of both m_ϕ and m_ν, neither of which are known; they both have some constraints as outlined in Fig. 4 for the normal mass ordering (currently preferred at $\sim 3\sigma$ [47,48]). At the upper end of the m_ϕ allowable mass range ~ 5 MeV IceCube will have very good sensitivity as there will be resonances at $E_\nu \gtrsim 250$ TeV independent of the absolute mass scale and possibly additional features as well.

As the mass of m_ϕ decreases the resonance energy decreases. At the lower end $m_\phi \sim 0.2$ MeV it is the lightest

neutrino that will provide the resonance in IceCube's region of interest. Note that when the lightest neutrino mass drops below the CνB temperature, the resonance energy becomes independent of the lightest neutrino mass as it becomes relativistic, meaning that the blue curves should level out to the left of the gray band. In this case, unless the lightest neutrino is near the limit from cosmology, IceCube will have sensitivity to this case as well.

While identifying such a dip in the IceCube spectrum does not guarantee that the neutrinos are scattering off the CνB with such a model, it is an indication of some kind of new physics. Given a broad enough energy scan it could be possible to identify multiple peaks which would provide an indication that these dips were the result of scattering off the CνB. There is currently a hint of a dip at $\sim$500 TeV that has persisted for several years [49], although its significance is quite low. Up to small factors, this roughly corresponds to $m_\phi \simeq 5$ MeV for m_{lightest} near the upper limit, and $m_\phi \simeq 0.5$ MeV in the limit where m_{lightest} is relativistic.

It is important to note that the current IceCube analysis must assume some spectrum at the Earth since neutrino energies cannot be measured directly without a prior hypothesis. Typically that prior takes the form of a single power law.[3] We hope that in the future IceCube performs fits with different functions including those with dips for identifying resonant models. In addition, possible future measurements of neutrinos at even higher energies up to $E_\nu \sim 1$ EeV with Auger [51], ANITA [52], ARA [53], ARIANNA [54], GRAND [55] and POEMMA [56] could extend the reach to larger values of m_ϕ provided sufficient energy resolution. Also the presence of regeneration, a process wherein high energy neutrinos lose energy as they upscatter the CνB, could also lead to a distinct signal which could be relevant for cosmogenic neutrinos from the interactions of ultrahigh energy cosmic rays off the CνB scattered down to IceCube energies.

VI. CONCLUSIONS

The precision of cosmological data has moved us from testing the generic predictions of the inflationary paradigm to selecting individual models of inflation. Inflation is governed exclusively by two parameters, therefore extreme care is demanded when we extract these two numbers from data. While in the conventional picture inflation models are becoming somewhat constrained, the presence of new neutrino interactions enlarges the allowed values of these two numbers and therefore enlarges the number of models and changes the selection criteria.

This model also has a clear signature at IceCube and we hope that future analyses of the high energy astrophysical flux will look for dips in the spectrum. Such a dip would provide strong evidence of the CνB as well as a moderately constrained measurement on the new mediator at the MeV scale; with additional information on the absolute mass scale and the astrophysical sources it is conceivable that the mediator mass could become well measured. Finally, while the current dip in the IceCube data at $\sim$500 TeV is not yet significant, it is a tantalizing hint.

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[3]Another IceCube analysis considered a two-component power-law and found it was not preferred over a single power law [50].

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