Constraints on neutrino and dark radiation interactions using cosmological observations

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Observations of the cosmic microwave background (CMB) and large-scale structure (LSS) provide a unique opportunity to explore the fundamental properties of the constituents that compose the cosmic dark radiation background (CDRB), of which the three standard neutrinos are thought to be the dominant component. We report on the first constraint to the CDRB rest-frame sound speed, $c^2_{\rm eff}$, using the most recent CMB and LSS data. Additionally, we report improved constraints to the CDRB viscosity parameter, $c^2_{\rm vis}$. For a non-interacting species, these parameters both equal 1/3. Using current data we find that a standard CDRB, composed entirely of three non-interacting neutrino species, is ruled out at the 99% confidence level (C.L.) with $c^2_{\rm eff} = 0.30^{+0.027}_{-0.026}$ and $c^2_{\rm vis} = 0.44^{+0.27}_{-0.21}$ (95% C.L.). We also discuss how constraints to these parameters from current and future observations (such as the Planck satellite) allow us to explore the fundamental properties of any anomalous radiative energy density beyond the standard three neutrinos.

I. INTRODUCTION

A complete understanding of the basic building blocks of the universe hinges on understanding the elusive properties of neutrinos. As a result of having extremely weak interactions, neutrinos are the least accurately measured of the known fundamental particles. However, even with our limited knowledge of neutrino properties, the fact that they are massive [1] represents one of the most significant challenges to the Standard Model of particle physics. Therefore, any improved knowledge of the properties of neutrinos will not only serve to shed new light on a relatively poorly explored aspect of fundamental physics but may also provide further evidence of inadequacies of the Standard Model. Adding urgency to the exploration of the properties of neutrinos, a recent combination of data on anomalous neutrino mixing [2] along with observations of the neutrino flux from nuclear reactors [3] has indicated anomalous mixing between neutrino flavors.

An important consequence of these modifications to the neutrino sector is their imprint on cosmological observations. Within the Standard Model, a cosmological background of neutrinos is in thermodynamic equilibrium with the other cosmological species for temperatures $T_\nu \gtrsim 1$ MeV, after which the neutrino background decouples and only interacts through gravity. Neutrinos are thought to comprise a significant fraction of the radiative energy density during big bang nucleosynthesis (BBN) causing a measurable effect on the abundances of the primordial light elements [5] as well as during the formation of the cosmic microwave background (CMB) and large scale structure (LSS) [6].

Cosmological observations are able to place precise constraints on the effective number of neutrino species, $N_{\rm eff}$, defined so that the total radiative energy density is given by $\rho_{\rm rad} = \rho_\gamma[1 + N_{\rm eff}(7/8)(4/11)^{4/3}]$, where ρ_γ is the energy density in photons. The cosmological radiative content in addition to the photons is known as the cosmic dark radiation background (CDRB). In the standard cosmological model the only radiative energy density besides photons are the three known neutrino species so that $N_{\rm eff} = 3.046$, with the small correction due to finite temperature QED effects and neutrino flavor mixing [7].

Greatly adding to the intrigue, a combination of the most current observations of the CMB and LSS indicate that $N_{\rm eff} > 3$ at the 99.9% C.L., with $N_{\rm eff} = 4.0^{+0.58}_{-0.57}$ (95% C.L., see Table I). Cosmological constraints on $N_{\rm eff}$ are insensitive to anything but the total energy density contained in the CDRB. Most radiative backgrounds, including neutrinos, share the property that they are 'non-interacting', i.e., they only interact with other cosmological species through gravity. Examples of such backgrounds include axions [9] and short-wavelength gravitational-waves [10]. Any further interpretation of finding $N_{\rm eff} > 3$ requires information on other properties of the anomalous radiative energy density.

Here we constrain the values of two additional parameters which determine the properties of the CDRB: the rest-frame sound speed, $c_{\rm eff}$, and a viscosity parameter, $c_{\rm vis}$ [11]. As we will describe further, a standard, non-interacting, radiative background has $(c^2_{\rm eff}, c^2_{\rm vis}) = (1/3, 1/3)$. However, if the CDRB is composed of any non-standard species with significant interactions these parameters can take on different values (see, e.g., Refs. [12, 13]) which can have a significant impact on the observed CMB power spectrum, as shown in Fig. 2. If both $c^2_{\rm vis}$ and $c^2_{\rm eff}$ are found to be consistent with their standard value of 1/3 this would lend weight to the interpretation that observations indicate the existence of extra relativistic, non-interacting (i.e., neutrino-like) degrees of freedom. On the other hand, if either is found to be inconsistent with their standard values, any inferred anomalous radiative energy density cannot be composed of standard neutrinos (and may actually be the result of unaccounted for systematic effects).

Several previous studies have looked at observational

constraints on neutrino interactions [12, 14, 15]. In particular, Refs. [15] have used measurements of the CMB and LSS to constrain the value of $c_{\rm vis}$. However, this is the first study to place a constraint on the rest-frame sound speed, $c_{\rm eff}$. Constraints on $c_{\rm eff}$ are particularly interesting since models of neutrino interactions indicate it can differ from its canonical value by $\sim 30\%$ (e.g., Ref. [12]) and *current* observations can constrain its value to $\sim 10\%$ at the 95% confidence level (C.L.). Additionally, we report significantly improved constraints on $c_{\rm vis}$ by using the most recent measurements of the CMB and LSS lowering the uncertainty on $c^2_{\rm vis}$ by a factor of ~ 1.5.

II. PARAMETERIZATION

The modified evolution equations for the neutrino perturbations [1] are [11]

$$\dot\delta_\nu + k\left(q_\nu + \frac{2}{3k}\dot h\right) = \frac{\dot a}{a}(1-3c^2_{\rm eff})\left(\delta_\nu + 3\frac{\dot a}{a}\frac{q_\nu}{k}\right), \quad (1)$$

$$\dot q_\nu + \frac{\dot a}{a}q_\nu + \frac{2}{3}k\pi_\nu = kc^2_{\rm eff}\left(\delta_\nu + 3\frac{\dot a}{a}\frac{q_\nu}{k}\right), \quad (2)$$

$$\dot\pi_\nu + \frac{3}{5}kF_{\nu,3} = 3c^2_{\rm vis}\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right), \quad (3)$$

$$\frac{2l+1}{k}\dot F_{\nu,l} - lF_{\nu,l-1} = -(l+1)F_{\nu,l+1},\ l \geq 3, \quad (4)$$

where a is the scale-factor, k is the wavenumber, $c_{\rm eff}$ is the rest-frame sound-speed, $c_{\rm vis}$ is a viscosity parameter, δ_ν is the neutrino density contrast, q_ν is the neutrino velocity perturbation, π_ν is the neutrino anisotropic stress, $F_{\nu,l}$ are higher order moments of the neutrino distribution function, the shear, $\sigma = 1/(2k)(\dot h + 6\dot\eta)$, h and η are the scalar metric perturbations in synchronous gauge [16], and the higher order moments of the distribution function are truncated with appropriate boundary conditions (see, e.g., Ref. [17]).

We note that the modified evolution equations imply a modified set of initial conditions for the perturbation equations since neutrinos are a significant fraction of the total radiative energy density at early times when the initial conditions are set. Following the derivation outlined in Ref. [16] we set the initial conditions to the growing mode which reverts to the standard adiabatic mode when $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$ as shown in Appendix A.

Varying $c_{\rm vis}$ modifies the ability for neutrinos to free-stream out of a gravitational potential well [6, 11]. When $c^2_{\rm vis} = 0$ the CDRB becomes a perfect fluid and is capable of supporting undamped acoustic oscillations, shown in red (dot-dashed) on the left-hand panel of Fig. 1. An

[1] Although in this section we refer specifically to neutrinos, these equations apply without modification to any massless cosmological component.

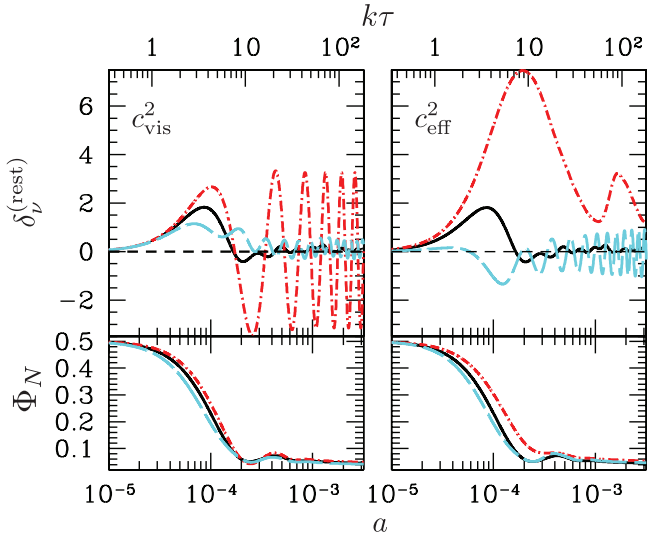

FIG. 1: The evolution of the neutrino density perturbation in its rest-frame for a mode with $k = 0.1\ h{\rm Mpc}^{-1}$ where h is the Hubble parameter in units of 100 km/(s Mpc), as a function of the scale-factor, a, or the conformal time, τ. The black solid curve gives the evolution for the standard case, i.e., when $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$. The left-hand panel shows the evolution when $c^2_{\rm vis} = 0$ (red, dot-dashed) and $c^2_{\rm vis} = 1$ (blue, dashed) with $c^2_{\rm eff} = 1/3$. With $c^2_{\rm vis} = 0$ (red, dot-dashed) the CDRB becomes a perfect fluid leading to undamped acoustic oscillations. The right-hand panel shows the evolution when $c^2_{\rm eff} = 0.1$ (red, dot-dashed) and $c^2_{\rm eff} = 0.8$ (blue, dashed) with $c^2_{\rm vis} = 1/3$. When $c^2_{\rm eff}$ is small (red, dot-dashed) the CDRB is partially able to overcome its internal pressure support and nearly cluster. The bottom panels show the corresponding evolution of the Newtonian potential, Φ_N.

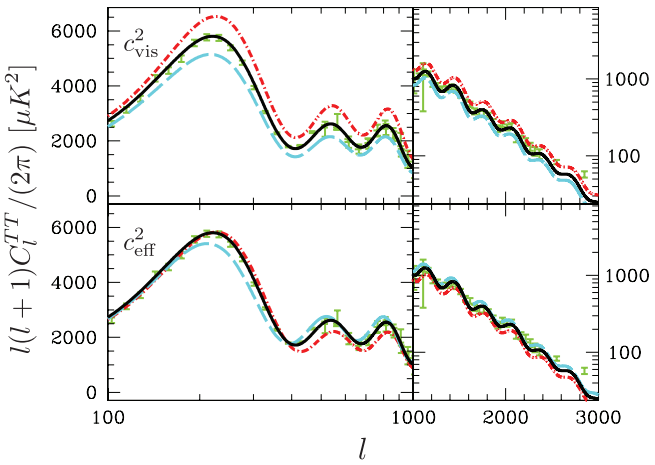

FIG. 2: Modifications to the CMB temperature power-spectrum, C_l^{TT}, as both $c^2_{\rm vis}$ (top panel) and $c^2_{\rm eff}$ (bottom panel) are varied in the same way as in Fig. 1: the black solid curve gives the evolution for the standard case; the top panel shows C_l^{TT} when $c^2_{\rm vis} = 0$ (red, dot-dashed) and $c^2_{\rm vis} = 1$ (blue, dashed); the bottom panel shows $c^2_{\rm eff} = 0.2$ (red, dot-dashed) and $c^2_{\rm eff} = 0.7$ (blue, dashed). The large angular scale measurements are from the 7-year WMAP release [19] and on small angular scales from ACT [21].

increased $c_{\rm vis}$ leads to an overdamping of the perturbations, shown in blue (dashed) in the left-hand panel of Fig. 1.

Changing $c_{\rm eff}$ allows for a neutrino pressure perturbation which is non-adiabatic, i.e., $(\delta p - \delta\rho/3)/\bar{\rho} = (c^2_{\rm eff} - 1/3)\delta^{\rm (rest)}_\nu$, where $\delta^{\rm (rest)}_\nu$ is the density perturbation in a frame where the neutrino velocity perturbation, $q_\nu = 0$. A value of $c^2_{\rm eff} < 1/3$ ($c^2_{\rm eff} > 1/3$) leads to a decreased (increased) pressure for the CDRB in its rest-frame, which in turn causes the amplitude of the neutrino density perturbations to increase (decrease), as seen on the right hand side of Fig. 1 in the red, dot-dashed (blue, dashed) curve.

This parameterization is related to a scenario in which neutrinos have a significant interaction cross-section. As an example, if neutrinos tightly couple to a perfect fluid then $c^2_{\rm vis} = 0$ and an analogy can be made between our parameterization and the tightly coupled photon-baryon fluid with a constant sound speed, c^2_s, related to $c^2_{\rm eff}$ through, $3c^2_s \approx \left(c^2_{\rm eff} + 2/3\right)$.

We show how the CMB temperature power-spectrum is modified in this parameterization in Fig. 2. Note that an increase (decrease) in $c_{\rm eff}$ leads to an increase (decrease) in the scales at which the neutrino perturbations affect the CMB. This is due to the increase (decrease) in the the neutrino sound horizon. These parameters have a similar effect on the polarization power-spectrum, not shown here. However, since the effects of the CDRB perturbations are negligible by the time large-scale structure forms, the change to the matter power-spectrum is negligible [11].

III. RESULTS

In order to measure these parameters we used a modified version of the publicly available Boltzmann code, CAMB [17] along with the publicly available Monte Carlo Markov chain code, CosmoMC [18]. We used a combination of CMB and LSS data including WMAP7 [19], ACBAR [20], ACT [21], SPT [22], the Sloan Digital Sky Survey (SDSS) DR7 LRG matter power spectrum [23], the SDSS small-scale matter power-spectrum measured from the Lyman-alpha forest [24] and the latest determination of the Hubble parameter, H_0, using the Hubble Space Telescope [25].

In addition to various combinations of $(N_{\rm eff}, c^2_{\rm vis}, c^2_{\rm eff})$ we allowed the standard six cosmological parameters, $(A_s, n_s, \tau, \theta, \Omega_b h^2, \Omega_{dm} h^2)$, to vary, where A_s is the amplitude of the primordial power-spectrum, n_s is the spectral index, τ is the optical depth, θ is the angular acoustic scale of the CMB, h is the Hubble parameter in units of 100 km/(s Mpc), Ω_b is the baryon density in units of the critical density, and Ω_{dm} is the dark matter density in units of the critical density. All constraints, except where noted, force the Helium fraction, Y_p, to be fixed by its BBN relationship to $\Omega_b h^2$ and $N_{\rm eff}$ [26]. We note that this parameterization only takes into account how a change in $N_{\rm eff}$ causes a change in the expansion rate during BBN. If the change in $N_{\rm eff}$ is due to a change in the physics of the neutrino sector the functional form $Y_p(N_{\rm eff})$ may not hold. We also consider a case where Y_p is an additional free parameter as discussed below.

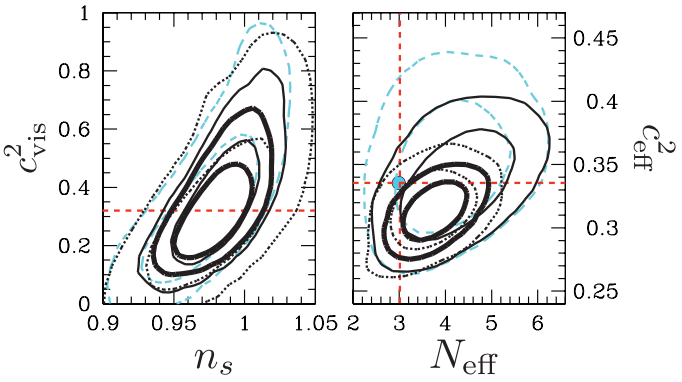

FIG. 3: Two dimensional contours (68% and 95% C.L.) showing the degeneracy between $c_{\rm vis}/n_s$ and $c_{\rm eff}/N_{\rm eff}$. The dotted contours show the constraints when only CMB data is used. The blue-dashed contours show the constraints when restricting the CMB to just WMAP7 and large-scale structure data, excluding the Lyman-alpha data. The thin-solid contours show constraints when restricting the CMB to just WMAP7 and with all large-scale structure data. The thick contours show the constraints when all of the data are included. The blue circle shows that the standard value of $c^2_{\rm eff} = 1/3$ and $N_{\rm eff} = 3$ is excluded at slightly higher than the 95% C.L.

A summary of our results can be found in Table I. Varying the number of effective neutrino species, $N_{\rm eff}$, with $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$ we recover a preference for an anomalous radiative energy density at the $\approx 99.9\%$ C.L. When we allow $c_{\rm vis}$ and $c_{\rm eff}$ to vary as well, the significance of any anomalous radiative energy density changes to 97.2% C.L. Additionally, the marginalized mean value of $c^2_{\rm eff} = 0.31 \pm 0.015$ is lower than the expected value of 1/3 at the 87.5% C.L. Therefore, as shown by the blue circle in the right-hand panel of Fig. 3, the standard value of $(N_{\rm eff}, c^2_{\rm eff}) = (3, 1/3)$ is still disfavored at higher than the 95% C.L.

Since a change in $c_{\rm eff}$ introduces a new length-scale (the neutrino sound-horizon) its affect on the CMB is only slightly correlated with the other parameters. This scale-dependence is clearly shown in Fig. 2 around the first peak. Because of its lack of strong correlations, the observations place a precise constraint on $c^2_{\rm eff}$ as shown in Fig. 3. Constraints to $c^2_{\rm vis}$ are not as precise because its affect on the CMB is scale-free leading to a degeneracy with, for example, the scalar spectral index, n_s, shown on the left-hand panel of Fig. 3.

Given the tentative evidence for an anomalously large radiative energy density, it is of interest to consider the case where the number of neutrinos (with $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$) is fixed to three and to constrain the values of $c^2_{\rm vis}$ and $c^2_{\rm eff}$ applied to an additional one or two effective

TABLE I:

Marginalized 1D constraints

$N_{\rm eff}$	$c^2_{\rm vis}$	$c^2_{\rm eff}$
$4.0^{+0.17+0.58}_{-0.18-0.57}$	$1/3$	$1/3$
$3.77^{+0.18+0.68}_{-0.19-0.65}$	$0.33^{+0.04+0.21}_{-0.06-0.15}$	$0.31 \pm 0.015^{+0.029}_{-0.030}$
3	$0.44^{+0.056+0.27}_{-0.085-0.21}$	$0.30 \pm 0.013^{+0.027}_{-0.026}$
$1^\dagger$	< 2.2	$0.29 \pm 0.043^{+0.1}_{-0.075}$
$2^\dagger$	< 0.51	$0.34 \pm 0.03^{+0.062}_{-0.052}$

NOTES.—Errors are 68%, 95% C.L.; upper limits are 95% C.L.
† For these chains, the number of effective relativistic degrees of freedom with $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$ is fixed to three while $c^2_{\rm vis}$ and $c^2_{\rm eff}$ applied to one or two extra degrees of freedom are allowed to vary.

species. We show the results of this analysis in Table I.

Since both $c_{\rm vis}$ and $c_{\rm eff}$ modulate the amplitude of small-scale power in the CMB we explored degeneracies with the running of the spectral index, $\alpha_s \equiv dn_s/d\ln k$. Excluding the Lyman-alpha data and fixing $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$ we find, $\alpha_s = -0.020 \pm 0.013 \pm 0.026$ and $N_{\rm eff} = 3.53 \pm 0.21 \pm 0.72$. Allowing both $c_{\rm vis}$ and $c_{\rm eff}$ to vary we find $\alpha_s = -0.019 \pm 0.016 \pm 0.03$, $N_{\rm eff} = 3.49 \pm 0.20^{+0.73}_{-0.70}$, $c^2_{\rm vis} = 0.29^{+0.05+0.27}_{-0.08-0.19}$and $c^2_{\rm eff} = 0.33 \pm 0.02^{+0.05}_{-0.04}$.

Although there are many radiative backgrounds which are unrelated to neutrinos, if the anomalous CDRB is explained by a modification to neutrino physics this may lead to a change the functional form of $Y_p(N_{\rm eff})$. Therefore it is important to consider the case where Y_p is an additional free parameter. Fixing $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$ we find $Y_p = 0.294 \pm 0.033^{+0.064}_{-0.067}$ and $N_{\rm eff} = 3.64^{+0.21+0.86}_{-0.24-0.79}$ which is in slight ($\sim 1.5\sigma$) disagreement with astrophysical measurements [28] and BBN predictions for Y_p [26]. However, when we also allow $c_{\rm vis}$ and $c_{\rm eff}$ to vary, the helium fraction preferred by the data decreases to $Y_p = 0.257 \pm 0.051 \pm 0.1$ which is in good agreement with the most recent astrophysical measurements, $Y_p = 0.2565 \pm 0.0010$ (stat) $\pm$ 0.0050 (syst) [28]. We find the number of effective neutrino species is $N_{\rm eff} = 3.73^{+0.24+0.98}_{-0.28-0.89}$ with $c^2_{\rm vis} = 0.33^{+0.04+0.22}_{-0.06-0.16}$ and $c^2_{\rm eff} = 0.315 \pm 0.018^{+0.037}_{-0.033}$. Using the astrophysical measurement of Y_p as a prior we find $N_{\rm eff} = 3.73 \pm 0.2 \pm 0.7$, $c^2_{\rm vis} = 0.34^{+0.03+0.21}_{-0.06-0.15}$, and $c^2_{\rm eff} = 0.313 \pm 0.014^{+0.028}_{-0.030}$.

We note that our modified perturbation equations only apply to massless degrees of freedom. However, since a non-zero mass predominately affects the late-time (post-recombination) evolution of the perturbations, its effects are separated in time (and hence we expect should be fairly uncorrelated) from the effects of varying $c_{\rm vis}$ and $c_{\rm eff}$, which are most important before and during recombination. We leave a simultaneous constraint on the neutrino mass, $c_{\rm vis}$ and $c_{\rm eff}$ to future work.

IV. CONCLUSIONS

We have used current CMB and LSS data to explore various properties of perturbations in the CDRB. In particular, we have parameterized the evolution of the neutrino perturbations with two additional parameters: a rest-frame sound speed, $c^2_{\rm eff}$, and a viscosity parameter $c^2_{\rm vis}$, which both equal 1/3 for the standard, non-interacting, CDRB. With $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$ we find that current data favors an anomalously large standard CDRB energy density at the 99.9% C.L.. When $c_{\rm vis}$ and $c_{\rm eff}$ are allowed to vary the data still shows that the standard value $(N_{\rm eff}, c^2_{\rm eff}) = (3, 1/3)$ is disfavored at slightly greater than the 95% C.L. relative to the 2D-marginalized contours.

Our results can be interpreted as providing tentative evidence that the extra relativistic degrees of freedom seen in observations of the CMB may have non-negligible interactions with $c^2_{\rm eff} < 1/3$ at the 87.5% C.L. Although, as shown in Fig. 3, this result is driven by the small-scale observations of the CMB and may be impacted by systematic errors, such as issues related to marginalizing over sources of secondary anisotropies. A more conclusive result must wait for data from future observations, such as the Planck satellite [29].

If any anomalous radiative energy density is due to a modification of the neutrino sector this may result in a change to the standard relationship $Y_p(N_{\rm eff})$. Allowing the helium fraction to also vary we find that the constraint on Y_p is in agreement with the most recent astrophysical measurements [28]. In addition the values of $c^2_{\rm eff}$ and $c^2_{\rm vis}$ are consistent with their non-interacting value of 1/3 and $N_{\rm eff}$ is larger than the expected value of 3 at the 90% C.L. Using the astrophysical measurement of Y_p as a prior we find $N_{\rm eff} > 3$ at the 95 % C.L., $c^2_{\rm vis}$ is fully consistent with the expected value of 1/3, and $c^2_{\rm eff}$ is less than 1/3 at the 85% C.L. Therefore we find that although fixing the helium fraction through its BBN relationship $Y_p(N_{\rm eff})$ may not be appropriate in general, when we allow Y_p to be a free parameter the constraint on $N_{\rm eff}$ is still significantly anomalous. Using the astrophysical measurement as a prior on Y_p only increases this significance and hints at a slightly low value for $c^2_{\rm eff}$.

Using a Fisher analysis we find that future observations of the CMB with the Planck satellite alone will provide a measurement of $N_{\rm eff} = 3.0 \pm 0.17$, $c^2_{\rm vis} = 0.333 \pm 0.026$, and $c^2_{\rm eff} = 0.333 \pm 0.004$. If future observations continue to provide evidence for the presence of extra relativistic energy density then, when applied to one additional effective neutrino degree of freedom, Planck will constrain $c^2_{\rm vis} = 0.3 \pm 0.1$ and $c^2_{\rm eff} = 0.333 \pm 0.017$. The improved sensitivity to these parameters will allow a constraint on the fundamental properties of any new radiative degrees of freedom.

Note added in proof: after a preprint of this paper appeared on the arXiv we became aware of a study, Ref. [30], which presents similar results.

Acknowledgments

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Appendix A: Initial conditions

Following the derivation outlined in Ref. [16] we set the initial conditions to the growing mode which reverts to the standard adiabatic mode when $c^2_{\rm vis} = c^2_{\rm eff} = 1/3$. For reference, these initial conditions are given in synchronous gauge by

$$\delta_c = \delta_b = \frac{3}{4}\delta_\nu^{MV} = \frac{3}{4}\delta_\gamma = -\frac{\chi}{3}k^2\tau^2, \tag{A1}$$

$$\delta_\nu^{ML} = \left\{\frac{2[10 + c^2_{\rm vis}(2 + 7R_\nu^{ML} + R_\nu^{MV})] - 3c^2_{\rm eff}[5 + 2c^2_{\rm vis}(2 + R_\nu^{ML} + R_\nu^{MV})]}{10 + 3c^2_{\rm eff} + 6(1 + 3c^2_{\rm eff})c^2_{\rm vis}R_\nu^{ML}}\right\}\delta_\gamma, \tag{A2}$$

$$q_\gamma = \frac{k\tau}{9}\delta_\gamma, \tag{A3}$$

$$q_\nu^{ML} = \left\{\frac{2c^2_{\rm vis}(2 + R_\nu^{ML} + R_\nu^{MV} + 3{c^2_{\rm eff}}^2[5 + 2c^2_{\rm vis}(2 + R_\nu^{ML} + R_\nu^{MV})]}{30 + 45c^2_{\rm eff} + 18(1 + 3c^2_{\rm eff})c^2_{\rm vis}R_\nu^{ML}}\right\}k\tau\delta_\gamma \tag{A4}$$

$$q_\nu^{MV} = \frac{1}{9}\left(1 + \frac{4(2 + R_\nu^{ML})}{15 + 4R_\nu^{MV}}\right)k\tau\delta_\gamma, \tag{A5}$$

$$\pi_\nu^{ML} = \chi\frac{2c^2_{\rm vis}\{c^2_{\rm eff}[6R_\nu^{ML} - 3(2 + R_\nu^{MV})] - 2(2 + R_\nu^{ML} + R_\nu^{MV})\}}{10 + 3c^2_{\rm eff} + 6(1 + 3c^2_{\rm eff})c^2_{\rm vis}R_\nu^{ML}}k^2\tau^2, \tag{A6}$$

$$\pi_\nu^{MV} = \chi\frac{2(2 + R_\nu^{ML}}{15 + 4R_\nu^{MV}}k^2\tau^2, \tag{A7}$$

$$z = -\frac{3}{2}\delta_\gamma, \tag{A8}$$

where ML denotes the massless neutrinos (parameterized by $c_{\rm eff}$ and $c_{\rm vis}$), MV denotes the standard massive neutrinos, δ_i are the density contrasts, q_i is the heat flux, π_i is the anisotropic stress, $z = \frac{1}{2}\dot{h}$ where h is the standard synchronous gauge potential (see Ref. [16]), $R_\nu^{ML} = \rho_\nu^{ML}/\rho^{\rm tot}_{\rm rad}$ is the fraction of the total radiation energy density in massless (non-standard) neutrinos, and $R_\nu^{MV} = \rho_\nu^{MV}/\rho^{\rm tot}_{\rm rad}$ is the fraction of the total radiation energy density in massive, standard, neutrinos. One can check that that for standard neutrinos ($c^2_{\rm eff} = c^2_{\rm vis} = 1/3$) these initial conditions revert back to the standard adiabatic initial conditions; for $c^2_{\rm eff} \neq 1/3$ the initial conditions are an admixture of adiabatic and isocurvature initial conditions.

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