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Recent cosmic microwave background (CMB) temperature and polarization anisotropy measurements from the Planck mission have significantly improved previous constraints on the neutrino masses as well as the bounds on extended models with massless or massive sterile neutrino states. However, due to parameter degeneracies, additional low redshift priors are mandatory in order to sharpen the CMB neutrino bounds. We explore here the role of different priors on low redshift quantities, such as the Hubble constant, the cluster mass bias, and the reionization optical depth τ. Concerning current priors on the Hubble constant and the cluster mass bias, the bounds on the neutrino parameters may differ appreciably depending on the choices adopted in the analyses. With regard to future improvements in the priors on the reionization optical depth, a value of $\tau = 0.05 \pm 0.01$, motivated by astrophysical estimates of the reionization redshift, would lead to $\sum m_\nu < 0.0926$ eV at 90% C.L., when combining the full *Planck* measurements, baryon acoustic oscillation, and Planck clusters data, thereby opening the window to unravel the neutrino mass hierarchy with existing cosmological probes.

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I. INTRODUCTION

Recent Plank measurements of the cosmic microwave background (CMB) temperature and polarization anisotropy offer a unique test of some particle properties which still remain unknown [1]. The absolute neutrino masses and their ordering are among the most frequently exploited topics in the literature (see, e.g., Refs. [1–4]). The most stringent bound quoted from the Planck collaboration, combining their CMB measurements with baryon acoustic oscillations (BAO) is $\sum m_\nu < 0.17$ eV at 95% C.L. [1]. However, this is certainly not the most restrictive constraint to date. Measurements of Lyman α absorption in distant quasar spectra tighten the previous bound to $\sum m_\nu < 0.12$ eV at 95% C.L. [5], based on new hydrodynamical simulations, especially devoted to keeping systematic uncertainties under control. Therefore, the role of low redshift observables (such as the Lyman α forest, the BAO signal, the Hubble constant H_0, or the constraints from the cluster redshift distribution) is crucial, as these measurements help enormously in pinning down the CMB neutrino mass constraint. Among these possible external data sets, we focus here on direct measurements of the Hubble constant H_0 and the cluster number counts, as their constraining power on $\sum m_\nu$ strongly depends of the choice of priors. Concerning the former, there are currently at least two possible H_0 measurements one may apply, which would lead to different $\sum m_\nu$ constraints. Regarding the latter, the prior on the cluster mass bias is a critical quantity which could even lead to nonzero neutrino masses. We will explore here the different neutrino mass bounds that are obtained with the possible prior choices on H_0 and on $1-b$, the cluster mass bias. Furthermore, we shall also illustrate the impact on neutrino mass bounds from a near future and improved prior on an additional low redshift quantity, the reionization optical depth τ. The prior used here focuses on a lower value of τ, and it is motivated by hints from high-redshift quasar absorption and Lyman α emitters.

The structure of the paper is as follows. We start in Sec. II with a description of the three different cosmological models explored here, which account for different neutrino parameters. The basic cosmological data sets used in our analyses are also detailed in this first section. Section III presents the results of our numerical analyses in each of the three neutrino scenarios considered here, focusing on the role of the Hubble constant, cluster mass bias, and reionization optical depth priors. We conclude in Sec. IV.

II. METHODOLOGY

We analyze here three different scenarios, by varying the following set of parameters:

$$\{\Omega_b h^2, \Omega_c h^2, \Theta_s, \tau, n_s, \log[10^{10} A_s], \sum m_\nu, m_s^{\rm eff}, N_{\rm eff}, \}, \quad (1)$$

where we have the six parameters of the ΛCDM model, i.e., the baryon $\Omega_b h^2$ and the cold dark matter $\Omega_c h^2$ energy densities, the ratio between the sound horizon and the angular diameter distance at decoupling Θ_s, the reionization optical depth τ, and the inflationary parameters, the scalar spectral index n_s, and the amplitude of the primordial spectrum A_s. Moreover, we allow for variations in this model, exploring three different scenarios, enlarging by one extra parameter each model. We first consider a ΛCDM model plus neutrino masses ($\sum m_\nu$), then we also consider the possibility of having additional relativistic degrees of freedom ($\sum m_\nu$ and $N_{\rm eff}$, with $N_{\rm eff}$-3.046 extra relativistic species), and lastly, we consider the possibility of massive sterile neutrinos ($\sum m_\nu$, $N_{\rm eff}$ and $m_s^{\rm eff}$, with $N_{\rm eff}$-3.046 extra massive species with a mass $m_s^{\rm eff}$). We have assumed that active neutrinos have a degenerate mass spectrum, with a minimum value $\sum m_\nu = 0.06$ eV, as indicated by neutrino oscillation data. In principle, one could also consider the lightest neutrino mass eigenstate as the free parameter (instead of $\sum m_\nu$) and derive, making use of the neutrino mass splittings, the total neutrino mass. In such a case, two different runs, one for the normal hierarchy and a separate one for the inverted hierarchy, would be needed. However, the bounds presented here will not change much in this situation, given the data sets exploited, which are mostly only sensitive to the total neutrino mass and not to the hierarchical structure of the neutrino mass, i.e., their mass distribution (see, for example, [6]).

For all these parameters, we use the flat priors listed in Table I.

A. Cosmological data

We constrain the cosmological parameters previously described by using several combination of data sets. Our CMB measurements are those from the full Planck 2015 release on temperature and polarization CMB angular power spectra [1,7]. The large angular scale temperature and polarization measured by the Planck LFI experiment is combined with the small-scale *TT* temperature spectrum measured by Planck HFI, and we refer to this data set as *Planck*. Moreover, when adding to this combination the small-scale *TE* and *EE* polarization spectra measured by Planck HFI, we shall refer to this data set as *Planck pol*.

TABLE I. External priors on the cosmological parameters assumed in this paper.

Parameter	Prior
$\Omega_b h^2$	[0.005, 0.1]
$\Omega_c h^2$	[0.001, 0.99]
Θ_s	[0.5, 10]
τ	[0.01, 0.8]
n_s	[0.8, 1.2]
$\log[10^{10} A_s]$	[2, 4]
$\sum m_\nu$ (eV)	[0.06, 3]
$m_s^{\rm eff}$ (eV)	[0,3]
$N_{\rm eff}$	[3.046,10]

We consider also measurements of the large scale structure of the Universe in their geometrical form, the baryon acoustic oscillations (BAO) data. We include the 6dFGS [8], SDSS-MGS [9], BOSS LOWZ [10], and CMASS-DR11 [10] measurements as in [1], referring to the combination of all of them as *BAO*.

Then, we study the impact of the most relevant low redshift priors (concerning neutrino physics limits). First, we impose five different Gaussian priors on the Hubble constant. Then, we consider the second Planck cluster catalog obtained through the Sunyaev-Zel'dovich (SZ) effect, analyzing the impact of the different cluster mass biases, referring to this data set as *SZ*. Finally, we study the effect of lowering the prior on the reionization optical depth τ, as preferred by astrophysical measurements. In particular, we use two Gaussian priors, $\tau = 0.06 \pm 0.01$ and $\tau = 0.05 \pm 0.01$.

Our constraints are obtained making use of the latest available version of the Monte Carlo Markov chain (MCMC) package COSMOMC [11,12] with a convergence diagnostic based on the Gelman and Rubin statistics. This includes the support for the Planck data release 2015 likelihood code [13] implementing an optimal sampling [12]. The foreground parameters are varied as in Refs. [1,13].

III. LOW-REDSHIFT PRIORS

A. Hubble constant priors

We consider here five possible constraints on the Hubble constant H_0, without making any preference for one value over another. The goal of our paper is indeed to discuss the impact of these different priors on neutrino physics without entering the current debate if one prior is more reliable than another. The first prior on H_0 arises from the recalibration of the authors of Ref. [14] combined with the original Hubble Space Telescope (HST) measurements [15], which leads to the value of $H_0 = 73.0 \pm 2.4$ km s^{-1} Mpc^{-1}, hereafter $H073p0$ (see also Refs. [16,17]). The second and the third possible choices exploited here for the prior on the Hubble constant arise from a recent reanalysis of [18]. One consists of a value $H_0 = 70.6 \pm 3.3$ km s^{-1} Mpc^{-1} (hereafter $H070p6$), in better agreement with Planck 2015 findings, which has been dubbed as a *conservative* estimate of the Hubble constant. The other value is $H_0 = 72.5 \pm 2.5$ km s^{-1} Mpc^{-1} (hereafter $H072p5$). For the fourth and fifth H_0 constraints, we shall consider the values obtained by [19], correlating the host galaxy with the intrinsic luminosity. In particular, the priors are: $H_0 = 70.6 \pm 2.6$ km s^{-1} Mpc^{-1} (hereafter $H070p6ref$), derived when using Cepheid distances calibrated to the megamaser NGC 4258, Milky Way parallaxes, and LMC distance, and $H_0 = 68.8 \pm 3.3$ km s^{-1} Mpc^{-1} (hereafter $H068p8$) obtained

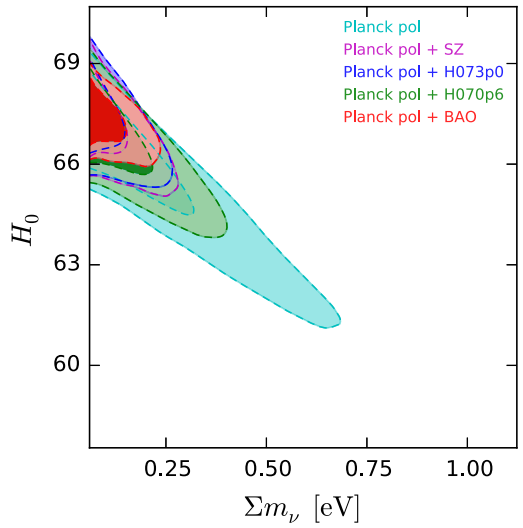

FIG. 1. 68% and 95% C.L. allowed regions in the ($\sum m_\nu$, H_0) plane illustrating the effect of the low redshift priors studied here.

when using Cepheid distances calibrated solely with the distance to the NGC 4258 megamaser. In the following, we shall explore the impact of all these possible priors on the neutrino parameters, without preferring one value over another, in order to avoid biases due to the choice. In fact, even if there is a tension at about 2σ between some of them, in particular $H073p0$, and the H_0 value we have from Planck data, we have no clear justification at the moment to consider them affected by systematics. Furthermore, the tension is considerably reduced when varying the neutrino effective number $N_{\rm eff}$. Moreover, the constraints obtained combining Planck pol with $H073p0$ are consistent with those ones obtained with BAO measurements, where there is no indication of bias. However, we again warn the reader not to immediately consider the constraints that contains the $H073p0$ prior at the same level of fidelity of those based on the inclusion of the BAO dataset or of more conservative Hubble constant priors, especially when they are ruling out at 95% C.L. significant regions of the neutrino parameter space.

There exists a strong, well-known degeneracy between the neutrino mass and the Hubble constant (see, e.g., [20] and Fig. 1). In the absence of an independent measurement of H_0, the change in the CMB temperature anisotropies induced by the presence of massive neutrinos (which shifts the location of the angular distance to the last scattering surface) can be easily compensated by a smaller value of the Hubble constant. Therefore, the parameters $\sum m_\nu$ and H_0, when extracted from CMB data only, exhibit a very large degeneracy, see the cyan contours of Fig. 1. Indeed, the 95% C.L. bound on $\sum m_\nu$ from *Planck* data set is 0.754 eV. The addition of high multipole polarization data (i.e., *Planck pol*) leads to $\sum m_\nu < 0.497$ eV at 95% C.L. The reason for this improvement is due to the fact that polarization measurements alleviate many parameter degeneracies, among others, the m_ν–τ degeneracy, with τ the reionization optical depth. The associated mean value of $H_0 = 66.3\ {\rm km\,s^{-1}\,Mpc^{-1}}$, see Table II, is considerably smaller than the value quoted by the Planck collaboration within the ΛCDM model scenario with $\sum m_\nu = 0.06$ eV ($H_0 = 67.3\ {\rm km\,s^{-1}\,Mpc^{-1}}$) due to the degeneracy with the neutrino mass. Notice, from Tables II and III, that adding a prior on H_0 improves enormously the bounds on $\sum m_\nu$. The addition of the $H073p0$ prior has a much larger impact than the other ones, since it is associated to a larger Hubble constant, and this quantity is anticorrelated with $\sum m_\nu$. The 95% C.L. on the total neutrino mass is 0.180 eV. From the results from our MCMC analyses (some of them not depicted in Table II), we conclude that the only data combination which provides competitive neutrino mass limits to those obtained with CMB measurements plus the $H073p0$ prior is the one obtained combining Planck with BAO data. Both full-shape halo measurements and the others priors on the Hubble constant lead to weaker neutrino mass constraints.

Concerning the effective number of relativistic species $N_{\rm eff}$, the addition of Planck polarization measurements leads to a major improvement in its 95% C.L. bound, see Table IV, in which we show the results within the $\sum m_\nu + N_{\rm eff}$ model for the same data combinations of

TABLE II. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the ΛCDM + Σm_ν model, focusing on the effect of the prior on H_0.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck pol +H070p6	Planck +H073p0	Planck pol +H073p0
$\Omega_c h^2$	$0.1202^{+0.0047}_{-0.0044}$	$0.1200^{+0.0031}_{-0.0030}$	$0.1188^{+0.0028}_{-0.0029}$	$0.1192^{+0.0023}_{-0.0023}$	$0.1193^{+0.0042}_{-0.0041}$	$0.1196^{+0.0028}_{-0.0028}$	$0.1179^{+0.0040}_{-0.0041}$	$0.1189^{+0.0029}_{-0.0028}$
Σm_ν [eV]	<0.754	<0.497	<0.220	<0.175	<0.337	<0.291	<0.195	<0.180
H_0	$65.5^{+4.4}_{-5.9}$	$66.3^{+2.9}_{-3.8}$	$67.6^{+1.3}_{-1.3}$	$67.5^{+1.1}_{-1.2}$	$67.1^{+2.8}_{-3.1}$	$67.0^{+2.1}_{-2.4}$	$68.2^{+2.0}_{-2.3}$	$67.7^{+1.7}_{-1.7}$
σ_8	$0.79^{+0.08}_{-0.11}$	$0.811^{+0.058}_{-0.076}$	$0.825^{+0.039}_{-0.042}$	$0.832^{+0.033}_{-0.034}$	$0.819^{+0.049}_{-0.057}$	$0.824^{+0.043}_{-0.049}$	$0.829^{+0.038}_{-0.040}$	$0.831^{+0.035}_{-0.036}$
$\Omega_{\rm m}$	$0.340^{+0.088}_{-0.063}$	$0.329^{+0.052}_{-0.039}$	$0.311^{+0.017}_{-0.016}$	$0.312^{+0.015}_{-0.014}$	$0.318^{+0.041}_{-0.037}$	$0.319^{+0.031}_{-0.027}$	$0.304^{+0.029}_{-0.028}$	$0.310^{+0.023}_{-0.022}$
τ	$0.080^{+0.038}_{-0.038}$	$0.081^{+0.033}_{-0.034}$	$0.082^{+0.038}_{-0.037}$	$0.083^{+0.033}_{-0.032}$	$0.082^{+0.038}_{-0.037}$	$0.082^{+0.034}_{-0.034}$	$0.085^{+0.039}_{-0.038}$	$0.083^{+0.032}_{-0.033}$

TABLE III. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the $\Lambda\mathrm{CDM} + \Sigma m_\nu$ model, focusing on the effect of the prior on H_0.

	Planck +H068p8	Planck pol +H068p8	Planck +H070p6ref	Planck pol +H070p6ref	Planck +H072p5	Planck pol +H072p5
$\Omega_c h^2$	$0.1195^{+0.0047}_{-0.0047}$	$0.1198^{+0.0029}_{-0.0028}$	$0.1187^{+0.0040}_{-0.0040}$	$0.1194^{+0.0028}_{-0.0028}$	$0.1181^{+0.0040}_{-0.0041}$	$0.1191^{+0.0028}_{-0.0028}$
Σm_ν [eV]	<0.388	<0.333	<0.265	<0.241	<0.211	<0.198
H_0	$66.8^{+2.9}_{-3.4}$	$66.8^{+2.2}_{-2.6}$	$67.5^{+2.4}_{-2.6}$	$67.3^{+1.9}_{-2.1}$	$68.0^{+2.2}_{-2.4}$	$67.6^{+1.8}_{-1.8}$
σ_8	$0.815^{+0.053}_{-0.064}$	$0.820^{+0.046}_{-0.054}$	$0.823^{+0.044}_{-0.048}$	$0.827^{+0.039}_{-0.043}$	$0.827^{+0.039}_{-0.042}$	$0.830^{+0.036}_{-0.038}$
Ω_m	$0.322^{+0.045}_{-0.039}$	$0.321^{+0.034}_{-0.029}$	$0.312^{+0.034}_{-0.032}$	$0.316^{+0.027}_{-0.025}$	$0.306^{+0.030}_{-0.029}$	$0.312^{+0.024}_{-0.023}$
τ	$0.080^{+0.039}_{-0.038}$	$0.081^{+0.033}_{-0.033}$	$0.082^{+0.039}_{-0.038}$	$0.082^{+0.032}_{-0.033}$	$0.084^{+0.039}_{-0.038}$	$0.083^{+0.032}_{-0.033}$

TABLE IV. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the $\Lambda\mathrm{CDM} + \Sigma m_\nu + N_{\mathrm{eff}}$ model, focusing on the effect of the prior on H_0.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck Pol +H070p6	Planck +H073p0	Planck Pol +H073p0
$\Omega_c h^2$	$0.1205^{+0.0080}_{-0.0077}$	$0.1192^{+0.0060}_{-0.0057}$	$0.1212^{+0.0077}_{-0.0071}$	$0.1193^{+0.0062}_{-0.0058}$	$0.1222^{+0.0074}_{-0.0073}$	$0.1190^{+0.0062}_{-0.0060}$	$0.1235^{+0.0071}_{-0.0070}$	$0.1215^{+0.0053}_{-0.0054}$
Σm_ν [eV]	<0.796	<0.582	<0.289	<0.224	<0.417	<0.365	<0.337	<0.249
N_{eff}	<3.592	<3.359	<3.636	<3.384	<3.707	<3.374	<3.961	<3.539
H_0 [km s^{-1} Mpc^{-1}]	$64.9^{+7.2}_{-8.4}$	$65.0^{+4.4}_{-5.0}$	$68.4^{+3.0}_{-2.8}$	$67.4^{+2.4}_{-2.3}$	$68.2^{+4.6}_{-4.7}$	$66.6^{+3.2}_{-3.5}$	$70.5^{+4.2}_{-4.1}$	$68.2^{+2.7}_{-2.8}$
σ_8	$0.781^{+0.091}_{-0.119}$	$0.794^{+0.067}_{-0.085}$	$0.823^{+0.042}_{-0.044}$	$0.823^{+0.037}_{-0.039}$	$0.819^{+0.057}_{-0.062}$	$0.813^{+0.047}_{-0.055}$	$0.835^{+0.047}_{-0.053}$	$0.831^{+0.038}_{-0.043}$
Ω_m	$0.351^{+0.104}_{-0.080}$	$0.342^{+0.061}_{-0.046}$	$0.310^{+0.019}_{-0.017}$	$0.315^{+0.017}_{-0.016}$	$0.316^{+0.044}_{-0.043}$	$0.326^{+0.035}_{-0.031}$	$0.298^{+0.034}_{-0.032}$	$0.313^{+0.024}_{-0.024}$
τ	$0.081^{+0.035}_{-0.035}$	$0.086^{+0.031}_{-0.034}$	$0.088^{+0.039}_{-0.038}$	$0.079^{+0.035}_{-0.046}$	$0.088^{+0.044}_{-0.041}$	$0.083^{+0.035}_{-0.035}$	$0.098^{+0.044}_{-0.041}$	$0.091^{+0.034}_{-0.035}$

Table II. The constraints on the total neutrino mass are less restrictive in this more general scenario, given the strong degeneracy between $\sum m_\nu$ and N_{eff}: a larger matter density can be compensated with an extra radiation component, and, consequently, $\sum m_\nu$ and N_{eff} are positively correlated. Figure 2 shows that the Hubble constant H_0 and N_{eff} are also positively correlated, as the shift induced in the matter-radiation equality era by a larger $N_{\mathrm{eff}} > 3.046$ can, in principle, be compensated with a larger value of the Hubble constant, assuming that the matter-radiation equality redshift and the angular size of the horizon at recombination are free parameters. The measurements from Planck of the CMB damping tail alleviate this degeneracy (as a value of $N_{\mathrm{eff}} > 3.046$ will induce a higher expansion rate, which is translated into an increased Silk damping at high multipoles ℓ). This is clear from the results shown in Table IV, where it can be noticed that the addition of the $H070p6$ prior to Planck measurements results in values of N_{eff} and H_0, which are considerably smaller than the ones obtained with the $H073p0$ prior. Interestingly, the values obtained in the $H070p6$ case are in very good agreement with those found when considering Planck plus BAO data, both in the cases of *Planck* and *Planck pol* data sets. The combination of *Planck* data plus the $H073p0$ prior allows for the presence of an extra sterile neutrino at the $\sim 2\sigma$ level. Therefore, polarization measurements play a major role in the constraints on the N_{eff} parameter, as once that they are considered, the bounds on N_{eff} become more robust and almost independent of the external priors.

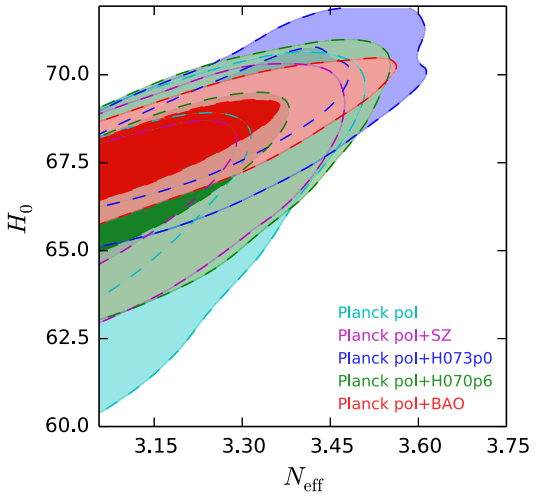

FIG. 2. As Fig. 1 panel but extending the neutrino mass model with N_{eff} dark radiation species, illustrating the (N_{eff}, H_0) plane.

However, the extra neutrino species could also be massive, as motivated by the so-called neutrino oscillation anomalies [21]. Massive sterile neutrinos do not necessarily need to have thermal abundances at decoupling, as their abundance is determined by their mixings with the active neutrino states [22]. In the following, we shall constrain simultaneously the $N_{\rm eff}$ massive sterile neutrino scenario and the sum of the three active neutrino masses $\sum m_\nu$. Therefore, the number of massive sterile neutrino species is given by $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$, and their mass is $m_s^{\rm eff}$. This mass is related to the physical mass by:

$$m_s^{\rm eff} = (T_s/T_\nu)^3 m_s = (\Delta N_{\rm eff})^{3/4} m_s, \tag{2}$$

in which T_s (T_ν) is the current temperature of the sterile (active) neutrinos, and we have assumed that the sterile states have a phase-space distribution similar to that of the active neutrino states. Table V shows the results for $\sum m_\nu$, $N_{\rm eff}$, $m_s^{\rm eff}$, and the other cosmological parameters previously considered as well. Notice that, in general, while the values of $N_{\rm eff}$ and Σm_ν are very similar to those obtained in the previous scenario, the value of the clustering parameter σ_8 is always reduced, as there is another source of suppression of the large scale structure growth, the sterile neutrino mass. We will see in the next section that the inclusion of the clustering data, which mostly constrain the clustering parameter σ_8 and the current Universe's matter density Ω_m, can help to break these degeneracies.

Concerning the reionization optical depth, its value is always increased with respect to its values in the other two previous neutrino mass models. The reason for that is due to the suppression of power on small scales induced by the presence of neutrino masses, an effect that can be compensated by increasing the amplitude of the primordial spectrum A_s. From CMB temperature data, there exists a strong degeneracy between A_s and τ (as long as the factor $A_s e^{-2\tau}$ is kept constant), which is broken, albeit only partially, by polarization measurements. A higher value of A_s can in turn be compensated by a larger τ, and therefore, the larger the total neutrino mass is (from both active and sterile states), the larger the reionization optical depth should be. The tightest constraints in the sterile neutrino effective mass are obtained, as expected, after applying the $H073p0$ prior, since the Hubble constant is anticorrelated with both the active and the sterile neutrino masses.

B. Planck SZ clusters

The largest virialized objects in the Universe are clusters of galaxies, providing a unique way to extract the cosmological parameters. Cluster surveys usually focus on the cluster number count function dN/dz, which measures the number of clusters of a certain mass M over a range of redshift:

$$\left.\frac{dN}{dz}\right|_{M>M_{\rm min}} = f_{\rm sky}\frac{dV(z)}{dz}\int_{M_{\rm min}}^{\infty} dM \frac{dn}{dM}(M,z), \tag{3}$$

with $f_{\rm sky} = \Delta\Omega/4\pi$ the fraction of sky covered by the survey and $\frac{dV(z)}{dz}$ the differential volume, which reads as

$$\frac{dV(z)}{dz} = \frac{4\pi}{H(z)}\int_0^z dz' \left(\frac{1}{H(z')}\right)^2. \tag{4}$$

The cluster number count function is then related to its predictions within an underlying cosmological model. The main uncertainties arise from the cluster mass, determined through four main available methods: x-rays, velocity dispersion, SZ effect, and weak lensing. Therefore, a crucial parameter in the analyses is the so-called cluster mass bias factor $1-b$, which accounts for deviations between the inferred x-ray cluster mass and the true cluster mass due to cluster physics and observational and/or selection effects. The overall error in the cluster mass determination is usually around $\Delta M/M \sim 10\%$. We exploit

TABLE V. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the $\Lambda{\rm CDM} + \Sigma m_\nu + N_{\rm eff} + m_s^{\rm eff}$ model, focusing on the effect of the prior on H_0.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck Pol +H070p6	Planck +H073p0	Planck Pol +H073p0
$\Omega_{\rm c}h^2$	$0.1215^{+0.0090}_{-0.0105}$	$0.1207^{+0.0061}_{-0.0071}$	$0.1214^{+0.0081}_{-0.0081}$	$0.1189^{+0.0068}_{-0.0081}$	$0.1217^{+0.0088}_{-0.0107}$	$0.1205^{+0.0068}_{-0.0077}$	$0.1235^{+0.0090}_{-0.0082}$	$0.1205^{+0.0064}_{-0.0071}$
Σm_ν [eV]	<0.676	<0.528	<0.263	<0.199	<0.422	<0.337	<0.291	<0.321
$m_s^{\rm eff}$ [eV]	<0.972	<0.820	<0.449	<0.694	<0.822	<0.773	<0.462	<0.630
$N_{\rm eff}$	<3.648	<3.401	<3.762	<3.405	<3.705	<3.445	<3.961	<3.434
$H_0[{\rm km\,s^{-1}\,Mpc^{-1}}]$	$65.7^{+5.7}_{-6.1}$	$65.5^{+3.2}_{-3.7}$	$67.7^{+1.8}_{-1.6}$	$68.7^{+2.8}_{-2.4}$	$67.4^{+4.4}_{-4.2}$	$66.5^{+2.7}_{-2.8}$	$70.0^{+4.6}_{-4.2}$	$67.4^{+2.3}_{-2.1}$
σ_8	$0.762^{+0.095}_{-0.107}$	$0.768^{+0.077}_{-0.087}$	$0.801^{+0.051}_{-0.058}$	$0.806^{+0.048}_{-0.054}$	$0.786^{+0.076}_{-0.083}$	$0.785^{+0.066}_{-0.075}$	$0.818^{+0.064}_{-0.068}$	$0.803^{+0.056}_{-0.062}$
$\Omega_{\rm m}$	$0.350^{+0.083}_{-0.069}$	$0.347^{+0.054}_{-0.045}$	$0.311^{+0.017}_{-0.017}$	$0.316^{+0.015}_{-0.015}$	$0.328^{+0.051}_{-0.045}$	$0.334^{+0.037}_{-0.034}$	$0.305^{+0.038}_{-0.037}$	$0.323^{+0.023}_{-0.027}$
τ	$0.088^{+0.043}_{-0.041}$	$0.087^{+0.035}_{-0.036}$	$0.095^{+0.041}_{-0.040}$	$0.089^{+0.034}_{-0.034}$	$0.090^{+0.042}_{-0.040}$	$0.087^{+0.035}_{-0.035}$	$0.103^{+0.043}_{-0.044}$	$0.091^{+0.036}_{-0.035}$

TABLE VI. As Table II, but including measurements from the Planck SZ cluster catalog.

	Planck +SZ	Planck pol +SZ	Planck +BAO + SZ	Planck pol +BAO +SZ	Planck +H073p0 +SZ	Planck pol +H073p0 +SZ	Planck +BAO +H073p0 +SZ	Planck pol +BAO +H073p0 +SZ
$\Omega_c h^2$	$0.1182^{+0.0041}_{-0.0041}$	$0.1191^{+0.0028}_{-0.0028}$	$0.1185^{+0.0026}_{-0.0027}$	$0.1189^{+0.0022}_{-0.0022}$	$0.1168^{+0.0039}_{-0.0038}$	$0.1183^{+0.0027}_{-0.0027}$	$0.1180^{+0.0025}_{-0.0027}$	$0.1186^{+0.0021}_{-0.0021}$
Σm_ν [eV]	<0.206	<0.184	<0.175	<0.147	<0.139	<0.129	<0.155	<0.126
H_0 [km s^{-1} Mpc^{-1}]	$68.0^{+2.2}_{-2.4}$	$67.6^{+1.9}_{-1.8}$	$67.9^{+1.2}_{-1.2}$	$67.8^{+1.0}_{-1.1}$	$68.8^{+1.9}_{-1.9}$	$68.2^{+1.3}_{-1.5}$	$68.2^{+1.1}_{-1.2}$	$68.0^{+1.0}_{-1.0}$
σ_8	$0.830^{+0.039}_{-0.041}$	$0.834^{+0.034}_{-0.036}$	$0.831^{+0.034}_{-0.039}$	$0.835^{+0.029}_{-0.032}$	$0.834^{+0.033}_{-0.036}$	$0.837^{+0.030}_{-0.031}$	$0.832^{+0.036}_{-0.037}$	$0.837^{+0.028}_{-0.031}$
Ω_m	$0.306^{+0.030}_{-0.029}$	$0.311^{+0.023}_{-0.022}$	$0.307^{+0.016}_{-0.015}$	$0.309^{+0.014}_{-0.013}$	$0.295^{+0.025}_{-0.023}$	$0.304^{+0.019}_{-0.018}$	$0.303^{+0.015}_{-0.014}$	$0.306^{+0.013}_{-0.012}$
τ	$0.087^{+0.038}_{-0.037}$	$0.085^{+0.033}_{-0.034}$	$0.085^{+0.036}_{-0.036}$	$0.085^{+0.032}_{-0.033}$	$0.092^{+0.038}_{-0.037}$	$0.088^{+0.032}_{-0.034}$	$0.086^{+0.036}_{-0.036}$	$0.087^{+0.032}_{-0.033}$

TABLE VII. As Table III, but including measurements from the Planck SZ cluster catalog.

	Planck +SZ + H068p8	Planck pol +SZ + H068p8	Planck +SZ + H070p6ref	Planck pol +SZ + H070p6ref	Planck +SZ + H072p5	Planck pol +SZ + H072p5
$\Omega_c h^2$	$0.1181^{+0.0040}_{-0.0039}$	$0.1190^{+0.0028}_{-0.0027}$	$0.1176^{+0.0039}_{-0.0038}$	$0.1187^{+0.0027}_{-0.0027}$	$0.1170^{+0.0039}_{-0.0038}$	$0.1184^{+0.0027}_{-0.0027}$
Σm_ν [eV]	<0.189	<0.179	<0.164	<0.154	<0.145	<0.136
H_0	$66.1^{+2.0}_{-2.2}$	$67.7^{+1.6}_{-1.7}$	$68.4^{+1.9}_{-2.0}$	$67.9^{+1.5}_{-1.6}$	$68.7^{+1.9}_{-2.0}$	$68.1^{+1.5}_{-1.5}$
σ_8	$0.831^{+0.037}_{-0.039}$	$0.834^{+0.034}_{-0.035}$	$0.832^{+0.036}_{-0.037}$	$0.836^{+0.032}_{-0.033}$	$0.833^{+0.033}_{-0.037}$	$0.837^{+0.031}_{-0.031}$
Ω_m	$0.305^{+0.028}_{-0.027}$	$0.310^{+0.022}_{-0.021}$	$0.301^{+0.026}_{-0.025}$	$0.307^{+0.020}_{-0.019}$	$0.297^{+0.026}_{-0.023}$	$0.305^{+0.020}_{-0.019}$
τ	$0.087^{+0.038}_{-0.037}$	$0.085^{+0.033}_{-0.034}$	$0.089^{+0.038}_{-0.037}$	$0.086^{+0.033}_{-0.034}$	$0.091^{+0.038}_{-0.037}$	$0.087^{+0.033}_{-0.034}$

here the Planck Sunyaev-Zeldovich (SZ) 2015 cluster catalog, which consists of 439 clusters [23,24]. As we shall see in the following, the prior assumptions on the cluster mass bias $1-b$ (assumed to be a constant) play a major role in the neutrino mass constraints. Tables VI and VII present the constraints on the neutrino mass and on a set of cosmological parameters, previously considered as well. The prior on the cluster mass bias quantity $1-b$ is freely varied in the [0.1, 1.3] range. Notice that, for this choice of the cluster mass bias prior, the 95% C.L. neutrino mass limit after combining with *Planck* is 0.206 eV, which is further reduced down to 0.184 eV when polarization measurements are also considered in the analysis. Furthermore, we find for these cases $1-b = 0.656 \pm 0.051$ and $1-b = 0.638 \pm 0.040$ at 68% C.L., respectively. Cluster number counts mostly constrain the clustering parameter σ_8 and the current Universe's matter density Ω_m, both involved in the calculation of the cluster mass function $dn(z,M)/dM$ through N-body simulations [25]. For the first case considered here, in which the cluster mass bias is a free parameter, the mean values of the parameter σ_8 obtained in the massive neutrino scenario are close to those obtained in the simple ΛCDM scenario with $\sum m_\nu = 0.06$ eV, and therefore, one can expect very tight neutrino mass bounds. Figure 3 illustrates the strong degeneracy between the neutrino mass $\sum m_\nu$ and the clustering parameter σ_8 for several of the data combinations considered here. The tightest 95% C.L. neutrino mass constraint we find is $\sum m_\nu < 0.126$ eV, arising from the combination of *Planck pol*, BAO, $H073p0$, and SZ data. As these three data sets (BAO, $H073p0$, and SZ) show no tension in the extraction of the different cosmological

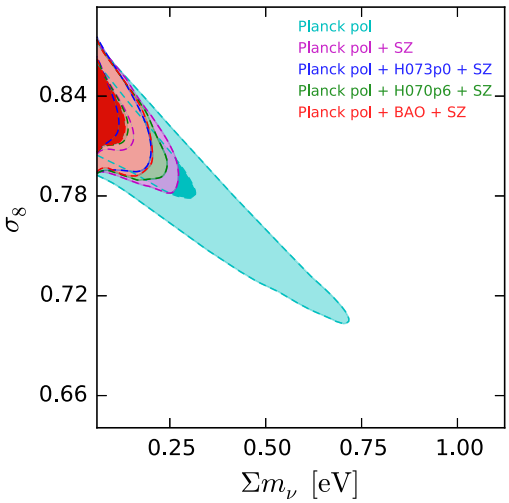

FIG. 3. 68% and 95% C.L. allowed regions in the ($\sum m_\nu$, σ_8) plane, illustrating the effect of the low redshift priors studied here.

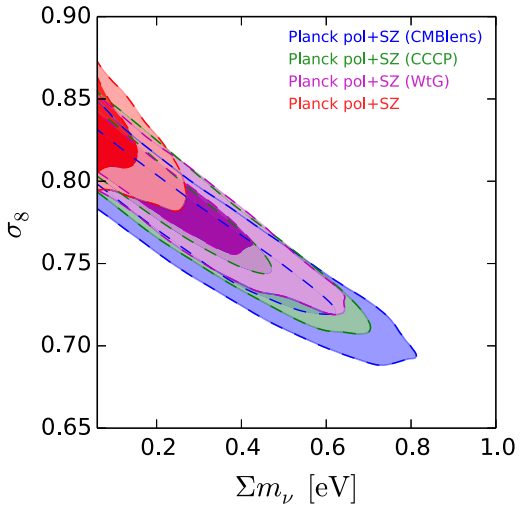

FIG. 4. 68% and 95% C.L. allowed regions in the combined two-dimensional planes for the parameters $\Omega_c h^2$, n_s,H_0, σ_8, and τ, together with their one-dimensional posterior probability distributions, arising from the combination of *Planck pol* plus BAO, *Planck pol* plus $H073p0$ and *Planck pol* plus SZ measurements.

parameters (see Fig. 4), the neutrino mass bound arising from their combination and above quoted should be regarded as a robust limit.

Nevertheless, there exist lensing estimates of the $1-b$ parameter, which we shall also exploit in the following [24]. The first two cluster mass bias priors arise from gravitational shear measurements from the weighing the giants (WtG) [26] and the Canadian cluster comparison project (CCCP) [24], which lead to $1-b=0.688\pm0.072$ and 0.780 ± 0.092, respectively. CMB lensing offers yet another way of estimating the cluster masses [27], leading to a constraint on $1/(1-b)=0.99\pm0.19$ [28]. Table VIII shows the 95% C.L. limits on the neutrino mass as well as the mean values and 95% C.L. associated errors on the remaining cosmological parameters explored here for each of the three possible cluster mass bias from lensing considerations. Notice that the values of the clustering parameter σ_8 are smaller, lying $1-2\sigma$ away from the values obtained in the case of a freely varying cluster mass bias $1-b$. A lower value of σ_8 implies smaller clustering. A larger value of the neutrino mass would therefore be favored, in order to suppress the small-scale clumping. Indeed, from the results depicted in Table VIII, one can notice that the CMB lensing cluster mass prior is the one which leads to the largest bounds on the value of the total neutrino mass, as it suggests the lowest value of σ_8. Nevertheless, the CMB and SZ data combination do not find evidence for a nonzero neutrino mass. The impact of the cluster mass bias prior in the neutrino mass constraints can be also inferred from the results depicted in Fig. 5, where it can be noticed that the four weak lensing cluster mass bias priors lead to a much larger degeneracy than for the free prior case, indicating a tension between primary CMB and SZ measurements of σ_8. The most extreme case corresponds to the CMBlens case, in which clusters would be much less massive than what primary CMB data seems to indicate, pointing therefore to a small value of σ_8, which in turn is translated into a relatively loose 95% C.L. constraint of $\sum m_\nu < 0.669$ eV. On the other hand, the WtG cluster mass bias prior would indicate more massive clusters, and therefore, the former limit is slightly tightened to $\sum m_\nu < 0.531$ eV, at 95% C.L.

The effects of the SZ prior in extended models (in which additional massless or massive species are also considered) are shown in Tables IX and X, from which we notice that, as in the ΛCDM-$\sum m_\nu$ scenario, the most constraining data set is the one from the combination of *Planck pol*, BAO, $H073p0$, and SZ data.

C. The reionization optical depth τ

The questions of when and how did cosmic reionization take place are still open issues which can be investigated via different cosmological and astrophysical observations. CMB measurements provide the most convincing constraints via the integrated optical depth τ, whose mean value

TABLE VIII. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the $\Lambda\mathrm{CDM}+\Sigma m_\nu$ model, focusing on the effect of the prior on the cluster mass bias, see text for details.

	Planck + SZ (CCCP)	Planck pol + SZ (CCCP)	Planck + SZ (WtG)	Planck pol + SZ (WtG)	Planck + SZ (CMBlens)	Planck pol + SZ (CMBlens)
$\Omega_c h^2$	$0.1190^{+0.0041}_{-0.0041}$	$0.1197^{+0.0029}_{-0.0028}$	$0.1193^{+0.0037}_{-0.0038}$	$0.1198^{+0.0028}_{-0.0028}$	$0.1182^{+0.0040}_{-0.0039}$	$0.1193^{+0.0027}_{-0.0027}$
Σm_ν [eV]	<0.542	<0.576	<0.506	<0.531	<0.634	<0.669
H_0 [km s^{-1} Mpc^{-1}]	$65.8^{+3.1}_{-3.2}$	$65.5^{+2.7}_{-2.9}$	$65.9^{+2.8}_{-3.0}$	$65.6^{+2.5}_{-2.8}$	$65.7^{+3.3}_{-3.4}$	$65.1^{+2.8}_{-3.0}$
σ_8	$0.780^{+0.056}_{-0.061}$	$0.783^{+0.056}_{-0.064}$	$0.788^{+0.050}_{-0.057}$	$0.789^{+0.048}_{-0.057}$	$0.763^{+0.059}_{-0.061}$	$0.764^{+0.062}_{-0.064}$
Ω_m	$0.333^{+0.045}_{-0.042}$	$0.338^{+0.042}_{-0.036}$	$0.333^{+0.042}_{-0.038}$	$0.337^{+0.040}_{0.035}$	$0.334^{+0.049}_{-0.045}$	$0.343^{+0.043}_{-0.041}$
τ	$0.077^{+0.037}_{-0.037}$	$0.079^{+0.034}_{-0.034}$	$0.079^{+0.038}_{-0.037}$	$0.080^{+0.033}_{-0.033}$	$0.074^{+0.039}_{-0.039}$	$0.075^{+0.036}_{-0.035}$

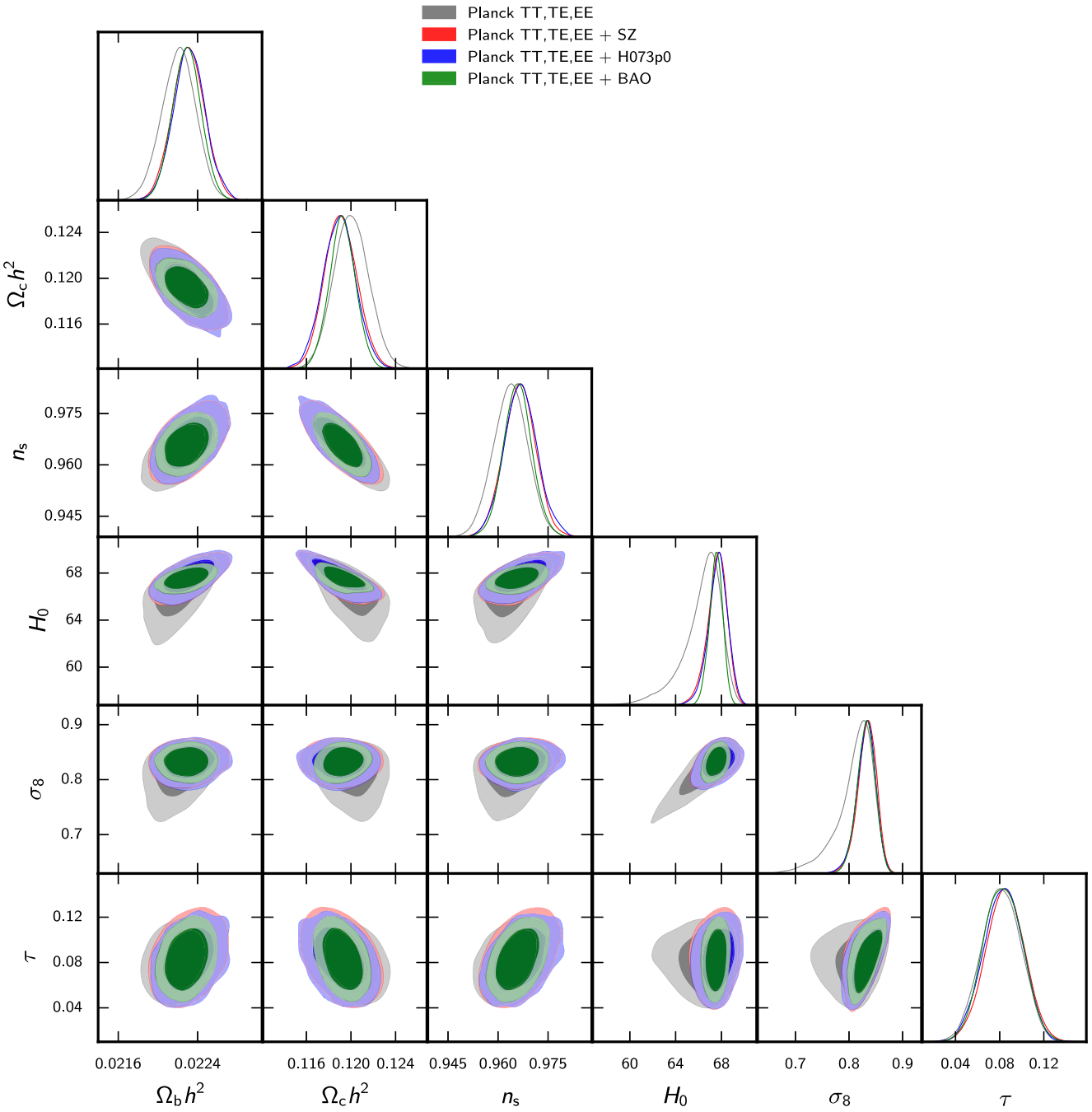

FIG. 5. 68% and 95% C.L. allowed regions in the ($\sum m_\nu$, σ_8) plane, focusing on the impact of the cluster mass bias prior.

is $\tau \simeq 0.078$, from recent Planck temperature and polarization 2015 measurements [1]. In the simplest model of reionization, the so-called *instantaneous* reionization scenario, the former mean values would imply a reionization redshift $8 < z_{\rm reio} < 10$. However, high-redshift quasar absorption spectra [29] and observations of Lyman α emitters [30,31] seem to conclude that the reionization redshift is $z_{\rm reio} \sim 7$. Because these cosmological and astrophysical estimations of the reionization redshift seem to indicate slightly lower values of τ ($z_{\rm reio} \simeq 7$ would correspond to $\tau = 0.05$) than those recently quoted by the Planck collaboration, we shall explore here the impact of a prior based on a lower value of τ. We shall assume in the following priors on τ of 0.05 ± 0.01 and 0.06 ± 0.01, which would approximately lead to $z_{\rm reio} = 7$ and $z_{\rm reio} = 8$, and we shall refer to these priors as *tau5* and *tau6*, respectively. Tables XI and XII show the constraints on the total neutrino mass after considering such priors on the reionization optical depth τ from future cosmological and/or astrophysical measurements. Notice that the most

TABLE IX. As Table IV, but including measurements from the Planck SZ cluster catalog.

	Planckl +SZ	Planck pol +SZ	Planck +BAO +SZ	Planck pol +BAO +SZ	Planck +SZ +H073p0	Planck pol +SZ +H073p0	Planck + BAO +H073p0 +SZ	Planck pol +BAO +H073p0 + SZ
$\Omega_c h^2$	$0.1209^{+0.0082}_{-0.0078}$	$0.1192^{+0.0059}_{-0.0057}$	$0.1209^{+0.0077}_{-0.0077}$	$0.1195^{+0.0062}_{-0.0061}$	$0.1237^{+0.0073}_{-0.0072}$	$0.1214^{+0.0055}_{-0.0054}$	$0.1235^{+0.0070}_{-0.0070}$	$0.1217^{+0.0058}_{-0.0058}$
Σm_ν [eV]	<0.434	<0.374	<0.299	<0.205	<0.326	<0.253	<0.331	<0.200
$N_{\rm eff}$	<3.635	<3.313	<3.648	<3.389	<3.858	3.571	<3.800	<3.561
H_0 [km s^{-1} Mpc^{-1}]	$66.8^{+5.3}_{-4.9}$	$65.8^{+3.4}_{-3.5}$	$68.3^{+3.0}_{-3.0}$	$67.4^{+2.4}_{-2.3}$	$70.3^{+3.8}_{-3.6}$	$68.2^{+3.0}_{-2.7}$	$69.7^{+2.6}_{-2.5}$	$68.5^{+2.0}_{-2.1}$
σ_8	$0.807^{+0.060}_{-0.063}$	$0.806^{+0.049}_{-0.054}$	$0.822^{+0.042}_{-0.046}$	$0.824^{+0.036}_{0.037}$	$0.833^{+0.048}_{-0.046}$	$0.312^{+0.024}_{-0.024}$	$0.831^{+0.042}_{-0.046}$	$0.834^{+0.035}_{-0.034}$
Ω_m	$0.327^{+0.049}_{-0.047}$	$0.332^{+0.036}_{-0.033}$	$0.310^{+0.018}_{-0.017}$	$0.315^{+0.016}_{-0.015}$	$0.300^{+0.030}_{-0.029}$	$0.312^{+0.024}_{-0.024}$	$0.304^{+0.016}_{-0.016}$	$0.309^{+0.014}_{-0.013}$
τ	$0.084^{+0.041}_{-0.040}$	$0.081^{+0.035}_{-0.035}$	$0.089^{+0.038}_{-0.037}$	$0.085^{+0.033}_{-0.034}$	$0.095^{+0.040}_{-0.040}$	$0.087^{+0.032}_{-0.032}$	$0.094^{+0.037}_{-0.037}$	$0.089^{+0.034}_{-0.033}$

TABLE X. As Table V, but including measurements from the Planck SZ cluster catalog.

	Planckl +SZ	Planck pol +SZ	Planck +BAO +SZ	Planck pol +BAO +SZ	PlanckSZ +H073p0	Planck polSZ +H073p0	Planck +BAO +H073p0 +SZ	Planck pol +BAO +H073p0 +SZ
$\Omega_c h^2$	$0.1220^{+0.0085}_{-0.0080}$	$0.1207^{+0.0057}_{-0.0060}$	$0.1215^{+0.0075}_{-0.0075}$	$0.1191^{+0.0070}_{-0.0078}$	$0.1235^{+0.0079}_{-0.0077}$	$0.1210^{+0.0065}_{-0.0063}$	$0.1237^{+0.0081}_{-0.0078}$	$0.1204^{+0.0070}_{-0.0075}$
Σm_ν [eV]	<0.370	<0.362	<0.265	<0.191	<0.297	<0.217	<0.275	<0.190
$m_s^{\rm eff}$ [eV]	<0.640	<0.630	<0.356	<0.659	<0.385	<0.512	<0.330	<0.506
$N_{\rm eff}$	<3.666	<3.412	<3.723	<3.405	<3.860	<3.525	<3.894	<3.478
H_0 [km s^{-1} Mpc^{-1}]	$67.1^{+4.0}_{-3.6}$	$66.3^{+2.4}_{-2.8}$	$68.7^{+2.5}_{-2.4}$	$67.7^{+1.8}_{-1.5}$	$69.7^{+3.5}_{-3.5}$	$67.7^{+2.6}_{-2.3}$	$69.7^{+1.6}_{-1.5}$	$68.3^{+1.8}_{-1.7}$
σ_8	$0.789^{+0.061}_{-0.066}$	$0.786^{+0.059}_{-0.065}$	$0.808^{+0.050}_{-0.051}$	$0.808^{+0.047}_{-0.052}$	$0.815^{+0.055}_{-0.057}$	$0.808^{+0.053}_{-0.057}$	$0.816^{+0.046}_{-0.051}$	$0.817^{+0.047}_{-0.051}$
Ω_m	$0.331^{+0.043}_{-0.041}$	$0.336^{+0.037}_{-0.032}$	$0.332^{+0.017}_{-0.017}$	$0.316^{+0.015}_{-0.014}$	$0.308^{+0.034}_{-0.031}$	$0.320^{+0.026}_{-0.026}$	$0.307^{+0.016}_{-0.015}$	$0.312^{+0.015}_{-0.013}$
τ	$0.090^{+0.041}_{-0.039}$	$0.088^{+0.040}_{-0.035}$	$0.094^{+0.040}_{-0.038}$	$0.090^{+0.034}_{-0.036}$	$0.100^{+0.040}_{-0.042}$	$0.092^{+0.033}_{-0.034}$	$0.098^{+0.040}_{-0.039}$	$0.091^{+0.033}_{-0.034}$

TABLE XI. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the ΛCDM + Σm_ν model, focusing on the effect of the prior on the reionization optical depth τ, see text for details.

	Planck pol +BAO + tau6	Planck pol +BAO + tau5	Planck pol + BAO +H072p5 + tau6	Planck pol + BAO +H072p5 + tau5	Planck pol + BAO +H072p5 +SZ + tau6	Planck pol + BAO +H072p5 +SZ + tau5
$\Omega_c h^2$	$0.1196^{+0.0027}_{-0.0026}$	$0.1198^{+0.0023}_{-0.0020}$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0022}_{-0.0020}$	$0.1191^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	<0.141	<0.128	<0.122	<0.116	<0.107	<0.101
H_0 [km s^{-1} Mpc^{-1}]	$67.4^{+1.0}_{-1.1}$	$67.4^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.84^{+0.96}_{-0.99}$	$67.79^{+0.96}_{-0.98}$
σ_8	$0.822^{+0.024}_{-0.027}$	$0.818^{+0.023}_{-0.025}$	$0.823^{+0.022}_{-0.025}$	$0.818^{+0.022}_{-0.024}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.313^{+0.014}_{-0.013}$	$0.314^{+0.014}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.311^{+0.014}_{-0.012}$	$0.308^{+0.013}_{-0.012}$	$0.309^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.018}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

stringent data combination used here (i.e., the one arising from *Planck pol*, BAO, $H073p0$, and SZ measurements) will provide a 95% C.L. bound on $\sum m_\nu$ of 0.0993 eV, assuming a prior on $\tau = 0.05 \pm 0.01$. Following the latest neutrino oscillation physics analyses [32], the minimum total neutrino mass in the inverted hierarchy is $\sum m_\nu = 0.0982 \pm 0.0010$ eV. Since the constraint could be biased by the tension of the H073p0 prior with the

TABLE XII. 95% C.L. constraints on the total neutrino mass and mean values (with their associated 95% C.L. errors) on other cosmological parameters illustrated here from some of the different combinations of data sets explored in the $\Lambda\mathrm{CDM} + \Sigma m_\nu$ model, focusing on the effect of the prior on the reionization optical depth τ, see text for details.

	Planck pol +BAO +SZ + tau6	Planck pol +BAO + SZ +tau5	Planck pol H073p0 +SZ + tau6	Planck pol H073p0 +SZ + tau5	Planck pol + BAO +H073p0 +SZ + tau6	Planck pol + BAO +H073p0 +SZ + tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	<0.122	<0.116	<0.112	<0.107	<0.104	<0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

Planck results, we repeated the analysis with the same combination of data but excluding this prior. We have found a constraint of $\sum m_\nu < 0.0926$ eV at 90% C.L., i.e., still hinting for a cosmological tension for the neutrino inverted hierarchy. Therefore, such a prior on τ could imply that with current data we are already able to test the neutrino mass hierarchy, albeit in a not significant way. If future combined measurements of the reionization optical depth agree with the astrophysical expectations, cosmology could offer a window to test the neutrino mass hierarchy.

IV. CONCLUSIONS

Cosmological limits on neutrino masses rely strongly on the particular choice of the low redshift observables which are used in combination with cosmic microwave background (CMB) measurements. Here, we have examined the different limits in the sum of the three active neutrino masses as well as on the possible extra sterile states (both in its massless and massive versions) arising from different existing priors on the Hubble constant and the cluster mass bias.

In the Hubble constant case, the prior on H_0 from a reanalysis of [18], $H_0 = 70.6 \pm 3.3$ km s^{-1} Mpc^{-1}, and dubbed here as $H070p6$, leads to larger upper bounds on $\sum m_\nu$ than the recalibrated value of Riess *et al.* [15] ($H_0 = 73.0 \pm 2.4$ km s^{-1} Mpc^{-1}), due to the anticorrelation between the Hubble constant and the neutrino mass.

When additional sterile neutrino species are also considered in the analyses, the constraints on $N_{\rm eff}$ obtained with the $H070p6$ prior are very similar to those obtained from the combination of CMB measurements and baryon acoustic oscillation data. However, in the case of the other possible H_0 prior and neglecting polarization data, an extra sterile massless or massive neutrino is allowed at the $\sim 2\sigma$ level. Therefore, polarization measurements are essential to ensure the robustness of the bounds on $N_{\rm eff}$.

In the case of the Planck Sunyaev-Zeldovich (SZ) cluster catalog, the crucial prior is the cluster mass bias, taken as constant. If the cluster mass bias parameter is allowed to freely vary, we obtain the tightest 95% C.L. neutrino mass constraint found here, which is $\sum m_\nu < 0.126$ eV, and arises from the combination of *Planck pol*, BAO, the $H073p0$ prior, and SZ data. We have explored as well other estimates of the cluster mass bias, as those coming from weak lensing measurements. For these cases, the value of the clustering parameter σ_8 is smaller and lies $1-2\sigma$ away from the values obtained in the case of a freely varying cluster mass bias. This implies smaller clustering and, consequently, a larger value of the neutrino mass is allowed: the 95% C.L. upper bounds on $\sum m_\nu$ range from 0.669 eV to $\sum m_\nu < 0.531$ eV. Therefore, the tension between the measurements of σ_8 from Planck and from SZ clusters is translated into a large range of possibilities for $\sum m_\nu$.

Another tension is that related to CMB and astrophysical measurements of the reionization optical depth. While the former prefers a higher τ (and consequently, a reionization redshift $z_{\rm reio} \simeq 8$–10), Lyman α and quasar data point to a lower value, $z_{\rm reio} \simeq 7$. Assuming the discrepancy between these two measurements of τ is solved, we illustrate here the cases $z_{\rm reio} = 7$ and $z_{\rm reio} = 8$ by imposing priors on τ of 0.05 ± 0.01 and 0.06 ± 0.01. Interestingly, for the lower prior case, and after combining *Planck pol* with BAO, $H073p0$, and SZ data, a 95% (90%) C.L. bound on $\sum m_\nu$ of 0.0993 (0.0788) eV is obtained, values that lie in the range in which a cosmological measurement of the neutrino mass hierarchy is at reach. This result is robust against the choice of the H_0 prior, as using instead the $H_0 = 70.6 \pm 3.3$ km s^{-1} Mpc^{-1} measurement for the Hubble constant with the same data sets quoted above and the *tau5* prior, the 90% C.L. constraint on $\sum m_\nu$ is 0.0962 eV. Removing the H_0 prior would result in a bound of $\sum m_\nu < 0.0926$ eV at 90% C.L.

Given the current spread of values in the low redshift priors considered, it is clearly reasonable to ask if these priors could be of any use for current precision cosmology. In case of the H0 prior, a better understanding of the several anchors, as discussed in [18], is mandatory. However, considering a large number of priors, without preferring one value over another, as we performed in this paper is probably the best way to present the results and avoid biases from the choice of a single, low redshift prior. Moreover, none of the priors considered suggest the presence of a neutrino mass, and they are all compatible with the results coming from a Planck + BAO analysis that provides the strongest constraint on neutrino masses.

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