PHYSICAL REVIEW D **94,** 083522 (2016)

Improvement of cosmological neutrino mass bounds

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(Received 25 July 2016; published 26 October 2016)

The most recent measurements of the temperature and low-multipole polarization anisotropies of the cosmic microwave background from the Planck satellite, when combined with galaxy clustering data from the Baryon Oscillation Spectroscopic Survey in the form of the full shape of the power spectrum, and with baryon acoustic oscillation measurements, provide a 95% confidence level (C.L.) upper bound on the sum of the three active neutrinos $\sum m_\nu < 0.183$ eV, among the tightest neutrino mass bounds in the literature, to date, when the same data sets are taken into account. This very same data combination is able to set, at ~70% C.L., an upper limit on $\sum m_\nu$ of 0.0968 eV, a value that approximately corresponds to the minimal mass expected in the inverted neutrino mass hierarchy scenario. If high-multipole polarization data from Planck is also considered, the 95% C.L. upper bound is tightened to $\sum m_\nu < 0.176$ eV. Further improvements are obtained by considering recent measurements of the Hubble parameter. These limits are obtained assuming a specific nondegenerate neutrino mass spectrum; they slightly worsen when considering other degenerate neutrino mass schemes. Low-redshift quantities, such as the Hubble constant or the reionization optical depth, play a very important role when setting the neutrino mass constraints. We also comment on the eventual shifts in the cosmological bounds on $\sum m_\nu$ when possible variations in the former two quantities are addressed.

DOI: 10.1103/PhysRevD.94.083522

I. INTRODUCTION

Neutrinos are sub-eV elementary particles which, apart from gravity, only interact via weak interactions, decoupling from the thermal bath as ultrarelativistic states and constituting a hot dark matter component in our Universe. From neutrino mixing experiments we know that neutrinos have masses, implying the first departure from the Standard Model of particle physics [1,2]. However, oscillation experiments are not sensitive to the absolute neutrino mass scale; they only provide information on the squared mass differences. In the minimal three neutrino scenario, the best-fit value for the solar mass splitting is $\Delta m^2_{12} \simeq 7.5 \times 10^{-5}$ eV^2 and for the atmospheric mass splitting is $|\Delta m^2_{3i}| \simeq 2.45 \times 10^{-3}$ eV^2 [1], with $i = 1$ (2) for the normal (inverted) mass scheme. Notice that the sign of the largest mass splitting remains unknown, leading to two possible hierarchical scenarios: *normal* ($\Delta m^2_{31} > 0$) and *inverted* ($\Delta m^2_{32} < 0$). In the normal hierarchy, $\sum m_\nu \gtrsim 0.06$ eV, while in the inverted hierarchy, $\sum m_\nu \gtrsim 0.10$ eV, with $\sum m_\nu$ representing the total neutrino mass.

Neutrinos, as hot dark matter particles, possess large thermal velocities, clustering only at $k < k_{\rm fs}$, i.e., at scales below the neutrino free streaming wave number $k_{\rm fs}$, and suppressing structure formation at $k > k_{\rm fs}$ [3,4]. The presence of massive neutrinos also affects the cosmic microwave background (CMB), as these particles may become nonrelativistic around the photon decoupling period. In particular, they change the matter-radiation equality causing a small shift in the peaks of the CMB and a mild increase of their heights due to the Sachs-Wolfe effect. In addition, current CMB experiments allow one to explore the impact of massive neutrinos at small scales (i.e., at high multipoles ℓ), because they are sensitive to the smearing of the acoustic peaks caused by the gravitational lensing of CMB photons [5]. Cosmology can therefore weigh relic neutrinos. Recent studies dealing with the cosmological constraints on $\sum m_\nu$ have reported 95% C.L. upper bounds of 0.754 eV and 0.497 eV from Planck temperature anisotropies and Planck temperature and polarization measurements, respectively [6]. In order to improve these CMB neutrino mass limits, additional

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information from additional dark matter tracers and/or other geometrical standard rulers are needed. Current cosmological upper bounds on $\sum m_\nu$, which combine CMB temperature and polarization anisotropies measurements with different observations of the large scale structure of the Universe, range from 0.12 eV to 0.13 eV at 95% C.L. [7–10]. These limits are extremely close to the predictions from neutrino oscillation experiments in the inverted hierarchical spectrum. However, we note that the strongest limits among the ones quoted above have been obtained by employing Planck polarization measurements at small scales [11], which could be affected by a small residual level of systematics.[1]

Here we follow a more conservative approach. We exploit the effect of the neutrino masses in galaxy clustering, focusing on the full three-dimensional (3D) galaxy power spectrum shape from the Baryon Oscillation Spectroscopic Survey (BOSS) [12] Data Release 9 (DR9) [13] (which is among the largest sets of galaxy spectra publicly available to date), in combination with the Planck CMB 2015 full data in temperature, complemented with large scale polarization measurements [14]. This is our baseline combination. When we combine two data sets—independent large scale structure measurements in the form of baryon acoustic oscillations (BAO) and different priors on the Hubble parameter [15,16]—the minimal value of the mass expected in the inverted neutrino mass hierarchical scenario (see text below for a definition of minimal value in this context), $\sum m_\nu = 0.0968$ eV, is excluded up to a significance of 90% C.L. This indicates that current cosmological measurements show a mild preference for the region of the parameter space corresponding to the normal hierarchical scheme for the neutrino mass eigenstates. Moreover, cosmological data start to show differences in the neutrino mass bounds for the different possible neutrino mass schemes. We also illustrate the very important role played by low redshift observables and how they affect the limit quoted above.

II. ANALYSIS AND DATA

In the following section, the cosmological model we assume is the standard ΛCDM scenario, described by its usual six parameters, plus the sum of the neutrino masses $\sum m_\nu$. In particular, the model parameters are the baryon $\Omega_b h^2$ and the cold dark matter $\Omega_c h^2$ physical mass-energy densities, the ratio between the sound horizon and the angular diameter distance at decoupling Θ_s, the reionization optical depth τ, the scalar spectral index n_s, and the amplitude of the primordial spectrum A_s. We follow here the Planck ΛCDM model assumption of two massless neutrino states and a massive one. In addition, we also present the limits obtained when assuming one massless plus two massive neutrino states instead. We compare these bounds to those in the three degenerate massive neutrino scheme. In doing so, we are motivated by the fact that current limits on $\sum m_\nu$ start excluding the degenerate region at a high significance. As a result, it is timely to investigate the impact of our assumptions on how the total mass is distributed among the massive eigenstates. More detailed analyses will be carried out in an upcoming work [17], while a recent attempt has been carried out in [18].

Measurements of the CMB anisotropy temperature, polarization, and cross-correlation spectra are exploited with the full Planck 2015 data release [11,14]. We present results arising from the combination of the full temperature data with the large scale polarization measurements (i.e., the Planck low-ℓ multipole likelihood that extends from $\ell = 2$ to $\ell = 29$), referring to it as *Planck TT*. When combined with DR9, we refer to it as our *Base* data set. Furthermore, we also consider for the sake of comparison the addition of the small-scale polarization and cross-correlation spectra as measured by the Planck High Frequency Instrument (HFI), which in the following will be named *Planck pol*. We refer to the combination of *Planck pol* and DR9 as *Basepol*. We analyze Planck CMB data sets, making use of the Planck likelihood [19]. With respect to the different parameters involved in the CMB foreground analyses, we vary them following Refs. [11,19]. Because of a possible residual level of systematics in the coadded polarization spectra at high multipoles, the Planck Collaboration suggests treating the full temperature and polarization results with caution [11]. For this reason, we shall assume the *Planck TT* as our CMB baseline data and provide results from *Planck pol* for the sake of comparison with other recent works [7,10].

Together with Planck CMB temperature and polarization measurements, we exploit here the DR9 CMASS sample of galaxies [13], as previously done in Refs. [20,21]. This galaxy sample contains 264283 massive galaxies over 3275 $\deg^2$ of the sky. The redshift range of this galaxy sample is $0.43 < z < 0.7$, with a mean redshift of $z_{\rm eff} = 0.57$. The measured galaxy power spectrum $P_{\rm meas}(k)$ is identical to the one exploited for the BAO analyses [22], and it is affected by several systematic uncertainties, as carefully studied in [23,24]. Following this previous work, we add an extra free parameter to account for systematics in the measured power spectrum: $P_{\rm meas}(k) = P_{\rm meas,w}(k) - S[P_{\rm meas,nw}(k) - P_{\rm meas,w}(k)]$, where $P_{\rm meas,w}(k)$ is the measured power spectrum after accounting for systematic uncertainties, $P_{\rm meas,nw}(k)$ refers to the measured power spectrum without these effects, and S is an extra nuisance parameter that will be marginalized over. Previous works [20,24] have applied a Gaussian prior with

[1]We also note that, even though results from [7] are shown in combination with Planck temperature (i.e., without small scale polarization), they come from a frequentist analysis. As detailed below, we are going to show results obtained within the Bayesian framework. As a result, a direct comparison between our limits and [7] is hard to assess.

a standard deviation of 0.1 to the S parameter, based on the mocks of Ref. [23]. Here we follow the same assumption for the systematics parameter S.

The expectation value of the matter power spectrum requires a previous convolution of the true power spectrum with the window functions. These functions describe the correlation of the data at different scales k due to the survey geometry, to be convolved with the theoretical power spectrum, i.e., the predicted power spectrum as a function of cosmological parameters extracted at each step of the Monte Carlo. The model galaxy power spectrum $P^g_{\rm th}(k)$ is computed as $P^g_{\rm th}(k,z) = b^2_{\rm HF} P^{\rm m}_{{\rm HF}\nu}(k;z) + P^{\rm s}_{\rm HF}$, where $P^{\rm m}_{{\rm HF}\nu}$ is the model matter power spectrum, with the scale independent parameters $b_{\rm HF}$ and $P^{\rm s}_{\rm HF}$ referring to the bias and the shot-noise contribution, respectively; see [20] for their adopted priors. The subscript HF refers to the HALOFIT prescription. Indeeed, we obtained the theoretical matter power spectrum by making use of the HALOFIT method [25,26], following corrections for modeling in the presence of massive neutrinos from [27]. In order to reduce the impact of nonlinearities, we adopt the conservative choice of a maximum wave number of $k_{\rm max} = 0.2\ h/{\rm Mpc}$. As we can see in Fig. 1, this region is safe against very large and uncertain nonlinear corrections in the modeled theoretical spectra. Furthermore, this choice is also convenient for comparison purposes with recent related work; see, e.g., [10].

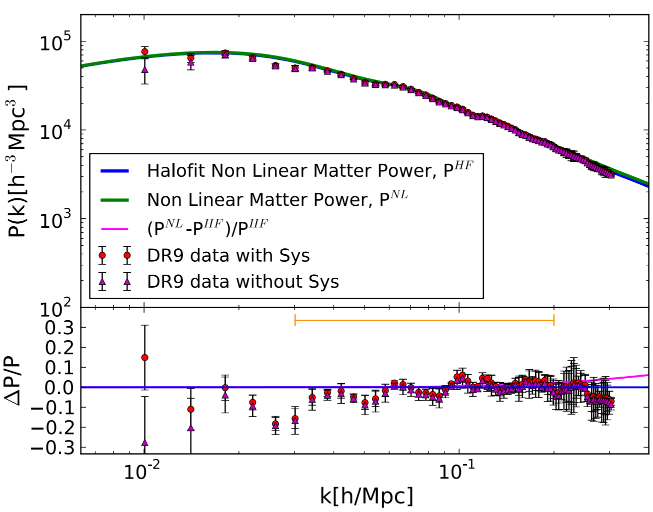

FIG. 1. *Top*: Nonlinear matter power spectrum computed using the HALOFIT method with the CAMB code [28] (blue line) and the Coyote emulator (green line) of Kwan *et al.* (2015) [29] at $z = 0.57$ for the ΛCDM best-fit parameters from *Planck TT* 2015 data. Data points are the clustering measurements from the BOSS Data Release 9 (DR9) CMASS sample. The error bars are computed from the diagonal elements C_{ii} of the covariance matrix. We also illustrate the data after applying a maximal correction for systematics, i.e., $S = 1$; see text for details. *Bottom*: Residuals with respect to the nonlinear model with HALOFIT. The orange horizontal line indicates the k range used in our analysis.

Even if the well-known degeneracy between the neutrino mass and the Hubble constant H_0 [30] can be improved with large scale structure data, an additional prior on the Hubble parameter helps in further pinning down the cosmological neutrino mass limits, as we shall see in the following sections. A recent study [8] has shown that the choice of the low redshift priors plays a crucial role when constraining $\sum m_\nu$. In particular, when considering the *Planck pol* and Hubble constant measurements, the 95% C.L. limit on $\sum m_\nu$ was between 0.34 and 0.18 eV, depending on the value of H_0 used in the analyses. Therefore, we also consider the combination of Planck and DR9 measurements with three different H_0 priors, two of which arise from the reanalysis carried out in Ref. [16], consisting of a lower estimate ($H_0 = 70.6 \pm 3.3\ {\rm km\,s^{-1}\,Mpc^{-1}}$) and a higher estimate ($H_0 = 72.5 \pm 2.5\ {\rm km\,s^{-1}\,Mpc^{-1}}$) of the Hubble parameter. The third H_0 measurement used here relies on the recent measurement reported in Ref. [15], $H_0 = 73.02 \pm 1.79\ {\rm km\,s^{-1}\,Mpc^{-1}}$, by means of observations of Cepheids variables from the Hubble Space Telescope (HST) in a number of novel host galaxies. This new estimate of the Hubble constant from HST has reduced its previous uncertainty (see, e.g., [31]) to the 2.4% level and has led to the tightest neutrino mass constraints, which we present in the following sections. Notice that these results should be considered as the less conservative ones obtained in our study, since the value of $H_0 = 73.02 \pm 1.79\ {\rm km\,s^{-1}\,Mpc^{-1}}$ is 3σ higher than the Planck CMB H_0 value. Unaccounted systematic effects for both measurements may be the origin for this discrepancy. Nevertheless, the findings of [16], yielding $H_0 = 72.5 \pm 2.5\ {\rm km\,s^{-1}\,Mpc^{-1}}$, are also in tension with the Planck Hubble constant estimates (albeit in this case the tension is milder, at the 2σ level). For the lower estimate of $H_0 = 70.6 \pm 3.3\ {\rm km\,s^{-1}\,Mpc^{-1}}$ from [16], the tension is much less significant. In order to illustrate the very important role of the Hubble constant prior, and how its choice may bias significantly the results concerning the neutrino mass ordering preferred by current cosmological data, we will present the neutrino mass limits for the three possible cases described above and named *H070p6*, *H072p5*, and *H073p02*.

To provide a comparison with previous limits in the literature, we combine the Planck CMB plus DR9 large scale structure measurements with additional large scale structure information in the form of the BAO clustering signature. We exploit BAO data results at $z_{\rm eff} = 0.106$ from the 6dF Galaxy Survey (6dFGS) [32], $z_{\rm eff} = 0.44$, 0.6, and 0.73 from the WiggleZ Dark Energy Survey [33], and $z_{\rm eff} = 0.32$ from BOSS Data Release 11 LOWZ sample [34]. The combination of these three data sets will be referred to as BAO.[2]

[2]The authors of Ref. [10] exploit both the LOWZ and the CMASS BOSS measurements and, therefore, the impact of the BAO data is larger for that case [35].

TABLE I. The 95% C.L. upper bounds on $\sum m_\nu$ (in eV), mean values, and their associated 95% C.L. errors of the reionization optical depth τ and the Hubble constant parameter H_0 (in $\mathrm{km\,s^{-1}\,Mpc^{-1}}$) for different combinations of cosmological data sets. The first, second, and third columns show the results for 1, 2, and 3 massive neutrino states, respectively. The *Base* case refers to the combination of *Planck TT* plus DR9, with bias, shot, and a Gaussian prior on systematics included.

	1 massive state			*2 massive states*			*Degenerate spectrum*		
Data set	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck TT	<0.662	$0.080^{+0.038}_{-0.037}$	$65.5^{+3.7}_{-4.3}$	<0.724	$0.081^{+0.039}_{-0.038}$	$65.4^{+4.2}_{-5.3}$	<0.720	$0.080^{+0.038}_{-0.037}$	$65.6^{+4.2}_{-5.7}$
Base	<0.269	0.073 ± 0.037	$66.8^{+2.1}_{-2.3}$	<0.281	$0.073^{+0.037}_{-0.036}$	$66.8^{+2.1}_{-2.3}$	<0.297	$0.073^{+0.036}_{-0.037}$	$66.8^{+2.1}_{-2.3}$
Base + BAO	<0.183	0.075 ± 0.036	$67.5^{+1.4}_{-1.6}$	<0.191	$0.075^{+0.037}_{-0.036}$	$67.6^{+1.4}_{-1.6}$	<0.202	$0.075^{+0.037}_{-0.038}$	67.6 ± 1.5
Base + H070p6	<0.230	0.074 ± 0.036	$67.1^{+1.9}_{-2.1}$	<0.238	$0.074^{+0.037}_{-0.036}$	$67.2^{+1.9}_{-2.0}$	<0.255	$0.074^{+0.039}_{-0.037}$	$67.1^{+1.9}_{-2.1}$
Base + H072p5	<0.182	$0.076^{+0.037}_{-0.036}$	$67.6^{+1.7}_{-1.8}$	<0.195	0.076 ± 0.037	$67.6^{+1.7}_{-1.8}$	<0.201	$0.076^{+0.038}_{-0.037}$	$67.6^{+1.6}_{-1.8}$
Base + H073p02	<0.137	$0.078^{+0.035}_{-0.036}$	$68.2^{+1.4}_{-1.6}$	<0.145	0.079 ± 0.037	$68.2^{+1.4}_{-1.6}$	<0.153	$0.079^{+0.037}_{-0.036}$	68.2 ± 1.5
Base + BAO + H070p6	<0.175	0.076 ± 0.036	$67.7^{+1.4}_{-1.5}$	<0.180	0.075 ± 0.036	$67.7^{+1.4}_{-1.5}$	<0.187	$0.076^{+0.036}_{-0.037}$	$67.7^{+1.4}_{-1.5}$
Base + BAO + H072p5	<0.151	0.077 ± 0.036	$67.9^{+1.3}_{-1.4}$	<0.160	$0.078^{+0.036}_{-0.035}$	$68.0^{+1.3}_{-1.4}$	<0.168	$0.077^{+0.036}_{-0.037}$	$67.9^{+1.3}_{-1.4}$
Base + BAO + H073p02	<0.125	0.079 ± 0.036	$68.3^{+1.2}_{-1.3}$	<0.135	$0.079^{+0.037}_{-0.037}$	68.3 ± 1.3	<0.139	0.079 ± 0.036	68.3 ± 1.3

In order to derive the cosmological constraints on the parameters, we use the Monte Carlo Markov chain package COSMOMC [36,37], using the Gelman and Rubin statistics [38] for the convergence of the generated chains.

III. RESULTS ON $\sum m_\nu$

In the following, we present the limits on the total neutrino mass $\sum m_\nu$, imposing $\sum m_\nu > 0$, as in Refs. [7,10], and mainly focusing on the case with one massive and two massless neutrino states, although we also quote and discuss the bounds for other possible assumptions concerning the neutrino mass spectrum. Even if the cases of one massive plus two massless and two massive plus one massless can be naively regarded as an approximation of the normal (with $m_3 \gg m_1 \simeq m_2$) and the inverted (with $m_1 \simeq m_2 \gg m_3$) hierarchy, respectively,[3] an assessment about the preference of one scheme with respect to others is beyond the scope of the present work. Our goal is to highlight possible variations of the limits on $\sum m_\nu$ when assuming different mass schemes as a proxy of the sensitivity of cosmological probes. Table I shows our results in terms of the 95% C.L. upper limits on $\sum m_\nu$ (in eV) and the mean values, together with their associated 95% C.L. errors of the low redshift observables τ and H_0, for the *Base* combination of *Planck TT* plus DR9 galaxy clustering measurements, together with other external data sets. The three possible neutrino mass spectral cases are illustrated. Notice that the tightest limits are obtained for the case of one massive state, for which we obtain a slight improvement of $\Delta\chi^2 \simeq 2$ with respect to the other two mass scenarios when considering the *H073p02* prior in the analyses. This is due to the fact that a pure radiation component in the universe at late times alleviates the tension between local and high-redshift estimates of the Hubble constant. The associated one-dimensional posterior probabilities for $\sum m_\nu$ (in eV) are depicted in Fig. 2, where we show the comparison among different data sets for both the one and the two massive neutrino assumptions.

The tightest 95% C.L. upper bound on the neutrino mass is obtained for the *Base* combination together with the BAO and the *H073p02* data sets, which notably help in improving the neutrino mass limits, as we find $\sum m_\nu < 0.125$ eV,

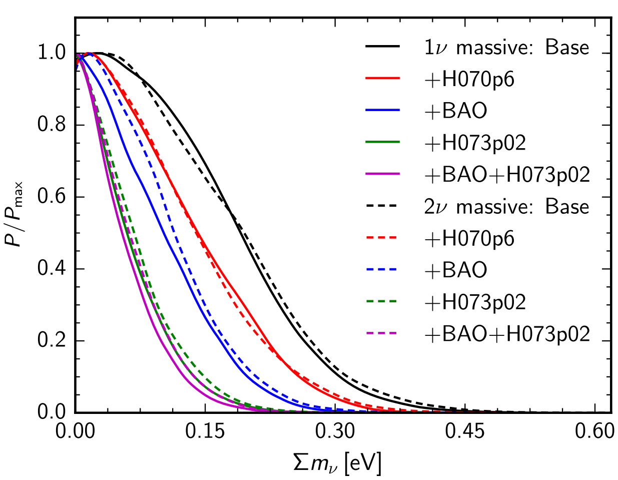

FIG. 2. One-dimensional posterior probability for $\sum m_\nu$ for the *Base* combination, which consists of *Planck TT* and DR9 galaxy clustering measurements, and also combined with other possible data sets. Both the one (solid lines) and the two (dashed lines) massive neutrino cases are illustrated.

[3]Indeed, the authors of Ref. [39] have pointed out that especially the one massive case could not completely match the normal hierarchical scenario for values of $\sum m_\nu \gg 0.06$, i.e., the minimum value allowed by oscillation measurements when assuming normal hierarchy.

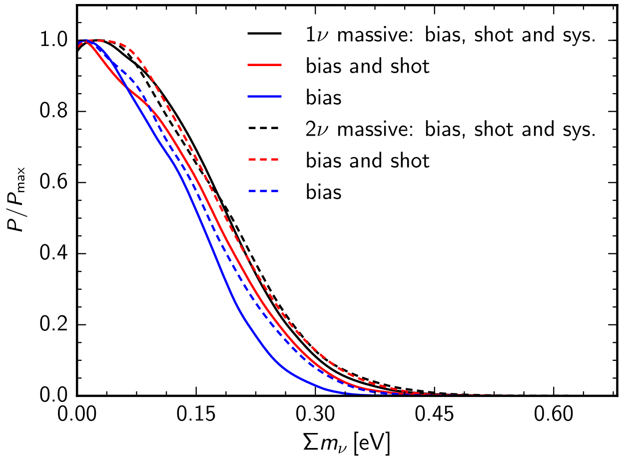

FIG. 3. As in Fig. 2 but focusing on the *Base* combination only. Different curves show the impact of marginalizing over bias, shot noise, and systematics; see text for details.

$\sum m_\nu < 0.135$ eV, and $\sum m_\nu < 0.139$ eV for the one massive, two massive, and degenerate spectrum cases, respectively. According to the latest results on neutrino oscillation physics from global fits [1], in the inverted hierarchy, the minimal value allowed for the total neutrino mass is $\sum m_\nu = 0.0968$ eV. We choose to define the minimal value as the one obtained by setting the lightest eigenstate to zero and considering the 3σ allowed ranges of the mass differences from [1] (see [40] for a more detailed discussion about the definition of the minimal mass value). The minimal neutrino mass in the inverted hierarchy scenario (0.0968 eV) is excluded by the *Base* combination, BAO, and the *H073p02* prior on the Hubble constant at 88% C.L. This exclusion becomes less significant when the one massive neutrino scenario assumption is relaxed and the hot dark matter energy density is shared by either two or three massive neutrino states, cases for which we can exclude the region above $\sum m_\nu = 0.0968$ eV at more modest significance levels (85% and 84%, respectively).

Notice that the bounds noted above are among the strongest ones in the literature and are derived using *Planck TT* data only in combination with DR9 galaxy clustering measurements, BAO, and the *H073p02* prior on the Hubble constant. The tightest limit quoted in Ref. [7], obtained with a different large scale structure tracer, namely, the Lyman α forest power spectrum, $\sum m_\nu < 0.12$ eV at 95% C.L., is very close to our bound, as well as the bound $\sum m_\nu < 0.13$ eV at 95% from [10]. However, we recall here that our limit $\sum m_\nu < 0.125$ eV is obtained with a Bayesian analysis and with *Planck TT* data only plus DR9, BAO, and *H073p02* data sets. Furthermore, our limits arise from a conservative analysis accounting for all the possible factors which, in principle, may drastically reduce the constraining power of the DR9 large scale structure data. This can be noticed in the results depicted in Fig. 3, which shows the one-dimensional probability distribution for $\sum m_\nu$ considering the *Base* data set for both the one and the two massive schemes resulting from different marginalizations (bias only, bias and shot-noise only, and, finally, with systematics also included). Notice that, while systematic corrections do not affect our results, shot-noise contributions have a major impact. Indeed, we get $\sum m_\nu < 0.220$ eV at 95% C.L. for the *Base* combination of data sets without the shot-noise contribution, whereas we get $\sum m_\nu < 0.269$ eV at 95% C.L. when marginalizing over bias and shot-noise for the same data. On the other hand, the limits quoted above rely on the one massive neutrino assumption as well as on the addition of the recently derived *H073p02* prior. We shall comment on the impact of these two factors below.

For the sake of comparison with previous results in the literature [7,10], we also present here the constraints obtained when high-multipole polarization data are also

TABLE II. As Table I but for the *Basepol* case, which refers to the combination of *Planck pol* plus DR9, with bias, shot, and a Gaussian prior on systematics included; see text for details.

	1 massive state			*2 massive states*			*Degenerate spectrum*		
Data set	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0	$\sum m_\nu$	τ	H_0
Planck pol	<0.623	$0.083^{+0.033}_{-0.034}$	$65.7^{+3.1}_{-3.8}$	<0.549	$0.084^{+0.036}_{-0.034}$	$65.6^{+3.2}_{-4.3}$	<0.487	$0.082^{+0.035}_{-0.034}$	$65.2^{+2.9}_{-3.8}$
Basepol	<0.256	$0.075^{+0.035}_{-0.033}$	$66.8^{+1.8}_{-2.0}$	<0.270	0.075 ± 0.034	$66.8^{+1.8}_{-2.1}$	<0.276	$0.076^{+0.035}_{-0.034}$	$66.8^{+1.8}_{-2.0}$
Basepol + BAO	<0.176	$0.076^{+0.033}_{-0.034}$	$67.4^{+1.3}_{-1.5}$	<0.194	0.076 ± 0.033	$67.5^{+1.4}_{-1.5}$	<0.185	$0.077^{+0.033}_{-0.034}$	$67.5^{+1.3}_{-1.4}$
Basepol + H070p6	<0.220	$0.077^{+0.033}_{-0.034}$	$67.0^{+1.7}_{-1.9}$	<0.224	$0.075^{+0.033}_{-0.033}$	$67.1^{+1.6}_{-1.8}$	<0.223	$0.076^{+0.033}_{-0.034}$	$67.1^{+1.6}_{-1.7}$
Basepol + H072p5	<0.175	$0.077^{+0.034}_{-0.036}$	67.4 ± 1.5	<0.186	$0.075^{+0.035}_{-0.033}$	$67.5^{+1.5}_{-1.6}$	<0.198	$0.076^{+0.032}_{-0.034}$	$67.1^{+1.6}_{-1.7}$
Basepol + H073p02	<0.125	$0.079^{+0.033}_{-0.034}$	67.9 ± 1.3	<0.131	$0.079^{+0.034}_{-0.033}$	$67.9^{+1.4}_{-1.3}$	<0.143	$0.078^{+0.33}_{-0.034}$	67.9 ± 1.3
Basepol + BAO + H070p6	<0.153	$0.076^{+0.033}_{-0.034}$	$67.6^{+1.3}_{-1.2}$	<0.157	0.072 ± 0.033	$67.6^{+1.1}_{-1.2}$	<0.166	0.077 ± 0.033	$67.6^{+1.2}_{-1.3}$
Basepol + BAO + H072p5	<0.135	$0.078^{+0.033}_{-0.034}$	67.8 ± 1.2	<0.140	$0.078^{+0.033}_{-0.031}$	$67.7^{+1.1}_{-1.2}$	<0.149	$0.078^{+0.031}_{-0.032}$	$67.6^{+1.1}_{-1.2}$
Basepol + BAO + H073p02	<0.123	$0.078^{+0.032}_{-0.033}$	$68.1^{+1.1}_{-1.2}$	<0.113	$0.079^{+0.033}_{-0.034}$	68.0 ± 1.1	<0.124	$0.079^{+0.033}_{-0.032}$	$68.0^{+1.0}_{-1.1}$

included in the analyses. Table II shows the 95% C.L. upper bound on $\sum m_\nu$ (in eV) and the mean values, together with their associated 95% C.L. errors, of the low redshift observables τ and H_0, arising from the analyses of *Planck pol* plus DR9 data (combination named as *Basepol*). In general, the results follow the same pattern as the ones obtained before in the absence of polarization measurements: the combination of *Basepol* plus the *H073p02* prior sets an upper 95% C.L. bound on $\sum m_\nu$ of 0.125 eV in the one massive neutrino case. If BAO measurements are added to the former combination, the 95% C.L. upper bounds on the total neutrino mass reach very tight limits, corresponding to $\sum m_\nu < 0.123$ eV, $\sum m_\nu < 0.113$ eV, and $\sum m_\nu < 0.124$ eV in the one massive, two massive, and degenerate neutrino mass spectra, respectively. The minimal neutrino mass in the inverted hierarchy scenario (0.0968 eV) is excluded by the *Basepol* combination, BAO, and the *H073p02* prior on the Hubble constant at 90% C.L. in the one massive neutrino scenario. In the two massive and degenerate neutrino scenarios the significance of the exclusion is 91.8% and 88.6% C.L., respectively.

As previously stated, there is a tension between the *H072p5* and *H073p02* priors and the Planck estimates of the Hubble constant. Given the well-known degeneracy between H_0 and $\sum m_\nu$ [30], this tension should be carefully examined when interpreting the $\sum m_\nu$ limits obtained here. Notice that the highest H_0 priors (*H072p5* and *H073p02*) lead to the tightest neutrino mass constraints here; therefore, these limits should be regarded as our less conservative bounds. As a rough test, we can compare the $\Delta\chi^2$ with respect to the *Base* model: we get $\Delta\chi^2 = 4$ and 8 when *H072p5* and *H073p02* priors are employed, respectively. Future accurate local determinations of the Hubble constant could be shifted to larger (smaller) values, tightening (softening) the constraints found here. Another low-redshift observable which has a large impact on the cosmological bounds on $\sum m_\nu$ is the reionization optical depth, τ. A recent estimation of the optical depth from the Planck Collaboration, based on refined analyses of the polarization data of the Planck HFI on large angular scales, gives $\tau = 0.055 \pm 0.009$ [41], a value which is in better agreement with astrophysical measurements of Lyman-α emitters or high-redshift quasars [42–44] than previous CMB estimates. This new value of τ will strengthen the bounds quoted here (see, e.g., [8]), as a smaller value of τ is translated into a smaller clustering amplitude. To avoid further reductions of the clustering amplitude, the contribution from massive neutrinos must be reduced.

Notice that there exists a small difference in the bounds for the three neutrino mass schemes. This effect can be understood by means of the suppression induced by relativistic and nonrelativistic neutrino species in the growth of matter fluctuations. While in the two massive (or in the degenerate) neutrino scenario, there is only one (none) neutrino species which is relativistic today; in the one massive neutrino scheme, two neutrino species are relativistic at the current epoch.[4] In the two-massive case, the power spectrum of matter fluctuations is suppressed due to the existence of two hot dark matter particles and one relativistic state that does not contribute to clustering. In the one massive case, the suppression of the growth of matter perturbations is larger, as there are two massless states that will not contribute to clustering. In addition, the free streaming wave number $k_{\rm fs}$ associated with the massive state is larger than in the two massive or degenerate scenarios; therefore, there are more available modes to be exploited with the neutrino signature imprinted, benefiting as well from smaller error bars. Notice that, for the very same reasons, the different distribution of the total mass $\sum m_\nu$ among the massive eigenstates also affects the shape of the CMB power spectra, mainly due to the gravitational lensing effects.

This should be regarded as an example of how close we are to the limit at which the usual approximations followed when exploring the ΛCDM $+ \sum m_\nu$ scenario with cosmological probes become relevant. While statistical fluctuations could originate some tiny shifts in the neutrino mass limits obtained in the three possible neutrino mass spectrum scenarios,[5] current cosmological data already exclude the degenerate region (with $\sum m_\nu$ well above 0.2 eV) at a high significance, cornering the validity of the standard degenerate neutrino assumption. Analyses involving an accurate inclusion of information from oscillation measurements, along with a statistical model comparison able to assess the preference for a hierarchy, become pressing and will be performed elsewhere [17] (see some previous related work in Ref. [45]). In addition, the forecasted sensitivity to $\sum m_\nu$ from future surveys makes the more rigorous approach outlined above unavoidable.

IV. CONCLUSIONS

The limit found here for the total neutrino mass, $\sum m_\nu <$ 0.183 at 95% C.L., is among the tightest ones in the literature when using the same data sets, and it goes in the same direction as other existing bounds in the literature [7–10]. If high-multipole polarization measurements are added in the data analyses, the former 95% C.L. limit is further tightened ($\sum m_\nu < 0.176$ eV). All these findings imply that (a) the degenerate neutrino mass spectrum is highly disfavored by current cosmological measurements; and (b) the minimal value of $\sum m_\nu$ allowed in the inverted

[4]As previously stated, this could be regarded as an approximation of normal and inverted hierarchical distribution of mass among the massive eigenstates.

[5]By requiring a convergence level (quantified by the Gelman and Rubin statistics R [38]) of $R - 1 \sim 0.01$, the contribution from statistical fluctuations can be roughly estimated to be a few percent of the limits quoted in Tables I and II.

hierarchical scenario by neutrino oscillation data corresponds at 70% C.L. Nevertheless, in the scenario in which the neutrino mass hierarchy turns out to be inverted, a direct measurement of the total neutrino mass from cosmological probes could be fast approaching. If the neutrino mass hierarchy turns out to be normal (as mildly hinted by current results), our neutrino mass limits may tell us something about future directions for searches for neutrinoless double beta decay, $0\nu2\beta$, a rare decay which is currently the only probe able to test the neutrino identity, i.e., the *Dirac* versus the *Majorana* character [46]. A huge effort has been devoted to assess the sensitivity of future $0\nu2\beta$ experiments [47,48], commonly expressed as bounds on the decaying isotope half-life. The latter is related to the so-called effective Majorana mass of the electron neutrino, the $m_{\beta\beta}$ parameter through the relevant nuclear matrix elements (NME). The tightest current bound is $m_{\beta\beta} < 60$ meV, quoted very recently by the KamLAND-Zen experiment [49], reaching the bottom limit of the degenerate neutrino mass region. In the normal neutrino mass scheme, future $0\nu2\beta$ experiments would be required to reach a sensitivity in $m_{\beta\beta}$ below 20 meV; see Ref. [40]. Some fraction of next-generation $0\nu2\beta$ experiments could reach that value, being competitive with cosmological bounds and potentially leading to evidence of $0\nu2\beta$, provided that neutrinos are Majorana particles and that the mixing parameters chosen by nature do not arrange such that $m_{\beta\beta} = 0$. In order to achieve these goals and also to perform a successful combination of cosmological and laboratory data sets, it is crucial to keep also NME uncertainties under control [40,48]. Finally, a precise description of the possible neutrino mass scenarios including neutrinos oscillation measurements seems unavoidable. Upcoming measurements of galaxy clustering, supported by some robust model comparison, can help enormously in unraveling which scenario describes better the observational findings.

ACKNOWLEDGMENTS

We would like to thank Massimiliano Lattanzi, Julien Lesgourgues, and David Spergel for precious discussions and Luca Pagano for useful comments on the draft. E. G. is supported by NSF Grant No. AST1412966. M. G., S. V., and K. F. acknowledge support by the Vetenskapsrå det (Swedish Research Council). O. M. is supported by PROMETEO II/2014/050, by the Spanish Grant No. FPA2014–57816-P of the MINECO, by the MINECO Grant No. SEV-2014-0398, and by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skodowska-Curie Grant Agreements No. 690575 and No. 674896. S. H. acknowledges support by NASA-EUCLID11-0004, NSF AST1517593, and NSF AST1412966.

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