On the improvement of cosmological neutrino mass bounds

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The most recent measurements of the temperature and low-multipole polarization anisotropies of the Cosmic Microwave Background (CMB) from the Planck satellite, when combined with galaxy clustering data from the Baryon Oscillation Spectroscopic Survey (BOSS) in the form of the full shape of the power spectrum, and with Baryon Acoustic Oscillation measurements, provide a 95% confidence level (CL) 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 datasets are taken into account. This very same data combination is able to set, at $\sim 70\%$ CL, 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%CL 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 non-degenerate neutrino mass spectrum; they slightly worsen when considering other degenerate neutrino mass schemes. Current cosmological data, therefore, start to be mildly sensitive to the neutrino mass ordering. 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.

I. INTRODUCTION

Neutrinos are sub-eV elementary particles which, apart from gravity, only interact via weak interactions, decoupling from the thermal bath as ultra-relativistic 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 (SM) 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 $\Delta m^2_{12} \approx 7.5 \times 10^{-5}$ eV$^2$ and for the atmospheric mass splitting is $|\Delta m^2_{31}| \approx 2.45 \times 10^{-3}$ 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 $k < k_{fs}$, i.e. at scales below the neutrino free streaming wavenumber $k_{fs}$, and suppressing structure formation at $k > k_{fs}$ [3,4]. The presence of massive neutrinos also affects the CMB, as these particles may become non-relativistic 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 $\ell$), 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% CL 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 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% CL [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

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limits among the ones quoted above have been obtained by employing Planck polarization measurements at small scales \[16\], which could be affected by a small residual level of systematics \[17\].

Here we follow a more conservative approach. We exploit the effect of the neutrino masses in galaxy clustering, focusing on the full 3D galaxy power spectrum shape from the Baryon Oscillation Spectroscopic Survey (BOSS) \[11\] Data Release 9 (DR9) \[12\] (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 \[17\]. 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 \[13\] - 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% CL. 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.

\[\text{II. ANALYSIS AND DATA}\]

In the following section, the cosmological model we assume is the standard \(\Lambda\)CDM 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 \(\Theta_s\), the reionization optical depth \(\tau\), the scalar spectral index \(n_s\) and the amplitude of the primordial spectrum \(A_s\).

We follow here the Planck \(\Lambda\)CDM 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 \[13\].

Measurements of the CMB anisotropy temperature, polarization, and cross-correlation spectra are exploited with the full Planck 2015 data release \[16\] \[17\]. We present results arising from the combination of the full temperature data with the large scale polarization measurements (i.e. the Planck low-\(\ell\) multipole likelihood that extends from \(\ell = 2\) to \(\ell = 29\)), referring to it as \textit{Planck TT}. When combined with DR9, we refer to it as our \textit{Base} dataset. 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 \textit{Planck pol}. We refer to the combination of \textit{Planck pol} and DR9 as \textit{Basepol}. We analyze Planck CMB datasets, making use of the Planck likelihood \[18\]. With respect to the different parameters involved in the CMB foreground analyses, we vary them following Refs. \[16\] \[18\]. 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 \[16\]. For this reason, we shall assume the \textit{Planck TT} as our CMB baseline data and provide results from \textit{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 \[12\], as previously done in Refs. \[19\] \[20\]. This galaxy sample contains 264 283 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 \(z_{\text{eff}} = 0.57\). The measured galaxy power spectrum \(P_{\text{meas}}(k)\) is identical to the one exploited for the BAO analyses \[21\], and it is affected by several systematic uncertainties, as carefully studied in \[22\] \[23\]. Following this previous work, we add an extra free parameter to account for systematics in the measured power spectrum: \(P_{\text{meas}}(k) = P_{\text{meas}, w}(k) - S(P_{\text{meas}, \text{ew}}(k) - P_{\text{meas}, w}(k))\), where \(P_{\text{meas}, w}(k)\) is the measured power spectrum after accounting for systematic uncertainties, \(P_{\text{meas}, \text{ew}}(k)\) refers to the measured power spectrum without these effects, and \(S\) is an extra nuisance parameter that will be marginalized over. Previous works \[19\] \[23\] have applied a gaussian prior with a standard deviation of 0.1 to the \(S\) parameter, based on the mocks of Ref. \[22\]. 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 ex-

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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.
contrasted at each step of the Monte Carlo. The model galaxy power spectrum $P^g_{\chi k}(k)$ is computed as $P^g_{\chi k}(k, z) = b^2_{HF} P^g_{HF}(k; z) + P^m_{HF}$, where $P^m_{HF}$ is the model matter power spectrum, with the scale independent parameters $b_{HF}$ and $P^m_{HF}$ referring to the bias and the shot-noise contribution respectively; see [19] for their adopted priors. The subscript HF refers to the HaloFit prescription. Indeed, we obtained the theoretical matter power spectrum by making use of the HaloFit method [24, 25], following corrections for modeling in the presence of mass tractions. This new estimate of the Hubble constant from HST effects for both measurements may be the origin for this discrepancy. Nevertheless, the findings of [14], yielding $H_0 = 73.02 \pm 1.79$ 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 [14], yielding $H_0 = 72.5 \pm 2.5$ 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 es-

![Figure 1](image-url)

**FIG. 1.** Top: Non-linear matter power spectrum computed using the HaloFit method with the CAMB code [27] (blue line) and the Coyote emulator (green line) of Kwan et al. (2015) [28] at $z=0.57$ for the LCDM 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 non linear model with HaloFit. The orange horizontal line indicates the $k$ range used in our analysis.
timate of $H_0 = 70.6 \pm 3.3$ km s$^{-1}$ Mpc$^{-1}$ from [14], 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 concern-
ning the neutrino mass ordering preferred by current cos-
ological 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 $z_{\text{eff}} = 0.106$
from the 6dF Galaxy Survey (6dFGS) [31], $z_{\text{eff}} = 0.44,$
0.6 and 0.73 from the WiggleZ Dark Energy Survey [32]
and $z_{\text{eff}} = 0.32$ from BOSS Data Release 11 LOWZ sam-
ples [33]. The combination of these three datasets will be
referred to as $BAO$ [4].

In order to derive the cosmological constraints on
the parameters, we use the Monte Carlo Markov Chain
(MCMC) package $\text{cosmomc}$ [35, 36], using the Gelman
and Rubin statistics $\chi^2$ for the convergence of the gen-
erated chains.

III. RESULTS ON $\sum m_\nu$

In the following, we present the limits on the total neu-
trino 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 con-
cerning the neutrino mass spectrum. Even if the cases
of one massive plus two massless and two massive plus
one massless can be regarded as an approximation of the normal (with $m_3 \gg m_1 \simeq m_2$) and inverted (with $m_1 \simeq m_2 \gg m_3$) hierarchy, respectively, an assessment
about the preference of one scheme with respect to oth-
ers 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 to the neutrino mass hi-
erarchy. Table I shows our results in terms of the 95% CL
upper limits on $\sum m_\nu$ (in eV) and the mean values, to-
gether with their associated 95% CL errors of the low
redshift observables $\tau$ and $H_0$, for the $Base$ combination
of Planck TT plus DR9 galaxy clustering measurements,
together with other external data sets. The three pos-
sible neutrino mass spectral cases are illustrated. No-
tice that the tightest limits are obtained for the case
of one massive state, for which we obtain a slight im-
provement 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 rad-
ation 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% CL 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, $\sum m_\nu < 0.135$ 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 to-
tal 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 al-
lowed ranges of the mass differences from [1] (see [37]
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% CL. 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 us-
using $Planck$ TT data only. The tightest limit quoted
in Ref. [7], obtained with a different large scale struc-
ture tracer, namely, the Lyman $\alpha$ forest power spec-
trum, $\sum m_\nu < 0.12$ eV at 95% CL, 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. Furthermore, our lim-
its 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 de-
picted in Fig. 2 which shows the one dimensional prob-
bility distribution for $\sum m_\nu$ considering the $base$ dataset
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 im-
port. Indeed, we get $\sum m_\nu < 0.220$ eV at 95% CL for
the $Base$ combination of datasets without the shot-noise
contribution, whereas we get $\sum m_\nu < 0.269$ eV at 95%
CL 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 included in the analyses. Table IV shows the 95% CL upper bound on $\sum m_{\nu}$ (in eV) and the mean values, together with their associated 95% CL errors, of the low redshift observables $\tau$ 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% CL 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% CL 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% CL 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% CL, 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 $\sum m_{\nu}$ [29], 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, $\tau$. 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 $\tau = 0.055 \pm 0.009$ [38], value which is in a better agreement with astrophysical measurements of Lyman-\(\alpha\) emitters or high-redshift quasars [39–41] than previous CMB estimates. This new value of $\tau$ will strengthen the bounds quoted here, see e.g. [8], as a smaller value of $\tau$ is translated into a smaller clustering amplitude. To avoid further reductions of the clustering amplitude, the contribution from massive neutrinos must be reduced.

A highly motivating effect is the fact that, even if there exists a small difference in the bounds for the three possible neutrino mass schemes, they are indeed different, implying that present cosmological measurements are mildly sensitive to the distribution of hot dark matter and radiation at late times. This effect can be understood by means of the suppression induced by relativistic and non-relativistic 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 wavenumber $k_{fs}$ 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 $\Lambda$CDM+$\sum m_{\nu}$ 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 [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 [15] (see some previous related work in Ref. [42]). 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% CL, is among the tightest ones

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

4 By requiring a convergence level (quantified by the Gelman and Rubin statistics $R$ [23]) of $R - 1 \sim 0.01$, the contribution from statistical fluctuations can be roughly estimated to be a few percent the limits quoted in Tables [4] and [11].
in the literature when using the same data sets, and it goes in the same direction than other existing bounds in the literature [7–10]. If high-multipole polarization measurements are added in the data analyses, the former 95% CL limit is further tightened ($\sum m_\nu < 0.176$ eV).

All these findings imply that (a) the degenerate neutrino mass spectrum is highly disfavoured by current cosmological measurements; and (b) the minimal value of $\sum m_\nu$ allowed in the inverted hierarchical scenario by neutrino oscillation data is discarded at 70% CL. 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, $0\nu\beta\beta$, a rare decay which is currently the only probe able to test the neutrino identity, i.e. the Dirac versus the Majorana character [14]. A huge effort has been devoted to assess the sensitivity of future $0\nu\beta\beta$ experiments [45–49], 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 [47], reaching the bottom limit of the degenerate neutrino mass region. In the normal neutrino mass scheme, future $0\nu\beta\beta$ experiments would be required to reach a sensitivity in $m_{\beta\beta}$ below 20 meV, see Ref. [37]. Some fraction of next-generation $0\nu\beta\beta$ experiments could reach that value, being competitive with cosmological bounds and potentially leading to an evidence of $0\nu\beta\beta$, 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 dataset, it is crucial to keep also NME uncertainties under control [37–40]. Finally, the results reported here show a mild dependence on the neutrino mass scheme choice. Upcoming measurements of galaxy clustering, supported by some robust model comparison, can help enormously in unraveling which scenario describes better the observational findings.

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### TABLE I. 95% CL upper bounds on $\sum m_\nu$ (in eV), mean values and their associated 95% CL errors of the reionization optical depth $\tau$ and the Hubble constant parameter $H_0$ (in km s$^{-1}$ Mpc$^{-1}$) for different combination of cosmological datasets. The first, second and third column 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.

| Dataset            | $\sum m_\nu$ | $\tau$ | $H_0$ | $\sum m_\nu$ | $\tau$ | $H_0$ | $\sum m_\nu$ | $\tau$ | $H_0$ |
|--------------------|--------------|--------|-------|--------------|--------|-------|--------------|--------|-------|
| **Planck TT**      |              |        |       |              |        |       |              |        |       |
| base               | <0.662       | 0.080+0.034−0.037 | 65.3±3.1 | <0.724       | 0.081+0.035−0.036 | 65.4±3.1 | <0.720       | 0.080+0.037−0.037 | 65.6±3.1 |
| base+BAO           | <0.269       | 0.073±0.037 | 66.8±2.3 | <0.281       | 0.073±0.037 | 66.8±2.3 | <0.297       | 0.073±0.037 | 66.8±2.3 |
| base+H070p6        | <0.183       | 0.075±0.036 | 67.5±1.9 | <0.191       | 0.075±0.036 | 67.6±1.9 | <0.202       | 0.075±0.036 | 67.6±1.9 |
| base+H072p6        | <0.230       | 0.074±0.036 | 67.1±2.1 | <0.238       | 0.074±0.036 | 67.2±2.1 | <0.255       | 0.074±0.037 | 67.1±1.9 |
| base+H072p5        | <0.182       | 0.076±0.036 | 67.6±1.8 | <0.195       | 0.076±0.037 | 67.6±1.8 | <0.201       | 0.076±0.037 | 67.6±1.8 |
| base+H073p02       | <0.137       | 0.078±0.035 | 68.2±1.4 | <0.145       | 0.079±0.037 | 68.2±1.4 | <0.153       | 0.079±0.037 | 68.2±1.5 |
| base+BAO+H070p6    | <0.175       | 0.076±0.036 | 67.7±1.6 | <0.180       | 0.075±0.036 | 67.7±1.6 | <0.187       | 0.076±0.036 | 67.7±1.4 |
| base+BAO+H072p5    | <0.151       | 0.077±0.036 | 67.9±1.3 | <0.160       | 0.078±0.037 | 68.0±1.3 | <0.168       | 0.077±0.037 | 67.9±1.3 |
| base+BAO+H073p02   | <0.125       | 0.079±0.036 | 68.3±1.3 | <0.135       | 0.079±0.037 | 68.3±1.3 | <0.139       | 0.079±0.036 | 68.3±1.3 |

### TABLE II. As Tab. 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.

| Dataset            | $\sum m_\nu$ | $\tau$ | $H_0$ | $\sum m_\nu$ | $\tau$ | $H_0$ | $\sum m_\nu$ | $\tau$ | $H_0$ |
|--------------------|--------------|--------|-------|--------------|--------|-------|--------------|--------|-------|
| **Planck pol**     |              |        |       |              |        |       |              |        |       |
| basepol            | <0.623       | 0.083+0.034−0.033 | 65.7±3.1 | <0.620       | 0.084+0.034−0.034 | 65.6±3.1 | <0.487       | 0.082+0.034−0.034 | 65.2±3.1 |
| basepol+BAO        | <0.256       | 0.075±0.033 | 66.8±1.8 | <0.270       | 0.075±0.034 | 66.8±1.8 | <0.276       | 0.076±0.034 | 66.8±1.8 |
| basepol+H070p6     | <0.176       | 0.076±0.033 | 67.4±1.3 | <0.194       | 0.076±0.033 | 67.5±1.4 | <0.185       | 0.077±0.033 | 67.5±1.3 |
| basepol+H072p6     | <0.220       | 0.077±0.033 | 67.0±1.9 | <0.224       | 0.075±0.033 | 67.1±1.6 | <0.223       | 0.076±0.034 | 67.1±1.7 |
| basepol+H072p5     | <0.175       | 0.077±0.034 | 67.4±1.5 | <0.186       | 0.075±0.034 | 67.5±1.5 | <0.198       | 0.076±0.032 | 67.1±1.6 |
| basepol+H073p02    | <0.125       | 0.079±0.033 | 67.9±1.6 | <0.131       | 0.079±0.033 | 67.9±1.4 | <0.143       | 0.078±0.034 | 67.9±1.3 |
| basepol+BAO+H070p6 | <0.153       | 0.076±0.033 | 67.6±1.3 | <0.157       | 0.072±0.033 | 67.6±1.3 | <0.166       | 0.077±0.033 | 67.6±1.2 |
| basepol+BAO+H072p5 | <0.135       | 0.078±0.033 | 67.8±1.2 | <0.140       | 0.078±0.033 | 67.7±1.2 | <0.149       | 0.078±0.031 | 67.6±1.2 |
| basepol+BAO+H073p02| <0.123       | 0.078±0.032 | 68.1±1.3 | <0.113       | 0.079±0.032 | 68.0±1.1 | <0.124       | 0.079±0.032 | 68.0±1.1 |