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Neutrino Mass Bounds in the Era of Tension Cosmology

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Abstract

The measurements of cosmic microwave background (CMB) anisotropies made by the Planck satellite provide extremely tight upper bounds on the total neutrino mass scale ($\Sigma m_\nu < 0.26$ eV at 95% C.L.). However, as recently discussed in the literature, the Planck data show anomalies that could affect this result. Here we provide new constraints on neutrino masses using the recent and complementary CMB measurements from the Atacama Cosmology Telescope DR4 and the South Pole Telescope SPT-3G experiments. We found that both the ACT-DR4 and SPT-3G data, when combined with WMAP, mildly suggest a neutrino mass with $\Sigma m_\nu = 0.68 \pm 0.31$ and $0.46^{+0.14}_{-0.36}$ eV at 68% C.L., respectively. Moreover, when CMB lensing from the Planck experiment is included, the ACT-DR4 data now indicate a neutrino mass above the two standard deviations, with $\Sigma m_\nu = 0.60^{+0.44}_{-0.50}$ eV at 95% C.L., while WMAP+SPT-3G provides a weak upper limit of $\Sigma m_\nu < 0.37$ eV at 68% C.L. Interestingly, these results are consistent with the Planck CMB+lensing constraint of $\Sigma m_\nu = 0.41^{+0.17}_{-0.25}$ eV at 68% C.L. when variations in the $A_{\rm lens}$ parameter are considered. We also show that these indications are still present after the inclusion of BAO or Type Ia supernova data in extended cosmologies that are usually considered to solve the so-called Hubble tension. In this respect, we note that in these models, CMB+BAO constraints prefer a higher neutrino mass for higher values of the Hubble constant. A combination of ACT-DR4, WMAP, BAO, and constraints on the Hubble constant from the SH0ES collaboration gives $\Sigma m_\nu = 0.39^{+0.13}_{-0.25}$ eV at 68% C.L. in extended cosmologies.

Unified Astronomy Thesaurus concepts: Cosmological neutrinos (338); Cosmological parameters (339)

1. Introduction

It has been extensively shown that cosmic microwave background (CMB) anisotropies alone can provide a clean and robust constraint on the neutrino global mass scale Σm_ν (see, e.g., Kaplinghat et al. 2003; Lesgourgues & Pastor 2006; Pascoli et al. 2006; Gonzalez-Garcia & Maltoni 2008; Abazajian et al. 2015; De Salas et al. 2018; Lattanzi & Gerbino 2018). The Planck experiment, in combination with atmospheric and solar neutrino oscillation experiments, provides at the moment no indication for a neutrino mass with a reported limit on the sum of the three active neutrinos of $\Sigma m_\nu < 0.26$ eV at 95% C.L. (Aghanim et al. 2020a) from CMB angular spectra data. This constraint is further improved to $\Sigma m_\nu < 0.12$ eV at 95% C.L. when baryon acoustic oscillation (BAO) data are included (Aghanim et al. 2020a). A recent combination of Planck data with Type Ia supernova luminosity distances, BAO, and determinations of the growth rate parameter set the most constraining bound to date, $\Sigma m_\nu < 0.09$ eV at 95% C.L. (Di Valentino et al. 2021a). While these constraints are based on the assumption of the ΛCDM model and can be clearly relaxed in a extended parameter scenario, they have obviously important consequences for current and planned laboratory experiments devoted to neutrino mass detection (see, e.g., Capozzi et al. 2021). We remind the reader that an effective neutrino mass m_β can be measured through beta-decay experiments, while an effective mass $m_{\beta\beta}$ can be obtained from neutrinoless double beta-decay experiments ($0\nu\beta\beta$) if the neutrinos are Majorana fermions. The Planck limit, in combination with neutrino oscillation data, suggests values of m_β and $m_{\beta\beta}$ below 100 meV (see, e.g., Capozzi et al. 2021). These values are clearly challenging for current $0\nu\beta\beta$ experiments and out of the reach of sensitivity of KATRIN, the ongoing, state-of-the art beta-decay experiment (Aker et al. 2019).

It is, however, also well known that the cosmological limits could be plagued by the so-called lensing anomaly present in the Planck angular spectra data (Aghanim et al. 2020a; Di Valentino et al. 2020). Planck power spectra are indeed suggesting a larger gravitational lensing amplitude (described by the $A_{\rm lens}$ parameter as defined in Calabrese et al. 2008) from dark matter fluctuations than expected at about 99% C.L. Since gravitational lensing anticorrelates with a neutrino component that prevents clustering, an anomalous higher value for $A_{\rm lens}$, as seen in the Planck data, can bias the neutrino mass constraints toward lower values (Capozzi et al. 2021). While at the moment it is not clear if the $A_{\rm lens}$ anomaly is due to a systematic error or new physics, its presence suggests that the Planck limits on neutrino masses should be taken with a grain of salt.

A possible solution to the problem, as we point out in this Letter, comes from the new and exquisite CMB measurements provided by the Atacama Cosmology Telescope Data Release 4 (ACT-DR4; Aiola et al. 2020) and the South Pole Telescope (SPT-3G; Dutcher et al. (2021). When combined with previous data from the Wilkinson Microwave Anisotropy Probe (WMAP) satellite (Hinshaw et al. 2013), ACT-DR4 and SPT-3G can provide limits on cosmological parameters with a constraining power comparable to Planck. These experiments show no $A_{\rm lens}$ anomaly and are therefore ideal for constraining neutrino masses and double-checking the Planck constraints. It is therefore extremely timely to revisit the cosmological constraints on neutrino masses using these new CMB data.

There is, however, one additional caveat. While both ACT-DR4 and SPT-3G are consistent with a standard lensing amplitude, they are less consistent with other standard expectations. The ACT-DR4 release, in particular, seems to suggest a neutrino effective number $N_{\rm eff}$ lower than 3.04 (Aiola et al. 2020), a running of the spectral index $dn/d\ln k < 0$ at about one to two standard deviations (Aiola et al. 2020; Forconi et al. (2021), and an early dark energy at more than 99% C.L. (Hill et al. 2021; Poulin et al. 2021). The SPT-3G data, on the other hand, appear more in agreement with a higher value for $N_{\rm eff}$ (Dutcher et al. 2021). These small anomalies could also correlate with the constraints on neutrino masses, and it is therefore important to perform an analysis in an extended parameter space (that also includes variations in $N_{\rm eff}$ and $dn/d\ln k$) to check the model dependence of the neutrino constraints. Considering an extended parameter space with respect to the six-parameter ΛCDM model is also useful in view of the reported tensions present on the values of the Hubble constant (Verde et al. 2019; Di Valentino et al. 2021c, 2021d; Freedman 2021; Perivolaropoulos & Skara 2021; Shah et al. 2021) and the S_8 parameter (Di Valentino et al. 2021e; Perivolaropoulos & Skara 2021) between the CMB and local observables.

In what follows, we will therefore use two approaches. First, we present the constraints on neutrino masses under the assumption of a ΛCDM scenario, while as a second step, we also consider a more general framework, where many additional parameters are considered following the approach used in Di Valentino et al. (2015, 2016, 2017, 2020, 2021b).

This Letter is structured in the following way. In Section 2, we describe the data sets and the method used to extract the cosmological constraints; in Section 3, we present the results obtained for the different cases; and finally, in Section 4, we derive our conclusions.

2. Method and Data Sets

In this section, we describe the methodology used in our analysis and the cosmological data sets used to derive our results. Our data analysis method follows the same procedure already used in several previous papers for the CMB data. In practice, the constraints on the cosmological parameters are obtained adopting a Monte Carlo Markov Chain algorithm using the publicly available CosmoMC package (Lewis et al. 2000; Lewis & Bridle 2002), and the convergence of the chains is tested using the Gelman–Rubin criterion (Gelman & Rubin 1992).

Regarding the data sets considered, we instead have the following.

1. *Planck*: Planck 2018 temperature and polarization anisotropy angular power spectra *plikTTTEEE+lowl+lowE* from the legacy release (Aghanim et al. 2020a, 2020b; Akrami et al. 2020).
2. *ACT-DR4*: Atacama Cosmology Telescope DR4 likelihood (Aiola et al. 2020) considering the multipoles $\ell > 600$ in TT and 350 in TE and EE.
3. *SPT-3G*: South Pole Telescope polarization measurements SPT-3G (Dutcher et al. 2021) considering the multipoles $300 < \ell < 3000$ in TE and EE.
4. WMAP: WMAP 9 yr observation data (Hinshaw et al. 2013) considering the multipoles $20 < \ell < 1200$ in TT and $24 < \ell < 800$ in TE.
5. *Lensing*: Planck 2018 lensing reconstruction power spectrum obtained from the CMB trispectrum analysis (Aghanim et al. 2020c).
6. *taupriorr*: Gaussian prior on the optical depth $\tau = 0.065 \pm 0.015$ as used in Aiola et al. (2020).
7. *BAO*: baryon acoustic oscillation measurements from the 6dFGS (Beutler et al. 2011), SDSS MGS (Ross et al. 2015), and BOSS DR12 (Alam et al. 2017) surveys.
8. *Pantheon*: Pantheon sample (Scolnic et al. 2018) of Type Ia supernovae, consisting of 1048 data points distributed in the redshift interval $0.01 \leqslant z \leqslant 2.3$.
9. *R20*: Gaussian prior on the Hubble constant as measured by the SH0ES collaboration (Riess et al. 2021), i.e., $H_0 = 73.2 \pm 1.3$ km s^{-1} Mpc^{-1}.
10. *F21*: Gaussian prior on the Hubble constant as measured by Freedman in her review (Freedman 2021), i.e., $H_0 = 69.8 \pm 1.7$ km s^{-1} Mpc^{-1}.

Table 1
List of the Parameter Priors

Parameter	Prior
$\Omega_b h^2$	[0.005, 0.1]
$\Omega_c h^2$	[0.001, 0.99]
$100\,\theta_{\rm MC}$	[0.5, 10]
τ	[0.01, 0.8]
$\log(10^{10} A_S)$	[1.61, 3.91]
n_s	[0.8, 1.2]
Σm_ν [eV]	[0.06, 5]
w	[−3, 1]
$N_{\rm eff}$	[0.05, 10]
$dn/d\ln k$	[−1, 1]
$A_{\rm lens}$	[0, 10]

Our baseline parameter space consists of the six parameters of the ΛCDM model (baryon $\Omega_b h^2$ and cold dark matter $\Omega_c h^2$ energy densities, angular size of the horizon at the last scattering surface $\theta_{\rm MC}$, optical depth τ, amplitude and spectral index of primordial scalar perturbation A_s and n_s) plus a total neutrino mass Σm_ν free to vary (i.e., seven parameters in total), but we also consider a second 10-parameter scenario, where we include at the same time the effective neutrino number $N_{\rm eff}$, the dark energy equation of state w, and the running of the scalar spectral index $dn/d\ln k$. Only when the Planck data are included in the analysis do we also consider variations in the $A_{\rm lens}$ parameter in order to marginalize over the anomaly (or possible systematic error) present in the Planck data; i.e., we will have eight parameters varying in the baseline case and 11 parameters in the extended case. For all of the cosmological parameters varied in our analysis, we choose flat prior distributions as listed in Table 1.

3. Results

In this section, we describe the results we obtained with different data set combinations in the ΛCDM+Σm_ν case and the extended ΛCDM scenario with multiple parameters free to vary.

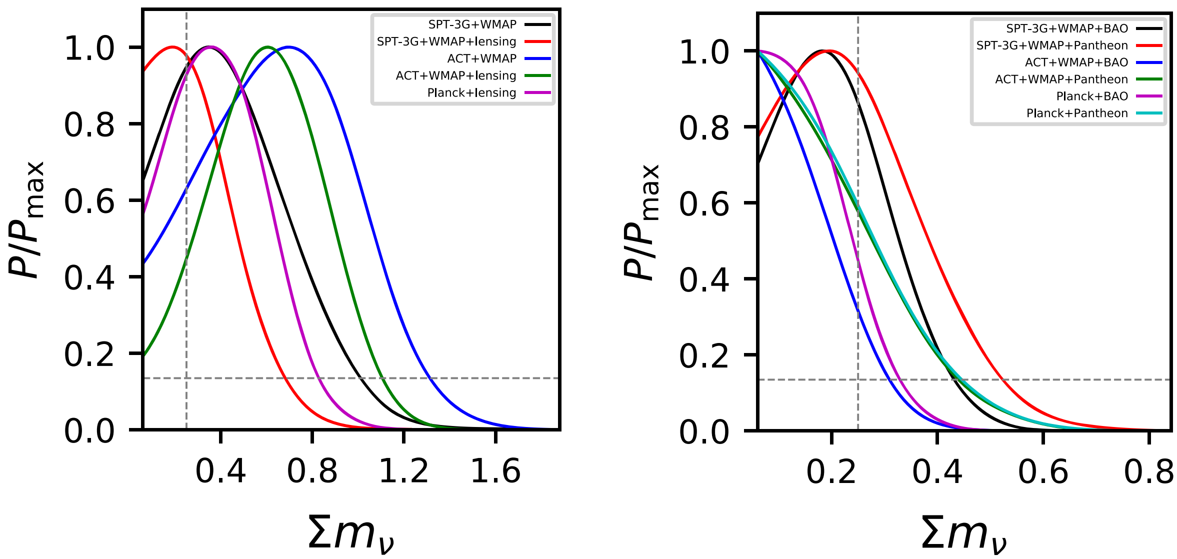

Figure 1. One-dimensional posterior distributions for Σm_ν for several combinations of data sets under the assumption of a ΛCDM model (Planck analysis includes variation in the $A_{\rm lens}$ parameter). A prior on the optical depth (tauprior) is present every time the ACT-DR4 and SPT-3G data are considered but neglected in the legend for brevity. The vertical dashed line identifies the value $\Sigma m_\nu = 0.26$ eV, while the horizontal line is for $P = 0.135$, i.e., where a Gaussian distribution is at two standard deviations from the maximum. None of the posteriors exclude a value of $\Sigma m_\nu = 0.26$ eV.

Table 2
Constraints on the Sum of Neutrino Masses Σm_ν at 68% C.L. from a Combination of Different Data Sets in the Case of the ΛCDM+Σm_ν Scenario

Data Set	Σm_ν (eV)
Planck (+$A_{\rm lens}$)	<0.51
Planck+BAO (+$A_{\rm lens}$)	<0.19
Planck+Pantheon (+$A_{\rm lens}$)	<0.25
Planck+lensing (+$A_{\rm lens}$)	$0.41^{+0.17}_{-0.25}$
ACT-DR4+WMAP	0.68 ± 0.31
ACT-DR4+WMAP+BAO	<0.19
ACT-DR4+WMAP+Pantheon	<0.25
ACT-DR4+WMAP+lensing	0.60 ± 0.25
SPT-3G+WMAP	$0.46^{+0.14}_{-0.36}$
SPT-3G+WMAP+BAO	$0.22^{+0.056}_{-0.14}$
SPT-3G+WMAP+Pantheon	$0.25^{+0.052}_{-0.19}$
SPT-3G+WMAP+lensing	<0.37

Note. A prior on the optical depth (tauprior) is included in all of the analysis involving the ACT and SPT data sets.

3.1. *ΛCDM+Σm$_\nu$ Case*

We report the constraints on the sum of neutrino masses Σm_ν obtained under the assumption of ΛCDM+Σm_ν in Table 2 and Figure 1. The constraints obtained with the use of the Planck data set also assume a variation in the $A_{\rm lens}$ parameter. As one can see, we found no combination of data sets that can exclude a value of $\Sigma m_\nu > 0.26$ eV at more than 95% C.L.

In particular, we have that both ACT-DR4 and SPT-3G data, in their combination with WMAP and the tauprior, in order to be "Planck-independent," mildly suggest a neutrino mass with $\Sigma m_\nu = 0.68 \pm 0.31$ and $0.46^{+0.14}_{-0.36}$ eV at 68% C.L., respectively. If we then include the lensing data set from the Planck experiment, the ACT-DR4+WMAP+tauprior+lensing data prefer a neutrino mass above two standard deviations, with $\Sigma m_\nu = 0.60 \pm 0.25$ eV at 68% C.L., while SPT-3G+WMAP + tauprior + lensing provides a weak upper limit of $\Sigma m_\nu < 0.37$ eV at 68% C.L. Interestingly, these results are completely consistent with the Planck+lensing constraint of $\Sigma m_\nu = 0.41^{+0.17}_{-0.25}$ eV at 68% C.L. when variations in the $A_{\rm lens}$ parameter are considered.

We can also notice that these indications are not in strong disagreement with the data after the inclusion of BAO or Pantheon measurements. As expected, the more stringent constraints are obtained when CMB and BAO data are

Table 3
Constraints on the Sum of Neutrino Masses Σm_ν at 68% C.L. from a Combination of Different Data Sets in the Case of the ΛCDM+Σm_ν+w+$N_{\rm eff}$+$dn/d\ln k$ Scenario

Data Set	Σm_ν (eV)
Planck (+$A_{\rm lens}$)	<0.50
Planck+BAO (+$A_{\rm lens}$)	<0.22
Planck+Pantheon (+$A_{\rm lens}$)	<0.47
Planck+lensing (+$A_{\rm lens}$)	$0.38^{+0.12}_{-0.28}$
ACT-DR4+WMAP	0.81 ± 0.28
ACT-DR4+WMAP+BAO	<0.27
ACT-DR4+WMAP+Pantheon	0.71 ± 0.28
ACT-DR4+WMAP+lensing	0.56 ± 0.21
ACT-DR4+WMAP+R20	0.83 ± 0.230
ACT-DR4+WMAP+F21	$0.85^{+0.27}_{-0.33}$
ACT-DR4+WMAP+BAO+R20	$0.39^{+0.13}_{-0.25}$
ACT-DR4+WMAP+BAO+F21	<0.34
SPT-3G+WMAP	<0.56
SPT-3G+WMAP+BAO	<0.28
SPT-3G+WMAP+Pantheon	$0.46^{+0.11}_{-0.39}$
SPT-3G+WMAP+lensing	<0.39
SPT-3G+WMAP+R20	$0.49^{+0.12}_{-0.42}$
SPT-3G+WMAP+F21	<0.60
SPT-3G+WMAP+BAO+R20	$0.37^{+0.13}_{-0.25}$
SPT-3G+WMAP+BAO+F21	<0.32

Note. A prior on the optical depth (tauprior) is included in all of the analysis involving the ACT and SPT data sets.

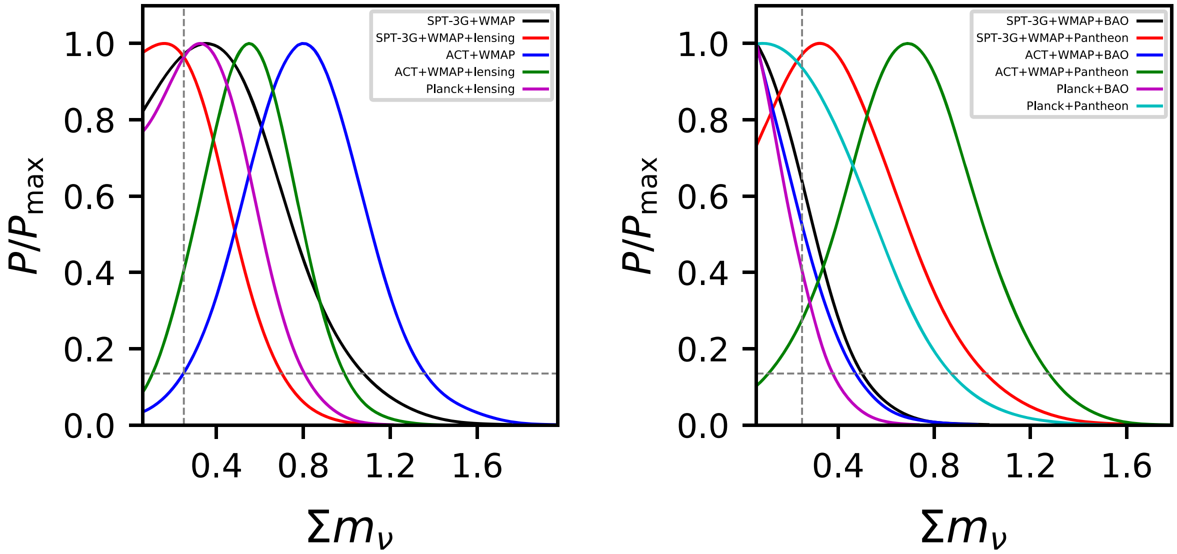

Figure 2. One-dimensional posterior distributions for Σm_ν for several combinations of data sets under the assumption of an extended ΛCDM model (Planck analysis includes variation in the A_{lens} parameter). A prior on the optical depth (tauprior) is present every time the ACT-DR4 and SPT-3G data are considered but neglected in the legend for brevity. The vertical dashed line identifies the value $\Sigma m_\nu = 0.26$ eV, while the horizontal line is for $P = 0.135$, i.e., where a Gaussian distribution is at two standard deviations from the maximum. None of the posteriors exclude a value of $\Sigma m_\nu = 0.26$ eV.

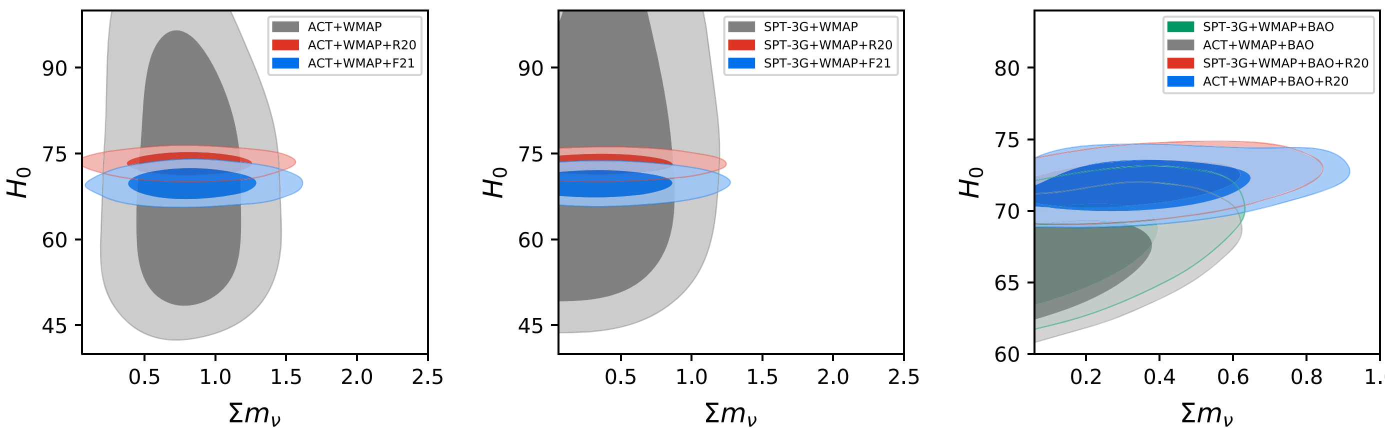

Figure 3. Two-dimensional contour plots for Σm_ν vs. H_0 for the ACT-DR4 (left panel) and SPT-3G (middle panel) combinations with WMAP and the Gaussian priors on the Hubble constant R20 and F21 (a prior on the optical depth (tauprior) is present everywhere but neglected in the legend for brevity), and with the addition of BAO (right panel), under the assumption of an extended ΛCDM model.

combined together. However, while Planck+BAO and ACT-DR4+WMAP+tauprior+BAO exclude $\Sigma m_\nu > 0.26$ eV just by $\sim 1.3\sigma$, the combination of SPT-3G+WMAP+tauprior+BAO shows a mild preference for $\Sigma m_\nu \sim 0.22$ eV at about one standard deviation. Interestingly, all of the other data combinations, including those with Pantheon, show a value of $\Sigma m_\nu = 0.26$ eV well inside one standard deviation or even prefer a neutrino mass above this limit. While there is no clear indication for a neutrino mass, we can also conclude that there is no data combination that could strongly disfavor a neutrino mass such that $\Sigma m_\nu = 0.26$ eV.

3.2. Extended ΛCDM

Given the current tensions between the cosmological data sets, we also perform an analysis in an extended ΛCDM scenario. Besides the usual six parameters of the ΛCDM model, we also consider variations in the effective neutrino number N_{eff}, the dark energy equation of state w, and the running of the scalar spectral index $dn/d\ln k$. The results are reported in Table 3, and the posterior distributions shown in Figure 2. The first thing we can notice is that the constraints on the neutrino mass are only slightly affected in this extended scenario with respect to the ΛCDM+Σm_ν case.

In particular, ACT-DR4+WMAP+tauprior now suggests a neutrino mass with $\Sigma m_\nu = 0.81 \pm 0.28$ eV at 68% C.L. shifted toward higher values but with comparable error bars with respect to the ΛCDM+Σm_ν case. On the contrary, SPT-3G +WMAP+tauprior now has only an upper limit $\Sigma m_\nu < 0.56$ eV at 68% C.L. The inclusion of the lensing data set instead gives for ACT-DR4+WMAP+tauprior+lensing a total neutrino mass bound of $\Sigma m_\nu = 0.56 \pm 0.21$ eV at 68% C.L. and for SPT-3G+WMAP+tauprior+lensing a weak upper limit of $\Sigma m_\nu < 0.39$ eV at 68% C.L., i.e., very similar to the bounds obtained in Table 2. Also in this extended scenario, these results are in agreement with Planck+lensing that finds $\Sigma m_\nu = 0.38^{+0.12}_{-0.28}$ eV at 68% C.L., where A_{lens} is free to vary.

In this scenario, when the CMB and BAO data are combined together, the value of $\Sigma m_\nu = 0.26$ eV is well inside one standard deviation.

Another interesting point is that ACT-DR4+WMAP+tauprior and SPT-3G+WMAP+tauprior both give the Hubble constant almost unconstrained in this extended scenario. For this reason, it is possible here to safely use a Gaussian prior on this parameter and evaluate the effect on the neutrino masses. We can notice that the inclusion of the R20 or F21 priors does not affect the total neutrino mass constraints because H_0 and Σm_ν do not show any correlation (see Figure 3). Moreover, in this case, it has also alleviated the long-standing S_8 tension (Di Valentino et al. 2021e) with the weak lensing measurements, and we find that ACT-DR4+WMAP+tauprior+R20 gives $S_8 = 0.726 \pm 0.037$ at 68% C.L., while SPT-3G+WMAP+tauprior+R20 gives $S_8 = 0.732 \pm 0.037$ at 68% C.L.

Interestingly, as we can see from the last plot on the right of Figure 3, when CMB and BAO constraints are considered in these extended cosmologies, they provide constraints on the Σm_ν versus H_0 plane that clearly show a correlation between these two parameters (higher neutrino masses are in better agreement with higher values of the Hubble constant). This degeneracy is exactly the opposite of what is obtained under standard ΛCDM, where higher neutrino masses prefer lower values of the Hubble constant. Therefore, in extended cosmologies that could solve the Hubble tension (Di Valentino et al. 2016, 2020, 2021b), a neutrino mass is preferred by the cosmological data, as we can also see from the ACT-DR4+WMAP+tauprior+BAO+R20 and SPT-3G+WMAP+tauprior+BAO+R20 constraints, which are $\Sigma m_\nu = 0.39^{+0.13}_{-0.25}$ and $0.37^{+0.13}_{-0.25}$ eV at 68% C.L. from Table 3, respectively.

4. Conclusions

In this Letter, we constrained the total neutrino mass, making use of recent CMB experiments such as ACT-DR4 and SPT-3G combined with WMAP and a prior on the optical depth. In this way, we obtained a neutrino mass estimate that is independent of the Planck data that appears as affected by the lensing anomaly $A_{\rm lens}$, possibly originating from an undetected systematic error. We found that both the ACT and SPT experiments are well compatible (and, in some cases, also mildly suggesting) a value for the total neutrino mass larger than the standard value, usually assumed in the literature to be equal to 0.06 eV. Interestingly, when the lensing data set from Planck is included in the data analysis, ACT-DR4 hints at a neutrino mass above the two standard deviations, with $\Sigma m_\nu = 0.60^{+0.44}_{-0.50}$ eV at 95% C.L., that is perfectly consistent with the Planck CMB+lensing constraint of $\Sigma m_\nu = 0.41^{+0.17}_{-0.25}$ eV at 68% C.L. when one marginalizes over the $A_{\rm lens}$ parameter. This indication of massive neutrinos is still present after the inclusion of BAO or Type Ia supernova data in extended cosmologies, involving additional parameters like the effective neutrino number $N_{\rm eff}$, the dark energy equation of state w, and the running of the scalar spectral index $dn/d\ln k$. In this respect, we have noted that in these extended scenarios, CMB+BAO constraints prefer a higher neutrino mass for higher values of the Hubble constant. A combination of ACT-DR4, WMAP, BAO, and constraints on the Hubble constant from the SH0ES collaboration (Riess et al. 2021) gives $\Sigma m_\nu = 0.39^{+0.13}_{-0.25}$ eV at 68% C.L. in extended cosmologies.

We conclude that a total neutrino mass above the 0.26 eV limit still provides an excellent fit to several cosmological data, and that, in light of the current cosmological tensions, future cosmological data must be considered before safely ruling it out.

Note. During the writing of this Letter, we noticed that the recent analysis of Sgier et al. (2021) that combines Planck 2018 data, spectroscopic galaxy samples from BOSS DR12, and the latest Kilo-Degree Survey tomographic weak lensing shear data also suggests a neutrino mass around $\Sigma m_\nu \sim 0.5$ eV at more than two standard deviations.

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