Dark Radiation after Planck

Najla Said,1 Eleonora Di Valentino,1 and Martina Gerbino1

1Physics Department and INFN, Università di Roma “La Sapienza”, P.le Aldo Moro 2, 00185, Rome, Italy

We present new constraints on the relativistic neutrino effective number $N_{\text{eff}}$ and on the Cosmic Microwave Background power spectrum lensing amplitude $A_L$ from the recent Planck 2013 data release. Including observations of the CMB large angular scale polarization from the WMAP satellite, we obtain the bounds $N_{\text{eff}} = 3.71 \pm 0.40$ and $A_L = 1.25 \pm 0.13$ at 68% c.l.. The Planck dataset alone is therefore suggesting the presence of a dark radiation component at 91.1% c.l. and hinting for a higher power spectrum lensing amplitude at 94.3% c.l.. We discuss the agreement of these results with the previous constraints obtained from the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT). Considering the constraints on the cosmological parameters, we found a very good agreement with the previous WMAP+ACT analysis but a tension with the WMAP+ACT results, with the only exception of the lensing amplitude.

PACS numbers: 98.80.Es, 98.80.Jk, 95.30.Sf

I. INTRODUCTION

The recent precise measurements of the Cosmic Microwave Background (CMB hereafter) temperature anisotropies released by the Planck collaboration [1] are providing the tightest constraints on cosmological parameters to date [2].

In this paper, we use this new dataset to constrain two parameters that affect the CMB “damping tail” regime, at small angular scales, namely the neutrino effective number $N_{\text{eff}}$ and the lensing amplitude $A_L$, that, from previous experiments, have been reported as not consistent with the standard expectations [3].

We remind here that $N_{\text{eff}}$ effectively measures the number of relativistic degrees of freedom at recombination and is related to the energy density in relativistic “dark” particles $\rho_\gamma$ by:

$$\rho_\gamma = \frac{7}{8} \left( \frac{4}{11} \right)^{\frac{4}{3}} N_{\text{eff}} \rho_\gamma,$$  \hspace{1cm} (1)

where $\rho_\gamma$ is the CMB photon energy density, with value today $\rho_{\gamma,0} \approx 4.8 \times 10^{-34}$ g cm$^{-3}$.

In the standard scenario, assuming three relativistic neutrino families, the expected value is $N_{\text{eff}} = 3.046$. Observation of a different value could point to new physics, related to the neutrino sector, such as non standard neutrino decoupling, sterile neutrinos, etc., or to even more exotic physics, such as axions, extra dimensions, early dark energy (see e.g. [3] and [4] and references therein).

On the other hand, the $A_L$ parameter is a phenomenological parameter introduced in [6], that simply rescales the lensing potential:

$$C^{\phi\phi}_\ell \rightarrow A_L C^{\phi\phi}_\ell$$  \hspace{1cm} (2)

where $C^{\phi\phi}_\ell$ is the power spectrum of the lensing field. The expected value for this parameter in the standard framework is $A_L = 1$. A value different from one could indicate either the presence of a systematic, or the presence of new physics (see e.g. [3] and [7]).

The previous CMB measurements obtained by the Atacama Cosmology Telescope (ACT, [8]) and the South Pole Telescope (SPT, [9]), when combined with the latest observations from the WMAP satellite (WMAP9, [10]), have indeed provided different values for these two parameters, that are in tension at the level of two standard deviations. As showed in [3], the ACT dataset gives $N_{\text{eff}} = 2.85 \pm 0.56$ and $A_L = 1.64 \pm 0.36$ at 68% c.l., while the SPT dataset gives $N_{\text{eff}} = 3.72 \pm 0.46$ and $A_L = 0.85 \pm 0.13$ at 68% c.l..

Given this tension, it is certainly timely to investigate the constraints that can be obtained for $N_{\text{eff}}$ and $A_L$ from the new data from the Planck satellite.

The Planck collaboration has already presented results in [2] on $N_{\text{eff}}$ and $A_L$ separately. Here we extend this analysis by varying $N_{\text{eff}}$ and $A_L$ simultaneously, i.e. taking into account the possible correlations between these two parameters as in [3], and by properly comparing the results with the previous ACT and SPT measurements in the $N_{\text{eff}}$-$A_L$ plane.

Our paper is simply organized as follows: in the next section we describe the analysis method, in Section III we present our results also considering Baryon Acoustic Oscillation (BAO) surveys and $H_0$ measurements, while in Section IV we derive our conclusions.

II. DATA ANALYSIS METHOD

Our main CMB dataset consists in the Planck public data release of March 2013 [1]. We compare this dataset with the theoretical models using the CAMspec likelihood version 6.2 for high multipoles and the commander version 4.1 likelihood for low multipoles [11]. We also consider the WMAP low-$\ell$ likelihood for polarization [10]. This dataset is identical to the “PLANCK+WP” case presented in the Planck papers [2,11].

For BAO surveys we include the following datasets: SDSS-DR7 [12] at redshift $z = 0.35$, SDSS-DR9 [13] at
TABLE I. Constraints at 68% confidence level on cosmological parameters from our analysis using Planck+WP, WMAP9+SPT and WMAP9+ACT.

| Parameter | Planck+WP | WMAP9+SPT | WMAP9+ACT |
|-----------|-----------|-----------|-----------|
| $\Omega_b h^2$ | 0.02306 ± 0.00051 | 0.02264 ± 0.00051 | 0.02283 ± 0.00052 |
| $\Omega_c h^2$ | 0.1239 ± 0.0054 | 0.1232 ± 0.0080 | 0.110 ± 0.010 |
| $\theta$ | 1.04124 ± 0.00077 | 1.0415 ± 0.0012 | 1.0412 ± 0.0025 |
| $\tau$ | 0.095 ± 0.015 | 0.088 ± 0.014 | 0.090 ± 0.014 |
| $n_s$ | 0.996 ± 0.018 | 0.982 ± 0.018 | 0.969 ± 0.019 |
| $\log[10^{10} A_s]$ | 3.111 ± 0.034 | 3.169 ± 0.048 | 3.174 ± 0.045 |
| $N_{\text{eff}}$ | 3.71 ± 0.40 | 3.72 ± 0.46 | 2.85 ± 0.56 |
| $A_L$ | 1.25 ± 0.13 | 0.85 ± 0.13 | 1.64 ± 0.36 |
| $\Omega_A$ | 0.736 ± 0.022 | 0.736 ± 0.023 | 0.728 ± 0.025 |
| $t_0$ [Gyr] | 13.08 ± 0.38 | 13.14 ± 0.43 | 13.90 ± 0.55 |
| $\Omega_m$ | 0.264 ± 0.022 | 0.264 ± 0.023 | 0.272 ± 0.025 |
| $H_0$ [km/s/Mpc] | 74.9 ± 3.7 | 74.6 ± 3.7 | 69.9 ± 3.7 |

Finally, we include the recent measurements for the Hubble constant $H_0$ from the analysis of [14] and we refer to this dataset as HST.

For the analysis method we use the publicly available Monte Carlo Markov Chain package cosmomc [10] which relies on a convergence diagnostic based on the Gelman and Rubin statistic. We use the latest version (March 2013) which includes the support for the Planck Likelihood Code v1.0 (see [http://cosmologist.info/cosmomc/](http://cosmologist.info/cosmomc/)). The plots shown in this work are obtained via the python codes included in the cosmomc package.

We run over the six-dimensional space of standard cosmological parameters: the baryon and cold dark matter densities $\Omega_b$ and $\Omega_c$, the ratio of the sound horizon to the angular diameter distance at decoupling $\theta$, the reionization optical depth $\tau$, the scalar spectral index $n_s$, and the overall normalization of the spectrum $A_S$ at $k = 0.05$ Mpc$^{-1}$. We consider purely adiabatic initial conditions and we impose spatial flatness. In addition to these parameters we let the number of neutrinos species (assumed massless) $N_{\text{eff}}$ and the lensing amplitude parameter $A_L$ to vary, assuming the following flat priors: $1.047 \leq N_{\text{eff}} \leq 10$ and $0.0 \leq A_L \leq 4.0$.

In our runs, we also marginalise over the foreground parameters as in [2, 11]. Since the correlations between the cosmological and foreground parameters is minimal, we do not report their values in this paper. The posteriors on foregrounds are in excellent agreement with those reported in [2].

FIG. 1. Comparison of the results for Planck+WP, WMAP9+SPT and WMAP9+ACT datasets in terms of the 1-D posterior distribution functions for the parameters $N_{\text{eff}}$ (left) and $A_L$ (right).
between these two parameters and that fixing analysis clearly shows that there is a small correlation between the WMAP9+SPT result on $A_L$. However, this constraint is obtained with the constraint of $N_{\text{eff}}$. As shown in Table I, as we can see, the Planck+WP result previously obtained in [3] for the ACT and SPT datasets, vice versa, the WMAP9+ACT constraint is slightly bias the constraints on $N_{\text{eff}}$ as well, giving $N_{\text{eff}} = 3.56 \pm 0.27$, which also remains at almost 2$\sigma$ away from the standard value.

IV. CONCLUSIONS

In this brief paper we have reported new joint constraints on the neutrino effective number $N_{\text{eff}}$ and the CMB lensing amplitude $A_L$ from the new Planck dataset.
We have shown that the Planck+WP dataset is hinting for both a presence of dark radiation (at the level of 91.1%) and for an anomalous amplitude for the lensing parameter (at the level of 94.3%). The Planck+WP constraints on $N_{\text{eff}}$ and other parameters, such as the Hubble constant and the matter density, are in very good agreement with those obtained from the WMAP9+SPT dataset. It is clearly worth to note that two very different datasets provide an indication for a larger value of the effective neutrino number. In general, we found a tension on the derived parameters between the Planck+WP and the WMAP9+ACT datasets. This clearly indicates that the inclusion of the ACT dataset in a combined Planck+ACT has to be carefully considered.

The anomalous lensing amplitude from Planck+WP is more consistent with the results obtained from the WMAP9+ACT dataset, which also provide a $\sim 2\sigma$ indication for a larger value. However, since the same signal is not found in the trispectrum analysis [18], the nature of this anomalous lensing amplitude needs further investigation. Moreover, our analysis clearly demonstrates a correlation between $A_L$ and the main cosmological parameters.

The hints for new physics from the Planck+WP dataset are confirmed when the HST measurements are included and are weakened when the BAO dataset is considered. The CMB+HST+BAO analysis also suggests the presence of anomalous values but at smaller statistical significance.

It will be probably duty of the next Planck data re-

| Parameter                  | CMB+HST          | CMB+BAO          | CMB+BAO+HST       |
|----------------------------|------------------|------------------|-------------------|
| $\Omega_b h^2$            | 0.022953 ± 0.00035 | 0.02246 ± 0.00031 | 0.02262 ± 0.00028 |
| $\Omega_c h^2$            | 0.1234 ± 0.0050  | 0.1232 ± 0.0053  | 0.1260 ± 0.0049   |
| $\theta$                  | 1.04123 ± 0.00077 | 1.04112 ± 0.00078 | 1.04085 ± 0.00075 |
| $\tau$                    | 0.094 ± 0.014    | 0.087 ± 0.013    | 0.089 ± 0.013     |
| $n_s$                      | 0.992 ± 0.011    | 0.974 ± 0.011    | 0.9815 ± 0.0088   |
| $\log[10^{10} A_s]$       | 3.108 ± 0.030    | 3.093 ± 0.030    | 3.103 ± 0.029     |
| $N_{\text{eff}}$          | 3.63 ± 0.27      | 3.35 ± 0.31      | 3.56 ± 0.27       |
| $A_L$                      | 1.24 ± 0.12      | 1.16 ± 0.10      | 1.17 ± 0.10       |
| $\Omega_{\Lambda}$        | 0.733 ± 0.014    | 0.706 ± 0.011    | 0.7119 ± 0.0094   |
| $t_0$ [Gyr]               | 13.15 ± 0.23     | 13.47 ± 0.28     | 13.27 ± 0.23      |
| $\Omega_m$                | 0.267 ± 0.014    | 0.294 ± 0.011    | 0.2881 ± 0.0094   |
| $H_0$ [km/s/Mpc]          | 74.0 ± 2.0       | 70.4 ± 1.9       | 71.8 ± 1.6        |

TABLE II. Constraints at 68% confidence level on cosmological parameters from our analysis using CMB+HST, CMB+BAO and CMB+BAO+HST.

FIG. 3. Comparison of the 1-D posterior distribution functions from the CMB-only (Planck+WP), CMB+HST, CMB+BAO and CMB+BAO+HST datasets for $N_{\text{eff}}$ (left) and $A_L$ (right).
FIG. 4. Comparison of the 2-D posterior distribution functions from the CMB-only, CMB+HST, CMB+BAO and CMB+BAO+HST datasets in the $N_{\text{eff}} - A_L$ parameters plane.

lease, with the full mission and polarization data, to provide more precise, CMB only, constraints on the neutrino number and the lensing amplitude and to confirm or falsify these current hints for new physics from Planck.

Acknowledgements

It is a pleasure to thank Andrea Marchini and Valentina Salvatelli for helpful discussions.

[1] P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5062 [astro-ph.CO].
[2] P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO].
[3] E. Di Valentino, S. Galli, M. Lattanzi, A. Melchiorri, P. Natoli, L. Pagano and N. Said, arXiv:1301.7343 [astro-ph.CO].
[4] E. Di Valentino, A. Melchiorri and O. Men, arXiv:1304.5981 [astro-ph.CO].
[5] M. Archidiacono, E. Calabrese and A. Melchiorri, Phys. Rev. D 84 (2011) 123008 arXiv:1109.2767 [astro-ph.CO].
[6] E. Calabrese, A. Slosar, A. Melchiorri, G. F. Smoot and O. Zahn, Phys. Rev. D 77, 123531 (2008) arXiv:0803.2309 [astro-ph].
[7] A. Marchini, A. Melchiorri, V. Salvatelli and L. Pagano, arXiv:1302.2593 [astro-ph.CO].
[8] J. L. Sievers, R. A. Hlozek, M. R. Nolta, V. Acquaviva, G. E. Addison, P. A. R. Ade, P. Aguirre and M. Amiri et al., arXiv:1301.0824 [astro-ph.CO].
[9] Z. Hou, C. L. Reichardt, K. T. Story, B. Follin, R. Keisler, K. A. Aird, B. A. Benson and L. E. Bleem et al., arXiv:1212.6297 [astro-ph.CO].
[10] C. L. Bennett, D. Larson, J. L. Weiland, N. Jarosik, G. Hinshaw, N. Odegard, K. M. Smith and R. S. Hill et al., arXiv:1212.5225 [astro-ph.CO].
[11] P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5075 [astro-ph.CO].
[12] N. Padmanabhan, X. Xu, D. J. Eisenstein, R. Scalzo, A. J. Cuesta, K. T. Mehta and E. Kazin, arXiv:1202.0090 [astro-ph.CO].
[13] L. Anderson, E. Aubourg, S. Bailey, D. Bizyaev, M. Blanton, A. S. Bolton, J. Brinkmann and J. R. Brownstein et al., Mon. Not. Roy. Astron. Soc. 428, 1036 (2013) arXiv:1203.6594 [astro-ph.CO].
[14] C. Blake, T. Davis, G. Poole, D. Parkinson, S. Brough, M. Colless, C. Contreras and W. Couch et al., Mon. Not. Roy. Astron. Soc. 415, 2892 (2011) arXiv:1105.2862 [astro-ph.CO].
[15] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, A. V. Filippenko, S. W. Jha and W. Li et al., Astrophys. J. 730, 119 (2011) [Erratum-ibid. 732, 129 (2011)] arXiv:1103.2976 [astro-ph.CO].
[16] A. Lewis and S. Bridle, Phys. Rev. D 66, 103511 (2002) astro-ph/0205436.
[17] Talk given by John Carlstrom at the 47 ESLAB Planck conference. [http://www.rssd.esa.int/SA/PLANCK/docs/eslab47/Session13_Wrap-up_and_Conclusions/47ESLAB_April_05_2013_15_10_Carlstrom.pdf](http://www.rssd.esa.int/SA/PLANCK/docs/eslab47/Session13_Wrap-up_and_Conclusions/47ESLAB_April_05_2013_15_10_Carlstrom.pdf)
[18] P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5077 [astro-ph.CO].