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We present cosmological constraints from the combination of the full mission nine-year WMAP release and small-scale temperature data from the pre-Planck Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT) generation of instruments. This is an update of the analysis presented in Calabrese et al. [Phys. Rev. D 87, 103012 (2013)], and highlights the impact on $\Lambda$CDM cosmology of a 0.06 eV massive neutrino—which was assumed in the Planck analysis but not in the ACT/SPT analyses—and a Planck-cleaned measurement of the optical depth to reionization. We show that cosmological constraints are now strong enough that small differences in assumptions about reionization and neutrino mass give systematic differences which are clearly detectable in the data. We recommend that these updated results be used when comparing cosmological constraints from WMAP, ACT and SPT with other surveys or with current and future full-mission Planck cosmology. Cosmological parameter chains are publicly available on the NASA’s LAMBDA data archive.

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I. INTRODUCTION

In Calabrese et al. [1] (hereafter C13) we presented cosmological results from the combination of cosmic microwave background (CMB) experiments preceding the first data release of the Planck satellite [2]. We used data from the WMAP satellite after the completion of the mission including nine years of large-scale CMB temperature and polarization observations [3,4], complemented by the final release of small-scale CMB temperature observations from the first generation of instruments of the Atacama Cosmology Telescope (ACT) [5–7] and the South Pole Telescope (SPT) [8,9].

The results in C13 are sometimes used in comparison with the cosmological constraints obtained by the Planck satellite, with low-redshift cosmology from galaxy surveys, and with local measurements of the expansion rate of the universe.
TABLE I. Standard ΛCDM parameters with 68% confidence level from the combination of WMAP9, ACT and SPT, and including a τ prior folding in recent Planck HFI measurements [21]. The last two columns report a direct comparison with constraints from Planck 2015 data derived with the same τ prior.

| Parameter | WMAP9 + ACT | WMAP9 + SPT | WMAP9 + ACT + SPT | (2017)–(2013) (in units of σ) | PlanckTT | PlanckTTTEEE |
|-----------|-------------|-------------|------------------|-----------------------------|-----------|--------------|
| 100ΩCh²   | 2.243 ± 0.040 | 2.223 ± 0.033 | 2.242 ± 0.032 | −0.25 | 2.217 ± 0.021 | 2.222 ± 0.015 |
| 100Ωm²h²  | 11.56 ± 0.43   | 11.26 ± 0.36 | 11.34 ± 0.36 | +0.41 | 12.05 ± 0.21 | 12.03 ± 0.14 |
| 10⁴θ     | 103.95 ± 0.19 | 104.23 ± 0.10 | 104.24 ± 0.10 | −0.21 | 104.078 ± 0.047 | 104.069 ± 0.032 |
| τ      | 0.060 ± 0.009   | 0.057 ± 0.009 | 0.058 ± 0.009 | −2.1 | 0.064 ± 0.010 | 0.065 ± 0.009 |
| n_s     | 0.966 ± 0.010 | 0.9610 ± 0.0089 | 0.9638 ± 0.0087 | −0.37 | 0.9625 ± 0.0056 | 0.9626 ± 0.0044 |
| ln (10¹⁰A_s) | 3.037 ± 0.023 | 3.018 ± 0.021 | 3.025 ± 0.021 | −1.9 | 3.064 ± 0.020 | 3.067 ± 0.019 |
| ΩΛ a  | 0.703 ± 0.025 | 0.726 ± 0.019 | 0.723 ± 0.019 | −0.71 | 0.680 ± 0.013 | 0.6812 ± 0.0086 |
| Ωm     | 0.296 ± 0.025 | 0.273 ± 0.019 | 0.277 ± 0.019 | +0.71 | 0.320 ± 0.013 | 0.3188 ± 0.0086 |
| σ₈    | 0.792 ± 0.020 | 0.774 ± 0.018 | 0.780 ± 0.017 | −1.5 | 0.820 ± 0.010 | 0.8212 ± 0.0086 |
| τ₀   | 13.813 ± 0.093 | 13.729 ± 0.063 | 13.715 ± 0.062 | +0.81 | 13.823 ± 0.035 | 13.822 ± 0.025 |
| H₀     | 68.5 ± 2.0 | 70.5 ± 1.6 | 70.3 ± 1.6 | −0.74 | 67.00 ± 0.90 | 67.03 ± 0.61 |

a-Derived parameters: Dark energy density, total matter density, the amplitude of matter fluctuations on 8 h⁻¹ Mpc scales, the age of the Universe in Gyr, and the Hubble constant in units of km/s/Mpc.

The Universe (see e.g. [10–16]). In this brief paper we want to highlight that cosmological constraints are now strong enough that small differences in assumptions about reionization and neutrino mass give systematic differences which are clearly detectable in the data. We show that to have a direct comparison to Planck cosmology [17,18] or to galaxy constraints on the matter density and amplitude of matter fluctuations, two main things need to be updated in the C13 analysis:

1. Starting in 2013, following the Planck analyses [17], estimates of cosmological parameters assume as baseline in a ΛCDM model a nonzero neutrino mass of 0.06 eV; this was not the case in C13 where neutrinos were treated as relativistic particles.

2. A reanalysis of the large-scale WMAP polarization by the Planck team, using the new Planck 353 GHz channel as thermal dust tracer, highlighted residual foreground contamination in the WMAP data leading to a 1σ bias in the estimate of the optical depth to reionization parameter, τ (see discussion in Refs. [18–20]). A new and tighter measurement of τ has now been derived with Planck HFI data [21] and should replace the WMAP one used in C13.

Although this Planck result came after the WMAP/ACT/ SPT measurements, it informs the comparison and so its effects are included here. We note that τ is the most uncertain of the cosmological parameters and the most likely to evolve with future measurements.

In light of this, we present here a revised cosmology from WMAP9 + ACT + SPT and recommend that these updated constraints be used for comparisons with other surveys. The cosmological parameter chains are available on NASA’s LAMBDA data archive at http://lambda.gsfc.nasa.gov/product/act/act_prod_table.cfm. The likelihood code for ACT and SPT is the same used in C13 and is available on LAMBDA (http://lambda.gsfc.nasa.gov/product/act) and on the ACT website (http://www.physics.princeton.edu/act/).

II. ANALYSIS AND RESULTS

As in C13 (to which we refer for details) we make use of the foreground-marginalized ACT + SPT CMB likelihood and combine it with the WMAP public likelihood code. We however do not retain WMAP large-scale polarization and set the flag “use_WMAP_lowl_pol=F” in the WMAP likelihood options module. We call the likelihoods within the publicly available COSMOMC software [22] to estimate the basic six ΛCDM cosmological parameters: the baryon and cold dark matter densities, Ω_bh² and Ω_mh², the angular scale of the acoustic horizon at decoupling, θ, the reionization optical depth, τ, and the amplitude and the scalar spectral index of primordial adiabatic density perturbations, A_s and n_s, both defined at a pivot scale k₀ = 0.05 Mpc⁻¹.

We assume a single family of massive neutrinos carrying a total mass of Σm_ν = 0.06 eV, and fold in the new Planck τ measurement by imposing a Gaussian prior of τ = 0.06 ± 0.01. We note that in C13 τ was measured to be 0.085 ± 0.013 using WMAP polarization at ℓ < 23.

A. ΛCDM

The updated constraints on the ΛCDM basic parameters are reported in Table I and shown in Fig. 1. A direct

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1We use a prior because the measurement presented in Ref. [21] has not been yet accompanied by a likelihood software. This is a conservative choice slightly larger than the Planck result of τ = 0.055 ± 0.009 but leading to the same conclusions.
The largest difference is a 1.9σ shift of the amplitude parameter which is degenerate with both τ and the neutrino mass. This shift in \( A_s \) will affect most of the derived parameters and in particular the matter density and the amplitude of matter fluctuations. The Hubble constant also moves a non-negligible amount and is 1.7σ lower than local measurements [14].

Table I also reports the constraints from Planck data derived with the same τ prior replacing the Planck low-\( \ell \) polarization.

The comparison between C13 and this revised analysis is reported in the fifth column of Table I in terms of shift in cosmological parameters in units of the standard error on that parameter marginalized over the other parameters (basic ΛCDM posteriors are also compared in Fig. 1). The largest difference is a 1.9σ shift of the amplitude parameter which is degenerate with both τ and the neutrino mass. This shift in \( A_s \) will affect most of the derived parameters and in particular the matter density and the amplitude of matter fluctuations. The Hubble constant also moves a non-negligible amount and is 1.7σ lower than local measurements [14].

Table I also reports the constraints from Planck data derived with the same τ prior replacing the Planck low-\( \ell \) polarization.
reionization from the Planck satellite. Unlike in C13, we include as baseline in our cosmological model a single family of massive neutrinos with a total mass of 0.06 eV and impose a prior $\tau = 0.06 \pm 0.01$, replacing the WMAP large-scale polarization information. We show that all basic cosmological parameters shift because of this and highlight the importance of using these revised constraints when comparing different CMB results or when assessing agreement with low-redshift probes.

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