Cosmological parameters from pre-Planck CMB measurements: A 2017 update

Erminia Calabrese,[1] Renée A. Hložek,[2] J. Richard Bond,[3] Mark J. Devlin,[4] Joanna Dunkley,[5,6] Mark Halpern,[7] Adam D. Hincks,[8] Kent D. Irwin,[9] Arthur Kosowsky,[10] Kavilan Moodley,[11] Laura B. Newburgh,[12] Michael D. Niemack,[13] Lyman A. Page,[5] Blake D. Sherwin,[14] Jonathan L. Sievers,[15,16] David N. Spergel,[6,17] Suzanne T. Staggs,[5] and Edward J. Wollack[18]

[1]*Sub-department of Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*
[2]*Dunlap Institute and Department of Astronomy and Astrophysics, University of Toronto, 50 St George Street, Toronto, Ontario M5S 3H4, Canada*
[3]*CITA, University of Toronto, Toronto, Ontario M5S 3H8, Canada*
[4]*Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, Pennsylvania 19104, USA*
[5]*Joseph Henry Laboratories of Physics, Jadwin Hall, Princeton University, Princeton, New Jersey 08544, USA*
[6]*Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, New Jersey 08544, USA*
[7]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada*
[8]*Department of Physics, University of Rome "La Sapienza," Piazzale Aldo Moro 5, I-00185 Rome, Italy*
[9]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[10]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[11]*Astrophysics and Cosmology Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Durban 4041, South Africa*
[12]*Department of Physics, Yale University, New Haven, Connecticut 06520, USA*
[13]*Department of Physics, Cornell University, Ithaca, New York 14853, USA*
[14]*Berkeley Center for Cosmological Physics, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[15]*Astrophysics and Cosmology Research Unit, School of Chemistry and Physics, University of KwaZulu-Natal, Durban 4041, South Africa*
[16]*National Institute for Theoretical Physics (NITheP), KZN node, Durban 4001, South Africa*
[17]*Center for Computational Astrophysics, Flatiron Institute, New York, New York 10010, USA*
[18]*NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*

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 ΛCDM 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.

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

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
$100\Omega_b h^2$	2.243 ± 0.040	2.223 ± 0.033	2.242 ± 0.032	-0.25	2.217 ± 0.021	2.222 ± 0.015
$100\Omega_c h^2$	11.56 ± 0.43	11.26 ± 0.36	11.34 ± 0.36	$+0.41$	12.05 ± 0.21	12.03 ± 0.14
$10^4\theta$	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
$\ln(10^{10}A_s)$	3.037 ± 0.023	3.018 ± 0.021	3.025 ± 0.021	-1.9	3.064 ± 0.020	3.067 ± 0.019
Ω_Λ [a]	0.703 ± 0.025	0.726 ± 0.019	0.723 ± 0.019	-0.71	0.680 ± 0.013	0.6812 ± 0.0086
Ω_m	0.296 ± 0.025	0.273 ± 0.019	0.277 ± 0.019	$+0.71$	0.320 ± 0.013	0.3188 ± 0.0086
σ_8	0.792 ± 0.020	0.774 ± 0.018	0.780 ± 0.017	-1.5	0.820 ± 0.010	0.8212 ± 0.0086
t_0	13.813 ± 0.093	13.729 ± 0.063	13.715 ± 0.062	$+0.81$	13.823 ± 0.035	13.822 ± 0.025
H_0	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.

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, $\Omega_b h^2$ and $\Omega_c h^2$, 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 $k_0 = 0.05$ Mpc^{-1}.

We assume a single family of massive neutrinos carrying a total mass of $\Sigma m_\nu = 0.06$ eV, and fold in the new Planck τ measurement by imposing a Gaussian prior of $\tau = 0.06 \pm 0.01$.[1] We note that in C13 τ was measured to be 0.085 ± 0.013 using WMAP polarization at $\ell < 23$.

A. ΛCDM

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

_____

[1]We 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 $\tau = 0.055 \pm 0.009$ but leading to the same conclusions.
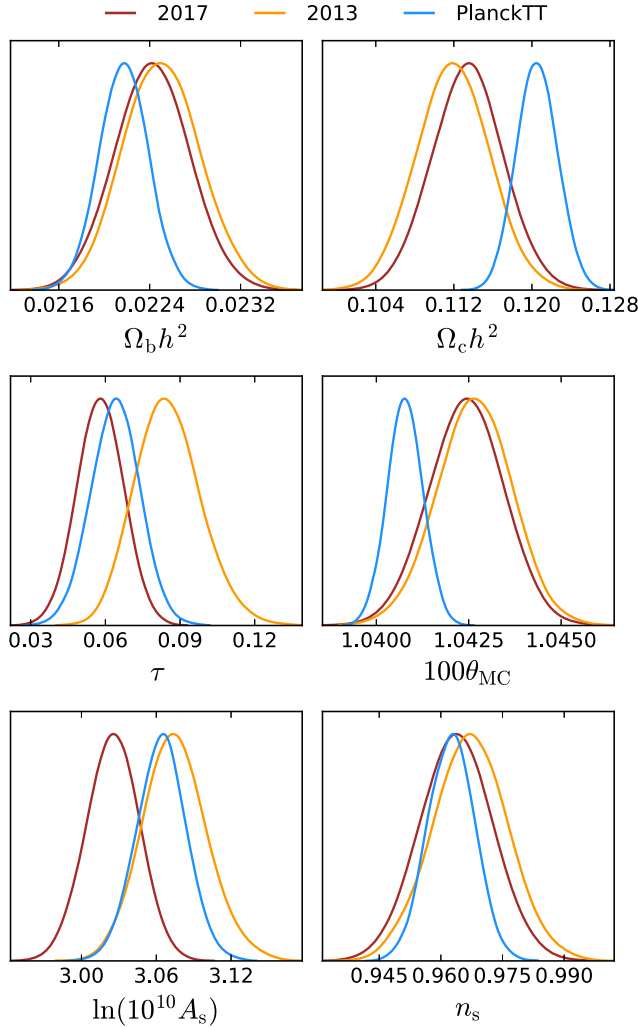
FIG. 1. One-dimensional posterior distributions for the six basic ΛCDM parameters as obtained in Calabrese *et al.* [1] and with this revised analysis. We also show a direct comparison with the constraints from the Planck baseline data set [18], analyzed with the same assumptions (see also Table I).

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-ℓ polarization.
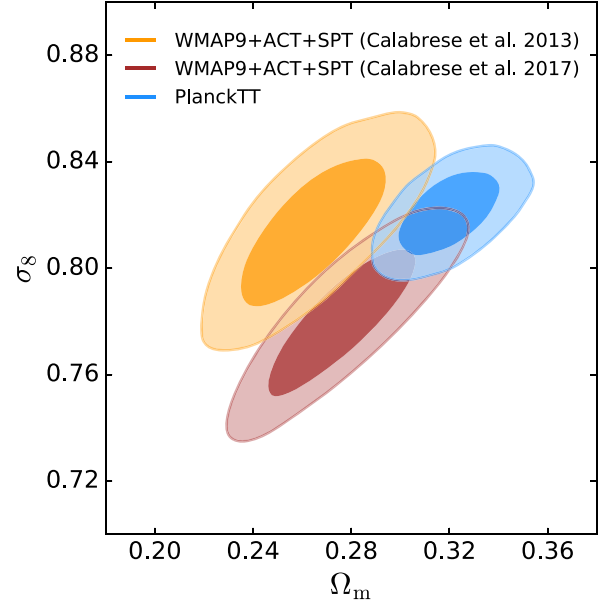

FIG. 2. Two-dimensional contour regions at 68% and 95% confidence for the matter density, Ω_m, and the amplitude of matter fluctuations on 8 h^{-1} Mpc scales, σ_8. A 1.5σ shift towards lower values of σ_8 is found in this revised analysis.

B. Ω_m and σ_8

The comparison between CMB and low-redshift constraints is usually reported in terms of the matter density and the amplitude of matter fluctuations on 8 h^{-1} Mpc scales, $\Omega_m - \sigma_8$. We want to stress here that the revised WMAP9 + ACT + SPT contours move by more than 1σ in the $\Omega_m - \sigma_8$ plane compared to C13, as shown in Fig. 2. This shift receives equal contribution either from having a different, lower τ or from having nonzero neutrino masses: we find that both parameters move the contours vertically by roughly the same amount.

These updated contours move along the galaxy weak lensing $\Omega_m - \sigma_8$ degeneracy line and therefore the overall agreement between 2013 CMB data and galaxy shear is unchanged; however, we note that the WMAP9 + ACT + SPT contours also overlap at the 1σ level with the Planck CMB contours (when using the same τ prior) and show better consistency between CMB experiments. This consistency is currently supported but not strengthened by CMB lensing: the addition of Planck lensing cuts the high $\Omega_m - \sigma_8$ region of the parameter space while ACT/SPT lensing provides only marginal improvement to the WMAP9 + ACT + SPT contours, without then modifying the overlapping region.

III. CONCLUSIONS

In this short paper we have updated the analysis of WMAP, ACT and SPT data presented in Calabrese *et al.* [1] in light of new, commonly used conventions for neutrino masses and a new measurement of the optical depth to

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.

[1] E. Calabrese *et al.*, Phys. Rev. D **87**, 103012 (2013).

[2] P. A. R. Ade *et al.* (Planck Collaboration), Astron. Astrophys. **571**, A1 (2014).

[3] C. L. Bennett *et al.*, Astrophys. J. Suppl. Ser. **208**, 20 (2013).

[4] G. Hinshaw *et al.*, Astrophys. J. Suppl. Ser. **208**, 19 (2013).

[5] S. Das *et al.*, J. Cosmol. Astropart. Phys. 04 (2014) 014.

[6] J. Dunkley *et al.*, J. Cosmol. Astropart. Phys. 07 (2013) 025.

[7] J. L. Sievers *et al.* (Atacama Cosmology Telescope Collaboration), J. Cosmol. Astropart. Phys. 10 (2013) 060.

[8] K. T. Story, C. L. Reichardt, Z. Hou, R. Keisler *et al.*, Astrophys. J. **779**, 86 (2013).

[9] Z. Hou, C. L. Reichardt, K. T. Story, B. Follin, R. Keisler *et al.*, Astrophys. J. **782**, 74 (2014).

[10] D. N. Spergel, R. Flauger, and R. Hložek, Phys. Rev. D **91**, 023518 (2015).

[11] L. Anderson *et al.*, Mon. Not. R. Astron. Soc. **441**, 24 (2014).

[12] T. Delubac *et al.*, Astron. Astrophys. **574**, A59 (2015).

[13] G. E. Addison, Y. Huang, D. J. Watts, C. L. Bennett, M. Halpern, G. Hinshaw, and J. L. Weiland, Astrophys. J. **818**, 132 (2016).

[14] A. G. Riess, L. M. Macri, S. L. Hoffmann, D. Scolnic, S. Casertano, A. V. Filippenko, B. E. Tucker, M. J. Reid, D. O. Jones, J. M. Silverman, R. Chornock, P. Challis, W. Yuan, P. J. Brown, and R. J. Foley, Astrophys. J. **826**, 56 (2016).

[15] E.-M. Mueller, W. Percival, E. Linder, S. Alam, G.-B. Zhao, A. G. Sánchez, and F. Beutler, arXiv:1612.00812.

[16] S. Joudaki *et al.*, arXiv:1610.04606.

[17] P. A. R. Ade *et al.* (Planck Collaboration), Astron. Astrophys. **571**, A16 (2014).

[18] P. A. R. Ade *et al.* (Planck Collaboration), Astron. Astrophys. **594**, A13 (2016).

[19] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **594**, A11 (2016).

[20] M. Lattanzi, C. Burigana, M. Gerbino, A. Gruppuso, N. Mandolesi, P. Natoli, G. Polenta, L. Salvati, and T. Trombetti, J. Cosmol. Astropart. Phys. 02 (2017) 041.

[21] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **596**, A107 (2016).

[22] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).