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Citation

Calabrese, E., Hlozek, R., Battaglia, N., Battistelli, E., Bond, J., Chluba, J., ... Wollack, E. (2013). Cosmological parameters from pre-planck cosmic microwave background measurements. *Physical Review D*, 87(10), 103012. doi:10.1103/PhysRevD.87.103012

Version: Not Applicable (or Unknown)

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Note: To cite this publication please use the final published version (if applicable).

Cosmological parameters from pre-planck cosmic microwave background measurements

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(Received 12 February 2013; published 20 May 2013)

Recent data from the WMAP, ACT and SPT experiments provide precise measurements of the cosmic microwave background temperature power spectrum over a wide range of angular scales. The combination of these observations is well fit by the standard, spatially flat Λ CDM cosmological model, constraining six free parameters to within a few percent. The scalar spectral index, $n_s = 0.9690 \pm 0.0089$, is less than unity at the 3.5σ level, consistent with simple models of inflation. The damping tail of the power spectrum at high resolution, combined with the amplitude of gravitational lensing measured by ACT and SPT, constrains the effective number of relativistic species to be $N_{\text{eff}} = 3.28 \pm 0.40$, in agreement with the standard model’s three species of light neutrinos.

DOI: [10.1103/PhysRevD.87.103012](https://doi.org/10.1103/PhysRevD.87.103012)

PACS numbers: 98.70.Vc, 98.80.Es

I. INTRODUCTION

It has long been appreciated that the cosmic microwave background (CMB) power spectrum contains enough information to precisely determine the standard model of cosmology [1–4]. This promise has been realized through a series of increasingly sensitive experiments, most recently with the WMAP satellite’s nine-year full-sky observations [5,6] and the arcminute-resolution maps from the Atacama Cosmology Telescope (ACT) [7–9] and the South Pole Telescope (SPT) [10,11]. The combination of these measurements probes the temperature power spectrum on angular scales ranging from 90 degrees to 4 arcminutes, scales at which the primary cosmological temperature

fluctuations dominate. The primordial fluctuations are well approximated as a Gaussian random field [5,12], but ACT and SPT have also detected the non-Gaussian features due to gravitational lensing of the microwave radiation by the intervening large-scale structures [13,14]. In this paper we present a joint analysis of the ACT, SPT, and final WMAP nine-year power spectra to obtain an estimate of the cosmological parameters from microwave background data alone.

II. DATA AND ANALYSIS METHOD

In Fig. 1 we show the compilation of CMB temperature power spectra used in this analysis. At large angular scales

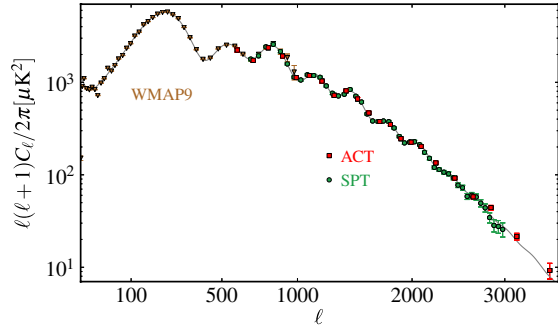


FIG. 1 (color online). WMAP9 temperature data and ACT and SPT CMB lensed bandpowers marginalized over secondary emissions. The ACT bandpowers are estimated separately for ACT-S and ACT-E and coadded here with an inverse variance weighting. The SPT bins are highly correlated, 50%–65% at small scales, $\ell \gtrsim 2000$, due to foreground uncertainty. The correlation is about 5% between neighboring ACT bins. The solid line shows the lensed CMB best fit obtained by combining the three data sets. The ACT and SPT bandpowers are available on LAMBDA [35].

we use the temperature and polarization data, and associated likelihood, from the nine-year WMAP analysis (hereafter WMAP9) [6]. This measures the Sachs-Wolfe plateau and the first three acoustic peaks, $2 < \ell \leq 1000$. At smaller scales, $500 < \ell < 3500$, we use data from ACT and SPT.

Here we follow the method introduced in Ref. [8] to estimate the primary CMB bandpowers from both sets of spectra, marginalizing over the possible additional power from Galactic and extragalactic emission, and the Sunyaev-Zel’dovich effects. We use a Gibbs sampling method to simultaneously estimate CMB bandpowers and a set of ten secondary parameters. For ACT we extract primary CMB bandpowers from the 148 and 218 GHz auto and cross power spectra from two regions (ACT-E and ACT-S [7]) of the sky [15], taking the multifrequency bandpowers in the range $500 < \ell < 10000$. We include SPT 150 GHz data [10] from $650 < \ell < 3000$, and marginalize over a common model for secondary components [17]. We impose a Gaussian prior of $12.3 \pm 3.5 \mu\text{K}^2$ at $\ell = 3000$ on the SPT radio source Poisson power, having subtracted $7 \mu\text{K}^2$ of cosmic infrared background Poisson power, treated separately in our likelihood, from the total expected Poisson level [10,18]. The resulting ACT and SPT lensed bandpowers are shown in Fig. 1, and the secondary parameters are consistent with those reported in Refs. [8,9]. The errors shown are the diagonal elements of the covariance matrix, with the SPT calibration error removed for consistency with ACT. The full covariance matrix includes correlations due to foreground uncertainty, beam error, and the overall calibration for SPT.

We then construct an ACT + SPT likelihood from these CMB bandpowers, which can also be used for each experiment on its own. This is a Gaussian distribution using 42

data points from ACT (21 each from ACT-E and ACT-S) and 47 from SPT, with an associated covariance matrix. For ACT we only use $\ell < 3500$ bandpowers in the likelihood, where their distributions are Gaussian. When combining ACT with SPT, we use only ACT-E data to eliminate the covariance between ACT-S and SPT, which observe overlapping sky regions. We combine this likelihood with WMAP9, using the CosmoMC code [19] to estimate cosmological parameters.

We consider the basic spatially flat ΛCDM cosmological model defined by six 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_A ; the reionization optical depth, τ ; the amplitude and the scalar spectral index of primordial adiabatic density perturbations, $\Delta_{\mathcal{R}}^2$ and n_s (at a pivot scale $k_0 = 0.05 \text{ Mpc}^{-1}$). We also extend the standard model to include a seventh parameter N_{eff} , the effective number of relativistic species at decoupling. The high- ℓ damping tail measured by ACT and SPT is particularly sensitive to this parameter.

III. RESULTS AND DISCUSSION

The simple ΛCDM model fits all the data well, with the estimated parameters shown in Table I and Fig. 2. We find $\chi^2/\text{d.o.f.} = 37.9/42$ [probability to exceed (PTE) = 0.65] for ACT and 53.2/47 (PTE = 0.25) for SPT when combined individually with WMAP9, assuming the degrees of freedom equal the number of additional data points. The best-fitting parameters for ACT are all within about 1σ of the corresponding best-fitting parameters for SPT. For the combined analysis, the ACT + SPT best fit $\chi^2/\text{d.o.f.}$ is 78.9/68 (PTE = 0.17). Compared to the joint best-fit model, the SPT-only best fit has $\Delta\chi^2 = 2.5$ worse and the ACT-only best fit (for ACT-S+ACT-E) has $\Delta\chi^2 = 2.2$, indicating that the common model fits both data sets. Figure 3 shows the residual power for the high- ℓ data sets after subtracting the joint best-fitting model. We do not observe any particular features in ACT; the SPT power is more suppressed at multipoles $\ell \gtrsim 1500$, but the points include an uncertain correlated extragalactic foreground contribution, whose dominant term is a Poisson shape.

The addition of ACT and SPT helps WMAP constrain the basic six parameters due to a more precise determination of the higher order acoustic peak positions and amplitudes. The measurement of θ_A improves by a factor of 2.2 and the error on the baryon density is a factor of 1.6 smaller compared to WMAP9 alone. However, as noted in Ref. [11], the increased acoustic horizon scale leads to a predicted distance, D_V , to objects at redshift $z = 0.57$, in units of the sound horizon at recombination, r_s , of $100r_s/D_V = 7.66 \pm 0.14$, more than 2σ larger than measured by the BOSS experiment ([20], $100r_s/D_V = 7.3 \pm 0.1$). The prediction at $z = 0.35$, $100r_s/D_V = 11.57 \pm 0.26$, is consistent at 1σ with the SDSS DR-7 observations ([21], $100r_s/D_V = 11.3 \pm 0.2$). We find a

TABLE I. Standard Λ CDM parameters from the combination of WMAP9, ACT and SPT.

Parameter	WMAP9 + ACT	WMAP9 + SPT	WMAP9 + ACT + SPT ^a
$100\Omega_b h^2$	2.260 ± 0.041	2.231 ± 0.034	2.252 ± 0.033
$100\Omega_c h^2$	11.46 ± 0.43	11.16 ± 0.36	11.22 ± 0.36
$100\theta_A$	1.0396 ± 0.0019	1.0422 ± 0.0010	1.0424 ± 0.0010
τ	0.090 ± 0.014	0.082 ± 0.013	0.085 ± 0.013
n_s	0.973 ± 0.011	0.9650 ± 0.0093	0.9690 ± 0.0089
$10^9 \Delta_{\mathcal{R}}^2$	2.22 ± 0.10	2.15 ± 0.10	2.17 ± 0.10
Ω_Λ^b	0.716 ± 0.024	0.737 ± 0.019	0.735 ± 0.019
σ_8	0.830 ± 0.021	0.808 ± 0.018	0.814 ± 0.018
t_0	13.752 ± 0.096	13.686 ± 0.065	13.665 ± 0.063
H_0	69.7 ± 2.0	71.5 ± 1.7	71.4 ± 1.6
$100r_s/D_{V0.57}$	7.50 ± 0.17	7.65 ± 0.14	7.66 ± 0.14
$100r_s/D_{V0.35}$	11.29 ± 0.31	11.56 ± 0.26	11.57 ± 0.26
Best fit χ^2	7596.0	7617.1	7640.7

^aThe combination ACT + SPT uses ACT-E data only. We report errors at 68% confidence levels.

^bDerived parameters: Dark energy density, the amplitude of matter fluctuations on $8 h^{-1}$ Mpc scales, the age of the Universe in Gyr, the Hubble constant in units of km/s/Mpc, and the galaxy correlation scales at redshifts 0.57 and 0.35.

preference for a scale-dependent primordial power spectrum at 3.5σ from the CMB, with $n_s = 0.9690 \pm 0.0089$ at 68% confidence.

The CMB power spectrum is sensitive to the composition of the Universe. The radiation energy density is the energy density in photons plus the sum of the energy density in relativistic species that do not couple electromagnetically, including standard model neutrinos. We parametrize the energy density in other relativistic particles through N_{eff} . In the standard cosmological model, $N_{\text{eff}} = 3.046$ [22–24] describes the three known neutrino species. If there is an extra neutrino species that decouples at the same temperature as the standard neutrinos then $N_{\text{eff}} \simeq 4$. If, instead, there is another light weakly interacting stable particle that decouples earlier, it will increase N_{eff} by the cube of the ratio of the decoupling temperatures. The extra

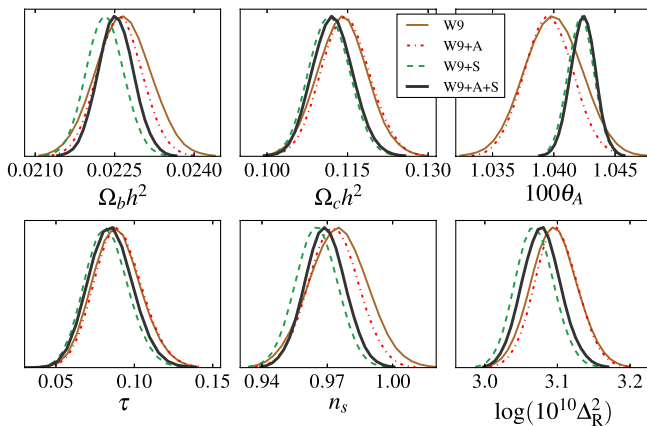


FIG. 2 (color online). Marginalized one-dimensional distributions for the six basic Λ CDM parameters, for combinations of WMAP9 (W9), ACT (A) and SPT (S) data.

energy density in relativistic species has three noticeable effects on the CMB power spectrum [25–28]: (1) it increases the expansion rate of the Universe, which impacts both the acoustic and damping scale, an effect that is mostly degenerate with increasing the matter density, $\Omega_m h^2$; (2) it modulates the helium abundance from big bang nucleosynthesis, which in turn modifies the damping tail through free electrons available at recombination; and (3) the relativistic particles will free stream out of density fluctuations and suppress the amplitude of the power spectrum on small angular scales (an effect partially degenerate

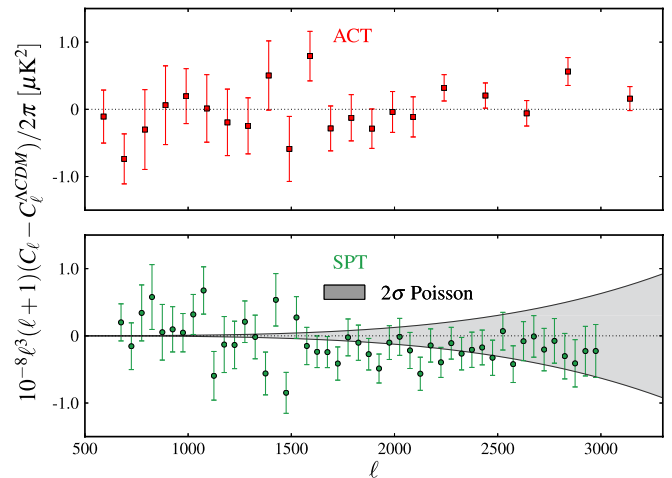


FIG. 3 (color online). Residual power after subtracting the same best-fitting lensed CMB model. The reduced $\chi^2/\text{d.o.f.}$ for ACT is 40.1/42 (PTE = 0.55) and for SPT 55.7/47 (PTE = 0.18). We show ACT-E and ACT-S coadded residuals. The grey band in the bottom panel shows the 2σ uncertainty in the Poisson source component. Overall calibration errors are not included.

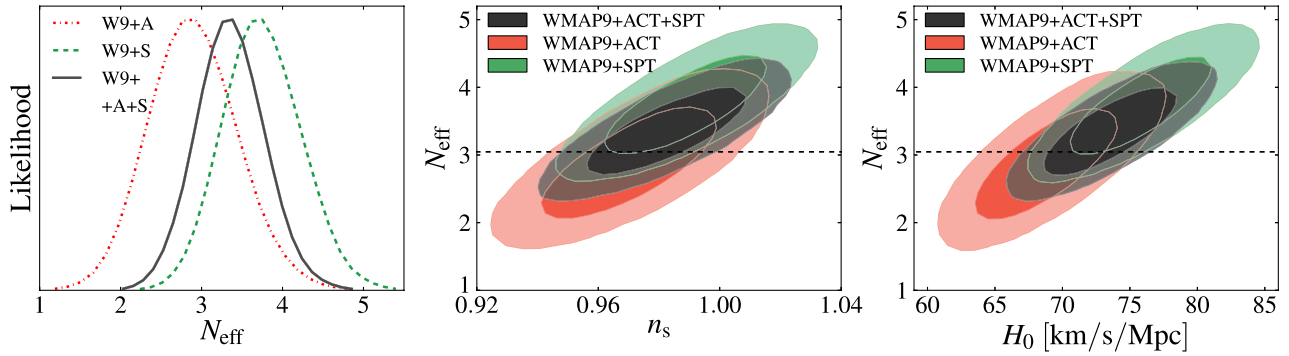


FIG. 4 (color online). Left: Marginalized distribution of N_{eff} for different data combinations, showing consistency with three neutrino species. Middle and right panels: Marginalized 68% and 95% contours in the $N_{\text{eff}}-n_s$ and $N_{\text{eff}}-H_0$ planes; N_{eff} is correlated with both parameters. The standard model expectation of $N_{\text{eff}} = 3.046$ is indicated with dashed lines.

with increasing n_s , which enhances the amplitude of the power spectrum on those scales).

In our analysis, we vary N_{eff} as a free parameter and we assume that the same relativistic species are present at nucleosynthesis. We keep other quantities that describe the damping tail set to standard values: the total available electron abundance (determined by the primordial helium abundance Y_p) is consistent with standard big bang nucleosynthesis; the higher precision determination of recombination is used [29], as implemented in Ref. [30]. Combining the data we are considering in this work we find at 68% confidence level

$$\begin{aligned} N_{\text{eff}} &= 2.90 \pm 0.53 \quad (\text{WMAP9} + \text{ACT}) \\ N_{\text{eff}} &= 3.75 \pm 0.47 \quad (\text{WMAP9} + \text{SPT}) \\ N_{\text{eff}} &= 3.37 \pm 0.42 \quad (\text{WMAP9} + \text{ACT} + \text{SPT}). \end{aligned}$$

In Fig. 4 we show the distribution for N_{eff} from WMAP9 combined with ACT and SPT separately, and together. There is a 1.2σ difference between the ACT and SPT estimates; as noted in Ref. [11], the SPT data prefer a higher value, indicating more suppression of the small-scale spectrum. The probability that this variation is given by statistical scatter is around 50% [31]. Based on the difference in the damping tail measurements, the authors of Ref. [33] decided not to combine the ACT and SPT data. In this paper we take a different approach and view the consistency sufficient for combination. As noted in Ref. [34], a Bayesian model comparison shows no evidence in favor of adding an additional N_{eff} parameter beyond those of the standard cosmology.

The correlations among N_{eff} , n_s , and H_0 are also shown in Fig. 4; the suppression of small-scale power due to larger values of N_{eff} can be partially compensated by increasing n_s and $\Omega_m h^2$. This leads to a larger derived value of H_0 if the CMB peak positions are held fixed.

Since a higher value for N_{eff} requires a higher matter density today, it gives a higher amplitude of gravitational potential fluctuations and an increased gravitational

lensing signal. Measurements of the four-point function of the CMB temperature maps provide a measurement of the lensing deflection signal. The ACT [7] and SPT [14] data constrain the amplitude of the lensing potential power spectrum at $\ell = 400$ to be $C_{400}^{\kappa\kappa} = (3.69 \pm 0.80) \times 10^{-8}$ for ACT and $C_{400}^{\kappa\kappa} = (2.92 \pm 0.54) \times 10^{-8}$ for SPT, yielding a combined $C_{400}^{\kappa\kappa} = (3.17 \pm 0.45) \times 10^{-8}$. Adding this constraint gives

$$\begin{aligned} N_{\text{eff}} &= 3.28 \pm 0.40 \\ &(\text{WMAP9} + \text{ACT} + \text{SPT} + \text{Lensing}), \end{aligned}$$

consistent with three neutrino species.

IV. CONCLUSIONS

Current microwave background power spectrum measurements are consistent with the standard Λ CDM cosmological model, and independent data sets are consistent with each other, with a mild tension between the ACT and SPT damping tails. Upcoming maps from the Planck satellite will provide independent measurements of the same sky regions with excellent foreground characterization.

ACKNOWLEDGMENTS

This work was supported by the U.S. National Science Foundation through Grants No. AST-0408698 and No. AST-0965625 for the ACT project, as well as Grants No. PHY-0855887 and No. PHY-1214379. Funding was also provided by Princeton University, the University of Pennsylvania, and a Canada Foundation for Innovation (CFI) award to UBC. ACT operates in the Parque Astronómico Atacama in northern Chile under the auspices of the Comisión Nacional de Investigación Científica y Tecnológica de Chile (CONICYT). Computations were performed on the GPC supercomputer at the SciNet HPC Consortium. SciNet is funded by the CFI under the auspices of Compute Canada, the Government of Ontario, the

Ontario Research Fund—Research Excellence; and the University of Toronto. Funding from ERC Grant No. 259505 supports E. C., J.D., and T.L. We acknowledge the use of the Legacy Archive for Microwave

Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science. The likelihood code will be made public through LAMBDA [36] and the ACT website [37].

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