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CMB IN (RELATIVE) TENSION

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Abstract. With Planck's CMB measurements, we have achieved high precision on the ΛCDM cosmological parameters with no need for model extensions. Many measurements are consistent with the predictions of the ΛCDM model fitted to Planck data. However, when compared to some cosmological probes, the CMB data exhibits some deviations which have been examined extensively for the last few years. We will describe the stability of the CMB results with respect to the fit of cosmological models and review the main so-called "tensions".

Keywords: cosmology: observations, cosmic background radiation, cosmological parameters, methods: data analysis

1 Introduction

The Planck satellite mission provided accurate measurements of the Cosmic Microwave Background radiation on the entire sky which gives powerful constraints on the Universe's content and geometry. Indeed, statistics from the measured CMB anisotropies can be compared to model predictions allowing the free parameters from specific cosmological models to be determined. The current standard model (so-called ΛCDM) can be described by 6 parameters in its simplest version but fits accurately the current cosmological observations.

In this model, we assume purely adiabatic, nearly scale-invariant perturbations at very early times, with curvature-mode (scalar) power spectrum parameterized by a power law $\mathcal{P}(k) = A_s\,(k/k_0)^{n_s-1}$, where A_s is the initial super-horizon amplitude for curvature modes and n_s i s the primordial index for scalar perturbations taken to be constant. The late-time parameters, on the other hand, determine the linear evolution of perturbations after they re-enter the Hubble radius: $\Omega_{\rm b}h^2$ the baryon density today, $\Omega_{\rm c}h^2$ the cold dark matter density today, H_0 the Hubble constant characterising the expansion of the Universe today, and τ the reionization optical depth.

With the current CMB measurements, the 6 parameters from the ΛCDM model are known at better than percent level with the exception of the reionization optical depth τ (Planck Collaboration VI 2020).

Planck provided the community with angular power spectra of CMB anisotropies in temperature (the so-called TT power spectrum) but also in polarisation (EE power-spectrum) and in cross-correlation temperature-polarization (TE power spectrum) (Planck Collaboration V 2020). Beyond the CMB anisotropies, Planck was also able to provide the first full-sky measurement of the gravitational amplitude through the lensing of CMB photons integrated along the line of side (so-called lensing power spectrum or $\phi\phi$).

Power spectra are plotted in Fig. 1. The uncertainties of the TT spectrum are dominated by sampling variance, rather than by noise or foreground residuals, at all scales below about $\ell = 1800$, the scale at which the CMB information is essentially exhausted within the framework of the ΛCDM model. The TE spectrum is about as constraining as the TT one, while the EE spectrum still has a sizeable contribution from noise.

From CMB data, the constraints obtained on the cosmological parameters are both consistent between the different mode (TT, TE, EE, as shown in Fig. 2) and stable with time (over the last decade). Moreover, the impact of the major instrumental systematic effects have been shown to be lower than 0.5σ of the published statistical uncertainties (Planck Collaboration VI 2020).

The ΛCDM model provides a good fit to the CMB data as well as to other astrophysical observations indicating that we have a good understanding of the physics to model cosmic history. Moreover, with the increase of sensitivity achieved by Planck, we have been able to constrain extensions from the standard model

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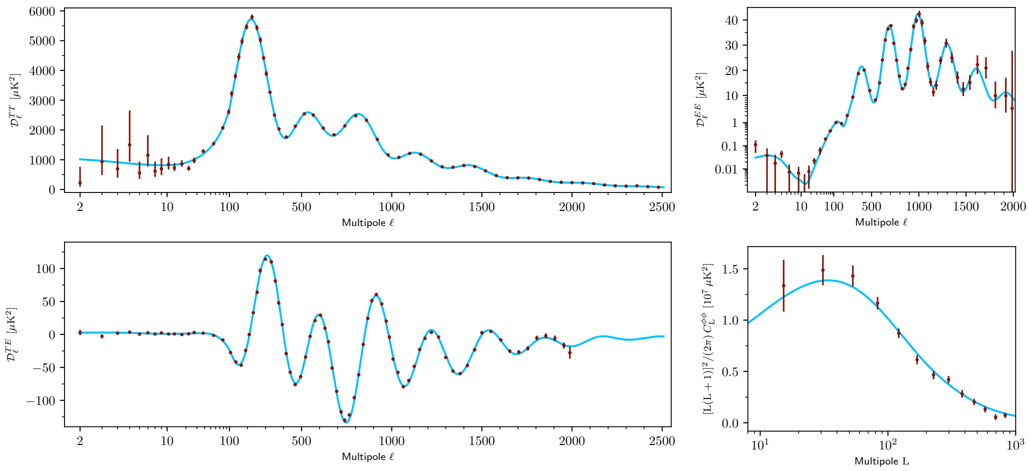

Fig. 1. Planck CMB power spectra for the temperature (top left), the temperature-polarization cross-spectrum (bottom left), the E-mode of polarization (top right), and the lensing potential (bottom right). The blue lines show the best-fitting ΛCDM model. *Extracted from* (Planck Collaboration I 2020).

with high precision (see Table 5 in Planck Collaboration VI 2020). This includes in particular: the flatness of the spatial hyperspaces; the neutrino masses; the number of relativistic species at decoupling; the running of power-laws for matter power spectra.

Nevertheless, despite these successes, some puzzling tensions have been highlighted after the Planck 2018 release and discussed in the literature since then. The most popular ones are as follows:

- the amplitude of lensing deduced from the CMB power spectra A_L which is inferred to be higher than the ΛCDM prediction,
- the Hubble constant H_0 from the inverse distance ladder which is discordant with measures of the distance scale from the nearby supernovae,
- the amplitude of the fluctuations σ_8 predicted by Planck which sits high compared to cosmic shear and cluster count inferred values

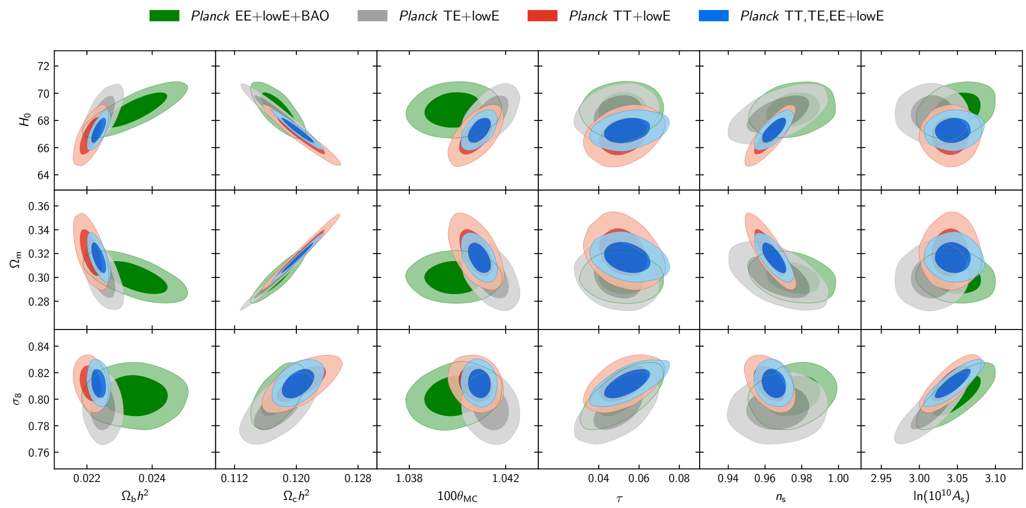

Fig. 2. Constraints on parameters of the base-ΛCDM model from the separate Planck EE, TE, and TT high-ℓ spectra combined with low-ℓ polarization (lowE), and, in the case of EE also with BAO, compared to the joint result using Planck TT,TE,EE+lowE. *Extracted from* (Planck Collaboration VI 2020).

2 The lensing amplitude A_L

Weak lensing enters the prediction of the CMB spectrum through a convolution of the unlensed spectrum with the lensing potential power spectrum. The effect of lensing is a smearing of the acoustic peaks as well as a redistribution of power towards the high multipoles (above $\ell \sim 3000$).

As originally proposed in Calabrese et al. (2008), a phenomenological parameter, A_L, that rescales the lensing potential, is introduced, allowing an internal check of the consistency of the lensing effect with the cosmology. Indeed, measuring a value of A_L deviating from one indicates either a problem with the model (modification of the gravity), or residual systematics in the data.

When estimated with the $\phi\phi$ power spectrum, this allows the measurement of the significance of the detection of the CMB lensing and compare to the ΛCDM prediction ($A_L = 1$). In Planck Collaboration VI (2020), the Planck lensing measurements is perfectly compatible with the model:

$$A_L = 1.011 \pm 0.028 \quad \text{(Planck } \phi\phi\text{)}$$

The lensing amplitude can also be estimated from the CMB anisotropies by looking for the impact on the angular power spectra. Since its first release, the Planck Collaboration has a reported a value of the A_L parameter that is discrepant with one by more than 2σ. The results from the different power spectra (TT, TE, EE) are barely compatible (see left panel in Fig. 3 and Planck Collaboration VI 2020). Moreover, as already discussed in Couchot et al. (2017), the fitted value depends on the CMB likelihood used. Indeed, the three different likelihoods used on Planck 2018 data (PR3*) give:

$$A_L = 1.243 \pm 0.096 \qquad \text{(TT+lowE [Plik])} \tag{2.1}$$
$$A_L = 1.246 \pm 0.095 \qquad \text{(TT+lowE [CamSpec])} \tag{2.2}$$
$$A_L = 1.160 \pm 0.075 \qquad \text{(TT+lowE [Hillipop])} \tag{2.3}$$

Even if there is still some tension at about 2σ, this indicates that the A_L deviation from unity is sensitive to the details of the likelihood implementations and in particular to the modelling of the foregrounds. Using the last release of Planck maps (PR4*, Planck Collaboration Int. LVII 2020), and with a more complete description of the low multipoles in polarisation, one can recover even lower estimates of A_L (Tristram et al. 2021) with similar uncertainty reinforcing the impact of systematic residuals in Planck 2018 data.

Ground-based telescopes measuring CMB anisotropies (such as ACT or SPT3g) recover A_L compatible with unity (see right panel in Fig. 3):

$$A_L = 1.01 \pm 0.11 \qquad \text{(ACT, Aiola et al. 2020)} \tag{2.4}$$
$$A_L = 0.98 \pm 0.12 \qquad \text{(SPT3g, Dutcher et al. 2021)} \tag{2.5}$$

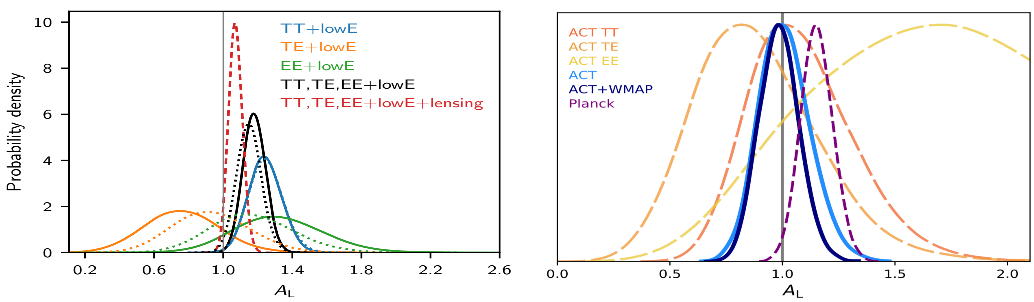

Fig. 3. Constraints on the value of the consistency parameter A_L. **Left:** Results using various combinations of Planck data. When only power spectrum data are used, $A_L > 1$ is favoured at about 3σ. The dotted lines show equivalent results for the CamSpec likelihood. *Extracted from* Planck Collaboration VI (2020). **Right:** Results as measured by ACT, by the individual TT, TE and EE spectra from ACT, and ACT combined with WMAP. The Planck measurement is shown for comparison. *Extracted from* Aiola et al. (2020).

*available at `http://pla.esac.esa.int`

3 The Hubble constant H_0

With the reduction of the uncertainties on the estimation of the Hubble constant, a notable discrepancy arises between the local measurements at the very lowest redshifts and the indirect measurements from the early Universe. There have been, and remain still, many studies around this significant tension which can reach up to 5σ.

Figure 4 shows a compilation of the results (in the left panel) as well as a summary of the tension between early Universe and local distance measurements (in the right panel). So called "early Universe" measurements do include CMB but also the Baryon Acoustic Oscillations (BAO) in combination with primordial element abundances whereas "local measurements" refer to distances of Type IA supernovae using different calibrations such as the Cepheid (Riess et al. 2021) or the Tip of the Red Giant Branch (Freedman et al. 2020).

As discussed in Linder (2021), it is difficult for early measurements to result in a large value of H_0. Indeed, CMB data tightly constrain H_0 within ΛCDM models. Combining CMB with another cosmic probe, such as Baryon Acoustic Oscillation (BAO) or Type Ia Supernovae (SNIa), breaks the degeneracy for models where the dark energy equation of state differs from -1 but still indicates a value of H_0 lower than 70.

On the contrary, the local measurements differ by about 2σ depending on the calibration method. The impact of the environment of the SNIa in the Cepheids is debated as a potential explanation for such variations as well as potential extinction by extra-galactic dust Mortsell et al. (2021).

New independent measurements from strong lensing time delays seem to show a transition between low and high H_0 values (Millon et al. 2020; Liao et al. 2020) but currently the sample is still small and the results may depend on the lensing object more than reported.

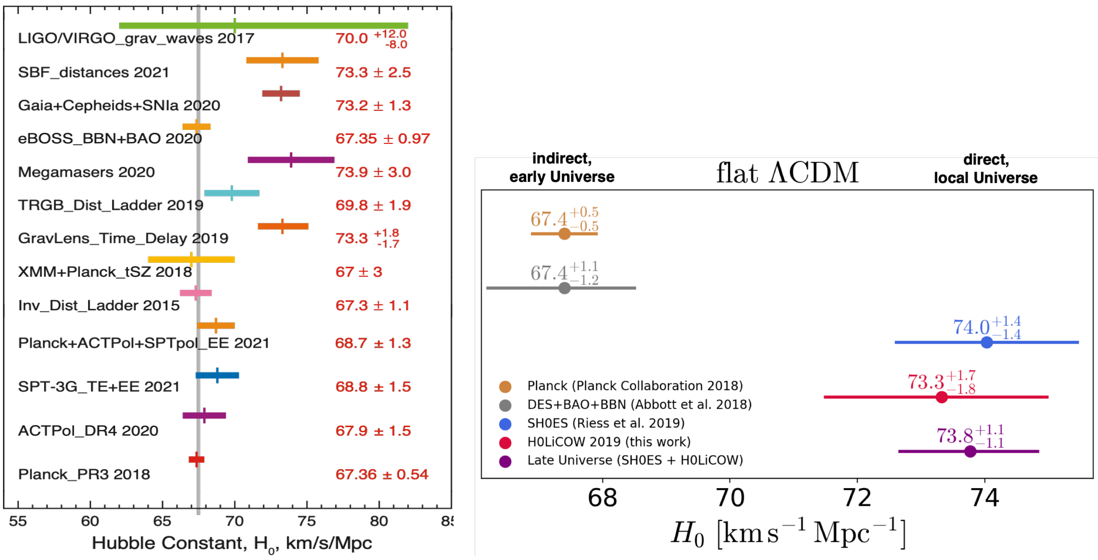

Fig. 4. Left: Hubble constant results from distance ladder determinations (labeled HST Key Project, Cepheids+SNIa, Distance Ladder, TRGB Dist Ladder), indirect CMB measurements (WMAP9, Planck PR3, both of which combine CMB with other data), BAO in combination with baryon abundance (BAO+D/H), the thermal SZ effect (CHANDRA+tSZ, XMM+Planck tSZ), strong gravitational lensing (Gravlens Time Delay) and gravitational waves (LIGO/Virgo grav waves). *Extracted from* LAMBDA (`https://lambda.gsfc.nasa.gov`). **Right:** Comparison of H_0 constraints for early- and late-Universe probes in a flat ΛCDM cosmology. The early-Universe probes shown here are from Planck (orange; Planck Collaboration VI 2020) and a combination of clustering and weak lensing data, BAO, and big bang nucleosynthesis (grey; Abbott et al. 2018). The late-Universe probes shown are the latest results from SH0ES (Riess et al. 2019, blue;) and H0LiCOW (red; Wong et al. 2019). When combining the late-Universe probes (purple), we find a 5.3σ tension with Planck. *Extracted from* Wong et al. (2019).

4 The amplitude of fluctuations σ_8

From both galaxy cluster counts as well as weak lensing from distant galaxies through large scale structure (also called "cosmic shear"), one can constrain the amplitude of fluctuations σ_8 (or equivalently $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$) and compare to the prediction from the ΛCDM model fitted on CMB data.

In Planck 2015, using cluster counts, Planck Collaboration XXIV (2016) reported a value of σ_8 between 2 and 3σ lower than the primary CMB results depending on the mass bias prior. Salvati et al. (2018) showed that using a more recent value of the reionization optical depth τ (Planck Collaboration Int. XLVII 2016), tension was released so that CMB results and combined tSZ results on σ_8 agree within 1.3σ (see left panel of Fig. 5). This was then confirmed with the 2018 Planck data (Planck Collaboration VI 2020) in which the subset of clusters used as a sample for cosmological constraints has been significantly increased (from 439 in 2015 to more than 1000 in 2018).

Cosmic shear measurements available from several collaborations originally found a modest tension with the Planck ΛCDM cosmology, preferring lower values of Ω_m and σ_8. However, the last release of the Dark Energy Survey (DES-Y3, DES Collaboration et al. 2021) found no significant evidence of inconsistency with Planck CMB at 0.7-1.5σ despite the significantly improved precision of both (see right panel of Fig. 5).

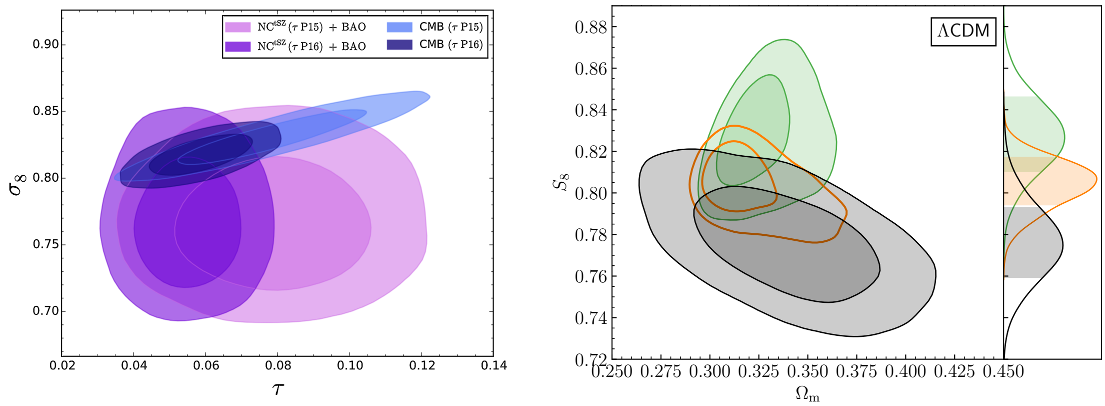

Fig. 5. Left: Two-dimensional probability distributions for τ and σ_8 for various values of optical depths. We compare results for SZ number counts alone (pink and purple) and for CMB data alone (blue and light blue). *Extracted from* Salvati et al. (2018). **Right:** A comparison of the marginalized parameter constraints in the ΛCDM model from the Dark Energy Survey with predictions from Planck CMB data (no lensing; green). We show the fiducial 3x2pt (solid black) and the combined Y3 3x2pt and Planck (orange) results. *Extracted from* DES Collaboration et al. (2021).

5 Conclusions

We have shown here that constraints from CMB data (essentially Planck) are robust and stable: with time (from WMAP to the last release of Planck); for the various spectra (the anisotropies TT, TE, EE and the lensing $\phi\phi$); with respect to extensions to the simple ΛCDM model, when adding extra parameters one at a time. There are many measurements that are consistent with the predictions of the ΛCDM model fitted to Planck data. The remaining areas of discordance have been discussed in this paper.

Internal consistency (amplitude of lensing A_L) As we have seen, the value of A_L is sensitive to choices made in the Planck CMB likelihoods and the tension is significantly reduced with the latest Planck release (PR4). Ground-based measurements are fully compatible with ΛCDM predictions. There is no evidence for new physics or statistical fluctuations. However, if the remaining impact of $A_L \neq 1$ on ΛCDM parameters is negligible, it can play a role in allowing model extensions as for example the reionization history, the curvature (Ω_k), or the sum of the neutrino masses ($\sum m_\nu$).

Expansion rate (Hubble constant H_0) CMB data gives tight constraints on the Hubble constant in the context of the ΛCDM. The constraints are also compatible for dark energy models when combined with BAO data. In both cases, it is very hard for "early Universe" data to result in a value of H_0 higher than 70, even in the case of model extensions (such as non-flat Universe, or when fitting neutrino masses). In order for the CMB data to match $H_0 > 70$, one needs to rely on very exotic models such as non-standard thermal history or radiation, existence of early dark energy (e.g. Poulin et al. 2019), or non-standard neutrino interactions (e.g. Kreisch et al. 2020). Local measurements show large variations depending on the first distance ladder which suggest there is still some physics to be understood in order to reach precision at the percent level on H_0. Independent measurements coming from time delay with strong lensing might help to further understand the current situation but the sample is still small. Measurements from gravitational waves are also interesting to consider but the need for a detected electromagnetic counterpart in order to estimate the redshift makes it difficult to increase the number of samples.

Amplitude of matter fluctuations (σ_8 or S_8) The estimation of the fluctuation amplitude σ_8 with CMB data shows a large degeneracy with the dark energy sector. However, even in the case of models with free dark energy equation of state (wCDM), the last release of DES data (DES Collaboration et al. 2021) finds all three independent data set combinations (DES 3x2pt; BAO, RSD, and SNe Ia; and Planck CMB) to be mutually consistent within ΛCDM. Tension with the estimation from cluster counts was also released after updating the value of the reionization optical depth τ while increasing the sample of clusters used for cosmology.

Given the uncertainties on cosmological parameters (at the percent level for most of them), error bars on the observational data need to be very accurate and to include systematic effects. Systematics arise from the instrument but can also be of astrophysical origin (such as the Galactic emissions for the CMB). In order to propagate correctly the systematics up to the cosmological parameters, one need reliable Monte-Carlo simulations. From those, one can extract the remaining bias from residual systematic effects (if there is one) but also estimate the increase of the uncertainties, including the correlation between the different effects involved. For Planck data, a huge effort has been made in the last release (PR4, Planck Collaboration Int. LVII 2020) to provide Monte-Carlo simulations associated to the released data and including all relevant systematic effects of Planck. However, CMB simulations make use of fixed template for foregrounds as we still miss a realistic stochastic description of the foregrounds.

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