Easing cosmic tensions with an open and hotter universe

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Despite the great observational success of the standard cosmological model some discrepancies in the inferred parameter constraints have manifested among a number of cosmological data sets. These include a tension between the expansion rate of our Cosmos as inferred from the cosmic microwave background (CMB) and as found from local measurements, the preference for an enhanced amplitude of CMB lensing, a somewhat low quadrupole moment of the CMB fluctuations as well as a preference for a lower amplitude of matter fluctuations in large-scale structure surveys than inferred from the CMB. We analyse these observational tensions under the addition of spatial curvature and a free CMB background temperature that may deviate from its locally measured value. With inclusion of these parameters, we observe a trend in the parameter constraints from cosmic microwave background and baryon acoustic oscillation data towards an open and hotter universe with larger current expansion rate, standard CMB lensing amplitudes, lower amplitude of matter fluctuations, and lower CMB quadrupole moment, consistently reducing the individual tensions among the cosmological data sets. Combining this data, we find a preference for an open and hotter universe. Finally, we briefly discuss a local void as a possible source for a deviation of the locally measured CMB temperature from its background value and as mimic of negative spatial curvature for CMB photons, which when correctly implemented may further ease parameter tensions.

Introduction. — The standard model of cosmology (ΛCDM) has been very successful in reproducing the wealth of cosmological observations conducted over the past few decades. Despite its successes, there remain a number of smaller and larger tensions among the data sets. Perhaps the oldest yet relatively small discrepancy (< 2σ) is the measurement of a somewhat low quadrupole moment in the cosmic microwave background (CMB) with respect to its ΛCDM prediction. This was already noticed with COBE [1] and has motivated studies of alternative cosmologies in the three decades since. Another discrepancy in the CMB (∼ 3σ) is observed in the imprint of the effect of weak gravitational lensing on the CMB spectra, which is enhanced with respect to the lensing that would be caused by the cosmological parameters inferred from early-time CMB physics [2]. When considering the power spectrum of the reconstructed lensing potential, however, the preference for this enhancement is reduced again, which may perhaps be another indicator of an underlying inconsistency. Clearly the strongest tension is observed in measurements of the current expansion rate of the Cosmos, where specifically CMB data and the local distance ladder measurement are in 4.4σ disagreement [3]. Finally, another discrepancy (∼ 2σ) manifests between the current amplitude of large-scale matter density fluctuations as predicted by the cosmological parameters inferred from the CMB and measurements from large-scale structure surveys [4, 5].

Many exotic explanations and new physics models have been invoked to remedy these tensions (see for example Refs. [6–8]). But also the variation of more conventional parameters has been considered. Specifically, nonvanishing spatial curvature [9] or the variation of the CMB temperature [10] have separately been studied as a means to ease the cosmic tensions. While the variation of these parameters can reduce discrepancies among part of the data, the preference for new parameters is typically reduced when complementing the analysis with other data sets. For instance, preferences for spatial curvature or a modified CMB lensing amplitude are suppressed when including baryonic acoustic oscillation data (BAO) or the power spectrum of the reconstructed CMB lensing potential [2]. As we will show in this brief communication, it is crucial to vary both spatial curvature and the CMB background temperature simultaneously to consistently ease the tensions among all the data sets.

We will first discuss the effects on the CMB power spectra and cross correlations from varying spatial curvature and the background temperature as well as the implications of that for the cosmic tensions. We will then perform a parameter estimation analysis with different combinations of CMB, CMB lensing, BAO, and background expansion data and compare the constraints inferred on the extended parameter space against bounds from large-scale structure surveys and the local distance ladder. Finally, we will discuss a local void as a possible source for a change of the locally measured CMB temperature with respect to that of the background and apparent spatial curvature.

An open and hotter universe. — To understand the impact on CMB fluctuations from nonvanishing spatial curvature and the change of the current CMB background temperature T_{CMB} from the local FIRAS measurement T_{FIRAS} = (2.72548 ± 0.00057) K [11], let us first examine how the early-time effects on the temperature and polarisation anisotropy power spectra and cross correlations transform under these variations. Since recombination physics is governed by the ratios between the baryonic, cold dark matter, and photon energy densities, it is not difficult to deduce a scaling of cosmolog-
tical parameters that keeps the oscillations in the CMB anisotropies fixed. To preserve these ratios at the given recombination temperature \( T_0 \), using \( T_0 = T_0(1 + z_s) \), we can simply fix \( H_0^2 \Omega_m / T_0^3 \). \( i = m, b \), where \( z_s \) is the redshift of recombination, \( H_0 \) is the Hubble constant, and \( \Omega_m \) and \( \Omega_b \) denote the fractional baryonic and total matter energy density parameters. Furthermore, the CMB acoustic peak positions are determined by \( \ell_A = \pi D_A / s_\text{D} \), where \( D_A \) is the angular diameter distance to recombination and \( s_\text{D} \) is the sound horizon at recombination. To preserve these positions under variation of \( T_0 \), we can therefore either change \( H_0 \) or we change the spatial curvature, giving rise to a geometric degeneracy between these three parameters. Finally, a variation of \( T_0 \) also changes the overall amplitude of the anisotropies, which can be absorbed into a rescaling of the initial amplitude of density fluctuations \( A_s \).

Of course, these degeneracies only apply to the primary anisotropies. Given the recombination temperature, the measurement of the current CMB temperature \( T_0 \) is essentially a measurement of how much the universe has expanded since recombination. Hence, a change in \( T_0 \) will therefore alter the late-time integrated Sachs-Wolfe (ISW) effect and CMB lensing. Whereas the detectability of changes in the ISW effect are strongly limited by cosmic variance, our observations are very sensitive to changes in the effect of CMB lensing. It is also worth noting that varying the amount of expansion since recombination as well as the amplitude of initial perturbations \( A_s \) will change the amplitude of current matter density fluctuations \( \sigma_8 \).

For illustration, let us for example consider a rise in the temperature \( T_0 \) from the FIRAS value. To keep the primary CMB anisotropies fixed, we need to raise \( H_0^2 \Omega_m \) and \( H_0^2 \Omega_b \). We could now lower \( H_0 \) to keep the peak positions fixed or we could introduce negative spatial curvature \( k < 0 \) to keep \( H_0 \) fixed or even raise it to bring it into accordance with local measurements. Finally, we will also need to raise \( A_s \) to keep the amplitude of the temperature fluctuations \( \delta T_0 / T_0 \) fixed. In contrast, the increase of \( T_0 \) changes the secondary anisotropies. By raising \( \Omega_m \), we also lower the ISW effect and reduce the small discrepancy between prediction and measurement of the quadrupole moment. Another interesting effect is that because we raise \( A_s \) and \( T_0 \) we no longer need to enhance the lensing amplitude \( A_L \) from its standard value of unity. Finally, since higher \( T_0 \) implies less expansion since recombination until today, this also lowers \( \sigma_8 \), despite the increase of \( A_s \).

**Observational results.**—Given the promising phenomenological features arising from introducing variations in spatial curvature and \( T_0 \), let us now turn to a data analysis to explore their direct impact on the measurements. As the base data sets in this analysis we will use the CMB temperature, polarisation, and cross correlation data from Planck 2018\(^1\) (TT, TE, EE + lowE). In addition to that, we will also perform a further analysis with the additional inclusion of the CMB lensing power spectrum. The reason for the separate analyses being that we want to study changes in the constraints on \( A_L \) when including the reconstructed lensing data and when omitting it. We then perform a set of analyses, where in addition to the CMB measurements, we use the BAO observations from the Baryon Oscillation Spectroscopic Survey (BOSS) DR12 release \([13]\). Finally, we compare the results from the CMB and CMB+BAO analyses against local \( H_0 \) measurements from SH0ES \([3]\). We also conduct analyses using all data sets.

For the parameter estimations on this data we perform Markov Chain Monte Carlo (MCMC) sampling using the cosmosis \([12]\) package. As our base cosmological parameters we chose

\[
\theta_{\text{base}} = \{ \Omega_b, \Omega_m, H_0, n_s, \tau, A_s \}.
\]

We first conduct an analysis for the base parameters with the different combinations of the data sets. We then augment the parameter space with the additional parameters: the fractional energy density parameter attributed

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\(^1\)The implementation of the Planck 2018 likelihood into cosmosis \([12]\) is currently undergoing testing, and we defer an analysis with the newer data to a later date, although we do not expect significant changes in our findings. Also note that we adopt the default vanishing total neutrino mass of the code.
to spatial curvature $\Omega_k$, the modification of the lensing amplitude $A_L$, and the free CMB background temperature $T_0$. The parameters are then constrained for the different combinations of the data as well as the alternate combinations in the addition of the extra parameters.

Our main result is given in Fig. 1 which shows a preference for an open ($\Omega_k > 0$) and hotter ($T_0 > T_{\text{FIRAS}}$) universe near the 95% confidence level from the combination of all the data. We have performed analyses two analyses, one sampling $\theta_{\text{case}}$ with $A_L$ and another with $\sigma_8$ instead. The posteriors do not shift significantly in the $T_0$ vs $\Omega_k$ plane, but we have noted a shift of the mean of $\sigma_8$ to slightly larger values when sampling in $A_L$ ($\sigma_8$ is calculated as a derived parameter in this case). We leave this curiosity to a future work where we consider other large scale structure data sets such as the KiDS cosmic shear measurements. Fig. 1 shows the sampling in $\sigma_8$.

In Fig. 2 we summarise how the parameter constraints shift under inclusion of $A_L$, $\Omega_k$, and $T_0$ as well as additional data. We find that with the preference for negative spatial curvature ($k < 0$, $\Omega_k > 0$) and hotter temperature ($T_0 > T_{\text{FIRAS}}$) there is no longer any preference for an enhanced amplitude of CMB lensing $A_L > 1$. The parameter constraints centre around the standard value $A_L = 1$ regardless if the reconstructed power spectrum of the CMB lensing potential or BAO data is included or not. The CMB and BAO data also favour a larger current expansion rate $H_0$ in better agreement with local measurements as well as a lower amplitude of matter fluctuations $\sigma_8$ as preferred by large-scale structure surveys. In particular KiDS has reported a measurement of $S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3} = 0.745 \pm 0.039$ [4]. Note, however, that this constraint does not include a variation of spatial curvature and can therefore not be directly compared to the results in Fig. 2. Parameter estimation analyses including spatial curvature with KiDS data have been conducted in Ref. [14] and with DES in Ref. [15]. Interestingly, the DES analysis reported a constraint of $\Omega_k = 0.16_{-0.09}^{+0.09}$ consistent with the trend towards an open universe exhibited in Fig. 1. Finally, a further effect of the open and hotter universe illustrated in Fig. 2 is a slight lowering of the CMB quadrupole moment towards the measurement.

**Local void as a possible interpretation.**—As a possible candidate for the enhanced CMB background temperature over its locally measured value, let us briefly examine the effects that would arise from residing in a local void. As a simple picture of the local underdensity, we may consider a top-hat matter density fluctuation. This implies that our local universe can be interpreted within the separate universe ansatz. The local expansion is then described by the usual Friedmann equations, which are however governed by the local matter density rather than that of the background. The local and background metrics are related by a time $t$ dependent conformal transformation $\tilde{a}(t) = C(t)a(t)$, where $\tilde{a}$ and $a$ denote the local and background scale factors and $C = (1 + \delta)^{-1/3}$ is the conformal factor specified by the matter density fluctuation $\delta$ [16]. There is also a disformal factor that gives rise to the local spatial curvature, which is however not of cosmological relevance and was not considered in Ref. [16]. Importantly, conformal factors change the temperature and expansion rate as $T_0 = T_0/C_0$ and $H_0 = H_0 + C_0/C_0$, where the dot indicates a time derivative and the zero indices refer to current time. Thus, in a local underdensity $\delta_0 < 0$ the CMB temperature is lower and the expansion rate is higher than in the background. As was shown in Ref. [16], as a consequence of that, the local distance ladder is really a measurement of the local expansion rate $H_0$ set by the environment between us and the absolute distance anchor at $\sim 10$ Mpc. Hence, adopting the local void as explanation for the enhanced

![FIG. 2. With the additional variation of $\Omega_k$ and $T_0$ there is no longer any preference for an enhanced amplitude of CMB lensing $A_L > 1$. The CMB and BAO data also favour a larger current expansion rate $H_0$ in better agreement with local measurements as well as a lower amplitude of matter fluctuations $\sigma_8$ as preferred by large-scale structure surveys. A further effect is a slight lowering of the predicted CMB quadrupole towards the measurement.](image-url)
$T_0$ further reduces the slight tension remaining in $H_0$ in Fig. 2. Although, it should be noted that due to the already eased tension in $H_0$ this underdensity would be less pronounced than what was inferred in Ref. [16]. This would however also make it a statistically more likely fluctuation given cosmic variance. Finally, it is also worth noting that due to the relatively small extent of this local void, its spatial curvature would not affect the CMB and BAO distances at a detectable level. But the angular diameter distance transforms as $\hat{D}_A = C D_A$ and gets elongated, which mimics negative spatial curvature such that the true cosmological background may actually be indeed hotter but flat.

Conclusions.— Concordance cosmology has been very successful in reproducing our cosmological observations, but some smaller and larger discrepancies in the inferred parameter constraints have manifested among a number of our data sets. We analysed these observational tensions under the addition of spatial curvature and a free CMB background temperature allowed to deviate from its locally measured value. The inclusion of these parameters produce a trend in the constraints inferred from CMB and BAO data towards an open and hotter universe with larger current expansion rate, standard CMB lensing amplitudes, lower amplitude of matter fluctuations, and lower CMB quadrupole moment. This trend consistently eases the individual tensions among the cosmological data sets. As a consequence, when combining the data, we found a preference for an open and hotter universe. We then briefly discussed how a local void may serve as an explanation for the deviation of the CMB background temperature from its locally measured value and mimic negative spatial curvature for CMB photons. We argued that for the correct implementation of the impact of the local void on the different measurements, further effects must be accounted for that may likely further ease the current parameter tensions.

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