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Background photon temperature $\bar{T}$: A new cosmological Parameter?

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The background photon temperature $\bar{T}$ is one of the fundamental cosmological parameters, and it is often set equal to the precise measurement $\langle T\rangle^{\rm obs}$ of the comic microwave background (CMB) temperature by the COBE Far Infrared Absolute Spectrometer (FIRAS). However, even in future CMB experiments, $\bar{T}$ will remain unknown due to the unknown monopole contribution Θ_0 at our position to the observed (angle-averaged) temperature $\langle T\rangle^{\rm obs}$. Using the Fisher formalism, we find that the standard analysis with $\bar{T}\equiv\langle T\rangle^{\rm obs}$ underestimates the error bars on cosmological parameters by $1\%\sim2\%$ of the present errors, and the best-fit parameters obtained in the analysis are biased by $\sim1\%$ of their standard deviation. These systematic errors are negligible for the Planck data analysis, providing a justification to the standard practice. However, with $\bar{T}\equiv\langle T\rangle^{\rm obs}$, these systematic errors will always be present and irreducible, and future cosmological surveys might misinterpret the measurements.

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I. INTRODUCTION

Cosmology has seen enormous development in recent decades (see, e.g., Ref. [1] for a review). In particular, the cosmic microwave background (CMB) experiments have greatly improved in recent years with the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellites [2,3]. The primary cosmological parameters are now constrained at the subpercent level [4,5], and the angular scale of the acoustic peak is even better constrained by an order of magnitude. This level of precision in cosmological parameter estimation demands a matching accuracy in our theoretical predictions.

The background CMB temperature $\bar{T}$ is one of the fundamental cosmological parameters that characterize the evolution of the Universe. In particular, it is tantamount to the photon energy density ω_γ, and it sets the total radiation density ω_r (and hence the epoch $z_{\rm eq}$ of the matter-radiation equality) once the other cosmological parameters such as the matter density ω_m and the neutrino masses m_ν are provided. Despite its significant role in cosmology, the background CMB temperature $\bar{T}$ has rarely been treated as a free cosmological parameter in literature, because of the pioneering work [6–8] by the COBE Far Infrared Absolute Spectrometer (FIRAS) in 1990, which provided precise measurements of the observed CMB temperature $\langle T\rangle^{\rm obs}$ at our position by averaging the CMB temperature measurements over the sky.

The final released value [7] of the COBE FIRAS measurements is $\langle T\rangle^{\rm obs}=2.728\pm0.004$ K, and the measurements were later further calibrated in Ref. [8] by using the WMAP differential temperature measurements [9]: $\langle T\rangle^{\rm obs}=2.7255\pm5.7\times10^{-4}$ K. This measurement of the CMB temperature with exquisite precision underpins the standard practice in which the background CMB temperature $\bar{T}$ is set equal to the observed CMB temperature $\langle T\rangle^{\rm obs}$ *without any error* associated with this number. Reference [10] investigated the impact of the measurement error of $\langle T\rangle^{\rm obs}$ on the other cosmological parameters and found a negligible inflation of their error bars.

In this paper, we show that this practice is *formally incorrect*, because it neglects the uncertainty related to cosmic variance [11]: i.e., the fact that we can only observe a single light cone. Instead, $\bar{T}$ should *in principle* be considered as an extra free cosmological parameter to be varied in the Bayesian analysis. With $\bar{T}\equiv\langle T\rangle^{\rm obs}$, the standard practice leads to underestimation of the error bars on the cosmological parameters (consistent with the results in Ref. [10]) and to systematic biases in the cosmological parameter estimation (an effect absent in Ref. [10]), even in the era of future CMB experiments with virtually *no* measurement errors in $\langle T\rangle^{\rm obs}$. Although the overall impact on parameter estimation is negligible today, it might become relevant in the future.

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II. THE COSMOLOGICAL PARAMETER $\bar{T}$

The background CMB temperature $\bar{T}$ is really another of the cosmological parameters, such as the background matter density ω_m or the (background) Hubble parameter H_0, that are defined in a homogeneous and isotropic universe and control the evolution of the perturbations in an inhomogeneous universe. The observed CMB temperature $\langle T\rangle^{\rm obs}$ from the COBE FIRAS is, on the other hand, obtained by averaging the CMB temperature measurements on the sky, and it differs from the background CMB temperature $\bar{T}$ due to the monopole perturbation Θ_0. As with any other physical quantities, the CMB temperature at a given position x and direction $\hat{n}$ in general includes not only the background $\bar{T}$, but also the perturbation $\Theta(x,\hat{n})$, and the separation of the background and the perturbation is made for our theoretical convenience. Therefore, when averaged over the sky at our position x_o, the observed CMB temperature can be expressed as $\langle T\rangle^{\rm obs}=\bar{T}(1+\Theta_0)$, where the monopole perturbation is

$$\Theta_0 \coloneqq \int \frac{d^2\hat{n}}{4\pi}\Theta(x_o,\hat{n}), \tag{1}$$

and we suppress the dependence of Θ_0 on the observer position x_o.

Compared to the other multipole moments Θ_l $(l\geq 1)$ in the CMB, the monopole is *not* an observable, as it is absorbed into the observed CMB temperature $\langle T\rangle^{\rm obs}$ together with the background temperature $\bar{T}$. Despite this peculiarity, the monopole perturbation Θ_0 at our position is very unlikely to be zero. The ergodic theorem states that once the fluctuations are averaged over a sufficiently large volume, the resulting average is equivalent to the ensemble average, or the average over many realizations of our Universe. While the ensemble average of the monopole is zero, it is shown in Ref. [11] that the angle average is *not* quite the ensemble average, as it is obtained only at our own position. This implies that if we were to perform the angle average of the CMB temperature at the Andromeda galaxy, we would obtain a value of $\langle T\rangle^{\rm obs}$ different from the COBE FIRAS result, due to the fluctuation of the monopole from place to place. Only if we could average the CMB temperature $\langle T\rangle^{\rm obs}(x)$ over all the possible observer positions would we be able to replace the average with the ensemble average and obtain the background CMB temperature $\bar{T}$. As this procedure is impossible, the background CMB temperature $\bar{T}$ can *never* be measured and needs to be treated as a free cosmological parameter, as with the other cosmological parameters.

As an extra cosmological parameter in the Bayesian analysis, the prior distribution of $\bar{T}$ should have a mean of $\langle T\rangle^{\rm obs}$ and a standard deviation $\sigma_{\ln\bar{T}}\simeq(\sigma^2_{\Theta_0}+\sigma^2_m)^{1/2}$, where $\sigma_m\sim 2\times 10^{-4}$ is the current measurement uncertainty and $\sigma_{\Theta_0}\sim 10^{-5}$ is the cosmic variance contribution of the monopole. Since currently $\sigma_m\sim 20\sigma_{\Theta_0}$, the effect of cosmic variance will be negligible as well. However, the fact that σ_m is already close to σ_{Θ_0} implies that future CMB measurements might cross the threshold. Note that the Planck team did allow $\bar{T}$ to vary in their analysis [12], but by *ignoring* the COBE FIRAS input at the prior level. The aim of this exercise was to establish how well $\bar{T}$ can be constrained by the anisotropy and galaxy clustering data *alone* and whether the result would be consistent with the COBE FIRAS measurement of $\langle T\rangle^{\rm obs}$, under the assumption $\bar{T}\equiv\langle T\rangle^{\rm obs}$.

III. CMB OBSERVATIONS AND THEORETICAL PREDICTIONS

In observations, the CMB temperature map as well as the polarization map obtained in the CMB experiments is decomposed with spherical harmonics Y_{lm} as $T^{\rm obs}(\hat{n})\coloneqq\sum_{lm}T^{\rm obs}_{lm}Y_{lm}(\hat{n})$, and the angular multipoles T_{lm} are used to construct the observed CMB power spectra $D^{\rm obs}_l\coloneqq\sum_m|T^{\rm obs}_{lm}|^2/(2l+1)$ for $l\geq 1$. The angle average of the CMB temperature is equivalent to the monopole $\langle T\rangle^{\rm obs}\equiv T^{\rm obs}_{00}/\sqrt{4\pi}$. The theoretical predictions are, however, based on the separation of the background and the perturbation around it, so that the CMB temperature is modeled as $T^{\rm obs}(\hat{n})\coloneqq\bar{T}(1+\Theta)$, and the angular decomposition of the temperature anisotropies $\Theta(\hat{n})\coloneqq\sum_{lm}a_{lm}Y_{lm}(\hat{n})$ yields the angular multipole a_{lm} and their power spectra $C_l\coloneqq\langle|a_{lm}|^2\rangle$, where the angular multipoles and the power spectra are both dimensionless, as opposed to the dimensionful quantities $T^{\rm obs}_{lm}$ and $D^{\rm obs}_l$ in observation.

The conversion between these quantities is trivial in theory: $T_{lm}\equiv\bar{T}a_{lm}$ and $D_l\equiv\bar{T}^2C_l$ for $l\geq 1$, but it is impossible in observation, as the background CMB temperature $\bar{T}$ is unknown. However, this poses *no* problem, as we can include an additional cosmological parameter $\bar{T}$ in our data analysis and obtain the best-fit value for $\bar{T}$ as the other (unknown) cosmological parameters in a given model. The problems arise because the data analysis is performed by fixing $\bar{T}\equiv\langle T\rangle^{\rm obs}$ by hand. This procedure results in two problems: (1) the background evolution in our theoretical predictions never matches the correct background in our Universe, unless the monopole at our position happens to be zero; and (2) by using $\langle T\rangle^{\rm obs}$ instead of $\bar{T}$, the observed temperature and the CMB power spectra are in practice compared to $T^{\rm obs}_{lm}/\langle T\rangle^{\rm obs}=a_{lm}/(1+\Theta_0)$ and

$$C^{\rm biased}_l\coloneqq\left\langle\frac{|a_{lm}|^2}{(1+\Theta_0)^2}\right\rangle=C_l\left(1+\frac{3}{4\pi}C_0+\cdots\right), \tag{2}$$

where the monopole of the power spectrum is $C_0\simeq 1.7\times 10^{-9}$ in our fiducial ΛCDM model. Though negligible in the Planck data analysis, point (1) causes systematic errors in the standard data analysis larger than point (2).

IV. UNDERESTIMATION OF THE ERROR BARS

One immediate consequence of the standard practice with $\bar{T} \equiv \langle T \rangle^{\rm obs}$ is the underestimation of the error bars on the cosmological parameters in a given model, as there exists one fewer degree of freedom in the parameter estimation than in reality. The true error bars on the cosmological parameters can be estimated by considering the full model with the extra cosmological parameter $p_0 \coloneqq \ln \bar{T}$ in addition to the standard model parameters p_i $(i = 1, \ldots, N)$, and by marginalizing over the nuisance parameter p_0. To estimate the inflation of the error bars, we adopt the Fisher information matrix formalism. For the Gaussian fluctuations on the sky, the Fisher matrix takes the standard form with one critical difference: the observables contain both the background and the perturbation. For CMB, the observables are $T_{lm}^{\rm obs}$ and $D_l^{\rm obs}$, and the Fisher matrix is then obtained in Ref. [13] as

$$F_{00} = \frac{4\pi}{C_0} + \sum_{l=2}^{\infty} \frac{2l+1}{2C_l^2} \left(2C_l + \frac{\partial C_l}{\partial \ln \bar{T}} \right)^2, \qquad (3)$$

$$F_{i0} = \sum_{l=2}^{\infty} \frac{2l+1}{2C_l^2} \left(\frac{\partial}{\partial p_i} C_l \right) \left(2C_l + \frac{\partial C_l}{\partial \ln \bar{T}} \right), \qquad (4)$$

$$F_{ij} = \sum_{l=2}^{\infty} \frac{2l+1}{2C_l^2} \left(\frac{\partial}{\partial p_i} C_l \right) \left(\frac{\partial}{\partial p_j} C_l \right), \qquad (5)$$

where the standard Fisher analysis corresponds to the submatrix of the full Fisher matrix ($F_{ij}^{\rm std} \equiv F_{ij}$). The true error bars on the cosmological parameters after marginalizing over p_0 can be obtained as the diagonal elements of the N-N submatrix

$$\sigma_p^2 = {\rm diag.} \left(F_{ij} - \frac{F_{i0} F_{0j}}{F_{00}} \right)^{-1} \qquad (6)$$

of the inverse of the full Fisher information matrix.

For the proof of concept, we apply the Fisher formalism to a CMB experiment like the Planck satellite, where we used the temperature $C_l^{\rm TT}$ at $l = 2 \sim 2500$, the polarization $C_l^{\rm EE}$ at $l = 2 \sim 2000$, and the cross $C_l^{\rm TE}$ power spectra at $l = 30 \sim 2000$ as our CMB observables. The Fisher matrix is computed by accounting for the covariance among the temperature and the polarization observables [14,15]. We adopt that the sky coverage is $f_{\rm sky} = 0.86$, the detector pixel noise is $\Delta_T^2 = (0.55\ \mu{\rm K\ deg})^2$, and the beam size is $\sigma_b = 7.22$ arcmin in FWHM for the 143 GHz channel. These specifications are taken into consideration in the Fisher matrix by modifying the factor $(2l+1)/2C_l^2$. Finally, for our fiducial cosmological parameters, we adopt the best-fit ΛCDM model parameters reported in Table 7 of the Planck 2018 results [5] (Planck alone). The CMB power spectra are computed by using the CLASS Boltzmann code [16].

Figure 1 illustrates the underestimation of the true error bars on the cosmological parameters in the standard practice. We consider three cases, in which the observed CMB temperature $\langle T \rangle^{\rm obs}$ is constrained with different precision: no measurement uncertainty ($\sigma_m \equiv 0$; solid), COBE FIRAS measurement uncertainty calibrated with the WMAP measurements (dotted), and original COBE FIRAS measurement uncertainty (dashed). In *none* of these three cases do we have the precise information about the background CMB temperature $\bar{T}$. However, given the monopole power $C_0 \simeq 1.7 \times 10^{-9}$, the 1σ rms fluctuation of the monopole is $\Theta_0 \equiv a_{00}/\sqrt{4\pi} \sim 1.2 \times 10^{-5}$, so the background CMB temperature $\bar{T}$ is likely to be within the current measurement uncertainty 6×10^{-4} K from $\langle T \rangle^{\rm obs} = 2.7255$ K.

Under the assumption that the monopole happens to vanish at our position, the standard data analysis underestimates the error bars on the cosmological parameters, for instance, by *two percent* for the baryon density ω_b, when the measurement of $\langle T \rangle^{\rm obs}$ from COBE FIRAS is calibrated with the WMAP measurements and by *tens of percent* when the original COBE FIRAS measurement is used. Note that the inflation of error bars in Fig. 1 is relative to the error bar in the standard practice. The amplitude A_s of the curvature perturbation is equally affected, while the angular size θ and the spectral index n_s are less sensitive. The inflation of the error bars is largely determined by two

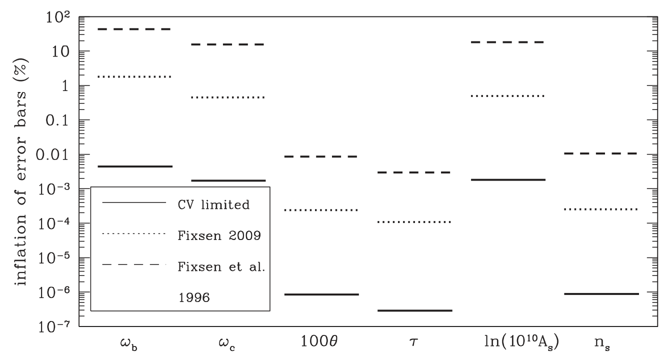

FIG. 1. Inflation of the error bars on the ΛCDM cosmological parameters, after the unknown background temperature $\bar{T}$ is accounted for. The errors are relative; e.g., 1% in the plot means that the true error bar σ is larger than $\sigma_{\rm std}$ in the standard practice by 1%: $\sigma = 1.01\sigma_{\rm std}$. By fixing $\bar{T} \equiv \langle T \rangle^{\rm obs}$, the error bars on the cosmological parameters are *underestimated* in the standard data analysis. Solid lines represent the future CMB experiment, in which *no* measurement errors exist in the observed CMB temperature $\langle T \rangle^{\rm obs}$ and only the cosmic variance contributes to the difference between $\bar{T}$ and $\langle T \rangle^{\rm obs}$. Dotted lines show the current status, in which the temperature measurement by FIRAS was calibrated with the WMAP data [8]: $\langle T \rangle^{\rm obs} = 2.7255 \pm 5.7 \times 10^{-4}$ K. Dashed lines show the previous status, representing the original FIRAS temperature measurement [7]: $\langle T \rangle^{\rm obs} = 2.728 \pm 0.004$ K.

factors: the uncertainty in $\bar{T}$ (or C_0 in F_{00}), and the correlation F_{i0} of the parameter p_i and the temperature $\bar{T}$ variations. F_{i0} is stronger for ω_b and ω_c, and this trend is amplified by the correlation $F^{-1}_{\rm std}$ among the model parameters. The error bars in A_s are enhanced largely by the parameter correlation. With an order-of-magnitude reduction of the uncertainty in $\langle T\rangle^{\rm obs}$ in Ref. [8], the inflation of the error bars (dotted) is less than a few percent for the ΛCDM cosmological parameters. Propagating the errors on ω_b, ω_c, and 100θ, we obtain the inflation of the error on the Hubble parameter h: 2%, 0.04%, 10^{-4}% for the three cases. What is important is to note that the error bars are *always* underestimated (solid lines) in the standard data analysis, even with *no* measurement uncertainty in $\langle T\rangle^{\rm obs}$ from future CMB experiments.

V. COSMOLOGICAL PARAMETER BIAS

By fixing $\bar{T}\equiv\langle T\rangle^{\rm obs}$, the standard data analysis contains systematic errors in terms of biases in the cosmological parameter estimation. Assuming that the systematic errors are small, the best-fit cosmological parameters p^b_μ are characterized by the parameter biases δp_μ from the true parameter set p^t_μ as $p^b_\mu \coloneqq p^t_\mu+\delta p_\mu$ $(\mu=0,1,\ldots,N)$, where in the standard practice $p^b_0\equiv \ln\langle T\rangle^{\rm obs}=\ln[\bar{T}(1+\Theta_0)]\simeq\ln\bar{T}+\Theta_0$, so that the parameter bias for $p_0=\ln\bar{T}$ is the unknown monopole at our position: $\delta p_0\equiv\Theta_0$.

The relation between two parameter sets can be obtained by considering that the likelihood $\mathcal{L}(p_\mu)$ of the CMB observables is maximized at the best-fit parameters p^b_μ:

$$0=\frac{\partial}{\partial p_i}\mathcal{L}\bigg|_{p^b_\mu}={\rm Tr}[\tilde{\mathbf{C}}^{-1}\tilde{\mathbf{C}}_{,i}] - {\rm Tr}[\tilde{\mathbf{C}}^{-1}\tilde{\mathbf{C}}_{,i}\tilde{\mathbf{C}}^{-1}(d^{\rm obs}-\tilde{\mu})(d^{\rm obs}-\tilde{\mu})^{\rm T}], \tag{7}$$

where the commas represent derivatives of the covariance matrix $\mathbf{C}$ with respect to the parameter p_i, and the observed data set $d^{\rm obs}$ includes the observed temperature and polarization anisotropies. The covariance matrix $\mathbf{C}(p_\mu)$ and the mean $\mu(p_\mu)$ are the theoretical predictions in a given model, where $\mu=\bar{T}$ for temperature anisotropies and $\mu=0$ for polarization anisotropies. However, due to the assumption $\bar{T}\equiv\langle T\rangle^{\rm obs}$ in the standard practice, the theoretical predictions for $\mathbf{C}$ and μ depend only on the model parameters p_i, but *not* on $\bar{T}$, and we use the tilde to represent that the theoretical predictions are evaluated at p^b_μ, not at p^t_μ.

Using the spherical harmonics decomposition, the condition for the best-fit parameter set is expressed as

$$0=\sum_{l=2}^{\infty}(2l+1)\tilde{C}_l^{-1}\frac{\partial}{\partial p_i}\tilde{C}_l\left[1-\frac{1}{2l+1}\sum_m\frac{\bar{T}^2|a^{\rm obs}_{lm}|^2}{(\langle T\rangle^{\rm obs})^2\tilde{C}_l}\right], \tag{8}$$

where the power spectra $\tilde{C}_l$ account for the covariance among the temperature, the polarization, and their cross power spectra together with the detector noise and beam smoothing [14,15]. To make further progress, we take the ensemble average to replace the ratio of $a^{\rm obs}_{lm}$ and $\langle T\rangle^{\rm obs}$ with $C^{\rm biased}_l$ and expand the power spectra around p^b_μ as

$$C^{\rm biased}_l(p^t_\mu)\simeq\tilde{C}_l\left(1+\frac{3}{4\pi}\tilde{C}_0-\frac{\partial\ln\tilde{C}_l}{\partial\ln\bar{T}}\Theta_0-\frac{\partial\ln\tilde{C}_l}{\partial p_i}\delta p_i\right), \tag{9}$$

where the first correction arises from $C^{\rm biased}_l$ and the remaining corrections arise due to the difference between p^b_μ and p^t_μ. Ignoring the small correction due to the first term, the cosmological parameter bias can be neatly expressed as

$$\delta p_i=-(F^{-1}_{\rm std})_{ij}F_{j0}\Theta_0, \tag{10}$$

and it is in proportion to the amplitude of the unknown monopole at our position, while it is independent of the measurement uncertainty in $\langle T\rangle^{\rm obs}$, given our assumption $p^t_\mu\simeq p^b_\mu$.

Figure 2 shows the bias δp_i in units of the parameter's standard deviation σ_{p_i} in the best-fit cosmological parameters with Θ_0 assumed to be at 1σ fluctuation. If the monopole happened to *vanish* at our position, there would be *no* bias in the cosmological parameters by using the standard practice. However, if the monopole at our position is *nonzero*, the standard analysis yields the biases in the

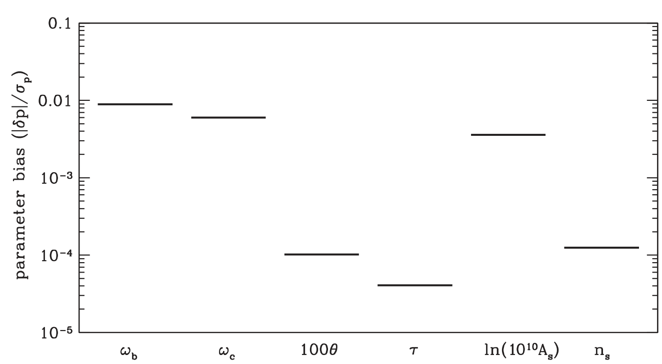

FIG. 2. Bias, δp_i, in the best-fit cosmological parameters, in terms of the standard deviation σ_{p_i}. The amplitude of the monopole at our position is assumed to be at 1σ fluctuation: $\Theta_0\equiv1.2\times10^{-5}$. The cosmological parameter bias is independent of the measurement uncertainty in $\langle T\rangle^{\rm obs}$, but in proportion to the amplitude of the monopole.

best-fit cosmological parameters in proportion to the unknown amplitude of the monopole. For instance, the baryon density parameter ω_b is off by $0.01\,\sigma_{\omega_b}$ at 1σ fluctuation of Θ_0, and this level of bias is *readily tolerable* today. While the biases in ω_c and $\ln(10^{10}A_s)$ are of similar magnitude, their error bars are larger, and hence the impacts are slightly smaller. The impacts for 100θ, τ, and n_s are negligible.

VI. CONCLUSIONS

We showed that in principle, the background CMB temperature $\bar{T}$ has to be considered as an unknown cosmological parameter, because the observed (angle-average) CMB temperature $\langle T\rangle^{\mathrm{obs}}$ includes the unknown monopole contribution at our position. We investigated the impact of this "new" cosmological parameter $\bar{T}$ on the CMB data analysis. With the current uncertainty in $\langle T\rangle^{\mathrm{obs}}$, the standard data analysis underestimates the error bars on the cosmological parameters by a relative amount of up to 2%, and if the monopole is *nonvanishing* at our position, the best-fit cosmological parameters in the standard analysis are biased by about 1% of their current standard deviation, or 1σ error bar.

We conclude that these systematic errors are *negligible* in the Planck data analysis, providing a further justification to the standard practice. However, these systematic errors are *always* present and irreducible in the standard data analysis, so that cosmological measurements might be misinterpreted in future experiments with better precision than the Planck satellite. Of course, these systematic errors can be readily avoided by including one extra cosmological parameter $\bar{T}$.

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