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Probing the primordial Universe from the low-multipole CMB data

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ABSTRACT

Since the temperature fluctuations in the cosmic microwave background (CMB) on large-angular scales probe length scales that were super-horizon sized at photon decoupling and hence insensitive to microphysical processes, the low-multipole CMB data are supposed to be a good probe to the physics of the primordial Universe. In this letter we will constrain the cosmological parameters in the base ΛCDM model with tensor perturbations by only using the low-multipole CMB data, including Background Imaging of Cosmic Extragalactic Polarization (B2), Planck data released in 2013 (P13) and Wilkinson Microwaves Anisotropy Probe 9-year data (W9). We find that either sign of the index of the tensor power spectrum is compatible with the data, but a blue-tilted power spectrum of scalar perturbations on large scales is preferred at around 2σ confidence level.

The cosmic microwave background (CMB) is the oldest light in the Universe, dating to the epoch of photon decoupling. Since the CMB encodes important physics about the Universe, the precise measurements of the CMB are critical to cosmology. See a nice review about the CMB in [1]. In particular, the temperature fluctuations measured between two points separated by a large angle ($\gtrsim 1°$) arise mainly due to the difference in the gravitational potential between the two points on the last-scattering surface. This is known as the Sachs–Wolfe effect [2]. On such large scales any causal effects have not had time to operate. Considering that the evolution of the gravitational potential caused by the dark energy which becomes dominant in the late-time Universe, the integrated Sachs–Wolfe effect [2] should not be completely ignored. Once we go to angular scales below the Sachs–Wolfe plateau, the C_ℓ curves depend sensitively on a lot of microphysics characterized by a large number of parameters, such as the total mass of active neutrinos ($\sum m_\nu$), the number of relativistic species ($N_{\rm eff}$), the gravitational lensing, the abundance of light elements and so on.

Nowadays inflation [3–5] becomes the dominant paradigm for the early Universe. Not only does it solve the puzzles of the hot big bang model, such as the flatness problem, the horizon problem and so on, but it provides a causal origin of the density perturbations even on the large scales that were outside the horizon at the time of recombination. According to general relativity, there are three kinds of perturbations, namely scalar, vector and tensor (gravitational waves) perturbations. At the linear order, these three kinds of perturbations evolve independently and therefore we can analyze them separately. Since there are no rotational velocity fields during inflation, the vector perturbations are not excited. Thus we only need to consider the scalar and gravitational waves perturbations.

An adiabatic, Gaussian and nearly scale-invariant power spectrum of scalar perturbations has been confirmed by many cosmological observations, such as Wilkinson Microwaves Anisotropy Probe 9-year data (W9) [6] and Planck data released in 2013 (P13) [7]. Actually the gravitational waves can make contributions to the temperature and polarization power spectra in the CMB [8–16] as well. In the last decades, many groups tried their best to hunt for the signal of gravitational waves. Even though some hints of it were revealed in the CMB in [17,18], the statistic significances were quite low (around 1σ confidence level). Since the relic gravitational waves damp significantly inside the horizon, one could only expect to find the relic gravitational waves on very large scales.

Recently Background Imaging of Cosmic Extragalactic Polarization (B2) [19] detected an excess of B-mode power over the base lensed-ΛCDM expectation in the range of $30 \lesssim \ell \lesssim 150$ multipoles. The signal can be interpreted either as a detection of the primordial gravitational waves or as the microwave emission by the polarized dust [20,21]. Even though the BICEP2 Collaboration also agreed that the external public data cannot sufficiently exclude the possibility of dust emission in the published version [19],

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here we suppose that it mainly comes from the primordial gravitational waves and then

$$r = 0.20^{+0.07}_{-0.05}, \tag{1}$$

and $r = 0$ is disfavored at 7.0σ, where r is the so-called tensor-to-scalar ratio which is nothing but the ratio between the amplitudes of relic gravitational waves and scalar perturbations. However, in 2013 the Planck Collaboration claimed that there is no signal for the relic gravitational waves at all, and the upper bound on the tensor-to-scalar ratio is given by $r < 0.11$ at 95% confidence level [7] in the base six-parameter ΛCDM model where a power-law scalar power spectrum is assumed. Obviously there is a strong tension between B2 [19] and P13 [7]. Considering the CMB spectra generated by the relic gravitational waves are significant only on large scales, in [18] we combined the low-ℓ TT spectrum from P13 and TE spectrum from W9, and found that $r > 0$ is preferred at more than 68% confidence level. A possible explanation is that the apparent tension between B2 and P13 is coming from the "wrong" theoretical model, namely the base ΛCDM model with a power-law scalar power spectrum, adopted by the Planck Collaboration.

In order to reduce the possible effects from the other complicated microphysics, we propose to only utilize the low-ℓ CMB data to probe the physics of the primordial Universe because the large-angle anisotropies in the CMB are not affected by any microphysics at the time of recombination. Since the Sachs–Wolfe effect becomes dominant on large angles ($\gtrsim 1^\circ$) roughly corresponding to the multipoles smaller than $\ell_\theta = \pi/\theta \simeq 180$ and an excess of B-mode power over the base lensed-ΛCDM expectation was detected by B2 in the range of $30 \lesssim \ell \lesssim 150$ multipoles [19], we suppose to choose $\ell_{\max} = 150$ as the upper cutoff of CMB multipoles. In this letter we will consider two combinations of CMB data with $\ell_{\max} = 150$:

- one is B2+W9 (including EE, EB and BB from B2 and TT and TE from W9);
- the other is B2+P13+WP (including EE, EB and BB from B2, TT from P13 and TE from W9).

Here the ΛCDM model with tensor perturbations is adopted. The physics of the primordial Universe is assumed to be encoded in both power spectra of the scalar perturbations and relic gravitational waves which are respectively parameterized by

$$P_s(k) = A_s\left(\frac{k}{k_p}\right)^{n_s-1}, \tag{2}$$

$$P_t(k) = rA_s\left(\frac{k}{k_p}\right)^{n_t}, \tag{3}$$

where n_s and n_t are the spectral indices of the scalar and relic gravitational waves spectra respectively. In this letter the pivot scale is fixed to be $k_p = 0.004\ \mathrm{Mpc}^{-1}$. Since $\ell_{\max} = 150$ and the data do not cover a wide perturbation modes, the power-law spectra of both scalar and relic gravitational waves in Eqs. (2) and (3) are assumed to be applicable. The other free cosmological parameters are the baryon density today ($\Omega_b h^2$), the cold dark matter density today ($\Omega_c h^2$), the 100× angular scale of the sound horizon at last-scattering ($100\theta_{\mathrm{MC}}$) and the Thomson scattering optical depth due to the reionization (τ).

First of all, we take the tilt of the tensor power spectrum as a free parameter n_t. We run the CosmoMC [22] to fit the eight free running cosmological parameters, namely $\{\Omega_b h^2, \Omega_c h^2, \theta, \tau, A_s, n_s, r, n_t\}$. Our results show up in Table 1 and Fig. 1. From Table 1 and Fig. 1, we see that the constraints on the cosmological parameters from the low-ℓ B2+W9 are consistent with those from

Table 1
Constraints on the cosmological parameters from low-ℓ CMB data in the ΛCDM + r model with n_t free.

n_t free	B2+W9 ($\ell_{\max} = 150$)		B2+P13+WP ($\ell_{\max} = 150$)	
Parameters	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.0235	$0.0248^{+0.0070}_{-0.0113}$	0.0283	$0.0264^{+0.0078}_{-0.0141}$
$\Omega_c h^2$	0.159	$0.160^{+0.033}_{-0.045}$	0.157	$0.141^{+0.018}_{-0.030}$
$100\theta_{\mathrm{MC}}$	1.145	$1.108^{+0.050}_{-0.038}$	1.140	$1.100^{+0.044}_{-0.026}$
τ	0.102	$0.097^{+0.015}_{-0.018}$	0.109	$0.098^{+0.015}_{-0.018}$
$\ln(10^{10}A_s)$	3.058	$3.068^{+0.071}_{-0.059}$	3.035	$3.058^{+0.068}_{-0.053}$
n_s	1.117	$1.109^{+0.070}_{-0.056}$	1.082	$1.047^{+0.065}_{-0.054}$
r	0.22	$0.22^{+0.08}_{-0.12}$	0.16	$0.20^{+0.07}_{-0.14}$
n_t	0.01	$0.07^{+0.26}_{-0.51}$	0.44	$0.43^{+0.36}_{-0.67}$

low-ℓ B2+P13+WP. We find that either sign of the index of the tensor power spectrum is compatible with the combinations of both B2+W9 and B2+P13+WP with $\ell_{\max} = 150$. It is consistent with our previous results in [23] where only B2 data are adopted.

From now on, let's switch to constrain the canonical single-field slow-roll inflation model in which there is a consistency relation between the tensor-to-scalar ratio r and the tilt of the tensor power spectrum n_t, namely $n_t = -r/8$ [24]. Therefore here are seven free running parameters: $\{\Omega_b h^2, \Omega_c h^2, \theta, \tau, A_s, n_s, r\}$. Similar to the former case, we also run the CosmoMC [22] to work out the constraints on these cosmological parameters. See the results in Table 2 and Fig. 2. The combinations of both B2+W9 and B2+P13+WP with $\ell_{\max} = 150$ give similar results. In [25] we used all of data in B2 and W9 to constrain the cosmological parameters. Compared to [25], we see that there is no tension between the results we get in this letter and those in [25]. But here a blue-tilted scalar power spectrum is preferred at 2.0σ level from B2+W9 and at 1.8σ level from B2+P13+WP respectively if only the low-ℓ CMB data ($\ell_{\max} = 150$) are adopted. Here we need to stress that the low-ℓ CMB data can significantly reduce the possible effects from the complicated microphysics at the time of recombination, and the results in this letter are supposed to directly response to the physics in the primordial Universe.

In this letter we only consider the CMB data from $\ell = 2$ to $\ell = 150$ which roughly correspond to $\Delta N = \ln(150/2) \simeq 4.3$ e-folding numbers during inflation. During this short period, the inflaton field changes by $|\Delta\phi|/M_p = \sqrt{r/8}\Delta N \simeq 0.7$. Similar to [25], we consider several large field inflation models. Because the contours in the left panel of Fig. 2 stay on the right hand side of the red solid line corresponding to $V(\phi) \sim \phi$, it implies that the potential of the inflaton field is convex. The region between the two gray dashed lines corresponds to the prediction of the chaotic inflation [26] with potential $V(\phi) \sim \phi^n$ for $n > 0$, and the green dashed line corresponds to the prediction of the power-law inflation [27] where the potential of the inflaton field goes like $V(\phi) = V_0 \exp(-\sqrt{2/p}\,\phi/M_p)$. Compared to the constraints from low-ℓ CMB data, both the chaotic and power-law inflation models are marginally disfavored at around 2σ confidence level. But the inflation model with inverse power-law potential $V(\phi) \sim 1/\phi^n$ for $n > 0$ [25,28] predicts $n_s = 1 - \frac{n-2}{8n} r$ which implies that the scalar power spectrum is blue-tilted if $n < 2$. For an instance, the prediction in the model with $n = 1/2$ corresponds to the black solid line in the left panel of Fig. 2, and we see that such a model can fit the data quite well.

In addition, space–time is in general non-commutative in string theory [29–31], namely

$$\Delta t \Delta x \gtrsim l_s^2, \tag{4}$$

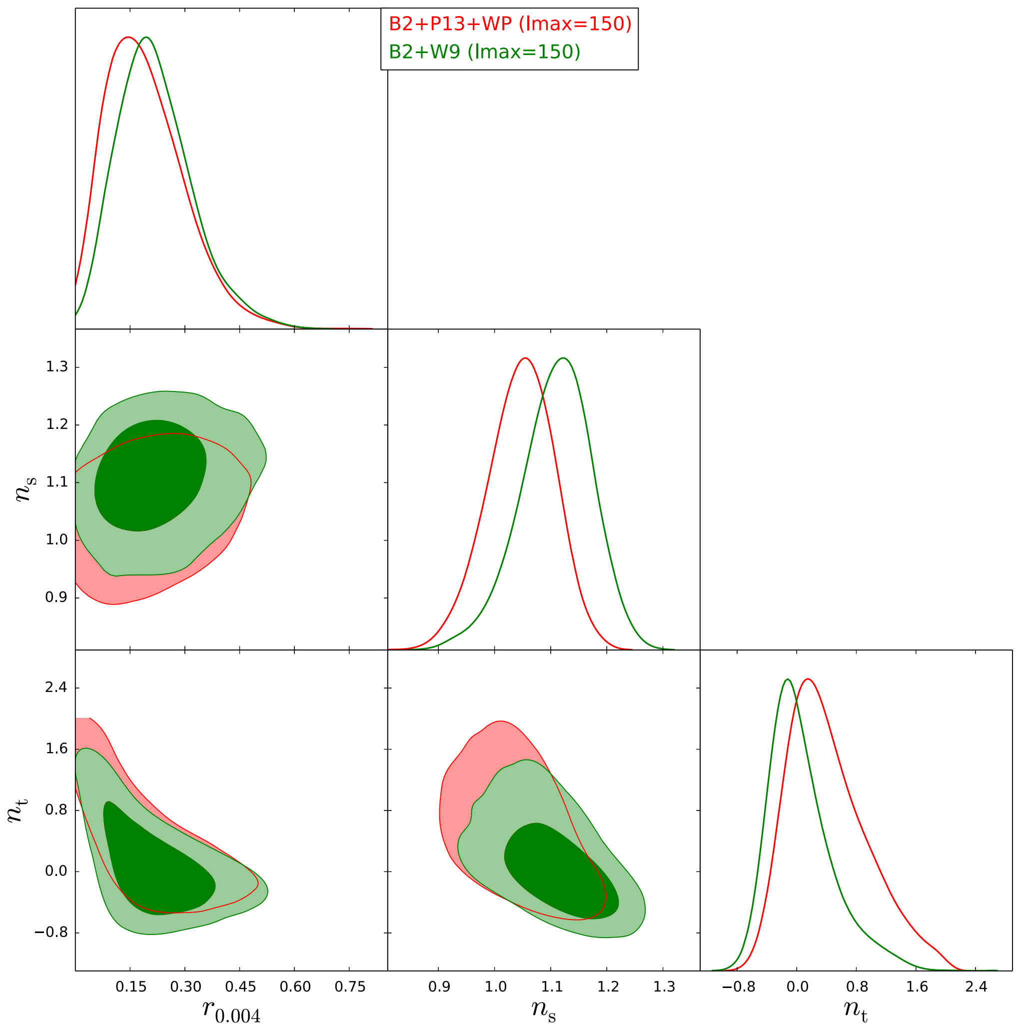

Fig. 1. The contour plots for r, n_s and n_t and their likelihood distributions from low-ℓ CMB data in the ΛCDM + r model with n_t free.

Table 2
Constraints on the cosmological parameters from low-ℓ CMB data in the ΛCDM + r model with $n_t = -r/8$.

$n_t = -r/8$	B2+W9 ($\ell_{max} = 150$)		B2+P13+WP ($\ell_{max} = 150$)	
Parameters	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.0192	$0.0270^{+0.0074}_{-0.0104}$	0.0209	$0.0263^{+0.0077}_{-0.0149}$
$\Omega_c h^2$	0.140	$0.166^{+0.029}_{-0.046}$	0.141	$0.141^{+0.018}_{-0.038}$
$100\theta_{MC}$	1.116	$1.104^{+0.046}_{-0.048}$	1.142	$1.098^{+0.044}_{-0.027}$
τ	0.095	$0.099^{+0.015}_{-0.018}$	0.105	$0.099^{+0.015}_{-0.018}$
$\ln(10^{10} A_s)$	3.106	$3.051^{+0.061}_{-0.054}$	3.021	$3.024^{+0.065}_{-0.057}$
n_s	1.098	$1.104^{+0.052}_{-0.051}$	1.120	$1.074^{+0.056}_{-0.042}$
r	0.19	$0.26^{+0.07}_{-0.11}$	0.23	$0.28^{+0.07}_{-0.12}$

where $l_s = 1/M_s$ is the string length scale. In [32–34], the effect of space–time non-commutativity makes an extra contribution to the spectral index in the canonical single-field slow-roll inflation model,

$$n_s = 1 - 6\epsilon + 2\eta + 16\epsilon\mu, \quad (5)$$

where $\epsilon = \frac{M_p^2}{2}(\frac{V'}{V})^2$ and $\eta = M_p^2 \frac{V''}{V}$ are the slow-roll parameters, and $\mu = H^2 p^2 / M_s^4$. Here H is the Hubble parameter during inflation and $p = k/a$ is the physical momentum mode of perturbation with comoving Fourier mode k. The tensor-to-scalar ratio in the space–time non-commutative inflation is still given by $r = 16\epsilon$, and thus the correction to the spectral index from the effect of space–time non-commutativity is $\Delta n_s = +r\mu$. For example, for $r \simeq 0.2$ and $\mu \simeq 1/2$, $\Delta n_s \simeq 0.1$ which implies that the effect of the space–time non-commutativity may help both the chaotic and power-law inflation models to fit the data if the effect of the space–time non-commutativity is not negligibly small, or equivalently $\mu \sim \mathcal{O}(1)$. For example, for the power-law inflation model with $p = 80$, the tensor-to-scalar ratio is $r = 16/p = 0.2$ and the spectral index of the scalar power spectrum is $n_s = 1 - 2/p + r\mu = 1.075$ if $\mu = 1/2$. A comprehensive discussion about the inflation model in the non-commutative space–time shall be done elsewhere in the near future.

To summarize, we propose to adopt the low-ℓ CMB data to probe the physics of the primordial Universe. We find that either sign of the index of the tensor power spectrum is compatible with the data quite well, but the scalar power spectrum is preferred to be blue-tilted at around 2σ confidence level. The constraints on the cosmological parameters from the combination of B2+W9 are roughly the same as those from B2+P13+WP. It is reasonable because the statistic errors in the low-ℓ CMB data are dominated by the cosmic variance.

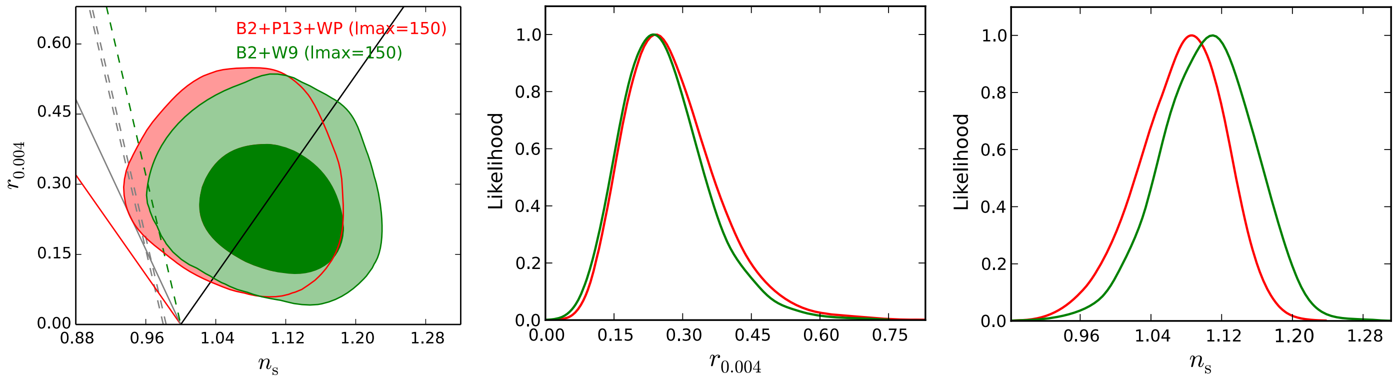

Fig. 2. The contour plot of r and n_s and their likelihood distributions from low-ℓ CMB data in the ΛCDM + r model with $n_t = -r/8$. The red solid line corresponds to the inflation model with $V(\phi) \sim \phi$. The region between the two gray dashed lines corresponds to the e-folding number within $N \in [50, 60]$ for the inflation models with potential $V(\phi) \sim \phi^n$, and the gray solid line corresponds to $V(\phi) \sim \phi^2$. The green dashed line shows the prediction of the power-law inflation with potential $V(\phi) = V_0 \exp(-\sqrt{2/p}\phi/M_p)$. The black solid line corresponds to the prediction of the inflation model with inverse power-law potential $V(\phi) \sim 1/\phi^{1/2}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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