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Blue gravity waves from BICEP2?

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We present new constraints on the spectral index n_T of tensor fluctuations from the recent data obtained by the BICEP2 experiment. We found that the BICEP2 data alone slightly prefer a positive, "blue," spectral index with $n_T = 1.36 \pm 0.83$ at 68% C.L. However, when a TT prior on the tensor amplitude coming from temperature anisotropy measurements is assumed, we get $n_T = 1.67 \pm 0.53$ at 68% C.L., ruling out a scale-invariant $n_T = 0$ spectrum at more than three standard deviations. These results are at odds with current bounds on the tensor spectral index coming from pulsar timing, big bang nucleosynthesis, and direct measurements from the LIGO experiment. Considering only the possibility of a "red" $n_T < 0$ spectral index, we obtain the lower limit $n_T > -0.76$ at 68% C.L. ($n_T > -0.09$ when a TT prior is included).

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I. INTRODUCTION

The recent detection of B-mode polarization made by the BICEP2 experiment [1] clearly represents one of the major discoveries in cosmology in the past 20 years. While the BICEP2 result clearly needs to be confirmed by future experiments, it is timely and important to fully analyze the BICEP2 data and to identify all possible inconsistencies at the theoretical level.

In this brief paper, we focus our attention on the spectral index of tensor fluctuations n_T. Indeed, a crucial prediction of inflation is the production of a stochastic background of gravity waves [2] with a slightly tilted spectrum,

$$n_T = -2\epsilon, \tag{1}$$

where $\epsilon = -\dot{H}/H^2$ denotes a slow-roll parameter from inflation (H is the Hubble rate during the inflationary stage).

In standard inflation, ϵ is strictly positive [4], and in the usual parameter estimation routines, the tensor spectral index is assumed to be "red," or negligible.

However, in recent years, a set of inflationary models has been elaborated where the spectral index of tensor modes could be positive, $n_T > 0$, i.e., "blue" [3].

A first attempt to compare these models with observational data has been made in [5].

The main theoretical problem for the production of a blue spectrum of gravitational waves (BGW) is that the stress-energy tensor must violate the so-called null energy condition (NEC). In a spatially flat Friedman-Robertson-Walker metric, a violation of NEC indeed corresponds to the inequality $\dot{H} < 0$ and is ultimately the reason for the red tensor spectrum in standard inflation.

Models that violate NEC have been already presented. For example, in the so-called superinflation models [10], where inflation is driven by a component violating the NEC, a BGW spectrum is expected. Blue tensor spectra are also robust predictions of the pre-big bang scenario [8]. Models based on string gas cosmology as in [6], where scalar metric perturbations are thought to originate from initial string thermodynamic fluctuations [7], can also explain a BGW background. A BGW spectrum is also a generic prediction of a class of four-dimensional models with a bouncing phase of the Universe [9]. To induce the bounce, the stress-energy tensor must violate the NEC. G inflation [11] has a Galileon-like nonlinear derivative interaction in the Lagrangian with the resultant equations of motion being of second order. In this model, violation of the NEC can occur, and the spectral index of tensor modes can be blue. BGW may also be present in scalar-tensor theories and $f(R)$ gravity theories.

It is therefore timely to investigate the constraints on the tensor spectral index n_T from the BICEP2 data. Strangely enough, no constraint on this parameter has been presented by the BICEP2 collaboration while, as we discuss in the next section, we found that the BICEP2 data could provide interesting results on this parameter.

II. ANALYSIS METHOD

Our analysis method is based on the Boltzmann CAMB code [13] and a Monte Carlo Markov Chain (MCMC) analysis based on the MCMC package COSMOMC [12] (version December 2013). We have implemented in the MCMC package the likelihood code provided by the BICEP2 team (we just use B-mode Polarization Power Spectrum data) and considered as free parameters the ratio of the tensor to scalar amplitude r at $0.01h\,\mathrm{Mpc}^{-1}$, defined as $r_{0.01}$, and the tensor spectral index n_T. We prefer to use the pivot scale at $k = 0.01h\,\mathrm{Mpc}^{-1}$ since the BICEP2 data are most sensitive to multipole $l \sim 150$ and using the approximate formula $l \sim 1.35 \times 10^4 k$.

All of the remaining parameters have been kept fixed at the Planck + WP best fit values for the LCDM + r scenario (see [14]) with the running of the scalar spectral index fixed to zero.

Moreover, since the tensor amplitude should also be consistent with the upper limits on r coming from measurements of the temperature power spectrum, we have

TABLE I. Constraints at 68% C.L. on $r_{0.01}$ and n_T parameters for the cases described in the text. A blue spectral index ($n_T > 0$) is strongly suggested when a TT prior of $r_{0.002} < 0.11$ at 95% C.L. is included in the analysis.

Case	$r_{0.01}$	n_T
n_T free	0.19 ± 0.06	1.36 ± 0.83
TT prior + n_T free	0.18 ± 0.05	1.67 ± 0.53
$n_T < 0$	0.22 ± 0.06	$n_T > -0.76$
TT prior + $n_T < 0$	0.15 ± 0.03	$n_T > -0.09$

assumed a prior of $r_{0.002} < 0.11$ at 95% C.L. (see [15]). We refer to this prior as the "TT" prior.

Note that the TT prior is taken at much larger scales, $k = 0.002h\,\mathrm{Mpc}^{-1}$, than those sampled by the BICEP2 experiments. As we show in the next section, this prior is extremely important for the constraints on n_T.

III. RESULTS

The results of our analysis are reported in Table I and Fig. 1. We consider four cases: n_T free, n_T free but with the TT prior, n_T assumed to be negative ($n_T < 0$), and n_T assumed to be negative plus the TT prior.

We can derive the following conclusions:

(i) The BICEP2 data alone slightly prefer a positive spectral index. The case $n_T = 0$ is consistent with the data in between two standard deviations.

(ii) When a TT prior of $r_{0.002} < 0.11$ at 95% C.L. is assumed, the BICEP2 data strongly prefer a blue spectral index with $n_T \leq 0$ excluded at more than three standard deviations.

(iii) If we restrict the analysis to negative n_T, we obtain a lower limit of $n_T > -0.76$ at 68% C.L. ($n_T > -0.09$ in case of the TT prior).

A crucial point in discussing the reliability of the BICEP2 result is the possible contamination from galactic dust. In [1], a galactic dust template was presented (named "DDM1") using the best available information on this component. However, since there is virtually no experimental constraint on the amplitude of the dust component, it is interesting to investigate the possible impact of dust on the conclusions presented here on the tensor index n_T.

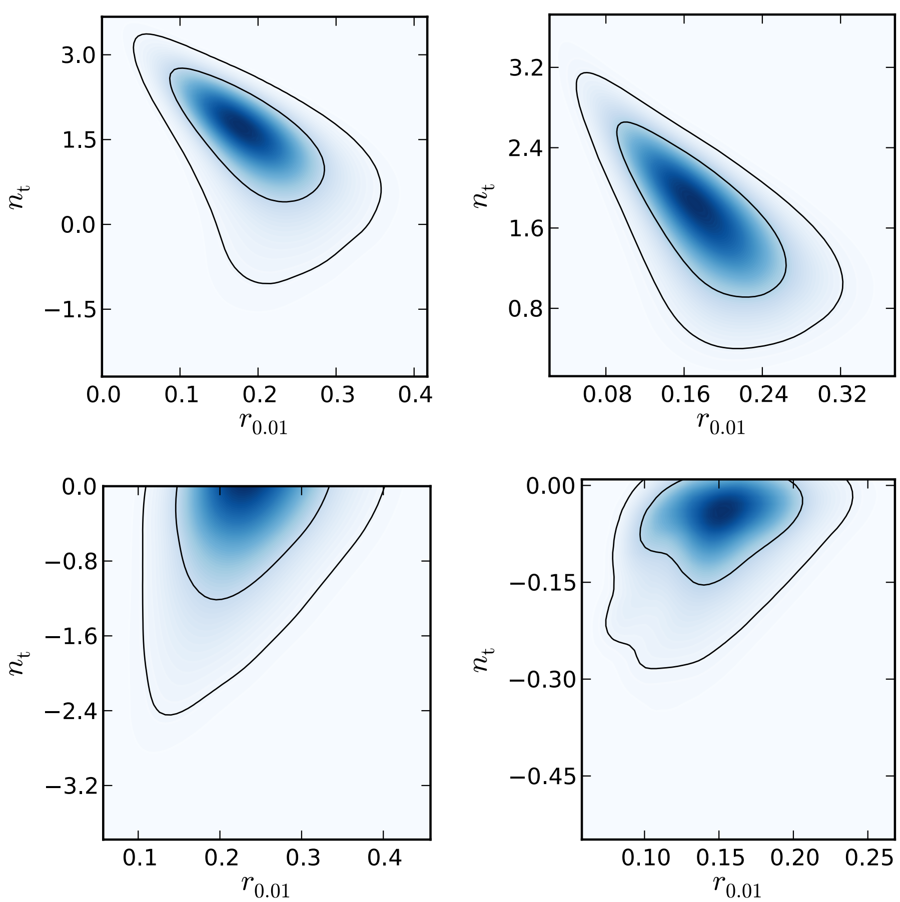

FIG. 1 (color online). Constraints on the n_T vs $r_{0.01}$ plane for the four cases discussed in the analysis. (Top left) No prior on n_T. (Top right) No prior on n_T but TT prior on $r_{0.002}$. (Bottom left) $n_T < 0$ (bottom left). (Bottom right) $n_T < 0$ and TT prior on $r_{0.002}$.

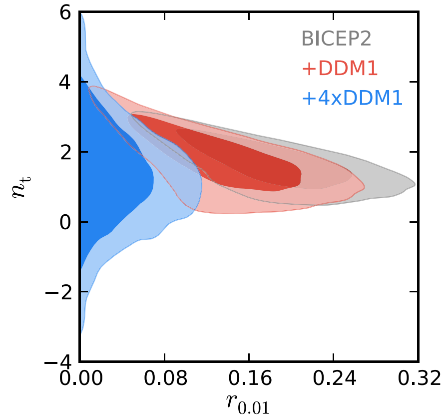

FIG. 2 (color online). Constraints on the $r_{0.01}$ vs n_T plane for BICEP2 + TT prior case for three different dust components: no dust component, DDM1 template, and a component four times larger than the DDM1 estimate.

In this respect, we repeated our analysis, allowing the possibility of a dust component. We considered two possible cases: a dust component compatible with the DDM1 template and a component with an amplitude four times larger than the DDM1 template.

The results of this analysis are reported in Fig. 2. As we see, allowing for a DDM1 component does not change significantly our results for the BICEP2 plus TT prior case, with $r_{0.01} = 0.13 \pm 0.05$ and $n_T = 1.79 \pm 0.77$ at 68% C.L. That is, if the real dust component is in agreement with the estimates made by the BICEP2 team, the evidence for a blue tensor spectrum is still present, and vice versa, if the real dust component is larger by a factor of 4 with respect to the BICEP2 estimates, then we found $r_{0.01} < 0.044$ and n_T as unconstrained; i.e., not only there is no evidence for a blue GW spectrum but also the BICEP2 indication for a GW background vanishes.

IV. CONCLUSIONS

In this brief paper, we have presented the first constraints on the spectral index n_T of tensor fluctuations from the recent data obtained by the BICEP2 experiment. We found that the BICEP2 data alone slightly prefer a positive, blue, spectral index with $n_T = 1.36 \pm 0.83$ at 68% C.L. However, when a TT prior on the tensor amplitude coming from temperature anisotropy measurements is assumed, we get $n_T = 1.67 \pm 0.53$ at 68% C.L., ruling out a scale-invariant $n_T = 0$ spectrum at more than three standard deviations. Considering only the possibility of a red $n_T < 0$ spectral index, we obtain the lower limit $n_T > -0.76$ at 68% C.L. ($n_T > -0.09$ when a TT prior is included).

These results are at odds with current upper limits on the tensor spectral index coming from observations of pulsar timing, big bang nucleosynthesis, and direct upper limits from the LIGO experiment (see, e.g., [16]).

Considering $r_{0.01} = 0.2$ and using the method adopted in [16], we found the current upper limits on n_T: $n_T \leq 0.52$, $n_T \leq 0.28$, and $n_T \leq 0.12$ at 68% C.L. from pulsar timing, LIGO [19] and BBN, respectively. The LIGO and BBN limits are in strong tension with the BICEP2 + CMB value. Therefore, a positive spectral index does not provide an acceptable solution to the tension between the BICEP2 data and current upper limits on r from temperature anisotropies. While all of these limits are on scales of significantly different order of magnitude, this may indicate either the need of further extensions to the LCDM model (as a running of the scalar spectral index [1] or extra neutrino species [17]) to relax the CMB temperature bound on $r_{0.002}$ or the presence of unresolved systematics. In this respect, we investigated the impact of a possible unaccounted dust component. We have found that while a dust component compatible with the DDM1 template presented in [1] does not alter the conclusions presented in this paper, considering a component four times larger will drastically change our results. Since at the moment there are no experimental data available that can clarify the real amplitude of this component, the results presented here on the tensor spectral index need to be considered with great caution.

During the submission of this paper, other works appeared discussing the possibility of a BGW from BICEP2 (see [18]), but without presenting numerical constraints on n_T and an independent analysis of the BICEP2 data. We also point out the discussion on the cosmocoffee.info website, where results similar to ours have been presented by Antony Lewis.

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