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Observational Hints of a Pre–Inflationary Scale?

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Abstract

We argue that the lack of power exhibited by cosmic microwave background (CMB) anisotropies at large angular scales might be linked to the onset of inflation. We highlight observational features and theoretical hints that support this view, and present a preliminary estimate of the physical scale that would underlie the phenomenon.

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Introduction. It is usually stated that the large scale Universe is fully characterized by the six parameters of the ΛCDM model [1, 2, 3]. Some features, however, are not well captured, and for instance anomalies occur at the largest CMB angular scales (see *e.g* [4]), although they are often regarded as mere curiosities. In this essay, we focus on one of these anomalies, the lack of correlation [5, 6, 7, 8, 9, 10, 11, 12, 13] and explain why, in our opinion, it deserves attention. The low variance anomaly [14, 15, 16, 17] is a closely related observation [12], so that we shall use the terms "lack of power" and "lack of correlation" interchangeably.

Lack of power at large angular scales. There is a lack of power, with respect to ΛCDM, in the two-point correlation function of CMB temperature anisotropies for angles larger than $\sim 60°$. This intriguing discrepancy was originally noted with COBE data [5], and was then confirmed by the WMAP team already in their first year release [6]. In [7] this feature was associated to missing power in the quadrupole. WMAP3 and WMAP5 data were then used to show [8, 9] that a lack of correlation occurs only in 0.03% of the ΛCDM realizations. A subsequent analysis [10] confirmed the anomaly using WMAP5 data, and at the same time found, with a Bayesian approach, that the ΛCDM model cannot be excluded. WMAP7 data were taken into account in [11], while WMAP9 data were considered in [12], where the lack of correlation was studied against the Galactic masking. Planck 2013 and WMAP9 data were analyzed in [13], which confirmed for this anomaly a significance at the level of 99.97%.

Interesting features of this anomaly. The two-point correlation function for CMB temperature anisotropies is defined as

$$C_{TT}(\theta) = \sum_{\ell \geq 2}^{\ell_{max}} \frac{(2\ell+1)}{4\pi} \, C_\ell \, P_\ell(\cos\theta) \,, \tag{1}$$

where the P_ℓ are Legendre polynomials and the C_ℓ are angular power spectrum (APS) coefficients. In [12], $C_{TT}(\theta)$ was built via eq. (1) with a quadratic maximum likelihood estimator [18, 19, 20, 21, 22]. With it, one can compute the estimator [6]

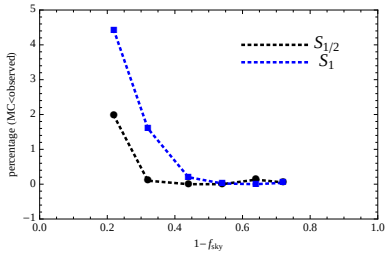
$$S_{1/2} = \int_{\pi/3}^{\pi} d\theta \, \left(C_{TT}(\theta)\right)^2 \sin\theta \,, \tag{2}$$

together with its natural counterpart for the whole angular range [12],

$$S_1 = \int_{0}^{\pi} d\theta \, \left(C_{TT}(\theta)\right)^2 \sin\theta \,, \tag{3}$$

which does not suffer from any a posteriori bias because it does not rest on an arbitrary choice of integration region. The estimators $S_{1/2}$ and S_1 were evaluated in [12] for six different observed sky fractions f_{sky}, relying on realistic (signal plus noise) ΛCDM Monte Carlo (MC) simulations. The Galactic masks were built extending the edges of the official kq85 WMAP mask by 4, 8, 12, 16 and 20 degrees (see the table in fig. 1). These MCs were confronted with the values of $S_{1/2}$ and S_1 obtained from the ILC WMAP9 map, and the WMAP9 observations displayed in general more compatibility with no correlation when the mask was enlarged. For $S_{1/2}$, the probability to find a sky as the one observed by WMAP9 is $< 0.01\%$ for a Galactic mask preserving a sky fraction $f_{sky} = 0.46$. An anomalous probability below 0.01% for $f_{sky} = 0.36$ is also obtained for S_1. The percentages of compatibility are plotted in fig. 1, which shows how the anomaly increases with the masked area.

Why does this anomaly deserve attention? The observational facts reviewed in the previous section call for an explanation, since a statistical fluke remains possible only insofar as one accepts to be living in a very rare ΛCDM realization. Why is this anomaly unlikely to originate from artifacts or spurious effects? We can advocate at least three reasons for this. To begin with, it is not natural to ascribe the lack of power to a foreground (*e.g.* Galactic emission) that was not fully removed, since Galactic and cosmological emissions are expected



f_{sky}	$S_{1/2}$	S_1	N_{sims}
0.78	1.96	4.41	10^4
0.68	0.1	1.6	10^3
0.56	< 0.1	0.20	10^3
0.46	< 0.01	0.02	10^4
0.36	0.13	< 0.01	10^4
0.28	0.05	0.04	10^4

Figure 1: Percentage anomaly, or lower tail probability, of $S_{1/2}$ and S_1 versus the fraction of masked sky, for the standard mask and five extensions (left), and percentage probabilities to obtain smaller values than what observed by WMAP9 (right), from [12]. N_{sims} denotes the number of realizations. Notice how the larger sampling variance accompanying lower values of f_{sky} does not prevent this type of analysis.

to be uncorrelated. Therefore any residual foreground emission should increase rather than reduce the observed power [23, 24]. Second, it is not natural to ascribe the effect to instrumental systematics, since two independent experiments, WMAP and Planck, have observed the same features [13]. Third, the anomaly is not only stable but its significance grows when the Galactic mask is increased, thus considering a smaller portion of the sky [12]. This behavior, displayed in fig. 1, is really remarkable, since the exclusion of regions close to the Galactic plane is in principle a very conservative choice.

A new scale in Cosmology? Let us now elaborate on a possible fundamental origin for this effect. At large angular scales the CMB anisotropy is governed by the Sachs-Wolfe (SW) effect, which is due to the gravitational potential at decoupling, *i.e.* for $z \sim 1100$, and by the Integrated Sachs-Wolfe (ISW) effect, which accounts for the more recent transition, at $z \sim 0.5$, between matter and dark energy domination. The former effect is definitely more important, since the latter contributes less than 20 % in terms of temperature anisotropies (see *e.g.* [25, 26]). Hence it appears reasonable, and even more conservative, to embed possible new mechanisms in the SW contribution. On the other hand, ISW modifications would seem more contrived, since for one matter they should be fine-tuned in order not to affect the amount of dark energy, and thus the high–multipole peaks that are strongly constrained by observations.

The APS induced by the SW effect results from a Bessel–like transform [27], which projects on the sphere the primordial spectrum $\mathcal{P}(k)$ of scalar perturbations as

$$C_\ell \;=\; \frac{4\pi}{9}\,\int_0^\infty \frac{dk}{k}\,\mathcal{P}\big(k\big)\,j_\ell{}^2\big[k\,(\eta_0-\eta_{LS})\big]\;, \tag{4}$$

where η_0 and η_{LS} denote the conformal times at present and at last scattering. In ΛCDM $\mathcal{P}(k)$ is parameterized as [28]

$$\mathcal{P}(k) \;=\; A\,k^{n_s-1}\;, \tag{5}$$

in terms of an amplitude A and a tilt $n_s - 1$.

Lack of power at large angular scales is a typical manifestation of early departures from slow–roll, which follow naturally the emergence from an initial singularity. As explained in [29, 30], when this occurs the power spectrum approaches in the infrared the limiting behavior

$$\mathcal{P}(k) = A\,\frac{k^3}{(k^2+\Delta^2)^{2-n_s/2}}\;, \tag{6}$$

which brings along a new physical scale Δ. An infrared depression of the APS presents itself naturally in String Theory [31], in orientifold vacua [32] with high–scale supersymmetry breaking [33]. In these models a scalar field emerges at high speed from an initial singularity, to then bounce against a steep exponential potential before attaining an eventual slow–roll regime. The key ingredient is the steep exponential, whose logarithmic slope is predicted by String Theory [34, 35, 36], and a number of exactly solvable systems provide explicit realizations of this peculiar dynamics [36].

Here we confine our attention to the simple deformation of eq. (6) of the almost scale invariant power spectrum (5), leaving aside other secondary features introduced by a bounce [30]. These

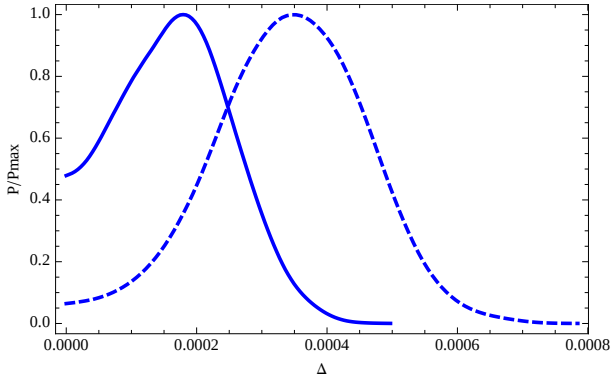


Figure 2: Posterior probabilities of Δ (solid line for the standard mask with $f_{sky} \simeq 90\%$, and dashed line for an extended mask with $f_{sky} \simeq 40\%$).

include pre–inflationary peaks well separated from the limiting almost scale invariant profile (5), to be contrasted with those accompanying ordinary transitions to slow roll, which occur next to it [37].

The results of a preliminary Bayesian analysis extended to all standard cosmological parameters and based on PLANCK data are shown in fig. 2, where posteriors for Δ are given for two choices of the Galactic mask: the standard mask, with $f_{sky} \simeq 90\%$ (solid line), and an extended mask with $f_{sky} \simeq 40\%$. The estimated value of the new scale Δ for the latter choice is

$$\Delta = (0.340 \pm 0.115) \times 10^{-3}\,\mathrm{Mpc}^{-1}\,. \tag{7}$$

Interestingly, Δ in eq. (7) is found to differ from 0 at 99% C.L. and its magnitude appears reasonable, as we shall see shortly. Moreover, in analogy with the lack of power anomaly, fig. 2 shows that the significance of this result increases sizably when a larger Galactic mask is used.

The string–inspired models of [34, 29, 30] rest on the energy scale of string excitations, which determines the scalar potential and lies typically a few orders of magnitude below the Planck scale. Inflation generally lasts $\mathcal{O}(100)$ times the corresponding time scale, and combining these results with the standard evolution of the Universe, one can turn eq. (7) into a primordial energy scale at the onset of inflation,

$$\Delta^{Infl} \;=\; 4 \times 10^{15}\; e^{N-60} \times \sqrt{\frac{H_{Infl}}{100\, M_{Pl}}}\;\; \mathrm{GeV}\;. \tag{8}$$

This result depends on the number of e–folds, and demanding that Δ^{Infl} exceed slightly typical values of H_{Infl} yields the inequality

$$e^{N-60} \;\gtrsim\; \frac{M_{Pl}(\mathrm{GeV})}{4 \times 10^{15}} \sqrt{\frac{100\; H_{Infl}}{M_{Pl}}}\;. \tag{9}$$

For an inflationary scale of about 10^{14} GeV this implies the reasonable bound $N > 65$. Conversely, PLANCK set the upper bound [38]

$$\frac{H_{Infl}}{M_{Pl}} \;<\; 3.6 \times 10^{-5}\;, \tag{10}$$

and making use of this result in eq. (8) yields

$$\Delta^{Infl} \;\lesssim\; 2.4 \times 10^{12}\; e^{N-60}\;\mathrm{GeV}\;, \tag{11}$$

which is again around 10^{14} GeV for $N \simeq 65$.

In conclusion, the considerations in [29, 30], inspired by String Theory, and in particular by the supersymmetry breaking mechanism of [33] and the related cosmological dynamics of [34], provided the original motivation for the present analysis. The resulting scenario would associate Δ, and hence the corresponding primordial energy scale Δ^{Infl}, to the onset of the inflationary

phase, and as we have seen our estimates appear compatible with this interpretation. Collecting more information on the infrared tail of the APS might tell us something more definite about how an inflationary regime was originally attained.

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