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Solving the tension between high-scale inflation and axion isocurvature perturbations

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ABSTRACT

The BICEP2 experiment determined the Hubble parameter during inflation to be about 10^{14} GeV. Such high inflation scale is in tension with the QCD axion dark matter if the Peccei–Quinn (PQ) symmetry remains broken during and after inflation, because too large axion isocurvature perturbations would be generated. The axion isocurvature perturbations can be suppressed if the axion acquires a sufficiently heavy mass during inflation. We show that this is realized if the PQ symmetry is explicitly broken down to a discrete symmetry and if the breaking is enhanced during inflation. We also show that, even when the PQ symmetry becomes spontaneously broken after inflation, such a temporarily enhanced PQ symmetry breaking relaxes the constraint on the axion decay constant.

1. Introduction

The identity of dark matter is one of the central issues in cosmology and particle physics. Among various candidates for dark matter, the QCD axion is a plausible and interesting candidate. The axion, a, arises as a pseudo-Nambu–Goldstone (pNG) boson in association with the spontaneous breakdown of a global $U(1)_{PQ}$ Peccei–Quinn (PQ) symmetry [1,2]. If the $U(1)_{PQ}$ symmetry is explicitly broken only by the QCD anomaly, the axion is stabilized at vacuum with a vanishing CP phase, solving the strong CP problem. More important, the dynamical relaxation necessarily induces coherent oscillations of axions, which contribute to cold dark matter (CDM). We focus on the axion CDM which accounts for the total dark matter density, throughout this letter.

The axion mass receives contributions from the QCD anomaly,

$$m_a^{\rm QCD} \simeq 6\times 10^{-6}\ {\rm eV}\left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)^{-1}, \tag{1}$$

where f_a is the axion decay constant. Because of the light mass, the axion generically acquires quantum fluctuations of $\delta a \simeq H_{\rm inf}/2\pi$ during inflation, leading to CDM isocurvature perturbations. Here $H_{\rm inf}$ is the Hubble parameter during inflation. The mixture of the isocurvature perturbations is tightly constrained by the Planck observations [3], which reads

$$H_{\rm inf} < 0.87\times 10^{7}\ {\rm GeV}\left(\frac{f_a}{10^{11}\ {\rm GeV}}\right)^{0.408} \quad (95\%\ {\rm CL}), \tag{2}$$

neglecting anharmonic effects [4–8]. In particular, a large-field inflation such as chaotic inflation [9] is in conflict with the isocurvature bound. Recently the BICEP2 experiment announced the discovery of the primordial B-mode polarization [10], which determines the inflation scale as

$$H_{\rm inf} \simeq 1.0\times 10^{14}\ {\rm GeV}\left(\frac{r}{0.16}\right)^{\frac{1}{2}}, \tag{3}$$

$$r = 0.20^{+0.07}_{-0.05} \quad (68\%\ {\rm CL}), \tag{4}$$

where r denotes the tensor-to-scalar ratio.[1] After subtracting the best available estimate for foreground dust, the allowed range is modified to $r = 0.16^{+0.06}_{-0.05}$. Therefore one can see from (2) and (3) that there is a clear tension between the inflation scale determined by the BICEP2 and the QCD axion dark matter.[2]

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[1] Such large tensor-to-scalar ratio can be explained in various large field inflation; see e.g. [11–24]. The tension with the Planck result can be relaxed in the presence of small modulations in the inflaton potential [25] or hot dark matter/dark radiation.

[2] The isocurvature perturbation bound similarly applies to the so-called axion-like particles, or general pseudo-Nambu–Goldstone bosons, which are produced by the initial misalignment mechanism and contribute to dark matter.

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There are various known ways to suppress the axion CDM isocurvature perturbations. First, if the PQ symmetry is restored during inflation (or reheating), there is no axion CDM isocurvature perturbations, as the axion appears only when the PQ symmetry is spontaneously broken some time after inflation [26,27]. In this case topological defects such as axionic cosmic strings and domain walls are generated, and in particular the domain wall number $N_{\rm DW}$ must be unity to avoid the cosmological catastrophe [28]. Second, if the kinetic term coefficient for the phase of the PQ scalar was larger during inflation than at present, the quantum fluctuations, δa, can be suppressed after inflation. This is possible if the radial component of the PQ scalar takes a larger value during inflation [26,29]. The scenario can be implemented easily in a supersymmetric (SUSY) theory, as the saxion potential is relatively flat, lifted by SUSY breaking effects. Interestingly, a similar effect is possible if there is a non-minimal coupling to gravity [30]. Third, the axion may acquire a heavy mass during inflation so that its quantum fluctuations get suppressed [31]. In Ref. [31] two of the present authors (K.S.J. and F.T.) showed that the QCD interactions become strong at an intermediate or high energy scale in the very early Universe, if the Higgs field has a sufficiently large expectation value.[3]

In fact, the second solution of Refs. [26,29] is only marginally consistent with the BICEP2 result (3), if the field value of the PQ scalar is below the Planck scale. Also the third solution of Ref. [31] is consistent with the BICEP2 result only in a corner of the parameter space. Therefore, we need another solution to suppress the axion isocurvature perturbations, as long as we assume that the PQ symmetry remains broken during and after inflation.

In this letter, we propose a simple mechanism to suppress the axion CDM isocurvature perturbations along the line of the third solution. Instead of making the QCD interactions strong during inflation, we introduce a PQ symmetry breaking operator, which becomes relevant only during inflation. If the axion acquires a sufficiently heavy mass during inflation, the axion CDM isocurvature perturbations practically vanish, evading the isocurvature bound on the inflation scale. After inflation, the explicit PQ breaking term should become sufficiently small so that it does not spoil the axion solution to the strong CP problem.

There are various possibilities to realize such temporal enhancement of the axion mass. If, during inflation, the radial component of the PQ scalar, i.e. the saxion, takes a large field value, the PQ symmetry breaking operator is enhanced and the axion becomes heavy. After inflation, the saxion settles down at the low-energy minimum located at a smaller field value where the explicit PQ breaking term is sufficiently small. Alternatively we can consider a case in which the PQ symmetry breaking operators are present only during inflation. This is the case if the inflaton is coupled to the PQ symmetry breaking operators; during inflation, the operators are enhanced due to a large vacuum expectation value (VEV) of the inflaton, whereas they are suppressed if the inflaton is stabilized at much smaller field values after inflation. This can be nicely implemented in a large-field inflation model where the inflaton field value evolves significantly.

Later in this letter we also briefly consider the first solution to the tension between the BICEP2 results and the axion CDM isocurvature perturbations, i.e., the PQ symmetry restoration during or after inflation. We will show that, even in this case, the temporarily enhanced PQ symmetry breaking relaxes the bound on the axion decay constant, allowing $f_a \gtrsim 10^{10}$ GeV and also $N_{\rm DW} \neq 1$.

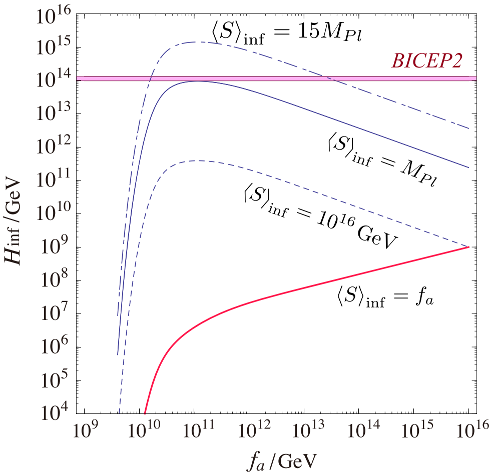

Fig. 1. Constraint on the inflation scale from the axion CDM isocurvature perturbation. The isocurvature constraint (2) is shown by the solid (red) line, where the anharmonic effect is taken into account [8]. The relaxed constraints for $\langle S\rangle_{\rm inf} = 10^{16}$ GeV, M_{Pl} and $15M_{Pl}$ are shown by the dashed, solid, and dot-dashed lines, respectively. The horizontal band is the BICEP2 result (3). If the axion acquires a heavy mass during inflation, all these constraints disappear as shown in the text.

2. Isocurvature constraints on the axion CDM

The axion, if exists during inflation, acquires quantum fluctuations, $\delta a = H_{\rm inf}/2\pi$, giving rise to the axion CDM isocurvature perturbations. The isocurvature constraint on the axion CDM leads to the upper bound on the Hubble parameter during inflation as in Eq. (2), which is shown by the solid (red) line Fig. 1. Here the anharmonic effect is taken into account [8]; the axion CDM isocurvature perturbations get significantly enhanced as the initial field value approaches the hilltop, as can be seen for $f_a \lesssim 10^{11}$ GeV. Note that we assume that the axion produced by the initial misalignment mechanism accounts for the total CDM density in the figure.

Let us here briefly study how much the second solution mentioned in the Introduction can relax the isocurvature bounds on the Hubble parameter. To see this, we write the kinetic term of the PQ scalar, S, whose expectation value determines the axion decay constant, as:

$$\mathcal{L}_K = \zeta^2 \partial S^\dagger \partial S \supset \zeta^2 |S|^2 (\partial\theta)^2, \tag{5}$$

where we define $S = |S|e^{i\theta}$, and $\zeta(> 0)$ parametrizes a possible deviation from the canonically normalization. In general, ζ may depend on S, the inflaton or other fields: $\zeta = \zeta(\Phi)$, where Φ denotes such fields collectively. During inflation, the canonically normalized axion, $a = \langle \zeta|S|\rangle_{\rm inf}\theta$, acquires quantum fluctuations of order $H_{\rm inf}$ at the horizon exit, namely,

$$\delta\theta = \frac{H_{\rm inf}}{2\pi \langle \zeta|S|\rangle_{\rm inf}}. \tag{6}$$

Note that the quantum fluctuations, $\delta\theta$, at super-horizon scales remain constant, even if $\zeta^2|S|^2$ evolves in time during and after inflation. Thus, the quantum fluctuations of the canonically normalized axion in the low energy is given by

$$\delta a = \frac{\langle \zeta|S|\rangle_0}{\langle \zeta|S|\rangle_{\rm inf}} \frac{H_{\rm inf}}{2\pi}, \tag{7}$$

where the subindices 0 and inf denote that the variables are estimated in the low energy and during inflation, respectively. For $\zeta = 1$, if $|S|$ takes a large VEV during inflation and settles down at

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[3] The idea of heavy QCD axions during inflation was considered in Refs. [32–34] to suppress the axion abundance, not the isocurvature perturbations.