Physics Letters B 751 (2015) 195–200

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Inflationary predictions and moduli masses

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ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form 14 October 2015
Accepted 14 October 2015
Available online 19 October 2015
Editor: M. Trodden

ABSTRACT

A generic feature of inflationary models in supergravity/string constructions is vacuum misalignment for the moduli fields. The associated production of moduli particles leads to an epoch in the post-inflationary history in which the energy density is dominated by cold moduli particles. This modification of the post-inflationary history implies that the preferred range for the number of e-foldings between horizon exit of the modes relevant for CMB observations and the end of inflation (N_k) depends on moduli masses. This in turn implies that the precision CMB observables n_s and r are sensitive to moduli masses. We analyse this sensitivity for some representative models of inflation and find the effect to be highly relevant for confronting inflationary models with observations.

1. Introduction

Precision measurements of the cosmic microwave background (CMB) have put the inflationary paradigm as the leading candidate for a theory of early universe cosmology. The data is in perfect agreement with the basic qualitative predictions of inflation i.e. an approximately scale invariant and adiabatic power spectrum. Upcoming observations are expected to probe the CMB with an even greater accuracy and provide us information regarding the strengths of the tensor to scalar ratio and non-gaussianities.

On the theoretical front, there are many challenges. The inflationary slow roll conditions are ultraviolet sensitive; we should embed models of inflation in a quantum theory of gravity. In this light, an important direction of research is study of the effects that can arise as a result of ultraviolet completion of inflationary models. String theory provides a setting where one can hope to carry out a systematic study of such effects.

A generic feature of supergravity/string models is the moduli fields. The vacuum expectation value of moduli fields set the strength and form of the low energy effective action of string models, hence moduli fields play a central role in string phenomenology. There has been an extremely useful interplay between studies of moduli stabilisation and inflationary model building in string theory, see e.g. [1–3]. In this paper, we will examine the sensitivity of precision CMB observables – the spectral tilt (n_s) and the tensor to scalar ratio (r) to the mass of the lightest modulus field.

Given a model of inflation, one can express n_s and r in terms of the number of e-foldings between horizon exit of the modes relevant for CMB observations and the end of inflation (N_k). Predictions for n_s and r are then made by using the "preferred range" of N_k in these formulae. The preferred range for N_k is determined by tracking the history of the universe for the time of horizon exit to the present epoch i.e. the computation is sensitive to the post-inflationary history of the universe. For the standard cosmological timeline (which has the epochs inflation, reheating, radiation domination, matter domination, accelerated expansion) the preferred range for N_k is 50 to 60.

From the very early days of inflationary model building in supergravity, it was realised that a generic implication of having moduli fields is a non-standard post-inflationary cosmological timeline [5–10] (often referred to as the modular cosmology timeline). The modular cosmology timeline sets in as a result of vacuum misalignment of moduli fields during the inflationary epoch. The associated production of moduli particles leads to an epoch in the post-inflationary history of the universe in which the energy density is dominated by cold moduli particles. The history is thermal after the decay of the moduli particles.[1] Reference [11] derived

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[1] The successes of big bang nucleosynthesis imply that the decay of the modulus has to take place before nucleosynthesis.

http://dx.doi.org/10.1016/j.physletb.2015.10.041
0370-2693/

the preferred range of N_k for the modular cosmology timeline[2] and found it to be

$$\left(55 - \frac{1}{4}N_{\rm mod}\right) \pm 5, \tag{1}$$

where $N_{\rm mod}$ is the number of e-foldings of the universe during the epoch that the energy density is dominated by cold moduli particles. As we will see in Section 2.1, in generic models is $N_{\rm mod}$ essentially determined by the post-inflationary mass[3] of the lightest modulus field (m_φ).

In this paper our goal is to explore in detail the phenomenological implications of (1). The dependence of the preferred range of N_k on the mass of the lightest modulus implies that n_s *and* r *are sensitive to the mass of the lightest modulus.* We will examine this sensitivity for some representative models of inflation ($m^2\chi^2$ [18], axion monodromy [19], natural inflation [20] and the Starobinsky model [21]). Motivated by the varied spectra of phenomenologically viable supergravity models we will treat the mass of the lightest modulus (m_φ) as a parameter. We will analyse our results in the context of PLANCK 2015 data [22]. The implications are very interesting; the changes in inflationary predictions can significantly affect the scorecard for models.

2. Review

2.1. Modular cosmology

At tree level, string compactifications have massless scalar fields which interact via Planck suppressed interactions (the moduli). Moduli acquire masses from sub-leading effects, their masses are typically well below the string scale and hence moduli are part of the low energy effective action.

Moduli fields usually have curvature couplings; this makes their masses and potential dependent on the expectation value of the inflaton. As a result, the minimum of the potential for a modulus of post-inflationary mass less than Hubble during inflation ($m_\varphi < H_{\rm infl}$) is different during the inflationary and post-inflationary epochs – such a modulus finds itself displaced from its post-inflationary minimum at the end of inflation. This "initial displacement" is typically of the order of $M_{\rm pl}$ [13–17].

As discussed in the introduction, this "misalignment" implies a non-standard cosmological timeline. We briefly review this timeline and refer the reader to [5–10] for a more complete discussion. Let us begin by describing the case when there is a single modulus whose post-inflationary mass m_φ is below the Hubble scale during inflation. At the end of inflation the universe reheats, the energy density associated with the inflaton gets converted to radiation. At this stage, the energy density of the universe consists of two components – radiation, and the energy associated with the modulus displaced from its minimum.[4] Also, the high value of the Hubble friction keeps the modulus pinned at its initial displacement. As the universe cools, the Hubble constant drops. When the Hubble friction falls below the mass of the modulus, the modulus begins to oscillate about its post-inflationary minimum. With this, the associated energy density dilutes as matter i.e. much slower than that of the radiation. Eventually the energy density associated with the modulus dominates the energy density of the universe; the universe enters into the epoch of modulus domination. This epoch lasts until the decay of the moduli particles. The universe reheats for a second time after the decay of the modulus, after which the history is thermal. In summary, the modular cosmology timeline consists of the following epochs – inflation, reheating (associated with inflaton decay), radiation domination, modulus domination, reheating (associated with modulus decay), radiation domination, matter domination and finally the present epoch of acceleration.

In models with multiple moduli with post inflationary mass below Hubble during inflation, there are multiple epochs of modulus domination and reheating associated with the moduli. In cases where there is a separation of scale between the mass of the lightest modulus and the mass of other moduli the lightest modulus outlives the others and sets the time scale for the epoch of modulus domination. The dynamics of the system can be effectively described by a model with a single modulus; with the effect of the heavy moduli being incorporated in the reheating epoch after inflation.[5] In models in which there is no distinct lightest modulus the dynamics is more complicated to analyse; this was discussed briefly in [11]. We will confine ourselves to situations in which there is a distinct lightest modulus in this paper.

2.2. The preferred range of N_k in modular cosmology

In this section we briefly review the results of [11] relevant for our analysis. Our focus will be on models in which adiabatic perturbations are generated as a result of quantum fluctuations during the inflationary epoch. The strength of the inhomogeneities generated is given by

$$A_s = \frac{2}{3\pi^2 r}\left(\frac{\rho_k}{M_{\rm pl}^4}\right),$$

where A_s is the amplitude of the scalar perturbations, ρ_k the energy density of the universe at the time of horizon exit and r the tensor to scalar ratio. We review the details of generation of density perturbations in the context of modular cosmology in Appendix A. The scalar amplitude A_s is constant to a very good approximation until the point of horizon re-entry. The strength of temperature fluctuations in the CMB can be obtained by tracking its subsequent evolution. Thus the measurement of the strength of temperature fluctuations gives us the value of the energy density of the universe at the time of horizon exit (modulo r). CMB observations also give us the value of the energy density today (ρ_0) via determination of the Hubble constant. Thus any theoretical proposal for the history of the universe between horizon exit and the present epoch must be such that ρ_k evolves to ρ_0. Reference [11] applied this consistency condition to the modular cosmology timeline described in Section 2.1. This gave the relation[6]

$$N_k + \frac{1}{4}N_{\rm mod} + \frac{1}{4}(1-3w_{\rm re1})N_{\rm re1} + \frac{1}{4}(1-3w_{\rm re2})N_{\rm re2} \approx 55.43 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_k}{\rho_{\rm end}}\right), \tag{3}$$

where N_k is the number of e-foldings between horizon exit of the modes relevant for CMB observations and the end of inflation, $N_{\rm mod}$ is the number of e-foldings that the universe undergoes during the epoch of modulus domination, $w_{\rm re1}$ and $w_{\rm re2}$ are the

[2] See [12] for a systematic discussion of various effects that can affect the preferred range for N_k.

[3] Curvature couplings imply that the mass of a modulus field can be significantly different during the inflationary and post-inflationary epochs.

[4] Since $m_\varphi < H_{\rm infl}$, right after reheating the energy density associated with radiation dominates over the energy density associated with the displaced modulus.

[5] Moduli decay via Planck suppressed interactions. Hence the lifetime scales as m_φ^{-3}, this implies that this effective description can be useful even for a moderate separation between the mass of the lightest moduli and the heavier ones.

[6] The analogous relation for the standard cosmological timeline is

$$N_k + \frac{1}{4}(1-3w_{\rm re})N_{\rm re} \approx 55.43 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_k}{\rho_{\rm end}}\right). \tag{2}$$

effective equation of state parameters during the two reheating epochs, $N_{\rm re1}$ and $N_{\rm re2}$ are the number of e-foldings during the two reheating epochs, ρ_k the energy density at the time of horizon exit and $\rho_{\rm end}$ the energy density at the end of inflation. The number of e-foldings of modulus domination was found to be

$$N_{\rm mod} \approx \frac{4}{3}\ln\left(\frac{\sqrt{16\pi}M_{\rm pl}Y^2}{m_\varphi}\right) \tag{4}$$

where Y is the initial displacement of the modulus from its post-inflationary minimum in Planck units. Equation (3) can be used to obtain the "preferred range" of N_k for modular cosmology. A discussion of the analogous analysis for the standard cosmological timeline can be found in [4]. Making the same generality assumptions regarding the reheating epoch, change in the energy density of the universe during inflation and the scale of inflation as in Section 2.3 of [4], equation (3) gives the preferred range for N_k to be

$$\left(55 - \frac{1}{4}N_{\rm mod}\right) \pm 5. \tag{5}$$

Note that this can be thought of as lowering of the central value of the preferred range of N_k by $N_{\rm mod}/4$. As mentioned earlier, there are general arguments [13–17] which imply Y is an $\mathcal{O}(1)$ quantity.[7] Thus the shift in the central value of N_k is essentially determined by m_φ.

Before ending this section we would like to emphasise that the relation (3) and expression (5) are valid only if the post inflationary mass of the modulus m_φ is below Hubble during inflation. If the post-inflationary mass of the lightest modulus is well above Hubble during inflation then the misalignment mechanism is not operational and the preferred range is 55 ± 5.

3. Implications for inflationary models

In this section, we will study the phenomenological implications of the results described in Section 2.2 for some representative models of inflation. Given the diverse spectra of phenomenologically viable supergravity models we will treat m_φ as a phenomenological parameter in our analysis. The central value of N_k also depends on Y. As discussed in Section 2.2 typically Y is $\mathcal{O}(1)$. We note that apart from the classical contributions to Y discussed in [15,16], quantum contributions to the effective potential of the field can also be present (see e.g. [39]), although if the mass of the modulus is of the order of Hubble during inflation one expects the classical contribution to be dominant. Exact determination of Y requires the knowledge of coupling between the inflaton and moduli fields; hence is sensitive to the embedding of a model of inflation in a compactification. For field displacement due to classical effects we will take $Y = 1/10$ (as is often taken in analysis of the cosmological moduli problem see e.g. [7]). So our choice of $Y = 1/10$ can be considered conservative; but this ensures better control over the effective field theory. We leave the exact computation of Y and its dependence on various parameters (such as the mass of the modulus) in specific compactifications for future work. The quantum effects become stronger as the field becomes lighter; for a modulus well below the Hubble scale the field displacement due to quantum effects can dominate over the classical contribution.

We will focus on four benchmark models of inflation – $V(\chi) = \frac{1}{2}m^2\chi^2$ [18] (we will denote the inflaton by χ), axion monodromy i.e. $V(\chi) = \hat{m}^{10/3}\chi^{2/3}$ [19], natural (pNGB) inflation [20] and the Starobinsky model [21]. Let us record n_s and r as a function of N_k for each of these models

- $m^2\chi^2$: $n_s = 1 - 2/N_k$, $r = 8/N_k$
- Axion monodromy: $n_s = 1 - 4/(3N_k)$, $r = 8/(3N_k)$
- Natural inflation: $n_s = 1 - \left[\frac{M_{\rm pl}}{f}\right]^2\left[\frac{1+\frac{e^{-x}}{p}}{1-\frac{e^{-x}}{p}}\right]$, $r = 8\left[\frac{M_{\rm pl}}{f}\right]^2\left[\frac{\frac{e^{-x}}{p}}{1-\frac{e^{-x}}{p}}\right]$ with $p = 1 + \frac{M_{\rm pl}^2}{2f^2}$, $x = \frac{N_k M_{\rm pl}^2}{f^2}$ where f is the axion decay constant
- Starobinsky model: $n_s = 1 - 2/N_k$, $r = 12/N_k^2$

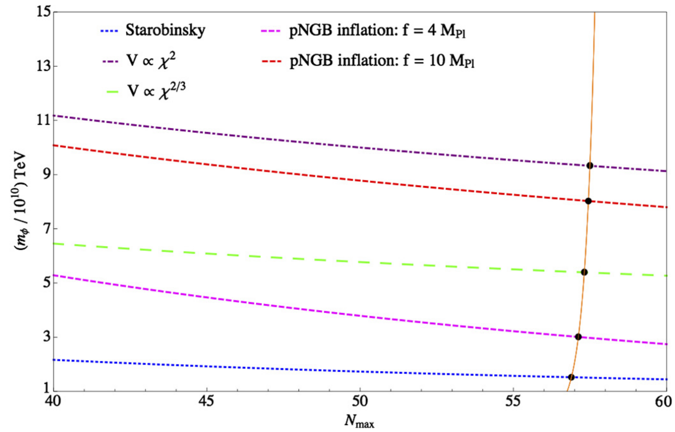

Fig. 1. Numerical solution for the condition $H_{\rm infl} > m_\varphi$. The solid curve is a plot of m_φ as a function of $N_{\rm max}$ as given by (7). The dashed curves are plots of the left hand side of (8) as a function of $N_{\rm max}$ for various models.

The change in the preferred range of N_k (5) occurs if m_φ is less than Hubble during inflation. We begin by implementing this condition for each of the models. The Hubble constant at the time of horizon exit is

$$H_k = \frac{\pi}{\sqrt{2}}(A_s r)^{1/2}M_{\rm pl} \tag{6}$$

Note that the right hand side of (6) depends on m_φ; since r is determined by N_k and the preferred range for N_k depends on m_φ. Also, r decreases with an increase in N_k. Therefore, the condition can be implemented over the entire preferred range by requiring that it holds for the maximum value of N_k

$$N_{\rm max} = 60 - \frac{1}{3}\ln\left(\frac{\sqrt{16\pi}M_{\rm pl}Y^2}{m_\varphi}\right). \tag{7}$$

Thus we want to impose the condition

$$\frac{\pi}{\sqrt{2}}(A_s r[N_{\rm max}])^{1/2}M_{\rm pl} > m_\varphi \tag{8}$$

with $N_{\rm max}$ as given by (7). We solve for this condition numerically in the plot shown in Fig. 1. The condition is most stringent for the Starobinsky model, for which the right hand side and left hand side of (8) are equal for $m_\varphi \approx 1.5 \times 10^{10}$ TeV. We will be conservative and study the implications of the shift in the central value of N_k if the mass of the modulus is at least two orders of magnitude below this i.e. $m_\varphi < 10^8$ TeV (this value will be used for all models).

On the other hand, the cosmological moduli problem (CMP) bound, based on the requirement of successful nucleosynthesis requires $m_\varphi > 30$ TeV [5–7,23]. We will use this consideration to set the lower value of m_φ in our analysis. In summary, we will use the range 10^2 TeV $< m_\varphi < 10^8$ TeV to study the effects of the epoch of modulus domination on inflationary predictions.

[7] These expectations have been borne out in explicit constructions of inflationary models in string compactifications, see e.g. [24].

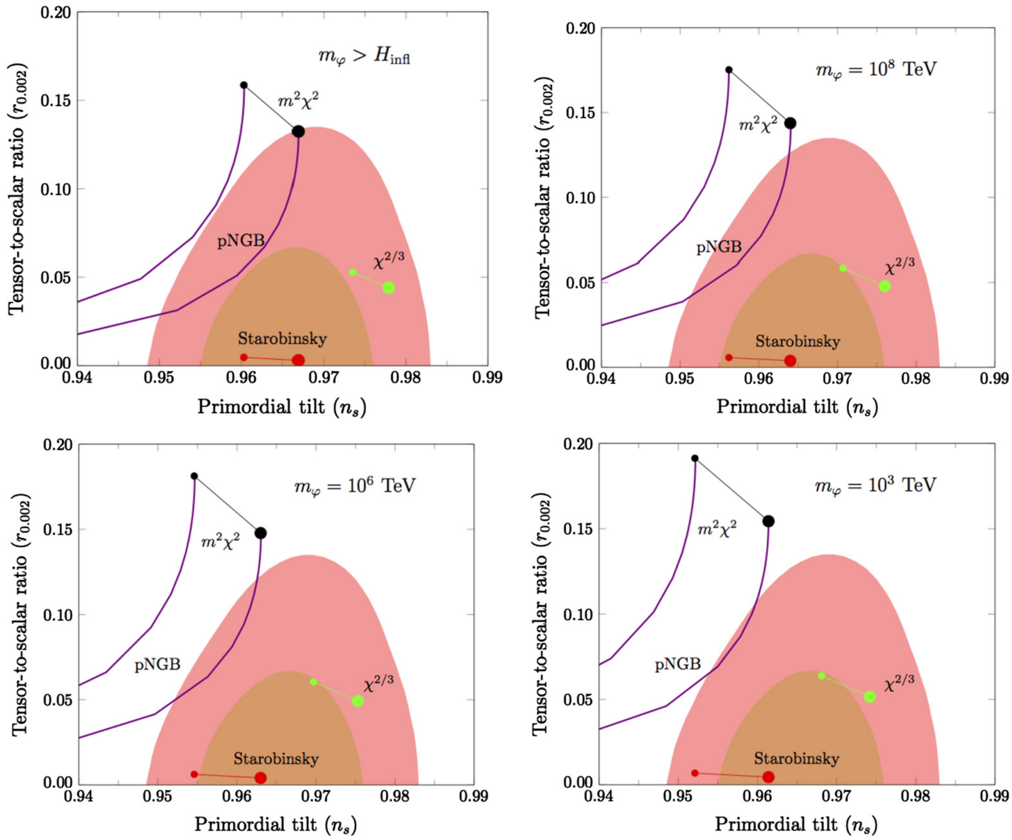

Fig. 2. Inflationary predictions for $m^2\chi^2$ (black), natural/pNGB inflation (purple), axion monodromy (green), Starobinsky model (red). For the cases of no misalignment ($m_\varphi > H_{\rm infl}$), $m_\varphi = 10^3, 10^6, 10^8$ TeV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We now have all the ingredients necessary to compute the predictions for n_s and r. We compute the predictions for n_s and r for $m_\varphi = 10^3, 10^6$ and 10^8 TeV. We begin by taking $Y = 1/10$, appropriate for a classical displacement. We will study the case of displacement due to quantum effects later in the section. The results are shown in Fig. 2, the plot for the standard cosmological timeline (which is equivalent to $m_\varphi > H_{\rm infl}$) is also included for reference. The shaded regions correspond to the 1-σ and 2-σ results for n_s and r from PLANCK 2015 analysis for TT modes and low P [22]. We find that for the $m^2\chi^2$ model even a very heavy modulus of mass 10^8 TeV implies predictions for n_s and r which are well outside the 2-σ region. The axion monodromy model moves inside the 1-σ region for m_φ below 10^5 TeV. The Starobinsky model remains in the 1-σ region for almost the entire mass range.

In the above analysis, we have taken $Y = 1/10$ even for a modulus mass of 10^3 TeV. For such a light field the quantum fluctuations can be large. The fluctuation squared is expected to be order of

$$\langle \varphi^2 \rangle = \frac{3H^4}{8\pi^2 m_\varphi^2},$$

see e.g. [39]. For a modulus of mass 10^3 TeV and the inflationary scale at the GUT scale this yields $Y \approx 10$, significantly larger that the value of Y used by us earlier. Thus for the modulus mass 10^3 TeV we compute the inflationary predictions taking $Y = 10$. The results are presented in Fig. 3.

Finally, we would like to mention a general implication. For gravity mediated models moduli masses are tied to the scale of supersymmetry breaking. Thus, for gravity mediated models our results correlate inflationary predictions with the scale of supersymmetry breaking. The effect is significant even for models with a high scale of supersymmetry breaking.

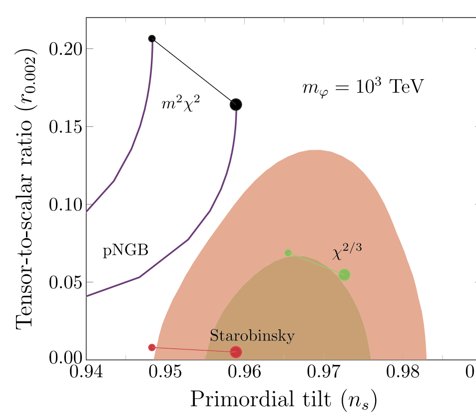

Fig. 3. Inflationary predictions for $m^2\chi^2$ (black), natural/pNGB inflation (purple), axion monodromy (green), Starobinsky model (red) for $m_\varphi = 10^3$ TeV, with the field displacement taken to be of quantum origin (this dominates over the classical effect). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. A bound on moduli masses

The consistency condition (3) can be used to obtain a bound on moduli masses given a model of inflation by taking input from observations on the value of n_s [11]. The approach can be considered complimentary to that of the previous section where we discussed inflationary predictions as a function of the mass of the late time decaying modulus. In this section, we analyse the bound for our representative models and update some of the discussion in [11] in light of the PLANCK 2015 data release [22].

The bound is obtained by combining the consistency condition (3) with expression for $N_{\rm mod}$ (4) and demanding that the reheat-

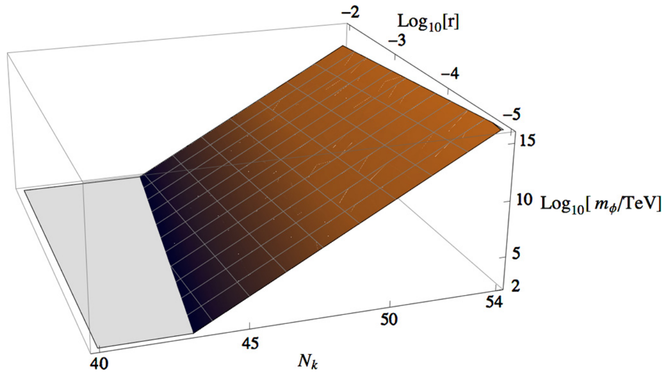

Fig. 4. Bound on the modulus mass for small field models. The allowed values of m_φ are in the region above the shaded plane. We have chosen $Y = 1/10$.

ing epochs are not exotic, i.e. $w_{\rm re1}, w_{\rm re2} < 1/3$ (see e.g. [4,29] for a discussion of on this condition on the effective equation of state during reheating). With this, one can arrive at a lower bound on m_φ

$$m_\varphi \gtrsim \sqrt{16\pi} M_{\rm pl} Y^2 \, e^{-3\left(55.43 - N_k + \frac{1}{4}\ln(\rho_{\rm k}/\rho_{\rm end}) + \frac{1}{4}\ln r\right)}. \tag{9}$$

The bound applies only if m_φ is less than Hubble during inflation (as equation (3) was derived under this assumption). Given a model of inflation and observational input on the value of n_s, one can explicitly compute the quantities in the exponent in the right hand side of (9). Typically, N_k is related to n_s by a relation of the form $N_k = \frac{\beta}{1-n_s}$, where β depends on the model of inflation. This makes the bound highly sensitive to the value of n_s. The PLANCK 2015 release [22] gives the central value of n_s to be 0.9680; there is a shift in the positive direction in comparison with the 2013 value of $n_s = 0.9603$ [4]. This implies an increase in N_k for inflationary models and thereby a more stringent bound.

Let us now discuss the bound in the context of our representative models. For the $m^2\chi^2$ model, the PLANCK 2015 central value of n_s gives the right hand side of (9) to be well above Hubble during inflation (as obtained in Fig. 1); modular cosmology is incompatible with this value of n_s. The lower end of the 1-σ value gives $m_\varphi > 10^{10}$ TeV. On the other hand, for the axion monodromy model (9) yields a value below the CMP bound based on nucleosynthesis considerations [5–7,23], thus is not of phenomenological interest as a bound. The fact that the bound is not strong for the axion monodromy model is consistent with the results shown in Fig. 2 – the axion monodromy model is in the 1-σ region for $m_\varphi = 10^3$ TeV. Similarly, in the case of the Starobinsky model and pNGB inflation the value of the bound is in keeping with the results shown in Fig. 2.

For small field models, the second term in the exponent of the right hand side of (9) (the term involving the ratio of the energy densities at the time of horizon exit and end of inflation) makes a negligible contribution. In Fig. 4 we show the allowed range for m_φ as a function of N_k and r. The plot illustrates that the scale for the bound is essentially set by N_k. For $N_k \gtrsim 50$ the bound is very strong; $m_\varphi \gtrsim 10^7$ TeV. The bound is stronger than the CMP bound as long as $N_k \gtrsim 44.5$. The plot in Fig. 4 can be used to read off the implications of the bound for any small field model. It will be interesting to explore the implications of this bound for inflationary model building in moduli stabilised string compactifications.

5. Discussion and conclusions

In this paper, we have studied the sensitivity of n_s and r to the mass of the lightest modulus in the context of modular cosmology. The results of Section 3 clearly exhibit that it is important to explicitly incorporate the effect of the epoch of modulus domination in obtaining the preferred range of N_k. The effect can significantly alter the inflationary predictions for n_s and r of string/supergravity models; being relevant even for very heavy moduli ($m_\varphi \approx 10^8$ TeV). Furthermore, future experiments [25] are likely to bring down the uncertainties in the measurement of n_s by one order of magnitude; making our analysis all the more relevant. Given that modular cosmology is generic in string/supergravity models [5–10] our results should have broad implications.

Our approach has been phenomenological; we have treated the mass of the lightest modulus as a free parameter and taken the initial displacement of the modulus (that results due to misalignment) to have a generic value. The results strongly motivate the study of specific models where the modulus mass takes a fixed value and it is possible to compute the value of the initial displacement explicitly. Some models worth exploring in this context are fibre inflation [24], Kahler moduli inflation [26], M-flation [27] and Gauged M-flation [28].

Another important direction in the study of specific models is first principles analysis of the reheating epoch. This can reduce the uncertainty in N_k, allowing for more precise predictions of n_s and r. This question has received much attention recently [29–31]. The methods developed in [31] can be useful in analysing the decay of moduli particles.

More generally, modular cosmology can also have implications for dark matter, structure formation and the phenomenology of SUSY models [32]. It is natural to look for correlations between our results for CMB observables and other phenomenological signatures.

Acknowledgements

We would like to thank Luis Aparicio, Mar Bastero-Gil, Michele Cicoli, Joseph Conlon, John Ellis, Henriette Elvang, Lucien Heurtier, Gordy Kane, Sven Krippendorf, Fernando Quevedo, Raghu Rangarajan, Gary Shiu, Kuver Sinha, Mark Srednicki, Fuminobu Takahashi, Scott Watson and Ivonne Zavala for useful discussions. K Dutta and AM would like to acknowledge support from their Ramanujan fellowships, Department of Science and Technology, India.

Appendix A. Density perturbations in modular cosmology

In this appendix we review the generation of density perturbations in the context of modular cosmology. As discussed in Section 2 the minimum of the potential of the late time decaying modulus depends on the inflaton expectation value; thus as the inflaton moves along its trajectory the expectation value of the late time decaying modulus (and potentially other moduli) necessarily changes. Thus, the trajectory in field space during inflation involves displacement along the inflaton direction, late time decaying modulus (and potentially other moduli). We will require the directions in field space orthogonal to the trajectory in field space during inflation to have mass of at least of the order of Hubble (this as we will see in what follows will ensure that isocurvature perturbations are suppressed). Infact, curvature couplings naturally lead to such mass terms of the order of Hubble (see e.g. [15,16]).

The perturbations generated are best understood in the formalism developed in [33] – coordinates in field space are chosen such that one of the coordinate directions is along the trajectory in field space (during the inflationary epoch) and the remaining are orthogonal to the trajectory in field space. The key result of [33] is that quantum fluctuations associated with the direction in field space parallel to the trajectory are adiabatic, while the ones orthogonal generate isocurvature perturbations. Thus, imposing the condition that the directions in field space orthogonal to the trajectory have mass at least of the order of Hubble ensures that isocurvature perturbations at the time of horizon exit are suppressed; the perturbations are to a very good approximation adiabatic at the time of horizon exit. We will denote the adiabatic perturbation at the time of horizon exit by $\mathcal{R}_*$ and the isocurvature perturbations by $\mathcal{S}_*^i$. These have to be evolved into the radiation epoch (after the decay of the modulus) to determine the strength of the temperature fluctuations they seed. The result of this evolution is given by a transfer matrix [34], which takes the general form (to keep the presentation simple we include one isocurvature direction, it is easily generalised to the case of multiple isocurvature perturbation directions)

$$\begin{bmatrix} \mathcal{R}_{\rm rad} \\ \mathcal{S}_{\rm rad} \end{bmatrix} = \begin{bmatrix} 1 & \mathcal{T}_{\rm RS} \\ 0 & \mathcal{T}_{\rm SS} \end{bmatrix} \begin{bmatrix} \mathcal{R}_* \\ \mathcal{S}_* \end{bmatrix}$$

where $\mathcal{R}_{\rm rad}$ and $\mathcal{S}_{\rm rad}$ are the isocurvature and adiabatic perturbations after the modulus decay. An important feature of the transfer matrix is that the entries in the first column are completely model independent [34] – they follow from the fact that a purely adiabatic perturbation is conserved and does not lead to any isocurvature perturbations. On the other hand, the transfer functions $\mathcal{T}_{\rm RS}$ and $\mathcal{T}_{\rm SS}$ are model dependent. But, the form of the transfer matrix implies that if $\mathcal{S}_* << \mathcal{R}_*$, then isocurvature perturbations remain suppressed and $\mathcal{R}_{\rm rad}$ is essentially determined by $\mathcal{R}_*$. Thus, for models in which the only light direction during the inflationary epoch is the trajectory in field space the density perturbations are adiabatic and determined by the curvature perturbation at the time of horizon exit.

Other scenarios to generate density perturbations are the curvaton scenario [35] and modulated fluctuations [36]. We shall not explore these possibilities here, see [37,38] for their realisations in string models.

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