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Brane inflation without slow-roll

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Abstract: The scenario of brane inflation without using the conventional slow-roll approximations has been investigated. Based on the mechanism of generating the curvature perturbations at the end of inflation, a new brane inflation paradigm was developed. The conditions for making a sufficiently large enough number of e-foldings and for generating the curvature perturbations without producing dangerous relics were also examined. Benefits of our scenario are subsequently discussed in detail.

Keywords: Flux compactifications, Cosmology of Theories beyond the SM, D-branes.

Contents

1. Introduction

In the standard scenario of the inflationary Universe, the observed density perturbations are produced by a light inflaton that rolls down its potential. When inflation ends, the inflaton oscillates about its potential minimum and decays to reheat the Universe. Adiabatic density perturbations are generated because the scale-invariant fluctuations of the light inflaton field are different in different patches. On the other hand, we know that in supersymmetric and superstring theories there is a serious problem called the "η-problem". Without the symmetry that protects the flatness of the inflaton field, a mass of the order of the Hubble constant will inevitably appear in the inflaton field, ruining the conventional slow-roll approximation, which has the typical parameter denoted by "η". Although it may be possible to construct some inflationary scenarios where the flatness of the inflaton potential is protected by symmetry, it is not straightforward to find a situation where the symmetry appears naturally and all the required conditions for inflation are satisfied without any fine-tuning.[1] Thus, we considered an alternative in this paper. A new inflationary paradigm is developed where the conventional slow-roll picture does not play an essential role either in obtaining a large number of e-foldings nor in generating the curvature perturbations. If such a new scenario is successful, it will perform even in cases where the inflaton mass

[1]It would be very fascinating if slow-roll inflation could be embedded in MSSM [1].

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is corrected to the order of the Hubble constant. To be more precise, we will consider a scenario where a "light field" is not identified with the inflaton. The most obvious example in this direction would be the curvaton models [2, 3]. In the curvaton models, the origin of the large-scale curvature perturbations in the Universe is the late-decay of a massive scalar field that is called the "curvaton". The curvaton is assumed to be light during a period of cosmological inflation such that it acquires scale-invariant fluctuations with the required spectrum. Then, after inflation, the curvaton starts to oscillate within a radiation background. The energy density of the curvaton experiences a growth pattern during this period. The density of the curvaton finally becomes the dominant part of the total density of the Universe, accounting for the cosmological curvature perturbations when it decays. The curvaton paradigm has attracted quite a bit of attention because it was thought to have obvious advantages. For example, since the curvaton is independent of the inflaton field, there was a hope [4] that the curvaton scenario, especially in models with a low inflationary scale, could cure serious fine-tunings of the inflation models.[2] However, Lyth suggested in his paper [7] that there is a strong bound for the Hubble parameter during inflation. The bound obtained in ref. [7] was a critical parameter in the inflationary model with a low inflation scale. It was later suggested in ref. [8, 9] that the difficulty could be avoided if an additional inflationary expansion or a phase transition was present.

More recently, it has been suggested by Lyth [10] that density perturbations can be generated "at the end of inflation" by the number of e-folding fluctuations δN induced by a light scalar field.[3] This novel mechanism is quite simple but very useful. One does not have to put severe conditions on the inflaton field, because the generation of the curvature perturbations is now due to the fluctuations of a light field, which is independent of the details of the inflaton dynamic details. The new mechanism is similar to the curvaton models on this point. However, there is an important advantage in the new mechanism; unlike the curvatons, one does not have to worry about the serious conditions that come from the requirement of the successful late-time dominance and reheating.

Using this idea, we studied in ref. [13] the generation of the curvature perturbations without using slow-roll approximations. We considered the fluctuations appeared on the equipotential surface of the multi-field potential. The condition considered in ref. [13] is very common in brane inflationary models when extra dimensions are added.[4] The benefit of the model is that concern over symmetry is not warranted, as the potential along the equipotential surface is flat by definition. We also considered a brane inflationary model where a light field appears "at a distance" from the moving brane. This idea fits in well with the generic requirements of the KKLT model. To be more precise, we demonstrated that the conventional η-problem related to the inflationary brane position is not a serious problem if there is a symmetry enhancement "at the tip" of the throat. This scenario is

[2]Many attempts has been made in this direction. See ref. [5] as an example, of which a complete list and discussion is beyond the scope of this paper. Cosmological defects may play an essential role in low-scale brane inflationary scenarios [6].

[3]See also ref. [11], where different models generating a contribution to the curvature perturbation were proposed.

[4]In ref. [14], one can find another useful discussions on this point.

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very natural in the brane Universe.

Although the generation of the density perturbations was successful in ref. [13], it is still ambiguous if one can achieve a large number of e-foldings without using the usual slow-roll approximations. Dangerous relics in this type of model should also be examined, since the isometry at the tip makes the Kaluza-Klein mode with the angular momentum very sustainable. Considering the above conditions, we studied a new paradigm of brane inflation, which is not restricted by the conventional slow-roll conditions nor by the curvaton conditions. We will show that our settings are very natural in the brane Universe and can successfully generate the required number of e-foldings, curvature perturbations and relic densities. We will consider a model where thermal inflation is followed by fast-roll inflation. In this model, the hybrid-type potential plays a critical role in both inflationary epochs. A moving brane is attracted to a distant brane during thermal inflation, and is subsequently detached at a low temperature. The moving brane rolls down the potential toward the point where inflation ends with a brane collision. Although thermal inflation is not essential in generating the curvature perturbations, it fixes the initial conditions and supports the succeeding stage of the fast-roll [24] or DBI [25] inflation. Unlike the conventional scenario of thermal inflation followed by fast-roll inflation, where massless modes play a significant role to generate the unwanted peaks in the spectrum, no such massless modes appear in our scenario. We will further discuss this point in section 2.

In our scenario, it is better to lower the scale of inflation so that one can obtain a large number of e-foldings.[5] On the other hand, as we will discuss in section 3, the requirements from the generation of the curvature perturbations places a lower bound on the inflationary scale, which cannot be satisfied by the condition obtained from e-foldings, if no fine-tunings are made. This problem can be solved if there is a preceding short period of inflationary expansion; the solution of which is similar to the mechanism discussed for the curvatons in ref. [8]. We will discuss this mechanism in section 3. Aside from the curvature perturbation generation, one might think that the dangerous overproduction of unwanted gravitational relics might be critical, since the enhanced isometries are known to make the Kaluza-Klein modes completely stable. It was discussed in ref. [21] that these "stable" relics put an unavoidable lower bound on the inflationary scale in the brane Universe. We will discuss this issue and the solution to the problem in section 4. We will examine these competing conditions and show that it is possible to construct realistic models of brane inflation using neither slow-roll nor fine-tunings. It is worth re-emphasizing that the conventional slow-roll approximations throughout this paper will not be used.

[5]We will derive this condition in section 2 by using the idea of fast-roll inflation. Alternatively, one may use the idea of DBI inflatio [25] to obtain a large enough number of e-foldings. In the latter case, however, "slow-roll" parameters appear in the theory. Since we are considering brane inflationary models where "slow-roll" is not essential, it should be unfair to claim that the problem of the number of e-foldings is solved by using the DBI inflationary models.

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2. Inflation in the brane Universe

2.1 Thermal Inflation in the brane Universe

Non-hybrid type. Let us first explain the basic idea of the original thermal inflationary model [15]. In supersymmetric theories where the potential of the scalar fields can be very flat, a field (flaton) can develop a large vacuum expectation value M even though its mass m is very small. The finite temperature in the early Universe can hold such a field at zero, corresponding to a false vacuum with energy density $V_0 \sim m^2M^2$. When the temperature falls below V_0, the thermal energy density becomes negligible and an era of "thermal inflation" begins. "Thermal inflation" ends when the field rolls away from zero at a temperature of order m, generating a number of e-foldings $N_e \sim \ln\left(\frac{T_i}{T_f}\right)$, where T_i and T_f denote the temperature at the beginning and at the end of thermal inflation, respectively. In the conventional scenario of thermal inflation, where T_i and T_f are given by $T_i \sim V_0^{1/4}$ and $T_f \sim m$, the number of e-foldings is given by the two hierarchical scales M and m,

$$N_e \sim \frac{1}{2}\ln\left(\frac{M}{m}\right). \tag{2.1}$$

The above idea of thermal inflation can be applied to the brane inflationary models, since at high temperatures the points of the enhanced gauge symmetries will be the local free energy minima, and the four-dimensional gauge dynamics can be reconstructed using brane dynamics. In ref. [16] Dvali argued that considering the coincident branes corresponding to the enhanced gauge symmetry points one might expect that branes are stabilized on top of each other. For the observer living in the effective four-dimensional Universe, the situation looks quite the same as the conventional thermal inflation condition.

Hybrid-type. A different approach in this direction is given in ref. [17], where thermal inflation is achieved with a hybrid-type potential. The thermal inflationary models with the hybrid-type potential are first discussed in the conventional four-dimensional theory, and then applied to the brane Universe [17]. The most obvious advantage in using the hybrid potential is (1) the enhanced number of e-foldings and (2) easy reheating. Since we are considering the hybrid potential, we can use a potential in which the vacuum energy during inflation does not depend on m. Assuming that $V_0 \sim M^4$, we obtained the number of e-foldings that is given by the two hierarchical scales M and m;

$$N'_e \sim \ln\left(\frac{M}{m}\right). \tag{2.2}$$

This result is twice as large as the original result given in eq. (2.1). Moreover, since we are considering the hybrid-type potential, the requirement for the successful reheating does not put any critical bound on m. In the hybrid-type model, the trigger field that is much heavier than the inflaton field induces reheating. As we will discuss later in this paper, thermal inflation with the hybrid-type potential is more natural in the brane Universe. We will use this idea to obtain the required initial conditions in the new paradigm of brane inflation. We schematically depict our basic idea in figure 1.[6]

[6] The "trapping" may be due to the non-trivial effect other than the thermal attraction. For example,

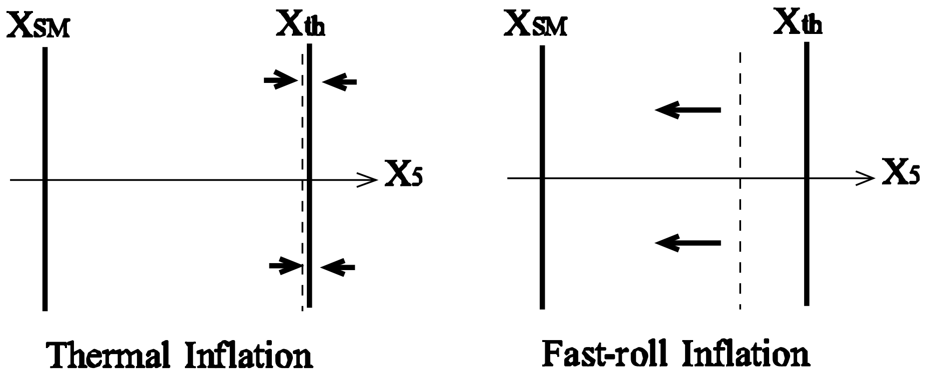

Figure 1: During thermal inflation, the moving brane is attracted to the fixed brane at the right-hand-side boundary. Then, at $T < T_f \sim m$, the moving brane is detached from the right-hand-side boundary and begins to roll down to the anti-brane waiting at the left-hand-side boundary.

2.2 Brane inflation without slow-roll (thermal inflation)

As discussed above, thermal brane inflation followed by fast-roll inflation is very natural in the brane Universe. However, it is still not clear if such an inflationary model can generate the required number of e-foldings and curvature perturbations without producing unwanted relics. In this section, we consider the inflationary expansion of the model and calculate the number of e-foldings. A typical example is shown in figure 1, where there is an extra dimension denoted by x_5, and a 3-brane sitting at $x_5 = X_{th}$ moving in this direction toward $x_5 = X_{SM}$ due to a potential that can be generated when supersymmetry is broken. We consider two more branes fixed at $x_5 = X_{th}$ and $x_5 = X_{SM}$. One may think that the fixed branes are the boundaries of the x_5 direction, or they are sitting at the fixed points of a moduli space. The fixed branes may be 7-branes wrapping some four-cycle of the compactified space other than x_5. We need to introduce at least one "anti"-brane sitting at $x_5 = X_{SM}$, which is required to produce a hybrid-type inflation followed by brane annihilation.

It is assumed that initially the temperature is so high that the thermal effects on the branes are so strong that they attract the moving brane to the fixed brane at $x_5 = X_{th}$. As the temperature drops during thermal inflation, the attractive force becomes weaker, and finally the force becomes so weak that the moving brane rolls down the potential toward the "anti"-brane sitting at $x_5 = X_{SM}$. Reheating is induced by the brane-antibrane annihilation at $x_5 = X_{SM}$.

To understand the characteristics of the model, we should first examine the effect of the potential that induces the brane motion. Since we are not considering slow-roll inflation, we must assume that the potential is lifted at least by the $O(H_I)$ mass term,

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Kofman et.al. observed in ref. [18] that a scalar field trapped on a steep potential can induce a stage of universe acceleration, which is called "trapped inflation".

$V_{\rm eff}(\varphi) \simeq \frac{\alpha^2}{2}H^2\varphi^2$. The generic form of the potential at a high temperature is given by

$$V(\varphi, T) = \pm\frac{1}{2}m^2(\varphi \pm \Delta)^2 + aT^2\varphi^2 + M^4, \tag{2.3}$$

where $\varphi \propto x_5$ is a real scalar field which parameterizes the position of the moving brane, and a is a constant. Here we set the field φ such that thermal inflation occurs at $\varphi = 0$ and annihilation occurs at $\varphi = \varphi_{SM}$. We introduced a new parameter $\Delta \neq 0$ because the minimum of the potential might be shifted from either $\varphi = 0$ or φ_{SM}. We have assumed that the brane-antibrane attractive force is negligible as far as the separation is significant. We will also assume (for simplicity) that the potential is a monotonic function in the interval $\varphi_{SM} + M < \varphi < 0$. Here M is the typical mass scale of the inflating brane. It is easy to calculate the minimum of the potential at a temperature $T > m$, which is given by

$$\varphi_{\rm min}(T) = \frac{-m^2\Delta/2}{\pm m^2/2 + aT^2}. \tag{2.4}$$

The thermal excitation of the gauge field is significant as long as the temperature is much higher than $T_f \equiv |g\varphi_{\rm min}|$, where g is a gauge coupling constant. On the other hand, at a temperature lower than T_f there is no significant thermal excitation, and thus the attractive force cannot keep the moving brane at the right-hand-side boundary. Here we would like to assume $g \sim 1$ for simplicity. In the brane picture, the gauge field corresponds to the open string stretched between branes. Assuming a modest condition $m \ll \Delta \ll \varphi_{th}$, one can find that thermal inflation is ended when the final temperature is

$$T_f \sim (m^2|\Delta|/a)^{1/3} \gg T_c, \tag{2.5}$$

where $T_c = m/\sqrt{a}$ is the "usual" value of the final temperature. It should be noted here that in the "usual" scenario there is an undesired massless excitation at $T = T_c$, which induces an unwanted steep spectrum.[7] On the other hand, in our new scenario, the brane separation $\varphi_{\rm min}(T)$ becomes significant before such massless excitations appear. Therefore, the effective mass of the inflaton $m_{\rm eff}^2 \equiv \pm m^2 + 2aT^2$ cannot become much smaller than the Hubble constant $H \sim m$ even if the original mass term appears with a negative sign. Moreover, unlike the non-hybrid type of the thermal inflationary model, we can use a positive mass term for the field φ, which cannot be canceled by the thermal mass term. Introducing new constants $\alpha \equiv m/H$ and $\beta \equiv V_0^{1/4}/M$, we obtained the number of e-foldings during thermal inflation as

$$\begin{aligned} N_{e,1} &\simeq \ln\left(\frac{T_i}{T_f}\right) \\ &\simeq \frac{1}{3}\ln\left(\frac{M_p}{M}\right) + \frac{1}{3}\ln\left(\frac{M_p}{\Delta}\right) + \frac{1}{3}\ln a + \frac{1}{3}\ln\left(\alpha^2\beta\right). \end{aligned} \tag{2.6}$$

[7] See ref. [23] for example. This is the problem which can always appear in the so-called "shoulder inflation".

2.3 Brane inflation without slow-roll (Fast-roll inflation)

After thermal inflation the motion of the moving brane is determined by the $O(H)$ mass term. Then, there will be another inflationary expansion called "fast-roll" inflation [24]. Since we will consider inflation in the KS throat in a later section, it should be convenient to consider a case when the potential has a minimum at $\varphi = \varphi_{SM}$ and the mass term appears with a positive sign. Then, it will be convenient to redefine the inflaton field φ such that the potential is given by

$$V(\varphi,\sigma) = \frac{1}{2}m^2\varphi^2 + \frac{1}{2}\varphi^2\sigma^2 + \frac{1}{4}\left(\sigma^2 - M^2\right)^2, \tag{2.7}$$

where σ is the waterfall field. The number of e-foldings elapsed during fast-roll inflation is given by [32]

$$N_{e,2} \simeq \frac{1}{F}\ln\left(\frac{\varphi_{th}}{M}\right), \tag{2.8}$$

where F is given by

$$F \equiv \frac{3}{2}\left(1 - \frac{\sqrt{9-4\alpha^2}}{3}\right). \tag{2.9}$$

Adding $N_{e,1}$ and $N_{e,2}$, we obtained the total number of e-foldings

$$N_e \simeq \frac{1}{3}\ln\left(\frac{M_p}{M}\right) + \frac{1}{3}\ln\left(\frac{M_p}{\Delta}\right) + \frac{1}{F}\ln\left(\frac{\phi_{th}}{M}\right) + \frac{1}{3}lna + \frac{1}{3}\ln\left(\alpha^2\beta\right). \tag{2.10}$$

The required condition for the successful inflationary scenario is [36]

$$N_e + N_{\rm pre} + N_{\rm add} \geq N_{\rm min} = 53 + \frac{2}{3}\ln\left(\frac{M}{10^{14}GeV}\right) + \frac{1}{3}\ln\left(\frac{T_R}{10^{10}GeV}\right), \tag{2.11}$$

where $N_{\rm pre}$ and $N_{\rm add}$ denotes the number of e-foldings elapsed during a preceding(bulk) and an additional(weak) inflationary expansions, if they existed. From eq. (2.10) and eq. (2.11), it would be fair to conclude that an inflationary scale higher than 10^{12}GeV seems unlikely in this model, if there is no fine-tunings nor large number of $N_{\rm pre} + N_{\rm add}$. From the above result, it is easy to understand that the total number of e-foldings becomes larger as the inflationary scale M becomes smaller. Thus, in this model, in order to make a sufficient number of e-foldings, we must be careful about a lower bound for the inflationary scale M. We will examine this problem in the following section.

3. Generating the curvature perturbations at the end of brane inflation

Since the slow-roll potential is not the essential requirement in this paper, it should be explained how one could obtain the required spectrum of the curvature perturbations without using the usual mechanism. It is well understood that adiabatic perturbations produced at later stages of the fast-roll inflation have a much smaller amplitude (and a very steep red spectrum), thus they cannot lead to desirable consequences. Besides adiabatic perturbations, fast-roll inflation may produce isocurvature fluctuations with a flat spectrum related to the perturbations of light fields other than the inflaton field. Such perturbations may be converted to adiabatic ones if the light field plays the role of the curvaton, or it plays the essential role in the Lyth's mechanism of generating the curvature perturbations at the end of inflation. In our case, since it was assumed that thermal inflation occurs prior to fast-roll inflation, the required mechanism for generating the adiabatic perturbations must be consistent also with thermal inflation. Since the vacuum energy is almost static during thermal inflation, thermal inflation produces isocurvature perturbations with a flat spectrum related to the perturbations of light fields if they (the light fields) are protected by a symmetry and are "not" thermalized during thermal inflation.

Let us consider a specific example. Here we consider a light field placed at the tip of the inflationary throat. The light field is decoupled from the thermal plasma on the distant brane in the bulk, and is very light due to the approximate isometries at the tip of the KS throat. As we will discuss in section 4, the approximate isometries will make the Kaluza-Klein modes with the angular momentum dangerously long-lived. Thus, sooner or later, we must examine if the stable Kaluza-Klein modes do not violate the conventional bounds for unwanted stable relics. Our setups are quite generic in the brane Universe. At first, there can be many D_3 and $\overline{D}_3$-branes moving in the bulk. Some of them may roll toward a $D7$-brane which wraps some four-cycle in the bulk, and might be subsequently "trapped" for a period of time [18]. A mechanism of the "trapping" is discussed in ref. [18]. Some of the trapped D_3 and $\overline{D}_3$-branes will annihilate each other, reheating the Universe to make thermal inflation possible at the D_7-brane. It is also possible to consider a thermal inflationary model where $N(N>1)$ D_3-branes are attracted to a fixed brane.

3.1 The basic idea

When one considers brane inflation, one may simply assume that the typical inflaton field that determines the brane motion is the only field that parameterizes the brane distance between the moving brane and the waiting anti-brane. This idea is not completely incorrect, but requires further consideration. For example, let us consider two inflaton fields (i.e. two directions in the extra dimensions) (ϕ_1, ϕ_2) with a hybrid-type potential

$$V(\phi_1, \phi_2, \sigma) = \frac{m_1^2}{2}\phi_1^2 + \frac{m_2^2}{2}\phi_2^2 + \frac{\lambda}{2}\phi_r^2\sigma^2 + \frac{1}{4}(\sigma^2 - M^2)^2, \tag{3.1}$$

where ϕ_i $(i = 1, 2)$ and σ are taken to be real scalar fields. The above potential has global minima at

$$(\phi_i, |\sigma|) = (0, M), \tag{3.2}$$

and an unstable saddle point at

$$(\phi_i, \sigma) = (0, 0). \tag{3.3}$$

Here $\phi_r \equiv \sqrt{\phi_1^2 + \phi_2^2}$ denotes the brane-antibrane distance.[8] In a common case, there is no exact symmetry that protects all the masses of the position moduli, and thus the equipotential surface of the potential becomes an ellipsoid [13]. On the other hand, if there is an isometry in the compactified space, we can choose the field ϕ_2 to parameterize the

[8]It would be useful to note here that the usual "brane distance" is given by $r^2 = \sum_i x_i^2$, where x_i are the brane distances in the directions perpendicular to the inflating branes.

massless direction, while a massive inflaton field ϕ_1 determines the dynamics of the brane inflation.[9] As a consequence, we introduce a hierarchy between the mass scales; $m_1 \gg m_2$. Inflation starts at large ϕ_1 and ends at the point on the surface $\phi_1^2 + \phi_2^2 = M^2/\lambda$, where the branes annihilate to reheat the Universe.

Since the secondary field ϕ_2 is light during inflation, the fluctuations along this direction is $\delta\phi_2 \simeq H_I/2\pi$, where H_I denotes the Hubble constant $H_I \sim M^2/M_p$ during inflation.

If the mass m_1 is not much heavier than H_I and satisfies the condition $m_1 < \frac{3}{2}H_I$, the fast-roll inflation induced by the inflaton field ϕ_1 has the number of e-foldings

$$N = \frac{1}{F} \ln\left(\frac{\phi_{1,0}}{\phi_{1,e}}\right) \tag{3.4}$$

where $\phi_{1,0}$ and $\phi_{1,e}$ denotes the initial and the final value of the inflaton field ϕ_1. Although there are no sensible fluctuations related to the perturbations of the inflaton field ϕ_1, there is a generation of the curvature perturbations due to $\delta\phi_2$ at the end of inflation. In the above formula for N, ϕ_2-dependence appears in $\phi_{1,e} = \sqrt{M^2 - \phi_{2,e}^2}$.

The curvature perturbation ζ can now be calculated using the method advocated in ref. [10], which takes the form

$$\zeta = \frac{\partial N}{\partial \phi_1}\frac{\partial \phi_1}{\partial \phi_2}\delta\phi_2 + \frac{1}{2}\left\{2\frac{\partial^2 N}{\partial \phi_1^2}\left(\frac{\partial \phi_1}{\partial \phi_2}\right)^2 + \frac{\partial N}{\partial \phi_1}\frac{\partial^2 \phi_1}{\partial \phi_2^2}\right\}(\delta\phi_2)^2. \tag{3.5}$$

It is amazing that this mechanism is still successful in generating the desirable curvature perturbations even if the inflaton field ϕ_1 does "not" satisfy the slow-roll conditions. Taking the mean value of the field ϕ_2 as $\phi_2 \simeq \gamma M$ ($\gamma < 1$), we can calculate the curvature perturbations. Assuming that the inflaton ϕ_1 satisfies the fast-roll condition [24], it is easy to obtain

$$\begin{aligned} \left.\frac{\partial N}{\partial \phi_1}\right|_e &= -\frac{1}{F_1 \phi_{1e}} \\ \left.\frac{\partial^2 N}{\partial \phi_1^2}\right|_e &= \frac{1}{F_1 \phi_{1e}^2}, \end{aligned} \tag{3.6}$$

and

$$\begin{aligned} \left.\frac{\partial \phi_1}{\partial \phi_2}\right|_e &= -\frac{\phi_{2e}}{\phi_{1e}} \\ \left.\frac{\partial^2 \phi_1}{\partial \phi_2^2}\right|_e &= -\frac{1}{\phi_{1e}}\left(\frac{\phi_{2e}^2}{\phi_{1e}^2} + 1\right). \end{aligned} \tag{3.7}$$

As a result, we obtained $\zeta_\Delta(x)$ which is given by

$$\zeta_\Delta(x) = \frac{\gamma H_I}{2\pi F_1 (1-\gamma^2) M} + \frac{(2\gamma^2+1) H_I^2}{8\pi^2 F_1 (1-\gamma^2)^2 M^2}. \tag{3.8}$$

[9] Unlike the conventional models of "successful brane inflationary models", we do not assume any isometry that protects the flatness of the inflaton ϕ_1. The field that is protected by an isometry is the secondary field ϕ_2, which is not the "inflaton".

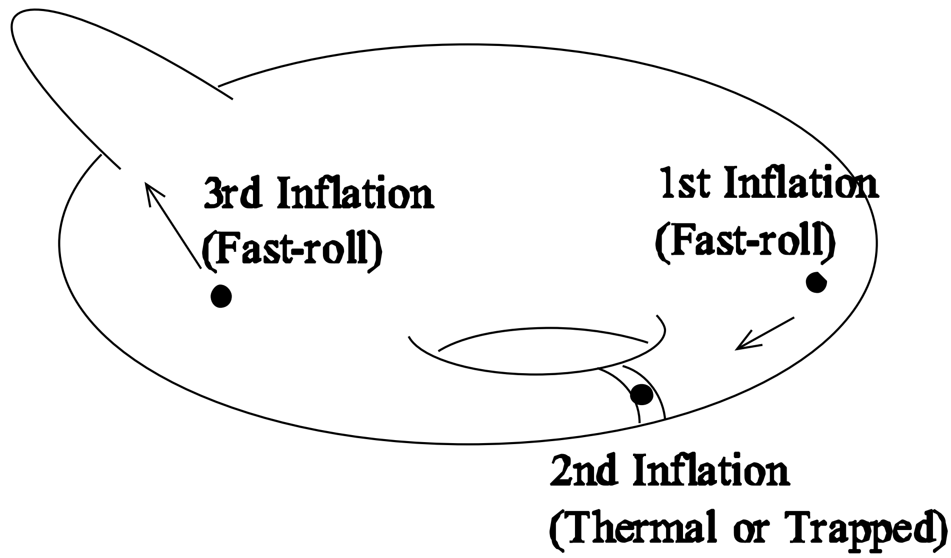

Figure 2: A typical situation in the brane Universe

As far as one is considering the single-shot inflation in the brane Universe, the typical scale of the Hubble constant during inflation is given by $H_I \simeq M^2/M_p$, suggesting that the above result puts a strict bound on the inflationary scale $M/M_p \sim 10^{-5}$, if there is no fine-tunings. However, it is always possible to consider an additional stage of inflation in the bulk (or in a different throat), which can produce another inflationary scale $H_I' \gg H_I$. For example, let us consider a case where initially many D_3 and $\overline{D}_3$-branes are moving in the bulk. Some of them rolls toward a fixed D_7-brane in the bulk, where they will be "trapped" for a period of time [18]. Some of the trapped D_3 and $\overline{D}_3$-branes will annihilate each other, reheating the Universe to make thermal inflation possible. During this period, the light field ϕ_2 at the bottom of a throat is protected by an approximate isometry at the tip of the KS throat where the final target-brane lives. If so, the fluctuation related to the light field ϕ_2 is given by $\delta\phi_2 \simeq H_I'/2\pi$, which is much larger than $H_I/2\pi$. See figure 2 to understand a typical situation. The strict bound $M/M_p \sim 10^{-5}$ obtained above can be removed if there is an additional period of inflation, which has an energy scale higher than the energy scale of the last inflation. The lowest scale of the last inflation would be realized when it occurs in the standard-model throat, where the inflationary scale M is as low as O(TeV). In this extreme case, the inflationary scale in the bulk could be as low as $M' \sim 10^8$GeV.

4. Comment on dangerous relics and baryogenesis

4.1 Dangerous relics

As we have discussed above, this new scenario favors a low inflationary scale since a large number of e-foldings requires a low inflationary scale in the order of $M < 10^{12}$GeV, if

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there are no fine-tunings. Although (naively) the mechanism for generating the curvature perturbations at the end of inflation cannot produce enough perturbations if the inflationary scale is lower than 10^{13}GeV, this problem can be solved by introducing a preceding stage of inflation in the bulk, which has the Hubble constant $H'_I \sim 10^{-5}M$. If so, fast-roll brane inflation in the KS throat may occur in the standard-model throat, generating a large enough number of e-foldings provided that a preceding inflationary stage has the inflationary scale $M' \sim 10^8$GeV.

The question as to whether there are constraints coming from other cosmological considerations requires an answer. Do they disrupt the above scenarios? It is assumed the reader is knowledgeable in the various constraints in this direction, however the constraints are sometimes based on some specific conditions that are highly model-dependent. Thus, it would be helpful to start with historical arguments. Let us first consider a generic condition that places a significant bound on the scale of the usual hybrid-type inflationary model. During hybrid inflation, the inflaton field should have a significant coupling to the trigger field. As discussed in ref. [19], this coupling may induce a one-loop contribution to the inflaton potential, which may then ruin the slow-roll approximation and the generation of the structure of the Universe. Therefore, as far as one is considering a scenario where the slow-roll approximation plays a significant role, one cannot have a successful model of hybrid inflation with a scale lower than 10^9 GeV. It might be thought that this bound contradicts the above argument, and start to suspect that the last inflation cannot occur in the standard-model throat. However, in the analysis of ref. [19], the crucial condition came from the requirement of generating the curvature perturbations from the "slow-roll" inflaton field. Thus, our model does not suffer from this condition. One may think that the TeV-scale inflation could be successful if the curvaton plays its role. However, as we have discussed in section 1, there is a strict bound on the inflation scale even if the curvaton is introduced [7]. This serious bound could be avoided by introducing additional inflation [8], however this mechanism would require many non-trivial assumptions in order to make the additional phase transitions viable in this scenario. Besides the above conditions, other conditions coming from the fact that the typical mass scale of the brane bound the maximum value of a scalar field on the brane must be considered; in models with a low fundamental scale $M \sim$O(TeV), the inflation field must be a bulk field if it "rolls in" from a distance. In this case, one cannot exclude the serious constraint coming from the decaying Kaluza-Klein mode [20], since such bulk fields always couple to the Kaluza-Klein states. The constraint appears even if one discards the generation of the curvature perturbations due to the "slow-roll" inflaton field. Recently, it has been suggested in ref. [21] that the constraint coming from the Kaluza-Klein mode becomes much more serious in the brane inflationary models with some isometries in the compactified space. In the brane Universe, the stability of the Kaluza-Klein mode with the angular momentum related to the isometry depends on the scale of the inflation scale M, giving the stringent condition $M > 10^{12}$GeV [21] for the "safe-decay". Of course, the above condition is quite significant in our scenario and seems to exclude low-scale inflation in the standard-model throat. More recently, however, it has been discussed in ref. [22] that studying a more detailed thermodynamic evolution of the heating process, especially that of the KK particles, many qualitatively different results compared to the original result can be found. The new result obtained in ref. [22] is quite helpful in reducing the scale of inflation, since it allows inflation in the standard-model throat.[10]

One may also worry about dangerous cosmological defects that may be produced during brane annihilation. Although cosmic strings can put an upper bound on the inflationary scale of the last inflation [35], it is looser than the above bound obtained in the calculation of the number of e-foldings. Besides the cosmic strings, monopoles and walls may be produced as a consequence of brane creation or brane deformation that may occur during or after the reheating epoch [34]. It is known that these defects might put a strict upper bound on the inflationary scale [33], if there is a non-trivial structure in the compactified space. A natural solution to the domain wall problem in a typical supergravity model is discussed in ref. [37], where the required magnitude of the gap in the quasi-degenerated vacua is induced by W_0 in the superpotential. The mechanism discussed in ref. [37] is natural since the constant term W_0 in the superpotential is necessary so as to cancel the cosmological constant. The bound obtained in ref. [33] is severe, but it is also known that the structure that is required to produce the dangerous defect configuration of the brane does not appear in the known example of the KS throat. Of course, it is not clearly understood whether it is possible to obtain the complete Standard Model(SM) in the known example of the KS throat. Thus, it should be fair to conclude here that this problem is unsolved and requires further investigation together with the construction of the complete set of the SM model in the brane Universe.

4.2 Baryogenesis

In lowering the inflationary scale it might be thought that it would be difficult in obtaining enough baryon number asymmetry of the Universe (BAU), since the requirement of the proton stability puts a strict bound on the baryon-number-violating interactions. This speculation is indeed true. The old scenario of the baryogenesis with a decaying heavy particle cannot work if the fundamental scale becomes as low as the O (TeV) scale [26]. One can solve this problem by introducing cosmological defects that enhance the breaking of the baryon number conservation in the core [27]. There is also a problem in the scenario of Affleck-Dine baryogenesis [31], since the expectation value of a field on a brane cannot become much larger than the typical mass scale of the brane [28]. One can solve this problem by introducing non-trivial defect configuration structures [29]. Moreover, in ref. [30], the reader will find more arguments about the mechanism of baryogenesis with low-scale inflationary scale. Although there is no ultimate solution to this problem, it is not incorrect to expect that baryogenesis could be successful even if the inflationary scale is as low as the TeV scale.

5. Conclusions and discussions

We studied a typical situation in brane inflationary models without using the conventional slow-roll approximations. Based on the sensible idea advocated recently in ref. [10], we

[10] A conserved angular momentum may be significant [38, 40]

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have found a new brane inflation paradigm. We examined the conditions for constructing a large enough number of e-foldings and for generating the curvature perturbations. We also examined whether dangerous unwanted relics could be produced. Benefits of our scenario are obvious: we do not have to be concerned about the famous η-problem if an isometry appears in the structure of the compactified space. The most useful isometry example is the one appearing at the KS throat, which is, of course, a natural candidate for the "realistic" brane Universe.

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A. More on the junctions

Our scenario is based on the simple idea that (1) thermal brane inflation is generically supposed to occur after primary inflation and (2) there could be some inflationary stage after thermal brane inflation, which is sometimes called by the name "shoulder inflation". Hence generically one should consider three different kinds of inflation if the inflationary model contains thermal inflation. However, such shoulder inflation has been supposed to be very short or simply disregarded, because of the serious problem related to the overproduction of PBHs. The PBH overproduction puts a severe bound on models with conventional shoulder inflation [23]. One of the important advantages in our scenario is that this condition does not apply to brane inflation models in which the potential is not the rigorous function of the brane distance.[11] Of course, if the broken isometry of the internal space is simply due to the existence of the other brane, the potential that lifts the flat direction related to the isometry must be a rigorous function of the brane distance. On the other hand, if the isometry is explicitly broken due to the non-trivial structure of the compactified space, for example by the existence of fluxes or warping, the potential for the brane position could be a function determined by the structure of the compactified space. In this case, the potential for the brane position is not a rigorous function of the brane distance. Using a simple inflationary model in which thermal brane inflation occurs at a boundary (or at a fixed brane) in the x_5 direction, we showed that the serious bound related to the unwanted PBH production can be avoided if the potential for the moving brane is not the rigorous function of the brane distance. The boundary in the x_5 direction is the thermal attractor during thermal inflation, and a "shift" from the thermal attractor grows during thermal inflation. This "shift" induces the desired mass for the unwanted massless mode, and reduces the overproduction of unwanted PBHs. It would be important to note again that in our analysis the potential is not the rigorous function of the brane distance. This is what happens in generic models with warped internal space, or moduli stabilization by the fluxes [12]. The idea that the potential for the brane position is not the rigorous function of the brane distance plays the most important role in our analysis

[11] A similar situation has been considered in ref. [18].

of generating the curvature perturbation at the end of inflation. In our present model the potential for ϕ_1 and ϕ_2 should not be the rigorous function of the brane distance that is given by ϕ_r. The difference between m_1 and m_2 cannot be justified if the potential is the rigorous function of the brane distance. In order to make $m_1 \gg m_2$, we have assumed that the light field ϕ_2 is related to some enhanced angular isometry of the compactified space. This is a typical situation in the KS-throat where angular isometries are enhanced at the tip of the throat [13, 14][12] and what happens in the potential eq. (3.1) for large ϕ_r. On the other hand, the end-line of the hybrid inflation is determined by the brane distance ϕ_r if the brane-brane interaction triggers the end of inflation. We think some comments are required to explain the origin of the enhanced isometries in the KS throat. Consider the dS background of KKLT [12]. The idea is that the stabilization of the Kähler modulus leads to a vacuum with a negative cosmological constant, however the vacuum can be lifted by adding an $\overline{D3}$-brane that sits at the tip of the throat. Introducing an $\overline{D3}$-brane to the warped background one will find new moduli that corresponds to the position of the $\overline{D3}$-brane on the compact space. The potential for the moduli in the KKLT background is not trivial. The $\overline{D3}$-brane is not free to move in the throat direction since they have a potential proportional to the warp factor which stabilizes the $\overline{D3}$-brane at the tip of the throat. Although the throat direction is stabilized by the potential, the $\overline{D3}$-brane can still move on the S^3 at the tip of the throat. In the exact KS solution, S^3 at the tip of the throat is exact. The symmetry of S^3 is broken by placing the $\overline{D3}$-brane as SO(4) $\rightarrow$ SO(3), which gives rise to three massless moduli. The moduli correspond to the three coordinates of the position of the $\overline{D3}$-brane on the S^3. Besides the corrections in the IR-boundary which is expected to be small, there would be another correction from the UV-boundary. Generically the UV-boundary is supposed to be the Calabi-Yau manifold where the background deviates from the original KS solution away from the tip. The corrections from the UV-boundary may explicitly break the SO(4) symmetry generating masses for the moduli. Although the deformation of the theory generates $O(H)$ mass for the moduli at the UV-side, the contribution is exponentially smaller than the typical mass scale at the tip. Therefore, in a brane inflationary scenario where the $\overline{D3}$-brane is fixed at the tip of the throat while the moving brane comes from the root, the fluctuation of the $\overline{D3}$-brane in the direction of S^3 is important although the fluctuation is negligible for the moving brane at the UV-side. The target brane fluctuates in the direction of S^3 but the moving brane does not fluctuate. Angular isometry may appear in other string models, which may or may not protect the mass of the light field ϕ_2.

Here we would like to explain more for the three inflationary stages; primary inflation, thermal inflation and shoulder inflation. In order to induce thermal brane inflation after the primary inflation, there should be a moving brane that feels the thermal attractive force from the fixed brane(or the boundary). The required situation is also explained in the original paper [16], however one might think the conditions are artificial. We think the most artificial point is the existence of a moving brane, which is supposed to appear

[12]Of course there could be many other cases in which some angular isometries remain in realistic compactifications. We do not exclude other models with angular isometries.

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not at the stable point of the potential but at the unstable point near the boundary, and then sticks to the boundary due to the thermal attractive force. Of course it is possible to assume that the boundary is the quasi-stable point during the primary inflation, since there could be corrections of $O(H)$ during primary inflation which might give large positive mass to the open string mode.[13] This is the common ambiguity that exists whenever one considers thermal brane inflation. This is the weak point of our argument.

Another thing that we believe to be explained more is the origin of the large-scale fluctuation of ϕ_2. One might think that $\delta\phi_2$ must be generated during the last (shoulder) inflationary period since the curvature perturbation is generated at the end of this period. This is not the case in Lyth's scenario for generating the curvature perturbation at the end of inflation [10]. Since the curvature perturbation depends on the fluctuation δN, where N is the total number of e-foldings elapsed after horizon exit, the large-scale fluctuation of the light field ϕ_2 must be generated at the initial few e-foldings of N. Hence, the required large-scale fluctuation of the light field ϕ_2 should be generated during the preceding inflationary periods, if the last (shoulder) inflationary expansion is not enough.

We would like to consider the natural range of the number of e-foldings related to the last (shoulder) inflation. If one excludes "small" mass $m < 0.1H$, the upper limit for the number of the e-foldings elapsed during shoulder inflation is given by eq. (2.8), where $F \simeq 0.003$ for $m = 0.1H$. This "minimum" value for the inflaton mass $m \simeq 0.1H$ leads to the "maximum" value for the number of the e-foldings $N_{\max} > 100$, which is obviously large. On the other hand, for the inflaton mass $m = H$ the factor F is enhanced up to $F \simeq 0.38$ and it seems unlikely to have $N = 60$ without considering additional thermal or primary inflation.

References

[1] R. Allahverdi, K. Enqvist, J. Garcia-Bellido and A. Mazumdar, *Gauge invariant MSSM inflaton*, *Phys. Rev. Lett.* **97** (2006) 191304 [hep-ph/0605035];
R. Allahverdi, A. Kusenko and A. Mazumdar, *A-term inflation and the smallness of neutrino masses*, hep-ph/0608138.

[2] S. Mollerach, *Isocurvature baryon perturbations and inflation*, *Phys. Rev.* **D 42** (1990) 313;
A.D. Linde and V.F. Mukhanov, *Nongaussian isocurvature perturbations from inflation*, *Phys. Rev.* **D 56** (1997) 535 [astro-ph/9610219];
K. Enqvist and M.S. Sloth, *Adiabatic CMB perturbations in pre big bang string cosmology*, *Nucl. Phys.* **B 626** (2002) 395 [hep-ph/0109214].

[3] T. Moroi and T. Takahashi, *Effects of cosmological moduli fields on cosmic microwave background*, *Phys. Lett.* **B 522** (2001) 215 [hep-ph/0110096];
D.H. Lyth and D. Wands, *Generating the curvature perturbation without an inflaton*, *Phys. Lett.* **B 524** (2002) 5 [hep-ph/0110002].

[4] K. Dimopoulos and D.H. Lyth, *Models of inflation liberated by the curvaton hypothesis*, *Phys. Rev.* **D 69** (2004) 123509 [hep-ph/0209180];
M. Giovannini, *Tracking curvaton(s)?*, *Phys. Rev.* **D 69** (2004) 083509 [hep-ph/0310024].

[13] Alternatively, one may consider "trapped inflation" [18] instead of thermal brane inflation.

[5] P. Kanti and K.A. Olive, *Assisted chaotic inflation in higher dimensional theories*, *Phys. Lett.* **B 464** (1999) 192 [hep-ph/9906331];
N. Arkani-Hamed, S. Dimopoulos, N. Kaloper and J. March-Russell, *Rapid asymmetric inflation and early cosmology in theories with sub-millimeter dimensions*, *Nucl. Phys.* **B 567** (2000) 189 [hep-ph/9903224];
R.N. Mohapatra, A. Perez-Lorenzana and C.A. de Sousa Pires, *Inflation in models with large extra dimensions driven by a bulk scalar field*, *Phys. Rev.* **D 62** (2000) 105030 [hep-ph/0003089];
A. Mazumdar, S. Panda and A. Perez-Lorenzana, *Assisted inflation via tachyon condensation*, *Nucl. Phys.* **B 614** (2001) 101 [hep-ph/0107058];
A. Mazumdar, *Extra dimensions and inflation*, *Phys. Lett.* **B 469** (1999) 55 [hep-ph/9902381];
A.M. Green and A. Mazumdar, *Dynamics of a large extra dimension inspired hybrid inflation model*, *Phys. Rev.* **D 65** (2002) 105022 [hep-ph/0201209];
T. Matsuda, *Non-tachyonic brane inflation*, *Phys. Rev.* **D 67** (2003) 083519 [hep-ph/0302035]; *F-term, D-term and hybrid brane inflation*, *JCAP* **11** (2003) 003 [hep-ph/0302078]; *Successful D-term inflation with moduli*, *Phys. Lett.* **B 423** (1998) 35 [hep-ph/9705448].

[6] T. Matsuda, *Topological hybrid inflation in brane world*, *JCAP* **06** (2003) 007 [hep-ph/0302204];
T. Matsuda, *Q ball inflation*, *Phys. Rev.* **D 68** (2003) 127302 [hep-ph/0309339];
T. Matsuda, *Brane q-ball, branonium and brane q-ball inflation*, *JCAP* **10** (2004) 014 [hep-ph/0402223].

[7] D.H. Lyth, *Can the curvaton paradigm accommodate a low inflation scale*, *Phys. Lett.* **B 579** (2004) 239 [hep-th/0308110].

[8] T. Matsuda, *Curvaton paradigm can accommodate multiple low inflation scales*, *Class. and Quant. Grav.* **21** (2004) L11 [hep-ph/0312058].

[9] K. Dimopoulos and G. Lazarides, *Modular inflation and the orthogonal axion as curvaton*, *Phys. Rev.* **D 73** (2006) 023525 [hep-ph/0511310]; *Modular inflation and the orthogonal axion as curvaton*, *Phys. Rev.* **D 73** (2006) 023525 [hep-ph/0511310];
K. Dimopoulos, *Inflation at the TeV scale with a PNGB curvaton*, *Phys. Lett.* **B 634** (2006) 331 [hep-th/0511268].

[10] D.H. Lyth, *Generating the curvature perturbation at the end of inflation*, *JCAP* **11** (2005) 006 [astro-ph/0510443].

[11] F. Bernardeau, L. Kofman and J.-P. Uzan, *Modulated fluctuations from hybrid inflation*, *Phys. Rev.* **D 70** (2004) 083004 [astro-ph/0403315];
K. Enqvist, A. Mazumdar and M. Postma, *Challenges in generating density perturbations from a fluctuating inflaton coupling*, *Phys. Rev.* **D 67** (2003) 121303 [astro-ph/0304187];
A. Mazumdar and M. Postma, *Evolution of primordial perturbations and a fluctuating decay rate*, *Phys. Lett.* **B 573** (2003) 5 [astro-ph/0306509].

[12] S. Kachru, R. Kallosh, A. Linde and S.P. Trivedi, *De Sitter vacua in string theory*, *Phys. Rev.* **D 68** (2003) 046005 [hep-th/0301240];
S. Kachru et al., *Towards inflation in string theory*, *JCAP* **10** (2003) 013 [hep-th/0308055].

[13] T. Matsuda, *Elliptic inflation: generating the curvature perturbation without slow-roll*, *JCAP* **09** (2006) 003 [hep-ph/0606137].

[14] D.H. Lyth and A. Riotto, *Generating the curvature perturbation at the end of inflation in string theory*, *Phys. Rev. Lett.* **97** (2006) 121301 [astro-ph/0607326].

JHEP03(2007)096

[15] D.H. Lyth and E.D. Stewart, *Thermal inflation and the moduli problem*, *Phys. Rev.* **D 53** (1996) 1784 [hep-ph/9510204].

[16] G.R. Dvali, *Infrared hierarchy, thermal brane inflation and superstrings as superheavy dark matter*, *Phys. Lett.* **B 459** (1999) 489 [hep-ph/9905204].

[17] T. Matsuda, *Thermal hybrid inflation in brane world*, *Phys. Rev.* **D 68** (2003) 047702 [hep-ph/0302253].

[18] L. Kofman et al., *Beauty is attractive: moduli trapping at enhanced symmetry points*, *JHEP* **05** (2004) 030 [hep-th/0403001].

[19] D.H. Lyth, *Constraints on TeV-scale hybrid inflation and comments on non-hybrid alternatives*, *Phys. Lett.* **B 466** (1999) 85 [hep-ph/9908219].

[20] T. Matsuda, *Kaluza-Klein modes in hybrid inflation*, *Phys. Rev.* **D 66** (2002) 107301 [hep-ph/0209214].

[21] L. Kofman and P. Yi, *Reheating the universe after string theory inflation*, *Phys. Rev.* **D 72** (2005) 106001 [hep-th/0507257].

[22] D. Chialva, G. Shiu and B. Underwood, *Warped reheating in multi-throat brane inflation*, *JHEP* **01** (2006) 014 [hep-th/0508229];
X. Chen and S.H.H. Tye, *Heating in brane inflation and hidden dark matter*, *JCAP* **06** (2006) 011 [hep-th/0602136].

[23] J.-O. Gong, *Modular thermal inflation without slow-roll approximation*, *Phys. Lett.* **B 637** (2006) 149 [hep-ph/0602106].

[24] A. Linde, *Fast-roll inflation*, *JHEP* **11** (2001) 052 [hep-th/0110195].

[25] M. Alishahiha, E. Silverstein and D. Tong, *DBI in the sky*, *Phys. Rev.* **D 70** (2004) 123505 [hep-th/0404084].

[26] A. Masiero, M. Peloso, L. Sorbo and R. Tabbash, *Baryogenesis vs. proton stability in theories with extra dimensions*, *Phys. Rev.* **D 62** (2000) 063515 [hep-ph/0003312].

[27] T. Matsuda, *Baryon number violation, baryogenesis and defects with extra dimensions*, *Phys. Rev.* **D 66** (2002) 023508 [hep-ph/0204307]; *Enhanced baryon number violation due to cosmological defects with localized fermions along extra dimension*, *Phys. Rev.* **D 65** (2002) 107302 [hep-ph/0202258].

[28] R. Allahverdi, K. Enqvist, A. Mazumdar and A. Perez-Lorenzana, *Baryogenesis in theories with large extra spatial dimensions*, *Nucl. Phys.* **B 618** (2001) 277 [hep-ph/0108225].

[29] T. Matsuda, *Affleck-Dine baryogenesis in the local domain*, *Phys. Rev.* **D 65** (2002) 103502 [hep-ph/0202211]; *Hybridized Affleck-Dine baryogenesis*, *Phys. Rev.* **D 67** (2003) 127302 [hep-ph/0303132]; *Affleck-Dine baryogenesis after thermal brane inflation*, *Phys. Rev.* **D 65** (2002) 103501 [hep-ph/0202209].

[30] G.R. Dvali and G. Gabadadze, *Non-conservation of global charges in the brane universe and baryogenesis*, *Phys. Lett.* **B 460** (1999) 47 [hep-ph/9904221];
A. Pilaftsis, *Leptogenesis in theories with large extra dimensions*, *Phys. Rev.* **D 60** (1999) 105023 [hep-ph/9906265];
S. Davidson, M. Losada and A. Riotto, *Baryogenesis at low reheating temperatures*, *Phys. Rev. Lett.* **84** (2000) 4284 [hep-ph/0001301];

T. Matsuda, *Activated sphalerons and large extra dimensions*, *Phys. Rev.* **D 66** (2002) 047301 [hep-ph/0205331]; *Electroweak baryogenesis mediated by locally supersymmetry-breaking defects*, *Phys. Rev.* **D 64** (2001) 083512 [hep-ph/0107314]; *Defect-mediated electroweak baryogenesis and hierarchy*, hep-ph/0102040.

[31] I. Affleck and M. Dine, *A new mechanism for baryogenesis*, *Nucl. Phys.* **B 249** (1985) 361.

[32] K. Dimopoulos and M. Axenides, *Hybrid inflation without flat directions and without primordial black holes*, *JCAP* **06** (2005) 008 [hep-ph/0310194].

[33] T. Matsuda, *Brane necklaces and brane coils*, *JHEP* **05** (2005) 015 [hep-ph/0412290]; *Primordial black holes from cosmic necklaces*, *JHEP* **04** (2006) 017 [hep-ph/0509062]; *Dark matter production from cosmic necklaces*, *JCAP* **04** (2006) 005 [hep-ph/0509064];
A. Avgoustidis and E.P.S. Shellard, *Cycloops: dark matter or a monopole problem for brane inflation?*, *JHEP* **08** (2005) 092 [hep-ph/0504049];
T. Matsuda, *Primordial black holes from monopoles connected by strings*, hep-ph/0509061.

[34] T. Matsuda, *Formation of monopoles and domain walls after brane inflation*, *JHEP* **10** (2004) 042 [hep-ph/0406064]; *Formation of cosmological brane defects*, *JHEP* **11** (2004) 039 [hep-ph/0402232]; *Incidental brane defects*, *JHEP* **09** (2003) 064 [hep-th/0309266].

[35] T. Damour and A. Vilenkin, *Gravitational radiation from cosmic (super)strings: bursts, stochastic background and observational windows*, *Phys. Rev.* **D 71** (2005) 063510 [hep-th/0410222];
T. Matsuda, *String production after angled brane inflation*, *Phys. Rev.* **D 70** (2004) 023502 [hep-ph/0403092].

[36] E.W. Kolb and M.S. Turner, *The early Universe*, Addison-Wesley, U.S.A. (1990).

[37] T. Matsuda, *Weak scale inflation and unstable domain walls*, *Phys. Lett.* **B 486** (2000) 300 [hep-ph/0002194]; *On the cosmological domain wall problem in supersymmetric models*, *Phys. Lett.* **B 436** (1998) 264 [hep-ph/9804409].

[38] E. Papantonopoulos and V. Zamarias, *AdS/CFT correspondence and the reheating of the brane-Universe*, *JHEP* **10** (2004) 051 [hep-th/0408227];

[39] N. Barnaby and J.M. Cline, *Nongaussianity from tachyonic preheating in hybrid inflation*, astro-ph/0611750; *Nongaussian and nonscale-invariant perturbations from tachyonic preheating in hybrid inflation*, *Phys. Rev.* **D 73** (2006) 106012 [astro-ph/0601481].

[40] C. Germani, N.E. Grandi and A. Kehagias, *A stringy alternative to inflation: the cosmological slingshot scenario*, hep-th/0611246.

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