Physics Letters B 680 (2009) 395–398

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

N-flation from multiple DBI type actions

Yi-Fu Cai [a,*], Wei Xue [a,b]

[a] Institute of High Energy Physics, Chinese Academy of Sciences, PO Box 918-4, Beijing 100049, PR China
[b] School of Physics, Peking University, Beijing 100871, PR China

ARTICLE INFO

Article history:
Received 9 June 2009
Received in revised form 18 September 2009
Accepted 19 September 2009
Available online 23 September 2009
Editor: T. Yanagida

ABSTRACT

In this Letter we present a new inflationary model composed of multiple scalar fields where each of them has its own DBI action. We show that the dependence of the e-folding number and of the curvature perturbation on the number of fields changes compared with the normal N-flation model. Our model is also quite different from the usual DBI N-flation which is still based on one DBI action but involves many moduli components. Some specific examples of our model have been analyzed.

Inflation naturally resolves the flatness, homogeneity and primordial monopole problems of standard cosmology [1,2], and predicts a scale-invariant primordial perturbation spectrum consistent with current cosmological observations [3] very well. It has therefore become the prevalent paradigm to understand the initial stage of our universe. However, an inflationary model with a single scalar field generally suffers from fine tuning problems on the parameters of its potential, such as the mass and coupling of this field.

It was first noticed by Liddle et al. [4] that such limits can be relaxed when a number of scalar fields are involved. In such models, many fields are able to work cooperatively to give a enough long inflationary stage, even if none of them can sustain inflation separately. Models of this type have been considered later in Refs. [5–8]. These analyses showed that both the e-folding number $\mathcal{N}$ and the curvature perturbation ζ are approximately proportional to the number of scalars N. Later, the model of N-flation was proposed by Dimopoulos et al. [9], which showed that a number of axions predicted by string theory can give rise to a radiatively stable inflationary period. This model has the possibility for an attractive embedding of multi-field inflation in string theory.

Over the past several years, based on the recent developments in string theory, there have been many cosmological studies on its applications to the early universe, especially to inflation. However, authors still often encounter fine tuning and inconsistency problems when they try to combine string theory with cosmology. Examples include deficiencies in tachyon inflation as pointed out by Kofman and Linde in Ref. [10], as well as the η-problem in slow-roll brane inflation as reviewed in Ref. [11]. It is usually suggested that N-flation is able to relax these issues and thus allow plausible constructions of stringy cosmology. For instance, Piao et al. have successfully applied the assisted inflation mechanism to amend the problems of tachyon inflation [12]. There are also many other works that have investigated multi-field inflation models in string-inspired cosmology, for example see Refs. [13–16].

A particularly interesting inflationary mode with a non-canonical kinetic term inspired by string theory has recently attracted significant interest in the literature. This model is described by a Dirac–Born–Infeld-like (DBI) action [17,18]. The inflationary model with a single DBI field was investigated in detail in Refs. [19–21]. In this model, a warping factor was applied to provide a speed limit which keeps the inflaton near the top of a potential even if the potential is steep. DBI inflation therefore opens a up a range of inflationary models which do not necessitate a flat potential.

In this Letter, we study a multi-field inflationary model, where each field is described by a DBI action and the total action is constructed by the sum of them. Therefore, it is worth emphasizing that our model is different from the usual DBI N-flation in which multiple moduli fields are involved in a single DBI action [22–25]. In contrast, a multiple-DBI action can be achieved if we consider a number of D3-branes in a background metric field with negligible covariant derivatives of field strengths and we assume that these branes are decoupled from others. In addition, we neglect the backreaction of those branes on the background geometry, as is standard in brane inflation models. In this scenario, the scalars are able to work cooperatively like those in usual N-flation models. However, since their kinetic terms are of non-canonical form, the cumulative effect from multiple fields does not grow in linear form. From our analysis, the e-folding number $\mathcal{N}$ is no longer proportional to N, but rather to $\sqrt{N}$. Furthermore, the curvature per-

* Corresponding author.
E-mail address: wei.xue@mail.mcgill.ca (W. Xue).

0370-2693
doi:10.1016/j.physletb.2009.09.043

turbation ζ is approximately proportional to $N^{3/2}$. Thus, N-flation of this type shows quite different features from those in the usual N-flation model.

Our model is given by the following action

$$S = \int d^4x\sqrt{-g}\left[\sum_I P_I(X_I, \phi_I)\right], \tag{1}$$

which involves N scalar fields, with

$$P_I(X_I, \phi_I) = \frac{1}{f(\phi_I)}\left[1 - \sqrt{1 - 2f(\phi_I)X_I}\right] - V_I(\phi_I), \tag{2}$$

and we have defined $X_I \equiv -\frac{1}{2}g^{\mu\nu}\partial_\mu\phi_I\partial_\nu\phi_I$. The metric signature we use in this Letter is $(-,+,+,+)$. This model involves multiple DBI-type actions which give the effective description of D-brane dynamics (for example see Refs. [18,26]). Considering a system constructed by a number of D3-branes in a background metric field with negligible covariant derivatives of the field strengths and assuming that these branes are decoupled from each other, this system could be described by the above action whose stringy origin is shown in Ref. [27].

Here the scalar ϕ_I is interpreted as the position of the I-th brane, and the warping factor $f(\phi_I) = \frac{\lambda}{\phi_I^4}$ is suitable for all scalars when we take an AdS-like throat and neglect the backreaction of the branes upon the background geometry. This assumption can be satisfied when the contribution of the background flux is much larger than that from the branes.[1]

We now define a series of useful parameters (i.e. the sound speeds), for the scalars

$$c_{sI} \equiv \sqrt{1 - 2f(\phi_I)X_I}, \tag{3}$$

which lead to interesting features of the model. We assume spatial homogeneity and isotropy, i.e. take a flat Friedmann–Robertson–Walker metric ansatz $ds^2 = -dt^2 + a^2\,dx^i\,dx^i$, where $a(t)$ is the scale factor of the universe. Then Eq. (3) yields

$$|\dot{\phi}_I| = \phi_I^2\left(\frac{1 - c_{sI}^2}{\lambda}\right)^{\frac{1}{2}}. \tag{4}$$

If $c_{sI} \sim 1$, this model returns to the slow-roll version. However, if $c_{sI} \sim 0$, then $|\dot{\phi}_I| \simeq \phi_I^2/\sqrt{\lambda}$, and in this case there is an interesting relation for all the scalars:

$$\Delta\phi_I^{-1} = \frac{\Delta t}{\sqrt{\lambda}}, \tag{5}$$

which means that for a fixed time interval Δt, the variations of ϕ_I^{-1} for all the scalar fields are identical.

By varying with respect to the scalar, we obtain the equations of motion:

$$\ddot{\phi}_I + 3H\dot{\phi}_I - \frac{\dot{c}_{sI}}{c_{sI}}\dot{\phi}_I - c_{sI}P_{I,I} = 0, \tag{6}$$

where "," denotes the derivative with respect to the scalar ϕ_I, and H is the Hubble parameter defined as $\dot{a}/a$.

As an example, we focus on the case of IR type potential

$$V_I = V_{0I} - \frac{1}{2}m_I^2\phi_I^2. \tag{7}$$

The first part of the potential V_{0I} comes from the anti-brane tension from another throat. In IR DBI inflation, D-branes roll from the tip of the throat, thus the potential contains tachyonic terms. We will assume $s_I \equiv \frac{\dot{c}_{sI}}{Hc_{sI}}$ to be small numbers for simplicity, and take the normalization $8\pi G = 1$. Due to the warping factor $f(\phi_I)$, those scalars are able to stay near the top of their potentials, and so we have $H^2 \simeq \frac{1}{3}\sum_I V_{0I}$. These assumptions are consistent with Eq. (6) for a single field as shown in [21]. In the following we will examine the background in detail to prove that this consistency can be generalized to the case of multiple fields.

In our model the total Lagrangian is a sum of a number of DBI Lagrangians. Each of these is constructed from a single scalar field which has its own distinct speed of sound. We therefore have N sound speeds, and so can rewrite Eq. (6) as follows,

$$\frac{d}{dt}\left(\frac{\dot{\phi}_I}{c_{sI}}\right) + 3H\frac{\dot{\phi}_I}{c_{sI}} + \frac{f_{,I}}{f^2}(1 - c_{sI}) - \frac{f_{,I}\dot{\phi}_I^2}{2fc_{sI}} + V_{,I} = 0. \tag{8}$$

In the relativistic limit of the scalars we have an ansatz solution [21],

$$\phi_I = -\frac{\sqrt{\lambda}}{t}\left(1 - \frac{\alpha_I}{(-t)^{p_I}} + \cdots\right), \tag{9}$$

where we set $t \to -\infty$ at the beginning of inflation. Therefore, upon inserting the ansatz into the above equation, we find the leading terms in Eq. (8) come from the term:

$$\frac{3H\sqrt{\lambda}}{\sqrt{2\alpha_I(p_I - 1)}(-t)^{2 - \frac{p_I}{2}}} \tag{10}$$

and the potential term which is equal to:

$$\frac{\sqrt{\lambda}m_I^2}{t}. \tag{11}$$

The others are suppressed by $\frac{1}{Ht}$ which is negligible in inflation (where $|Ht| \gg 1$ or equivalently $\phi_I \ll \sqrt{\lambda}H$). This requirement is consistent with the assumption that the scalars lie on the top of potential during inflation. Finally, by matching the leading terms, we get $p_I = 2$ and $\alpha_I = \frac{9H^2}{2m_I^4}$, and so the solutions of the scalars are given by

$$\phi_I = -\frac{\sqrt{\lambda}}{t}\left(1 - \frac{9H^2}{2m_I^4t^2} + \cdots\right). \tag{12}$$

Making use of the solutions, we can see all the approximations are consistent with the equations of motion. Moreover, from the solutions we directly see that the variations of scalars are consistent with Eq. (5).

Applying the relation (5), the e-folding number of this multiple field inflation model can be evaluated as follows:

$$\mathcal{N} \equiv \int_i^f H\,dt \simeq \sqrt{\frac{\lambda}{3}\sum_I V_{0I}}\left\langle\frac{1}{\phi^i} - \frac{1}{\phi^f}\right\rangle$$
$$\simeq \sqrt{N}\sqrt{\frac{\lambda}{3}\langle V_0\rangle}\left\langle\frac{1}{\phi^i}\right\rangle, \tag{13}$$

under the assumption $c_{sI} \sim 0$. Here we define $\langle\mathcal{O}\rangle = (\sum_I \mathcal{O}_I)/N$, the average value of the variables $\mathcal{O}_I$, and the subscript "i" and "f" represent the initial and final state respectively. Since in IR-type models the scalars start rolling from the top of their potentials,[2] we have $\phi^i \ll \phi^f$, and we can neglect the contribution of ϕ^f

[1] One should be aware of the fact that single field DBI inflation often suffers from a backreaction problem for the relativistic brane in the throat, and so cannot provide enough long inflationary stage, as shown in Refs. [19,22]. To circumvent this problem, one has to finely tune the precise shape of the potential and the resulting model is rather delicate [28]. It is still an open question to construct a fully realistic model of inflation in string theory, but does not affect our phenomenological interests.

[2] The initial condition of inflation is essential; this was analyzed in [29,30].

in Eq. (13). Furthermore, from Eq. (13) we can deduce that the e-folding number in the multiple-DBI model is proportional to the square root of the number of scalars, i.e.

$$\mathcal{N} \propto \sqrt{N}. \tag{14}$$

This result is completely different from what was obtained in slow-roll N-flation which gives $\mathcal{N} \propto N$. This difference shows that in the inflationary model constructed by multiple DBI terms, although the fields work cooperatively, the cumulative effect from multiple fields does not grow linearly. This results in very interesting phenomenological effects which shall be examined next.

We now investigate the curvature perturbation of N-flation constructed by multiple DBIs. In the calculation, we use the Sasaki–Stewart formalism [31], in which the curvature perturbation on comoving slices can be expressed as the fluctuation of the e-folding number and thus can be given in terms of fluctuations of scalar fields $\delta\phi_I = \frac{H}{2\pi}$ on flat slices after horizon crossing. It is given by

$$P_\zeta^{\frac{1}{2}} = \sqrt{\sum_{IJ} \mathcal{N}_{,I}\mathcal{N}_{,J}\langle|\delta\phi_I\delta\phi_J|\rangle}$$

$$\simeq N^{\frac{3}{2}}\frac{\sqrt{\lambda}}{6\pi}\langle V_0\rangle\sqrt{\langle\phi^{-4}\rangle}, \tag{15}$$

where we have applied the general relation $\mathcal{N}_{,I} = \frac{H}{\dot\phi_I}$. This result is consistent with single DBI inflation model when $N = 1$, but if one introduces more fields, $P_\zeta^{1/2}$ grows proportional to $N^{\frac{3}{2}}$, which is more rapid than that obtained in normal N-flation (for example see Refs. [9,32] along with references therein). From Eqs. (13) and (15), we can establish the relation between the curvature perturbation and the e-folding number as follows,

$$P_\zeta = \frac{\mathcal{N}^4 N}{4\pi^2\lambda}\frac{\langle\phi^{-4}\rangle}{\langle\phi^{-1}\rangle^4}. \tag{16}$$

Moreover, for a set of the above uncoupled fields, we can derive the spectral index as follows,

$$n_s - 1 \equiv \frac{d\ln P_\zeta}{d\ln k}$$

$$\simeq -2\epsilon - \frac{\sum_I (s_I + \eta_I)/(c_{sI}\epsilon_I^2)}{\sum_J 1/(c_{sJ}\epsilon_J^2)}, \tag{17}$$

where we have defined the slow-roll parameters $\epsilon \equiv -\frac{\dot H}{H^2}$, $\epsilon_I \equiv \frac{\dot\phi_I}{\sqrt{2c_{sI}}H}$, and $\eta_I \equiv 2\frac{\dot\epsilon_I}{\epsilon_I H}$. When there is only one scalar field, the above spectral index returns to the standard form of single DBI model [33]. Note that there is a relation $\epsilon = \sum_I \epsilon_I^2 \simeq \sum_I \frac{3\phi_I^4}{2c_{sI}\lambda}/\sum_J V_{0I}$, and this quantity can be very small when λ is taken to be sufficiently large. If $\epsilon \ll 1$, each positive component ϵ_I becomes negligible automatically. Explicitly, for the case of IR-type potentials we are considering, the spectral index can be given by

$$n_s - 1 \simeq -\frac{4}{\mathcal{N}}\frac{\langle\phi^{-1}\rangle\langle\phi^{-3}\rangle}{\langle\phi^{-4}\rangle}. \tag{18}$$

Although it is hard to judge in general whether the spectral index of our model is redder or bluer than that of its corresponding single scalar model, this may be determined in certain limiting cases. For example, the spectral index coincides with that of the corresponding single field model when all the scalars at the horizon-crossing time have the same value $\phi_I = \phi_0$.

Now let us consider some specific examples of this model. The simplest case is to choose all the scalars to have the same value: $\phi_I = \phi_0$ for $I = 1, \ldots, N$. Therefore we obtain

$$P_\zeta = \frac{\mathcal{N}^4 N}{4\pi^2\lambda}, \qquad n_s = 1 - \frac{4}{\mathcal{N}}. \tag{19}$$

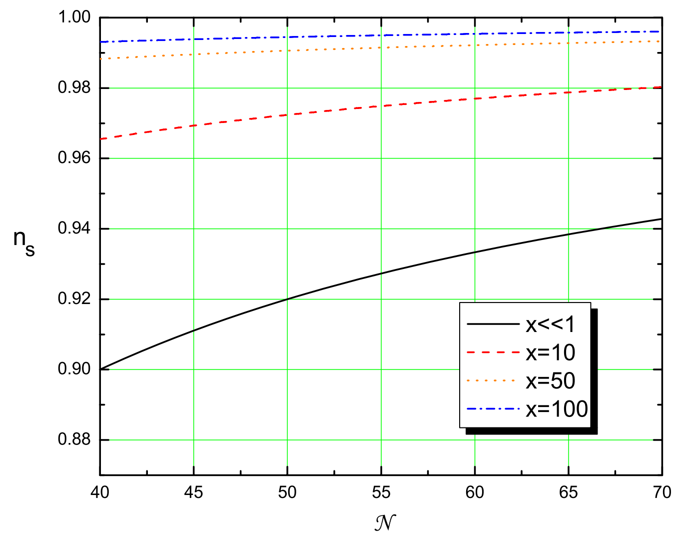

Fig. 1. n_s as the function of the e-folding number $\mathcal{N}$ for different values of the variable x ($\equiv N\cdot\Delta/\phi_0$). The black solid line denotes the spectral index in the first case when all the scalars have the same value at horizon-crossing; the red dashed line denotes the spectral index in the second case with $x = 10$; the orange dotted line $x = 50$; the blue dash-dotted line $x = 100$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

As is known, we need the e-folding number for inflation $\mathcal{N} \simeq 60$ to explain the present-day flatness of our universe. From the above equation, one can easily obtain a scale-invariant spectrum with an amplitude of order $\mathcal{O}(10^{-9})$ (required by cosmological observations, such as Ref. [3]) if $\lambda/N \sim 10^{14}$.

Another interesting example is $\phi_I = \phi_0 + I\cdot\Delta$ for $I = 1, \ldots, N$. In order to make this case quite different from the first one, we assume $\phi_0 \gg \Delta$ but $N\cdot\Delta \gg \phi_0$. To solve this system, we apply the useful expression

$$\langle\phi^{-l}\rangle = (-)^l\frac{\psi^{(l-1)}(1+\frac{\phi_0}{\Delta}) - \psi^{(l-1)}(1+\frac{\phi_0}{\Delta}+N)}{(l-1)!\Delta^l N}, \tag{20}$$

where $\psi^l(z)$ is the l-th derivative of the digamma function $\psi(z) \equiv \Gamma'(z)/\Gamma(z)$. We can use the Stirling formula to simplify the digamma function as $\psi(z) \simeq \ln z - \frac{1}{2z}$ when z is large enough. Accordingly, we obtain the results

$$P_\zeta \simeq \frac{\mathcal{N}^4 N}{4\pi^2\lambda}\frac{x^3}{3(\ln x)^4}, \qquad n_s \simeq 1 - \frac{6}{\mathcal{N}}\frac{\ln x}{x}, \tag{21}$$

with $x \equiv (N\cdot\Delta)/\phi_0$ in this case. From Eq. (21), for a given the e-folding number $\mathcal{N}$, one can find that the tilt of the spectral index in the multiple-DBI model is strongly suppressed by the variable x. The dependence of n_s on the e-folding number $\mathcal{N}$ for different values of the variable x is plotted in Fig. 1. From the figure, we can see that the spectrum of the multiple-DBI model is generally closer to scale-invariance when x is larger.

Inflation with multiple fields avoids some difficulties of single field inflation models, and so is regarded as an attractive implementation of inflation. In recent years, there have been a number of works studying this, such as Refs. [34–38], and there is a good review on this field Ref. [39]. In this Letter, we have presented a new N-flation model in which a collection of DBI fields drives inflation simultaneously.[3] These scalars possess non-standard kinetic terms, and so some non-linear information is involved when we

[3] The action of this model is similar to the ones considered in Refs. [12,40], but with different motivations. Our model is also different from those appeared in [41,42] concerning both motivations and detailed examples.

investigate the background evolution and curvature perturbation. For example, the e-folding number of this model is no longer proportional to the number of scalars, but rather to its square root, as shown in Eq. (13). In the detailed calculation, we considered a tachyonic potential and specifically chose two different cases. In the first case, we took all the scalars to have the same value at the horizon-crossing time, and the spectral index in this case coincides with that in the single DBI model; while in the second case, we assumed that the collection of the scalars at the horizon-crossing time is an arithmetic progression, and we found that the spectral index becomes closer to 1 if the height of this progression is much larger than the value of the first scalar.

We should note that in this Letter we merely studied the adiabatic perturbations during inflation. However, in a model with a number of scalars involved, there should be entropy perturbations generated during inflation. In particular, when the kinetic terms are of non-linear form, the dispersion relations for entropy modes are modified. If they contribute to curvature perturbation at late times, they may lead to new features. Namely, a large local type non-Gaussianity, which is difficult to obtain in usual inflation models [33], could be obtained in a model of DBI-curvaton as proposed in Ref. [43]. One source of entropy perturbation is the correlation of different field fluctuations [24,41]. However, in our model, the propagations for the field fluctuations are quite independent of others. Consequently, the contribution of correlations among field fluctuations is subdominant. In this case, the treatment given in the current Letter is quite reliable. A more detailed study is performed in Ref. [44].

Finally, we would like to highlight the importance of the present study. As is known, in most of current inflation models, the propagation of perturbations is characterized by a single sound speed. In slow roll inflation, this sound speed is exactly the speed of light, while for DBI inflation it can be smaller than unity. However, from the well established perturbation theory at late times of the cosmological evolution, plentiful phenomena, such as baryon acoustic oscillation, dark energy perturbations, and the formation of large scale structure, etc., are based on the existence of multiple components, each of which has its own sound speed. It therefore seems pertinent to ask, what would happen if we have a number of sound speeds in the very early universe? As shown in this Letter and [44], potential phenomenological results include unusual consistency relations, variation of the scalar spectral index, and large local non-Gaussianity. Therefore, the consideration of inflationary models with multiple sound speeds is rather robust and useful.

Acknowledgements

We would like to thank Robert Brandenberger, Bin Chen, Xingang Chen, Yun-Song Piao, Yi Wang and Xinmin Zhang for useful discussions and valuable comments. We also thank A. Vincent for carefully checking typographic errors. This work is supported in part by National Natural Science Foundation of China under Grant Nos. 10533010 and 10675136 and by the Chinese Academy of Science under Grant No. KJCX3-SYW-N2.

References

[1] A.H. Guth, Phys. Rev. D 23 (1981) 347;
A.D. Linde, Phys. Lett. B 108 (1982) 389;
A. Albrecht, P.J. Steinhardt, Phys. Rev. Lett. 48 (1982) 1220.
[2] For some early attempts we refer to: A.A. Starobinsky, Phys. Lett. B 91 (1980) 99;
K. Sato, Mon. Not. R. Astron. Soc. 195 (1981) 467.
[3] E. Komatsu, et al., WMAP Collaboration, Astrophys. J. Suppl. 180 (2009) 330.
[4] A.R. Liddle, A. Mazumdar, F.E. Schunck, Phys. Rev. D 58 (1998) 061301.
[5] K.A. Malik, D. Wands, Phys. Rev. D 59 (1999) 123501.
[6] P. Kanti, K.A. Olive, Phys. Rev. D 60 (1999) 043502.
[7] E.J. Copeland, A. Mazumdar, N.J. Nunes, Phys. Rev. D 60 (1999) 083506.
[8] A.M. Green, J.E. Lidsey, Phys. Rev. D 61 (2000) 067301.
[9] S. Dimopoulos, S. Kachru, J. McGreevy, J.G. Wacker, JCAP 0808 (2008) 003.
[10] L. Kofman, A. Linde, JHEP 0207 (2002) 004.
[11] J.M. Cline, arXiv:hep-th/0612129.
[12] Y.S. Piao, R.G. Cai, X.M. Zhang, Y.Z. Zhang, Phys. Rev. D 66 (2002) 121301.
[13] M. Majumdar, A.C. Davis, Phys. Rev. D 69 (2004) 103504.
[14] R. Brandenberger, P.M. Ho, H.C. Kao, JCAP 0411 (2004) 011.
[15] K. Becker, M. Becker, A. Krause, Nucl. Phys. B 715 (2005) 349;
A. Ashoorioon, A. Krause, arXiv:hep-th/0607001;
F. Gmeiner, C.D. White, JCAP 0802 (2008) 012.
[16] J.M. Cline, H. Stoica, Phys. Rev. D 72 (2005) 126004.
[17] O. Aharony, S.S. Gubser, J.M. Maldacena, H. Ooguri, Y. Oz, Phys. Rep. 323 (2000) 183.
[18] R.C. Myers, JHEP 9912 (1999) 022.
[19] E. Silverstein, D. Tong, Phys. Rev. D 70 (2004) 103505;
M. Alishahiha, E. Silverstein, D. Tong, Phys. Rev. D 70 (2004) 123505.
[20] X. Chen, Phys. Rev. D 71 (2005) 063506.
[21] X. Chen, JHEP 0508 (2005) 045.
[22] D.A. Easson, R. Gregory, D.F. Mota, G. Tasinato, I. Zavala, JCAP 0802 (2008) 010.
[23] M.X. Huang, G. Shiu, B. Underwood, Phys. Rev. D 77 (2008) 023511.
[24] D. Langlois, S. Renaux-Petel, D.A. Steer, T. Tanaka, Phys. Rev. Lett. 101 (2008) 061301.
[25] C.R. Contaldi, G. Nicholson, H. Stoica, arXiv:0807.2331 [hep-th].
[26] J.M. Maldacena, Adv. Theor. Math. Phys. 2 (1998) 231.
[27] W. Taylor, M. Van Raamsdonk, Nucl. Phys. B 573 (2000) 703.
[28] D. Baumann, A. Dymarsky, I.R. Klebanov, L. McAllister, P.J. Steinhardt, Phys. Rev. Lett. 99 (2007) 141601.
[29] D.S. Goldwirth, T. Piran, Phys. Rep. 214 (1992) 223.
[30] R. Brandenberger, G. Geshnizjani, S. Watson, Phys. Rev. D 67 (2003) 123510.
[31] M. Sasaki, E.D. Stewart, Prog. Theor. Phys. 95 (1996) 71.
[32] S.A. Kim, A.R. Liddle, Phys. Rev. D 74 (2006) 023513.
[33] X. Chen, M.X. Huang, S. Kachru, G. Shiu, JCAP 0701 (2007) 002.
[34] Y.S. Piao, Phys. Rev. D 74 (2006) 047302;
I. Ahmad, Y.S. Piao, C.F. Qiao, JCAP 0806 (2008) 023.
[35] M.E. Olsson, JCAP 0704 (2007) 019.
[36] K.Y. Choi, J.O. Gong, JCAP 0706 (2007) 007.
[37] G. Panotopoulos, Phys. Rev. D 75 (2007) 107302.
[38] D. Battefeld, T. Battefeld, A.C. Davis, JCAP 0810 (2008) 032;
T. Battefeld, arXiv:0809.3242 [astro-ph].
[39] D. Wands, Lect. Notes Phys. 738 (2008) 275.
[40] S. Thomas, J. Ward, Phys. Rev. D 76 (2007) 023509.
[41] F. Arroja, S. Mizuno, K. Koyama, JCAP 0808 (2008) 015.
[42] D. Langlois, S. Renaux-Petel, D.A. Steer, T. Tanaka, Phys. Rev. D 78 (2008) 063523.
[43] S. Li, Y.F. Cai, Y.S. Piao, Phys. Lett. B 671 (2009) 423.
[44] Y.F. Cai, H.Y. Xia, Phys. Lett. B 677 (2009) 226.