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Braneworld Inflation in Supergravity with a Shift Symmetric Kähler Potential

Z. Mounzi[1,2], M. Ferricha-Alami[1,2,3], A. Safsafi[1,2,3] & M. Bennai[1,3,*]
[1]*Laboratoire de Physique de la Matière Condensée, Equipe Physique Quantique et Application, Faculté des Sciences Ben M'sik, B.P. 7955, Université Hassan II, Casablanca, Morocco.*
[2]*Equipe de Recherche Subatomique et Application, Faculté des Sciences Ben M'sik, Université Hassan II, Casablanca, Morocco.*
[3]*Centre de Physique Mathématique (CPM), Focal Point Lab UFR-PHE, Rabat, Morocco.*
[*]*e-mail: mdbennai@yahoo.fr*

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Abstract. We propose a new solution to the η-problem in supergravity using a shift symmetric Kähler potential in the context of the Randall–Sundrum type II model. We focus on a F-term supergravity inflation with a minimal Kähler potential taking into account the radiative corrections. The slow-roll conditions are ensured by the shift symmetry where a very small value of $\eta(\eta \ll 1)$ is obtained. In this context, we derive all known spectrum inflationary parameters which are widely consistent with Planck 2015 data for a particular choice of brane tension and coupling constant values. A suitable observational central value of $n_s = 0.96$ is also obtained in the case of minimal Kähler potential.

Key words. Shift symmetry—Kähler potential—braneworld—perturbation spectrum—Planck 2015.

1. Introduction

Recently, the supersymmetric hybrid model and its extensions have been proposed to assure the natural inflationary scenario (Lyth & Stewart 1996; Enqvist & McDonald 1998; Clesse *et al.* 2014), since it provides an interesting possibility of occurring inflation in the grand unified theories (Civiletti *et al.* 2014), which provides an attractive solution to the hierarchy problem of the standard model of particle physics and the unification of the three gauge couplings.

In the standard version of supersymmetric hybrid inflation (Dine *et al.* 1995), gauge symmetry is usually broken at the end of inflation. This implies that the topological defects (such as monopoles, walls, cosmic strings...) are produced after the inflation and their presence is in contradiction with the experimental observations. In order to avoid these problems, several extensions of the standard supersymmetric hybrid scenario have been proposed, among them, the smooth hybrid inflation scenario (Lazarides & Vamvasakis 2007), where the smooth variant of SUSY hybrid inflation is naturally realized within an extended SUSY GUT standard hybrid inflation model based on the Pati–Salam (PS) group GPS (Pati & Salam 1974).

In particular, supergravity (Rehman *et al.* 2010), can provide a solution to the hierarchy problem associated with such new physics at high energies. Further inflationary theory could be investigated in the framework of supergravity. Nevertheless, when trying to do this, one encounters a dangerous problem implying that one of the slow-roll parameter η gets values larger than the one which violates one of the conditions that should be satisfied for a successful inflation (Antusch *et al.* 2009a, b, Dutta *et al.* 2009). That issue emerges from the fact that the inflaton acquires the effective mass squared $3H^2$, giving a contribution in the order unit to the slow-roll parameter η (Masahide 2011). This is known as η-problem in supergravity (Copeland *et al.* 1994). Also in other inflationary models (non supergravity), η-problem occurs as in the case of hybrid inflation supersymmetric F-term with non-minimal Kähler potential (Bastero-Gil *et al.* 2007).

Several approaches have been proposed to avoid this problem. Some of them impose symmetries on Kähler potential and/or superpotential, which ensures the flatness of the potential. As a category symmetry solution to the η-problem, the use of a Heisenberg symmetry has been proposed in Sasaki and Stewart (1996). Heisenberg symmetry appears, for instance, in string theory in heterotic orbifold compactifications, where it is a property of the tree-level Kähler potential of untwisted matter fields (Gaillard *et al.* 1995). Another common solution to the η-problem is to invoke a shift symmetry in the superpotential which protects the inflaton direction from steepening (Antusch & Cefala 2013; Gaillard *et al.* 1995), and get a large field model $\phi \gg m_{\mathrm{p}}$ as explained in Kawasaki *et al.* (2000). Such a symmetry may be broken at the Planck-scale and receive dangerous corrections which could spoil inflation. The main danger comes from the fact that the symmetry is a global or discrete symmetry and cannot be a true symmetry at the Planck scale (Lazarides & Pallis 2008; Ben-Dayan & Einhorn 2010).

On the other hand, in the modern cosmology, the brane-world models became a central paradigm of inflation (Brax *et al.* 2004; Calcagni *et al.* 2014). In this context, the standard model of particles is confined to the brane, while gravitation propagates into the bulk space-time, where the extra dimensions were introduced in the Friedmann equation (Shiromizu *et al.* 2000; Binetruy *et al.* 2000). One of the brane inflation scenarios is the Randall–Sundrum II (RSII) model (Randall & Sundrum 1999), in which our four dimensional Universe is considered as a 3-brane embedded in five-dimensional anti-de Sitter space-time.

In this paper, we are interested on SUGRA F-term model in braneworld inflation. We have considered a minimal Kähler potential where a Nambu–Goldstone-like shift symmetry is applied to protect the inflaton direction from large SUGRA mass contributions. In contrast to the 'standard' models of hybrid inflation in SUGRA, our scenario has the novel result of having $\eta \ll 1$. Here, we show that η-problem is solved for some values of a coupling constant and brane tension λ. Within the proposed class of models, we address a second challenge to SUGRA models of hybrid inflation, namely the consistency between the predicted spectral index and the latest

Planck data (Adam *et al.* 2015), which favor a value of $n_s \sim 0.96$ for small tensor-to-scalar ratio r. In fact, 'standard' SUSY hybrid inflation models with flat inflation potential at tree-level predict a spectral index above $n_s \sim 0.98$ (Bastero-Gil *et al.* 2007) as in braneworld scenario in the case of a minimal Kähler potential (Zarrouki *et al.* 2011). In this context, we show that the spectral index can be lowered and the best-fit value for n_s can be realized. We also calculate other spectrum inflation parameters and show that observational bounds from Planck data are satisfied.

The paper is organized as follows: in the next section, we first begin by recalling briefly the shift symmetric Kähler potential in supergravity and the η-problem. In section 3, we present our results for a shift symmetric Kähler potential inflation on the brane motivated by the recent Planck 2015 results (Adam *et al.* 2015). The last section is devoted to conclusion.

2. Shift symmetry and η-problem

In this section, we shortly review some basic facts on inflation potential in supergravity. The potential V of scalar fields S_i has two contributions: F-term and D-term. In supergravity theories, interactions of gauge singlet fields are described by a Kähler function. In this context, the F-term supergravity potential is by Bento *et al.* (2003):

$$V_F = \mathrm{e}^{\frac{K}{m_\mathrm{p}^2}} \left[D_{s_i} W K^{-1}_{ij*} D_{s_j^*} W^* - \frac{3}{m_\mathrm{p}^2} |W|^2 \right], \tag{1}$$

where $D_{s_i} W = \frac{\partial W}{\partial S_i} + \frac{\partial K}{\partial S_i} W$ and m_p is the reduced Planck mass.

The Kähler potential is chosen to be of the form

$$K = \frac{1}{2}(\Phi + \Phi)^2 + |H|^2 , \tag{2}$$

where we require the Kähler potential to be invariant under a shift symmetry transformation $\Phi \longrightarrow \Phi + i\mu$, where μ denotes a real transformation parameter. The invariant combination in the Kähler potential is then given by $\phi + \phi^* = 2\mathrm{Re}(\Phi)$. Therefore, the imaginary part $\mathrm{Im}(\phi)$ is a good inflation direction since it gets protected by the shift symmetry.

A important feature of the Kähler potential $\Phi \longrightarrow \Phi + i\mu$ is that the shift symmetric form does not destroy canonical normalition of the kinetic terms, since just as for the minimal Kähler potential, $K_{i\bar{j}} = \delta_{i\bar{j}}$. The general superpotential is written as follows (Bastero-Gil *et al.* 2007):

$$W = \kappa\Phi(H^2 - M^2). \tag{3}$$

Since we focus our attention to directions in which the real part of the superfield is taken to be zero, the above derivative is reduced to the following expression : $DW = -\kappa M^2$, which imply that the first term is written as

$$D_{s_i} W K^{-1}_{ij*} D_{s_j^*} W^* = \kappa^2 M^4, \tag{4}$$

and the second term of the F-term potential has the form

$$\frac{-3}{m_{\rm p}^2}|W|^2 = \frac{-3}{m_{\rm p}^2}|\kappa\Phi(H^2 - M^2)|^2.$$

In the inflationary trajectory, we impose the condition $H = 0$ and we decompose the inflation scalar component into canonically normalized real and imaginary part $\Phi = \frac{1}{\sqrt{2}}(\phi_{\rm R} + i\phi)$. In equation (2), the shift symmetry protects the canonically normalized imaginary part $\phi = \sqrt{2}{\rm Im}(\Phi)$ from obtaining large SUGRA corrections while the latter stabilize the real part $\phi_{\rm R} = \sqrt{2}{\rm Re}(\Phi)$ at zero. From the equations and the expressions above, in the inflationary trajectory, the resulting potential could be written as

$$V_{\rm F} = \exp\left(\frac{K}{m_{\rm p}^2}\right)\left(\kappa^2 M^4 - \frac{3}{2}\frac{\kappa^2 M^4}{m_{\rm p}^2}\phi^2\right). \tag{5}$$

Since the field values are small enough with respect to Planck scale, the exponential factor is reduced to one. In which case, the scalar field takes the final form

$$V_{\rm F} = \kappa^2 M^4\left(1 - \frac{3}{2}\frac{\phi^2}{m_{\rm p}^2}\right). \tag{6}$$

It is interesting to note that the loop quantum correction play a crucial role in analysing the vacuum structure of the theory. These radiative corrections are given by the Coleman–Weinberg formula (Coleman & Weinberg 1973):

$$\Delta V_{1-{\rm loop}} = \frac{1}{64\pi^2}\sum_i (-1)^{F_i} M_i^4 \ln\frac{M_i^2}{\Lambda^2}, \tag{7}$$

where the sum extends over all helicity states i, F_i and M_i^2 are the fermion number and mass squared of the i-th state and is a renormalization mass scale.

The scalar potential takes the form with the existence of one-loop radiative corrections to the potential on the inflationary valley:

$$V_{\rm F} \simeq \kappa^2 M^4\left(1 - \frac{3}{2}\frac{\phi^2}{m_{\rm p}^2}\right) + \frac{\kappa^4 M^4}{16\pi^2}\left(\ln\left(\frac{\kappa^2\phi^2}{2\Lambda^2}\right) + \frac{3}{2} + \cdots\right). \tag{8}$$

In the standard model, to realize the successful inflation, the slow-roll parameters $\epsilon = \frac{m_{\rm p}^2}{2}\frac{V'^2}{V^2}$ and $\eta = m_{\rm p}^2\frac{V''}{V}$ must be satisfy to the condition $\epsilon << 1$ and $\eta << 1$. The inflationary phase will terminate when the Universe heats up so that the condition $\varepsilon = 1$ (or $|\eta| = 1$) is satisfied.

The above potential leads to violation of one of the slow-roll parameters, such as the second slow-roll parameter which is

$$\eta \simeq -\left(3 + \frac{\kappa^2 m^2}{8\pi^2\phi^2}\right).$$

This implies that this model is not valid in the standard case. In the following, we shall consider a shift symmetric Kähler potential in braneworld inflation in order to eliminate the η-problem and to derive perturbation spectrum in relation to recent observation. The presence of such a contribution was the decisive factor in ruling out the model above. Therefore, the braneworld model turns out to have the right properties suitable for solving the η-problem via symmetries in the Kähler potential.

3. Shift symmetric Kähler potential on the brane

3.1 *Braneworld formalism*

The braneworld inflation models have been proposed to solve several problems that take place in the standard model. In this context, we will focus on the most popular and interesting brane-world scenario which is provided by the Randall–Sundrum single brane model (RS2) (Randall & Sundrum 1999). This is later characterized by brane tension parameter λ whose values are dependent on the model. We cite, for example, in Panotopoulos (2007), the author discussed the validity of chaotic braneworld model and found the values of the five-dimensional Planck mass m_5 up to 2.4×10^{17} GeV which implies that $\lambda \sim 10^{64}$ GeV^4. In another work, Safsafi *et al.* (2012) have shown that for some values of brane tension $\lambda \sim (10^{57}$ GeV$^4)$, the fine-tuning problem is eliminated and the value of the FI-term ξ is reduced in order to solve the problem of cosmic strings. Consequently, the spectrum inflation parameters are in good agreement with the WMAP observations. Moreover, to solve the problem related to the topological defects, caused by the instability of the magnetic monopoles with smooth hybrid inflation, the brane tension value was set to the order of $\lambda \sim 10^{52}$ GeV^4 (Ferricha-Alami *et al.* 2014).

On the other hand, inflation can occur only if some conditions on the scalar field, known as the slow roll approximation, are satisfied (Martin *et al.* 2013). This means that the kinetic term and the second derivative of the scalar field should be negligible with respect to the scalar potential and the friction term of the Klein–Gordon equation. These are expressed as $\dot{\phi}^2 \ll V(\phi)$ and $\ddot{\phi} \ll H\dot{\phi}$. Moreover, in the high energy limit, i.e. $V \gg 2\lambda$, the slow-roll parameters are given by $\epsilon = 2m_{\mathrm{p}}^2 \frac{\lambda V'^2}{V^3}$ and $\eta = 2m_{\mathrm{p}}^2 \frac{\lambda V''}{V^2}$ (Maartens *et al.* 2000), where $V'' = \frac{\mathrm{d}^2 V}{\mathrm{d}\phi^2}$. Note that one can use either the potential slow roll approximation which puts a constraint on the slope and the curvature of the potential or the Hubble slow roll approximation which is expressed in terms of the Hubble parameter during inflation. The inflationary spectrum perturbation is produced by quantum fluctuations of fields around their homogeneous background values. The small quantum fluctuations in the scalar field leads to fluctuations in the energy density and in the metric.

From these parameters, one can also define the scalar spectral index n_{s} , the ratio of tensor to scalar perturbations r and the running of the scalar spectral index $\frac{\mathrm{d}n_{\mathrm{s}}}{\mathrm{d}\ln(k)}$ as

$$n_{\mathrm{s}} \simeq -6\epsilon + 2\eta + 1, \;\; r \simeq 24\epsilon \;\; \text{and} \;\; \frac{\mathrm{d}n_s}{\mathrm{d}\ln(k)} \simeq \frac{4m_{\mathrm{p}}^2 \lambda V'}{V^2}\left(3\frac{\partial \varepsilon}{\partial \phi} - \frac{\partial \eta}{\partial \phi}\right). \tag{9}$$

The small quantum fluctuations in the scalar field leads to fluctuations in the energy density. For this reason, we define the power spectrum of the curvature perturbations by Langlois *et al.* (2000)

$$P_{\mathrm{R}}(k) \simeq \frac{1}{96\pi^2 m_{\mathrm{p}}^2} \frac{V^6}{V'^2 \lambda^3}. \tag{10}$$

Finally, the number of e-folds during inflation is Maartens *et al.* (2000)

$$N_e \simeq -\frac{1}{2m_{\mathrm{p}}^2\lambda}\int_{\phi_*}^{\phi_{\mathrm{end}}}\frac{V^2}{V'}\mathrm{d}\phi\ , \tag{11}$$

where ϕ_* denotes the value of the scalar field ϕ when Universe scale observed today crosses the Hubble horizon during inflation and ϕ_{end} is the value of the scalar field when the Universe exits the inflationary phase.

3.2 *Observational constraints*

We are mainly concerned in this section by the derivation of perturbation spectrum and the inflationary consequences of the F-term braneworld scenario. We have seen in equation (6) that the scalar potential takes the following form:

$$V_{\mathrm{F}} = \kappa^2 M^4\left(1-\frac{3}{2}\frac{\phi^2}{m_{\mathrm{p}}^2}\right)+\Delta V_{1-\mathrm{loop}}. \tag{12}$$

The two slow roll parameter takes the following form in terms of the scalar field:

$$\epsilon = \frac{1}{32\pi^2}\frac{\lambda(24\pi^2\phi^2-\kappa^2m^2)^2}{\kappa^2M^4m^2\phi^2}\quad \text{and}\quad \eta = -\frac{1}{4}\frac{\lambda(24\pi^2\phi^2-\kappa^2m^2)}{\kappa^2M^4\phi^2}. \tag{13}$$

An important point to make is that, the slow-roll parameter η is linearly proportional to the brane tension and inversly proportional to vaccum expactation value. Respecting the condition of high energy limit, i.e. $V \gg 2\lambda$, it is clear that η-problem could be eliminated.

On the other hand, the scalar field at the end of inflation is given by $\phi_e = \sqrt{2}M$. The number of e-folds, when integrated between ϕ_* and ϕ_e give the follwing expression:

$$N_e = \frac{\kappa^2M^4}{12\lambda}\ln\left(\frac{\kappa^2m^2-24\pi^2\phi_e^2}{\kappa^2m^2-24\pi^2\phi_*^2}\right). \tag{14}$$

In order to evaluate the corresponding inflaton field value ϕ_*, the number of e-fold formulas allow us to write:

$$\phi_* = \frac{\kappa m}{12\pi}\left[6\left(1-\left(1-\frac{48\pi^2M^2}{\kappa^2m^2}\right)\exp\left(-\frac{12N_e\lambda}{\kappa^2M^4}\right)\right)\right]^{\frac{1}{2}}. \tag{15}$$

Next, we consider the value of the power spectrum of the curvature perturbations given by Planck, $Pr(k) = (2.130 \pm 0.053)\times 10^{-9}$ (Adam *et al.* 2015). We can examine the variations of κ as function of brane tension λ and we take $M \simeq (0.8 - 2)\times 10^{15}$ GeV, value that are lower than the SUSY GUT scale $M_{\mathrm{GUT}} \simeq 2.86 \times 10^{16}$ GeV and $N = 50$. The aim of this, is to study the brane tension values when we vary the coupling constant κ related to the domain of compatibility of scalar curvature perturbation.

We determine the interval of brane tension, while allowing the scalar curvature perturbation to be in the range of the measured values, that is consistent with it for a particular choice of κ. We also find that in order to reproduce the allowed values of the scalar curvature perturbation given by Planck experiment, the brane tension interval shoud be $\lambda \sim (1-10) \times 10^{54}$ GeV^4 and the coupling constant take values from $\kappa = (0.01 - 1)$. In what follows we will take into account these values in calculating perturbation spectrum.

To make contact with the recent experimental measurement of the cosmic microwave background, the combination of Planck TT, TE, EE + lensing data gives the following results (Adam *et al.* 2015):

$$n_s = 0.9653 \pm 0.0048 \quad (68\%\text{CL}), \tag{16}$$

$$r < 0.112 \quad (95\%\text{CL}), \tag{17}$$

$$\frac{dn_s}{d\ln(k)} = -0.002^{+0.013}_{-0.013} \quad (95\%\text{CL}). \tag{18}$$

In order to analyse the perturbation spectrum parameters, high energy limit approximation should be satisfied ($V_0 \gg 2\lambda$). We study the evolution of these parameters as a function of brane tension for different values of κ.

For this purpose, we take the inflationary scale $M = 1 \times 10^{15}$ GeV and we vary the brane tension λ and the coupling constant κ, in order to obtain consistent perturbation spectrum parameters (n_s, r and $\frac{dn_s}{d\ln(k)}$) with recent Planck data.

In figure 1, we present the variations of scalar spectral index n_s as a function of brane tension λ. The scalar spectral index n_s have a decreasing behaviour as we increase the brane tension λ. We also note that the values of n_s are found to be consistent with the Planck data for large domain of brane tension and the central value of $n_s = 0.96$ is obtained. Note that, in the usual F-term supergravity inflation with a minimal Kähler potential, the value of n_s is required to be $n_s \sim 0.98$ (Bastero-Gil *et al.* 2007; Zarrouki *et al.* 2011).

Figure 2 shows the variation of the ratio r with respect to brane tension λ for different values of the coupling constant κ. Generally, the ratio r has a decreasing behaviour with respect to λ and gets extremely weak values especially for small values of $\kappa = 0.08$ compatible with the recent observational data.

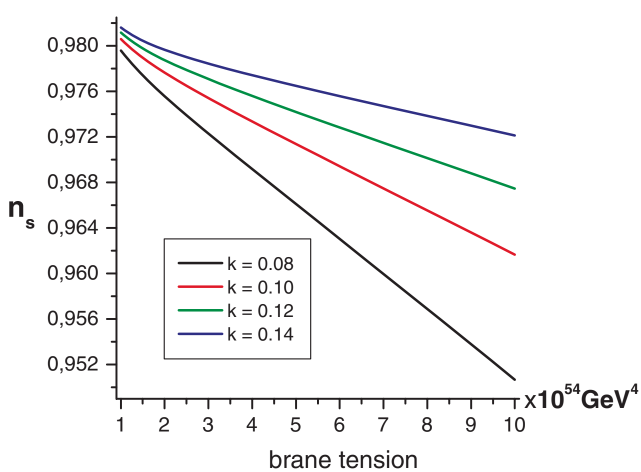

Figure 1. n_s vs. λ for different values of coupling constant κ.

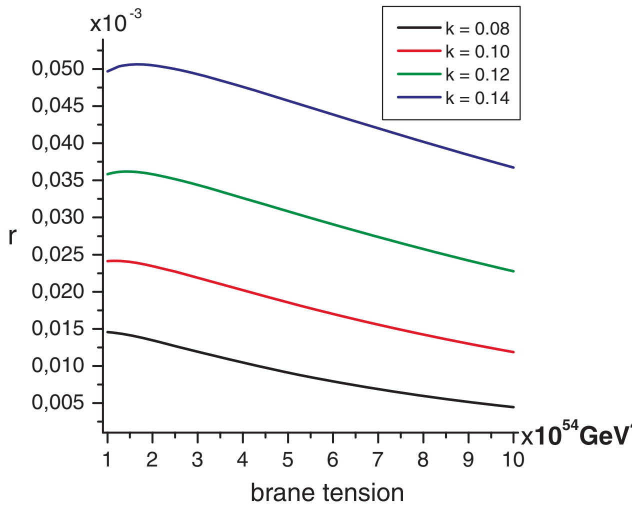

Figure 2. r vs. λ for different values of coupling constant κ.

In figure 3, we have obtained extremely weak values which are consistent with Planck data. A decreasing behaviour is found in $\frac{\mathrm{d}n_s}{\mathrm{d}\ln(k)}$ with respect to brane tension and that it gets smaller as we increase the coupling constant κ.

In summary, the results reviewed in the context of the Randall–Sundrum type II model are compatible with Planck 2015 data for a particular choice of brane tension and coupling constant values. This paper justifies certain methods used, solves some problems posed and proved that inflation, with a shift symmetry, can occur successfully for the SUGRA F-term inflationary models in the context of braneworld.

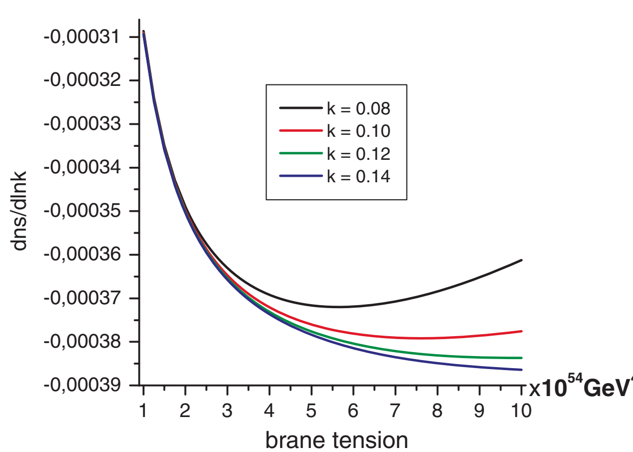

Figure 3. $\frac{\mathrm{d}n_s}{\mathrm{d}\ln k}$ vs. λ for different values of coupling constant κ.

4. Conclusion

In this paper, we have studied braneworld inflation model in which the η-problem of SUGRA hybrid inflation is resolved using a shift symmetric Kähler potential. We have adopted the slow-roll approximation in the high-energy limit to evaluate all perturbation spectrum parameters. We have demonstrated that, in these models, the slow-roll conditions are ensured by the shift symmetry where a very small value of η ($\eta \ll 1$) is obtained. Also, we have found that the inflationary parameters depend on the brane tension λ and coupling constant κ. Thus, we have obtained a central value of $n_{\rm s} = 0.96$ which is not allowed in the standard hybrid inflation, in particular, for a minimal Kähler potential. The values of the tensor to scalar ratio r and running of the spectral index $\frac{\mathrm{d}n_{\rm s}}{\mathrm{d}\ln(k)}$ are in excellent agreement with the latest observations of the Planck satellite for a particular choice of the parameter space of the model. Finally, we note that it is only in very special setups that the F-term hybrid inflation superpotential can be combined with a shift symmetric Kähler potential to give rise to viable inflation as it is the case in our braneworld model.

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