Large Field Inflation and String Moduli Stabilization

Ralph Blumenhagen

Max-Planck-Institut für Physik, München

(RB, Font, Fuchs, Herschmann, Plauschinn, arXiv:1503.01607)

(RB, Font, Fuchs, Herschmann, Plauschinn, Sekiguchi, Wolf, arXiv:1503.07634)

Introduction

Introduction

Moduli stabilization in string theory:

- Race-track scenario
- KKLT
- LARGE volume scenario

Based on instanton effects $\rightarrow$ exponential hierarchies $\rightarrow$ can generate $M_{\rm susy} \ll M_{\rm Pl}$

Experimentally:

- Supersymmetry not found at LHC with $M < 2$TeV.
- Not excluded large field inflation: $M_{\rm inf} \sim M_{\rm GUT}$

Contemplate scenario of moduli stabilization with only polynomial hierarchies $\rightarrow$ string tree-level with fluxes

Introduction

Introduction

PLANCK 2015 results:

- upper bound: $r < 0.113$
- spectral index: $n_s = 0.9667 \pm 0.004$ and its running $\alpha_s = -0.002 \pm 0.013$.
- amplitude of the scalar power spectrum $\mathcal{P} = (2.142 \pm 0.049) \cdot 10^{-9}$

Good fit to the data with plateau-like potentials. Example: Starobinsky potential:

$$V(\Theta) \simeq \frac{M_{\rm Pl}^4}{4\alpha}\left(1 - e^{-\sqrt{\frac{2}{3}}\Theta}\right)^2 ,$$

with $\alpha \sim 10^8$. Admits large-field inflation with $r = 0.003$.

Introduction

Introduction

Inflationary mass scales:

- Hubble constant during inflation: $H \sim 10^{14}$ GeV.
- mass scale of inflation: $V_{\rm inf} = M_{\rm inf}^4 = 3M_{\rm Pl}^2 H_{\rm inf}^2 \Rightarrow M_{\rm inf} \sim 10^{16}$ GeV
- mass of inflaton during inflation: $M_\Theta^2 = 3\eta H^2 \Rightarrow M_\Theta \sim 10^{13}$ GeV

Large field inflation:

- Makes it important to control Planck suppressed operators (eta-problem)
- Invoking a symmetry like the shift symmetry of axions helps

Axion inflation

Axion inflation

Axions are ubiquitous in string theory so that many scenarios have been proposed

- Natural inflation with a potential $V(\theta) = V_0(1 - \cos(\theta/f))$. Hard to realize in string theory, as $f > 1$ lies outside perturbative control. (Freese,Frieman,Olinto)
- Aligned inflation with two axions, $f_{eff} > 1$. (Kim,Nilles.Peloso)
- N-flation with many axions and $f_{eff} > 1$. (Dimopoulos,Kachru,McGreevy,Wacker)
- Monodromy inflation: Shift symmetry is broken by branes or fluxes unwrapping the compact axion $\rightarrow$ polynomial potential for θ. (Silverstein,Westphal)

Axion monodromy inflation

Axion monodromy inflation

Proposal: Realize axion monodromy inflation via the F-term scalar potential induced by background fluxes.

(Marchesano.Shiu,Uranga),(Hebecker, Kraus, Wittkowski),(Bhg, Plauschinn)

Advantages

- Avoids the explicit supersymmetry breaking of models with the monodromy induced by branes
- Supersymmetry is broken spontaneously by the very same effect by which usually moduli are stabilized
- Generic in the sense that the potential for the the axions arise from the type II Ramond-Ramond field strengths $F_{p+1} = dC_p + H \wedge C_{p-2}$ involving the gauge potentials C_{p-2} explicitly.

Objective

Objective

For a controllable single field inflationary scenario, all moduli need to be stabilized such that

$$M_{\rm Pl} > M_{\rm s} > M_{\rm KK} > M_{\rm inf} > M_{\rm mod} > H_{\rm inf} > |M_\Theta|$$

Aim: Systematic study of realizing single-field fluxed F-term axion monodromy inflation, taking into account the interplay with moduli stabilization.

Continues the studies from (Bhg,Herschmann,Plauschinn), (Hebecker, Mangat, Rombineve, Wittkowsky) by including the Kähler moduli.

Note:

- There exist a no-go theorem for having an unconstrained axion in supersymmetric minima of $N = 1$ supergravity models (Conlon)

Framework

Framework

Framework: Type IIB orientifolds on CY threefolds with geometric and non-geometric fluxes. (Shelton,Taylor,Wecht), (Aldazabal,Camara,Ibanez,Font), (Grana, Louis, Waldram), (Benmachiche, Grimm), (Micu, Palti, Tasinato)

Kähler potential

$$K = -\log\Big(-i\int\Omega\wedge\overline{\Omega}\Big) - \log\big(S+\overline{S}\big) - 2\log\mathcal{V}\,,$$

and the flux-induced superpotential

$$W = \int \Omega\wedge\big(\mathcal{D}(e^{B+iJ}) + \mathcal{D}(e^{B}C_{RR})\big)\,|_{\text{proj.}}$$

with

$$\mathcal{D} = d - H\wedge\ -F\circ\ -Q\bullet\ -R\llcorner$$

Framework

Framework

W can be expanded as

$$W = -\left(\mathfrak{f}_\lambda X^\lambda - \tilde{\mathfrak{f}}^\lambda F_\lambda\right) + i\,S\left(h_\lambda X^\lambda - \tilde{h}^\lambda F_\lambda\right)$$
$$- i\,G^a\left(f_{\lambda a} X^\lambda - \tilde{f}^\lambda{}_a F_\lambda\right) + i\,T_\alpha\left(q_\lambda{}^\alpha X^\lambda - \tilde{q}^{\lambda\alpha} F_\lambda\right)$$
$$+ \left(S\,T_\alpha + \frac{1}{2}\kappa_{\alpha bc} G^b G^c\right)\left(p_\lambda{}^\alpha X^\lambda - \tilde{p}^{\lambda\alpha} F_\lambda\right)$$

Scalar potential:

- related to GSUGRA: $V = V_{\mathrm{N=2\ GSUGRA}}$
- results from a dimensional reduction of double field theory on a fluxed CY manifold (Bhg, Font, Plauschinn, arXiv:1507.?????)

DFT on CY

DFT on CY

Result: Start with DFT in the flux formulation

$$S_{\mathrm{NS\,NS}} = \frac{1}{2\kappa_{10}^2} \int d^D X \; e^{-2d} \, \mathcal{F}_{ABC} \mathcal{F}_{A'B'C'} \left(\frac{1}{4} S^{AA'} \eta^{BB'} \eta^{CC'} - \frac{1}{12} S^{AA'} S^{BB'} S^{CC'} + \ldots \right)$$

Compactifying this on a fluxed CY three-fold, the action can be rewritten as

$$S_{\mathrm{NS\,NS}} = -\frac{1}{2\kappa_{10}^2} \int e^{-2\phi} \Big[\frac{1}{2} \chi \wedge \star \overline{\chi} + \frac{1}{2} \Psi \wedge \star \overline{\Psi} - \frac{1}{4} (\Omega \wedge \chi) \wedge \star (\overline{\Omega} \wedge \overline{\chi}) - \frac{1}{4} (\Omega \wedge \overline{\chi}) \wedge \star (\overline{\Omega} \wedge \chi) \Big] .$$

with $\chi = \mathfrak{D}\, e^{B+iJ}$ and $\Psi = \mathfrak{D}\,\Omega$, where $\mathfrak{D} = e^{-B} \mathcal{D} e^{+B}$.

Objective

Objective

Scheme of moduli stabilization such that the following aspects are realized:

- There exist non-supersymmetric minima stabilizing the saxions in their perturbative regime.
- All mass eigenvalues are positive semi-definite, where the massless states are only axions.
- For both the values of the moduli in the minima and the mass of the heavy moduli one has parametric control in terms of ratios of fluxes.
- One has either parametric or at least numerical control over the mass of the lightest (massive) axion, i.e. the inflaton candidate.
- The moduli masses are smaller than the string and the Kaluza-Klein scale.

A representative model

A representative model

Kähler potential is given by

$$K = -3\log(T+\overline{T}) - \log(S+\overline{S})\,.$$

Fluxes generate superpotential

$$W = -i\tilde{\mathfrak{f}} + i\,h\,S + i\,q\,T\,,$$

with $\tilde{\mathfrak{f}}, h, q \in \mathbb{Z}$. Resulting scalar potential

$$V = \frac{(hs+\tilde{\mathfrak{f}})^2}{16\,s\,\tau^3} - \frac{6hqs - 2q\tilde{\mathfrak{f}}}{16\,s\,\tau^2} - \frac{5q^2}{48\,s\,\tau} + \frac{\theta^2}{16\,s\,\tau^3}$$

A representative model

A representative model

Non-supersymmetric, tachyon-free minimum with

$$\tau_0 = \frac{6\tilde{\mathfrak{f}}}{5\,q}\,, \qquad s_0 = \frac{\tilde{\mathfrak{f}}}{h}\,, \qquad \theta_0 = 0\,.$$

D3- and a D7-brane tadpole:

$$N_{\mathrm{D3}} = -\tilde{\mathfrak{f}}\,h\,, \qquad N_{\mathrm{D7}} = -\tilde{\mathfrak{f}}\,q$$

Mass eigenvalues

$$M^2_{\mathrm{mod},i} = \mu_i\,\frac{h\,q^3}{16\,\tilde{\mathfrak{f}}^2}\,\frac{M^2_{\mathrm{Pl}}}{4\pi}\,,$$

with $\mu_i > 0$.

Mass scales

Mass scales

Gravitino-mass scale: $M_{\frac{3}{2}} \underset{p}{\simeq} M_{\rm mod}$

Cosmological constant in AdS minimum:

$$V_0 = -\mu_C \, \frac{h\, q^3}{16\, \tilde{\mathfrak{f}}^2} \, \frac{M_{\rm Pl}^4}{4\pi}$$

Perturbative regime: $\tau, s, v \underset{p}{\gtrsim} 1 \Rightarrow$ relation for the mass scales

$$M_{\rm up}^2 \underset{p}{\simeq} M_{\rm mod}\, M_{\rm Pl}\,, \qquad\qquad M_{\rm up} \underset{p}{\gtrsim} M_{\rm s}\,.$$

with uplift scale $M_{\rm up} = (-V_0)^{\frac{1}{4}}$.

Mass scales

Mass scales

String and KK-scale

$$M_{\mathrm{s}} = \frac{\sqrt{\pi} M_{\mathrm{Pl}}}{s^{\frac{1}{4}} \mathcal{V}^{\frac{1}{2}}}, \qquad M_{\mathrm{KK}} = \frac{M_{\mathrm{Pl}}}{\sqrt{4\pi}\, \mathcal{V}^{\frac{2}{3}}},$$

so that for the ratio

$$\frac{M_{\mathrm{s}}}{M_{\mathrm{KK}}} = 2\pi \left(\frac{12}{5}\right)^{\frac{1}{4}} \left(\frac{h}{q}\right)^{\frac{1}{4}}.$$

Ratio of KK-scale to the moduli mass scale:

$$\frac{M_{\mathrm{KK}}}{M_{\mathrm{mod}}} = \frac{10}{6\sqrt{\mu_i\, hq}},$$

Thus,

$$M_{\mathrm{s}} \underset{p}{\gtrsim} M_{\mathrm{KK}} \underset{p}{\simeq} M_{\mathrm{mod}}$$

Generalizations

Generalizations

Analyzed more models of this flux scaling type:

- complex structure U
- orientifold odd moduli G
- more Kähler moduli, $h^{11} > 1$ like K3 fibration or swiss cheese
- with non-geometric P-flux

Features:

- there exist non-supersymmetric, non-tachyonic minima
- except some axions, all moduli are stabilized
- For $h^{11} > 1$, new tachyons appear $\rightarrow$ tachyon-uplift via D-term
- With P-flux all moduli can be stabilized
- Uplift to de Sitter subtle: $V_{\rm up} \sim \frac{\epsilon}{\tau^{\beta}}$, $0 < \beta < 1/4$.

Axion inflaton

Axion inflaton

Generate a non-trivial scalar potential for the massless axion Θ by turning on additional fluxes $f_{\rm ax}$ and deform

$$W_{\rm inf} = \lambda W + f_{\rm ax} \, \Delta W \, .$$

This quite generically leads to

$$M_{\rm mod} \underset{p}{\gtrsim} M_{\Theta} \Longrightarrow M_{\rm mod} \underset{p}{\gtrsim} M_{\rm KK}$$

Tension with tadpole cancellation.

Toy model

Toy model

Model A with uplifted scalar potential

$$V = \lambda^2 \left(\frac{(hs + \tilde{\mathfrak{f}})^2}{16 s \tau^3} - \frac{6hqs - 2q\tilde{\mathfrak{f}}}{16 s \tau^2} - \frac{5q^2}{48 s \tau} \right) + \frac{\theta^2}{16 s \tau^3} + V_{\mathrm{up}} \,.$$

Backreaction of the other moduli adiabatically adjusting during the slow-roll of θ flattens the potential

(Dong,Horn,Silverstein,Westphal)

$$V_{\mathrm{back}}(\theta) = \frac{25\lambda^2 h q^3}{108 \tilde{\mathfrak{f}}^2} \frac{5\left(\frac{\theta}{\lambda}\right)^2 - 4\tilde{\mathfrak{f}}\left(4\tilde{\mathfrak{f}} - \sqrt{10\left(\frac{\theta}{\lambda}\right)^2 + 16\tilde{\mathfrak{f}}^2}\right)}{\left(4\tilde{\mathfrak{f}} + \sqrt{10\left(\frac{\theta}{\lambda}\right)^2 + 16\tilde{\mathfrak{f}}^2}\right)^2} .$$

Backreaction

Backreaction

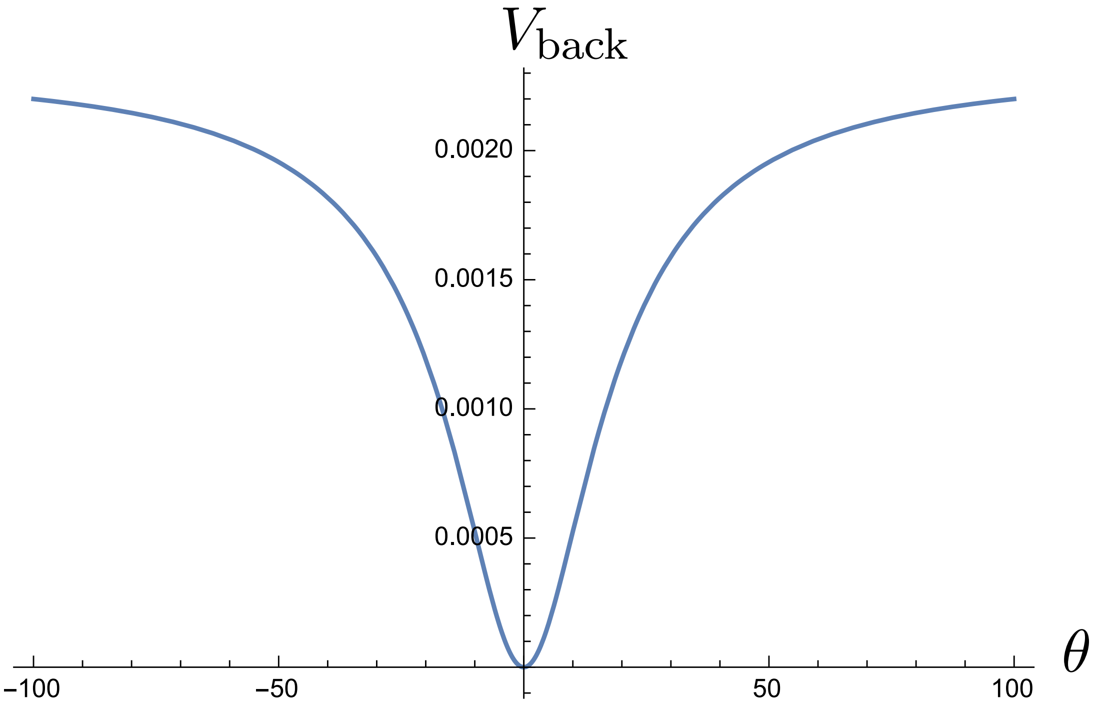


Figure 1: The potential $V_{\mathrm{back}}(\theta)$ for fluxes $h = 2$, $q = 1$, $\tilde{\mathfrak{f}} = 10$.

Effective potential

Effective potential

Large field regime: $\theta/\lambda \gg \tilde{\mathfrak{f}}$. The potential in the large-field regime becomes Starobinsky-like

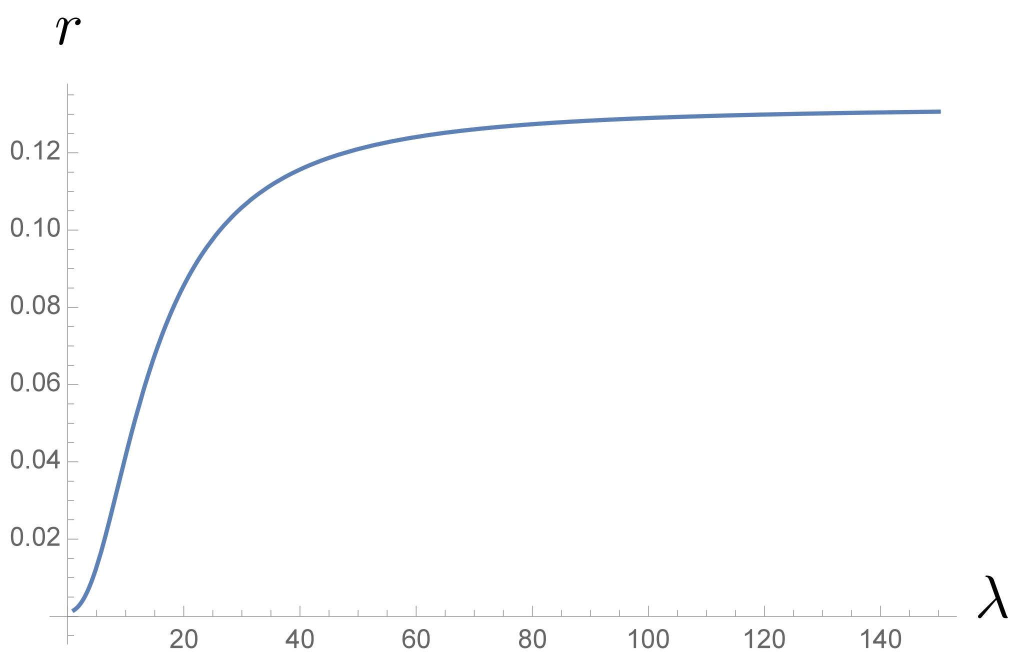
$$V_{\rm back}(\Theta) = \frac{25}{216}\,\frac{h\,q^3\,\lambda^2}{\tilde{\mathfrak{f}}^2}\Big(1 - e^{-\gamma\,\Theta}\Big)\,.$$

with $\gamma^2 = 28/(14 + 5\lambda^2)$.

- For $\theta/\lambda \ll \tilde{\mathfrak{f}}$: 60 e-foldings from the quadratic potential
- Intermediate regime: linear inflation
- For $\theta/\lambda \gg \tilde{\mathfrak{f}}$: Starobinsky inflation

Tensor-to-scalar ratio

Tensor-to-scalar ratio



With decreasing λ the model changes from chaotic to Starobinsky-like inflation.

Parametric control

Parametric control

From UV-complete theory point of view, large-field inflation models require a hierarchy of the form

$$M_{\rm Pl} > M_{\rm s} > M_{\rm KK} > M_{\rm mod} > H_{\rm inf} > M_\Theta \,,$$

where neighboring scales can differ by (only) a factor of $O(10)$.

Main observation

- the larger λ, the more difficult it becomes to separate the high scales on the left
- for small λ, the smaller (Hubble-related) scales on the right become difficult to separate.

Conclusions

Conclusions

- Systematically investigated the flux induced scalar potential for non-supersymmetric minima, where we have parametric control over moduli and the mass scales.
- All moduli are stabilized at tree-level $\rightarrow$ *the* framework for studying F-term axion monodromy inflation.
- As all mass scales are close to the Planck-scale, it is difficult to control all hierarchies. Does large field inflation necessarily must include stringy/KK effects?

Open questions

Open questions

- Parametrically controllable stable dS-vacua? (work in progress)
- Due to the absence of a dilute flux limit, it might be questionable whether a solution to the effective theory uplifts to a full solution of string theory.
- What is the 10D origin of the scalar potential? Double field theory (work in progress).