# High Scale Moduli Stabilization and Axion Inflation


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

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

# Introduction

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Moduli stabilization in string theory:

- Race-track scenario
- KKLT
- LARGE volume scenario

Based on instanton effects $\to$ exponential hierarchies $\to$ 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 $\to$ string tree-level with fluxes

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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 $r = 0.003$.

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Inflationary mass scales:

- Hubble constant during inflation: $H \sim 10^{14}$ GeV.
- mass scale of inflation: $V_{\text{inf}} = M_{\text{inf}}^4 = 3M_{\text{Pl}}^2 H_{\text{inf}}^2 \Rightarrow$ $M_{\text{inf}} \sim 10^{16}$ 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 $\theta$. (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.

# Axion monodromy inflation

# Axion monodromy inflation

Recently, a couple of a priori possible string realizations have been discussed. To name a few, the inflaton was given by:

- Wilson line and $(B_2, C_2)$ modulus with potential generated by geometric flux (Marchesano.Shiu,Uranga)
- The universal axion $c$ in type IIB flux compact. $\rightarrow$ natural reheating mechanism (Bhg, Plauschinn)
- D7-brane deformation modulus in the large complex structure limit (Hebecker, Kraus, Wittkowski)
- Higgs inflation (Ibanez, Valenzuela)

More proposals by Mc Allister, Buchmüller, Dudas, Gao, Grimm, Ibanez, Li, Kappl, Long, Mc Guirk, Nilles, Shukla, Silverstein, Valenzuela, Westphal, Winkler,...
(talks by Dudas, Hebecker, Kallosh, Linde, McAllister, Silverstein, Shiu)

# Objective

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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)

# Objective

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

Kähler potential

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

and the flux-induced superpotential

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

with

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

# Objective

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$W$ can be expanded as

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

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, Shukla, to appear)

# Objective

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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: $M_{\frac{3}{2}} \underset{p}{\simeq} M_{\text{mod}}$

Cosmological constant in AdS minimum:

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

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

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

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

# Mass scales

# Mass scales

String and KK-scale

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

so that for the ratio

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

Ratio of KK-scale to the moduli mass scale:

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

Thus,

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

# 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 $\Theta$ 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

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

Backreaction of the other moduli adiabatically adjusting during the slow-roll of $\theta$ flattens the potential

(Dong,Horn,Silverstein,Westphal)

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

# Backreaction

# Backreaction

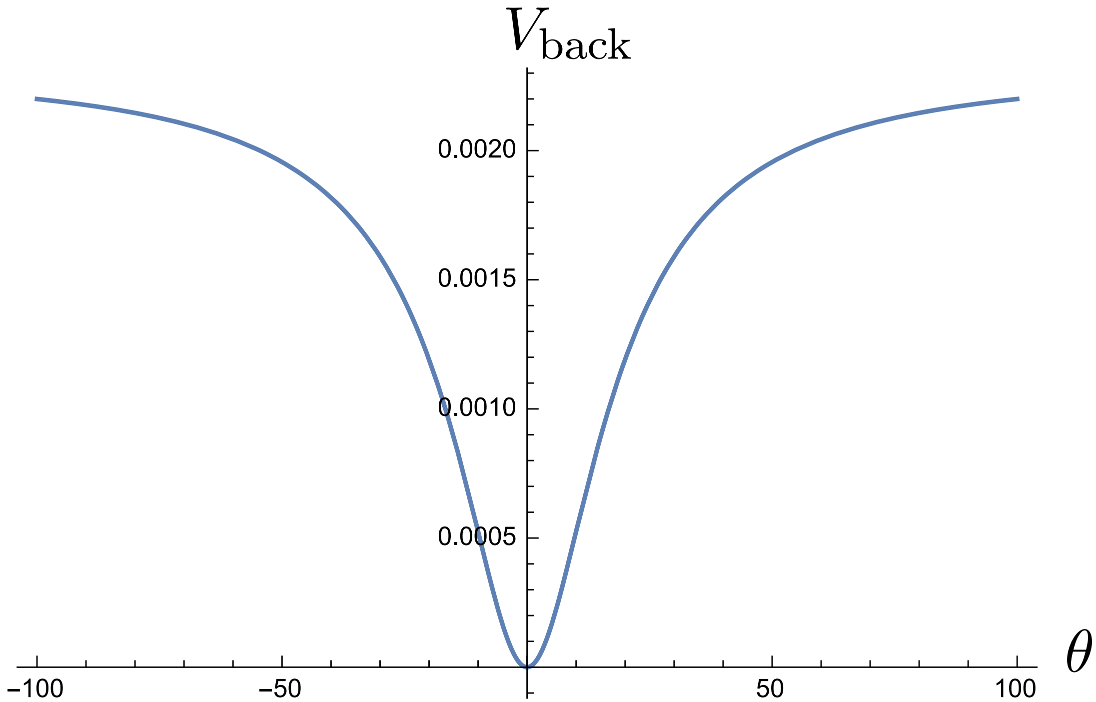


Figure 1: The potential $V_{\rm back}(\theta)$ for fluxes $h = 2$, $q = 1$, $\tilde{\mathfrak{f}} = 10$.

# Effective potential

# Effective potential

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

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

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

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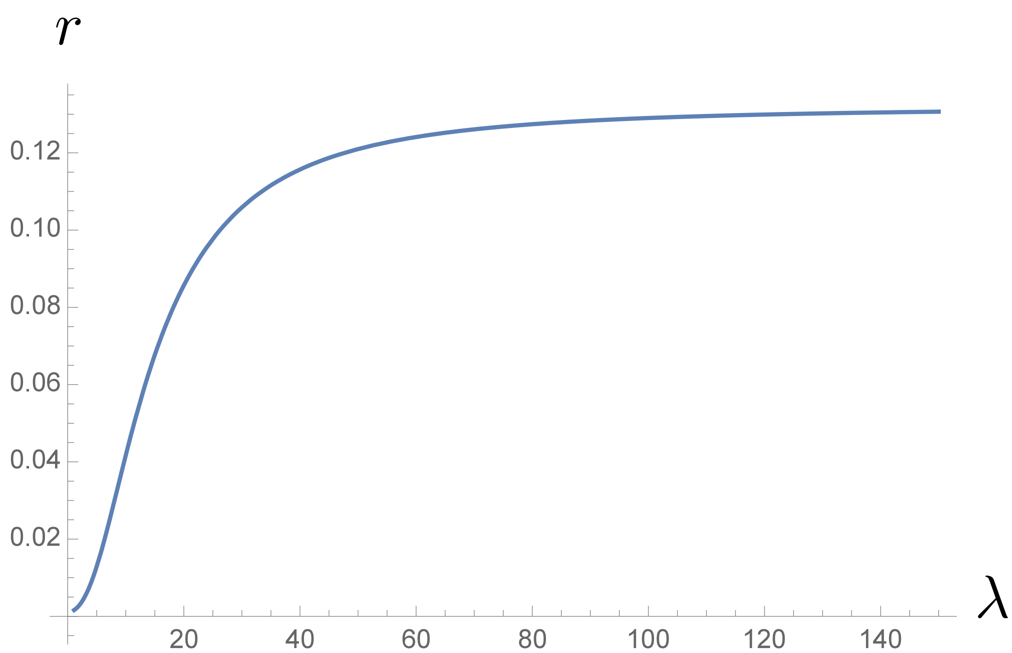


With decreasing $\lambda$ the model changes from chaotic to Starobinsky-like inflation.

# 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 $\lambda$, the more difficult it becomes to separate the high scales on the left
- for small $\lambda$, the smaller (Hubble-related) scales on the right become difficult to separate.

# Conclusions

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- 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

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- 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).