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:(talks by Kane, Quevedo)

- 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 $M < 1$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

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PLANCK 2015 results: (talks by Kleban, Flauger)

- 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

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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 with $\Delta\Phi > M_{\text{pl}}$:

- 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

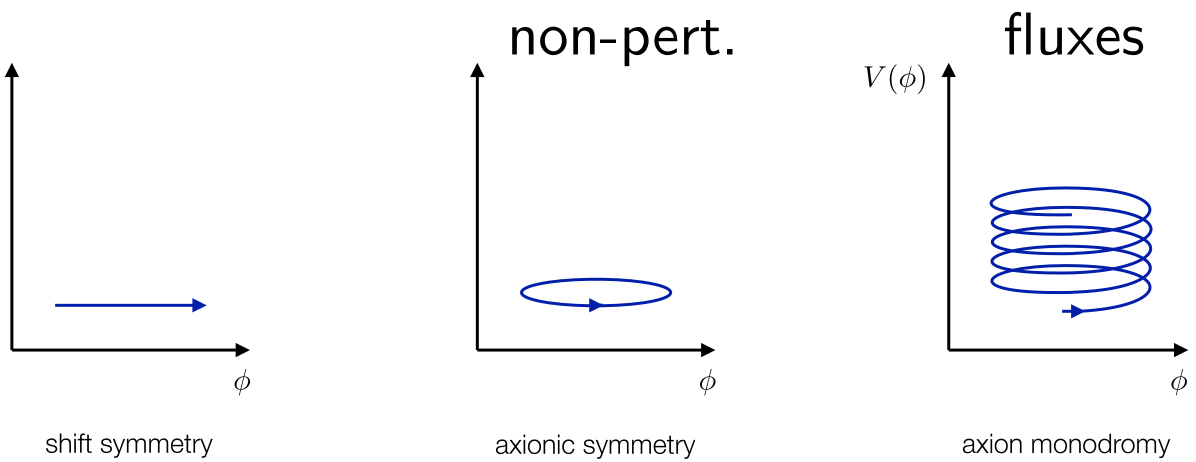
- Natural inflation with a potential $V(\theta) = Ae^{-S_{\mathrm{E}}}(1 - \cos(\theta/f))$. Hard to realize in string theory, as $f > 1$ lies outside perturbative control.
  (Freese,Frieman,Olinto)
- Aligned inflation with two axions, $f_{\mathrm{eff}} > 1$. (Kim,Nilles,Peloso)
- N-flation with many axions and $f_{\mathrm{eff}} > 1$.
  (Dimopoulos,Kachru,McGreevy,Wacker)

Comment: These models have come under pressure by the weak gravity conjecture, which for instantons was proposed to be $f \cdot S_{\mathrm{E}} < 1$. (Montero,Uranga,Valenzuela),(Brown,Cottrell,Shiu,Soler)

Axion monodromy inflation

Axion monodromy inflation

- Monodromy inflation: Shift symmetry is broken by branes or fluxes unwrapping the compact axion $\rightarrow$ polynomial potential for θ. (Kaloper, Sorbo), (Silverstein,Westphal)



Discrete shift symmetry acts also on the fluxes, i.e. one gets different branches $\rightarrow$ tunneling à la Coleman-de Lucia

Axion monodromy inflation

Axion monodromy inflation

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

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

Advantages

- Generating the inflaton potential, supersymmetry is broken spontaneously by the very same effect by which usually moduli are stabilized
- Generic, as the field strengths $F_{p+1} = dC_p + H \wedge C_{p-2}$ involves the gauge potentials C_{p-2}.

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

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

Relation to DFT

Relation to DFT

Compactifying the Double Field Theory action on a fluxed CY three-fold, the result can be expressed as (Bhg, Font, Plauschinn, arXiv:1507.08059)

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

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

Scalar potential:

- related to gauged supergravity: $V = V_{\mathrm{N=2\ GSUGRA}}$
- Orientifold projection: $V_{\mathrm{proj}} = V_F + V_D + V_{\mathrm{NS-tad}}$

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

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

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 $\mu_i > 0$.

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

Mass scales

Mass scales

Cosmological constant in AdS minimum:

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

Uplift: It is possible to find (new) scaling type minima with $V_0 \geq 0$ by including an uplifting $\overline{D3}$-brane (D-term)

$$V = V_F + \frac{A}{\mathcal{V}^{\frac{4}{3}}} + (V_D)$$

(Bhg, Damian, Font, Fuchs, Herschmann, Sun, arXiv:1509.nnnnn)

Relation of mass scales:

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

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

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

Toy model with uplifted scalar potential

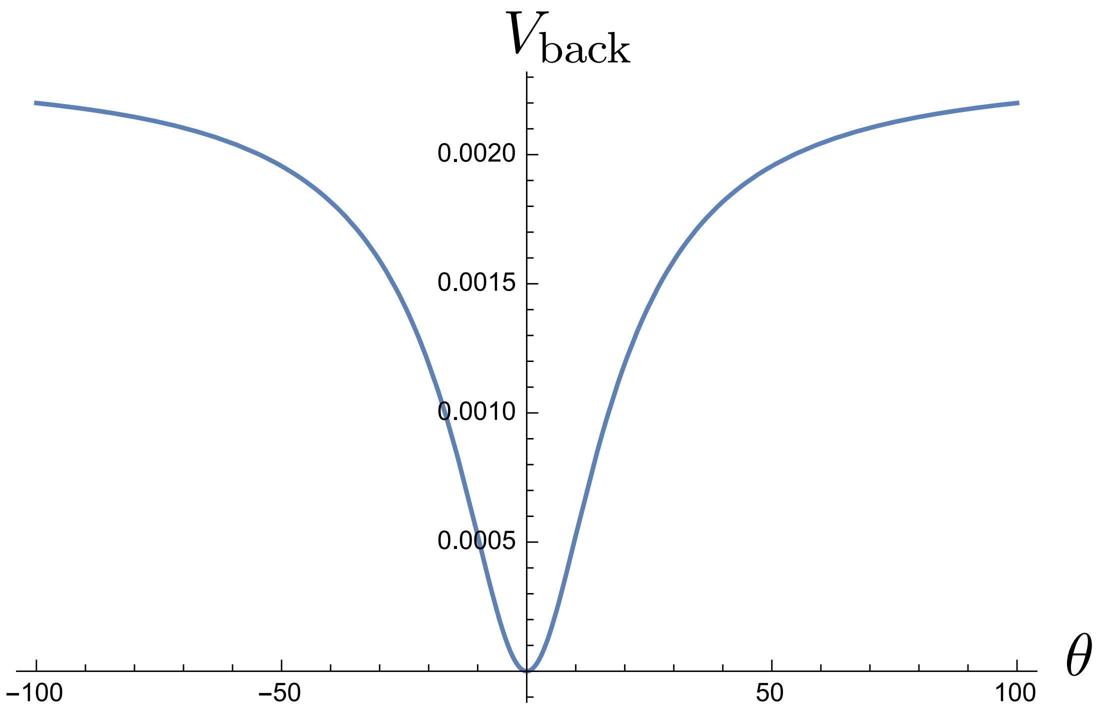
$$V = \lambda^2 \left(\frac{(hs + \tilde{\mathfrak{f}})^2}{16 s\tau^3} - \frac{6hqs - 2q\tilde{\mathfrak{f}}}{16 s\tau^2} - \frac{5q^2}{48 s\tau} \right) + \frac{\theta^2}{16 s\tau^3} + V_{\rm up}\,.$$

Toy model

Toy model

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

(Dong,Horn,Silverstein,Westphal)



Effective potential

Effective potential

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

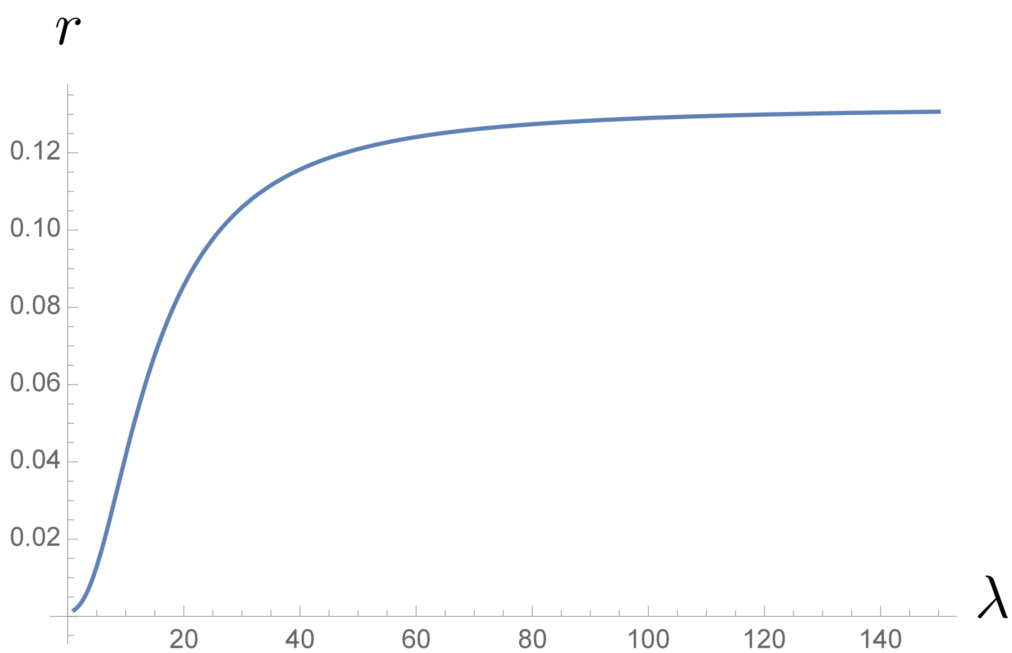
$$V_{\rm back}(\Theta) = \frac{25}{216}\frac{h\,q^3\,\lambda^2}{\tilde{\mathfrak{f}}^2}\left(1 - e^{-\gamma\,\Theta}\right).$$

with $\gamma^2 = 28/(14 + 5\lambda^2)$ (similar to Starobinsky-model).

- 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

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

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.
- Since the inflaton gets its mass from a tree-level effect, one gets a high susy breaking scale.
- 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?
- The (MS)SM could arise on a set of intersecting D7-branes $\rightarrow$ mutual constraints between fluxes and branes (Freed/Witten anomalies). Is sequestering, $M_{\rm soft} \ll M_{\frac{3}{2}}$, possible?

Thank You!