Non-geometric Strings and Axion Inflation

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(RB, Font, Fuchs, Herschmann, Plauschinn, arXiv:1503.01607, to be replaced)

(RB, Font, Fuchs,Herschmann, Plauschinn, Sekiguchi, Wolf, to appear))

Introduction

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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.
- 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:

- 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 $\mathcal{P} = (2.142 \pm 0.049) \cdot 10^{-9}$

Best 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: $V_{\rm inf} = M_{\rm inf}^4 = 3M_{\rm Pl}^2 H_{\rm inf}^2 \Rightarrow M_{\rm inf} \sim 10^{16}$ 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)

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, Gao, Grimm, Ibanez, Li, Long, Mc Guirk, Shukla, Silverstein, Valenzuela, Westphal,..

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)

Objective

Objective

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

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

Scalar potential: $V = V_{\mathrm{N=2\ GSUGRA}}$.

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

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

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: more details in D. Herschmann's talk

- 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: $V_{\rm up} \sim \frac{\epsilon}{\tau^{\beta}}$, $0 < \beta < 1/4$.

Comment on dilute flux

Comment on dilute flux

10D Einstein-frame DFT action including also the non-geometric Q-flux

$$S = \frac{1}{2}\int d^{10}x\,\sqrt{-g}\Big(\mathcal{L}^{HH} + \mathcal{L}_1^{QQ} + \mathcal{L}_2^{QQ} + \mathcal{L}^{HQ} + \mathcal{L}^{\rm RR}\Big)$$

with the kinetic terms given as

$$\begin{aligned}
\mathcal{L}^{HH} &\sim -e^{-\phi} H_{ijk}\, H_{i'j'k'}\, g^{ii'}\, g^{jj'}\, g^{kk'} \\
\mathcal{L}_1^{QQ} &\sim -e^{\phi} Q_k{}^{ij}\, Q_{k'}{}^{i'j'}\, g_{ii'} g_{jj'} g^{kk'} \\
\mathcal{L}_2^{QQ} &\sim -e^{\phi} Q_m{}^{ni}\, Q_n{}^{mi'}\, g_{ii'} \\
\mathcal{L}^{HQ} &\sim H_{mni}\, Q_{i'}{}^{mn}\, g^{ii'} \\
\mathcal{L}^{\rm RR} &\sim -e^{\phi}\, \mathfrak{F}_{ijk}\, \mathfrak{F}_{i'j'k'}\, g^{ii'}\, g^{jj'}\, g^{kk'}\ .
\end{aligned}$$

Comment on dilute flux

Comment on dilute flux

Flux scaling of dilaton and metric:

$$e^{-\phi} \sim s \sim \frac{\tilde{\mathfrak{f}}}{h}\,, \qquad g \sim \sqrt{\tau} \sim \frac{\tilde{\mathfrak{f}}^{\frac{1}{2}}}{q^{\frac{1}{2}}}\,, \qquad g^{-1} \sim \frac{q^{\frac{1}{2}}}{\tilde{\mathfrak{f}}^{\frac{1}{2}}}$$

so that

$$\mathcal{L}^{HH} \sim \mathcal{L}_1^{QQ} \sim \mathcal{L}_2^{QQ} \sim \mathcal{L}^{HQ} \sim \mathcal{L}^{\mathrm{RR}} \sim \frac{hq^{\frac{3}{2}}}{\tilde{\mathfrak{f}}^{\frac{1}{2}}}\,.$$

To control the backreaction of the fluxes, the energy-momentum tensor $T_{ij} = \frac{\partial \mathcal{L}}{\partial g^{ij}}$ is essential:

$$T_{ij}^{HH} \sim T_{1\,ij}^{QQ} \sim T_{2\,ij}^{QQ} \sim T_{ij}^{HQ} \sim T_{ij}^{\mathrm{RR}} \sim h\,q\,.$$

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

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

Concrete example with $h^{21} = 1$:

$$W_{\rm inf} = \lambda\Big(\hat{\mathfrak{f}}_1 U + i\,\tilde{\mathfrak{f}}^0 U^3 + 3i\,\tilde{h}^1 U^2\, S + 3i\,\tilde{q}^1 U^2\, T\Big) + i(h_0 S + q_0 T)\,.$$

Integrating out + uplift $\rightarrow$ effective quadratic potential

$$V_{\rm eff}(c) = \frac{1}{2^7}\Big(A\theta^2 + O(\mathfrak{f}_1^{-\frac{3}{2}})\Big)$$

Backreaction: Starobinsky-like behaviour for large θ

Axion inflation

Axion inflation

Moduli mass hierarchy:

$$\frac{M_\Theta^2}{M_{\rm mod}^2} \sim \frac{(\tilde{h}^1 q_0 - \tilde{q}^1 h_0)^2\,(\tilde{\mathfrak{f}}^0)^2}{\lambda^2(\tilde{h}^1\,\tilde{q}^1)^2\,\hat{\mathfrak{f}}_1^2}\,,$$

For $\lambda\hat{\mathfrak{f}}_1 \ll 1$, one controls $M_{\rm mod} \underset{p}{\gtrsim} M_\Theta$.

KK-scale: one finds the relation

$$\frac{M_\Theta^2}{M_{\rm mod}^2}\cdot\frac{M_{\rm mod}^8}{M_{\rm KK}^8} \sim \lambda^6(\tilde{h}^1)^2(\tilde{q}^1)^2(\tilde{h}^1 q_0 - \tilde{q}^1 h_0)^2 \geq 1\,.$$

Thus,

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

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?
- More technical details and application to phenomenology are discussed in D. Herschmann's talk.