String Moduli Stabilization and Large Field Inflation II

Ralph Blumenhagen

Max-Planck-Institut für Physik, München

Bhg, Valenzuela, Wolf, arXiv:170m.nnnnn

Axion inflation

Axion inflation

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

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

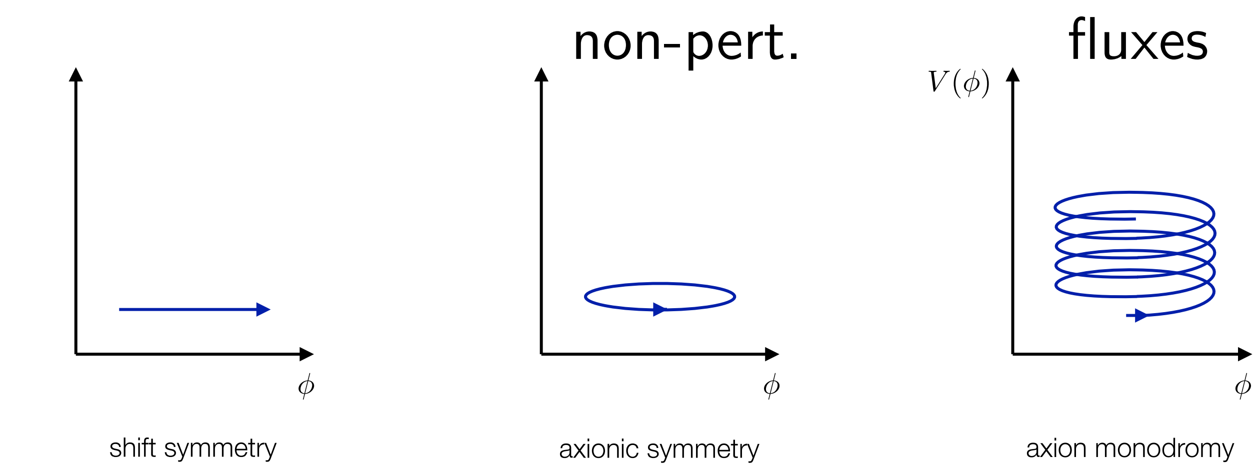
Comment: These models have come under pressure by the weak gravity conjecture, which for instantons was proposed to be $f \cdot S_{\rm E} < 1$.

(Rudelius),(Montero,Uranga,Valenzuela),(Brown,Cottrell,Shiu,Soler)

Axion monodromy

Axion monodromy

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



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

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

Mass hierarchies

Mass hierarchies

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

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

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

series of papers by Bhg,Font,Fuchs,Herschmann,Plauschinn,Sekiguchi,Sun,Wolf

and many papers by Buchmueller,Dudas,Escobar,Hebecker,Ibanez,Landete,Marchesano, McAllister,Regalado,Valenzuela,Westphal,Wieck,Winkler,Witkowski,...

Paradigm: Since the inflaton receives its potential/mass from a tree-level flux, generically all other moduli need to be stabilized at tree level, as well.

Tree-level moduli stabilization

Tree-level moduli stabilization

Framework: Type IIB orientifolds on CY threefolds with (non)-geometric fluxes and D7-branes.

- Scalar potential splits $V_{\rm N=2} = V_F + V_D + V_{\rm NS-tad}$
- Fits into 4d $N=1$ SUGRA, i.e. V_F can be computed via a Kähler and superpotential

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

and the flux-induced schematic superpotential

$$W = \int \Omega\wedge (F_3 - S\,H + T\,Q)$$

Tree-level moduli stabilization

Tree-level moduli stabilization

Include D7-brane position moduli

$$\Phi^I = \varphi^I + i\theta^I \qquad \text{with} \qquad I = 1, \dots, h^{2,0}_-(C_4)\,.$$

Holomorphic variable S gets modified

$$S \longrightarrow S - \tfrac{1}{2}\Phi\,\tfrac{\Phi+\overline{\Phi}}{U+\overline{U}}\,.$$

(Grimm,Vieira Lopes),(Kerstan,Weigand),(Carta,Marchesano,Stassens,Zoccarato)

For STU-model the Kähler potential reads

$$K = -3\log(T+\overline{T}) - \log\left[(S+\overline{S})(U+\overline{U}) - \tfrac{(\Phi+\overline{\Phi})^2}{2}\right] - 2\log(U+\overline{U})\,.$$

Tree-level moduli stabilization

Tree-level moduli stabilization

Open string superpotential:(Jockers,Louis),(Escobar, Landete, Marchesano, Regalado)

$$W_o = \int_{\Gamma_5} \Omega_3 \wedge (\iota^* B + F) + \Delta W_o$$

Obstruction: Moving the D7-brane, the flux $(\iota^* B + F)$ can develop a $(2,0)$-component.

Weak coupling limit of F-theory implies an additional term

$$\Delta W_o = \frac{i}{2\pi} \int_{\mathcal{M}} H \wedge \log\left(\frac{P_{D7}}{P_{O7}}\right) \Omega_3$$

(Arends, Hebecker, Heimpel, Kraus, Lüst, Mayrhofer, Schick, Weigand)

Swampland Conjecture

Swampland Conjecture

All attempts so far failed to provide a fully controllable model. Is there a fundamental reason? (Kläwer,Palti)

Swampland Conjecture: (Ooguri,Vafa)

For any point p_0 in the continuous scalar moduli space of a consistent quantum gravity theory, there exist other points p at arbitrarily large distance. As the distance $d(p_0, p)$ diverges, an infinite tower of states exponentially light in the distance appears, i.e. the mass scale of the tower varies as

$$m \sim m_0 \, e^{-\alpha d(p_0,p)} \, .$$

Here the distance is measured by the metric on the flat moduli space.

At this level, the axions have a shift symmetry and are compact.

Swampland Conjecture

Swampland Conjecture

Comments:

- number of states in the tower which are below any finite mass scale diverges as $d \to \infty$.
- Beyond $d(p_0, p) \sim \alpha^{-1}$ the exponential drop-off becomes essential
- Infinitely many light states $\to$ quantum gravity theory valid at the point p_0 only has a finite range d_c of validity

How is this related to large field inflation with non-compact and non-flat axions? Recall, the procedure

- stabilize the moduli: one light axion with mass hierarchy $M_\Theta < M_{\rm heavy}$
- Integrating out heavy moduli $\to V_{\rm eff}(\theta)$, potentially supporting large field inflation.

SC and large field inflation

SC and large field inflation

However, this picture is too naive, as: (Baume,Palti)

see also (Bhg,Font,Fuchs,Herschmann,Plauschinn).

- for trans-Planckian field excursion, one has to take the backreaction $s_{\rm heavy}(\theta)$ into account
- proper field distance:

$$\Theta = \int K_{\theta\theta}^{\frac{1}{2}}(s)\ d\theta \sim \int \frac{1}{s(\theta)} \sim \frac{1}{\lambda}\log(\theta)$$

  gives rise to $\Theta = \lambda^{-1}\log(\theta)$.

- Mass of KK-modes: $M_{\rm KK} \sim \theta^{-n} \sim \exp(-n\lambda\Theta)$

Thus, this the same behavior as in the swampland conjecture

Extend OV-swampland conjecture to axions: Following a single field axionic direction, taking the backreaction into account, one finds the swampland behavior.

SC and large field inflation

SC and large field inflation

Backreaction substantial for $\Theta_c \sim 1/\lambda$ and exponentially light modes spoil validity of LEEF.

What is the value of Θ_c?

Concrete closed string examples suggest that

$$\Theta_c \approx M_{\rm pl}$$

(Bhg,Font,Fuchs,Herschmann,Plauschinn), (Baume,Palti).

Led to the *Refined Swampland Conjecture* (Kläwer,Palti).

Proposal: Open string moduli could give rise to a parametrically larger value

$$\Theta_c \gg M_{\rm pl}$$

(Valenzuela),(Bielleman, Ibanez, Pedro, Valenzuela, Wieck)

see talk by Irene Valenzuela

Objectives

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- Revisit former attempts from this perspective
- Identify a simple, representative model of open string moduli stabilization to clarify the issue

Quantum gravity ingredients in the string effective action:

- The leading order Kähler potential always shows a logarithmic dependence on the saxions
- The moduli dependence of the various mass scales, resulting from dimensional reduction and moduli stabilization
- Fluxes are quantized

A representative model

A representative model

Kähler potential is given by

$$K = -3\log(T+\overline{T}) - \log\left[(S+\overline{S}) - \tfrac{1}{2}(\Phi+\overline{\Phi})^2\right] .$$

Fluxes generate superpotential

$$W = \mathfrak{f}_0 - h\,S - q\,T - \mu\Phi^2 \,,$$

with $\mathfrak{f}_0, h, q \in \mathbb{Z}$.

1. In type IIB $W = \int \iota^* B \wedge \Omega_3$ is not quantized.
2. However, in the backreacted F-theory picture μ is quantized.

(Arends, Hebecker, Heimpel, Kraus, Lüst, Mayrhofer, Schick, Weigand)

Moduli stabilization

Moduli stabilization

Non-supersymmetric, tachyon-free minimum with

$$\tau_0 = \frac{6\,\mathfrak{f}_0}{5\,q}\,, \qquad s_0 = \frac{\mathfrak{f}_0}{h}\,, \qquad \theta_0 = \phi_0 = \theta_0 = 0\,.$$

with masses for the canonically normalized fields

$$M^2_{\text{closed}} \simeq \frac{h\,q^3}{\mathfrak{f}_0^2}$$

and (for $\mu/h \ll 1$)

$$M^2_{\varphi} \simeq \frac{h\,q^3}{\mathfrak{f}_0^2}\,, \qquad M^2_{\theta} \simeq \frac{\mu\,q^3}{\mathfrak{f}_0^2}$$

Open string axion θ is parametrically lighter

$$\frac{M_{\text{heavy}}}{M_{\Theta}} \sim \sqrt{\frac{h}{\mu}} = \lambda^{-1}\,.$$

Backreaction: small excursions

Backreaction: small excursions

Backreaction of axion excursion

$$s \sim \frac{(\mathfrak{f}_0 + \mu\theta^2)}{5\,h}\,, \qquad \tau \sim \frac{6\,(\mathfrak{f}_0 + \mu\theta^2)}{5\,q}$$

with all other fields sitting in their minimum at zero.

Critical proper field distance:

$$\Theta_{\rm c} = \sqrt{\frac{h}{\mu}} = \frac{1}{\lambda}\,.$$

For $\Theta_c \gg 1$ and $\Theta \ll \Theta_{\rm c}$ the backreaction on the inflaton potential can be neglected.

Backreaction: large excursions

Backreaction: large excursions

Kinetic term for large field excursions

$$\mathcal{L}_{\rm kin}^{\rm ax} = \frac{1}{2}\frac{h}{\mu}\left(\frac{\partial\theta}{\theta}\right)^2$$

so that we get the logarithmic behavior

$$\Theta = \Theta_{\rm c}\,\log\left(\frac{\theta}{\theta_{\rm c}}\right) \simeq \frac{1}{\lambda}\log\theta \simeq \frac{M_{\rm heavy}}{M_\Theta}\log\theta$$

Backreacted scalar potential (after constant uplift):

$$V_{\rm back} \simeq |V_0|\left[1 - \exp\left(-4\frac{\Theta}{\Theta_{\rm c}}\right)\right].$$

of Starobinsky-like type.

Mass scales

Mass scales

Is $h \gg \mu$ consistent with the use of the low-energy effective field theory?

Some necessary parametrical mass hierarchy in

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

might be spoiled.

Not be concerned with model dependent numerical prefactors, but will focus on parametrical control (by fluxes).

Mass scales: minimum

Mass scales: minimum

Since we have dynamically stabilized S and T, we can compute

- String scale:

$$M_{\rm s}^2 \sim \frac{1}{\tau^{\frac{3}{2}}\, s^{\frac{1}{2}}} \sim \frac{h^{\frac{1}{2}}\, q^{\frac{3}{2}}}{\mathfrak{f}_0^2}\,.$$

- Kaluza-Klein scale:

$$M_{\rm KK}^2 \sim \frac{1}{\tau^2} \sim \frac{q^2}{\mathfrak{f}_0^2}\,.$$

- Recall moduli masses:

$$M_{\rm mod}^2 \sim \frac{h\, q^3}{\mathfrak{f}_0^2}\,, \qquad M_{\Theta}^2 \sim \frac{\mu\, q^3}{\mathfrak{f}_0^2}\,.$$

Mass scales: large field

Mass scales: large field

To relate to the Swampland Conjecture, we evaluate the various mass-scales in the large field regime:

$$M_{\rm i}^2 = M_{\rm i}^2\big|_0 \exp\left(-4\frac{\Theta}{\Theta_{\rm c}}\right) ,$$

where $M_{\rm i}^2|_0$ denotes the various mass scales in the minimum.

- All these mass scales show the expected exponential drop off
- For $\Theta/\Theta_c \gg 1$ this invalidates the use of the LEEA.
- This is all consistent with the Swampland Conjecture.

The question now is whether we also get constraints on the critical value $\Theta_{\rm c} \sim \lambda^{-1}$.

Constraint on Θ_c

Constraint on $\Theta_{\rm c}$

For this purpose, let us compute

$$\frac{M_{\rm KK}^2}{M_{\rm mod}^2} \sim \frac{1}{h\,q}\,.$$

This ratio is independent of Θ in the large field regime.

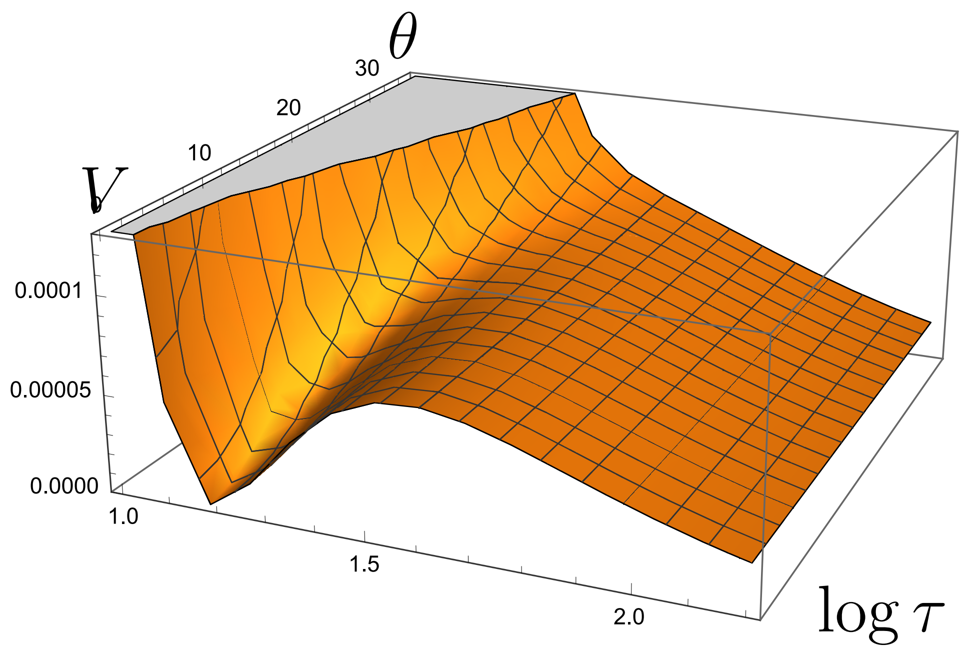
1. If we could tune $\Theta_c = \sqrt{h/\mu}$ small by choosing the open string flux μ small, there is no parametric problem with the mass hierarchies.
2. However, in the backreacted F-theory picture μ is quantized. Thus, for large H-flux h (i.e. $\lambda \ll 1$) one finds $M_{\rm mod} \underset{p}{\gtrsim} M_{\rm KK}$, invalidating LEEA.

For case 2. one has $\lambda \sim \Theta_{\rm c} \approx O(1)$ (*Refined Swampland Conjecture*).

Uplift

Uplift

For more realistic non-constant uplift potentials, in addition one finds that the trajectory destabilizes at a scale $\sim \Theta_c$.



Similar to backreaction for KKLT and LVS models with open string modulus (Buchmüller,Dudas,Heutier,Westphal,Wieck, Winkler), (Rühle,Wieck)

Comment on Type IIA model

Comment on Type IIA model

For those feeling uneasy with the non-geometric flux: Same findings for a Type IIA flux model with a mobile D6-brane: Kähler potential:

$$K = -3\log(U+\overline{U}) - 2\log(T+\overline{T}) - \log\left[(S+\overline{S})(T+\overline{T}) - \tfrac{1}{2}(\Phi+\overline{\Phi})^2\right] .$$

and superpotential

$$W = \mathfrak{f}_6 + 3\mathfrak{f}_2\,T^2 - f_0\,S\,T - f_1\,U\,T - \mu\,\Phi^2 .$$

Here $\mathfrak{f}_6$ denotes a R-R six-form flux, $\mathfrak{f}_2$ a R-R two-form flux and f_i geometric fluxes.

Conclusions

Conclusions

Thus we conclude: all the failing attempts, the Refined Swampland Conjecture support the conjecture:

> In string theory (quantum gravity) it is impossible to achieve a parametrically controllable model of large (single) field inflation. The tensor-to-scalar ratio is thus bounded from above $r \lessapprox 10^{-3}$.

Consistent with the entropy argument by (Conlon, *Quantum Gravity Constraints on Inflation*).

Should be checked in more instances: Kähler moduli stabilization via KKLT or LVS, other points in moduli space, fiber inflation (Cicoli et al),...

Conclusions

Conclusions

Can a landscape argument help: value of μ tuned in the landscape after integrating out other moduli?

Danger that one ''integrates out'' the moduli where the control issues arise and thus sweeps the problem under the carpet! For instance, there could be couplings like

$$V = \phi_{\text{heavy}}\, \phi_{\text{light}}\, \theta$$

that matter for large θ but vanish in the minimum at $\theta = 0$.

Proposal: Follow, a critical approach towards monodromy inflation and deconstruct

- Landscape tuning
- Effective theories around other points in moduli space
- Dante's inferno, multi-field inflation,. . .

Thank You!