The Swampland Conjecture and Large Field Inflation

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Bhg, Valenzuela, Wolf, arXiv:1703.05776
(cont. of talk by Irene Valenzuela)
Frequently asked questions
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FAQ II: Is there anything that cannot be realized in string theory (swampland)? Thus, can string theory be falsified?

Potential candidate: Large field inflation with $r > O(10^{-3})$. 
Axion inflation
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Large field inflationary models with periodic axions have come under pressure by the weak gravity conjecture.

What about F-term axion monodromy models based on tree-level fluxes?

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,…

All attempts so far failed to provide a fully controllable model respecting the hierarchy

\[ M_{Pl} > M_S > M_{KK} > M_{mod} > H_{inf} > |M_\Theta| \]

Why?
Swampland Conjecture
Swampland Conjecture

Proposal: axionic version of the swampland conjecture (Kläwer,Palti) (talk by Daniel Kläwer)

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

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

Here, distance is measured by the metric on the moduli space. Note, the swampland conjecture describes a property of models in the landscape!
Swampland Conjecture
Swampland Conjecture

Comments:

- Beyond $d(p_0, p) \sim \lambda^{-1}$ the exponential drop-off becomes essential

- Infinitely many light states $\rightarrow$ quantum gravity theory valid at the point $p_0$ only has a finite range $d_c$ of validity

- At this level, the axions have a shift symmetry and are compact, which is compatible with SC if $d(p_0, p) < \lambda^{-1}$
Swampland Conjecture

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- At this level, the axions have a shift symmetry and are compact, which is compatible with SC if $d(p_0, p) < \lambda^{-1}$.

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 $M_\Theta < M_{\text{heavy}}$.

- Integrating out heavy moduli $\to V_{\text{eff}}(\theta)$, potentially supporting large field inflation.
SC and large field inflation
SC and large field inflation

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

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

• proper field distance:

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

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

• Mass of KK-modes: $M_{\text{KK}} \sim \theta^{-n} \sim \exp(-n\lambda\Theta)$
SC and large field inflation
SC and large field inflation

- Can one extend OV-swampland conjecture to axions with a potential?
- What is the value of $\Theta_c$?
Can one extend OV-swampland conjecture to axions with a potential?

What is the value of $\Theta_c$?

Concrete closed string examples suggest that

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

(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

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

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

(Bhg, Valenzuela, Wolf)

- Revisit former attempts from this perspective
- Identify simple, representative models of open string moduli stabilization to clarify the issue
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- **Revisit** former attempts from this perspective
- **Identify** simple, representative models 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
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 $V_{N=2} = V_F + V_D + V_{NS-tad}$
- Fits into 4d $N = 1$ SUGRA, i.e. $V_F$ can be computed via a Kähler and superpotential

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

and the flux-induced schematic superpotential

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

(Important to include Kähler moduli $T$, as they enter KK mass-scales)
Tree-level moduli stabilization
Tree-level moduli stabilization

Include D7-brane position moduli

$$\Phi^I = \phi^I + i \theta^I$$ with $$I = 1, \ldots, h^{2,0}_{-}(C_4)$$.

Holomorphic variable $S$ gets modified

$$S \rightarrow S - \frac{1}{2} \Phi \frac{\Phi + \bar{\Phi}}{U + \bar{U}}.$$

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

For STU-model the Kähler potential reads

$$K = -3 \log(T + \bar{T}) - \log \left[ (S + \bar{S})(U + \bar{U}) - \frac{(\Phi + \bar{\Phi})^2}{2} \right]$$

$$- 2 \log(U + \bar{U}).$$
Tree-level moduli stabilization
Tree-level moduli stabilization

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

\[ W_o = \int_{\Gamma_5} \Omega_3 \wedge (i^* B + F) + \Delta W_o \]

Obstruction: Moving the D7-brane, the flux \((i^* B + F)\) 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)
A representative model
A representative model

Kähler potential is given by

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

Fluxes generate superpotential

\[ W = f_0 - h S - q T - \mu \Phi^2 , \]

with \( f_0, h, q \in \mathbb{Z} \).

1. In type IIB \( W = \int \iota^* B \wedge \Omega_3 \) is not quantized.

2. However, in the backreacted F-theory picture \( \mu \) is quantized.

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

Non-supersymmetric, tachyon-free minimum with

$$\tau_0 = \frac{6 f_0}{5 q}, \quad s_0 = \frac{f_0}{h}, \quad \theta_0 = \phi_0 = 0.$$  

with masses for the canonically normalized fields

$$M^2_{\text{closed}} \simeq \frac{h q^3}{f_0^2}$$

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

$$M^2_\varphi \simeq \frac{h q^3}{f_0^2}, \quad M^2_\theta \simeq \frac{\mu q^3}{f_0^2}$$

Open string axion $\theta$ is parametrically lighter

$$\frac{M_{\text{heavy}}}{M_\Theta} \sim \sqrt{\frac{h}{\mu}} = \lambda^{-1}.$$
Backreaction: small excursions
Backreaction of axion excursion

\[ s \sim \frac{(f_0 + \mu \theta^2)}{5h}, \quad \tau \sim \frac{6(f_0 + \mu \theta^2)}{5q} \]

with all other fields sitting in their minimum at zero.

Critical proper field distance:

\[ \Theta_c = \sqrt{\frac{h}{\mu}} = \frac{1}{\lambda}. \]

For \( \Theta_c \gg 1 \) and \( \Theta \ll \Theta_c \) the backreaction on the inflaton potential can be neglected.
Backreaction: large excursions
Backreaction: large excursions

Kinetic term for large field excursions

\[ \mathcal{L}_{\text{kin}}^{\text{ax}} = \frac{1}{2} h \left( \frac{\partial \theta}{\theta} \right)^2 \]

so that we get the logarithmic behavior

\[ \Theta = \Theta_c \log \left( \frac{\theta}{\theta_c} \right) \simeq \frac{1}{\lambda} \log \theta \simeq \frac{M_{\text{heavy}}}{M_\Theta} \log \theta \]

Backreacted scalar potential (after constant uplift):

\[ V_{\text{back}} \simeq |V_0| \left[ 1 - \exp \left( -4 \frac{\Theta}{\Theta_c} \right) \right] . \]

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

$$M_\text{pl} > M_s > M_{\text{KK}} > M_{\text{inf}} > M_{\text{mod}} > H_{\text{inf}} > M_\Theta$$

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:
  \[ M^2_s \sim \frac{1}{\tau^2 s^{1/2}} \sim \frac{h^{1/2} q^{3/2}}{f_0^2}. \]

- Kaluza-Klein scale:
  \[ M^2_{KK} \sim \frac{1}{\tau^2} \sim \frac{q^2}{f_0^2}. \]

- Recall moduli masses:
  \[ M^2_{\text{mod}} \sim \frac{h q^3}{f_0^2}, \quad M^2_{\Theta} \sim \frac{\mu q^3}{f_0^2}. \]
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:

\[ M_i^2 = M_i^2 |_0 \exp \left( -4 \frac{\Theta}{\Theta_c} \right), \]

where \( M_i^2 |_0 \) 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 EFT.
- This is all consistent with the Swampland Conjecture.

The question now is whether we also get constraints on the critical value \( \Theta_c \sim \lambda^{-1} \).
Constraint on $\Theta_c$
Constraint on $\Theta_c$

For this purpose, let us compute

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

This ratio is independent of $\Theta$ in the large field regime.

1. If we could tune $\Theta_c = \sqrt{h/\mu}$ small by choosing the open string flux $\mu$ small, there is no parametric problem with the mass hierarchies.

2. However, in the backreacted F-theory picture $\mu$ is quantized. Thus, for large $H$-flux $h$ (i.e. $\lambda \ll 1$) one finds $M_{mod} \gtrsim_p M_{KK}$, invalidating EFT.

For case 2. one has $\lambda \sim \Theta_c \approx O(1)$ (Refined Swampland Conjecture).
More models
More models

More examples have been checked with very similar results: (see talk by Florian Wolf)

- Closed and open string (toroidal-like) models with pure flux stabilization: $\lambda < 1$ implies $M_{\text{KK}} < M_{\text{mod}}$
- Kähler moduli stabilization via
  \[ \text{KKLT: } \mu < W_0 \quad \text{LVS: } \mu < \sqrt[6]{\mathcal{V}} \]
- Tuning effective $\mu_{\text{eff}}$ in the landscape:
  \[ W \sim (\mu_1 + \mu_2 U^2) \Phi^2 + \ldots, \Rightarrow \mu_{\text{eff}} \geq \frac{63}{64} \mu_1^2 \]

Running project:
- Numerical landscape analysis for axionic version of RSC
  (Bhg,Kläwer,Herschmann,Schlechter,Valenzuela,Wolf)
Summary

Invalidity of effective theory due to Swampland Conjecture

- sub-Planckian due to RSC
- Polynomial Inflation
- Starobinsky-like Inflation

Invalidity of effective theory due to Swampland Conjecture
Conclusions
Conclusions

Thus we conclude: all the failed attempts and the Refined Swampland Conjecture support the conjecture:

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