Quantum Gravity Constraints on Large Field Inflation

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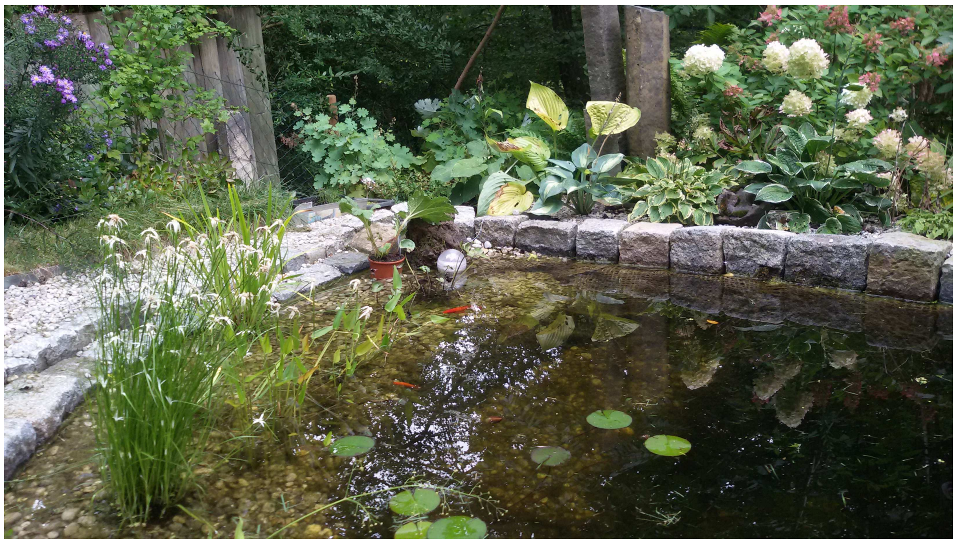

Bhg, Valenzuela, Wolf, arXiv:1703.05776

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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 $r > O(10^{-3})$.

Introduction

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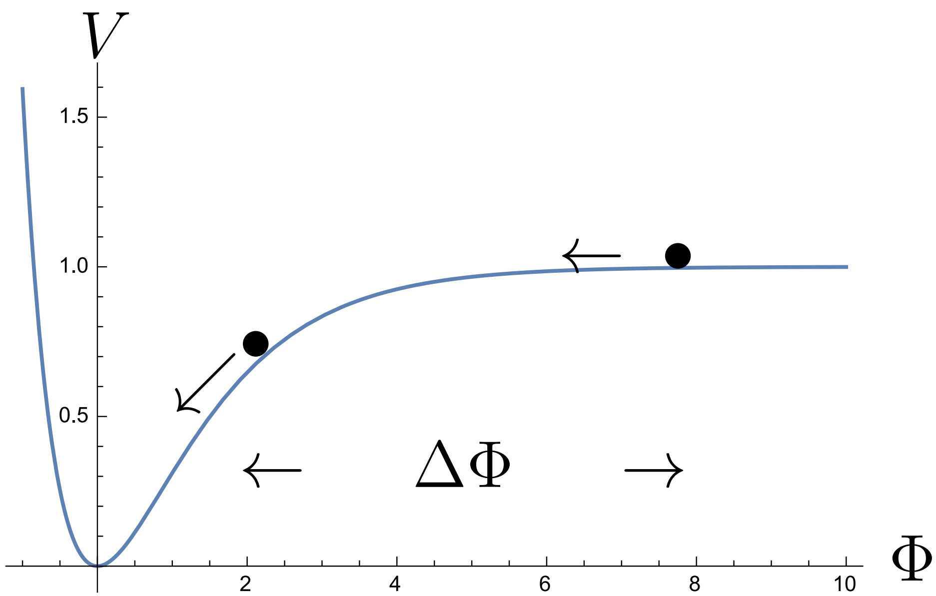
PLANCK 2015, BICEP2 results:

- upper bound: $r < 0.07$
- 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 $\mathcal{P} = (2.142 \pm 0.049) \cdot 10^{-9}$

Single field slow role inflation



Introduction

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If r is detected $\to$ large field inflation:
Lyth bound implies $\Delta\Phi > M_{\rm pl}$

$$\frac{\Delta\phi}{M_{\rm pl}} > O(1)\sqrt{\frac{r}{0.01}}$$

and

$$M_{\rm inf} = (V_{\rm inf})^{\frac{1}{4}} \sim \left(\frac{r}{0.1}\right)^{\frac{1}{4}} \times 1.8 \cdot 10^{16}\,\text{GeV}$$

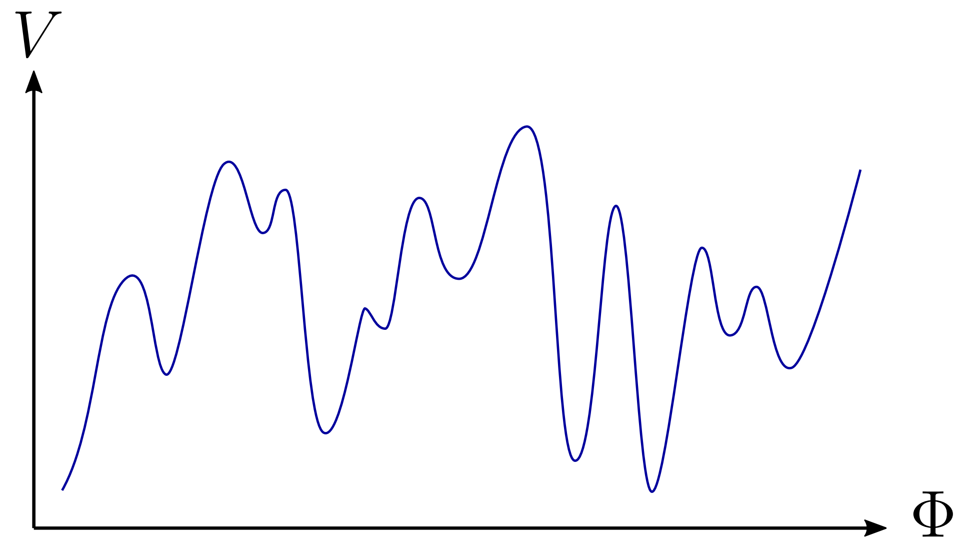
Inflationary mass scales:

- 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

UV sensitivity

UV sensitivity

Quantum gravity generates Planck suppressed operators of the form $(\Phi/M_{\rm pl})^n$



Impossible to control flatness over a large region in field space.

- 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 $f \cdot S_\mathrm{E} < 1$.

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

Natural inflation

Natural inflation

Shift symmetry $\theta \to \theta + c$ is broken via a non-perturbative effect $V(\theta) = Ae^{-S_{\rm inst}}(1 - \cos(\theta/f))$.

Weak gravity conjecture: gravity is the weakest force, i.e. for a U(1) gauge theory $m \leq q$ (Arkani-Hamad,Motl,Nicolis,Vafa)

- strong version: the lightest particle must satisfy this
- weak version: this holds for some particle

Claim: Any consistent theory of quantum gravity must satisfy the WGC.

Via T-duality is has been argued that there should exist such a relation for any p-form gauge field.

Natural inflation

Natural inflation

For a 0-form

$$m \to S_{\text{inst}} \qquad q \to 1/f$$

so that

$$f S_{\text{inst}} \leq 1 \,.$$

Large field inflation requires $\theta > 1 \Rightarrow f > 1 \Rightarrow S_{\text{inst}} < 1$.

However, this spoils the instanton expansion, as higher order terms cannot be neglected, i.e. large field regime $\theta > 1$ is not controlled.

More refined but similar arguments have been applied to aligned inflation.

Axion monodromy

Axion monodromy

A second mechanism to generate a potential for axions: axion monodromy

Field theory: Axion ϕ and a four-form field strength $F_4 = dC_3$ and a Lagrangian (Dvali), (Kaloper, Sorbo)

$$\mathcal{L} = -f^2 d\phi \wedge \star d\phi - F_4 \wedge \star F_4 + 2F_4(m\phi + f_0)$$

Equation of motion for C_3

$$d \star F_4 = d(m\phi + f_0) \quad \Rightarrow \quad \star F_4 = f_0 + m\phi$$

where f_0 can be considered as background value of the flux.

Scalar potential

$$V = (f_0 + m\phi)^2$$

Axion monodromy

Axion monodromy

The scalar potential and F_4 is invariant under the extended shift symmetry

$$\phi \to \phi - c/m \qquad f_0 \to f_0 + c$$

- The system still preserves the shift symmetry, that is broken spontaneously by a choice of branch f_0
- This shift symmetry and the gauge symmetry of C_3 highly constrains higher order corrections: they must be functions of F_4, i.e.

$$\delta V \sim \sum (F_4)^{2n} \sim \sum (V_0)^n$$

Even for $\delta\phi \gg 1$, as long as $\delta V \ll 1$ one controls the expansion.

Axion monodromy for Strings

Axion monodromy for Strings

- Monodromy inflation: Shift symmetry is broken by branes unwrapping the compact axion. (Silverstein,Westphal)

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 axions arise from the R-R field strengths $F_{p+1} = dC_p + H \wedge C_{p-2}$ involving the gauge potentials C_{p-2} explicitly.

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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

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

Why?

Swampland Conjecture

Swampland Conjecture

Proposal: axionic version of the swampland conjecture

(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

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

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

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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

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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 $\rightarrow V_{\text{eff}}(\theta)$, potentially supporting large field inflation.

SC and large field inflation

SC and large field inflation

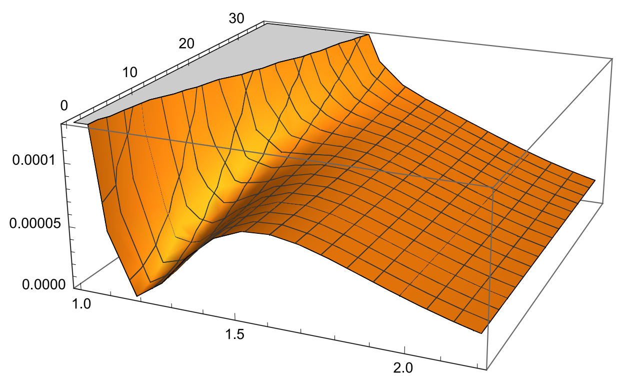
However, this picture is too naive, as: (Baume,Palti) (Bhg,Font,...).

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

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

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

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



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- What is the value of Θ_c?

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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)

Objectives

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(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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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

Mass scales: large field

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To relate to the Swampland Conjecture, we evaluated 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 and $\Theta_c \sim \sqrt{h/\mu}$ flux ratio.

- 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 $\Theta_{\rm c} \sim \lambda^{-1}$.

Constraint on Θ_c

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For this purpose, we computed

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

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

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

More models

More models

A couple of examples have been checked with very similar results:

- Closed and open string (toroidal-like) models with pure flux stabilization: $\Theta_c > 1$ implies $M_{\rm KK} < M_{\rm mod}$
- Kähler moduli stabilization via

$$\mathbf{KKLT}: \quad \mu < W_0 \qquad \mathbf{LVS}: \quad \mu < \mathcal{V}^{-\frac{1}{6}}$$

- Tuning effective $\mu_{\rm eff}$ in the landscape:

$$W \sim (\mu_1 + \mu_2 U^2)\Phi^2 + \ldots, \Rightarrow \mu_{\rm eff} \geq \frac{63}{64}\mu_1^2$$

- All this supports the refined SC

Summary

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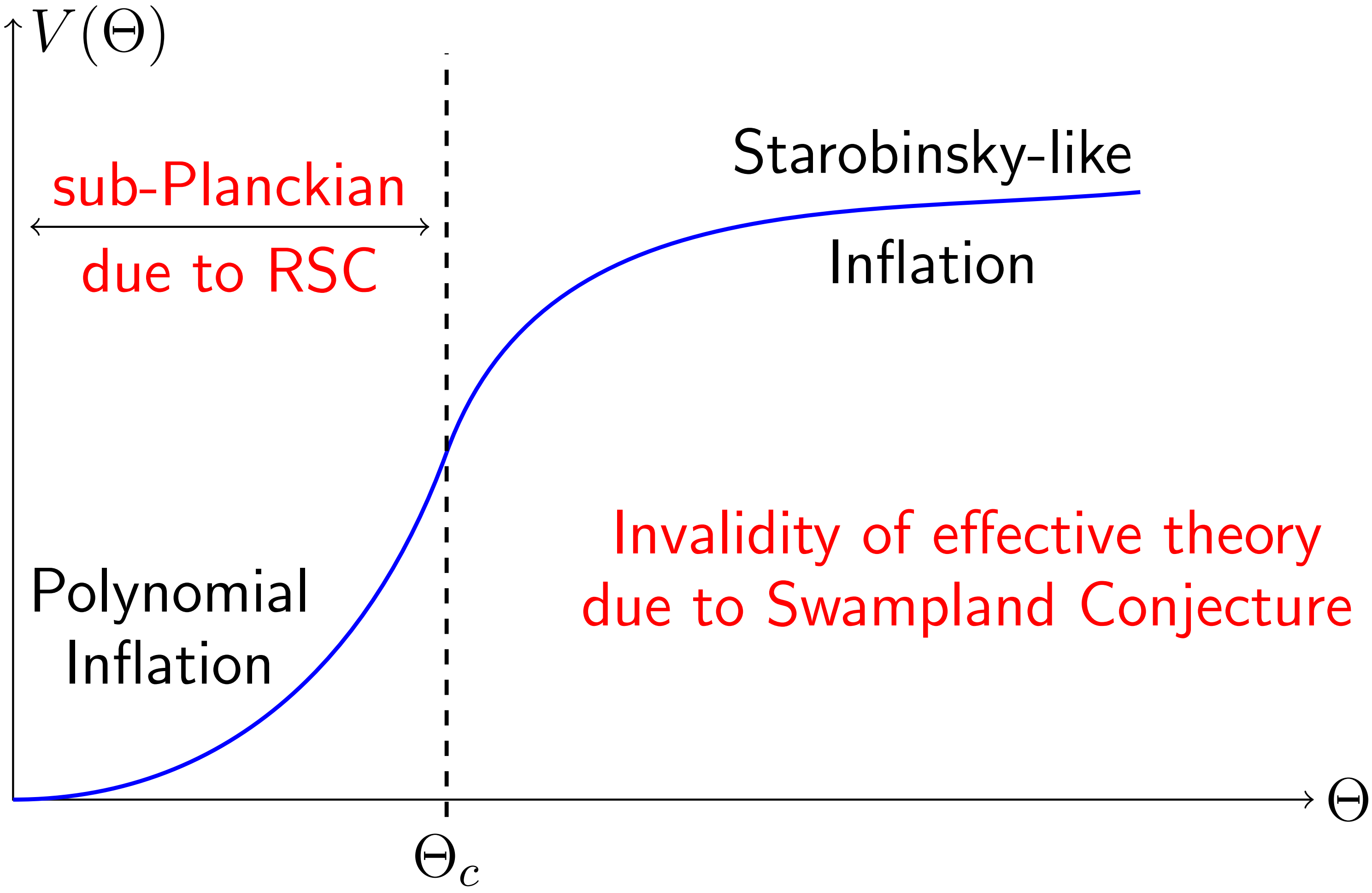

$V(\Theta)$
sub-Planckian
due to RSC
Starobinsky-like
Inflation
Invalidity of effective theory
due to Swampland Conjecture
Polynomial
Inflation
Θ
Θ_c

Conclusions

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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 $r \lessapprox 10^{-3}$.

Thank You!