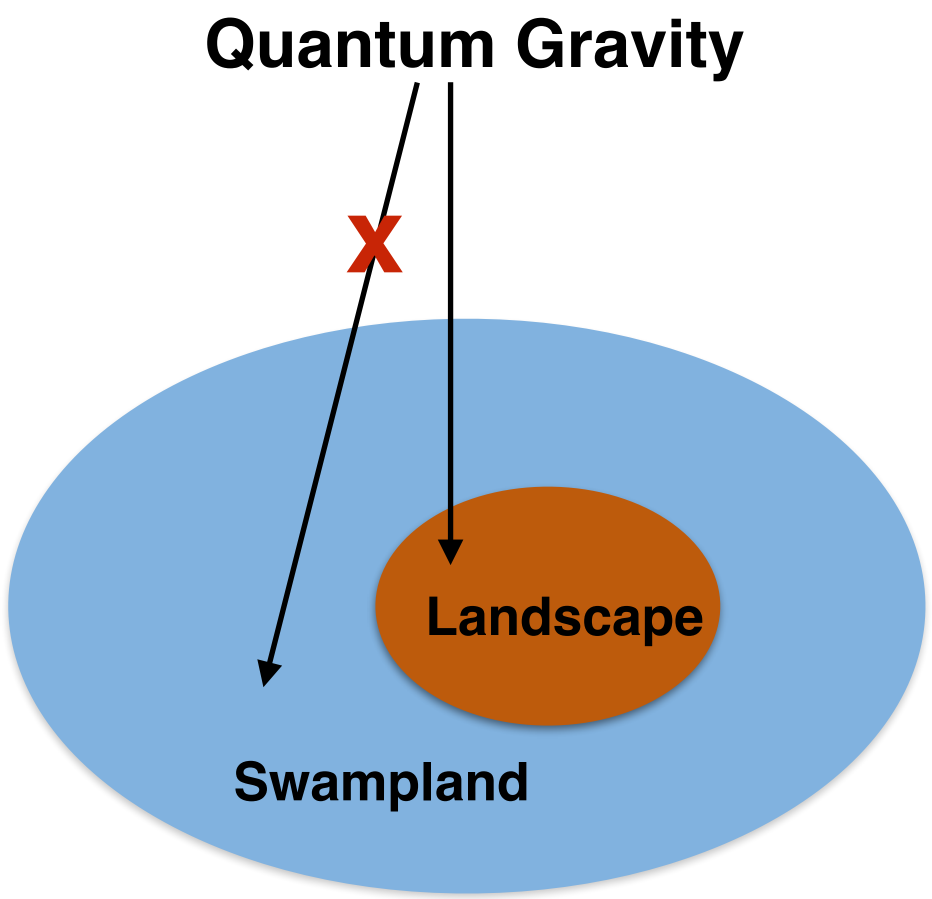
Conjectures from Quantum Gravity

- Exploring the Landscape inside the Swampland -

Florian Wolf

Young Scientists Workshop at Castle Ringberg on July 19, 2017

Swampland vs. Landscape



High energy, more dimensions,
e.g. String Theory

Consistent 4 dim
low energy effective
theory

[Vafa '04]

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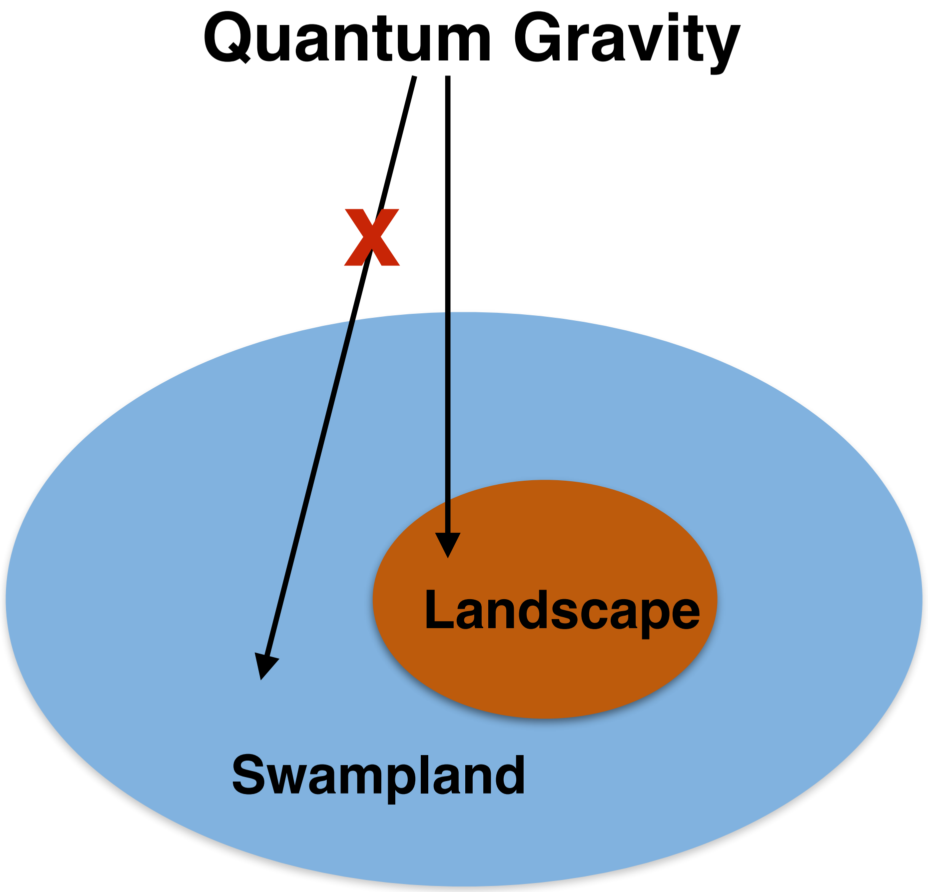

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What should 4 dim EFT look like if and only if it arises from Quantum Gravity?

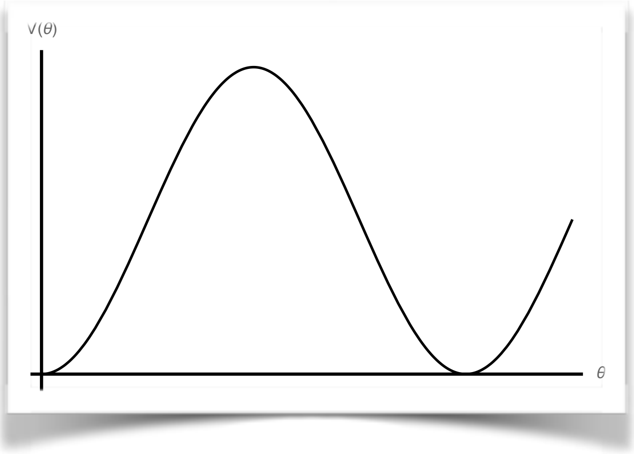
There are (so far) two conjectures deciding between landscape and swampland.

Application to Stringy Large-Field Inflation

Inflaton = axionic modulus from String Theoy

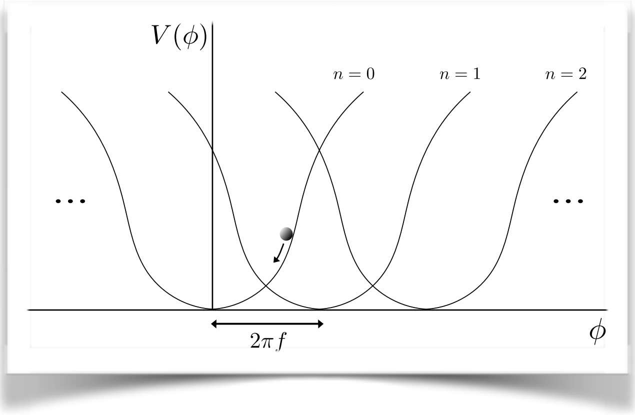
Periodic potential

Trans-planckian axion decay constant: $f > 1 M_{\rm Pl}$



Polynomial potential

Trans-planckian field movement: $\Delta\phi > 1 M_{\rm Pl}$



What are axions?

- ⟶ Scalars equipped with discrete shift symmetry $\phi \to \phi + 2\pi f$
- ⟶ Some moduli of String Theory are axions

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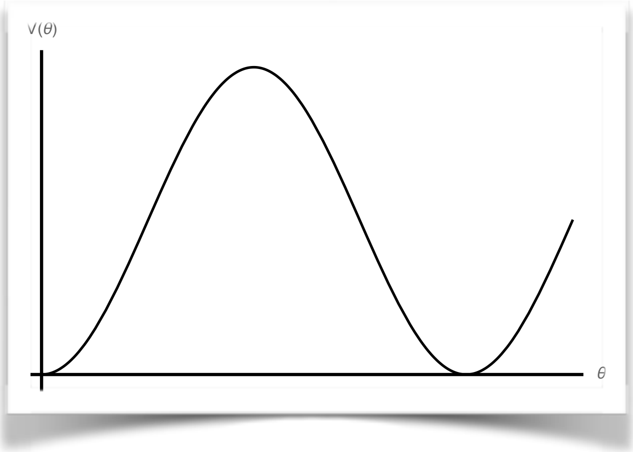

Constraints from Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa, …many more]

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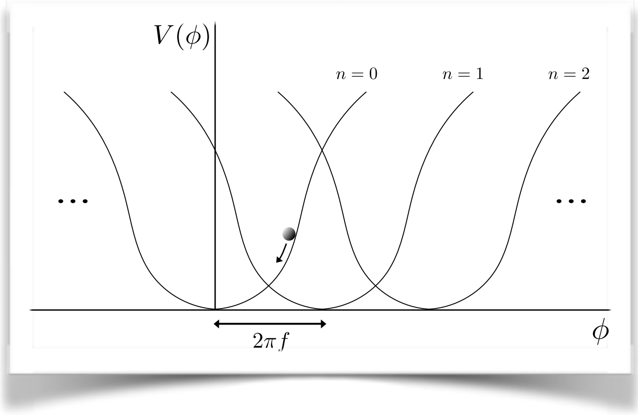

Constraints from Swampland Conjecture

[Vafa, Ooguri, Palti, Baume, Kläwer, Blumenhagen, Valenzuela, FW]

What are axions?

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Outline

✓ 1. Introduction

2. Weak Gravity Conjecture
    - Electric and Magnetic Versions
    - Application to Periodic Inflation

3. Swampland Conjecture
    - Extension to Axions via Backreaction
    - Critical Distance and Polynomial Inflation

4. Conclusion

The Weak Gravity Conjecture (WGC)

A simple observation of our world (and all consistent string compactifications):

Gravity is the weakest force

→ Promote to general principle

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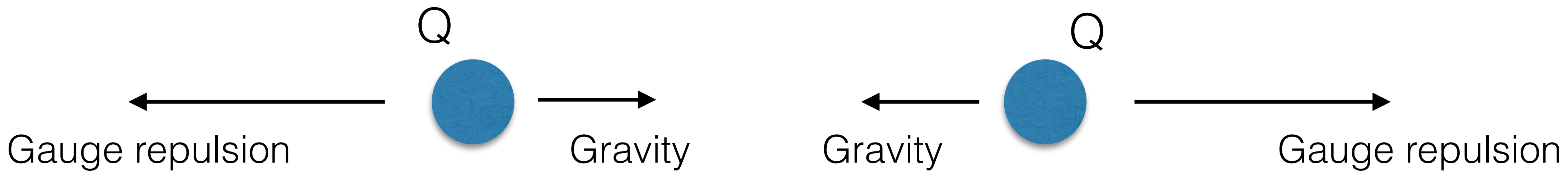
Consider 4 dim theory with gravity and U(1) gauge field with coupling g_{el}:

Electric WGC: There must exist a light charged particle Q with

[Arkani-Hamed, Motl, Nicolis, Vafa '06]

$$\boxed{m_{\mathrm{el}} \leq g_{\mathrm{el}} M_{\mathrm{Pl}}}$$



Magnetic Weak Gravity Conjecture

WGC formula should also hold for magnetic monopoles.

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What are magnetic monopoles?

Motivated by electric-magnetic symmetry of Maxwell's Eq.,

Dirac studied particles with net magnetic charge g_{mag}

Dirac quantisation condition: $g_{\mathrm{el}} \cdot g_{\mathrm{mag}} \in \mathbb{Z}$

Magnetic Weak Gravity Conjecture

WGC formula should also hold for magnetic monopoles.

$$m_{\mathrm{mag}} \leq g_{\mathrm{mag}} M_{\mathrm{Pl}}$$

EFT has cutoff Λ

$$m_{\mathrm{mag}} \sim g_{\mathrm{mag}}^2 \Lambda$$

From Dirac's quantisation condition

$$g_{\mathrm{mag}} \sim \frac{1}{g_{\mathrm{el}}}$$

Magnetic WGC:

$$\boxed{\Lambda \leq g_{\mathrm{el}} M_{\mathrm{Pl}}}$$

→ For small gauge coupling EFT breaks down at low scale!

→ Unexpected from 4 dim EFT point of view

WGC for Axions and Inflation

Generalising WGC to p-form gauge fields in arbitrary dimensions leads to axion version

$$\begin{tikzcd}
 & m_{\rm ax} \leq g_{\rm ax} M_{\rm Pl} \arrow[dl] \arrow[dr] & \\
m_{\rm ax} \sim \mathcal{S}_{\rm inst} & & g_{\rm ax} \sim \frac{1}{f}
\end{tikzcd}$$

Axion coupled to instanton with action $\mathcal{S}_{\rm inst}$

Axion decay constant f

Axionic WGC:

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Consequence for inflation:

- → instanton generates dangerous terms in inflaton potential: $V(\theta) \sim e^{-S_{\rm inst}} \cos\left(\frac{\theta}{f}\right) + \ldots$
- → Flat potential for slow-roll inflation requires: $\mathcal{S}_{\rm inst} > 1$

WGC implies: no trans-planckian axion decay constants

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No periodic inflation ↯

WGC implies: no trans-planckian axion decay constants

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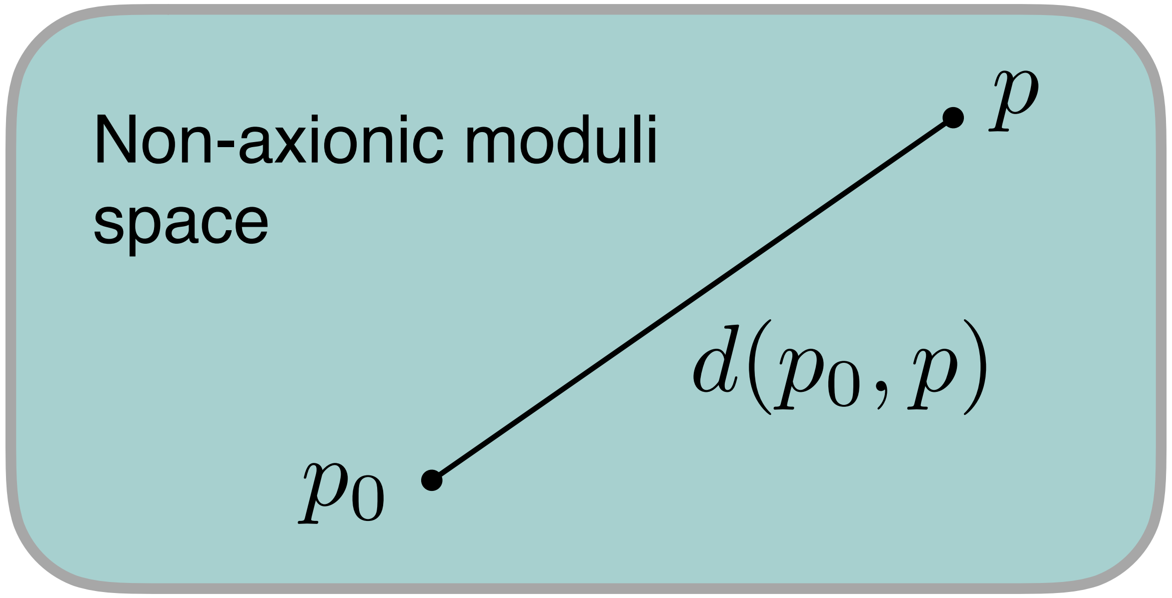
The Swampland Conjecture

Moduli = free parameter emerging during compactification



For $d(p_0,p) \to \infty$ an infinite tower of massive states becomes exponentially light: [Ooguri, Vafa '04]

$$\boxed{M \sim M_0\, e^{-\,\alpha\, d(p_0,p)}}$$

for theories in the landscape

→ Parameter α a priori undetermined

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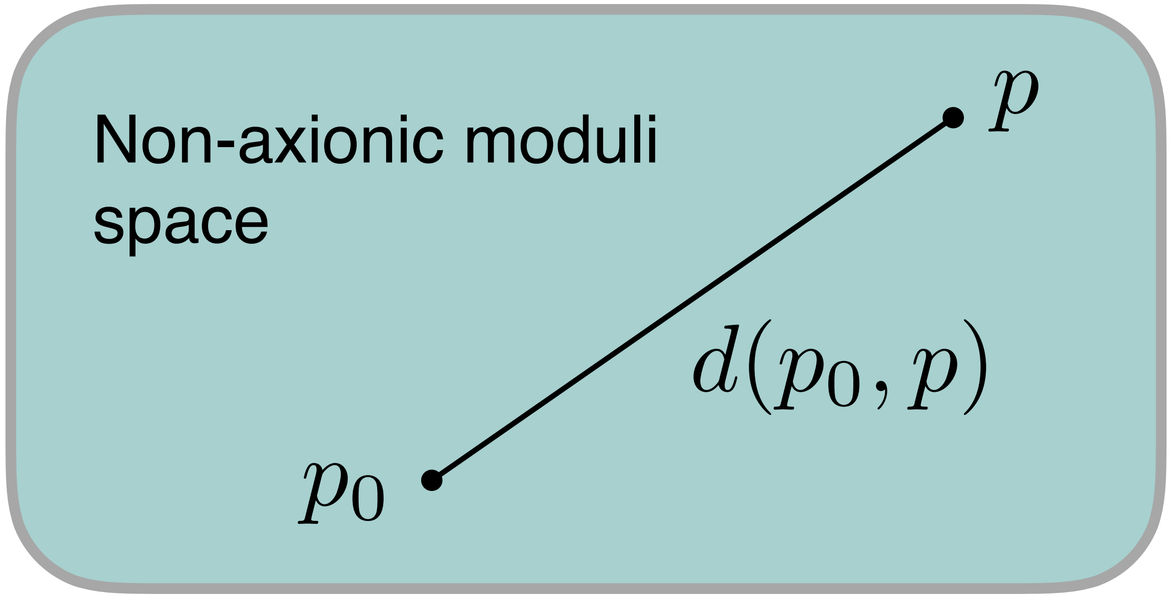

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Consequence:

EFT invalid if traversing distance $d(p_0, p) > \dfrac{1}{\alpha}$ ***in non-axionic moduli space!***

Extension to axions via Backreaction I

Generate a potential for moduli (s, θ) by turning on background fluxes.
Move one axionic modulus θ - called inflaton - from minimum.

Backreaction:

other moduli vev s_{Min} adjust according to inflaton movement.

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Kinetic term for axion derived from String Theory:

$$\mathcal{L}^{\theta}_{\text{kin}} \sim \frac{1}{s^2_{\text{Min}}}\,(\partial\theta)^2$$

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Extension to axions via Backreaction II

Canonical normalisation: $$\mathcal{L}^{\theta}_{\text{kin}} \sim \frac{1}{2}\left(\partial\Theta\right)^2$$

implies $$\boxed{\Theta \sim \exp(\lambda\theta)}$$

Extension to axions via Backreaction II

Canonical normalisation: $$\mathcal{L}^{\theta}_{\text{kin}} \sim \frac{1}{2} (\partial\Theta)^2$$

implies $$\boxed{\Theta \sim \exp(\lambda\theta)}$$

Consequence:

Some heavy modes (e.g. KK- or string modes) which have been integrated out in EFT, become light:

$$M_{\text{heavy}} \sim \frac{1}{s_{\text{Min}}(\theta)} \xrightarrow[\text{backreaction}]{\text{Strong}} \frac{1}{\theta} \sim e^{-\lambda\Theta}$$

→ EFT invalid above critical distance $\Theta_c \sim \frac{1}{\lambda}$

→ ***Swampland Conjecture for axions*** [Palti, Baume/Kläwer '16]

What is the Critical Field Range?
- An Illustrative Model -

Model on isotropic 6-torus with one D7-brane position modulus.

[Blumenhagen, Valenzuela, FW]

Superpotential:

$$W = \mathfrak{f}_0 + 3\mathfrak{f}_2\, \underset{\substack{\uparrow \\ \text{complex structure}}}{U}{}^2 - h\, \underset{\substack{\uparrow \\ \text{axio-dilaton}}}{S}\, U - q\, \underset{\substack{\uparrow \\ \text{Kähler}}}{T}\, U - \mu\, \underset{\substack{\uparrow \\ \text{open string modulus}}}{\Phi}{}^2$$

with quantised fluxes $\mathfrak{f}, \mathfrak{f}_2, h, q, \mu$

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Kähler potential:

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

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Compute the F-term scalar potential for moduli:

$$V_F = \frac{M_{\rm Pl}^4}{4\pi}\, e^K \left(K^{I\overline{J}} D_I W D_{\overline{J}} \overline{W} - 3\left|W\right|^2 \right)$$

What is the Critical Field Range?
- Refined Swampland Conjecture -

Moduli are stabilised at non-susy AdS minimum of the scalar potential with tuneable light axion.

Mass hierarchy reveals contradiction for quantised flux parameters:

$$\Theta_c \sim \frac{M_{\mathrm{mod}}}{M_{\Theta}} \sim \sqrt{\frac{h}{\mu}} \qquad \overset{\text{⚡}}{\longleftrightarrow} \qquad \frac{M^2_{\mathrm{KK,light}}}{M^2_{\mathrm{mod}}} \sim \frac{1}{h\,q}$$

with inflaton mass M_{Θ} and average mass of other moduli M_{mod} and light Kaluza-Klein modes $M_{\mathrm{KK,light}}$

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$\longrightarrow$ ***in agreement with Refined Swampland Conjecture*** $\Theta_c \sim \mathcal{O}(1)$

[Palti, Kläwer '16]

No polynomial large-field inflation ↯

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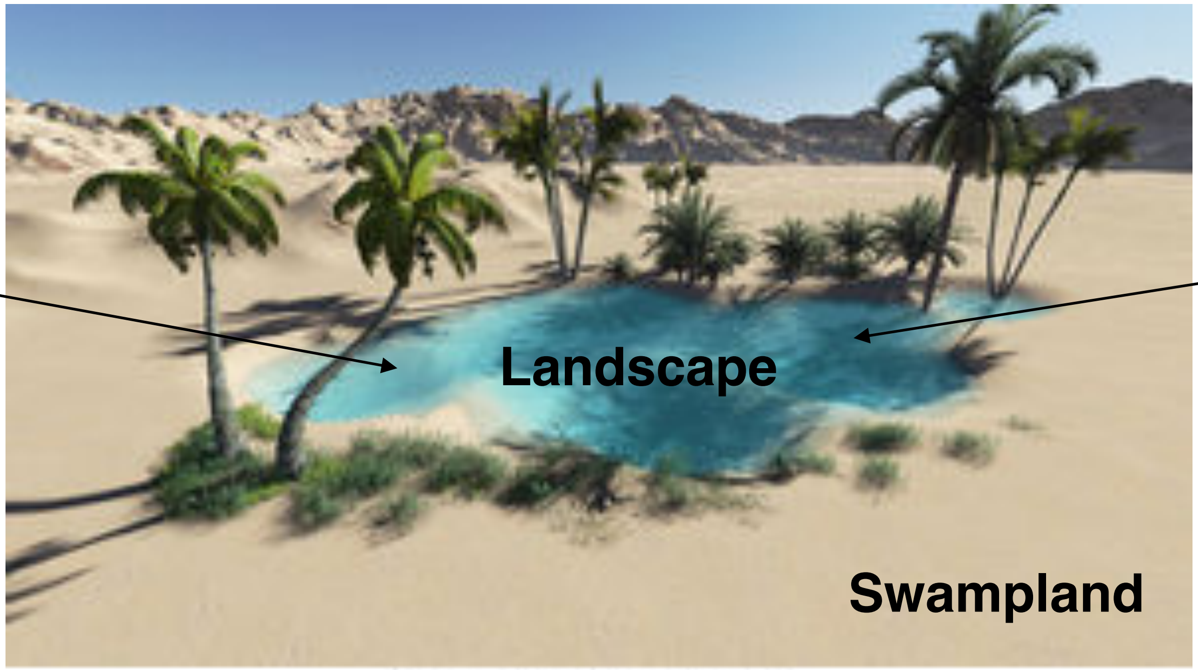

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→ Strong constraints on possible models on large-field inflation in String Theory

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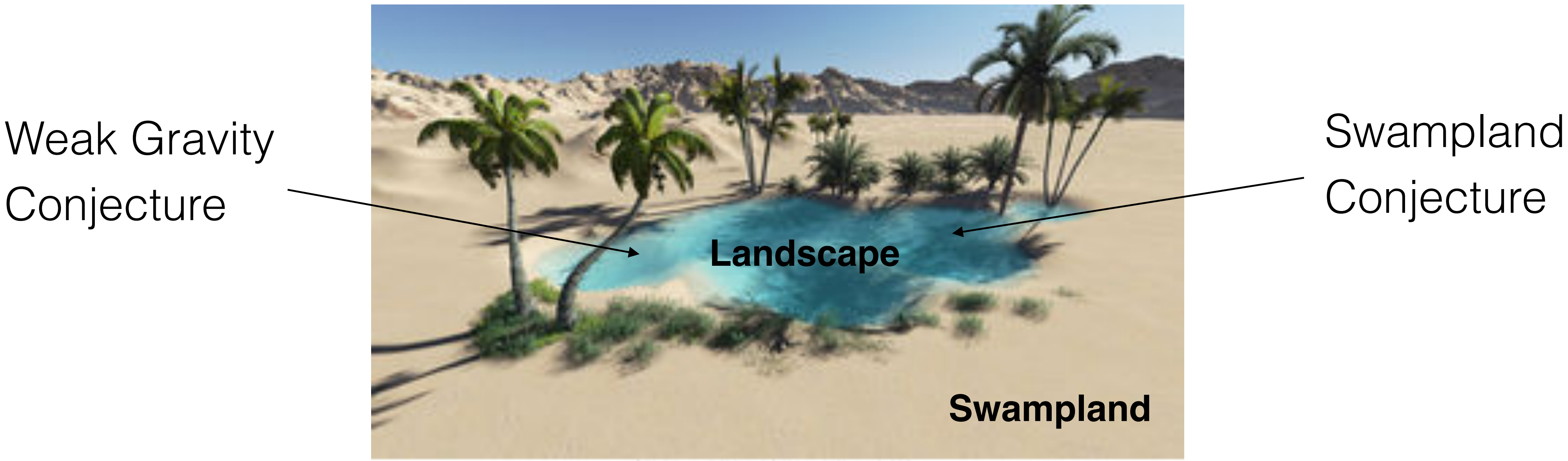

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Outlook:

- Proof of conjectures
- Can one rule out large-field inflation in String Theory?
- Multi-axion scenario

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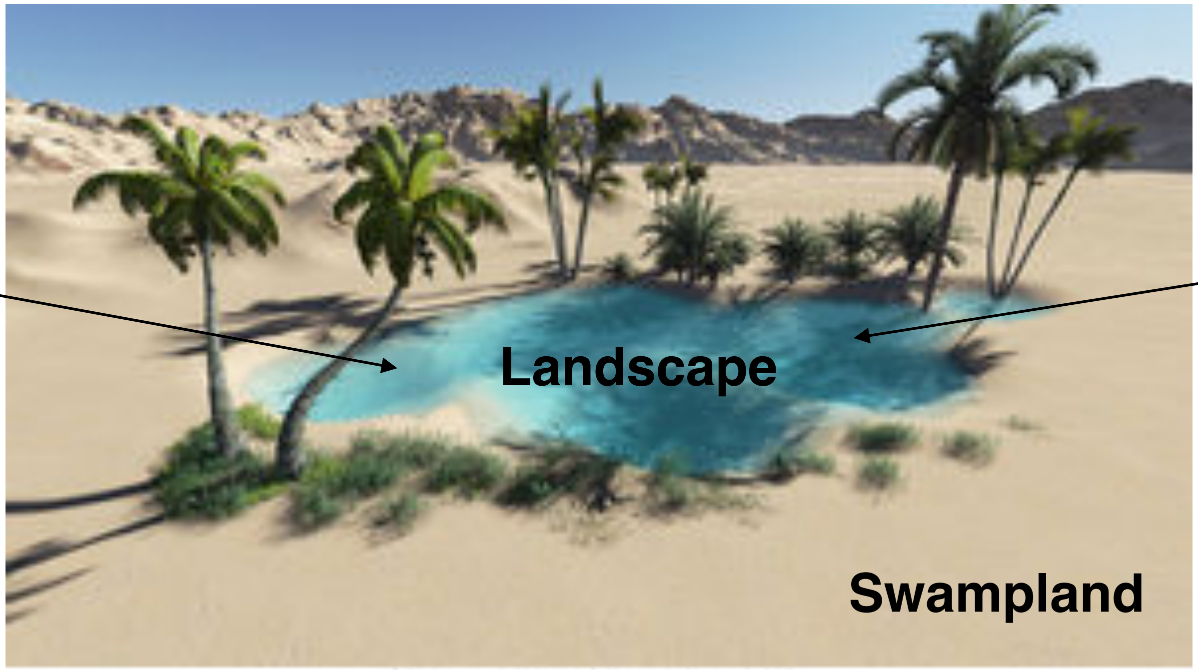

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Thank you!