On Swampland Conjectures in String Theory

Ralph Blumenhagen

Max-Planck-Institut für Physik, München

The swampland idea

The swampland idea

Can one characterize the features of the effective action that can or cannot be realized in string theory?

Problem: String theory as we understand it is a background dependent formulation of quantum gravity and can therefore be studied case by case $\rightarrow$ lamppost problem

By now we have a couple of swampland conjectures: Weak gravity, Swampland distance- , dS swampland-conjecture (etc) with evidence mostly from perturbative string vacua.

(Arkani-Hamed,Motl,Nicolis,Vafa),(Ooguri,Vafa),(Obied,Ooguri,Spodyneiko,Vafa),...

- A: Do they also hold in non-perturbative regimes?
- B: What are the consequences, if they are true?
- C: Can one circumvent their no-go consequences?

Introduction

Introduction

Prototype examples:

- Weak gravity conjecture $\rightarrow$ constraints for instanton generated axion inflation (Arkani-Hamed,Motl,Nicolis,Vafa, 2007)
- Swampland distance conjecture $\rightarrow$ constraints for axion monodromy inflation (Ooguri,Vafa, 2006)
- dS swampland conjecture, $|\nabla V| \geq cV$, $\rightarrow$ no dS minima, lower bound for slow-role parameter $\epsilon \gtrsim c^2$ (Obied,Ooguri,Spodyneiko,Vafa, 2018), (Dvali,Gomez, 2014)

Hot topic in string theory research during the last 2 years

"The Swampland: Introduction and Review" (Palti,arXiv:1903.06239)

Weak gravity conjecture

Weak gravity conjecture

The weak gravity conjecture claims that gravity is the weakest force. For Einstein-Maxwell theory this means there must exist a particle with

$$m \leq g\, q\, M_{\rm pl}$$

Electromagnetic repulsion is larger than gravitational attraction.

- Guarantees that any extremal BH with $M = Q$ can decay
- Satisfied for states in heterotic string theory
- Magnetic version: $\Lambda < g M_{\rm pl}$ implies that the $g \to 0$ limit is dramatic (no global symmetries in QG)

Instantons and the WGC

Instantons and the WGC

Via T-duality there should exist such a relation for any p-form gauge field. For a 0-form

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

so that

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

Large field inflation with axion potential

$$V(\theta) = Ae^{-S_{\rm inst}}(1 - \cos(\theta/f))$$

requires $\theta > 1 \Rightarrow f > 1 \Rightarrow S_{\rm inst} < 1$. However, this spoils the instanton expansion, as higher order terms cannot be neglected, i.e. large field regime $\theta > 1$ is not controlled.

Generalizations of WGC

Generalizations of WGC

Note: Quintessence requires $f \sim 1$, but $\exp(-S_{\text{inst}}) \sim 10^{-120}$
$\Rightarrow$ saxions as quintessence fields with potential

$$V(\phi) = V_0 \exp(-\lambda\phi) \,.$$

Problems: Time-varying coupling constants, fifth force

Generalizations of WGC:

- Generalization to theories also containing scalars (mediating interactions). (Palti, 2017), (Lüst, Palti, 2017)
- Generalization to theories with massive spin-2 particles (Lüst, Kläwer, Palti, 2018) **(talk by D. Lüst)**

Swampland Distance Conjecture

Swampland Distance Conjecture

Behavior of any QG/stringy effective action for large field excursions: Swampland distance conjecture (Ooguri,Vafa, 2006)

Intuition: Consider gravity compactified on a circle.

- Dimensional reduction of Einstein-gravity with the metric

$$G_{MN}dX^M dX^N = g_{\mu\nu}(x)dx^\mu dx^\nu + R(x)^2 dy^2$$

leads to an effective action for the field $R(x)$

$$S = \int d^4x \sqrt{g}\, \frac{1}{(\lambda R)^2}\, \partial_\mu R\, \partial^\mu R$$

Swampland Distance Conjecture

Swampland Distance Conjecture

- Canonically normalized field scales like

$$\Theta = \lambda^{-1} \log R$$

- Mass of Kaluza-Klein modes

$$M_{\mathrm{KK}} \sim \frac{n}{R} \sim n\, e^{-\lambda\Theta}$$

For $\Theta > \Theta_c = \lambda^{-1}$ a tower of states becomes exponentially light $\to$ breakdown of effective action

Ooguri/Vafa proposed that this behavior is a general property of any effective theory derived from string theory (quantum gravity).

Swampland Distance Conjecture

Swampland Distance Conjecture

Approaching points at infinite distance $\Theta \to \infty$ in the moduli space of an effective field theory, a tower of states becomes exponentially light

$$M_n \sim n\, e^{-\lambda\Theta}\,.$$

leading to a breakdown of effective action for $\Theta > \Theta_c$.

What is the scale Θ_c?

- Refinement: $\Theta_c = O(M_{\rm pl})$ (Kläwer,Palti, 2016)
- Tests of this conjecture for moduli space of Calabi-Yau compactifications (Blumenhagen,Kläwer,Schlechter,Wolf, 2018), (Joshi,Klemm, 2019), (Erkinger,Knapp, 2019)
- Consequences for inflation (Baume,Palti, 2016), (Blumenhagen,Valenzuela, Wolf, 2017)

Emergence proposal

Emergence proposal

Emergence proposal: (Grimm,Palti,Valenzuela, 2018)
(Heidenreich,Reece,Rudelius, 2018)

- The infinite distance in the IR appears from integrating out the tower of light states in the UV.

Light field ϕ and a tower of massive states h_n with mass $m_n = n\Delta m(\phi)$ governed by an effective action

$$S = M_{\rm pl}^2 \int d^4x \left(\frac{1}{2} g_{\phi\phi} \partial_\mu \phi \partial^\mu \phi + \sum_n \frac{1}{2} \partial_\mu h_n \partial^\mu h_n + \frac{1}{2} m_n^2(\phi) h_n^2 \right)$$

Cut-off is the species scale

$$\tilde{\Lambda}_{\rm sp} = \frac{M_{\rm pl}}{\sqrt{N_{\rm sp}}}$$

where $N_{\rm sp} = \tilde{\Lambda}_{\rm sp}/\Delta m(\phi)$.

Emergence proposal

Emergence proposal

Can be solved as

$$\tilde{\Lambda}_{\rm sp} = \Big(M_{\rm pl}^2\, \Delta m(\phi)\Big)^{\frac{1}{3}}\,, \qquad N_{\rm sp} = \left(\frac{M_{\rm pl}}{\Delta m(\phi)}\right)^{\frac{2}{3}}\,.$$

These light states below the cut-off correct $g_{\phi\phi}$ as

$$g_{\phi\phi}^{1-{\rm loop}} \sim M_{\rm pl}^{-2} \sum_{n=1}^{N_{\rm sp}} \Big(\partial_\phi m_n(\phi)\Big)^2 = M_{\rm pl}^{-2}\Big(\partial_\phi \Delta m(\phi)\Big)^2 \sum_{n=1}^{N_{\rm sp}} n^2$$

$$= \frac{N_{\rm sp}^3}{M_{\rm pl}^2}\Big(\partial_\phi \Delta m(\phi)\Big)^2 = \left(\frac{\partial_\phi \Delta m(\phi)}{\Delta m(\phi)}\right)^2\,.$$

Emergence of the typical log-behavior of the proper field distance

$$d(\phi_0,\phi_1) \sim \int_{\phi_0}^{\phi_1} d\phi\, \sqrt{g_{\phi\phi}} \sim \log\left(\frac{\Delta m(\phi_1)}{\Delta m(\phi_0)}\right)\,.$$

Maybe most surprising conjecture: related to dS vacua:


SPIEGEL ONLINE SPIEGEL+

Verdacht eines Physikers

Ist es möglich, dass es unser Universum gar nicht gibt?

SPIEGEL+ Exklusiv für Abonnenten

Ein hochgeachteter Physiker der Harvard-Universität äußert eine verwegene Hypothese - und erschüttert damit die Fachwelt. *Von Johann Grolle*

31. August 2018

Recall: de Sitter vacua

Recall: de Sitter vacua

- Generic flux compactifications gives AdS or Minkowski minima
- Constructions of de Sitter vacua rely on the existence of an uplift mechanisms
- Like in KKLT this is often an anti $D3$-brane in a warped throat (needs a tiny warp factor to tune Λ positive and small)

Arguments why this procedure might not be controllable have been given in the past

- Stability of $\overline{D}3$-brane in the warped throat (Bena,Grana,Halmagyi,2009)
- 10D compatibility starting with (Moritz,Retolalza,Westphal,2017)

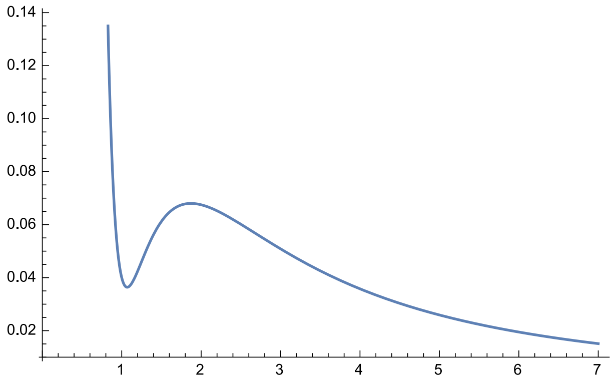
dS swampland conjecture

dS swampland conjecture

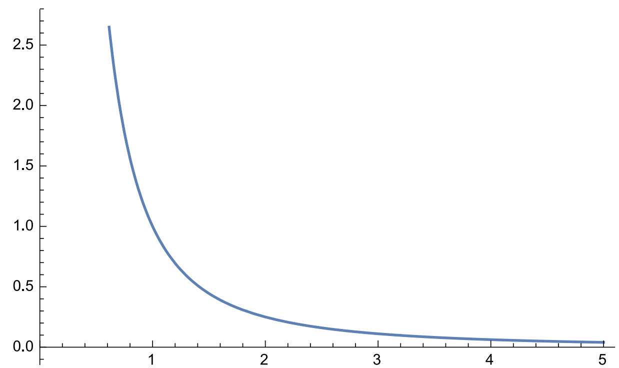
Refined version: The scalar potential in string theory satisfies either of the two properties

$$|\nabla V| \geq \frac{c}{M_{\rm pl}} \cdot V \qquad \text{or} \qquad \min(\nabla^2 V) \leq -\frac{c'}{M_{\rm pl}^2} \cdot V$$

forbidding de Sitter minima (Ooguri, Palti, Shiu, Vafa, 2019).



forbidden
(dS vacuum)



allowed
(quintessence)

Revisite KKLT

Revisite KKLT

Reanalyzed the KKLT scenario (Bhg,Kläwer,Schlechter,1902.07724) (based on (Bena,Dudas,Grana,S.Lüst,1809.06861)):

- For the uplift one has to invoke an effective action that is valid in the strongly warped regime.
- Such throats appear in CY moduli space close to a conifold singularity
- Is this action for the conifold modulus Z really under control?

Solving the six-dimensional warped Laplace equation

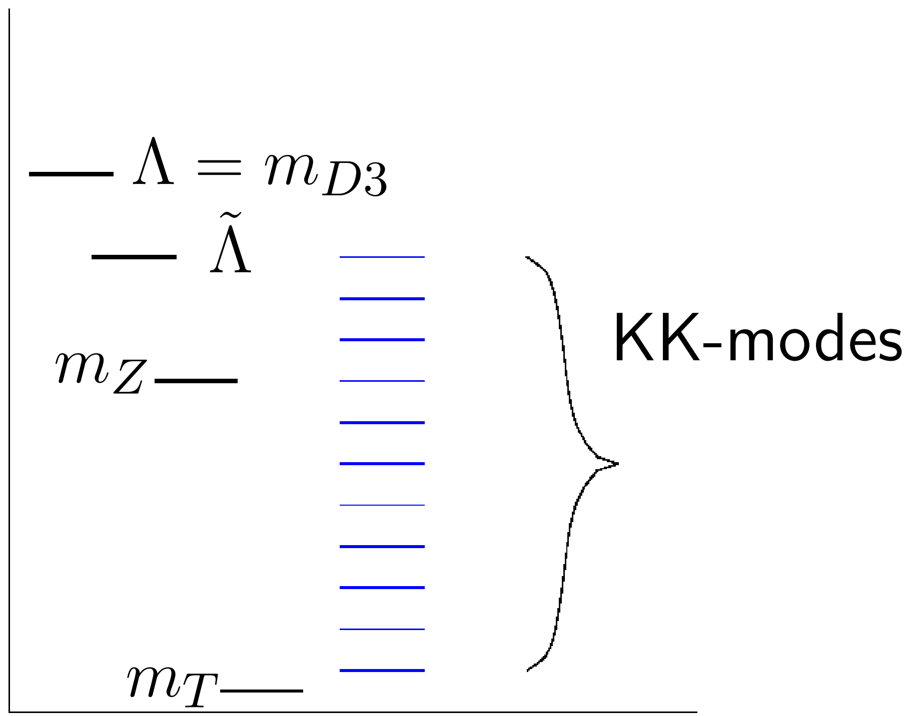
$$e^{4A(y)}\nabla^m\nabla_m\chi(y) - m^2\, e^{2A(y)}\chi(y) = -m^2_{\rm KK}\,\chi(y)\,.$$

we showed that there are light KK modes with mass $m_{\rm KK} \sim m_Z$.

Mass scales

Mass scales

The mass scales for the effective theory of the warped throat



- Finite number of KK modes lighter than the cut-off! EFT is not in the controlled regime.
- Existence of these KK modes is consistent with the emergence proposal.

Quintessence as a prediction(?)

Quintessence as a prediction(?)

Idea: Employ slow-rolling mechanism to explain dark energy.

- The mass scales of quintessence are very tiny
- The Hubble parameter today and the CC are

$$H \sim 10^{-33}\,\mathrm{eV}, \quad V_{\mathrm{quint}} = 10^{-120}\,M_{\mathrm{pl}}^4 \sim \left(10^{-3}\,\mathrm{eV}\right)^4.$$

- Equation of state $p = w\rho$ with $w = -1.006 \pm 0.045$ (Planck satellite). For slow-rolling

$$w \sim \frac{\varepsilon/3 - 1}{\varepsilon/3 + 1}, \qquad \varepsilon = \frac{M_{\mathrm{pl}}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,.$$

- For potential $V(\phi) = V_0 \exp(-\lambda\phi)$ one gets: $0.36 \gtrsim \lambda > c$ (and $m_\phi \sim H$), still compatible with experiments

Consequences of swampl. conject.

Consequences of swampl. conject.

Philosophy: Reveal interrelations among swampland conjectures to find further support or contradictions (similar to string dualities in the 1990ties).

In string theory there exist stable non-BPS branes

- Such branes can be part of the background. How do they effect minima of the potential?
- Old question: Must the K-theory charge be cancelled on a compact space? (Yes, as otherwise theories on probe-branes are inconsistent (Uranga,0011048))

It is argued that (Bhg,Brinkmann,Makridou,1906.06078)

Proposition: *If the dS swampland conjecture is correct, then the K-theory charge on a compact space has to be trivial.*

see also (Damian,Laoiza-Brito,1906.08766)

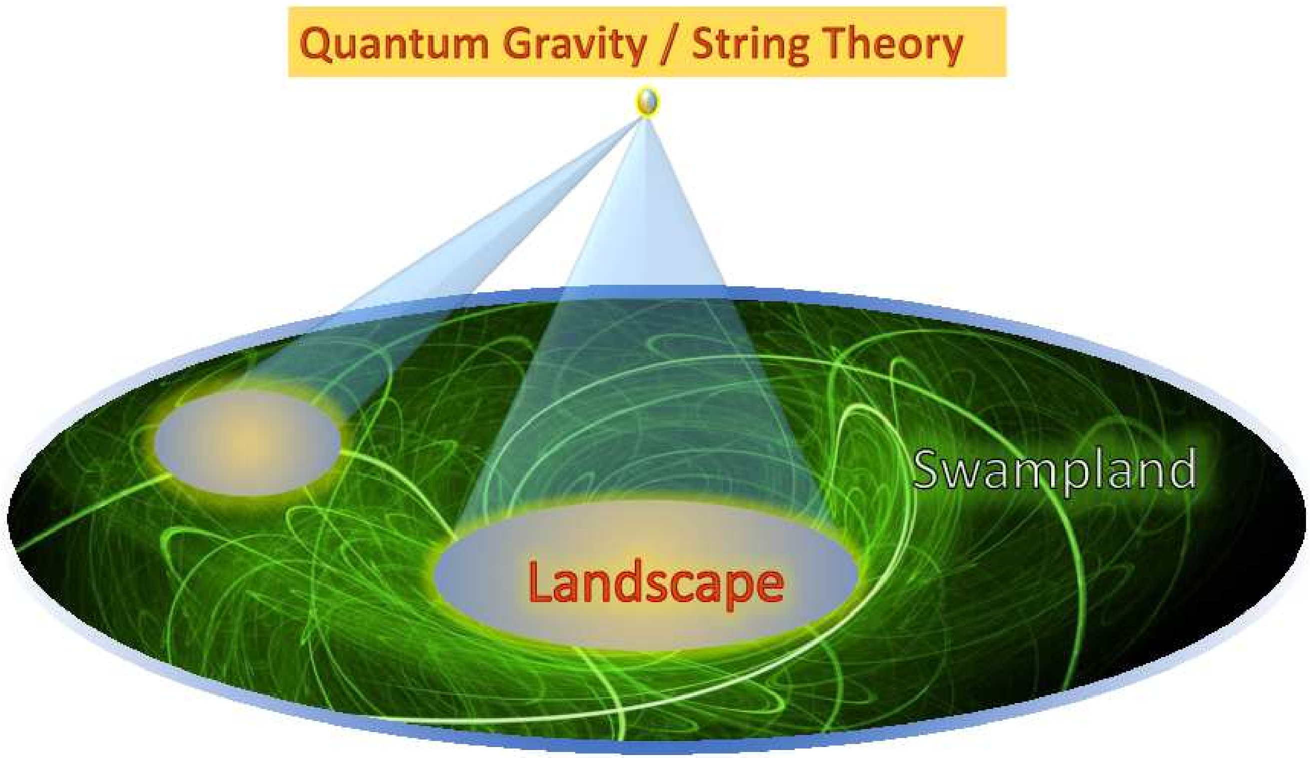
Conclusions

Conclusions

- Swampland conjectures try to bring order to the space of consistent string compactifications and their LEEA
- Leads to generic predictions of string theory and makes it in principle falsifiable
- dS swampland conjecture $\Rightarrow$ no metastable dS vacua $\Rightarrow$ CC Λ must change in time and $w \neq -1$

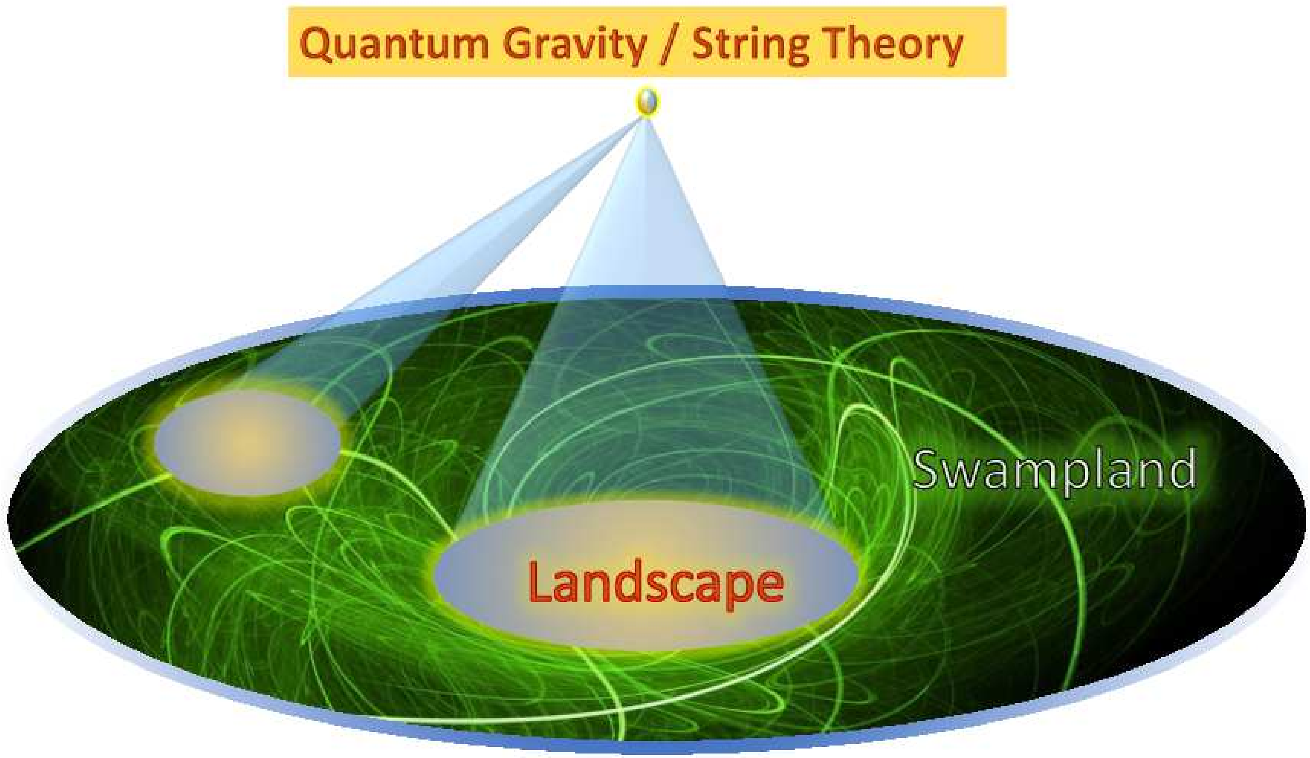
Maybe the string backgrounds investigated so far are not the natural habitat for dS spaces $\Rightarrow$ broaden the perspective

- Thermal effects: Thermal bath of hidden sector particles (dark radiation) of tiny mass (so that $T \gg m$) can lead to metastable dS minimum (Hardy,Parameswaran,1907.10141) .
- Exotic string theories, like the ones of (Hull,9807127) (proposed via T-duality along compact time-like directions) do admit dS solutions



(courtesy of Eran Palti)

Stay tuned - Thank you!



(courtesy of Eran Palti)

Stay tuned - Thank you!