Swampland constraints on scale separation and de Sitter

Niccolò Cribiori

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

DIP workshop on Holography and Swampland,

Ben Gurion University, 21-23 March 2023

Based on work with:
G. Dall'Agata, F. Farakos, C. Montella, G. Tringas

- Swampland conjectures are a window into quantum gravity.
- Encode consistency conditions that low energy EFTs must obey and that are not obvious from IR perspective.
- Explicit realization of the fact that quantum gravity mixes UV with IR.
- Typically tested in **top-down** constructions in string theory. Needed to gain confidence.

In this talk

I will explore a *complementary* approach:

- Assume swampland conjectures to be principles of QG
- Apply them to 4D and 5D supergravity (**bottom-up**)

The strategy is *coarse*, but it can lead to sharp results on

- Scale Separated vacua
- De Sitter vacua

For this approach, robust conjectures are preferable!

$\Rightarrow$ Weak Gravity Conjecture (WGC) $\Lambda_{UV} \lesssim g\, M_p$
[Arkani-Hamed, Motl, Nicolis, Vafa '06]

Simplest example

Consider 4d N=1 SUGRA with 1 vector multiplet. Turn on FI term

$$V_{FI} = \frac{1}{2} g^2 \xi^2 > 0$$

Assuming ξ quantized [Seiberg '10], we observe two related facts

- Limit $V_{FI} \to 0$ leads to global $U(1)_R$
  There cannot be global symmetries in QG
- The cosmological constant is of the order of the WGC cutoff

$$|V_{FI}| \simeq g^2 \overset{WGC}{\gtrsim} \Lambda_{UV}$$

Model not protected against corrections [NC, Farakos, Tringas '21]

$\Rightarrow$ **Pure FI terms are in the swampland**

(see also [Komargodski, Seiberg '09])

The strategy can be applied to models with $Q \geq 8$ supercharges.

In particular

- All gSUGRA with SUSY AdS: constraints on scale separation
- Certain gSUGRA with dS vacua

Caveat: WGC formulated in flat space. Extension to (A)dS not clear. Recent proposal: *Positive Binding Conjecture*. [Aharony, Palti '21; Palti, Sharon '22; Andriolo, Michel, Palti '22] See **O. Aharony's talk**

Here, I will *assume* that curvature corrections to

$$\Lambda_{UV} < g\, M_P$$

are small in the SUGRA regime. See e.g. [Huang, Li, Song '06].

Scale Separation

The problem

- No experimental evidence for extra dimensions.
- Critical string theory predicts extra dimensions.

observed dim $\sim L_H \sim 10^{27} m$ extra dim (naive) $< 1/E_{LHC} \sim 10^{-18} m$

Explaining this hierarchy of scales is an open problem

- Scale separation is necessary for defining $d < 10, 11$ EFTs
- Alternatives:
  brane-world scenarios, large (dark) extra dimensions; recent work [Montero, Vafa, Valenzuela '22]. See **M. Scalisi's talk**

Definition of scale separation

Consider a theory in d-dimensions with scalar potential V.

- On maximally symmetric vacuum $L_H^{-1} \sim |V|^{\frac{1}{2}}$
- Scale of the extra dimension L_{KK}

Scale separation is the requirement:

$$\frac{L_{KK}}{L_H} \ll 1$$

Note: estimating L_{KK} is non-trivial.

Typically $L_{KK} \sim \mathrm{Vol}^{\frac{1}{10-d}}$, but several effects (e.g. warping) can change it [Andriot, Tsimpis '18; De Luca, Tomasiello '21].

If $L_{KK}^{d-2} \sim \int R_d$, scale separation requires negative tension sources [Gautason, Schillo, Van Riet, Williams '15]

Swampland and scale separation

- Some swampland conjectures are relevant for scale separation [Gautason, Van Hemelryck, Van Riet '18; Lüst, Palti, Vafa '19; Blumenhagen, Brinkmann, Makridou '19...]

$$L_H \sim \sqrt{k}\,(L_{KK})^{\alpha} \qquad \text{e.g. } \alpha = 1 \text{ for } AdS_5 \times S^5$$

($\mathbb{Z}_k$ symmetry refinement [Buratti, Calderon, Mininno, Uranga '20])

- Counterexamples: "DGKT" vacua in IIA supergravity [Behrndt, Cvetic '04; Derendinger, Kounnas, Petropoulos, Zwirner '04; Lüst, Tsimpis, '04; DeWolfe, Giryavets, Kachru, Taylor '05]
  More recently double T-dual [NC, Junghans, Van Hemelryck, Van Riet, Wrase '21] and also in 3D [Farakos, Tringas, Van Riet '20]

- I will **not** assume any of the conjectures above.
  Rather, I will derive $L_{KK} \sim L_H$ using the WGC.

Weak Gravity vs Scale Separation(1/2)

[NC, Dall'Agata '22; NC, Montella '23]

- Consider gSUGRA with SUSY AdS vacua in 4D and 5D. The SUSY AdS vacuum energy is the gravitino mass

$$V_{AdS} = -m_{3/2}^2$$

- With at least 8 supercharges, SUSY relates

$$m_{3/2} \longleftrightarrow g$$

e.g. due to (very) special geometry.

- We can rewrite the vacuum energy as ($q = 1$, or quantized)

$$V_{AdS} = -g^2$$

- What is the gauge group?

Weak Gravity vs Scale Separation (2/2)

[NC, Dall'Agata '22; NC, Montella '23]

- According to [Louis, Lüst, Ruter '17] on SUSY AdS vacua

$$G \to H_R \times H_{mat}, \qquad H_R = \begin{cases} SO(N) & d=4 \\ [S]\,U(N/2) & d=5, \end{cases} \quad [N=8]$$

  - H_R gauged by graviphoton $\sim X^\Lambda A_\Lambda$
  - H_{mat} gauged by matter vectors $\sim \partial_i X^\Lambda A_\Lambda$

- We can split the contributions to the vacuum energy

$$V_{AdS} = -g^2 = -(g_R^2 + g_{mat}^2) < -g_R^2$$

$$i.e. \qquad L_H^{-2} = |V_{AdS}| \geq g_R^2 \overset{WGC}{\gtrsim} \Lambda_{UV}^2$$

- If $\Lambda_{UV} \sim \Lambda_{KK} \Rightarrow$ **no scale separation**.

An example

M-theory on SE_7 manifolds gives rise to 4D N=2 gSUGRA.
[Gauntlett, Kim, Varela, Waldram '09; Hristov, Looyestjin, Vandoren '09]
The theory is specified by

$$F = \sqrt{X^0(X^1)^3}$$

and quaternionic metric $ds^2 = \frac{1}{4\rho^2}\left(d\rho^2 + (d\sigma - i(\xi d\bar{\xi} - \bar{\xi} d\xi))^2\right) + \frac{1}{\rho} d\xi d\bar{\xi}$.
On the AdS vacuum a $U(1) \subset U(1)\times U(1)$ factor survives

$$\mathcal{P}^x_\Lambda = e_\Lambda \delta^{x3}, \qquad e_\Lambda = (1, -3).$$

The vacuum energy can be rewritten as

$$V_{AdS} = -12 = -6 g_R^2 q^2, \qquad g_R^2 q^2 = 2.$$

These vacua are not scale separated and thus not really 4D.

Results and implications

- In [NC, Dall'Agata '22] explicit argument given for minimal and maximal gSUGRA in 4D. Extended to 5D in [NC, Montella '23]. See also [Montero, Rocek, Vafa '22].

- No clear obstruction in going beyond 5D, or in specializing to $8 < Q < 32$.

- When combined with [Ooguri, Vafa '16], no $d > 4$ EFT in AdS, regardless of SUSY.

- $Q = 4$ still not covered (3D N=2 and 4D N=1). Interesting cases, due to known classes of scale separated $AdS_{3,4}$ vacua in type IIA compactifications.
  [DeWolfe, Giryavets, Kachru, Taylor '05; NC, Junghans, Van Hemelryck, Van Riet, Wrase '22; Farakos, Van Riet, Tringas '22]

Species scale, holography and scale separation

Species scale [Dvali '07; Dvali, Lüst '09; Dvali, Gomez, Lüst '12]

$$\Lambda_{sp} = \frac{M_P}{N_{sp}^{\frac{1}{d-2}}}$$

proposed as UV cutoff in EFTs with gravity. See talk by **D. Lüst**.

- In CFT [van de Heisteeg, Vafa, Wiesner, Xu '22] argued $c = a \simeq N_{sp}$
- In AdS, one has $|V_{AdS}| \simeq a^{-\frac{2}{3}}$

Combining, we get [NC, Montella '23]

$$\Lambda_{sp} \simeq \sqrt{|V_{AdS}|} \equiv L_H^{-1}$$

Parametrically small $|V_{AdS}|$ leads to parametrically small Λ_{sp}.
If $\Lambda_{sp} \sim \Lambda_{KK}$, **no scale separation**.

De Sitter vacua

Status of the art

As for scale separation, there is a dichotomy

- Experiments compatible with Dark Energy being a cosmological constant.
- Not clear if we can construct de Sitter vacua in string theory with computational control (quintessence seems hard as well).

Specifically

- No general consensus even for most studied scenarios, KKLT and LVS. For recent criticism, see e.g. [Gao, Hebecker, Junghans '20; Junghans '22; Lüst, Vafa, Wiesner, Xu '22]
- De Sitter vacua in supergravity seem generically highly constrained. Recent analysis in $3 \leq d \leq 10$ [Andriot, Horer, Marconnet '22; Andriot, Horer '22]. See also **A. Westphal**'s talk.

Given this situation, one can remain agnostic about the precise microscopic model, but rather study whether or not de Sitter vacua in **supergravity** are compatible with swampland conjectures.

Indeed, if a de Sitter vacuum is found in string theory in a controlled region, its low energy limit must be captured by supergravity.

The dS conjecture(s) [Obied, Ooguri, Spodyneiko, Vafa '18; Ooguri, Palti, Shiu, Vafa '19] forbids (stable) de Sitter vacua in quantum gravity. However, the motivation is empirical.

We do not assume any dS conjecture.
Rather, we use once more the WGC to exclude dS vacua.

Weak gravity versus de Sitter

[NC, Dall'Agata, Farakos '20; Dall'Agata, Emelin, Farakos, Morittu '21; NC, Montella '23]

- The scalar potential of gSUGRA is schematically

$$V = g^2 - m_{3/2}^2$$

- Assuming vanishing gravitino mass on the vacuum, we can repeat a similar analysis as for AdS

$$V_{dS} = g^2 = g_{WGC}^2 + g_{rest}^2$$
$$\geq g_{WGC}^2 \overset{WGC}{\gtrsim} \Lambda_{UV}^2$$

- In dS, natural IR cutoff $L_H^{-1} \sim H \sim \Lambda_{IR}$. Therefore

$$\Lambda_{IR}^2 \sim V_{dS} \gtrsim g_{WGC}^2 \sim \Lambda_{UV}^2$$

but a good EFT should have $\Lambda_{UV} \gg \Lambda_{IR}$!
These EFTs are in the swampland!

Results and implications

- Vacua with massless charged gravitini in tension with WGC. See also **Gravitino Conjecture** [NC, Lüst, Scalisi '21; Castellano, Font, Herraez, Ibanez '21]

- Independent from stability. Vacua allowed by the dS conjectures can be excluded by the WGC.

- All known stable dS_4 vacua in $N \geq 2$ gSUGRA [Fre, Trigiante, Van Proeyen '02] are in the swampland.
  However, stable dS_5 vacua [Cosemans, Smet '05; Ogetbil '08] evade the argument. To be investigated further.

- 4 supercharges at the Lagrangian level (e.g. 4D $N = 1$) seem promising chance to get de Sitter.
  Compatible with conjecture in [Andriot, Horer, Marconnet '22].

Conclusion

- Swampland conjectures directly imposed on gSUGRA lead to stringent constraints on EFTs.
- SUGRA good starting point to study quantum gravity. It might not have been the case a priori, since quantum gravity mixes UV and IR.
- Little room for scale separation and for de Sitter in gSUGRA with $Q > 4$.

Future directions

- Analysis performed in $d = 4, 5$.
  Extension to $d > 5$ seems straightforward.

- Understand why stable dS_5 vacua evade WGC-based argument. They seem to be different from stable dS_4 vacua.

- Holographic analysis for scale separation in AdS?
  [Collins, Jafferis, Vafa, Xu, Yau '22]

- Understand case with 4 supercharges.

- Is there a deeper reason why supergravity seems to be close to quantum gravity, at least in certain cases?

Thank you!

Extra slides

The argument in 4D (1/2)

Idea: We want to show that the vacuum energy is completely fixed by the WGC gauge coupling with no free parameter.

The SUSY AdS vacuum energy is given by the gravitino mass

$$V_{AdS} = -3\bar{L}^\Lambda L^\Sigma \mathcal{P}^x_\Lambda \mathcal{P}^x_\Sigma$$

There is a relation between gravitino mass and gauge couplings [Hristof, Looyestijn, Vandoren '09]

$$\bar{L}^\Lambda L^\Sigma \mathcal{P}^x_\Lambda \mathcal{P}^x_\Sigma = -\frac{1}{2}\left(\mathrm{Im}\mathcal{N}^{-1}\right)^{\Lambda\Sigma} \mathcal{P}^x_\Lambda \mathcal{P}^x_\Sigma$$

Thus we can express V_{AdS} in terms of the gauge coupling

$$V_{AdS} = 3\left(\mathrm{Im}\mathcal{N}^{-1}\right)^{\Lambda\Sigma} \mathrm{Tr}\,\mathrm{P}_\Lambda \mathrm{P}_\Sigma,$$

where $2\mathrm{P}_\Lambda = \mathbb{I}\mathcal{P}^0_\Lambda + \sigma^x \mathcal{P}^x_\Lambda$.

The argument in 4D (2/2)

Identify and canonically normalise the WGC U(1) vector

$$A_\mu^{WGC} = \Theta_\Lambda A_\mu^\Lambda, \qquad g^2 = -\Theta_\Lambda \left(\mathrm{Im}\mathcal{N}^{-1}\right)^{\Lambda\Sigma} \Theta_\Sigma$$

Finally split $\mathrm{P}_\Lambda = \mathrm{P}_\Lambda^\perp + \mathrm{P}_\Lambda^\parallel$ (wrt A_μ^{WGC}) and find

$$V_{AdS} = 3\left(\mathrm{Im}\mathcal{N}^{-1}\right)^{\Lambda\Sigma}\left(\mathrm{Tr}\mathrm{P}_\Lambda^\parallel \mathrm{P}_\Sigma^\parallel + \mathrm{Tr}\mathrm{P}_\Lambda^\perp \mathrm{P}_\Sigma^\perp\right)$$

$$\leq 3\left(\mathrm{Im}\mathcal{N}^{-1}\right)^{\Lambda\Sigma}\mathrm{Tr}\mathrm{P}_\Lambda^\parallel \mathrm{P}_\Sigma^\parallel = -3g^2\mathrm{Tr}(q^2)$$

i.e.

$$|V_{AdS}| \geq 3g^2\,\mathrm{Tr}\left(q^2\right) \overset{WGC}{\gtrsim} \mathrm{Tr}(q^2)\,\Lambda_{UV}^2$$

Thus if $\Lambda_{UV} \sim \Lambda_{KK}$ there is **no scale separation** (assuming charge quantisation).

Weak gravity versus de Sitter

[NC, Dall'Agata, Farakos '20; Dall'Agata, Emelin, Farakos, Morittu '21; NC, Montella '23]

- In dS there is a natural IR cutoff $L_H^{-1} \sim \Lambda_{IR}$.
- Assuming vanishing gravitino mass on the vacuum, with similar steps as before we can write

$$\begin{aligned} V_{dS} &\geq -(\mathrm{Im}\mathcal{N}^{-1})^{\Lambda\Sigma}\mathrm{P}_\Lambda \mathrm{P}_\Sigma \\ &\geq -(\mathrm{Im}\mathcal{N}^{-1})^{\Lambda\Sigma}\mathrm{P}^{\|}_\Lambda \mathrm{P}^{\|}_\Sigma \\ &\geq g^2 \mathrm{Tr}(q^2) \gtrsim \mathrm{Tr}(q^2)\Lambda_{UV}^2 \end{aligned}$$

  where we enforced the WGC.
- Therefore these vacua are not good EFTs, since

$$\Lambda_{IR}^2 \sim V_{dS} \sim g^2 \sim \Lambda_{UV}^2$$

  while a good EFT has $\Lambda_{UV} \gg \Lambda_{IR}$.