Weak Gravity versus Scale Separation

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Introduction and Motivation

Minimal requirements for (string) phenomenology

- No supersymmetry
- No observed extra dimensions

They might seem easy to implement in EFTs, but they are not.

They are in fact open problems.

Scale separation 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 problem

- Scale separation is necessary for defining 4D EFTs
- Alternatives: brane-world scenarios, large (dark) extra dimensions (recent work [Montero, Vafa, Valenzuela '22])

Definition of scale separation

Consider a theory in D-dimensions

$$S = \int d^D x \sqrt{g_D} \left(M_p^{D-2} R + \cdots - M_p^D V \right)$$

$$\text{EOM} \quad R = \frac{D}{D-2} M_p^2 V$$

On max symm vacuum ($|R| = D(D-1)/L_H^2$) there is a length scale

$$L_H^{-1} = \frac{M_p |V|^{\frac{1}{2}}}{\sqrt{(D-1)(D-2)}}$$

Scale separation is the requirement: $\frac{L_{KK}}{L_H} \ll 1$

Note: estimating L_{KK} is non-trivial.
E.g. $L_{KK} \sim \text{Vol}^{\frac{1}{6}}$, but several effects (warping,...) can change it.
(Recent work [Andriot, Tsimpis '18; De Luca, Tomasiello '21])

Modest attitude

Look at maximally symmetric vacua:

- **de Sitter**: not clear if under control
- **Minkowski**: automatically scale separated
- **Anti-de Sitter**: interesting and non-trivial. Unrealistic, but relevant for KKLT and LVS

Concentrate on AdS vacua, possibly with SUSY.

The problem can be addressed both from 4D and 10D.

For 10D analysis, **see talks by D. Andriot, F. Marchesano and T. Van Riet.**
For holographic analysis, **see talk by F. Apers.**

Swampland and scale separation

- Some swampland conjectures are relevant for scale separations [Gautason, Schillo, Van Riet, Williams '15; 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" [Behrndt, Cvetic '04; Derendinger, Kounnas, Petropoulos, Zwirner '04; Lüst, Tsimpis, '04; DeWolfe, Giryavets, Kachru, Taylor '05]
  More recently [Farakos, Tringas, Van Riet '20; NC, Junghans, Van Hemelryck, Van Riet, Wrase '21]
- I will **not** assume any of the conjectures above.
  Rather, I will use [Arkani-Hamed, Motl, Nicolis, Vafa '06]

$$\text{Magnetic WGC:} \quad \Lambda_{UV} \lesssim g M_p$$

Weak Gravity versus Scale Separation

[NC, Dall'Agata '22]

The strategy

- Consider 4D SUGRA with SUSY AdS vacua.
  This is a well-controlled setup.

- For $N > 1$, we can show that

$$L_H^{-2} \sim M_p^2 |V_{AdS}| \simeq q^2 g^2 M_p^2 \overset{WGC}{\gtrsim} q^2 \Lambda_{UV}^2$$

- Then, scale separation absent if $\Lambda_{UV} \sim \Lambda_{KK}$
  (assuming charge quantisation).

Way out: AdS_4 vacua with $N = 0, 1$ might evade the argument.

Note: The argument is relevant for any UV complete theory reducing to 4D SUGRA in the low energy

The argument (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 (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).

An example

M-theory on SE_7 manifolds gives rise to 4D N=2 SUGRA with abelian gaugings.

[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

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

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

Generalisations

- 4D N=8 SUGRA: both maximally SUSY and partially broken (N=2) AdS vacua [NC, Dall'Agata '22]. This is evidence for no scale separation in $2 \leq N \leq 8$ AdS_4 vacua. However, case by case analysis might be required.

- $D > 4$ extension seems straightforward too. It would forbid scale separation for $AdS_{D>4}$ with $N > 0$.

- $D = 4$, $N = 0, 1$ can evade the argument. Known class of scale separated AdS_4 vacua of type IIA CY orientifolds exists. [Behrndt, Cvetic '04; Deredinger, Kounnas, Petropoulos, Zwirner '04; Lüst, Tsimpis '04; DeWolfe, Giryavets, Kachru, Taylor '05]

- A similar argument can be used against dS vacua. [NC, Dall'Agata, Farakos '20; Dall'Agata, Emelin, Farakos, Morittu '21]

Conclusion

- Scale separation is a minimal requirement for phenomenology in theories with extra dimensions.

- Contrary to naive expectation, not easy to get even in bottom-up approach. Constrained by swampland conjectures.

- We gave evidence that $2 \leq N \leq 8$ AdS_4 vacua of gauged SUGRA are not scale separated if the WGC holds, regardless of the details of the UV completion.

- $N = 0, 1$ supersymmetry seem to be the most promising chances to get scale separated AdS_4 vacua. Interesting setups to investigate further.
  (Recent work [Andriot, Horer, Marconnet '22])

Thank you!

Extra slides

Weak gravity versus de Sitter

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

- 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

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

- Therefore these vacua are not good EFTs, since

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

while one would expect $\Lambda_{IR} \ll \Lambda_{UV}$

- N=0,1 SUGRA seem the most promising chances to get dS.