Quantum gravity constraints on scale separation and de Sitter in five dimensions

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Overview

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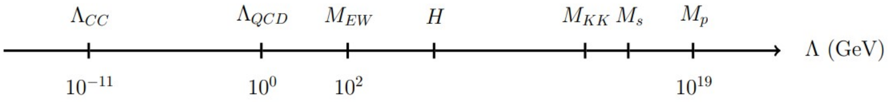
Five dimensional supergravity

Why should we study five dimensional supergravity?

- Low energy string theory **is** supergravity, but supergravity could be more (eleven-dimensional supergravity is low energy M-theory, ...)
- Supergravity + external inputs (swampland constraints, holography, . . .) provide a fundamental tool to investigate EFT of quantum gravity
- Two faces of the **same** medal: AdS_5 is dual to CFT_4.
  If we study five-dimensional supergravity, we study strongly coupled field theory in four-dimensions!
- A new proposal: Dark Dimension Scenario [Montero, Vafa, Valenzuela '22]

The scale separation problem

(Critical) String theory predicts extra dimensions, but there is no experimental evidence of them: $L_{Hubble} \simeq 10^{27}m \gg L_{LHC} \simeq 10^{-18}m > L_{extra\ dim.} \implies$ scale separation seems necessary to define low dimensional EFTs.[1]



It appears that our universe has a hierarchy of scales: this is an open problem, called **scale separation** problem.
In a proper language, scale separation requires

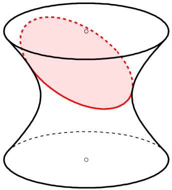
$$\frac{L_{KK}}{L_H} \ll 1 \tag{1}$$

[1] Alternatives: brane-world scenarios, large extra dimensions, ...

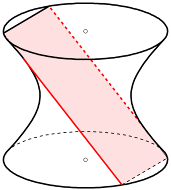
Maximally symmetric spaces

As we know, there are only three space-time which are maximally symmetric:

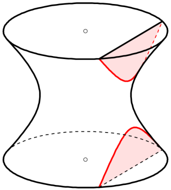
- **Minkowski**: automatically scale separated.
- **de Sitter**: today it's not clear if we have controlled examples in string theory.
- **Anti-de Sitter**: interesting for AdS/CFT correspondence, non-trivial and relevant for KKLT, . . . constructions.



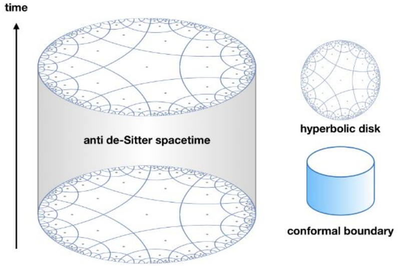
Closed spherical universe
Positive 3d curvature



Open flat universe
Zero 3d curvature



Open hyperboloid universe
Negative 3d curvature



The Swampland

The Swampland

Those apparently consistent (anomaly free) quantum EFTs that cannot be embedded in a UV consistent theory of quantum gravity [Valenzuela et al. '21]

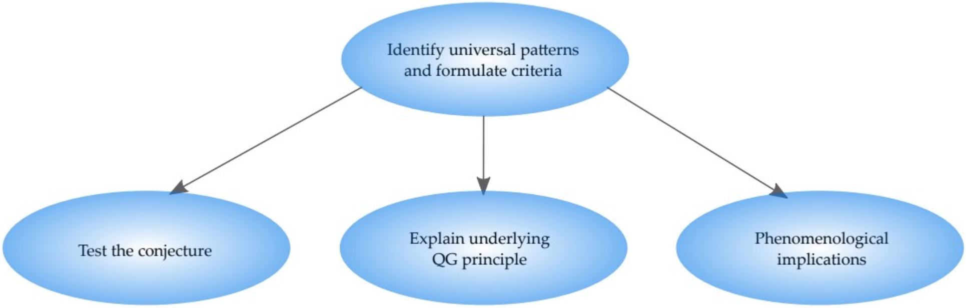
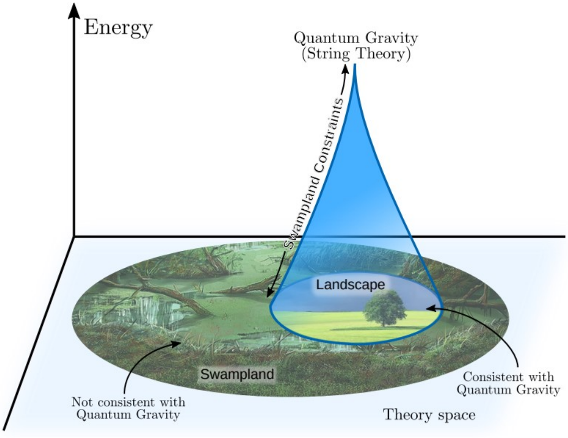


Figure: The **Swampland** and **Landscape** of EFTs. The space of consistent EFTs forms a cone because Swampland constraints become stronger at high energies. [Valenzuela et al. '21]



Weak Gravity Conjecture

Weak Gravity Conjecture - Magnetic [Arkani-Hamed, Motl, Nicolis and Vafa]

The EFT cut-off Λ_{EFT} is bounded from above by the gauge coupling

$$\Lambda_{EFT} \leq g M_p^{\frac{d-2}{2}} \tag{2}$$

- It provides a QG obstruction to restore a $U(1)$ global symmetry by sending $g \to 0$ (see also NO GLOBAL SYMMETRY); if $\Lambda_{EFT} \to 0$, then the EFT lose its predictability.[2]
- It allows extremal BHs to decay (mainly the electric version)

[2] To be precise, we will consider a generalisation of the WGC for (A)dS spacetime [Huang, Li, and Song '06]

The Argument

WGC vs. Scale Separation (1/2)

Underlying idea: THE GOAL IS TO SHOW THAT THE VACUUM ENERGY IS COMPLETELY FIXED BY THE WGC GAUGE COUPLING WITH NO FREE PARAMETER.

Let's start considering $\mathcal{N} = 1$ SUSY AdS vacuum energy[3]:

$$\mathcal{V}_{AdS} = -2g_R^2 P^{ij} P_{ij} = -2g_R^2 h^I h^J P_I^x P_J^x. \tag{3}$$

Then, we find a relation between the gravitino mass and the gauge kinetic function

$$\textit{null contributions} + h^I h^J P_I^x P_J^x \overset{SUSY}{=} a_{IJ} P_I^x P_J^x, \tag{4}$$

and finally we can express the scalar potential as

$$\mathcal{V}_{AdS} = -4g_R^2 a^{IJ} P_I^x P_J^x \tag{5}$$

[3] A similar argument can be used for 5D $\mathcal{N} = 8$ SUGRA, both maximally SUSY and partially broken AdS vacua

WGC vs. Scale Separation (2/2)

Why are we sure about the existence of an abelian gauge group in the vacuum? [Louis, Muranaka '16] shows that, in vacuum, a five-dimensional SUGRA theory breaks its gauge group G in $U(1) \times H$ with $H \subset G$.

Then, we identify and canonically normalise the WGC $U(1)$ vector[4]

$$A_\mu^{WGC} = \Theta_K A_\mu^K \quad g_{3/2}^2 = \Theta_K a^{KL} \Theta_L \tag{6}$$

and write the scalar potential as

$$|\mathcal{V}_{AdS}| = 2 g_{3/2}^2 Q^2 \geq \Lambda_{UV}^2 Q^2 \tag{7}$$

[4] From now on let's put $g_R \equiv 1$

The holographic argument

The ultraviolet cutoff of a d-dimensional effective theory of gravity coupled to a number N_{sp} of light species is the so-called species scale [Dvali et. all]

$$\Lambda_{sp} \simeq M_P N_{sp}^{-\frac{1}{d-2}} \tag{8}$$

Assuming that the number of light species in AdS_5 and its dual CFT_4 are equal, then we can estimate the latter at the central charge $a \simeq N_{sp}$ [Vafa et al. '22]
Finally, using the AdS/CFT dictionary, we know

$$M_P^2 |V_{AdS}| = a^{-\frac{2}{3}} \simeq (N_{sp})^{-\frac{2}{3}} \implies \Lambda_{sp} \sim \sqrt{|\mathscr{V}_{AdS}|} \tag{9}$$

This implies that (assuming $\Lambda_{sp} \equiv \Lambda_{UV}$)

$$\frac{L_{AdS}}{L_{UV}} \sim 1 \tag{10}$$

Weak gravity conjecture vs. de Sitter

In de Sitter there is a natural IR cut-off $\Lambda_{IR} \sim L_H^{-1}$.
Without excluding hyper- and vector- potential $\sim 2W^{\tilde{x}}W_{\tilde{x}} + 2\mathcal{N}_{iA}\mathcal{N}^{iA} \geq 0$ and assuming vanishing gravitino mass (but we could consider a weaker assumption [Dall'Agata, et all. ('21)]), with similar steps as before we can write

$$
\begin{aligned}
\mathcal{V}_{dS} &\geq a^{LK}P_L P_K \geq a^{KL}P_K^{||}P_L^{||} \\
&\geq g_{3/2}^2 Tr(q^2) \geq Tr(q^2)\Lambda_{UV}^2
\end{aligned}
$$

Therefore, these vacua are not good for EFTs

$$
\Lambda_{IR}^2 \sim \mathcal{V}_{dS} \geq \Lambda_{UV}^2 \tag{11}
$$

Independently from stability, vacua with massless charged gravitini, also allowed by the dS conjecture, can be excluded by the WGC.

Conclusions

- From [Cribiori, Dall'Agata '22] we know that, in four dimensions only $\mathcal{N}=1$ can evade the argument, due to its low supersymmetry. Instead, in five-dimensional supergravity we are able to exclude any SUSY AdS vacua.
- This proof, together with the "NON-SUPERSYMMETRIC ADS CONJECTURE" [Ooguri, Vafa '17], forbids any AdS vacua for **every** supergravity theories in five dimensions.
- Due to the form of the scalar potential and the geometric theory behind it, we think this argument is valid also for $d > 5$.

Future directions

- Predict proprieties of **strongly coupled theories** by means of $\mathrm{AdS}_5/\mathrm{CFT}_4$ correspondence.
- Through five-dimensional SUGRA, investigate the Dark Dimensions Scenario using the Swampland program.
- Understand how the Swampland program can help to approach the scale separation problem for $\mathcal{N}=1$, $D=4$ SUGRA!

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The End