New lights on the darkest corner of Quantum Gravity

Nicolò Petri

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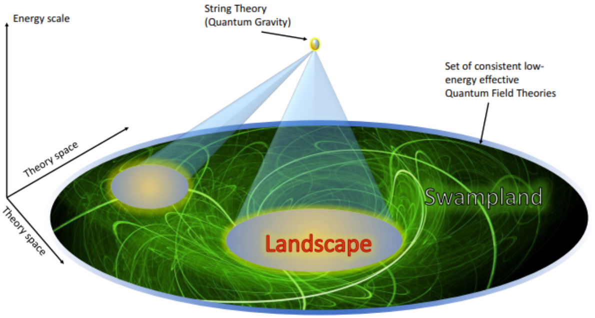
Talk based on research with Eran Palti (Ben-Gurion U.)

Refs: [Li, NP, Palti, 2306.02026]. [NP, Palti, 2405.01084]. [Palti, NP, To appear].

- Probably the biggest principle in physics is **scale separation**.
- String theory is the framework that tries to understand how to change the scale with gravity.
- Why gravity is so weak? Why the vacuum energy of the universe is so small? Is our universe a vacuum? Why we observe 3 spatial dimensions?
- Mistery of string theory: dualities seem suggesting that there are no fundamental quantities at all. The ultimate question is: **there exist a fundamental set of degrees of freedom of quantum gravity?**
- Research program: identify the **universal criteria** that any EFT should satisfy to admit a completion in a consistent theory of quantum gravity.



- **The Swampland**: the set of (apparently) consistent effective field theories (EFT) that cannot be completed into quantum gravity in the UV. [Vafa, 2005]. Main review: [Palti, 2019].
- We look at the self-consistency of EFTs, searching for quantum gravity imprints. We look at **string theory as an experimental setup**.

- In string theory the vacuum energy Λ is calculable and it is related with other quantities of the spacetime vacuum.

- **AdS conjecture** [Lüst, Palti, Vafa, '19]: Consider quantum gravity on (A)dS. There exists an infinite tower of states with mass scale m_∞ which, as $|\Lambda| \to 0$, behaves as

$$m_\infty \sim |\Lambda|^\alpha \qquad \text{with} \qquad \alpha \sim O(1)\,.$$

- Many evidences in string theory: a correlation is not a causation!

- At the foundation of the current top proposal in string pheno: **dark dimension scenario**. [Montero, Valenzuela, Vafa, '22].

- The conjecture rises deep consistency issues with "realistic" string theory compactification (that are not abundant...).

- Develop the ideas behind the conjecture and try to see if it makes sense.
- A way to give sense to all this story is to relate the variations of the vacuum energy to a notion of **distance** in the space of parameters:

$$\Lambda \to 0 \qquad \longleftrightarrow \qquad \Delta \to +\infty \qquad \longleftrightarrow \qquad m_\infty \sim e^{-\gamma\Delta} = |\Lambda|^\alpha$$

- How can we make sense to a notion of distance beteeen two (A)dS vacua with Λ_1 and Λ_2?
- To introduce a distance we need first to see if we can introduce a **metric** over the space of variations of gravitational vacua.

In classical gravity (A)dS solutions are labeled at least by one parameter associated to the AdS radius,

$$ds_4^2 = e^{2\sigma}\, ds^2_{\text{(A)dS}_4} \qquad \text{with} \qquad \frac{\Lambda}{\hat{\Lambda}} = e^{-2\sigma}\,.$$

We need a sort of universal prescription to get a distance contribution:

- Take a family of (A)dS solutions parametrized by a spatially constant parameter σ.
- Give this parameter an infinitesimal spatial dependence: $\sigma \to \sigma(x)$.
- Extract the two-derivative terms from the Einstein-Hilbert action: $S[\sigma(x)] \supset -\int K_{\sigma\sigma}(\partial\sigma)^2$

[Li, Palti, NP, '23], [Palti, NP, '24]

- **Vacuum energy variations**: $ds_4^2 = e^{2\sigma(x)}\, ds^2_{\text{(A)dS}_4}$
- They are Weyl rescalings: $R = e^{-2\,\sigma}\,\left(R_{\text{(A)dS}_4} - 6(\partial\,\sigma)^2 - 6\,\nabla^2\,\sigma\right)$
- $S = \frac{1}{2}\int d^4x\sqrt{-g}\,\left(R - K_{\sigma\sigma}(\partial\,\sigma)^2\right)$ with $K_{\sigma\sigma} = -6$
- This is the manifestation of the **Conformal Factor Problem** (a big deal). [De Witt, '67] [Gibbons, Hawking, Perry, '78]
- The conformal factor variation of AdS is just one contribution. **We must include all the contributions to the vacuum energy**. This may solve the issue of negativity.
- Let's include k extra dimensions: $ds^2_{10} = e^{2\sigma} ds^2_{\text{(A)dS}_4} + e^{2\tau} ds^2_k$

- We can compute exactly the contribution from the extra dimensions:

$$S \supset \frac{1}{2} \int \left[-K_{\sigma\sigma} (\partial\sigma)^2 - k^2 \left(\frac{3}{2} - \frac{k-1}{k} \right) (\partial\tau)^2 \right] .$$

- On-shell condition (EOM): $\quad ds^2_{10} = e^{2\sigma} ds^2_{\text{(A)dS}_4} + e^{2\tau} ds^2_k$

$$\tau = a\sigma \qquad \text{with} \qquad a = 1 \ : \ \text{no scale separation.}$$

- Strong scale separation leads to a negative metric.

$$K_{\text{tot}} = K_{\sigma\sigma} + K_{\tau\tau} = -6 + a^2 k^2 \left(\frac{3}{2} - \frac{k-1}{k} \right) ,$$

- $a = 1$: $\quad K_{\text{AdS}_4 \times S^7} = \frac{51}{2}, \qquad K_{\text{AdS}_5 \times S^5} = \frac{4}{3}, \qquad K_{\text{AdS}_7 \times S^4} = -\frac{114}{5}.$
- $a \neq 1$: $\quad K_{\text{DGKT}} = -\frac{10}{3}.$ (These vacua are very relevant).

- In string theory vacua geometries are featured by many ingredients, like p-form gauge fields and/or scalars.
- This may solve the issue of negativity of the metric!
- Simplest example is the Freund-Rubin vacuum in M-theory $\mathrm{AdS}_4 \times S^7$:

$$ds_{11}^2 = e^{2\sigma}\left(ds^2_{\mathsf{AdS}_4} + 4ds^2_{S^7}\right)\,, \qquad F_4 = -3e^{3\sigma}\,\mathrm{vol}_{\mathsf{AdS}_4}$$

- 11d action $S \subset \int d^{11}x\,\sqrt{g_{11}}\left(R_{11} - \frac{1}{2}\,|F_4|^2\right)$
- We found a rigid and well-defined procedure to take flux variations and compute their contribution to the metric.
- These computations are highly non-trivial and lead to positive results in all the cases we considered!

- We cured the negativity in the metric in some relevant examples.
- Our procudere allows to compute $m_\infty \sim e^{-\gamma\Delta}$, $\gamma = \frac{1}{\sqrt{K_{\text{tot}}}}$:
  - $\mathrm{AdS}_4 \times S^7$: $K_{\text{tot}} = \frac{1563}{8} \longrightarrow \gamma = 0.07$ [Li,Palti, NP, '24]
  - $\mathrm{AdS}_7 \times S^4$: $K_{\text{tot}} = \frac{516}{5} \longrightarrow \gamma = 0.1$ [Li,Palti, NP, '24]
  - $\mathrm{AdS}_5 \times S^5$: $K_{\text{tot}} = 116 \longrightarrow \gamma = 0.09$ [Li,Palti, NP, '24]
  - DGKT vacua : $K_{\text{tot}} = \frac{3376}{27} \longrightarrow \gamma = 0.06$ [Palti, NP, '24]
- These numbers are **universal** features of the vacuum and tell us that in the $\Lambda \to 0$ limit an infinite tower of light states emerges. These light states are the KK states of the compactification!
- **Metric positivity conjecture** : families of solutions in quantum gravity always have a positive metric on them.

  [Palti, NP, '24], [Palti, NP, To appear].