Swampland Conjectures and Particle Physics

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Dark World to Swampland

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SWAMP LAND
A NEW HOPE FOR STRING-PHENO
THE SWAMP THING
STRING PHENO

Plan for the talk

1. Motivation
2. PPWGC for U(1) interactions
3. PPWGC for scalars
4. PPWGC phenomenology
5. Outlook for PPWGC
6. AdS Distance Conjecture

Swampland

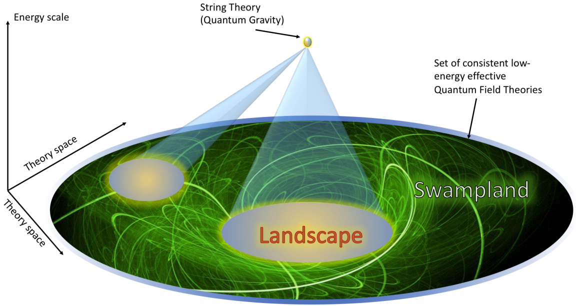
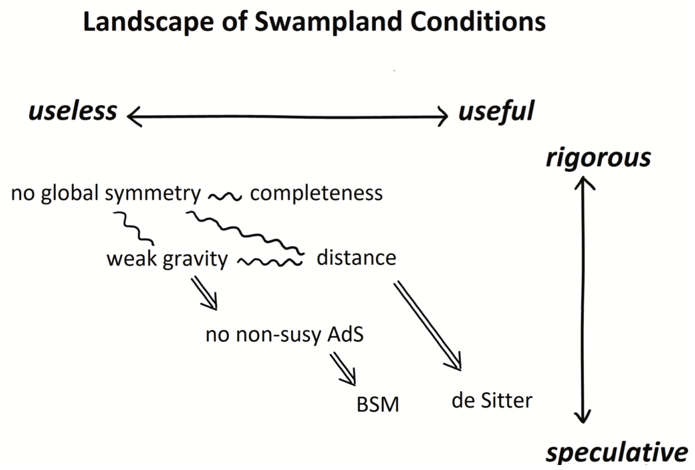


Figure: The landscape is the sub-set of self-consistent QFT which can be completed into quantum gravity in the UV. Other apparently consistent theories are in the Swampland [1]. Picture taken from Palti '19.

[1] Vafa '05, Ooguri and Vafa '06.


Landscape of Swampland Conditions
useless
useful
rigorous
speculative
no global symmetry
completeness
weak gravity
distance
no non-susy AdS
BSM
de Sitter

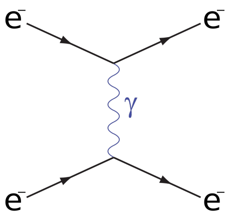
Weak Gravity Conjecture

- BH discharge. If extremal BH are stable then it is possible to have an arbitrarily large number of stable BH remnants, in tension with holographic bounds. Plus, the theory is afflicted with other pathologies.
- Consider, for example, a theory with a $U(1)^N$ gauge symmetry. An extremal BH of charge $\vec{Q}$ and mass $M_{BH} = |\vec{Q}|$ will be able to decay iff there is a multi-particle state such that $\vec{Q} = \sum_i n_i \vec{q}_i$ and $M_{BH} > \sum_i n_i m_i$ (Convex Hull Condition). For $N = 1$ this is simply $m \leq q$.

[1] N. Arkani-Hamed, L. Motl, A. Nicolis and C. Vafa '06
[2]G. 't Hooft (1993),R. Bousso(2002)
[3] L. Susskind (1995),S.B. Giddings(1992)

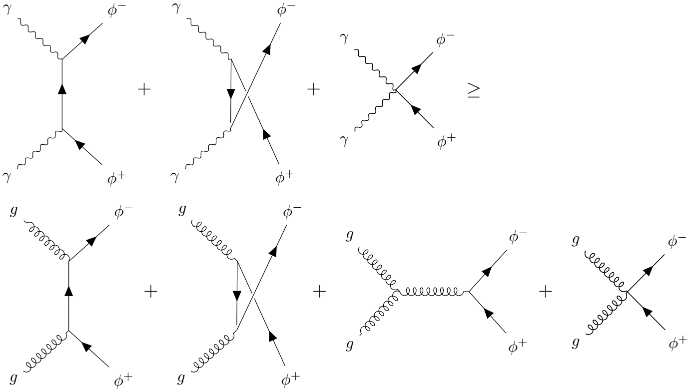
Motivation PPWGC

- A graviton gives rise to scalar fields and graviphotons under dimensional reduction. Thus, some kind of SWGC is expected to exist.
- We want to reformulate WGC in a way that can include scalar fields valid at least in 4D.
- Instead of having WGC particles exchanging massless particles, consider massless particles exchanging massive WGC particles.



Motivation PPWGC

- The diagrams we would like to consider depend of the theory. For SQED:



Motivation PPWGC

- A graviton gives rise to scalar fields and graviphotons under dimensional reduction. Thus, some kind of SWGC is expected to exist.
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1. Complementary information of gravity as the weakest interaction.
2. Perhaps pair production and annihilation is related to BH decay via Schwinger effect.

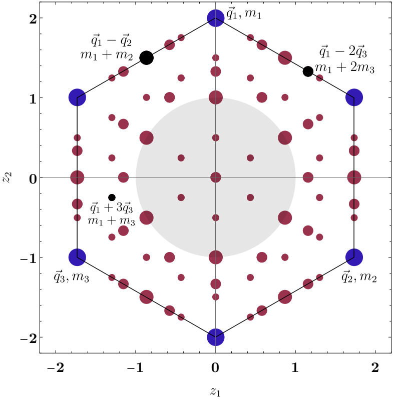
Weak Gravity Conjecture

- We will try to formulate a general principle that reduces to black-hole extremality bound in well-known situations such as the CHC in Multiple U(1).
- There are complementary approaches, like the Repulsive Force Conjecture [1,2]. The RFC is not able to provide a SWGC, it cannot compare the strength gravity with other attractive forces.
- Let us then start with the precise WGC statement for Multiple U(1)s.

[1] E. Palti '17
[2] B. Heidenreich, M. Reece, T. Rudelius '19

Weak Gravity Conjecture

- Extremal BH can decay to superextremal multiparticle states along their rational direction.
- Convex hull must enclose BH region. Multi-particle states populate the convex-hull.



- Extremal BH can decay to superextremal multiparticle states along their rational direction.
- Convex hull must enclose BH region. Multi-particle states populate the convex-hull.

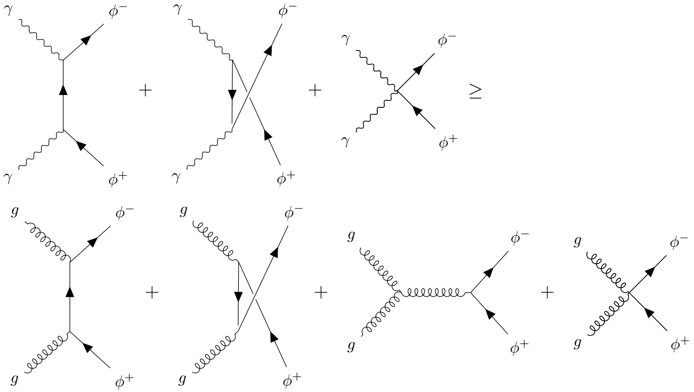
> For every rational direction in the charge lattice
> there is a superextremal multiparticle state

- That is, the convex hull encloses the BH region.

For any rational direction in the charge lattice $\vec{Q}$ and for every point in moduli space, there is a stable or metastable particle M of mass m whose pair production rate by gauge or scalar mediators at threshold is larger than its graviton production rate.

$$\boxed{|T(ij \longrightarrow MM^*)|^2_{\text{th}} \geq |T(gg \longrightarrow MM^*)|^2_{\text{th}}}$$

- Notice we are evaluating the diagrams at the scale of the massive propagators.
- It is purely quantum relativistic, not reduces to classical non-relativistic potential.


γ
ϕ^-
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ϕ^+
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γ
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$\geq$
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ϕ^+

$$\left(\frac{d\sigma}{dt}\right)^{\text{SQED}}_{\text{CM}} = \frac{|A|^2}{32\pi s^2} \quad ; \quad \left(\frac{d\sigma}{dt}\right)^{\text{Grav}\,\phi^*}_{\text{CM}} = \frac{|C|^2}{32\pi s^2} \ .$$

For the photon production amplitude one obtains

$$\mathrm{A}_{++} = \frac{2e^2\left(m^4 - ut\right)}{(t-m^2)(u-m^2)} \quad ; \qquad A_{+-} = -\frac{2e^2 m^2 s}{(t-m^2)(u-m^2)}.$$

$$|\mathrm{C}_{++}|^2 = |C_{--}|^2 = F^2|A_{++}|^4 \quad ; \qquad |C_{+-}|^2 = |C_{-+}|^2 = F^2|A_{+-}|^4,$$

$$\mathrm{F} = \frac{1}{4M_p^2 e^4}\frac{\left(t-m^2\right)\left(u-m^2\right)}{s}.$$

The PPWGC exactly matches the WGC!!

$$|\mathrm{A}|^2 \ \geq |C|^2 \ \longrightarrow \ \boxed{\sqrt{2}e \ \geq \ \frac{m}{M_p}}$$

- The extension for multiple $U(1)s$ gives the CHC condition.
- A charged state is **superproduced** if the rate to produce a pair at threshold is larger or equal to the rate to produce that pair from gravitons.

WGC. For every rational direction in the charge lattice there is a superextremal multiparticle state

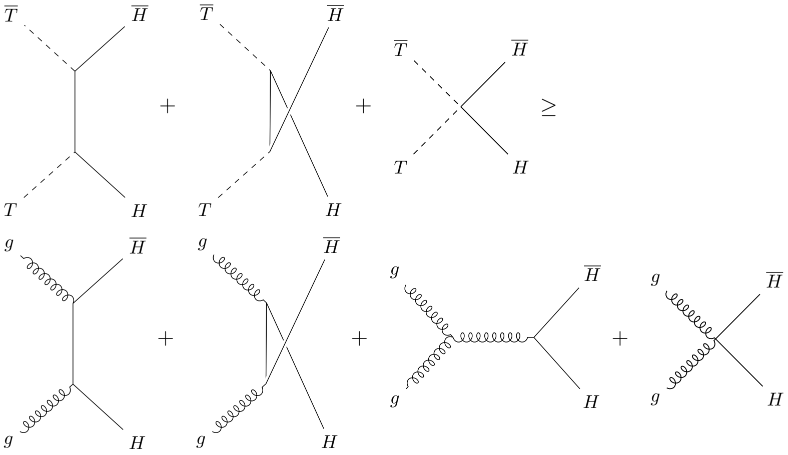
PPWGC. For every rational direction in the charge lattice there is a (meta)stable particle which is superproduced

- BH arguments do not care whether the scale is single or multi-particle state.

Tower-PPWGC. At any point $\vec{q}$ of the charge lattice there exists a positive integer n such that there is a superproduced particle of charge $n\vec{q}$.

Sublattice-PPWGC.There exists a positive integer n such that for any site $\vec{q}$ in the charge lattice there is a superproduced particle of charged $n\vec{q}$.

$$L_T = \partial_\mu H \partial^\mu \overline{H} + \partial_\mu T \partial^\mu \overline{T} \; - \; m^2(T, T^*)|H|^2$$



$$\boxed{\left|(\partial_T m^2)(\partial_{\overline{T}} m^2) \;-\; m^2\;\partial_T\partial_{\overline{T}} m^2\right| \;\geq\; \frac{m^4}{M_p^2}}$$

$$\boxed{\frac{g^{i\bar{j}}}{n}\;\left|(\partial_i m^2)(\partial_{\bar{j}} m^2) \;-\; m^2(\partial_i\partial_{\bar{j}} m^2)\right| \;\geq\; \frac{m^4}{M_p^2}}$$

- A similar equation was proposed by Palti [17'] based on an identity in $\mathcal{N} = 2$ SUGRA.
- The constraint is consistent with the properties of $N = 2$ BPS states.

$$\boxed{\frac{g^{i\bar{j}}}{n}\ \left|(\partial_i m^2)(\partial_{\bar{j}} m^2)\ -\ m^2(\partial_i\partial_{\bar{j}} m^2)\right|\ \geq\ \frac{m^4}{M_p^2}}$$

- $m^2 = M_p^2 e^F$ leads to $\boxed{g^{i\bar{j}}\left|F_{i\bar{j}}\right|\ \geq\ n}$, duality $F \leftrightarrow -F$.
- In all of the examples we study there are solutions for the massive extremal scalars which in the large field limit behave as KK or winding states with built-in duality symmetries.
- Test from towers of BPS particles in Type IIA CY, from Dp-branes wrapping even cycles. They saturate our bound.

$$\boxed{\left|(\partial_T m^2)(\partial_{\overline{T}} m^2) \; - \; m^2 \, \partial_T \partial_{\overline{T}} m^2\right| \; \geq \; \frac{m^4}{M_p^2}}$$

- The obtained bounds apply to the many string excited states coupled with mediators in the massless sector. They are very massive except in the asymptotic limits of moduli space.

Question:
Can we find constraints on (nearly) massless scalars with relevance in particle physics or cosmology?

- Assuming that the potential depends on moduli only through the masses of heavy states, one can obtain constraints on the potential of the moduli.
- If for example $V \simeq m^{2\gamma}$ one obtains a constraint:
- For dS minima (or AdS), this is similar to the refined dS conjecture.

$$\boxed{\left|(\frac{\nabla V}{V})^2 - \frac{\nabla^2 V}{V}\right| \geq \frac{\gamma}{M_p^2}}$$

$$\boxed{\left|(\partial_T m^2)(\partial_{\overline{T}} m^2) \; - \; m^2 \, \partial_T \partial_{\overline{T}} m^2\right| \; \geq \; \frac{m^4}{M_p^2}}$$

1. Assuming that the potential depends on moduli only through the masses of heavy moduli, one can obtain constraints on the potential of the moduli.
2. **Strong SWGC** [1].The moduli themselves acquire masses obeying the same constraint because their self-interaction needs to be stronger than gravity. Diagrammatic interpretation suggests $\xi = \frac{5}{3}$.

$$\boxed{\left|\xi(V''')^2 \; - \; (V'')(V'''')\right| \; \geq \; \frac{(V'')^2}{M_p^2}}$$

[1] E. G. and L. Ibáñez '19

- First direct derivation of a SWGC from a general principle that includes CHC condition.
- Saturating solutions display duality symmetries and this is related to the absolute value of the rates.
- Connection with the WGC is under study. Perhaps PPWGC is also related to black hole discharge.
- It would be interesting to perform the same computations in a background other than Minkowski.
- Test from towers of BPS particles in Type IIA CY, from *Dp*-branes wrapping even cycles. They saturate our bound. Require further testing in string compactifications.
- Include non-Abelian gauge groups.

AdS Distance Conjecture

There exists an infinite tower of states with mass scale m which, as $\Lambda \to 0$, behaves (in Planck units) as $m \sim |\Lambda|^{\alpha}$ where α is a positive $O(1)$ number conjectured to be 1/2 for supersymmetric AdS vacua.

- Consider the SM compactified in a circle. There are AdS vacua with $\Lambda_3 = V_0$.
- According to the conjecture, if in a certain direction of field space (i.e. Yukawa) $\Lambda_3 \to 0$, then some tower of states $m \sim |\Lambda_3|^{\alpha} = |V_0|^{\alpha}$ should become massless.

[1] E. G., L. Ibáñez and I. Valenzuela '20 [to be published]

AdC and the infrared sector of SM

$$S = \frac{(M_p^{4d})^2}{2} \int d^4x \sqrt{-g_4} (\mathcal{R}^{4d} - \Lambda^{4d}) - \frac{1}{4} \int d^4x \sqrt{-g_4} F^{4d}_{\mu\nu a} F_{4d}^{\mu\nu a}$$
$$+ \int d^4x \sqrt{-g_4} \sum_f \bar{\psi}_f \left(i\tilde{\gamma}^\mu D_\mu - m_f \right) \psi_f$$

$$g_{\mu\nu} = \begin{bmatrix} \frac{r^2}{R^2} g_{ij} & 0 \\ 0 & R^2 \end{bmatrix},$$

$$\Gamma = \int d^3x \sqrt{-g_3} \, (2\pi) \left[r \left(M_p^{4d} \right)^2 \frac{1}{2} \mathcal{R}^{3d} - r \left(\frac{r}{R} \right)^2 \rho_{\Lambda^{4d}} - \frac{1}{2\pi} V_{\text{eff}}(R) + \text{Kin.} \right]$$

If the fermionic degrees of freedom is low or the mass of the lightest neutrino is large enough compared with Λ^{4d}, we find AdS_3 minima, $V(R_0) = V_0 < 0$.

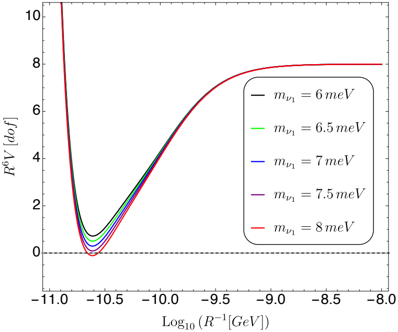


Figure: As the mass of the lightest neutrino gets smaller, the lightest neutrino gets smaller, $|V_0|$ becomes zero but R_0 is finite. This would be a violation of the AdS Distance Conjecture.

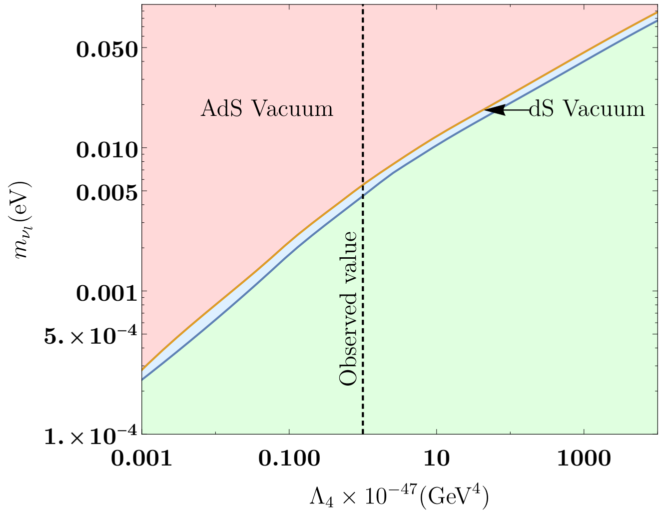


Figure: Bound on neutrino masses for 3 NH Dirac neutrinos.

$\Lambda_4 = 0$

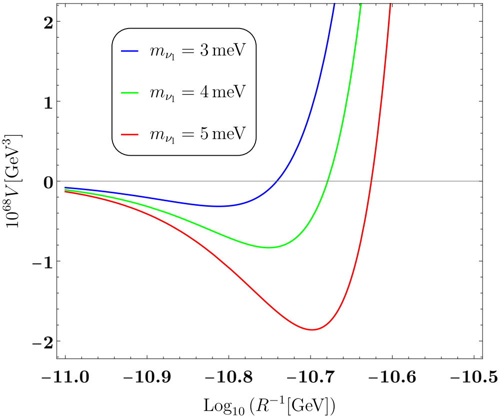


Figure: As the mass of the lightest neutrino gets smaller, $|V_0|$ gets smaller, R_0 gets larger. This is consistent with the AdS Distance Conjecture.

We have found:

$$M_{\text{KK}}^2 = \frac{n^2 r^2}{R^4}.$$

$$\Lambda^{3d} = \frac{V_{\text{eff}}(R_0)}{M_p^{3d}} = \frac{d(n_b, n_f, \Delta m_f) r^3}{R_0^6 M_p^{3d}}.$$

According to the AdS distance conjecture:

$$|V_0|^\alpha \sim M_{KK} \sim \frac{r}{R_0^2}$$

So we find $\alpha = 1/3$:

$$M_{KK} = \frac{(M_p^{3d})^{1/3}}{d^{1/3}} (\Lambda^{3d})^{1/3} = c(\Lambda^{3d})^{1/3}$$

For the mass differences in the SM we find $c = 21$. For three fermions of the same mass we find $c = 13$.

Results for the AdC

- $\Lambda_{4d} \neq 0$
  1. The mass lightest neutrino is bounded from above $m_\nu^4 \lesssim \Lambda_4$.
  2. Further consequences in upcoming work.
- $\Lambda_{4d} = 0$
  AdC combined with squared version of dS conjecture, $|\nabla V|^2 \geq c^2 V^2$ suggests $\alpha \geq \frac{1}{2}$.
  1. We find consistency with AdC but violation of $\alpha \geq \frac{1}{2}$, since we found $\alpha = \frac{1}{3}$.


THANK YOU FOR WATCHING
THE END