Pair Production and Gravity as the Weakest Force

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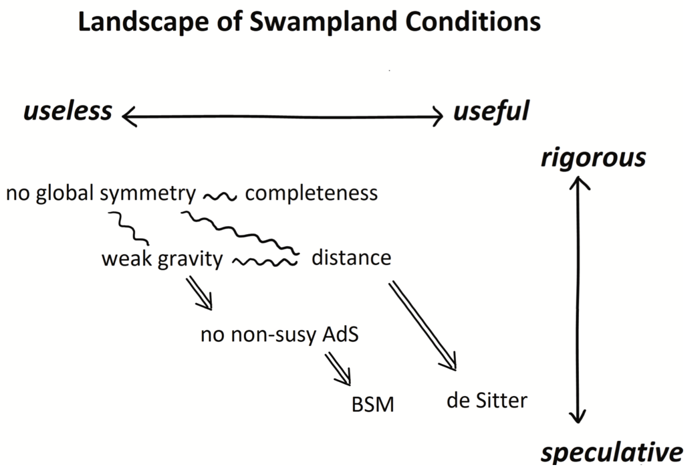
Summer Series on String Phenomenology


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

Plan for the talk


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

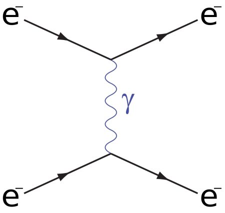
Weak Gravity Conjecture

- 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)

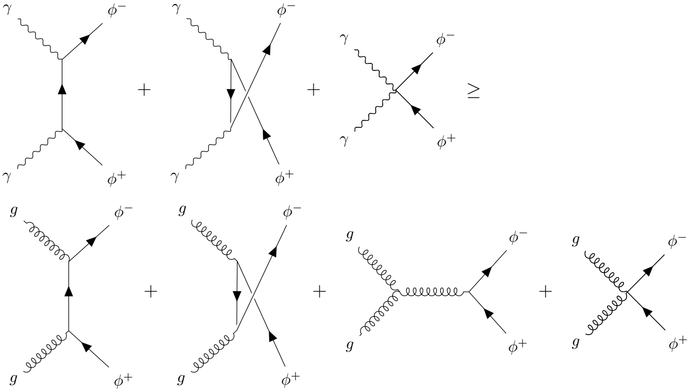
Motivation PPWGC

- 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:



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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.

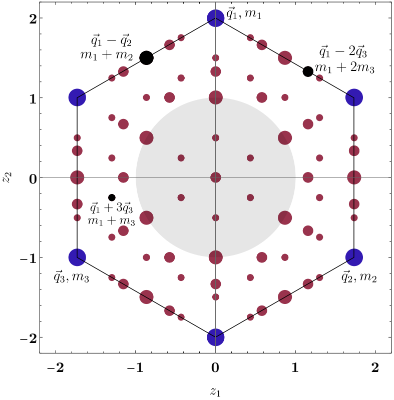
Weak Gravity Conjecture

- The idea is to use pair production/annihilation to arrive at a weak gravity condition which not only includes the requirements black-hole decay but also says something about massless scalar mediators.
- We will try to formulate a general principle that reduces to black-hole extremality 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.



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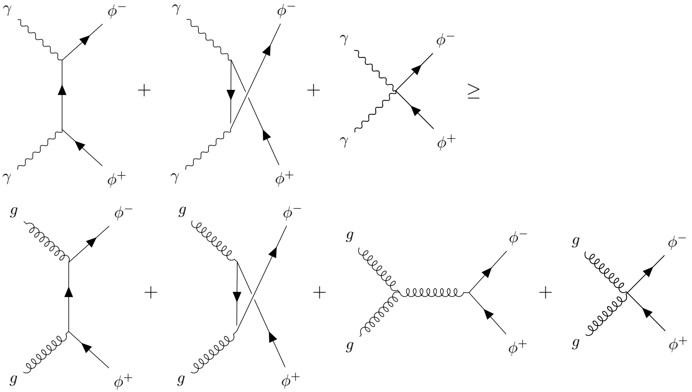
> For every rational direction in the charge lattice there is a superextremal multiparticle state

- That is, the convex hull encloses the BH region.
- Tower and Sublattice versions require infinitely many superextremal particles along each rational direction.

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 and 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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$+$
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ϕ^-
g
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

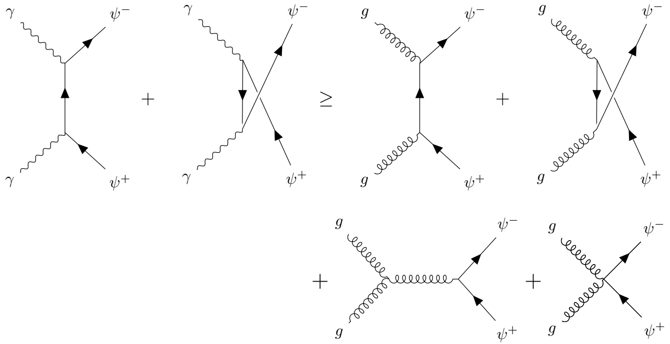
$$\mathrm{A}_{++} = \frac{2e^2\left(m^4 - ut\right)}{(t-m^2)(u-m^2)} \quad ; \qquad A_{+-} = -\frac{2e^2 m^2 s}{(t-m^2)(u-m^2)} .$$

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

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

The PPWGC then gives us:

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



γ
ψ^-
γ
ψ^+
$+$
$\geq$
g
ψ^-
g
ψ^+
$+$

- 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

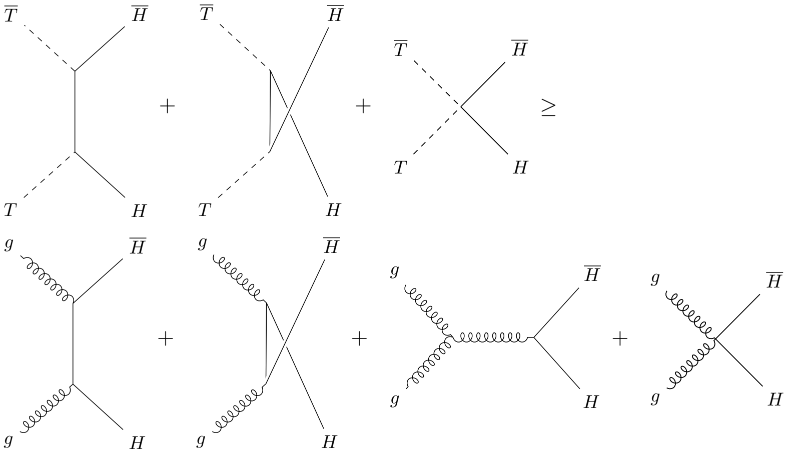
> PPWGC. For every rational direction in the charge lattice there is a (meta)stable particle which is superproduced

- 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.
- The constraint disappears as $M_p \to \infty$, unlike other versions of the WGC involving scalars.

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

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

- 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?

1. If the potential of scalar fields is a function of the mass of the WGC fields. Moduli mass arise from loops of heavy particle.
2. **Strong SWGC**.The moduli themselves acquire masses obeying the same constraint because their self-interaction needs to be stronger than gravity.

- **Strong SWGC**.The moduli themselves acquire masses obeying the same constraint because their self-interaction needs to be stronger than gravity.

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

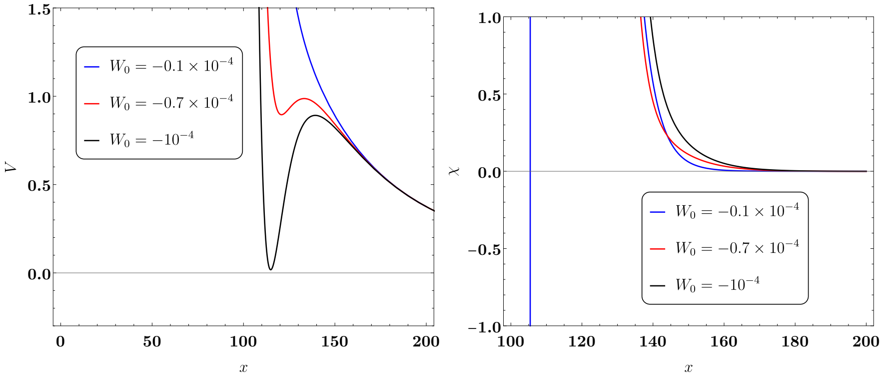
- Similar sSWGC as [1] but with absolute value: purely Swampland.
- Axion potential $V(\eta) = -M^4\cos(\eta/f)$ as long as the decay constant $f \leq M_p$.
- Higgs-like potential of the form $V = m_0^2\phi^2/2 + \lambda\phi^4/4!$:

$$\boxed{\left|(\lambda\phi)^2 \ - \ \lambda(m_0^2 \ + \ \frac{\lambda}{2}\phi^2)\right| \ \geq \ \frac{(m_0^2 + \frac{\lambda}{2}\phi^2)^2}{M_p^2}}$$

[1] E. Gonzalo and L. Ibañez '19

- The sSWGC without the absolute value can be violated at $\phi = 0$. Repulsive case would be in the Swampland.
- Based on this observation several counter-examples were argued in Freivogel, Gasenzer, Hebecker and Leonhardt '20.
- It would be interesting to generalize to more realistic case of the SM (gauge couplings, top Yukawa, running).
- In particular $\lambda(h) \to 0$ at $\sim 10^{11}$ GeV in the SM which would mean scalar interactions become weaker than gravity and signal new physics at or before this scale.

- Test on KKLT for example.



1. **WGC** determined by BH extremality bound.
2. **RFC** forbids gravitational bound states. It is determined by the non-relativistic potential.
3. **PPWGC** determined by pair production diagrammatics.

> **Question:**
> Do they coincide under some circumstances or assumptions?

- Connection between the first two has been studied in Lee, Lerche, Weigannd '19 and Gendler, Valenzuela '20.
- Studying the connection with the PPWGC is a work in progress.

- Take photons+moduli+gravity

$$|\mathrm{T}(\gamma\gamma \longrightarrow MM^*)|^2_{\text{th}} \geq$$
$$|\mathrm{T}(\mathrm{gg} \longrightarrow MM^*)|^2_{\text{th}} + |T(\phi_i\phi_j \longrightarrow MM^*)|^2_{\text{th}} + |T(\phi_i g \longrightarrow MM^*)|^2_{\text{th}}$$

For every rational direction in the charge lattice and for every point in moduli space there is a particle whose pair production by photons is larger than the sum of rates by gravitons and moduli.

- We leave further stringy tests and comparing this conjecture with WGC and RFC for future work.

- First direct derivation of a SWGC from a general principle that includes CHC condition.
- Purely Swampland, unlike other versions of the WGC involving scalars.
- The precise inequality depends on the Lagrangian.
- 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.


THANK YOU FOR WATCHING
THE END