Fermions and the Swampland

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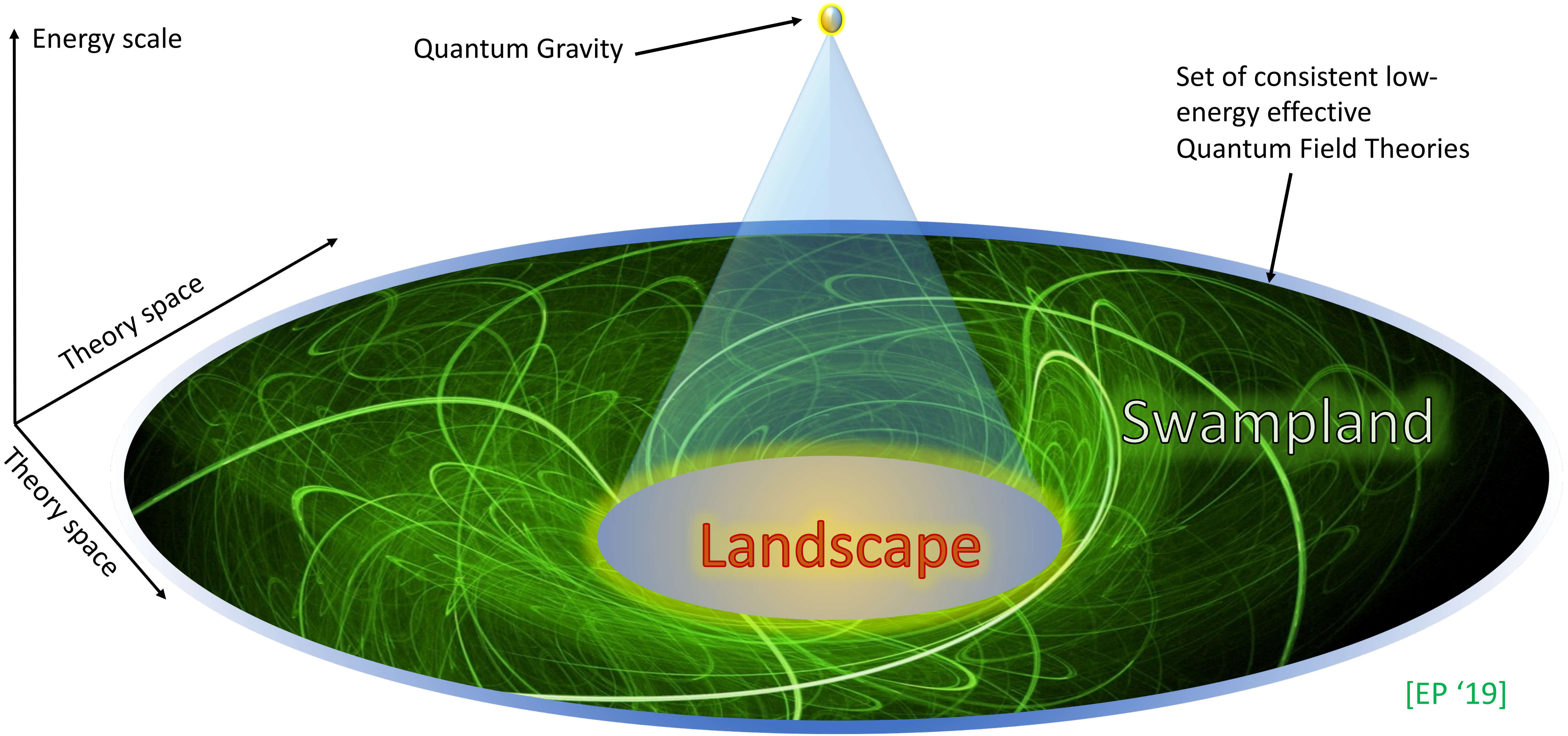
The **Swampland** is defined as all the apparently consistent effective theories that cannot be completed to Quantum Gravity in the ultraviolet

[Vafa '05]



[EP '19]

The **Weak Gravity Conjecture**

[Arkani-Hamed, Motl, Nicolis, Vafa '06]

$$S = \int \sqrt{-G}\left(M_p^2 R - \frac{1}{4g^2}F^2 + \cdots\right)$$

- *Must have a charged particle with mass smaller than charge*

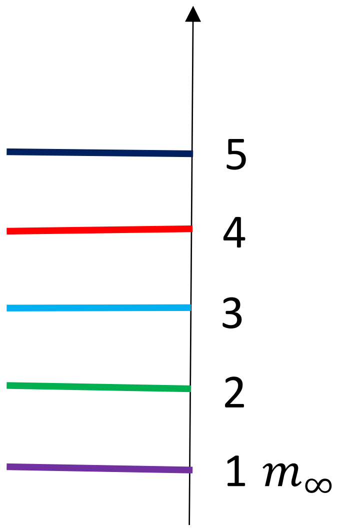
$$g\, q\, M_p \geq m$$

Electric WGC

- *There exists an infinite tower of states with mass scale* m_∞ *at*

$$m_\infty \sim g\, M_p$$

Magnetic WGC



[Heidenreich, Reece, Rudelius '15; Klaewer, EP '16; Montero, Shiu, Soler '16; Grimm, EP, Valenzuela '18; Lerche, Lee, Weigand '18; Andriolo, Junghans, Noumi, Shiu '18]

The **Distance Conjecture**: [Ooguri, Vafa '06; Baume, EP '16; Klaewer, EP '16]

$$S = \int \sqrt{-G}\left(M_p^2 R - \ (\partial\phi)^2 + \cdots\right)$$

There exists an infinite tower of states with mass scale m_∞ such that

$$\mathrm{m}_\infty \sim e^{-\alpha \frac{\phi}{M_p}} M_p$$

for $\phi > M_p$.

[… Cecotti '15, EP '17; Grimm, EP, Valenzuela '18; Lee, Lerche, Weigand '18+'19+'20; Grimm, Li, EP '18; Corvillain, Grimm, Valenzuela '18; Joshi, Klemm '19; Blumenhagen, Klaewer, Schlechter '19; Marchesano, Wiesner '19; Font, Herraez, Ibanez '19; Grimm, Van De Heisteeg '19; Erkinger, Knapp '19; Grimm, Li, Valenzuela '19; Cecotti '20; Gendler, Valenzuela '20; Lanza, Marchesano, Martucci, Valenzuela '20; Heidenreich, Rudelius '20; …]

Can write the distance conjecture as

$$\mathrm{m}_\infty \sim e^{-\alpha \frac{\phi}{M_p}} M_p$$

$$m_\infty \sim \mu\, M_p \qquad\qquad \mu \equiv \partial_\phi m_\infty$$

Distance conjecture: holds true for $\phi > M_p$

Magnetic Scalar WGC: holds true for $\mu \ll 1$ (and independently of ϕ)

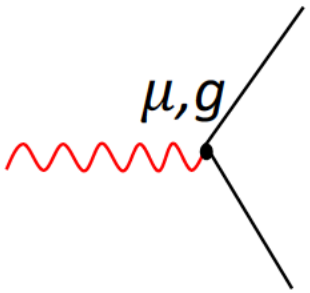
[EP ’17]

Passes simple tests in string theory (but as yet understudied)

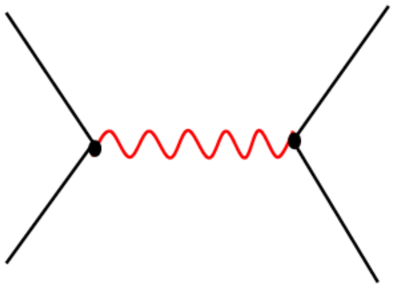
[EP ’20]

The conjectures take a similar form

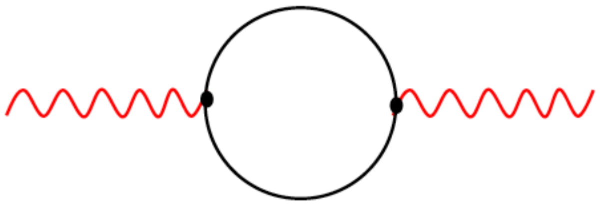
$$m_\infty \sim g\, M_p \qquad\qquad m_\infty \sim \mu\, M_p$$



Interpretation 1: Statement about self-force of particles



Interpretation 2: Statement about 1-loop running



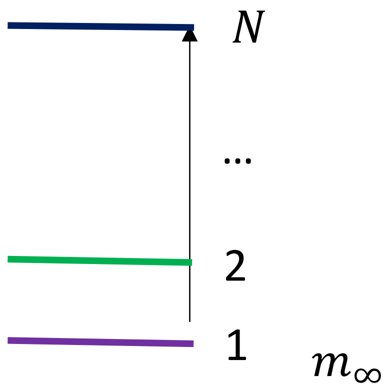
Can directly apply to the 3-point coupling

[Gonzalo, Ibanez ’20]

The 1-loop interpretation can be understood as the requirement of strong-coupling ‘unification’ (Emergence Proposal)

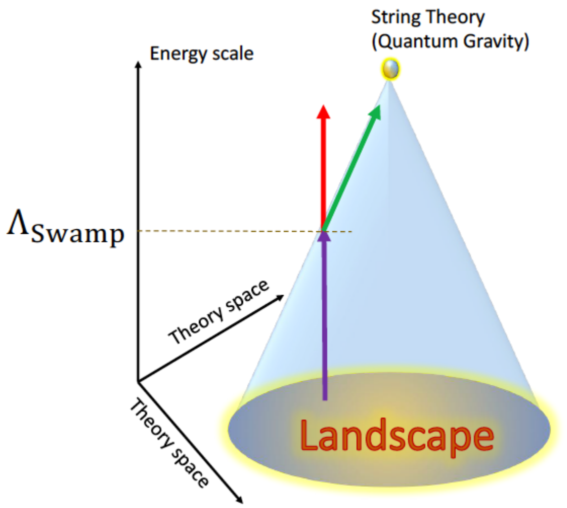
[Harlow ‘16; Grimm, EP, Valenzuela ’18; Heidenreich, Reece, Rudelius ‘17+’18; EP ’19]

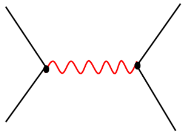
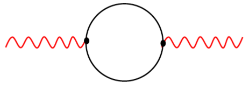
$$\frac{1}{g^2} \sim \sum_{n=1}^{N} q_n^2 \qquad N^3 \sim \left(\frac{m_\infty}{M_p}\right)^2 \qquad N\, m_\infty \sim \frac{M_p}{\sqrt{N}}$$



The WGC is equivalent to fixing the UV boundary condition to strong coupling at the Species scale

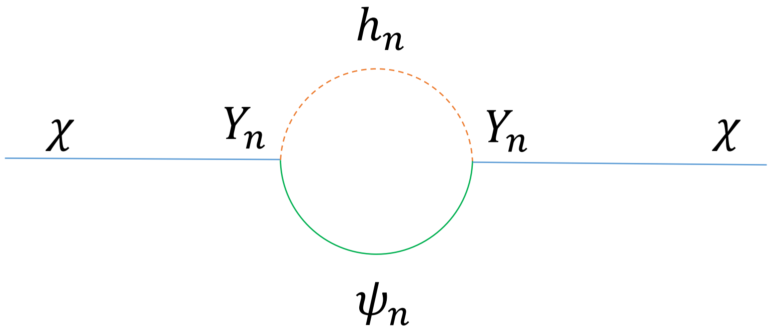
$$\frac{1}{g_{IR}^2} = \cancel{\frac{1}{g_{UV}^2}} + \sum_i^N \frac{q_i^2}{6\pi^2} log \frac{\Lambda}{m_i}$$



While  applies only to bosonic fields,  can be applied to Fermions

[EP ’20]

Fermionic WGC: $$S = \int \sqrt{-G}\left(M_p^2 R - \bar{\chi}\partial\chi + \cdots\right)$$



$$Y_n = n\, Y \qquad \boxed{m_\infty^Y \sim Y\, M_p}$$

Implies that the Fermion becomes ‘strongly coupled’ at same scale as the other dynamical fields

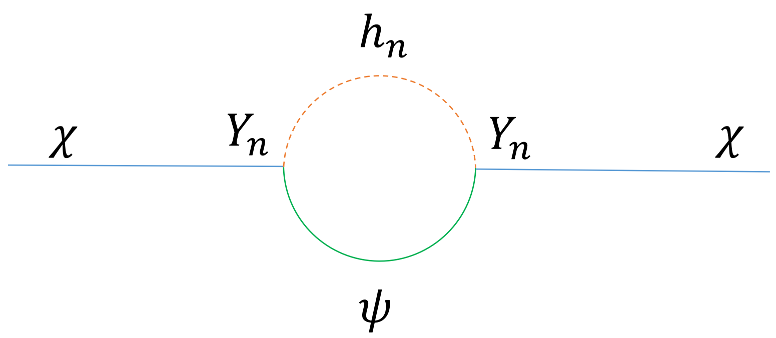
Importantly, the fermionic coupling has no normalization:

- Gauge (normalized): charge quantization implies g is universal, so small gauge coupling to one particle, implies small coupling to all particles.

- Scalar/Fermion (not normalized): can have a scalar/fermion couple with parametrically small coupling to one state, while coupling to other states strongly

Have a light tower of states only as a consequence of weak-coupling to the tower of states.

Theoretically possible to make work with only tower of scalars …



… but seems unlikely: what is ψ? How to handle charged fermions?

Also why a structure like $Y_n = n\,Y$?

A tower of fermion-scalar partners seems to imply: Supersymmetry!

Fermionic SUSY breaking conjecture: supersymmetry must be restored by the mass scale of the tower

$$m_{\cancel{SUSY}} < Y M_p$$

In a supersymmetric setting the Fermionic versions follow from bosonic:

- N=1 gauge multiplet: $\Upsilon = g$
- N=1 chiral multiplet: $\Upsilon = \mu$
- N=1 gravitino multiplet: Gravitino coupling $\frac{1}{M_p}\Psi_\mu\, S^\mu$ so 1-loop contribution to kinetic term from N particles goes as $N\left(\frac{\Lambda_s}{M_p}\right)^2 \sim 1$
- N=1 goldstino multiplet: works same as gravitino

$$\frac{1}{F}\overline{\chi}_G \partial_\mu S_m^\mu + \frac{1}{M_p}\chi_G \gamma_\mu \overline{S}_m^\mu$$

Possible to consider a **Strong SUSY breaking conjecture**:

$$m_{\cancel{SUSY}} < \{g, \mu, Y\}\, M_p$$

Significantly stronger because gauge coupling is normalized

Seems to pass simple tests in string theory [EP '20]

Highest scale of (effective) supersymmetry breaking is the string scale M_s

Can suppress coupling to all (including any tower) of states by string coupling

Extract string coupling dependence (in D dimensions)

$$\frac{1}{g_s^p} M_s^{(D-2)} (\partial\phi)^2 + \frac{1}{g_s^p} M_s^{(D-1)} \chi\partial\chi + \frac{1}{g_s^p} \hat{Y} M_s^D \phi\chi\chi$$

Find, $p = 1$ open strings, p=2 closed strings,

$$Y \sim \hat{Y} g_s^{\frac{\left(\frac{p}{2}-1\right)D+(4-p)}{D-2}} \qquad M_s \sim g_s^{\frac{2}{D-2}} M_p \qquad m_\infty^Y > M_s$$

Another high-scale SUSY breaking is Scherk-Schwarz reduction on circle

(This is related through various dualities to flux supersymmetry breaking)

Supersymmetry is broken at the Kaluza-Klein scale

Can universally suppress Yukawa couplings by making circle radius R large

$$\hat{M}_p^{(D-2)}\left(\partial\phi\right)^2+\hat{M}_p^{(D-1)}\chi\partial\chi+\hat{Y}\hat{M}_p^D\phi\chi\chi\;,\qquad \frac{\hat{M}_p}{M_p}\sim\frac{1}{\left(RM_p\right)^{\frac{1}{D-2}}}\qquad m_\infty^Y\sim YM_p\sim\hat{Y}\hat{M}_p\;.$$

$$M_{KK}\sim\frac{\hat{M}_p}{RM_p}\sim\frac{m_\infty^Y}{\hat{Y}RM_p}\;.$$

Can also consider more complicated string setups, e.g. Large Volume Scenario: $M_{SUSY}\sim Vol^{-1}, Y\sim Vol^0$ or $Vol^{-\frac{1}{2}}$ [BBCQ '05]

Summary

Quantum Gravity manifests certain apparently universal constraints on low-energy effective theories not to lie in the Swampland

Proposed constrains which arise from the presence of Fermions: must have a (tower of) states with mass less than their Yukawa coupling to the Fermion (in Planck units)

$$m_\infty^Y \sim Y\, M_p$$

Does not mean that a Fermion with a small Yukawa coupling to some particle implies a light tower

Proposed that supersymmetry must be restored at the tower mass scale

Strong version applies to gauge couplings too $\quad m_{\cancel{SUSY}} < g\, M_p$

Thank You