The Landscape and the Swampland: quantum gravity constraints on 4d effective field theories

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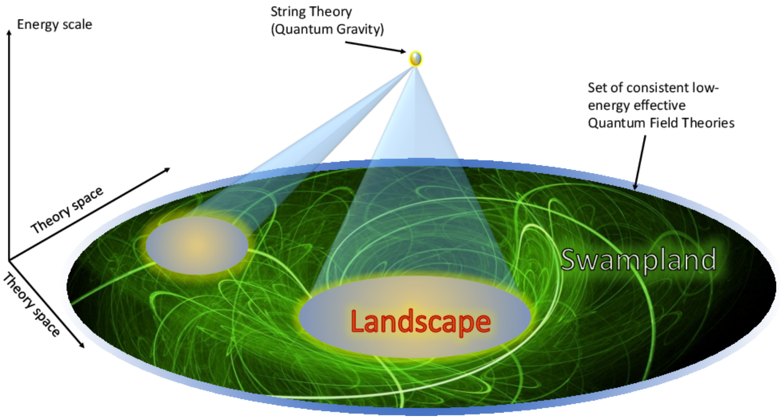
The Landscape and the Swampland

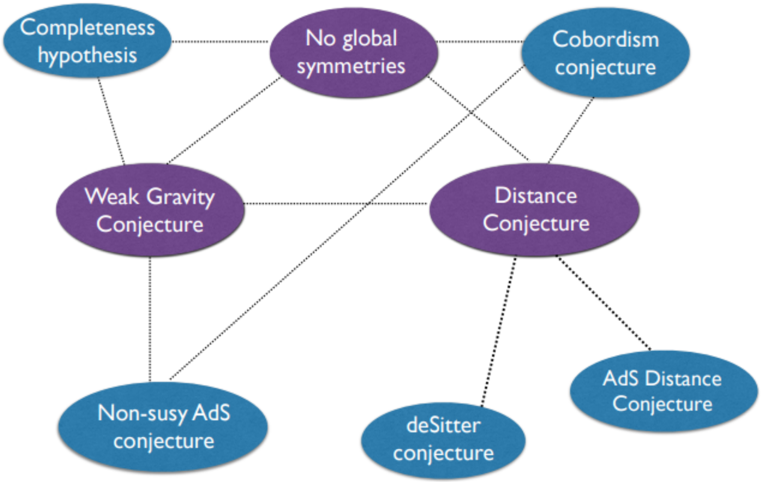


The Swampland Conjectures

The main Swampland Conjectures are:

- No-global-symmetries Conjecture
- Completeness Conjecture
- Infinite Distance Conjecture
- Weak Gravity Conjecture
- Anti-de Sitter Conjecture
- De Sitter/TC Conjecture

The Swampland Conjectures



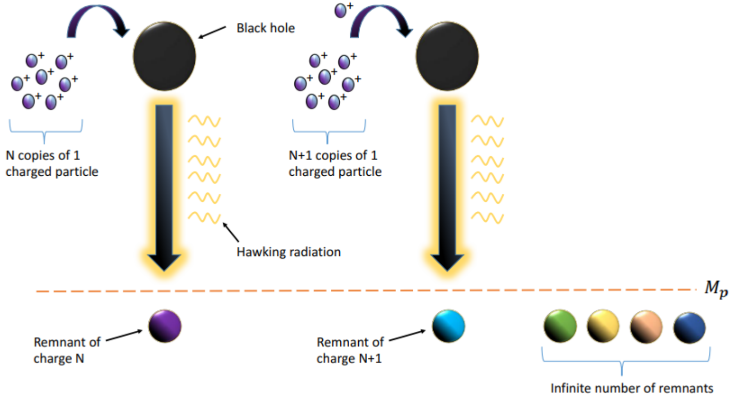
The No-Global Symmetries Conjecture

In a theory of quantum gravity, all global symmetries must be broken or gauged. Similarly, this should be true in any effective theory of gravity that might be UV completed to quantum gravity.

One of the most rigorous and old. Rooted in semi-classical black hole physics and entropy bounds. Unfortunately, it tells us little about concrete model building

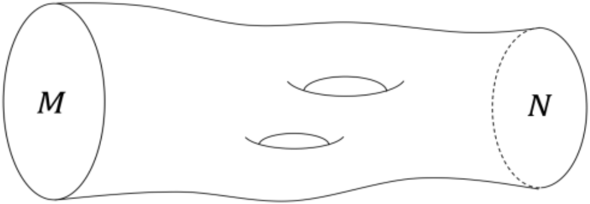
Cobordism conjecture closely linked

Why No-Global Symmetries?



The Cobordism Conjecture

We can associate a k-cobordism group Ω_k^{QG} to a d-dimensional (effective) theory of quantum gravity, and such group must be trivial $\Rightarrow \Omega_k^{QG} = 0$.



The Completeness Conjecture

A theory of quantum gravity should contain all possible (quantized) charged states under all the charges of the theory.

Validity strictly related to no-global symmetries through the breaking of Chern-Weyl global symmetries

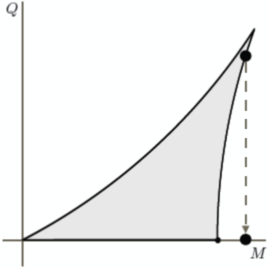
The Weak Gravity Conjecture

A theory of quantum gravity with $U(1)$ gauge symmetry should always contain a particle whose $U(1)$ charge to mass ratio is bigger than that of an extremal charged black hole in the same theory.

$$\frac{Q_i}{M_i} > \left(\frac{Q}{M}\right)_{ext} \tag{1}$$

Validity comes from the possibility to decay for extremal black holes.

The Festina Lente Bound



Strictly related to the WGC, the Festina Lente bound can be seen as an additional constraint for charged particles in de Sitter space-time coming from the same arguments of the WGC.

$$M_i^2 \gtrsim \sqrt{6} g M_{Pl} H \qquad (2)$$

While the WGC only tells us about the existence of a single particle state, the FL bound applies to all charged particles.

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The Distance Conjecture

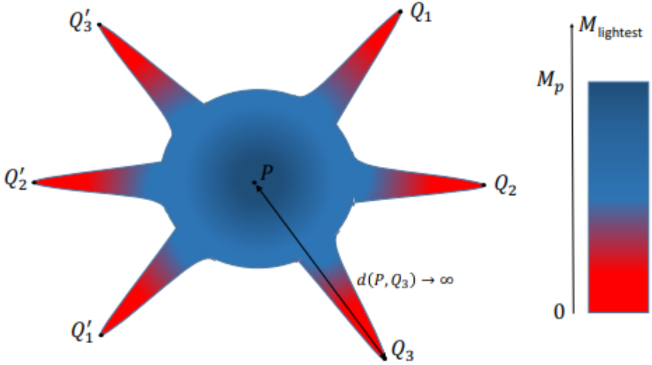
In an effective field theory of quantum gravity with a moduli space of scalar vevs, it is always possible to find a point in that moduli space whose distance from any other arbitrary point is arbitrarily large. In addition, the effective field theory will always break down at those infinite distance points due to the presence of an infinite tower of particle states becoming exponentially light with the distance in moduli space.

$$M_T(p) = M_P e^{-\lambda d(p_0,p)} \tag{3}$$

Always true in known examples from string theory. AdS conjecture

comes from it.
In its elementary form, it tells us nothing about the nature of the tower itself. Further refinement is the Emergent String Conjecture.

The Distance Conjecture



The de Sitter Conjecture

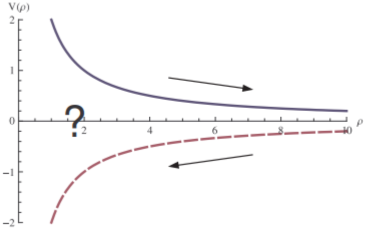
In an effective theory of quantum gravity with scalar potential V, in the asymptotic perturbative limit the following inequalities hold:

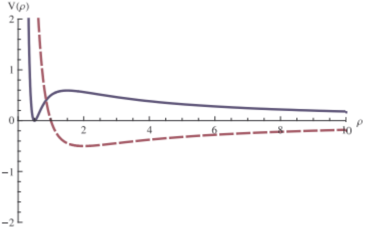
$$\frac{|\nabla V|}{|V|} \geq c_1 \quad \text{if} \quad |\nabla V| \neq 0 \tag{4}$$

$$\frac{|V''|}{|V|} \leq c_2 \quad \text{if} \quad |\nabla V| = 0 \tag{5}$$

Less rigorous than the previous ones, since based mainly on generalization of the Dine-Seiberg problem, explicit string examples in the perturbative limit known so far and arguments about de Sitter entropy and transplanckian modes.

Why de Sitter Conjecture?



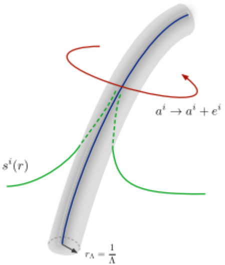


From Trans-Planckian Censorship arguments one gets

$$|V'| \geq \frac{2}{\sqrt{(d-1)(d-2)}} V \tag{6}$$

EFT Strings

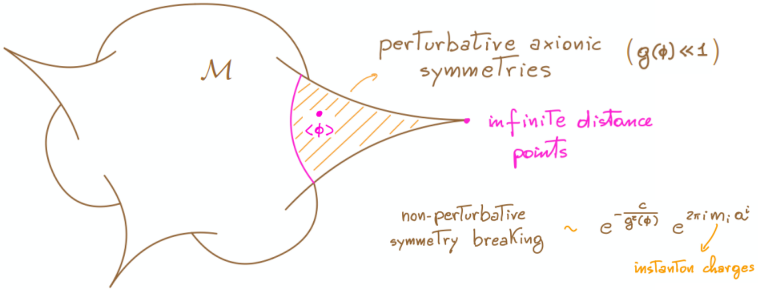
Extended (1+1)d objects appearing in 4d $N = 1$ supergravity due to the Completeness Conjecture.
They come from partially wrapped Dp-branes in concrete string theory examples.



They cannot be resolved by the field theory, they are in some sense "fundamental".
They possess axion charges, that it they act as a source for axion field profiles (and their corresponding saxion super-partners).

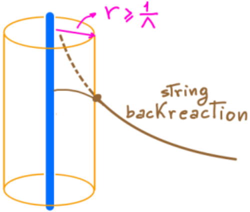
EFT Strings

The back-reaction induced by EFT strings on saxions can be interpreted as a RG flow and the limit in which we approach the string as an infinite distance limit. In such limit, an approximate global axionic symmetry emerges, broken by non-perturbative effects only.



EFT Strings

String probes has been already used in settings with more dimensions and supersymmetries in order to put constraints on the EFT [Kim,Shiu,Vafa '19, Katz,Kim,Tarazi,Vafa '20,...]. In 4d, the problem of low codimension arises. But EFT strings are such to admit anyway a weakly coupled description in terms of a (0,2) NLSM.



[Lanza-Marchesano-LM-Valenzuela '20-'21]

EFT strings strongly characterize the infinite distance asymptotic region of moduli space and their charges are quantized.

Anomaly Inflow

The mere existence of those strings in the effective theory limits the features of the theory itself. Not every 4d $N = 1$ supergravity theory can couple consistently to EFT strings.

In fact, their presence breaks gauge symmetries and Lorentz invariance at tree level. To see this, we can notice the theory will involve (s)axionic couplings of the form

$$-\frac{1}{2}\int\left(C_i s^i + \dots\right)\mathrm{Tr}(F\wedge * F) - \frac{1}{2}\int\left(C_i a^i + \dots\right)\mathrm{Tr}(F\wedge F) \quad (7)$$

$$-\frac{1}{48}\int\left(\tilde{C}_i s^i + \dots\right)\left[\mathrm{Tr}(R\wedge * R) + \dots\right] - \frac{1}{48}\int\left(\tilde{C}_i a^i + \dots\right)\mathrm{Tr}(R\wedge R) \quad (8)$$

Anomaly Inflow

That can be written as

$$\begin{aligned} S_{\text{bulk}} &\supset \int a^i I_{4,i} = -\int \mathrm{d}a^i \wedge I_{3,i} \\ \text{with} \quad I_{4,i} &= \mathrm{d}I_{3,i} = -\frac{1}{2} C_i \, \mathrm{Tr}(F \wedge F) - \frac{1}{48} \tilde{C}_i \, \mathrm{Tr}(R \wedge R) \end{aligned} \tag{9}$$

But in presence of the string we have

$$\mathrm{d}^2 a^i = e^i \delta_2(\Sigma) \tag{10}$$

Via the anomaly inflow mechanism, the breaking contribution is localized on the worldsheet of those strings.

$$\delta S_{\text{bulk}} = -e^i \int_\Sigma \delta I_{2,i} \neq 0 \tag{11}$$

Anomaly Matching

From the properties of EFT strings we immediately get

$$\{\langle \mathbf{C}^{AB}, \mathbf{e}\rangle\} \geq 0\,, \quad \langle \mathbf{C}^{I}, \mathbf{e}\rangle \geq 0\,, \qquad \forall \mathbf{e} \in \mathcal{C}_{\mathrm{S}}^{\mathrm{EFT}} \tag{12}$$

Furthermore, we have to require the matching between the anomaly from the bulk and the 1-loop anomaly of the matter on the worldsheet.

Fermion	#	$U(1)_{\mathrm{N}}$	$U(1)_A$	G_I repr.	(0,2) multiplet
ρ_+	1	$\frac{1}{2}$	0	$\mathbf{1}$	chiral U
χ_+	n_{C}	$-\frac{1}{2}$	$*$	$*$	chiral Φ
ψ_-	n_{F}	0	q_A	$\mathbf{r}_I$	Fermi Ψ_-
λ_-	n_{N}	$\frac{1}{2}$	0	$\mathbf{1}$	Fermi Λ_-

(13)

Anomaly Matching

By imposing cancellation with the chiral degrees of freedom living on the worldsheet

$$I^{\mathrm{ws}}_{4\,\mathbf{e}} = -\frac{n_{\mathrm{F}} - n_{\mathrm{C}} + n_{\mathrm{N}} - 1}{192\pi^2}\,\mathrm{tr}(R_W \wedge R_W) + \frac{n_{\mathrm{C}} - n_{\mathrm{N}} + 1}{32\pi^2} F_{\mathrm{N}} \wedge F_{\mathrm{N}} \tag{14}$$

We get a first non-trivial condition on the lagrangian coefficients

$$\langle \tilde{\mathbf{C}}, \mathbf{e} \rangle \in 3\mathbb{Z}_{\geq 0} \qquad \forall \mathbf{e} \in \mathcal{C}^{\mathrm{EFT}}_{\mathrm{S}} \tag{15}$$

This is interesting because it implies the positivity of the coefficient of the Gauss-Bonnet term in a susy setting, which is a result with already much evidence to support in literature, but never totally proved in 4d.

Bounds on the rank of the gauge group

But more importantly, we can use this information to derive an upper limit on the rank of the gauge group of the effective gravity theory.

$$r_{\mathrm{F}}(\mathbf{e}) \leq n_{\mathrm{F}} = \frac{4}{3}\langle \tilde{\mathbf{C}}, \mathbf{e} \rangle \tag{16}$$

It should be remarked that this "stronger" bound is derived in the assumption of only fermions contributing to the anomaly, that is true in many explicit cases.
In the general case, there is also a GS worldsheet term contributing, and we obtain a weaker bound:

$$r(\mathbf{e}) \leq \frac{4}{3}\langle \tilde{\mathbf{C}}, \mathbf{e} \rangle + \frac{2}{3}\langle \tilde{\mathbf{C}}, \mathbf{e} \rangle - 2 = 2\langle \tilde{\mathbf{C}}, \mathbf{e} \rangle - 2 \qquad \forall \mathbf{e} \in \mathcal{C}_{\mathrm{S}}^{\mathsf{EFT}} \tag{17}$$

That can be obtained also from CFT considerations.

Concrete examples: F-theory with O3-planes

Explicit check of the previous bounds has been carried out in concrete string theory constructions.

In the case of F-theory with no O7-planes an interesting result is

$$\tilde{C} = \frac{3}{16} n_{O3} \tag{18}$$

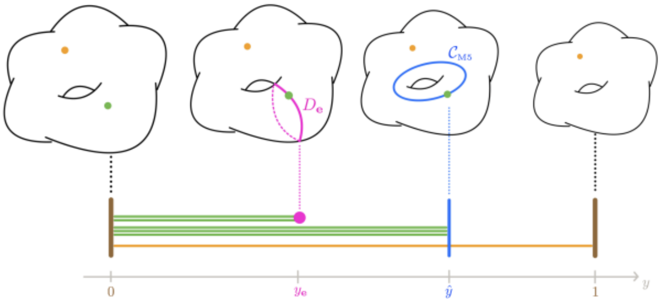
which tells us that the number of O3-planes must be a multiple of 16. But that's exactly what it was found in any consistent construction of F-theory background in various databases of Calabi-Yau orbifolds. In addition, it is forced by a theorem of algebraic geometry. The bound on the rank becomes the well-known tadpole bound.

Concrete examples: heterotic backgrounds

They were found to be always satisfied in 4d $N = 1$ EFTs coming from compactifications of $SO(32)$ and $E_8 \times E_8$ heterotic strings. The $E_8 \times E_8$ case with presence of NS5 branes was particularly interesting because our results hold in a non-trivial way, thanks to the interplay of various contribution to the effective lagrangian. Such computation was also confirmed by a dual description in the setting of Horava-Witten M-theory.

In particular for $SO(32)$ we find $\tilde{C}_i = 3n_i$, such that our conditions are automatically satisfied, while the expression for $E_8 \times E_8$ is more involved in terms of topological invariants of the compact manifold.

Concrete examples: heterotic backgrounds



The rank of the gauge sector was bounded as

$$r(\mathbf{e}_{F1/M2}) \leq 22$$
$$r(\mathbf{e}_{NS5/M5}) \leq 34 \qquad (19)$$

Those where exactly those that we would have expected from the counting of the worldsheet degrees of freedom of the fundamental string.

Concrete examples: F-theory backgrounds

The check in generic F-theory backgrounds was trickier. In this setting we find

$$\tilde{C}_i = 6\bar{K} \cdot \mathcal{C}_i \tag{20}$$

where $\bar{K}$ is the anti-canonical class of the compact manifold and $\mathcal{C}_i$ the effective curve of the D3-brane that is the EFT string from 4d perspective.

It is by performing this check that we realized the stronger bound is indeed too strong and only the weaker bound is always satisfied. The reason is the possibility of exotic matter content on the worldsheet coming from intersection on D7-branes with exceptional gauge sectors on them.

Concrete examples: F-theory backgrounds

Interestingly, when it is possible to apply the stronger bound, it results stronger than the well-known Kodaira bound coming from the Kodaira classification of singularity orders in F-theory

	$\mathrm{ord}(f)$	$\mathrm{ord}(g)$	$\mathrm{ord}(\Delta)$	singularity
I_0	≥ 0	≥ 0	0	none
$\mathrm{I}_n,\ n \geq 1$	0	0	n	A_{n-1}
II	1	1	≥ 2	none
III	1	≥ 2	3	A_1
IV	≥ 2	2	4	A_2
I_0^*	≥ 2	≥ 3	6	D_4
$\mathrm{I}_n^*,\ n \geq 1$	2	3	$6+n$	D_{4+n}
IV^*	≥ 3	4	8	E_6
III^*	3	≥ 5	9	E_7
II^*	≥ 4	5	10	E_8

Conclusions

- The Swampland conjectures help to distinguish between EFTs which can be consistently coupled to gravity and those which cannot, and might give us also non-trivial phenomenology;
- The presence of extended objects imposes strict constraints on the theory they couple to;
- EFT strings in particular are suitable to study those constraints, together with the asymptotic field space regions;
- Positivity of the GB term and upper bounds on the gauge group can be obtained from them and so far they are always satisfied in explicit string theory models.

Thanks for the attention