Branes and the Swampland

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String Pheno Turns 18!

Europe/Zurich English Login

String Phenomenology 2019

24-28 June 2019
CERN
Europe/Zurich timezone

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This conference is part of the String Geometry and String Phenomenology Institute (17-28 June).

The annual String Phenomenology conference discusses recent progress in compactifications of string theory and their relation to particle physics and cosmology.

Topics include:

- Swampland and Quantum Gravity Conjectures
- Formal and Mathematical Aspects of string compactifications (such as F-theory, G2 compactifications, heterotic compactifications, and other corners of the string landscape, e.g. non-geometric compactifications)
- String Model Building in particle physics and cosmology
- Machine Learning Techniques to explore the String Landscape

In this talk, I'll discuss our recent work in using strings/branes to probe the consistency of EFTs coupled to gravity:

- **Branes and the Swampland** **[Kim, GS, Vafa, 1905.08261]**

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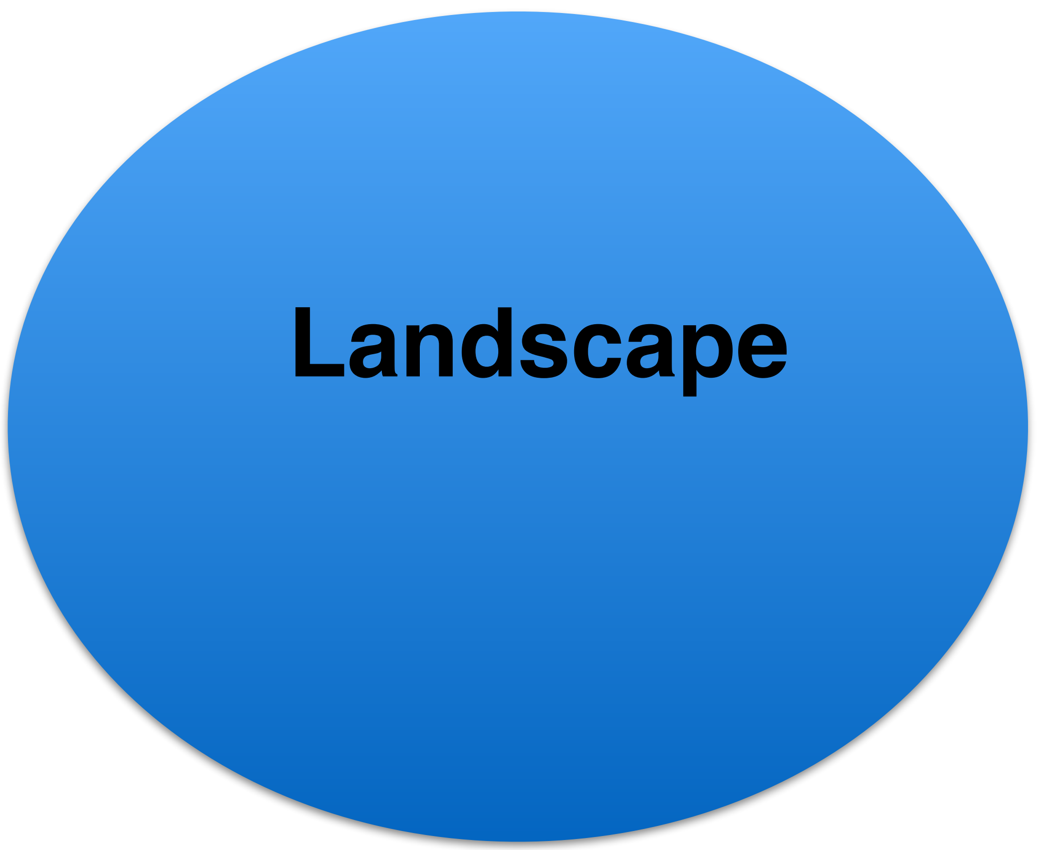
- **Branes and the Swampland [Kim, GS, Vafa, 1905.08261]**

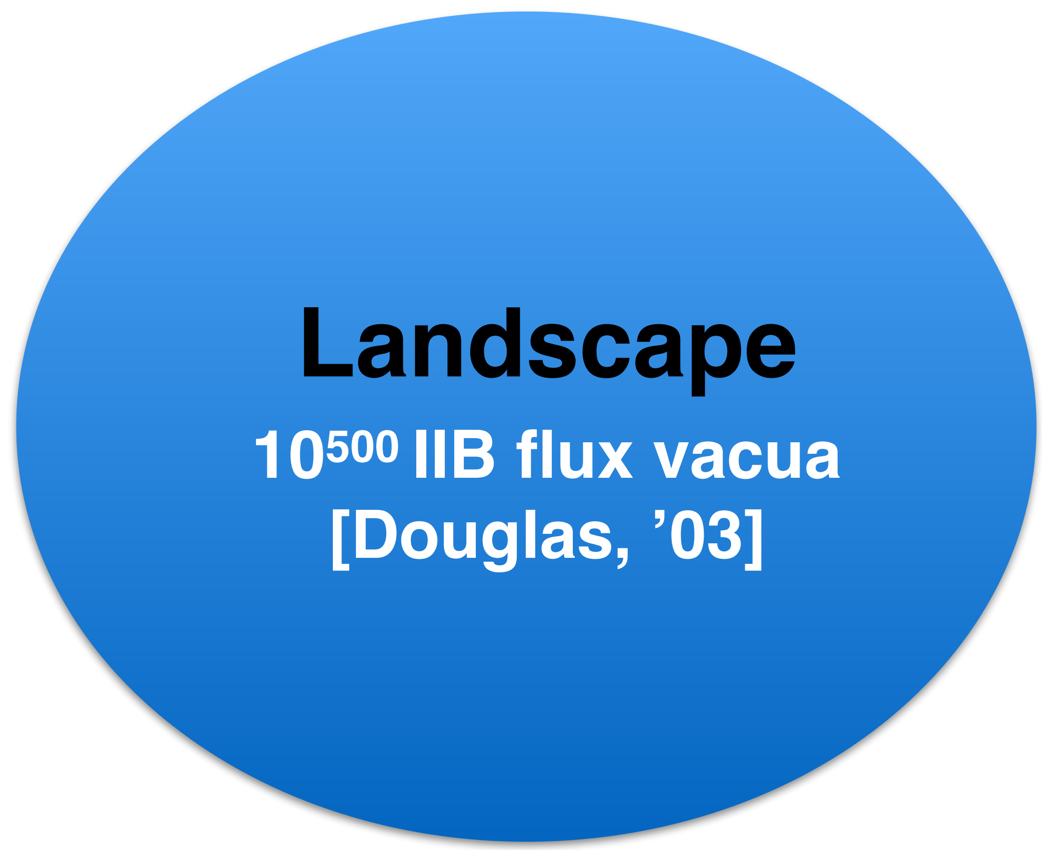
In the interest of time, I won't be able to cover other interesting works on:

- **Weak Gravity Conjecture (WGC):**
  - WGC, Black Hole Entropy, & Modular Invariance **[Aalsma, Cole, GS, '19]**
  - WGC from Unitarity and Causality **[Hamada, Noumi, GS, 18]**
  - Tower WGC **[Andriolo, Junghans, Noumi, GS, '18] (see Andriolo's talk)**
  - Strong WGC & Modular Bootstrap **[Montero, GS, '19] (see Montero's talk)**
- **de Sitter in String theory**
  - Distance and de Sitter Conjectures **[Ooguri, Palti, GS, Vafa, '18]**
  - Understanding KKLT from a 10d perspective **[Hamada, Hebecker, GS, Soler, '18, '19] (see Hebecker & Soler's talks)**
- **Data Science and String Theory:**
  - Topological Data Analysis **[Cole, GS, '18]** and Genetic Algorithm **[Cole, Schachner, GS, '19] (see Schachner's talk)** for the string landscape.

Landscape vs Swampland



Landscape vs Swampland



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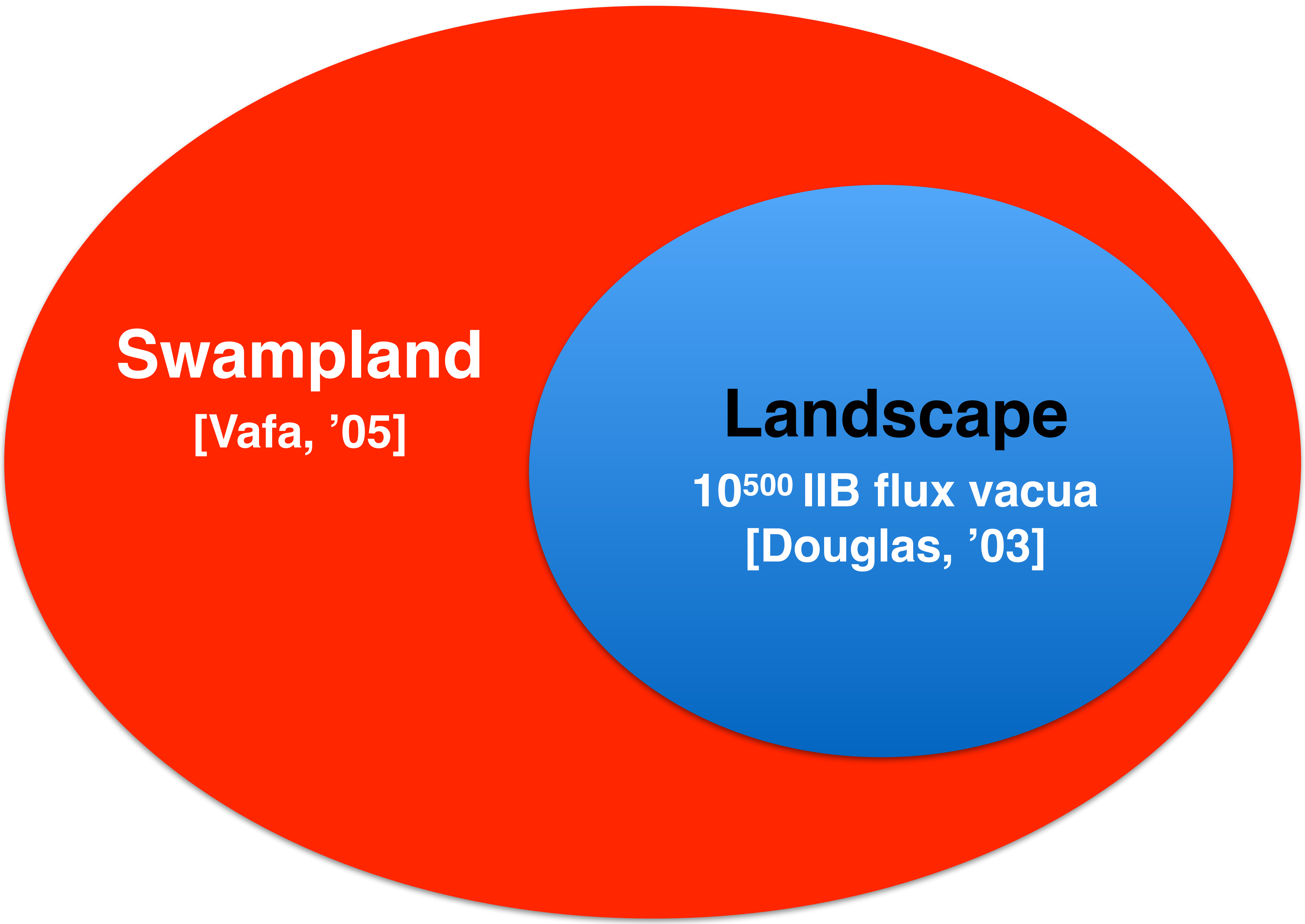

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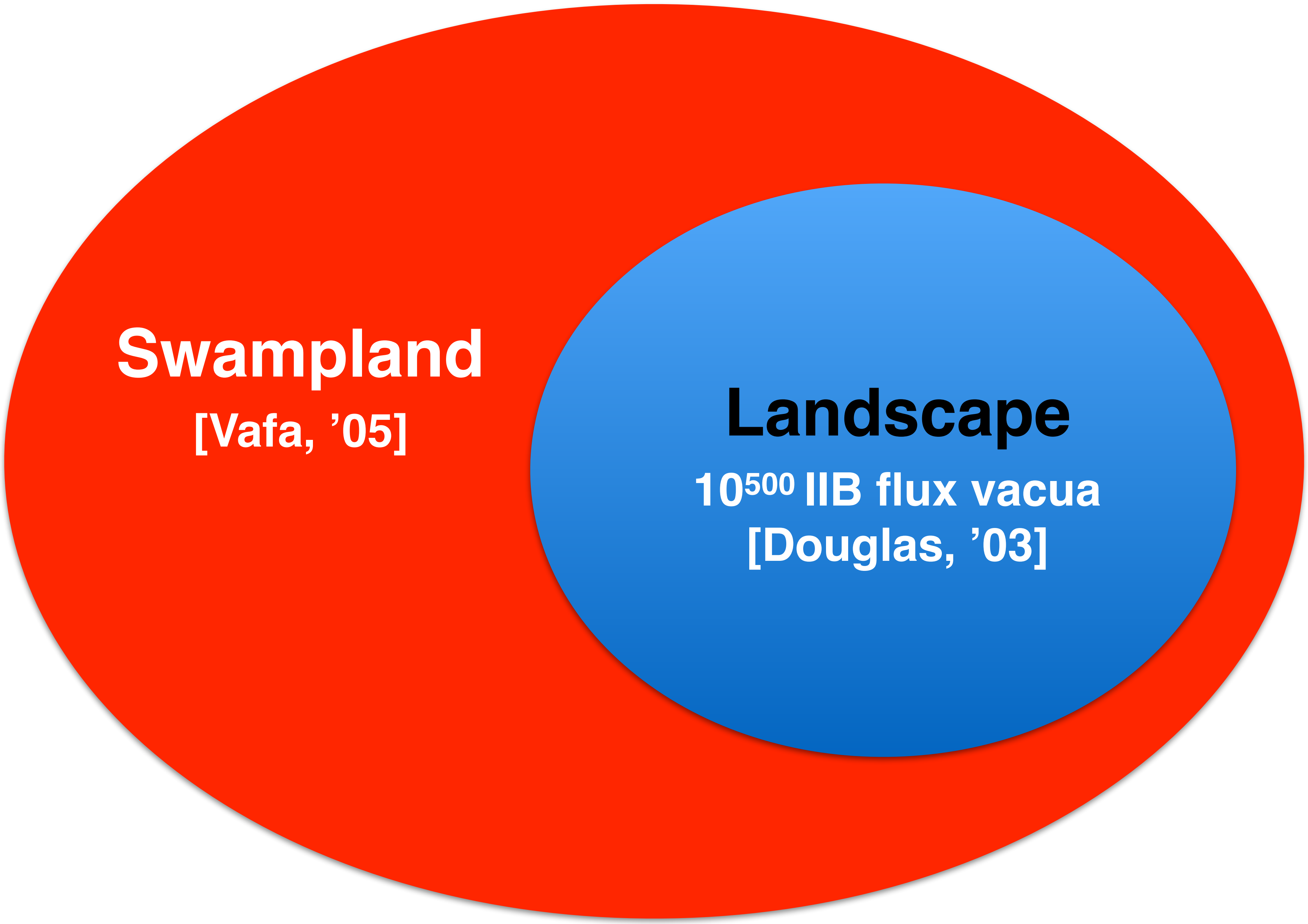
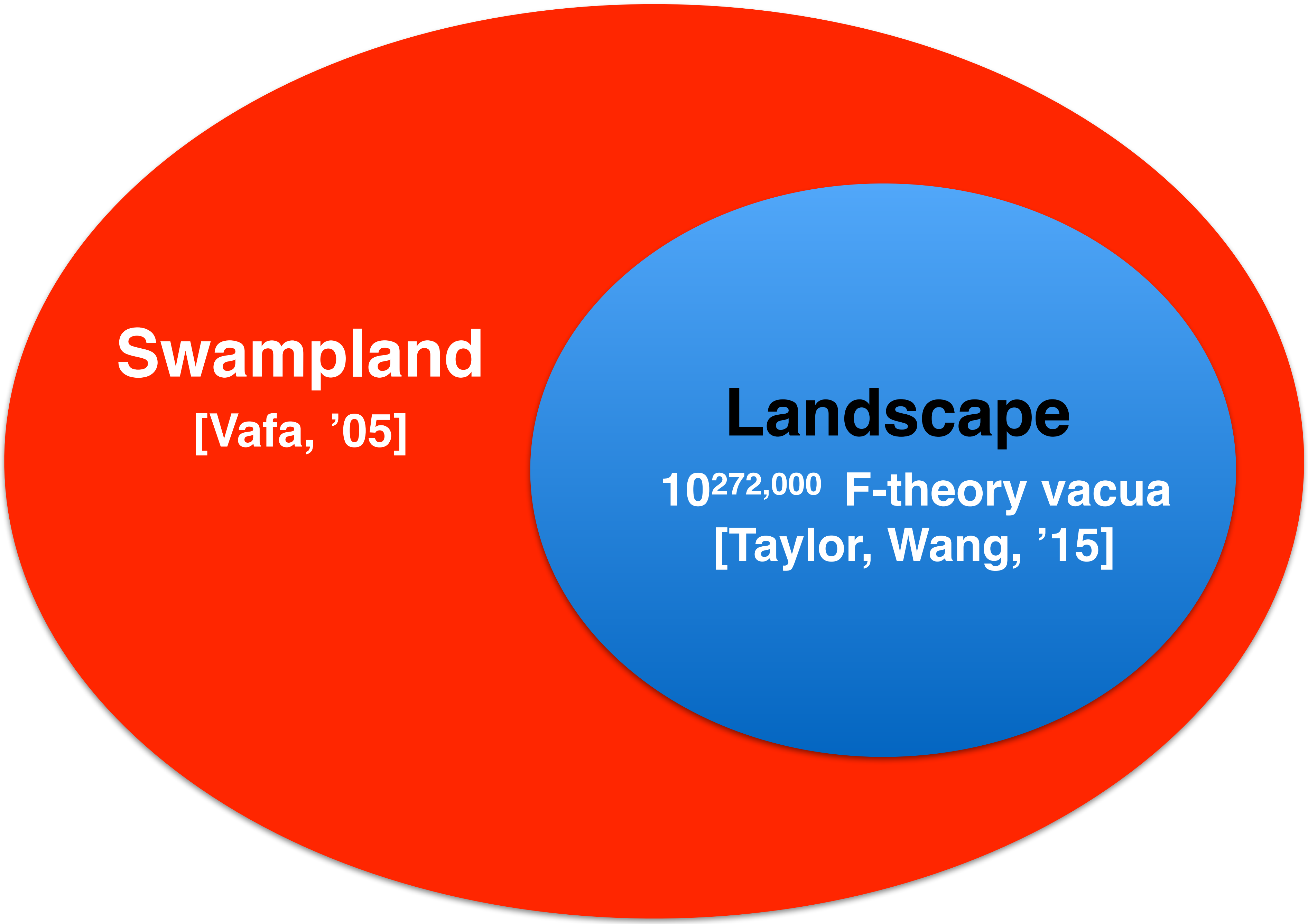


What properties delineate the landscape from the swampland?

What are the phenomenological implications? ***Is there a swampland?***

Landscape vs Swampland



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Swampland Criteria

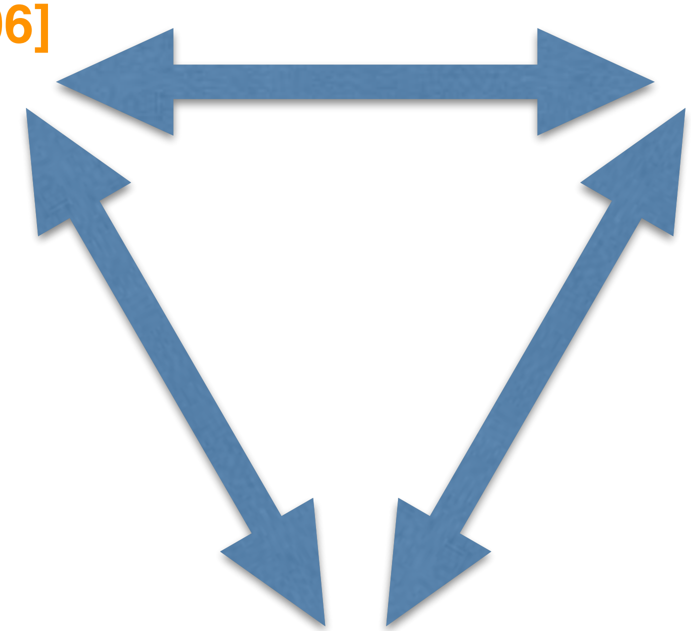
There are varying degrees of understanding for different swampland criteria and their interconnections:

Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa. ’06]

Distance Conjecture

[Ooguri, Vafa. ’06]



dS Conjecture

[Obied, Ooguri, Spodyneiko, Vafa,’18];
[Ooguri, Palti, GS, Vafa, ’18]

These criteria do not follow from purely low-energy EFT considerations.
Why are they necessary for consistency of quantum gravitational theories?

Branes and the Swampland

[Kim, GS, Vafa, ’19]

“Putting strings back into string pheno”

Branes and the Swampland

- Completeness of spectrum of charged branes **[Polchinski '03], [Banks, Seiberg, '10]:** use them to probe consistency of EFTs coupled to gravity.
- First consider N=(1,0) SUGRA theories in 10d & 6d as gauge and gravitational anomaly cancellations severely limit the possibilities.
- We illustrate the power of this approach with just a few examples and with only **string probes** but we expect this program of using **brane probes** to understand swampland criteria has wider applicabilities.
- We showed the 10d anomaly-free theories with $E_8 \times U(1)^{248}$ and $U(1)^{496}$ gauge groups that have no string realizations are in the swampland.
- Infinite families of anomaly-free 6d theories **[Kumar, Morrison, Taylor, '10]** with unbounded gauge group rank, or unbounded number of tensors or matter in exotic representations. We showed that **unitarity of current algebra on string probes** can rule out some of these infinite families.

Strings in 10d $N=(1,0)$ SUGRA

Anomaly Cancellation in 10d

- The gauge and gravitational anomalies of 10d N=(1,0) SUGRA theories can be cancelled by the Green-Schwarz mechanism **[Green, Schwarz, '84]** , allowing only 4 choices for gauge groups:

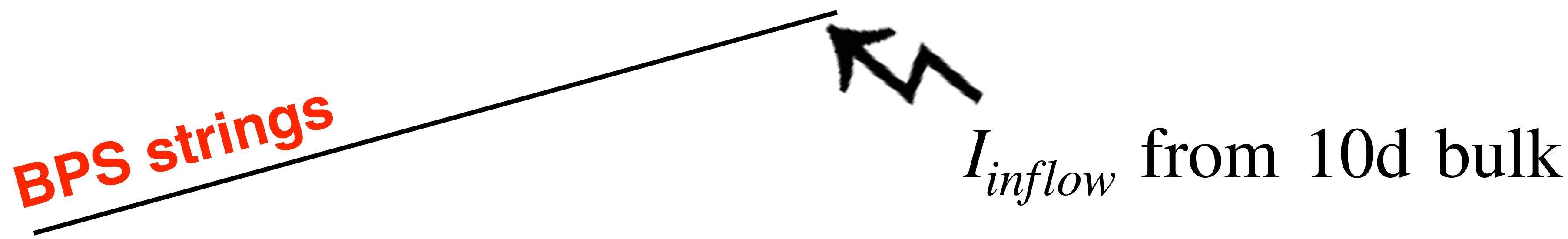
$$SO(32), \quad E_8 \times E_8, \quad E_8 \times U(1)^{248}, \quad U(1)^{496}$$

low energy limits of Type I and heterotic string theories

- The latter two were conjectured to be in the swampland **[Vafa '05]**.
- It was argued that anomaly cancellation cannot be made compatible with SUSY & Abelian gauge invariance **[Adams, DeWolfe, Taylor, '10]**
- In **[Kim, GS, Vafa, '19]**, we presented an independent argument ruling out the latter 2 theories by showing that the central charges on BPS strings in these theories are too small to realize the current algebra.

Strings in 10d

- Strings are sources for the 2-form tensor field B_2, which by the completeness assumption should exist; they are also stable ($\because$ BPS).



- A string with tensor charge Q adds to the 10d action:

$$S^{\rm str} = Q\int_{\mathcal{M}_{10}} B_2 \wedge \prod_{a=1}^{8} \delta(x^a)dx^a = Q\int_{\mathcal{M}_2} B \ .$$

- The 2-form B transforms under ***local gauge & Lorentz symmetries***:

$$B_2 \ \rightarrow \ B_2 - \frac{1}{4}\sum_i {\rm Tr}(\Lambda_i F_i) + {\rm tr}(\Theta R) \ ,$$

- The string action is ***not invariant***:

$$\delta_{\Lambda,\Theta} S^{\rm str} = Q\int_{\mathcal{M}_2}\left[-\frac{1}{4}\sum_i {\rm Tr}(\Lambda_i F_i) + {\rm tr}(\Theta R)\right] \ .$$

Anomaly Inflow

- Anomaly inflow along the worldsheet:

$$I_4^{\text{inflow}} = Q\left(-\frac{1}{4}\sum_i \mathrm{Tr}F_i^2 + \mathrm{tr}R^2\right)$$

- A **half-BPS string** in 10d gives rise to N=(0,8) SCFT at low energy: supercurrent on the worldsheet has a definite chirality (right-moving) and is opposite to that of the current for the group (left-moving).

- To cancel the anomaly inflow, the anomalies of the worldsheet SCFT:

$$I_4 = -I_4^{\text{inflow}} \;\; = Q\left[\frac{1}{2}p_1(T_2) - c_2(SO(8)) + \frac{1}{4}\sum_i \mathrm{Tr}F_i^2\right]$$

  where we used the decomposition:

$$\mathrm{tr}R^2 = -\frac{1}{2}p_1(T_2) + c_2(SO(8)) \;,$$

- The above result includes contributions from **center of mass dofs**.

Anomaly Inflow

- The com modes form a free (0,8) multiplet (X_μ , λ^I_+) with μ, I = 1, …8

$$X_\mu \text{ : motion in 8 transverse directions}$$

$$\lambda^I_+ \text{ : right – moving SO(8) spinor}$$

- The anomaly contribution from the center of mass modes:

$$I_4^{\rm com} = -\frac{1}{6}p_1(T_2) - c_2(SO(8)) \ .$$

- The anomaly of the interacting sector in the worldsheet SCFT (Q=1):

$$I_4' = I_4 - I_4^{com} = \frac{2}{3}p_1(T_2) + \frac{1}{4}\sum_i {\rm Tr} F_i^2 \ .$$

- The central charges & level of gauge algebras can be read off from:

$$I_4' = -\frac{c_R - c_L}{24}p_1(T_2) - \frac{c_R}{6}c_2(SO(8)) + \sum_i \frac{k_i}{4}F_i^2$$

Anomaly Cancellation on String Probes

- This gives: $c_L = 16\,, \quad c_R = 0\,, \quad k_i = 1$
- The central charges are constrained by **unitarity conditions** on the 2d CFTs which describe the IR dofs on the string.
- The central charge realizing level-k Kac-Moody algebra:

$$c_G = \frac{k \cdot \mathrm{dim} G}{k + h^\vee}$$

- For unitary CFT on a string:

$$\sum_i c_i = \sum_i \frac{k_i \cdot \mathrm{dim} G_i}{k_i + h_i^\vee} \leq c_L$$

- The unitary bound is violated for $E_8 \times U(1)^{248}$ and $U(1)^{496}$ **(they are in the swampland)** while it is saturated for SO(32) and $E_8 \times E_8$.

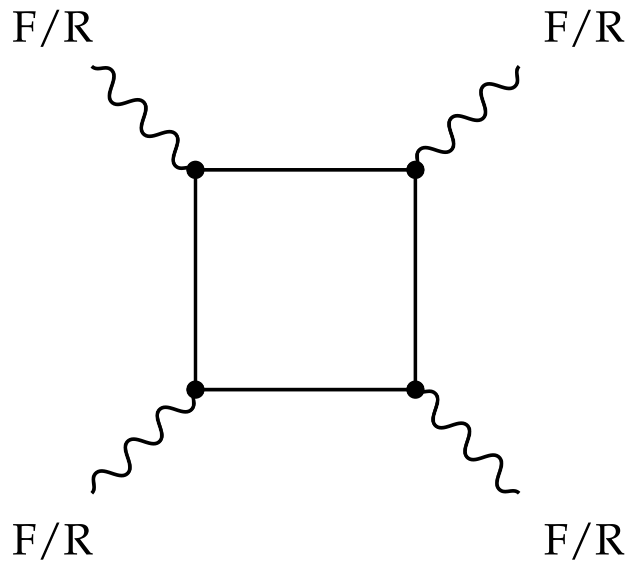
Strings in 6d $N=(1,0)$ SUGRA

Strings in 6d

- N=(1,0) SUGRA in 6d has 4 kinds of massless supermultiplets:

Multiplet	Matter Content
SUGRA	$(g_{\mu\nu}, B^{+}_{\mu\nu}, \psi^{-}_{\mu})$
Tensor (T)	$(B^{-}_{\mu\nu}, \phi, \chi^{+})$
Vector (V)	(A_{μ}, λ^{-})
Hyper (H)	$(4\varphi, \psi^{+})$

- The **chiral fields** (two-forms, gravitino, and other chiral fermions) contribute to the gauge and gravitational anomalies:



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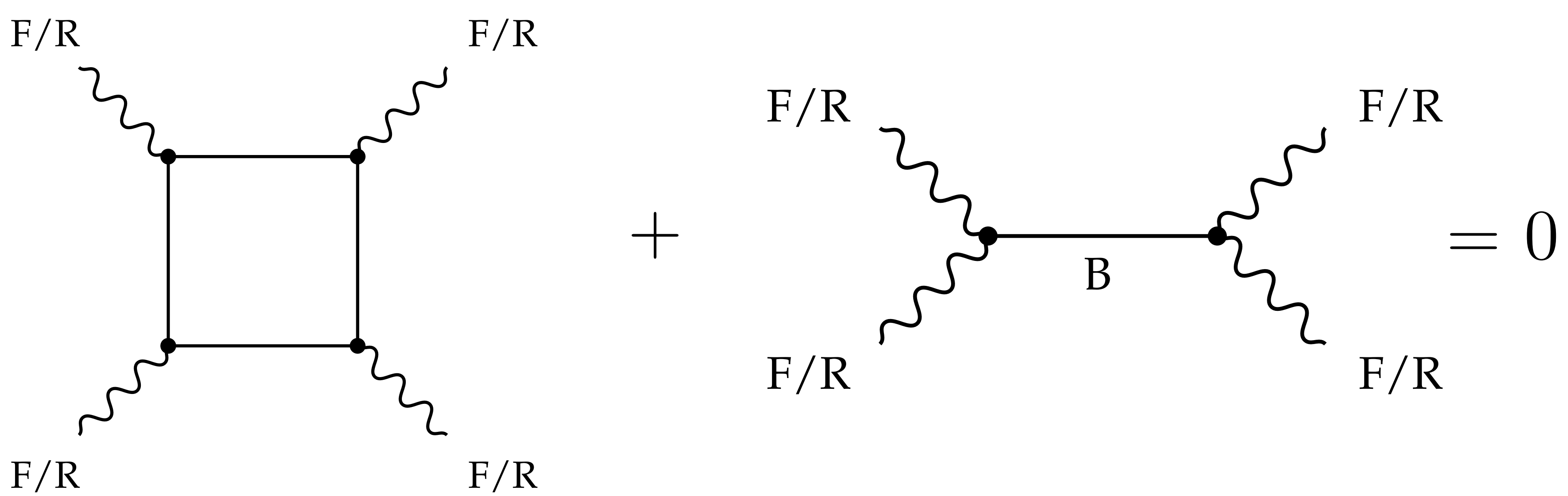

Green-Schwarz-Sagnotti Mechanism

- The anomaly polynomial factorizes:

[See Taylor's talk]

$$I_8^{1-loop} = \frac{1}{2}\Omega_{\alpha\beta}X_4^\alpha X_4^\beta \,,$$
$$X_4^\alpha = \frac{1}{2}a^\alpha \mathrm{tr}R^2 + \frac{1}{4}\sum_i b_i^\alpha \frac{2}{\lambda_i}\mathrm{tr}F_i^2 \,,$$

$\Omega_{\alpha\beta}$: symmetric with $(1,T)$ signature

$a^\alpha,\ b_i^\alpha$: vectors $\in \mathbb{R}^{1,T}$

- Factorization of the anomaly polynomial requires:

$$H - V = 273 - 29T \,, \quad a\cdot a = 9 - T \,,$$
$$0 = B^i_{\mathbf{adj}} - \sum_{\mathbf{R}} n^i_{\mathbf{R}} B^i_{\mathbf{R}} \,,$$
$$a\cdot b_i = \frac{\lambda_i}{6}\left(A^i_{\mathbf{adj}} - \sum_{\mathbf{R}} n^i_{\mathbf{R}} A^i_{\mathbf{R}}\right) \,,$$
$$b_i\cdot b_i = \frac{\lambda_i^2}{3}\left(\sum_{\mathbf{R}} n^i_{\mathbf{R}} C^i_R - C^i_{\mathbf{adj}}\right) \,,$$
$$b_i\cdot b_j = 2\lambda_i\lambda_j \sum_{\mathbf{R},\mathbf{S}} n^{ij}_{\mathbf{R},\mathbf{S}} A^i_{\mathbf{R}} A^j_{\mathbf{S}} \quad (i\neq j) \,,$$

$n^i_{\mathbf{R}}$ = # hypermultiplets in rep . $\mathbf{R}$ *of* G_i

$A_{\mathbf{R}}, B_{\mathbf{R}}, C_{\mathbf{R}}$ are group theory facotrs :

$$\mathrm{tr}_{\mathbf{R}}F^2 = A_{\mathbf{R}}\mathrm{tr}F^2 \,,$$
$$\mathrm{tr}_{\mathbf{R}}F^4 = B_{\mathbf{R}}\mathrm{tr}F^4 + C_{\mathbf{R}}(\mathrm{tr}F^2)^2 \,.$$

- Anomaly cancelled by the Green-Schwarz term: $S_{GS} = \int \Omega_{\alpha\beta}B_2^\alpha \wedge X_4^\beta$

String Probes of 6d SUGRA

- There are **infinitely many** anomaly-free N=(1,0) SUGRA in 6d. Are they all UV-completable in quantum gravity?
- Strings are sources for the (1+T) B_2 which should exist by the completeness assumption. BPS strings preserve 1/2 SUSY.
- The worldsheet theory is a (0,4) SCFT at low energy, with anomaly:

$$I_4 = \Omega_{\alpha\beta} Q^\alpha \left(\frac{1}{2} a^\alpha \mathrm{tr} R^2 + \frac{1}{4} \sum_i b_i^\alpha \mathrm{Tr} F_i^2 + \frac{1}{2} Q^\beta \chi_4(N_4) \right)$$
$$= -\frac{Q \cdot a}{4} p_1(T_2) + \frac{1}{4} \sum_i Q \cdot b_i \mathrm{Tr} F_i^2 \ - \frac{Q \cdot Q - Q \cdot a}{2} c_2(R) + \frac{Q \cdot Q + Q \cdot a}{2} c_2(l)$$

- This anomaly includes the com contributions: 4 bosons common to left- and right-movers, and 4 right-moving fermions:

$$I_4^{com} = -\frac{1}{12} p_1(T_2) - c_2(l) \ .$$

Central Charges

- The anomaly polynomial after removing contributions from the com dofs that decouple in the IR SCFT:

$$I_4' = I_4 - I_4^{com} \;\; = -\frac{3Q\cdot a-1}{12}p_1(T_2) + \frac{1}{4}\sum_i Q\cdot b_i \mathrm{Tr}F_i^2 - \frac{Q\cdot Q - Q\cdot a}{2}c_2(R) + \frac{Q\cdot Q + Q\cdot a + 2}{2}c_2(l)\,.$$

- The central charges can be read off from the coefficients of the gravitational anomaly and the R-symmetry anomaly.
- It is possible that an accidental symmetry emerges in the IR and becomes the R-symmetry. It is also possible that the worldsheet theory degenerates to a product of SCFTs with different IR R-symmetries.
- This happens for strings in local SCFTs or little string theories embedded in SUGRA.
- Completeness allows us to focus on strings that give rise to a single interacting SCFT at low energy without the accidental symmetry.

Central Charges

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$SO(4) = SU(2)_l \times SU(2)_R$: transverse $\mathbb{R}^4$

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Central Charges and F-theory

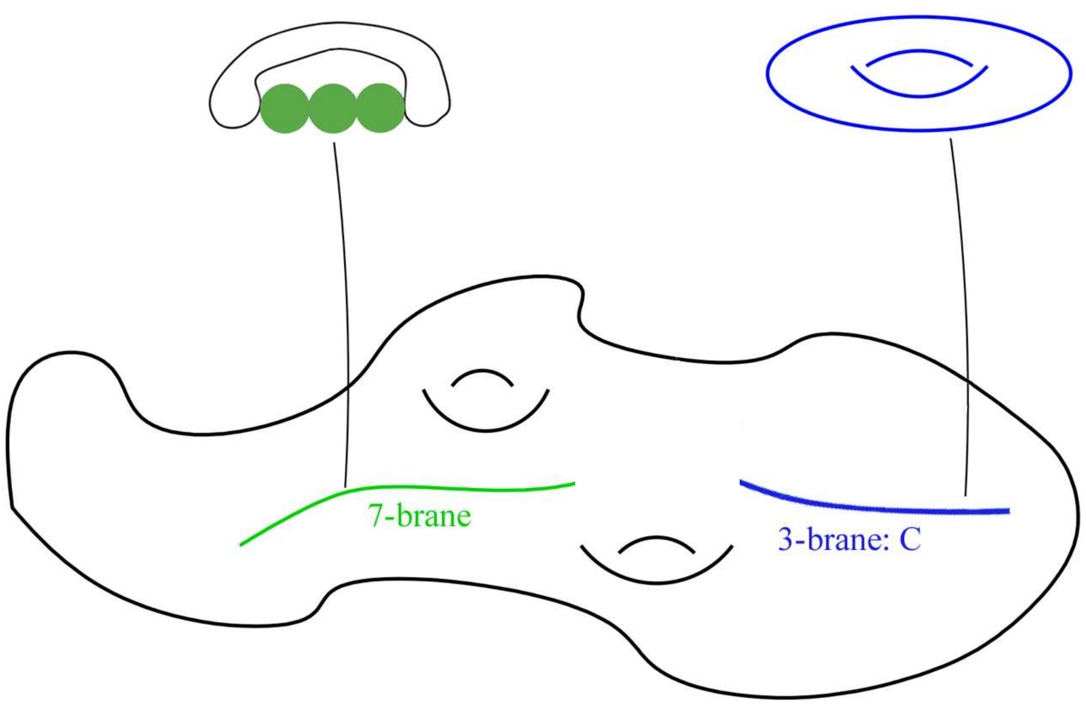
- For strings with a non-degenerate IR SCFT, R-symmetry = $SU(2)_R$:

$$c_L = 3Q \cdot Q - 9Q \cdot a + 2 \,, \quad c_R = 3Q \cdot Q - 3Q \cdot a$$

- The 't Hooft anomalies for the bulk gauge symmetries G_i and $SU(2)_l$:

$$k_i = Q \cdot b_i \;, \quad k_l = \frac{1}{2}(Q \cdot Q + Q \cdot a + 2)$$

- F-theory on elliptic Calabi-Yau 3-folds → 6d N=(1,0) SUGRA.



Strings with charge Q:
D3-branes wrapping genus g curve C=Q in the base

Comparison to F-theory

- The 2d SCFT for a D3-brane wrapping a genus g curve C inside B:

$$c'_L = 3C\cdot C - 9K\cdot C + 6\,, \quad c'_R = 3C\cdot C - 3K\cdot C + 6\,,$$

$$k'_l = g - 1\,.$$

[Haghighat, Murthy, Vafa, Vandoren, '16]

where K=canonical class of B, and the genus g of the curve can be computed by the Riemann-Roch theorem:

$$C \cdot C + K \cdot C = 2g - 2$$

- Again, this includes the com contributions:

$$c_L^{com} = 4, \quad c_R^{com} = 6, \quad k_l^{com} = -1$$

- Removing the com contributions gives perfect agreement with the anomaly inflow results by identifying:

$$\Omega \leftrightarrow \text{intersection form in } H_2(B, \mathbb{Z}), \quad a \leftrightarrow K$$

Consistency Conditions

- Consider the moduli space of a 6d SUGRA theory parametrized by scalars in the tensor multiplets + a scalar controls the overall volume.
- For this moduli space to be well-defined, ∃ a linear combination of these scalars J such that:

$$J \cdot J > 0 \,, \quad J \cdot b_i > 0 \,, \quad -J \cdot a > 0 \,.$$

- In F-theory, J is the Kahler form $J \in H^{1,1}(B)$. The above conditions define a positive-definite Kahler cone on B.
- The tension of a BPS string with charge Q is non-negative if

$$Q \cdot J \geq 0$$

- Unitarity on the IR SCFT of such a string give constraints on:

$$c_L, \quad c_R, \quad k_l, \quad k_i$$

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see [Hamada, Noumi, GS]

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Unitary CFT

- For a unitary CFT, the central charges must be non-negative

$$c_L, c_R \geq 0$$

- The SU(2)$_l$ current algebra is realized on the left-movers and has:

$$k_l \geq 0$$

In F-theory, this amounts to requiring g≥0.

- The level of the G$_i$ current algebra: $k_i = Q \cdot b_i \geq 0$

In F-theory, this is the condition that the curve class Q is effective and irreducible within the Mori cone of the Kahler base B.

- Unitarity of the SCFT requires:

$$\sum_i \frac{k_i \cdot \mathrm{dim} G_i}{k_i + h_i^\vee} \leq c_L$$

Example 1

- 6d SUGRA coupled to T=9 tensors with SU(N) x SU(N) gauge group and 2 bifunds. **[Kumar, Morrison, Taylor ‘10] ([Schwarz ‘96] for T=1 models).**
- Anomaly polynomial factorizes for any N but these models do not admit F-theory realizations at large enough N.
- The bilinear form Ω and the vectors a, b_1, b_2 are given by:

$$\Omega = \text{diag}(+1, (-1)^9) \ , \quad a = (-3, (+1)^9) \ ,$$
$$b_1 = (1, -1, -1, -1, 0^6) \ , \quad b_2 = (2, 0, 0, 0, (-1)^6) \ .$$

- In this basis, $J=(1,0^9)$ satisfies $J^2 > 0$, $J\cdot b > 0$, $J\cdot a < 0$.
- Consider a string with charge $Q=(q_0, q_1, \cdots, q_9)$ with $q_0 > 0$ for positive tension w.r.t. J. The unitarity conditions $c_R \geq 0$, $k_l \geq 0$:

$$q_0^2 - \sum_{i=1}^{9} q_i^2 \geq -1 \ , \quad q_0^2 - \sum_{i=1}^{9} q_i^2 - 3q_0 - q_{1:3} - q_{4:9} \geq -2 \ ,$$

Example 1

- The positivity of the level of the current algebra G_i :

$$k_1 = q_0 + q_{1:3} \geq 0 \,, \quad k_2 = 2q_0 + q_{4:9} \geq 0 \,,$$

where

$$q_{1:3} \equiv \sum_{i=1}^{3} q_i \text{ and } q_{4:9} \equiv \sum_{i=4}^{9} q_i.$$

- The **unitarity bound** on the level:

$$\frac{k_1(N^2-1)}{k_1+N} + \frac{k_2(N^2-1)}{k_2+N} \leq \; c_L = 3(q_0^2 - \sum_{i=1}^{9} q_i^2) + 9(3q_0 + q_{1:3} + q_{4:9}) + 2$$

- The strongest bound on N is given by a string with

$$q_0^2 - \sum_{i=1}^{9} q_i^2 = -1 \text{ and } k_1 = 0, \, k_2 = 1$$

which occurs for $Q=(1,-1,0,0,-1,0^5)$.

Example 1

- The central charge bound for the string worldsheet to be unitary:

$$\frac{k_2(N^2-1)}{k_2+N} \leq c_L \;\rightarrow\; \frac{N^2-1}{1+N} \leq 8 \;\rightarrow\; N \leq 9\,.$$

- **6d anomaly-free theories with N > 9 belong to the swampland.**
- **Stronger than the Kodaira condition in F-theory: N ≤ 12:** anomaly argument can teach us something about elliptic Calabi-Yau 3-folds!
- Reassuring that the swampland bound does not rule out the string realization for N=8 in terms of a K3 orientifold **[Dabholkar, Park, '96].**
- Remarkably, we obtain a bound on the rank of the gauge groups that is consistent with F-theory argument and known string realization.
- Interesting to see if the N=9 case can be constructed.

Example 2

- 6d SUGRA with T=1 & SU(N) gauge group coupled to one symmetric + (N-8) fundamental hypermultiplets is anomaly free for N ≤ 30.

$$\Omega = \mathrm{diag}(1,-1)\ , \quad a = (-3,1)\ , \quad b = (0,-1)$$

[Kumar, Morrison, Taylor '10]

- The Kahler form can be chosen as J = (n,1) with $n^2 > 1$ and n > 0.
- No F-theory realization: when the base B is identified with Hirzebruch surface F^1, b cannot be mapped to an effective curve class.
- Consider a string with charge $Q=(q_1, q_2)$ satisfying $c_R \geq 0$, $k_l \geq 0$:

$$q_1^2 - q_2^2 \geq -1\ , \quad q_1^2 - q_2^2 - 3q_1 - q_2 \geq -2\ ,$$
$$k = Q\cdot b = q_2 \geq 0\ .$$

- This string has positive tension if:

$$nq_1 > q_2 \text{ from } J\cdot Q > 0.$$

Example 2

- These constraints can be simplified as:

$$q_1 \geq 3 \qquad q_1 - 2 \geq q_2 > 0$$

- The unitarity bound on the central charge:

$$\frac{q_2(N^2-1)}{q_2+N} \leq 3(q_1^2 - q_2^2) + 9(3q_1 + q_2) + 2$$

- The most stringent bound is N ≤ 117 which occurs when Q=(3,1).
- This bound is weaker than the bound from anomaly cancellation.
- Interesting to see if there are inconsistencies revealed by other means or else construct N≤ 30 models from other string theories.

Example 3

- We found a bound on a family of 6d models with T=8k+9 and gauge group G=$(E_8)^k$ for arbitrary k introduced in **[Kumar, Morrison, Taylor '10]**
- The anomaly coefficients of 6d SUGRA:

$$a\cdot b_i = 10,\ b_i\cdot b_j = -2\delta_{ij} \text{ with } i,j=1,\cdots,k.$$

- For k ≥ 3, one can choose a basis of tensors:

$$\Omega = \text{diag}(1,(-1)^{8k+9})\ , \quad a = (-3, 1^{8k+9})\ ,$$
$$b_i = (-1,-1,0^{4(i-1)},(-1)^3,-3,0^{8k+8-4i})\ ,$$

- The Kahler form can be chosen:

$$J = (-j_0, 0^{4k+1}, 1^{4k+8})\ ,\ \ (4k+8)/3 > j_0 > \sqrt{4k+8}\ .$$

- Consider a string with charge Q=(-q, 0^{8k+9}) whose tension is positive if q > 0. Furthermore, $c_R \geq 0$, $k_l \geq 0$ can be satisfied for q > 2.

Example 3

- However, the bound on the levels of the current algebras $k_i = Q\cdot b_i = q$:

$$\sum_{i=1}^{k} \frac{248k_i}{k_i+30} \le c_L \quad \to \quad k\frac{248q}{q+30} \le 3q(q-9)+2$$

is not satisfied by strings with 3 ≤ q ≤ 14 for any k ≥ 3 (→ **swampland**)

- This anomaly inflow argument does not rule out models for k ≤ 2.
- For k=1,2, there exists another solutions of Ω and a, b_i:

k=1

$$\Omega = \mathrm{diag}(1,(-1)^{17}) , \quad a = (-3,1^{17}) ,$$
$$b_1 = (0,1,(-1)^{11},0^5) ,$$

k=2

$$\Omega = \mathrm{diag}(1,(-1)^{25}) , \quad a = (-3,1^{25}) ,$$
$$b_1 = (0,1,(-1)^{11},0^{13}) , \quad b_2 = (0,0^{13},1,(-1)^{11}) ,$$

- The above analysis do not apply. Indeed, the k=2 model can be realized by compactification of M theory on K3 x ($S^1/\mathbb{Z}_2$) with 24 M5-branes on the interval **[Seiberg, Witten '96]**.

Example 4

- 6d SUGRA with T=0 and gauge group SU(8) coupled to an exotic hypermultiplet in the "box" representation **[Kumar, Park, Taylor, '10].**
- Admits no F-theory realization. 6d anomaly cancellation sets

$$a = -3, \quad b = 8$$

- Strings with Q > 0 satisfy $c_R \geq 0$, $k_l \geq 0$, $k_i \geq 0$.
- Most stringent constraint on c_L is given by strings with minimal Q=1:

$$\frac{k \times 63}{k+8} \leq c_L \quad \to \quad 31.5 \leq 32 \quad \text{for } k = Q \cdot b = 8 \; .$$

which is marginally satisfied!

Summary

Summary

- String pheno continues to be a vital field that aims at extracting fundamental predictions on low energy physics from string theory/quantum gravity.
- The Swampland program aims to identify the boundary of possibilities for QFTs that can be consistently coupled to gravity. Results of such investigations have broad phenomenological implications.
- We initiated a program of using brane probes for a deeper understanding of the swampland conditions.
- The method presented in **[Kim, GS, Vafa]** was recently used to bound the number of abelian gauge group factors in 6d gravitational theories with minimal SUSY and in their F-theoretic realizations **[Lee, Weigand]**.
- Consistency between various types of branes and their interactions with one another may provide further constraints on the swampland.
- This program may allow us to substantially cut down the # of string vacua, and more broadly deepens our understanding of the swampland criteria.