The String Lamppost And The Swampland
Cumrun Vafa
Introduction
Some Swampland Criteria
N=32 Supercharges
N=16 Supercharges
N=8 Supercharges
Conclusion

The String Lamppost And The Swampland

Cumrun Vafa

Harvard University

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Based on

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Introduction

What constitutes a consistent quantum field theory (without gravity) is now rather well understood. However the same cannot be said about quantum gravitational theories.

The first attempt in quantizing gravity failed [Feynman,1963]. We later learned that string theory cures the problem. However, this is an inaccurate description of what string theory accomplished.

Feynman's problem with quantizing gravity still holds: QFT's that can consistently couple to gravity seem to be measure 0.

Swampland program

Find conditions which can rule out QFT's as arising in low energy limit of quantum gravitational theories.

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But how do we find the Swampland criteria?

We consider vast classes of string constructions which lead to consistent theories and see what QFT's are missing and try to understand whether their lack can be explained by basic principles: Consistency with black hole physics, unitarity, etc.

This will reassure us that we are not suffering from the string lamppost effect. In fact the main aim of my talk is to provide evidence for

The String Lamppost Principle

All consistent quantum gravity theories are part of the string landscape

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The plan for my talk:

- Review some swampland conditions
- Application to supersymmetric theories with 32 supercharges (e.g. $\mathcal{N} = 8, d = 4$)
- Application to supersymmetric theories with 16 supercharges (e.g. $\mathcal{N} = 4, d = 4$)
- Application to supersymmetric theories with 8 supercharges (e.g. $\mathcal{N} = 2, d = 4$)
- Conclusion

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Some Swampland Criteria

Completeness of Spectra

For a p+1-form gauge field in QG, every charged p-brane state appears in the spectrum

This principle which is deeply related to lack of global symmetries in consistent theories of gravity (in $d > 2$) is deeply related to the existence and quantum consistency of black holes and black branes [Misner & Wheeler, Polchinski, Banks & Seiberg, Harlow & Ooguri].

In this talk I assume a stronger version of this:

In a supergravity theory, for all the charged states allowed by BPS conditions, there is a BPS state in the spectrum.

Completeness of spectrum is a consequence of a more general swampland conjecture: [McNamara & V.]

Cobordism Conjecture

All the cobordism classes in a consistent theory of QG vanish

As a special example, if the charge spectrum is not complete, it leads to non-trivial cobordism classes.

The triviality of cobordism classes is far stronger and has additional consequences. One of them we will need today:

If a theory has a discrete gauge symmetry, it can be used (perhaps accompanied by additional group action on spacetime) to create orbifolds which are consistent quantum gravity backgrounds. The orbifold singularities should be "allowed".

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A side remark: An extension of the cobordism conjecture motivated by uniqueness of QG [McNamara & V.]

Baby Universe Hypothesis

Baby Universe Hilbert space is 1 dimensional ($d > 3$)

Ensemble interpretation of holography is not valid in $d > 3$. Moreover for $d \leq 3$ the ensemble interpretation of holography should be viewed as incomplete. It is a manifestation of computing observables in a standard, non-ensemble, higher dimensional holographic theory.

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Example: JT gravity which realizes an ensemble interpretation of holography [Saad, Shenker & Stanford] can also be viewed as computing standard Wilson loop observables in a higher dimensional theory:

$$\int dJ \exp(-S(J)) \prod_i \mathrm{Tr} \exp(-iH_i^J t_i)$$

$$\Longleftrightarrow \int DA \exp(-S(A)) \prod_{\mathrm{i}} \mathrm{Tr}\ \mathrm{Pexp}(i \oint_i A)$$

$$Ensemble\ J \leftrightarrow A \qquad H_i t_i \leftrightarrow -\oint_i A$$

Large N 't Hooft Riemann surfaces= worldsheet theory of the 6d topological string theory on the CY 3-fold $y^2 + sin^2\sqrt{x} + u^2 + v^2 = 0$ (= Mirzakhani's model). Matrix model ensemble description of JT gravity is a manifestation of standard holography in this 6d theory. This is an example of SLP: JT gravity arises from type IIB string on a local CY3-fold twisted by Ω-background of Nekrasov.

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Unitarity

Every QG is Unitary

This is one of the basic assumptions, related to no loss of information. A famous application of it is in the context of black hole physics and its unitary evolution. It should also apply to the effective theory on all the stable branes, and in particular BPS branes in the theory.

E.g., if we have a 1-brane in the theory, with central charge (c_L, c_R), we must have $c_L, c_R \geq 0$. Similarly if we have a gauge symmetry group G in the theory, it leads to a conserved global current on the brane. Assuming left-moving J_L with level k_L (related to its anomaly) we must have $k_L \geq 0$ and from WZW

$$c_G = \frac{k_L dimG}{k_L + h_G} \leq c_L$$

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No Anomalies

Every QG is free of gravitational, mixed or other anomalies

This is perhaps too obvious to even state. Of course QFT's are anomaly free and if you add gravity to the mix, you must also make sure, gravity is also anomaly free. In addition we should also make sure there are no mixed gravitational/gauge anomalies.

In the presence of defects, the bulk gravitational theories may appear anomalous, but their anomaly is cancelled due to the opposite anomaly on the defect through the anomaly inflow.[Callan & Harvey; Freed, Harvey, Minasian & Moore]
For example for a 1-brane with field strength H satisfying:

$$dH = \frac{a}{24} p_1(T) - \frac{b}{4} \mathrm{Tr} F^2$$

$$a = c_L - c_R \qquad b = k_L - k_R$$

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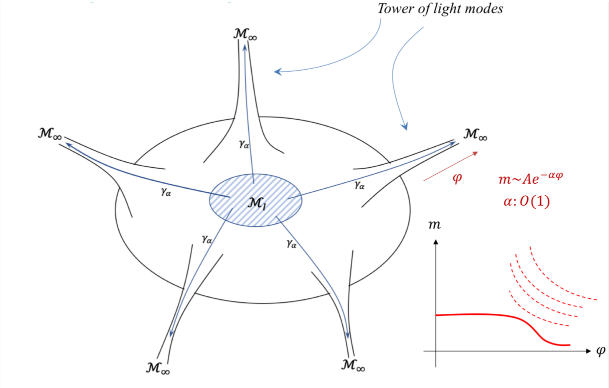
We also need a strong version of the distance conjecture [Ooguri & V.]:

Swampland Distance Conjecture

In a quantum theory of gravity, a large excursion in expectation value of a massless scalar leads to an exponentialy light tower of states



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The distance conjecture is a rephrasing of the expectation that at large distances in fields space we end up with dual descriptions.

A stronger version of this conjecture: At large distance in field space the tower of light states we get constitute the degrees of freedom of a dual description. We will assume this stronger version in this talk, at least for the case of theories with 16 supercharges.

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Supersymmetric theories with N=32 supercharges

We will be interested in supergravity theories in Minkowski background. Start with maximum amount of supersymmetry: N=32.
Low energy limit is completely fixed by supersymmetry.

$d = 11$: realized by M-theory.
$d = 10$: two types, $\mathcal{N} = (2,0)$ supersymmetry (IIB strings), and $\mathcal{N} = (1,1)$ (IIA or equivalently M-theory on circle)
$d < 10$: toroidal compactifications of the above.

Already this simple case should be taken as our first evidence of the String Lamppost Principle (SLP): It did not have to be that the theories which appear consistent in supersymmetric quantum gravity had to be part of the string landscape. They all are at least for the case of N=32 supercharges!

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Supersymmetric theories with N=16 supercharges

The maximum dimension allowed by supersymmetry for $N = 16$ is d=10, $\mathcal{N} = (1, 0)$.
Anomalous unless the gauge group G is

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

Only the first two are realized in the string landscape. Could it be that the latter two are the first counter-examples to the SLP?
It turns out the simple swampland criteria we discussed rule out the latter two theories, consistent with the fact that they do not appear in the string landscape [Kim, Shiu & V.] (another argument [Adams, DeWolfe & Taylor])

The argument is based on the fact that this theory has a 2-form gauge field B. According to the completeness conjecture we must have a BPS string with $(0, 8)$ supersymmetry. Using the anomaly inflow (taking into account supersymmetry) one finds that (ignoring the c.o.m contribution)

$$c_L = 16, c_R = 0; k_L = 1$$

This implies the current must be left-moving and $c^G \leq 16$.
$E^8 \times E^8$ and $SO(32) : c^G = 16 \leq 16$.
$E_8 \times U(1)^{248} : c^G = 8 + 248 = 256 > 16$.
$U(1)^{496} : c^G = 496 > 16$.

So the combination of completeness and unitarity of the theory rules out these two theories.

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If anomaly is crucial, how about $d < 10$?

The only such chiral theory is $d = 6$, $\mathcal{N} = (2, 0)$. Matter content fixed by anomaly; It is realized by type IIB on $K3$. Again a good illustration of SLP!

The theory is non-chiral for all the rest. How do we rule out theories? Are all ranks allowed as naively expected?

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Simplest toroidal compactifications give $r_G = 26 - d$.

More sophisticated known compactifications:
$d = 9$: $r_G = 1, 9, 17$

$r_G = 1$: M-theory on Klein Bottle
$r_G = 9$: Heterotic CHL string $E_8 \times U(1)$
$r_G = 17$: circle compactification of heterotic, $E_8 \times E_8 \times U(1)$

Global gravitational anomalies in this case implies that
r_G=odd. [Alvarez-Gaume & Witten],[Dabholkar & Harvey]

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Simplest toroidal compactification give $r_G = 26 - d$.

More sophisticated known compactifications:
$d = 9$: $r_G = 1, 9, 17$
$d = 8$: $r_G = 2, 10, 18$
$d = 7$: $r_G = 3, 5, 7, 11, 19$
$d = 6$: ....

We see that in all dimensions there is an upper bound $r_G = 26 - d$.

Moreover the ranks seem to appear in $(1 \bmod 8,\ 2 \bmod 8,\ 1 \bmod 2)$ in $d = (9, 8, 7)$.

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All these theories admit BPS strings. Supergravity not powerful enough to fix the anomaly coefficients. Two possible IR susy on the string $(0,8)$ or $(8,8)$. $(0,8)$ case leads to [Kim, Tarazi & V.]:

$$c_L = 24\kappa + 2 - d \qquad c_R = 12(\kappa - 1)$$

Strong version of distance conjecture powerful due to high supersymmetry: Winding BPS string in the limit of small radius should be dual to momentum modes of a dual graviton. Ground states of BPS string should have spin less than or equal to 2. Implying

$$\kappa \leq 1 \Longrightarrow \kappa = 1 \Longrightarrow c_L = 26 - d \Longrightarrow r_G \leq 26 - d$$

For $\mathcal{N} = (8,8)$ (as in KB compactification of M-theory) same reasoning leads to

$$(c_L, c_R) = (10 - d, 0) \rightarrow r_G \leq 10 - d$$

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This result in particular implies that in $d = 4$ for $\mathcal{N} = 4$ SYM, theories with $r_G > 22$ are in the swampland. In particular $\mathcal{N} = 4$ $SU(N)$ SYM for $N > 23$ is in the swampland ($SU(23)$ is in the heterotic landscape).

This is a striking example: Even a beautiful, finite QFT can belong to the swampland, and in fact almost all of them do!

This of course does not mean that we cannot have $\mathcal{N} = 4$, $SU(N)$ SYM realized in string theory. In particular they are realized on N D3 branes in 10d. But gravity is dynamical in $d = 10$, not $d = 4$.

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But there is more structure in what we can get in string landscape than rank. We can also apply swampland ideas to those [Montero & V.]. Consider specifically $d = 9$, $r_G = 1, 9, 17$.

The supergravity theory has PC symmetry. According to the cobordism conjecture the orbifold of the type $T^3/\mathbb{Z}_2$ accompanied by PC should exist. This gives a theory in $d = 6$ with $\mathcal{N} = (1, 0)$.

$$n_T = 1 + 8n^T_{f.p.}, \qquad n_V = 8n^V_{f.p.}, \qquad n_H = 3 + r_G + 8n^H_{f.p.}$$

That $n^*_{f.p.} \in \mathbb{Z}$ follows from Dirac quantization arguments [Tachikawa & Yonekura]. Cancellation of $6d$ anomalies

$$273 = 29T + n_V - n_H \Longrightarrow r_G = 1 \bmod 8$$

Similar argument for d=8,7 compactification on $T^3/\mathbb{Z}_2$ and $S^1/\mathbb{Z}_2$ and absence of global anomaly in 5d and chiral anomaly in 6d respectively, leads to

$$d = 8: \;\; r_G = 2 \bmod 8; \qquad d = 7: \;\; r_G = 1 \bmod 2$$

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Supersymmetric theories with N=8 supercharges

The highest dimension with $N = 8$ supercharges is $d = 6$, $\mathcal{N} = (1, 0)$. Theory is chiral and anomaly cancellation puts severe restrictions [Taylor & collaborators].

On the other hand these theories admit many different kinds of strings (tensor multiplets). Derive restrictions via anomaly inflow and unitarity on the strings.
Example: $T = 8k + 9$ and gauge group $G = (E8)^k$ for arbitrarily large k, cancel anomalies.

$$\sum_{i=1}^{k} \frac{248 k_i}{k_i + 30} \leq c_L$$

cannot be satisfied for $k > 2$ [Kim, Shiu & V]. The only examples that have been constructed using F-theory are $k = 1, k = 2$. Many similar cases can be ruled out [Lee & Weigand], but there are still infinite classes which cannot.

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Similarly we can consider $\mathcal{N} = 1$ theories in $d = 5$ (which have $N = 8$ supercharges).

These theories also have BPS strings. Unitarity bounds and the anomaly inflow leads to restrictions, just as in the other cases.

Example: Consider a theory without vector multiplets, but with hypermultiplets and with graviphoton CS terms:

$$5d \text{ CS}: \ \frac{k}{24\pi^2} \int A \wedge F \wedge F + \frac{k'}{192\pi^2} \int A \wedge R \wedge R$$

At special loci on hypermultiplet moduli space we may get enhanced non-abelian gauge symmetry G.

Possible to show for non-abelian G, using unitarity on strings [Katz, Kim, Tarazi & V.]:

$$r_G \leq k + k' - 3$$

For the case of M-theory on CY quintic this gives $r_G \leq 52$, which is consistent with the geometrical bound in this case $r_G \leq 44$.

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We have found further evidence for String Lamppost Principle: Swampland criteria which are potentially valid beyond string theory, at least in theories with higher supersymmetries, reproduce the string landscape!

To Do: Extend to more refined questions such as not just the rank, but the actual gauge groups.

Explore more deeply the case with $N = 8$. The first goal is to show there are only a finite number of possible theories as we did for $N = 16, 32$, starting with $d = 6$, $\mathcal{N} = (1, 0)$.

Lower supersymmetric cases? Going to be more challenging: Except for those which are secretly related to higher supersymmetric theories, the rest seem to receive superpotential corrections [Palti,Weigand & V.].