Recent Explorations

between Landscape and Swampland

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Van Long Wetland, by Hoa Nguyen, Wikpedia

Recent Explorations

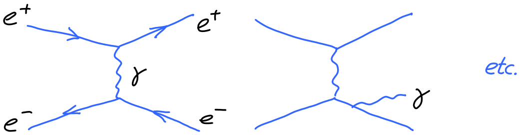
between Landscape and Swampland

Outline

- Preliminaries: From Field Theory to Quantum Gravity
- String theory in 10 dimensions – a "reminder"
- Compactifications to 4 dimensions
- The (flux-) Landscape
- The concept of the Swampland
- Examples of Swampland conjectures
- Key open question: Is de Sitter in the Swampland?

From Particles/Fields to Quantum Gravity

- Naive picture of particle physics:



- Theoretical description: Quantum Field Theory
- Usually defined by an action:

$$S_{(Q)ED} = \int d^4x \, F_{\mu\nu} \, F_{\rho\sigma} \, g^{\mu\rho} \, g^{\nu\sigma}$$

with

$$F_{\mu\nu} = \frac{\partial A_\mu}{\partial x^\nu} - \frac{\partial A_\nu}{\partial x^\mu} = \begin{pmatrix} 0 & \overline{E}^T \\ -\overline{E} & \varepsilon B \end{pmatrix}$$

Gravity is in principle very similar:

- The metric $g_{\mu\nu}$ becomes a field, more precisely

$$S_G = \int d^4x \sqrt{-g}\; R[g_{\mu\nu}] \;\; ,$$

where R measures the curvature of space-time

- In more detail: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

- Now, with $h_{\mu\nu}$ playing the role of A_μ, we find

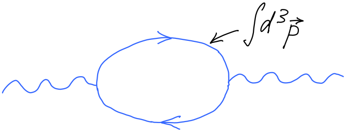
$$S_G = \int d^4x \; (\partial_\rho h_{\mu\nu})\,(\partial^\rho h^{\mu\nu}) + \cdots$$

- Waves of $h_{\mu\nu}$ correspond to gravitons,
just like waves of A_μ correspond to photons

- Now, replace S_{QED} with $S_{Standard\ Model}$ (that's just a minor complication....) and write

$$S = S_G + S_{SM} \ .$$

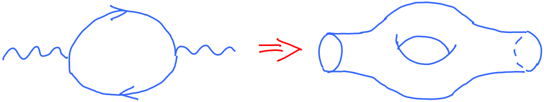
This could be our 'Theory of Everything', but there are divergences ....



- Divergences are a hard but solvable problem for QFT
- However, these very same divergences make it very difficult to even define quantum gravity at $E \sim M_{Planck}$

String theory: ‘to know is to love’

- String theory solves this problem in 10 dimensions:



- The divergences at $\vec{k} \to \infty$ are now removed (roughly because the ‘singular’ interaction point is gone).

- Thus, in 10 dimensions but at low energy ($E \ll 1/l_{string}$), we get an (essentially) unique 10d QFT:

$$\mathcal{L} = R[g_{\mu\nu}] + F_{\mu\nu\rho}F^{\mu\nu\rho} + H_{\mu\nu\rho}H^{\mu\nu\rho} + \cdots$$

'Kaluza-Klein Compactification' to 4 dimensions

- To get the idea, let us first imagine we had a 2d theory, but need a 1d theory
- We can simply consider space to have the form of a cylinder or 'the surface of a rope':

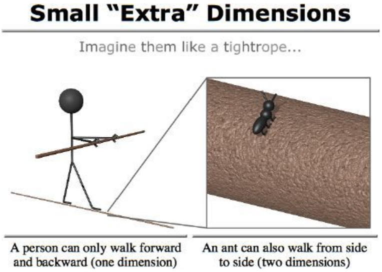
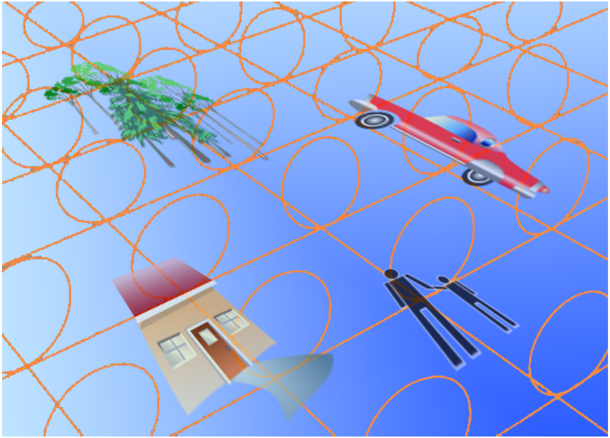


Image by S. Edwards on wikispaces

- Here we have compactified on a circle or an S^1

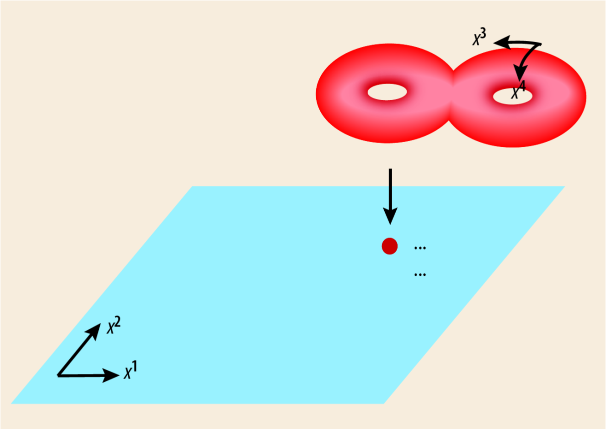
‘Compactification’ continued

- Quite analogously, we can compactify on S^1 from 3d to 2d, i.e. using $\mathbb{R}^2 \times S^1$ as our space:



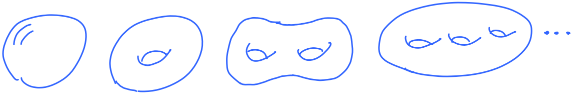
'Compactification' continued

- We can compactify on Riemann surfaces from 4d to 2d:



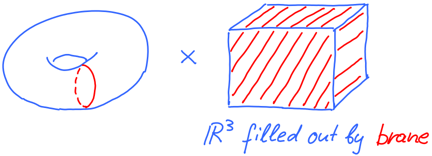
‘Compactification’ continued

- Fairly obviously, there is an infinite series of such 2d compact spaces (Riemann surfaces):



- Crucially, string compactifications involve D-branes (non-perturbative extended objects, on which gauge theories are localized)

- Here is a picture of going from 5d to 3d on a torus, with a 4-dim. brane also present:



Closer to reality:

- To go from 10d to 4d, i.e. we need 6d compact spaces
- We also want these spaces to solve Einstein's equations ($R_{\mu\nu} = 0$)
- Such geometries are called 'Calabi-Yau spaces' and $\sim 10^4$ of them are known (finiteness is conjectured but not established)

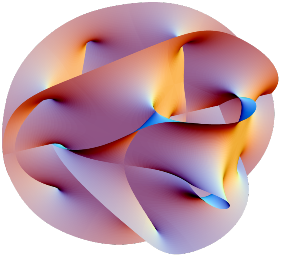
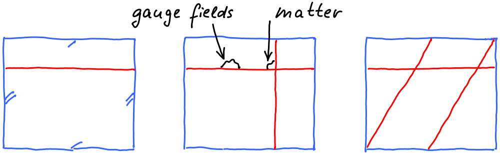


Image by J.F. Colonna

Closer to reality:

- In fact, there are many more possibilities, due to the presence of branes

- For example, a torus has two '1-cycles' on which branes can be 'wrapped':

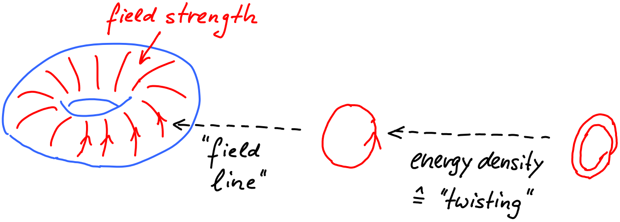


- In this context (with CYs instead of tori), building the Standard Model leads to highly non-trivial geometrical questions (cf. work of H. Jockers and many colleagues...)

- But this is not yet 'the landscape' ....

Next crucial ingredient: Fluxes

- Fluxes are field strengths of (higher-dimensional analogues) of gauge fields, such as $F_{\mu\nu\rho}$, $G_{\mu\nu\rho}$
- They are crucial for the landscape since they stabilize the geometry and lead to $\sim 10^{500}$ possibilites
- Simplest version of an explanation:



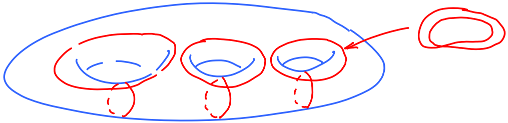
- This illustrates a flux wrapped on a 1-cycle of the torus

Better explanation:

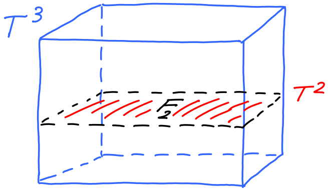
(For those who know about quantization
of magnetic monopole charges.)

- Consider magnetic monopole in $\mathbb{R}^3$
- For reasons of quantum mechanical consistency, the charge is quantized in units of the electron charge
- In fact, this can be seen focussing only on the field strength on an S^2 surrounding this monople
- The field strength on this S^2 is 'twisted' in analogy to the twisted band on the previous slide
- Here, we are dealing with an $F_{\mu\nu}$-flux on a 2-cycle (the S^2)

- Quite generally, fluxes ‘live’ on cycles of the compact space
- Example: several 1-cycles in 2d space



- Crucial: Higher-dimensional cycles (with fluxes) exist in higher-dimensional spaces
- Example: a 2-cycle in T^3



The string theory landscape

- Typcial CYs have $\mathcal{O}(300)$ 3-cycles
- Each can carry some integer number of flux of $F_{\mu\nu\rho}$, $H_{\mu\nu\rho}$
- With, for example, $N_{flux} \in \{-5, \ldots, 5\}$ on gets

$$(10^2)^{300} \;\sim\; 10^{600} \text{ possibilities}$$

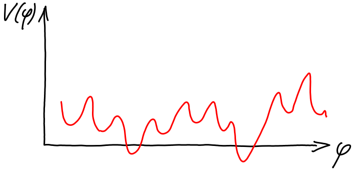
- This is the string theory landscape!
- To appreciate the complexity, recall that there are only $\sim 10^{80}$ atoms in our universe

...our mistake is not that we take our theories too seriously, but that we do not take them seriously enough.

S. Weinberg

The string theory landscape (continued)

- Each of these geometries corresponds to a solution ('vacuum') of the same, unique fundamental theory
- As an analogy: Think of all the different macromolecules that can be built in quantum mechanics from, e.g., nuclei of carbon, hydrogen and sulfur together with electrons
- Each solution has a different vacuum energy

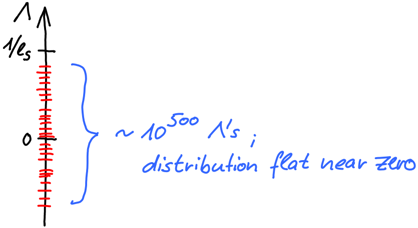


Here φ corresponds to $\{\varphi_1, \ldots, \varphi_n\}$, parametrizing the shape of the CY

The cosmological constant in the landscape

- Crucially, at least for part of the landscape, the statistical distribution of $\Lambda = V(\varphi_{\text{min}})$ can be calculated.

  It has been argued to be 'flat' in the region near $\Lambda = 0$



- Thus, while having $\Lambda \sim 10^{-120}$ (as is measured) is extremely unlikely, it is known that such vacua do exist

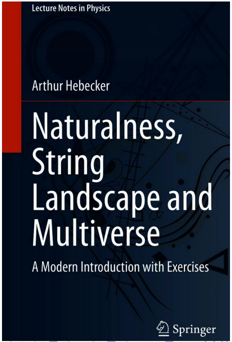
- One can appeal to anthropic arguments to explain why we find ourselves in such an 'rare' vacuum

- If accepted, the above corresponds to a paradigm change in fundamental physics similar to the Copernican Revolution

- In brief: Our fundamental (4d) theory is not special - it is just one of many possibilities

  Weinberg '87
  Bousso/Polchinski '00
  Giddings/Kachru/Polchinski '01 (GKP)
  Kachru/Kallosh/Linde/Trivedi '03 (KKLT)
  Denef/Douglas '04

  For introductory lectures (about 1 semester) see:

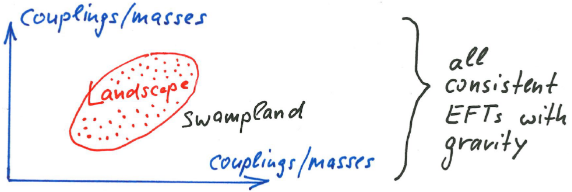


The concept of the 'Swampland'

Vafa '05, Ooguri/Vafa '06

- In view of the above 10^{500+} vacua, some form of 'anything goes' attitude may appear warranted.

- However, this is almost certainly false:
  Certain rules/correlations between available multiplets / couplings/ masses do hold in the string landscape.



- Yet, it is not easy to find (even less derive) such rules.
  Proposing and checking (rarely proving) corresponding 'Swampland Conjectures' appears to be the method of choice.

The concept of the 'Swampland' – continued

- While the concept is from '05, it only 'took off' around '15, in the aftermath of BICEP (I will explain...).

- Many detailed reviews have recently appeared:

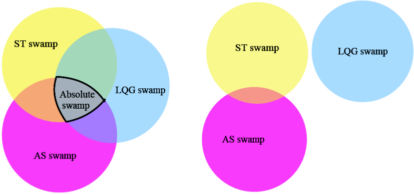
  Brennan/Carta/Vafa '17, Palti '19, van Beest/Calderon/ Mirfendereski/Valenzuela '21, Agmon/Bedroya/Kang/Vafa '22

A personal aside:

- The main 'swampland story' assumes string theory in the UV. But one may also consider 'UV completion in any quantum gravity' (e.g. Asymptotic Safety, Loop QG, ...)

- This is largely open....

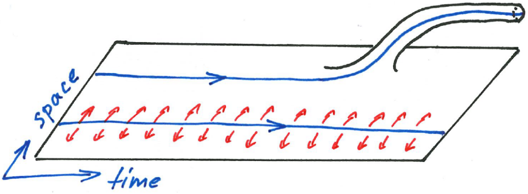
Eichhorn/AH/Pawlowski/Walcher '24



Example 1: No-global-symmetries conjecture

Banks/Dixon '88, Giddings/Strominger, Kamionkowski/March-Russell '92, ...

- Conjecture: 'A low-energy EFT consistently coupled to ST (quantum gravity?) has no exact global symmetries'.
- Proofs in perturbative ST and in AdS (using AdS/CFT) exist.
  Harlow/Ooguri '18
- Naive (oversimplified) argument based on topology change:
  Exact global symmetry ⇒ Particles can be absolutely stable
  (even if not protected by gauge field).



Example 1: No-global-symmetries conjecture – continued

- But: Maybe the famous black-hole argument makes this conjecture (largely) trivial?

  (particle falls into BH — BH evaporates — particle gone)

- But: The quantitative implications are VERY weak (the violation can be exponentially small).

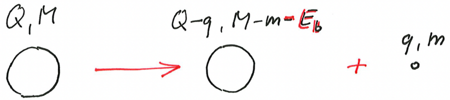
Example 2: Weak gravity conjecture

Arkani-Hamed/Motl/Nicolis/Vafa '06

- Historically very important and inspirational
- Very rough statement: 'Gravity is the weakest force'.

Example 2: Weak gravity conjecture – continued

- A possible motivation: No bound state should be completely stable (not even a charged, extremal BH).
- To understand the implications, think in Planck units: $M_P = 1$.
- Extremal BHs have charge $Q = M$.
  $Q > M$ is forbidden (naked singularity appears).
- Hence, an extremal BH can only decay if a particle with $q > m$ exists:



- Given that $q = g \times$ 'integer charge', this limits the smallness of gauge couplings or enforces light charged states.

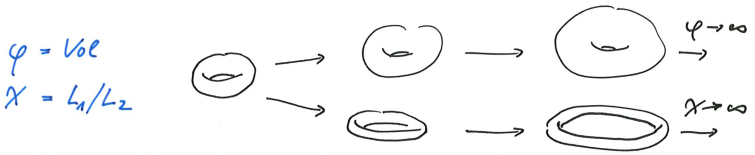
Example 3: Distance Conjecture

Formulated in original work by Ooguri and Vafa, developed and sharpened by many authors: Palti, Lee/Lerche/Weigand, Heidenreich/Rudelius/....

- Conjecture: When going to infinite distance in field space, the cutoff of the EFT goes to zero exponentially fast.
- In most cases, the cutoff will be a 'Kaluza-Klein tower' (i.e. the 'extra-dimensional' compact space will become so large, that our 4d effective description breaks down).
- Indeed, this is very natural in string theory because (almost) all fields come from the geometry of the compact space.
- Moreover, the only way to deform a compact space 'indefinitely' is by making it larger and larger.

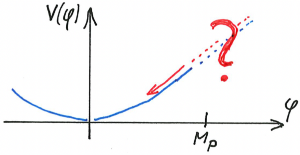
Example 3: Distance Conjecture – continued

Illustration of possible infinities in deforming the compact space:



- Observation and general claim:
  The cutoff comes down (exponentially fast!).

- This clearly has implications for (large-field) inflation.
  (In the context of BICEP's 'discovery' of tensor modes, this was crucial for reigniting interest in the Swampland.)



- This also relates to the generalization of the WGC to axions and axion inflation.

My last Example: de Sitter Conjecture

(Arguably the most important and most questionable one of our list!)

- Many different versions:
  - No stable de Sitter in String Theory;
  - No de Sitter in asymptotic regimes of String Theory;
  - No metastable de Sitter in String Theory (but slow-roll OK);
  - No de Sitter and no slow-roll in String Theory;
  - .....

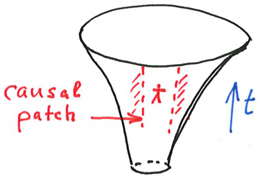
  Danielson/Van Riet, Obied/Ooguri/Spodyneiko/Vafa/Palti/Shiu, Garg/Krishnan '19 (some early claims too strong – cf. Denef/AH/Wrase '19)

- Also, analogous claims of varying strength exist in Quantum Gravity in general (going back over decades)

  Ford '85, ... Tsamis/Woodard ... Mottola, Polyakov ... Dvali '14

  (personally, I am not convinced the arguments here are strong...)

de Sitter Conjecture – continued

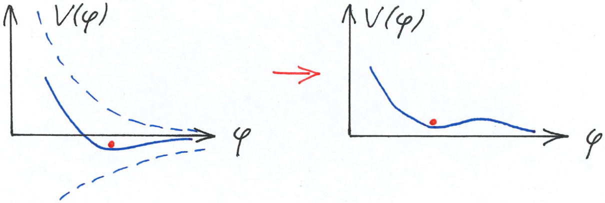


Some background:

- de Sitter space corresponds to eternal, exponential expansion ('accelerated cosmological expansion').
- An especially puzzling feature is the 'cosmological horizon'.
- There is evidence for accelerated expansion in our far past ('cosmological inflation') and today (supernovae, Planck).
- Thus, if some of the stronger forms of the conjecture turn out to hold in string theory, it may be ruled out!
- Conceptually, the problems of (Super-)String Theory with de Sitter may be due to its inconsistency with supersymmetry.

de Sitter Conjecture – continued

- Technically, the problem is rather moduli stabilization.
- Specifically, the volume modulus (say 'φ') can not be stabilized by fluxes as discussed earlier.
- It only receives simple, exponentially falling potentials from other energeic effects.
- Combining two such terms can at best give a minimum at negative potential and hence Anti-de-Sitter solutions.



- At least 3 potential terms with different falloff and appropriate coefficients are needed to get dS.

Technical aside for 'insiders':

- The generic result of a compactification with volume $\mathcal{V}$ (and some positive-energy source in the compact space) is

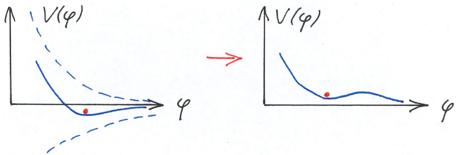
$$\mathcal{L} \sim \mathcal{V}\left[\mathcal{R}_4 - \frac{(\partial\mathcal{V})^2}{\mathcal{V}^2} - E\right] .$$

- After Weyl-rescaling to the Einstein frame and introducing the canonical field $\varphi = \ln(\mathcal{V})$, one finds

$$\mathcal{L} \sim \left[\mathcal{R}_4 - (\partial\varphi)^2 - E\, e^{-\varphi}\right] .$$

- Even worse: The exponent is usually $\mathcal{O}(1)$, so the simplest compactifications lead to steep exponential potentials: $|V'|/V \sim \mathcal{O}(1)$.

de Sitter Conjecture – continued



- The earliest scenario for realizing dS with 3 such terms is

KKLT

Kachru/Kallosh/Linde/Trivedi '03

A (conceptually similar) alternative is the
'large volume scenario' or LVS

Balasubramanian/Berglund/Conlon/Quevedo '05

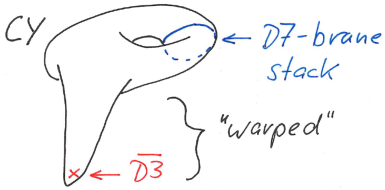
(We have no time to discuss it here.)

KKLT

- 1st exponential term: Confinement-type effect in a gauge-theory on a D7-brane stack ('gaugino condensate').

- 2nd exponential term: Interplay of the former with fluxes (cf. beginning of talk)

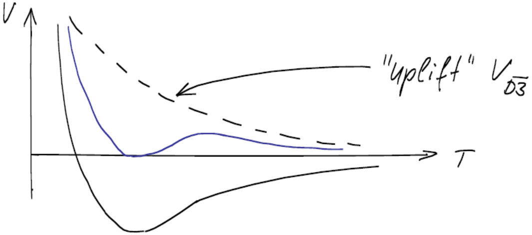
- 3rd exponential term: Small uplift by $\overline{\text{D3}}$-brane in a warped throat* :



* A high-redshift region, where the Calabi-Yau geometry is strongly deformed.

KKLT – continued

- The uplift potential is the most critical point.



- It has remained plausible in spite of longstanding concerns based on flux backreaction.

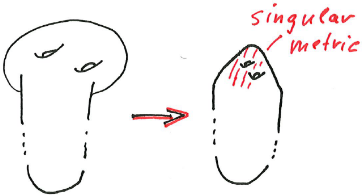
Bena, Grana, Danielsson, Van Riet, ...

- But more recently, significant doubts have arisen concerning the warping effects in the 'bulk' (the main part of the CY).

Carta/Moritz/Westphal '17, Gao/AH/Junghans '20

'Singular bulk problem of KKLT'

- Correct size of uplift requires 'very thick' throat.
- This, in turn, leads to strong backreaction in the 'bulk', large parts of which become singular.



- Curvature effects in the throat require it to be even thicker for the uplift to remain (meta-)stable. This also affects the LVS.
  Junghans, AH/Schreyer/Venken '22
- But: There is also progress in constructing better/new dS vacua.....
  ..., De Luca/Silverstein/Torroba, AH/Leonhardt Moritz/Mcallister/Nally/Schachner, Krippendorf/Schachner, ...
- In my opinion, the problem of dS is simply unsolved!

Reminder of Outline

- String theory in 10 dimensions – a "reminder"
- Compactifications to 4 dimensions
- The (flux-) landscape
- The concept of the Swampland
- Examples of Swampland Conjectures
- Key open question: Is de Sitter in the Swampland?

'Conclusion'

- Surprisingly, 20 years after the advent of the string landscape, fundamental issues appear to be as open (and exciting!) as at the beginning of the 'multiverse revolution'.