From String Landscape and Swampland to Cobordism and Wormholes

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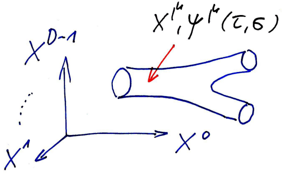
Outline

- Reminder of the Basics of the String Theory Landscape.
- The recent Swampland debate and the subsequent scrutiny of ‘accepted’ constructions (de Sitter models of KKLT/LVS).
- Further Swampland-related current issues (Wormholes; Cobordism Conjecture).

10d Superstring

- Almost unqiue starting point:
  worldsheet with 2d supergravity, embedded in D dimensions:



- $\Rightarrow$ $D = 10$ uniquely fixed;
  (almost) unique 10d theory: Type IIB supergravity

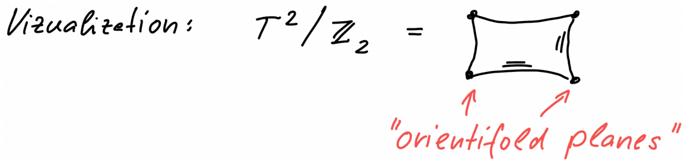
$$S_{IIB} \sim \int_{10d} e^{-2\phi}\Big(R + (\partial\phi)^2 - H_3^2\Big) - \sum_{p=1,3,5} F_p^2 - C_4 \wedge H_3 \wedge F_3$$

with $F_p = dC_{p-1}$ and $g_s = e^{\phi}$.

Towards the String Landscape (2000 .... 2018)

Bousso/Polchinski, GKP, Denef/Douglas, KKLT, LVS

- To solve vacuum EOMs, compactify to 4d on Calabi-Yaus.
- More precisly, consider geometry $\mathbb{R}^{1,3} \times X$ with $X = CY/K$.
- Here K is some discrete group
  and hence X is a 'Calabi-Yau-orientifold'.



- Dimension of the O-plane may vary (key for us: O3 and O7).

String Landscape (continued)

- Obtain 4d EFT, including in particular moduli of X:

$$\mathcal{L}_{4d} \quad \supset \quad K(z)_{i\bar{\jmath}}(\partial z)^i(\partial\bar{z})^{\bar{\jmath}} \;+\; K(T)_{\alpha\bar{\beta}}(\partial T)^\alpha(\partial\overline{T})^{\bar{\beta}}$$

  Where:
  z: complex structure moduli (3-cycle volumes)
  T: Kahler moduli (2-and 4-cycle volumes).

- Next key step:
  Introduce (quantized) fluxes, i.e. field strengths of F_3/H_3.

- This is encoded in integer vectors $\{f^i\}$ and $\{h^i\}$.

- It induces a superpotential $W(z) \sim (f - (i/g_s + C_0)h) \cdot \Pi(z)$;
  'Period vector' $\Pi(z)$ encodes features of the specific CY.

String Landscape (continued)

- This implies a scalar potential,

$$V(z,\bar{z}) \;\sim\; K(z)^{i\bar{\jmath}}\, D_i W\, D_{\bar{\jmath}} \overline{W} \qquad \text{with} \qquad D_i W \equiv \partial_i W + K_i W\,,$$

  stabilizing the z^i in terms of the flux $\{f^i, h^i\}$.

- But the flux $F_3 \wedge H_3$ sources F_5. So do the orientifold-planes.

$$\Rightarrow \quad 0 = \int d * F_5 = \int F_3 \wedge H_3 + \int j_{loc} \equiv N + Q\,.$$

- Thus, the flux is limited by the 'tadpole' contribution j_{loc} of the O-planes:

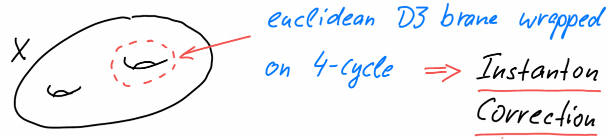
$$N = f \cdot h\,, \qquad -Q = \frac{1}{4} N_{O3} + \frac{1}{2}\chi(O7)\,.$$

$\Rightarrow$ Finite Landscape!

Denef/Douglas '05 ..... Grimm '21

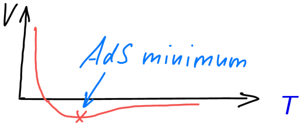
String Landscape (continued)

- At this point, the Kahler moduli are still flat directions. (In the simplest case this is just the volume.)
- To discover their potential, one needs to study the model with more precision:



$\Rightarrow \quad W = W_0 + e^{-T} \;,$ (where W_0 is the previous flux effect)

$\Rightarrow$ Kahler modulus stabilized (controlled for $W_0 \ll 1$).



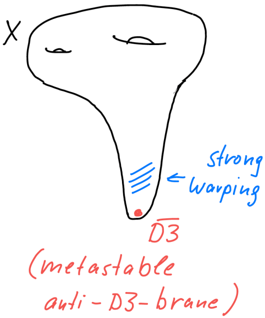
KKLT

- This construction of a fully stabilized AdS minimum is known as 'Step 1' of the KKLT construction.

- 'Step 2' involves 'uplifing' to dS by adding an anti-D3-brane.

- This requires a 'strongly warped region' or 'Klebanov-Strassler throat' to avoid destabilization.

- The latter is achieved by introducing a large amount of flux on an appropriate (conifold) region of the CY.

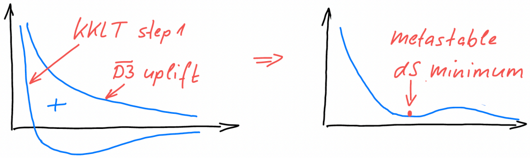


Warping:

$$ds^2 = dx^2 + dy_{CY}^2 \quad \Rightarrow \quad ds^2 = h^{-1/2}(y)dx^2 + h^{1/2}(y)dy_{CY}^2$$

KKLT (continued)

- If everything works, one obtains the desired deformation of the potential:



But full explicitness has remained elusive since:

- Finding fluxes which lead to $W_0 \ll 1$ is extremely hard.
- The anti-D3 in the strongly warped region is only controlled in 10d supergravity (no stringy or SUSY analysis).

Landscape – More Recent Developments

- This, and some important variants (like 'LVS') has remained the main evidence for 'stringy dS'.

- It has been proposed that stringy dS is impossible as a matter of principle ('is in the Swampland').

Danielsson/Van Riet; Obied/Ooguri/Spodyneiko/Vafa '18
(see also Bena, Grana, Sethi, Dvali, ...)

- Subsequently, constructions like KKLT and LVS have been subjected to intense scrutiny (with varying success).

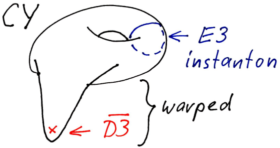
- I will focus on what I feel is most critical.....

Singular Bulk Problem of KKLT

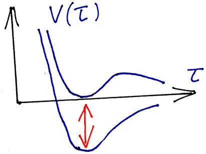
Carta/Moritz/Westphal '19; Gao/AH/Junghans '20

(see however: Carta/Moritz; McAllister et al. '21...'23)

- Reminder:



$\Rightarrow$



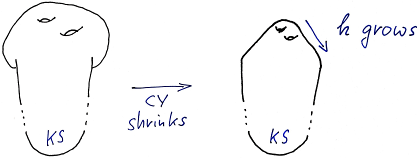
- The dS vacuum relies on the competition of two small quantities:

$$V_{AdS} \sim \exp(-T) \qquad \text{and} \qquad V_{up} \sim \exp(-\text{`Throat-Flux'})$$

This matching implies that
the throat can not be parametrically smaller than the bulk....

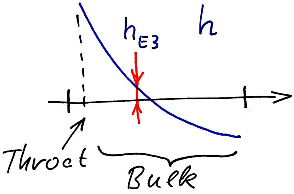
Singular Bulk Problem of KKLT (continued)

- As a result, strong warping sets in already in the bulk:



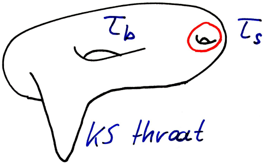
- This implies the (potentially deadly) 'singular bulk problem':

$$ds_{10}^2 = h(y)^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + h(y)^{1/2}\tilde{g}_{mn}dy^m dy^n$$



Does this problem extend to the 'Large Volume Scenario' (LVS)?

- The LVS is a close cousin of KKLT with a crucial twist: There are two 4-cycles and one of them grows exponentially large.



- Naively, the LVS is safe since the volume $\mathcal{V} \sim T_b^{3/2} \sim \exp(-T_s) \sim \exp(-1/g_s)$ is exponentially large:

- However, due to higher curvature corrections of the type $R + R^2 + R^3 + \cdots$ control is nevertheless lost in many cases.

Junghans '22

- Control can be maintained if a sufficiently large D3-tadpole is available:

$\rightarrow$ LVS Parametric Tadpole Constraint

Gao/AH/Schreyer/Venken '22

The LVS Parametric Tadpole Constraint

- We are driven to the following situation:

$$N = N_{bulk} + N_{th.} \leq |Q|_{max}$$

$$N_{th.} \gg 1 \text{ needed for control}$$

- $\Rightarrow$ Would like to keep N_{bulk} small.

- This becomes worse in view of higher curvature corrections in the throat, since controlling those enforces very large $N_{th.}$

AH/Venken/Schreyer '22

The Tadpole Conjecture

- Given that known geometries have limited $|Q|_{max}$,
one wants to stabilize all complex-structure moduli with a small bulk tadpole N_{bulk}.
- However, the Tadpole Conjecture claims this to be impossible:

> If some flux vector stabilizes a large number n of complex-structure moduli, then $N_{flux} > \alpha n$ with $\alpha = \mathcal{O}(1)$.

Bena/Blaback/Grana/S.Lüst '20

- This conjecture has several (stronger and weaker) forms and counterexamples of varying strength have been suggested.
- There is an ongoing debate about this conjecture,
the quality-of-control issue for KKLT and LVS,
as well as efforts to find geometries with large $|Q|_{max}$....

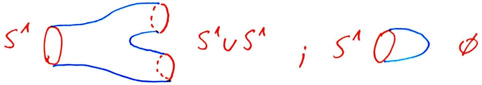
cf. e.g. Lüst/Wiesner, Coudarchet/Marchesano/... ,
Crino/Quevedo/Schachner/Valandro, Demirtas/McAllister/Moritz,....

.... and now for something completely different:

Cobordism

- Two manifolds of dimension d are cobordant if they form the boundary of a manifold of dimension $d+1$.

- Examples:



Cobordims Conjecture:

In quantum gravity, all cobordims groups are trivial.

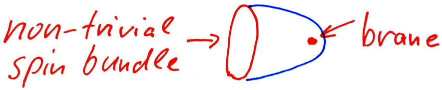
McNamara/Vafa '19

(Much subsequent work,
e.g. by Heckman, Ooguri, Montero, Valenzuela, Blumenhagen, ...)

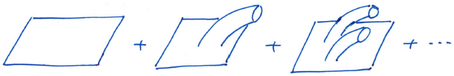
- One of the key arguments given for the conjecture is based on the 'No global symmetries conjecture'
(one of the most highly regarded Swampland conjectures)

Cobordism and wormholes / baby universes

- The implications are highly non-trivial, e.g. through the prediction of new defects or ‘branes’:



- Another obvious implication is that the creation of baby universes can not be avoided:



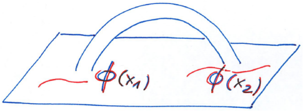
- The latter is of course a very old story....

Giddings/Strominger, Coleman, Preskill ’88 ......

(for a review see AH/Mikhail/Soler ’18)

Cobordism and wormholes / baby universes (continued)

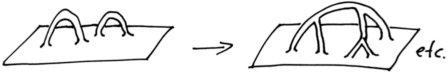
- Coleman's original analysis 'saved' us from non-locality by discovering the rewriting in terms of α paramters:



$$\exp\left(\int_{x_1}\int_{x_2}\Phi(x_1)\Phi(x_2)\right) \rightarrow \int_\alpha \exp\left(-\frac{1}{2}\alpha^2+\alpha\int_x\Phi(x)\right)$$

- Recently, the celebrated Marolf-Maxfield model provided the first (2d toy-mode) exact calculation:

Marolf/Maxfield '20



Reducing the baby-universe Hilbert space?

- The Marolf-Maxfield toy model features an unexpected reduction of the Hilbert space relevant for observations.

- On this basis, it has been conjectured that in $d = 4$ this reduction is so strong that the Hilbert space of baby universes/α-parameters becomes 1-dimensional.

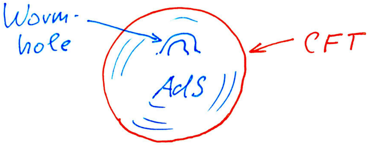
  McNamara/Vafa '20

- Many others have struggled with the question whether string theory really possesses the underlying wormhole solutions.

Maldacena/Maoz '04, Arkani-Hamed/Orgera/Polchisnki '07,
Van Riet '04 ... '23, Hertog, Van der Schaar, Soler, Trigiante, Shiu, ...

Reducing the baby-universe Hilbert space? (continued)

- A key problem: Even after Coleman's resummation the fundamental non-locality still clashes with the locality of AdS/CFT.



- On the other hand, the recent success of wormholes in the BH entropy context (e.g. derivation of Island Formula) suggests that wormholes are relevant.

- The wormhole/baby universe issue remains mysterious....

cf. the recent literature discussing Marolf/Maxfield and McNamara/Vafa

Summary / Conclusions

- String Theory remains a leading candidate for a fundamental theory of quantum gravity.
- The 'realistic' landscape of flux vacua with SUSY-breaking and positive cosmological constant has come under pressure due to doubts raised in the 'Swampland debate'.
- On the positive side, this has lead to a new 'precision era' in the construction of explicit string compactifications.

- The old story of euclidean wormholes/baby universes has seen a revival due to the prominent role of wormholes in the BH-entropy context.
- Explicit toy models and new ideas for avoiding the problematic implications of the 'baby universe state' are being discussed.