On Stringy de Sitter Vacua

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(including work with **Xin Gao, Daniel Junghans, Simon Schreyer, Victoria Venken**)

Outline

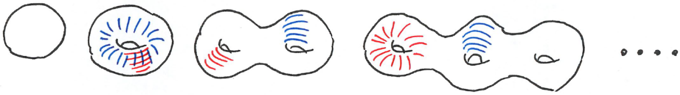
- Why is de Sitter hard to get?
  Why is quintessence not an easy way out?
- The 'Singular Bulk Problem' of KKLT.
- The 'Parametric Tadpole Constraint' of LVS
- Making things worse: α' corrections to the NS5 brane in the throat.
- Possible ways forward.

To get started: The 'classical' landscape

- String theory provides an (essentially unique) and UV-complete field theory in 10d: $$S_{IIB} = \int_{10} \mathcal{R} - |F_{\mu\nu\rho}|^2 + \cdots$$

- Compactifying on Calabi-Yau-Orientifolds, one preserves $\mathcal{N} = 1$ SUSY and (classically) zero 4d cosmological constant.

- The extra ingredient of fluxes induces an exponentially large landscape of discrete solutions.



Bousso/Polchinski, Giddings/Kachru/Polchinski, Denef/Douglas '04

- This has lead to an overly optimstic **'anything goes'** attitude (in the sense that more or or less any EFT can be realized).

A new perspective: The Swampland paradigm

- However, it is very reasonable to take the opposite perspective and ask which EFTs **can not** be found in the landscape.

Vafa '05, Ooguri/Vafa '07

- This turned out to be very fruitful and inspiring (though much has remained at the level of conjectures ....)

  See e.g. recent papers and talks by
  Montero, Valenzuala, Weigand, ...

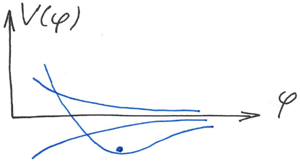
  And in part also by Antoniadis, Angelantonj, Basile,
  Dall'Agata, Dvali, Kehagias, Tomasiello, Westphal, ...

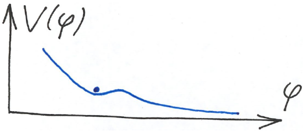
- In what follows, I can only attempt a review of (some of...) the recent developments concerning **one** of the many conjectures:

  The absence of (quasi-) de Sitter vacua in the landscape.

String compactifications: beyond leading order

- Let's assume complex structure moduli are stabilized by fluxes.
- The Kahler moduli (let's say just the volume) get a (much smaller) potential from quantum corrections.
- The simplest solutions are runaway.
  The next-simplest are SUSY-AdS.
- It takes a conspiracy between at least three 'runaway potentials' to get meta-stable de-Sitter vacua.





On the genericity of ‘runaway potentials’

- Let us briefly pause and explain why ‘runaway potentials’ are hard to avoid.

- Consider a generic compactification with volume $\mathcal{V}$ and some energy source induced by (quantum) corrections:

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

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

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

- The exponent is usually $\mathcal{O}(1)$, so fast runaway is the rule.

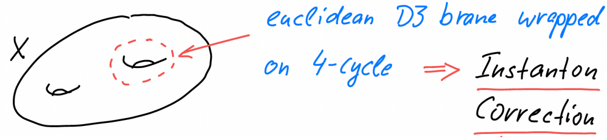
- Nevertheless, three such effects can conspire to give dS!

The historical prime example: KKLT

Kachru/Kallosh/Linde/Trivedi

- Recall that Kahler moduli are still flat directions. Assume there is just one: the volume.

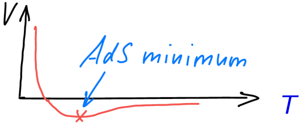
- To discover its potential, one needs to study the model with more precision:



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

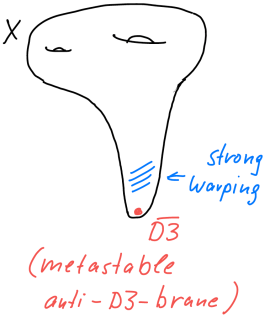
$\Rightarrow \quad V \sim e^{-2T} - |W_0| e^{-T}$

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



KKLT (continued)

- This construction of a fully stabilized AdS minimum is known as 'Step 1' of the KKLT construction.
- 'Step 2' involves 'uplifting' 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.

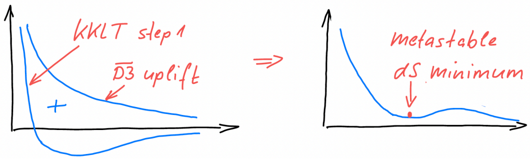


Warping:

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

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.

  Recent progress: e.g. Krippendorf/Schachner/... & McAllister et al.

- The anti-D3 in the strongly warped region is only controlled in 10d supergravity (no stringy or SUSY-QFT analysis).

The dS conjecture

- This, and some important variants (like 'LVS') have remained the main evidence for 'stringy dS'.
- No analogues in type-I, IIA, heterotic, 11d SUGRA were found.
- Based on this, 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).

  Bena/Grana/Van Riet, Van Riet, Moritz/Retolaza/Westphal, Gautason/Van Hemelryck/Van Riet, Hamada/AH/Shiu/Soler, Bena/Dudas/Grana/Lüst, Lüst/Randall, ...

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

....but before doing so, let us consider an apparently obvious way out:

(Stringy) Quintessence:

- In a nutshell: It does not help!
  (in spite of many attempts...)

  Selection of older and recent work: Cicoli/Pedro/Tasinato/Burgess; Cicoli/DeAlwis/Maharana/Muia/Quevedo; Acharya/Maharana/Muia; Emelin/Tatar; Hardy/Parameswaran; Cicoli/Cunillera/Padilla/Pedro; ....

- One (in my opinion key) argument goes as follows:

  (cf. 'F-Term Problem' in AH/Skrzypek/Wittner '19)

  Our world has SUSY broken at TeV, i.e.

$$|F|^2 \quad \sim \quad e^K |DW|^2 \quad \sim \quad \text{TeV}^4$$

  (This part of the superpotential can not be rolling to zero – we would see that!)

Quintessence (continued)

- As a result, an 'uplift-type' cancellation in the C.C. is still needed:

$$e^K |DW|^2 \qquad \gg \qquad \left| e^K (|DW|^2 - 3|W|^2) \right|$$

- The familiar no-scale cancellation does not help since, in our world, the particle spectrum is non-SUSY at TeV.

  $\Rightarrow$ Loop corrections spoil any 'natural' cancellation.

- **In short:** Rolling toward SYSY-Minkowski is very natural in string theory. But this is not what's going in our universe.

  (cf. Bousso's analogy to 'looking for cheese on the Moon.')

Final insider comment: In my understanding, the 'Dark Dimension scenario' relies on a yet-to-be-discovered solution of the CC problem.

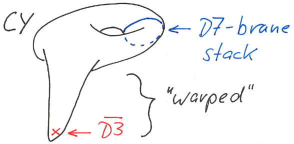
(cf. Montero/Vafa/Valenzuela '22)

...with this in mind, let us return to scrutinizing KKLT:

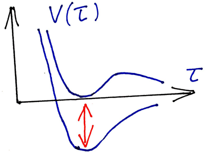
Singular Bulk Problem of KKLT

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

- Reminder:



$\Rightarrow$

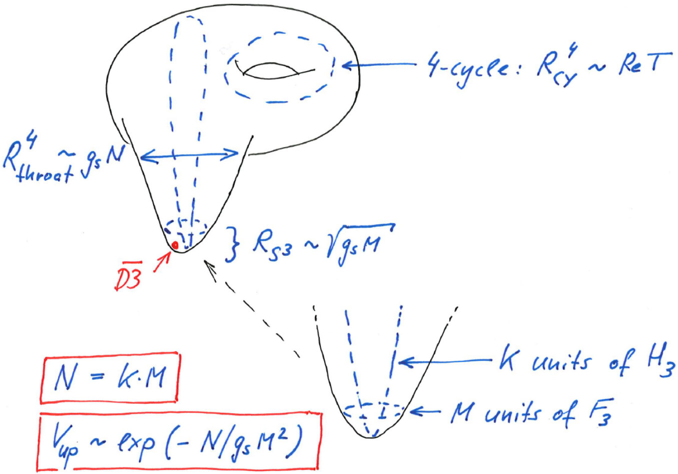


- The dS vacuum relies on the competition of two small quantities: (with the definitions $(Volume)^{2/3}/g_s \sim \text{Re}\, T \sim \tau$)

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

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

Some geometric details:



$\Rightarrow$ 'Throat gluing problem'

- Thus, we need the approximate equality of

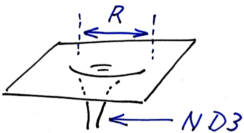
$$V_{AdS} \sim -e^{-4\pi \mathrm{Re}(T)} \quad \text{and} \quad V_{Uplift} \sim e^{-8\pi N/3g_s M^2} .$$

- This implies

$$\mathrm{Re}(T) \simeq N/g_s M^2 .$$

- At the same time, the throat carries $N = KM$ units of D3 charge, giving it a radius

$$R^4_{throat} \simeq g_s N .$$



- Recalling $(Vol)^{2/3} \sim g_s T$, the 'gluing of the throat into the CY' then needs:

$$g_s N < g_s N / g_s M^2$$

- But this is problematic since

$$g_s M \simeq R_{S^3}^2 \gtrsim 1$$

  for supergravity control

  KS, KPV, Klebanov/Herzog/Ouyang '01

- ... and since

$$M \gtrsim 12$$

  for metastability of the anti-D3-brane.

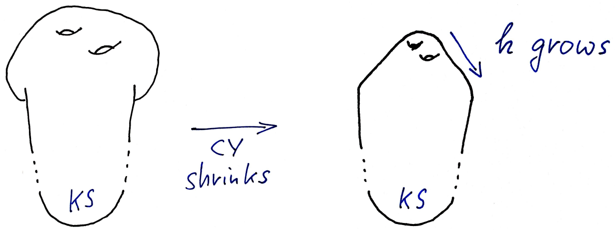
  KPV (see also Bena/Dudas/Grana/Lüst, Blumenhagen/Kläwer/Schlechter Lüst/Randall)

Is this deadly ?

- Not yet, since a priori the warp factor $h(y)$ of

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

may indeed allow the bulk to be smaller than the throat:

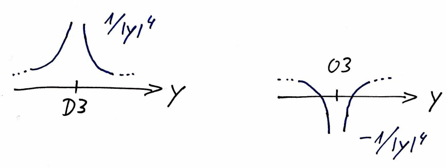


- However, the regime of KKLT generically enforces $h < 0$ in a large portion of the CY geometry. And that is real problem!

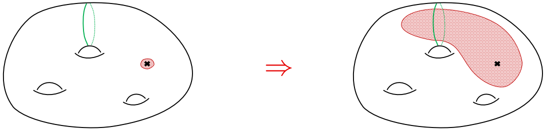
The singular-bulk problem (continued)

- Of course, small negative-h regions near O-planes are OK,

$h(y)$:



But our analysis reveals that a situation like this is generic:



The singular-bulk problem (continued)

- For quantifying the problem, a key insight is that the warped E3 size $\mathcal{V}_{E3}$ determines the exponential effect:

$$\mathrm{Re}(T) \sim N/g_s M^2 \qquad \Rightarrow \qquad \mathcal{V}_{E3} \sim N/M^2$$

  with

$$\mathcal{V}_{E3} = \int_{E3} \sqrt{\tilde{g}}\, h(y) = \tilde{\mathcal{V}}_{E3} \langle\, h \,\rangle_{E3} \,.$$

- W.l.o.g., we use a CY-metric such that $\tilde{\mathcal{V}} = \int_{CY} \sqrt{\tilde{g}} = 1$. Hence $\tilde{\mathcal{V}}_{E3}$ is an $\mathcal{O}(1)$ number.

  $\Rightarrow$ We are constraining the warp factor on the E3 cycle:

$$\boxed{\langle\, h \,\rangle_{E3} \sim N/M^2}$$

The singular-bulk problem (continued)

- At the same time, h solves a Poisson-equation:

$$-\tilde{\nabla}^2 h = \tilde{\rho}_{D3} \qquad \text{with} \qquad \tilde{\rho}_{D3} \sim g_s N\,.$$

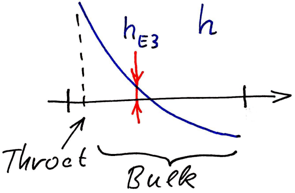
- So h is a compact-space Green's function for a charge distribution of

  $g_s N$ units of positive charge, localized at conifold

  $-g_s N$ units of negative charge, scattered in the CY.

  $\Rightarrow$ $\boxed{-\tilde{\nabla}^2 h \simeq g_s N}$

- Combined with $h_{E3} \simeq N/M^2 \ll \tilde{\nabla}^2 h$, this leads to large negative regions.

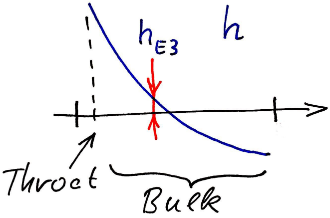


The singular-bulk problem (continued)

- Even more explicitly: $$\frac{|\tilde{\nabla} h|}{h_{E3}} \gtrsim g_s M^2 \gg 1$$
- By Taylor expanding at a point y_0 of the E3,

$$h(y_0 + \delta y) \approx h(y_0) + \partial_m h(y_0)\, \delta y^m \,,$$

we see that h runs negative near the E3: $|\tilde{\delta} y| \lesssim 1/g_s M^2$.



Escape routes

- One option is a very special arrangement of the O3s (or the curved O7/D7s), avoiding our 'genericity' arguments.

- Another option is to fight our 'small parameter' by replacing the E3 with gaugino condensation:

$$1/g_s M^2 \quad \rightarrow \quad N_c/g_s M^2 \,.$$

- However, $N_c \gg 1$ appears to always come with $h^{1,1} \gg 1$.
  Louis/Rummel/Valandro/Westphal '12, Carta/Moritz/Westphal '19

- But large $h^{1,1}$ is problematic due to the scaling

$$\tau \sim (h^{1,1})^{3.2\cdots4.3}\,, \quad \mathcal{V} \sim (h^{1,1})^{6.2\cdots7.2} \qquad (h^{1,1} \gg 1)\,.$$

Demirtas/Long/McAllister/Stillman '18

- One ends up with τ and hence the total tadpole too large ....

Escape routes (continued)

- One may try to accept (or even use to once advantage) the large number of 2/4-cycles, if one can control geometries with many string-sized ones.

  cf. several papers by McAllister et al....

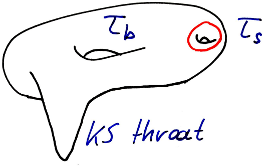
- Another logical possibility is to just accept the singularities and ask how string theory resolves them.

  Carta/Moritz '21

In summary, while not being ruled out, KKLT is not any more the simple, analytically understandable model we were used to.

Related problems in the 'Large Volume Scenario' (LVS):

Balasubramanian/Berglund/Conlon/Quevedo



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

  $$\mathcal{V} \sim \tau_b^{3/2} \sim \exp(-\tau_s) \sim \exp(-1/g_s)$$

- However, due to higher curvature corrections of the type $R + R^4 + \cdots$ 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 and Curvature Corrections

- The amount of 3-form flux (specifically $\int F_3 \wedge H_3$) is bounded by the negative D3-charge or 'tadpole' of the CY geometry.
- The crucial 'Klebanov Strassler Throat' with the anti-brane uplift, needs a lot of flux and uses up a lot of this tadpole.
- As above, the warping it provides is $\exp(-N/g_s M^2)$, with N the tadpole contribution and M the flux on the S^3 at the bottom of the throat.
- 'Control' needs large M. Given a certain desired warping suppression, this drives N large – in fact: marginally too large.

The LVS Parametric Tadpole Constraint and Curvature Corrections

- Explicitly, one finds the tadpole constraint

$$|Q_3| \gtrsim N_* \left(\frac{1}{3} N_* + \mathcal{O}(10) \right) .$$

Here $N_* \simeq g_s M^2/5$ and the $\mathcal{O}(10)$–constant depends on the desired quality of control.

- This could still be marginally OK with the maximal available tadpole $|Q_3| = 252$ for CY orientifolds.

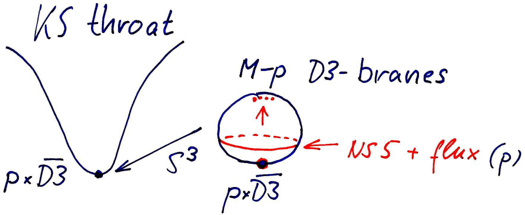
Crino/Quevedo/Schachner/Valandro '22

- <u>But:</u> The resulting constraints become worse if curvature corrections are included....

NS5-brane curvature corrections

AH/Schreyer/Venken '22; Schreyer/Venken '22

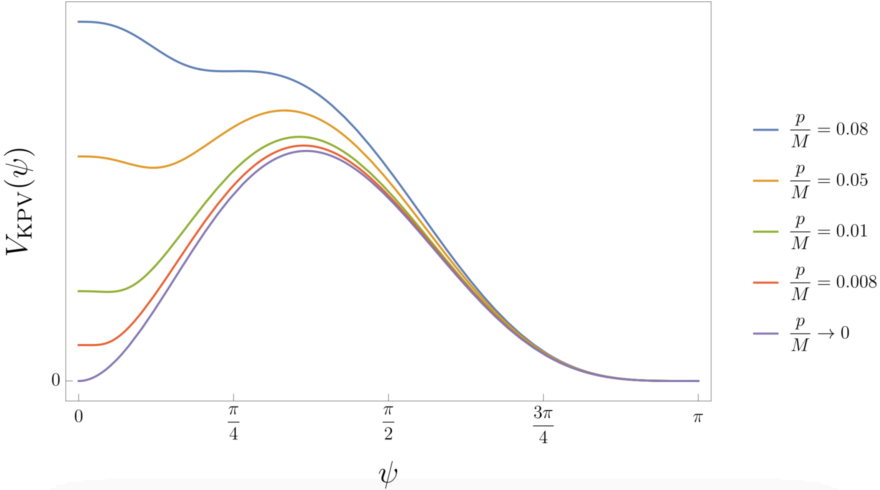
- The $\overline{\mathrm{D3}}$ has a well-known 'KPV' NS5-brane decay channel:



- The curvature at the tip is controlled by $g_s M$, in particular $R_{S^3} \sim \sqrt{g_s M}$.

- At small $g_s M$, the NS5-brane curvature corrections endanger the stability of the KPV-potential

Reminder of KPV potential (with ψ the NS5-brane altitude)



Curvature and higher-order-flux-corrected KPV potential

- The famous 'KPV potential' above demonstrates that we need $M \geq 12$ (for $p = 1$).
- But the key quantity to constrain is $g_s M^2$, appearing in $\exp(-N/g_s M^2)$.
- Until now, everybody has been using the parametric statement $g_s M \sim R^2_{S^3} \gtrsim 1$.
- But this story is about $\mathcal{O}(1)$ numbers, and the only way to get them is to look at higher curvature corrections (in this case to the NS5 brane):

$$S_{NS5} \sim -\frac{1}{g_s^2} \int_{NS5} \sqrt{g + \mathcal{F}} \left(1 - \alpha'^2 R^2\right)$$

(conjectured on the basis of known D5 results....)

Curvature and higher-order-flux-corrected KPV potential

- Knowing these corrections (and analogous higher-flux terms), including the precise numerical prefactors, one can determine...

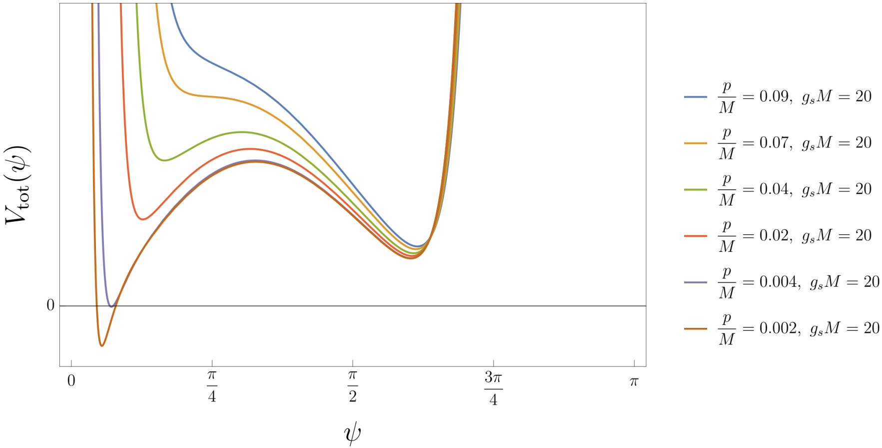
  ...which value of $g_s M$ is necessary to preserve the qualitative shape of the KPV potential.

- This value turns out to be relatively high: $g_s M \sim 20$, cf. next slide ......

- The uncomfortable implication is that $g_s M^2 \gtrsim 100$.

Curvature and higher-order-flux-corrected KPV potential

AH/Schreyer/Venken '22
Schreyer/Venken '22 (using results of Robbins/Wang, Garousi, Babaei/Jalali)



Key implication: Need $g_s M \gg 1$ to maintain KPV result
$\Rightarrow$ KKLT/LVS much more fragile.

Summary / Conclusions

- One should not simply believe that metastable stringy de Sitter is possible/impossible but try to demonstrate it.
- KKLT suffers from the bulk singularity problem.
- The escape routes involve controlling many small cycles or controlling large singular regions ('$h < 0$').
- The LVS has a related but finer-level problem: curvature corrections.
- But since the LVS relies on finer-level corrections, it is still in trouble. (It could be saved by a large tadpole, but that's in general not available.)
- Both problems become much worse due to curvature corrections to the KPV decay process.

Summary / Conclusions

- KKLT/LVS appear to be on much more shaky footing than we thought. More work needed!
- Personally, I would bet less on 'saving' KKLT/LVS and more on the F-term uplift, i.e. on 'accidental' non-SUSY minima of

$$V \sim e^K (|DW_0|^2 - 3|W_0|^2) \, .$$

- If all fails, we need to rethink strings and string pheno from scratch. [I personally do not believe quintessence is a way out.]
- But even in case of sucess (i.e. existence of stringy dS), these vacua may be much more rare and fragile than thought. (which may have interesting implications for landscape statistics etc.)