KKLT, LVS and all that

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(including work with **Xin Gao, Daniel Junghans, Severin Lüst, Andreas Schachner, Simon Schreyer, Victoria Venken,**)

Outline

- Our world is (approximately) de Sitter.
  But why is this so hard to get in string theory?
  And why is quintessence not an easy way out?
- KKLT and its 'Singular Bulk Problem'.
- The LVS and its 'Parametric Tadpole Constraint'
- Making things worse: α' corrections to anti-D3-brane-decay.
- Possible ways forward **(in particular: F-term uplift)**.

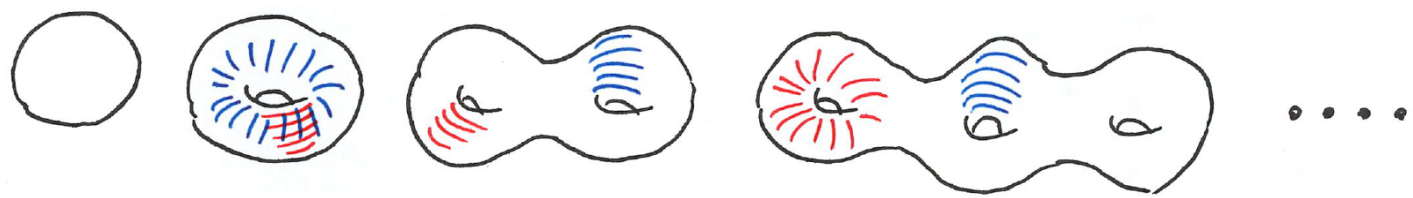
To get started: The 'classical' landscape

- 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 (i.e. $\langle F_{\mu\nu\rho} \rangle \neq 0$) induces an exponentially large landscape of discrete solutions.



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

(Many other options exist – cf. talk Acharya'a talk)

The classical landscape (continued)

- A key part of string pheno is 'getting the SM fields and couplings right'. This can be done e.g. in heterotic ($E_8 \to$ SM) or type-IIB-intersecting-brane models.

cf. Quevedo's talk

- My focus here will be different:
  Stabilizing moduli + breaking SUSY + getting the C.C. right

- Recall that a torus is characterized by its shape and volume:

- For Calabi-Yaus (6d, Ricci-flat compact manifolds), this corresponds to ratios of 3-cycles and 4-cycle-volumes. Technical terms: complex structure and Kahler moduli.

(All that follows is in 'type IIB', where the story is best understood.)

The historical prime example: KKLT

Kachru/Kallosh/Linde/Trivedi

- First, fluxes generically stabilize all complex-structure moduli.
- At this (classical) level, Kahler moduli remain flat directions. Assume there is just one: the volume.
- To discover its potential, one needs to study the model with more precision:

euclidean D3 brane wrapped on 4-cycle $\Rightarrow$ Instanton Correction

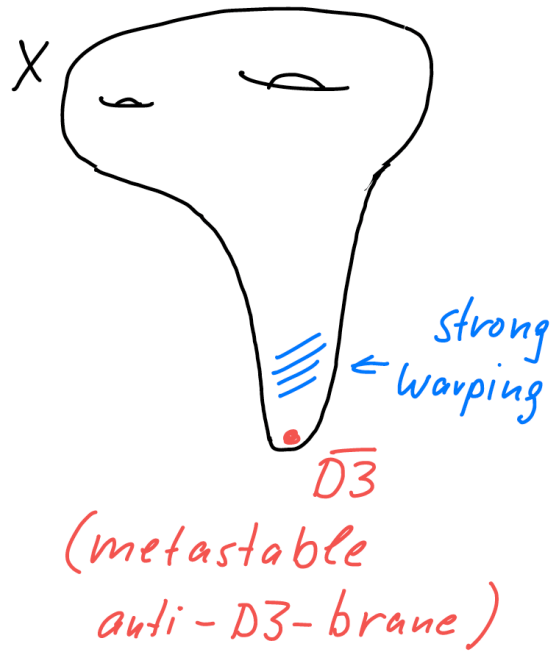
$\Rightarrow \quad W = W_0 + e^{-T}$, (where W_0 is the previous flux effect)

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

$\Rightarrow$ 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 in an appropriate (conifold) region of the CY.

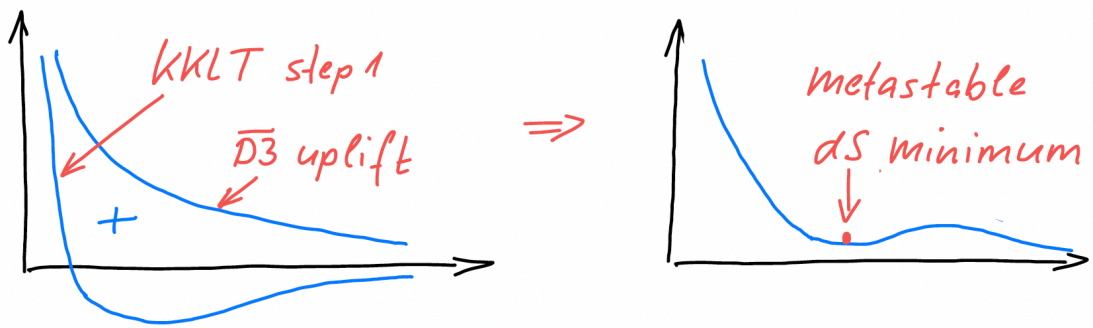


Warping:

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

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.

  Denef-Douglas '04, ... , 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 a key development of it, known as the 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, Kallosh, 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:

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

- 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.

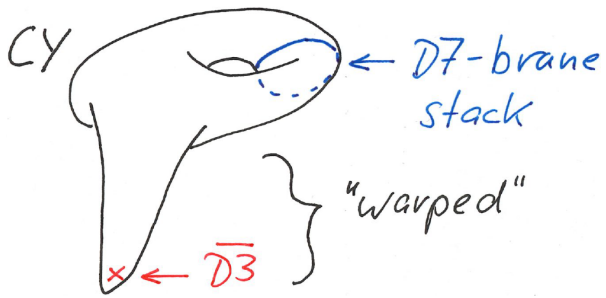
(cf. Montero/Vafa/Valenzuela '22)

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

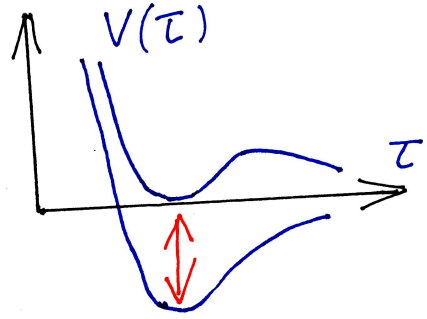
Singular Bulk Problem of KKLT

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

- Reminder:



$\Rightarrow$



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

(with the definitions $(Volume)^{2/3}/g_s \sim \mathrm{Re}\, T \sim \tau$)

$$V_{AdS} \sim \exp(-\tau) \qquad \text{and} \qquad V_{up} \sim \exp(-\text{'Throat-Flux'}) \sim \exp(-N/g_s M^2)$$

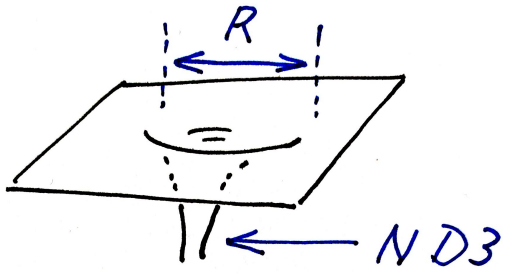
- This has key implications....

- First, the exponents must be roughly equal:

$$\tau \simeq N/g_s M^2 .$$

- The integer N measures the D3 charge in the throat, giving it a radius

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



- Recalling $(Vol)^{2/3} \sim g_s \tau$, 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

$$g_s M \simeq R^2_{S^3} \gtrsim 1 \qquad \text{and} \qquad M \gtrsim 12$$

for supergravity control and metastability of the anti-D3-brane.

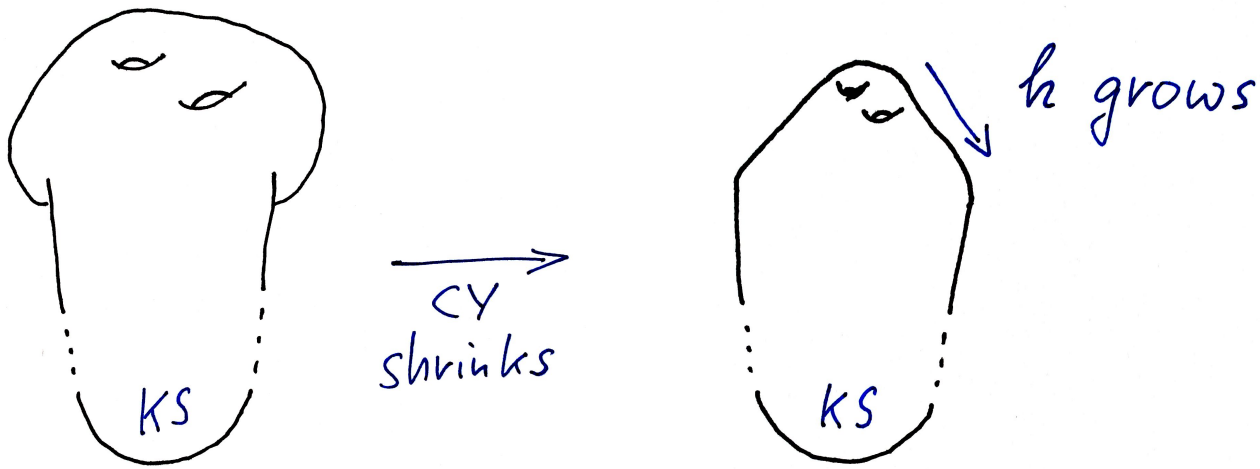
Klebanov/Strassler, Klebanov/Pearson/Verlinde (see also Bena/Dudas/Grana/Lüst, Blumenhagen/Kläwer/Schlechter, Lüst/Randall)

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!

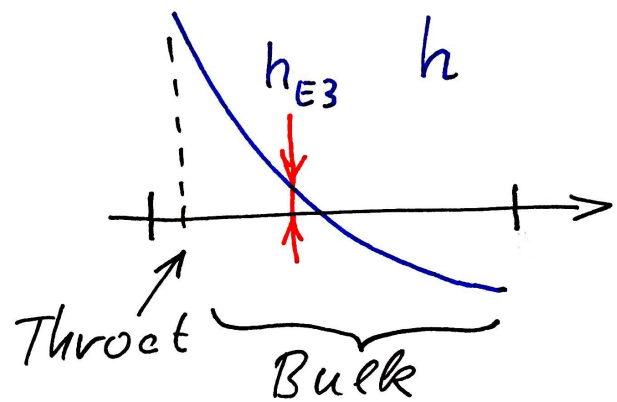
The singular-bulk problem (continued)

- Indeed, h solves a Poisson-equation:

$$-\tilde{\nabla}^2 h \;=\; g_s N\, \delta^6(y - y_{\text{throat}})\,.$$

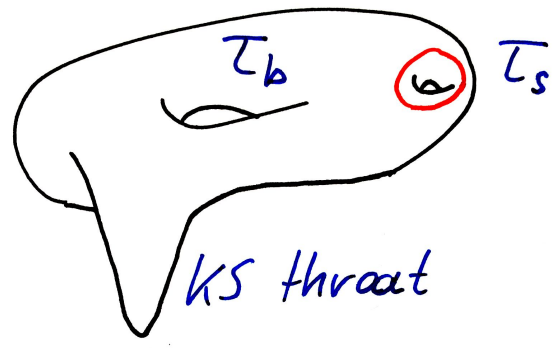
- At the locus of the instanton (known as 'E3 brane'), the value of h is fixed by the KKLT regime:
  $h_{E3} \simeq N/M^2 \ll \tilde{\nabla}^2 h$

- This generically implies large negative-h regions and hence complete breakdown of control.



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

Balasubramanian/Berglund/Conlon/Quevedo



- The LVS is a relative of KKLT but with a crucial twist:

  There are two 4-cycles and one of them is fixed at exponentially large value:

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

- 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

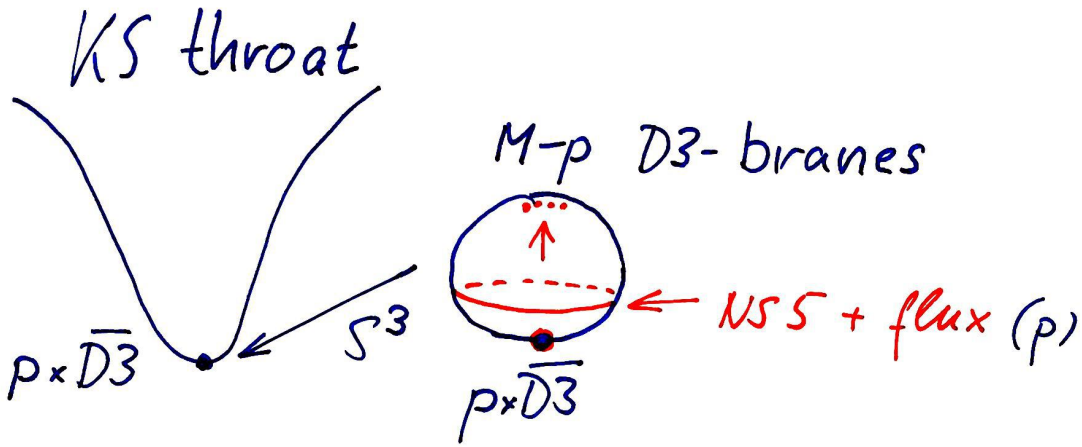
The LVS Parametric Tadpole Constraint and Curvature Corrections

- 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.

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

- Explicitly: $g_s M^2 \gtrsim 12 \quad \longrightarrow \quad g_s M^2 \gtrsim 100$,
  making the problems above much worse!

Summary / Conclusions

- KKLT/LVS appear to be on much more shaky footing than we thought. More work needed!

Possible ways out:

- KKLT/LVS could work in concrete cases without 'parametric control'. (But that's hard to establish!)

- The KKLT singular-bulk problem can be avoided for $h^{1,1} \gg 1$, but one needs to control many sub-stringy cycles.

  Gao/AH/Junghans, McAllister/Moritz/Nelly/Schachner

- The LVS tadpole constraint can be satisfied in F-theory, but the key α' correction then needs numerical analysis.

- The (problematic!) anti-brane uplift may be replaced by an uplift from spontaneous SUSY-breaking in matter-sector.

  M. Dine's talk?

Possible ways out (continued)

- The anti-brane uplift may be replaced by a complex-structure F-term uplift.

  (This is based on ad-hoc non-SUSY minima of $V \sim |D_z W|^2$.)

  Saltman/Silverstein, ..., Linde et al., ..., Krippendorf/Schachner

  Recent finding: OK for LVS but uncontrolled for KKLT.

  AH/Lüst/Schachner/Schreyer

Further Conclusions

- The grossly underestimated difficulty of the uplift may strongly influence all sorts of statistical landscape predictions.

  ...., Linde, Dine, Baer, Salam, Zhang, Gendler ..... , Hassfeld/AH/Westphal

- String Theory has a 'Photoverse/Photinoverse'. The (hidden) photino masses crucially depend on the complex-structure F-term $|D_z W|$. $\Rightarrow$ Unique opportunity to test F-term vs. anti-brane uplift.

  Coudarchet/AH/Jaeckel/Steiner