De Sitter Swampland Conjectures and KKLT

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including recent work with F. Denef / T. Wrase / Y. Hamada / G. Shiu / P. Soler

Outline

- Landscape vs. Swampland – a brief introduction.
- The $|V'|/V$ de Sitter conjecture and its problems.
- The 'mild' and the 'asymptotic' de Sitter conjecture (and potential loopholes).
- Stringy de Sitter models: KKLT and its issues.
- Towards a 10d understanding of KKLT.

String Compactifications

- String theory provides an (essentially unique) and UV-complete field theory in 10d:

$$S = \int_{10} \mathcal{R} - |F_{\mu\nu\rho}|^2 + \cdots$$

- At the very least, this is a useful toy-model for a well-defined gravitational theory.

- One may go for more by compactifying on Calabi-Yaus (6d spaces with vanishing Ricci tensor).

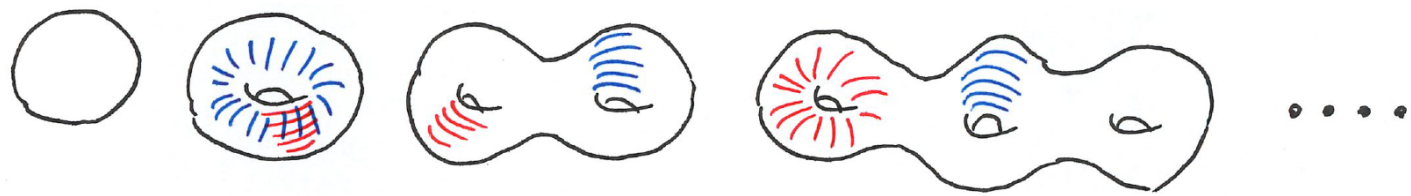
- One ends up with

  (A) unrealistic moduli-space field theories ($\mathcal{N} = 2$ SUSY)

  (B) very flat and poorly controlles field spaces ($\mathcal{N} = 1$ SUSY)
  [it remains unclear how $\Lambda \sim 10^{-120}$ can occur].

String compactifications: flux landscape

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



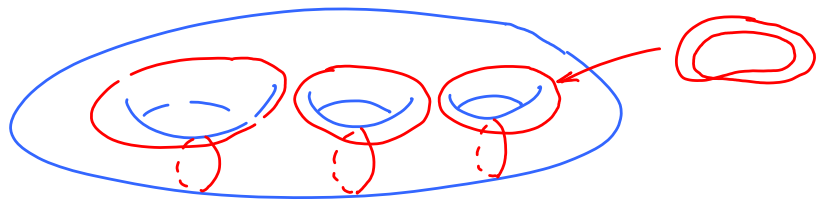
Bousso/Polchinski '00, Giddings/Kachru/Polchinski '01 (GKP)
Kachru/Kallosh/Linde/Trivedi '03 (KKLT), Denef/Douglas '04
Balasubramanian/Berglund/Conlon/Quevedo '05 (LVS)

- Key to the historical number 10^{500} (by now rather $10^{300.000}$) is not the abundance of Calabi-Yaus ($\sim 10^9$), but the discrete flux choice:

$$\oint_{3-cycle} F_{\mu\nu\rho} \in \mathbb{Z}$$

String compactifications: flux landscape

- To understand the discreteness ('flux quantization'), one may think of the twisting of a gauge-theory $U(1)$ bundle:

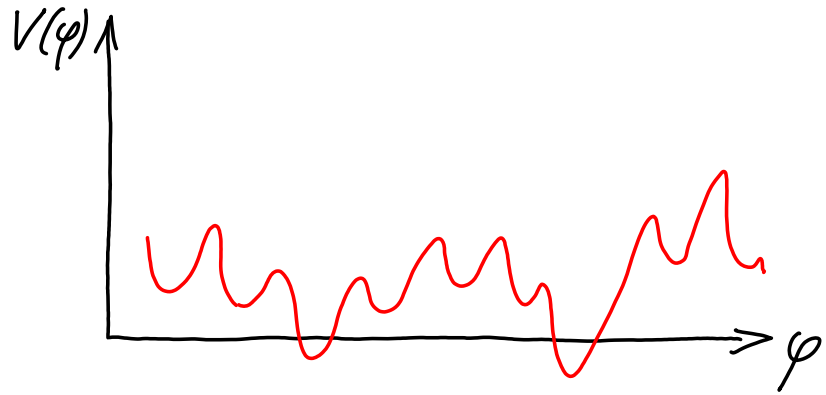


- Typcial CYs have $\mathcal{O}(300)$ 3-cycles.
- Each can carry some integer number of flux of $F_{\mu\nu\rho}$, $H_{\mu\nu\rho}$.
- With, for example, $N_{flux} \in \{-10, \ldots, 10\}$ on gets

$$(2 \times 20)^{300} \sim 10^{500} \text{ possibilities.}$$

String compactifications: flux landscape

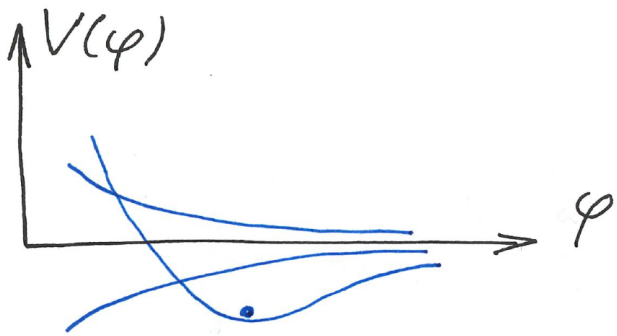
- One may visualize the emerging situation like (just with $\varphi \rightarrow \{\varphi_1, \cdots, \varphi_N\}$):

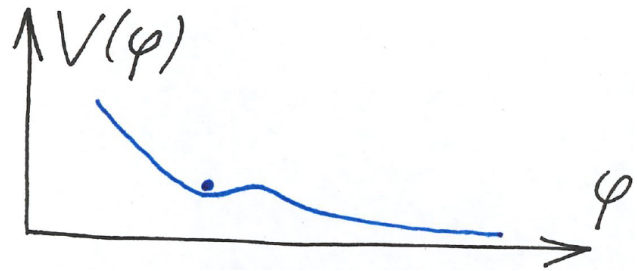


But ususally this only works for
the shape ('complex structure') moduli,
the size ('Kahler') moduli remain flat.

String compactifications: flux landscape

- The size moduli (let's say just the volume) get a (much smaller) potential from quantum corrections.
- While the simplest solutions are runaway or SUSY-AdS, there is (in my opinion) evidence for meta-stable de-Sitter vacua .....



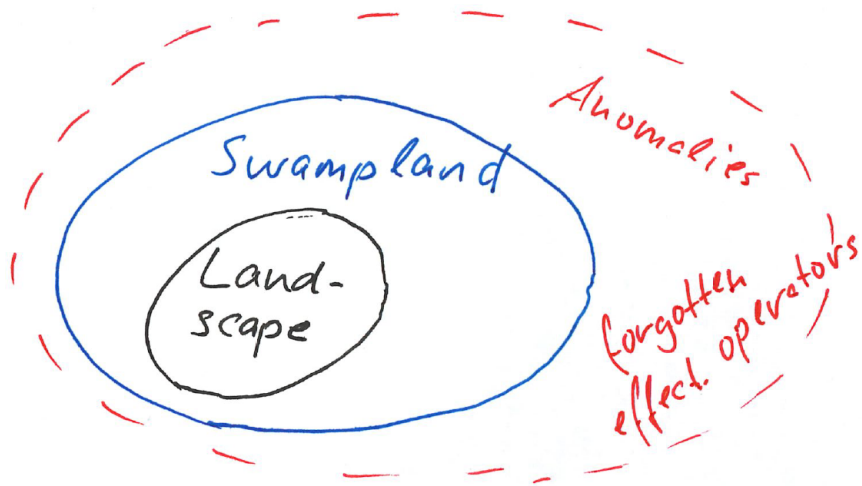


Landscape vs. Swampland

- Before coming to de Sitter, let us clarify the concepts of Landscape and Swampland:

  Landscape: Any EFT obtained from string theory as above.

  Swampland: Any other naively consistent EFT (always including gravity).

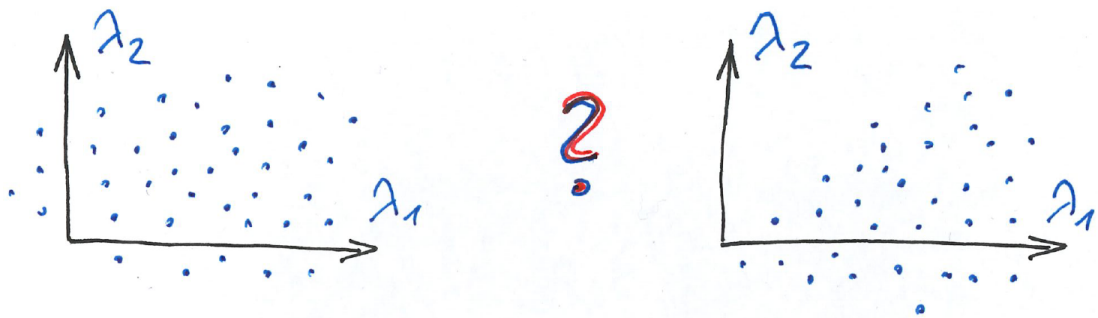


- The existence of a swampland is, of course, one key possibility of how the string landscape could be predictive.

Landscape vs. Swampland

- In a way, this *existence* might however be alomost trivial:
  The landscape is discrete, the space of EFTs is continuous.
  $\Rightarrow$ Almost any EFT is in the Swampland.

- What is less obvious is the presence of well-defined
  'empty' regions in the field-parameter space:



- Thus, this presence of unaccessible regions in parameter space might be the more useful 'swampland' definition.

- Another twist: Demand 'consistency in quantum gravity' (not necessarily string theory). This is of course poorly defined....

Concrete 'Swampland Criteria'

- Specific quantum-gravity consistency citeria have been discussed since a long time ....

  No exact global symmetries

  Completeness — see e.g. Banks/Seiberg '10 and refs. therein

  [the charge lattice is fully occupied]

  The swampland distance conjecture

  [infinite distances in moduli space come with exponentially light states]

  The weak gravity conjecture — Vafa '05, Ooguri/Vafa '06

  Arkani-Hamed/Motl/Nicolis/Vafa '06

- If any of those criteria were relevant experimentally...
  $\rightarrow$ unique opportunity to confront quantum gravity & reality!

De Sitter swampland conjectures

- One possible constraint is clearly $\Lambda_{cosm.} \leq 0$.
- Indeed, a longstanding unease about the status of de Sitter space in quantum gravity exists.

  Dvali, Woodard, Danielsson, Van Riet, Bena, Grana, Sethi, ...

  The motivations are diverse, e.g. ...

- Backreaction of perturbations leaving the horizon.
- Possible problems with an interpretation of the 'inside-horizon region' as the full QM system.

  (Personally, I do not fully understand this unease.)

- In string theory, dS space can only be metastable (one may always decay to the many Mink. or AdS vacua).

The $|V'|/V$ de Sitter conjecture

- Recently, a very strong version of the doubts concerning (even metastable) dS vacua has been put forward:

$$|V'|/V > c \qquad \text{(in Planck units and with } c \sim \mathcal{O}(1)\text{)}$$

Obied/Ooguri/Spodyneiko/Vafa
Agrawal/Obied/Steinhardt/Vafa '18

- Intriguingly, this does not immediately clash with late cosmology:

Indeed, a simple quintessence model with $V \sim e^{-c\varphi}$ and $c \sim \mathcal{O}(1)$ can satisfy the conjecture and replace $\Lambda_{cosm.}$.

A lot of phenomenological work (both late-time and inflation) has followed.

e.g. Bartelmann et al.
Dias/Fazer/Retolaza/Westphal, ...

The $|V'|/V$ de Sitter conjecture

- Let us briefly pause and (attempt to) explain how such an incredibly strong conjecture might be motivated.

- 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

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

- The exponent is usually $\mathcal{O}(1)$, so the simplest compactifications do indeed obey the $|V'|/V$ conjecture.

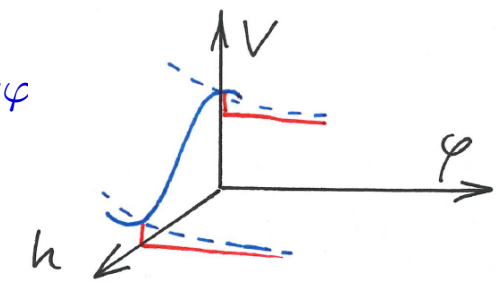
The $|V'|/V$ dS conjecture and the Higgs

- However, if this were unavoidable, we would be in deep trouble.

Denef/AH/Wrase

- Indeed, in presence of the SM, an additive quintessence contribution does not save the conjecture:

$$V = \lambda(h^2 - v^2)^2 \; + \; \Lambda_{cosm.}\, e^{-c\varphi}$$



clearly violates the conjecture at $h = v$.

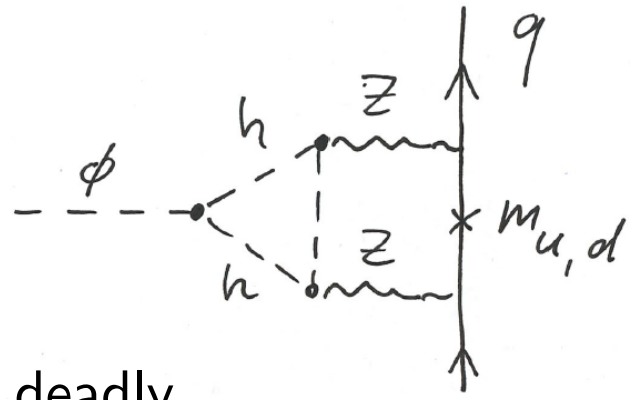
- An (apparent) remedy is also easily found:

$$V = \left[\lambda(h^2 - v^2)^2 \; + \; \Lambda_{cosm.}\right] e^{-c\varphi}$$

The $|V'|/V$ dS conjecture and the Higgs (continued)

- An immediate problem is that this is a coupled / interacting quintessence model – extreme tuning (of many operators) is now required.

- Also: Equivalence Principle Violation from diagrams like



is relevant but not deadly.

- Others have since strengthened the constraints and extended the logic from the Higgs to the pion.

Choi/Chway/Shin '18

Cicoli/De Alwis/Maharana/Muia/Quevedo;
Murayama/Yamazaki/Yanagida; Marsh; ....

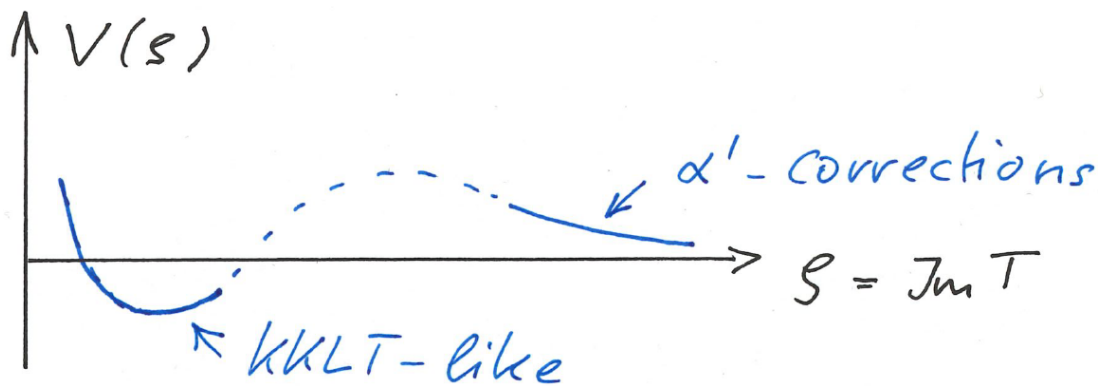
The $|V'|/V$ dS conjecture and the Higgs (summary)

- The $|V'|/V$ conjecture might fall (has fallen?) on phenomenological grounds.
- As a logical possibility, the conjecture may still hold in string theory (which hence does not describe the real world!).
- However, critical points at $V > 0$ may exist even in ST.

see work by Lüst, Wrase, Andriot, Shiu, Danielsson, Van Riet, ...

- As a particularly simple, recent argument uses the potential..

Conlon '18



The 'mild' dS Swampland conjecture

- One may say 'the conjecture is *really* about forbidding metastable de Sitter' (sacrificing $|V'|/V$).
- Such formulations have indeed been proposed:

  Garg/Krishnan,
  Ooguri/Palti/Shiu/Vafa

  One of the two must always hold:

$$|V'|/V > c_1 \qquad \text{or} \qquad V''/V < -c_2\,.$$

- In words: No continued exponential expansion.
- Technically, this puts us 'back to square one': The old debate about realizing de Sitter (or just inflation) in string theory.
- Such a critical debate is clearly needed (see below), but at this time I do not see strong *new* reasons against dS.

The 'asymptotic' dS Swampland conjecture

- One of the above papers gave arguments against 'asymptotic' de Sitter vacua.

  Ooguri/Palti/Shiu/Vafa

- Here asymptotic means at asymptotically large field distance, corresponding e.g. to 'large volume'.

The argument is:

- By the Swampland distance conjecture:
  large $\varphi \quad \Rightarrow \quad$ tower of light states at $m \sim e^{-\varphi}$.
- New assumption: This number of states behaves as $n(\varphi)\, e^{-\varphi}$ with $n(\varphi)$ monotonic.
- New assumption: Those states should saturate dS entropyy $S \sim R_{dS}^2 \sim 1/V$.
- Accepting all of this does indeed imply that V decays exponentially at $\varphi \to \infty$.

The 'asymptotic' dS Swampland conjecture

- Clearly, many highly non-trivial new assumptions are invoked.
- In fact, one may argue much more directly:

  Large φ $\Rightarrow$ many light states

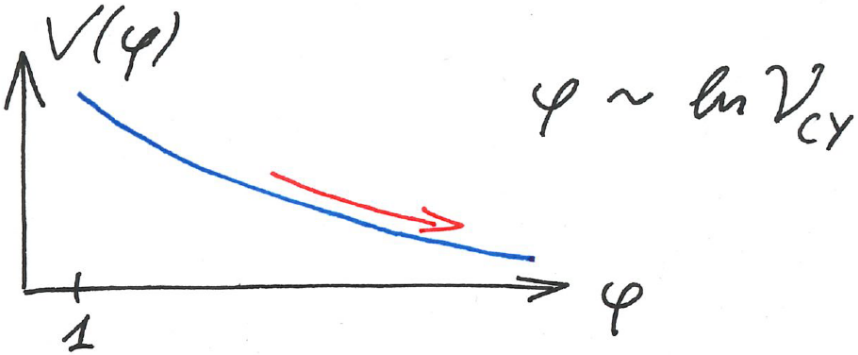
  Reece, AH/Wrase

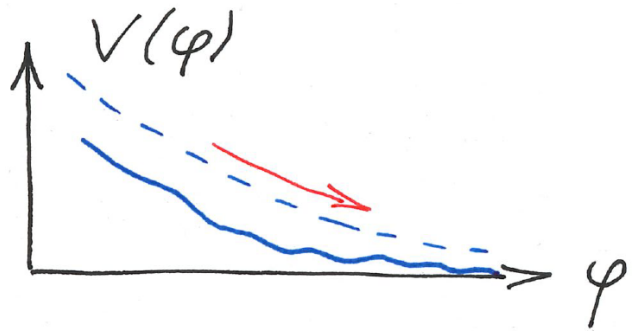
  Many light states $\Rightarrow$ low cutoff Λ (Dvali's species bound).

  Low cutoff $\Rightarrow$ small potential ($V \sim 1/R_{dS}^2 \lesssim \Lambda^2$).

- But: This gives only an upper bound, wiggles and hence minima not ruled out (closely related: flux vacua at $\varphi \to \infty$).

  AH/Wrase, Junghans





dS Swampland conjectures: intermediate summary

- The above 'oscillations loophole' has a counterpart in the mononotonicity assumption of the entropy argument.
- Given our limited understanding of dS entropy, this does not appear easy to close.
- Quite generally, even the most widely accepted Swampland conjectures are hard to defend rigorously.
- Much harder: Rule out dS also in the regime of 'large but not asymptotically large' volume.
- Alternative approach: Do not fight the landscape, but try to establish it by studying best concrete models, e.g. KKLT

KKLT

Kachru/Kallosh/Linde/Trivedi '03

- KKLT is one of the leading concrete dS models in string theory (the other being the 'large volume scenario' or LVS).
- The present 'no-dS' debate was sparked off (among others) by a concrete criticism of KKLT in Moritz/Retolaza/Westphal '17
- Before discussing the criticism, let us discuss the proposal.
- We start with a CY with fluxes with all 'shape moduli' (complex structure moduli) fixed by fluxes.
- The only field that is left is $T = \tau + ic$ with $\tau \sim \mathcal{V}^{2/3}$.

KKLT

- T parameterizes a complex 1-dimensional manifold (the moduli space).
- That space is Kahler and the **Kahler potential** reads

$$K(T,\overline{T}) = -3\ln(T+\overline{T})\,.$$

- In 4d supergravity, this means

$$\mathcal{L} = K_{T\overline{T}}|\partial T|^2 - V(T,\overline{T}) + \cdots\,.$$

where $K_{T\overline{T}} \equiv \partial_T \partial_{\overline{T}} K(T,\overline{T})$ and

$$V \equiv e^K \left(K^{T\overline{T}} \left| \partial_T + K_T W \right|^2 - 3|W|^2 \right)\,.$$

with $W = W(T)$ the **superpotential**.

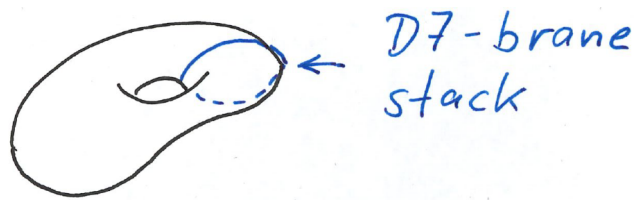
KKLT

- The fluxes give $W = W_0 = \text{const.}$, which implies (through a miraculous cancellation called 'no-scale')

$$V \equiv 0\,.$$

- Thus, we are in Minkowski space and the volume of our manifold is 'an exactly flat direction'.

- Next, we put a *D7 brane stack* (on which a non-abelian gauge theory lives) in our CY.

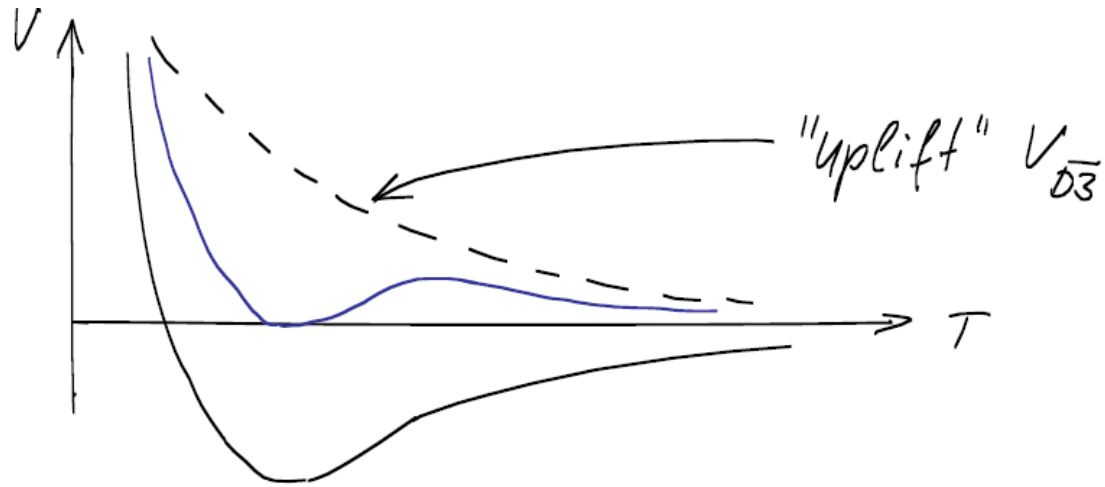


The gauge theory coupling runs and leads to confinement at low energies.

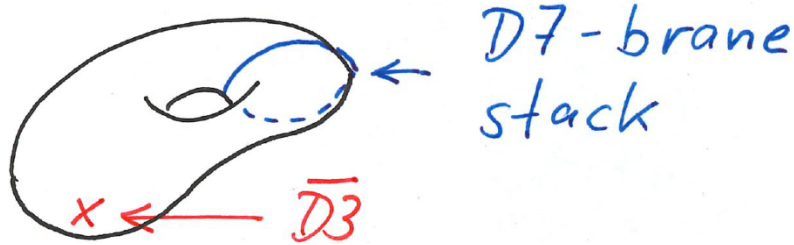
$$\Rightarrow \quad W = W_0 + e^{-T}$$

KKLT

- This stabilizes T and hence the CY volume:



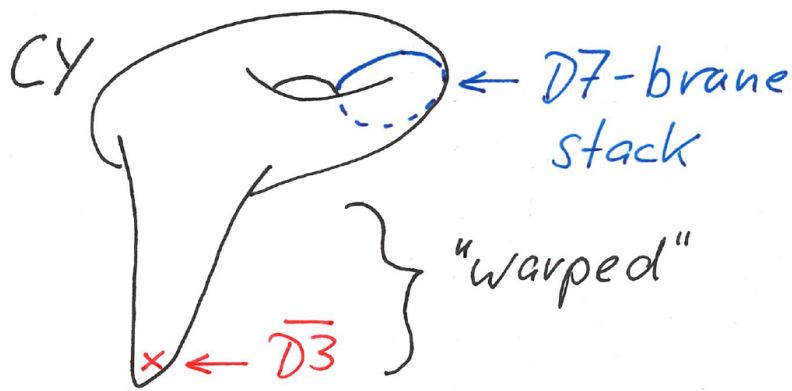
- But the stabilization is in AdS, and an extra positive energy source (an anti-D3-brane) must be introduced to 'uplift' to positive energy.



KKLT

- In fact, to make the uplift small enough the $\overline{D3}$ brane must sit in a 'strongly warped' region.

- Such regions are introduced automatically by fluxes.
  They are 'large-redshift regions' (like near a black hole).



KKLT under attack

Now we can come to the recent criticism:

- Roughly, it doubts the (very indirect, 4d SUGRA) method of KKLT.
- Instead, it proposes to directly solve 10d Einstein equations.
- This requires a 10d model for the gauge theory confinement (In SUSY: Non-zero gaugino condensate $\langle \overline{\psi}\psi \rangle \neq 0$.)
- This seems possible, since the crucial coupling to fluxes in 10d is known:

$$\mathcal{L}_{10} \supset (F_{\mu\nu\rho})^2 + F_{\mu\nu\rho} \langle \overline{\psi}\psi \rangle \delta_{D7} \ .$$

(Here δ_{D7} is a δ-function localized along the D7-brane stack.)

KKLT under attack

$$\mathcal{L}_{10} \supset (F_{\mu\nu\rho})^2 + F_{\mu\nu\rho} \langle \overline{\psi}\psi \rangle \delta_{D7} \ .$$

- It is clear what to expect:
  $F_{\mu\nu\rho}$ backreacts, becoming itself singular at the brane.
- Plugging this back into the action,
  one gets a divergent effect of type $(\delta_{D7})^2$.
- Assuming this to be regularized by string theory, one may argue that at least the sign is fixed, and check how this contributes to 10d Einstein equations.
- It can then be concluded that
  the 'uplift' can not work in principle.

KKLT rescued

Hamada/AH/Shiu/Soler '18,'19; Kallosh '19; Carta/Moritz/Westphal '19

- Such singular gaugino effects have been observed before, in other string models.

  Dine/Rohm/Seiberg/Witten '85
  Horava/Witten '96

- It has been shown that a highly singular $\langle\overline{\psi}\psi\rangle^2$-term saves the day by 'completing the square'. Applied to our case:

$$\mathcal{L}_{10} \supset \left(F_{\mu\nu\rho} + \langle\overline{\psi}\psi\rangle\,\delta_{D7}\right)^2 .$$

- Very roughly speaking, one now writes $F_{\mu\nu\rho} = F^{flux}_{\mu\nu\rho} + \delta F_{\mu\nu\rho}$ and lets the second term cancel (most of) the δ-function.

  The result is

$$\mathcal{L}_{10} \supset \left(F^{flux}_{\mu\nu\rho} + \langle\overline{\psi}\psi\rangle\right)^2 \quad \rightarrow \quad \left(W_0 + e^{-T}\right)^2 .$$

KKLT rescued ?

- One can plug this into the 10d Einstein equations and obtain the 'correct' 4d curvature (with uplift!).
- Here by 'correct' we mean the result of 'effective potential' or energy-balance considerations (either in 4d or in 10d).
- However, a different group disagrees (with the treatment of the volume- or T-dependence in the 10d E-M-tensor).

  Gautason/Van Hemelryck/Van Riet/Venken '19
- Also, new concerns have been raised (about the volume needed to house the complicated topology needed for the D7-brane stack)

  Carta/Moritz/Westphal

  (see also Louis/Rummel/Valandro/Westphal '12)
- Nevertheless, I believe one may be more optimistic about KKLT today compared to a few months back.

Summary / Conclusions

- It may be that dS space (even metastable) does not exist for fundamental reasons.
- To me, this has not (yet?) been convincingly argued.
- Phenomenologically, quintessence is certainly a good way out. (Also inflation may still survive in a slightly more contrived form.)
- For string theory that may imply that we will never succeed in stabilizing the compact volume at $\Lambda_4 > 0$.
- This would probably kill string phenomenology as we know it today (not everybody agrees).

Summary / Conclusions

- In that (worst case) scenario, I see two options:

  (A) String theory has nothing to do with the real world.

  (B) It relates to the real world in a way very different from the compactifications studied so far.

- I still do not want to go down either of those roads:
  dS may be fine with string theory and KKLT
  (or some variant thereof) might work.

- I hope that our recent work has removed one small stumbling block for such models.

- How many more such blocks must be removed?
  (Or will dS in string theory eventually be ruled out?).

- Either way, we should keep studying this fundamental issue!