The flatness of axionic potentials and KKLT in 10d

Arthur Hebecker (Heidelberg)

Part I: Flat Axion Potentials

work with Henkenjohann and Leonhardt / Moritz / Westphal

- Swampland constraints on the flatness of axionic potentials and on fermionic U(1)s ?

Part II: Towards a 10d understanding of KKLT

work with Hamada / Shiu / Soler

- Consistently coupling 7-brane gauginos to 10d fields.

- Including the gaugino condensates in 10d EOMs.

Flat Axionic Potentials - Motivation

- WGC and Swampland ideas have seen a revival because of phenomenological interest in large field inflation.
- But, going beyond this 'large-f' motivation, one should ask for new / alternative phenomenological goals.
- Recall that the U(1) WGC scale is $g\,M_P$, which is generically out of reach.
- By contrast, the Axionic WGC scale is $A\,e^{-M_P/f}$, which can easily be low enough to affect phenomenology.
- Thus, constraints on light axions may be THE new target.

Urbano/Alonso, AH/Mikhail/Soler, Reece, $\cdots$

Flat Axionic Potentials - Constraints and Relation to Fermions

recent work: AH/Henkenjohann

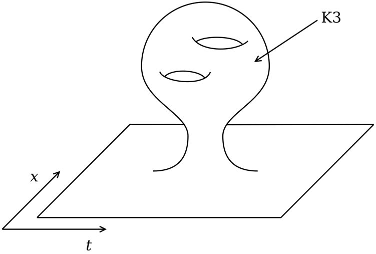
- Well known:
  The prefactor A in $V(\varphi) \sim A\, e^{-M_P/f} \cos(\varphi)$ may be small.

  de la Fuente/Sundrum/Saraswat, AH/Mikhail/Soler, Staessens/Shiu,...

- The most natural way to achieve this:
  Light fermions suppress instantons.

- This motivates the conjecture: $A \gtrsim \mu^\alpha M_P^{4-\alpha}$
  with $\alpha > 0$ and μ the cutoff of the purely axionic theory.

- Also: pure gravity effect
  on fermionic global U(1)s
  from K3 instantons.

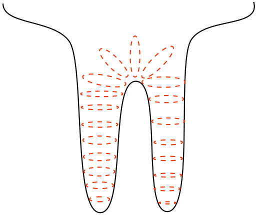


Flat Axionic Potentials:

A new type of counterexample to standard constraints:

recent work: AH/Leonhardt/Moritz/Westphal

- A double-throat system possesses a light axion, $c = \int C_2$, in spite of the absence of an actual 2-cycle.
- The M units of F_3 flux supporting the throat link the excursion of the C_2-axion to a 'throat angle' ($\varphi = \mathrm{Arg}\, z$).
- This connection, $c = \varphi M$, gives rise to a finite (M-fold) monodromy
- Apparently, this allows for a violation of the bound $S \lesssim 1/f$.



KKLT in a 10d approach

with Hamada / Shiu / Soler '18 / '19

Preliminaries:

- KKLT is one leading concrete dS models in string theory (Also: 'Large Volume Scenario' or LVS; Kahler uplifting)

  Kachru/Kallosh/Linde/Trivedi '03

- The present 'no-dS' debate

  Danielsson/VanRiet; Obied/Ooguri/Spodyneiko/Vafa; Ooguri/Palti/Shiu/Vafa; Garg/Krishnan; $\cdots$

  was sparked off (among others) by a concrete criticism of KKLT in

  Moritz/Retolaza/Westphal '17

  For further recent (and old) 'problems of KKLT' see, e.g. ...

  ... McOrist/Sethi, Bena/Dudas/Grana/Lüst, Blumenhagen/Kläwer/Schlechter, Das/Haque/Underwood,....

(2-slide reminder of) KKLT

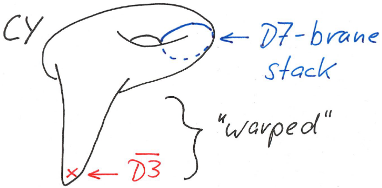
- CY with all complex-structure moduli fixed by fluxes;
  The only field left: Kahler modulus $T = \tau + ic$ with $\tau \sim \mathcal{V}^{2/3}$.

- $K = -3\ln(T + \overline{T})$; fluxes give $W = W_0 =$ const.,

  $\Rightarrow \quad V \equiv 0 \quad$ ('no scale') .

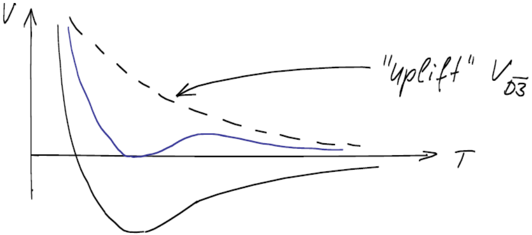
- Gaugino condensation on D7 brane stack: $W = W_0 + e^{-T}$.

- Small uplift by $\overline{\text{D3}}$-brane
  in a warped throat:
  $V \to V + c/\tau^2$.



KKLT

- The scalar potential is changed first to SUSY-AdS, then to an 'uplifted' meta-stable de Sitter potential:



- A longstanding critical debate has targeted the metastability of the $\overline{D3}$ in view of flux-backreaction.

  (My take on this is that metastability remains plausible.)

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

KKLT under attack

Now we can come to the recent criticism:

Moritz/Retolaza/Westphal '17
Gautason/Van Hemelryck/Van Riet '18

- Roughly, it doubts the (somewhat indirect, 4d SUGRA) method of KKLT.

- Instead, it proposes to directly solve 10d Einstein equations.

- This requires a 10d model for gaugino condensation ($\langle \lambda\lambda \rangle \neq 0$).

- This seems possible, since the crucial coupling to fluxes in 10d is known:

Camara/Ibanez/Uranga '04, Koerber/Martucci '07
Baumann/Dymarsky/Klebanov/Maldacena/McAllister '06

$$\mathcal{L}_{10} \supset |G_3|^2 + G_3 \cdot \Omega_3 \, \langle \lambda\lambda \rangle \, \delta_{D7} \; .$$

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

KKLT under attack

$$\mathcal{L}_{10} \supset |G_3|^2 + G_3 \cdot \Omega_3 \langle \lambda\lambda \rangle \delta_{D7} \; .$$

- It is clear what to expect:
  G_3 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 the (trace-reversed) 10d Einstein equations.
- One may then try to infer that
  the 'uplift' can not work in principle.

The trace-reverse Einstein equations argument

- In 10 dimensions: $$\mathcal{R}_{MN} = T_{MN} - \frac{1}{8} T\, g_{MN}\,.$$
- Ansatz: $$ds^2 = \omega(y)^2\, \eta_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}\, dy^m\, dy^n\,.$$
- It follows (generically):

$$\mathcal{V}\, \mathcal{R}_\eta = \int_6 (-2\omega^4\, \Delta) \qquad \text{with} \qquad \Delta = \frac{1}{4}(T_m^m - T_\mu^\mu)\,.$$

... or specifically in GKP (ignoring g_s and other $\mathcal{O}(1)$ factors):

$$\mathcal{V}\, \mathcal{R}_\eta = \int_6 \left(-|\partial\Phi^-|^2 - \omega^8 |G_3^-|^2 - 2\omega^8 \Delta^{other}\right)\,.$$

The (supposedly) key issue is the wrong-sign contribution of a positive-tension object to Δ.

MN, GKP, Giddings/Maharana, De Alwis, Danielsson et al. ...

KKLT rescued

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

- Singular gaugino effects have been observed before, in other string models. Horava/Witten '96

  (see also Ferrara/Girardello/Nilles '83
  Dine/Rohm/Seiberg/Witten '85
  Cardoso/Curio/Dall'Agata/Lüst '03)

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

$$\mathcal{L}_{10} \supset \left| G_3 + \Omega_3 \langle\lambda\lambda\rangle \, \delta_{D7} \right|^2 .$$

- Very roughly speaking, one now writes $G_3 = G_3^{flux} + \delta G_3$ and lets the second term cancel (most of) the δ-function.

  The result is (**very** roughly):

$$\mathcal{L}_{10} \supset \left| G_3^{flux} + \langle\lambda\lambda\rangle \right|^2 \qquad \rightarrow \qquad \left| W_0 + e^{-T} \right|^2 .$$

The perfect square structure in more detail

- The established part of the story is in M-theory (with x^{11} compactified on $S^1/\mathbb{Z}_2$). There, one has

$$S \sim -\int_{11} \left(G_4^2 \;-\; \delta(x^{11})(G_4)_{ABC\,11}\, j^{ABC} \right),$$

where $j^{ABC} \sim \overline{\lambda}\, \Gamma^{ABC} \lambda$.

- It is well-known that the divergence problem is resolved by the proposal (enforced by SUSY)

Horava/Witten

$$S \sim -\int_{11} \left(G_4 - \frac{1}{2}\delta(x^{11})\, j \right)^2 .$$

The perfect square structure in more detail

- Let us first understand this better in a 5d toy-model, (with $x^5 \equiv y$ compactified on $S^1/\mathbb{Z}_2$):

(inspired by Mirabelli/Peskin '97)

$$S = -\int_5 (d\varphi - j\delta(y)\,dy) \wedge *(d\varphi - j\delta(y)\,dy)\,.$$

- The equation of motion is

$$d * (\, d\varphi - j\delta(y)\,dy) = 0\,,$$

which is solved by

$$d\varphi = j\delta(y)dy + \alpha_M\,dx^M\,.$$

- Crucially, $\alpha = \alpha_M\,dx^M$ is co-closed: $d * \alpha = 0$.

The perfect square structure in more detail

- Excluding x^μ-dependence, we can focus on $\alpha = \alpha_5 dy$ with $\alpha_5 = \text{const.}$

- Flux quantization, $\int_{S^1} d\varphi \in \mathbb{Z}$, implies

$$\int dy\, \partial_y \varphi \; = \; j + \alpha_5 = n$$

  such that $\alpha_5 = n - j$ and $d\varphi = j\delta(y)dy + \alpha_5 dy$.

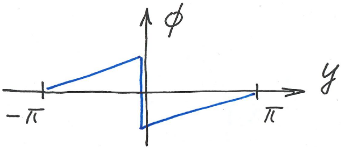
  The resulting action is

$$S = -(n-j)^2\,.$$

- $d\varphi$ has cancelled the singular term and supplied a finite effect.

The perfect square structure in more detail

- Illustration for $n = 0$:



- The case of interest is not co-dimension one but rather co-dimension two:.

$$j\,\delta(y)\,dy \qquad \to \qquad j\,dz\,\delta^2(z,\bar{z})\,.$$

- One important novelty: The singular term is $dz\,\delta^2(z,\bar{z})$ is not closed and requires a corresponding projection

$\to$ parallel talk by P. Soler

KKLT rescued

- Now the generalization to the realistic case is straightforward:

$$\mathcal{L} \supset \left| \overline{G}_3 - P\left(\lambda\lambda\, \Omega_3\, \delta_{D7}\right) \right|^2 .$$

- From this, we can work out the quartic gaugino terms of 4d SUGRA (finding agreement with known results).

- We can also derive the 4d effective potential, without and with the $\overline{D}3$ brane uplift, in agreement with KKLT.

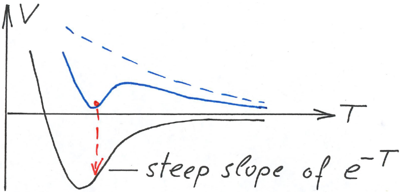
cf. same result from different approach in talk by McAllister

- One can plug this into the 10d Einstein equations and, again, obtain the expected 4d curvature (with or without uplift).

KKLT rescued ?

- Crucially, we know this must work out since 4d EOMs imply the integrated 10d Einstein eqs.

  ('Δ_{other}' from steep slope)



cf. Hamada/AH/Soler/Shiu & Carta/Moritz/Westphal

- 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

- Let us comment on this concern in more detail ......

An aside on the E-M tensor of the gaugino condensate:

- Our approach:

$$g_{mn}\frac{\delta}{\delta g_{mn}}\,S_{eff}\quad\rightarrow\quad T\frac{\partial}{\partial T}S_{eff}\quad\rightarrow\quad T\frac{\partial}{\partial T}\,e^{-T}$$

- The derivative acting on e^{-T} gives the crucial, dominant term stopping the runaway to large volume

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- The approach of Gautason et al. (disregarding the red part):

$$T\frac{\partial}{\partial T}\,S_{class.}\quad\text{with}\quad S_{class.}\supset T\,[G_3\,\lambda^2+(F_{\mu\nu})^2]$$

- Subsequent quantum averaging gives $\langle\lambda^2\rangle\sim e^{-T}$, but the T-derivative never gets to act on the exponential.

- We believe this is insufficient and the key effect (in this approach) will come from terms like $\langle G_3\lambda^2(F_{\mu\nu})^2\rangle$.

(for details on this point see added comment in v3 of our paper)

Furthermore:

- New concerns have been raised (about the large volume required to house the complicated topology needed for the D7-brane stack)

  Carta/Moritz/Westphal

- For further recent issues see...

  Das/Haque/Underwood,
  Bena/Dudas/Grana/Lüst,
  Blumenhagen/Kläwer/Schlechter
  ....

- Nevertheless, I believe one may be more optimistic about KKLT than last year.

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 Kahler moduli 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!