Gaugino condensation and KKLT from a 10d perspective

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based on published and ongoing work with: Hamada / Shiu / Soler

Outline:

- Introductory remarks / Comment on quintessence
- Consistently coupling 7-brane gauginos to 10d fields.
- Comments on related work by other groups / Perspective of Generalized Complex Geometry
- Including the gaugino condensates in 10d EOMs.

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; ⋯

  and especially Moritz/Retolaza/Westphal '17

  triggered interest in a 10d understanding of KKLT.

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

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

An Aside on Quintessence:

- Of course, in spite of all that's going to be said, KKLT (and other dS constructions) might in the end fail.

- Quintessence is natural way out, but this also difficult..

see in particular Cicoli/Pedro/Tasinato '12
(also: Cicoli/Burgess/Quevedo '11)

- In particular, one faces an *F*-Term Problem:

AH/Skrzypek/Wittner

- Namely, one needs large volume, where phenomenological SUSY-breaking implies:

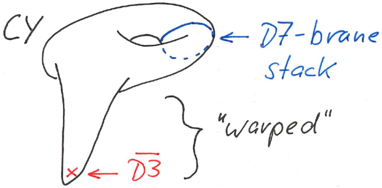
$$e^K |D_x W|^2 \qquad \gg \qquad \left| e^K (|D_T W|^2 - 3|W|^2) \right|$$

$\Rightarrow$ completely new scalar-potential term needed!

Selection of recent work: Cicoli/DeAlwis/Maharana/Muia/Quevedo; Acharya/Maharana/Muia; Emelin/Tatar; Hardy/Parameswaran; $\cdots$

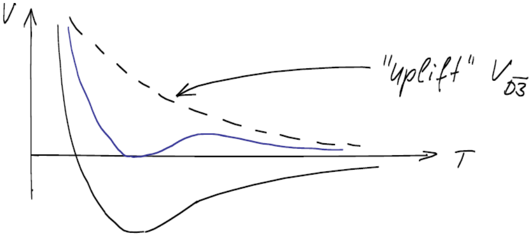
(2-slide reminder of) KKLT

- 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.,
  $\Rightarrow \quad V \equiv 0$ ('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

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

- Recent criticism was rooted in possibly too simpistic treatment of D7-gaugino–bulk-coupling:

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

Camara/Ibanez/Uranga '04, Koerber/Martucci '07
Baumann/Dymarsky/Klebanov/Maldacena/McAllister '06
Heidenreich/McAllister/Torroba '10

- 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 $(\delta_{D7})^2$.

- Now anything can happen....

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):

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

The perfect square structure in M-theory

- 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

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

Understanding the M-theory case in a toy model

- 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: $d * \alpha = 0$.

Obtaining a finite action

- Excluding x^μ-dependence, we can write the EOM as

$$\partial_y \left[\partial_y \varphi - j\delta(y) \right] = 0$$

and the solution as

$$\partial_y \varphi = j\delta(y) + \alpha_5 \qquad \text{with} \qquad \alpha_5 = \text{const.}$$

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

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

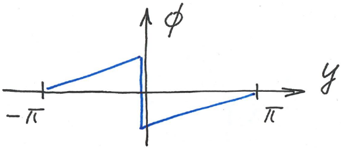
such that $\alpha_5 = n - j$. The resulting action is

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

- We see: $\partial_y \varphi$ cancels the singular term
  and develops a finite part $\sim (n - j)$.

Obtaining a finite action (continued)

- Illustration for $n = 0$:



- The 'step' in $\partial_y \varphi$ cancels the source term $j\delta(y)$.

- Compactness and continuity of φ ($\equiv$ flux quantization) enforce a non-trival slope proportional to this 'step'.

- If $n \neq 0$, continuity is replaced by an extra step of size n at the boundary. Hence:

$$\mathcal{L} = \int_R |d\varphi - j\delta|^2 = -(n-j)^2/R\,.$$

- Crucial: Radius dependence of j^2 term.

The co-dimension two case

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

  $\Rightarrow$ Generalize our toy-model to 6d
  (equivantly, consider type IIB compactified to d=8)

- In principle, everything goes through as before.
  The lagrangian is:

$$\mathcal{L} = -\int d^2z \left(|G_1|^2 - G_1 \cdot \bar{\jmath}_1 + \text{c.c.} \right) \quad \text{with} \quad \bar{\jmath}_1 = j\, dz\, \delta^2(z, \bar{z})\,.$$

- The naive perfect-square proposal would be

$$\mathcal{L} = -\int d^2z\, |G_1 - \bar{\jmath}_1|^2\,.$$

The co-dimension two case (continued)

- But: The singular 'source-form' is not closed,

$$d\left(j\,dz\,\delta^2(z,\bar{z})\right) \neq 0\,.$$

To allow 'G_1' (assumed to be closed) to compensate, we must project on the closed part using the unique decomposition

$$\omega = \alpha + d\beta + d^\dagger\gamma\,.$$

In other words, one drops '$d^\dagger\gamma$'. This does not change EOMs.

- Using indices h, e, c for harmonic, exact and co-exact:

$$\mathcal{L} = \int_z -\left|\overline{G}_1^h + \overline{G}_1^e - j_1^h - j_1^e\right|^2\,.$$

Here $\overline{G}_1^e$ compensates j_1^e, so these terms drop out.

From toy-model to D7 brane case

- We are left with:

$$\mathcal{L} = \int_z - \left| \overline{G}_1^h - j_1^h \right|^2 \, .$$

But $\overline{G}_1^h \equiv \overline{G}_1^{(0)}$ is the quantized flux,
so it can not compensate for the continuous $j_1^h \sim \lambda^2 \, dz/A_\perp$.

(Here $A_\perp$ is the 'brane-transverse' compact volume.)

- Thus, this perfect square of quantized flux and (finite) λ^2 term is the sole remainder of the calculation.

- Now the generalization to the realistic case is straightforward:

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

(Here P is the closed-form projection, as before.)

Cross checks / getting the KKLT-result

- As before, the singular parts cancel and, using $\int G_3^{(0)} \wedge \Omega \sim W_0$, one arrives at (after 4d-normalization of the gauginos)

$$K^{T\overline{T}} \left| e^{K/2} K_T W_0 + \lambda\lambda \right|^2$$

- This is precisely the perfect square structure that also appears in the SUGRA+gauge theory formulae of Wess/Bagger.

- With the substitution $e^{-K/2}\lambda\lambda \;\rightarrow\; e^{-T}$ one arrives at (pre-uplift) KKLT:

$$e^K K^{T\overline{T}} \left| D_T(W_0 + e^{-T}) \right|^2 .$$

- Note: In this last step we neglect terms subleading in $1/T$. To get those right, one needs loop corrections in the running from UV to IR.

Kaplunovsky/Louis

Recent related work by other groups

Bena/Grana/Kovensky/Retolaza
Kachru/Kim/McAllister/Zimet

- The method used is Generalized Complex Geometry.
- Here, two 6d spinors η^1, η^2 define polyforms

$$\Psi_1 \sim \sum_p \eta^{2\,\dagger} \Gamma_{m_1 \cdots m_p} \eta^1 \, dy^{m_1} \cdots dy^{m_p} \,, \qquad \Psi_2 \sim \text{similar, with } \eta^{*\dagger}$$

  which encode the full metric and background field information.
- SUSY conditions (and hence EOMs) are easily written down.
- Using 4d SUSY, the AdS parameter can be related to a parameter in 10d SUSY conditions.
  $\Rightarrow$ fully 10d-local check of pre-uplift KKLT   Bena et al.

Recent related work by other groups (continued)

- Kachru/Kim/McAllister/Zimet go further by using the Generalized Complex Geometry to discuss
  - the cancellation of singular terms and
  - the 10d component-field-derivation of KKLT.
- However, one potentially confusing issue is the (T-duality-derived) non-local 10d D7-brane λ^4 term they use:

$$\mu_7 \int \sqrt{-G_8}\,\frac{1}{A_\perp}\lambda^4\,.$$

- Another concern is that, while the cancellation of the divergence in $G_3\lambda^2$ is discussed, the cancellation of the divergence in the kinetic term

$$\int_6 |G_3|^2\;,\;\; G_3 \sim \delta_{D7} + \frac{1}{z^2}$$

is not explicitly demonstrated.

Back to our proposal

- While SUSY and Generalized Complex Geometry arguments may be elegant, having a dow-to-earth 10d component analysis is also useful.
- The latter is obviously plagues by divergences in $|G_3|^2$.
- To me, our 'Horava-Witten-style' perfect-square singularity subtraction is still the leading candidate for this goal.
- It also has its troubles:

  When subtracting $|j_3|^2$, we left out $|j_3^c|^2 \supset \left(\frac{1}{z^2}\right)^2$.
- This last piece has a non-local tail.
- By contrast, the full source $j_3 = j_3^h + j_3^e + j_3^c$ is completely D7-localized.

Electric-magnetic interpetation of $G_3\lambda^2$ coupling

- An unconventional re-interpetation of our perfect square action might hence start with the full source:

$$|G_3 + j_3|^2 \qquad \text{with} \qquad j_3 \sim \lambda^2 \delta_{D7}\overline{\Omega}\,.$$

- Observe that, in the term

$$G_3 \wedge *\bar{\jmath}_3 = G_3 \wedge *(\bar{\jmath}_3^h + \bar{\jmath}_3^e + \bar{\jmath}_3^c)\,,$$

  the sources $\bar{\jmath}_3^e$ and $\bar{\jmath}_3^c$ correspond precisely to electric and magnetic currents.

- For example:

$$G_3 \wedge *\bar{\jmath}_3^c \;\sim\; *G_3 \wedge \bar{\jmath}_3^c \;\sim\; G_7 \wedge \bar{\jmath}_3^c \;\sim\; dA_6 \wedge \bar{\jmath}_3^c \;\sim\; A_6 \wedge J_{mag}.$$

  Here, $\bar{\jmath}_3^e$ would not have contributed since it is exact.
  Vice versa, $\bar{\jmath}_3^e$ couples analogously to the 2-form potential.

Electric-magnetic interpetation of $G_3\lambda^2$ coupling (continued)

- In summary, one would have

$$|G_3 + j_3|^2 \qquad \text{with} \qquad j_3 \sim \lambda^2 \delta_{D7}\overline{\Omega}\,.$$

and the EOMs

$$dG_3 = J_{mag.} \equiv d\bar{\jmath}_3^e \qquad \text{and} \qquad d * G_3 = J_{el.} \equiv d\bar{\jmath}_3^c\,.$$

In this way, the non-flux part of G_3 would cancel all but the harmonic part of j_3.

- As a result, one has added a completely local term $|j_3|^3$, and still finds the finite result:

$$|G_3^{(0)} + j_3^h| \sim |G_3^{(0)} + \lambda^2\Omega/A_\perp|^2$$

- The details are still work in progress ...

KKLT rescued

- Concerning KKLT, the above are fine points. In any case, one has in the end (possibly without the need for the 'P'):

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

- From this, one derives the 4d effective potential, without and with the $\overline{D3}$ brane uplift, in agreement with KKLT.

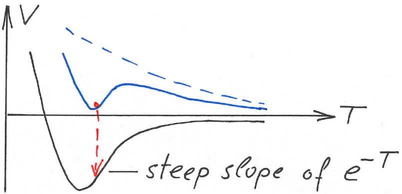
- One can plug this into the 10d Einstein equations and, again, obtain the expected 4d curvature (with or without uplift).

agreement with Carta/Moritz/Westphal,
still (partial) disagreement with Gautason/Van Hemelryck/Van Riet/Venken

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

- One should certainly not simply believe in metastable stringy de Sitter but try to establish it.
- Concerning the recent '10d-line-of-attack', KKLT appears to in better shape now than a year ago.
- An interesting (partially open) issue in this context is the detailed structure of the D7-gaugino-bulk coupling.
- I view the a Horava-Witten-style divergence-cancelling $\lambda^4\delta(z)^2$ term as a central and new feature.
- In parallel to establishing KKLT in more and more detail, getting stringy quintessence to work is the natural alternative.
- This is not easy....(cf. recent paper on the F-term problem)