Gauginos on D7-branes: from 10d to 4d

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with Y. Hamada, A. Hebecker & G. Shiu -1812.06097, 1902.01410 + (to appear)

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Motivation

- Non-perturbative effects (e.g. gaugino condensation) are crucial ingredients in string phenomenology, in particular for moduli stabilization and construction of AdS/dS vacua (e.g. KKLT and LVS)

- Gaugino condensation is an IR effect which is typically understood in the 4d EFT
  - Its description in the UV 10d theory is somewhat obscure.

- However, the 10d perspective can provide insights difficult to observe directly on the 4d EFT: e.g. no-go theorems a la Maldacena-Nunez.

- Our goal is to understand these effects from the 10d perspective (setup: type IIB orientifold compactifications with D7-branes).

Motivation

- Consider a minimal KKLT setup: D7-brane stacks and 3-form fluxes on a CY orientifold with Kahler modulus T
  - N=1 SYM with $K = -3\log(T+\bar{T}) + \ldots$ and $W_0 = \int G \wedge \Omega$

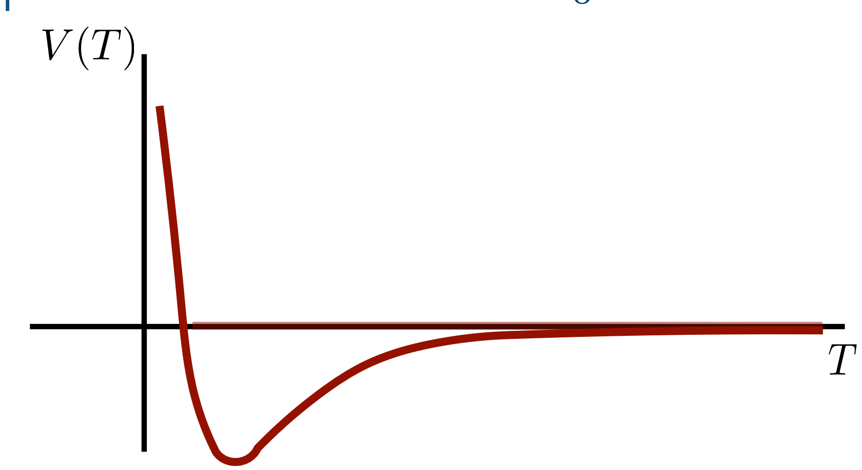
$$\mathcal{L} = -\,\mathrm{Re}\,(T)\left(\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\lambda}\bar{\sigma}^{\mu}\partial_{\mu}\lambda\right) - \lambda\lambda\, e^{K/2}K^{T\bar{T}}\,D_T\overline{W_0} + \text{c.c.} - \frac{1}{16}\lambda\lambda\,\overline{\lambda\lambda}\,K^{T\bar{T}} + \ldots$$

- Gaugino condensation occurs in the **4d EFT**: $\langle\lambda\lambda\rangle \sim e^{K/2}\,e^{-aT}$

$$\mathcal{L}(\langle\lambda\lambda\rangle) \sim -e^{K}\,K^{T\bar{T}}\left(K_T\overline{W_0}e^{-a\,T} + \text{c.c.} - \frac{1}{16}e^{-2a\,T}\right) \sim \frac{1}{T^2}W_0\,e^{-a\,T} - \frac{a}{T}e^{-2a\,T}$$

  - These are the leading terms (in 1/T) of the F-term potential with $W = W_0 + Ae^{-a\,T}$

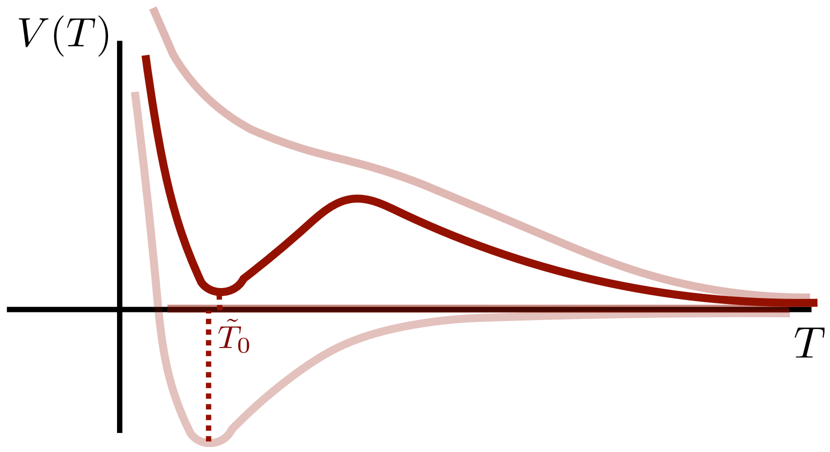
$$V(T) = -e^{K}\left(K^{T\bar{T}}D_TW\,D_{\bar{T}}\overline{W} - 3W\,\overline{W}\right)$$



Motivation

- Upon inclusion of a mild SUSY-breaking ingredient (e.g. anti D3-branes down a warped throat), this may be lifted to a dS vacuum

$$V(T) = -e^K \left(K^{T\bar{T}} D_T W \, D_{\bar{T}} \overline{W} - 3W \, \overline{W} \right) + \frac{\mu_3}{T^2}$$



  - Uplift to dS require a fine balance between W_0 and the warped anti-D3 tension μ_3

- Here I will only discuss how, under the assumptions made, the KKLT vacua can be described directly in the 10d theory.

- Studying whether the underlying assumptions are valid and an uplift to dS is possible or not is the subject of the swampland program
  - The 10d perspective should help in this task

Outline

- Localized gaugino interactions in 10d
  - Gauginos on co-dimension one branes (Horava-Witten)
  - Gauginos on co-dimension two (D7-) branes
- KKLT vacua from 10d
  - The AdS KKLT vacuum
  - Anti-branes and dS uplift
- Conclusions

Localized gaugino interactions

Hamada, Hebecker, Shiu, PS ’18 + (to appear)

Gauginos on co-dimension one

- Consider a 5d toy-model on $M_4 x S^1$ with localized 3-branes and one-form flux $G_1 = d\phi$

We typically know the action up to quadratic gaugino order

$$S \sim \int \Big(G_1 \wedge *G_1 - 2\, G_1 \wedge * \, \lambda\lambda \, \delta(y) dy \Big)$$

Solving for G_1 one obtains a **divergent** action (quartic in gauginos)

$$G_1 = \lambda\lambda \, \delta(y) \, dy + G_1^{(0)} \qquad \Longrightarrow \qquad S \sim \langle \lambda\lambda \rangle^2 \delta(0)$$ ✗

- Resolution (required by SUSY): complete to perfect-square form

$$S \sim \int \Big(G_1 - \lambda\lambda \, \delta(y) dy \Big) \wedge * \Big(G_1 - \lambda\lambda \, \delta(y) dy \Big)$$

$$\Longrightarrow \qquad G_1 = \lambda\lambda \, \delta(y) dy + G_1^{(0)} \qquad \Longrightarrow \qquad S \sim \int G_1^{(0)} \wedge * \, G_1^{(0)}$$ ✓

Perfectly finite

$G^{(0)}$ subject to flux quantization

Horava, Witten '96; Horava '96; Mirabelli, Peskin '97

Gauginos on co-dimension two

- The case of D7-branes is similar, but much more subtle: the quadratic action is

Camara, Ibanez, Uranga '04
c.f. Grana, Kovensky, Retolaza '20

$$S_{\lambda\lambda} \sim \int \Big(G_3 \wedge * \overline{G_3} - G_3 \wedge \overline{\lambda\lambda}\, \delta_{D7} \, * \Omega_3 + \text{c.c.} \Big)$$

Again, solving for G3 leads to a divergence: S~|λλ|²δ(0)

- Completing squares looks good but there is a problem:

$$S_{|\lambda\lambda|^2} \xrightarrow{?} \int \Big| G_3 - \lambda\lambda\, \delta_{D7} \, \overline{\Omega}_3 \Big|^2$$

Solving for $G_3 \stackrel{?}{=} \lambda\lambda\, \delta_{D7} \, * \overline{\Omega}_3 \quad \Longrightarrow \quad dG_3 \neq 0$ ~~Bianchi identity~~

The action is still divergent. We need another way to regularize the quartic action

Gauginos on co-dimension two

- Our original proposal: project the source onto the subspace of closed forms (drop its co-exact component), with projector $\mathcal{P}$

$$S \sim \int \left| G_3 - \lambda\lambda\, \delta_{D7}\, \overline{\Omega}_3 \right|^2 \;\longrightarrow\; \int \left| G_3 - \mathcal{P}\big(\lambda\lambda\, \delta_{D7}\, \overline{\Omega}_3\big) \right|^2$$

  - G_3 equations and solution unmodified — Hamada, Hebecker, Shiu, PS '18
  - Upon integrating out G_3: $S \sim \int \left| G_3^{(0)} - \frac{\lambda\lambda}{A_\perp}\, \overline{\Omega}_3 \right|^2$ ✓

Reproduces parametrically 4d SUGRA gaugino terms (including GVW superpotential).

- BUT!! The projector $\mathcal{P}$ is a **non-local** operator: $\Delta S \overset{?}{\sim} \frac{\mathbf{1}}{\mathbf{A}_\perp} \int_{D7} |\lambda\lambda|^2$ ✗

Same problem afflicts a subsequent proposal by Kachru, Kim, McAllister, Zimet '19 based on T-duality (D7 branes are "smeared")

A finite, local gaugino action

- Take the quadratic action including the Chern-Simons contribution and an arbitrary number of D7-brane stacks $(*G_\pm = \pm i G_\pm)$

$$\mathcal{L}_{\lambda\lambda} = -\frac{1}{2} G_3 \wedge * \overline{G_3} + \left(\sum_{i \in D7} G_3 \wedge \overline{\lambda\lambda}_i \, \delta_i \; * \Omega_3 + \text{c.c.} \right) - \frac{i}{2} G_3 \wedge \overline{G}_3$$

$$= -\Big| G_+ - \sum_{i \in D7} \lambda\lambda_i \delta_i \overline{\Omega}_3 \Big|^2 + |G_-^{(0)}|^2 - |G_+^{(0)}|^2 + \sum_{ij} \delta_i \delta_j \, \lambda\lambda_i \overline{\lambda\lambda}_j |\Omega|^2$$

  - Only the last term diverges (for i=j), but it also contains crucial finite contributions from (self) intersections of D7-stacks

$$\int \delta_i \delta_j \, \Omega * \overline{\Omega} = \int \delta_i \delta_j \, J \wedge J \wedge J = 3! \int \delta_i^{(2)} \wedge \delta_j^{(2)} \wedge J = 3! d_i^\alpha d_j^\beta \mathcal{K}_{\alpha\beta}$$

  - Given a basis $\{\omega_\alpha\}$ of $H_+^{(1,1)}$, we expand $\quad \delta_i^{(2)} = \sum_\alpha d_i^\alpha \omega_\alpha$
  - $\mathcal{K}_{\alpha\beta}$ are CY intersection numbers: $\quad \mathcal{K}_{\alpha\beta} = \int \omega_\alpha \wedge \omega_\beta \wedge J$

Hamada, Hebecker, Shiu, PS, to appear

A finite, local gaugino action

- With this insight, we can write the local finite action:

$$S = -\int_{10d} \Big| G_+ - \sum_i \lambda\lambda_i \delta_i \overline{\Omega}_3 \Big|^2 + \int_{10d} |G_-^{(0)}|^2 - \int_{10d} |G_+^{(0)}|^2$$
$$+ 3! \sum_{i \neq j} \underbrace{\int_{10d} \lambda\lambda_i \overline{\lambda\lambda}_j \, \delta_i^{(2)} \wedge \delta_j^{(2)} \wedge J}_{D7_i - D7_j \text{ intersection}} + 3! \sum_i \underbrace{\int_{D7_i} |\lambda\lambda_i|^2 \, c_1(N_i) \wedge J}_{D7_i \text{ self-intersection}}$$

- Upon solving for G, and dimensionally reducing, this can be matched in detail with the 4d gaugino SUGRA action

- This is quite non-trivial: intersection terms play an important role

Hamada, Hebecker, Shiu, PS, to appear

KKLT vacua from 10d

Hamada, Hebecker, Shiu, PS '19

KKLT from 10d perspective

- Gaugino condensation (an IR effect) is treated by giving a vev to gaugino bilinears $<\lambda\lambda> \sim e^{-aT}$ in the 10d action
  - This approach is difficult to motivate microscopically but has been successfully used in several setups.

    Koerber, Martucci '07, '08; Baumann et al. '10; Heidenreich et al. '10; Dymarsky, Martucci '10;...

  - These long-distance effects induce an effective non-locality in the 10d action (different from 'smearing' previously discussed).

    Hamada et al. '19; Gautason et al. '19

- Notice: backreaction of the metric to gaugino condensates requires going from CY into Generalized Complex Geometry (GCG)
  - We have not taken this backreaction into account (yet), but still reproduce the relevant features of KKLT vacua.

    Work in progress: relate to the GCG analysis of Kachru et al. '19; Bena et al. '19; Graña et al. '20

KKLT from 10d perspective

- Consider Einstein equation in 10d and its trace over 4d indices:

$$\mathcal{R}_{MN} = T_{MN} - \frac{1}{8} g_{MN} T^L_L \implies R^\mu_\mu = \frac{1}{2}\left(T^\mu_\mu - T^m_m\right) \equiv -2\Delta$$

- For a warped ansatz: $ds^2_{10} = \Omega^2(y)\ (\eta_{\mu\nu}\, dx^\mu\, dx^\nu + g_{mn}\, dy^m\, dy^n)$

$$\mathcal{V}_6\, \mathcal{R}(\eta) = \int d^6y\, \sqrt{g}\ \Omega^8(y)\, \mathcal{R}(\eta) = -2\int d^6y\, \sqrt{g}\ \Omega^{10}(y)\Delta$$

Useful for no-go theorems: positivity arguments on Δ constrain compactifications with $\mathcal{R}(\eta) \geq 0$.

Maldacena, Nuñez ’00; …

- Starting point: GKP flux compactification $\Delta = \mathcal{R}(\eta) = 0$

KKLT from 10d revisited

- **10d KKLT AdS** (single Kahler modulus T)**:**

$$\mathcal{V}_6\, \mathcal{R}(\eta) = -2 \int d^6y \sqrt{g}\; \Omega^{10}(y) \Delta^{\langle\lambda\lambda\rangle}$$

Where $\Delta^{\langle\lambda\lambda\rangle} = \frac{1}{4}\left(-T^{\mu}_{\mu} + T^{m}_{m}\right)_{\langle\lambda\lambda\rangle} = \frac{1}{2}\left(\mathcal{L}_{\langle\lambda\lambda\rangle} - g^{mn}\frac{\delta\mathcal{L}_{\langle\lambda\lambda\rangle}}{\delta g^{mn}}\right)$

- Using our proposed 10d action and $<\lambda\lambda>\sim e^{-aT}$ we obtain

$$\mathcal{V}_6 \mathcal{R}_\eta \sim -\, a\, T^2 \left(T\, e^{-2aT} - W_0\, e^{-aT}\right) + \frac{1}{2}\, T^2 e^{-2aT} \quad \xrightarrow{\text{on-shell}} \quad T_0^3\, V_{\mathrm{KKLT}}^{\langle\lambda\lambda\rangle}(T_0) < 0$$

On-shell, **same as KKLT** AdS result (up to small corrections):

KKLT from 10d revisited

- **10d KKLT dS** (single Kahler modulus T)**:**

$$\mathcal{V}_6\,\mathcal{R}(\eta) = -2\int d^6y\,\sqrt{g}\;\Omega^{10}(y)\left(\Delta^{\langle\lambda\lambda\rangle} + \Delta^{\overline{D3}}\right)$$

Where $\Delta^{\overline{D3}} = \frac{1}{4}\left(-T^{\mu}_{\mu} + T^{m}_{m}\right)_{\overline{D3}} = \frac{1}{2}\left(\mathcal{L}_{\overline{D3}} - g^{mn}\frac{\delta\mathcal{L}_{\overline{D3}}}{\delta g^{mn}}\right)$

- Down a highly warped throat, $0<\Omega^8(y_0)\Delta^{D3} <<1$

$\Delta^{\overline{D3}}$ contribution is negligible. Uplift???

$$\mathcal{V}_6\mathcal{R}_\eta \sim -\,a\,T^2\left(T\,e^{-2aT} - W_0\,e^{-aT}\right) + \frac{1}{2}\,T^2 e^{-2aT} \quad \xrightarrow{\text{on-shell}} \quad \tilde{T}_0^3\,V_{\text{KKLT}}^{\langle\lambda\lambda\rangle+\overline{D3}}(\tilde{T}_0) > 0$$

Small shift in minimum $T_0 \to \tilde{T}_0$ induced by $\overline{\text{D3}}$ backreacts on $\Delta^{<\lambda\lambda>}$ and generates **KKLT uplift.**

Conclusions

- The 10d perspective is crucial in understanding swampland constraints and no-go theorems in string compactifications

- We proposed a *local* λ^4-action on D7-branes

  Avoid previous divergences and reproduce 4d SUGRA results

  c.f. Kallosh '19; Kachru et al. '19; Graña et al. '20

- Checked on-shell equivalence of 4d and 10d approaches to KKLT

  4d Einstein + Kahler moduli e.o.m. $\Longleftrightarrow$ 10d Einstein eq.

  c.f. Giddings, Maharana '05;...
  Moritz et al. '17, '18, '19; Gautason et al. '18; '19; Kachru et al. '19; Bena et al. '19

- We have not analysed the validity of assumptions underlying KKLT. Much recent work within the swampland program

Hamada, Hebecker, Shiu, PS '18, '19, '20 (to appear)