de Sitter Vacua from Ten Dimensions

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de Sitter Constructions in String Theory
Dec 10, 2019.

Based on work with S. Kachru, L. McAllister, and M. Zimet [1908.04788v2].

Outline

Review of KKLT

10D Description of KKLT

- 10-dimensional equations of motion
- D7-brane gaugino action
- F-term potential/AdS vacuum
- Uplift to dS vacuum

Conclusions

KKLT in a nutshell

Setup

- Take Type IIB on an $O3/O7$ CY3-orientifold X with $h^{1,1}_{+} = 1$.

- A divisor $D \subset X$ supports $SU(N_c)$ D7-brane gauge theory with no matter.

- Resulting 4d effective supergravity consists of the following data
  - Closed string sector moduli : T, ξ_a, and τ.
  - Kähler potential

$$\kappa_4^2 K = -3 \log(T + \bar{T}) - \log(-i(\tau - \bar{\tau})) - \log(i \int e^{-4A} \Omega \wedge \overline{\Omega}).$$

  - Tree-level superpotential

$$W_{tree} = \pi \int G \wedge \Omega.$$

    Gukov, Vafa, Witten 99
  - D7-brane gauge theories.

KKLT in a Nutshell

Claims

- Below KK and complex structure mass scale, the effective supergravity theory consists of the following data
  - Kähler modulus T.
  - Kähler potential
  $$\kappa_4^2 K = -3\log(T+\bar{T}).$$
  - Superpotential
  $$W = W_0 + W_{np},$$
  where $W_0 := \left\langle \pi \int G \wedge \Omega \right\rangle$, $W_{np} := \Lambda_{N_c}^3 = Ae^{-2\pi T/N_c}$.

Assumptions

- $|W_0| \ll 1$.
- Exist a strongly warped region, where $e^{4A} \ll 1$, in X that is far away from the gaugino condensation.

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- The effective theory exhibits a supersymmetric AdS_4 vacuum.

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Outcome

- $V = V_F + 2p\mu_3\, e^{4A-12u}$ exhibits a metastable dS_4 vacuum.

Some of the Issues with KKLT

that I will not address :

- Is small W_0 achievable?
- Can there be a strongly warped region?
- Are anti-D3-branes even well described in supergravity?
- Is there even a single example of CY3 orientifold that provides : small W_0, strongly warped region, W_{np}?

Giryavets, Kachru, Tripathy, Trivedi 03, Denef, Douglas 04, Denef, Douglas, Florea, Grassi, Kachru 05, Bena, Graña, Halmagyi 09, Dymarsky 11, Banks 12, Bena, Giecold, Graña, Halmagyi, Massai 11, Bena, Graña, Kuperstein, Massai 14, Michel, Mintun, Polchinski, Puhm, Saad 14, Cohen-Maldonado, Diaz, Van Riet, Vercnocke 15, Armas, Nguyen, Niarchos, Obers, Van Riet 18, Obied, Ooguri, Spodyneiko, Vafa 18, Bena, Dudas, Graña, Lüst 18, Blumenhagen, Klawer, Schlechter 19, Blaback, Gautason, Ruipèrez, Van Riet 19

[cf. talks by Wrase, Van Riet, Niarchos, Underwood, and Moritz]

Question I Will Adress

Can there be any overlooked 10D corrections to 4d EFT that can spoil the dS vacuum even if there is X with the desired properties?

Moritz, Retolaza, Westphal 17, Hamada, Hebecker, Shiu, Soler 18, Gautason, Van Hemelryck, Van Riet 18, Carta, Moritz, Westphal 19, Gautason, Van Hemelryck, Van Riet, Venken 19, Hamada, Hebecker, Shiu, Soler 19, Bena, Graña, Kovensky, Retolaza 19, Kallosh 19

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Towards 10D Description of KKLT

Plan

- Set up the equation that relates $\mathcal{R}_4$ to 10D $T_{\mu\nu}$.
- Derive the D7-brane gaugino action.
- Compute $\mathcal{R}_4$ and $T^{\lambda\lambda}_{\mu\nu}$ of $\langle\lambda\lambda\rangle$ from 10 dimensions.
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Equations of Motion

- Take the ansatz

$$ds^2 = G_{AB}dX^A dX^B = e^{-6u(x)+2A(y)}g_{\mu\nu}dx^\mu dx^\nu + e^{2u(x)-2A(y)}g_{ab}dy^a dy^b,$$

$$\tilde{F}_5 = (1 + \star_{10})e^{-12u}d\alpha \wedge dx^0 \wedge dx^1 \wedge dx^2 \wedge dx^3.$$

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- Trace reversed Einstein equations plus Bianchi identity

$$\boxed{M_{pl}^2 \mathcal{R}_4 = -\int_X \left[e^{-4A} T^{D7}_{\mu\nu} g^{\mu\nu} - 8\mu_3 e^{-12u+4A} \rho_{\overline{D3}} + \frac{2e^{-8u}}{\kappa_{10}^2} \mathcal{R}_6 - \frac{e^{-8u-8A}}{\kappa_{10}^2} |\partial \Phi_-|^2 \right]},$$

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- Should understand the D7-brane gaugino action to compute $T^{D7}_{\mu\nu}$.

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- D7-brane gaugino action up to four-fermi term was predicted with consistency checks.

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- Perform T-duality and $SL(2,\mathbb{Z})$ covariantize the action.

$$S_{ferm} = -\mu_7 \int_{\mathbb{R}^{7,1}} \Big[e^{-\phi} \bar{\chi} \Gamma^a D_a \chi - \frac{e^{\phi/2}}{24} \bar{\chi} \Gamma^{ABC} (\tilde{F}_{ABC} \sigma_1 + e^{-\phi} H_{ABC} \sigma_3) \chi + \frac{1}{192 t} \left(\bar{\chi} \Gamma^{ABC} \sigma_1 \chi \right)^2 \Big],$$

χ is 32-component Majorana fermion and t is the volume of $T^2/\mathbb{Z}_2$.

Spinor Ansatz

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  Graña, Minasian, Petrini, Tomasiello 05, Koerber Martucci 07, Dymarsky, Martucci 10, Heidenreich, McAllister, Torroba 10

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$$\Phi_1 := -8ie^{-A}\eta_1 \otimes \eta_2^\dagger = e^{iJ}\left(1 - \varphi \mathrm{Re}\Omega_2\right) + \mathcal{O}(\varphi^2),$$
$$\Phi_2 := -8ie^{-A}\eta_1 \otimes \eta_2^T = \Omega + \varphi\, v \wedge \left(1 - \frac{1}{2} J_2 \wedge J_2\right) + \mathcal{O}(\varphi^2).$$

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$$\chi_1 \propto \lambda \otimes \eta_1 + c.c,$$

$$\chi_2 \propto \lambda \otimes \eta_2 + c.c.$$

D7-brane Gaugino Action

- Consider $\varphi = 0$ as a first step, then we derive.

$$\mathcal{L}_{\lambda\lambda} = -\frac{i}{4\pi} e^{-4A+4u} \bar{\lambda}\bar{\sigma}^{\mu}\partial_{\mu}\lambda + \frac{i}{32\pi} e^{-2u+\phi/2} G \cdot \Omega\bar{\lambda}\bar{\lambda} + c.c. - \frac{\nu e^{8u-4A}}{6144\pi^3} \Omega \cdot \overline{\Omega} \lambda\lambda\bar{\lambda}\bar{\lambda},$$

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- Any correction from $SU(2)$ structure, $\varphi \neq 0$?

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$$\mathfrak{G} := G + id\mathfrak{t},$$

$$\mathfrak{t} := \mathrm{Re}\left(-8ie^{-\phi/2-3A}\eta_1 \otimes \eta_2^{\dagger}\right).$$

- $SU(2)$ structure corrects gaugino-flux coupling.
  Cámara, Ibáñez, Uranga 04
- $G + id\mathfrak{t}$ is the proper 'holomorphic' variable with generalized complex structure.
  Benmachiche, Grimm 06, Koerber, Martucci 07, Koerber 10, Dymarsky, Martucci 10
- $W = \pi \int \mathfrak{G} \wedge \mathcal{Z} = \pi \int \mathfrak{G} \wedge \Omega + \mathcal{O}(\langle\lambda\lambda\rangle^2)$ from gravitino mass.
- Broken perfect square structure will enable the perfect match.

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F-term Potential

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- $\Phi_-^{(0)} = 0$ and $\delta \Phi_- = \mathcal{O}(\langle \lambda\lambda \rangle^2)$. Hence

$$\int_X e^{-8u-8A} |\partial \Phi_-|^2 = \mathcal{O}(\langle \lambda\lambda \rangle^4).$$

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- Compute the energy-momentum tensor associated with $\langle\lambda\lambda\rangle$.

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$$-\frac{1}{4}\int_X e^{-4A}T^{\lambda\lambda}_{\mu\nu}g^{\mu\nu} = \kappa_4^2 e^{\kappa_4^2 K}K^{T\bar{T}}\partial_T W K_{\bar{T}}\overline{W} + c.c.$$

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F-term Potential

Upon including vev of $\langle\lambda\lambda\rangle$, we compute

$$\boxed{\frac{1}{4}M_{pl}^2\mathcal{R}_4 = e^{\kappa_4^2 K}\left(K^{T\bar{T}}D_T W D_{\bar{T}}\overline{W} - 3\kappa_4^2 W\overline{W}\right) + \mathcal{O}(\langle\lambda\lambda\rangle^3).}$$

- $\langle\lambda\lambda\rangle$ reproduces V_F in 10D supergravity!!

Comment on the variation of $\langle\lambda\lambda\rangle$.

- Variation of $\langle\lambda\lambda\rangle$ has been one of the most controversial subject.

  Gautason, Van Hemelryck, Van Riet, Venken 19, Carta, Moritz, and Westhpal 19, Hamada, Hebecker, Shiu, and Soler 19.

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$$24 M_{pl}^2 \Box u = \int_X \left[4 e^{-8u} \left(\mathcal{R}_6[g] - 8 \partial_a A \partial^a A \right) - \frac{\delta \mathcal{L}}{\delta u} \right],$$

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- Hence, even in the 10D supergravity, upon the variation under u, $\langle\lambda\lambda\rangle$ should behave according to

$$\langle\lambda\lambda\rangle = -\frac{32\pi^2}{N_c}e^{\kappa_4^2 K/2}\mathcal{A}e^{-\frac{2\pi T}{N_c}}.$$

Towards 10D Description of KKLT

Plan

- Set up the equation that relates $\mathcal{R}_4$ to 10D $T_{\mu\nu}$.
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- Resulting energy is

$$\boxed{\frac{1}{4} M_{pl}^2 \mathcal{R}_4 = V_F + 2\mu_3 e^{-12u} e^{4A}(z_{\overline{D3}}) + \mathcal{O}(\langle\lambda\lambda\rangle^3).}$$

- 10D analysis agrees with EFT of KKLT!!

Summary

Assumptions

Given a CY3-orientifold X,

- Small value of W_0 is possible,
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Future Direction

- We should find an explicit example of KKLT!

Thank You!

Order of Variation w.r.t. the metric for $\langle \lambda\lambda \rangle$

Compute the equation of motion for u in three different ways.

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$$\frac{\delta}{\delta u}\int_M 12M_{pl}^2\partial_\mu u\partial^\mu u = -\frac{1}{4}\frac{\delta}{\delta u}\int_M e^{-4A}T_{\mu\nu}^{\langle\lambda\lambda\rangle}g^{\mu\nu}.$$

Order of Variation w.r.t. the metric for $\langle\lambda\lambda\rangle$

Compute the equation of motion for u in three different ways.

$$ds^2 = G_{AB}dX^A dX^B = e^{-6u(x)+2A(y)} g_{\mu\nu}dx^\mu dx^\nu + e^{2u(x)-2A(y)} g_{ab}dy^a dy^b,$$

$$24M_{pl}^2 \Box u = \int_X \left[4e^{-8u}\left(\mathcal{R}_6[g] - 8\partial_a A\partial^a A\right) - \frac{\delta\mathcal{L}}{\delta u}\right],$$

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For those three answers to agree, one should assign vev to $\langle\lambda\lambda\rangle$ and then varies it w.r.t. the metric.

10D Description of D7-brane Gaugino Condensation

Claim

- Assign vev to gaugino bilinear $\lambda\lambda$ in 10D supergravity action.
  Baumann, Dymarsky, Kachru, Klebanov, McAllister 10

Consistency Check

- Consider D3-branes probing KKLT AdS_4.

$$\kappa_4^2 K = -3\log(T + \bar{T} - \gamma k(z, \bar{z})),$$

$$W = W_0 + \mathcal{A}(z)e^{-2\pi T/N_c},$$

$$T = \int_D e^{-4A+4u} + i\int_D C_4.$$

Cite lots of papers

- Impose $D_T W = 0$.

$$V_F(z, \bar{z}) = e^{\kappa_4^2 K}(K^{a\bar{b}} D_a W D_{\bar{b}}\overline{W} - 3\kappa_4^2 |W|^2).$$

- Can we reproduce $e^{\kappa_4^2 K} K^{a\bar{b}} D_a W D_{\bar{b}}\overline{W}$ with $\langle\lambda\lambda\rangle$?

10D Description of D7-brane Gaugino Condensation

Goal

- Reproduce $e^{\kappa_4^2 K} K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W}$ with $\langle \lambda\lambda \rangle$.

Consistency Check

- Take the ansatz

$$ds^2 = e^{-6u(x)+2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{2u(x)-2A(y)} g_{ab} dy^a dy^b,$$

$$\tilde{F}_5 = (1 + \star_{10}) e^{-12u} d\alpha \wedge dx^0 \wedge dx^1 \wedge dx^2 \wedge dx^3.$$

- Probe D3-branes add energy

$$\sum_i e^{-12u} \Phi_-(y_i),$$

$\Phi_- = e^{4A} - \alpha.$

- Φ_- should 'correspond' to $e^{\kappa_4^2 K} K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W}$!

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- Φ_- should 'correspond' to $e^{\kappa_4^2 K} K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W}$!
- $\nabla^2 \Phi_- = e^{8A} |G_-|^2 + C_{\Phi_-}$, $G_- = (\star_6 - i) G_3/2$.

10D Description of D7-brane Gaugino Condensation

Goal

- Reproduce $e^{\kappa_4^2 K} K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W}$ with $\langle \lambda\lambda \rangle$.

Consistency Check

- Gaugino soft mass term sources G_3.

$$-\frac{i}{32\pi} e^{-2u+\phi/2} G_3 \cdot \Omega \bar{\lambda}\bar{\lambda} + c.c$$

cite ciu

$$(G_-)_{ac\bar{d}} = -e^{-4A-\phi/2+8u} \partial_a \partial_b G_{(2)}(z; z_{D7}) g^{b\bar{b}} \overline{\Omega}_{\bar{b}\bar{c}\bar{d}} \frac{\langle \lambda\lambda \rangle}{32\pi^2}.$$

cite papers

- G_- precisely sources

$$\Phi_{-,G} := \int G_{(6)}(z; z') \frac{e^{8A}}{\mathrm{Im}\tau} |G_-|^2 = e^{\kappa_4^2 K} K^{a\bar{b}} D_a W D_{\bar{b}} \overline{W}.$$

The Recent Criticisms

- Recall eqn. (2.30) of GKP

$$\nabla^2\Phi_- = e^{-4A}|\partial\Phi_-|^2 + \frac{e^{8A}}{\mathrm{Im}\tau}|G_-|^2 + \Delta_{loc} + \mathcal{R}_4^{GKP},$$

$$\Delta_{loc} = 2\kappa_{10}^2\left(\frac{1}{4}\left(\hat{T}_{ab}G^{ab} - \hat{T}_{\mu\nu}G^{\mu\nu}\right) - \mu_3 e^{8A}\rho^{D3}\right).$$

- Suppose there is a 'good enough' solution Φ_-, s.t. $\int_X \nabla^2\Phi_- = 0$.

$$\mathcal{V}\mathcal{R}_4^{GKP} = -\int_X \left[e^{-4A}|\partial\Phi_-|^2 + \frac{e^{8A}}{\mathrm{Im}\tau}|G_-|^2 + \Delta_{loc}\right],$$

$$\mathcal{V} := \int_X \sqrt{g_6}.$$

- Anti-D3-branes give positive contribution to $\Delta_{loc} = 2\mu_3 e^{8A}$, hence seem to induce negative energy.
- Two kinds of seemingly dangerous singularities : from $|G_-|^2$ and G_+, which is localized on the gaugino stack.

Any issues with the criticisms?

- Claimed $\mathcal{R}_4$ computed in 10D comes with unwarped volume $\mathcal{V}$. But, in 4D EFT, warped volumes are related to observables.

$$M_{pl}^2 = 4\pi \mathcal{V}_w,$$

$$\mathcal{V}_w := \int_X e^{-4A}.$$

- Even the energy shift due to anti-D3-branes come with the wrong suppression e^{8A} rather than e^{4A}. Same issue for the divergences.
- One could try

$$\int_X e^{-4A}\nabla^2\Phi_- = \int_X \left[e^{-8A}|\partial\Phi_-|^2 + \frac{e^{4A}}{\mathrm{Im}\tau}|G_-|^2 + e^{-4A}\Delta_{loc} + e^{-4A}\mathcal{R}_4^{GKP} \right]$$

- Integration by parts for fields, whose explicit forms are unknown, is subtle.
- Computing Δ_{loc} for gaugino condensation is subtle. cite papers
- $\mathcal{R}_4^{GKP} = \mathcal{R}_4 + 12\Box u - 24\partial_\mu u \partial^\mu u.$
- We need a different form of the equation that contains equivalent information with respect to (2.30) of GKP.

Singularities?

Singularity due to

$$\int e^{4A}|G_-|^2,$$

where

$$(G_-)_{ac\bar{d}} = -e^{-4A-\phi/2+8u}\partial_a\partial_b G_{(2)}(z;z_{D7})g^{b\bar{b}}\overline{\Omega}_{\bar{b}\bar{c}\bar{d}}\frac{\langle\lambda\lambda\rangle}{32\pi^2},$$

that corresponds to

$$\int \nabla^2(e^{-4A})e^{8A}|G_-|^2 = \int \rho_{D3}G_{(6)}e^{8A}|G_-|^2 = \sum \Phi_-.$$

Singularity due to

$$G_+ = -\frac{e^{-4A}}{16\pi^2}\sqrt{\mathrm{Im}\tau}\lambda\lambda\overline{\Omega}\delta^{(0)},$$

is cancelled due to the SU(2) structure correction.

What does 'correspond' mean?

$$M_{pl}^2 \mathcal{R}_4 = \int_X \Big[-e^{-4A} T^{D7}_{\mu\nu} g^{\mu\nu} + 4\mu_3 e^{-12u} (\Phi_- \rho_{D3} + \Phi_+ \rho_{\overline{D3}}) - \frac{2e^{-8u}}{\kappa_{10}^2} \mathcal{R}_6 + \frac{e^{-8u-8A}}{\kappa_{10}^2} \partial_a \Phi_+ \partial^a \Phi_- \Big]$$

$$\nabla^2 \Phi_- = e^{-4A} |\partial \Phi_-|^2 + \frac{e^{8A}}{\mathrm{Im}\tau} |G_-|^2 + \Delta_{loc} + \mathcal{R}_4^{GKP},$$

$$\Delta_{loc} = 2\kappa_{10}^2 \left(\frac{1}{4} \left(\hat{T}_{ab} G^{ab} - \hat{T}_{\mu\nu} G^{\mu\nu} \right) - \mu_3 e^{8A} \rho^{D3} \right).$$