de Sitter Vacua from Ten Dimensions

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Based on work to appear with

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Goal

Study the de Sitter vacua of KKLT using the 10d EOM.

Consider a type IIB warped flux compactification containing

i. anti-D3-branes

ii. gaugino condensate on D7-branes

KKLT: after dimensional reduction of (i),(ii) separately, the EOM of the 4d EFT lead to a 4d de Sitter vacuum.

Kachru, Kallosh, Linde, Trivedi 03

We ask: do the 10d EOM lead to the same 4d de Sitter vacuum?

Or does the 10d perspective reveal corrections or obstructions?

[cf. talks by Blumenhagen, Cribiori, Dudas, Graña, Hebecker, Klaewer, S. Lüst, Moritz, Retolaza, Scalisi, Sethi, Soler, Tomasiello, Van Riet, Wrase]

Plan

I. Equations of motion

II. Stress-energy of gaugino condensate

III. SUSY AdS_4 vacuum

IV. de Sitter vacuum

Setup

Type IIB string theory compactified on O3/O7 orientifold, X, of a CY_3.

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

Consider a stack of D7-branes supporting $SU(N_c)$ SYM.

Take $h_+^{1,1} = 1 :\ e^{4u} = \mathrm{Re}(T)$.

$4d\ \mathcal{N} = 1$ supergravity:

$$\mathcal{K} = -3\log(T + \overline{T}) \qquad\qquad W = W_0 + \mathcal{A}e^{-aT}$$

$$W_{\mathrm{classical}} = \int_X G_3 \wedge \Omega \equiv W_0$$

$$W_{\mathrm{np}} = -\frac{N_c}{32\pi^2}\langle\lambda\lambda\rangle = \mathcal{A}e^{-aT}$$

Giddings, Kachru, Polchinski 01

Kachru, Kallosh, Linde, Trivedi 03

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Consider a stack of D7-branes supporting $SU(N_c)$ SYM.

Take $h^{1,1}_+ = 1$: $e^{4u} = \mathrm{Re}(T)$.

$4d$ $\mathcal{N} = 1$ supergravity:

$$\mathcal{K} = -3\log(T+\overline{T}) \qquad W = W_0 + \mathcal{A}e^{-aT}$$

$$V_F = e^{\mathcal{K}}\left(K^{T\overline{T}} D_T W \overline{D_T W} - 3W\overline{W}\right)$$

This supergravity theory has a SUSY AdS_4 minimum.

KKLT

Setup

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Consider a stack of D7-branes supporting $SU(N_c)$ SYM.

Introduce p anti-D3-branes at the tip of a Klebanov-Strassler throat.

$S_{\text{DBI+CS}} \Rightarrow V_{\overline{D3}} = 2p T_3 e^{4A} e^{-8u}$ Kachru, Pearson, Verlinde 01

To the extent that the antibranes affect the gaugino condensate
only by contributing to the EOM for u,

it follows that $V_{\text{tot}} \approx V_{\overline{D3}} + V_F$.

This theory has a metastable dS_4 minimum. KKLT

One should ask:

Do there exist consistent global models with:

i. Quantized fluxes giving small classical superpotential

ii. D7-brane stack(s) supporting gaugino condensate

iii. Weakly-curved Klebanov-Strassler throat

In such a model, are all parameters simultaneously in controllable regime?

Do anti-D3-branes create important instabilities besides decompactification?

We will not improve the answers to these questions.

Denef, Douglas, Florea, Grassi, Kachru 05
Bena, Graña, Halmagyi 09
Dymarsky 11
Bena, Giecold, Graña, Halmagyi, Massai 11
Bena, Graña, Kuperstein, Massai 14
Michel, Mintun, Polchinski, Puhm, Saad 14
Cohen-Maldonado, Diaz, Van Riet, Vercnocke 15
Obied, Ooguri, Spodyneiko, Vafa 18
Bena, Dudas, Graña, Lüst 18
Blumenhagen, Klaewer, Schlechter 19

We will only ask, and answer:

Does ten-dimensional supergravity,
including only the sources already invoked,
reproduce the de Sitter vacuum computed in the 4d EFT?

[cf. talks by Blumenhagen, Cribiori, Dudas, Graña, Hebecker, Klaewer, S. Lüst, Moritz, Retolaza, Scalisi, Sethi, Soler, Tomasiello, Van Riet, Wrase]

Equations of motion

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

$$\Phi_\pm := e^{4A} \pm \alpha \qquad G_\pm := (1 \mp i\star_6)G_3$$

$$\nabla^2\Phi_- = \mathcal{R}_4 + \frac{e^{8A}}{24\,\mathrm{Im}(\tau)}|G_-|^2 + e^{-4A}|\partial\Phi_-|^2 + 2\kappa_{10}^2\mu_3 e^{8A}\rho_{\overline{D3}}$$

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Adding a D3-$\overline{\text{D3}}$ pair appears to require $\Delta\mathcal{R}_4 \propto -e^{8A}$

whereas $S_{\text{DBI+CS}} \Rightarrow V_{\overline{D3}} = +2p\,T_3 e^{4A}e^{-8u}$

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$$\nabla^2\Phi_- = \mathcal{R}_4^{GKP} + \frac{e^{8A}}{24\,\mathrm{Im}(\tau)}|G_-|^2 + e^{-4A}|\partial\Phi_-|^2 + 2\kappa_{10}^2\mu_3 e^{8A}\rho_{\overline{D3}}$$

$$\mathcal{R}_4^{GKP} = \mathcal{R}_4[g] + 12\Box u - 24(\partial u)^2$$

$$M_{\rm pl}^2\mathcal{R}_4[g] = 24\,M_{\rm pl}^2\partial_\mu u\partial^\mu u + \int_X \sqrt{g_6}\left(-e^{-4A}\hat{T}^{D7}_{\mu\nu}g^{\mu\nu} + 8T_3e^{4A}e^{-12u}\rho_{\overline{D3}} - \frac{2e^{-8u}}{\kappa_{10}^2}\mathcal{R}_6[g_6] + \frac{1}{\kappa_{10}^2}e^{-8A-8u}|\partial\Phi_-|^2\right)$$

$$M_{\rm pl}^2\mathcal{R}_4[g] \approx 24\,M_{\rm pl}^2\partial_\mu u\partial^\mu u + \int_X \sqrt{g_6}\left(-e^{-4A}\hat{T}_{D7,\mu\nu}g^{\mu\nu} + 8T_3e^{4A}e^{-12u}\rho_{\overline{D3}}\right)$$

$$M_{\rm pl}^2\mathcal{R}_4[g] = -T^{4d} \approx 4V$$

Giddings, Maharana 05
Moritz, Retolaza, Westphal 17,18
Hamada, Hebecker, Shiu, Soler 18,19
Carta, Moritz, Westphal 19
Gautason, Van Hemelryck, Van Riet, Venken 19
Kachru, Kim, L.M., Zimet

Adding a D3-$\overline{\rm D3}$ pair appears to require $\Delta\mathcal{R}_4 \propto -e^{8A}$

Adding a D3-$\overline{\rm D3}$ pair requires $M_{\rm pl}^2\Delta\mathcal{R}_4[g] = 4V$ ✓

whereas $S_{\rm DBI+CS} \Rightarrow 2\rho T_3 e^{4A} \rho_{\overline{D3}} e^{-8u}$

Recap

So far: with careful treatment of breathing mode,
effects of $\overline{D3}$ (alone: no D7-branes yet) match between 10d and 4d.
Runaway decompactification, at expected rate.
No mysteries, no obstructions.

Next: in same spirit, include only D7-brane gaugino condensate, no $\overline{D3}$.
Do 10d EOM imply SUSY AdS_4 vacuum?

Stress-energy of gaugino condensate

Consider a stack of D7-branes supporting $SU(N_c)$ SYM.

$$S_{G\lambda\lambda} = -\frac{i}{(4\pi^2\alpha')^2}\int \sqrt{g}e^{-4A}e^{\phi}G_3\cdot\Omega\frac{\bar{\lambda}\bar{\lambda}}{16\pi}\delta^{(0)} + c.c.$$

Cámara, Ibáñez, Uranga 03

G_3 causes D7-brane gaugino mass $\Leftrightarrow$ $\langle\lambda\lambda\rangle$ sources G_3.

$$(G_-)_{a\bar{c}\bar{d}} = -e^{-4A}\sqrt{\mathrm{Im}\tau}\frac{\lambda\lambda}{16\pi^2}\partial_a\partial_b G_{(2)}(z;z_{D7})g^{b\bar{b}}\overline{\Omega}_{\bar{b}\bar{c}\bar{d}},$$

Strong consistency check: D3-brane potential.

Koerber, Martucci 07
Baumann, Dymarsky, Kachru, Klebanov, L.M. 10
Dymarsky, Martucci 10
Heidenreich, L.M, Torroba 10
Moritz, Retolaza, Westphal 17
Gautason, Van Hemelryck, Van Riet 18

Setup

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Consider a stack of D7-branes supporting $SU(N_c)$ SYM.

Include a D3-brane at z.

$4d$ $\mathcal{N} = 1$ supergravity:

$$\mathcal{K} = -3 \log(T + \overline{T} - \gamma\, k(z, \bar{z}))$$

DeWolfe, Giddings 02

$$W_{\text{classical}} = \int_X G_3 \wedge \Omega \equiv W_0$$

Gukov, Vafa, Witten 99

$$W_{\text{np}} = \frac{-N_c}{32\pi^2} \langle \lambda\lambda \rangle(z) = \mathcal{A}(z) e^{-aT}$$

Ganor 96
Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi 03
Berg, Haack, Körs 04
Baumann, Dymarsky, Klebanov, Maldacena, L.M., Murugan 06
Koerber, Martucci 07
Baumann, Dymarsky, Kachru, Klebanov, L.M. 10

$$W = W_0 + \mathcal{A}(z) e^{-aT}$$

$$V_F = V_F \left[\mathcal{K}(T, \overline{T}, z, \bar{z}), W_{\text{np}}(T, z) \right]$$

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Strong consistency check: D3-brane potential.

$$\boxed{V_{\mathrm{DBI+CS}} = V_F\left[\mathcal{K}(T,\overline{T},z,\bar{z}),W_{\mathrm{np}}(T,z)\right]}$$

Baumann, Dymarsky, Kachru, Klebanov, L.M. 10
Dymarsky, Martucci 10

The 4d F-term potential due to $W_{\mathrm{np}}(T,z)$
matches
the 10d DBI+CS potential due to G_3 sourced by $\langle\lambda\lambda\rangle$.

$$V_{\mathrm{DBI+CS}}^{\mathrm{noncompact}} = e^{\mathcal{K}}K^{a\bar{b}}\partial_a W\overline{\partial_b W} \qquad V_{\mathrm{DBI+CS}}^{\mathrm{compact}} = e^{\mathcal{K}}K^{a\bar{b}}D_a W\overline{D_b W}$$

Kachru, Kim, L.M., Zimet

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Cámara, Ibáñez, Uranga 03

G_3 causes D7-brane gaugino mass $\Leftrightarrow$ $\langle\lambda\lambda\rangle$ sources G_3.

Promote to GCG:

$$t := -e^{-\phi}\frac{8i}{|\eta|^2}\eta_+^{(1)}\otimes\eta_-^{(2)\dagger} = e^{i\theta}e^{iJ}$$

Graña, Minasian, Petrini, Tomasiello 05
Koerber, Martucci 07
Dymarsky, Martucci 10

$$S_{G\lambda\lambda} = -\frac{i}{(4\pi^2\alpha')^2}\int \sqrt{g}e^{-4A}e^{\phi}(G_3 + id\mathrm{Re}t)\cdot\Omega\frac{\bar{\lambda}\bar{\lambda}}{16\pi}\delta^{(0)} + c.c.$$

Benmachiche, Grimm 06
Koerber, Martucci 07

Stress-energy of gaugino condensate

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Compelling evidence that gaugino condensation sources flux via $S_{G\lambda\lambda}$.

Compute the associated 10d stress-energy:

$$T^{G\lambda\lambda}_{\mu\nu}\Big|_{\mathrm{SUSY}} = -\frac{ie^{4A}}{(4\pi^2\alpha')^2}(G_3 + id\mathrm{Re}t)\cdot\Omega\frac{\bar{\lambda}\bar{\lambda}}{16\pi}\delta^{(0)}g_{\mu\nu} + c.c.$$

Kachru, Kim, L.M., Zimet

$$G_3 + id\mathrm{Re}t = \frac{W\overline{\Omega}}{\pi\int_X \Omega\wedge\overline{\Omega}} \quad \Rightarrow -\int_X \sqrt{g}e^{-4A}g^{\mu\nu}T^{G\lambda\lambda}_{\mu\nu}\Big|_{\mathrm{SUSY}} = -12e^{\mathcal{K}}|W|^2.$$

$$M_{\mathrm{pl}}^2\mathcal{R}_4[g] = \int_X \sqrt{g_6}\left(-e^{-4A}g^{\mu\nu}T^{G\lambda\lambda}_{\mu\nu}\right)$$

$$\boxed{M_{\mathrm{pl}}^2\mathcal{R}_4[g] = -12e^{\mathcal{K}}|W|^2 = 4V^{\mathrm{KKLT}}_{\mathrm{AdS}}}$$

Match is exact.

Kachru, Kim, L.M., Zimet

Recap

First: with careful treatment of breathing mode,

effects of $\overline{D3}$ (alone: no D7-branes yet) match between 10d and 4d.

Runaway decompactification, at expected rate.

Next: only D7-brane gaugino condensate, no $\overline{D3}$.

10d EOM imply SUSY AdS_4 vacuum:

10d stress-energy due to CIU gaugino-flux coupling

precisely reproduces KKLT SUSY AdS.

$$\boxed{\text{GKP+CIU=KKLT AdS}}$$

Koerber, Martucci 07
Baumann, Dymarsky, Kachru, Klebanov, L.M. 10
Dymarsky, Martucci 10
Moritz, Retolaza, Westphal 17,18
Hamada, Hebecker, Shiu, Soler 18,19
Gautason, Van Hemelryck, Van Riet 18
Gautason, Van Hemelryck, Van Riet, Venken 19
Carta, Moritz, Westphal 19
Kachru, Kim, L.M., Zimet

Stress-energy of gaugino condensate

$$\int_X \sqrt{g} e^{-4A} g^{\mu\nu} T^{G\lambda\lambda}_{\mu\nu} \Big|_{\mathrm{SUSY}} = 12 e^{\mathcal{K}} |W|^2$$

$$M_{\mathrm{pl}}^2 \mathcal{R}_4[g] = -12 e^{\mathcal{K}} |W|^2 = 4 V_{\mathrm{AdS}}^{\mathrm{KKLT}}$$

If SUSY now spontaneously broken by $\langle T \rangle$, 4d supergravity guarantees that

$$M_{\mathrm{pl}}^2 \mathcal{R}_4[g] = 4 V_F^{\mathrm{KKLT}}$$

Would be instructive to verify in 10d.

Kachru, Kim, L.M., Zimet

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precisely reproduces KKLT SUSY AdS.

GKP+CIU=KKLT AdS.

Finally: both D7-brane gaugino condensate and $\overline{D3}$.

Do the 10d EOM imply dS_4 vacuum?

GKP+CIU+KPV $\stackrel{?}{=}$ KKLT dS.

Sequestering

Consider an anti-D3-brane in a Klebanov-Strassler throat.

Calculate in 10d its effect on $T^{G\lambda\lambda}_{\mu\nu}$, for D7-branes just outside the throat.

Moritz, Retolaza, Westphal 17

Method: enumerate lowest-dimension operators in CFT dual to throat.

Aharony, Antebi, Berkooz 05
Kachru, L.M., Sundrum 07
Baumann, Dymarsky, Kachru, Klebanov, L.M. 10
Gandhi, L.M., Sjörs 12

Result: anti-D3-brane is sequestered. $T^{G\lambda\lambda}_{\mu\nu}\Big|_{\overline{D3}} \approx T^{G\lambda\lambda}_{\mu\nu}\Big|_{\rm SUSY}$

Only non-negligible effect on $T^{G\lambda\lambda}_{\mu\nu}$ mediated by overall volume, $\mathrm{Re}\,T = e^{4u}$.

$$\int_X \sqrt{g}e^{-4A}g^{\mu\nu}T^{G\lambda\lambda}_{\mu\nu}\Big|_{\rm SUSY} = 12e^{\mathcal{K}}|W|^2 = -4V_F[\mathcal{K},W]\Big|_{\rm SUSY}$$

$$\int_X \sqrt{g}e^{-4A}g^{\mu\nu}T^{G\lambda\lambda}_{\mu\nu}(u \neq u_{\rm SUSY}) = -4V_F[\mathcal{K},W]\Big|_u$$

To find value of u in presence of anti-D3-brane, solve u EOM.

Antibrane and condensate

$$\boldsymbol{\frac{1}{4} M_{pl}^2 \mathcal{R}_4[g] = \underbrace{2T_3 e^{-12u} e^{4A}(z_{\overline{D3}})}_{V_{\overline{D3}}} - \frac{1}{4}\int_X \sqrt{g_6}\, e^{-4A} g^{\mu\nu} T^{G\lambda\lambda}_{\mu\nu}}$$

$$-\frac{1}{4}\int_X \sqrt{g}\, e^{-4A} g^{\mu\nu} T^{G\lambda\lambda}_{\mu\nu}(u \neq u_{\mathrm{SUSY}}) = V_F[\mathcal{K}, W]\Big|_u$$

$$\boxed{\frac{1}{4} M_{pl}^2 \mathcal{R}_4[g] = V_{\overline{D3}} + V_F = V_{\mathrm{KKLT}}}$$

Summary

First: with careful treatment of breathing mode,
effects of $\overline{D3}$ (alone: no D7-branes yet) match between 10d and 4d.
Runaway decompactification, at expected rate.

Next: only D7-brane gaugino condensate, no $\overline{D3}$.
10d EOM imply SUSY AdS_4 vacuum.
10d stress-energy due to CIU gaugino-flux coupling
precisely reproduces KKLT SUSY AdS.
GKP+CIU=KKLT AdS.

Finally: both D7-brane gaugino condensate and $\overline{D3}$.
Effects of $\overline{D3}$ mediated by overall volume.
10d stress-energy from gaugino-flux coupling, and of $\overline{D3}$,
precisely reproduces KKLT de Sitter.
GKP+CIU+KPV = KKLT dS.

Assumptions:

Existence of anti-D3-branes in Klebanov-Strassler throat.

Existence of gaugino condensate on D7-branes.

Einstein equations and Bianchi identity, for sufficiently general ansatz.

DBI+CS action for D3-branes and anti-D3-branes.

Gaugino-flux coupling from supersymmetric DBI action,
generalized appropriately to GCG.

Results:

Anti-D3-brane contributes as expected to Einstein equations.

Stress-energy of gaugino-flux coupling yields SUSY AdS of KKLT.

Effects of anti-D3-brane on $T^{G\lambda\lambda}_{\mu\nu}$ negligible except via overall volume.

$$\frac{M_{\rm pl}^2}{4}\mathcal{R}_4[g] \approx V_{\overline{D3}} + V_F = V_{KKLT}$$

Outlook

No sign of inconsistency or obstruction from 10d EOM.

Dimensional reduction of sources assumed by KKLT gives a 4d EFT.

10d EOM including these sources precisely agree with EOM of 4d EFT.

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Not everything is *local* in 10d: breathing mode is 10d zero mode.

Hamada, Hebecker, Shiu, Soler 19
Gautason, Van Hemelryck, Van Riet, Venken 19
Carta, Moritz, Westphal 19

Some further 10d checks may be possible, e.g. $V_F(u \neq u_{\rm SUSY})$.

Singularities from $G\lambda\lambda$ have appeared problematic.
In our approach, $\mathcal{R}_4[g]$ is finite.

Moritz, Retolaza, Westphal 17,18
Hamada, Hebecker, Shiu, Soler 18,19
Gautason, Van Hemelryck, Van Riet 18
Gautason, Van Hemelryck, Van Riet, Venken 19

Open problem: do sources coexist in region of control in explicit CY_3?

Conclusion

Considerable promise for exhibiting controlled de Sitter vacua via increasingly precise and ambitious 10d/4d computations.

Thanks!