Towards de Sitter from 10D

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1707.08678 by Jakob Moritz, A.R. & Alexander Westphal
Plan of the talk

1. Motivation
2. A 4d proposal to reach de Sitter: $\overline{D3}$-brane uplift (KKLT)
3. Higher dimensional considerations
4. 10d picture of KKLT: a problem & a way out
5. Summary
Motivation

- The expansion rate of the universe is accelerating: a positive Cosmological Constant $\Lambda > 0$ can describe this phenomenon.
- There are so many interesting questions regarding $\Lambda$, probably the biggest one being: why is it so small?
Motivation

- The expansion rate of the universe is accelerating: a positive Cosmological Constant $\Lambda > 0$ can describe this phenomenon.
- There are so many interesting questions regarding $\Lambda$, probably the biggest one being: why is it so small?
- String Theory is nowadays our best candidate to describe gravity at the quantum level, including the ingredients to embed (non)-abelian gauge groups, charged chiral matter...
  - If String Theory provides a UV completion of all fundamental physics, one should be able to embed $\Lambda > 0$.
  - This happens not be trivial (as we will see).
A 4d proposal to reach de Sitter: $D_3$-brane uplift (KKLT)

[Kachru, Kallosh, Linde, Trivedi '03]
Constructing 4d String Theory Vacua

Compactify Type IIB String Theory \((D = 10)\) to \(d = 4\):

\[
ds^2 = e^{2A(y)} g^{4\mu\nu}(x) dx^\mu dx^\nu + g^{6mn}(y) dy^m dy^n
\]

- If \(g_{mn}^6\) is a Calabi-Yau orientifold, 4d theory is \(\mathcal{N} = 1\) Super Gravity
- Many massless scalar fields (moduli) in 4d. We must give them a mass by using the other fields (fluxes) and objects in Type IIB ST.

\[
V_{4d} = e^K \left( K^{\bar{i}j} D_i W D_j \bar{W} - 3|W|^2 \right)
\]

where \(D_i W = \partial_i W + (\partial_i K) W\) and \(K^{\bar{i}j} \partial_i \partial_j K = \delta^i_j\).
Constructing 4D String Theory Vacua

\[ V_{4d} = e^K \left( K^{i\bar{j}} D_i W \, D_j \bar{W} - 3 |W|^2 \right) \]

Moduli stabilization:

- Complex structure moduli & \( \tau \) get masses from fluxes

\[ m_{CS} \sim \alpha' / R^3 \]

[Guok, Vafa, Witten '99]

\[ K = K_0 = - \log \int \bar{\Omega}_3 \wedge \Omega_3 \quad ; \quad W = W_0 = \int G_3 \wedge \Omega_3 \quad ; \quad G_3 \equiv F_3 - \tau H_3 \]
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2. Kähler moduli get masses from non-perturbative effects: \( m_{CS} \gg m_\rho \)

   Take \( h_{1,1} = 1 \). Volume modulus \( \text{Im}(\rho) \) appears in \( W \) via \( \langle \lambda\lambda \rangle = Ae^{i\rho} \)

   \[ W = W_0 + Ae^{i\rho} \quad ; \quad K = K_0 - 3 \log[-i(\rho - \bar{\rho})] \]
Constructing 4d String Theory Vacua

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   \[ W = W_0 + A e^{i\rho} \quad ; \quad K = K_0 - 3 \log[-i(\rho - \bar{\rho})] \]

AdS\(_4\) with

\[ V_0 \sim -m_{\rho}^2 M_P^2 \sim -|\langle \lambda \lambda \rangle|^2 M_P^2 \]
Constructing 4d String Theory Vacua

Uplifting with an anti-D3-brane on a warped throat:

[Kachru, Pearson, Verlinde ’01; Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi ’03]

Then

\[ V_{AdS} \rightarrow V_{AdS} + \Delta V_{D3} \quad (\text{> 0 for de Sitter}) \quad ; \quad \Delta V_{D3} = \frac{e^{4A_0} T_3}{(\text{Im } \rho)\rho} \]

- KKLT: \( e^{4A_0} \) tunnably small, can ignore possible backreaction: \( \rho = \rho_0 \)
- But this is a ’probe potential’
Constructing 4d String Theory Vacua

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Then \( V_{AdS} \rightarrow V_{AdS} + \Delta V_{D3} \) ( > 0 for de Sitter) ; \( \Delta V_{D3} = \frac{e^{4A_0} T_3}{(\text{Im } \rho)^\rho} \)

- KKLT: \( e^{4A_0} \) tunnably small, can ignore possible backreaction: \( \rho = \rho_0 \)
- But this is a ’probe potential’
- And. \( V_{AdS} \simeq -|\langle \lambda \lambda \rangle|^2 M_P^2 \) , so \( \Delta V \sim |V_{AdS}| \sim |\langle \lambda \lambda \rangle|^2 (\rho) M_P^2 \)

Can we really decouple Kähler moduli stabilization from the uplift?
Higher dimensional considerations

[Maldacena, Núñez ’00]
Higher dimensional considerations

Consider a gravity theory with $d$ compact extra dimensions:

$$ds^2 = e^{2A(y)} g_\mu^\nu(x) dx^\mu dx^\nu + g_{mn}(y) dy^m dy^n$$

Using the trace reversed Einstein’s Equations ($M_P = 1$)

$$R_{MN} = T_{MN} - g_{MN} \frac{T_P^P}{d+2} \Rightarrow R_4 \sim \int_{\mathcal{M}_d} \sqrt{g^d} e^{4A} \frac{(d-2) T_\mu^\mu - 4 T_m^m}{d+2}$$

- Can find $R_4$ only from matter content (not full potential $V$).
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- For de Sitter to be possible, at least one ingredient with

  $$(d-2)T_\mu^\mu - 4T_m^m > 0 \quad (T_\mu^\mu - T_m^m > 0 \text{ in String Theory})$$

  **Not common at all!**
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In particular, for an anti-D3-brane: $T^\mu_\mu - T^m_m < 0$ !!
Higher dimensional considerations: a toy model example

Consider a 6d theory on $\mathcal{X}_4 \times S^2$ [Freund, Rubin ’80]

$$S_6 = \frac{1}{2} \int \left( *R_6 - \frac{1}{2} F_2 \wedge *F_2 \right)$$

- Stabilize $S^2$ radius by taking $\int_{S^2} F_2 \simeq N$. Using the formulas above:

$$L_0^2 = \frac{3N^2}{32} \quad \& \quad \frac{V_0}{M_P^4}(L) = - \frac{N^2}{128\pi L^6}$$

so $\mathcal{X}_4 = AdS_4$
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- Now we add a 3-brane of tension $T_3$.
- $S^2$ backreacts: it grows $L_0^2 \rightarrow L_1^2 = L_0^2 \left(1 - \frac{T_3}{4\pi}\right)^{-1}$
- This results in a 4d vacuum energy change

$$\frac{V_0}{M_P^4}(L_1) = \frac{V_0}{M_P^4}(L_0) \left(1 - \frac{T_3}{4\pi}\right)^3 = \frac{V_0}{M_P^4}(L_0) + \frac{T_3}{M_P^4} + \mathcal{O} \left(\left(\frac{T_3}{m_{KK} M_P^2}\right)^2\right) \leq 0$$

Can increase the energy, but the backreaction flattens out the ’uplift’. 
Higher dimensional considerations: a toy model example II

But if we put an 'object' with \((d - 2) T_\mu^\mu - 4 T_m^m > 0\)

For a 6d \(\Lambda_6\):

\[
\frac{V_0}{M_P^4}(L) = \frac{\Lambda_6}{8\pi L^2} - \frac{N^2}{128\pi L^6}
\]

It is possible to reach de Sitter
A little summary...

- KKLT uplift is based on an anti-D3-brane on warped throat

\[ V = V_{AdS} + \Delta V_{D3} > 0 \iff \Delta V_{D3} > |V_{AdS}| \sim m_p^2 \mathcal{M}_P^2 \]

Can we decouple Kähler stabilization from uplift?
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  \[ R_4 \sim \int_{\mathcal{M}_d} \sqrt{g^d} e^{4A} [(d - 2) T^{\mu}_{\mu} - 4 T^m_m] \]
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- Toy model: 3-brane increases vacuum energy but
  - Small energy density \( \Rightarrow \) \( V = V_0 + \Delta V_3 + \mathcal{O}(T_3/M_P^4) \)
  - Large energy density \( \Rightarrow \) Strong backreaction on volume
  - With \( \Lambda_6 \) we can reach de Sitter
10d picture of KKLT: a problem & a way out

[Moritz, AR, Westphal ’17]
10d picture of KKLT: setup

A generalization of [Giddings, Kachru, Polchinski ’01] vacua: Type IIB on

\[ ds^2 = e^{2A(y)} g_{\mu\nu}^4 dx^\mu dx^\nu + g_{mn}^6 dy^m dy^n \quad ; \quad F_5 = (1 + \star_{10}) d\alpha \wedge dx^4 \]

Using the previous ideas (combined with tadpole cancelation condition):

\[
\frac{V_0}{M_P^4} \sim \int d^6 y \sqrt{g^6} \left[ -|\partial(e^{4A} - \alpha)|^2 - e^{8A} \left( \frac{|G_3^-|^2}{6\text{Im}(\tau)} + \frac{\Delta^{\text{loc}}}{2\pi} \right) \right]
\]

where \( \star_6 G_3^- = -iG_3^- \) & \( \Delta^{\text{loc}} \equiv \frac{1}{4} (T_m^m - T_\mu^\mu)^{\text{loc}} - T_3 \rho_3^{\text{loc}} \)
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where $\star_6 G_3^- = -iG_3^-$ & $\Delta^{loc} \equiv \frac{1}{4} (T_m^m - T_{\mu}^\mu)^{loc} - T_3 \rho_3^{loc}$

- Localized objects with $\Delta^{loc} < 0$ are necessary to reach de Sitter.
10d picture of KKLT: moduli stabilization

- CS moduli & dilaton: via $G_3^+$ fluxes & with $(e^{4A} - \alpha) = 0$.
  [Giddings, Kachru, Polchinski '01]
10d picture of KKLT: moduli stabilization

- CS moduli & dilaton: via $G_3^+$ fluxes & with $(e^{4A} - \alpha) = 0$.
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- Kähler moduli: via $\langle \lambda \lambda \rangle$ on a stack of D7-branes.
  - How can we describe the gaugino condensate (a 4d effect) in 10d?
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- Kähler moduli: via $\langle \lambda \lambda \rangle$ on a stack of D7-branes.
  - How can we describe the gaugino condensate (a 4d effect) in 10d?
  - Prescription given by [Baumann, Dymarsky, Kachru, Klebanov, McAllister ’10]

$$S_{IIB} \rightarrow S_{IIB} + S_{\langle \lambda \lambda \rangle}$$

where

$$S_{\langle \lambda \lambda \rangle} \sim \int \sqrt{-g^4} \langle \lambda \lambda \rangle \int_{\mathcal{M}_6} \sqrt{g^6} \left( G_{3}^{(0,3)} \cdot \Omega_3 \right) \delta^{(2)}(h(z))$$

- Indeed, this reproduces $V_{D3}$ perfectly [Berg, Haack, Kors ’05]
  [Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan ’06]
10d picture of KKLT: the effect of $\langle \lambda \lambda \rangle$

$$S_{\langle \lambda \lambda \rangle} \sim \int \sqrt{-g} \langle \lambda \lambda \rangle \int_{\mathcal{M}_6} \sqrt{g^6} \left( G_3^{(0,3)} \cdot \Omega_3 \right) \delta^{(2)}(h(z))$$

It has several effects:

- $\langle \lambda \lambda \rangle$ sources $G_3$ flux:
  - $G_3^{(1,2)}$ (IASD) flux  [Baumann, Dymarsky, Kachru, Klebanov, McAllister ’10]
  - $G_3^{(0,3)}$ (ISD) localized flux  [Dymarsky, Martucci ’10]
  - Configuration is SUSY
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  - Configuration is SUSY

- And has gravitational effects: [Moritz, AR, Westphal ’17]
  - Local $G_3^{(0,3)}$: $-e^{8A} \frac{\Delta^\text{loc}_{\langle \lambda \lambda \rangle}}{2\pi} = +3|\langle \lambda \lambda \rangle|^2 |F(z)|^2 \geq 0$ (keep in mind)
  - Bulk $G_3^{(1,2)}$: $-e^{8A} \frac{|G_3^-|^2}{6\text{Im}(\tau)} = -4|\langle \lambda \lambda \rangle|^2 |F(z)|^2 \leq 0$

\[
\frac{V}{M_P^4} \sim \int \left[ -|\partial(e^{4A} - \alpha)|^2 - e^{8A} \left( \frac{|G_3^-|^2}{6\text{Im}(\tau)} + \frac{\Delta^\text{loc}}{2\pi} \right) \right]
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$$S_{\langle \lambda \lambda \rangle} \sim \int \sqrt{-g^4} \langle \lambda \lambda \rangle \int_{\mathcal{M}_6} \sqrt{g^6} \left( G_3^{(0,3)} \cdot \Omega_3 \right) \delta^{(2)}(h(z))$$

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  - $G_3^{(1,2)}$ (IASD) flux \cite{Baumann2010}
  - $G_3^{(0,3)}$ (ISD) localized flux \cite{Dymarsky2010}
- Configuration is SUSY
- And has gravitational effects: \cite{Moritz2017}
  - Local $G_3^{(0,3)}$: $-e^{8A} \frac{\Delta_{loc}}{2\pi \langle \lambda \lambda \rangle} = +3 |\langle \lambda \lambda \rangle|^2 |F(z)|^2 \geq 0$ (keep in mind)
  - Bulk $G_3^{(1,2)}$: $-e^{8A} \frac{|G_3^-|^2}{6\text{Im}(\tau)} = -4 |\langle \lambda \lambda \rangle|^2 |F(z)|^2 \leq 0$

$$\frac{V_{\langle \lambda \lambda \rangle}}{M_P^4} \sim \int \left[ -|\partial(e^{4A} - \alpha)|^2 - e^{8A} \left( \frac{|G_3^-|^2}{6\text{Im}(\tau)} + \frac{\Delta_{loc}}{2\pi} \right) \right] \sim -\frac{|\langle \lambda \lambda \rangle|^2}{4\pi} \int |F(z)|^2$$

**SUSY AdS$_4$** (with $G_3^{(0,3)} \sim W_0 \sim \langle \lambda \lambda \rangle$)

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Towards de Sitter from 10D
10d picture of KKLT: inclusion of the \(\overline{D3}\)

\[
\frac{V_0}{M_P^4} \sim \int d^6 y \sqrt{g^6} \left\[ -|\partial (e^{4A} - \alpha)|^2 - e^{8A} \left( \frac{|G_3^-|^2}{6 \text{Im}(\tau)} + \frac{\Delta^{loc}}{2\pi} \right) \right\]
\]

- Add \(\overline{D3}\)-brane (+ \(G_3^+\) fluxes for tadpoles) on warped throat (\(e^{4A}_{IR} \ll 1\)).
- In 10d picture, we don’t know details of \(\overline{D3}\) backreaction down the throat. (We assume there exists a stable solution)
10d picture of KKLT: inclusion of the $\overline{D3}$

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- In 10d picture, we don’t know details of $\overline{D3}$ backreaction down the throat. (We assume there exists a stable solution)
- In the probe limit we expect $\Delta V_{\overline{D3}} \sim e_{IR}^{4A}(2T_3) + ...$
- But $\Delta^{loc}_{\overline{D3}} = 2T_3$ is suppressed by $e_{IR}^{8A} \ll e_{IR}^{4A}$.
  - Throat contributions negligible: $\Delta^{loc}_{\overline{D3}} > 0$ irrelevant.
10d picture of KKLT: inclusion of the $\overline{D3}$

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- Add $\overline{D3}$-brane (+ $G_3^+$ fluxes for tadpoles) on warped throat ($e^{4A}_{iR} \ll 1$).
- In 10d picture, we don’t know details of $\overline{D3}$ backreaction down the throat. (We assume there exists a stable solution)
- In the probe limit we expect $\Delta V_{\overline{D3}} \sim e^{4A}_{iR} (2T_3) + ...$
- But $\Delta^{loc}_{\overline{D3}} = 2T_3$ is suppressed by $e^{8A}_{iR} \ll e^{4A}_{iR}$.
  - Throat contributions negligible: $\Delta^{loc}_{\overline{D3}} > 0$ irrelevant.
- Other possible backreactions:
  - All possible profiles fall off too rapidly when getting close to bulk
  - Only option: effect on volume modulus.

$$\frac{V_{\langle \lambda \lambda \rangle + \overline{D3}}}{M_P^4} \sim - \frac{\langle \lambda \lambda \rangle |^2}{4\pi} \int_{V_{\langle \lambda \lambda \rangle + \overline{D3}}} |F(z)|^2$$

**After the inclusion of the $\overline{D3}$-brane, we still have AdS$_4$!**

Of course, expect energy increase, but backreaction prevents de Sitter
Representing this in 4d SUGRA

The KKLT uplift term can be described in terms of a nilpotent goldstino $S$ [Ferrara, Kallosh, Linde ’14]

$$W = W_0 + A e^{i \rho} + \sqrt{e^{4A_0}} T_3 S \quad ; \quad K = -3 \log[-i(\rho - \bar{\rho}) - S\bar{S}]$$

![Graph showing the behavior of the uplift term as a function of the parameter.]
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$$W = W_0 + A e^{i \rho} + \sqrt{e^{4 A_0} T_3} S$$

$$K = -3 \log[-i(\rho - \bar{\rho}) - S\bar{S}]$$

But recall that $\Delta V_{D3} \sim |V_{AdS}| \sim |\langle \lambda \lambda \rangle|^2 M_P^2$. For $\Delta V_{D3} \sim |\langle \lambda \lambda \rangle|^2 (\rho) T_3$:

$$W = W_0 + A e^{i \rho} + \sqrt{T_3} S e^{i \rho}$$

$$K = -3 \log[-i(\rho - \bar{\rho}) - S\bar{S}]$$
A possibility to evade the 10D no-go?

- From the EFT perspective, for being safe we need $|V_0| \lesssim \Delta V \ll m_\rho M_P^2$
- Decouple the AdS scale $L_{AdS}$ from $m_\rho$, such that $m_\rho L_{AdS} \gg 1$
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- Racetrack stabilization: [Kallosh, Linde ‘04]

$$W = W_0 + A e^{i \rho} + B e^{i b \rho}$$
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- From 10d, we need $-\Delta^{loc} > 0$ **Gaugino condensate**

$$\frac{V_0}{M_P^4} \sim \int d^6 y \sqrt{g^6} \left[ -|\partial(e^{4A} - \alpha)|^2 - e^{8A} \left( \frac{|G_3^-|^2}{6\text{Im}(\tau)} + \frac{\Delta^{loc}}{2\pi} \right) \right]$$

- After Kähler moduli stabilization one may find $V_{\lambda\lambda} = 0$ due to

$$-e^{8A} \left( \frac{|G_3^-|^2}{6\text{Im}(\tau)} + \frac{\Delta^{loc}}{2\pi} \right) \sim -4 \left| \sum_a \langle \lambda\lambda \rangle_a F_a(z) \right|^2 + \sum_a 3 |\langle \lambda\lambda \rangle_a F_a(z) |^2$$
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- From 10d, we need $-\Delta^{loc} > 0$  
  **Gaugino condensates**

$$\frac{V_0}{M_P^4} \sim \int d^6 y \sqrt{g^6} \left[ -|\partial (e^{4A} - \alpha)|^2 - e^{8A} \left( \frac{|G^-_3|^2}{6\text{Im}(\tau)} + \frac{\Delta^{loc}}{2\pi} \right) \right]$$

- After Kähler moduli stabilization one may find $V_{\lambda\lambda} = 0$ due to

$$-e^{8A} \left( \frac{|G^-_3|^2}{6\text{Im}(\tau)} + \frac{\Delta^{loc}}{2\pi} \right) \sim -4 \left| \sum_a \langle \lambda\lambda \rangle_a F_a(z) \right|^2 + \sum_a 3 |\langle \lambda\lambda \rangle_a F_a(z)|^2$$

- Include a $\overline{D3}$ (probe limit): $\Delta V_{D3} = e^{4A}(2 T_3) + \ldots \Rightarrow V_0 + \Delta V_{D3} > 0$

So one would reach de Sitter while backreaction is under control
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  - Quantum corrected $V_{D3}$
  - $V_{AdS} \sim -|W_0|^2 \sim -|\langle \lambda \lambda \rangle|^2$
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- Still a lot to do...
  - 10D construction of racetrack?
  - What about LVS?
  - Understand well how to represent backreaction in 4d.
  - Quintessence?
Thank you :)
Funding acknowledgement:

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