Holography and the KKLT Scenario

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based on:

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[2204.07171]

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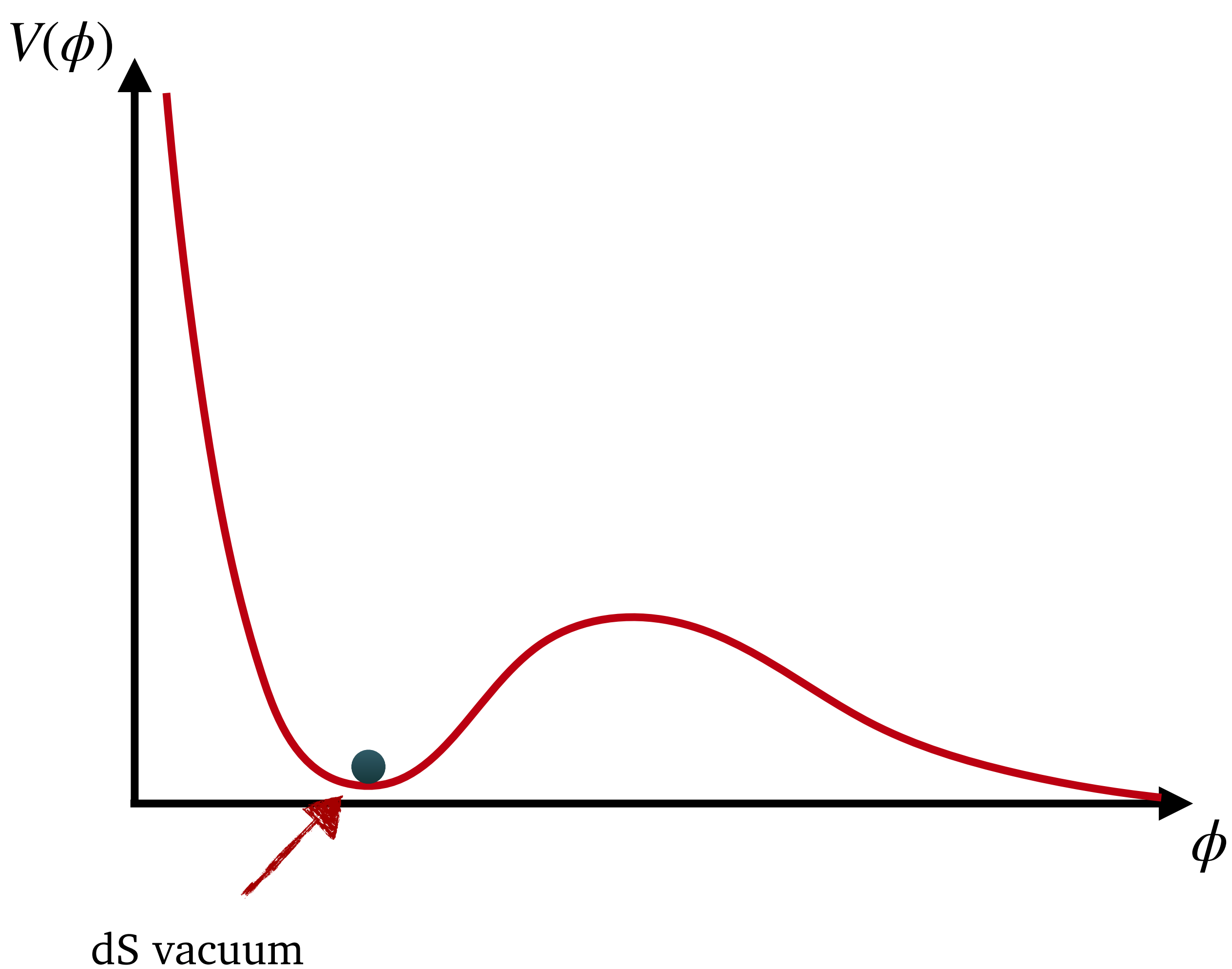
Introduction

At large scales, our Universe seems to be homogeneous and with small, but positive, cosmological constant: $\Lambda > 0$

$\rightarrow$ should be describable by a quasi-de Sitter geometry.

$\rightarrow$ look for models that allow for vacua with positive cosmological constant.



Problem: (quasi-)dS solutions are very difficult to obtain in consistent theory of gravity!

[Obied, Ooguri, Spodyneiko, Vafa '18]

e.g. weakly coupled String Theory:

$\rightarrow$ always get run-away potentials with slope $|V'/V|$ too big to realize quasi-dS

[Bedroya, Vafa '19; Bedroya, Brandenberger, Loverde, Vafa '19]

Review: KKLT Scenario (1st step)

Aim: Find dS not in strict weak coupling, but still controllable regime!

→ asymptotic arguments for shape of potential do not apply!

Example: KKLT scenario *(Get dS through uplift of supersymmetric AdS vacuum)*

[Kachru, Kallosh, Linde, Trivedi '03]

- Consider type IIB on Calabi-Yau orientifold $X_3/\mathbb{Z}_2$ in presence of RR/NS-three form flux F_3, H_3.

- Tadpole cancellation requires: $\frac{\chi(X_4)}{24} = N_{D3} + \frac{1}{2}\int F_3 \wedge H_3$

For orientifold: $\frac{\chi(X_4)}{24} = \frac{1}{4}\left(N_{O3} + \chi(O7)\right)$

- Scalar potential given by: $V = e^K\left(g^{a\bar{b}} D_a W \bar{D}_{\bar{b}} \bar{W} - 3|W|^2\right)$

- Supersymmetric vacuum corresponds to solutions to $D_a W = 0$

$$W = \int \Omega_3 \wedge (F_3 - \tau H_3) + \sum_{\mathbf{k}} \mathscr{A}_{\mathbf{k}}(z^i, F_3, H_3)\ e^{-2\pi k^\alpha T_\alpha}$$

Complex structure moduli

Kähler moduli

For perturbative control: $e^{-2\pi k^\alpha T_\alpha} \ll 1$

→ *Solving* $D_a W = 0$ *also requires* $\int \Omega \wedge (F_3 - \tau H_3) \ll 1$

Potential at the minimum given by: $V_0 = -3\underbrace{\left(e^K |W|^2\right)}_{\ll 1}\Big|_{D_a W = 0}$

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F-term equations and attractors

Question: Can the first step of KKLT be completed?

i.e. are there supersymmetric AdS vacua in type IIB/F-theory flux compactifications with exponentially small cosmological constant?

Strategy: Use dual supersymmetric brane picture!

Observation: if we define $|\mathscr{Z}| = e^{K/2}|W|$ the F-term equations $D_a W = 0$ translate to:

$\partial_a|\mathscr{Z}| = 0$ and cosmological constant is given by $\Lambda = -3|\mathscr{Z}|^2$

Reminiscent of attractor equations for black holes!

[Ferrara, Kallosh, Strominger '95]
cf. also [Kallosh '05]

Recall, e.g. $\frac{1}{2}$-BPS black holes in type IIB CY compactifications:

- D3-branes on special Lagrangian 3-cycles in CY 3-fold.

Define: $|Z| = \left|\frac{\int_{L_3}\Omega_3}{\int \Omega_3 \wedge \bar{\Omega}_3}\right|$

Attractor: $\partial|Z| = 0$.

Fix moduli at horizon of BH with near-horizon geometry $AdS_2 \times S^2$.

$|Z|_{\mathrm{crit}}$ can be identified with mass of black hole.

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Dualizing the Flux

Inspired by BPS black hole attractor, interpret F-term equations as attractor equations for BPS branes dual to flux.

- Here: Consider M-theory version of KKLT, i.e. M-theory on CY fourfold with G_4-flux
- Want to find KKLT-like AdS_3 vacua → statistical arguments for KKLT should equally well apply in this case.
- Similar to D3-brane BH example can dualize the G_4-flux into branes

$\Updownarrow$

cf. [Silverstein '03]

M5-branes
wrapping dual cycles

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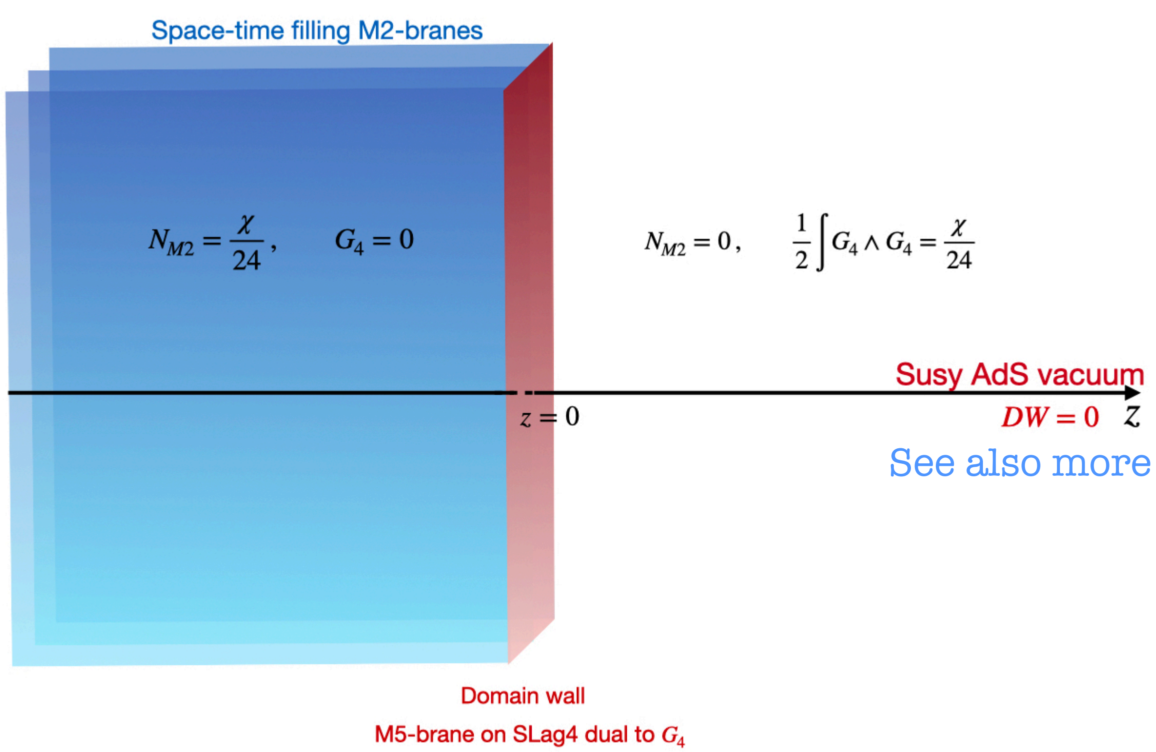

- BPS equations:

$$ds^2 = e^{2D(z)}(-dt^2 + dx^2) + dz^2 .$$

$$\frac{dD}{dz} = -\zeta |\mathcal{Z}|, \qquad \zeta = \pm 1$$

$$\frac{d\phi^a}{dz} = 2\zeta g^{a\bar{b}}\partial_{\bar{b}}|\mathcal{Z}|,$$

[Cvetic, Griffies, Rey '92]

See also more recent discussion in [Bandos, Farakos, Lanza, Martucci, Sorokin '18; Lanza, Marchesano, Martucci, Valenzuela '20]

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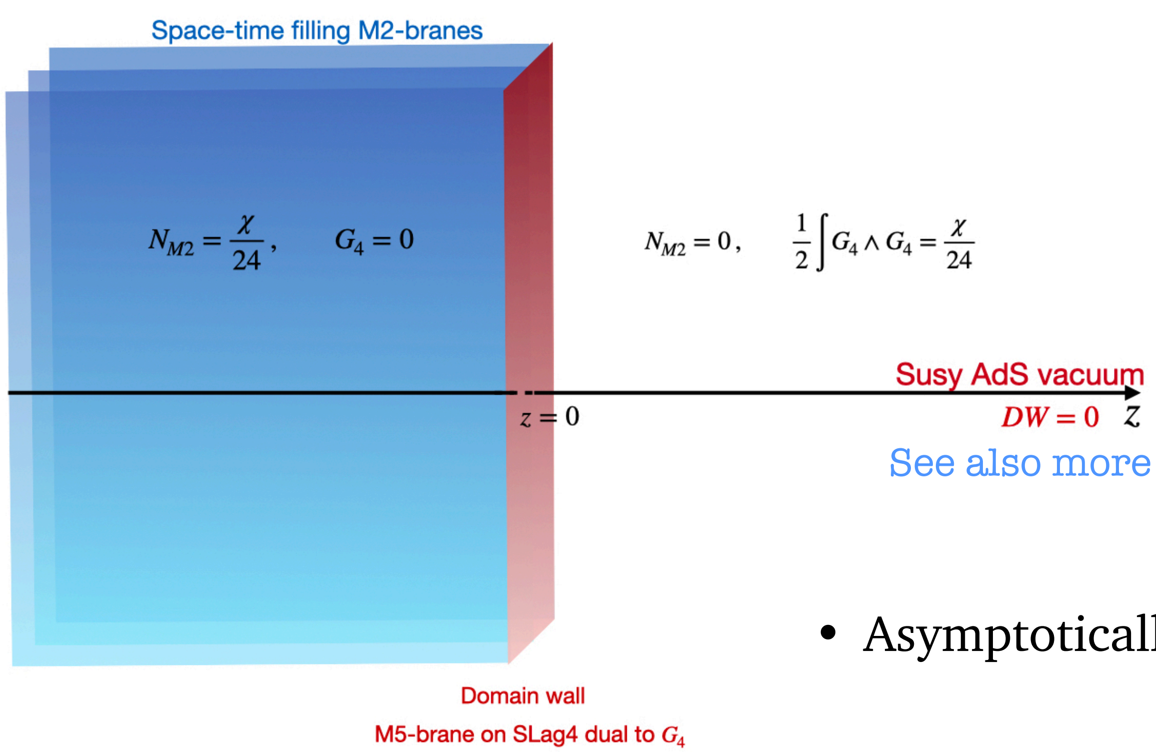

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- Asymptotically far away can realize supersymmetric AdS vacuum if $\partial|\mathcal{Z}| = 0$ and $D(z) = \text{const}\,.$
- If such supersymmetric solution exists: $|\mathcal{Z}|_{\text{crit}} = $ tension of domain wall

Membrane Picture

- Want supersymmetric AdS: Domain walls need to be 1/2-BPS.
- Only for 1/2 BPS domain wall can interpret $|\mathscr{Z}|_{\text{crit}}$ as tension of domain wall.

We are interested in primitive G_4-fluxes, i.e. $J \wedge G_4 = 0$:

$\rightarrow$ **BPS-domain wall obtained form M5-brane on Special Lagrangian cycles*!**

**this is a stronger condition than the usual self-duality condition on G_4*

- L_4 is special Lagrangian: $\quad J_4\Big|_{L_4} = 0\,, \qquad \mathrm{Im}\left(e^{i\alpha}\Omega_4\right)\Big|_{L_4} = 0$
- Tension of domain wall depends on all moduli (even without non-pert. corrections):

$$\mathscr{Z}_{\text{cl}} = e^{(K_{c.s.}+K_{qK})/2}\int_{L_4}\Omega_4$$

- Consequence of non-factorization of moduli space: $\mathscr{M} \neq \mathscr{M}_{c.s.} \times \mathscr{M}_{qK}$

Question: Can the tension of an M5-brane on Slag cycle be arbitrarily small at the attractor point?

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- $|\mathcal{Z}|_{\text{crit.}}$ related to the # of massless degrees of freedom on the brane.
- Worldvolume theory on M5-brane on Slag 4-cycle has $\mathcal{N} = (1,1)$ supersymmetry in 2d.
- Massless degrees of freedom correspond e.g. to deformations of 4-cycle.
- Classical geometry: Deformations of Slag cycles is exact moduli space!
- But $\mathcal{M}_{\text{M-theory}} \neq \mathcal{M}_{c.s.} \times \mathcal{M}_{\text{K}} \rightarrow$ deformations can be lifted by corrections!

$\mathcal{N} = (1,1)$ QFT in UV

$\mathcal{N} = (1,1)$ CFT in IR

Worldvolume theory on M5-brane in the UV just a QFT, but can flow in the IR to CFT dual to AdS vacuum!

- We can then identify: $l_{AdS_3} \sim c_{\text{IR}} \sim |\mathcal{Z}|^{-1}_{\text{crit.}}$
- By c-theorem $c_{\text{UV}} \geq c_{\text{IR}} \rightarrow$ to get a bound it is sufficient to count c_{UV}

Question: For cycles compatible with tadpole cancellation can the central charge be exponentially large?

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Central charge

Want to find parametric growth **of the UV central charge c_{UV} for WV theory on M5-brane on Slag 4-cycle.**

Parametric growth: How does c_{UV} behave under rescaling $L_4 \to NL_4$?

(Are interested in the large N regime where statistical arguments for flux compactifications should apply) [Bousso, Polchinski ’00; Douglas ’03; Denef, Douglas ‘04]

M5-brane on Slag $L_4 \subset CY_4$

What are the d.o.f. from the reduction of M5-brane action?

- 6d tensor multiplet yields $b_2^+(L_4)$ right-moving and $b_2^-(L_4)$ left-moving scalars.

- Tangent space of Slag deformations of L_4:

$$T_{L_4}(\mathscr{M}) = H^0(L_4, \mathscr{N}) = H^0(L_4, T^*L_4)$$

$$\to \quad \dim_{\mathbb{R}} \mathscr{M} = b_1(L_4)$$

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- $N_L = 1 + b_2^- + b_1 \qquad N_R = 1 + b_2^+ + b_1$
- Central charge:

$$c_{\mathrm{UV}} = \frac{3}{2}\left(2 + b_2^+ + b_2^- + 2b_1\right) = \frac{3}{2}(\chi(L_4) + 4b_1)$$

- For Slag cycle have: $\chi(L_4) = L_4 \,.\, L_4$

$$\rightarrow \; c_{\mathrm{UV}} = \frac{3}{2}\left(L_4 \,.\, L_4 + 4b_1\right)$$

- Expect c_{UV} to grow like: $c_{\mathrm{UV}}(NL_4) \sim N^2 c_{\mathrm{UV}}(L_4)$
- $b_1(L_4)$ should also not grow faster than $aL_4 \,.\, L_4$

(In orientifold limit can support this through black hole arguments)

see [Lüst, Vafa, MW, Xu '22]

- From RG flow: $c_{\mathrm{IR}} \leq c_{\mathrm{UV}} \lesssim \beta\chi(L_4)$
- Tadpole cancellation:

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Bounding l_{AdS}

UV central charge is parametrically bounded by $c_{\mathrm{UV}} \leq \beta\chi(L_4)$

- By tadpole cancellation $\chi(L_4)$ itself is bounded by $\chi(X_4)/24$.
- IR central charge and AdS radius related by $c_{IR} \sim l^{d-2}_{AdS_d}$.
- For AdS_3 vacua find:

$$l_{AdS_3} \leq \frac{\chi(X_4)}{24}$$

- Largest known Euler characteristic for CY four-fold 1 820 448
  $\rightarrow$ $l_{AdS_3} \lesssim \mathcal{O}(10^5)$ [Klemm, Lian, Roan, Yau '97; Taylor, Wang '15]

Question: Are these AdS vacua indeed weakly coupled as in the KKLT scenario?

Consider the species scale $\hat{=}$ scale at which gravity becomes strongly coupled in the presence of N light particle species. [Dvali '07]

$$\Lambda_{\text{species}} = \frac{M_{\text{pl}}}{N^{1/(d-2)}} \qquad \chi(X_4) = 6(8 + \underbrace{h^{3,1} + h^{1,1}}_{\sim N} - h^{2,1})\,,\ \text{such that parametrically } N \gtrsim \chi(X_4)$$

$$\Longrightarrow \quad \frac{\Lambda_{\text{species}}}{M_{\text{pl}}} \sim \frac{1}{\chi(X_4)}$$

Bounding l_{AdS}

UV central charge is parametrically bounded by $c_{\mathrm{UV}} \leq \beta\chi(L_4)$

- By tadpole cancellation $\chi(L_4)$ itself is bounded by $\chi(X_4)/24$.
- IR central charge and AdS radius related by $c_{IR} \sim l_{AdS_d}^{d-2}$.
- For AdS_3 vacua find:

$$l_{AdS_3} \leq \frac{\chi(X_4)}{24}$$

- Largest known Euler characteristic for CY four-fold 1 820 448
  $\rightarrow$ $l_{AdS_3} \lesssim \mathcal{O}(10^5)$ [Klemm, Lian, Roan, Yau '97; Taylor, Wang '15]

Question: Are these AdS vacua indeed weakly coupled as in the KKLT scenario?

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AdS scale vs. species scale

Compare species and AdS scale (here 3d):

$$\frac{\Lambda_{\mathrm{AdS}}}{M_{\mathrm{pl}}} \gtrsim \frac{1}{\chi(X_4)} \quad \longleftrightarrow \quad \frac{\Lambda_{\mathrm{species}}}{M_{\mathrm{pl}}} \lesssim \frac{1}{\chi(X_4)}$$

AdS scale is at or below the species scale!
→ AdS is necessarily strongly coupled.
→ Cannot trust even the vacua with small Λ.

Same also works in 4d, since species scale and AdS scale have the same dimension dependence:

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From this perspective: KKLT-like SUSY AdS vacua should not be realizable!!

Conclusions

- Considered the first step of KKLT scenario (supersymmetric AdS vacuum from flux compactification) from a dual brane perspective.

- Used ”conventional” holography and replaced flux by 5-branes.

cf. [Silverstein ’03]

- Supersymmetry equations $DW = 0$ identified as attractor equations
  $\rightarrow$ supersymmetric vacuum requires supersymmetric brane!

cf. [Kallosh ’05; Kounnas, Lüst, Petropoulos, Tsimpis ‘07]

- For simplicity: M-theory analogue of KKLT $\rightarrow$ supersymmetric vacua dual to branes on on Slag cycles!

Stronger condition than self-duality of G_4-flux!
Not taken into account in e.g.
[Demirtas, Kim, McAllister, Moritz, (Rios-Tascon) ’20,’21]

- AdS scale identified with tension of brane $|\mathscr{Z}|$ at attractor point.
  $\rightarrow$ related to IR degrees of freedom on brane worldvolume.

- UV central charge bounded as: $c_{\rm UV} \lesssim \frac{\chi(X_4)}{24}$ $\rightarrow$ AdS cosmological constant bounded by M2/D3-brane tadpole!

i.e. no large N limit for KKLT AdS vacua!

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Thank you!!