HOLOGRAPHY AND THE KKLT SCENARIO

[2204.07171] with C. Vafa, M. Wiesner, K. Xu

Severin Lüst

Harvard University

Back to the Swamp

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TWO SWAMPLAND CONJECTURES

No scale separated AdS vacua

[Gautason, Schillo, Van Riet, Williams '15]

[Gautason, Van Hemelryck, Van Riet '18]

[D. Lüst, Palti, Vafa '19]

No (long-lived) de Sitter vacua

[Obied, Ooguri, Spodyneiko, Vafa '18]

[Bedroya, Vafa '19]

Potential counterexample:

KKLT

[Kachru, Kallosh, Linde, Trivedi '03]

[Kachru, Kallosh, Linde, Trivedi '03]

CONTROLLED STRING THEORY DE SITTER VACUA

KKLT scenario: two step procedure:

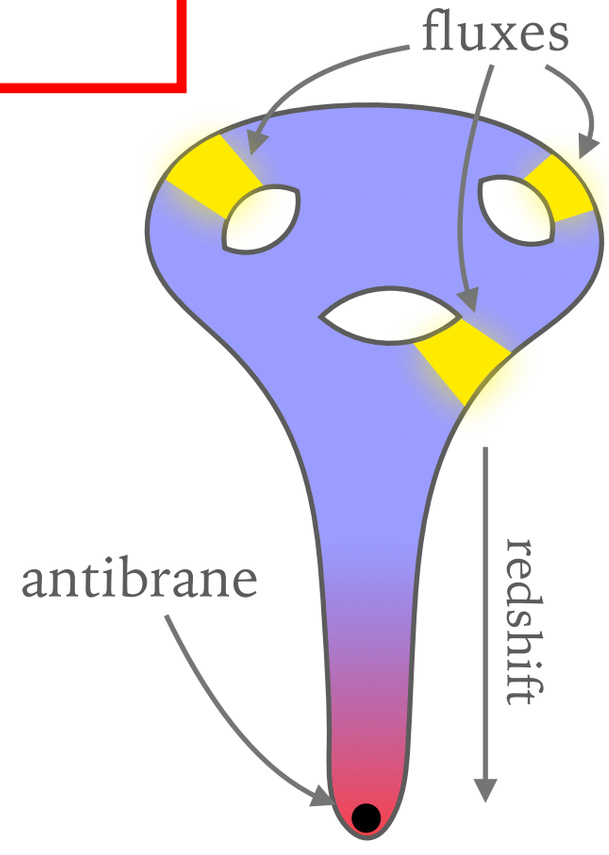
This Talk!

1. stabilize moduli with fluxes + non-pert. effects

$$\rightarrow \text{SUSY vacuum with } \Lambda < 0 \text{ (AdS)}$$

2. raise cosmological constant above zero
(perturb by antibrane in warped throat)

$$\rightarrow \text{broken SUSY and } \Lambda > 0$$



REVIEW:

KKLT ADS VACUA

COMPACTIFICATION ON CALABI-YAU MANIFOLDS

➤ IIB on Calabi-Yau:

$$M_{10} = M_4 \times_w CY_3$$

➥ two classes of moduli:

- $h^{1,1}$ Kähler moduli (volumes of 2 or 4-cycles)
- $h^{2,1}$ complex structure moduli (volumes of 3-cycles)

VEV for 3-form fields $F_3, H_3 \neq 0$ on 3-cycles („fluxes“) → fix size of 3-cycles → masses for complex structure moduli

MODULI STABILIZATION

- tree-level $\mathcal{N} = 1$ superpotential:

$$W = \int G_3 \wedge \Omega \qquad (G_3 = F_3 - \tau H_3)$$

Does not depend on Kähler moduli!

- F-term conditions

complex structure + axio-dilaton: $D_i W = 0 \Rightarrow \star\, G_3 = i G_3$

Kähler moduli: $D_\alpha W \sim W \Rightarrow$ SUSY broken unless $W = 0$

- Resolution: non-perturbative quantum corrections:

$$W = \int G_3 \wedge \Omega + \sum_{\mathbf{k}} \mathcal{A}_{\mathbf{k}}(z^i, G_3)\; e^{-2\pi k^\alpha T_\alpha}$$

Kähler moduli

→ W depends on Kähler moduli!

KKLT: ADS VACUUM

[Kachru, Kallosh, Linde, Trivedi '03]

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

- Supersymmetry conditions:

$$\textit{(for all moduli)} \qquad D_a W = 0$$

Notice:

Existence of classical flux vacuum does not guarantee existence of KKLT AdS vacuum!

- Supersymmetric AdS vacuum:

$$\Lambda_{AdS} = \langle V \rangle = -3 \left(e^K |W|^2 \right) \Big|_{D_a W = 0}$$

control over instanton expansion:

$$\left| e^{-2\pi k^\alpha T_\alpha} \right| \ll 1$$

$\longrightarrow$

controlled uplift to dS only possible if

$$\Lambda_{AdS} \ll 1$$

M-THEORY / F-THEORY

- M-theory on Calabi-Yau 4-fold (from 11D to 3D)

$h^{3,1}$ complex str. moduli (volumes of 4-cycles) $\longrightarrow$ stabilized by $G_4 \neq 0$ (4-form flux)

- Classical superpotential [Gukov, Vafa, Witten '99]:

$$W \sim \int_{CY_4} G_4 \wedge \Omega$$

- Non perturbative corrections:

$$W = \int G_4 \wedge \Omega + \sum_{\mathbf{k}} \mathscr{A}_{\mathbf{k}}(z^i, G_4)\ e^{-2\pi k^\alpha T_\alpha}$$

M-THEORY / F-THEORY

- classical flux vacua:

$$D_i W = \int G_4 \wedge \chi_i = 0 \quad \Rightarrow \quad G_4 = \star\, G_4$$

$$G_4 \in H^{4,0} \oplus H^{2,2}_{+} \oplus H^{0,4}$$

- KKLT like AdS vacua:

balance
- $G_4^{4,0} \neq 0$
- non-pert. corrections

$$\langle V \rangle = -4 \left(e^K |W|^2 \right) \Big|_{D_a W = 0} < 0$$

- Tadpole cancellation [Becker, Becker '96; Sethi, Vafa, Witten '96]:

$$N_{M2} + \frac{1}{2} \int_{CY_4} G_4 \wedge G_4 = \frac{\chi(CY_4)}{24}$$

$\chi(CY_4)$: Euler number of CY 4-fold

(F-theory: encodes IIB D7-charges)

A FIRST PUZZLE:

DOMAIN WALLS AND THE GVW POTENTIAL

FLUXES AND DUAL BRANES

[Gukov, Vafa, Witten '99]

- Idea: M5-branes on 4-cycle: G_4 flux (+ #M2-branes) jumps
- Consider two different flux vacua with $G_4 = G_A$ and $G_4 = G_B$ on the same CY (+ different numbers of M2-branes).
- M5 brane on 4-cycle C dual to $[G_A - G_B]$

→ *domain wall interpolating between the two vacua*

$$\text{Tension:} \qquad T \sim \int_C \Omega = \int \Omega \wedge (G_A - G_B)$$

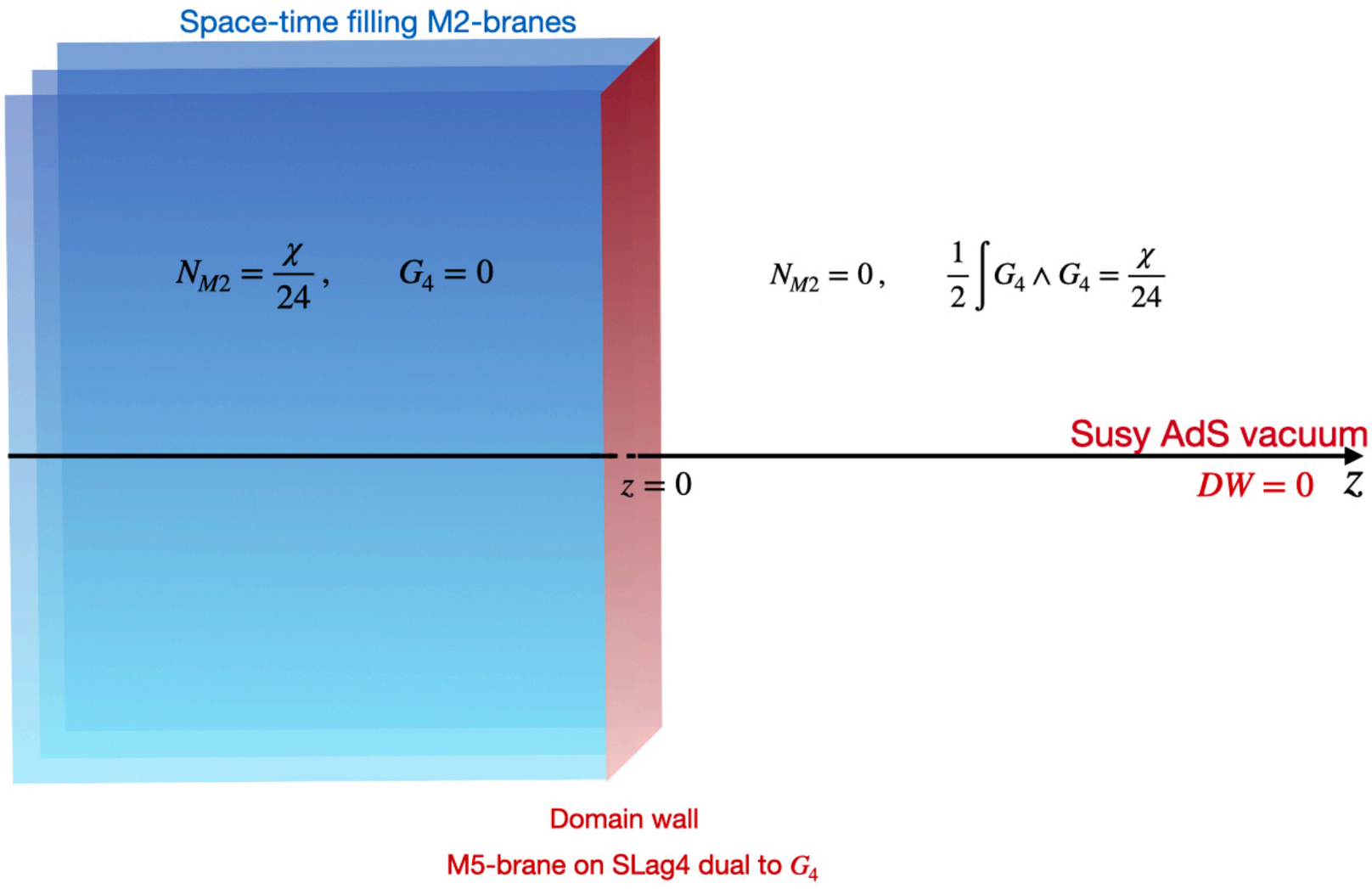
- Supergravity: Crossing of domain wall → W jumps:

$$\Delta W \sim T \qquad \Rightarrow \qquad W \sim \int \Omega \wedge G_4$$

GENERATING M5 BRANES

Extremal case: $G_B = 0$

$\rightarrow$ M5-brane on cycle dual to G_A:



BPS DOMAIN WALLS IN 3D SUPERGRAVITY

[Cvetic, Griffies, Rey '92]

see also: [Bandos, Farakos, Lanza, Martucci, Sorokin '18]
[Lanza, Marchesano, Martucci, Valenzuela '20]

- Metric ansatz:

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

- Tension:

SUGRA central charge: $|Z| = e^{K/2}|W|$

- attractor flow equations:

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

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

(compare with BPS black hole attractors!)

[Kallosh '05]

End point of the flow ($z \to \pm\infty$):

$$\partial_a|Z| = 0 \quad \Rightarrow \quad D_aW = 0$$

→ asymptotic AdS vacuum

SLAG CYCLES AND SELF DUAL FLUXES

➤ M5 branes: only supersymmetric on calibrated cycles!

classical calibration conditions:

$$J\big|_C = 0 \qquad \text{Im}\left(e^{i\alpha}\Omega\right)\big|_C = 0$$

"Lagrangian" *"special"*

→ *special Lagrangian "SLag"*

NB: "special Lagrangian":
property of submanifolds, i.e. cycle representatives!

➤ Slag representatives exist if

$$|Z| = \frac{\left|\int_C \Omega\right|}{\left(\int \Omega \wedge \overline{\Omega}\right)^{\frac{1}{2}}}$$ has an extremum

SLAG CYCLES AND SELF DUAL FLUXES (2)

- attractor flow and F-term conditions:

$$\partial_a \left|Z\right| = 0 \quad \overset{Z \neq 0}{\Leftrightarrow} \quad D_a W = 0$$

SLag representatives:
critical point is not enough!

need extremum of $\left|Z\right|$*!*

F-term minimum:
critical point sufficient

→ not every choice of self-dual fluxes is dual to a SLag cycle!

Example: "perturbatively flat" vacua by [Demirtas, Kim, McAllister, Moritz '19]

QUANTUM CORRECTED TENSION

- M5-brane tension: $|Z| = e^{K/2}\,|W|$
  same non-perturbative corrections as flux-superpotential

$$W = \int \Omega \wedge G_4 + \sum_{\mathbf{k}} \mathscr{A}_{\mathbf{k}}(z^i, G_4)\; e^{-2\pi k^\alpha T_\alpha}$$

→ attractor flow for complex structure + Kähler moduli

- also: correction of calibration conditions?!

KKLT assumption:
effect of corrections very small!

- However: existence of Slag representatives & BPS states:

topological properties ⟶ *no SUSY M5 branes on cycles without Slag representatives also at quantum level*

POSSIBLE RESOLUTIONS

Puzzle: not every choice of self-dual fluxes is dual to a SLag cycle!

Resolutions:

1. Quantum corrections modify calibration condition
   → supersymmetric branes without slag cycles?

2. Not every KKLT AdS vacuum
   generated by supersymmetric M5-brane domain walls?

3. Fluxes without dual slag cycles:
   no stable KKLT AdS vacua!

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HOLOGRAPHY AND KKLT

HOLOGRAPHIC PERSPECTIVE

➤ first step of KKLT requires

AdS vacuum with

$$\Lambda_{AdS} \ll 1$$

(consistency of EFT: $\Lambda_{AdS} \ll m_{KK}^2 \rightarrow$ scale separation)

➤ Is there a holographically dual CFT?

AdS/CFT duality:

$$\left|\Lambda_{AdS}\right| \sim \frac{1}{c}$$

central charge

(# degrees of freedom of CFT)

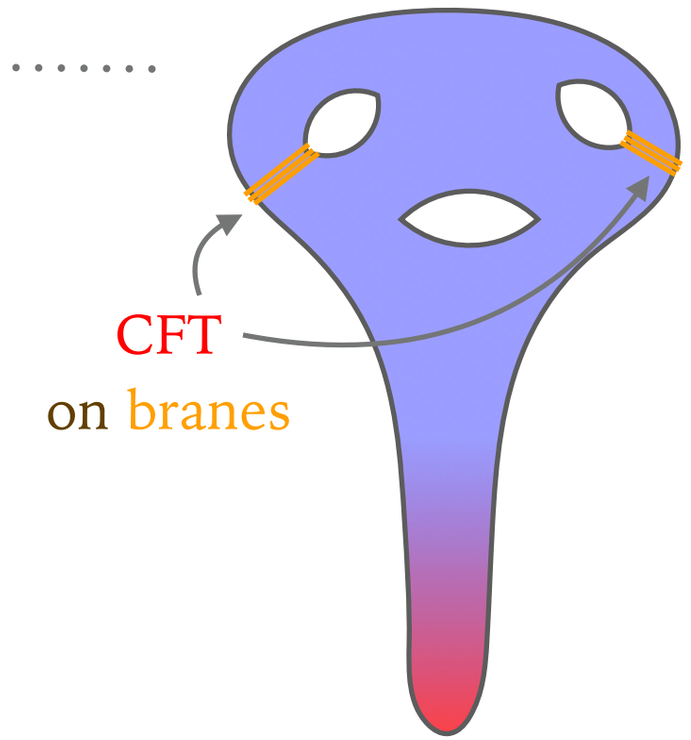
➡ Dual CFT must have $c \gg 1$

HOLOGRAPHICALLY DUAL BRANE THEORIES

[Silverstein '03]
[Kounnas, Lüst, Petropoulos, Tsimpis '07]
[SL, Vafa, Wiesner, Xu '22]

Conventional Holography:

Dualize Fluxes into Branes ⟶ *brane world volume theory flows to CFT*



- IIB with G_3 flux (KKLT):

D5 & NS5 branes ⟶ on special Lagrangian 3-cycles of CY_3 ⟶ SCFT in $d = 3$, $\mathcal{N} = 1$

- M-theory with G_4 flux (F-theory):

M5 branes ⟶ on special Lagrangian 4-cycles of CY_4 ⟶ SCFT in $d = 2$, $\mathcal{N} = (1,1)$

COUNTING DEGREES OF FREEDOM

[SL, Vafa, Wiesner, Xu '22]

- Brane world volume theory

UV: *supersymmetric but in general no CFT* —*RG-flow*→ *IR:* *supersymmetric CFT*

- c-theorem:

$$c_{UV} > c_{IR}$$

- AdS/CFT:

$$c_{IR} \sim \left|\Lambda_{AdS}\right|^{-1}$$

- Goal: Count degrees of freedom in UV

Determine c_{UV} for M5 branes on special Lagrangian cycle ⟶ *lower bound on Λ_{AdS}*

COUNTING DEGREES OF FREEDOM (2)

[SL, Vafa, Wiesner, Xu '22]

- M5 branes on special Lagrangian cycle L_4

parametric growth: $L_4 \to NL_4$ ⟶ *How does c_{UV} scale with N?*

- M5 brane world volume theory:

reduction of six-dim. $\mathcal{N} = (2,0)$ theory on L_4 ⟶ two-dimensional $\mathcal{N} = (1,1)$ theory

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

χ: Euler number

b_n: Betti numbers of L_4

COUNTING DEGREES OF FREEDOM (3)

[SL, Vafa, Wiesner, Xu '22]

- UV central charge:

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

- Self intersection of L_4: $\chi(L_4) = L_4 \cdot L_4$

$$c_{UV} = \frac{3}{2}\left(L_4 \cdot L_4 + 4b_1\right) \quad \Rightarrow \quad c_{UV} \propto N^2 \text{ for } L_4 \to NL_4$$

- Relation with Tadpole Condition:

$$\frac{1}{2} L_4 \cdot L_4 = \frac{1}{2}\int_{CY_4} G_4 \wedge G_4 \leq \frac{\chi(CY_4)}{24} \quad \Rightarrow \quad \boxed{c_{IR} \lesssim \beta\, \chi(CY_4)}$$

CONSEQUENCES

[SL, Vafa, Wiesner, Xu '22]

➤ central charge bounded by tadpole condition:

$$\Lambda_{AdS} \gtrsim \frac{1}{\chi(CY_4)}$$

Euler number:

$$\chi(CY_4) = 6(8 + h^{1,1} + h^{3,1} - h^{2,1})$$

(see also "tadpole conjecture" [Bena, Blåbäck, Graña, SL '20])

➤ effective cutoff in gravitational theories with N light d.o.f.

[Dvali '07]

species scale: $\Lambda_{species} \sim \frac{1}{N}$

Here:

$N \sim \chi(CY_4)$

$$\Rightarrow \quad \Lambda_{AdS} \gtrsim \Lambda_{\text{species}}$$

AdS scale is above cutoff of the EFT!

→ no sensible EFT description!

(see also [Blumenhagen, Gligovic, Kaddachi '22])

CONCLUSIONS

- Supersymmetric domain walls:

calibration condition (slag)
stronger than self-duality condition on fluxes

- Holography:

counting d.o.f. of M5-brane CFT:

$$\left|\Lambda_{AdS}\right| > \left(N_{moduli}\right)^{-1}$$

- comparison with species scale:

$$\Lambda_{AdS} \gtrsim \Lambda_{EFT} \longrightarrow$$

no scale separated KKLT like AdS vacua

THANK YOU!