HOLOGRAPHY AND KKLT

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

[2410.22400] with I. Bena and Y. Li

Severin Lüst

CNRS / Laboratoire Charles Coulomb
(Montpellier, France)

GRAVITY, STRING AND SUPERSYMMETRY BREAKING

Scuola Normale Superiore
Pisa, April 04, 2025

CHALLENGES FOR STRING PHENOMENOLOGY

Issues from compactification:

1. Deformations of compactification space

→ lots of massless scalar fields (moduli)
(Dine-Seiberg-like control issues)

2. Natural: AdS or Minkowski ($\Lambda \leq 0$)

de Sitter vacua ($\Lambda > 0$): extremely difficult

(Conjecture: no (long lived) de Sitter in Quantum Gravity [Vafa et al. '18, '19])

[Kachru, Kallosh, Linde, Trivedi '03]

CONTROLLED STRING THEORY DE SITTER VACUA

KKLT scenario: two step procedure:

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

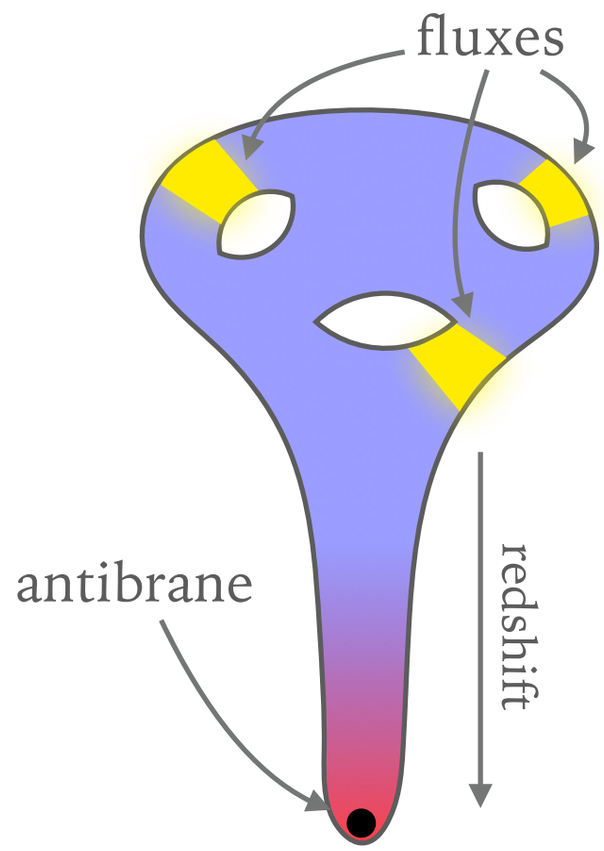
$$\rightarrow \text{SUSY vacuum with}$$

$$\Lambda < 0 \text{ (AdS)}$$

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

$$\rightarrow \text{broken SUSY and}$$

$$\Lambda > 0$$



[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

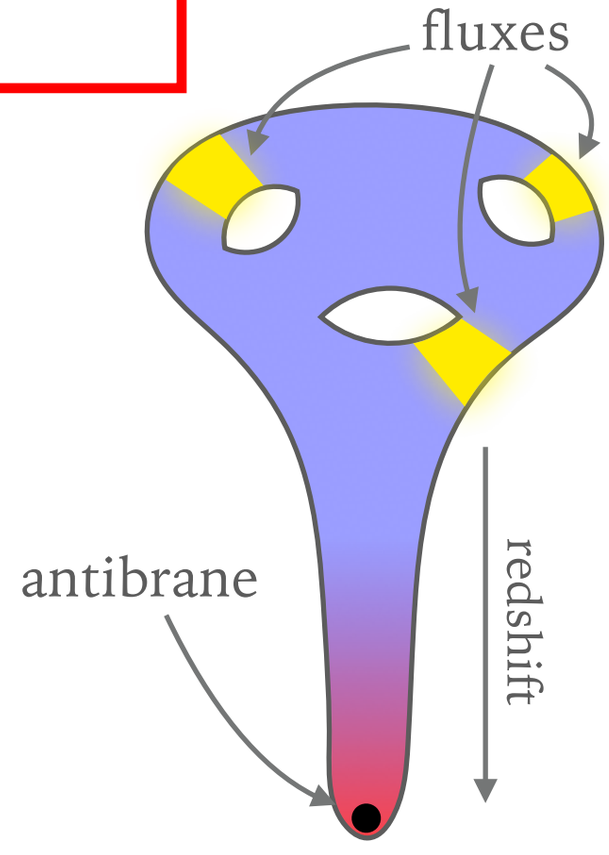
$$\rightarrow \text{SUSY vacuum with}$$

$$\Lambda < 0 \text{ (AdS)}$$

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 (orientifolds):

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

➥ 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: $D_\alpha W \sim W$ ⇒ 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:

(for all moduli) $D_a W = 0$

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:

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

⟶

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)

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:

➡ Dual CFT must have $c \gg 1$

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)

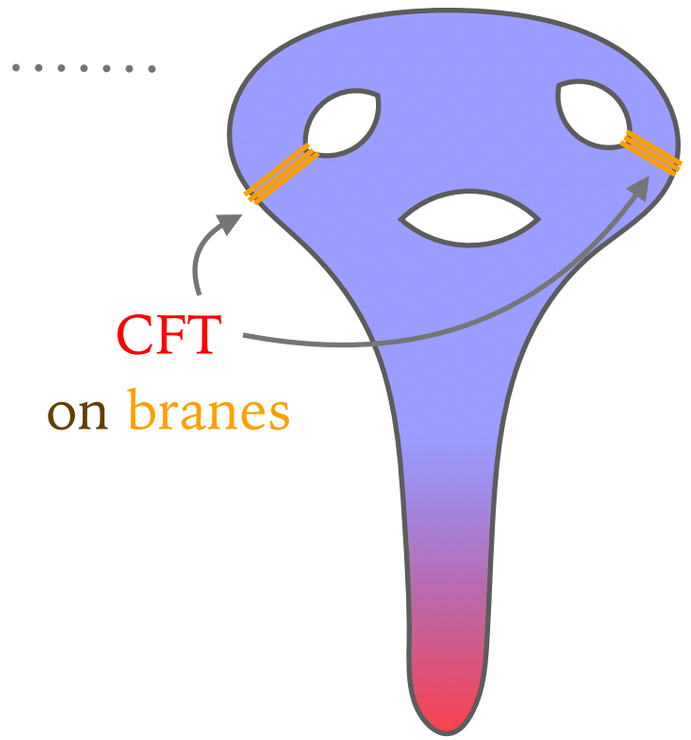
➡ Dual CFT must have $c \gg 1$

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 $d = 2$, $\mathcal{N} = (1,1)$

FLUXES AND DUAL BRANES

- 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 $[G_A - G_B]$ [Gukov, Vafa, Witten '99]

→ Domain Wall

interpolating between the two vacua

- Extremal case: $G_B = 0$

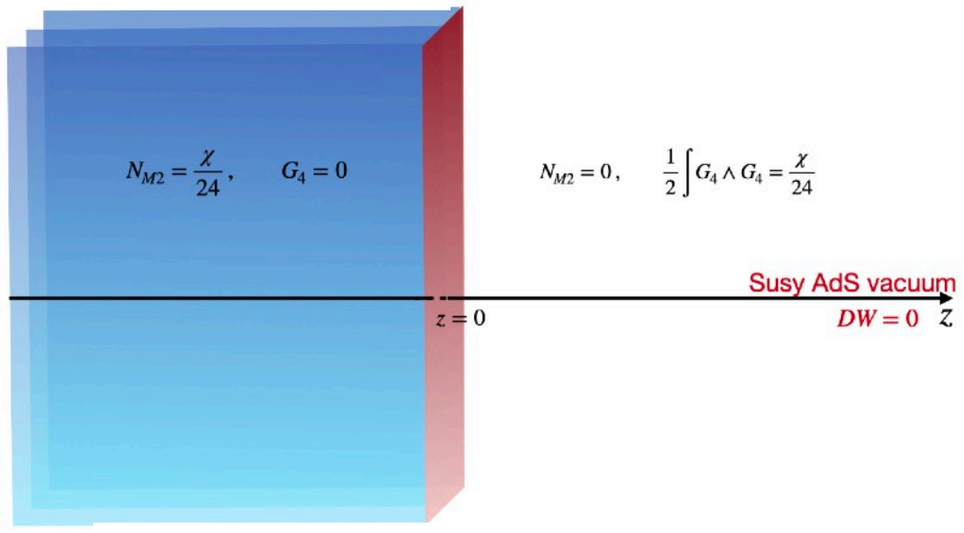
[SL, Vafa, Wiesner, Xu '22]
[Bena, Li, SL '24]

$W_{\text{GVW}} = 0$

existence of minimum at finite CY-volume unclear

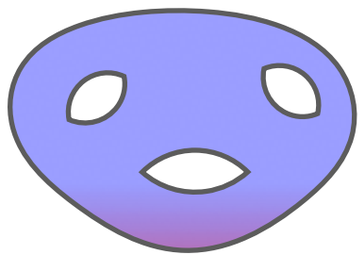
??

Space-time filling M2-branes



M5-brane on SLag4 dual to G_A

KKLT AdS-vacuum



$|\Lambda| \ll 1$

TOPOLOGICAL COUNT OF DEGREES OF FREEDOM

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:

➤ 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

[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 brane on sLag cycle L_4: world volume theory:

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

self-intersection of L_4

$$\textit{count moduli of } L_4 \quad \Rightarrow \quad c_{UV} = \frac{3}{2}(2 + b_2^+ + b_2^- + 2b_1) \lesssim \alpha\, L_4 \cdot L_4$$

b_n: *Betti numbers of* L_4

- Relation with Tadpole Condition:

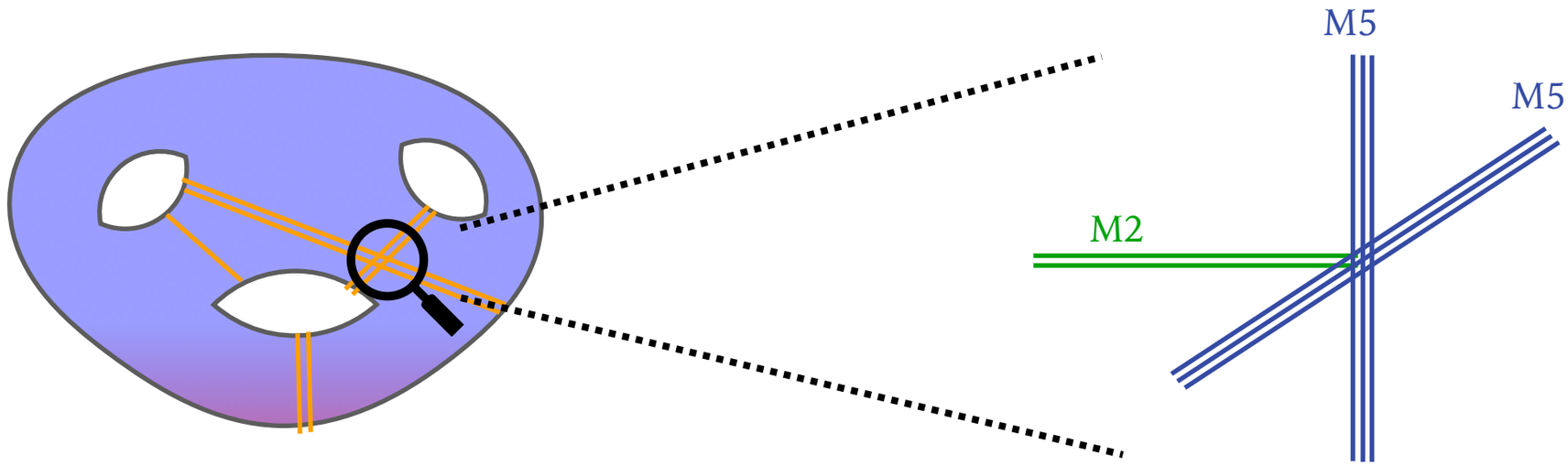
$$\frac{1}{2} L_4 \cdot L_4 = \frac{1}{2}\int_{CY_4} G_4 \wedge G_4 \leq \frac{\chi(CY_4)}{24} \quad \Rightarrow \quad \boxed{c_{IR} \lesssim \beta\, \chi(CY_4)}$$

DEGREES OF FREEDOM IN SUPERGRAVITY

COUNTING OF DEGREES OF FREEDOM IN SUPERGRAVITY

[Bena, Li, SL '24]

- Most degrees of freedom are localized at brane intersections:



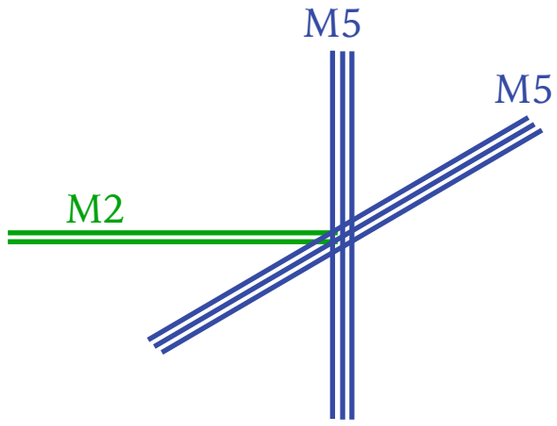
- Local description: Intersecting branes in flat space

- Goal: Find supergravity solution and count degrees of freedom holographically

INTERSECTING BRANES IN SUPERGRAVITY

- Local brane setup:

	t	y	z	1	2	3	4	5	6	7	8
M5	x	x		x	x	x	x				
M5	x	x						x	x	x	x
M2	x	x	x								



- Supergravity solution in the near horizon limit:

$$ds_{11}^2 = \underbrace{\left(\frac{u}{l_{\text{AdS}}}\right)(-dt^2 + dy^2) + \left(\frac{l_{\text{AdS}}}{u^2}\right)^2 du^2}_{\text{AdS}_3} + \underbrace{(n_T n_F)^{\frac{1}{3}} \left(d\Omega^2 + d\Omega'^2\right)}_{S^3 \times S^3} + \underbrace{d\lambda^2 + \left(\frac{n_F^2}{n_T}\right)^{\frac{2}{3}} dz^2}_{\mathbb{R}^2}$$

$$\textit{with} \quad l_{\text{AdS}} = \frac{1}{\sqrt{2}} (n_T n_F)^{\frac{1}{6}}$$

[de Boer, Pasquinucci, Skenderis '99]

HOLOGRAPHIC CENTRAL CHARGE

[Bena, Li, SL '24]

- Normalization of brane charges:

compactify formally

$$\mathbb{R}^2 \to S_\lambda \times S_z$$

with radii: R_λ, R_z

(later: $R_\lambda, R_z \to \infty$*)*

$$N_5 = \frac{1}{(2\pi)^3} \int_{S_z \times S^3} G_4 = R_z\, n_F$$

$$N_2 = \frac{1}{(2\pi)^6} \int_{S_\lambda \times S^3 \times S^3} \left(\star G_4 - \frac{1}{2} C_3 \wedge G_4\right) = \frac{\sqrt{2}}{4\pi} R_\lambda \left(n_T n_F\right)^{\frac{5}{6}}$$

- Central charge of dual CFT_2:

$$l_{\mathrm{AdS}_3} = \frac{1}{\sqrt{2}} \left(n_T n_F\right)^{\frac{1}{6}}$$

Tadpole cancellation:

$$N_2 = \frac{\chi(CY_4)}{24} \sim N_5^2$$

$$c = \frac{3}{2} \frac{l_{\mathrm{AdS}_3}}{G_{\mathrm{N}}^{(3)}} = 3 N_2 N_5 \sim N_5^3$$

$$\frac{1}{G_{\mathrm{N}}^{(3)}} = \mathrm{vol}\left(S^3 \times S^3 \times S_\lambda \times S_z\right) \sim R_z R_\lambda \left(n_T n_F\right)^{\frac{2}{3}} n_T$$

- Generic situation: branes intersect at many points:

each intersection:

$$c \sim \mathcal{O}(1)$$

$\times$ *#intersections:* N_5^2

$$c \sim N_5^2 \sim \chi(CY_4)$$

IIB: INTERSECTING D5 / NS5 BRANES ON CY3-ORIENTIFOLDS

[Bena, Li, SL '24]
(see Iosif's talk)

- Local brane setup:

	t	x	y	z	1	2	3	4	5	6
D5	x	x	x		x	x	x			
NS5	x	x	x					x	x	x
D3	x	x	x	x						

- Near brane geometry:

[D'Hoker, Estes, Gutperle '07 (2x)]
[Aharony, Berdichevsky, Berkooz, Shamir '11]
[Assel, Bachas, Estes, Gomis '11]

$$AdS_4 \times_w S^2 \times S^2 \times \Sigma_2$$

Riemann surface

- Scaling of central charge:

$$c \sim \frac{l_{AdS_4}}{G_N^{(4)}} \sim \left(N_{D5} N_{NS5}\right)^2$$

CONSEQUENCES FOR KKLT

CONSEQUENCES

[SL, Vafa, Wiesner, Xu '22]

- central charge bounded by tadpole condition:

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

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!

CONCLUSIONS

- Holographic dual to KKLT AdS vacua:

world-volume SCFT of
M5 (M-theory) / D5-NS5 (IIB) branes

- 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!