DIPARTIMENTO
DI FISICA
E ASTRONOMIA
Galileo Galilei

Anti-branes in string compactifications

Luca Martucci

- Recent swampland conjectures imply no de Sitter vacua in string theory!

[Obied, Ooguri, Spodyneiko, Vafa `18]

[Dvali, Gomez `18]

[Ooguri, Palti, Shiu, Vafa `18]

- Popular KKLT-like de Sitter models:

  * combines 10d and 4d EFT arguments
  * crucially involves anti-branes

Is there anything WRONG?

- In this talk:

  * 4d EFTs for anti-brane goldstino

    [Bandos-LM-Sorokin-Tonin`16]

    [Bandos-Heller-Kuzenko-LM-Sorokin`16]

  * KKLT from 10d

[Koerber, L.M. `08]

[Baumann, Dymarsky, Kachru, Klebanov, McAllister `10]

[Dymarsky, L.M. `10]

[Moriz, Retolaza Westaphal `17]

[Hamada, Hebecker, Shiu, Soler `18-`19]

[Kallosh `18]

[Carta, Moritz, Westphal `19]

[Gautason, Van Hemelryck, Van Riet, Venken `19]

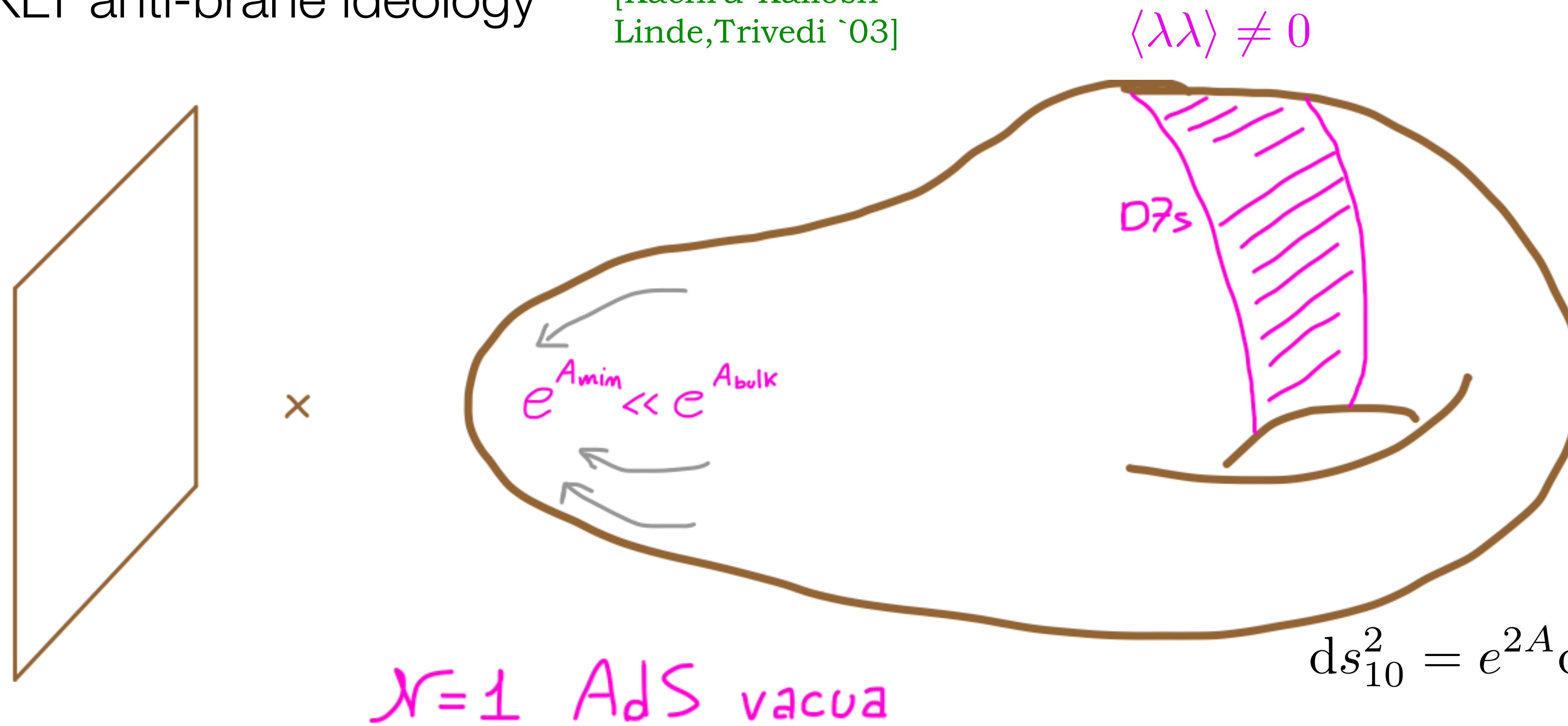
[Bena, Graña, Kovensky, Retolaza `19]

[Kachru, Kim, McAllister, Zimet `19]

Anti-branes, goldstino and EFTs

- KKLT anti-brane ideology

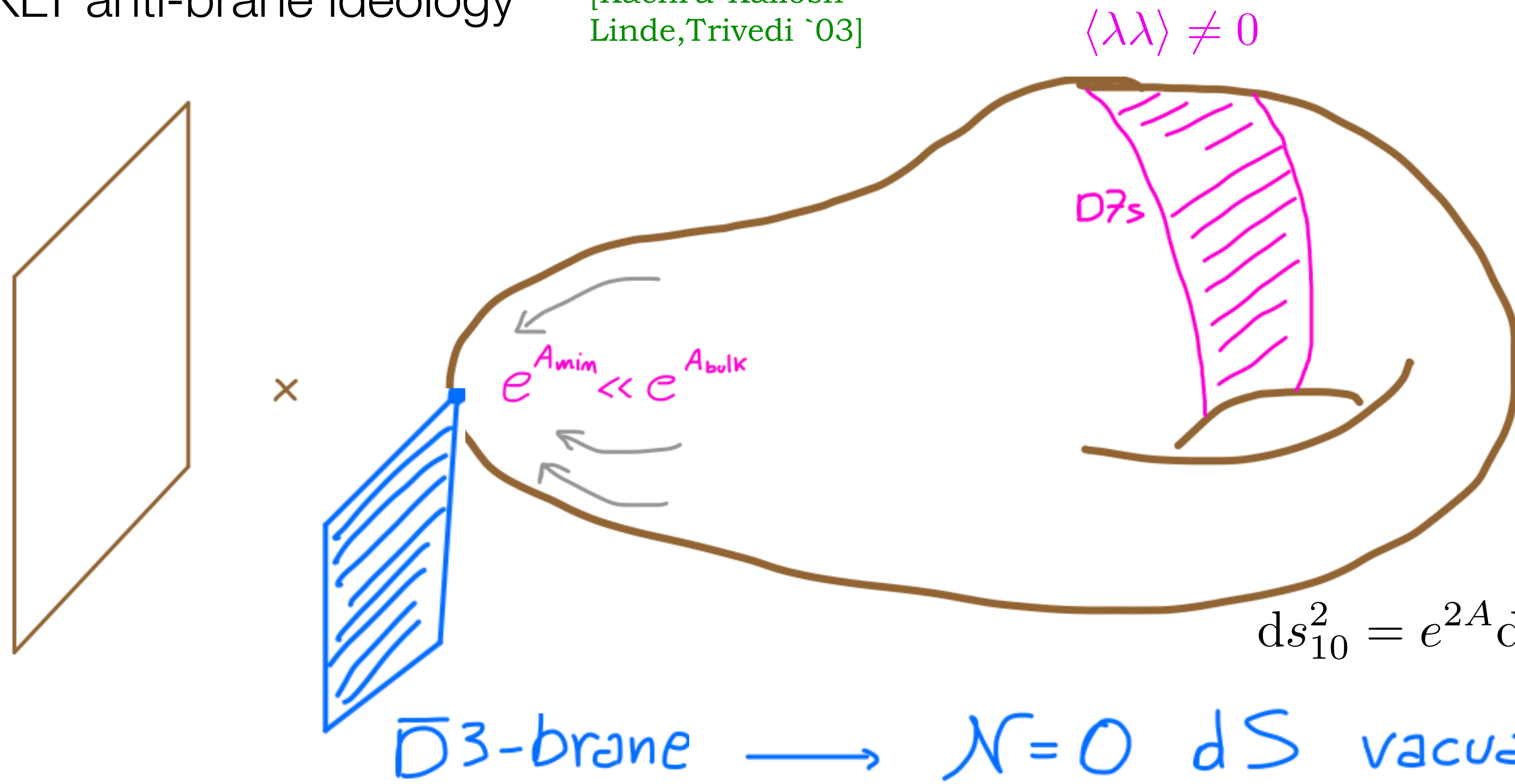
[Kachru-Kallosh-Linde,Trivedi `03]



$$\mathrm{d}s_{10}^2 = e^{2A}\mathrm{d}s_4^2 + e^{-2A}\mathrm{d}s_6$$

KKLT anti-brane ideology

[Kachru-Kallosh-Linde,Trivedi `03]



$$\mathrm{d}s_{10}^2 = e^{2A}\mathrm{d}s_4^2 + e^{-2A}\mathrm{d}s_6$$

10d Q's		4d Q's	
16 locally preserved	⟶ KK	0	(hidden susy broken at Λ_{KK})
16 spont. broken at Λ_{st}	⟶ KK	4	non-lin. realized

- 4d EFT? by probe approach:

$$K = -3\log(\mathrm{Im}\,\rho)$$

$$W = W_0 + A\,e^{\frac{2\pi i\rho}{N}}$$

N=1 SUSY EFT

+

$$V_{\overline{D3}} = \frac{\mu^4}{(\mathrm{Im}\,\rho)^2}$$

KKL(MM)T \`03

[KKLT+ Maldacena & McAllister \`03]

- Non-linear realizations through nilpotent superfield $S^2 = 0$

$$K = -3\log(\mathrm{Im}\,\rho - S\bar{S})$$

$$W = W_0 + A\,e^{2\pi i\rho} + \mu^2 M_P S$$

$\longrightarrow$

$$V_{\overline{D3}} = \frac{\mu^4}{(\mathrm{Im}\,\rho)^2}$$

[Ferrara-Kallosh-Linde \`14]

(neglecting scalar and U(1) gauge field on $\overline{\mathrm{D3}}$)

- Does it support probe result? Not really!

  * basically any potential (and non-susy interaction) can be supersymmetrized!

- "Elementary" constrained superfields:

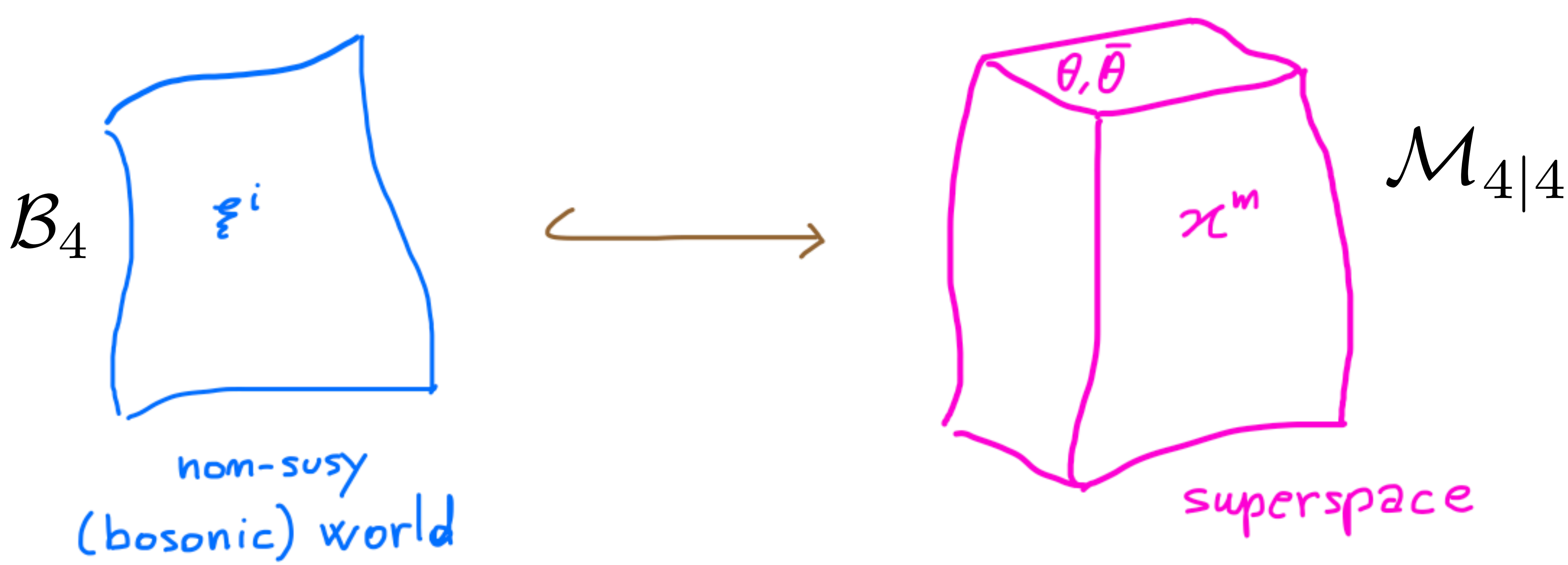
  natural EFT in 4d spontaneous SUSY-breaking

- Not the case in anti-brane models: alternative formulation?

  Goldstino brane

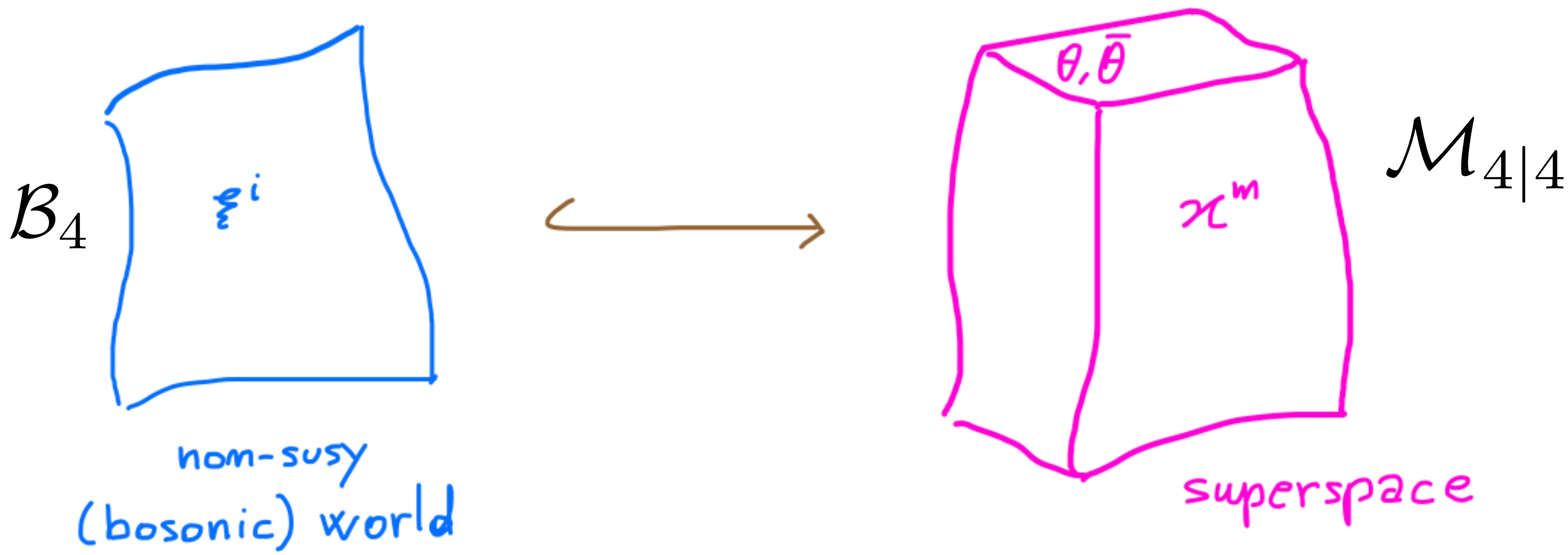
  [Bandos-LM-Sorokin-Tonin`16]
  [Bandos-Heller-Kuzenko-LM-Sorokin`16]

Goldstino Brane



- world-volume fields: $z^M(\xi) = (x^m(\xi), \theta^\alpha(\xi), \bar\theta_{\dot\alpha}(\xi))$
  - $\mathrm{Diff}(\mathcal{B}_4) \longrightarrow x^m(\xi)$ pure gauge
  - $\theta_\alpha(\xi) \longrightarrow$ Goldstino
- induced vielbein: $\mathbf{e}^a(\xi) = \partial_i z^M E_M{}^a(z(\xi))\mathrm{d}\xi^i$
- Simplest brane action: $S_{\mathrm{G}} = -f^2 \int_{\mathcal{B}_4} \mathrm{d}^4\xi \; \det \mathbf{e}(\xi)$ $\qquad [f] = (\mathrm{mass})^2$
  - $\mathrm{SDiff}(\mathcal{M}_{4|4})$ + local Lorentz $\longrightarrow$ (local) $\mathcal{N} = 1$

Goldstino Brane



- Simplest example: flat superspace

  * $E^a = \delta^a_m \mathrm{d}x^m + \mathrm{i}\theta\sigma^a \mathrm{d}\bar\theta - \mathrm{i}\mathrm{d}\theta\sigma^a\bar\theta$

  * static gauge: $x^m(\xi) = \delta^m_i \xi^i$

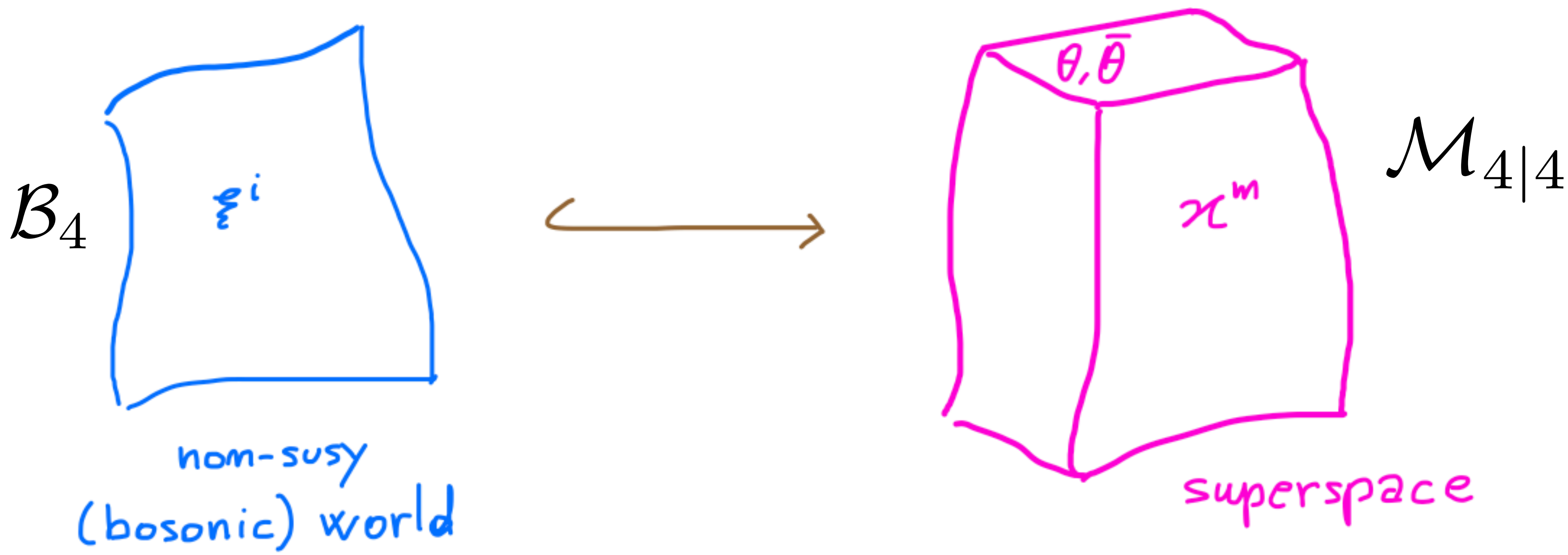
  * canonical goldstino: $\chi^\alpha(x) \equiv f\theta^\alpha(x)$

  * $\mathbf{e}^a = \delta^a_m \mathrm{d}x^m + \mathrm{i}\, f^{-2}\,(\chi\sigma^a \mathrm{d}\bar\chi - \mathrm{d}\chi\sigma^a\bar\chi)$

  * $S_{\mathrm{G}} = -f^2 \int_{\mathcal{B}_4} \mathrm{d}^4\xi \, \det \mathbf{e}(\xi) = -f^2 + \mathrm{i}\bar\chi\bar{\partial\!\!\!/}\chi + \ldots \equiv \mathcal{L}_{\mathrm{VA}}$

Volkov-Akulov goldstino action!

Goldstino Brane



- Coupling to supergravity immediate:

$$S = -3M_{\rm P}^2 \int {\rm d}^4x{\rm d}^4\theta\, E + 2\left(W_0 \int {\rm d}^4x{\rm d}^2\theta\,\mathcal{E} + {\rm c.c.}\right) - f^2 \int {\rm d}^4\xi \det \mathbf{e}(\xi)$$

$$= M_{\rm P}^2 \int {\rm d}^4x\sqrt{-g}\left(\frac{1}{2}R - \bar\psi_m\gamma^{mnp}\nabla_n\psi_p + W_0\,\bar\psi^R_m\gamma^{mn}\psi^{\rm R}_n + \dots\right) - \int {\rm d}^4x\sqrt{-g}\left(f^2 - \frac{3|W_0|^2}{M_{\rm P}^2}\right)$$

bulk

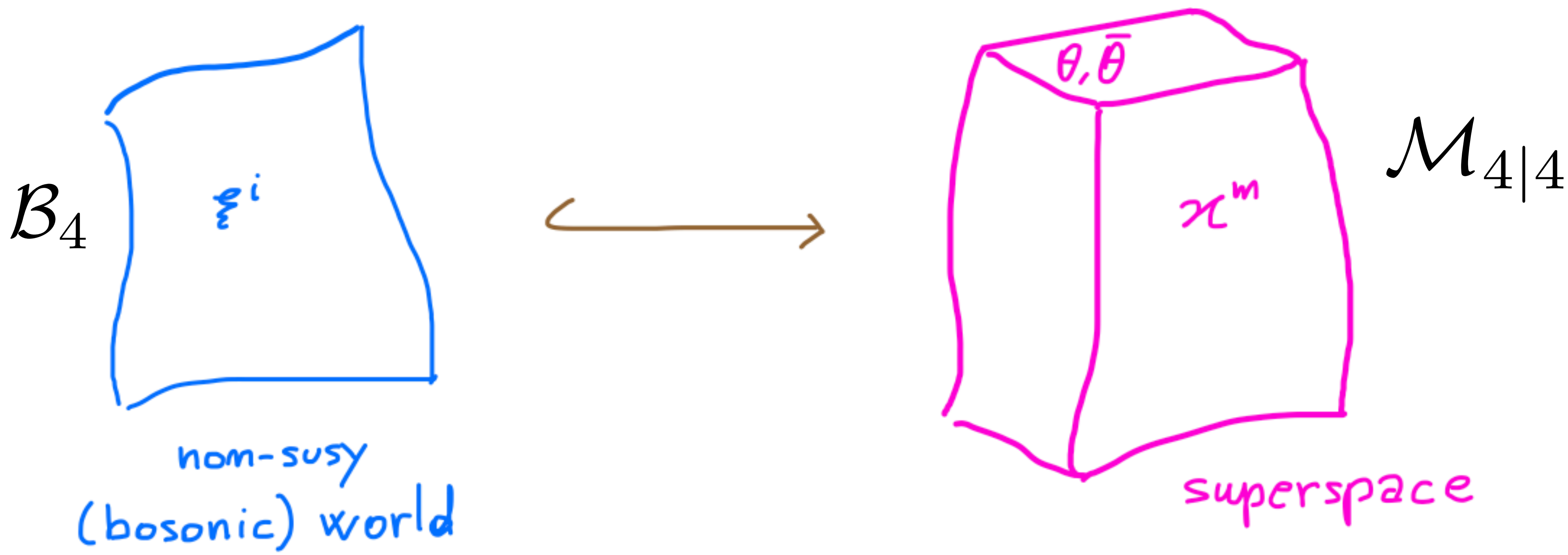
bulk WZ + static gauge

$\Lambda > 0$ if $f^2 > \frac{3|W_0|^2}{M_P^2}$

$$-\int\left(\bar\chi\nabla\!\!\!\!/\,\chi + f\bar\chi\gamma^m\psi_m + \frac{W_0}{M_{\rm P}^2}\bar\chi\chi + \dots\right)$$

brane

Goldstino Brane



- Coupling to NON-supersymmetric matter, e.g. world-volume scalar $\varphi(\xi)$:

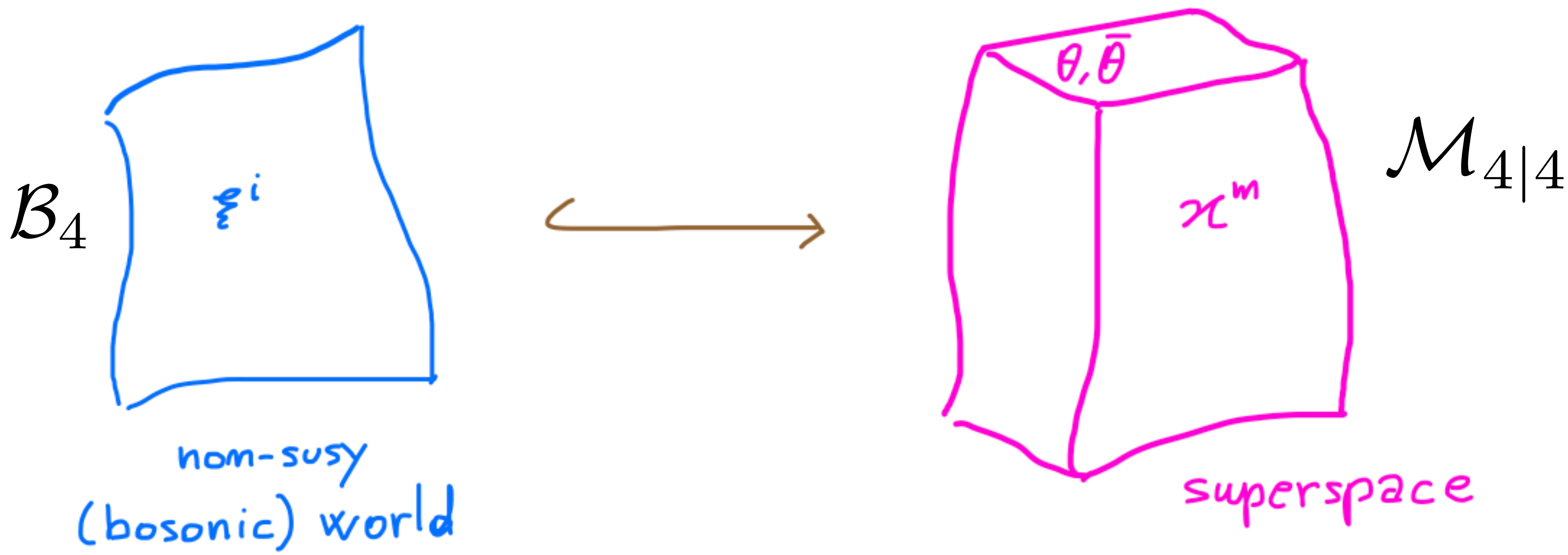
$$S = -\int \mathrm{d}^4\xi \, \det \mathbf{e}(\xi) \; \left(g^{ij}\partial_i\varphi\partial_j\varphi + V(\varphi)\right)$$

$$= -\int \mathrm{d}^4x\sqrt{-g}\;\left[g^{mn}\partial_m\varphi\partial_n\varphi + V(\varphi)\right] + (\text{goldstino+gravity multiplet})$$

bulK WZ
+ static gauge

can be applied to scalars and vector on
$\overline{\mathrm{D3}}$ in KKLT

Goldstino Brane



- Coupling to supersymmetric matter:

$$\Phi(z) = \phi(x) + \theta\psi(x) + \ldots \quad \longrightarrow \quad \Phi(z(\xi)) = \phi(x(\xi)) + f^{-1}\chi(\xi)\psi(x(\xi)) + \ldots$$

$$S_G = -\int V(\Phi(z(\xi)))\,\det \mathbf{e}(\xi)$$

E.g. $V_{\overline{D3}} = \dfrac{\mu^4}{(\mathrm{Im}\,\rho)^2}$ in KKLT

$$= \int \mathrm{d}^4x\sqrt{-g}\,V(\phi) + (\text{goldstino} + \text{gravity \& matter multiplets})$$

bulk WZ
+ static gauge

any potential can be directly supersymmetrized!

- Main point, so far: Goldstino brane as natural EFT for anti-branes

  * geometrizes (compensator) Stückelberg trick [Delacretaz-Gorbenko-Senatore `16]

  * manifest "brany" nature (GS-formulation)

  * natural coupling of brane non-susy and bulk susy matter

  * immediate generalization to $d \neq 4$ models

  application to Carlo's constructions?

- Nice… but a lot of freedom!

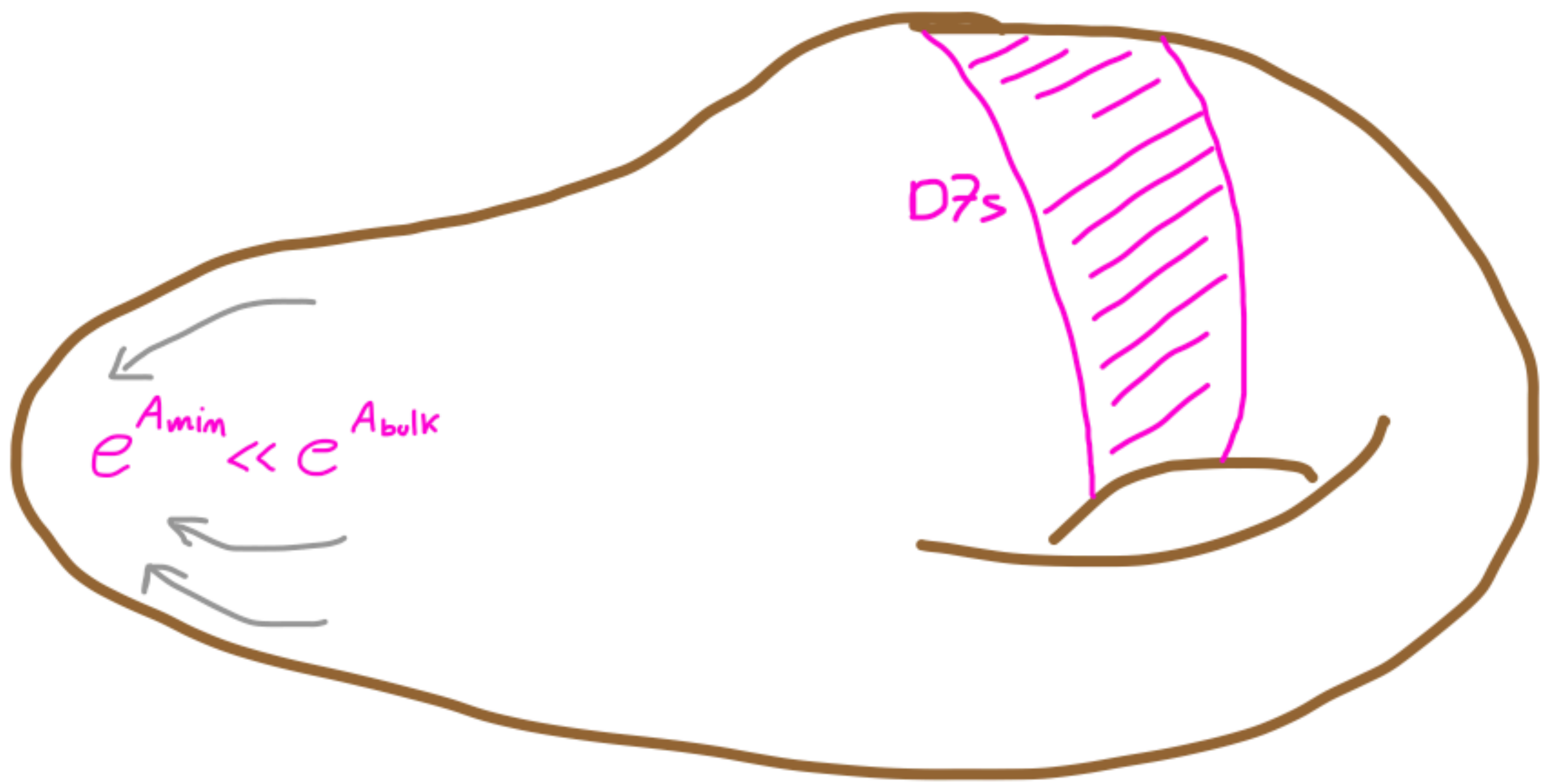
- Matching with UV-theory?

Back to string compactifications

The KKLT scenario

- Tree-level solution
  [Giddings-Kachru-Polchinski `01]

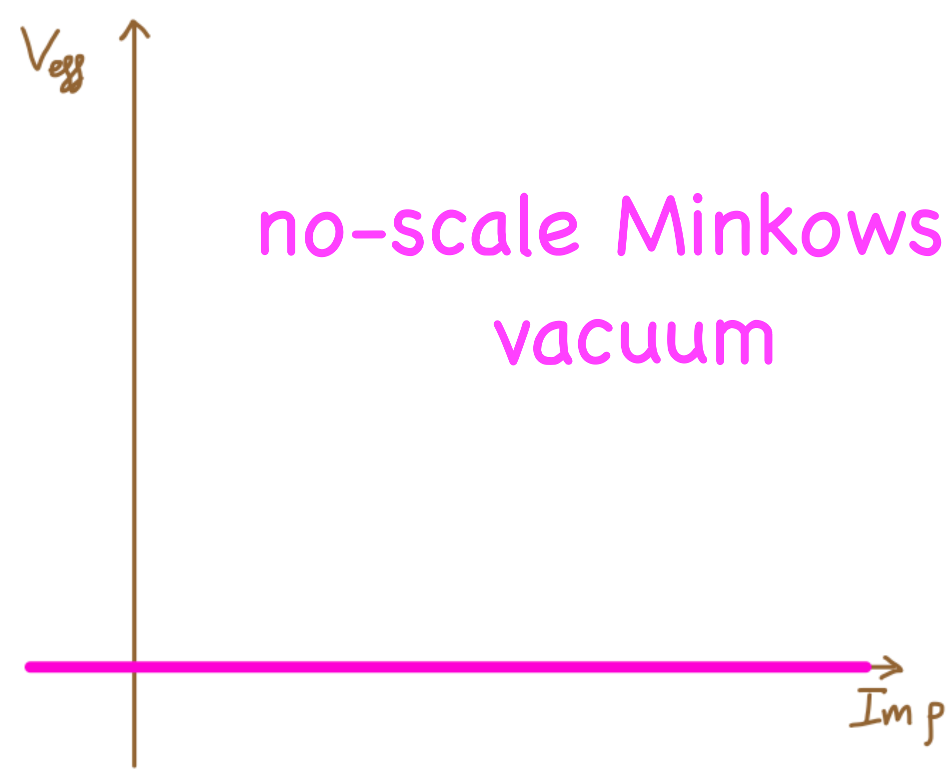
$$\mathrm{d}s_{10}^2 = e^{2A}\mathrm{d}s_4^2 + e^{-2A}\mathrm{d}s_6$$



- 4d EFT:

$$K = -3\log(\mathrm{Im}\,\rho)$$
$$W = W_0 = \int \Omega \wedge G_3$$

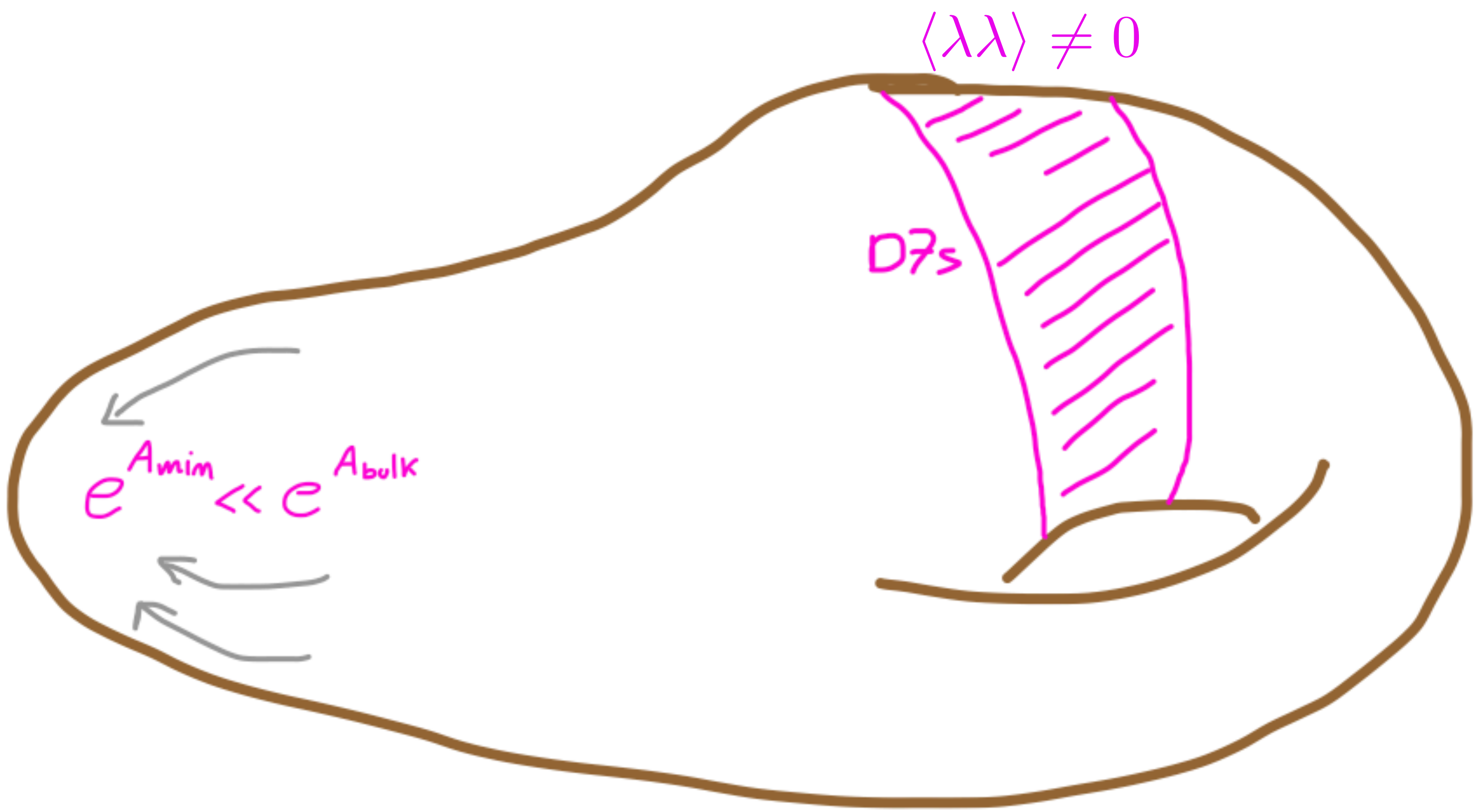
$\Longrightarrow$



The KKLT scenario

- Tree-level solution + gaugino condensate

$$ds^2_{10} = e^{2A} ds^2_4 + e^{-2A} ds_6$$



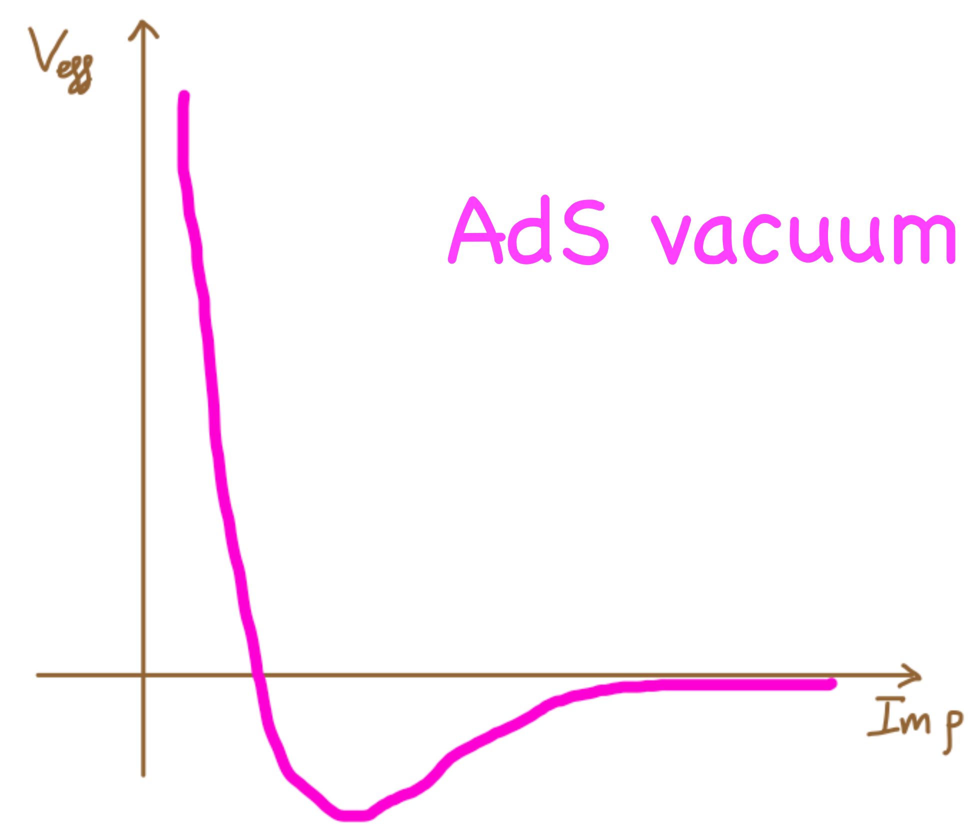
- 4d EFT:

$$K = -3\log(\mathrm{Im}\,\rho)$$

$$W = W_0 + \mathcal{A}\, e^{\frac{2\pi i \rho}{N}}$$

under control if: $\langle \mathrm{Im}\,\rho \rangle \sim \frac{2\pi}{N} \log \left| \frac{\mathcal{A}}{W_0} \right| \gg 1$

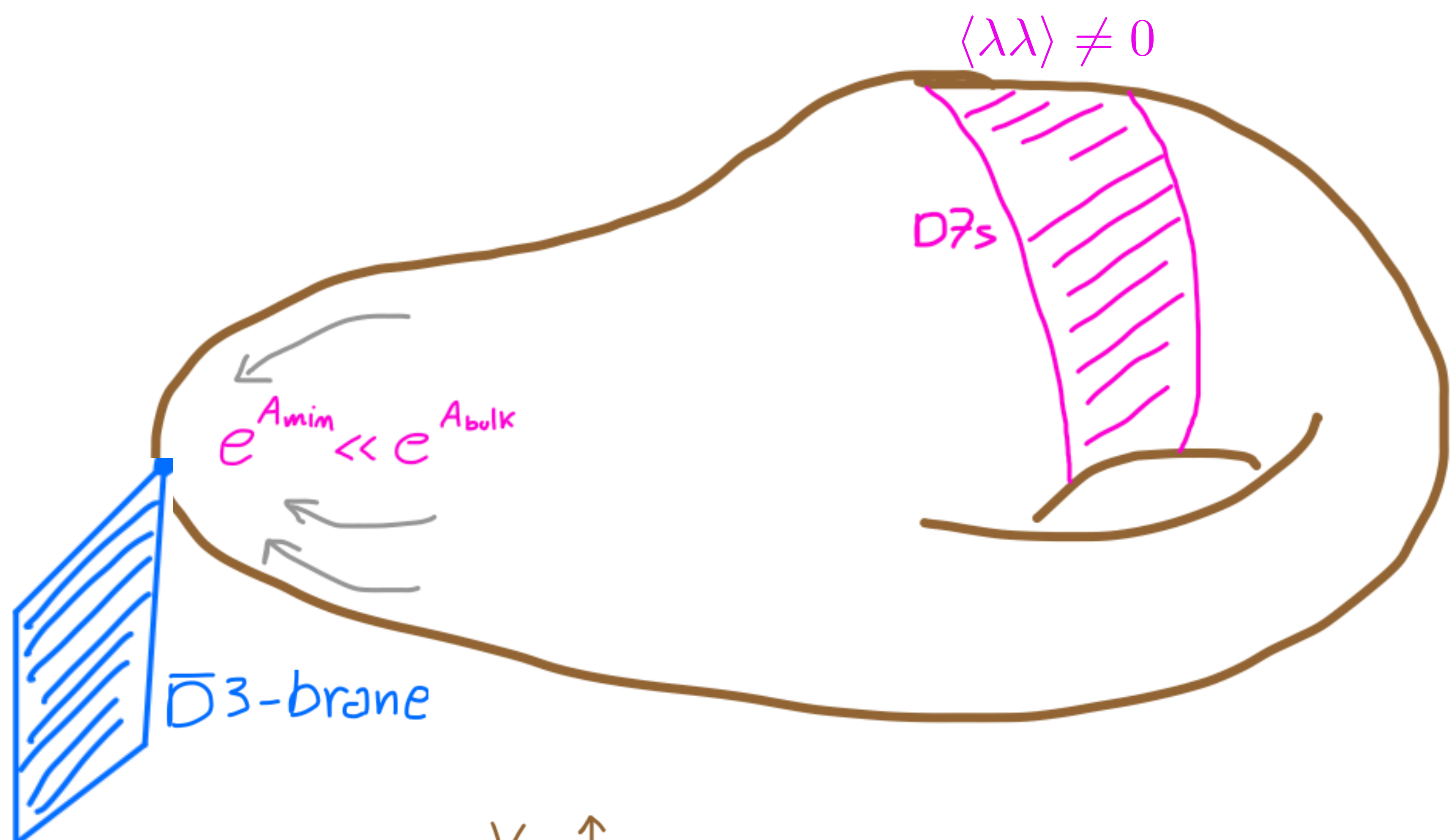
$$|W_0| \sim e^{-\frac{2\pi \langle \mathrm{Im}\,\rho \rangle}{N}} \ll 1 \quad \longrightarrow \quad |\langle V \rangle| \sim e^{-\frac{4\pi \langle \mathrm{Im}\,\rho \rangle}{N}} \ll 1$$



The KKLT scenario

- Tree-level solution + gaugino condensate+ anti-D3-brane

$$ds_{10}^2 = e^{2A} ds_4^2 + e^{-2A} ds_6$$

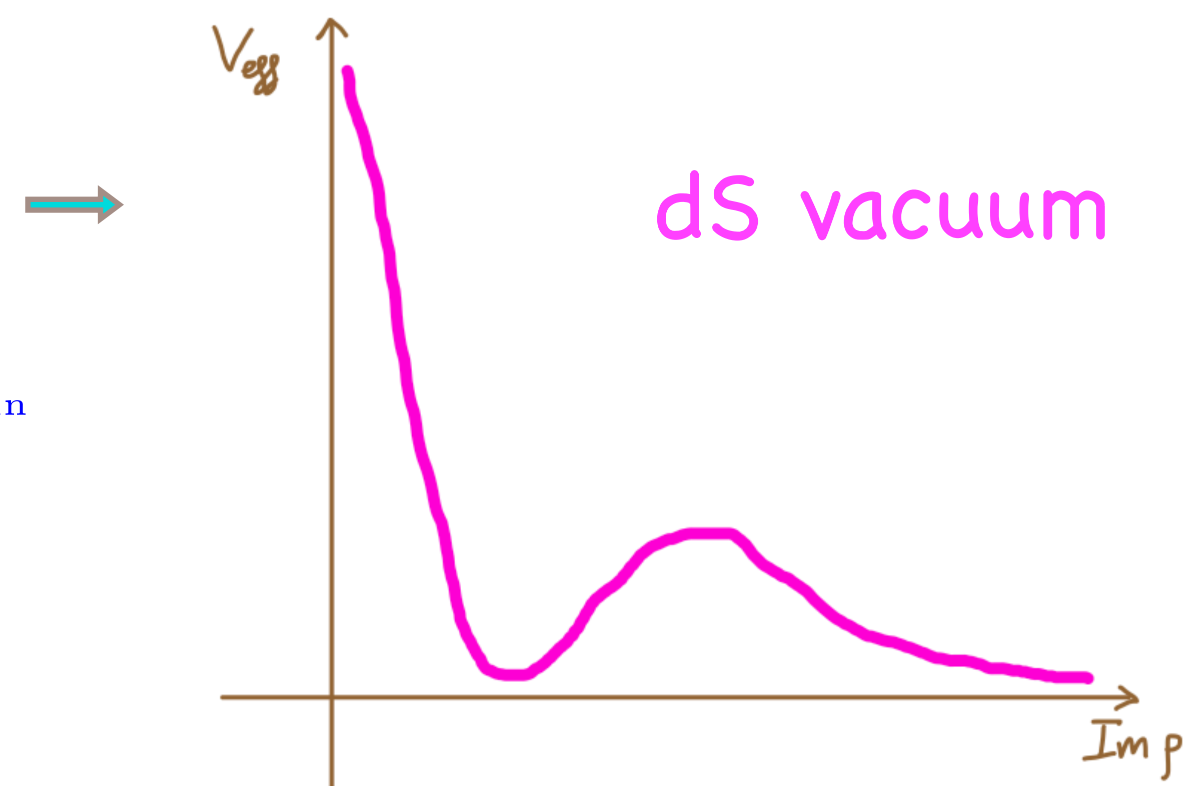


- 4d EFT: $K = -3\log(\mathrm{Im}\,\rho)$

$$W = W_0 + \mathcal{A}\, e^{\frac{2\pi i \rho}{N}}$$

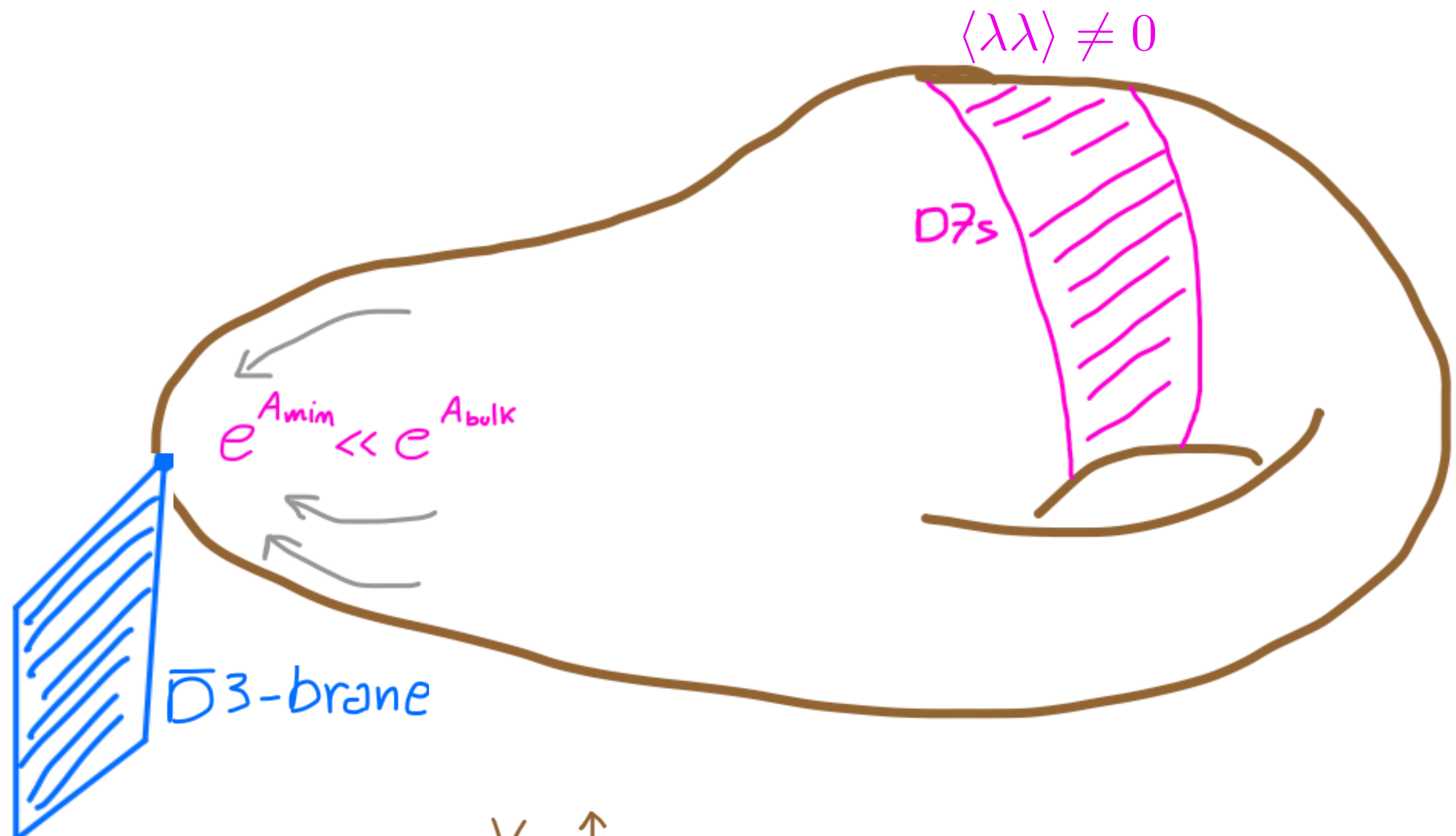
$$+\ V_{\overline{D3}} = \frac{\mu^4}{(\mathrm{Im}\,\rho)^2}\ ,\quad \mu^4 \propto e^{4A_{\min}}$$

under control if: $e^{4A_{\min}} \sim |W_0|^2 \ll 1$



The KKLT scenario

- Tree-level solution + gaugino condensate + anti-D3-brane



$$ds_{10}^2 = e^{2A} ds_4^2 + e^{-2A} ds_6$$

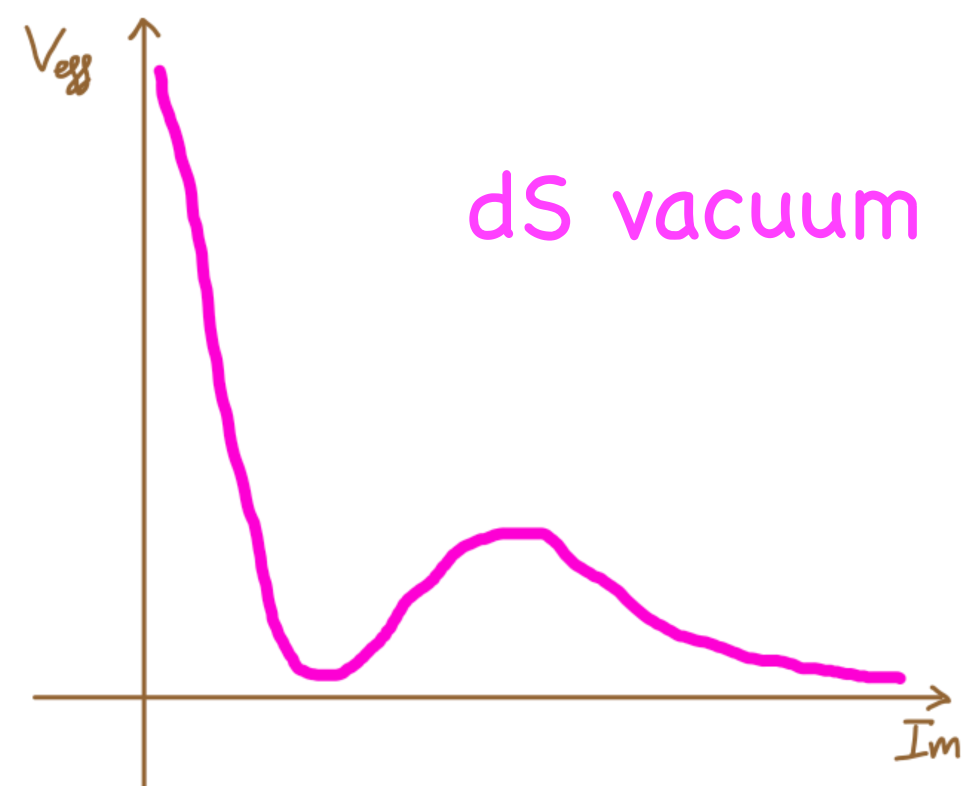
- 4d EFT:

$$K = -3 \log(\mathrm{Im}\,\rho)$$

$$W = W_0 + \mathcal{A}\, e^{\frac{2\pi i \rho}{N}}$$

$$+ \; V_{\overline{D3}} = \frac{\mu^4}{(\mathrm{Im}\,\rho)^2} \quad , \quad \mu^4 \propto e^{4A_{\mathrm{min}}}$$

$\Longrightarrow$

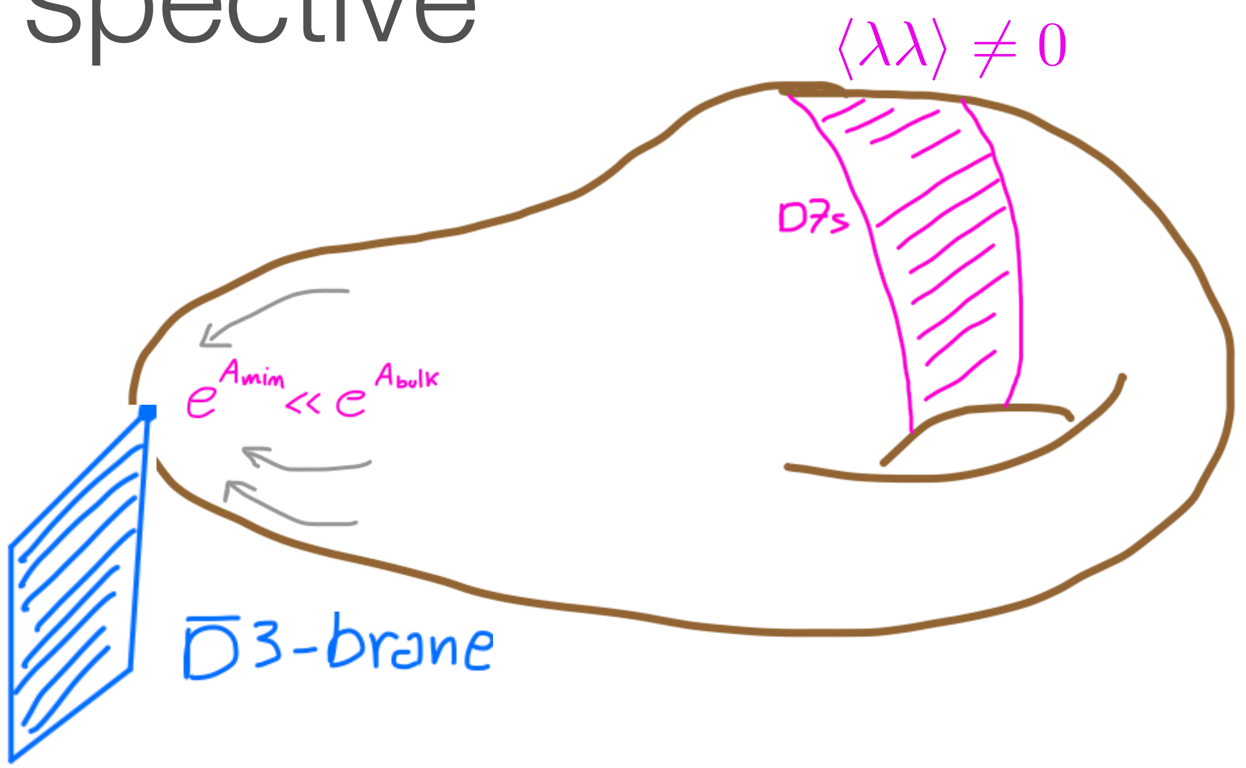


dS vacuum

Matching with 10d?

The 10d perspective

- Matching 4d-10d vacua:
  - Gaugino condensate in 10d?
  - Combination with anti-branes?



[Koerber, L.M. \`08]

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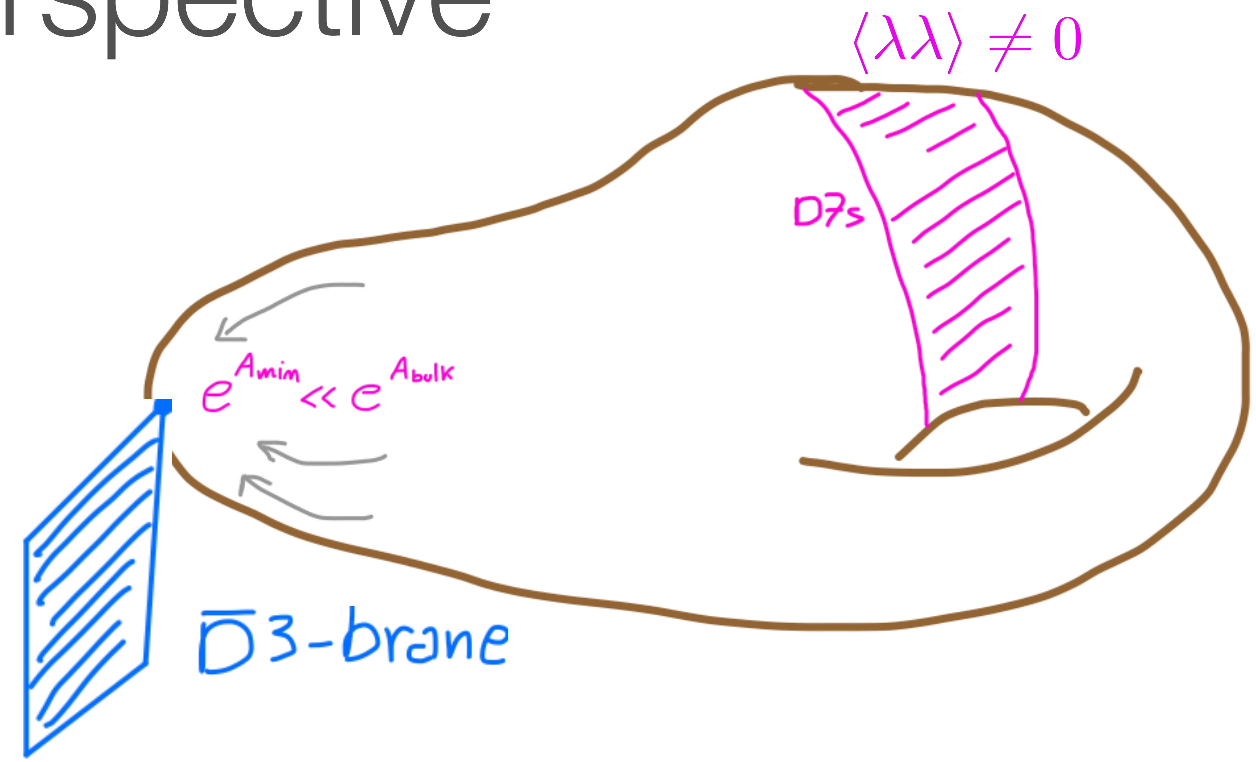
[Kachru, Kim, McAllister, Zimet \`19]

The 10d perspective



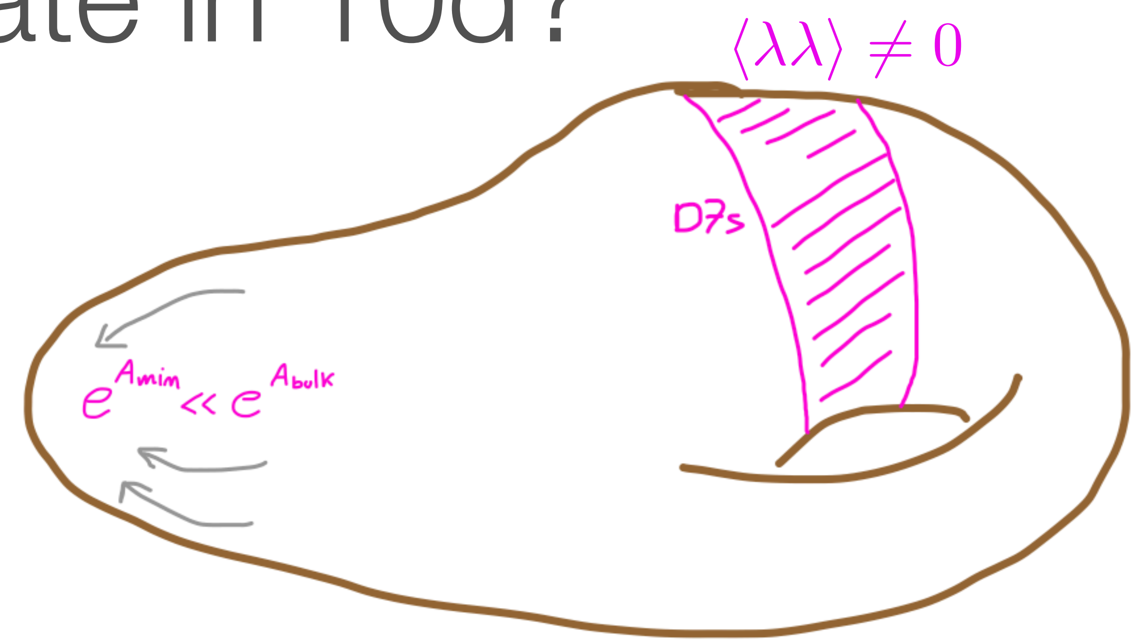
- Matching 4d-10d vacua:
  - Gaugino condensate in 10d?
  - Combination with anti-branes?

$$ds_{10}^2 = e^{2A} ds_4^2 + e^{-2A} ds_6$$

- Strategy:
  - compute 10d: $T_{MN} = T_{MN}^{\rm susy} + T_{MN}^{\langle\lambda\lambda\rangle} + T_{MN}^{\overline{\rm D3}}$ (bulk + D7s)
  - integrated 10d EoM: $M_P^2 \mathcal{R}_4 = -\int {\rm dvol}_6 \left(e^{-4A} g^{\mu\nu} T_{\mu\nu} + \ldots\right)$

$$4V_{\rm eff} = 4\left(V_{\rm eff}^{\rm bulk} + V_{\rm eff}^{\langle\lambda\lambda\rangle} + V_{\rm eff}^{\overline{\rm D3}}\right)$$

Gaugino condensate in 10d?



- Localized gaugino coupling

[Dymarsky, L.M. `10] [Kachru, Kim, McAllister, Zimet `19]

$$S_{\rm D7} \supset \int \mathrm{d}^4\sigma \int_\Sigma \mathrm{dvol}_\Sigma\, \lambda\lambda\, (G_3 + \ldots)\cdot(\Omega + \ldots) \quad + \int \mathrm{d}^4\sigma \int_\Sigma \mathrm{dvol}_\Sigma\, |\lambda\lambda|^2\, \Omega\cdot\Omega$$

integrating over internal space

$$\lambda\lambda \;\to\; \langle\lambda\lambda\rangle \sim e^{\frac{2\pi i \rho}{N}}$$

+ back-reaction (?)

[Kachru, Kim, McAllister, Zimet `19]

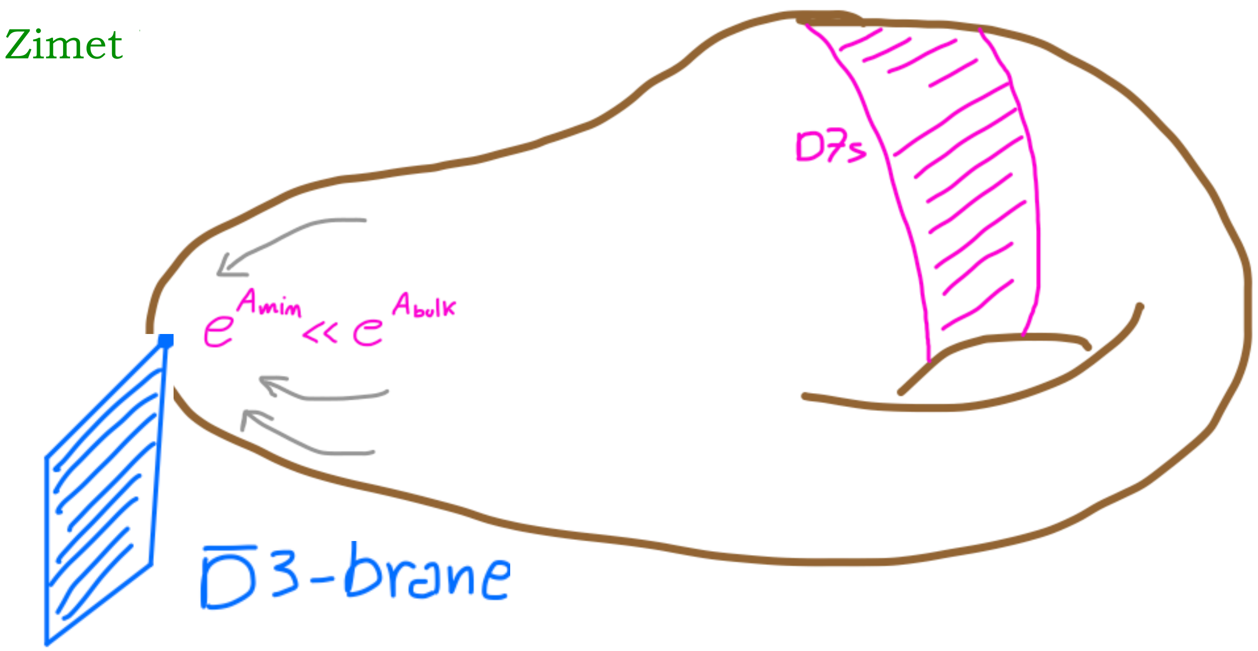
$$V_{\rm eff}^{\langle\lambda\lambda\rangle} = M_P^4 e^K \left[\overbrace{(K^{\rho\bar\rho} K_\rho W \partial_{\bar\rho}\bar W + \mathrm{c.c.})} + \overbrace{K^{\rho\bar\rho}\partial_\rho W \partial_{\bar\rho}\bar W}\right]$$

$$= M_{\rm P}^4\, e^K \left(K^{\rho\bar\rho} D_\rho W D_{\bar\rho}\bar W - 3|W|^2\right)$$

with $\quad W = W_{\rm KKLT} = \int \Omega\wedge G_3 + A e^{\frac{2\pi i\rho}{N}}$

Summing 10d contributions

[Kachru, Kim, McAllister, Zimet



- Localized gaugino coupling

$$V_{\rm eff}^{\langle\lambda\lambda\rangle} = V_{\rm KKLT}^{\rm susy}$$

- Anti D3-brane: $V_{\rm eff}^{\overline{\rm D3}} = V_{\rm KKLT}^{\overline{\rm D3}} + ({\rm subleading})$

probe

$\overline{\rm D3}$ + $\langle\lambda\lambda\rangle$ backreaction

- Hence: $V_{\rm eff} = V_{\rm KKLT}^{\rm susy} + V_{\rm KKLT}^{\overline{\rm D3}}$

10d-4d match! [Kachru, Kim, McAllister, Zimet `19]

SUSY completion through Goldstino brane or $S^2 = 0$

Conclusion

- Goldistino brane as efficient and natural way to parametrize anti-brane EFT contributions

- Main weakness: very unconstrained

- Main (technical) issue: 10d-4d matching

- Promising recent progress, but details to be clarified

- dS from anti-branes require further inspection

- E.g. More accurate probe potential from wEFT: [LM`14-`16] $e^{-4A} = a + e^{-4A_0}$

$$V_{\overline{\mathrm{D3}}} = \frac{M_{\mathrm{P}}^4}{(\mathrm{Im}\,\rho)^3\left(1+\frac{e^{-4A_0^{\mathrm{min}}}}{\mathrm{Im}\,\rho}\right)}$$

[Bandos-Heller-Kuzenko-LM-Sorokin`16]

$e^{-4A_0^{\mathrm{min}}} \ll \mathrm{Im}\,\rho$ → corrected KKLT

$e^{-4A_0^{\mathrm{min}}} \gg \mathrm{Im}\,\rho$ → KKLMMT