# Holography for KKLT: Anatomy of a Flow

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Holography and the Swampland

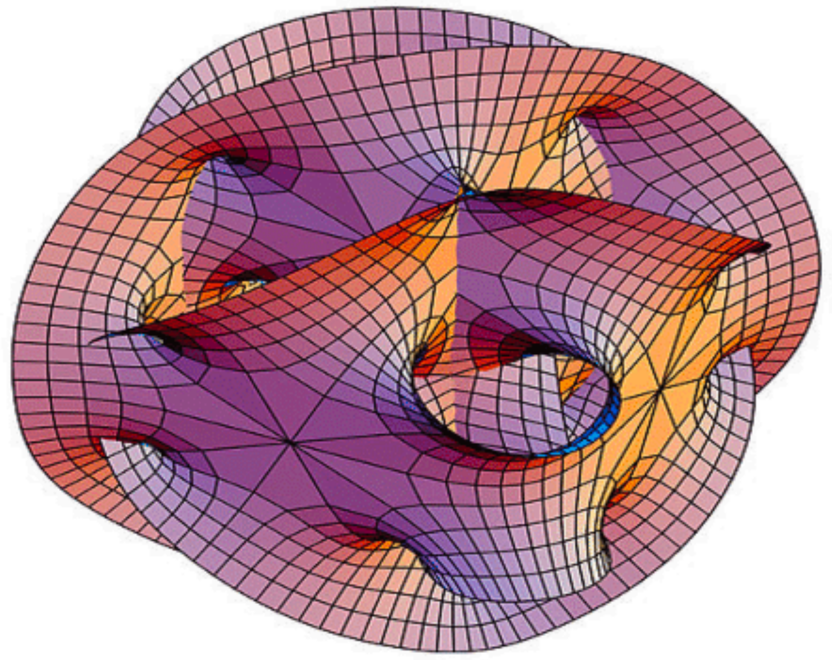
Work to appear with I. Bena and S. Lüst

*Sept. 3rd, 2024*

# The string landscape…

- String theory's paradigm to get real-world physics: compactifications

$$\mathscr{M}_4 \times X_6$$



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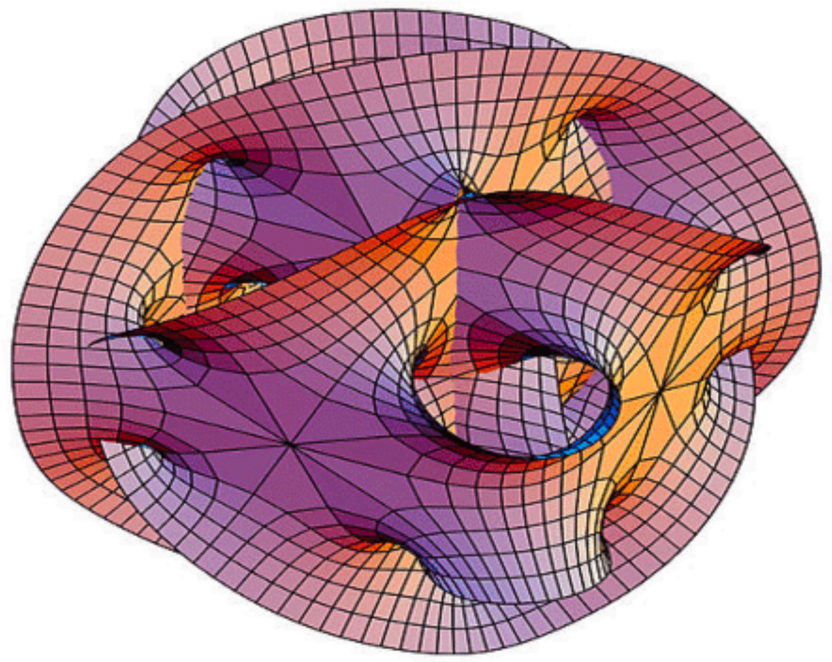

- To explain our 4d EFT, start from a 10d theory

- The higher-dimensional theory is very rich:

  → CY geometry can be very intricate

  → 10d field content on top

  → induce fluxes on the CY

$10^{500}$ solutions

[Ashok, Douglas '04]

→ surely one can get any EFT from those!

# … and the Swampland

## No scale-separated AdS vacua

[D. Lüst, Palti, Vafa '19]

As $\Lambda \to 0$, $\exists$ tower of states s.t.

$$m \sim |\Lambda|^{\alpha}$$

## No long-lived dS vacua

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$V(\phi)$ in consistent EFT should satisfy

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

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Counter-example (?):

KKLT

[Kachru, Kallosh, Linde, Trivedi '03]

[McAllister, Moritz, Nally, Schachner '24]

# The KKLT scenario

Two-step procedure:

1. Stabilise CY moduli with fluxes

   + non-perturbative corrections

   → SUSY, scale-separated AdS

   $\Lambda < 0$

2. Raise the C.C. to a positive value:

   add $\overline{\mathrm{D3}}$ branes at bottom of warped throat

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Study this step through holography and domain walls

# KKLT 101

- Complex-structure deformations (3-cycles) stabilised by fluxes,

$$W_{\mathrm{GVW}} = \int_{X_3} G_3 \wedge \Omega_3 \qquad G_3 = F_3 - \tau H_3$$

- Kähler moduli (2- and 4-cycles) stabilisation need D3 instanton corrections

$$W_{\mathrm{n.p.}} = \sum_{\mathbf{k}} \mathscr{A}_{\mathbf{k}}(z^i, G_3)\, e^{-2\pi k^\alpha T_\alpha}$$

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- Get C.C. in terms of stabilised Kähler modulus $\sigma_0$

$$\Lambda_{\rm AdS} = -3\left(e^K |W|^2\right)\Big|_{D_aW=0} = -\frac{a^2\mathscr{A}^2 e^{-2a\sigma_0}}{6\sigma_0} < 0$$

$$\boxed{\Rightarrow \ |\Lambda_{\rm AdS}| \ll 1}$$

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Idea: trade fluxes with branes

$\Rightarrow \; |\Lambda_{\rm AdS}| \ll 1$

# Fluxes/branes for KKLT

- **On $\mathrm{CY}_3$**: exchange the $(F_3, H_3)$ fluxes with D5/NS5 branes on dual cycles.

- 3d version of KKLT from M theory
- **On $\mathrm{CY}_4$**: trade the $G_4$ flux for M5 branes on dual cycle $L_4 \subset \mathrm{CY}_4$.

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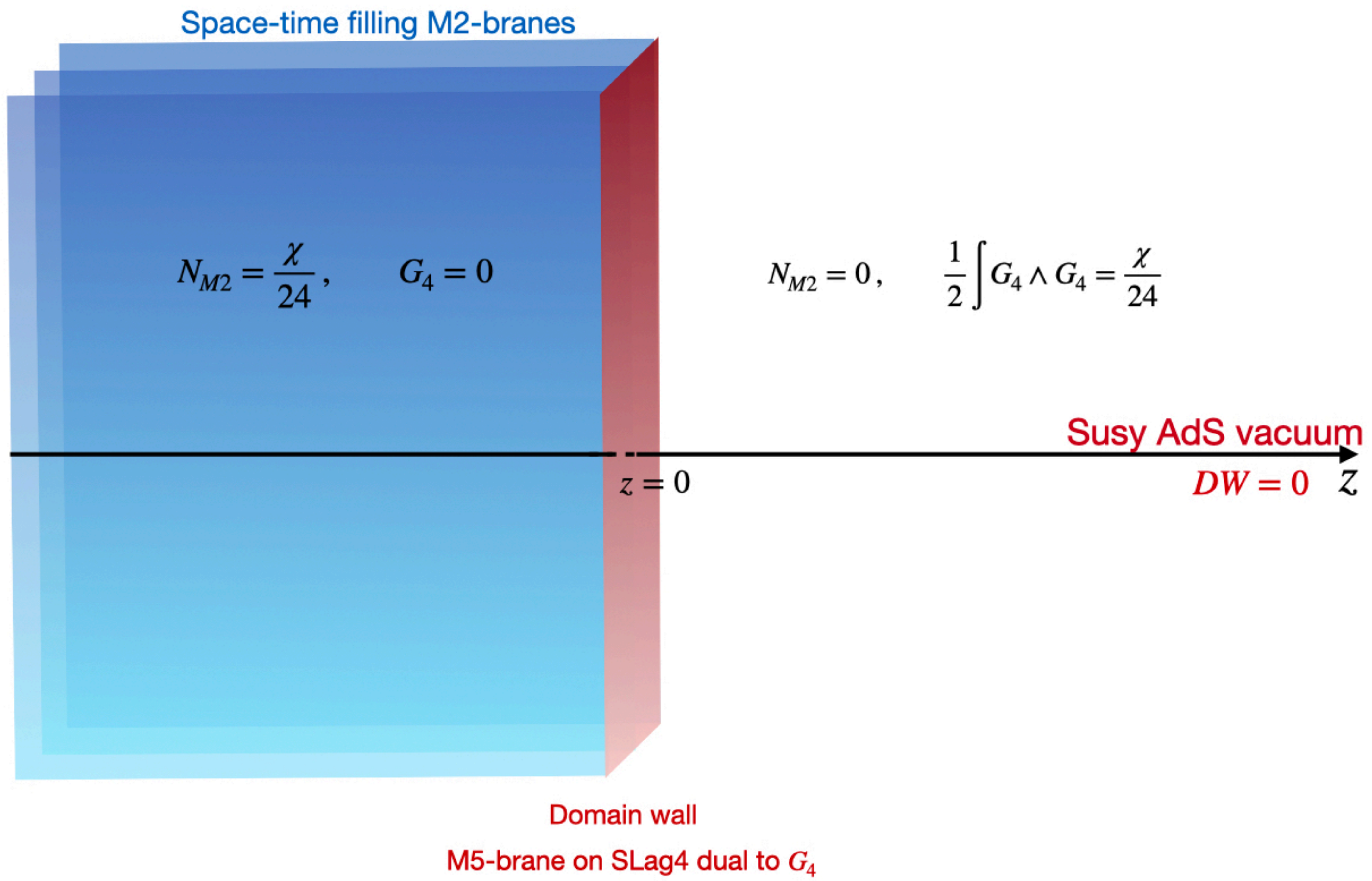
- **On** $CY_4$: trade the $G_4$ flux for M5 branes on dual cycle $L_4 \subset CY_4$.
  - $G_4 = \star\, G_4$, so locally looks like

| | | 0 | $y$ | $z$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Domain wall | M5 | — | — | $z{=}0$ ● | — | — | — | — | | | | |
| | M5 | — | — | $z{=}0$ ● | | | | | — | — | — | — |
| Tadpole | M2 | — | — | $z{<}0$ — | | | | | | | | |

# Domain-wall holography

[S. Lüst, Vafa, Wiesner, Xu '22]

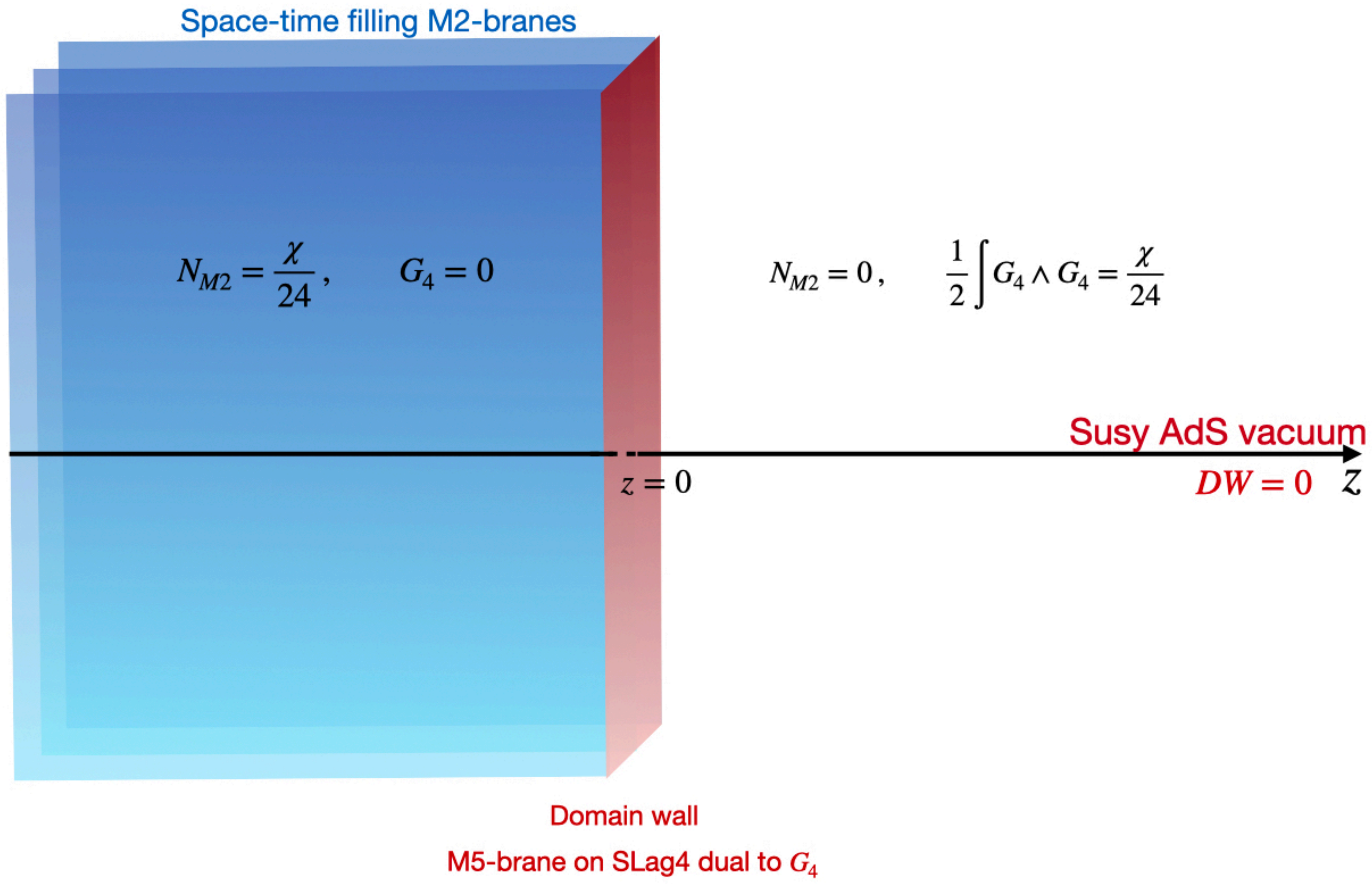



Susy AdS$_3$ from M-theory on $X_4$ in the presence of self-dual $G_4$ flux

DW: M5 brane on special Lagrangian $L_4$

# The holographic bound

[S. Lüst, Vafa, Wiesner, Xu '22]




The DW contains d.o.f.

$\sharp$ (d.o.f.) $\rightarrow$ « UV » central charge, $c_{\rm UV}$.

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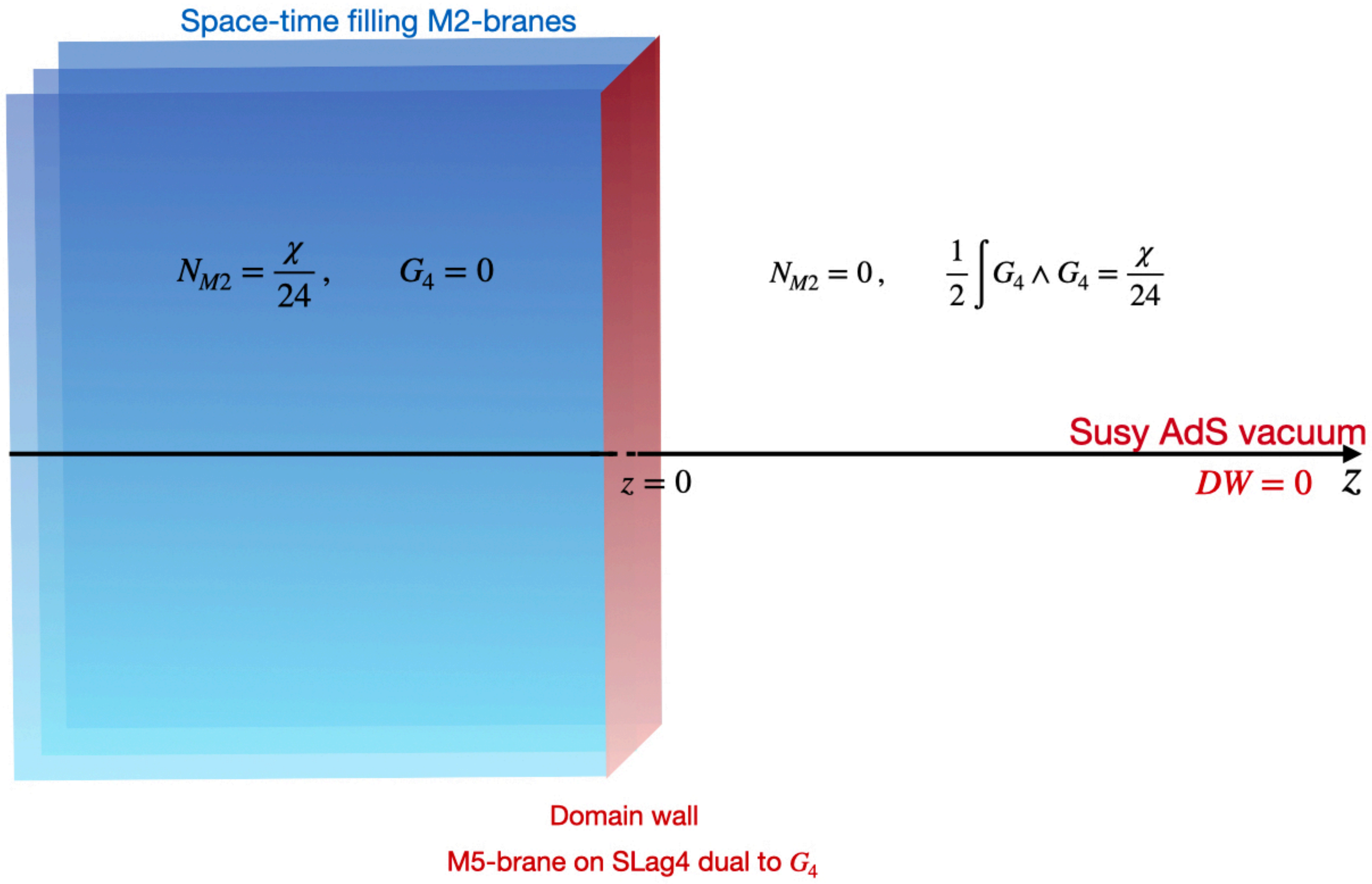


At $z = +\infty$, the IR central charge measures the radius of the $AdS_3$:

$$c_{\mathrm{IR}} = \frac{3}{2} l_{\mathrm{AdS}} \sim \frac{1}{|\Lambda|}$$

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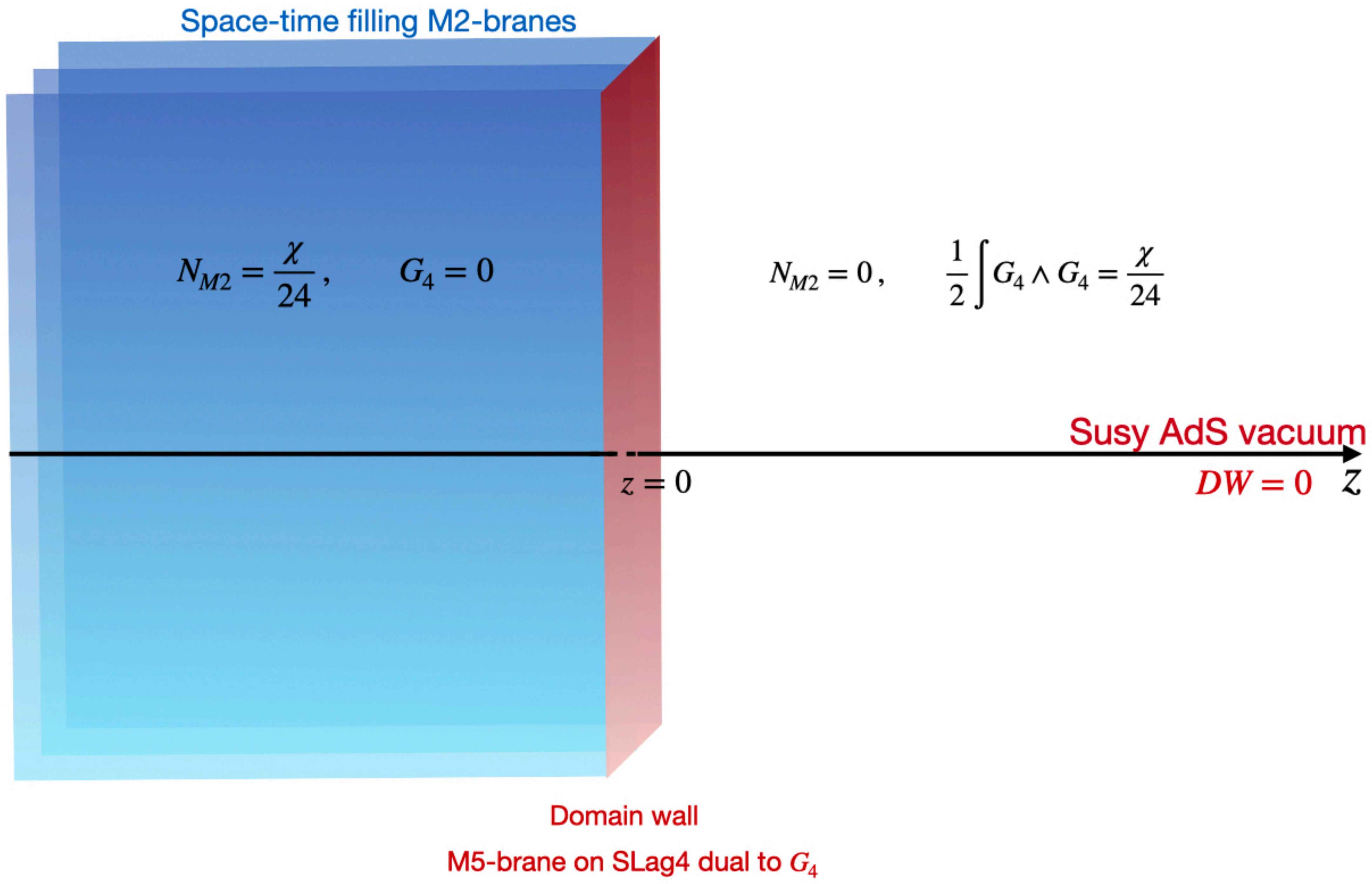


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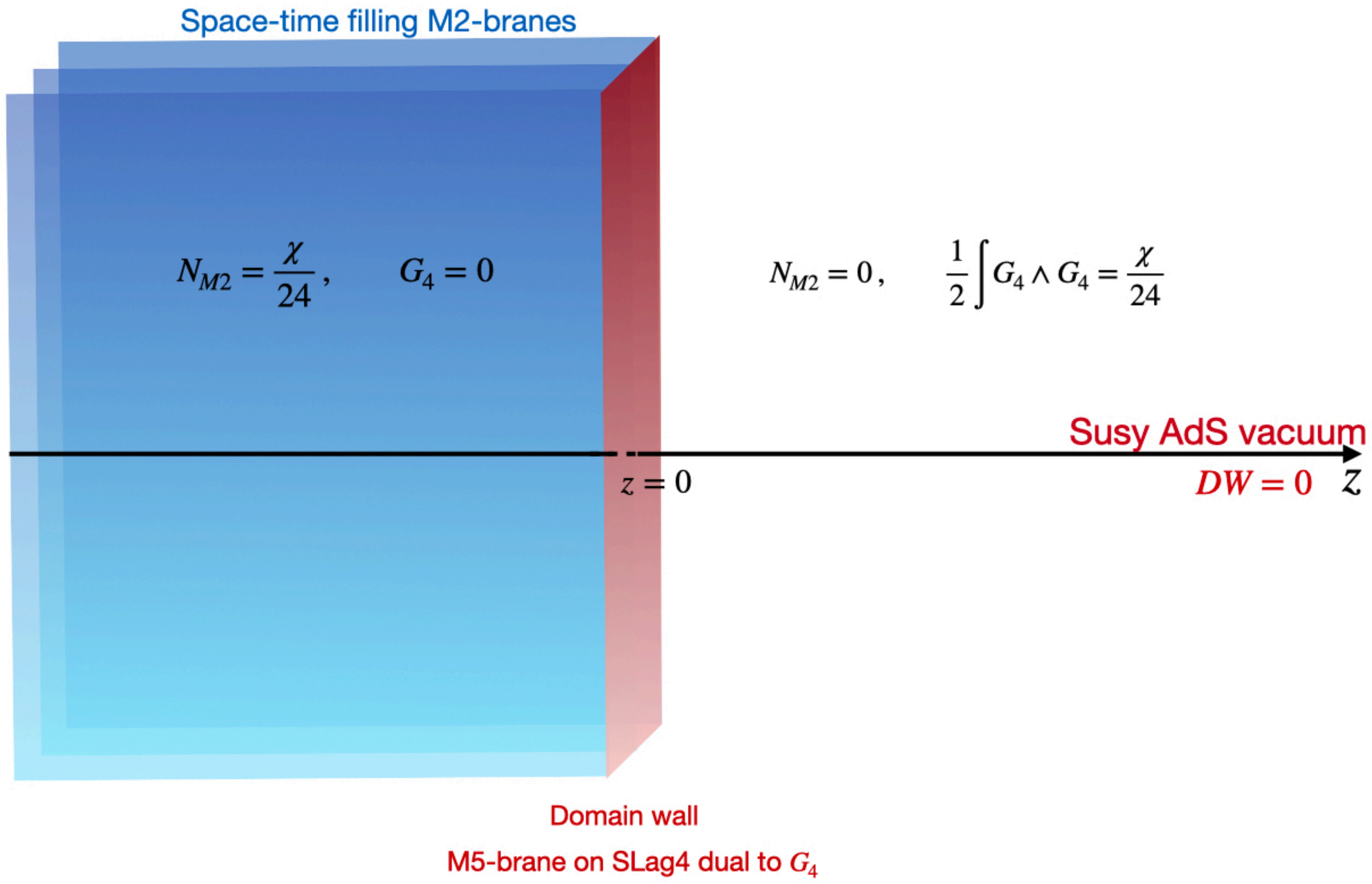


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Estimate $c_{\mathrm{UV}}$: deformations of SLag

$$c_{\mathrm{IR}} \leq c_{\mathrm{UV}} \sim (N_{\mathrm{flux}})^2$$

⇒ lower bound on $|\Lambda|$

$$|\Lambda_{\mathrm{AdS}}| \geq \mathcal{O}\left[\frac{1}{(N_{\mathrm{flux}})^2}\right]$$

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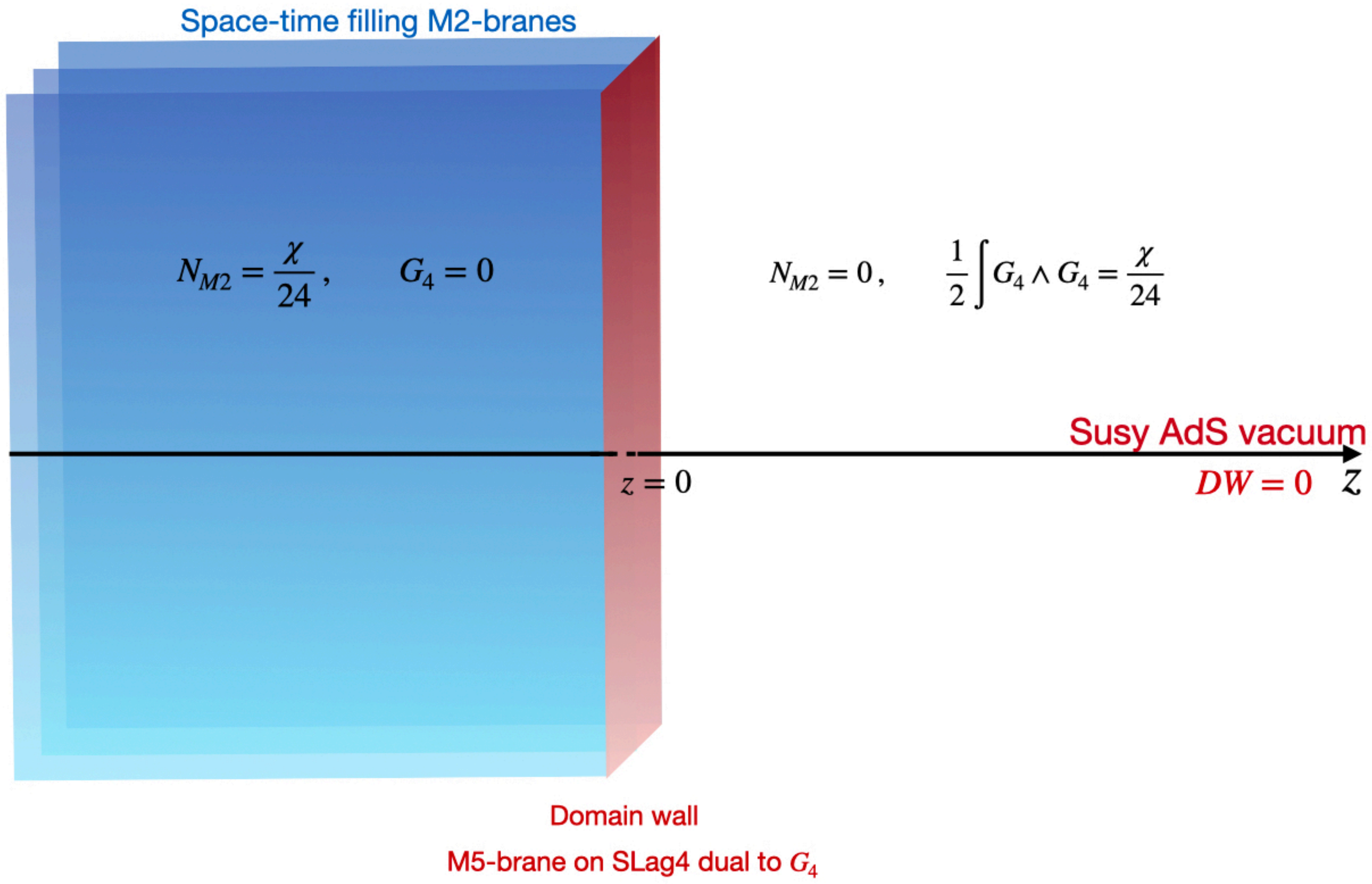


$\Rightarrow$ Not enough d.o.f. on the brane to get a sufficiently small C.C.!

Need it exponentially small

$$c_{\mathrm{IR}} \leq c_{\mathrm{UV}} \sim (N_{\mathrm{flux}})^2$$

$\Rightarrow$ lower bound on $|\Lambda|$

$$|\Lambda_{\mathrm{AdS}}| \geq \mathcal{O}\left[\frac{1}{(N_{\mathrm{flux}})^2}\right]$$

# Hidden degrees of freedom?

- They take a DW sourcing the KKLT AdS, and declare the UV d.o.f. to be the deformations of the SLag $L_4$.
- What if there are hidden d.o.f.?
  - At the M5-M5 brane intersections there could have much more d.o.f.
  - (D1-D5 system: central charge is $N_1 N_5$ instead of $N_1 + N_5$.)
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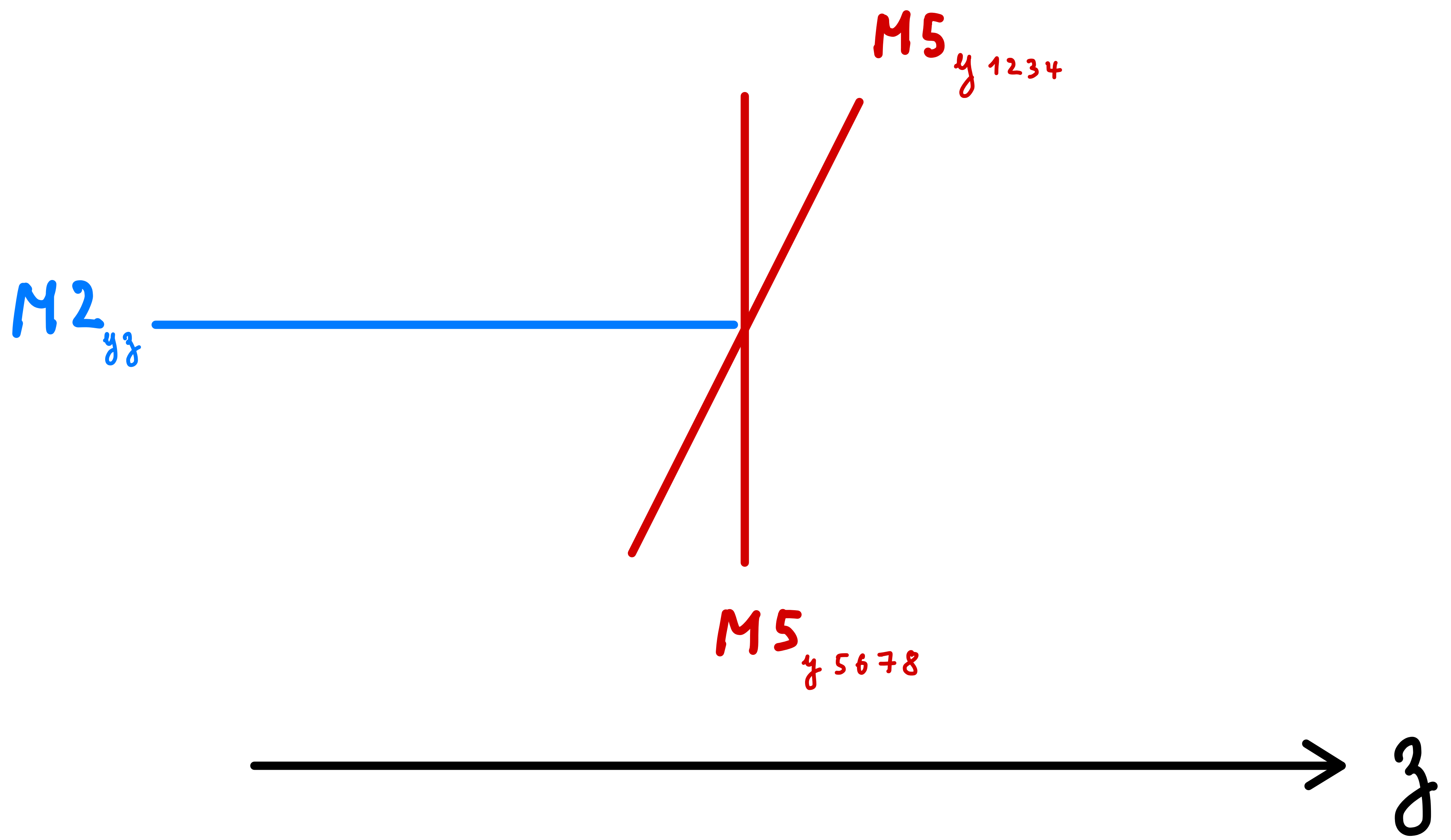
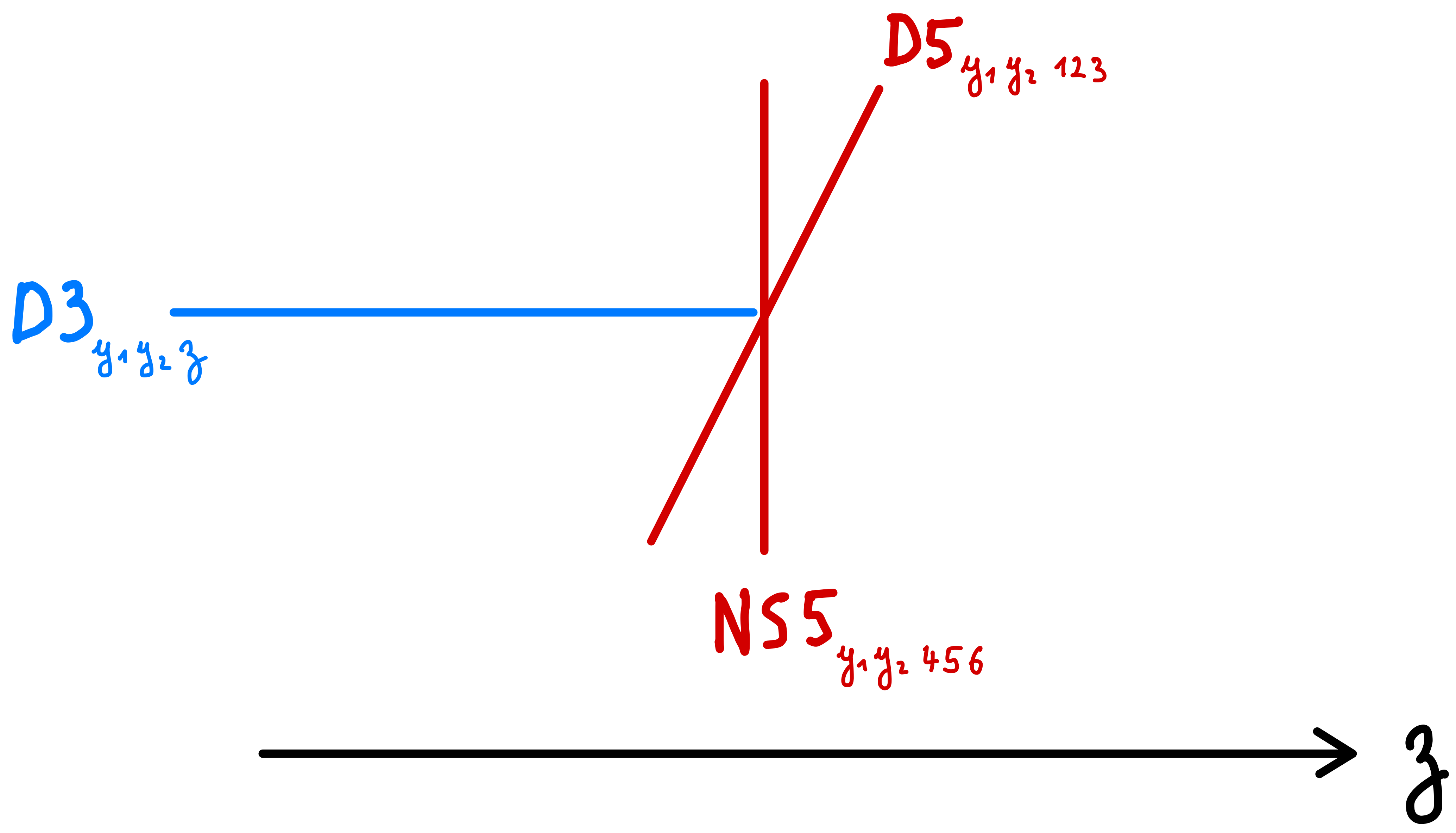
→ Need to evaluate the radius of the AdS corresponding to the brane intersection (with the most d.o.f.)!

# The most « entropic » domain wall

- Configuration with the most d.o.f.?
- Squeeze all branes at the same place → brane interaction enhanced



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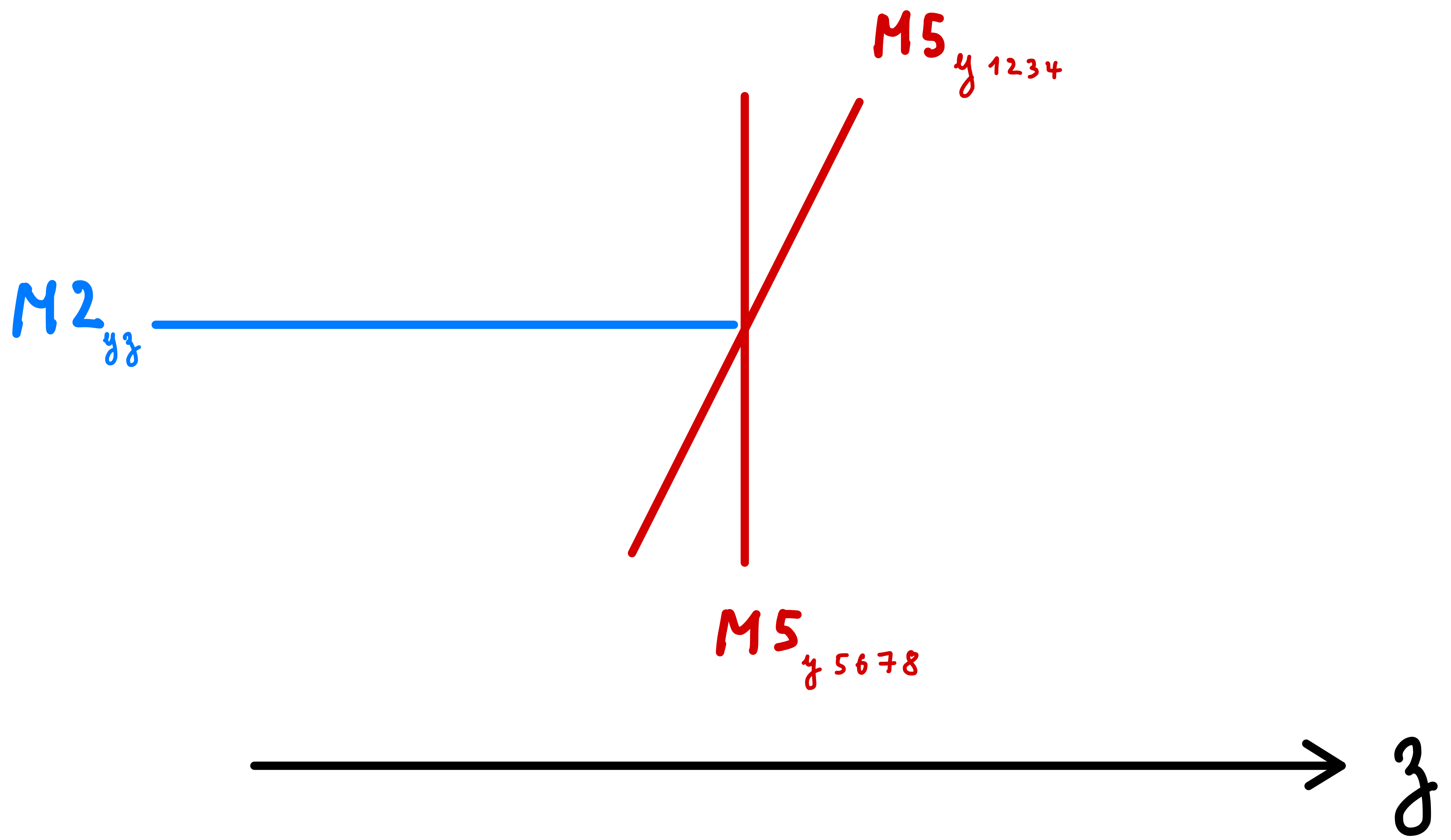
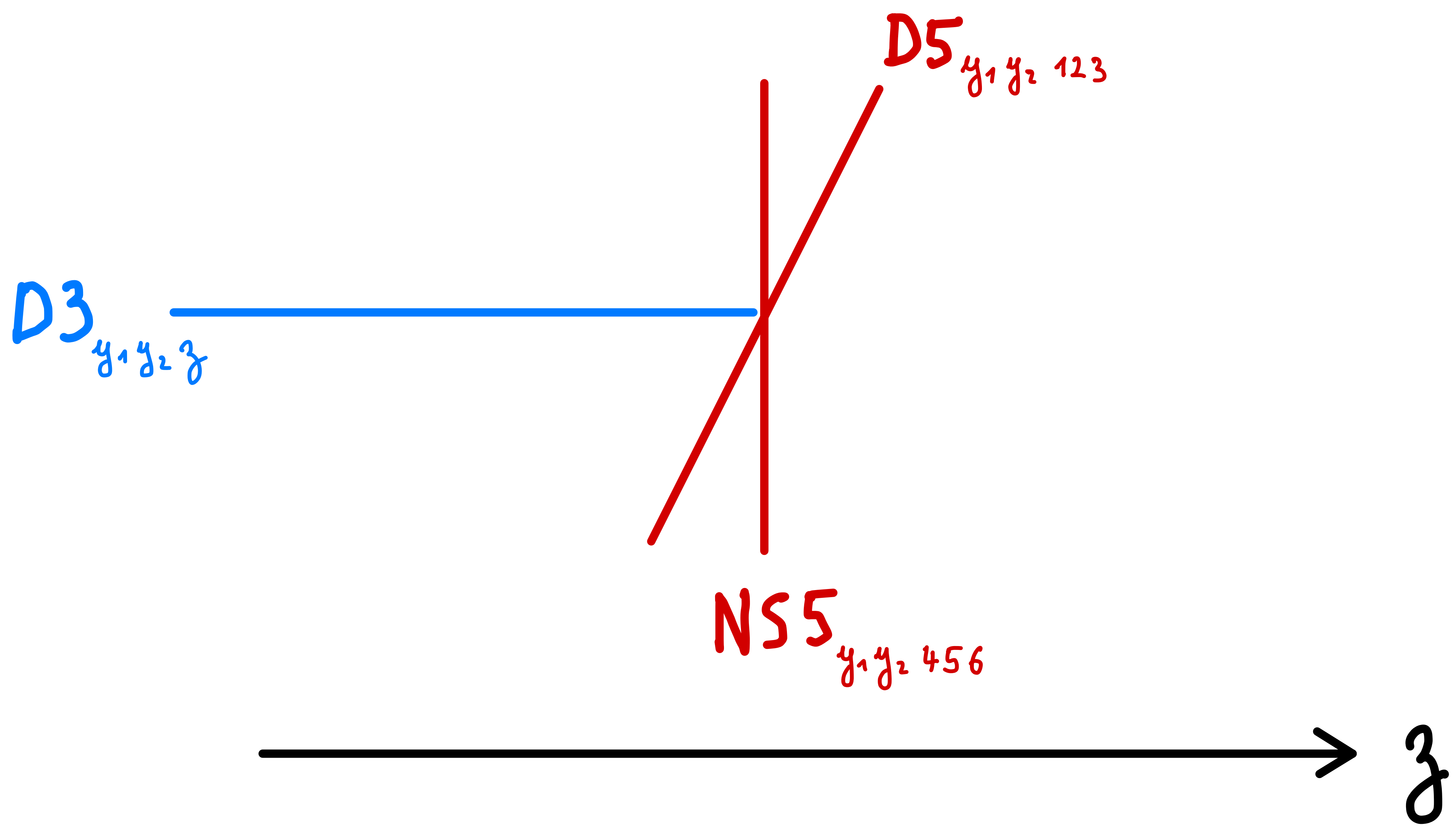
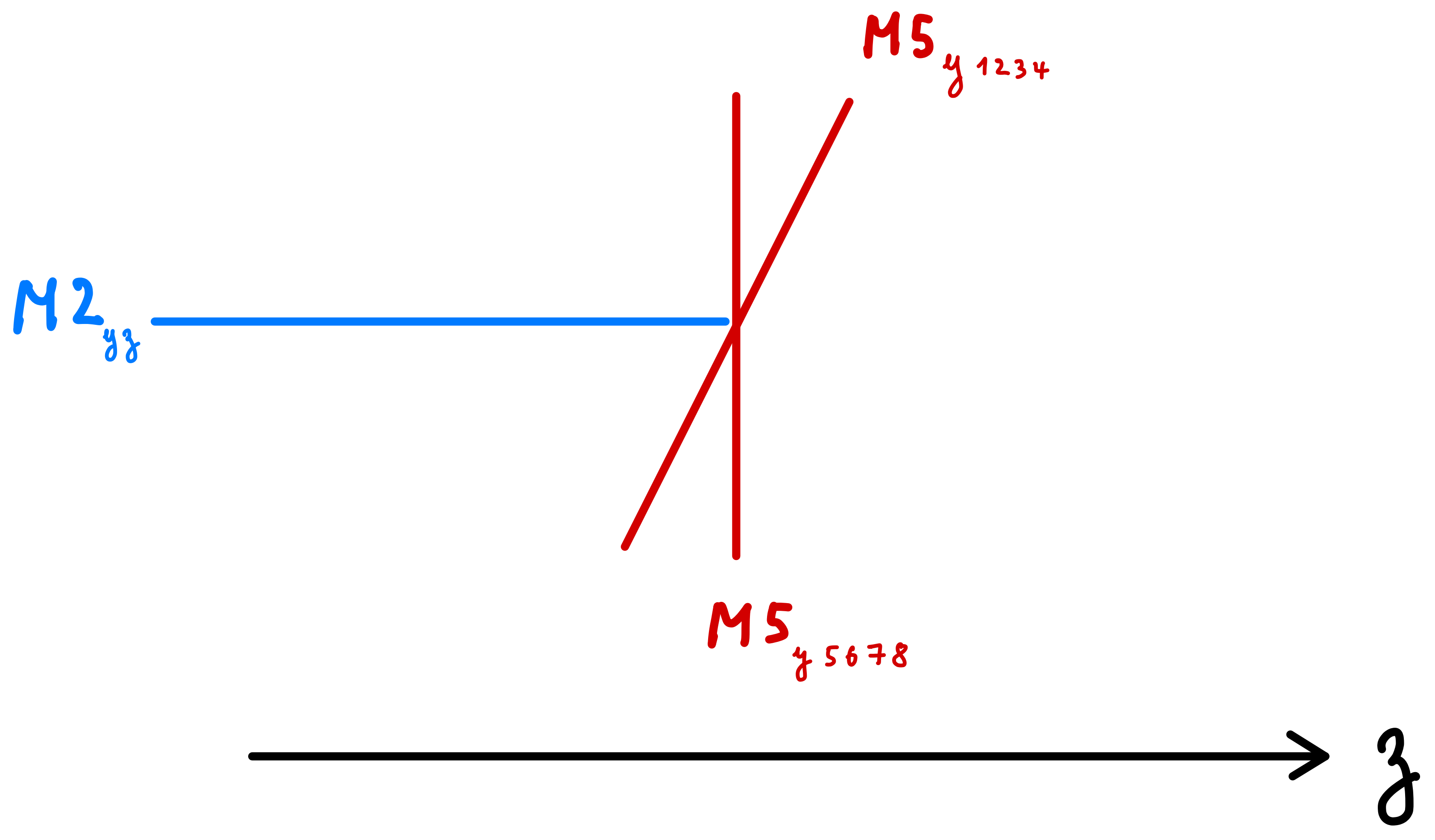


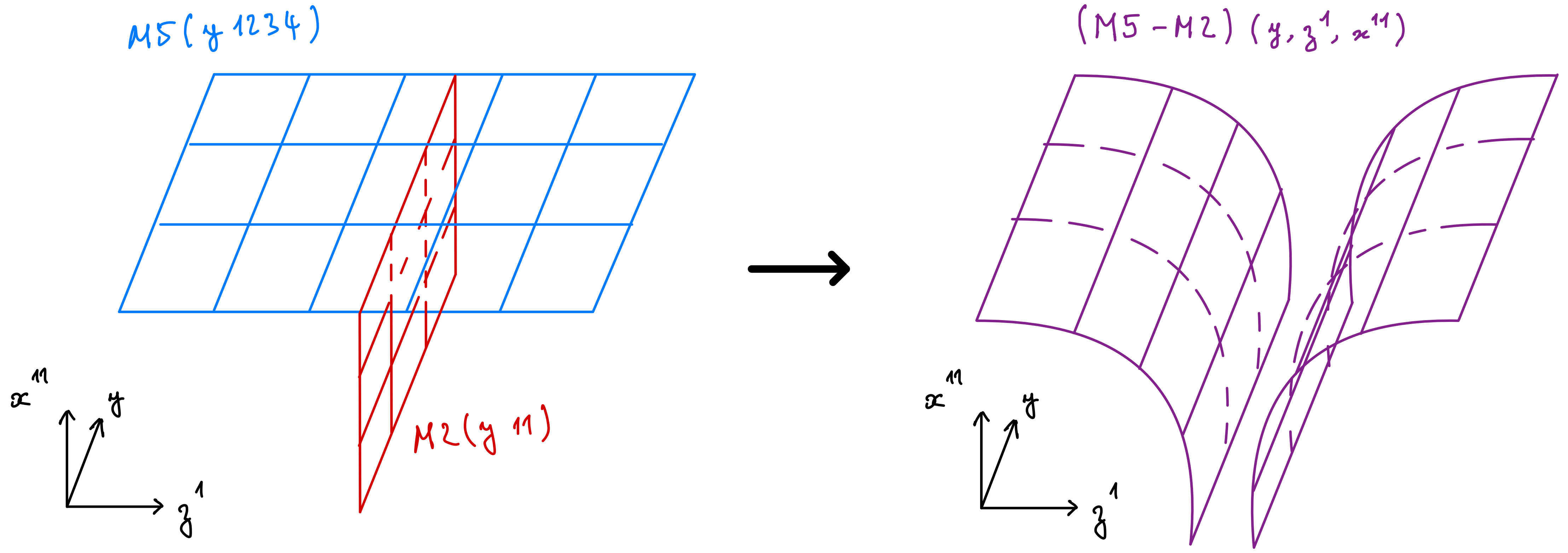




These configurations contain the maximum number of d.o.f. one can get from the branes

# Radius of a warped $\mathrm{AdS}_3$?

- How to get an AdS capturing the d.o.f. of intersection?
- Locally, M2 ending on M5-M5.
- The M2 pulls on the worldvolume of the M5





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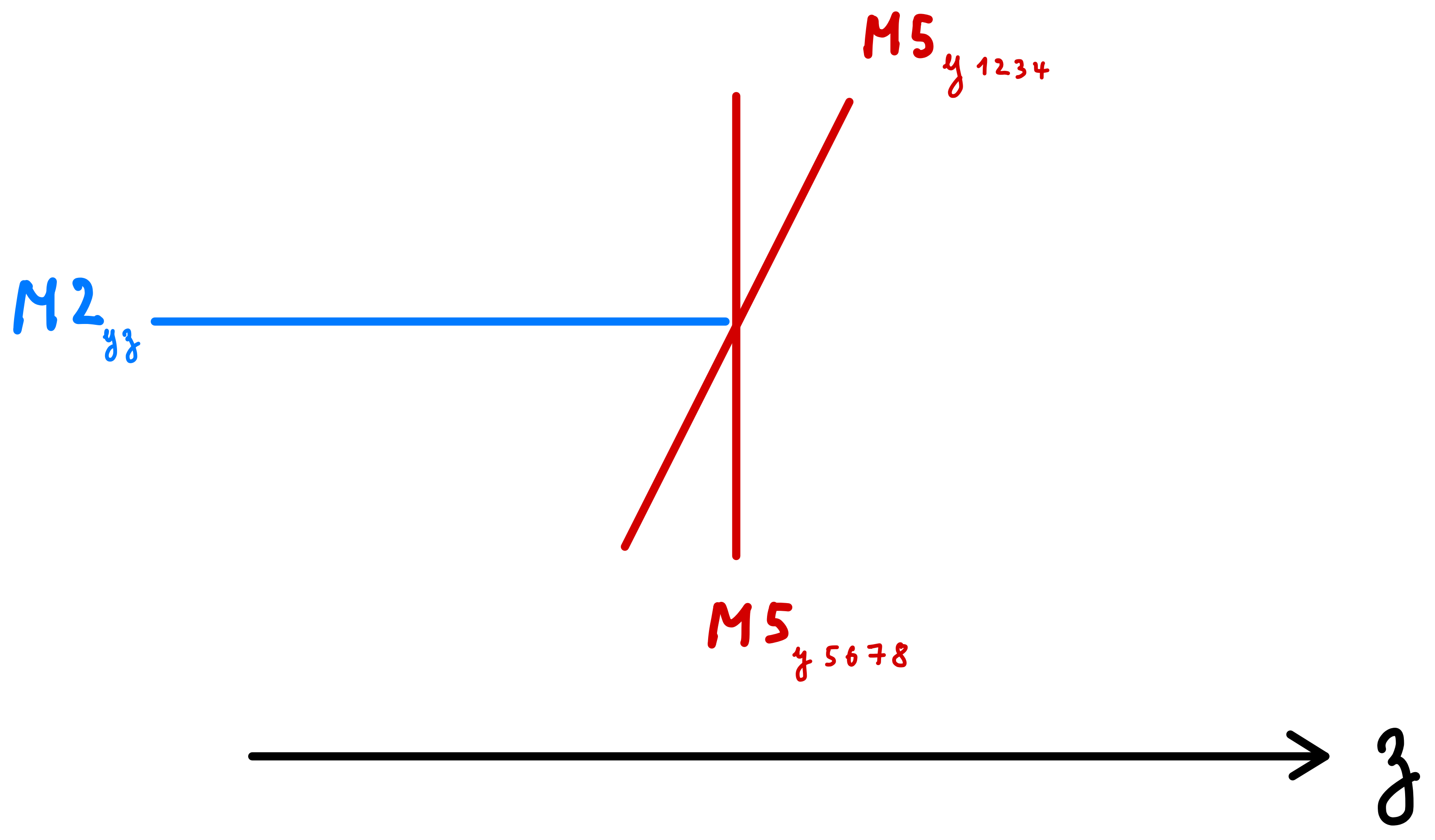

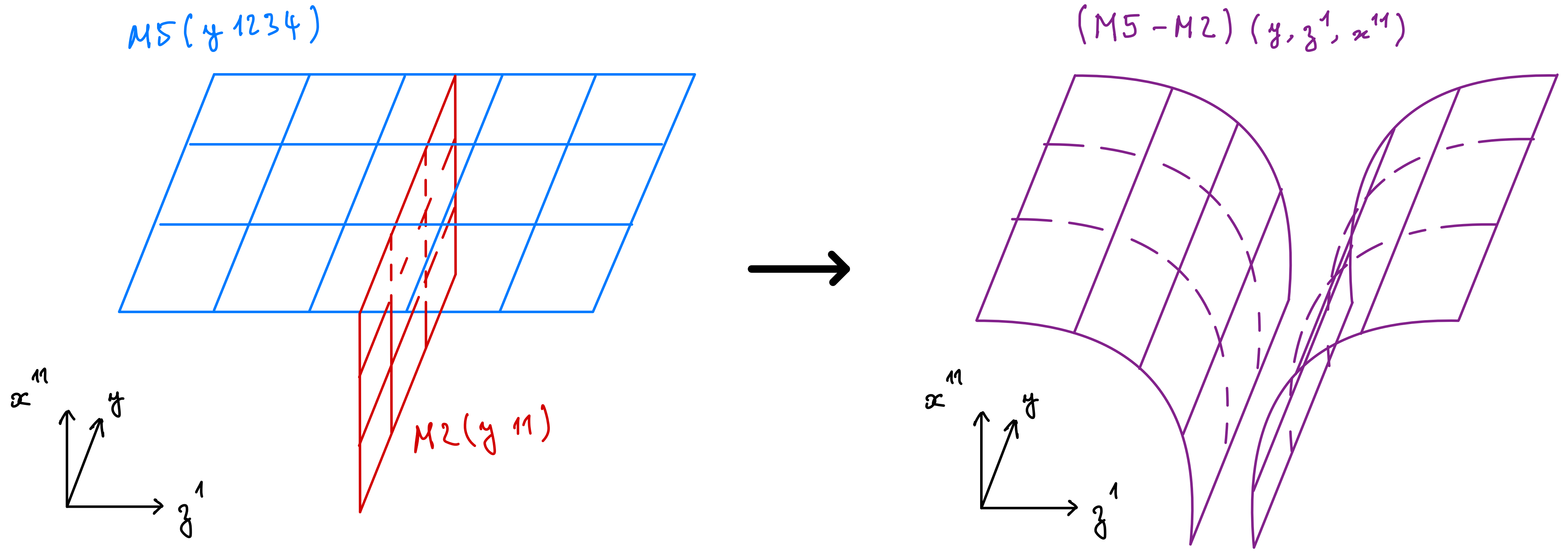

[Bena, Hampton, Houppe, **YL**, Toulikas '22]
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- Sugra solution, with infrared limit:

$$\mathrm{AdS}_3 \times S^3 \times S^3 \times_{\mathrm{w}} W_2$$

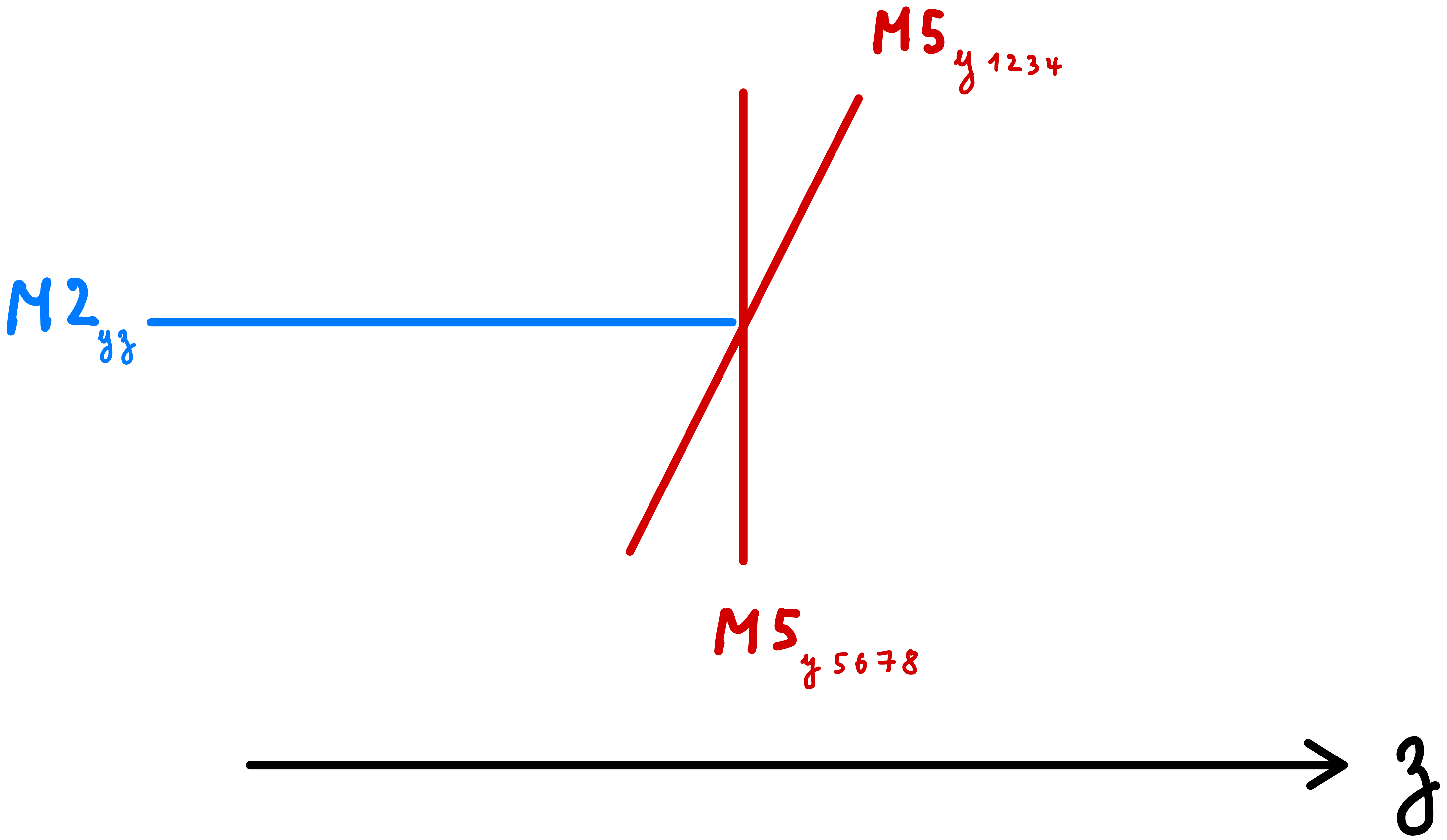
[Lunin '07] [Bachas, D'Hoker, Estes, Krym '13]
[Bena, Houppe, Toulikas, Warner '23]

- Reading off central charge is a mess

# A smeared M5-M5-M2 intersection

- Can compute central charge from a similar configuration.

| | 0 | $y$ | $z$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M5 | — | — | $z{=}0$ ● | — | — | — | — | | | | |
| M5 | — | — | $z{=}0$ ● | | | | | — | — | — | — |
| M2 | — | — | $z{<}0$ — | | | | | | | | |



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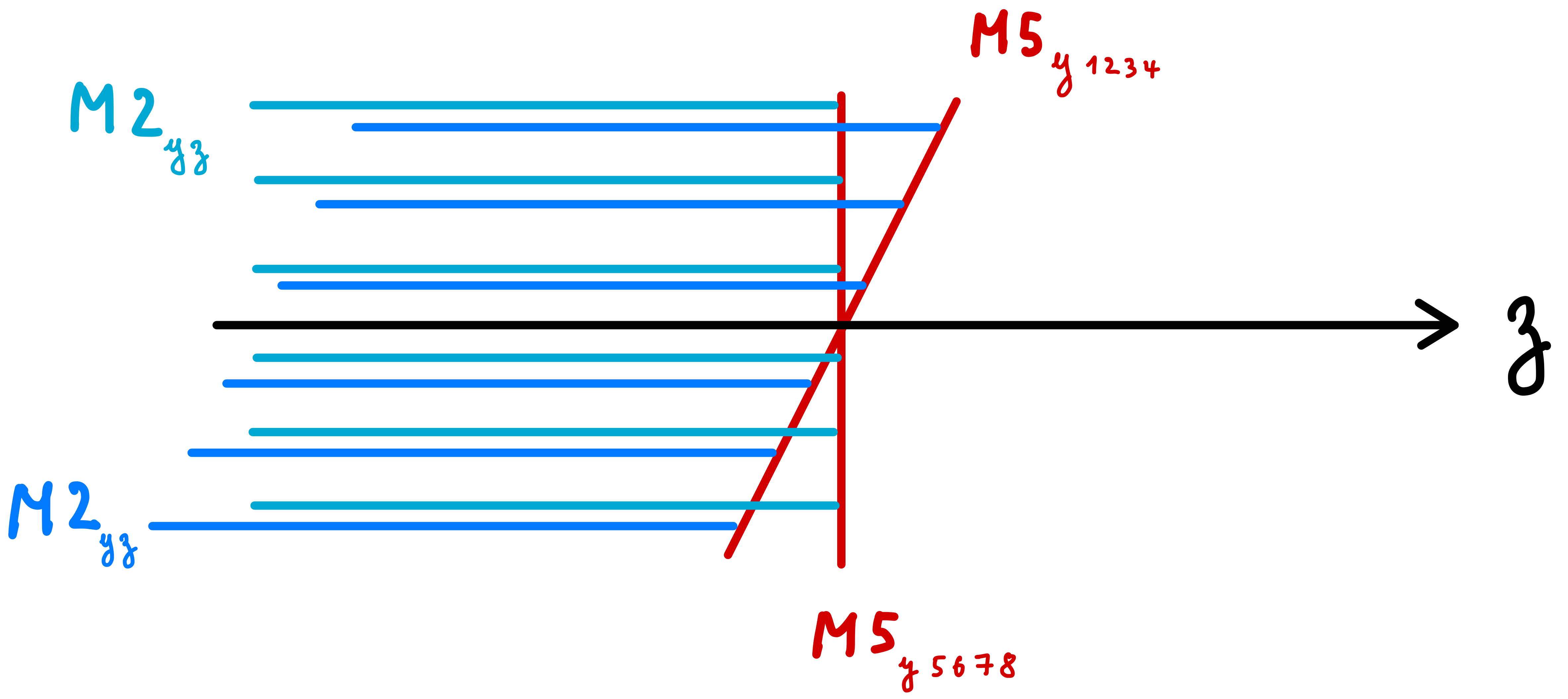


We propose:

- Put M2 charge ending on M5 branes (cross shape).
- Smear M5(1234,y) along z. Smear M5(5678,y) along z.
- Take near-horizon limit $\rightsquigarrow$ central charge

# Branes at M5 self-intersections

- There is a sugra solution corresponding to the smeared M5-M5-M2. [de Boer, Pasquinucci, Skenderis '99]

| | $y$ | $z$ | $(r,\Omega_3^{(1)})$ | $(r',\Omega_3^{(2)})$ |
|---|---|---|---|---|
| $\mathrm{M5}_1$ | $\otimes$ | $\sim$ | $\otimes$ | $\overset{r'=0}{\bullet}$ |
| $\mathrm{M5}_2$ | $\otimes$ | $\sim$ | $\overset{r=0}{\bullet}$ | $\otimes$ |
| $\mathrm{M2}_1$ | $\otimes$ | $\otimes$ | $\sim$ | $\overset{r'=0}{\bullet}$ |
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- Metric Ansatz:

$$\begin{aligned} ds^2 =& H_T^{-2/3}\left(H_F^{(1)}H_F^{(2)}\right)^{-1/3}\left(-dt^2+dx_1^2\right)+H_T^{-2/3}\left(H_F^{(1)}H_F^{(2)}\right)^{2/3}dx_2^2 \\ &+H_T^{1/3}\left(H_F^{(1)}\right)^{-1/3}\left(H_F^{(2)}\right)^{2/3}\left(dr^2+r^2d\Omega_{(1)}^2\right) \\ &+H_T^{1/3}\left(H_F^{(1)}\right)^{2/3}\left(H_F^{(2)}\right)^{-1/3}\left(dr'^2+r'^2d\Omega_{(2)}^2\right)\,. \end{aligned}$$

- (Localised) M5 harmonic functions: $$H_F^{(1)}=1+\frac{Q_F^1}{r'^2}\,,\qquad H_F^{(2)}=1+\frac{Q_F^2}{r^2}$$

- M2-charge function: $$H_T=(1+\frac{Q_T^{(1)}}{r'^2})(1+\frac{Q_T^{(2)}}{r^2})$$

[de Boer, Pasquinucci, Skenderis '99]

# The near-horizon limit

- Near-horizon limit:

[de Boer, Pasquinucci, Skenderis '99]

$$\mathrm{AdS}_3 \times S^3 \times S^3 \times T^2$$

$$(t, u, y) \qquad \Omega_3^{(2)} \qquad \Omega_3^{(1)} \qquad (z, \lambda)$$

$$r, r' \;\rightarrow\; u \propto r r' \,,\; \lambda = \log(r/r')$$

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$$\underset{\substack{\uparrow \\ (t,u,y)}}{\mathrm{AdS}_3} \times \underset{\substack{\uparrow \\ \Omega_3^{(2)}}}{S^3} \times \underset{\substack{\uparrow \\ \Omega_3^{(1)}}}{S^3} \times \underset{\substack{\uparrow \\ (z,\lambda)}}{T^2}$$

$$r, r' \;\rightarrow\; u \propto rr' \,,\; \lambda = \log(r/r')$$

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Used $N_2 = \dfrac{\chi(X_4)}{24} = \dfrac{1}{2}\int G_4 \wedge G_4$

- Central charge: $c \propto N_2 N_5 \;\propto (N_{\text{flux}})^3$

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- Central charge: $c \propto N_2 N_5 \;\propto (N_{\rm flux})^3 > (N_{\rm flux})^2$

[S. Lüst, Vafa, Wiesner, Xu '22]

→ Weaker bound on $\Lambda$ due to the M2 branes!

# Warped $\mathrm{AdS}_4$ in type IIB

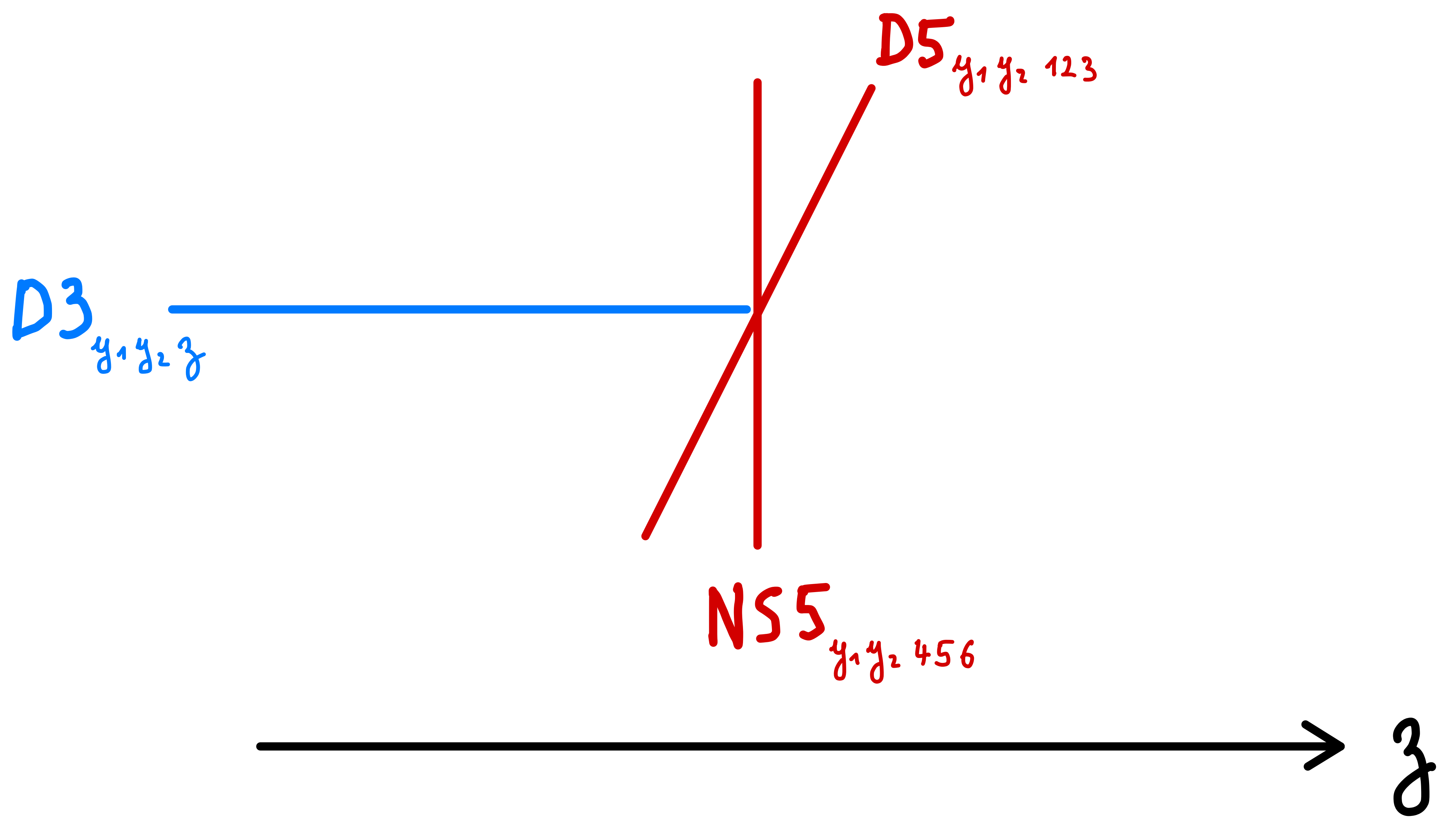
- Sugra solution for D5-NS5-D3 intersection is known.

[D'Hoker, Estes, Gutperle '07]

[Aharony, Berdichevsky, Berkooz, Shamir '11]

[Assel, Bachas, Estes, Gomis '11]

- The solution is an $\mathrm{AdS}_4 \times S^2 \times S^2 \times_w \Sigma_2$



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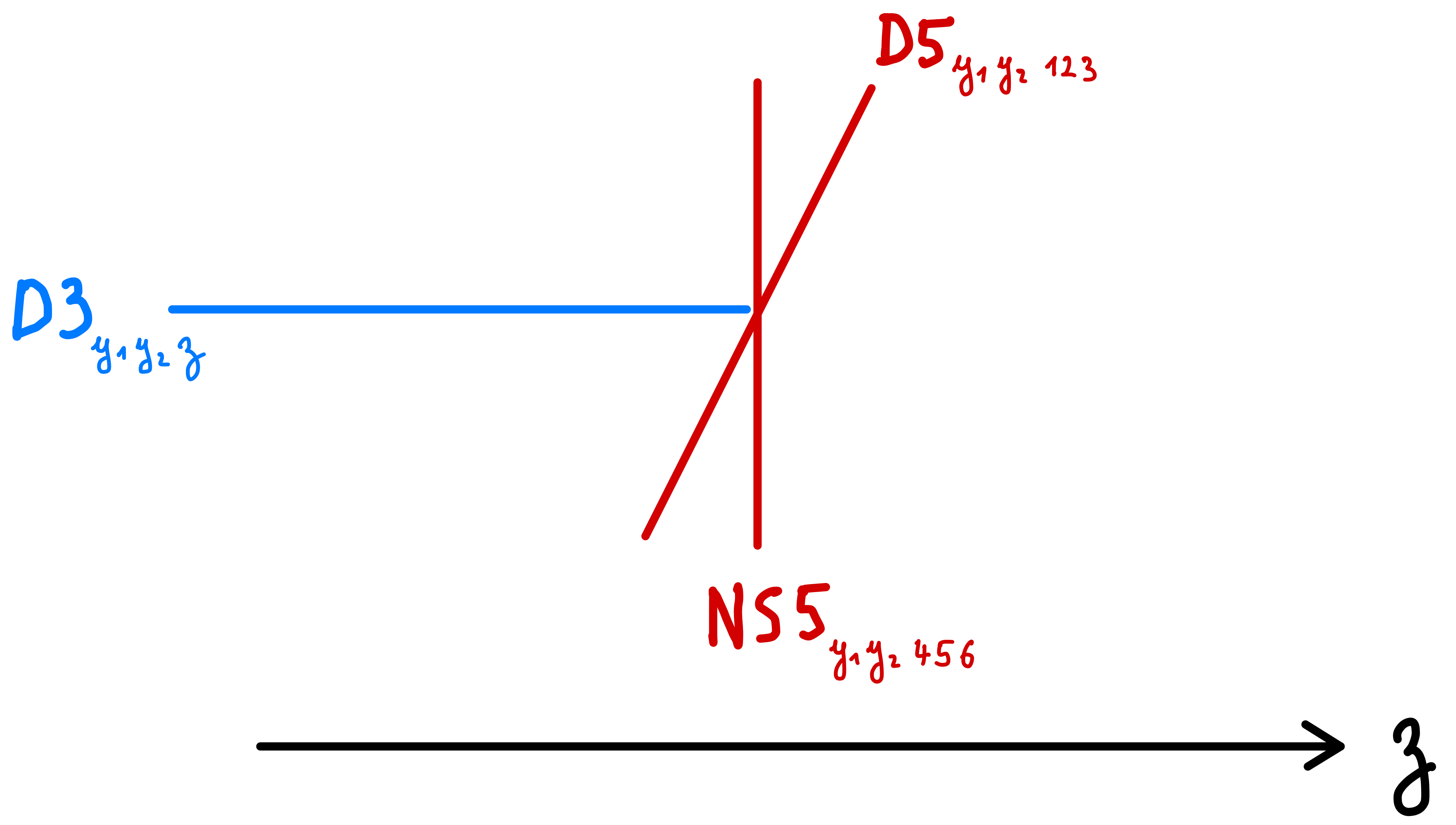
- The solution is an $\mathrm{AdS}_4 \times S^2 \times S^2 \times_w \Sigma_2$
- Compute of AdS radius in 4d Planck units:

$$\frac{l_{AdS}}{G_N} \sim (N_{\text{flux}})^4 \log(N_{\text{flux}})$$

[Assel, Estes, Yamazaki '12]




Matches the free energy of the 3d CFT!

[Assel, Estes, Yamazaki '12]

[Karch, Sun, Uhlemann '22]

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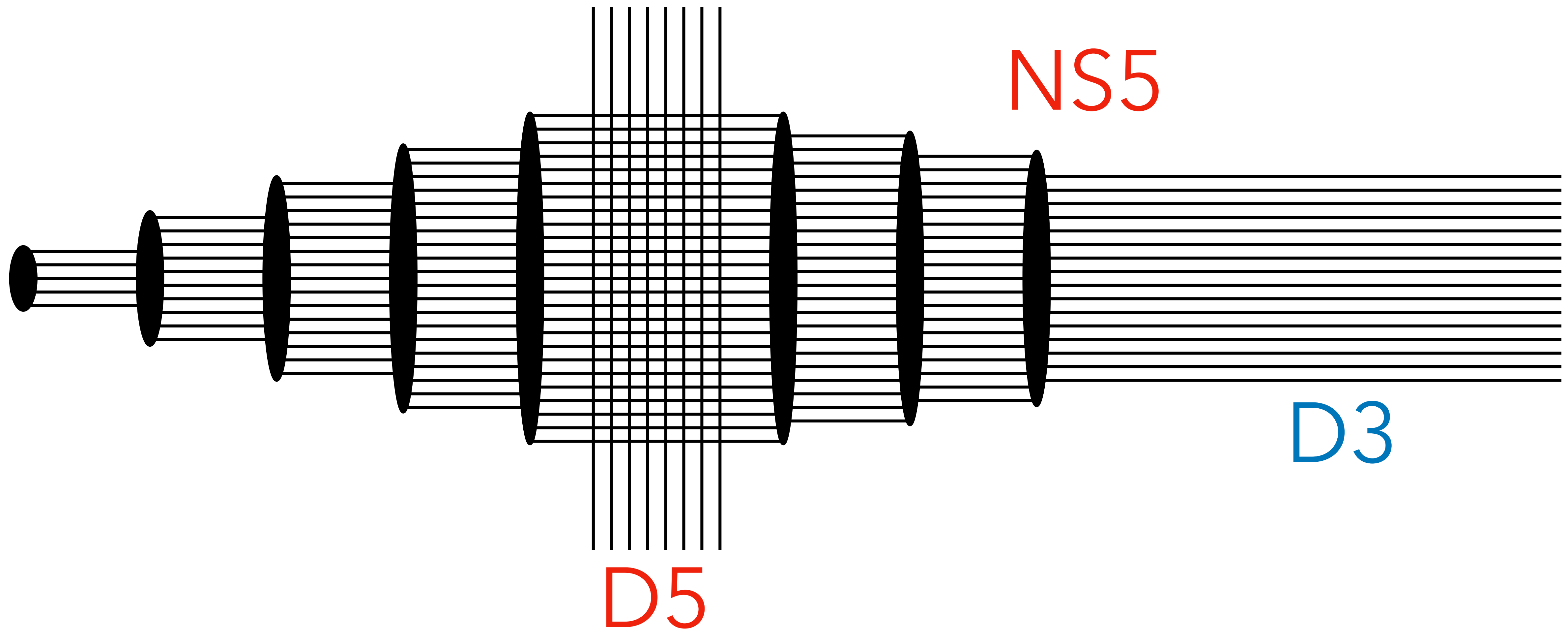


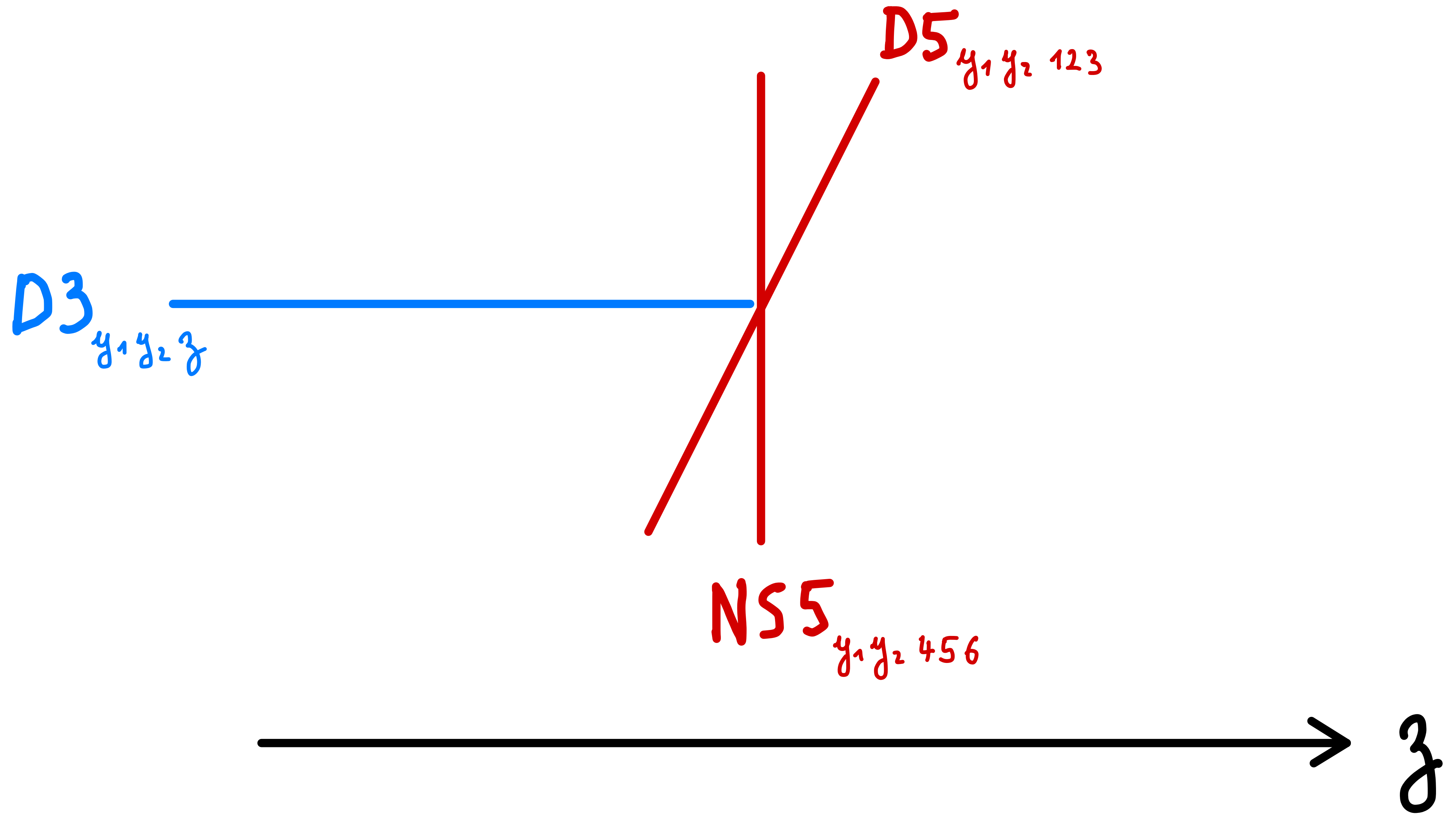


Matches the free energy of the 3d CFT!

[Assel, Estes, Yamazaki '12]

[Karch, Sun, Uhlemann '22]

# Conclusion

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- Studied local models for brane systems that source KKLT-type AdS vacua
- Computed AdS radius of the brane intersection (UV)
  - M theory: radius of the $AdS_3$

    $$\frac{l_{AdS}}{G_N} \sim (N_{\text{flux}})^3$$

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    Deformations of SLag

    [S. Lüst, Vafa, Wiesner, Xu '22]
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$$|\Lambda_{\text{AdS}}| \geq \mathcal{O}\left[\frac{1}{(N_{\text{flux}})^4}\right]$$

- Therefore there is not enough d.o.f. to get the AdS with $|\Lambda| \ll 1$ in the KKLT scenario.

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*Thank you!*

# Backup slides

# 3d version of KKLT

- Same story in dual version of KKLT in M theory on $\mathrm{CY}_4$

$$X_4 = (X_3 \times T^2)/\mathbb{Z}_2$$

$$\tau$$

- Same kind of superpotential, controlled by self-dual flux $G_4$

$$W = \int_{X_4} \Omega_4 \wedge G_4 + \sum_{\mathbf{k}} \mathscr{A}_{\mathbf{k}}(z^i, G_4)\ e^{-2\pi k^\alpha T_\alpha}$$

$$G_4 = F_3 \wedge a + H_3 \wedge b$$

- Get scale-separated $\mathrm{AdS}_3$

$$\frac{1}{l^2_{\mathrm{AdS}_3}} = -4e^K |W|^2 \Big|_{D_a W=0} \ll 1$$

Idea: trade fluxes with branes

# Fluxes/branes for black holes

4d « MSW » black hole:
[Maldacena, Stominger, Witten '97]

M5 brane wrapping $S^1_y$ and $L_4 \subset \mathrm{CY}_3$

| | | 0 | $\mathbb{R}^3$ | $S^1_y$ | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|---|---|---|
| | M5 | $-$ | $\overset{r=0}{\bullet}$ | $-$ | $-$ | $-$ | $-$ | $-$ | | |
| $p^i$ | M5 | $-$ | $\overset{r=0}{\bullet}$ | $-$ | | | $-$ | $-$ | $-$ | $-$ |
| | M5 | $-$ | $\overset{r=0}{\bullet}$ | $-$ | $-$ | $-$ | | | $-$ | $-$ |
| $q$ | P | $-$ | $\overset{r=0}{\bullet}$ | $\rightarrow$ | | | | | | |

The zoom-in of the branes at the triple intersections

- Moduli / CY shape are stabilised near horizon:

$$t^i = p^i \sqrt{\frac{q}{\frac{1}{6}C_{ijk}p^ip^jp^k}} \qquad \mathcal{V} = \sqrt{\frac{q^3}{\frac{1}{6}C_{ijk}p^ip^jp^k}}$$

11d: stabilisation from fluxes on CY

11d: competition between branes

- BH entropy:

$$S = 2\pi\sqrt{\frac{q}{6}c_L}$$

11d: triple intersections
$c_L = C_{ijk}p^ip^jp^k + c_{2,i}\,p^i$

Number d.o.f. $\leftrightarrow$ AdS$_2$ radius in 4d units

# Fluxes/branes for KKLT

- On CY$_4$ $X_4$: trade the $G_4$ flux for M5 branes on orthogonal cycle $L_4 \subset X_4$.
- $G_4 = \star\, G_4$, so locally looks like

| | 0 | $y$ | $z$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M5 | — | — | $\overset{z=0}{\bullet}$ | — | — | — | — | | | | |
| M5 | — | — | $\overset{z=0}{\bullet}$ | | | | | — | — | — | — |

- 3d: KKLT AdS$_3$ as sourced by a domain wall

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

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

At $z = +\infty$, reach KKLT AdS$_3$

tension of the wall

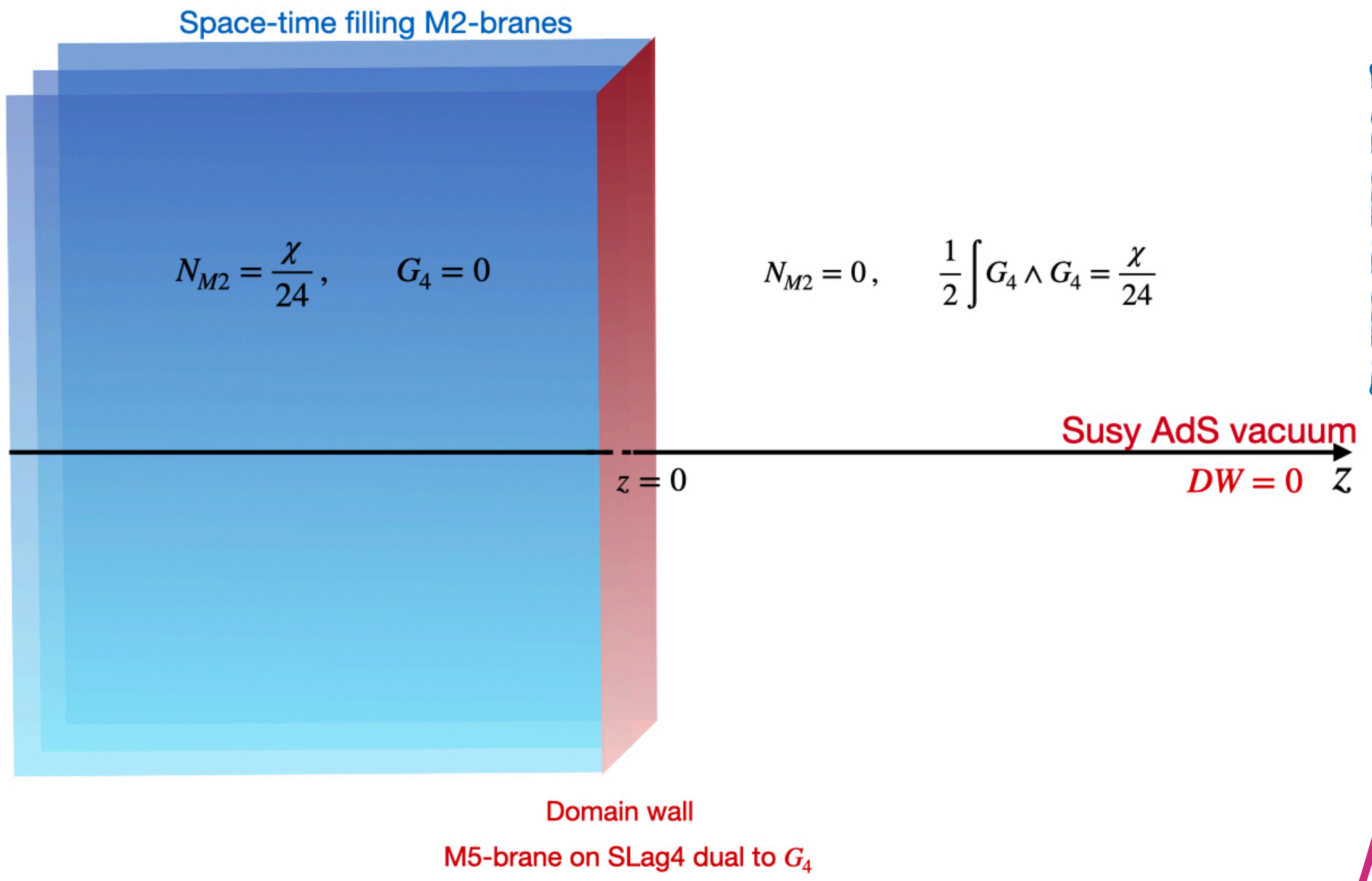
$|Z|^2 \sim \Delta \langle V \rangle$

# Domain-wall holography

[S. Lüst, Vafa, Wiesner, Xu '22]

No $G_4$ flux on $X_4$

$$\frac{\chi(X_4)}{24} = N_{\mathrm{M2}} + \frac{1}{2}\int \cancel{G_4 \wedge G_4}$$




Susy AdS$_3$ from M-theory on $X_4$ in the presence of self-dual $G_4$ flux

$$\frac{\chi(X_4)}{24} = \cancel{N_{\mathrm{M2}}} + \frac{1}{2}\int G_4 \wedge G_4$$

IR

DW: M5 brane on special Lagrangian $L_4$

(1+1)d QFT

UV

# The estimated UV CFT

[S. Lüst, Vafa, Wiesner, Xu '22]

- Count possible deformations of special Lagrangian $L_4$ in $X_4$

$$c_{\rm UV} = \left(1 + \frac{1}{2}\right) L_4 \cdot L_4 + \left(4 + \frac{4}{2}\right) b_1(L_4)$$

M5 self-intersections in $X_4$

$b_1$ independent M5-strips in $X_4$

Scale $L_4 \to N_{\rm flux}\, L_4$ : $\sim (N_{\rm flux})^2$ $\qquad \mathcal{O}[(N_{\rm flux})^2]$

Need it exponentially small

$$c_{\rm IR} \leq c_{\rm UV} \sim (N_{\rm flux})^2$$

$$|\Lambda_{\rm AdS}| \geq \mathcal{O}\left[\frac{1}{(N_{\rm flux})^2}\right]$$

$\Rightarrow$ Not enough d.o.f. on the brane to get a sufficiently small C.C.!

# The near-horizon limit

$$
\begin{aligned}
ds^2 =& H_T^{-2/3}\left(H_F^{(1)}H_F^{(2)}\right)^{-1/3}\left(-dt^2+dx_1^2\right)+H_T^{-2/3}\left(H_F^{(1)}H_F^{(2)}\right)^{2/3}dx_2^2 \\
&+H_T^{1/3}\left(H_F^{(1)}\right)^{-1/3}\left(H_F^{(2)}\right)^{2/3}\left(dr^2+r^2d\Omega_{(1)}^2\right) \\
&+H_T^{1/3}\left(H_F^{(1)}\right)^{2/3}\left(H_F^{(2)}\right)^{-1/3}\left(dr'^2+r'^2d\Omega_{(2)}^2\right)\,.
\end{aligned}
$$

| | $y$ | $z$ | $(r,\Omega_3^{(1)})$ | $(r',\Omega_3^{(2)})$ |
|---|---|---|---|---|
| $\mathrm{M5}_1$ | $\otimes$ | $\sim$ | $\otimes$ | $\overset{r'=0}{\bullet}$ |
| $\mathrm{M5}_2$ | $\otimes$ | $\sim$ | $\overset{r=0}{\bullet}$ | $\otimes$ |
| $\mathrm{M2}_1$ | $\otimes$ | $\otimes$ | $\sim$ | $\overset{r'=0}{\bullet}$ |
| $\mathrm{M2}_2$ | $\otimes$ | $\otimes$ | $\overset{r=0}{\bullet}$ | $\sim$ |

- Near-horizon limit: [de Boer, Pasquinucci, Skenderis '99]

$$l_p\to 0,\qquad U=\frac{r^2}{l_p^3}=\text{fixed},\qquad U'=\frac{r'^2}{l_p^3}=\text{fixed}.\qquad \longrightarrow \qquad \mathrm{AdS}_3\times T^2\times S^3\times S^3$$

$$u^2=l^2\frac{UU'}{Q_3},\qquad \lambda=\frac{l}{2}\left(\sqrt{\frac{Q_1}{Q_2}}\log U-\sqrt{\frac{Q_2}{Q_1}}\log U'\right),\qquad l=\sqrt{\frac{Q_1Q_2}{Q_1+Q_2}}$$

« radial » « angular »

$(t,u,y)$ $(z,\lambda)$ $\Omega_3^{(1)}$ $\Omega_3^{(2)}$

Used $N_2=\dfrac{\chi(X_4)}{24}=\dfrac{1}{2}\displaystyle\int G_4\wedge G_4$

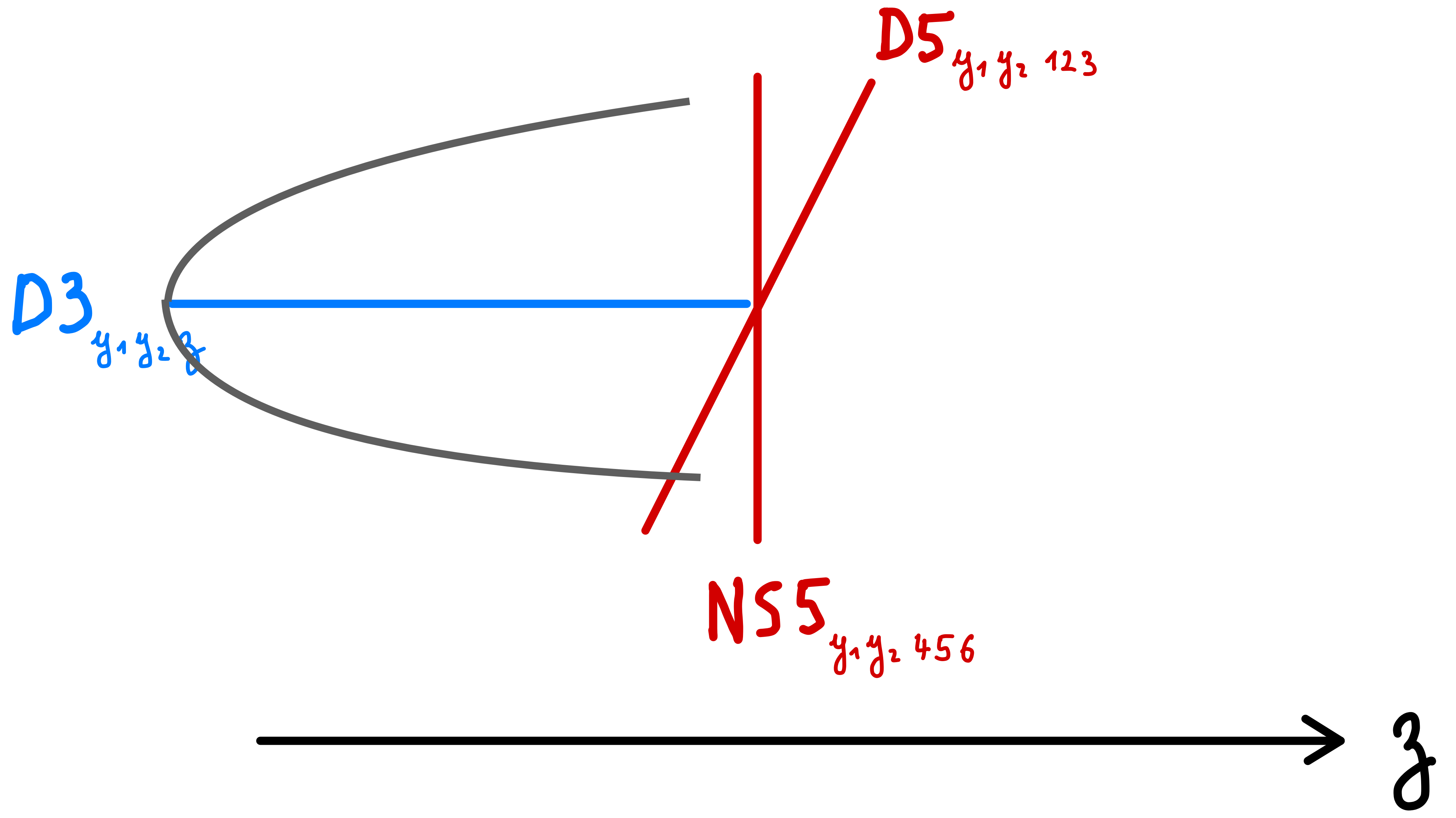
- Central charge: $c\propto N_2N_5\propto (N_{\text{flux}})^3 \;>(N_{\text{flux}})^2$

[S. Lüst, Vafa, Wiesner, Xu '22]

→ Weaker bound on Λ due to the M2 branes!

# KKLT *ex nihilo*

- In fact the D3 branes can have infinitely-many d.o.f.
- But we are interested in the d.o.f. of the intersection

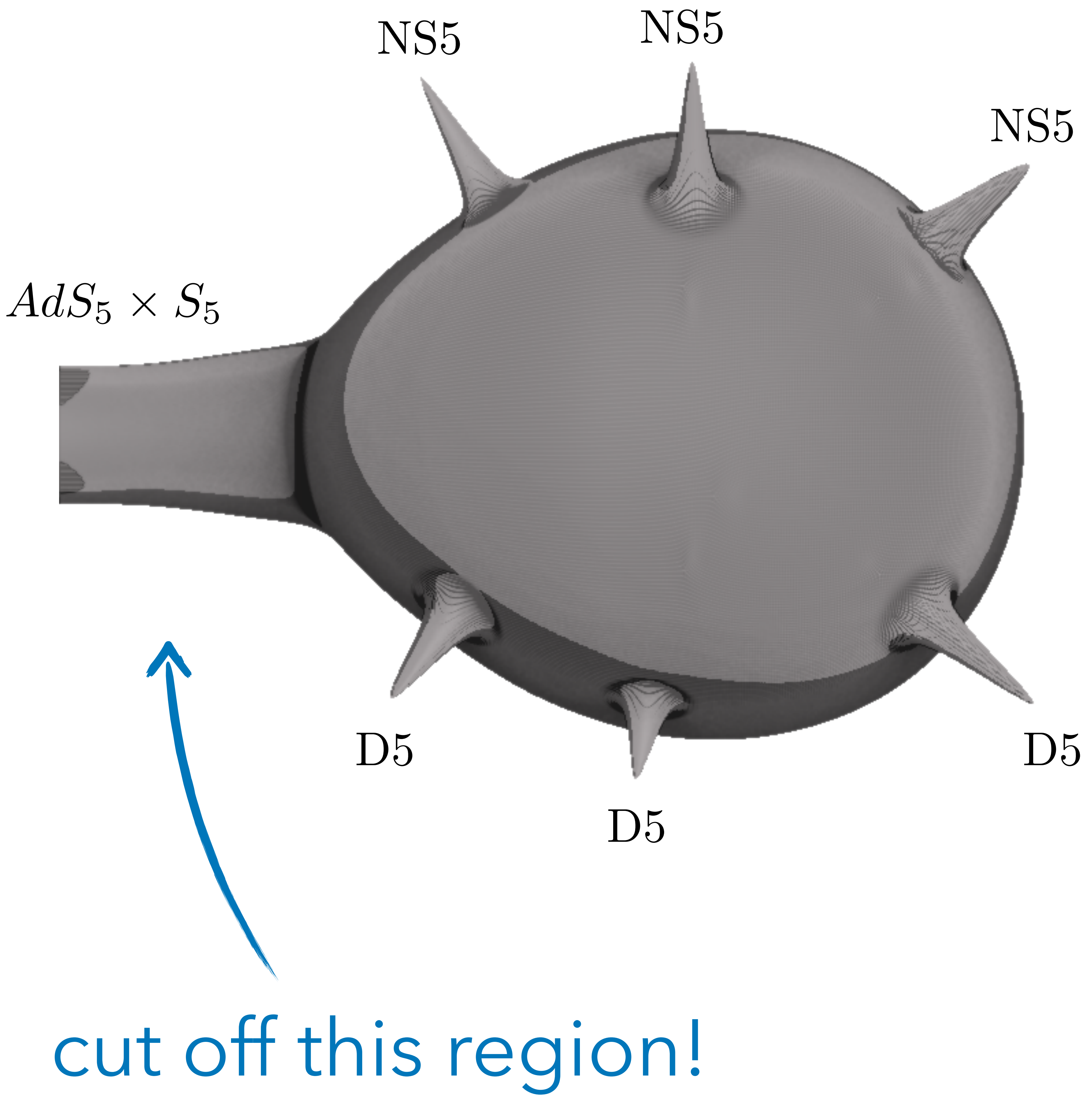



- The location of the D3 branes modifies $W_{n.p.}$.
  - → Choose it such that the CY shrinks on the left
  - → Space-time ends there
- This brane system sources the KKLT AdS *out of nothing.*

# Infinite central charge?

- Sugra solution for D3 ending on D5-NS5 is known.

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

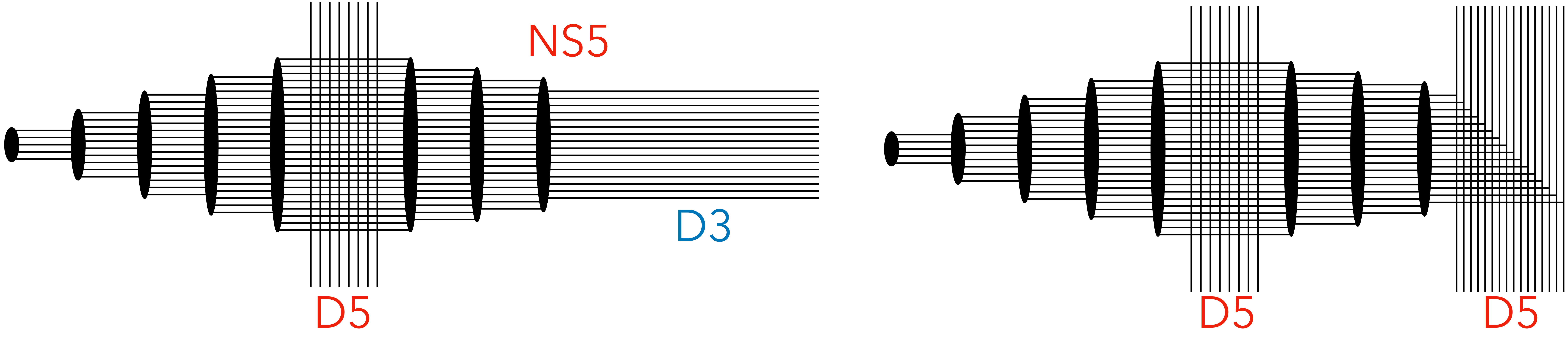



- The solution is an $\mathrm{AdS}_4 \times S^2 \times S^2 \times_w \Sigma_2$
- Need estimate of AdS radius in 4d Planck units: $c_{UV} \sim \dfrac{l_{AdS}}{G_N}$
- $V_6$ infinite because of the $\mathrm{AdS}_5$ region

# Finite central charge

- Trick to cut off infinite $AdS_5$ region from CFT: end the D3's on some D5's.

[Karch, Sun, Uhlemann '22]




- Compute free energy: $F \sim (N_{\text{flux}})^4 \log(N_{\text{flux}})$

The radius of the $AdS_4$ solution dual to this quiver has the same scaling!

[Assel, Estes, Yamazaki '12] [Bachas, Lavdas '17]