Holography for KKLT: Anatomy of a Flow

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Yixuan Li

MPI Munich

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

DFG
German-Israeli Project Cooperation (DIP)
Holography and the Swampland

Work to appear with I. Bena and S. Lüst

June 25th, 2024

Scale separation and de Sitter

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

[Obied, Ooguri, Spodyneiko, Vafa '18]

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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]

[See talks by A. Schachner and L. McAllister]

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

   → dS vacuum with broken SUSY

   $\Lambda > 0$

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Study this step through holography and domain walls

KKLT 101

- Complex-structure deformations (3-cycles) stabilised by fluxes,
- Kähler moduli (2- and 4-cycles) stabilisation need D3 instanton corrections

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

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

need to be $\ll 1$

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- Get C.C. in terms of stabilised Kähler modulus σ_0

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

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

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Idea: trade fluxes with branes

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

Fluxes/branes for KKLT

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

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

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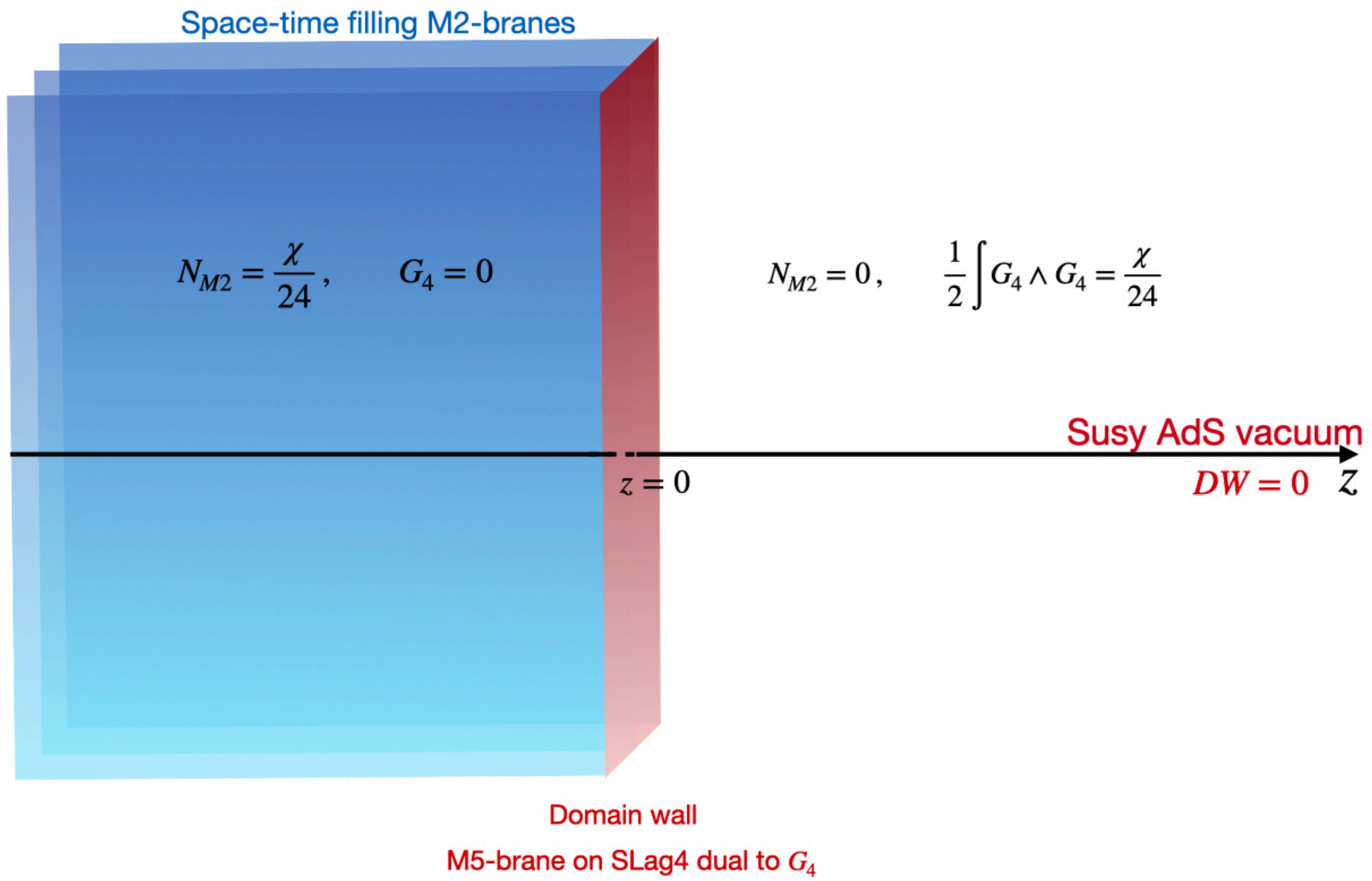
- 3d version of KKLT from M theory
- **On CY$_4$**: trade the G_4 flux for M5 branes on dual cycle $L_4 \subset$ CY$_4$.
  - $G_4 = \star\, G_4$, so locally looks like

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

Domain-wall holography

[S. Lüst, Vafa, Wiesner, Xu '22]

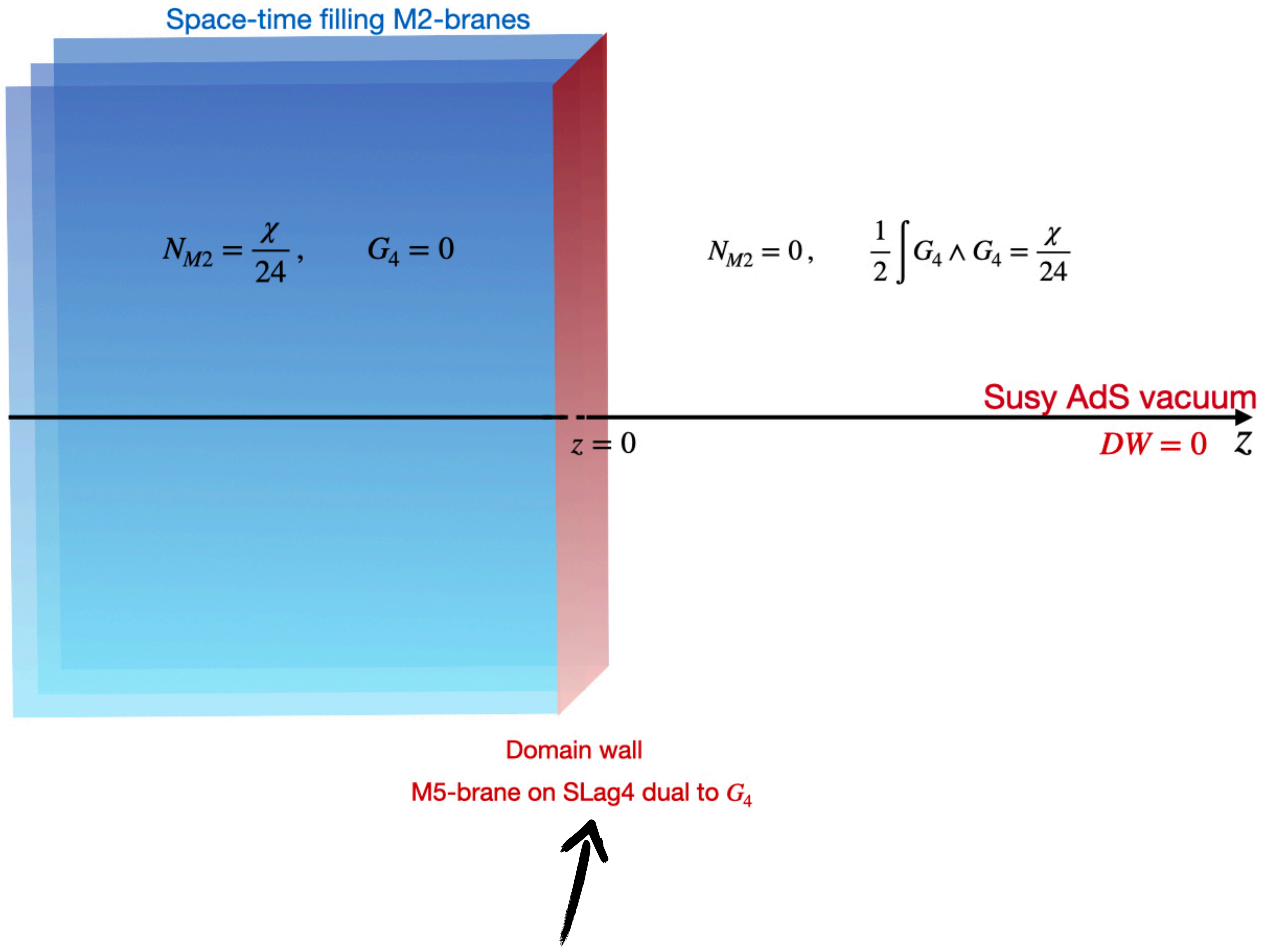
Susy AdS_3 from M-theory on X_4 in the presence of self-dual G_4 flux



DW: M5 brane on special Lagrangian L_4

The holographic bound

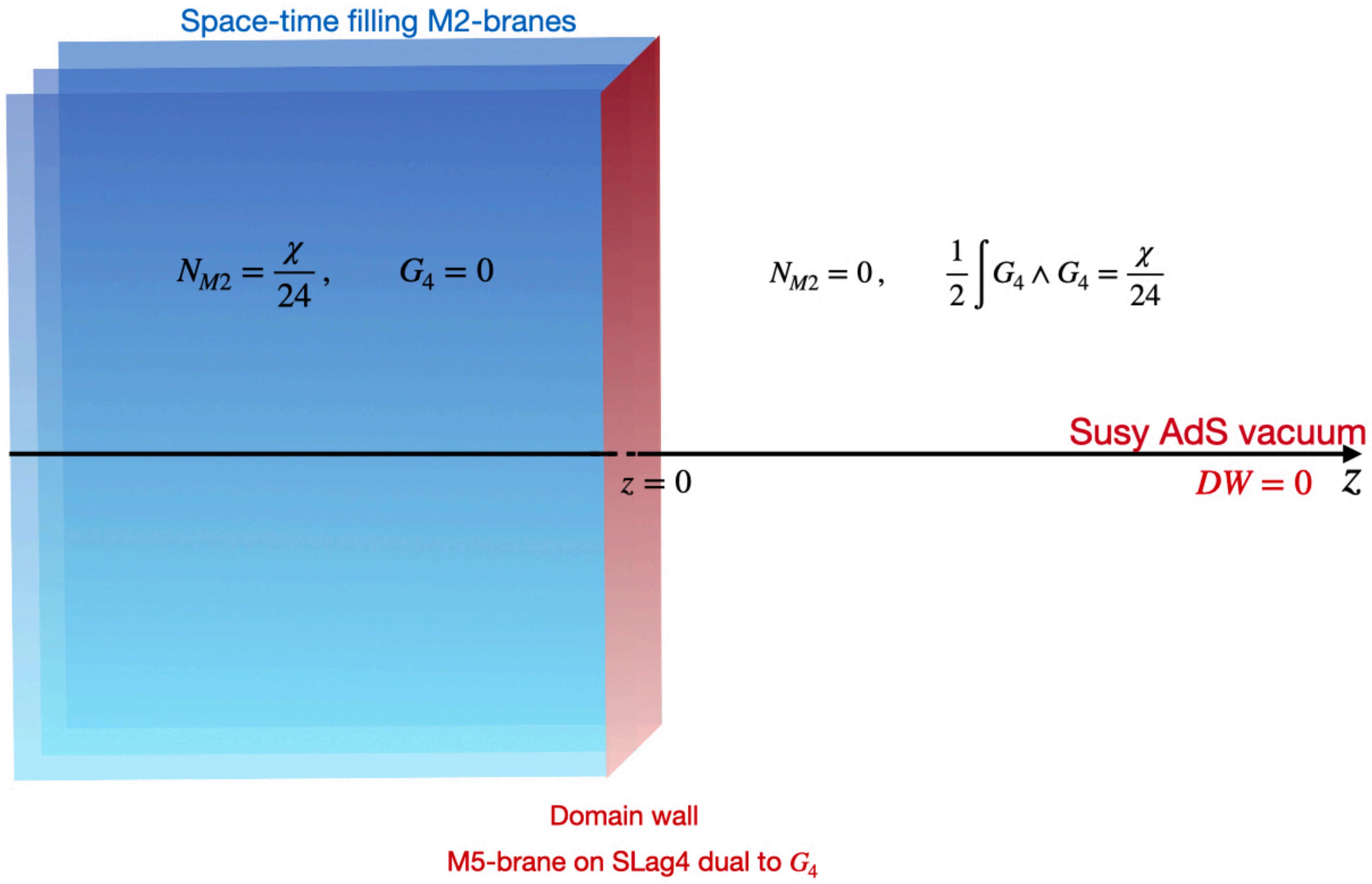
[S. Lüst, Vafa, Wiesner, Xu '22]



The DW contains d.o.f.

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

The holographic bound



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

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

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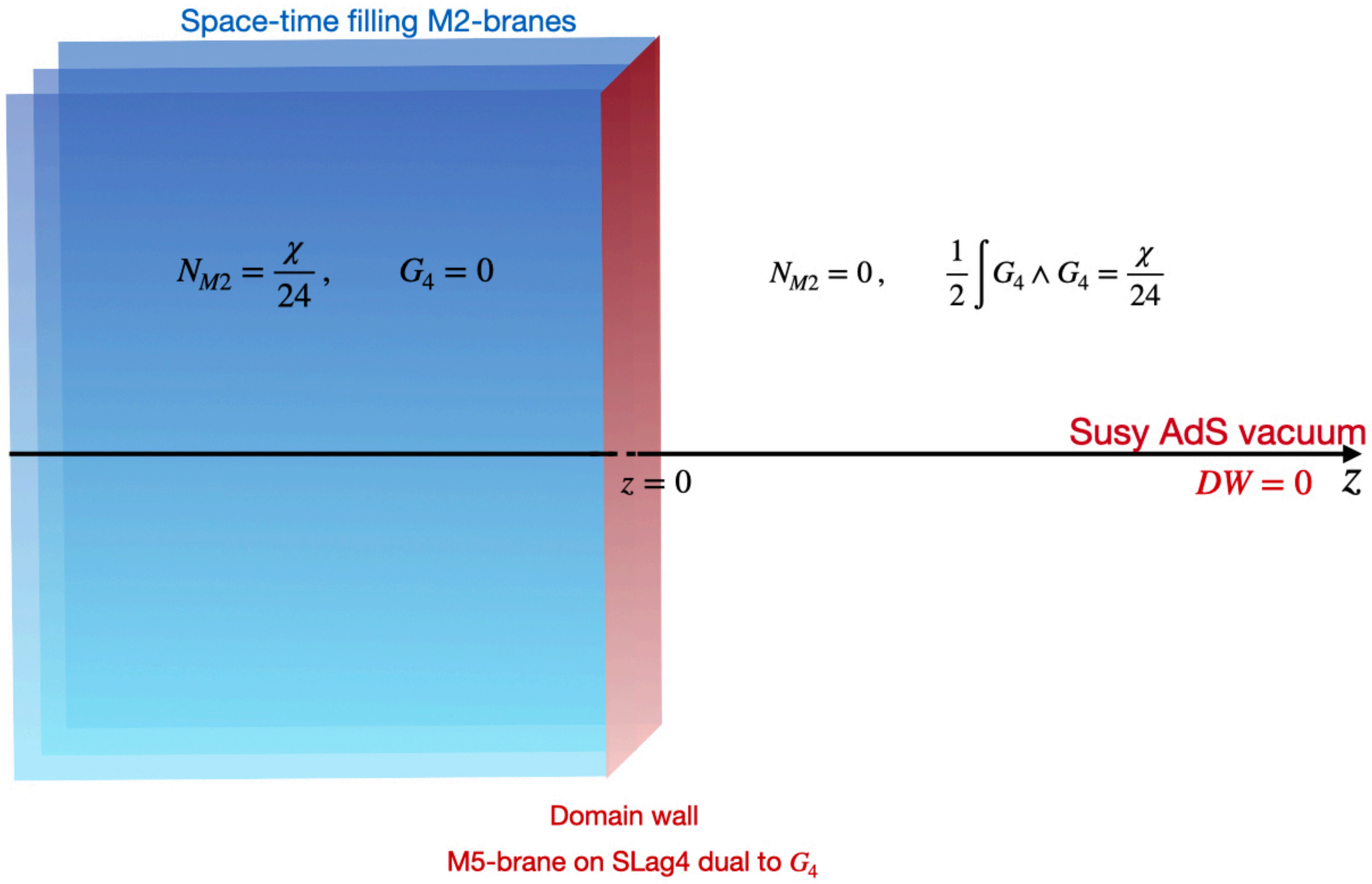

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♯ (d.o.f.) → « UV » central charge, $c_{\rm UV}$.

$$c_{\rm IR} \leq c_{\rm UV}$$

⇒ lower bound on $|\Lambda|$

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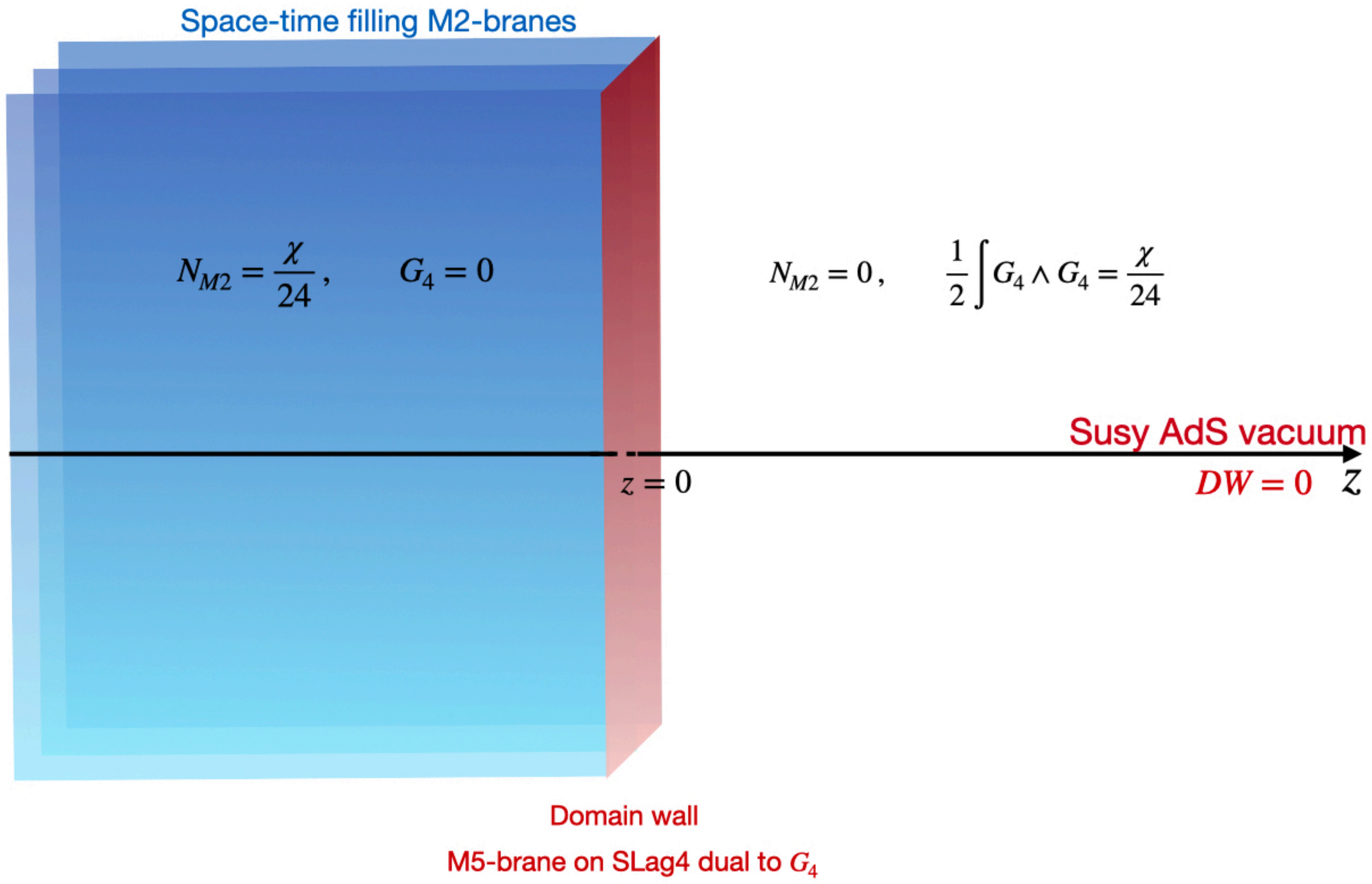

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At $z = +\infty$, the IR central charge measures the radius of the AdS_3:

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

The DW contains d.o.f.

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

Estimate c_{UV}: deformations of SLag

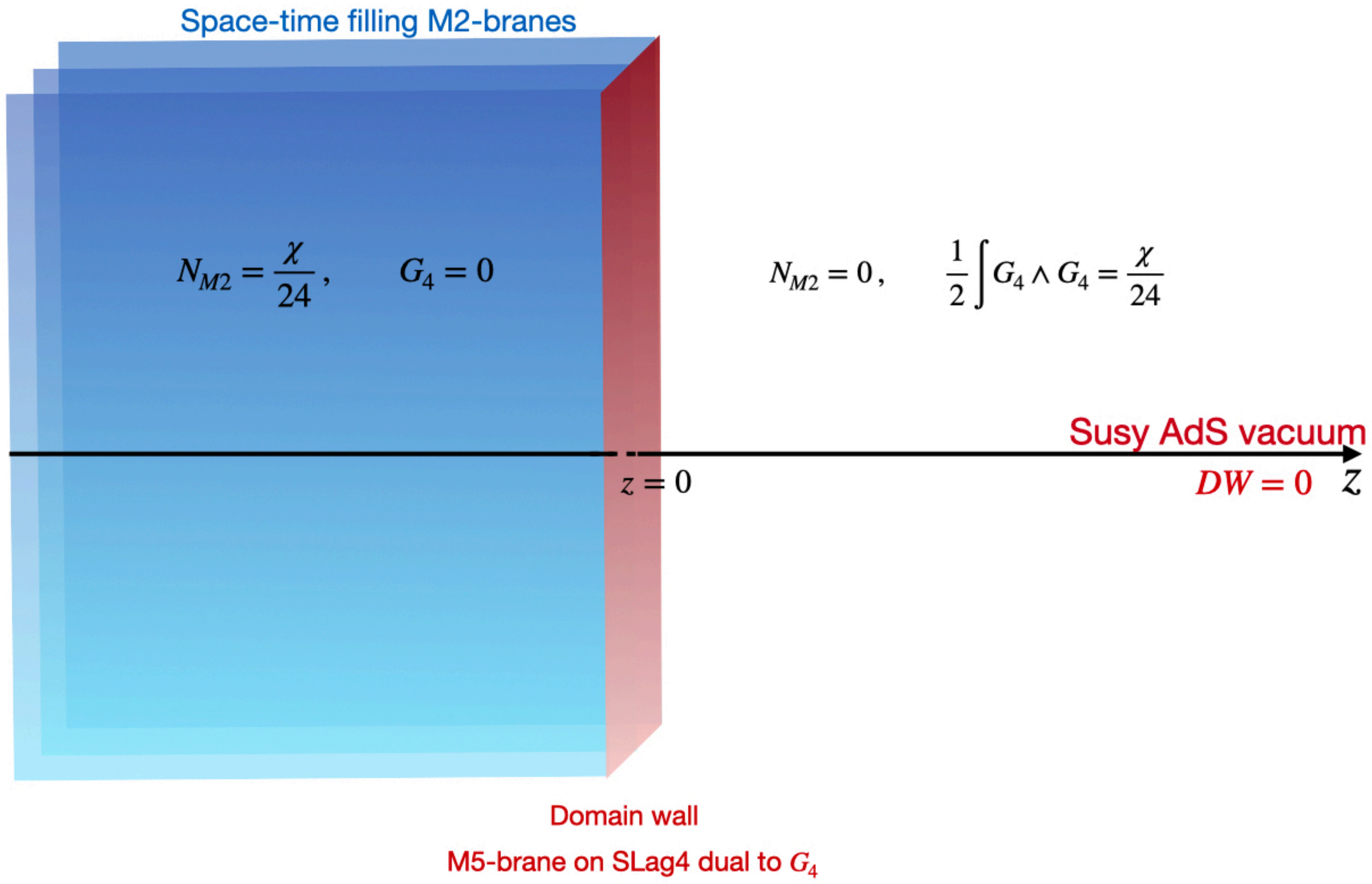
$$c_{\mathrm{IR}} \leq c_{\mathrm{UV}} \sim (N_{\mathrm{flux}})^2$$

⇒ lower bound on $|\Lambda|$

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

The holographic bound

[S. Lüst, Vafa, Wiesner, Xu '22]



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

Need it exponentially small

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

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

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

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 $N_1 + N_5$.)
  - Here: potentially d.o.f. from M2 branes ending on M5 branes

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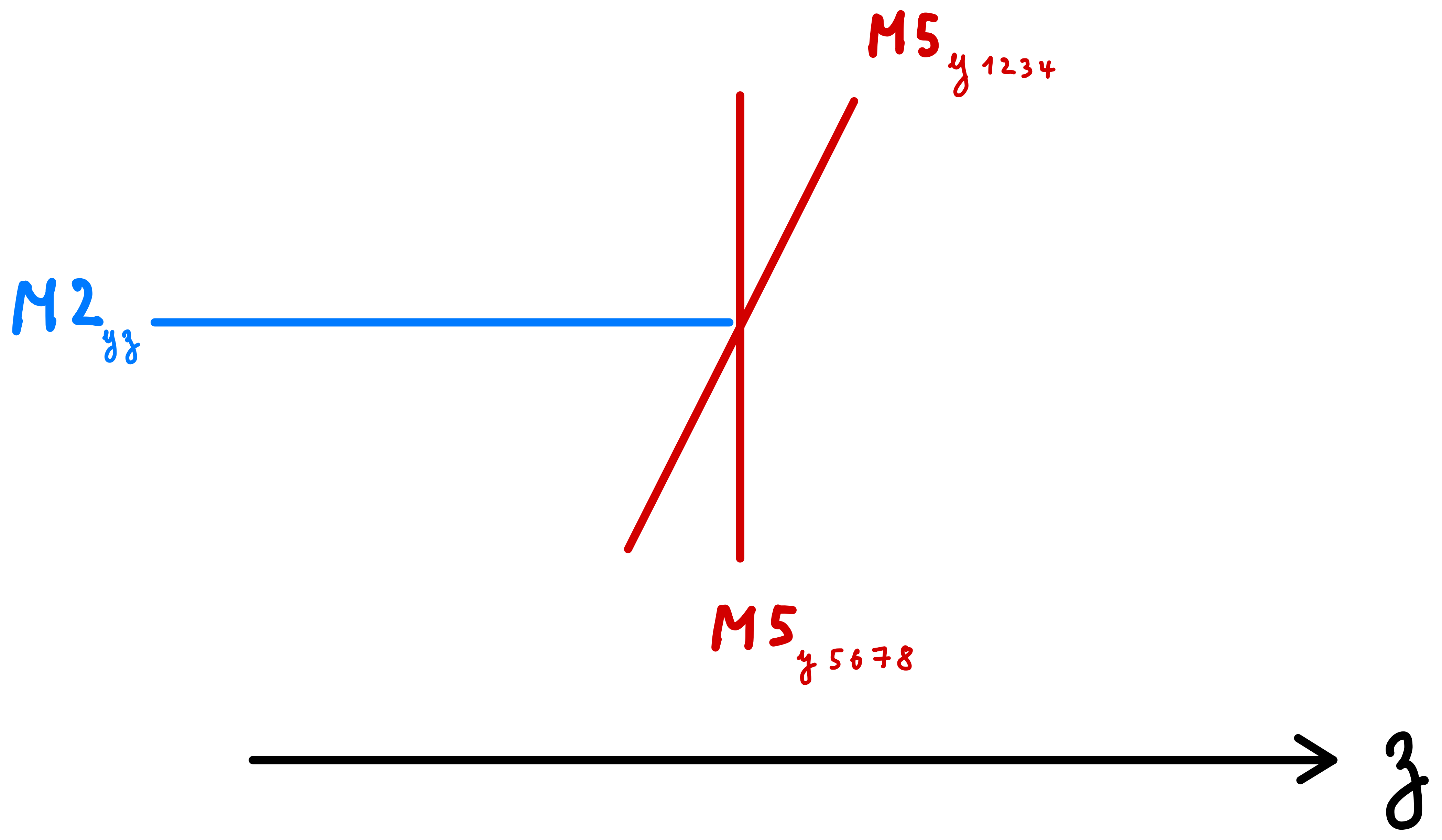
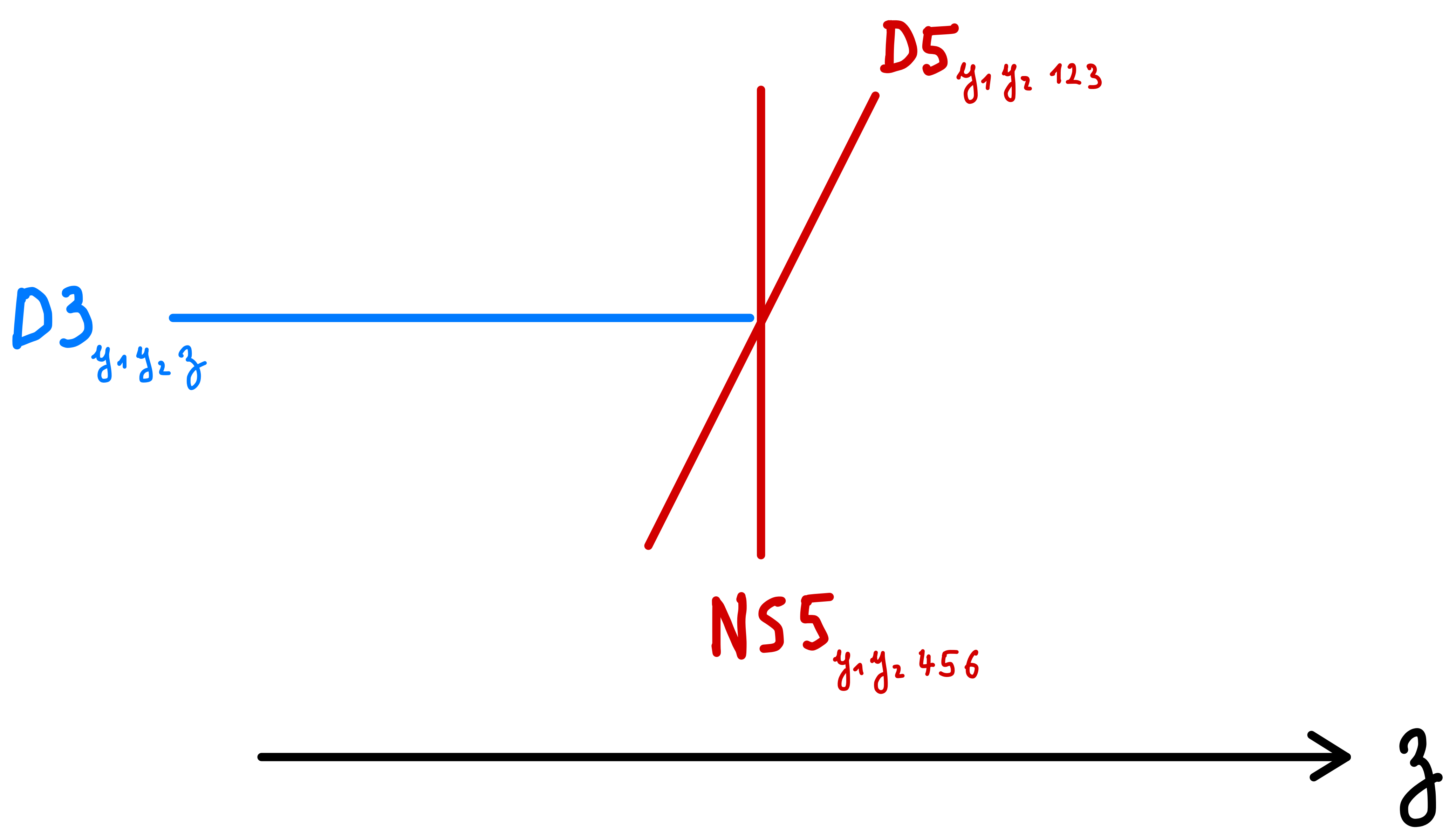
→ Need to evaluate the radius of the AdS corresponding to the brane intersection (with the most d.o.f.)!

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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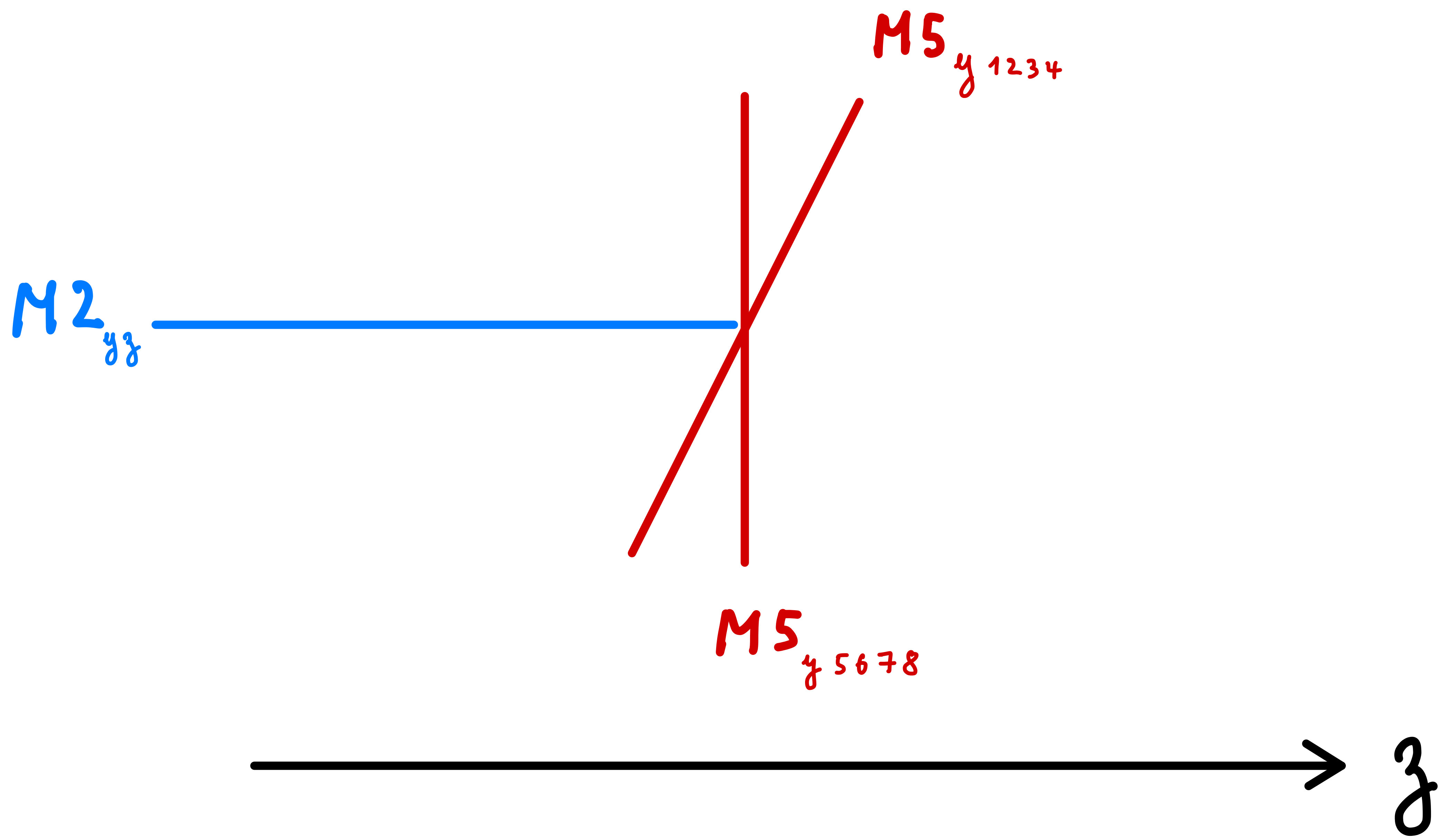
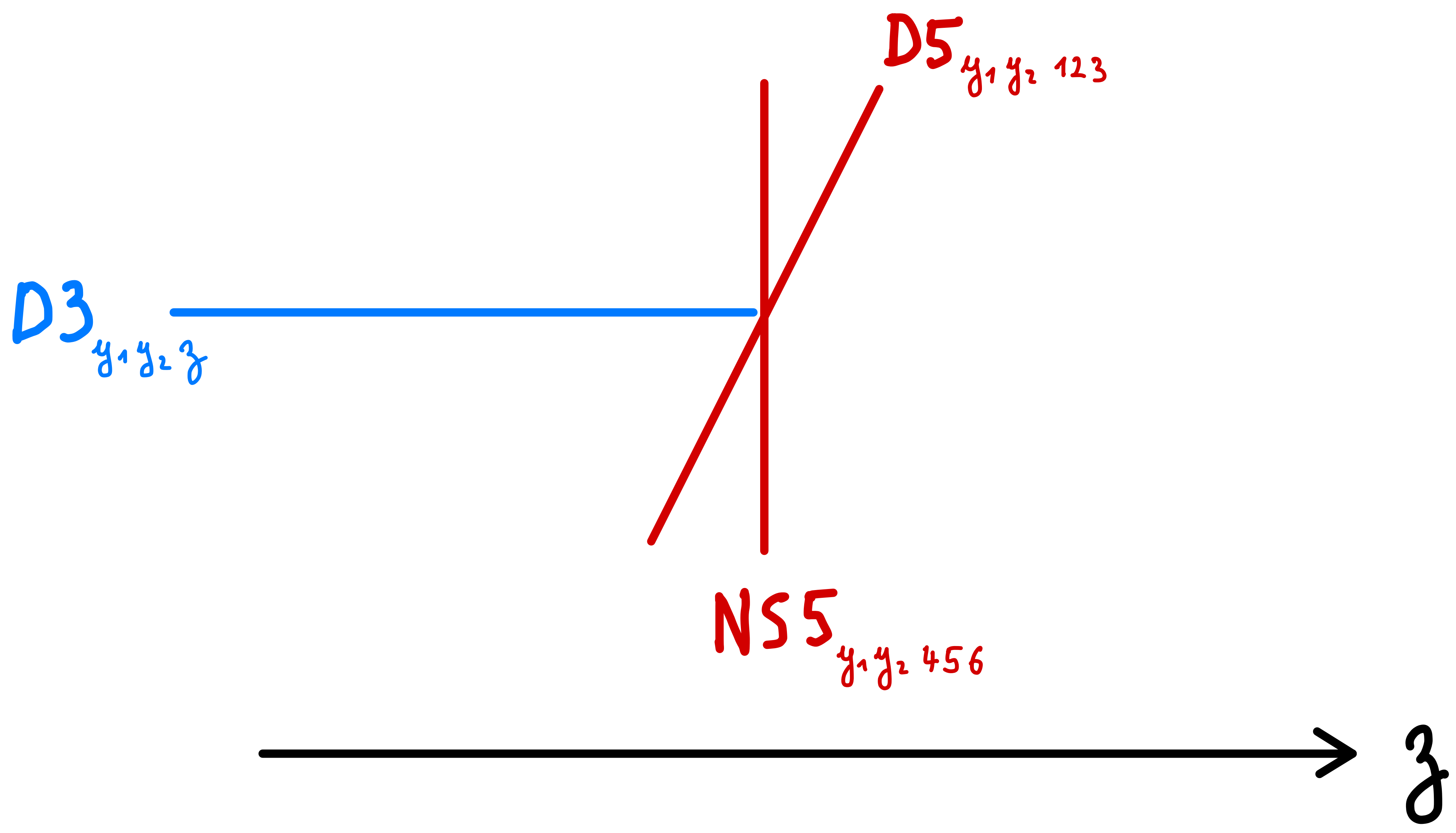
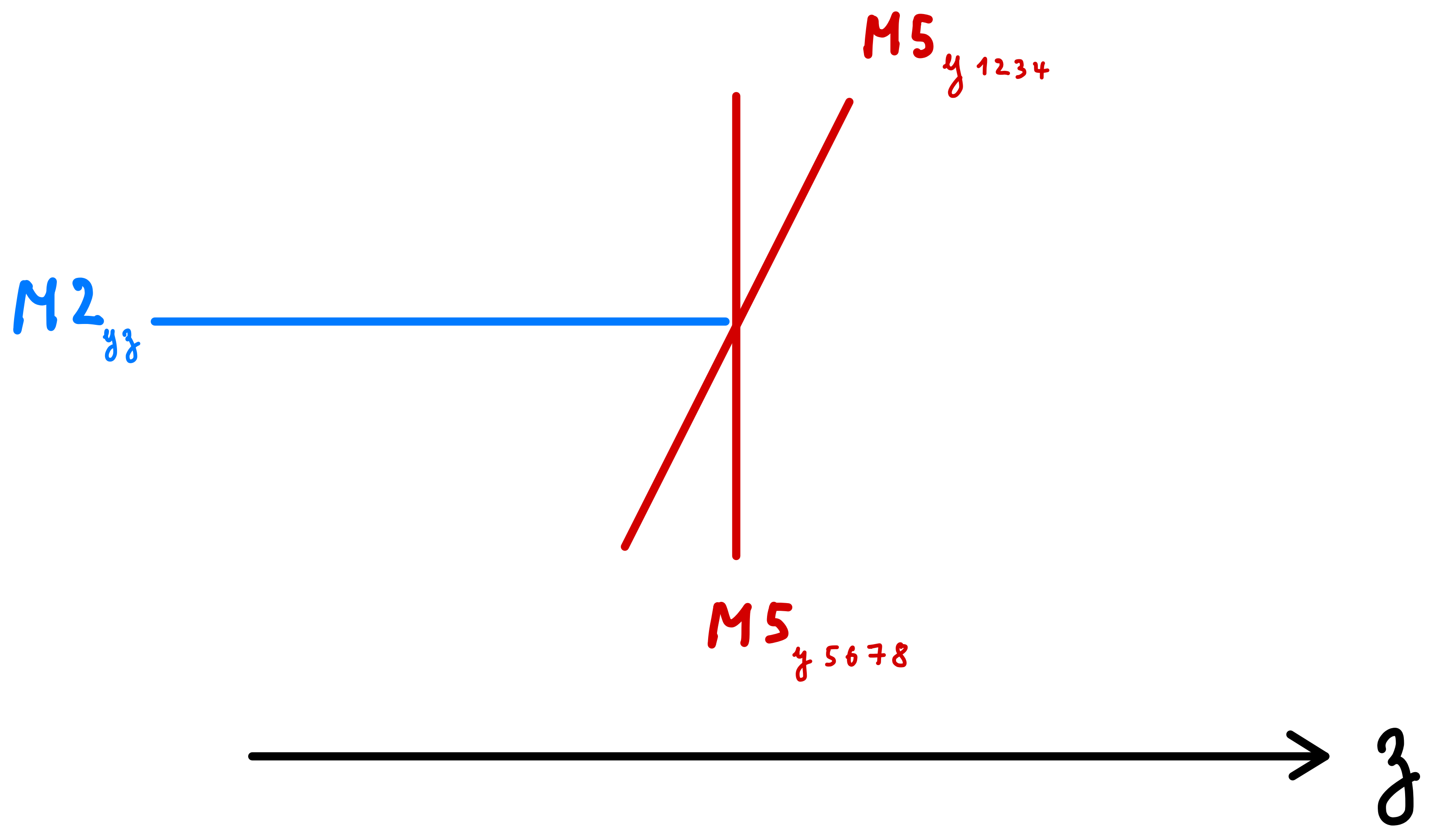


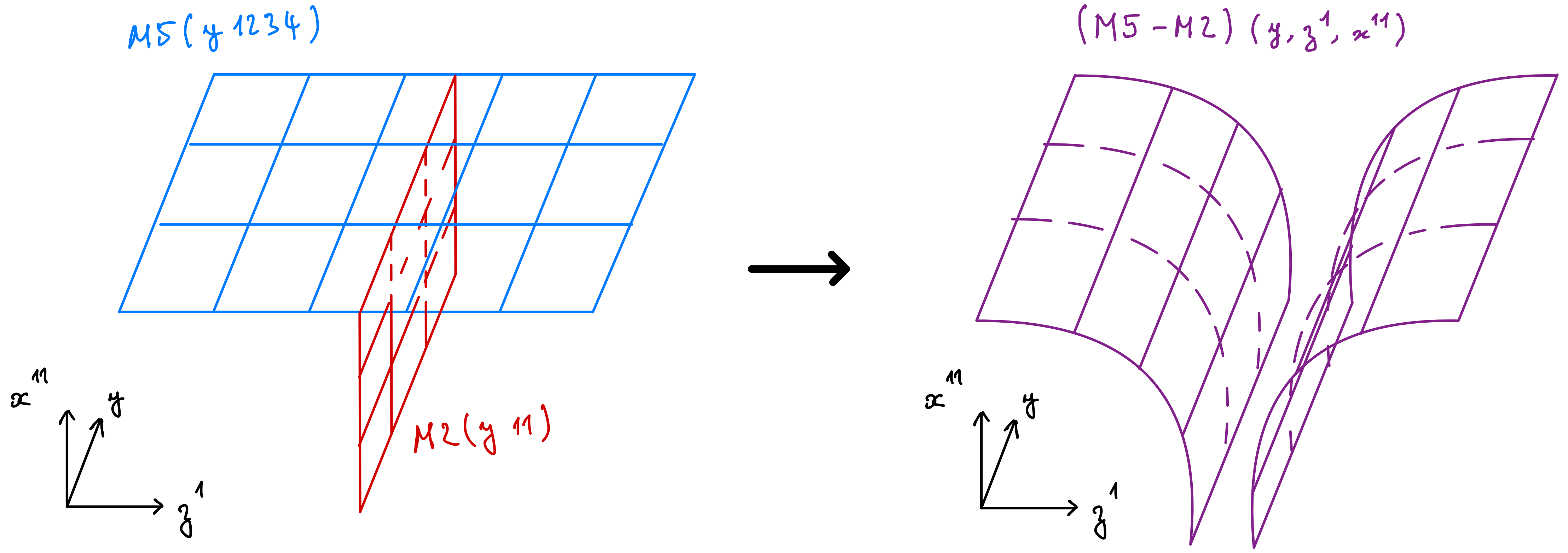


These configurations contain the maximum number of d.o.f. one can get from the branes

Radius of a warped 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





[Bena, Hampton, Houppe, **YL**, Toulikas '22]
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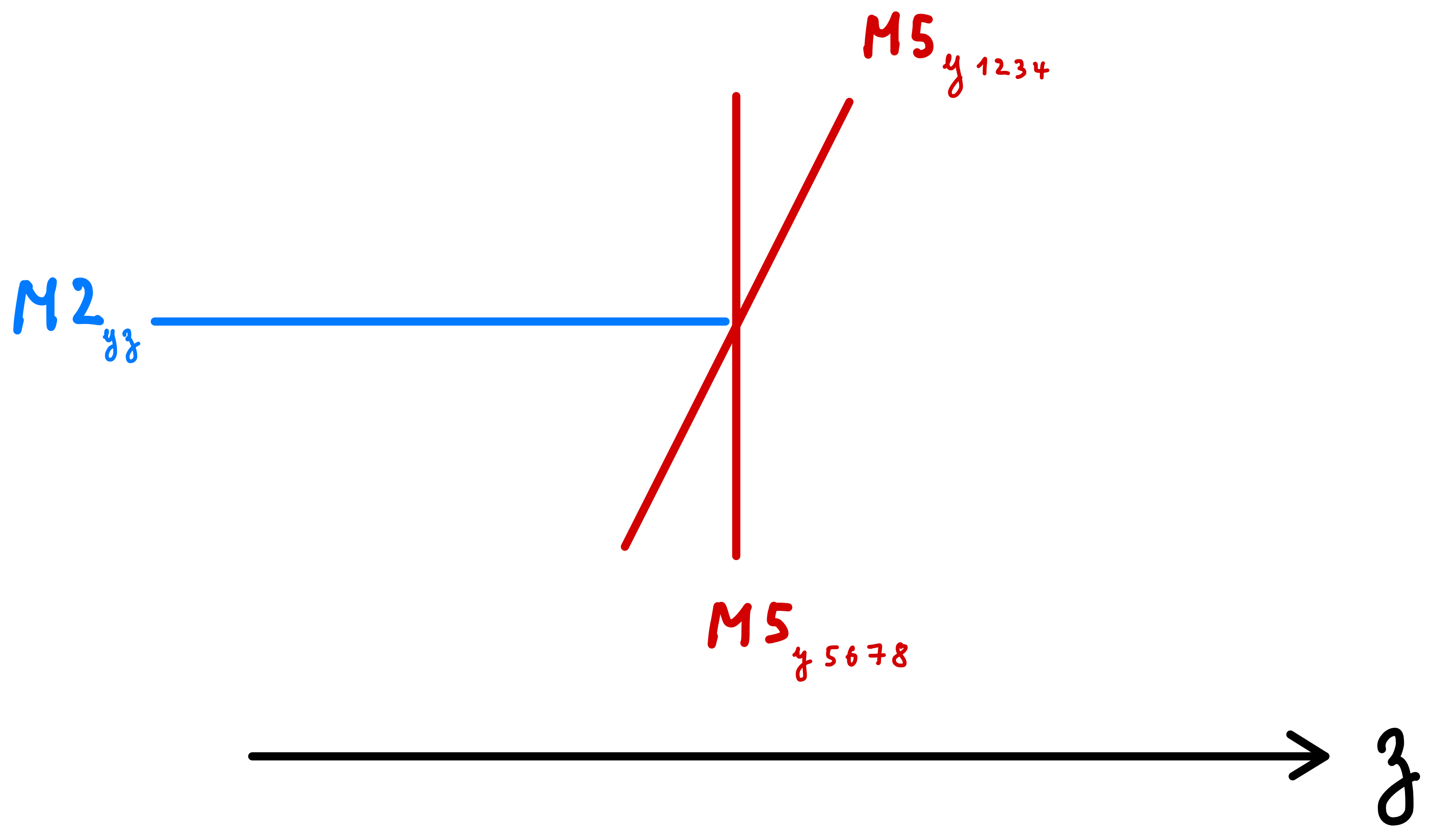

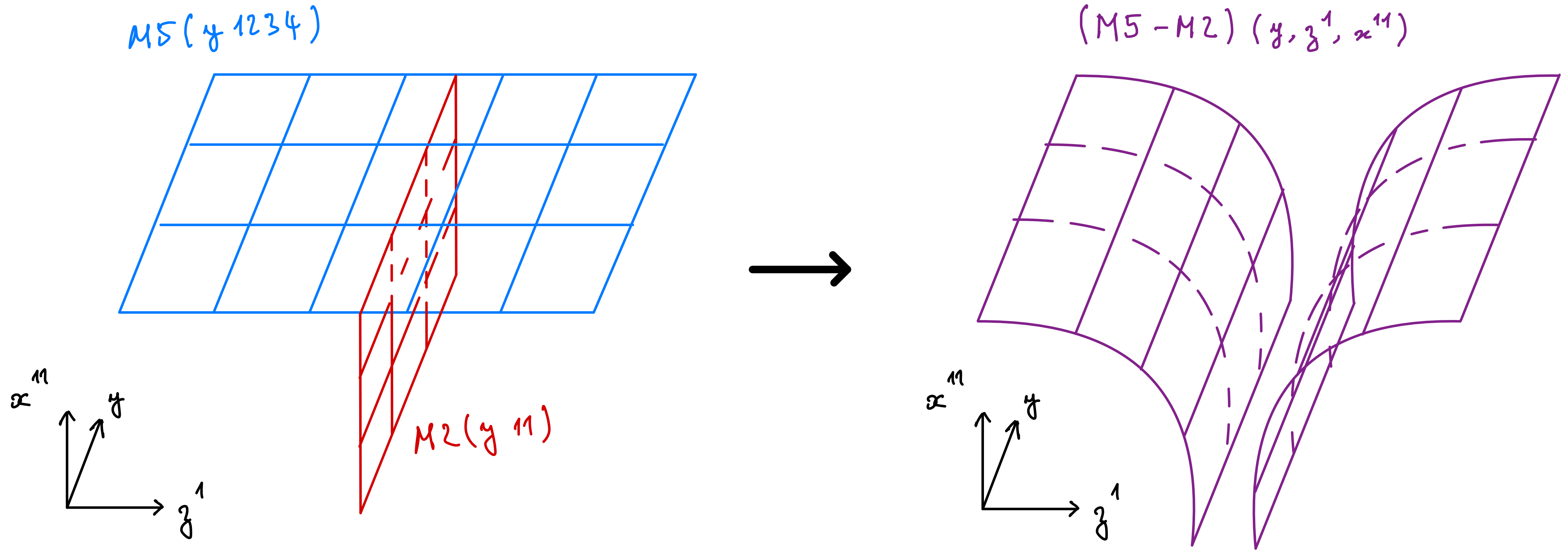

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- Sugra solution, with infrared limit:

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

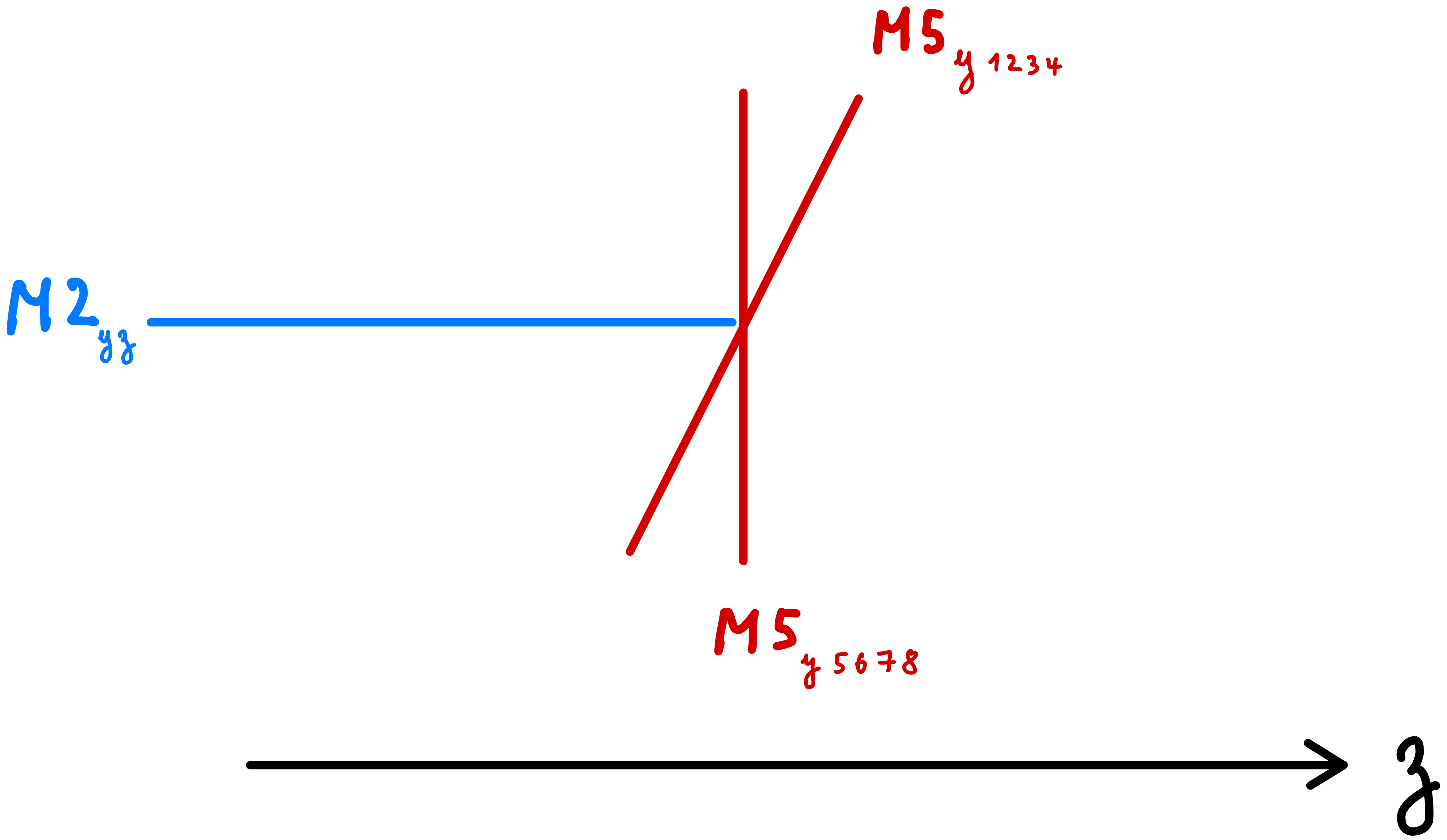
[Lunin '07] [Bachas, D'Hoker, Estes, Krym '13]
[Bena, Houppe, Toulikas, Warner '23]

- 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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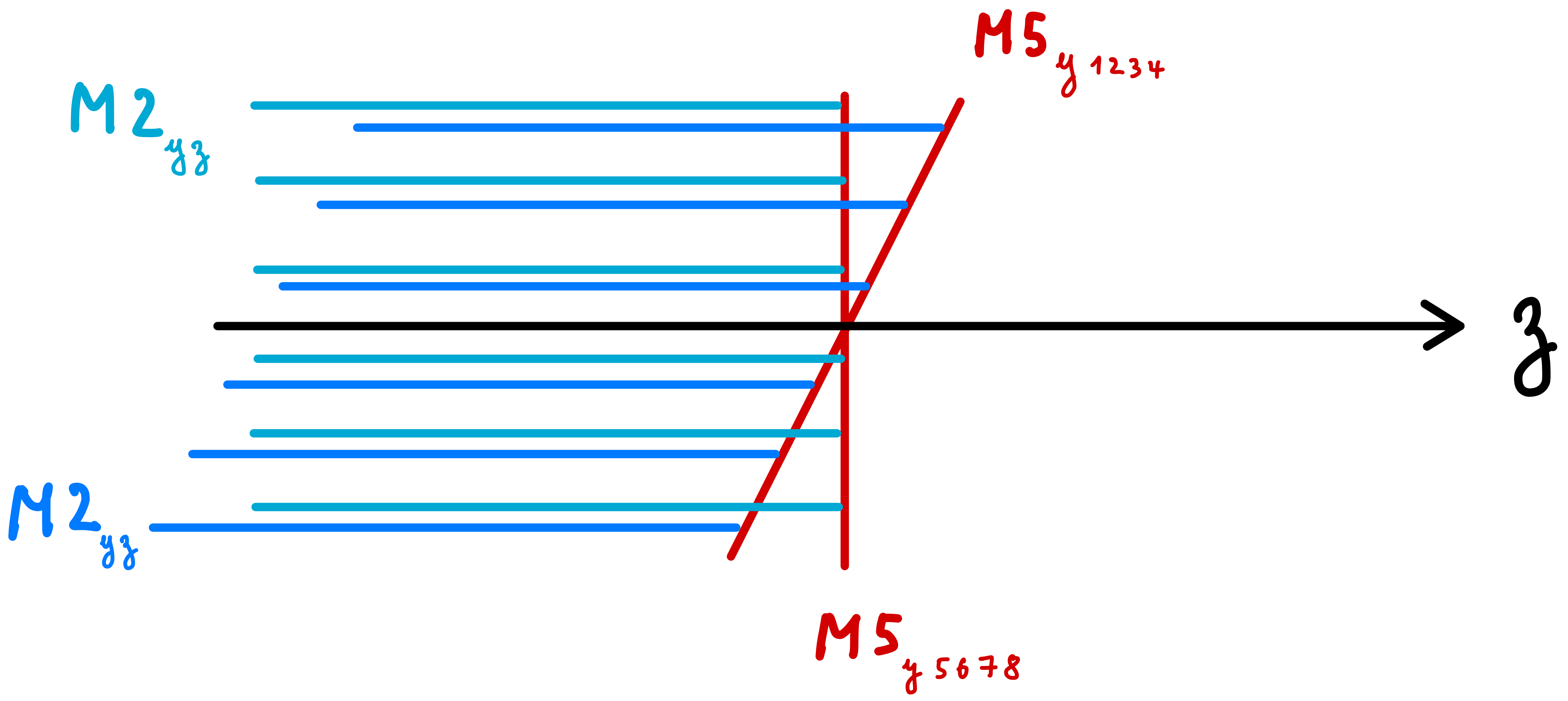

We propose:

- 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 ⇝ 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	$(r,\Omega_3^{(1)})$	$(r',\Omega_3^{(2)})$
$M5_1$	$\otimes$	$\sim$	$\otimes$	$\overset{r'=0}{\bullet}$
$M5_2$	$\otimes$	$\sim$	$\overset{r=0}{\bullet}$	$\otimes$
$M2_1$	$\otimes$	$\otimes$	$\sim$	$\overset{r'=0}{\bullet}$
$M2_2$	$\otimes$	$\otimes$	$\overset{r=0}{\bullet}$	$\sim$

- 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:

$$H_T = \left(1+\frac{Q_T^{(1)}}{r'^2}\right)\left(1+\frac{Q_T^{(2)}}{r^2}\right)$$

[de Boer, Pasquinucci, Skenderis '99]

The near-horizon limit

- Near-horizon limit:

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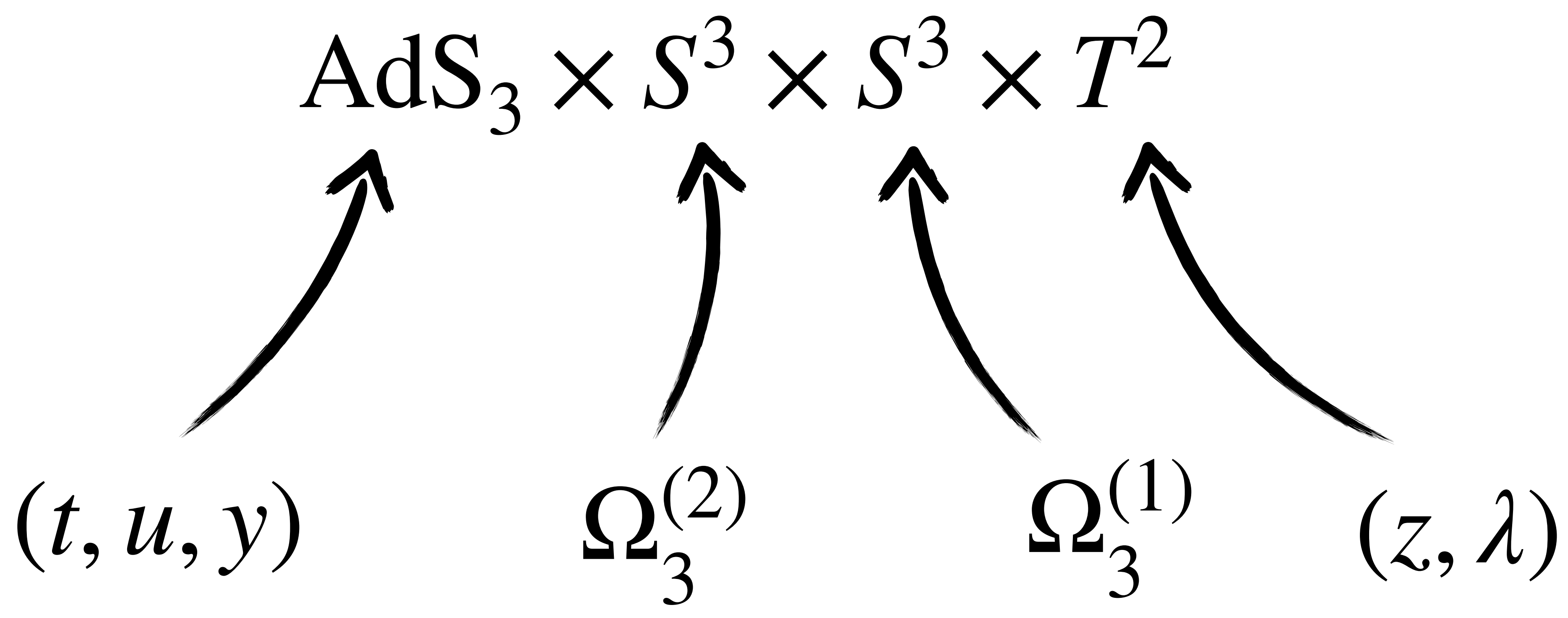

$$r, r' \;\rightarrow\; u \propto r r' \,,\; \lambda \approx \log r - \log r'$$

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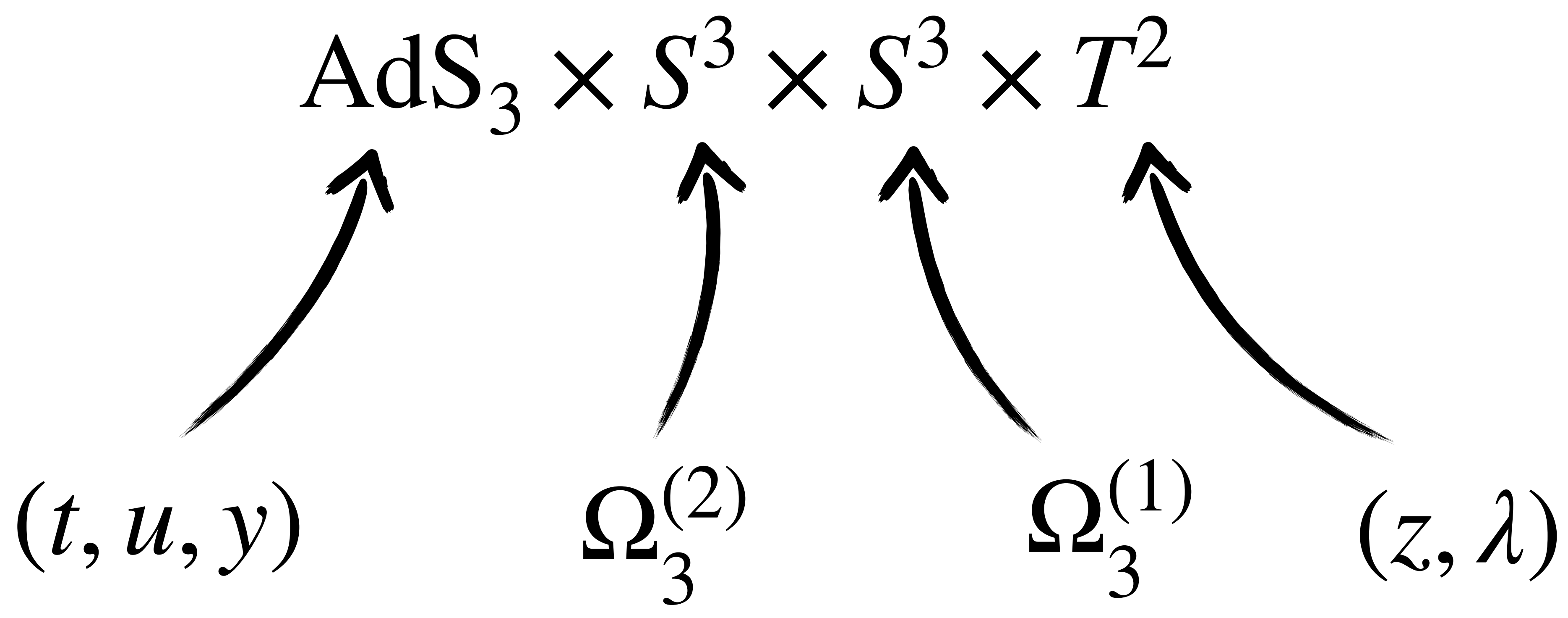

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Used $N_2 = \frac{\chi(X_4)}{24} = \frac{1}{2}\int G_4 \wedge G_4$

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

The near-horizon limit

- Near-horizon limit:

[de Boer, Pasquinucci, Skenderis '99]

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

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

$$r, r' \;\to\; u \propto r r' \,,\; \lambda \approx \log r - \log r'$$

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[S. Lüst, Vafa, Wiesner, Xu '22]

→ Weaker bound on Λ due to the M2 branes!

Warped AdS_4 in type IIB

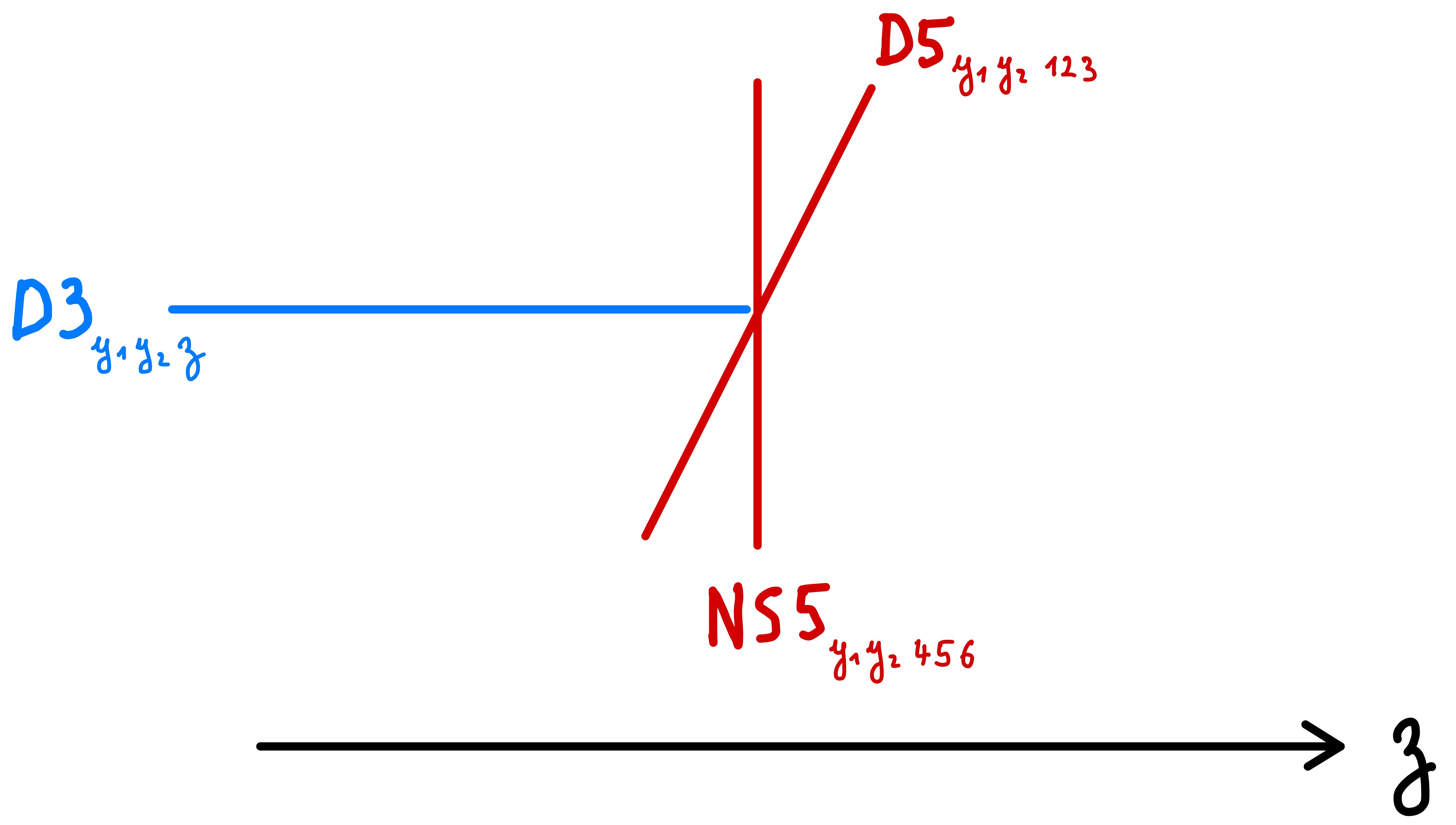
- Sugra solution for D5-NS5-D3 intersection is known.

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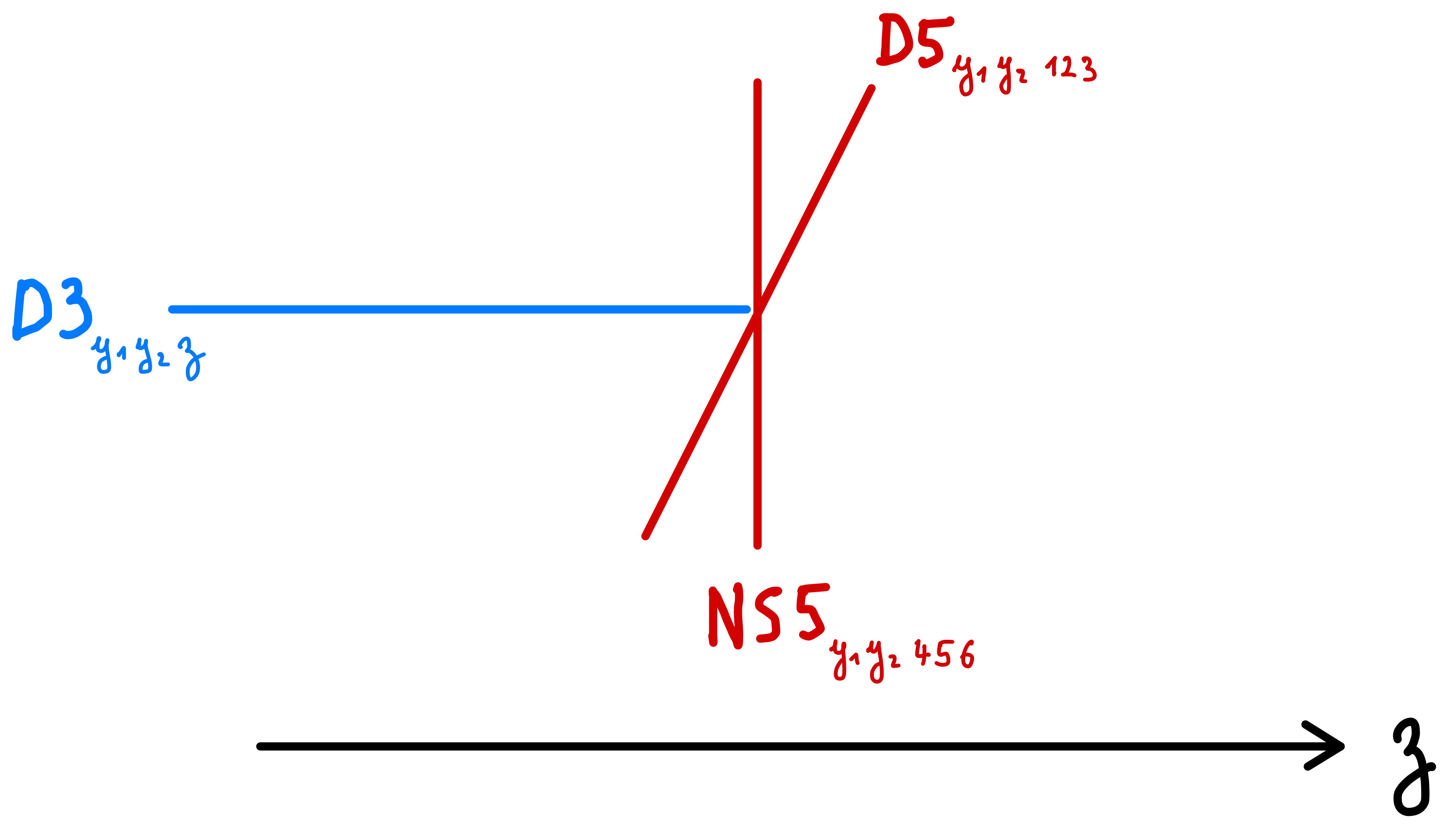
- The solution is an $\mathrm{AdS}_4 \times S^2 \times S^2 \times_w \Sigma_2$
- Compute of AdS radius in 4d Planck units:

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

[Assel, Estes, Yamazaki '12]



Matches the free energy of the 3d CFT!

[Assel, Estes, Yamazaki '12]

[Karch, Sun, Uhlemann '22]

Conclusion

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- Realised KKLT AdS as being sourced by a DW made of M5 or D5/NS5 branes
- Computed AdS radius of the brane intersection (UV)
  - M theory: radius of the AdS_3

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

  - IIB: radius of the AdS_4

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    ↑ Deformations of SLag

    [S. Lüst, Vafa, Wiesner, Xu '22]

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- Cannot have more d.o.f. than that, since we compute the radius of the UV AdS.

  $$|\Lambda_{\text{AdS}}| \geq \mathcal{O}\left[\frac{1}{(N_{\text{flux}})^4}\right]$$
- Therefore there is not enough d.o.f. to get the AdS with $|\Lambda| \ll 1$ in the KKLT scenario.

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    ↑ Hanany-Witten-like d.o.f.
- Cannot have more d.o.f. than that, since we compute the radius of the UV AdS.

$$|\Lambda_{\text{AdS}}| \geq \mathcal{O}\left[\frac{1}{(N_{\text{flux}})^4}\right]$$

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

Thank you!

Backup slides

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	—	—	$z=0$ ●	—	—	—	—				
M5	—	—	$z=0$ ●					—	—	—	—

- 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

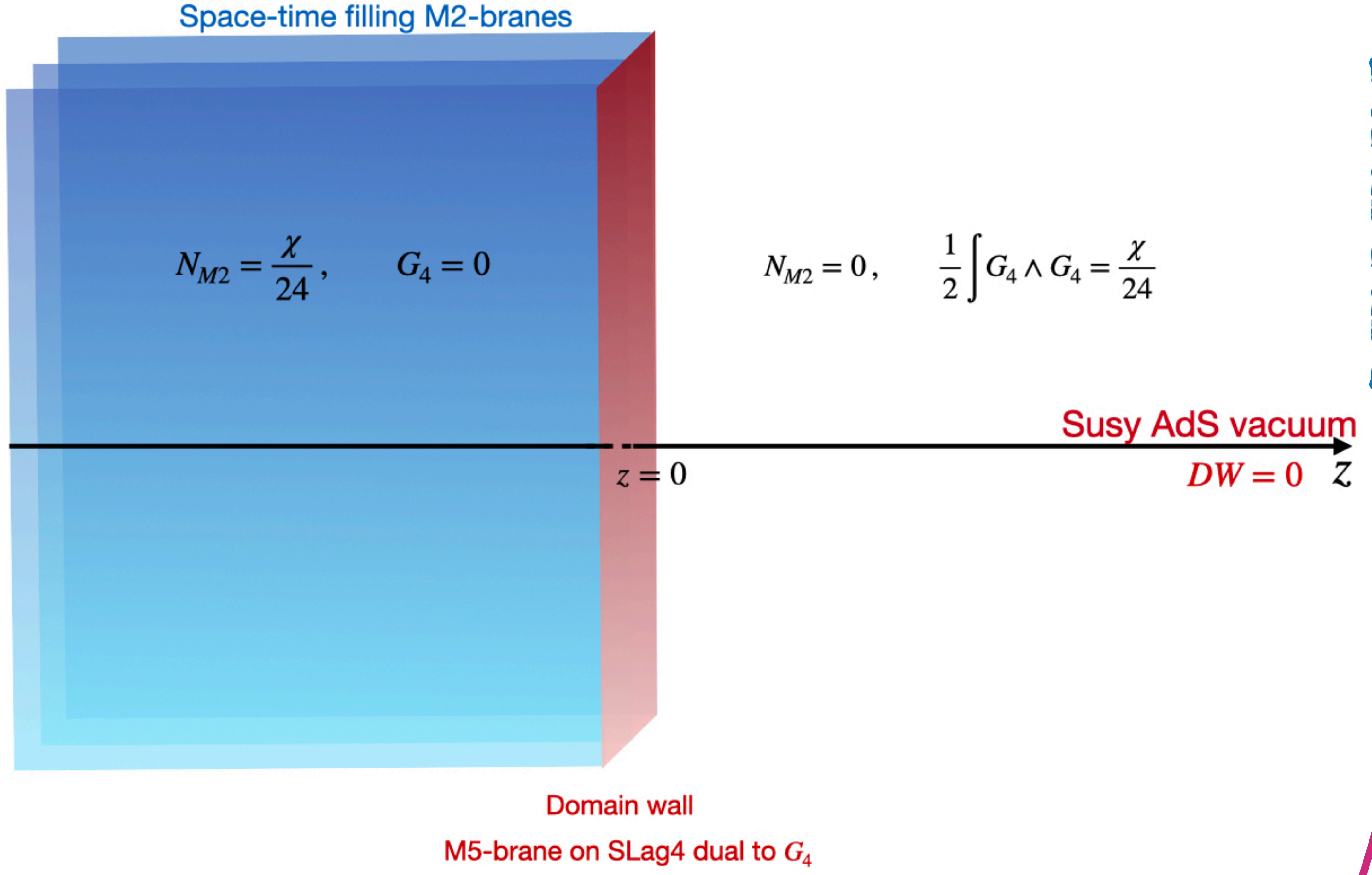
$|Z|^2 \sim \Delta\langle V\rangle$

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

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

M5 self-intersections in X_4

b_1 independent M5-strips in X_4

Scale $L_4 \to N_{\text{flux}} L_4$:

$\sim (N_{\text{flux}})^2$

$\mathcal{O}[(N_{\text{flux}})^2]$

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

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

Need it exponentially small

⇒ 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]

$$l_p \to 0, \qquad U=\frac{r^2}{l_p^3}=\text{fixed}, \qquad U'=\frac{r'^2}{l_p^3}=\text{fixed}.$$

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

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

« radial » « angular »

(t,u,y) → AdS_3, (z,λ) → T^2, $\Omega_3^{(1)}$ → S^3, $\Omega_3^{(2)}$ → S^3

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

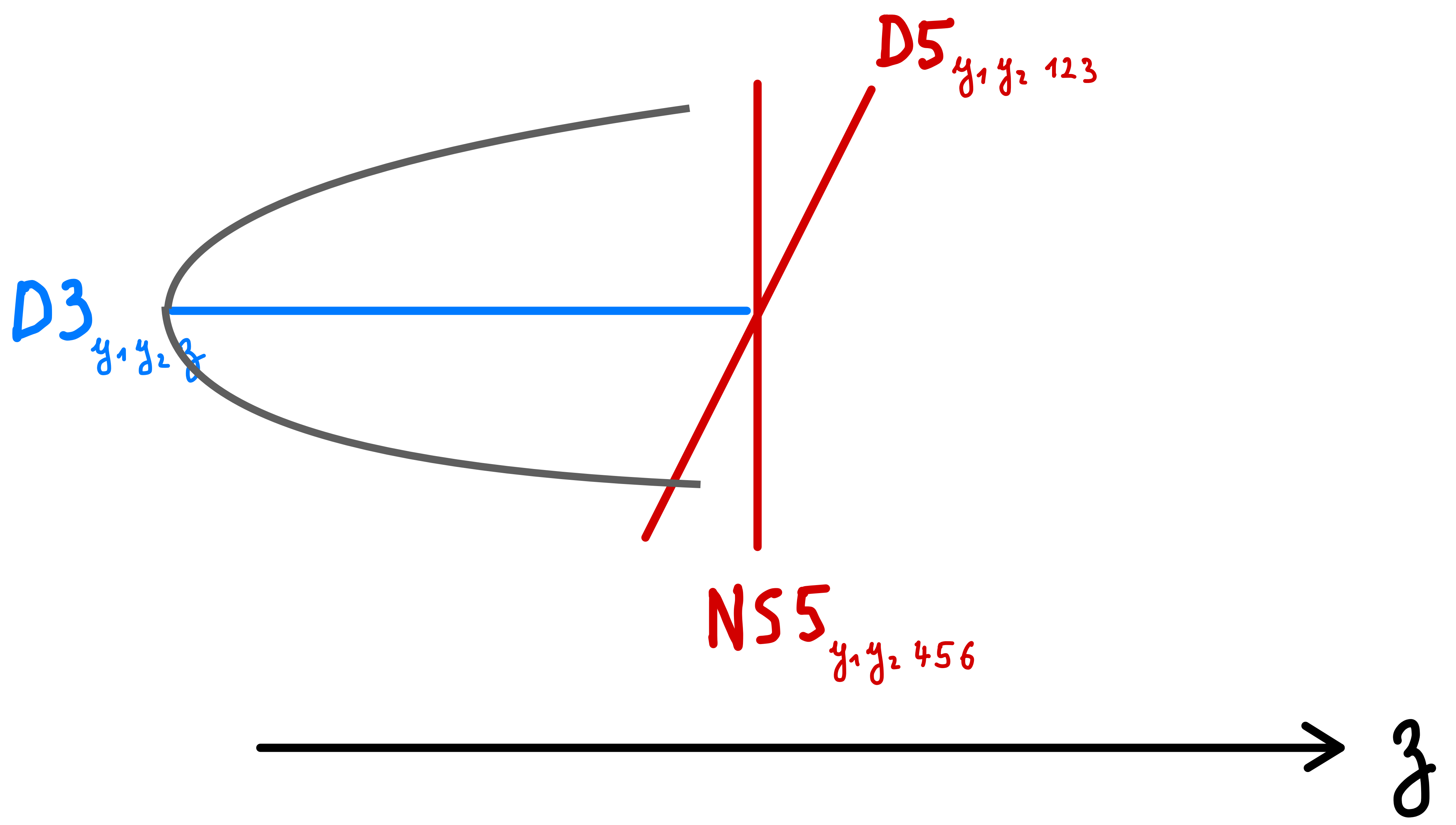
- Central charge: $c \propto N_2N_5 \propto (N_{\text{flux}})^3 > (N_{\text{flux}})^2$

[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

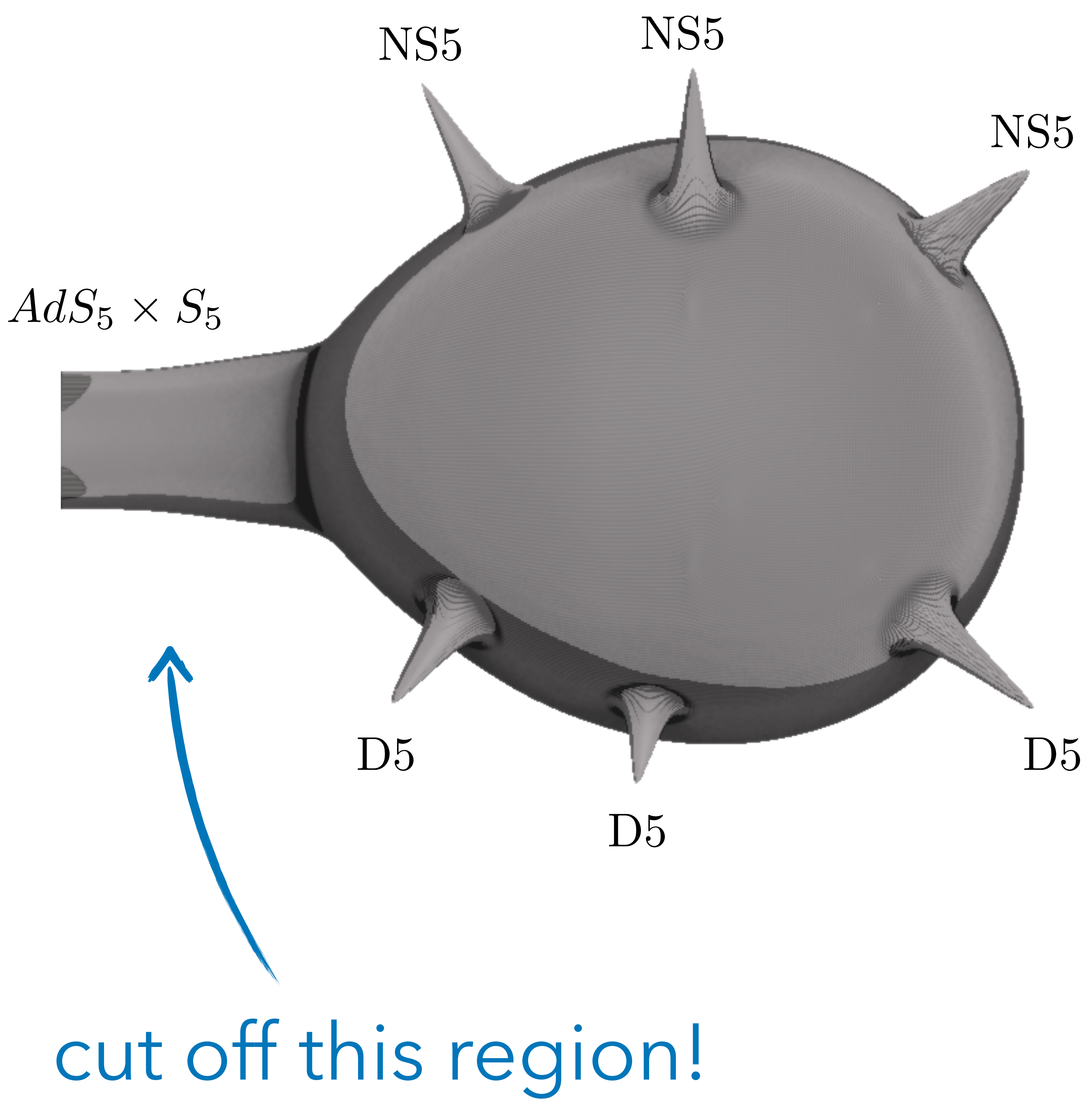


- The location of the D3 branes modify $W_{n.p.}$.
  → Choose it such that the CY shrinks on the left
  → Space-time ends there
- This brane system sources the KKLT AdS *out of nothing.*

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]

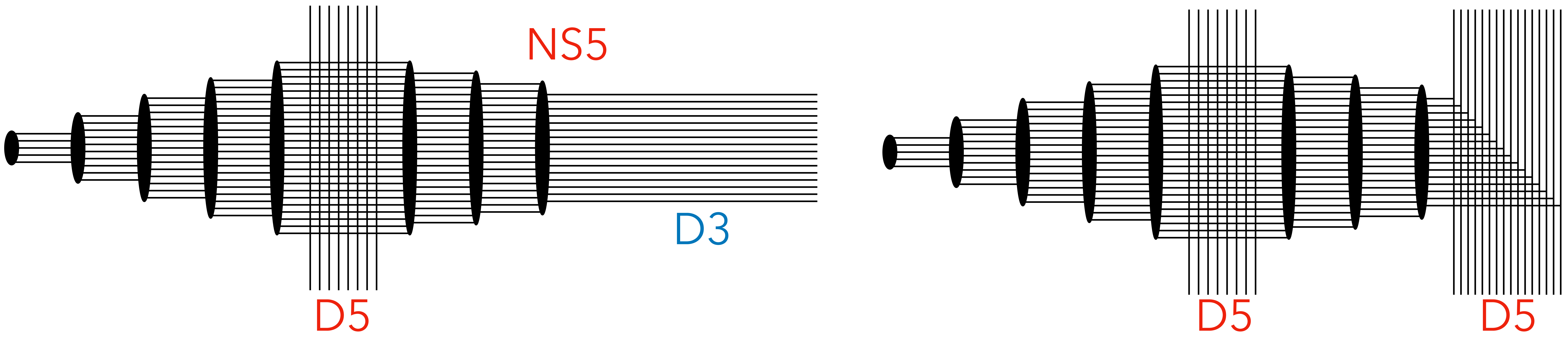


- The solution is an $AdS_4 \times S^2 \times S^2 \times_w \Sigma_2$
- Need estimate of AdS radius in 4d Planck units: $c_{UV} \sim \dfrac{l_{AdS}}{G_N}$
- V_6 infinite because of the AdS_5 region

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]