Holography for KKLT: Anatomy of a Flow

Theoretical Elementary Particle Physics Group Seminar,
Nagoya

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

Work to appear with I. Bena and S. Lüst

July 2nd, 2024

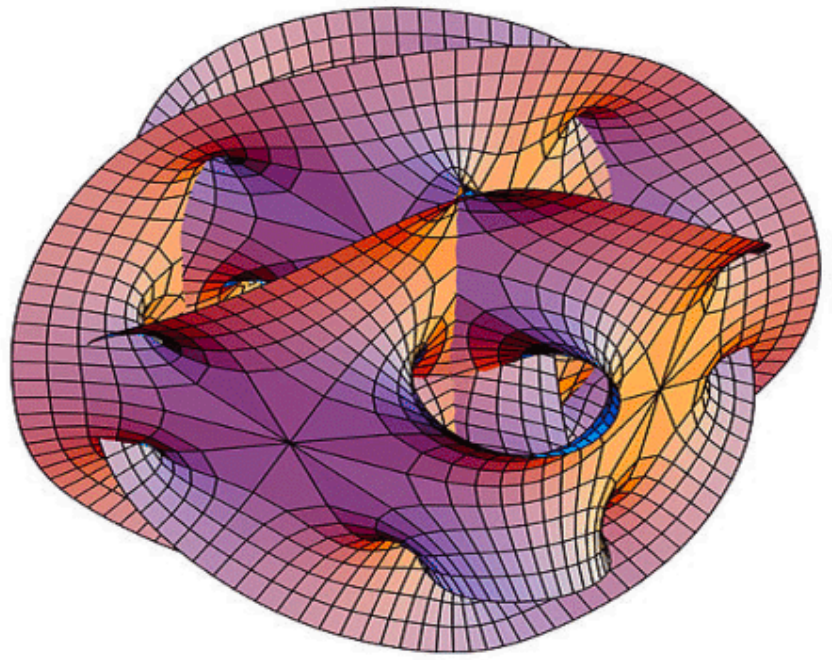
To describe our Universe, we want a unified framework comprising:

- Standard model of particle physics
- Mechanism for expanding Universe

The string landscape

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

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



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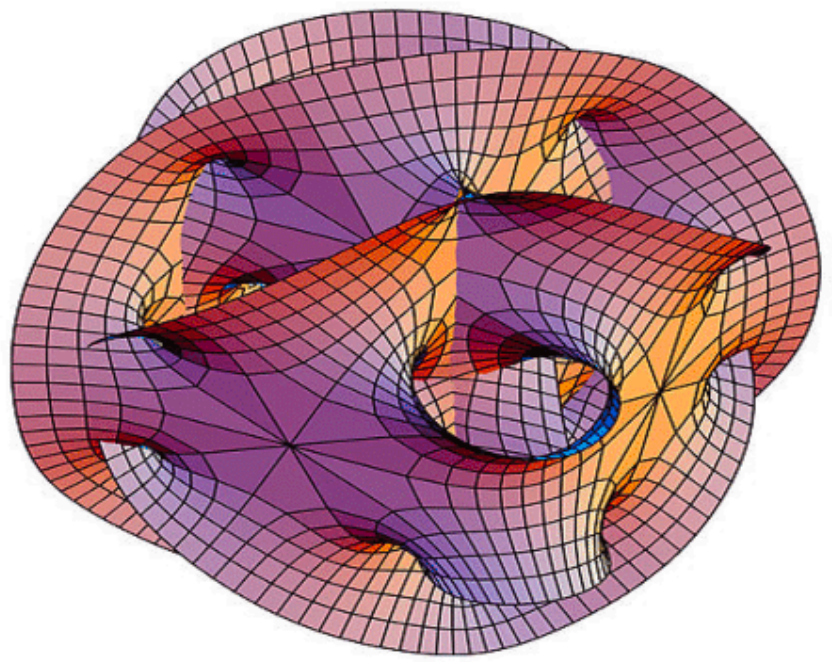

- To explain our 4d EFT, start from a 10d theory

- 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!

Challenge 1: scale separation

- The space of 4d EFT compatible with quantum gravity is very constrained

  → « Swampland programme »

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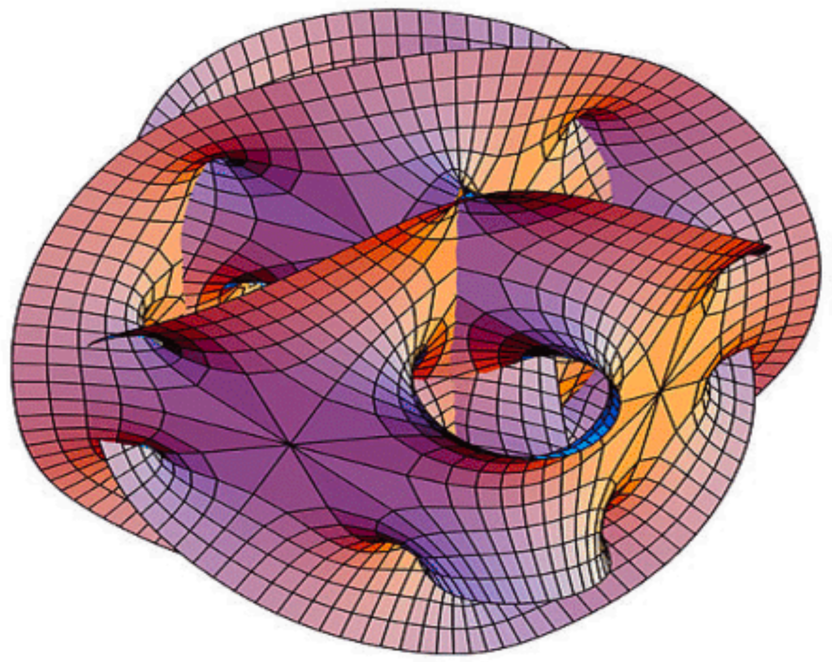
  - String theory examples ($\mathrm{AdS}_5 \times S^5, \ldots$)



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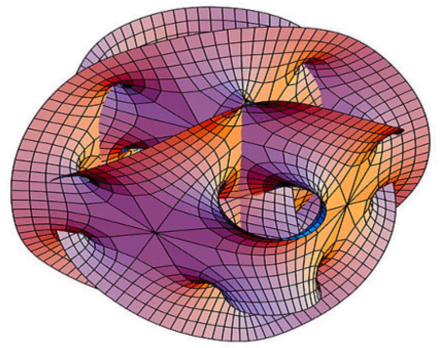

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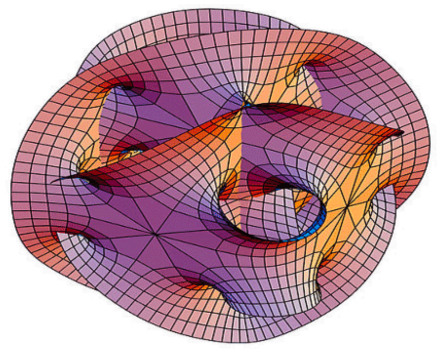
Conjecture:
No scale-separated AdS vacua
[D. Lüst, Palti, Vafa '19]

As $\Lambda \to 0$, $\exists$ tower of states s.t.
$$m \sim |\Lambda|^\alpha$$



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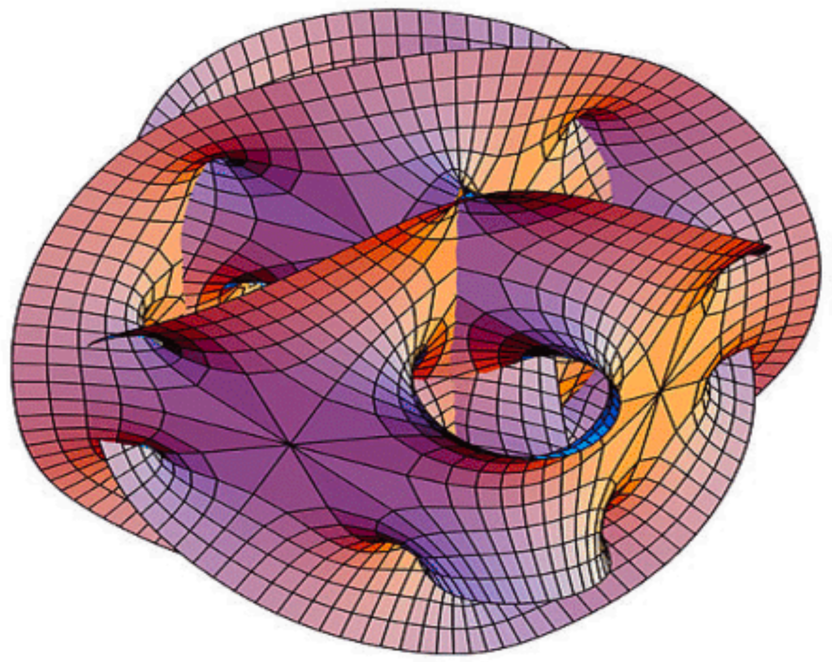

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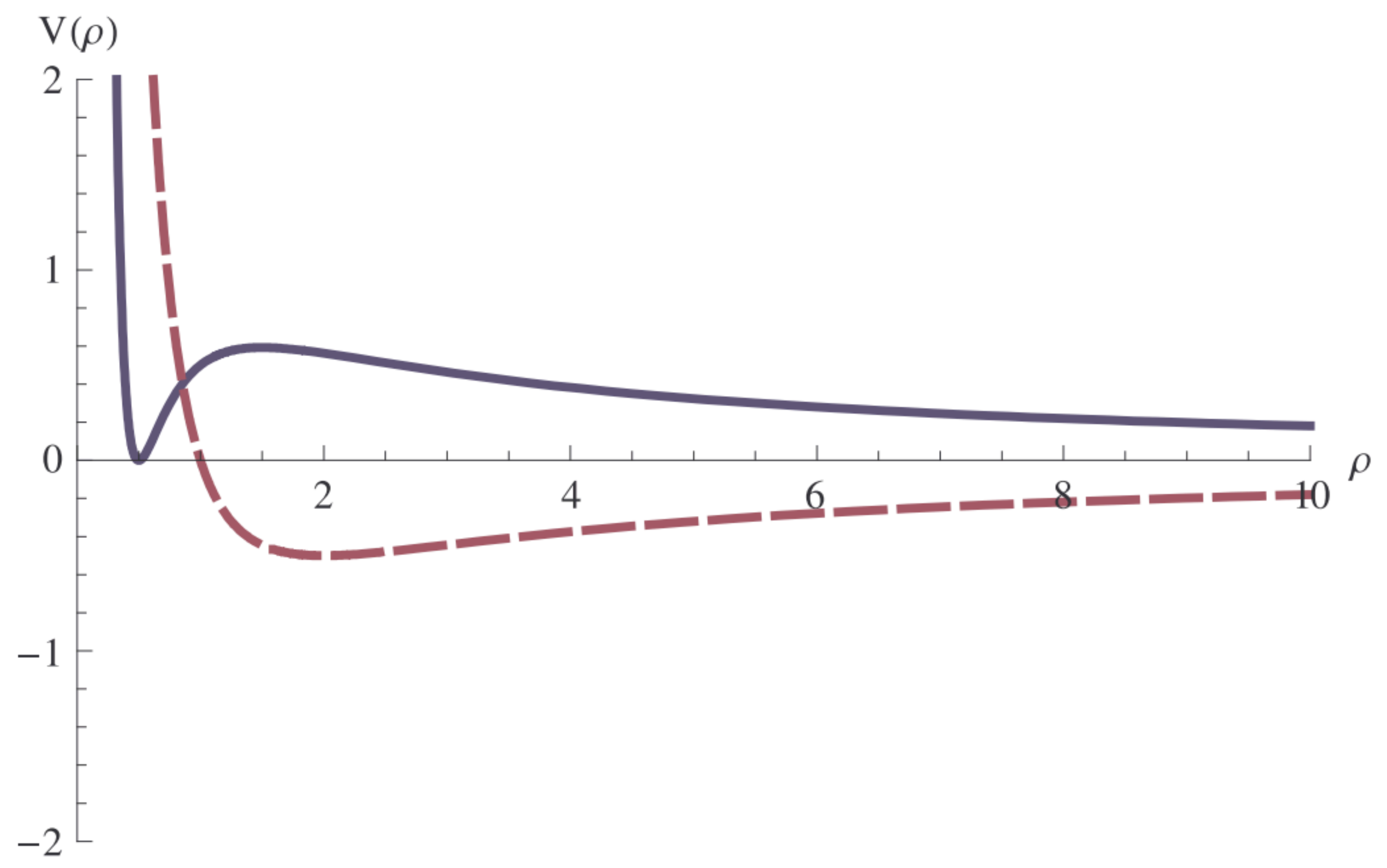
EFT p.o.v.: more and more particles below the cutoff

→ EFT breaks down!

Challenge 2: de Sitter in string theory

- Cosmological constant = minimum of a scalar potential, $V(\phi^i)$
- Positive, zero, negative $\Lambda \to$ dS, Mink., AdS.



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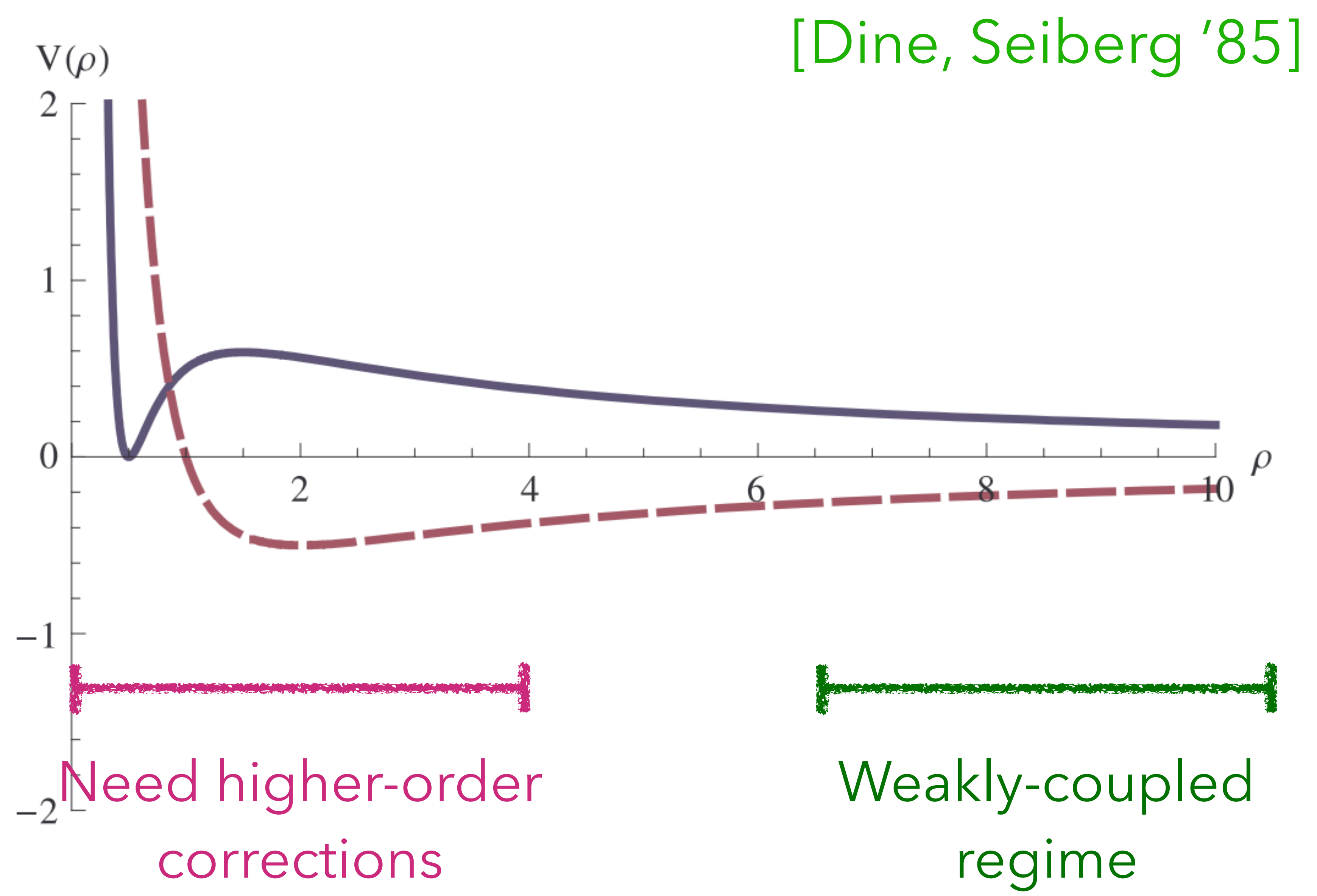

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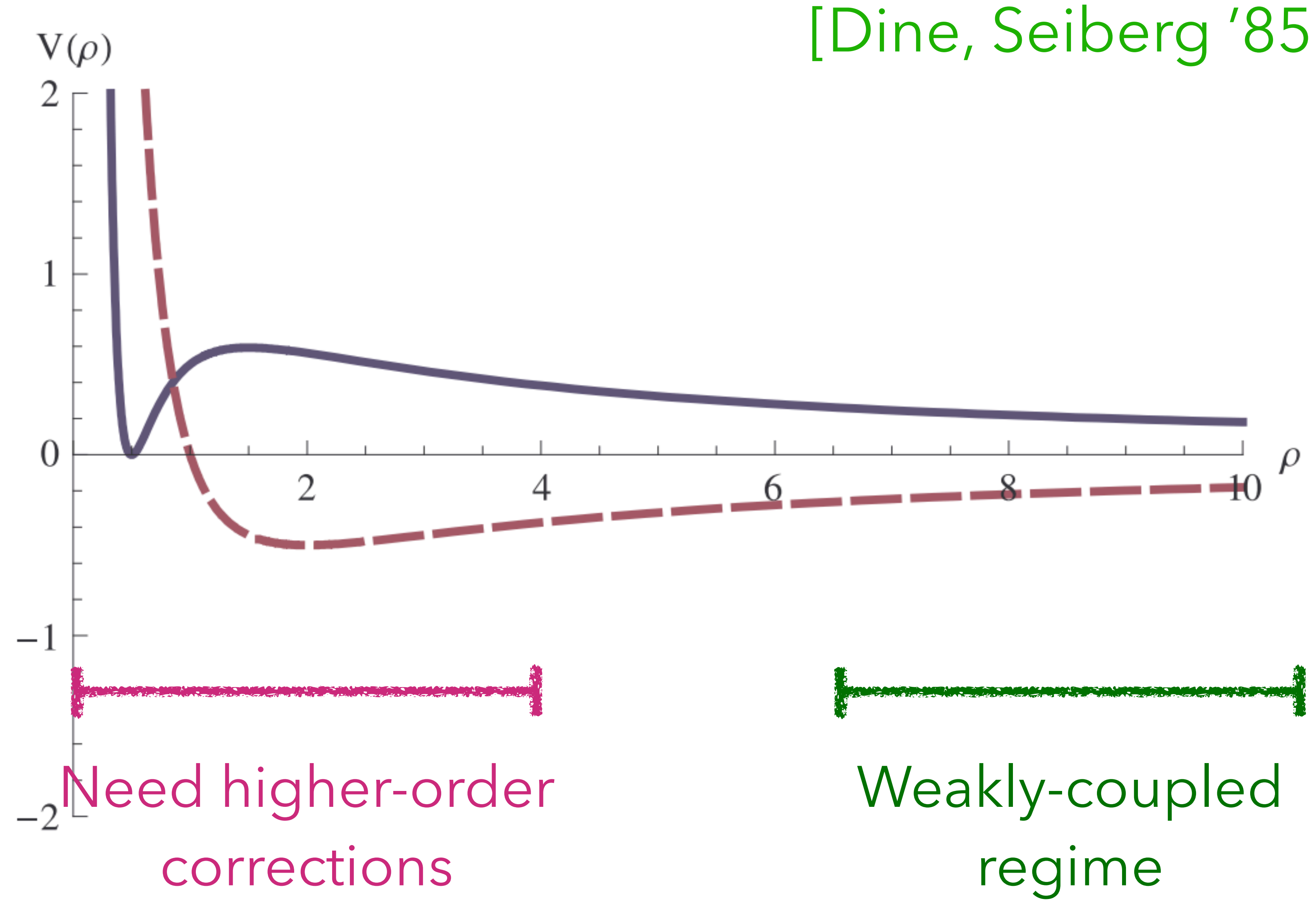
[Dine, Seiberg '85]



Candidate mechanism:

KKLT scenario

[Kachru, Kallosh, Linde, Trivedi '03]

Aim of this talk:

Study KKLT through holography

Outline

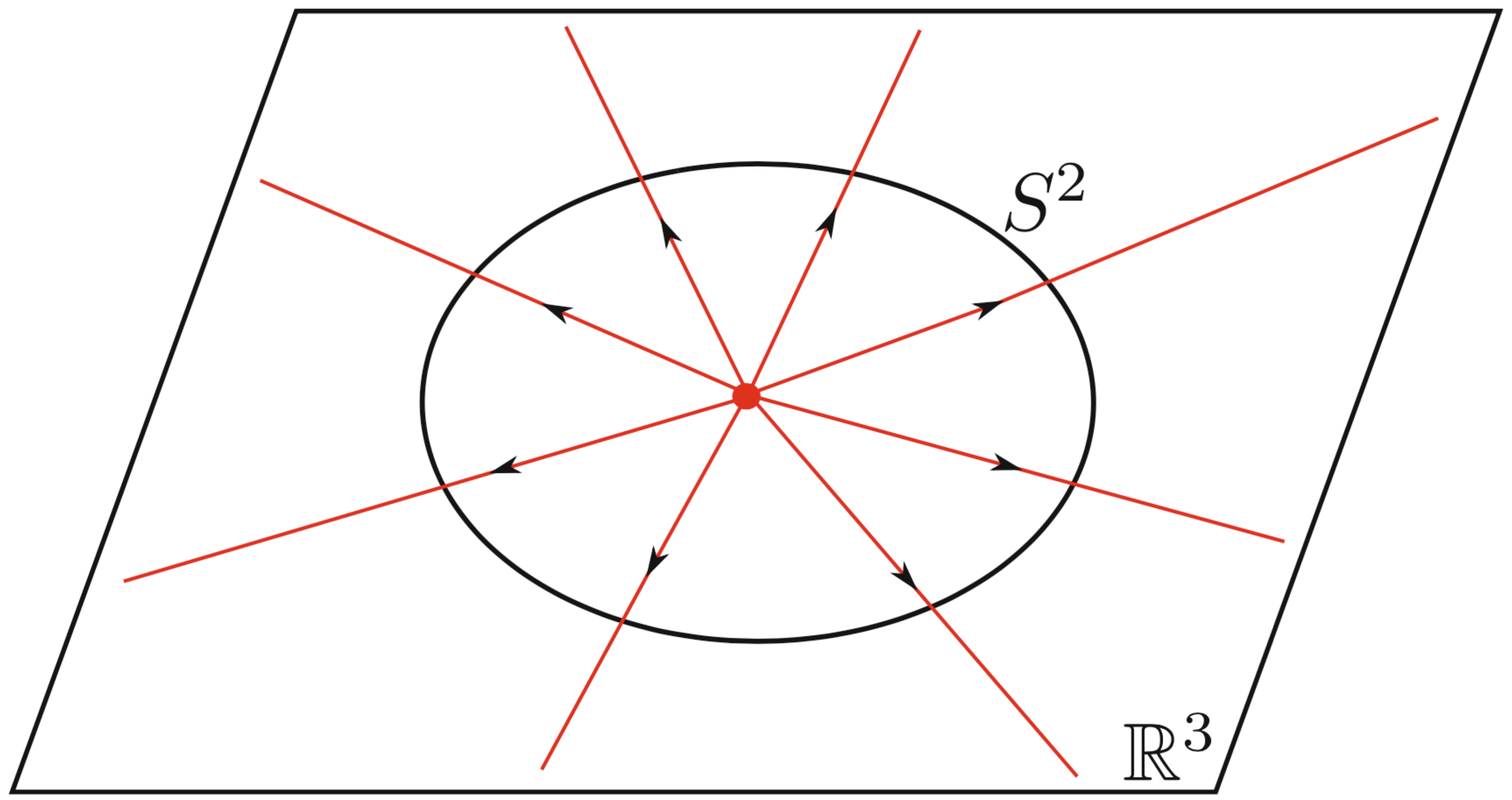
1. Explain what I mean by « studying KKLT through holography »

2. More classic « stringy » seminar

Pause for questions (1)

What are fluxes?

- Electron → electric field A_μ → field strength $F_{\mu\nu}$ (dynamical part)
- Electron in $\mathbb{R}^3$ → flux lines → Gauss' law gives electric charge



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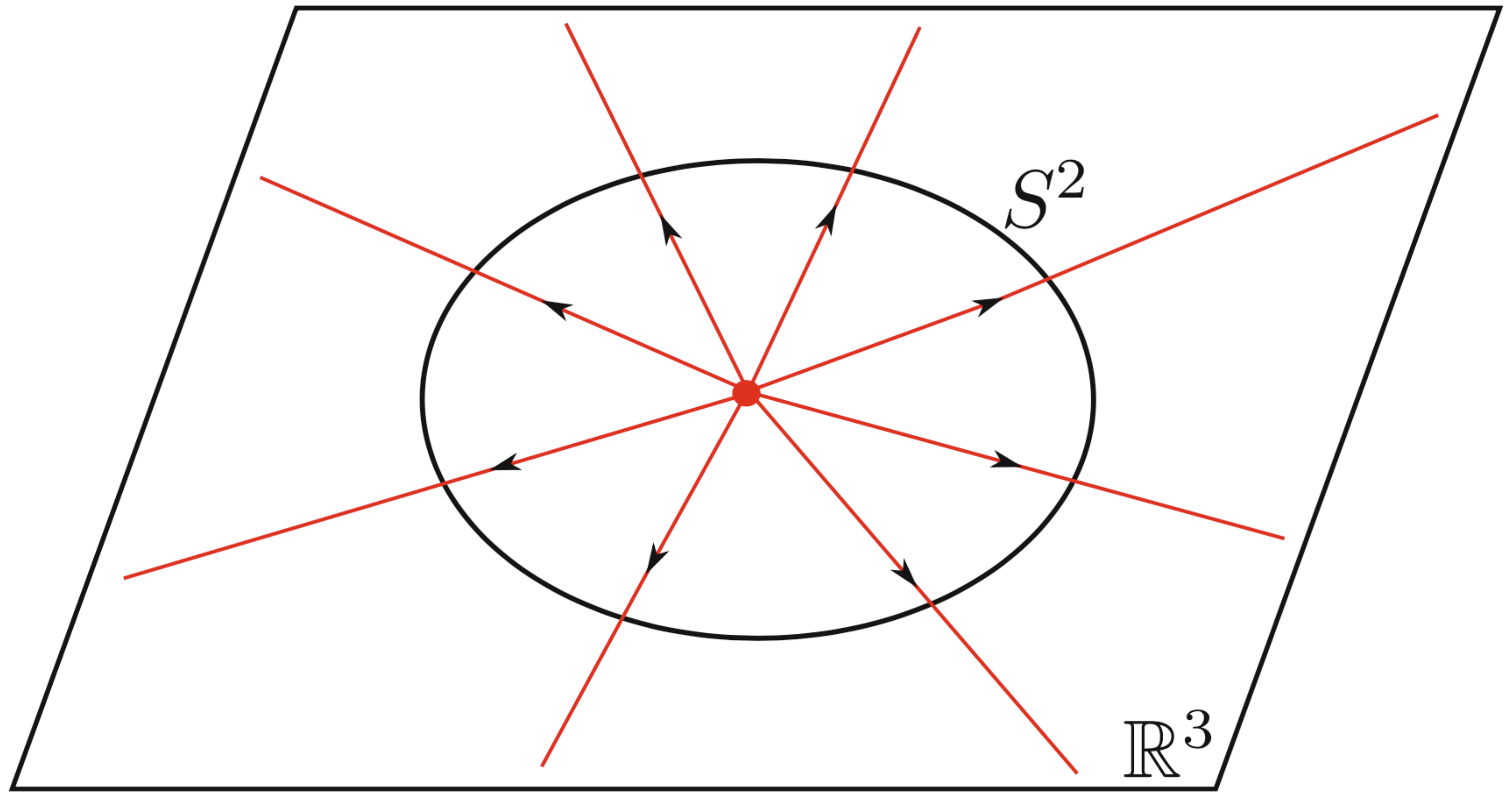
- Electron in $\mathbb{R}^3$ $\to$ flux lines $\to$ Gauss' law gives electric charge
- Electron on compact space $\to$ impossible!
  - But $F_{\mu\nu} = n \in \mathbb{Z}$ allowed by topology.



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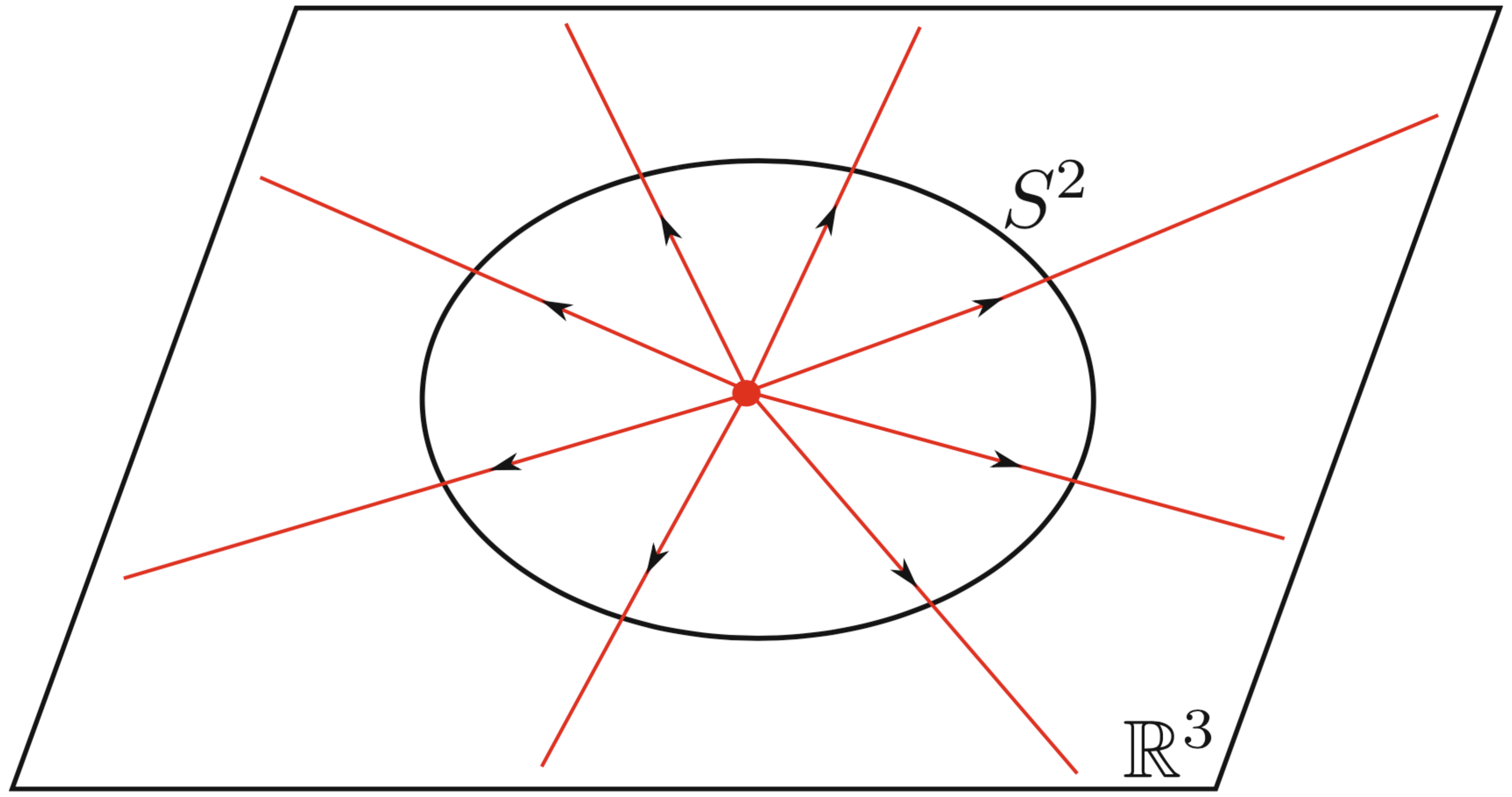


In string theory: string, Dp-branes → B_2, C_{p+1} → H_3, F_{p+2} .

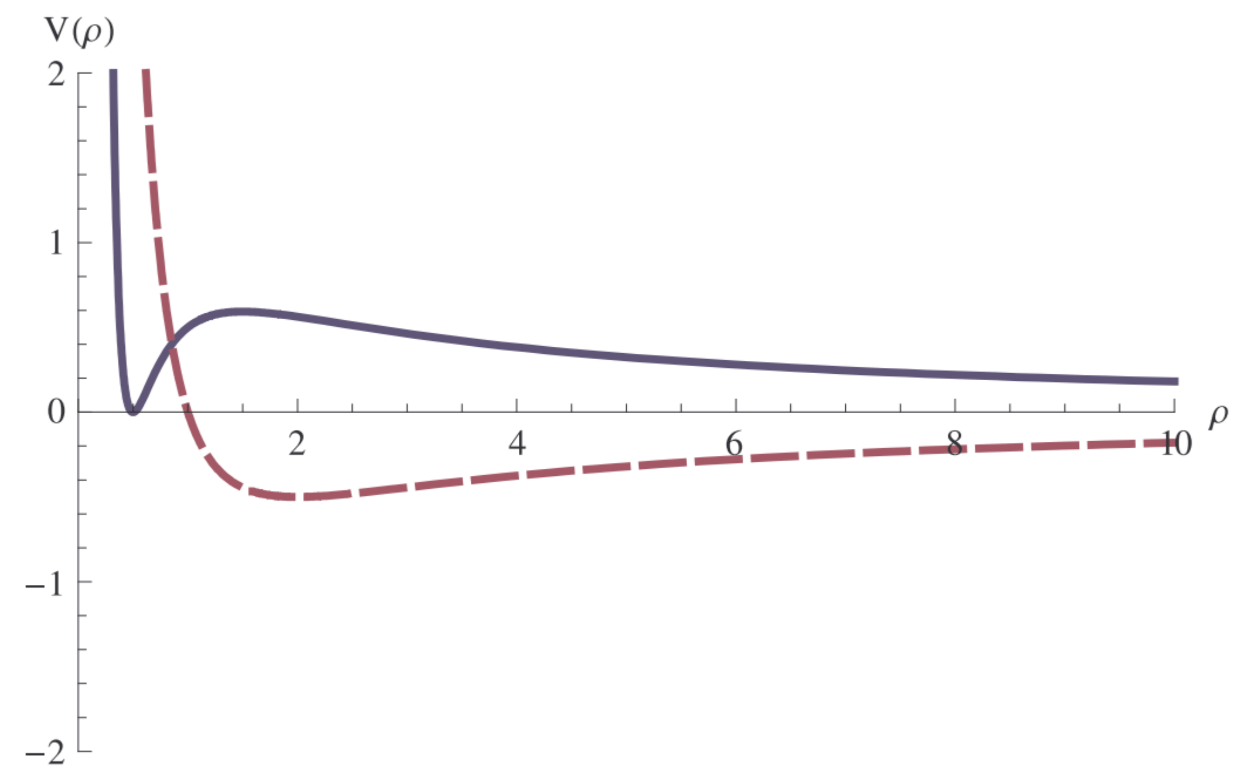
H_3, F_{p+2} have a constant part allowed by topology of compact space

→ « Fluxes »

From 10d to scalar potential

- How do we get the scalar potential from string theory?
- EFT describing low-energy dynamics: 4d $\mathcal{N} = 1$ SUSY

$$S_{\mathcal{N}=1} = \int d^4x \sqrt{-g} \left[\frac{R}{2} - g_{i\bar{j}} \partial \psi^i \partial \overline{\psi}^{\bar{j}} + V\left(\psi^i\right) + \ldots \right]$$



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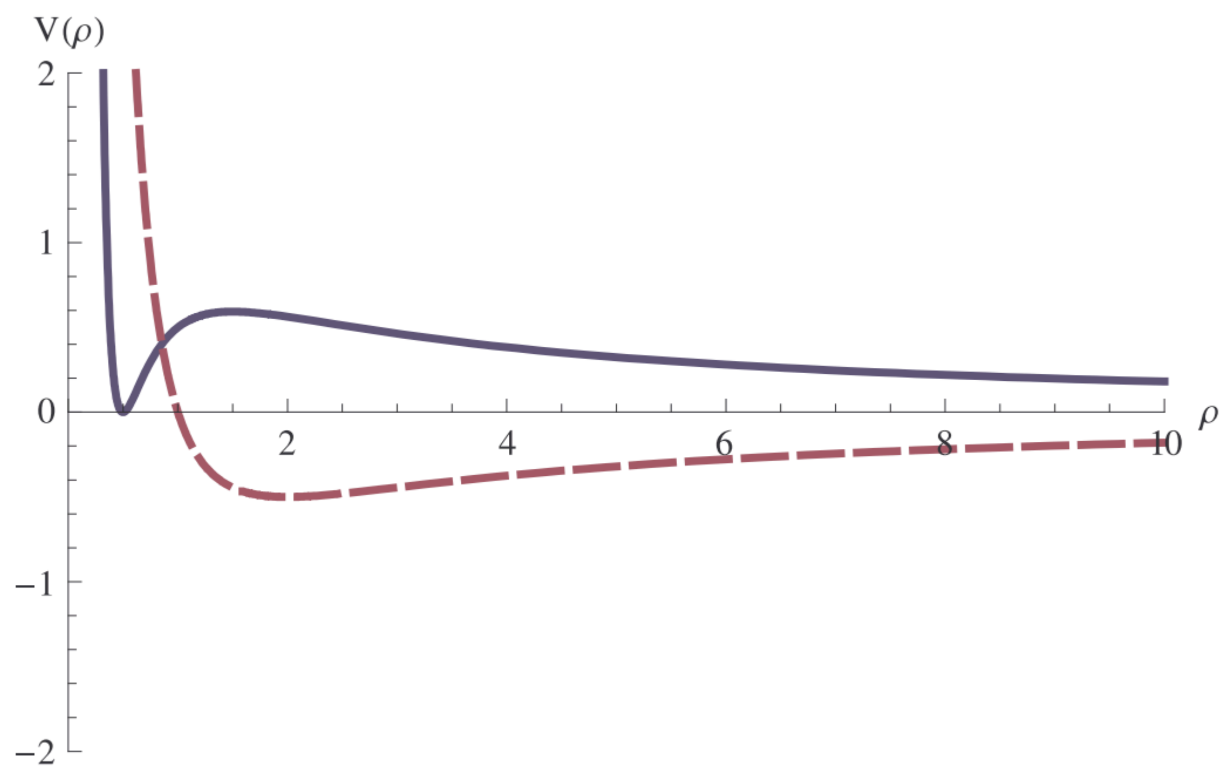

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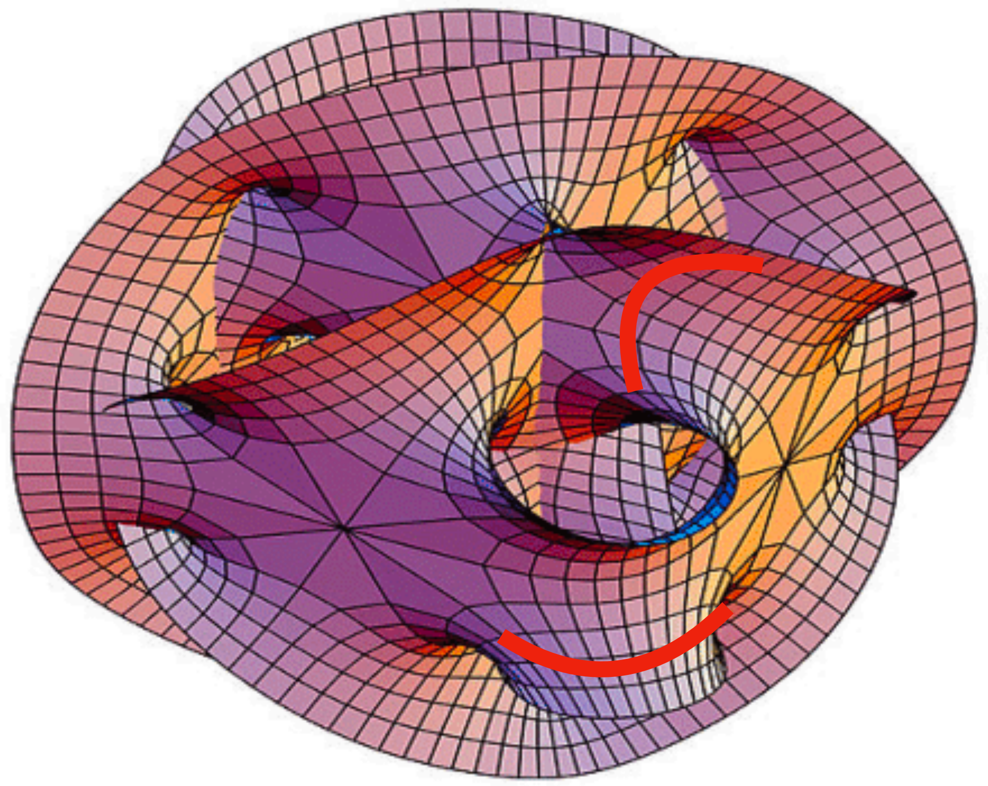
- V depends on 10d string-theory data

$$V = e^K\left[g^{i\bar{j}}D_iW\overline{D}_{\bar{j}}\overline{W} - 3|W|^2\right]$$



$$W_{\text{GVW}} = \int_{CY_3} G_3 \wedge \Omega_3$$

Fluxes on CY   CY geometry

The KKLT scenario

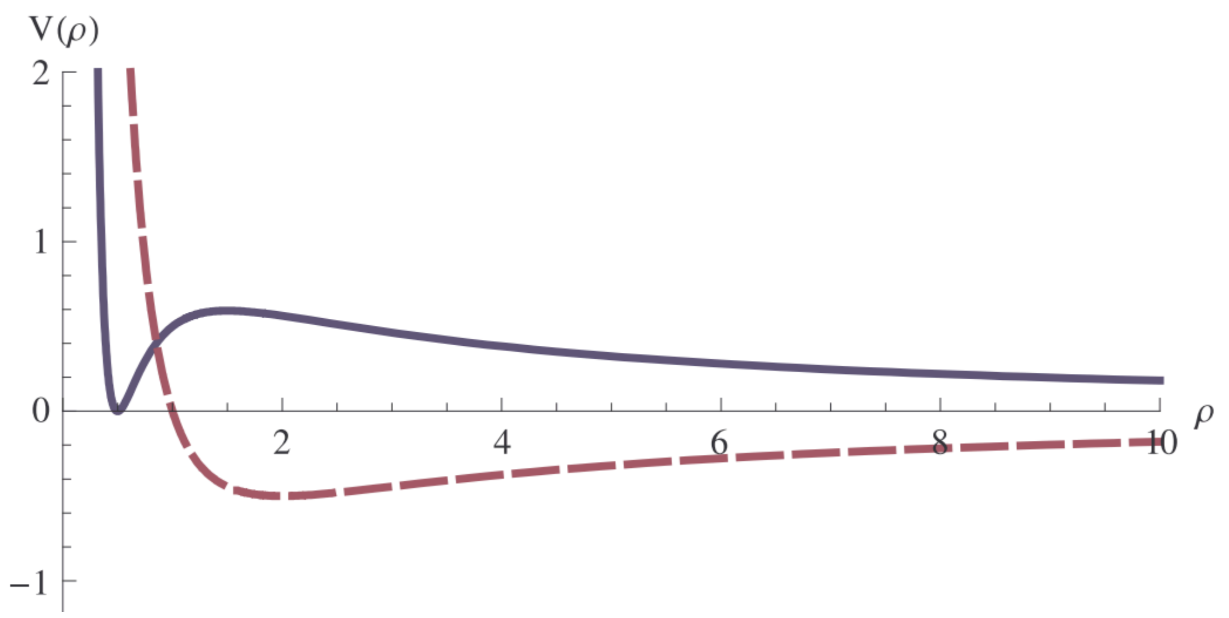
Two-step procedure:

1. Stabilise CY moduli with fluxes

& non-perturbative corrections

→ SUSY, scale-separated AdS

$\Lambda < 0$



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   add $\overline{\mathrm{D3}}$ branes and break SUSY a tiny bit

   → dS vacuum with broken SUSY

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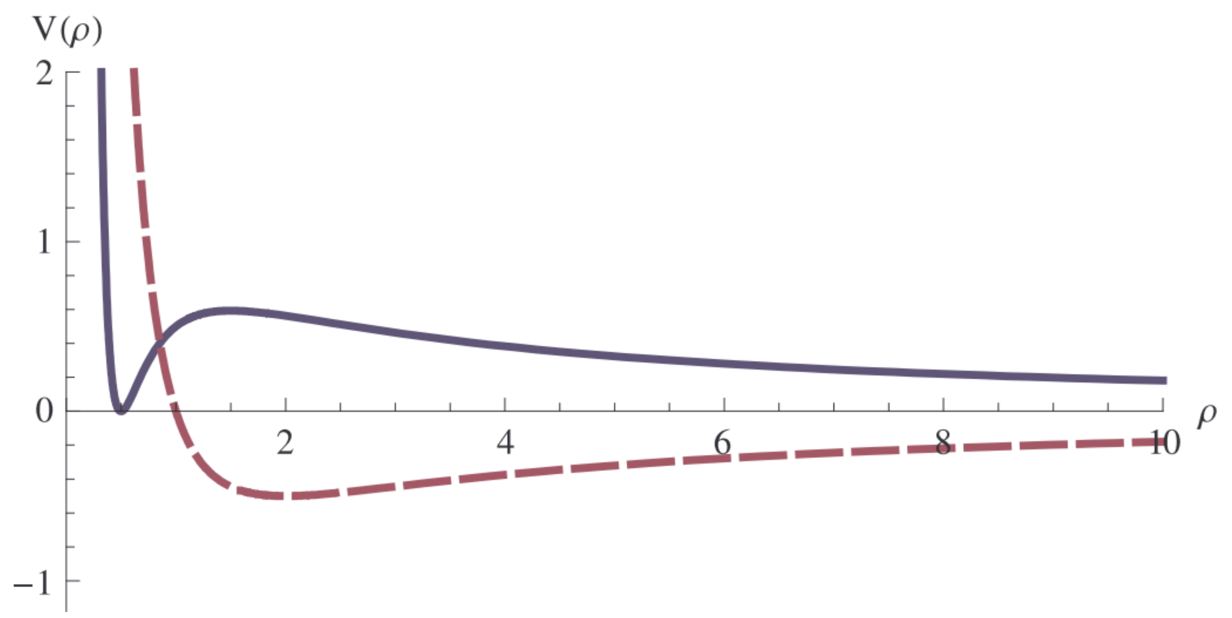

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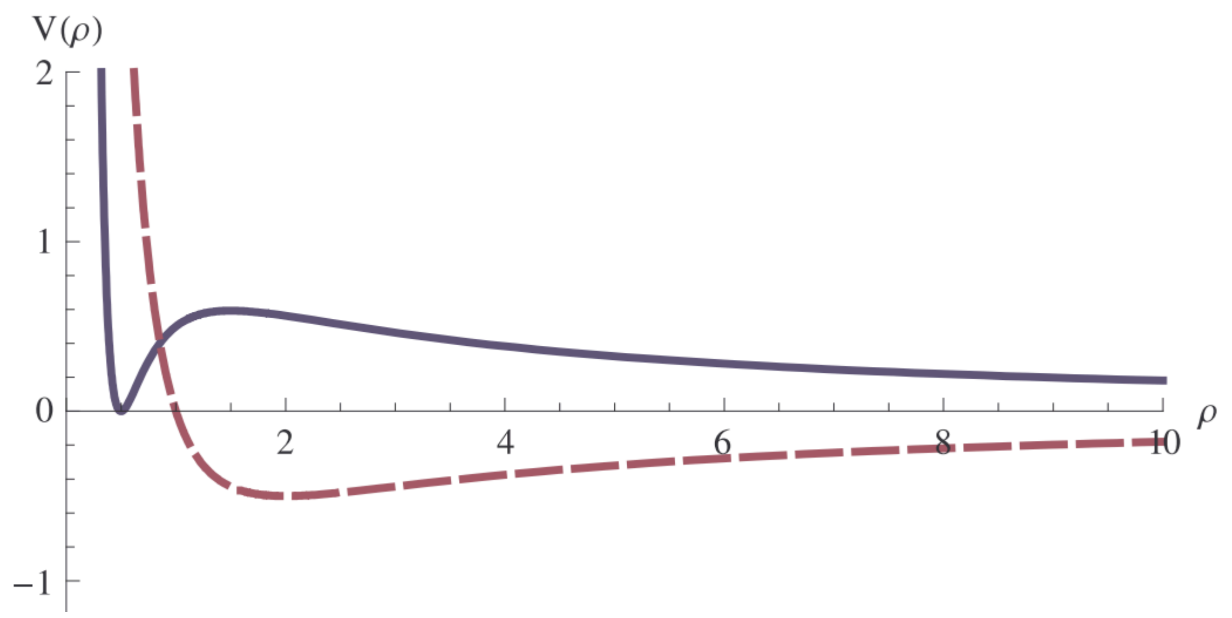

« Use solution of challenge 1 to solve challenge 2 »

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Study this step through holography and domain walls

Pause for questions (2)

Domain walls as intersecting branes

- Can realise BH and DW solutions from *intersecting BPS branes*:

	t	$\vec{w}$	$\vec{x}$	$\vec{y}$	$\vec{z}$
brane 1	$\bullet$	$\bullet$		$\bullet$	
brane 2	$\bullet$	$\bullet$	$\bullet$		

common directions

overall transverse directions

Domain walls as intersecting branes

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delocalise

« Harmonic function rule »

[Papadopoulos, Townsend '96]

[Tseytlin '96]

[Gauntlett, Kastor, Traschen '96]

$\Rightarrow$

Sugra solution:

BH or DW

Domain walls as intersecting branes

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Sugra solution:

$\mathrm{AdS} \times S \times X$ « near-horizon »

Black hole

if $\dim(\vec{z}) \geq 2$

Domain wall

if $\dim(\vec{z}) = 1$ (no S)

Fluxes/branes for black holes

4d « MSW » black hole:

[Maldacena, Strominger, 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	–	$\overset{r=0}{\bullet}$	–	–	–	–	–		
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P	–	$\overset{r=0}{\bullet}$	$\rightarrow$						

The zoom-in of the branes at the triple intersections

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- Moduli / CY shape are stabilised near horizon:

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

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11d: stabilisation from fluxes on CY

11d: competition between branes

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- BH entropy:

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

11d: stabilisation from fluxes on CY

11d: competition between branes

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

Number d.o.f. $\leftrightarrow$ AdS_2 radius in 4d units

KKLT 101

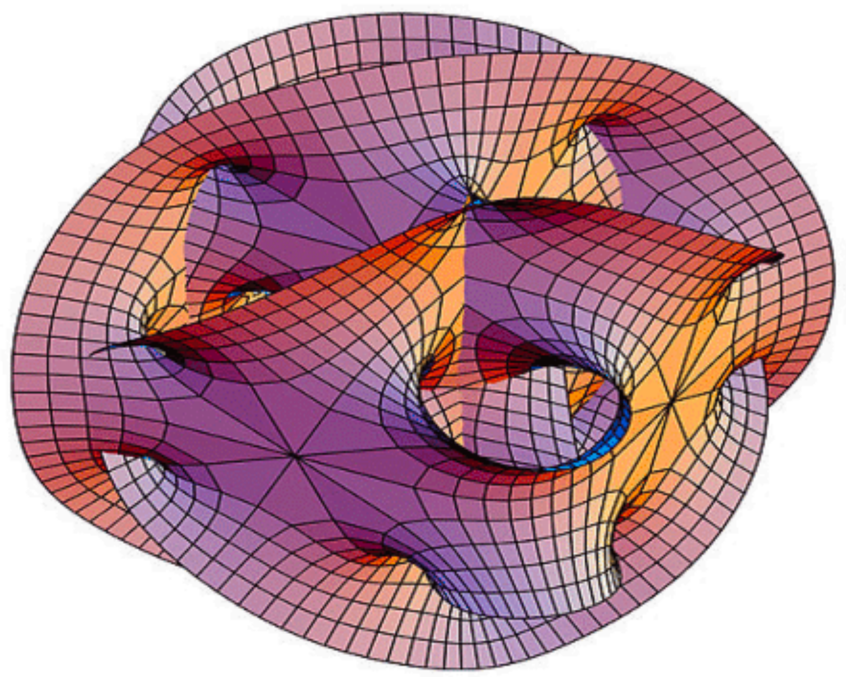
- Complex-structure deformations (3-cycles) stabilised by fluxes,

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

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

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

need to be $\ll 1$



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

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

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

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Idea: trade (F_3, H_3) fluxes with D5/NS5 branes on dual cycles

$$\boxed{\Rightarrow \quad |\Lambda_{\text{AdS}}| \ll 1}$$

Pause for questions (3)

3d version of KKLT

- Same story in dual version of KKLT in M theory on CY_4

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

$$\tau$$

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

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

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

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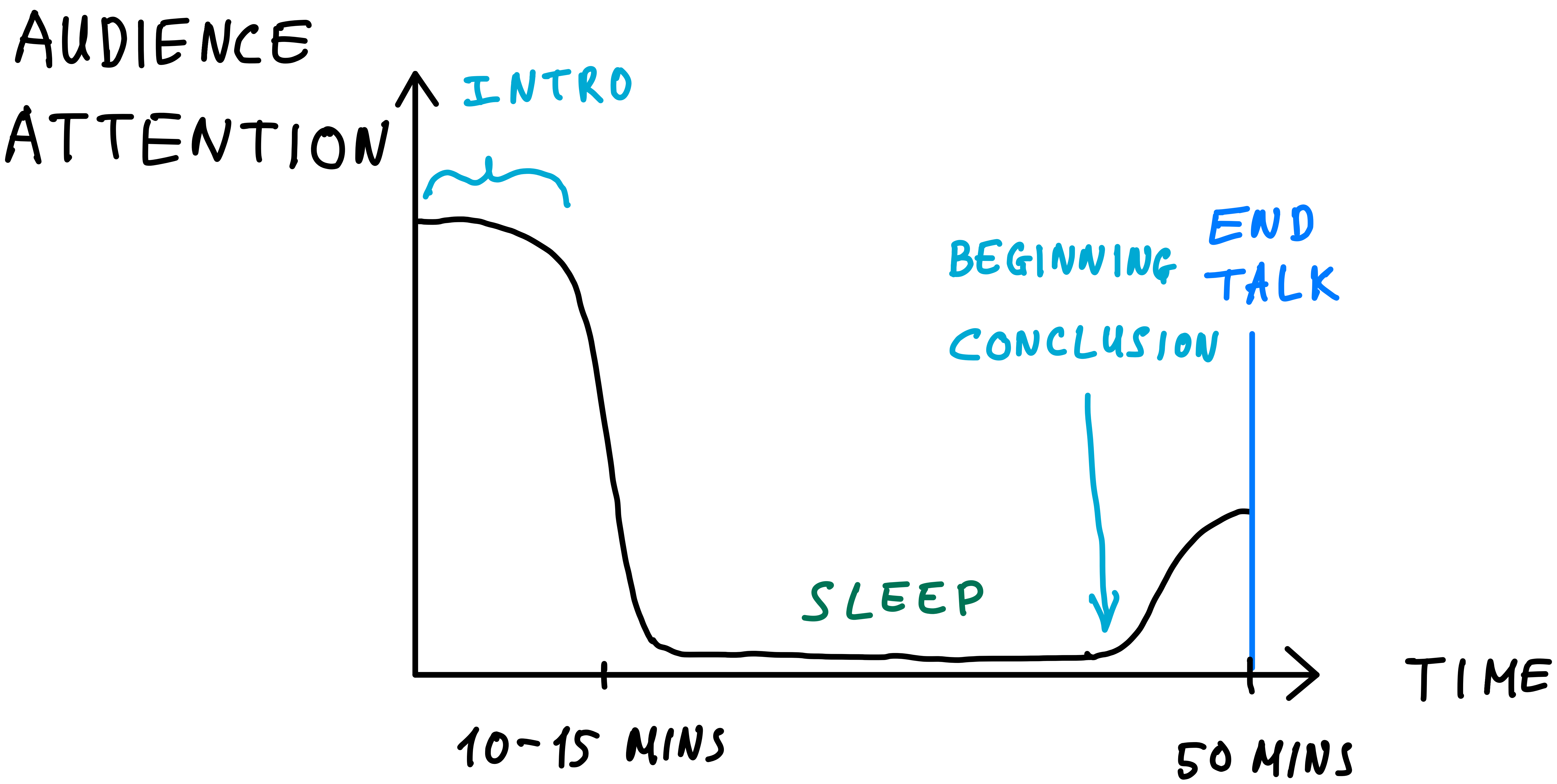
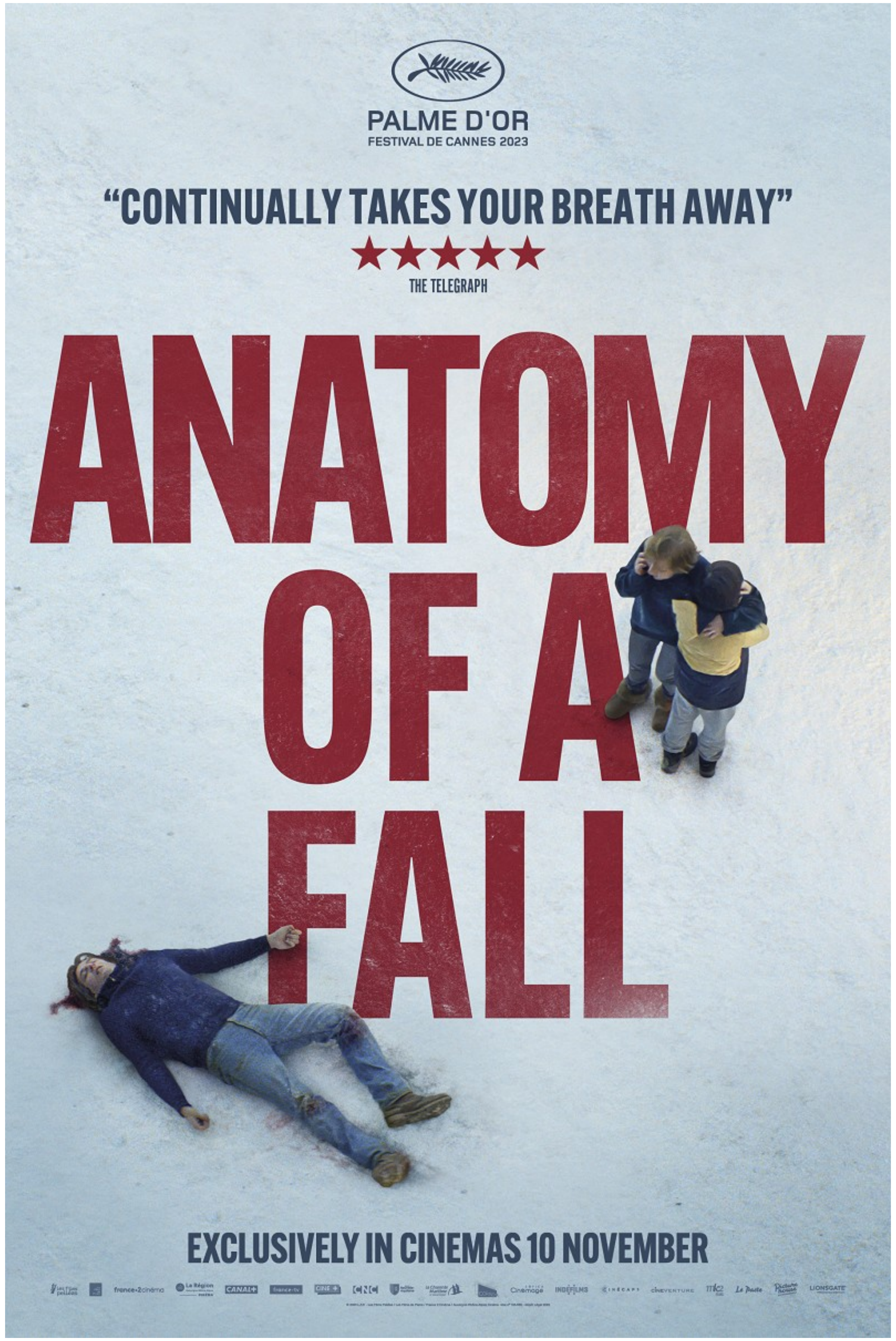
- Get scale-separated AdS_3

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

Idea: trade G_4 flux for M5 branes on dual cycle $L_4 \subset CY_4$.



AUDIENCE ATTENTION
INTRO
BEGINNING CONCLUSION
END TALK
SLEEP
TIME
10-15 MINS
50 MINS


PALME D'OR
FESTIVAL DE CANNES 2023
"CONTINUALLY TAKES YOUR BREATH AWAY"
★★★★★
THE TELEGRAPH
ANATOMY
OF A
FALL
EXCLUSIVELY IN CINEMAS 10 NOVEMBER

Part 1

Anatomy of a Fall?

The Fall of KKLT?

Claim: cannot construct AdS_3 (with X_4 stabilised) with $|\Lambda| \ll 1$.

[S. Lüst, Vafa, Wiesner, Xu '22]

The Fall of 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	—	—	$\overset{z=0}{\bullet}$	—	—	—	—				
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- 3d: KKLT AdS_3 as sourced by a domain wall

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

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

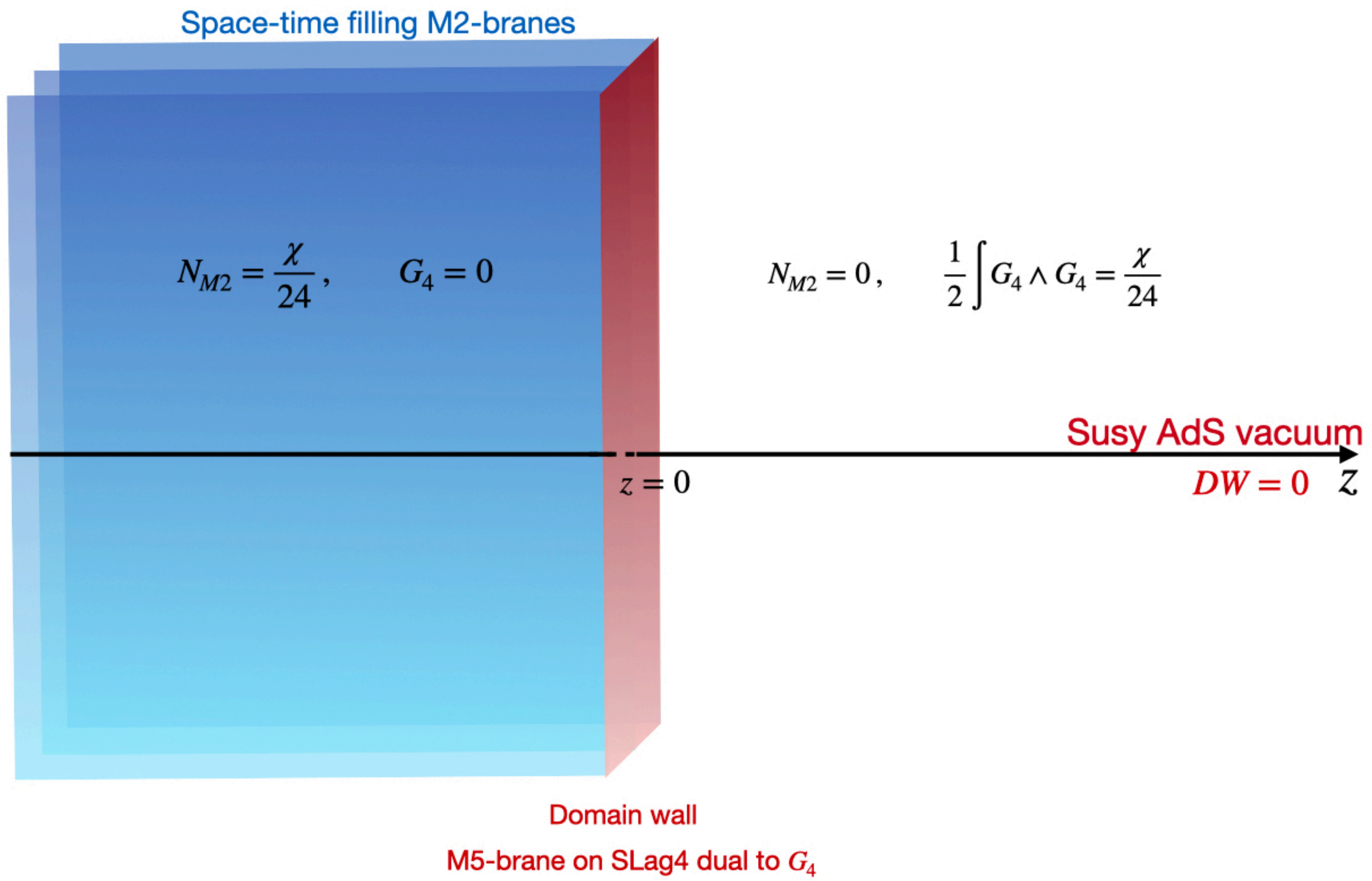
At $z = +\infty$, reach KKLT AdS_3

tension of the wall

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

Domain-wall holography

[S. Lüst, Vafa, Wiesner, Xu '22]



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

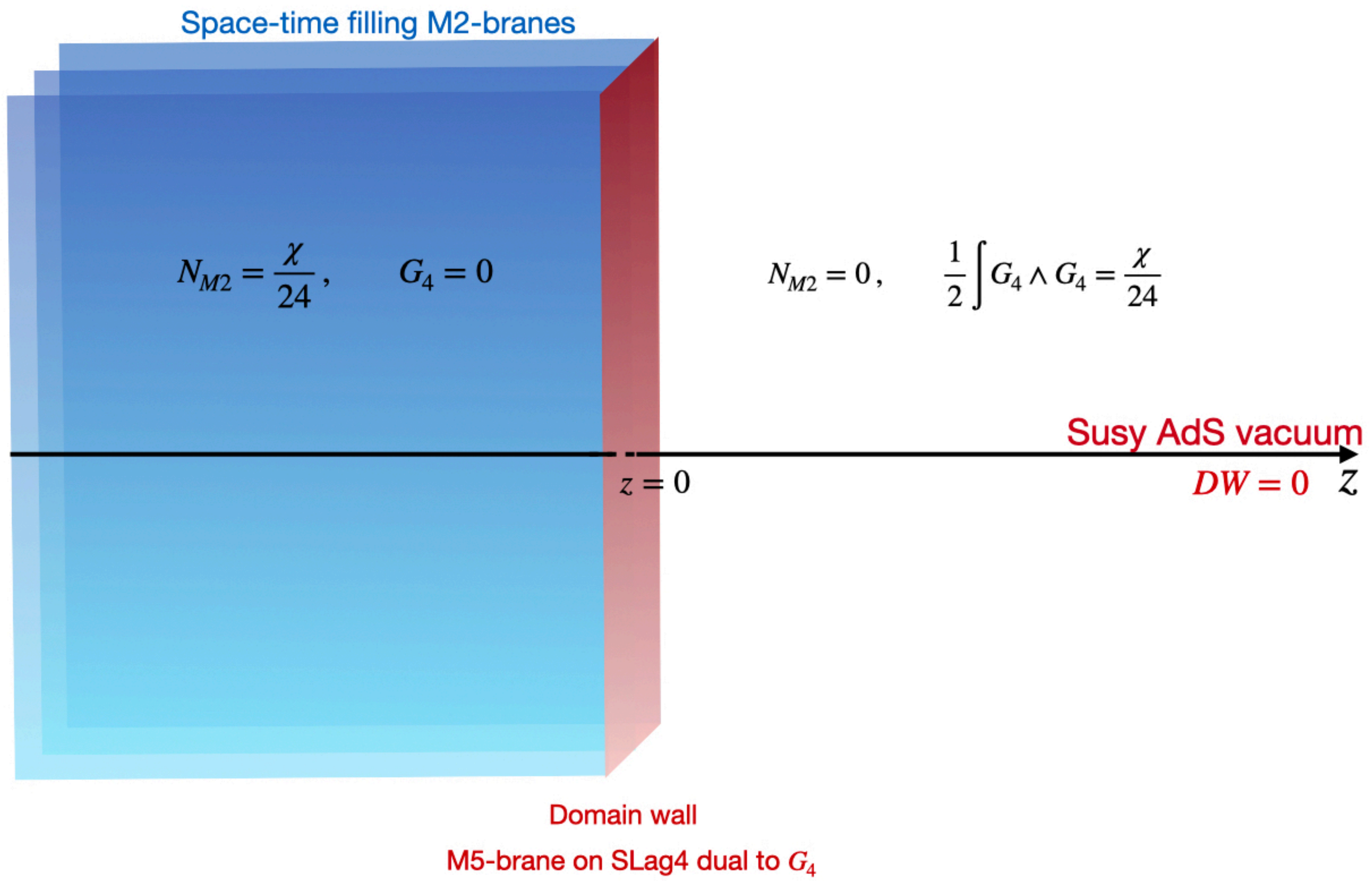
DW: M5 brane on special Lagrangian L_4

Domain-wall holography

[S. Lüst, Vafa, Wiesner, Xu '22]

No G_4 flux on X_4

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



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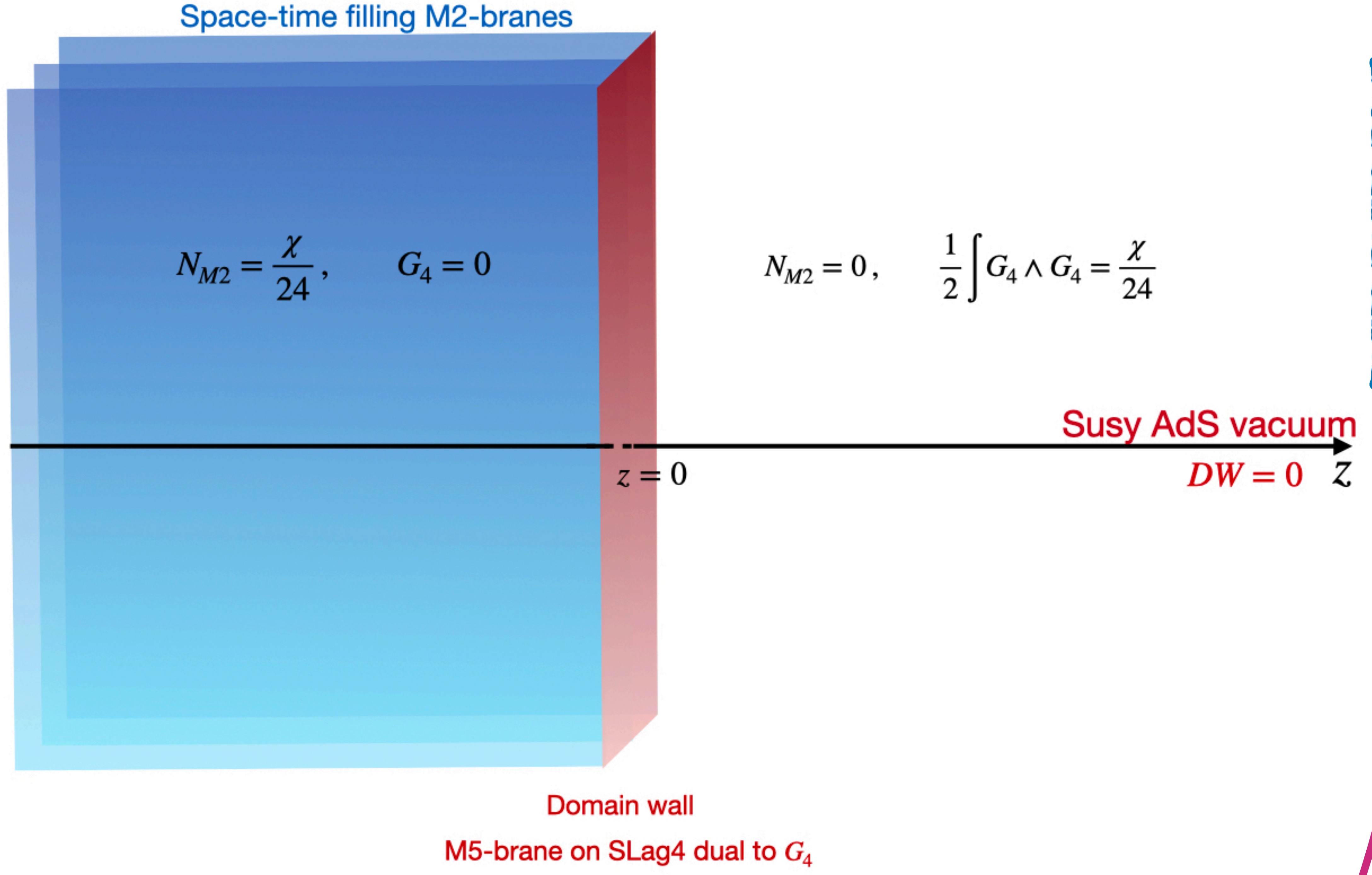

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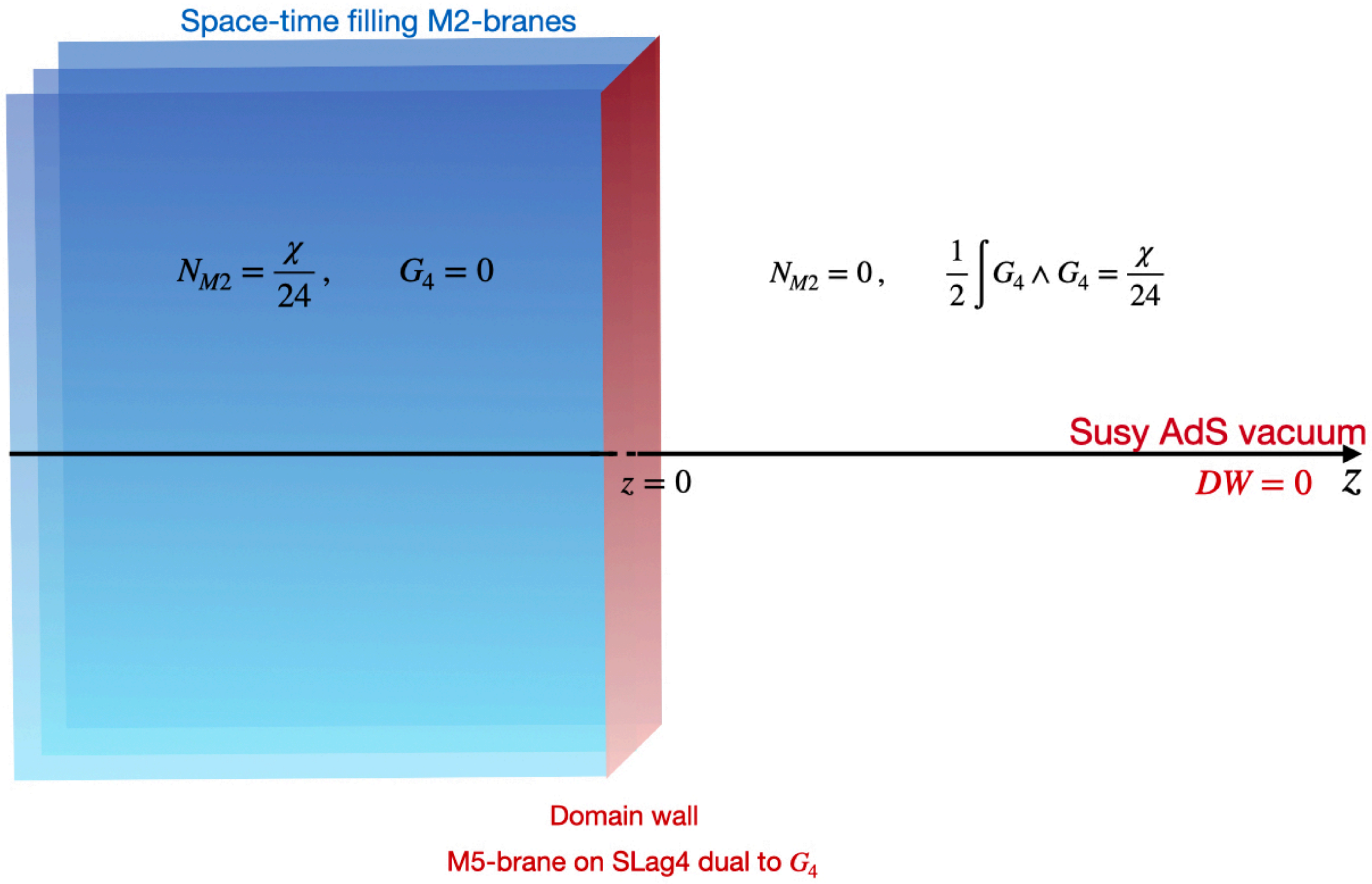
IR

DW: M5 brane on special Lagrangian L_4

(1+1)d QFT

UV

The holographic dual



[S. Lüst, Vafa, Wiesner, Xu '22]

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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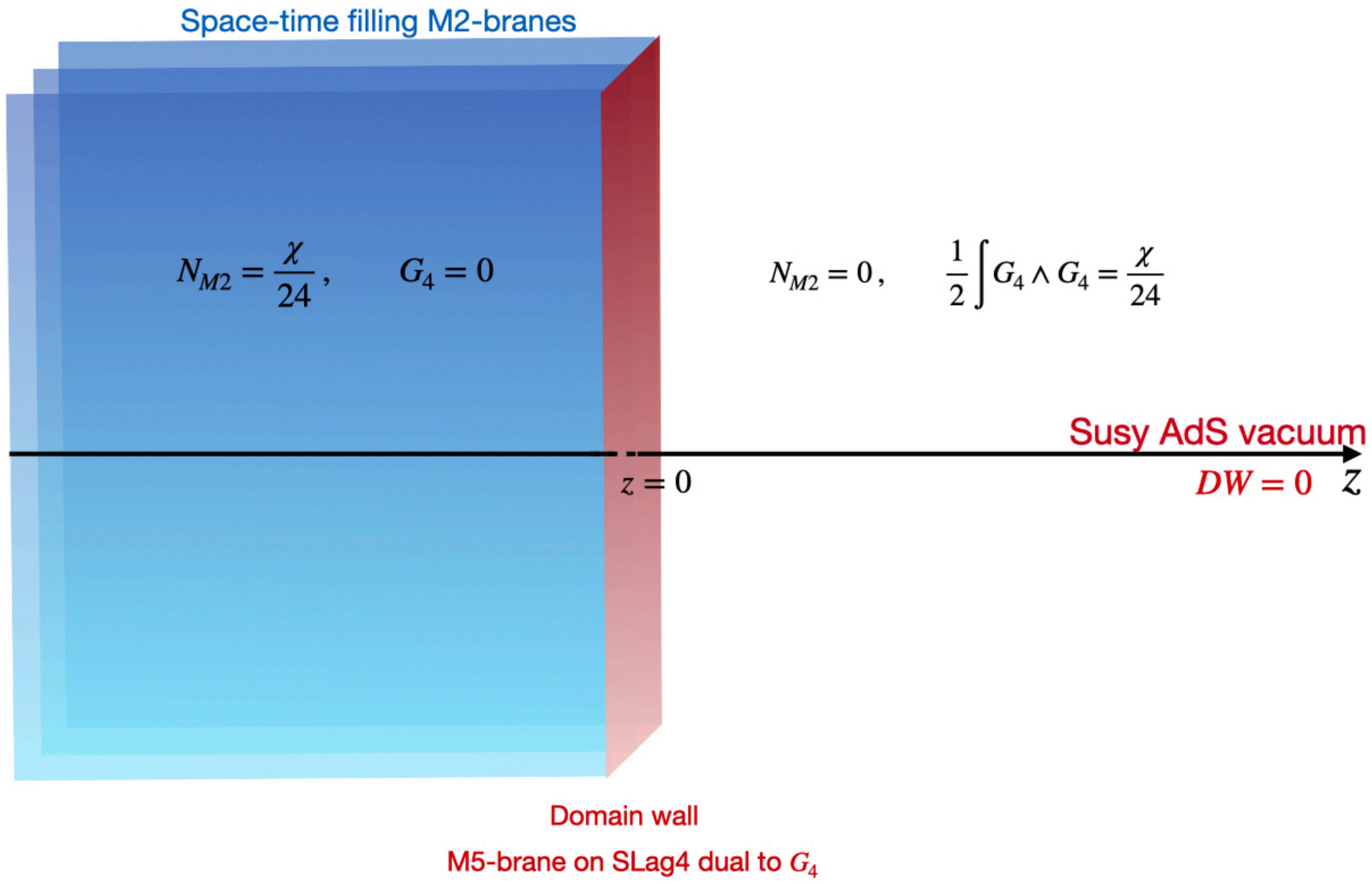

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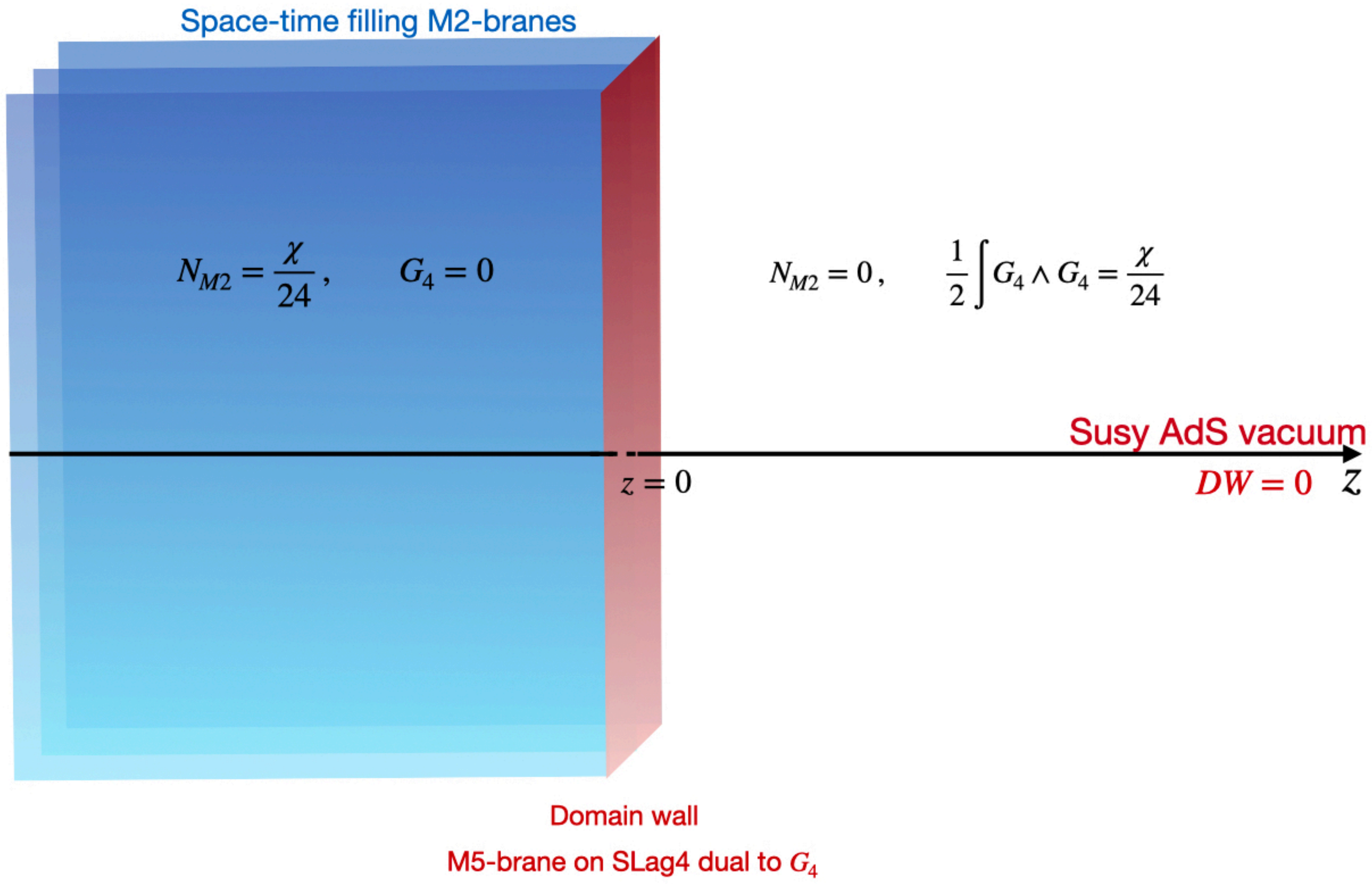

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c-theorem for 2d CFT:

$$\boxed{c_{\mathrm{UV}} \geq c_{\mathrm{IR}}}$$

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

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

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

b_1 independent M5-strips in X_4

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

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

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

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

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Scale $L_4 \to N_{\rm flux}\, L_4$:

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

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

Need it exponentially small

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

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

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

Pause for questions (4)

Part 2

Anatomy of a Flaw

A flaw in the argument?

- They take a DW sourcing the KKLT AdS, and the UV d.o.f. are 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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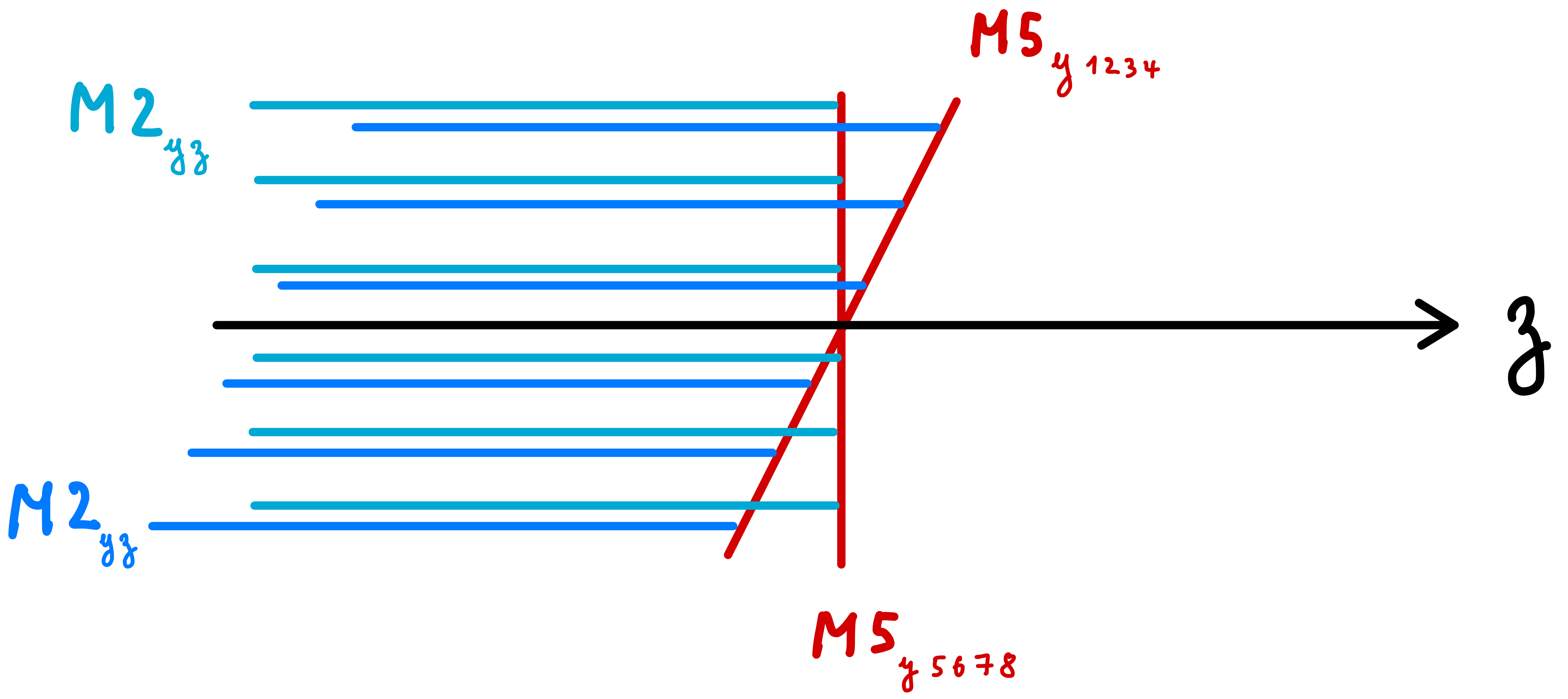
→ Need to evaluate the radius of the AdS corresponding to the brane intersection!

Taking into account the M2 branes for c_{UV}

- Brane configuration: M5(1234,y) – M5(5678,y) – M2(yz).

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



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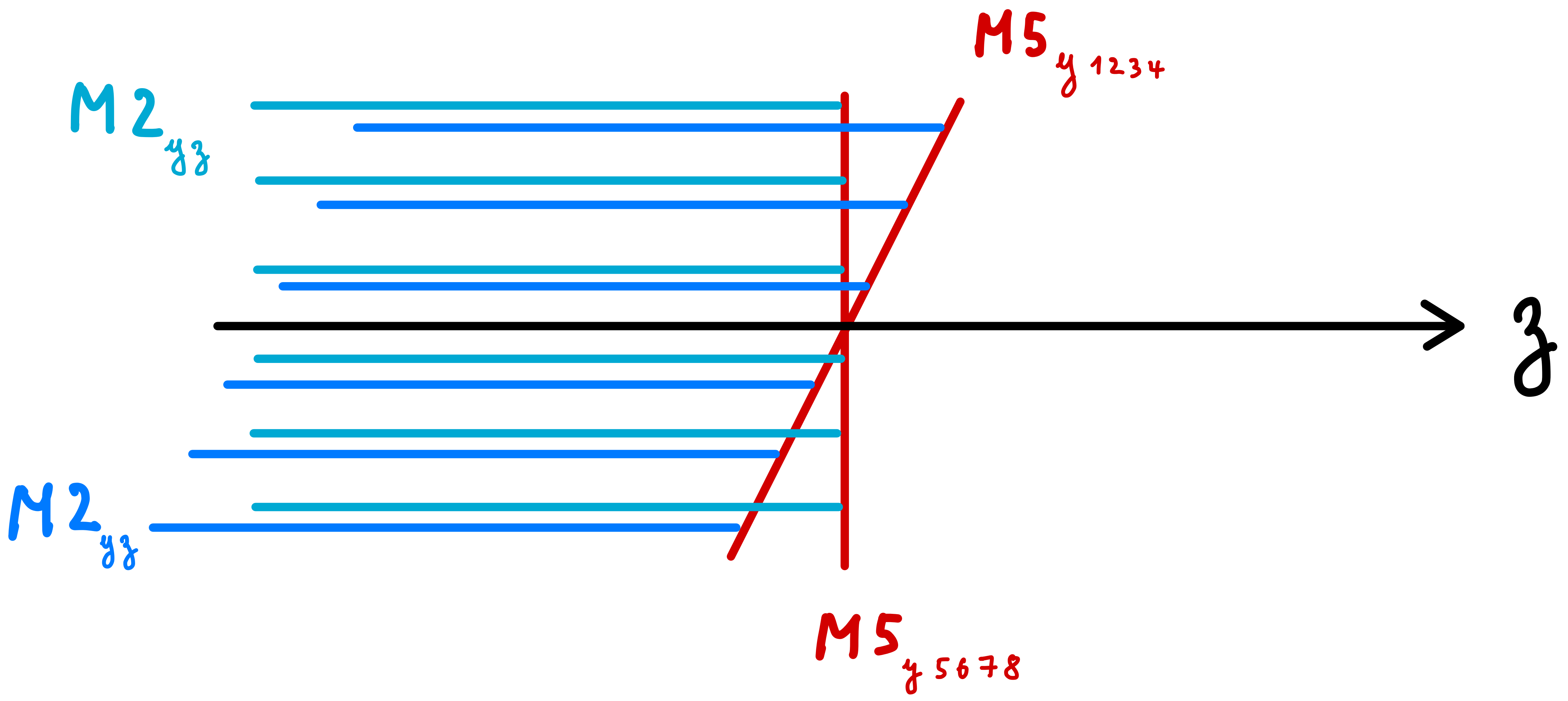

We propose:

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

- 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]

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

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

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[de Boer, Pasquinucci, Skenderis '99]

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

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

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[S. Lüst, Vafa, Wiesner, Xu '22]

→ Weaker bound on Λ due to the M2 branes!

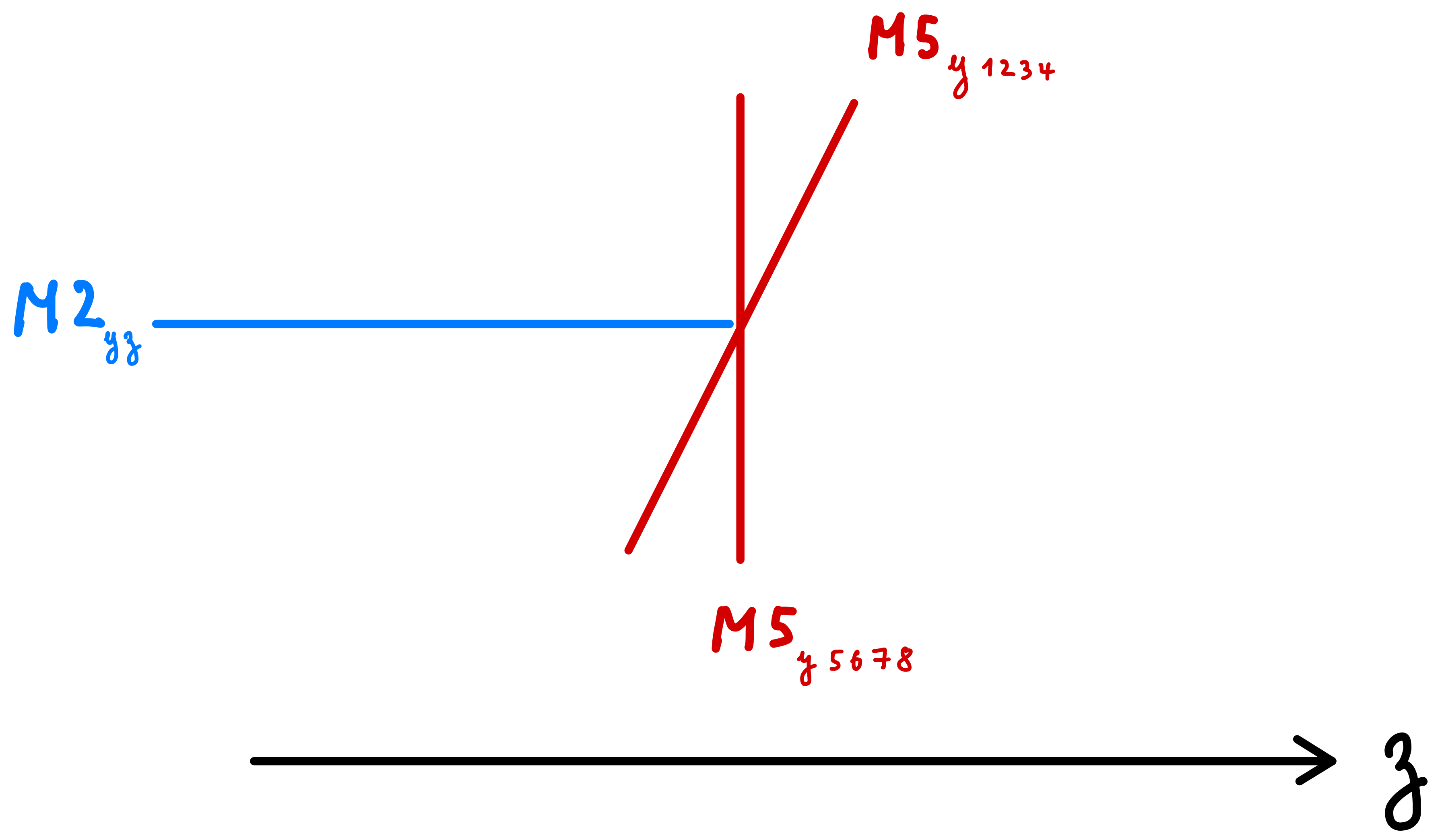
Pause for questions (5)

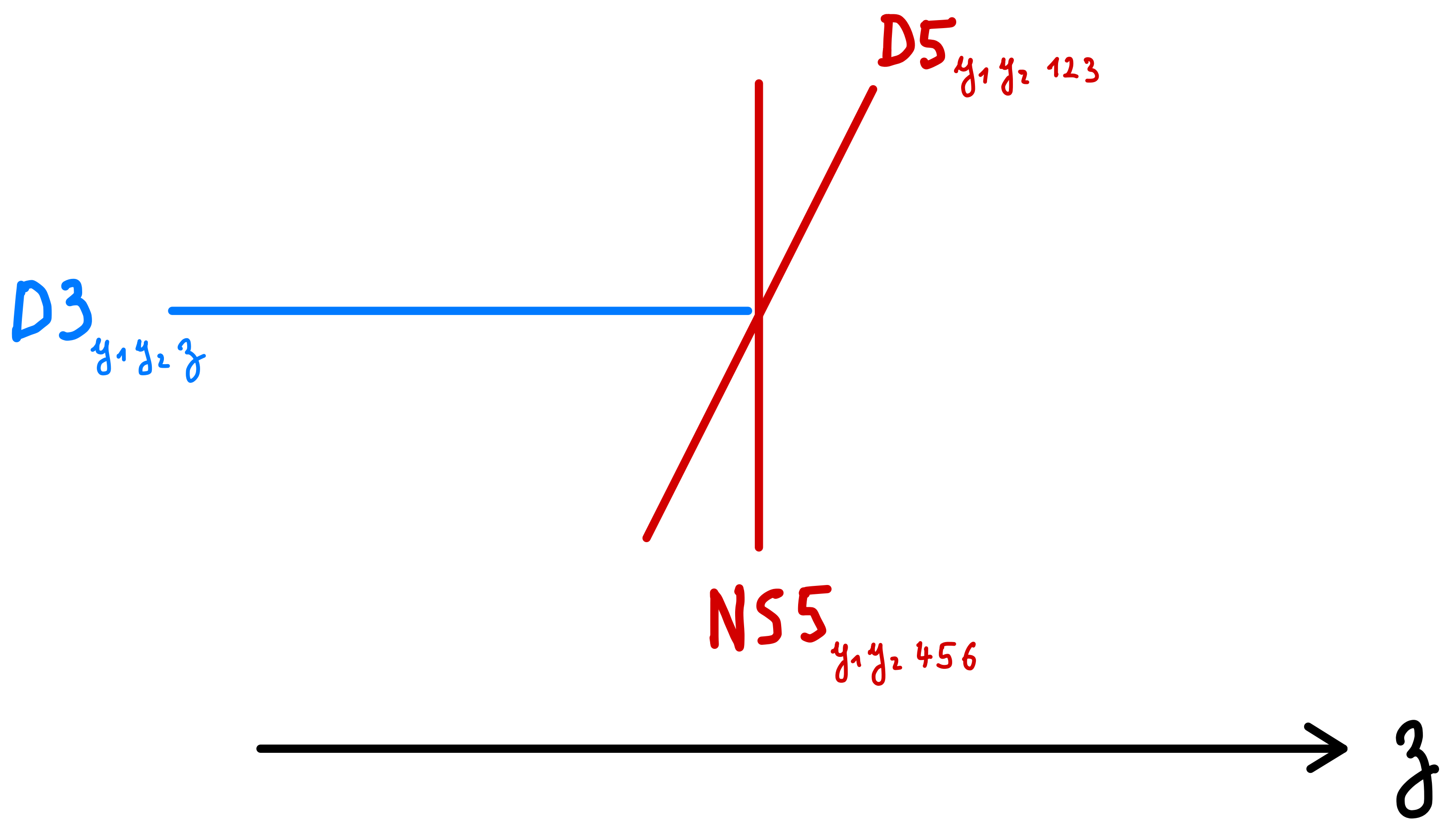
Part 3

Anatomy of a Flow

The most « entropic » domain wall

- Previous section: compare AdS_3 with AdS_3, but smeared the M5 branes.
- Configuration with the most d.o.f.?
- Squeeze all branes at the same place → brane interaction enhanced





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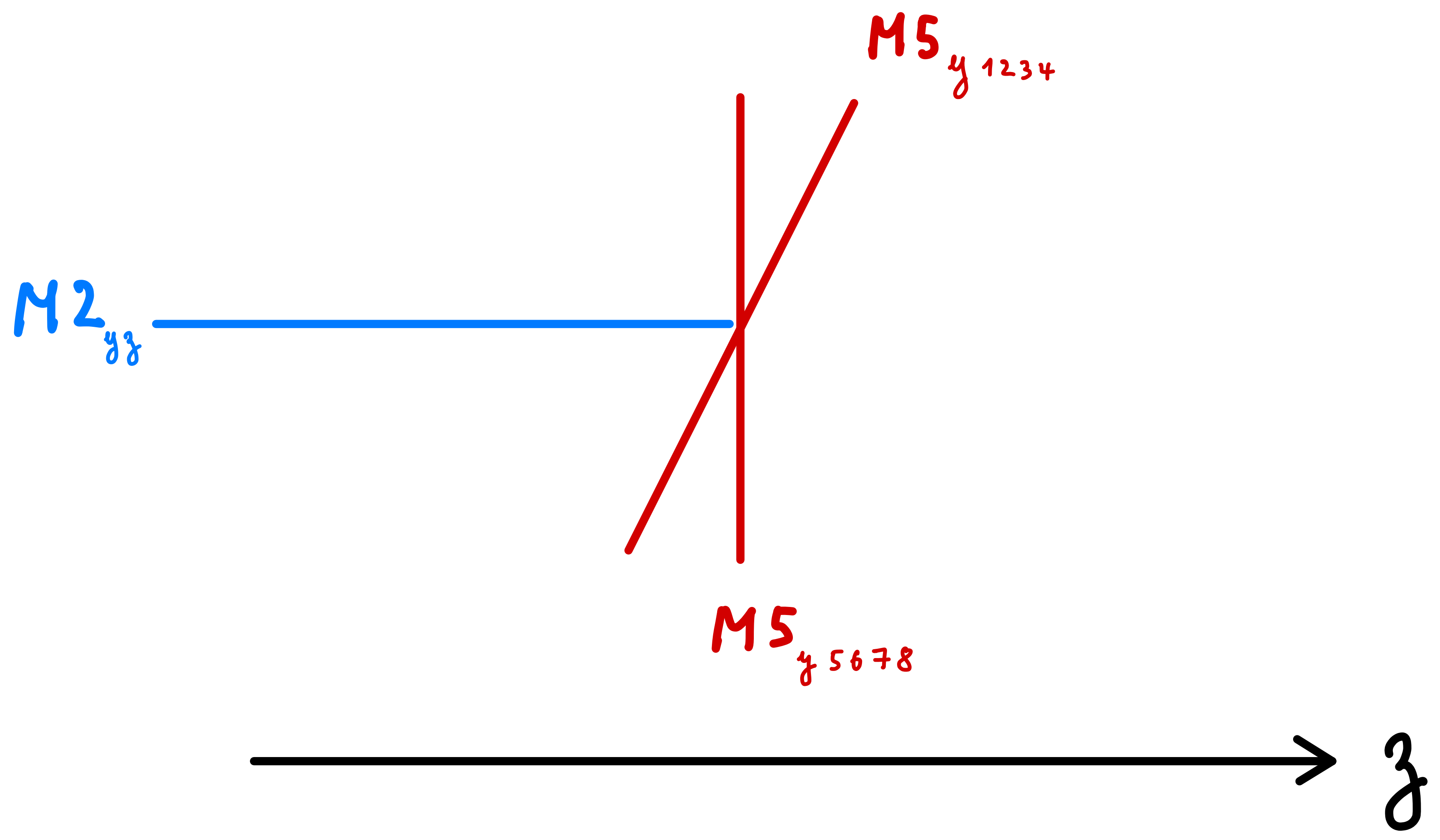
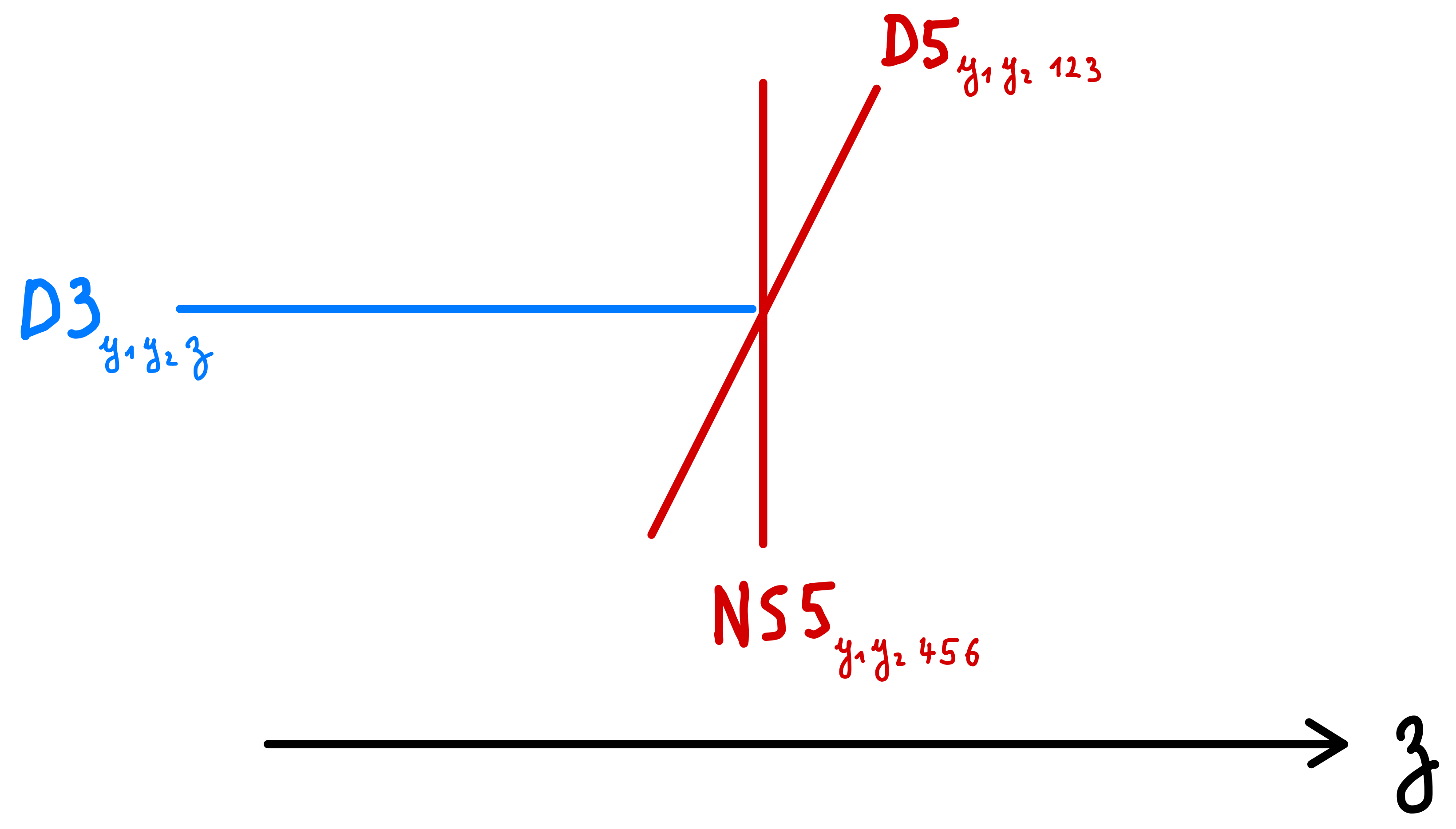
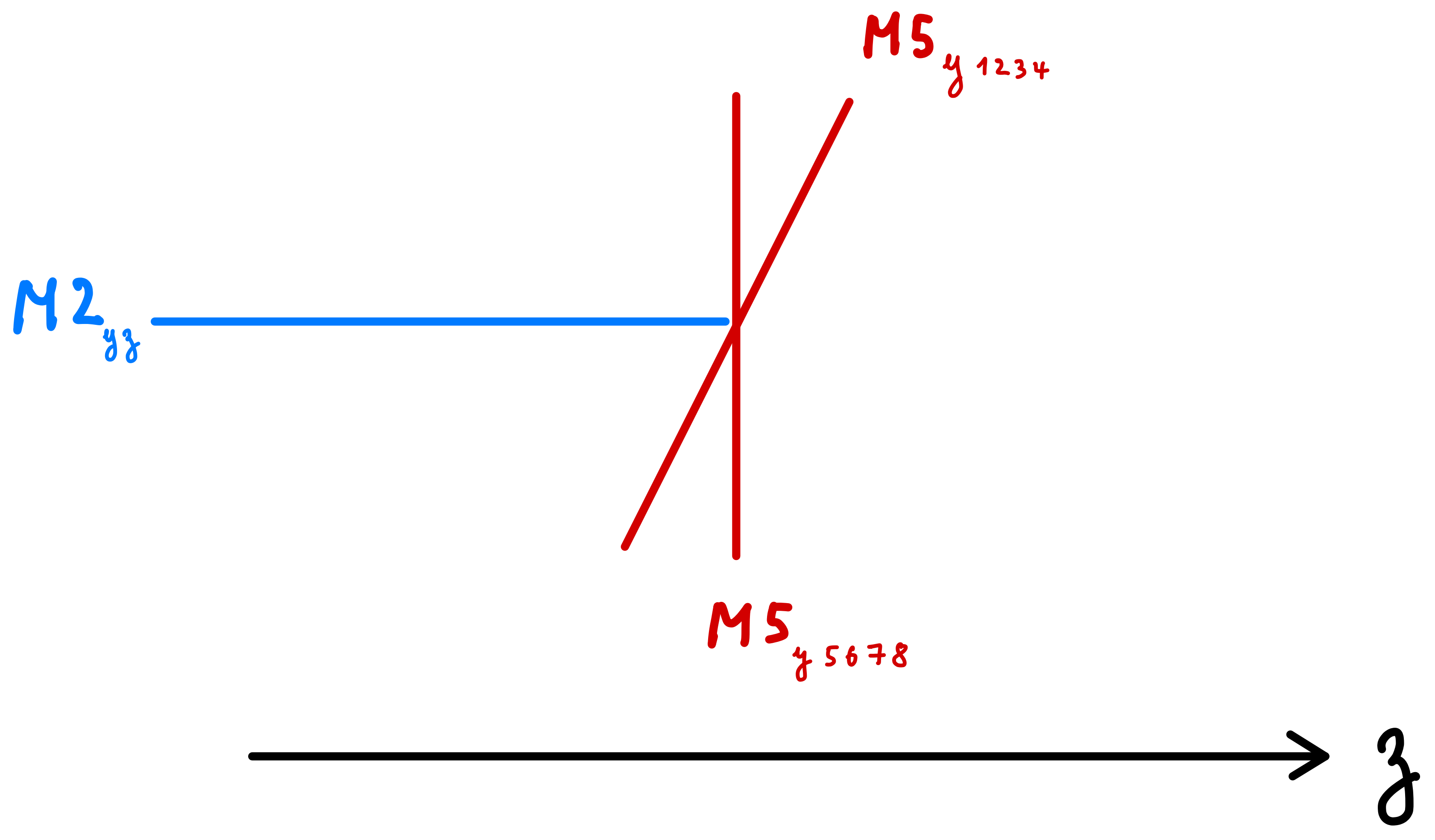


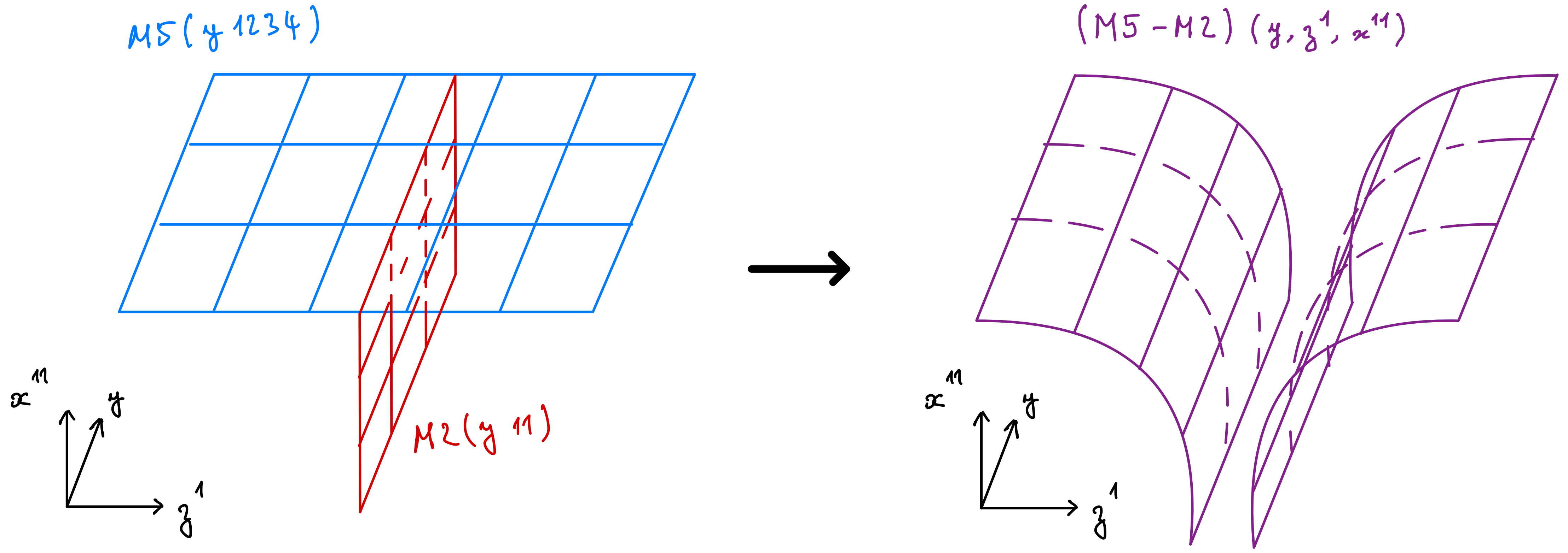


These configurations contain the maximum number of d.o.f. one can get from the branes

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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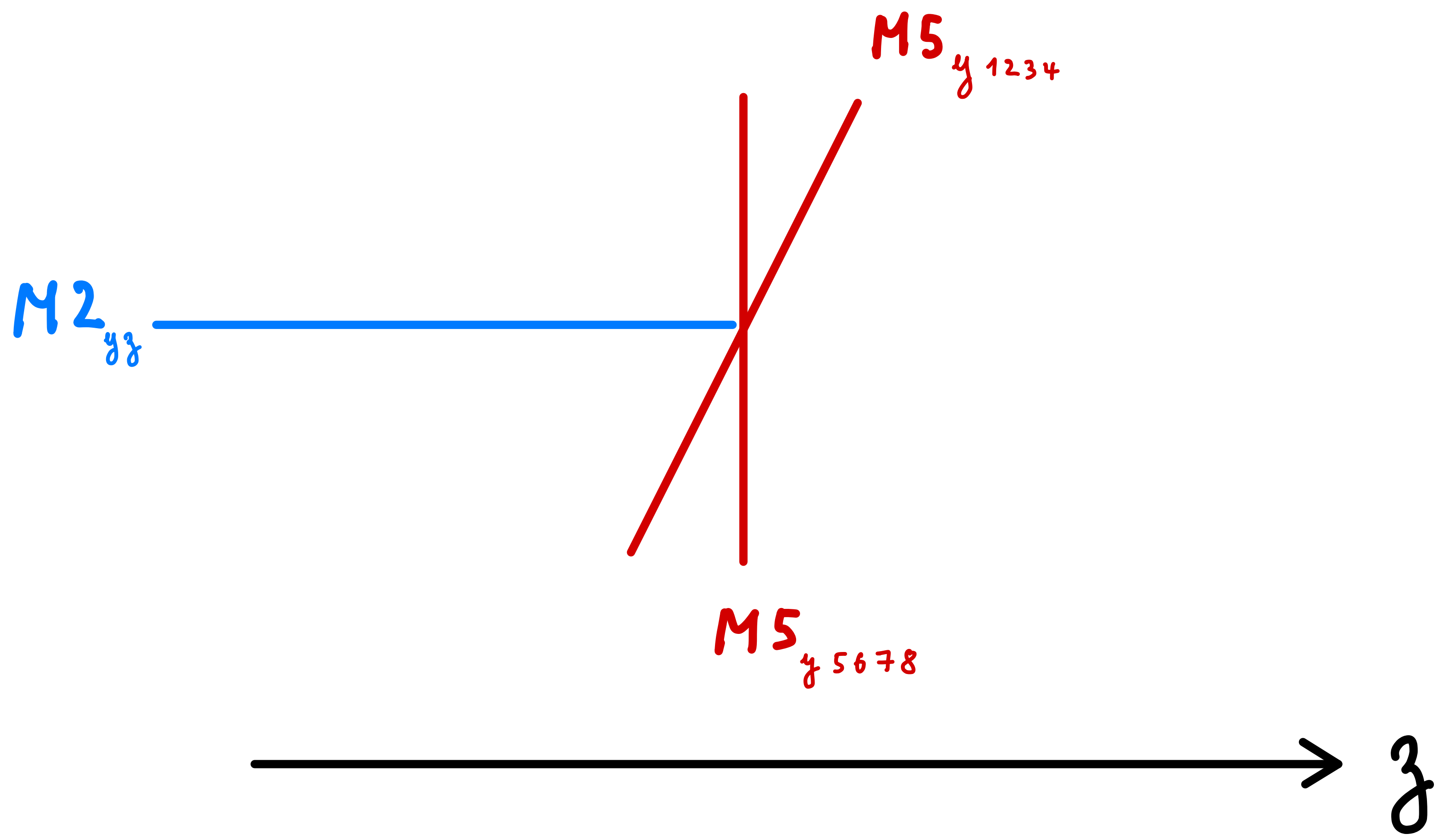
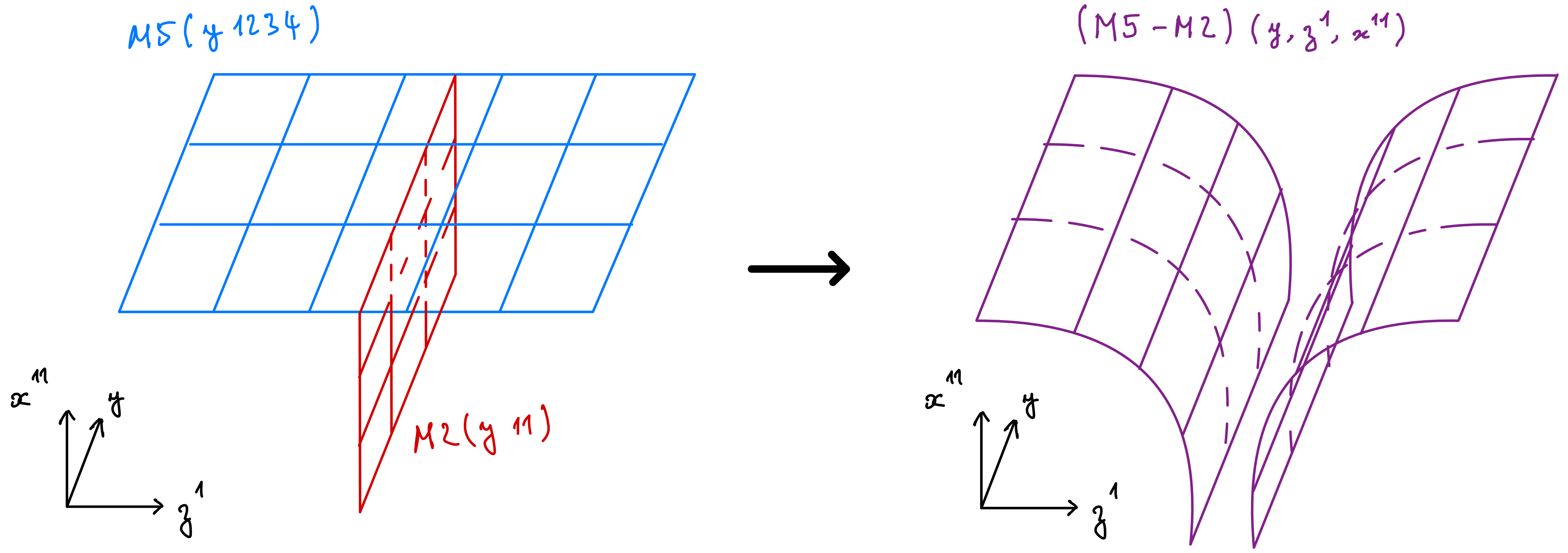




[Bena, Hampton, Houppe, **YL**, Toulikas '22]
[Eckardt, **YL** '23]

- 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

Warped AdS_4 in type IIB

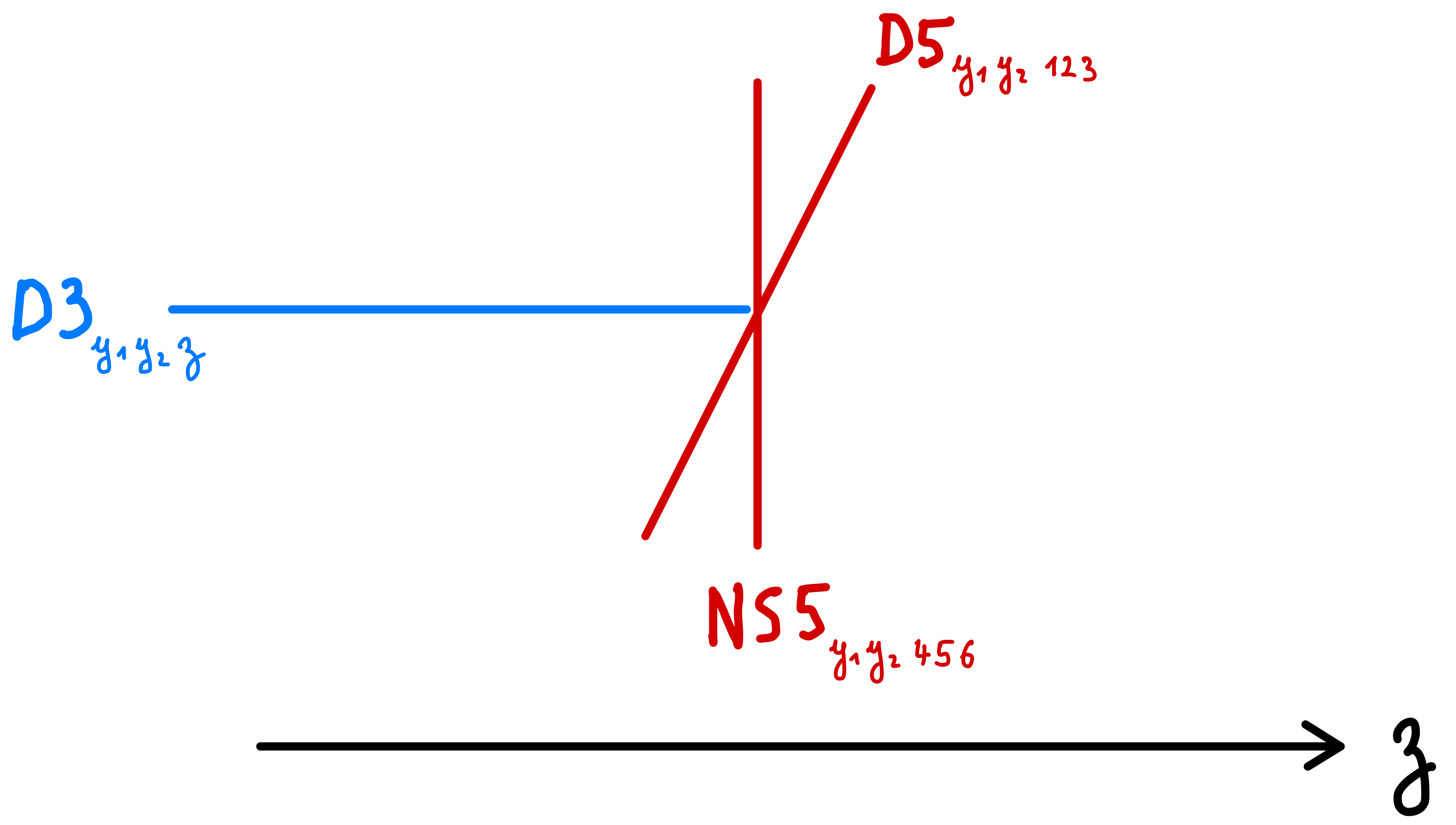
- Sugra solution for D5-NS5-D3 intersection is known.

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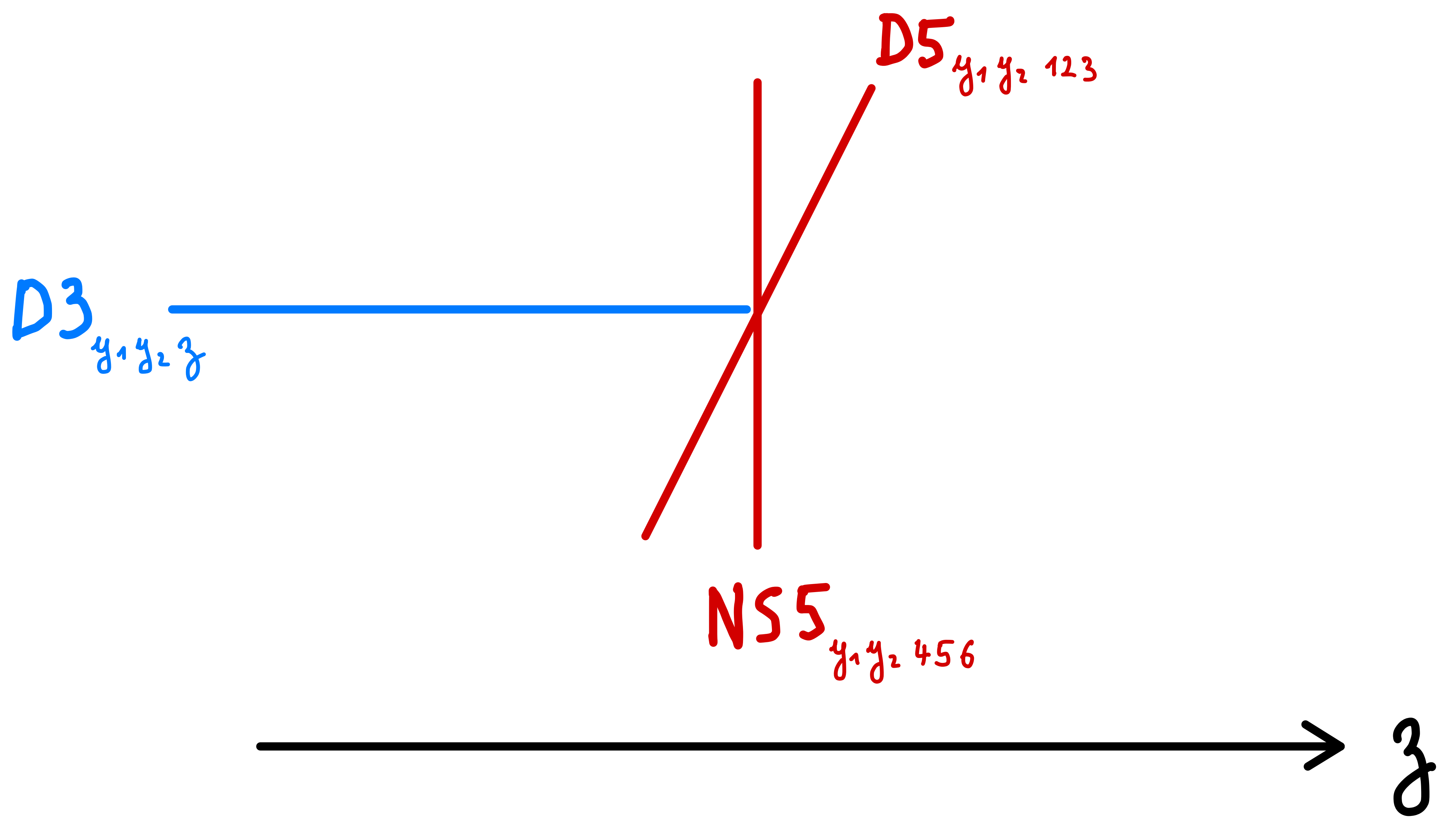
- The solution is an $\mathrm{AdS}_4 \times S^2 \times S^2 \times_w \Sigma_2$
- Compute of AdS radius in 4d Planck units:

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

[Assel, Estes, Yamazaki '12]



Matches the free energy of the 3d CFT!

[Assel, Estes, Yamazaki '12]
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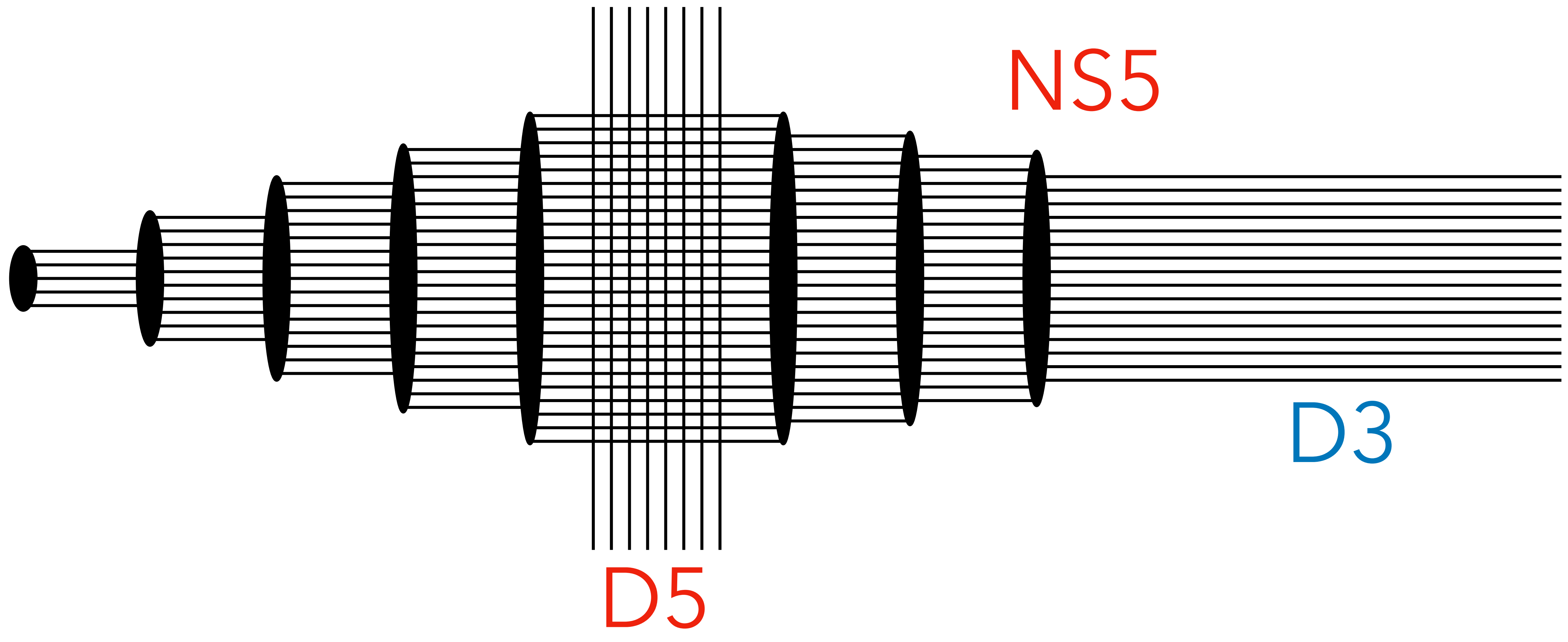

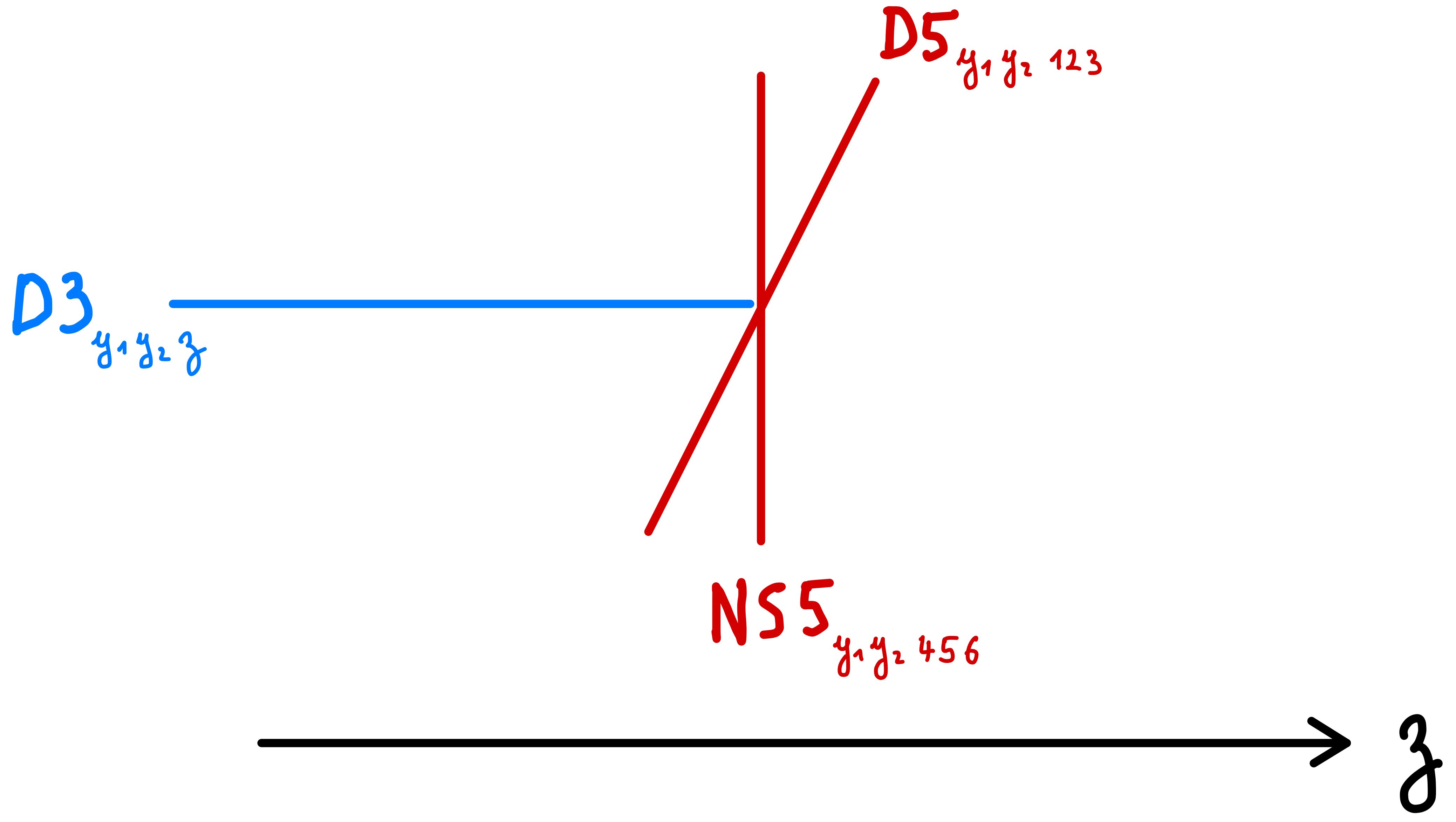

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Conclusion

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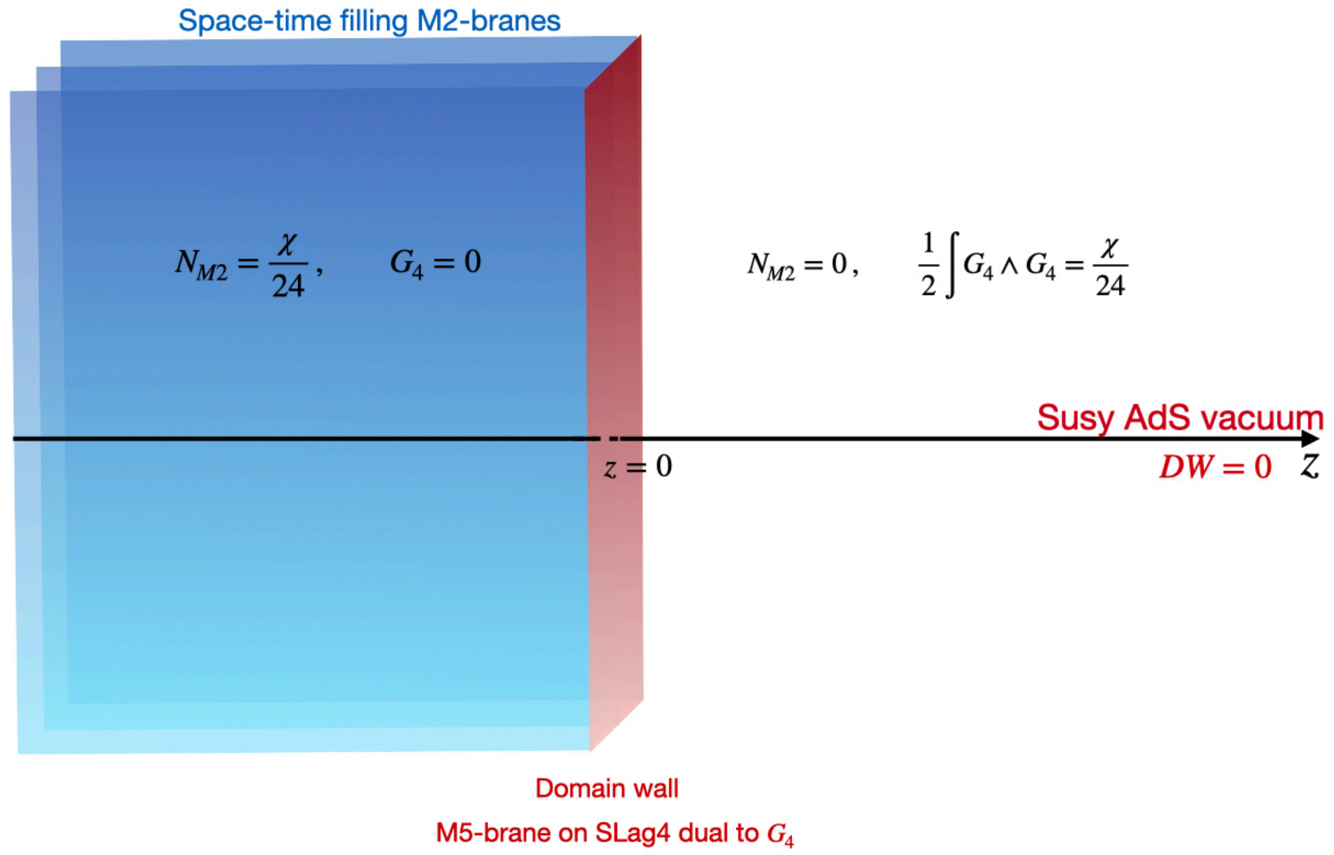
- Study DW configurations for KKLT
  - Assume scale-separated KKLT AdS exists
  - Realise it as being sourced by a DW made of M5 or D5/NS5 branes
  - c-theorem puts lower bound on $|\Lambda|$



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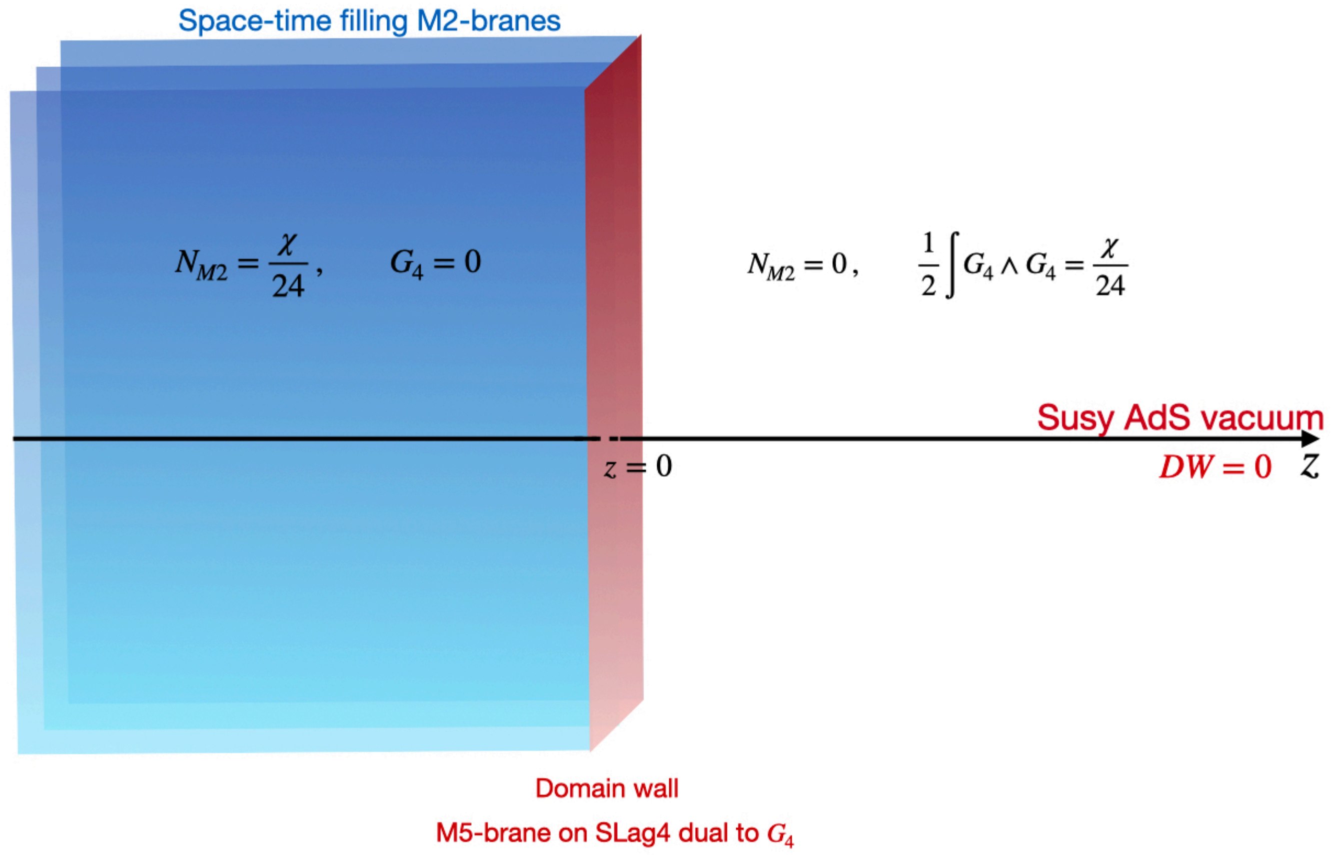


- Previously proposed to count the UV central charge – possible deformation of the SLag wrapped by the M5 branes [S. Lüst, Vafa, Wiesner, Xu '22]

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

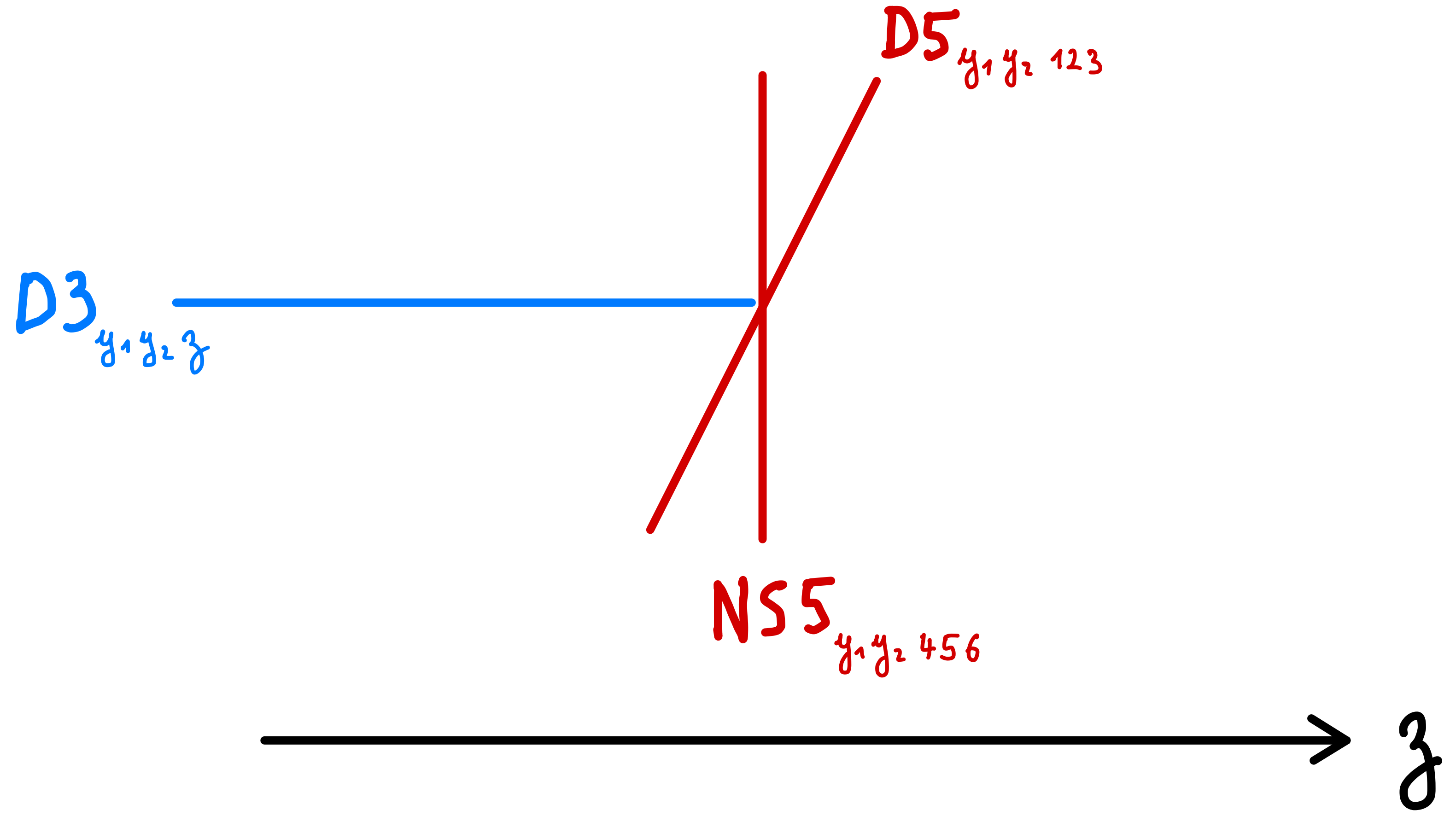
- Flaw in the argument: could have *hidden d.o.f.*

Conclusion

- The intuition was right, there can be indeed more d.o.f. than originally thought

$$F \sim (N_{\text{flux}})^4 \log(N_{\text{flux}})$$

- They correspond to Hanany-Witten-like d.o.f. at the five-brane intersections.



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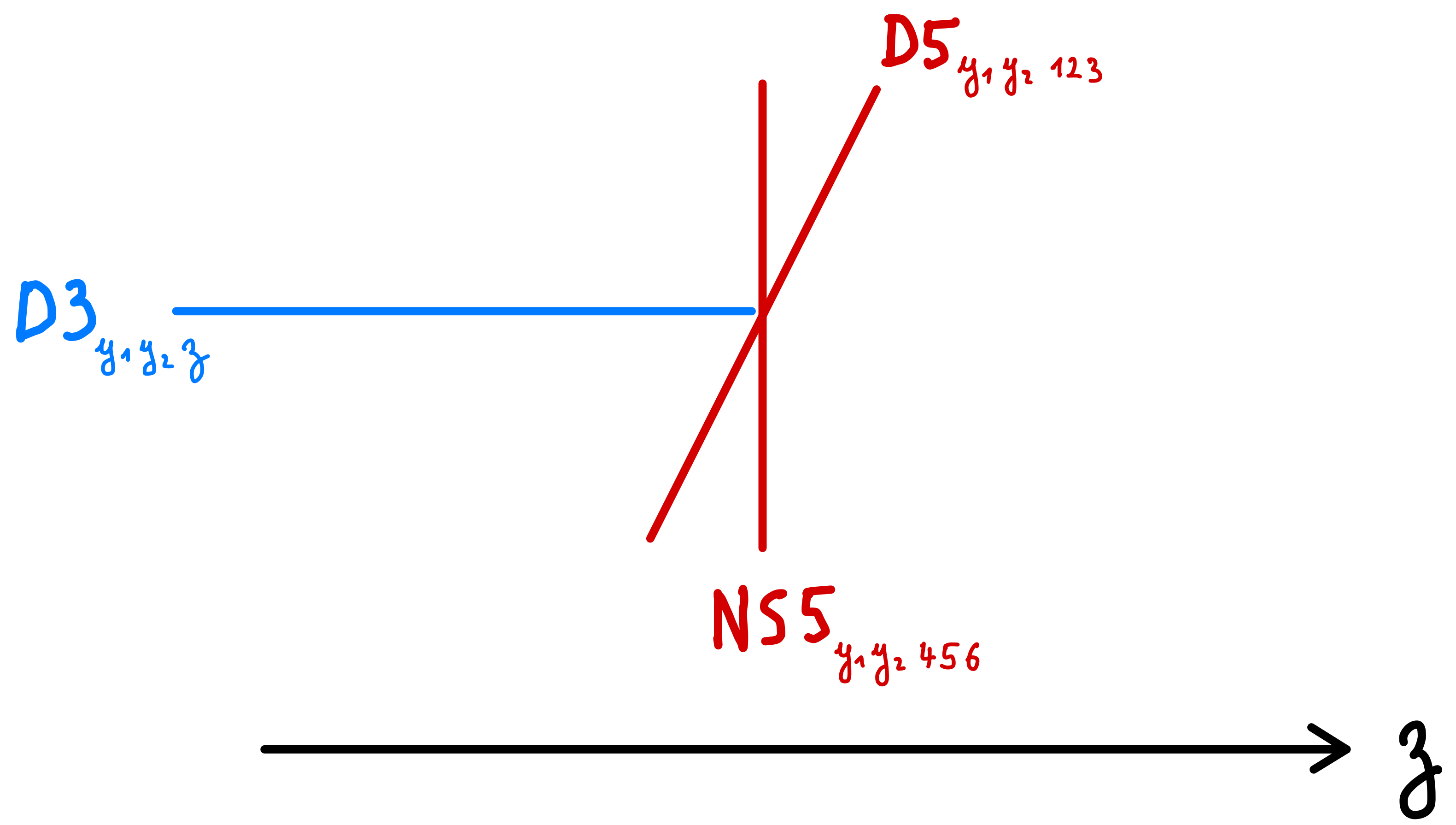

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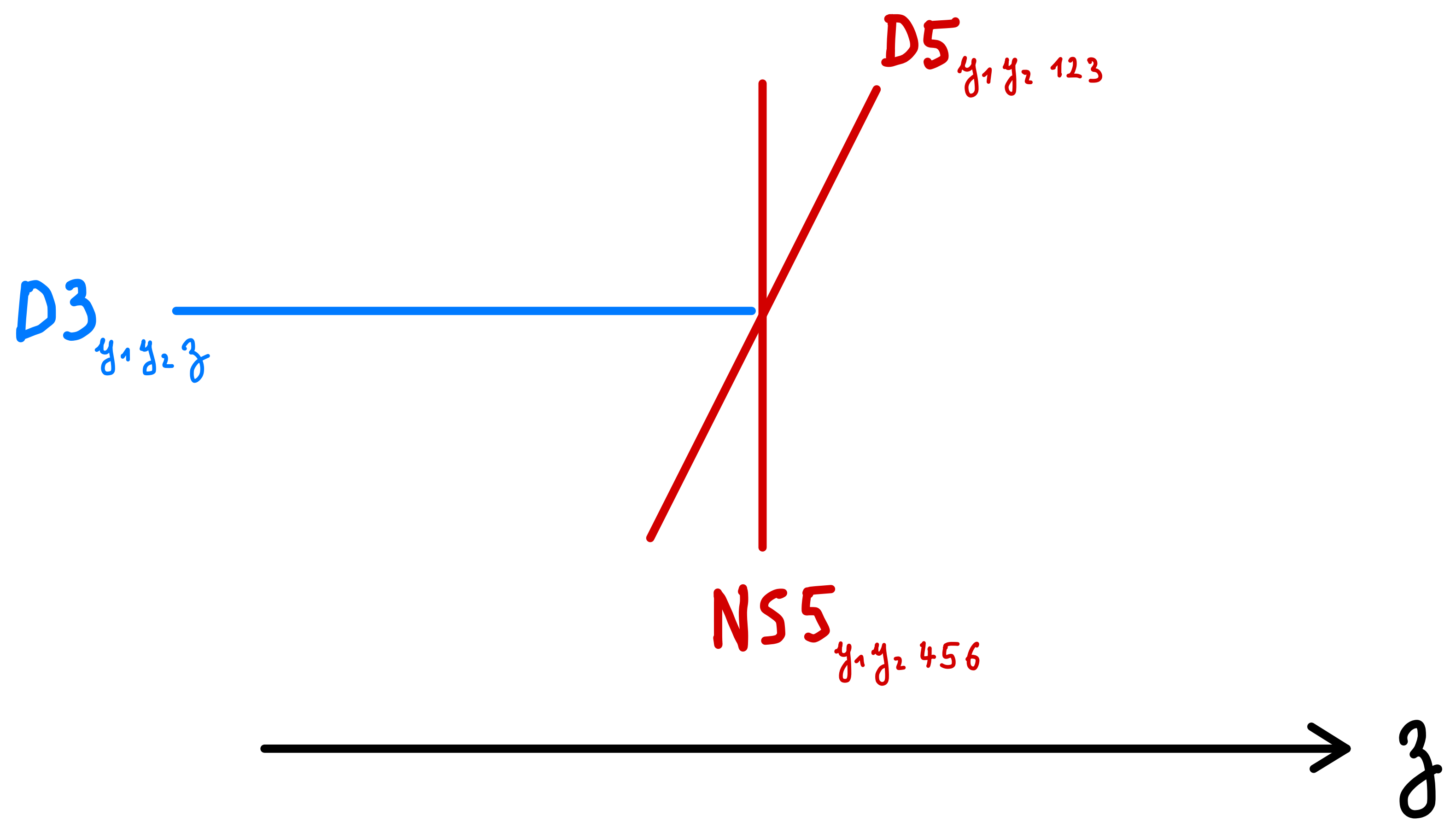

Thank you!