Local supersymmetry enhancement and the entropy of three-charge black holes

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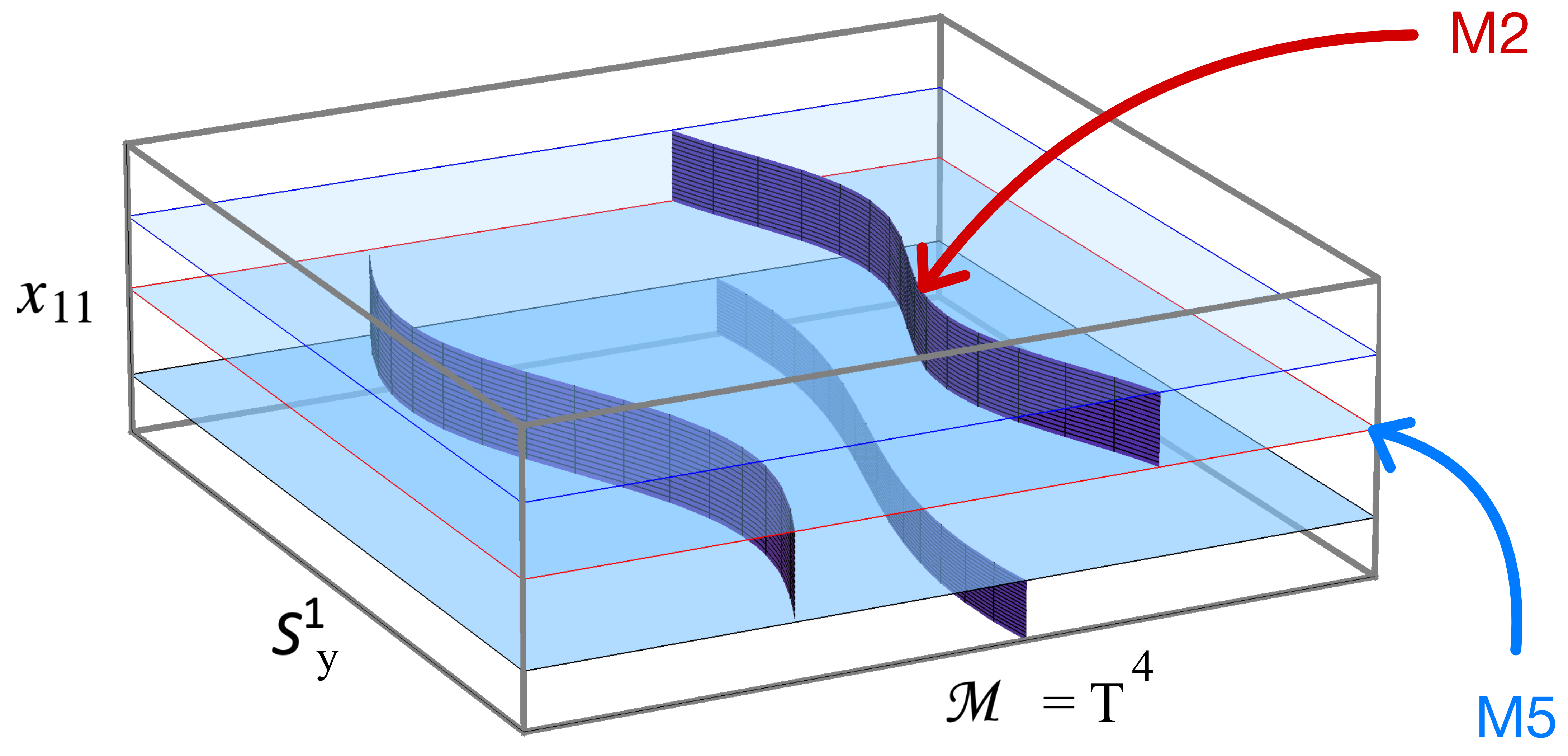
German-Israeli Project Cooperation (DIP)
Holography and the Swampland

Based on [2211.14326] with I. Bena, S. Hampton, A. Houppe and D. Toulikas

January 12th, 2023

What this talk is about



« Dijkgraaf-Verlinde-Verlinde -Maldacena microstates »

- **M5-M2(-P) black hole:** The microstates that are made of **fractionated M2 branes** account for the entropy.
- We found: They can transition into microstates with 16 local supersymmetries.

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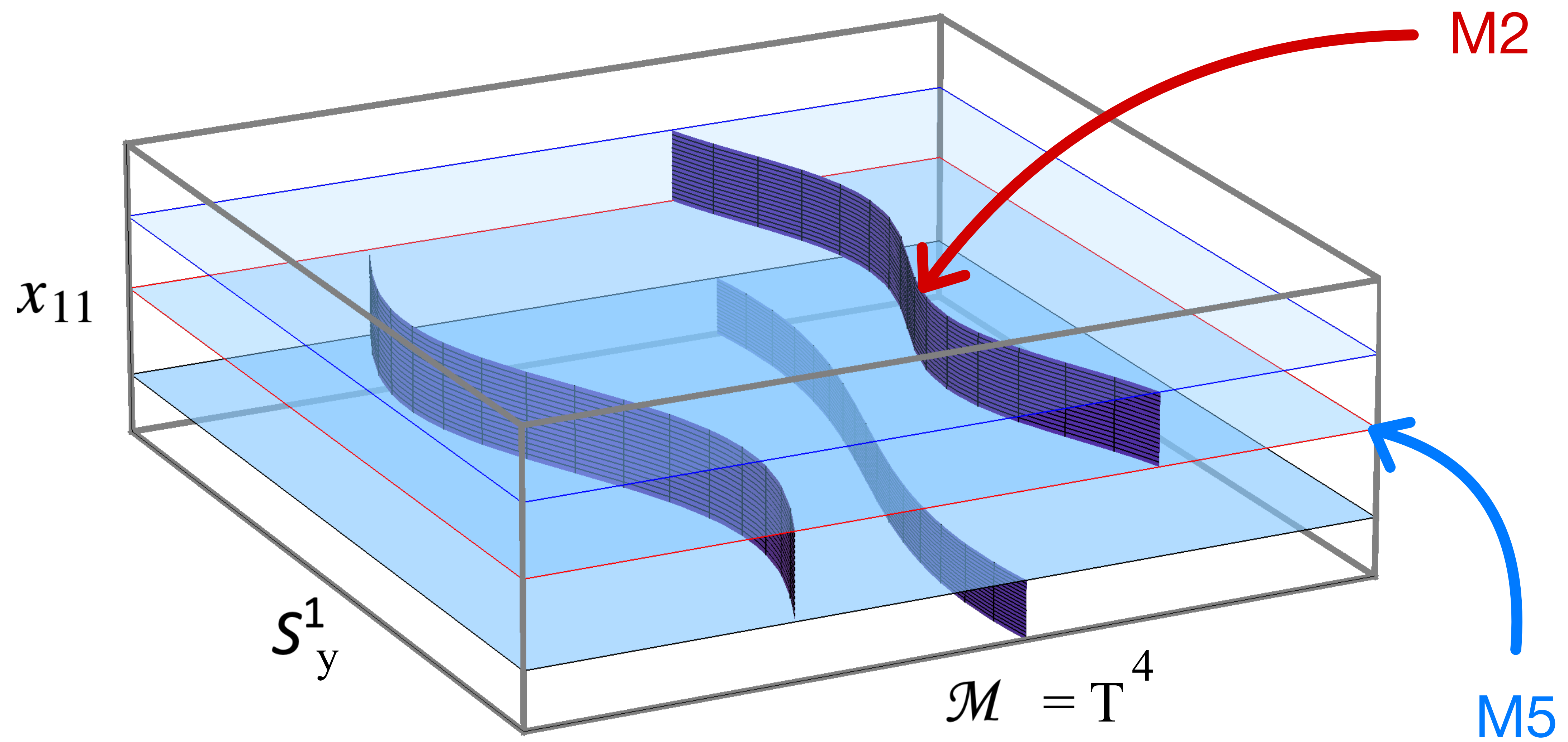

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- **M5-M2(-P) black hole:** The microstates that are made of **fractionated M2 branes** account for the entropy.
- We found: They can transition into microstates with 16 local supersymmetries.

  Microstates with 16 local susys account for the black-hole entropy!

- We expect their backreaction to be horizonless microstates.

Outline

1. Local supersymmetry enhancement and black-hole microstates

2. The new M5-M2-P microstates with 16 local supersymmetries

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The 3-charge black hole and near-horizon geometry

- Type IIA/IIB: $\mathbb{R}^{4,1} \times S^1_y \times T^4$
- Take brane system with 3 charges:

  D5(y, T^4), D1(y), P(y)

  or NS5(y, T^4), F1(y), P(y)

  $\Rightarrow$ naively, 1/8-BPS everywhere

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  - Use harmonic function rule

$$ds^2 = -\frac{2}{\sqrt{H_1 H_5}}\left[dt^2 + dy^2 + (H_P - 1)^{-1}(dy - dt)^2\right] + \sqrt{H_1 H_5}\, ds^2_{\mathbb{R}^4} + (H_1 H_5)^{-1/2} ds^2_{T^4}$$

with

$$H_{1,5,P} = 1 + \frac{Q_{1,5,P}}{r^2}\,.$$

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Possible conclusion:

Global charges and supersymmetries seem to control near-horizon geometry.

Therefore all brane systems develop the same horizon:
To have access the information about the microstates, probe singularity region, where supergravity breaks down.

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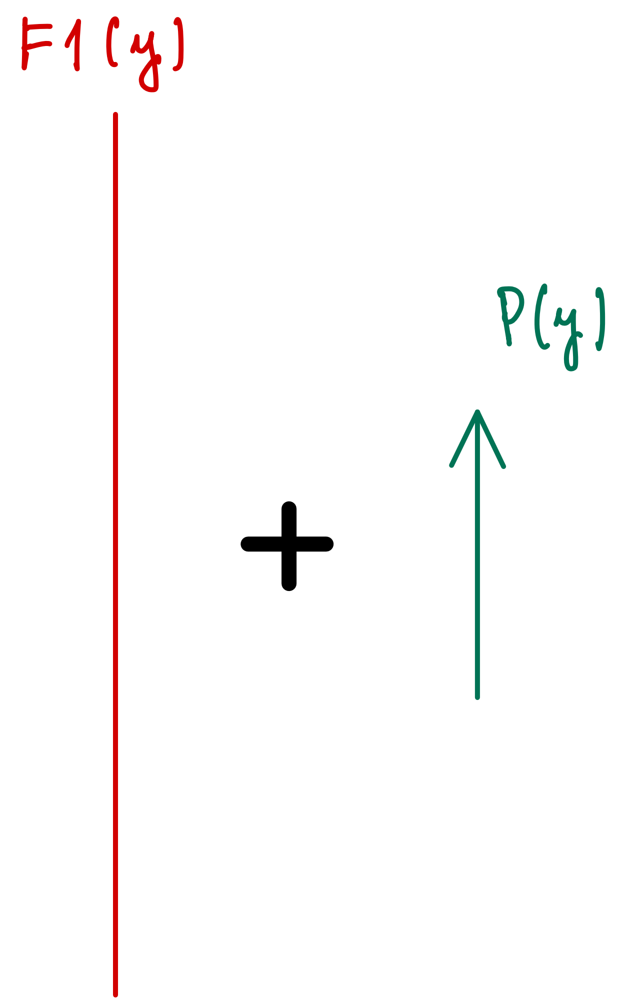
- *Local supersymmetry enhancement:*

  String-theory excitations (branes, strings) combine together to form a *bound state* that is locally 1/2-BPS (*16 susies*).

Local SUSY enhancement – example

- Ex.: F1(y) and parallel P(y):



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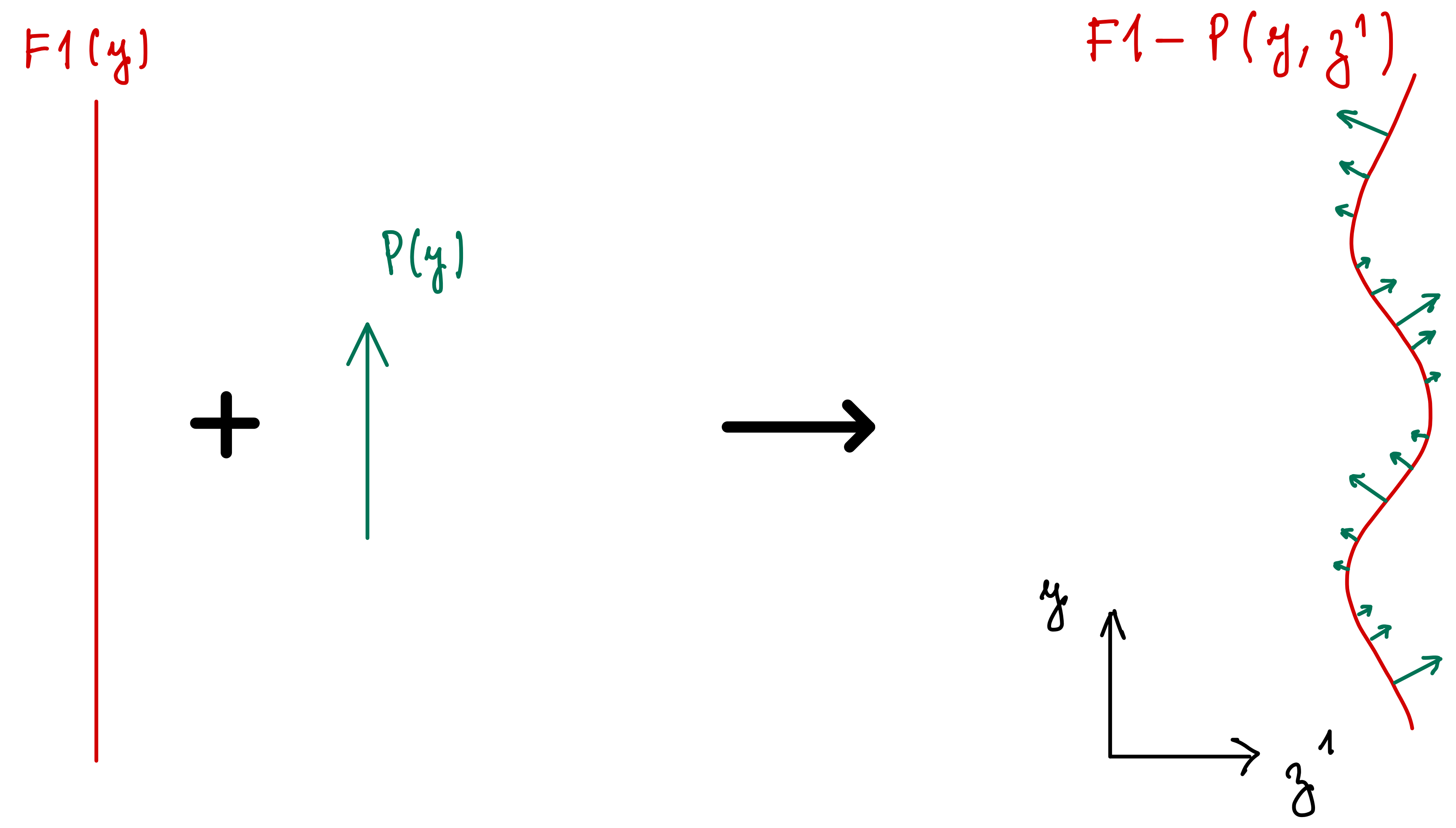

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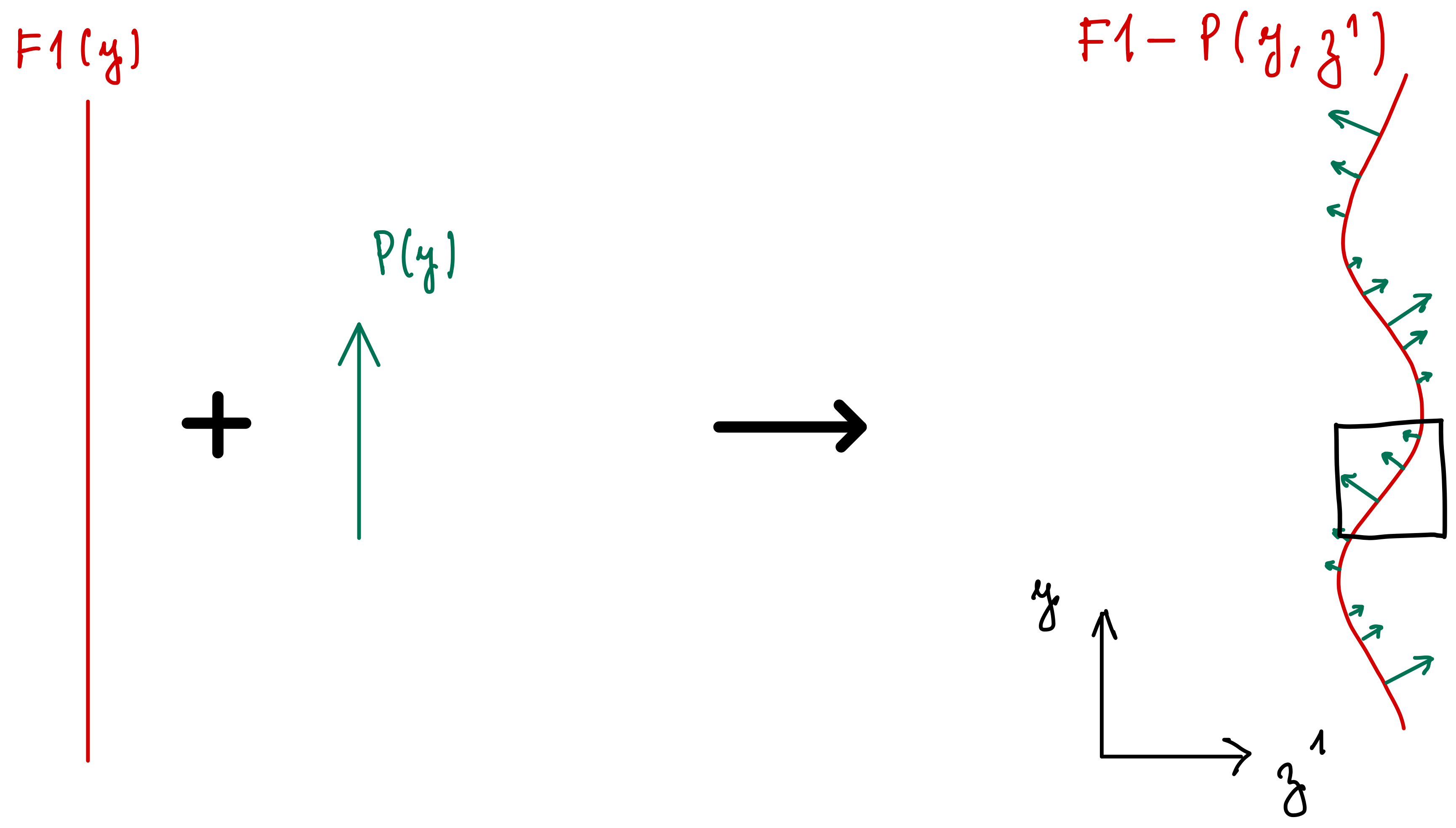

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- Actually the string can carry momentum: *profile*
- The F1-P profile preserves the same global supersymmetries…
  - …but locally it is a F1($\hat{y}$) boosted by orthogonal P($\hat{y}^{\perp}$)
  - F1($\hat{y}$)-P($\hat{y}^{\perp}$) preserves 16 supercharges

Local supersymmetry
→ information on microstate?

Local VS global supersymmetries

See e.g. [Bena, Hampton, Houppe, **YL**, Toulikas '22]

- Branes, strings → constraint on ϵ:

$$\Pi\,\epsilon \equiv \frac{1}{2}(1+P)\,\epsilon = 0$$

Killing spinor

Projector

$$\Pi^2 = \Pi$$

Traceless involution

$$P^2 = 1$$

$$\mathrm{tr}(P) = 0$$

→ Constraint halves number of supersymmetries

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- Combine k different excitations:

$$\epsilon \in \ker(\Pi_1) \cap \ldots \cap \ker(\Pi_k)$$

$\rightarrow \sharp$ (*global supersymmetries*)

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→ ♯ (*global supersymmetries*)

- Add other involutions $(P_{k+1}, \ldots, P_n)$ and weights $(\alpha_1, \ldots, \alpha_n)$ s.t. $\alpha_1 + \ldots + \alpha_n = 1.$

- $$\hat{\Pi}\,\epsilon \equiv \frac{1}{2}\left(1 + \alpha_1 P_1 + \ldots + \alpha_n P_n\right)\epsilon$$

Mix of excitations (branes, etc) with different charges:

$$\alpha_i = \frac{Q_i}{M}$$

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Not necessarily a projector!

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One can enhance supersymmetries

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- $\{\alpha_i\}$ not unique → $\{\alpha_i\,(x)\}$

$$\hat{\Pi}(x)\,\epsilon(x) = 0$$

along the bound state

ϵ promoted to be a function

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At x, $\epsilon(x) \in \ker(\hat{\Pi}(x))$ → *local supersymmetry*

- While for *global supersymmetry*:

$$\epsilon \in \bigcap_x \ker\left(\hat{\Pi}(x)\right).$$

♯ (*global susies*) ≤ ♯ (*local susies*)

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Local supersymmetry enhancement:

Given a set of global supersymmetries, there sometimes exists a whole moduli space of brane/string systems, parameterised by $\{\alpha_i(x)\}$, preserving those same global supersymmetries, but whose number of local supersymmetries is enhanced.

– identify the additional excitations (« glues ») to make a bound state

– determine the charge-to-mass ratios $\{\alpha_i(x)\}$.

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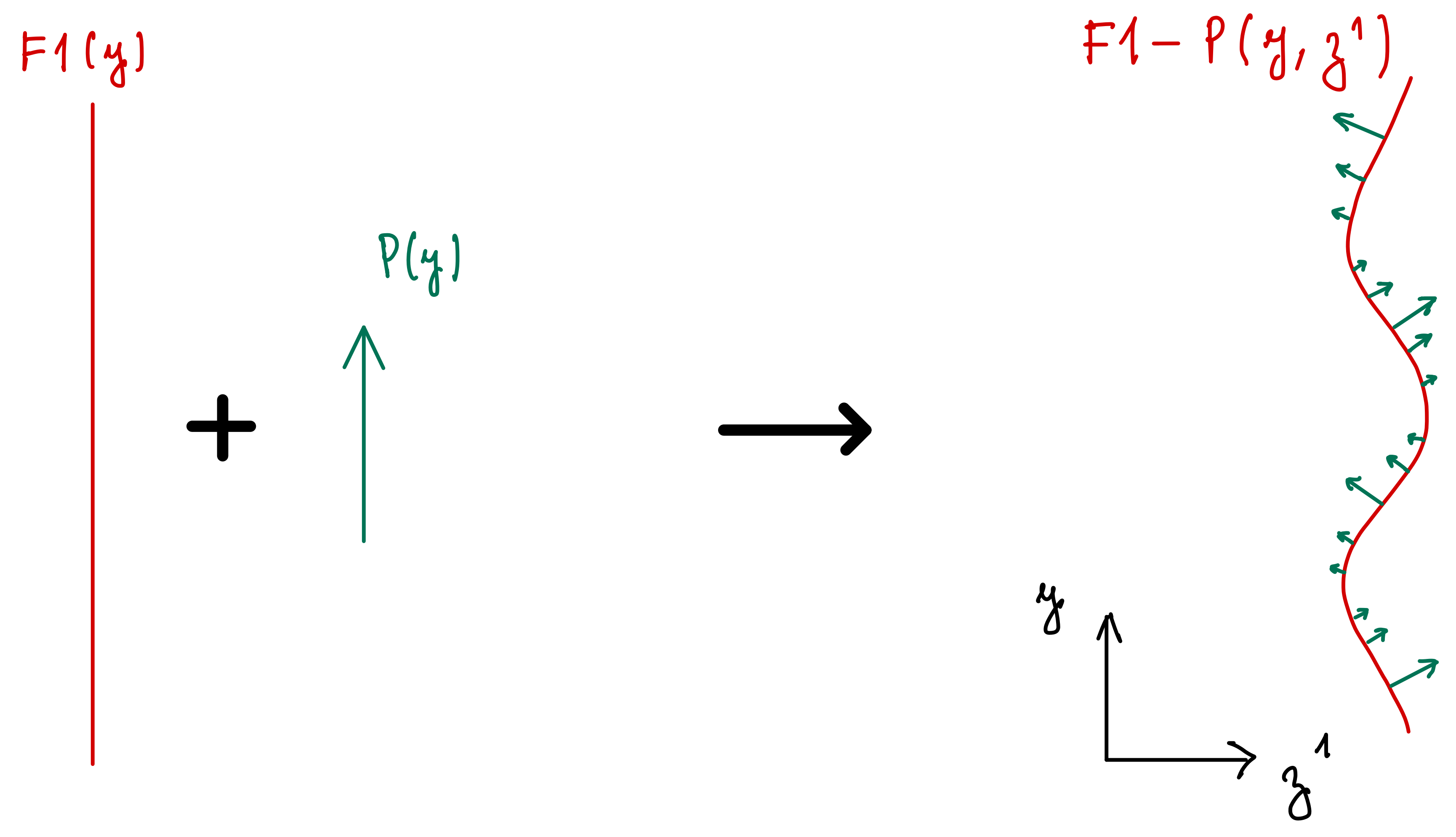

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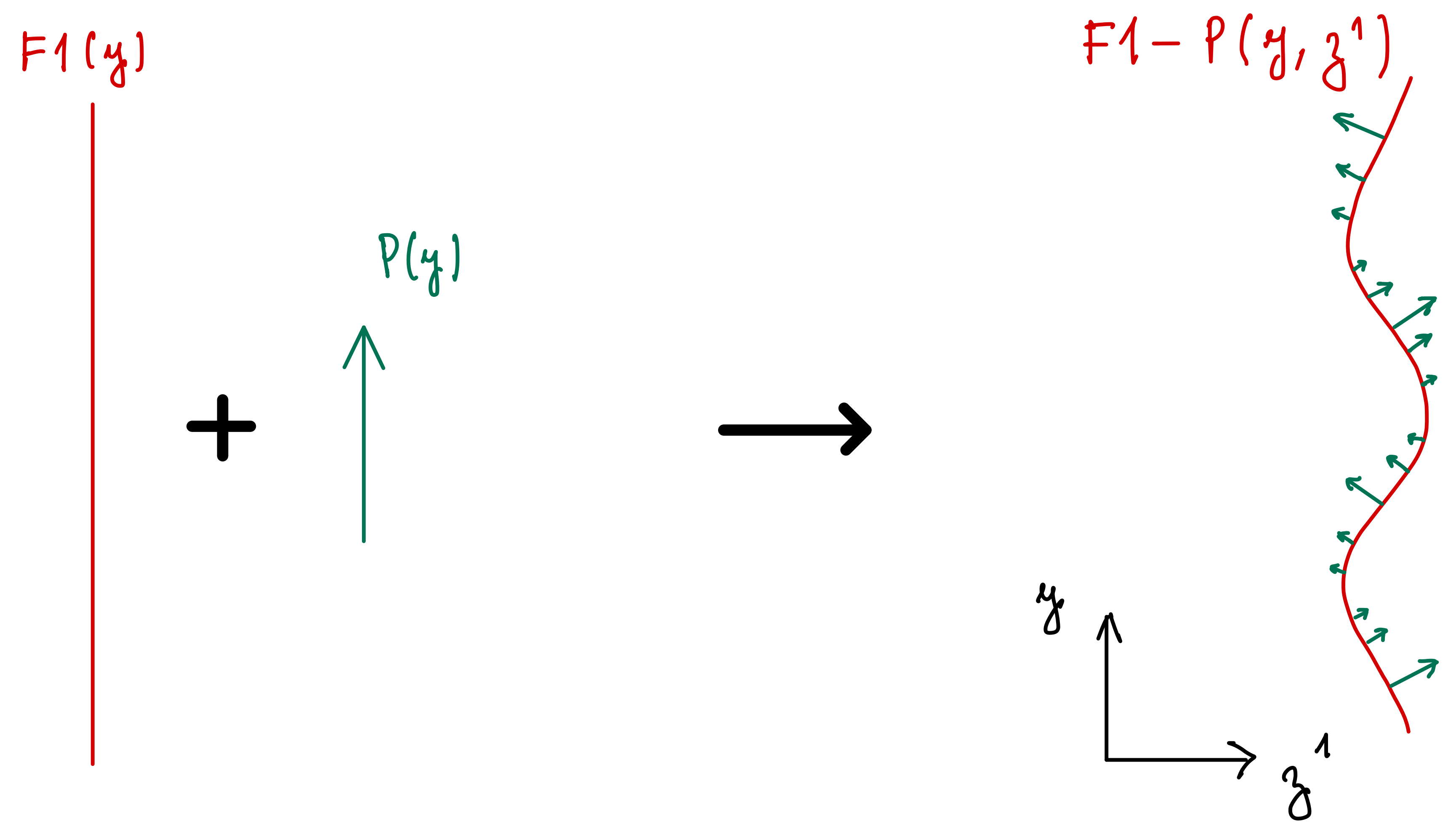

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Step 0

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defining the global supersymmetries

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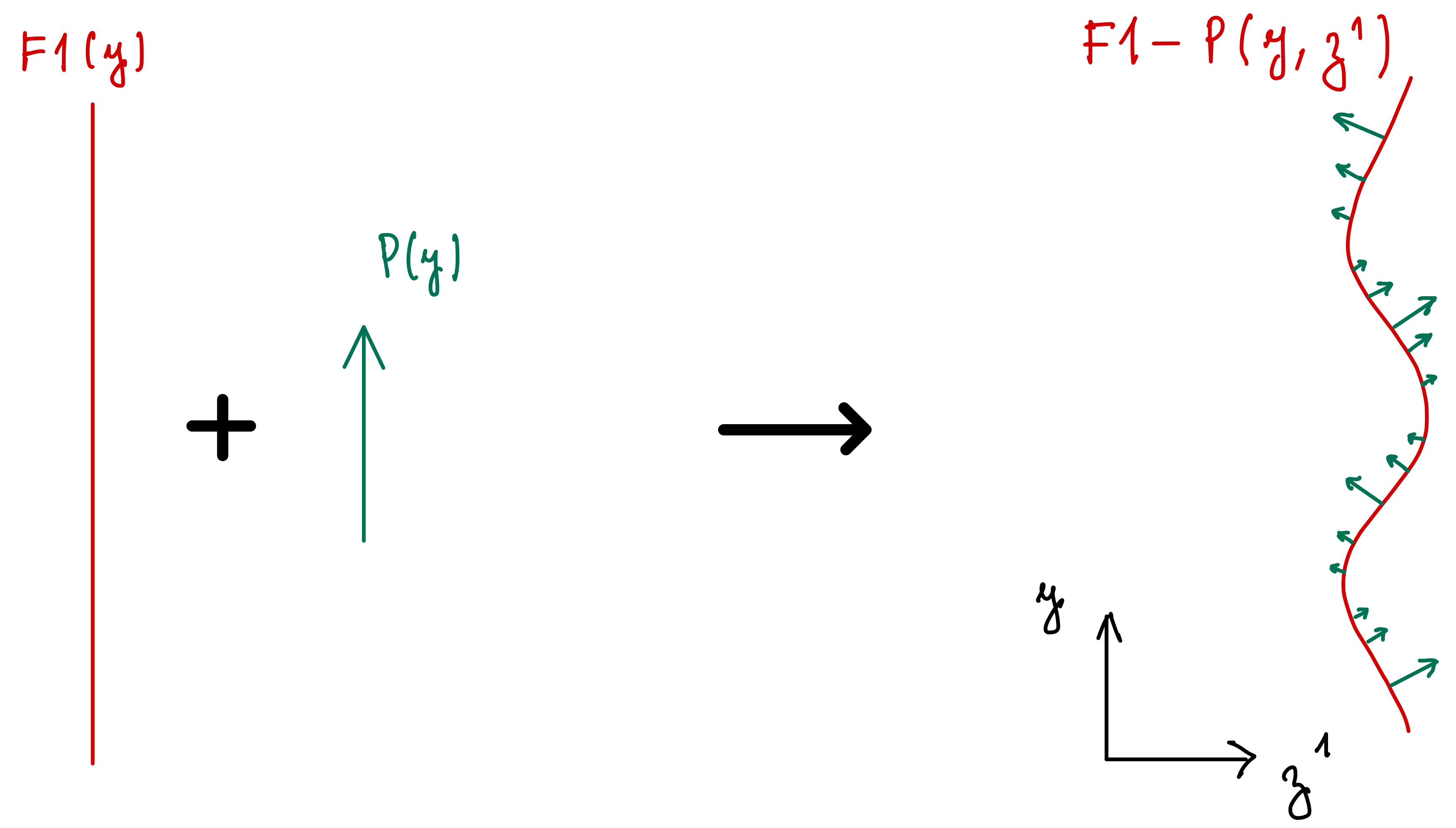

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defining the global supersymmetries

« glues », dipoles

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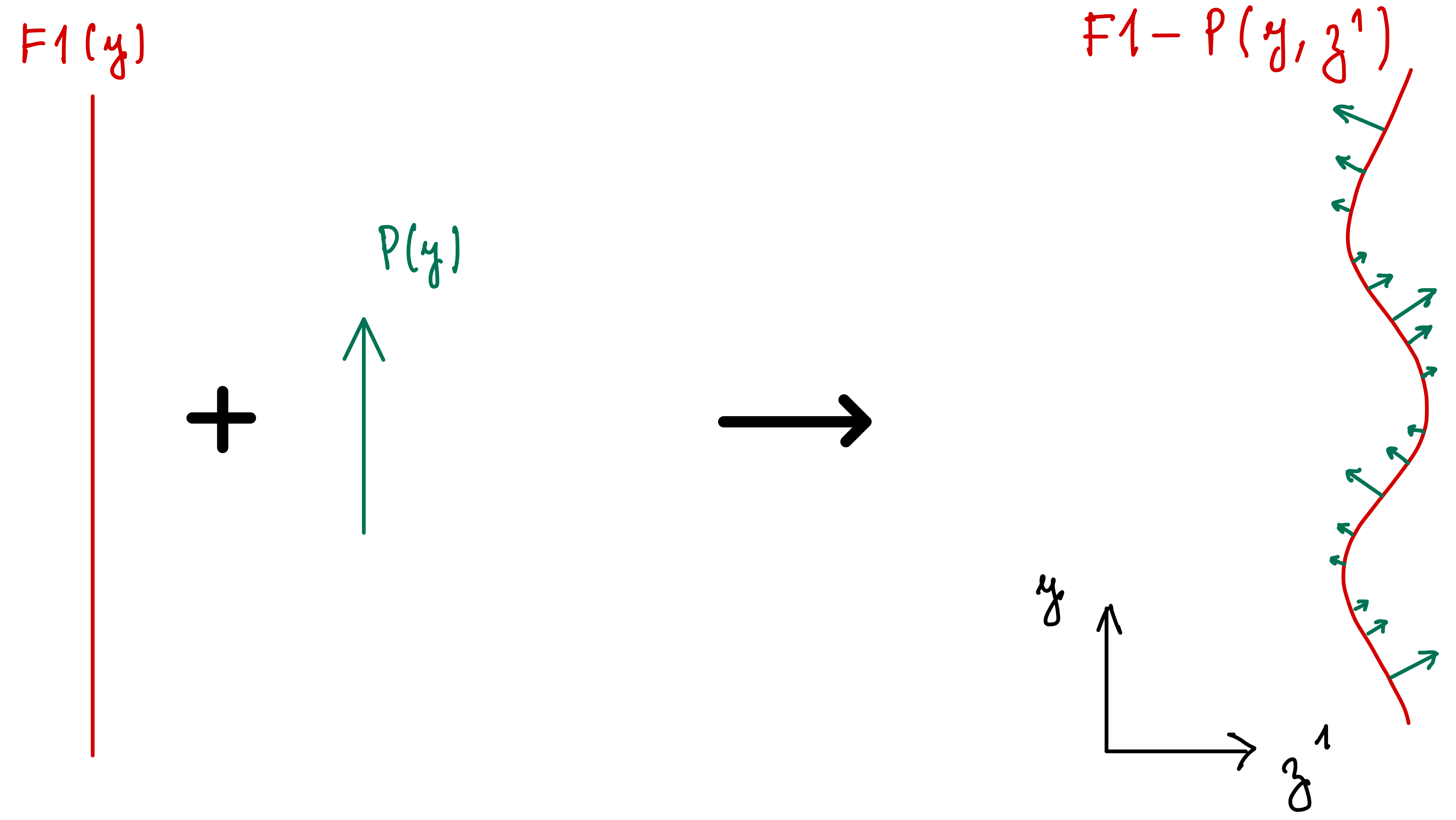

Step 2

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$\cos^2\alpha$ $\quad\sin^2\alpha$ $\quad\cos\alpha\sin\alpha$ $\quad-\cos\alpha\sin\alpha$

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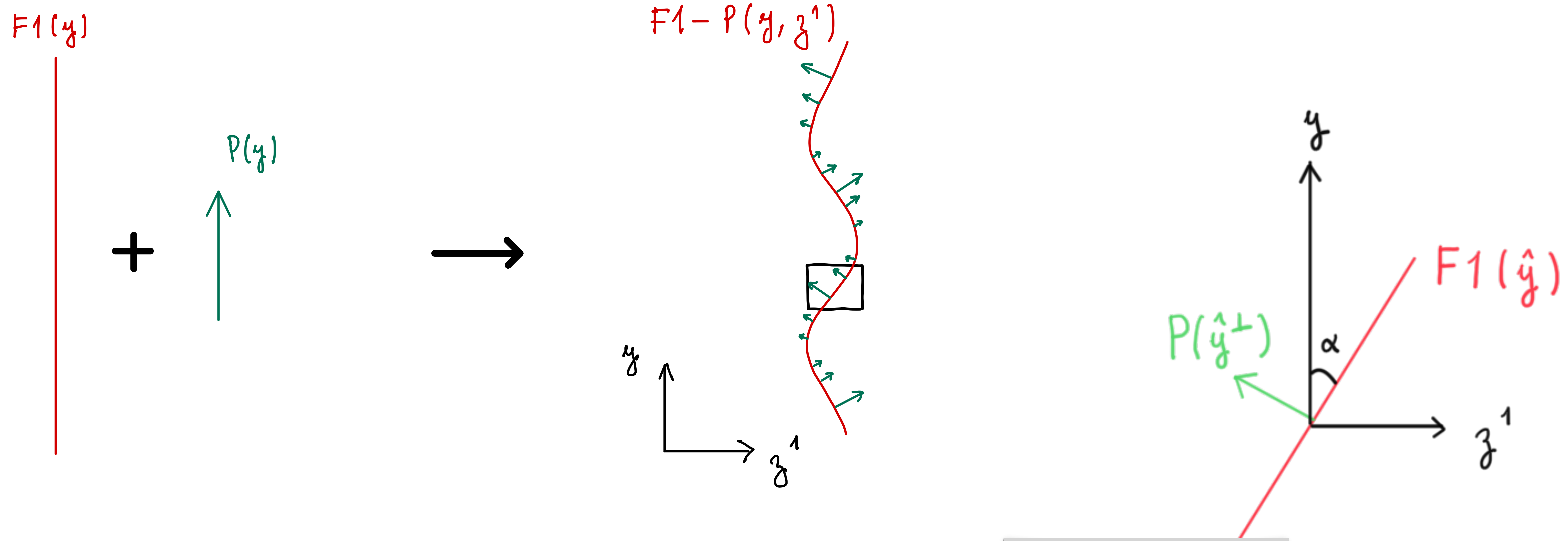

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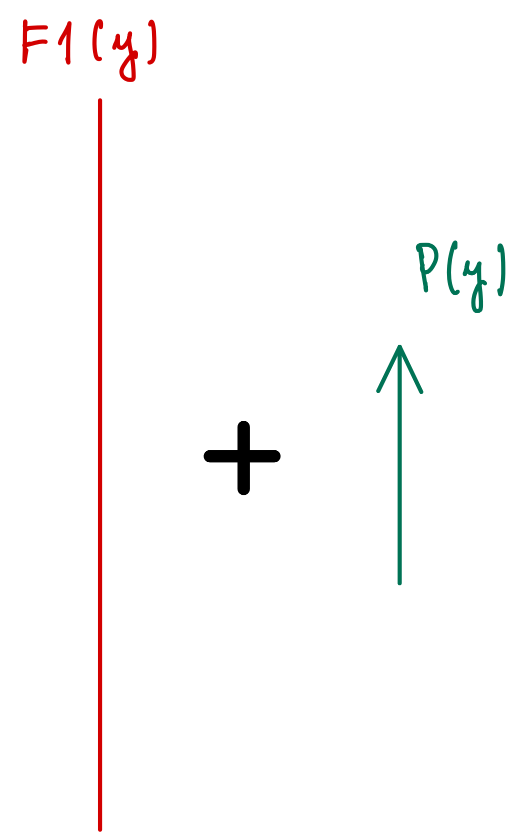
Microstates of the F1-P black hole



- Harmonic rule:

$$ds^2_{string} \quad = \quad H[-dudv + Kdv^2] + \sum_{i=1}^{4} dx_i dx_i + \sum_{a=1}^{4} dz_a dz_a$$

→ black hole with horizon at $r = 0$.

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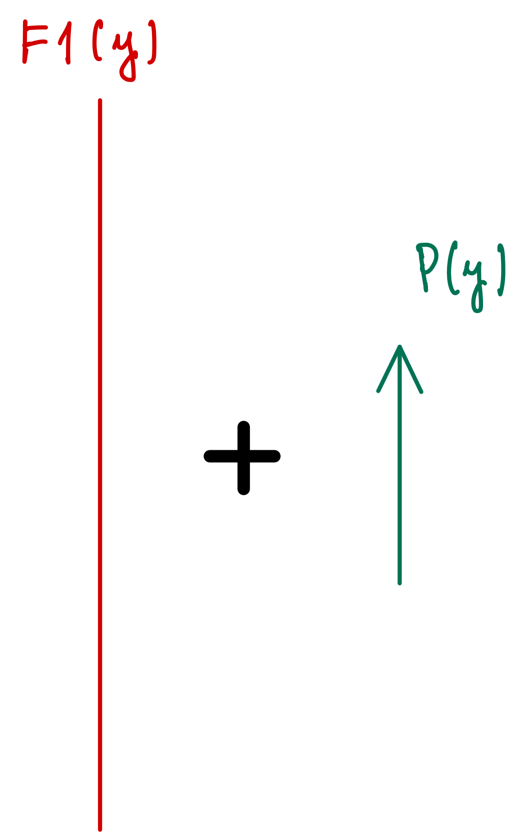

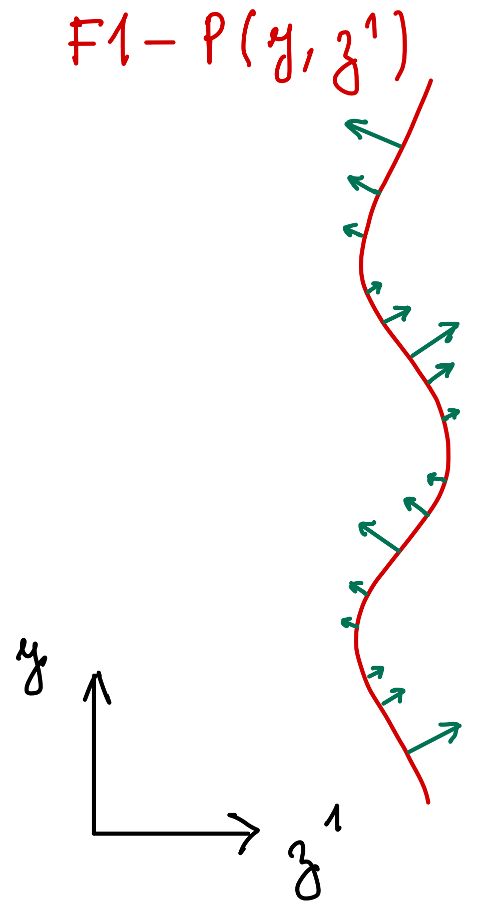

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[Dabhorkar, Gauntlett, Harvey, Waldram '95]

→ smooth, horizonless solution.

Microstates of the F1-P black hole

The massive string states accounting for the F1-P black-hole entropy can be described in supergravity.

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2-charge VS 3-charge black holes

- Such « classical » string profiles, through *geometric quantization*, account for the F1-P black-hole entropy: [Lunin, Mathur '01], [Rychkov '05]

$$S = 2\pi\sqrt{N_1 N_P}$$

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- 3-charge black holes: singularity and horizon separated.

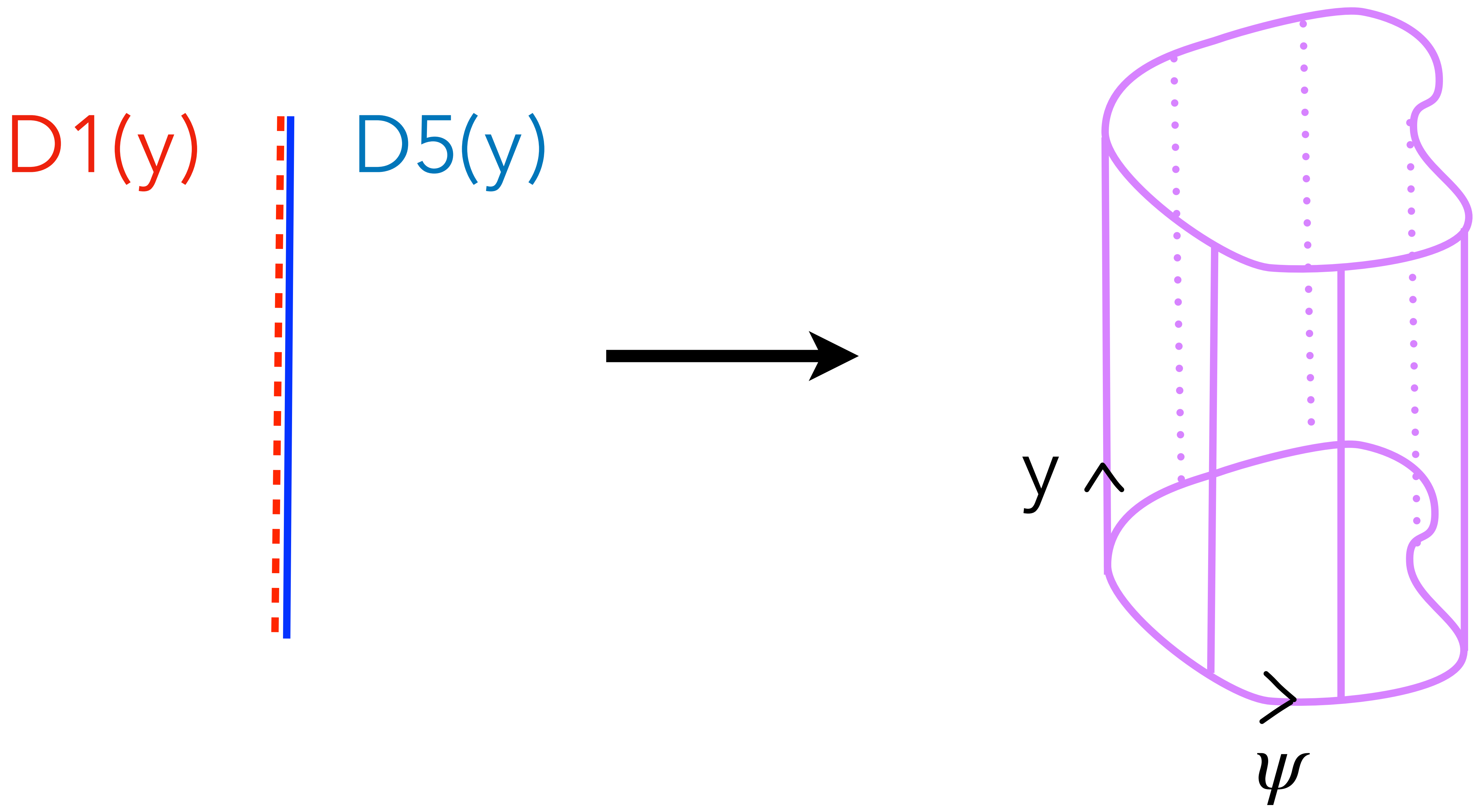
→ in particular D1-D5-P or F1-NS5-P

1st approach: enhancing D1-D5 through KKM

- D1(y), D5(y1234) ⟶ KKM(1234 ψ, y), P(ψ) dipoles
    - The D1-D5 brane system *gains* a dimension through the KKM

→ « supertube »

[Emparan, Mateos, Townsend '01]



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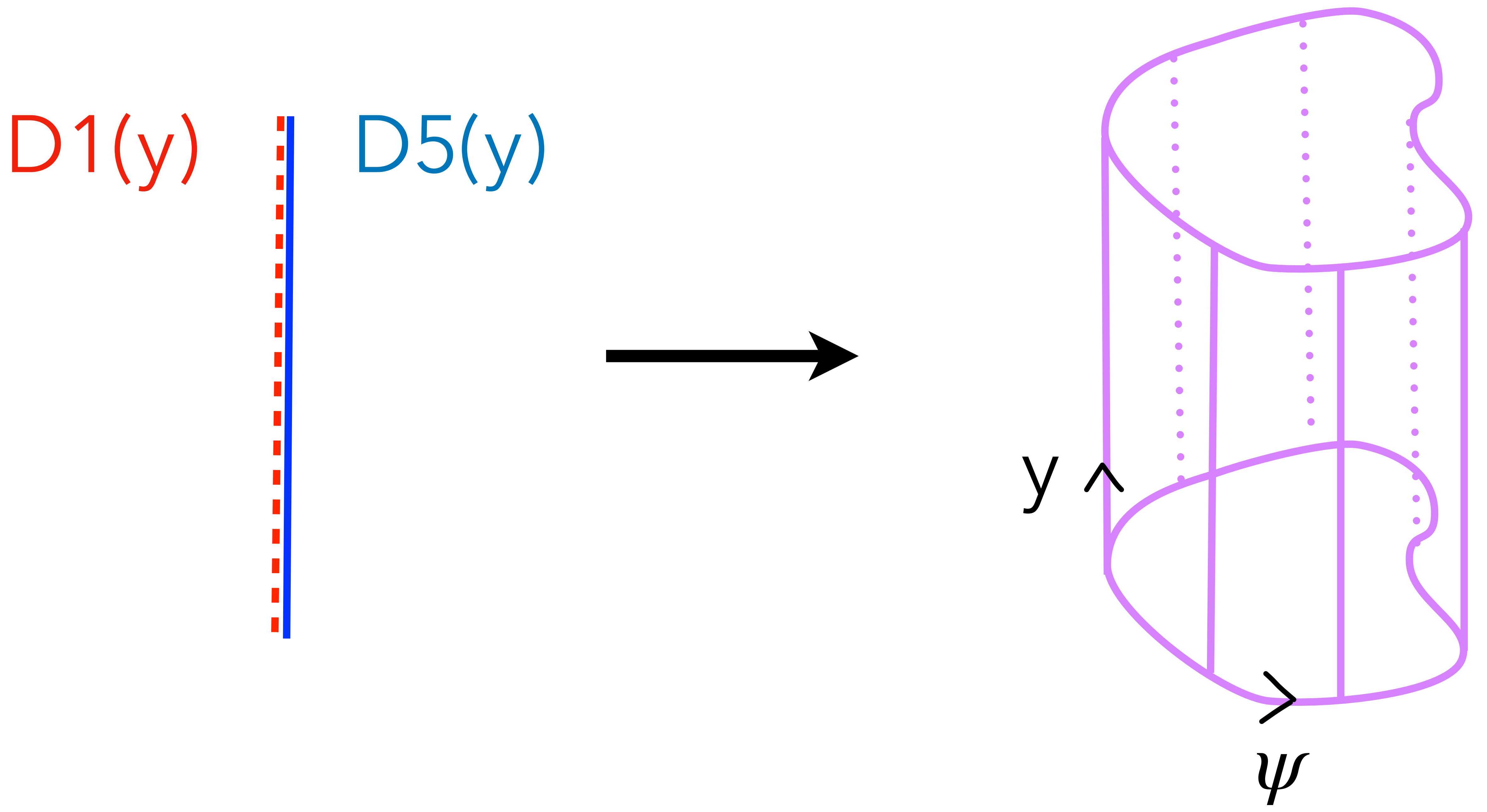

→ replace the delta-function brane singularity by a source extended in the non-compact dimensions

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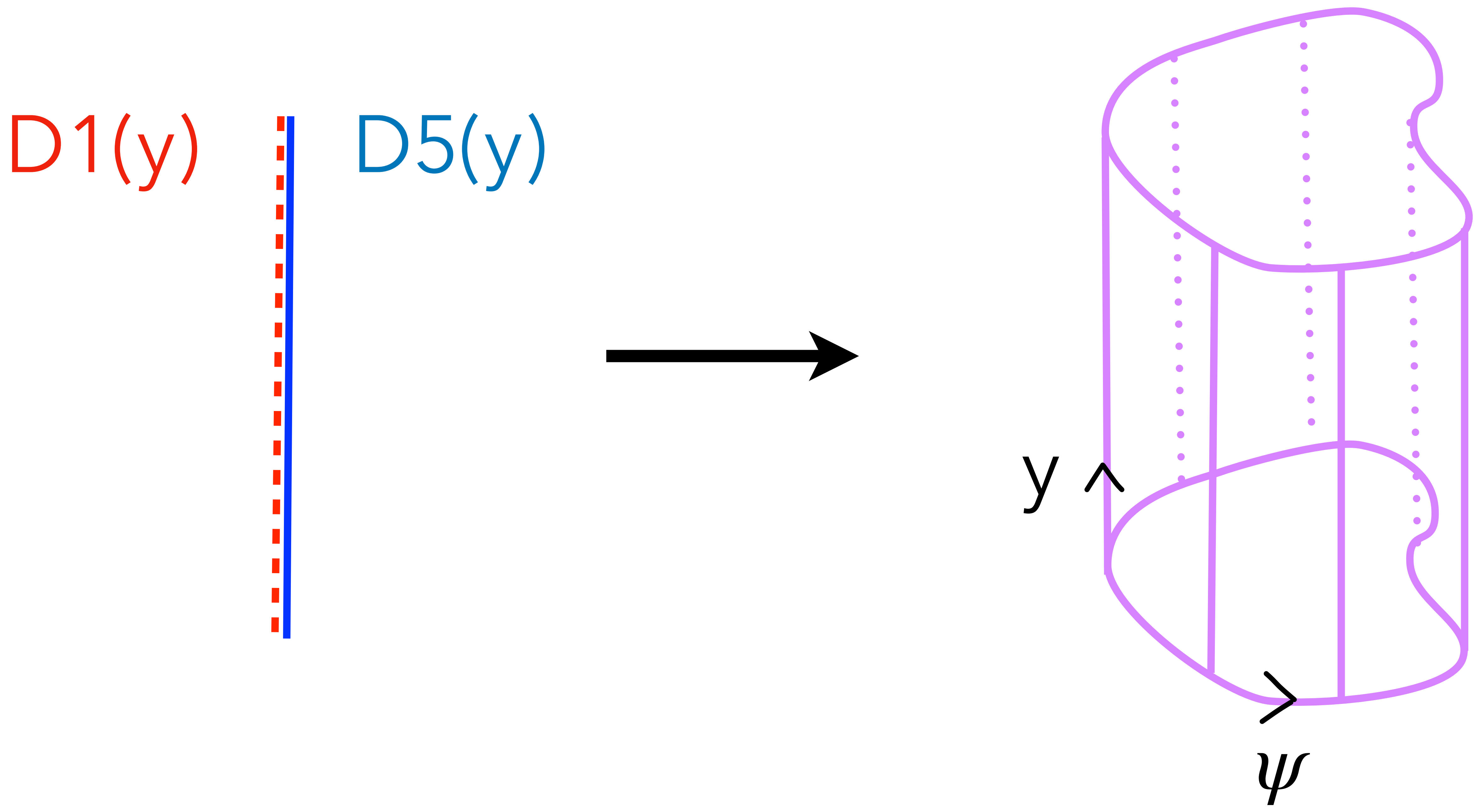

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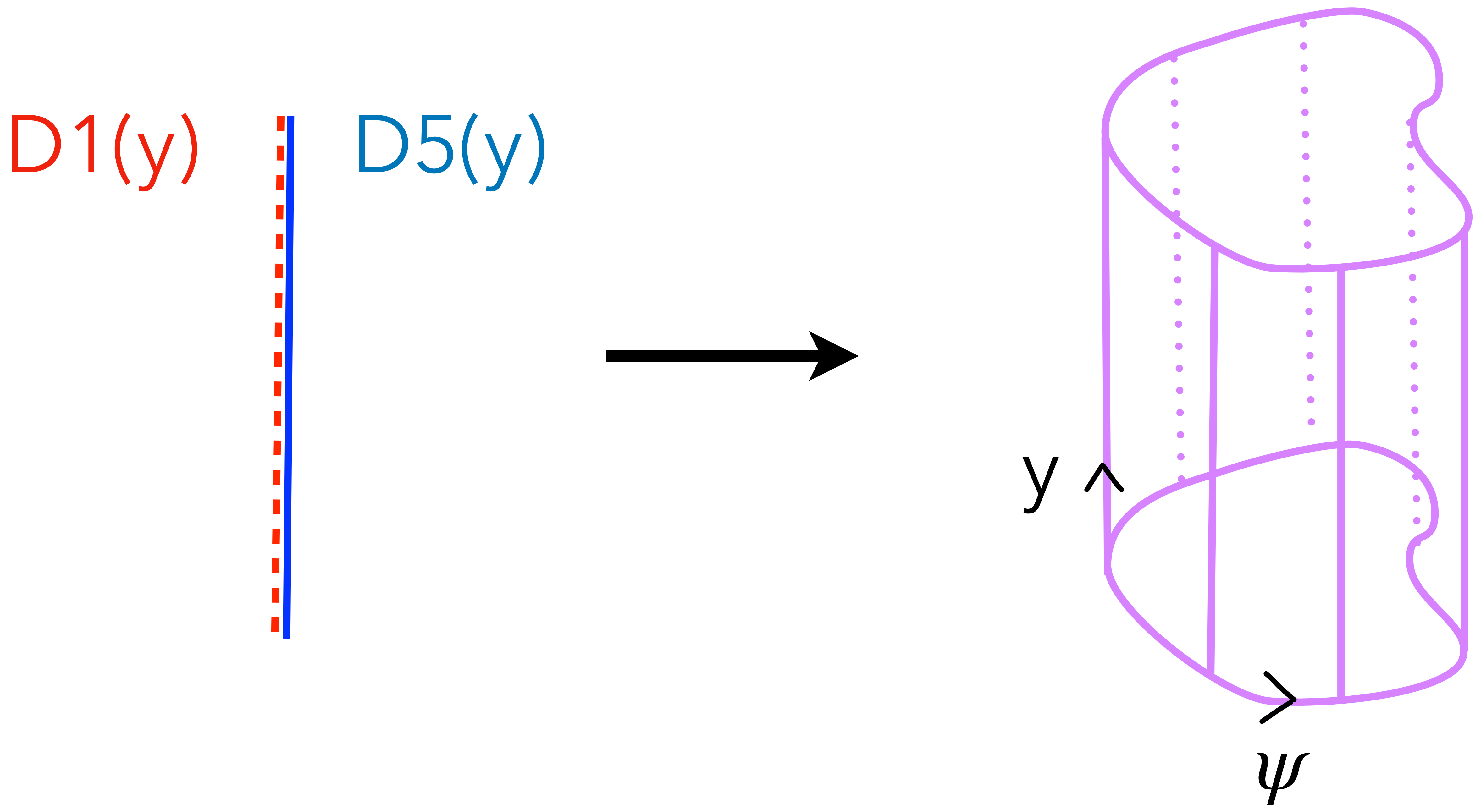

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- Then add consistently P and keep locally 1/2-BPS

→ ***« superstrata »***

[Bena, de Boer, Shigemori, Warner '11]

[Bena, Giusto, Martinec, Russo, Shigemori, Turton, Warner '16]

Superstrata and their limits

- In supergravity, *superstrata* are horizonless solutions with same charges as the D1-D5-P black hole

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Fuzzball hypothesis:

*Individual black-hole microstates differ from themselves and from the BH solution at the **horizon scale.***

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Drawbacks:

1. $S \sim \sqrt{N_1 N_5 N_P^{1/4}} \ll \sqrt{N_1 N_5 N_P}$
   [Shigemori '19]

2. Have a non-vanishing angular momentum in $\mathbb{R}^4$
   $\Rightarrow$ could be atypical
   $\uparrow$ are not ***exactly spherically symmetric***
   See also [Lin, Maldacena, Rozenberg, Shan '22]

Outline

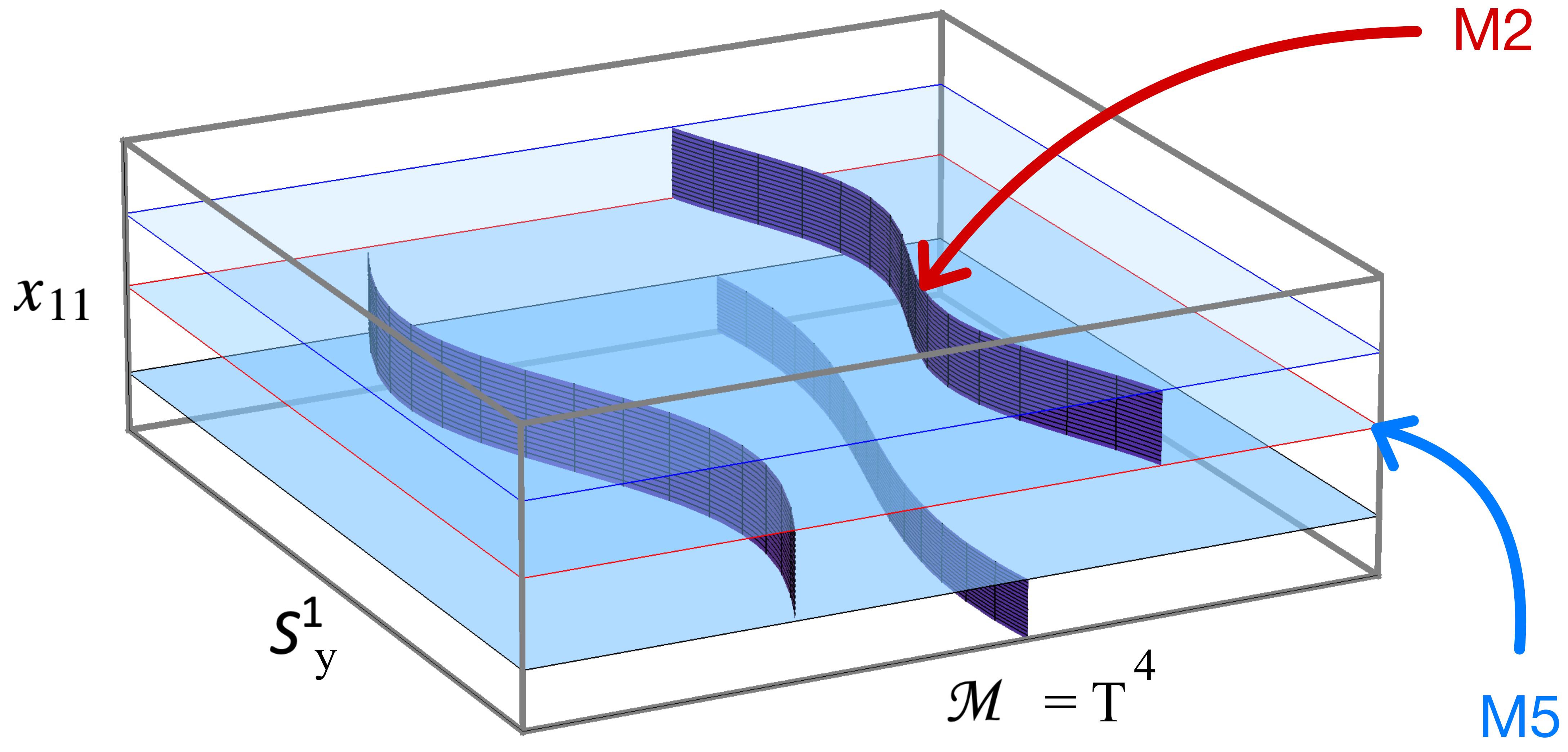
1. Local supersymmetry enhancement and black-hole microstates

2. The new M5-M2-P microstates with 16 local supersymmetries

2nd approach: internal dimensions

- For the NS5-F1-P black hole (IIA), we know where the entropy is coming from: little strings / fractionated (M2) branes

See e.g. [Martinec, Massai, Turton '19]



« Dijkgraaf-Verlinde-Verlinde -Maldacena microstates »

[Dijkgraaf-Verlinde-Verlinde '96], [Maldacena,'96]

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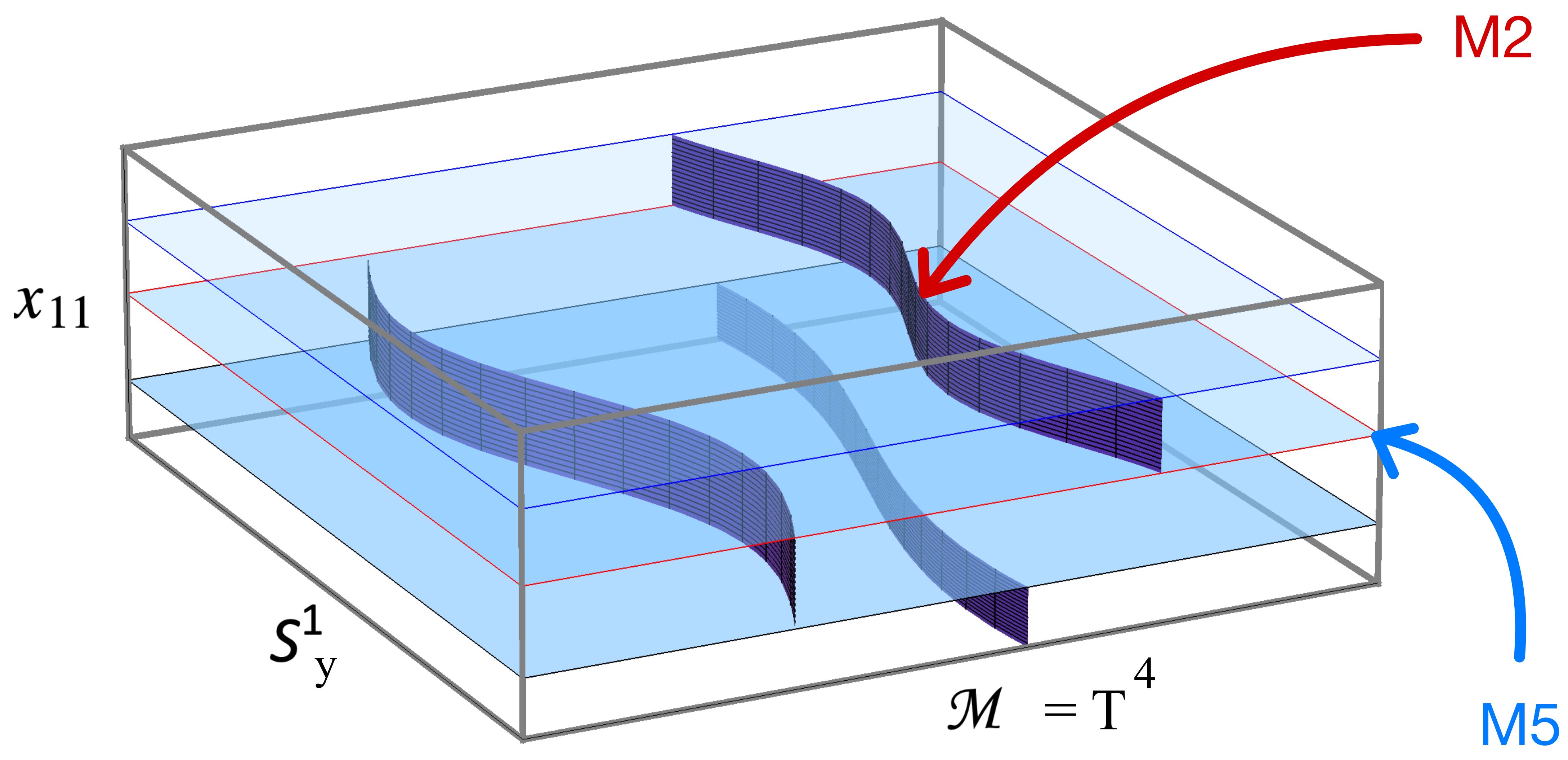

- The momentum is carried by the fractionated M2's through their motion in the T^4

  → *reproduce entropy*.

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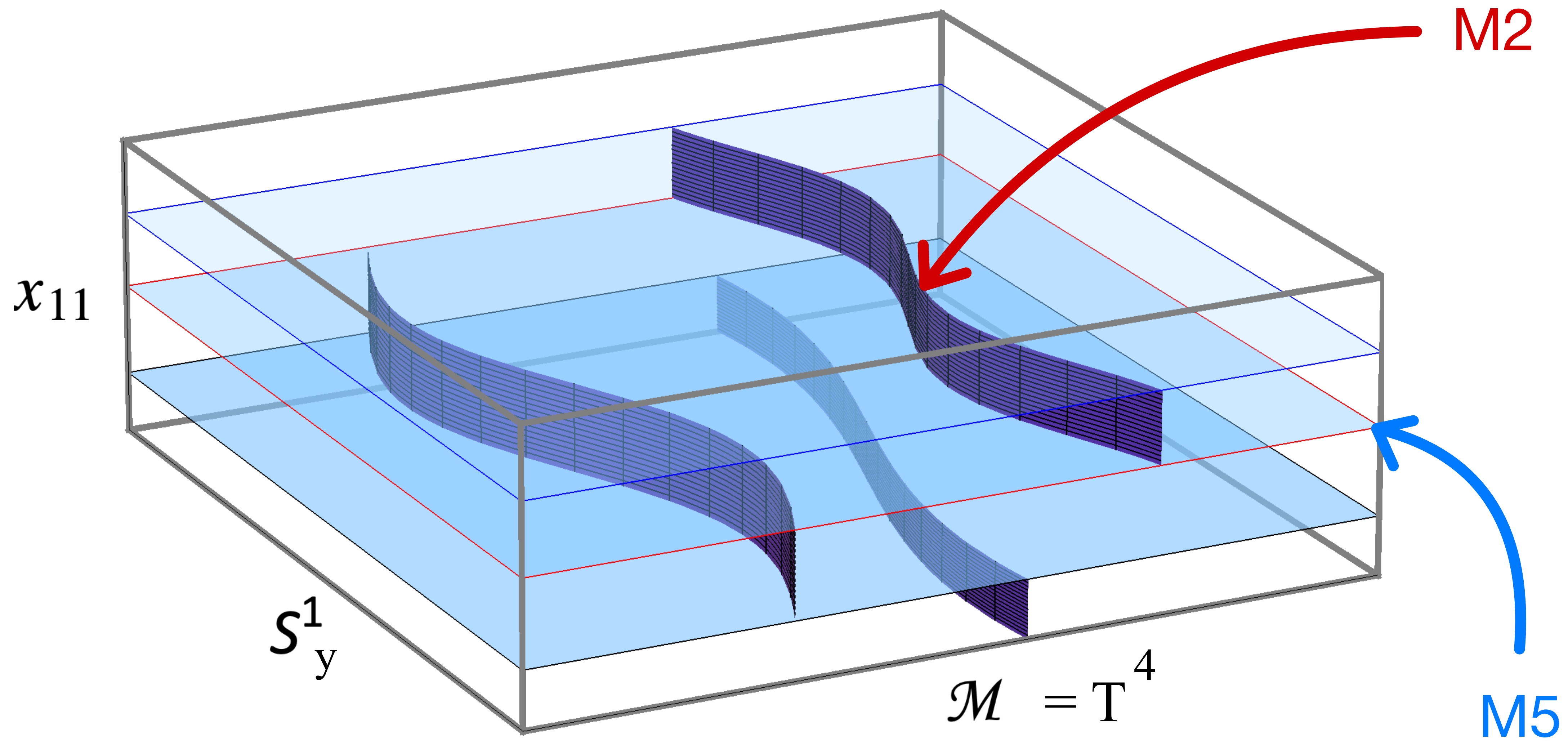

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$$S = 2\pi\sqrt{cN_P/6}\,, \quad c = 6N_1N_5$$

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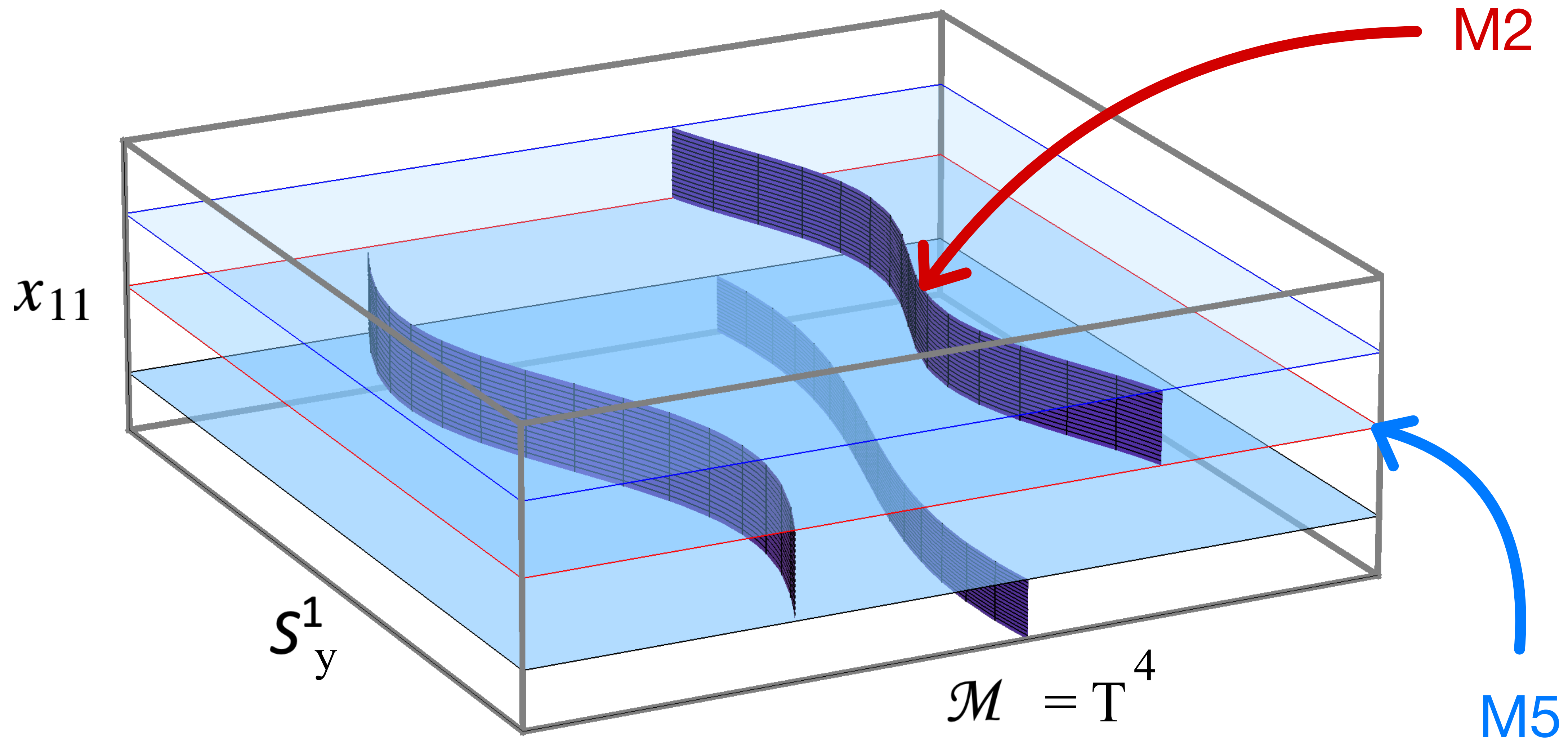

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- The brane system is point-like in the non-compact spatial dimensions

  → *exact spherical symmetry.*

Enhancing the DVVM microstates

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

- We enhanced the local supersymmetries of the Dijkgraaf-Verlinde-Verlinde-Maldacena (DVVM) microstates.

Enhancing the DVVM microstates

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

- We enhanced the local supersymmetries of the Dijkgraaf-Verlinde-Verlinde-Maldacena (DVVM) microstates.
- We found the *supersymmetric projector*
    - preserving the supersymmetries of NS5(y, T^4), F1(y), P(y) (IIA)
    - corresponding to an object with 16 local supersymmetries:

$$\Pi_{\mathrm{NS5-F1-P}} = \frac{1}{2}\Big[1 + a^2 P^{\mathrm{IIA}}_{\mathrm{NS5}(y1234)} + b^2 P_{\mathrm{F1}(y)} + c^2 P_{\mathrm{P}(y)} + ab\left(P_{\mathrm{D4}(y234)} - P_{\mathrm{D2}(y1)}\right) + bc\left(P_{\mathrm{P}(1)} - P_{\mathrm{F1}(1)}\right) + ca\left(P_{\mathrm{D4}(1234)} - P_{\mathrm{D0}}\right)\Big] .$$

First look at the projector

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Excitations defining the global supersymmetries

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Excitations corresponding to the glues

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BPS condition:

$$a^2 + b^2 + c^2 = 1$$

$$\begin{aligned} P_{\mathrm{P}} &= \Gamma^{01} \\ P^{\mathrm{IIA}}_{\mathrm{NS5}} &= \Gamma^{012345} \\ P^{\mathrm{IIA}}_{\mathrm{KKM}(12345;6)} &= \Gamma^{012345}\sigma_3 = \Gamma^{6789} \\ P_{\mathrm{D0}} &= \Gamma^{0} i\sigma_2 \\ P_{\mathrm{D2}} &= \Gamma^{012}\sigma_1 \\ P_{\mathrm{D4}} &= \Gamma^{01234} i\sigma_2 \\ P_{\mathrm{D6}} &= \Gamma^{0123456}\sigma_1 \end{aligned}$$

$$\begin{aligned} P_{\mathrm{F1}} &= \Gamma^{01}\sigma_3 \\ P^{\mathrm{IIB}}_{\mathrm{NS5}} &= \Gamma^{012345}\sigma_3 \\ P^{\mathrm{IIB}}_{\mathrm{KKM}(12345;6)} &= \Gamma^{012345} = \Gamma^{6789} \\ P_{\mathrm{D1}} &= \Gamma^{01}\sigma_1 \\ P_{\mathrm{D3}} &= \Gamma^{0123} i\sigma_2 \\ P_{\mathrm{D5}} &= \Gamma^{012345}\sigma_1 \end{aligned}$$

Glueing NS5 and F1

$$\Pi_{\mathrm{NS5-F1-P}} = \frac{1}{2}\Big[1 + a^2 P^{\mathrm{IIA}}_{\mathrm{NS5}(y1234)} + b^2 P_{\mathrm{F1}(y)} + c^2 P_{\mathrm{P}(y)}$$

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- Put $c = 0$
- NS5(y, T^4), F1(y) $\longrightarrow$ local D4(y234), D2(y1)

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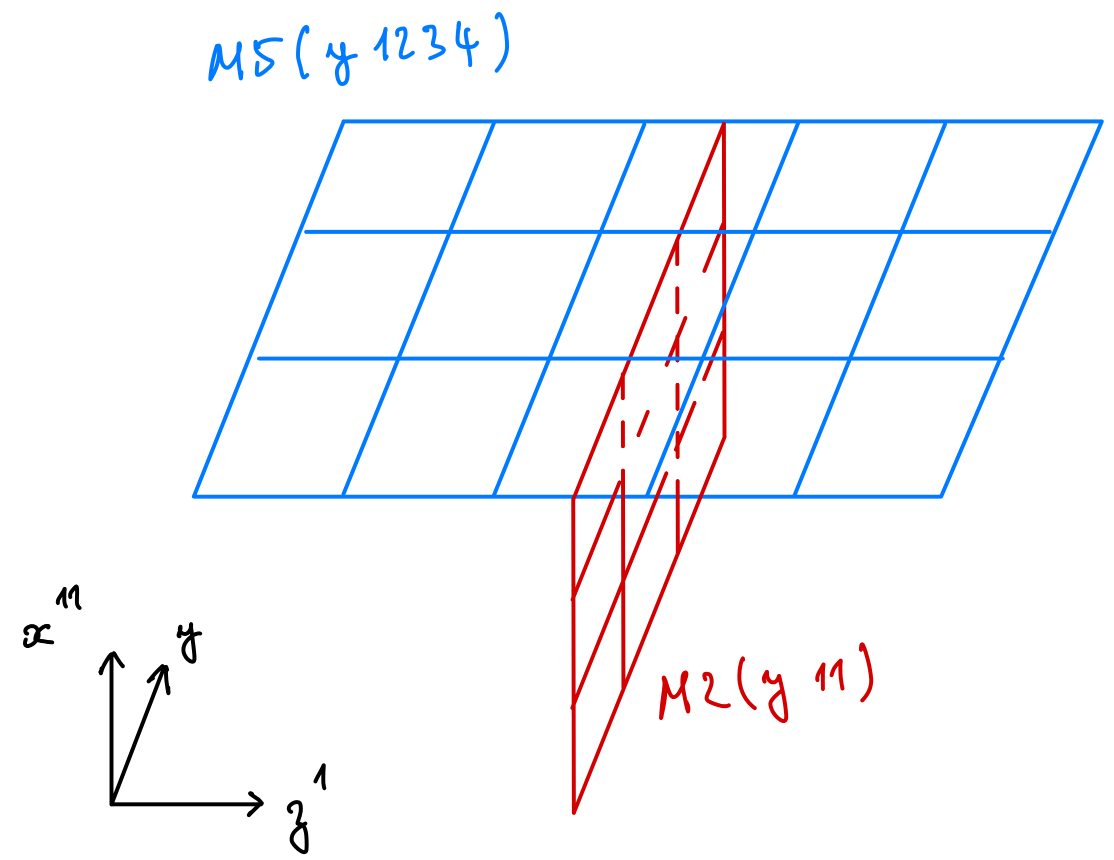

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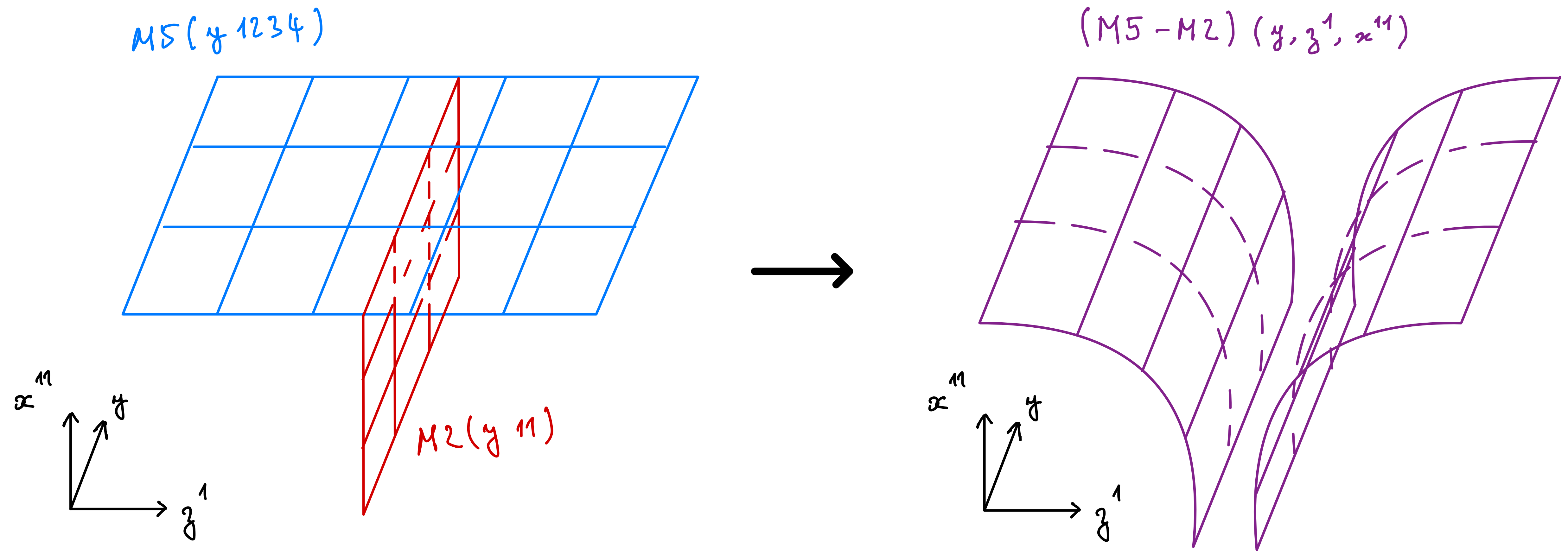
- Put $c = 0$
- NS5(y, T^4), F1(y) $\longrightarrow$ local D4(y234), D2(y1)
- Rough angles between M5's and M2's become *smooth*:

  → new brane system looks like a *furrow* along y.



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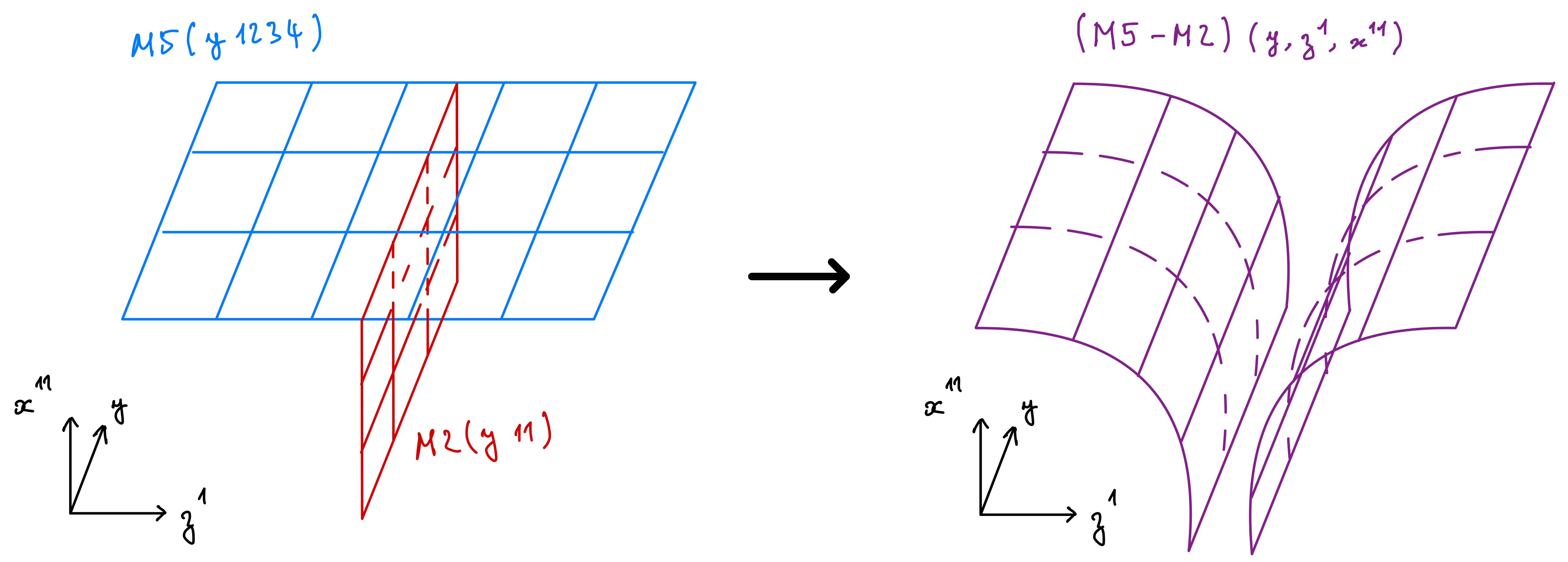

↑ This M5-M2 furrow is dual to a D4-F1 Callan-Maldacena spike

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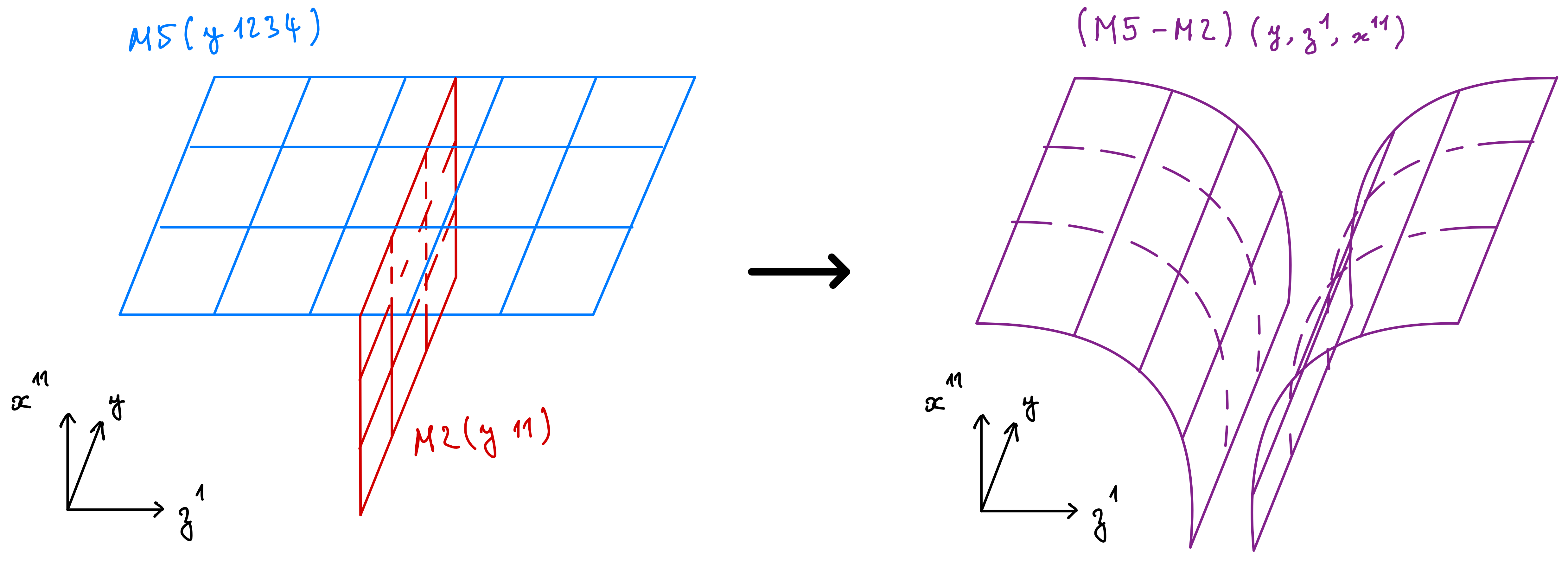
- The furrow interpolates between M5 and M2:

$$a = \cos\beta\,, \quad b = \sin\beta$$

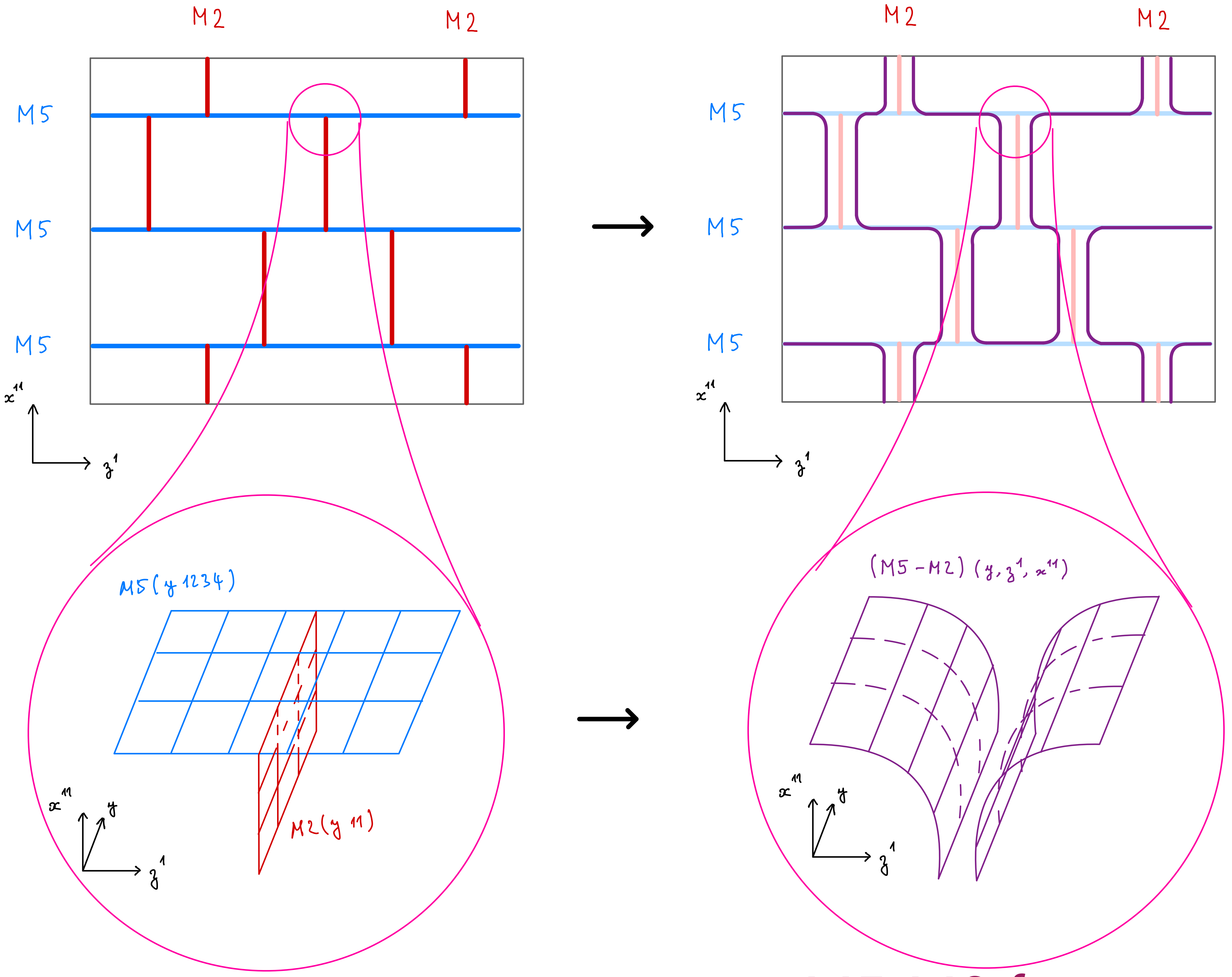
$\Rightarrow$ The orientation of a local piece of the furrow determines the ratio between M5 and M2 charges.



Transition of a M5-M2 black-hole microstate

- Local transition ⇒ a M5-M2 black-hole microstate will transition into a « labyrinth/maze »

→ « super-maze »



« M5-M2 furrow »

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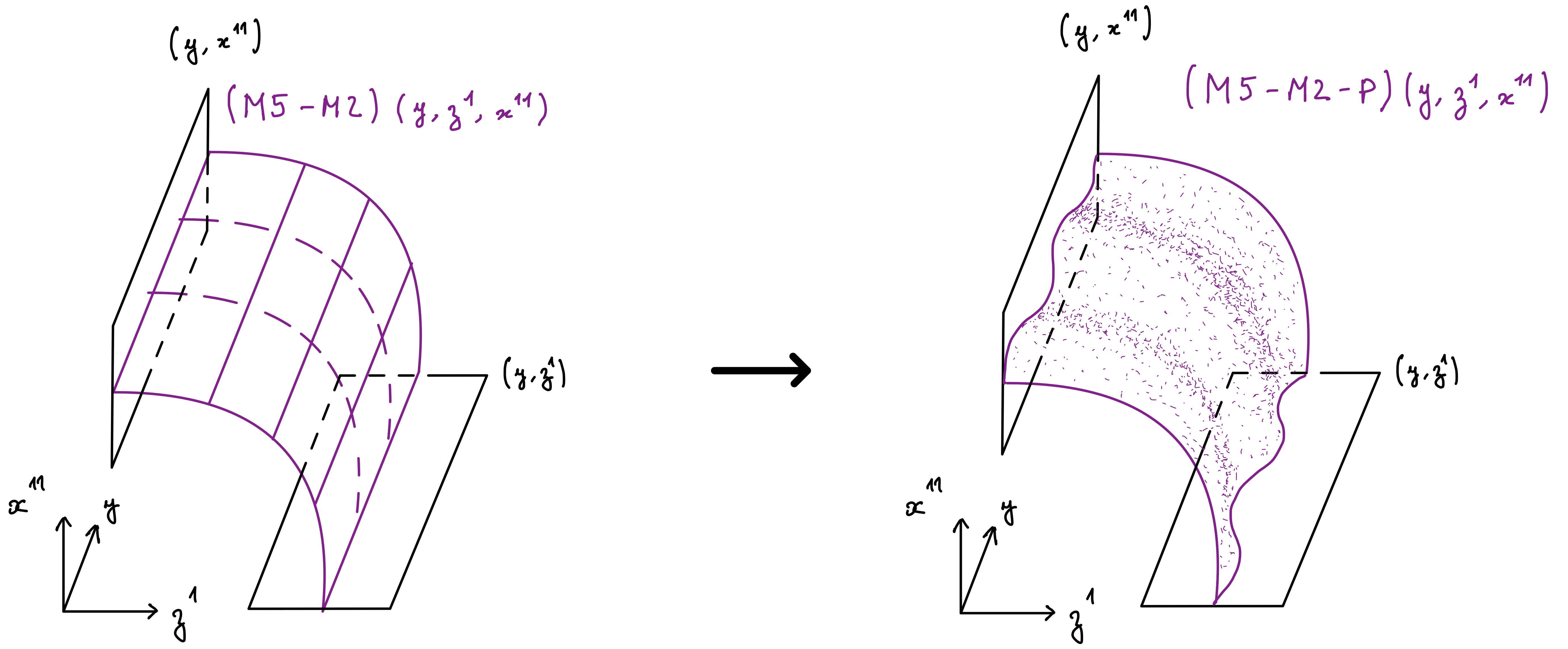
- The M5-M2 furrow carries momentum through *ripples* modulated orthogonally to its surface

$$a = \cos\alpha\cos\beta$$
$$b = \cos\alpha\sin\beta$$
$$c = \sin\alpha$$



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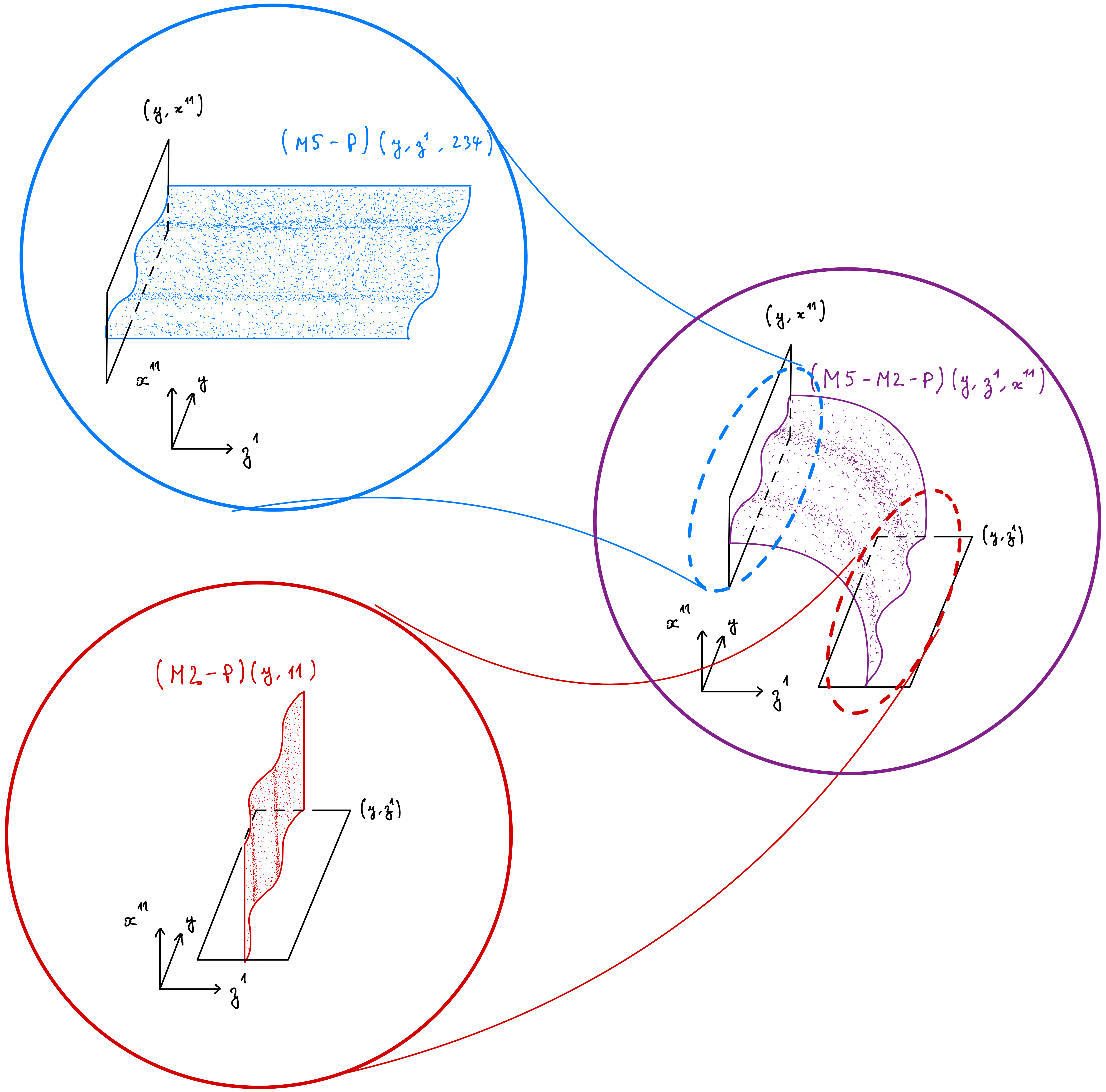
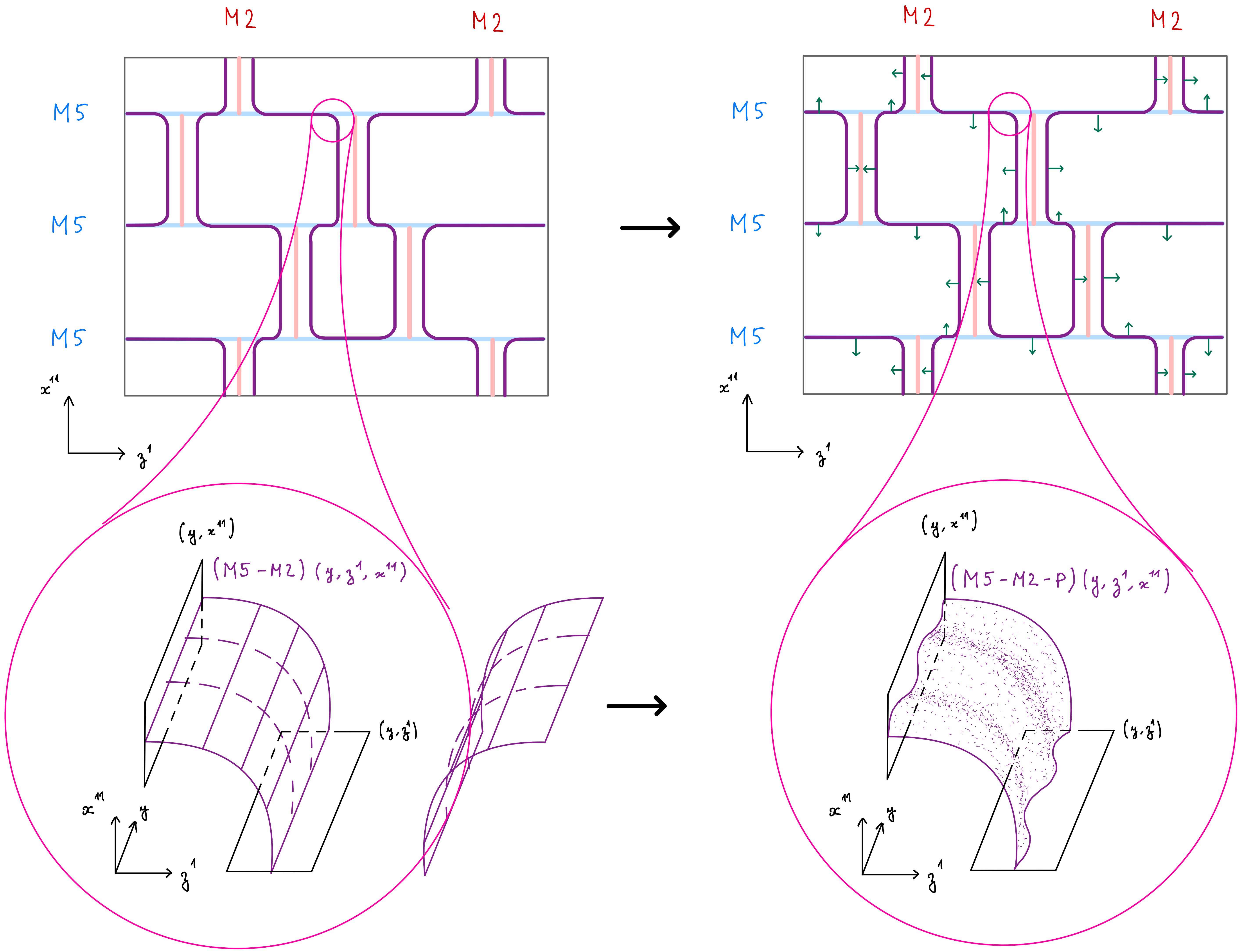
- β controls the bending angle of the furrow; α controls the angle of ripples orthogonal to the furrow.



Consequence on a M5-M2-P microstate

- The *ripples* of the furrow correspond to *shape modes* of the M5-M2 labyrinth
- The *shape modes* are the way 16-susy microstates carry momentum.



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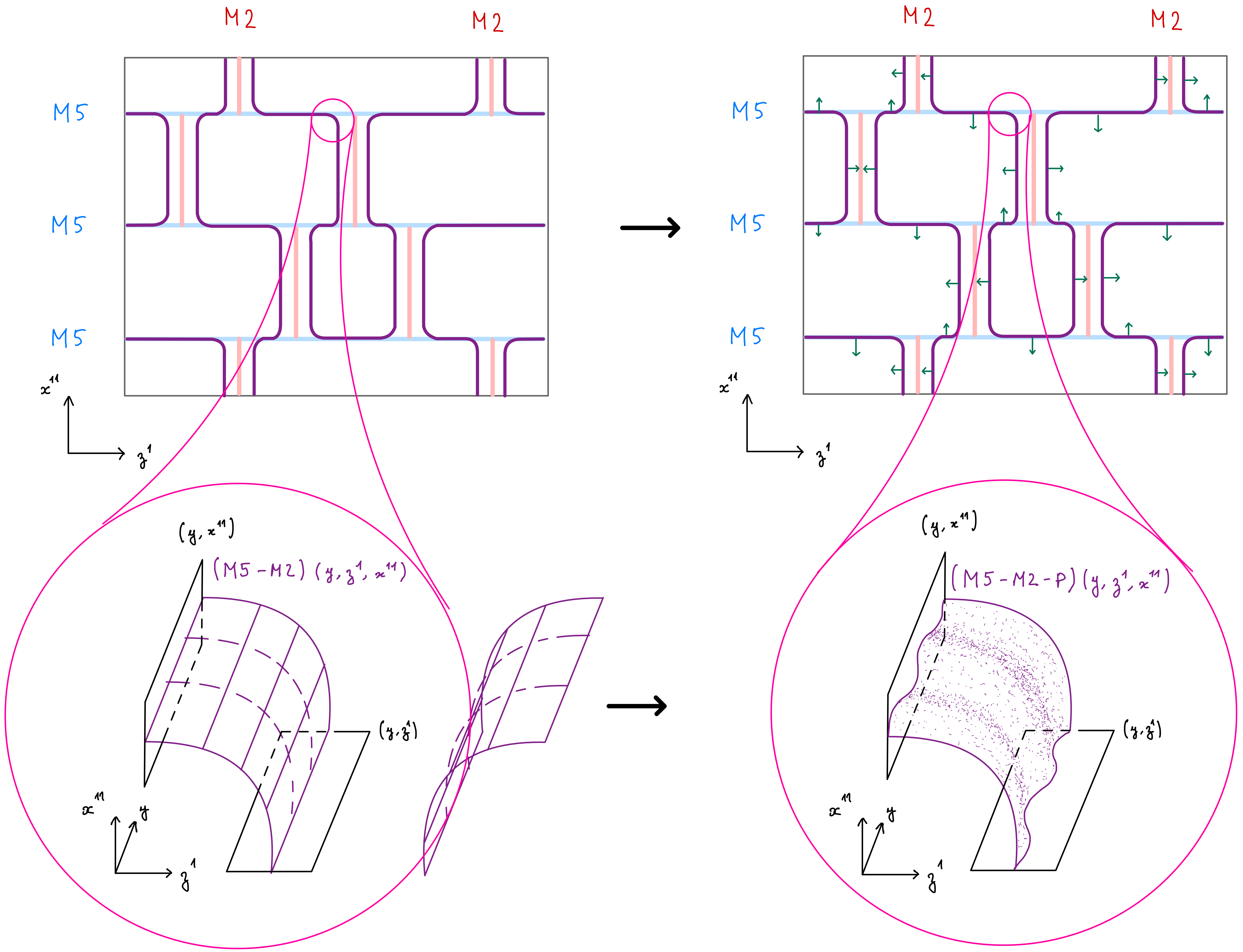

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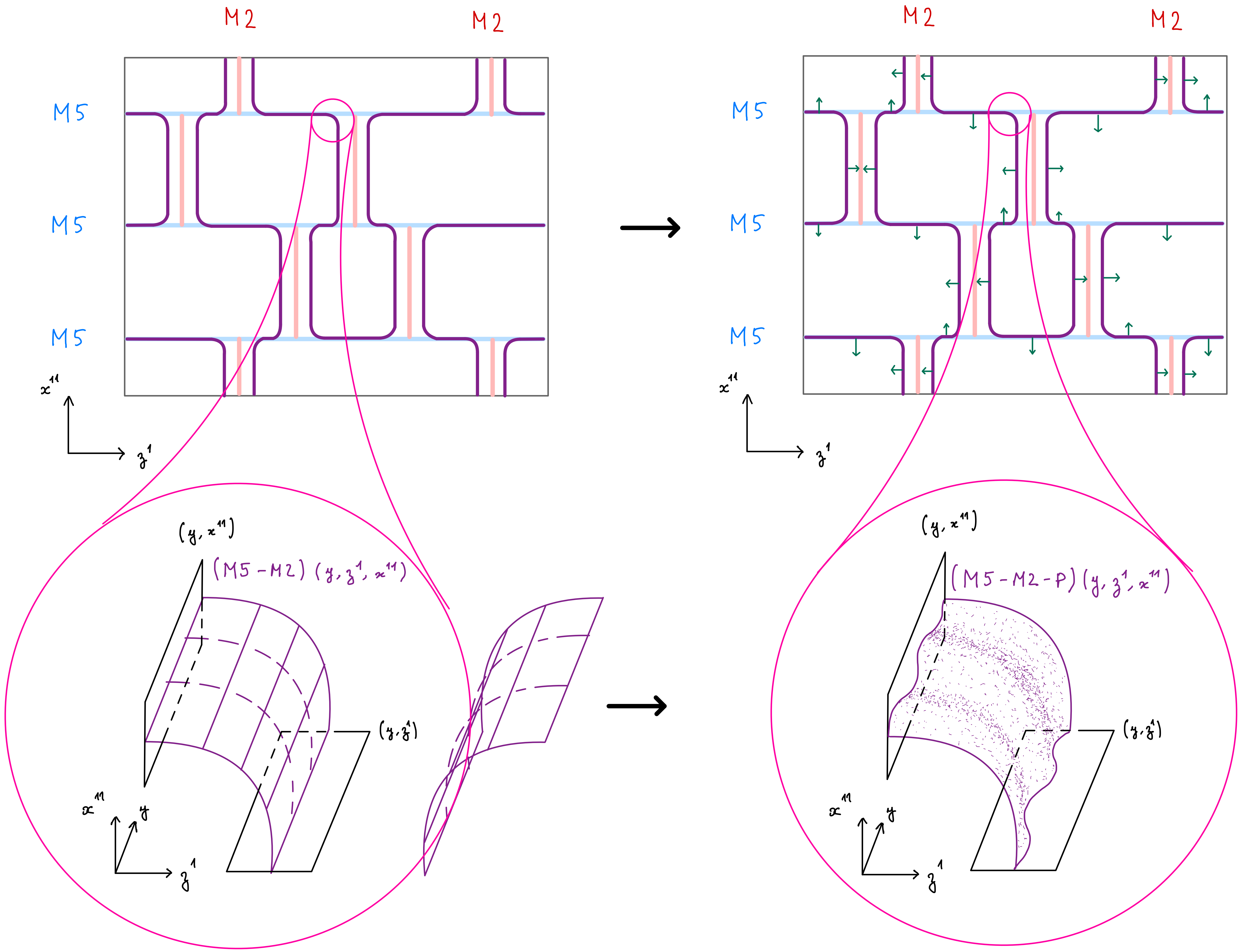
- The *ripples* of the furrow correspond to *shape modes* of the M5-M2 maze
- The *shape modes* are the way 16-local-susy microstates carry momentum.

⇒ The microstates are ensured to have *exact spherical symmetry.*



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e.g. [Martinec, Massai, Turton '22]

- But in the M2-M5-P frame, the basic ingredient of the super-maze is a M5 brane with M2 flux on it. The supergravity description of it is valid close to the branes as well.

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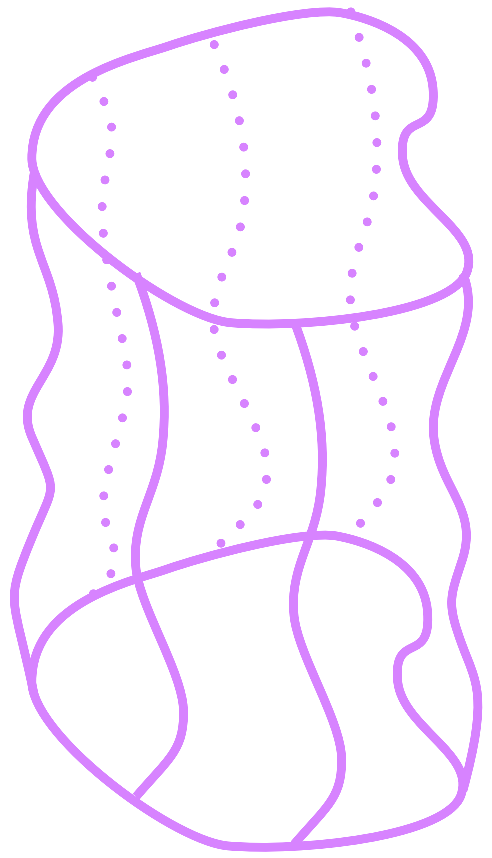
- The microstate geometries programme used to replace D1-D5-P horizons with brane systems that **extend in** $\mathbb{R}^4$

↑ But this approach seems to have limits: entropy, typicality…



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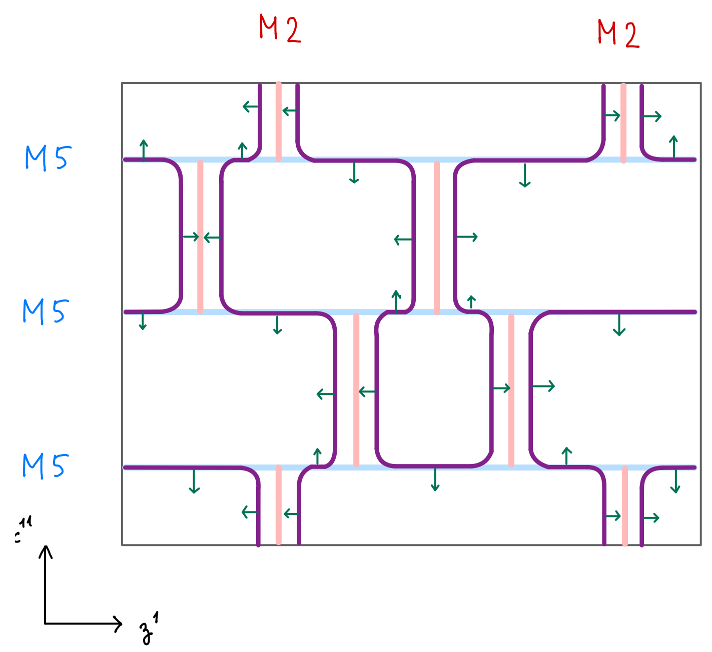

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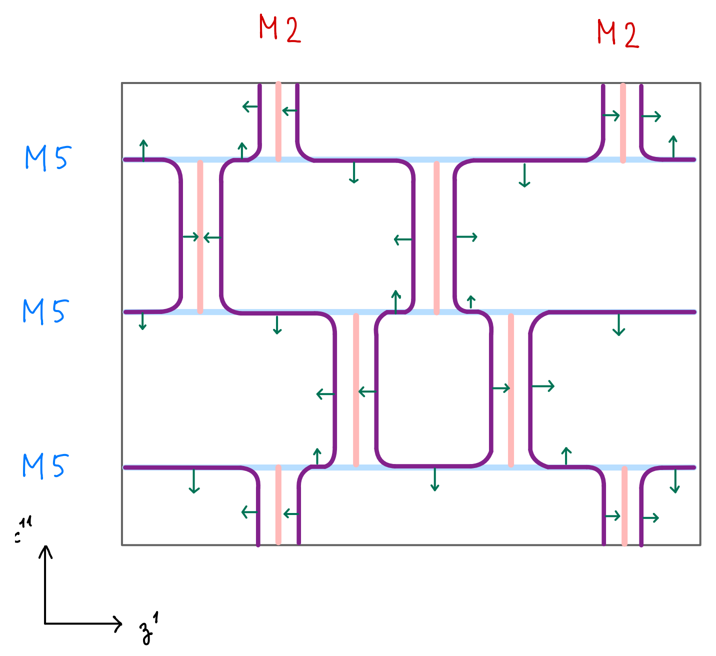
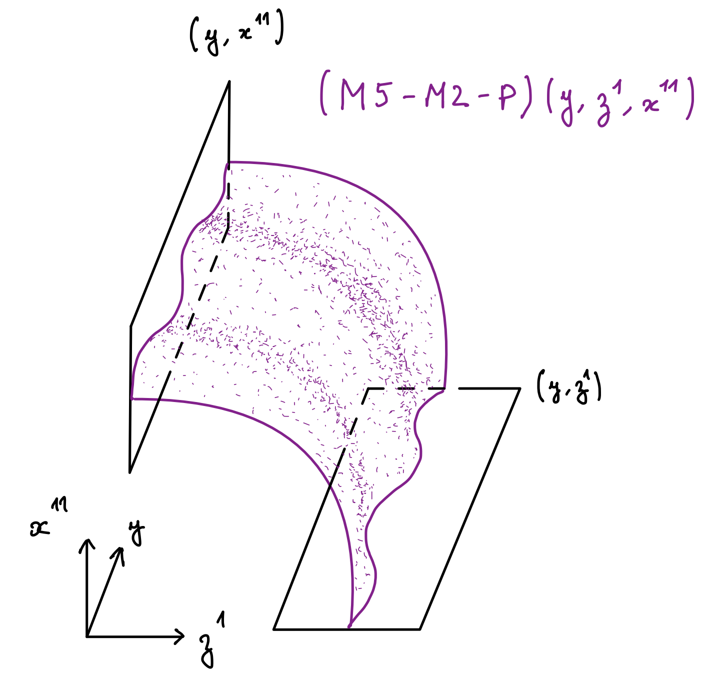
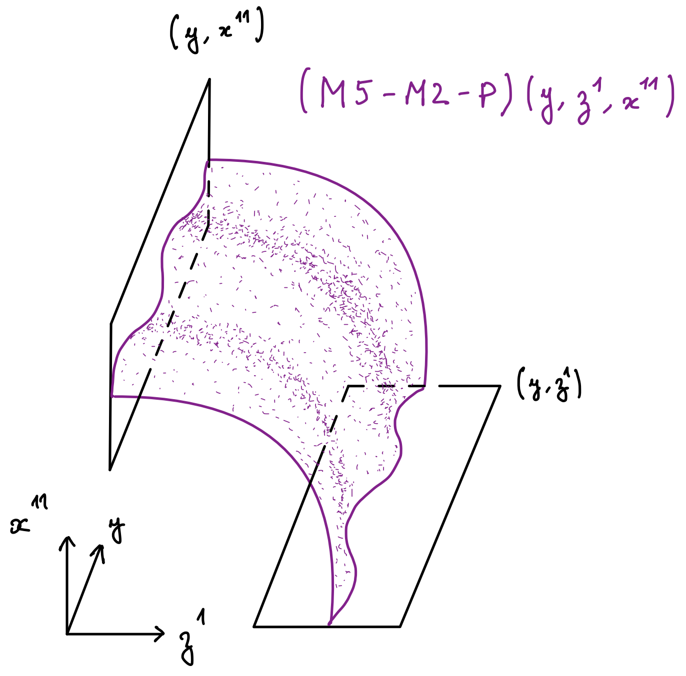
- These « super-mazes » have 16 local susys, just like the superstrata, but without having their drawbacks.





Outlook

- 16 local susys is a smoking gun for horizonless microstate solutions



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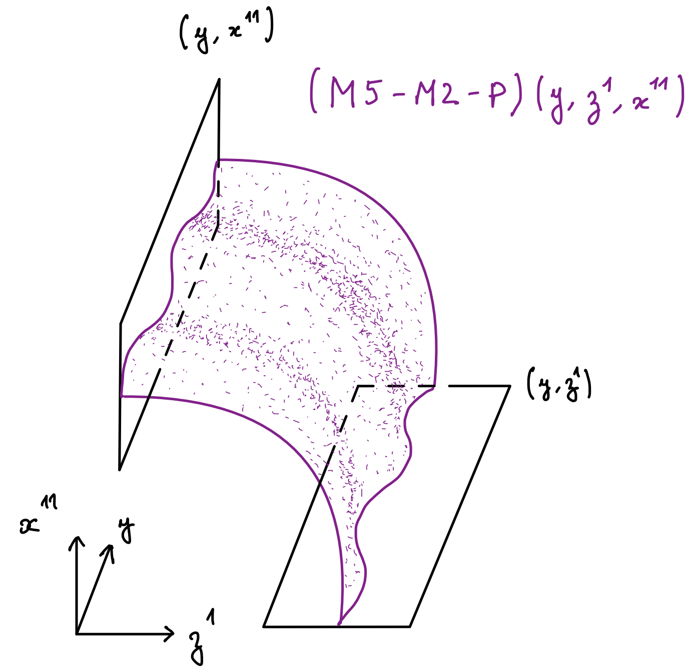

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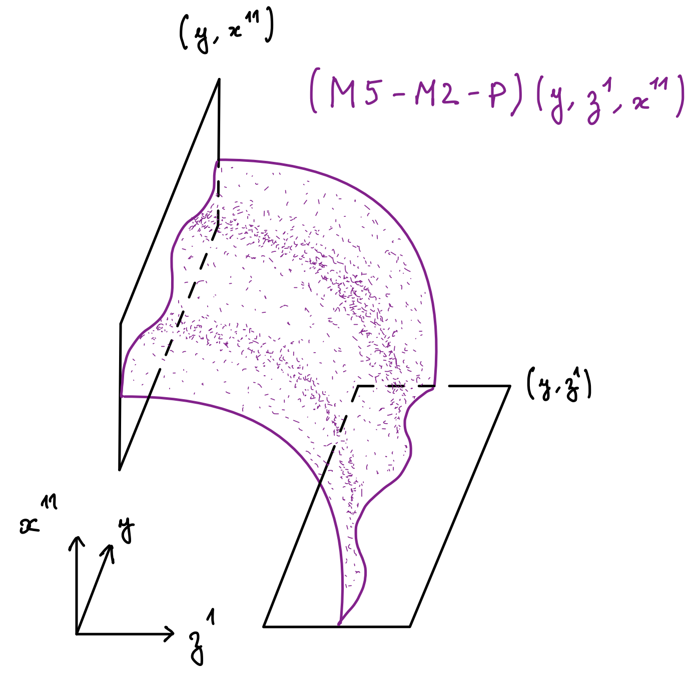
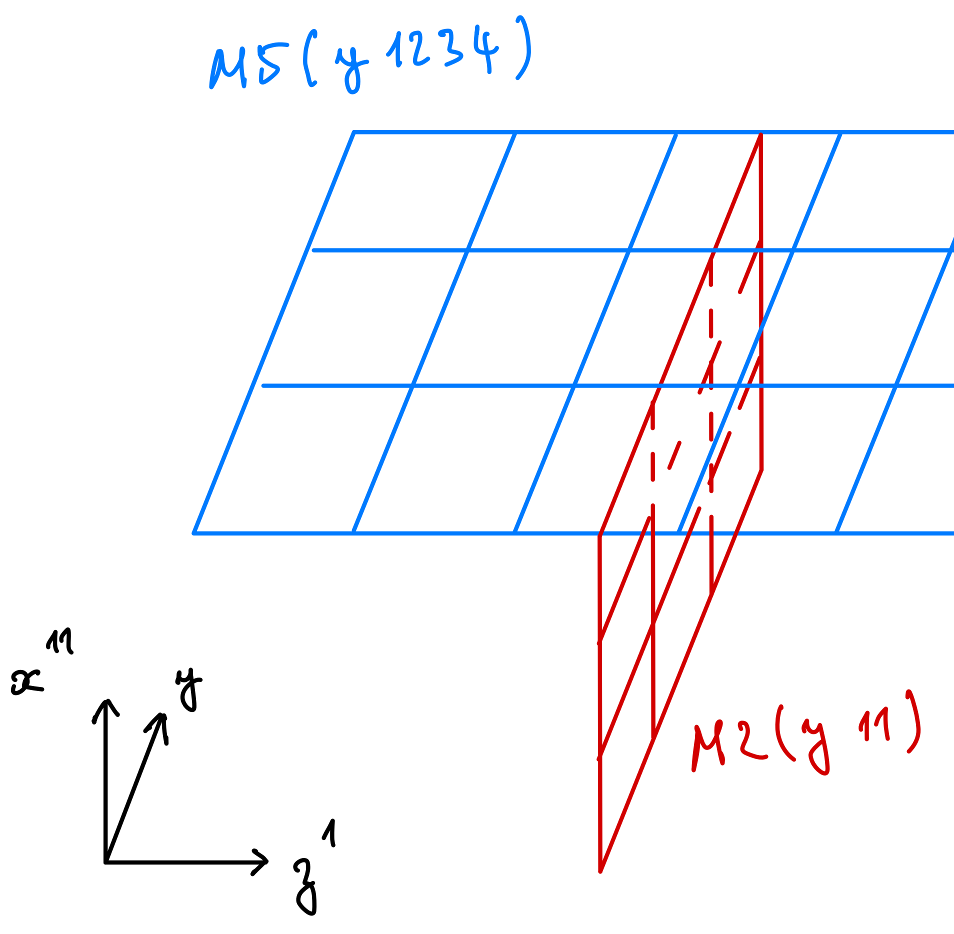
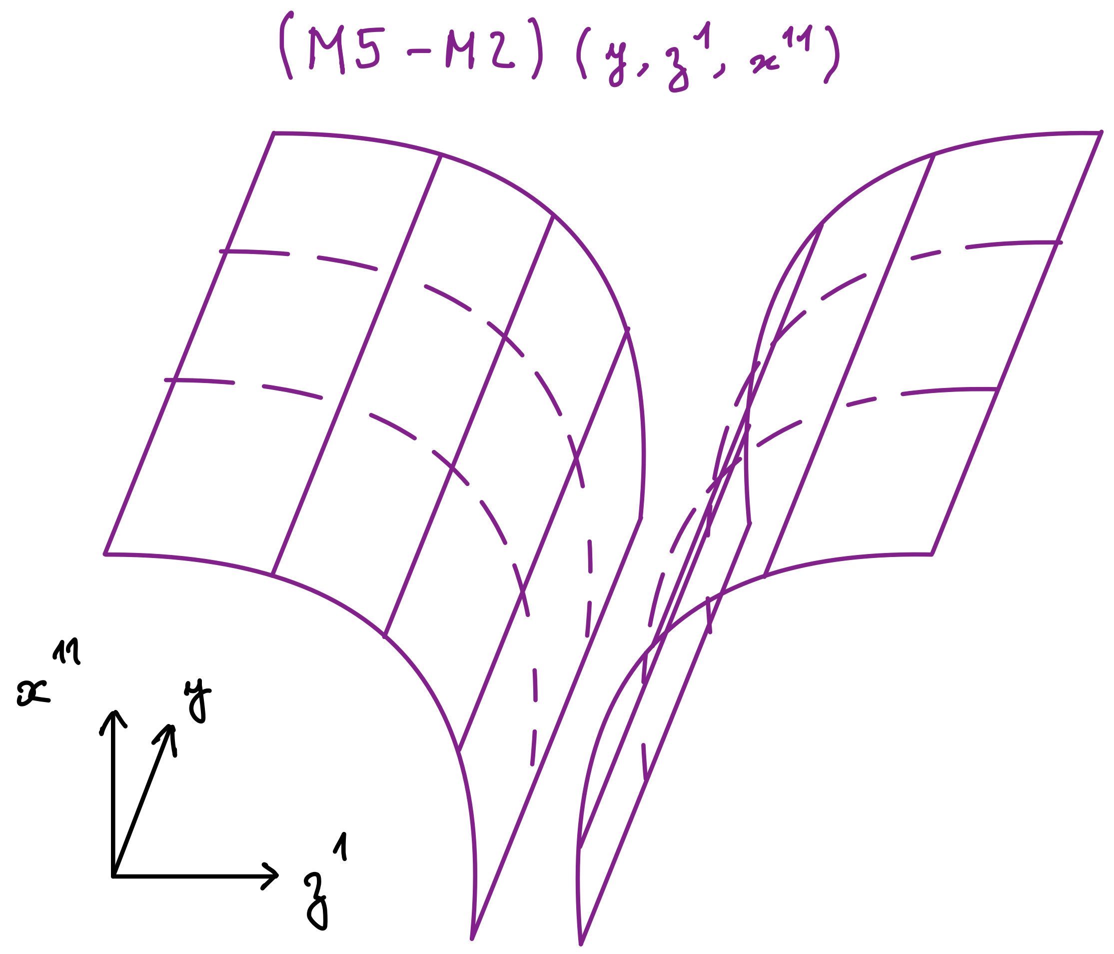
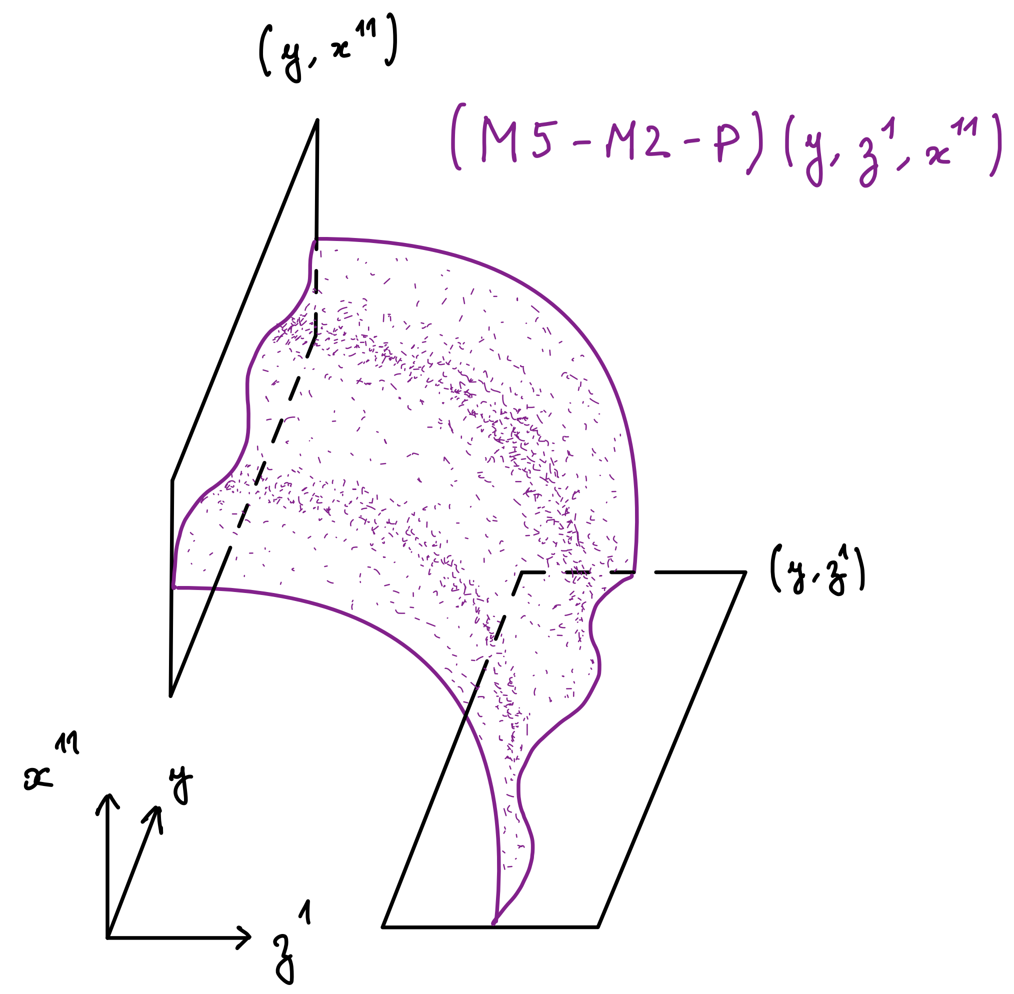


- End goal:

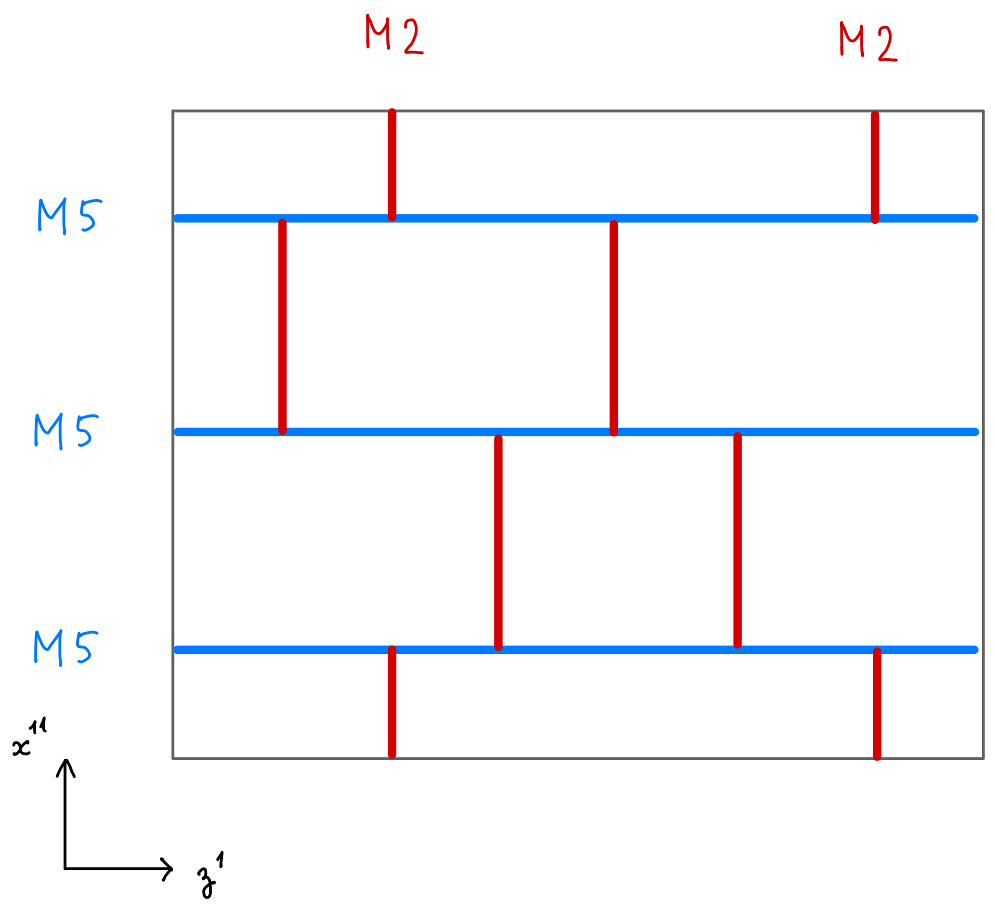
  « Where » is the information about the black-hole microstate?

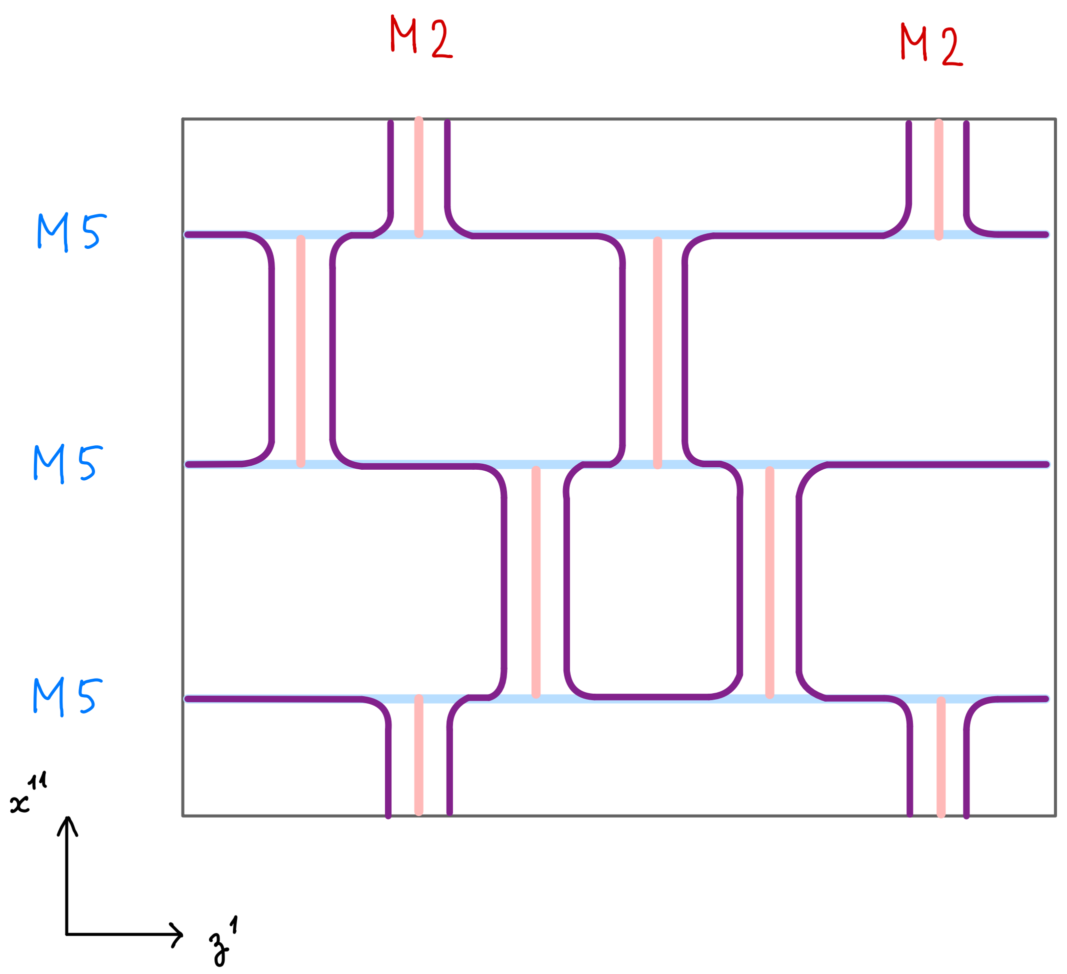


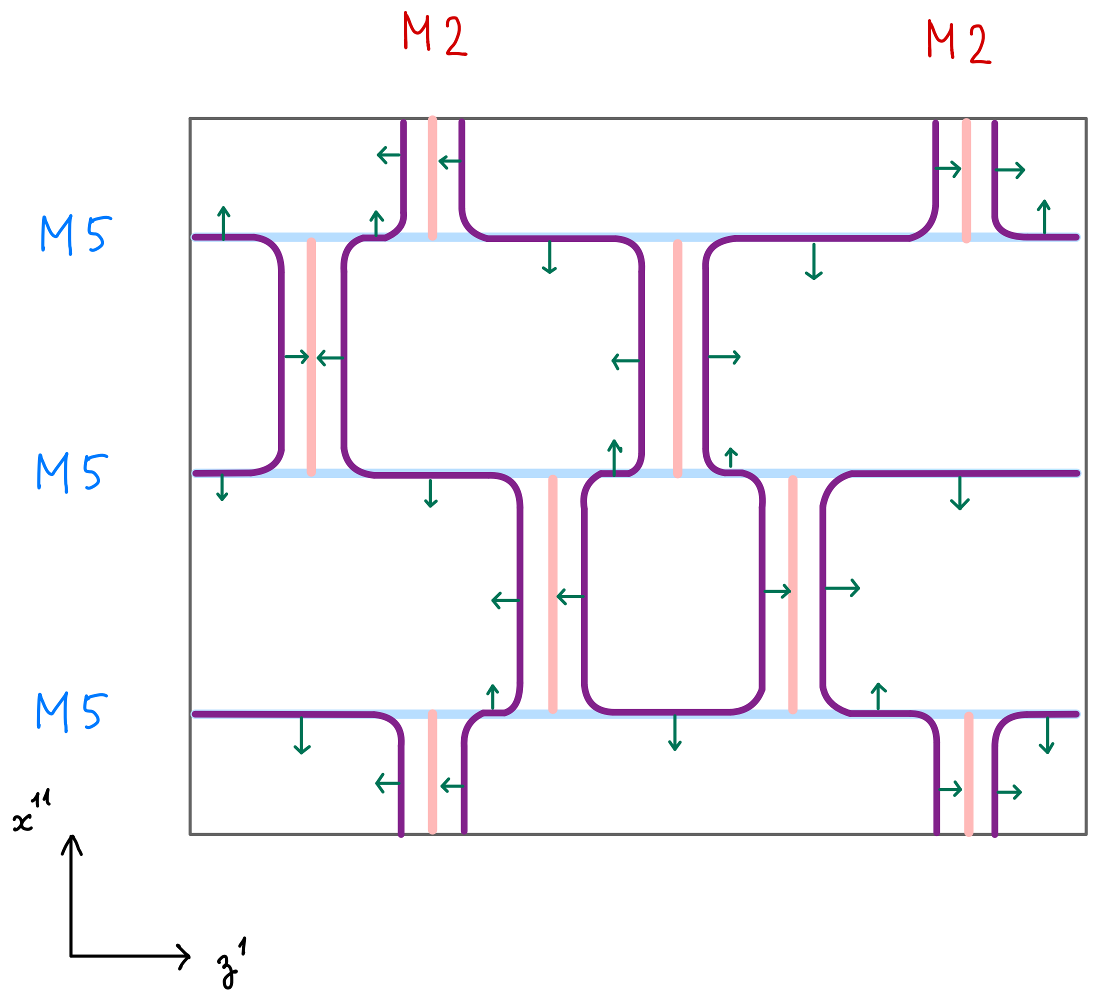




Thank you for your attention !!!!!







Back-up slide