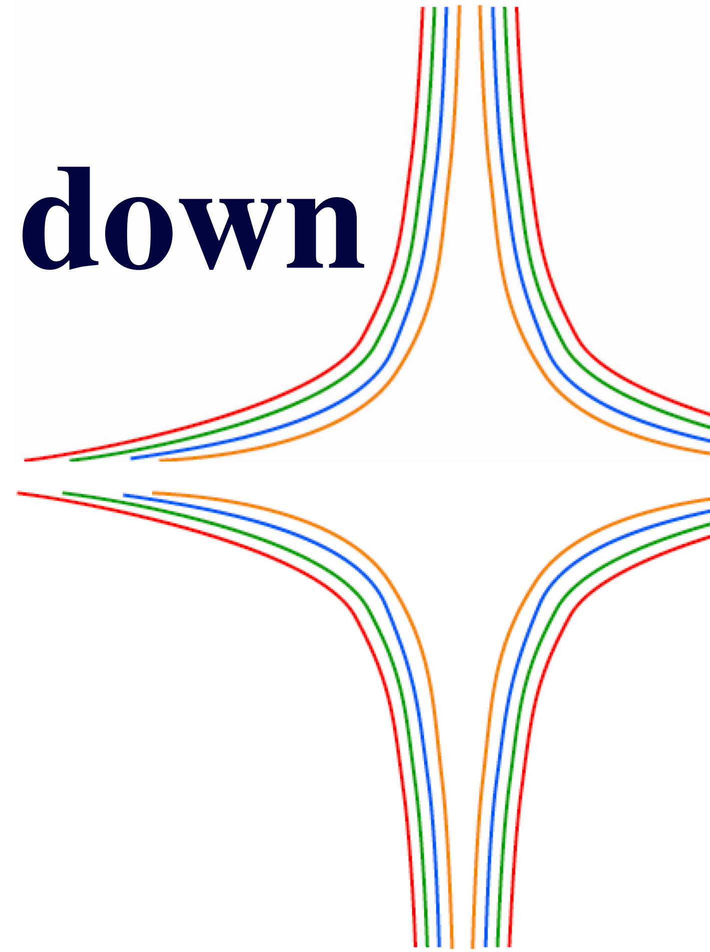
Spikes all the way down



Iosif Bena

IPhT, CEA

Université Paris-Saclay

Dimitrios Toulikas, Soumangsu Chakraborty, Raphaël Dulac, Zixia Wei,
Angèle Lochet, Yixuan Li, Nejc Čeplak, Shaun Hampton, Anthony Houppe,
Nick Warner, Pierre Heidmann, Antoine Bourget, Severin Lüst

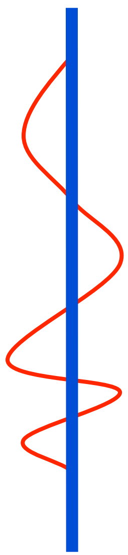
An amazing success of String Theory: Strominger, Vafa '96

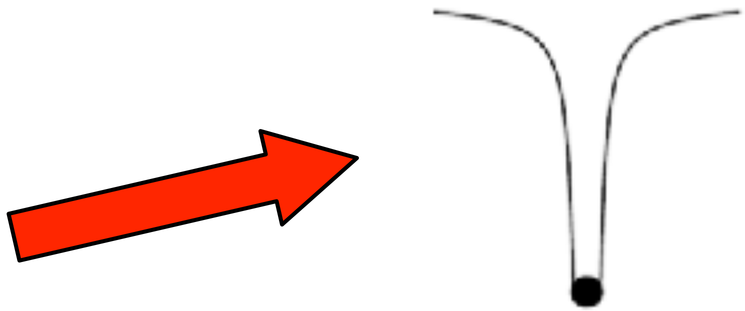
Count Black Hole Microstates (branes + strings)

Correctly match B.H. entropy !!!

Zero Gravity

One Particular Microstate at Finite Gravity:





Standard lore:

As gravity becomes stronger,
- brane configuration becomes smaller
- horizon develops and engulfs it
- recover standard black hole

Susskind
Horowitz, Polchinski
Chen, Maldacena, Witten

An amazing success of String Theory:

Strominger, Vafa '96

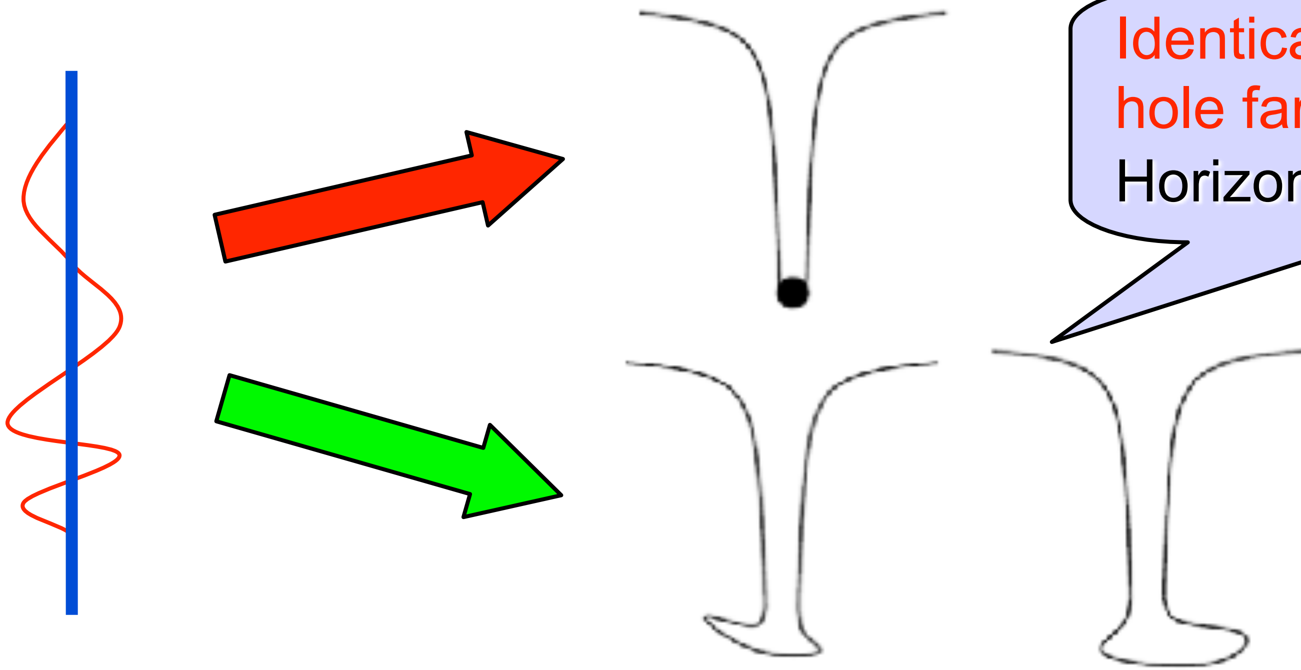
Count Black Hole Microstates (branes + strings)

Zero Gravity

Correctly match B.H. entropy !!!

One Particular Microstate at Finite Gravity:

Identical to black hole far away.
Horizon ⟶ Smooth cap



past 20 years

BIG QUESTION: Are there enough geometries with no horizon to span BH Hilbert space ?

Analogy with ideal gas:

Thermodynamics

(Air = ideal fluid)

P V = n R T

dE = T dS + P dV

Statistical Physics

(Air -- molecules)

e^S microstates

typical

atypical

Thermodynamics

Black-Hole Solution

Statistical Physics

Horizonless microstate geometries

Long distance physics

Gravitational lensing

Physics at horizon

Information loss

Gravity waves ?

Two routes

1. Build lots of solutions with black-hole mass and charges, but no horizon 2004-now
   - Bubbling geometries, superstrata
   - Many features of typical microstates (mass gap = $2/N_1 N_5$)
   - $S \sim (Q_1\ Q_5)^{1/2}(Q_p)^{1/4} < S_{BH} \sim (Q_1\ Q_5\ Q_p)^{1/2}$ Mayerson, Shigemori '20
   - Non-supersymmetric solutions (essentially adding antibranes) Heidmann, Bah '20-now

2. Track String-Theory microstates from no-gravity regime where they are counted

Best starting point: IIA F1-NS5

One F1 inside N_5 NS5 branes ➙ N_5 little strings.

Dijkgraaf, Verlinde, Verlinde

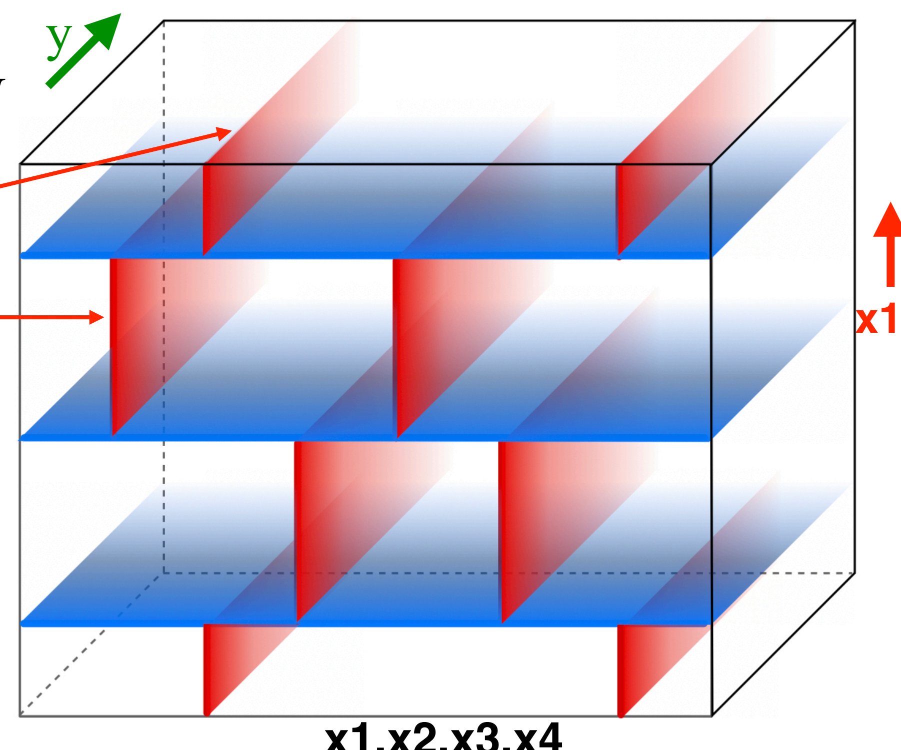
- Visible as M2 brane strips in M-theory
- Total $N_1 N_5$ independent momentum carriers
- each has 4 oscillation directions (T^4) + 4 fermionic partners

$$S = 2\pi\sqrt{\frac{4+2}{6}N_1 N_5 N_p} = S_{BH}$$

M2 along y, 11

M5 along y,1234

P along y

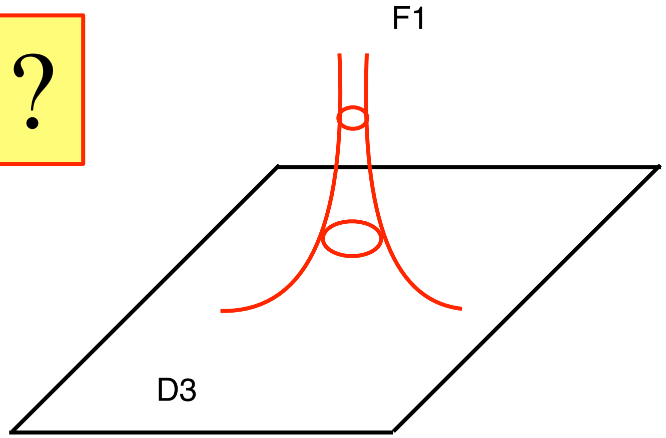


D1-D5: fractionated P

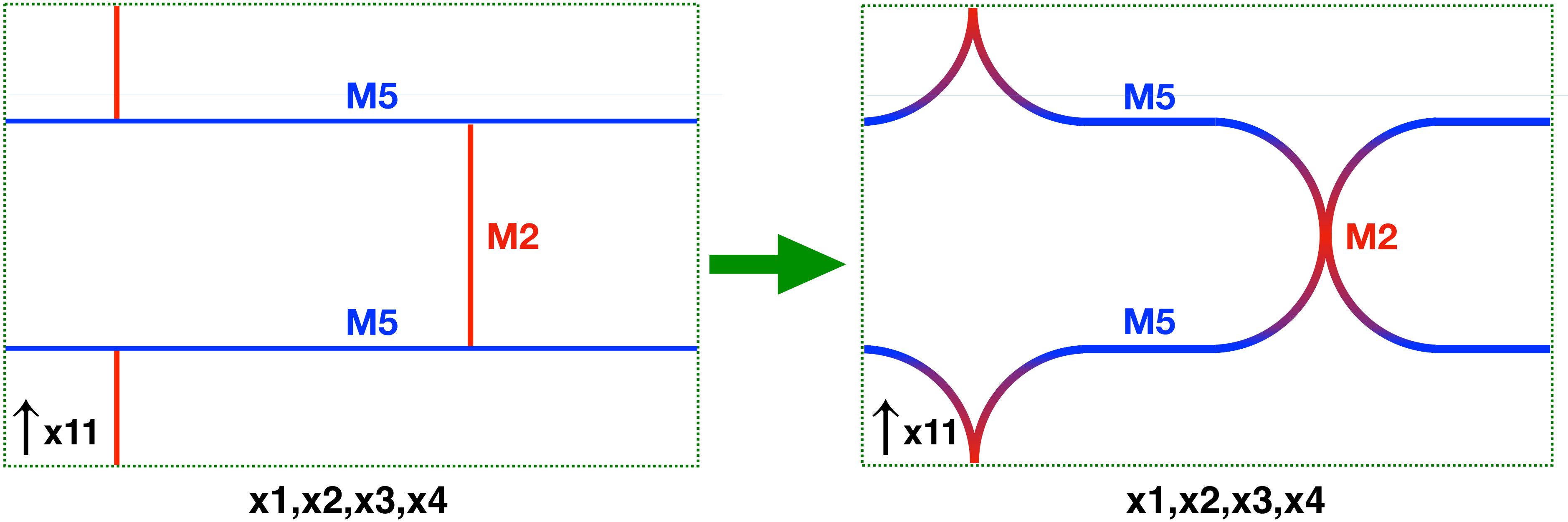
F1-NS5: fractionated F1

zero-coupling picture

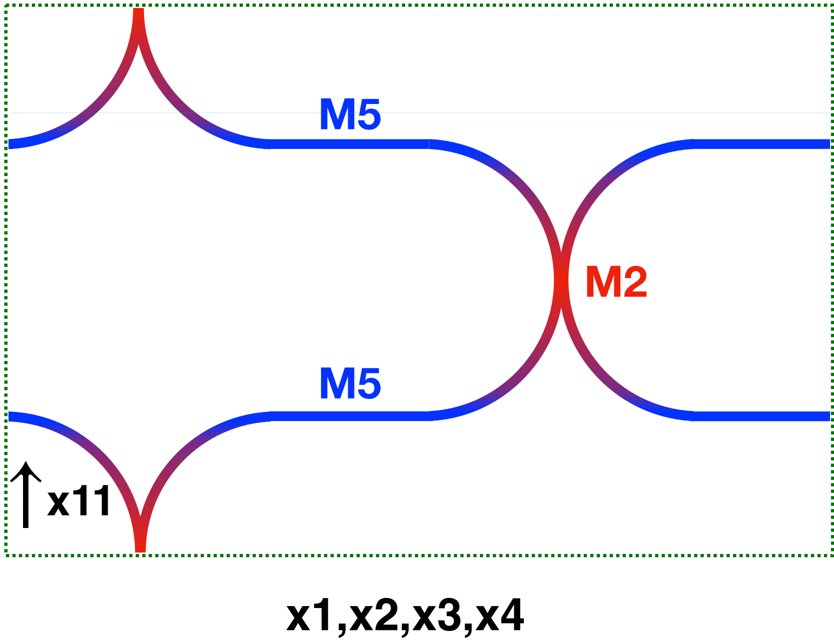
What about finite coupling ?

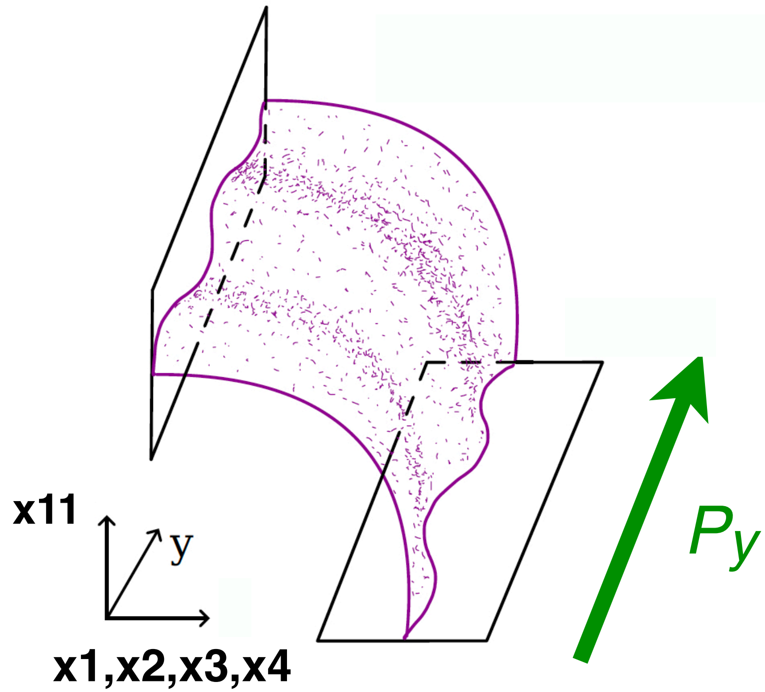


- Reminder:
  Callan-Maldacena spike formed by F1 pulling on an orthogonal D3
- M2 branes also pull on the M5 brane
- Maze of supersymmetric branes: super-maze



Spike → *furrow* carrying momentum waves along common M2-M5 direction (y)





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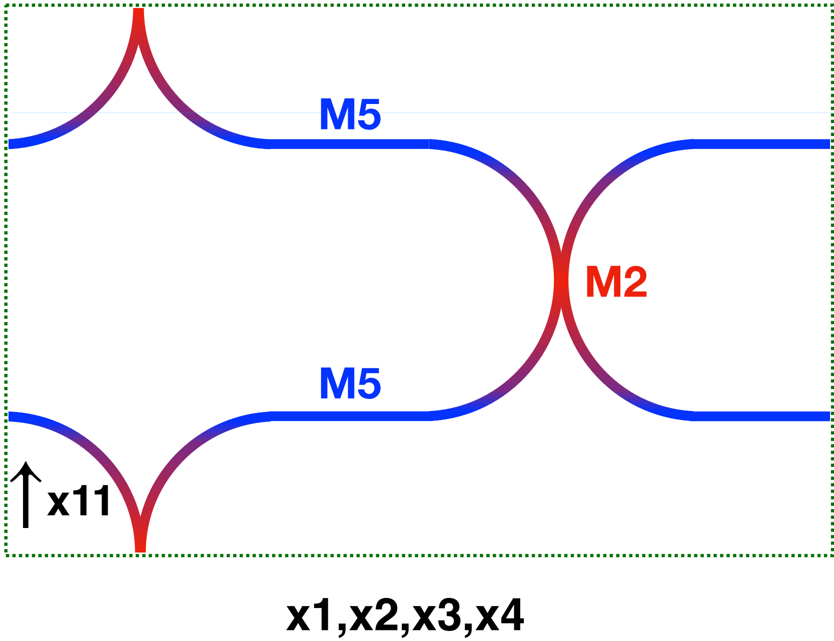
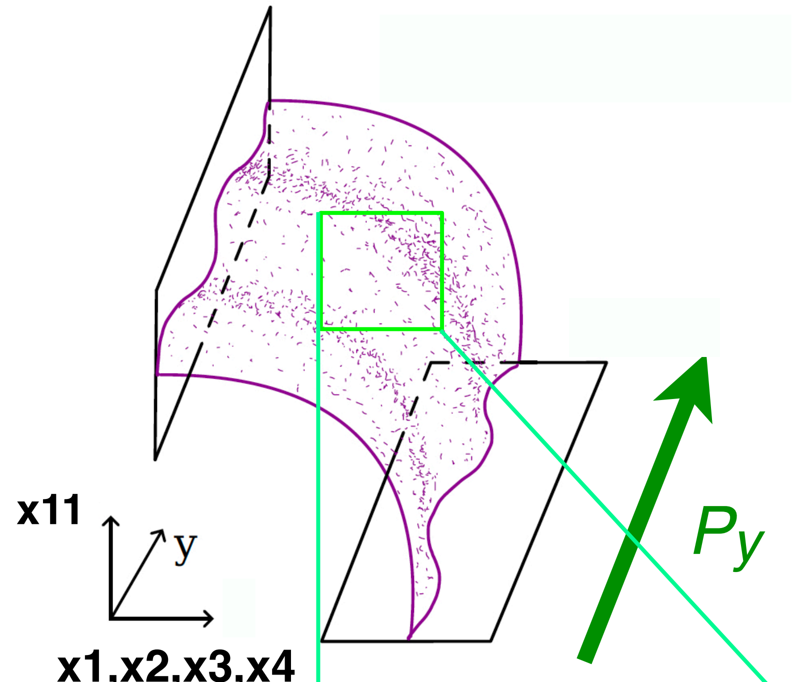




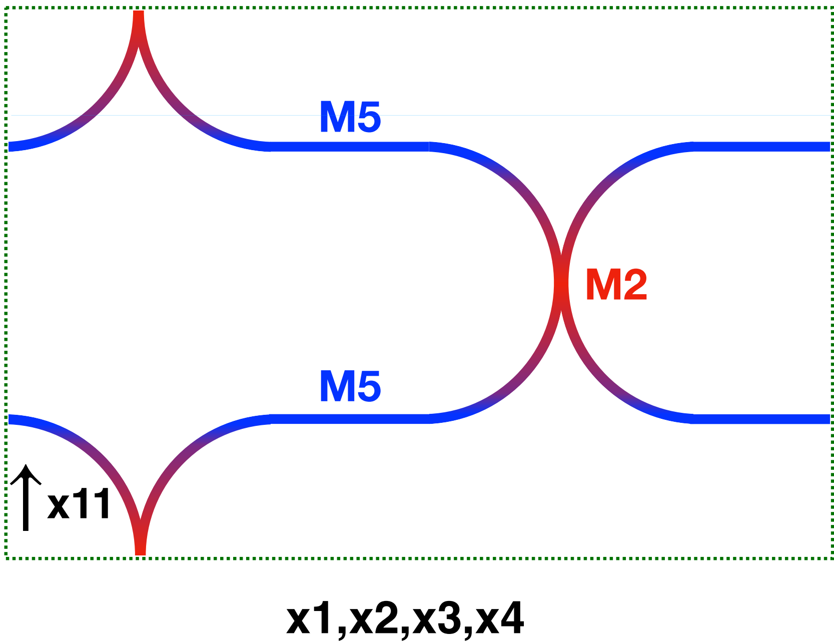
Zoom in on the furrow carrying momentum: **nine** local brane charges: $\mathbf{M2_{x11,y}}$ $\mathbf{M5_{y,x1,x2,x3,x4}}$ $\mathbf{P_y}$

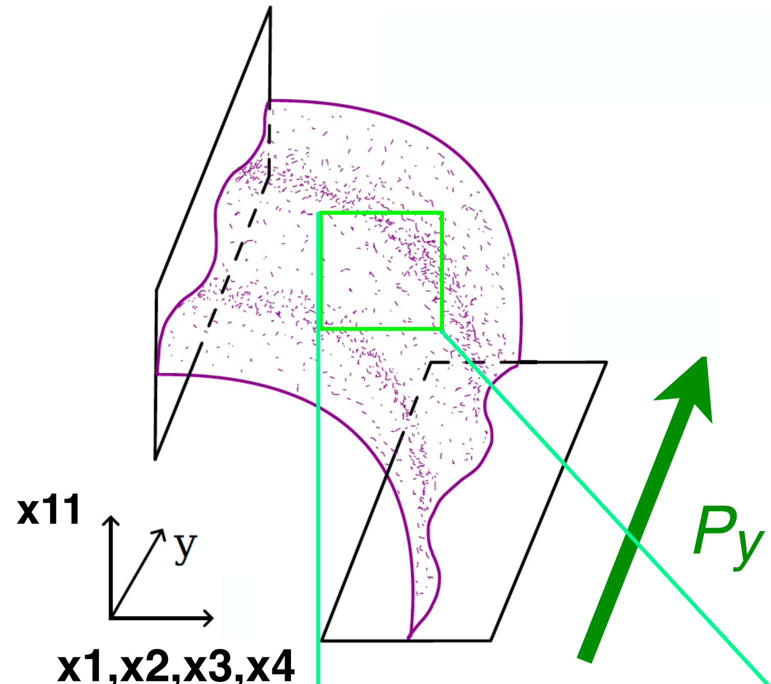
$M2_{x1,x11}$ $M5_{x11,y,x2,x3,x4}$ $M2_{x1,y}$ $M5_{x11,x1,x2,x3,x4}$ P_{x11} P_{x1}

4→16 supercharges !

Bena, Hampton, Houppe, Li, Toulikas

Spike → *furrow* carrying momentum waves along common M2-M5 direction (y)





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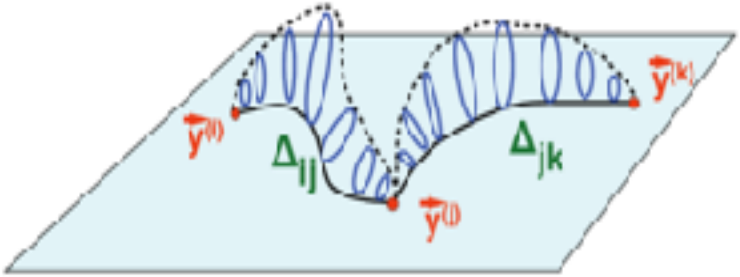
Bena, Hampton, Houppe, Li, Toulikas

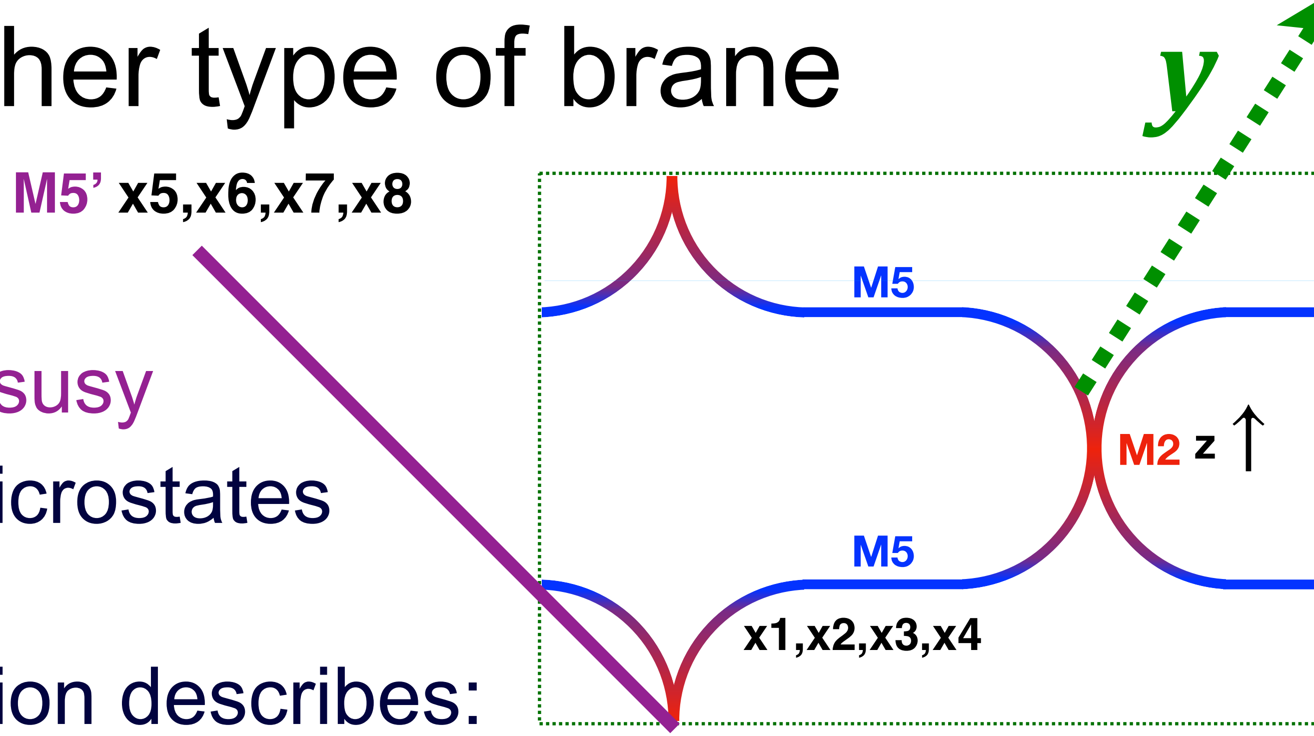
Smoking gun of smooth horizonless solutions

A bit of history



- First microstate geometries
  - Horizonless bubbling solutions Bena, Warner '06
  - ⇔ Multicenter fluxed D6 branes Balasubramanian & al '06
  - 16 susy at every center, 4 globally
  - Entropy much smaller than BH de Boer & friends
- Microstate geometries with supertubes
  - Functions of one variable Bena, Bobev, Giusto, Ruef, Warner '10
  - Smooth ⇔ 16 susy when zooming on supertube
- Superstrata. conjectured in Bena, de Boer, Shigemori, Warner '11
  - Fns. of 2 variables; 16 susy locally, 4 globally
  - **HABEMUS:** Smooth. Bena, Giusto, Russo, Shigemori, Warner '15
- **Smooth horizonless sols ⇔ brane config. with 16 susy locally, 4 globally**
- **Big Goal: build the super-maze solutions**

Add another type of brane



- + M5' - still 8 susy
- bad for BH microstates (space filling)
- Generic solution describes:
  - M2 suspended between M5 and M5'
  - infinite M2 spikes ending on M5 or on M5'
  - M2 between two M5 or two M5'
  - M2 crossing M5 or M5' but not ending on them

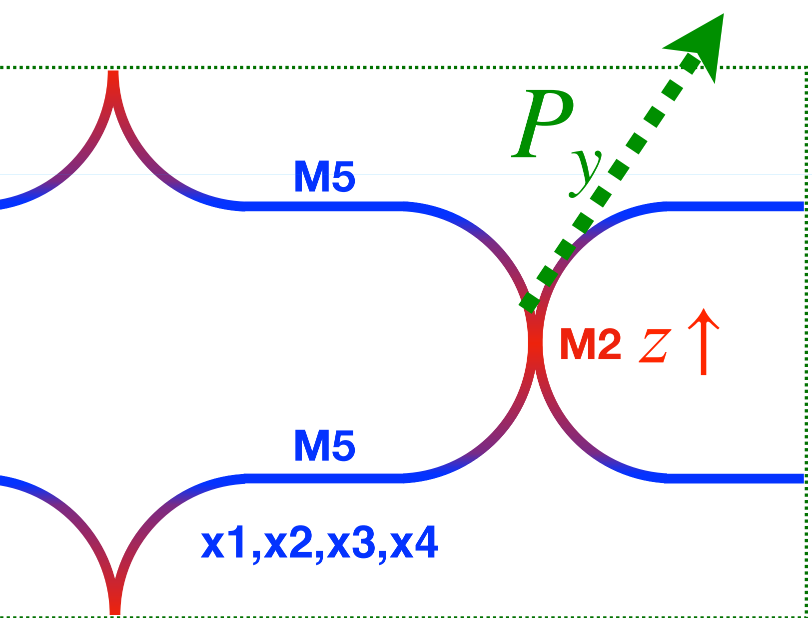
Monge-Ampère equation:

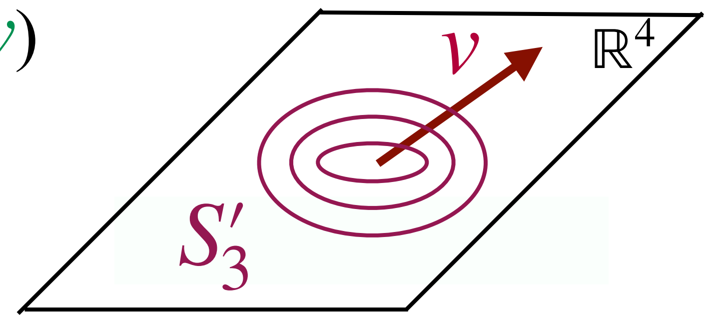
$$\mathcal{L}_v G_0 \; = \; (\mathcal{L}_u G_0)\,(\partial_z\partial_z G_0) \; - \; (\nabla_{\vec{u}}\partial_z G_0)\cdot(\nabla_{\vec{u}}\partial_z G_0)$$

Simplest relevant solution: $SO(4) \times SO(4) \times U(1)_y$ invariant on $S^3 \in$ M5, on $S^3 \in$ M5', no P_y

M2: 0, y, z
M5: 0, y, u, S_3
M5': 0, y, v, S_3'

- **Monge-Ampère:** $G_0(z,u,v)$ - hard
- Brane sources $\Rightarrow \exists$ solution (singular) Lunin
- **Black-hole charges** $\mathrm{M2}_{zy}$+$\mathrm{M5}_{1234y}$+$P_y \Rightarrow$
  at least *cohomogeneity-4* (z,u,v,y)





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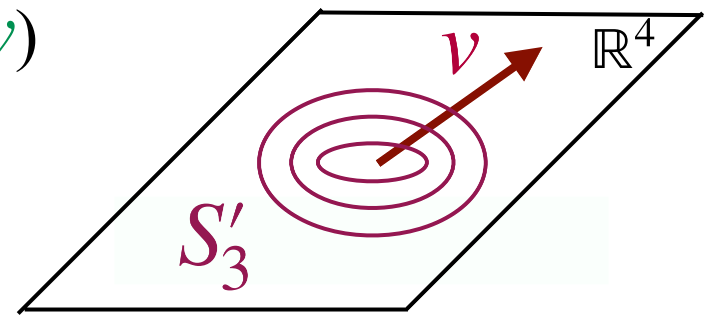
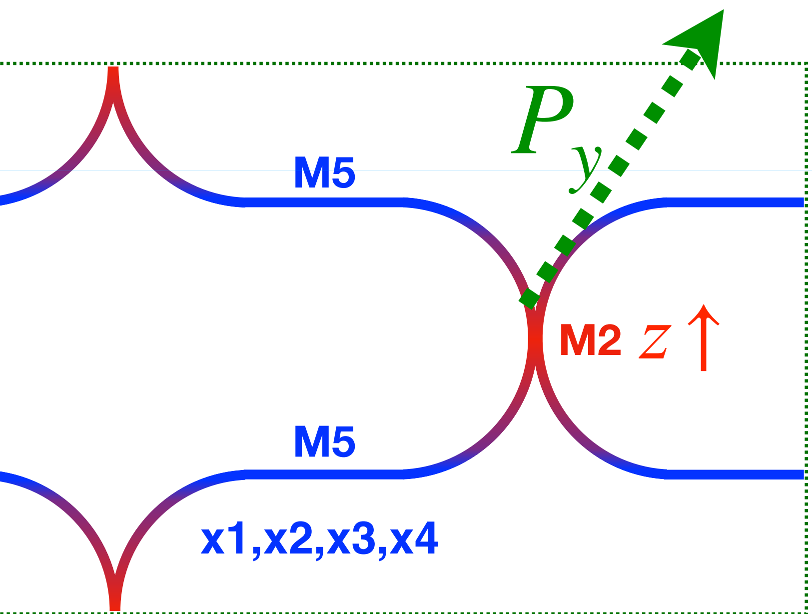
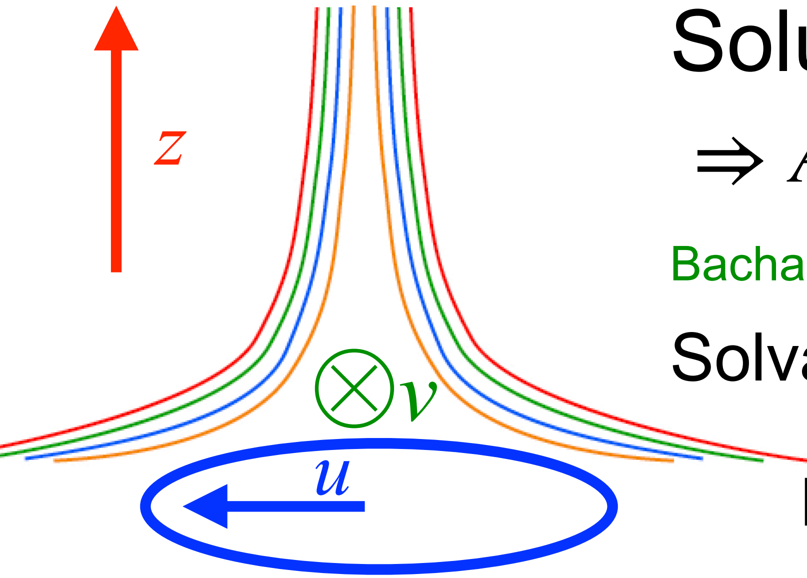




But …To the blind bird God sometimes makes the nest

Romanian proverb

Zoom in on brane profile



Solution with $SO(4) \times SO(4) \times \mathbb{R}^{1,1}$

$\Rightarrow AdS_3 \times S^3 \times S^3 \times$ Riemann surface

Bachas, Estes, D'Hoker, Krym   Cohom $3 \rightarrow 2$!

Solvable in a **linear** algorithm !

Brane coordinates:
M2: 0, y, z
M5: 0, y, u, S_3
M5': 0, y, v, S_3'

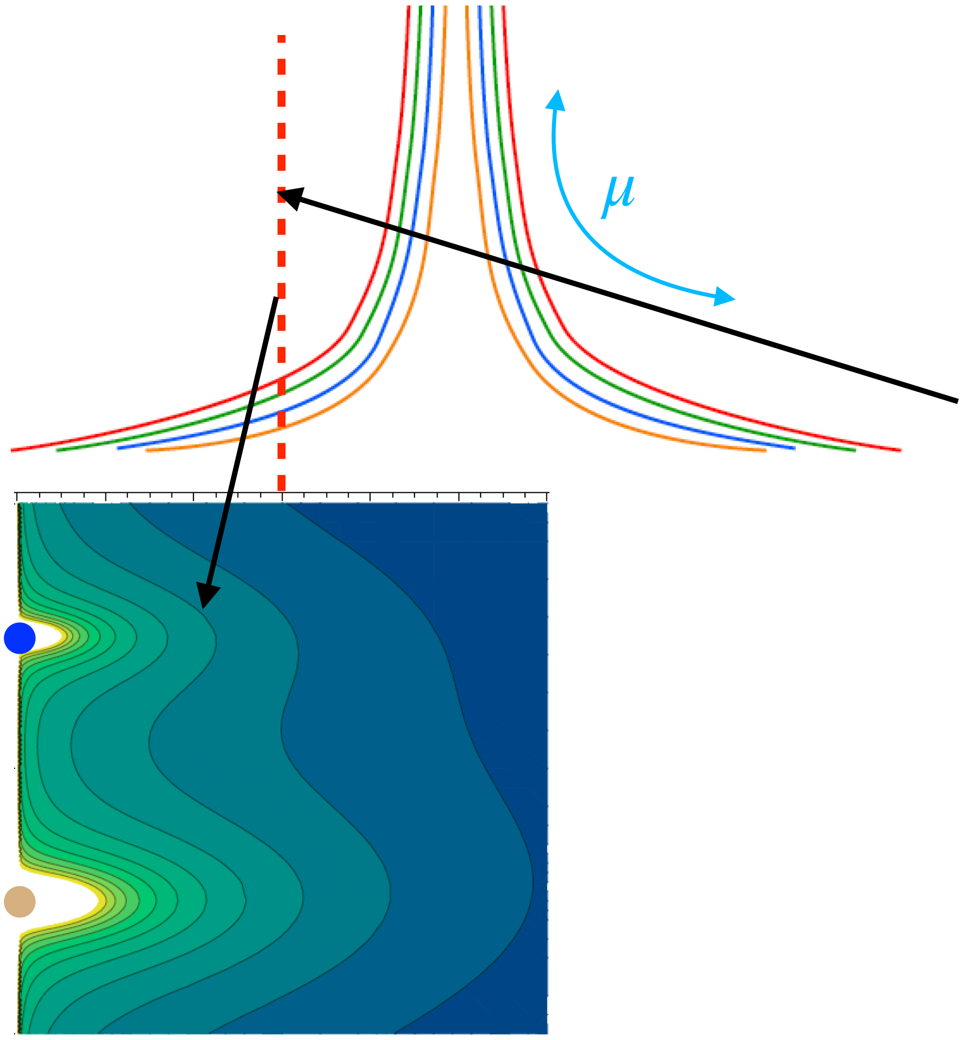
$$ds^2_{\mathrm{AdS}_3} = \mu^2(-dt^2 + dy^2) + \frac{d\mu^2}{\mu^2}$$

μ + Riemann surface coordinates: x, y = functions of z, u, v

$AdS_3 \times S^3 \times S^3$ solution = backreaction of M2-M5 spikes

Bena, Chakraborty, Houppe, Toulikas, Warner

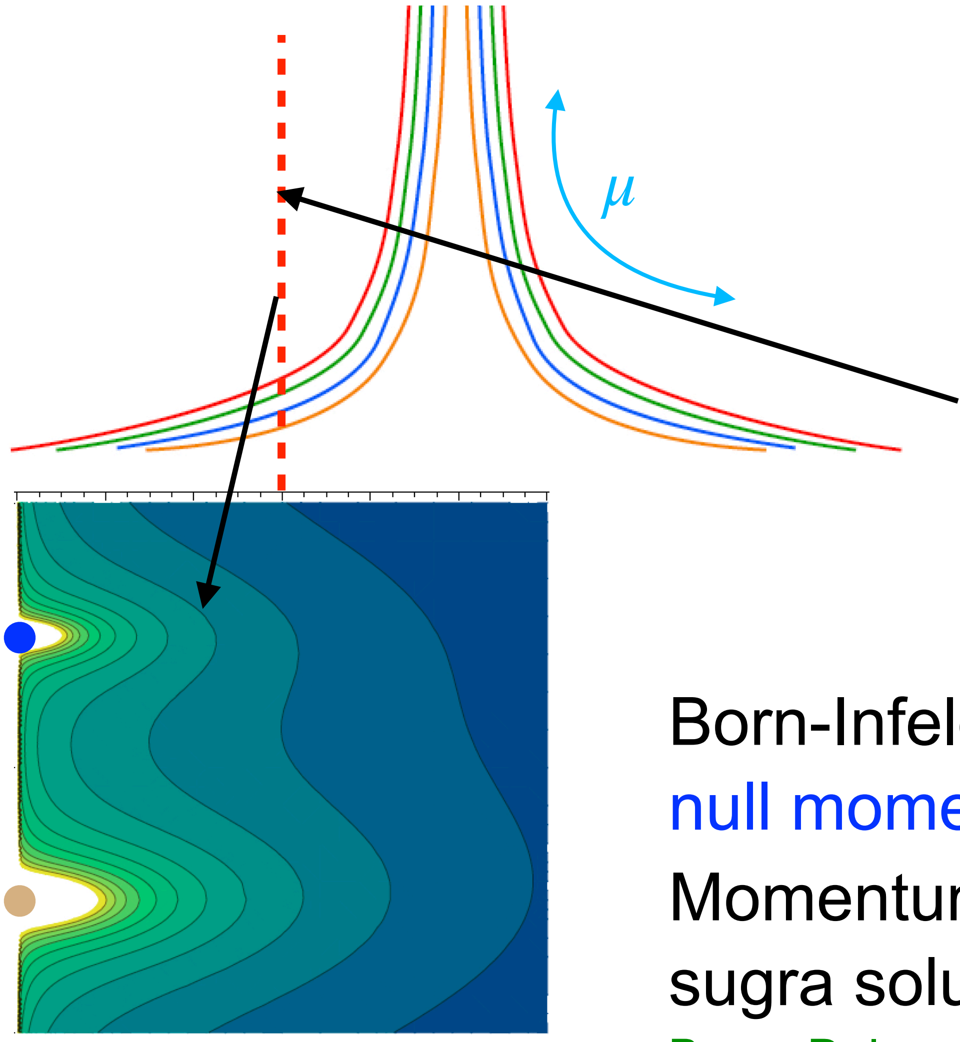
Zoom in on brane profile



Point on Riemann surface: $z\,u^2$ = constant. M2-M5 spike spanned by μ

M2 along z, at constant u, v = curve on Riemann surface $x(\mu)$, $y(\mu)$

Zoom in on brane profile



Point on Riemann surface:

$z\,u^2$ = constant. M2-M5 spike spanned by μ

M2 along z, at constant u, v = curve on Riemann surface

$x(\mu)$, $y(\mu)$

Born-Infeld construction of supermaze + null momentum wave

Bena, Dulac

Momentum wave can be added to the sugra solution following linear algorithm !

Bena, Dulac, Houppe, Toulikas, Warner

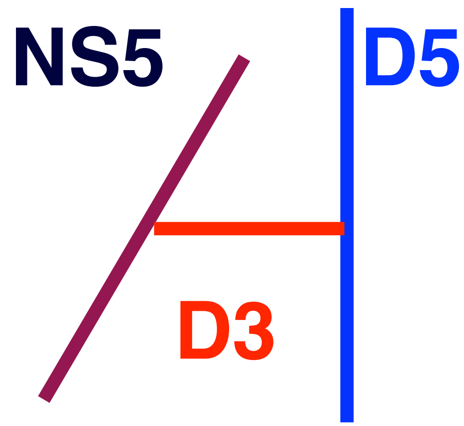
+ Arbitrary function of null coordinate ⇒ cohomogeneity 2 !!!

A similar system

$D3: \quad 0,1,2, z$

$D5: \quad 0,1,2, u, S_2$

$NS5: 0,1,2, v, S_2'$



- Generic solution describes:
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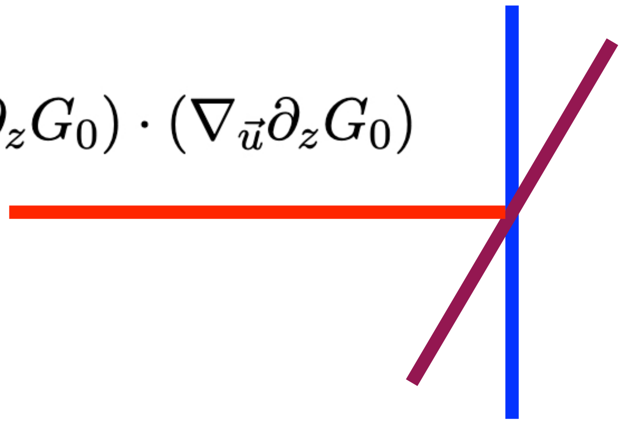


Link with AdS_4 solutions

D3-D5-NS5 solution with $SO(3) \times SO(3) \times \mathbb{R}^{2,1}$

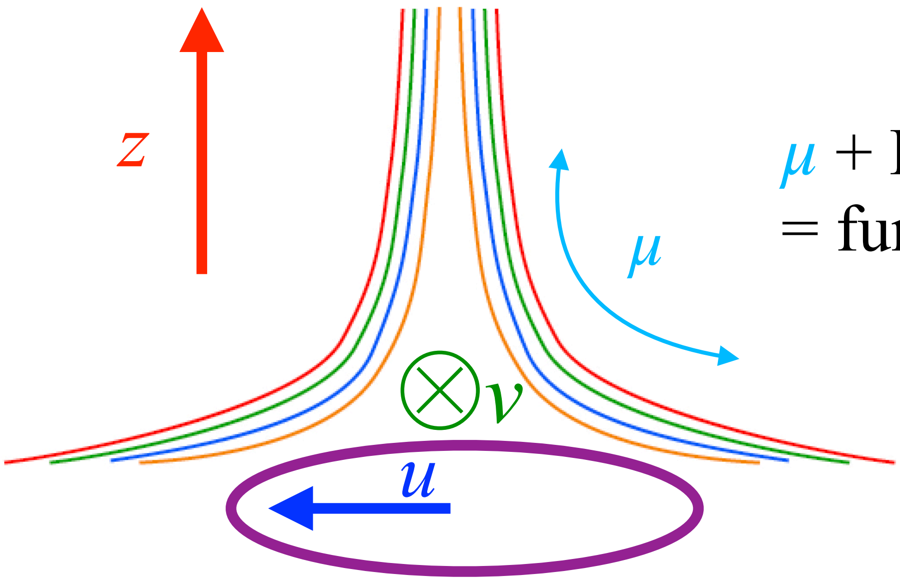
(Monge-Ampère) $\Rightarrow AdS_4 \times S^2 \times S^2 \times$ Riemann surface

Brane coordinates: D3: 012, z

D5: 012, $\boldsymbol{u}$, S_2

NS5: 012, $\boldsymbol{v}$, S_2'

$$ds^2_{\mathrm{AdS}_4} = \mu^2(-dt^2 + dx_1^2 + dx_2^2) + \frac{d\mu^2}{\mu^2}$$



μ + Riemann-surface coordinates x, y
= functions of z, $\boldsymbol{u}$, $\boldsymbol{v}$

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$z\,u$ = constant. D3-D5 spike
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(Monge-Ampère) ⇒ $AdS_4\times S^2\times S^2\times$ Riemann surface

Brane coordinates: D3: $012,\ z$

D5: $012,\ \boldsymbol{u},\ S_2$

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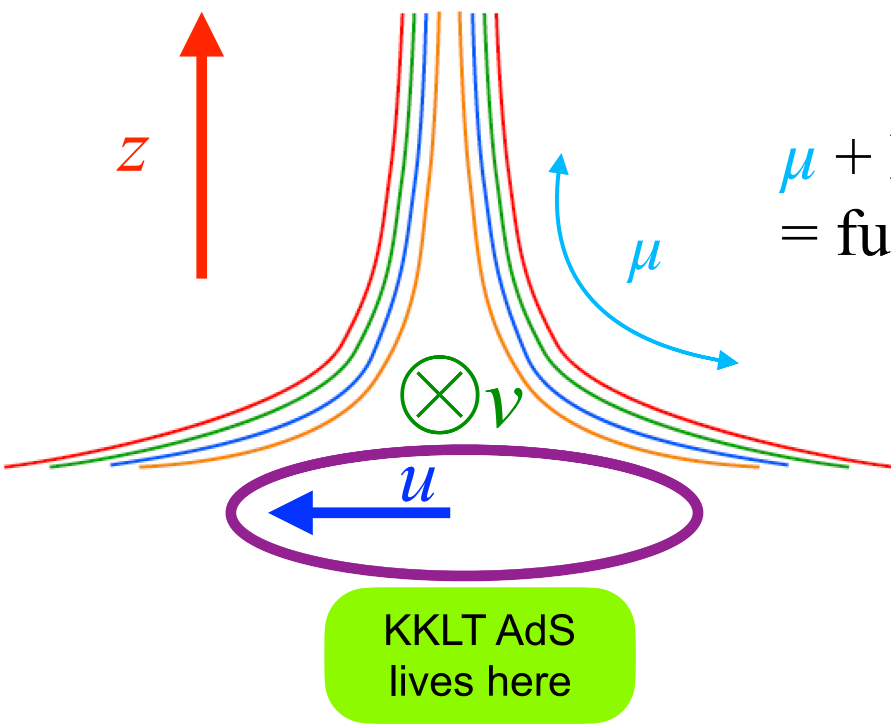

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KKLT = hot-potato field *(sulfureux)*

Compactify to 4D on 6D manifold (Calabi-Yau)
Lots of unphysical massless scalars (moduli)

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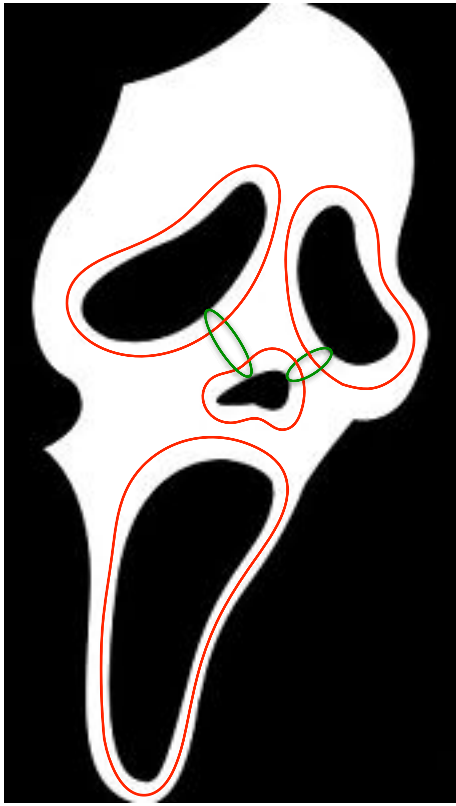
2. gaugino cond. → fix Kähler moduli
   → 10^{500} stable AdS vacua



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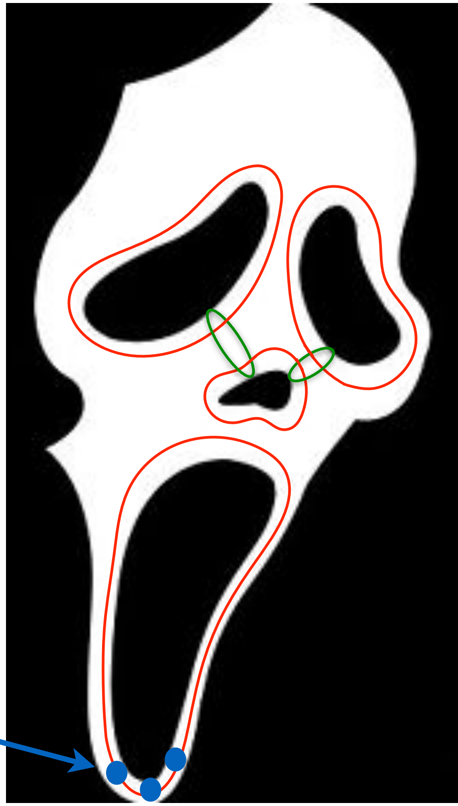

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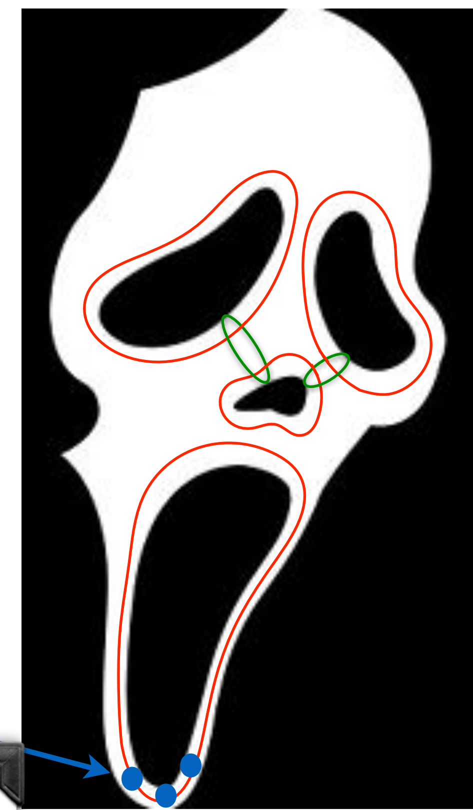
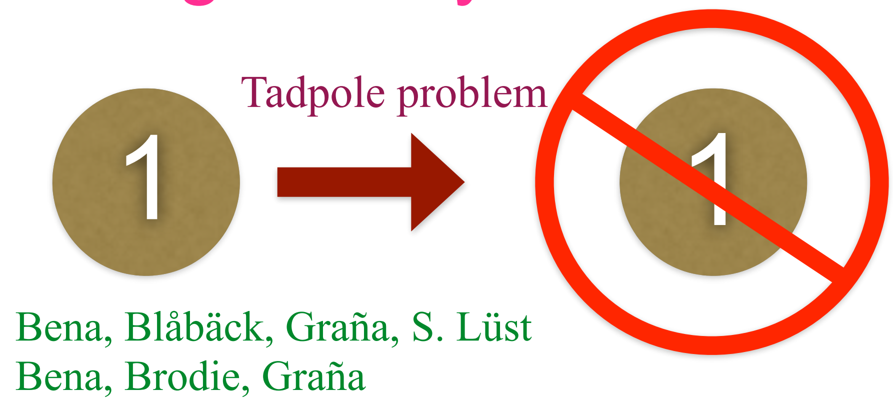


THE LANDSCAPE

Why the sulfurosity ?

Steps 1,2,3: low-energy effective field theory using String-Theory-derived ingredients

Nontrivial interactions in String Theory



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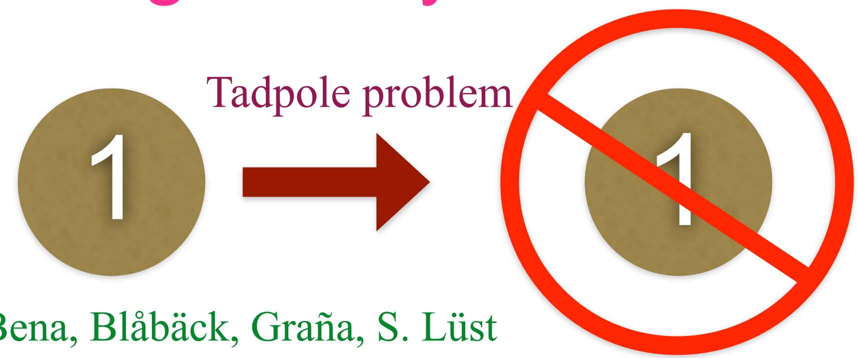
Bena, Dudaș, Graña, S. Lüst



Bena, Blåbäck, Graña, S. Lüst
Bena, Brodie, Graña

+ lots of swampland-type conjectures:
scale separated dS and AdS ***not possible***

hard to convince KKLT fans …

Do not pray to the saint who does not help you !

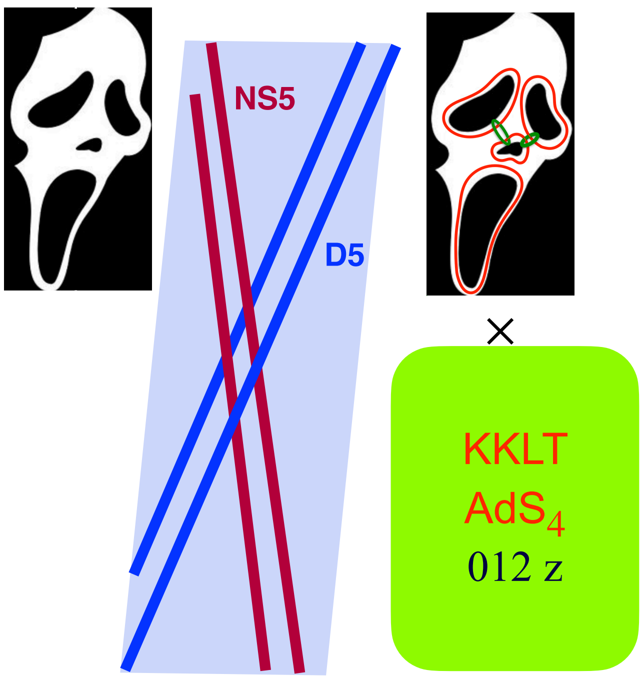
Romanian proverb

The KKLT domain wall

S.Lüst, Vafa, Wiesner, Xu

- Compactification fluxes eaten by branes on dual cycles
- $F_{\text{UV domain wall}} > \left(\frac{\ell^{\text{KKLT}}_{AdS_4}}{l^{4D}_{\text{Planck}}}\right)^2$
- Bound on $\ell^{\text{KKLT}}_{AdS_4}$

$F^{\text{perturbative}}_{\text{UV}} \sim N^2$



D5: $012 \times \Omega_3$
NS5: $012 \times \Omega'_3$
Domain wall: $012 \times$ CY

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What is on the left ?

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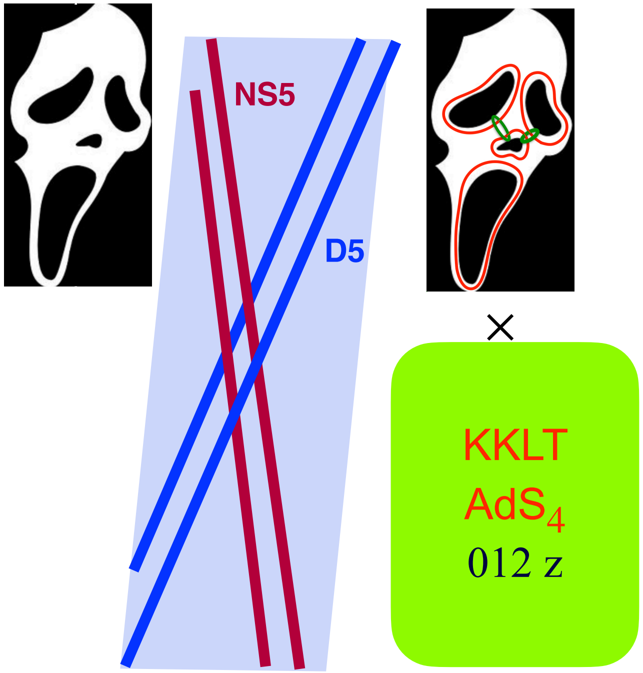

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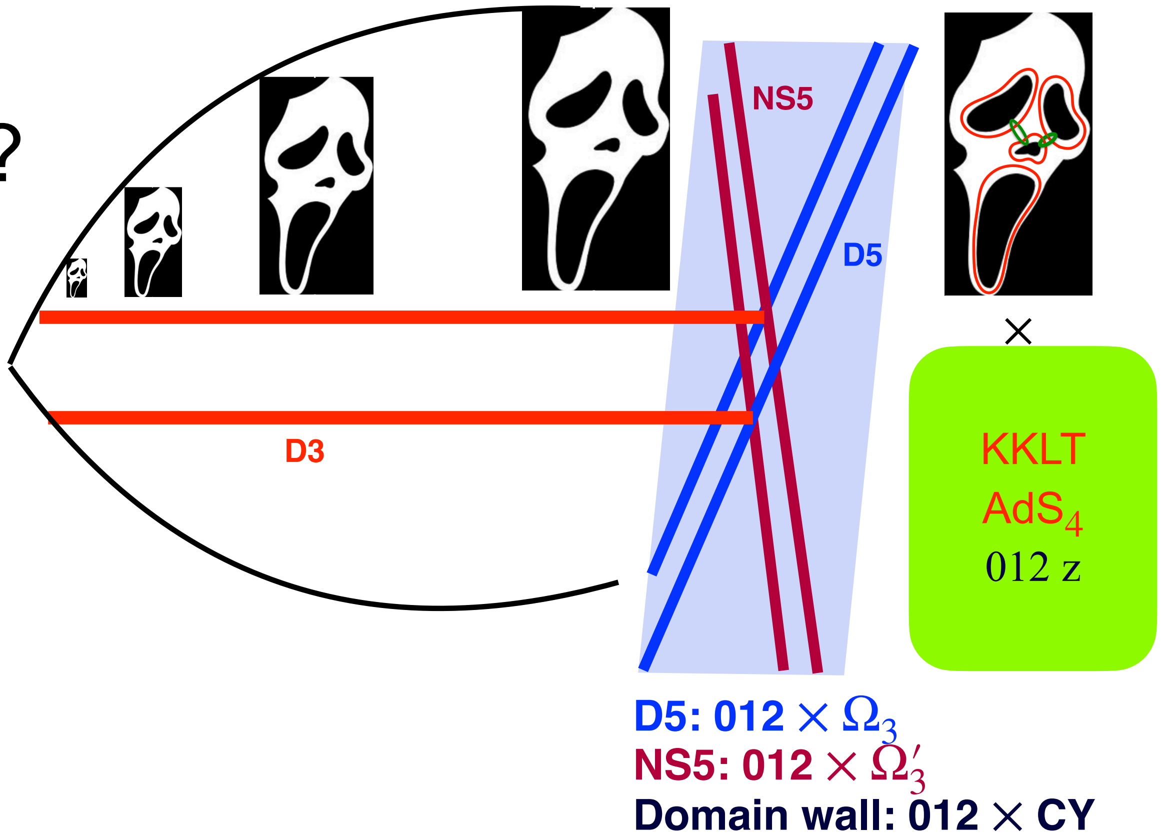

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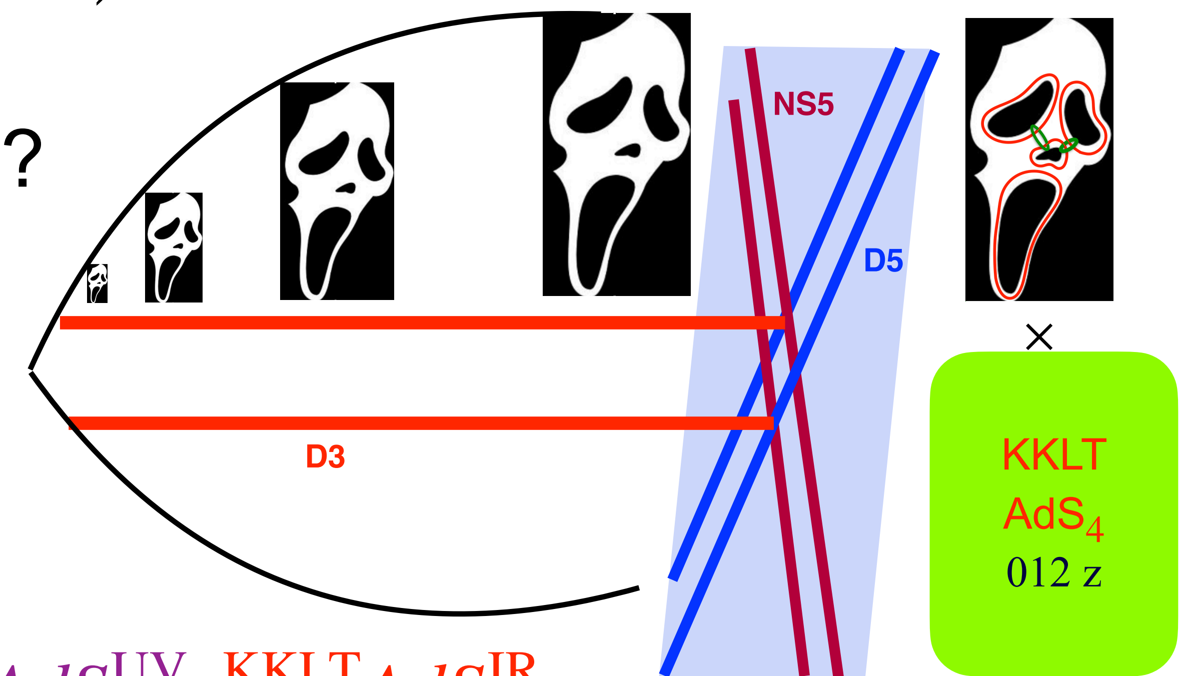
- Bound on $\ell^{\text{KKLT}}_{AdS_4}$

What is on the left ?

- CY shrinks
- Universe ends
- *KKLT ex nihilo*
  Bena, Li, S.Lüst
- D3-D5-NS5 spikes
- Spike backreaction $\Rightarrow AdS_4^{\text{UV}}$, ${}^{\text{KKLT}}AdS_4^{\text{IR}}$
- $\ell^{UV}_{AdS_4} > \ell^{\text{KKLT}}_{AdS_4}$
- $F^{\text{UV}}_{\text{CFT}} \sim N^4 \ni$ all domain wall d.o.f. Not enough for KKLT AdS_4



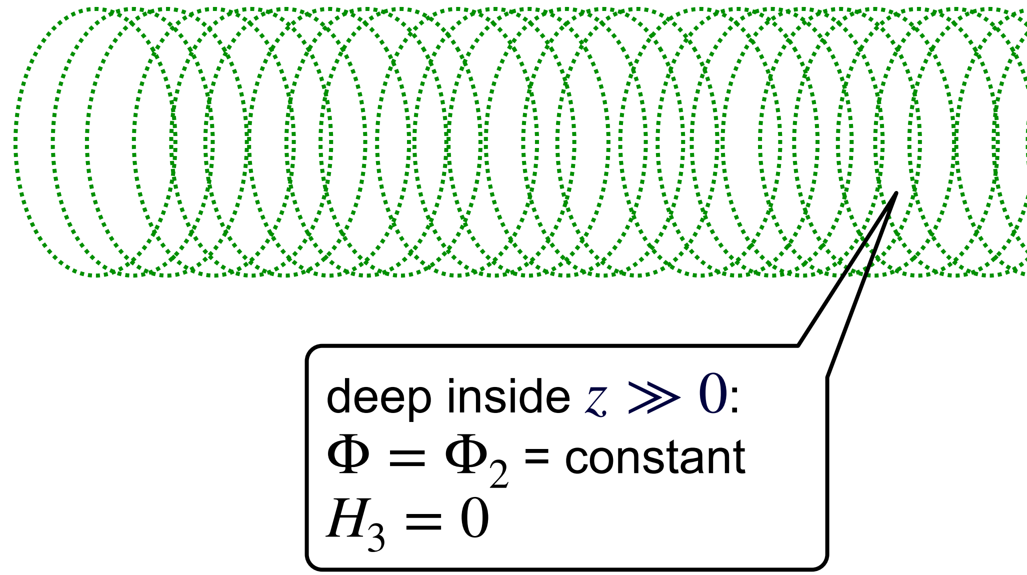
D5: 012 $\times\ \Omega_3$
NS5: 012 $\times\ \Omega'_3$
Domain wall: 012 $\times$ CY

$AdS_4 \times S^2 \times S^2 \times \Sigma$ solutions: 3 classes

1. **Two AdS_5 ends: Janus**

NS5 smeared on $S^2 \times z^+$
codimension-1 for $z > 0$

$$\Phi = \Phi_1$$



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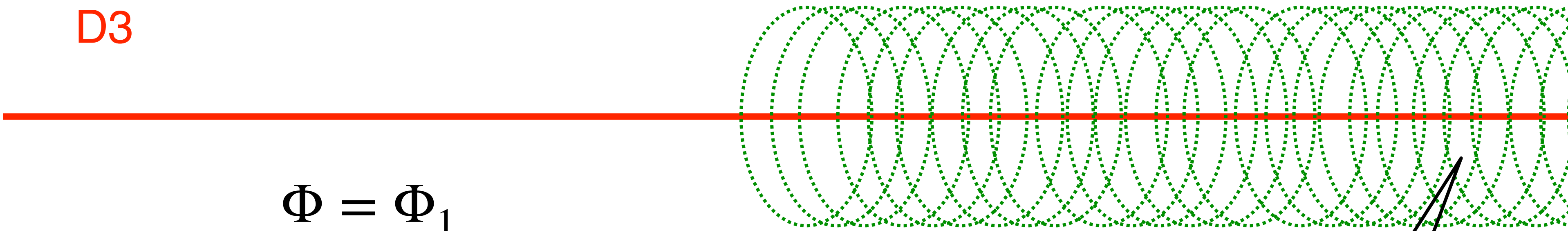
D3



$\Phi = \Phi_1$

deep inside $z \gg 0$:
$\Phi = \Phi_2$ = constant
$H_3 = 0$

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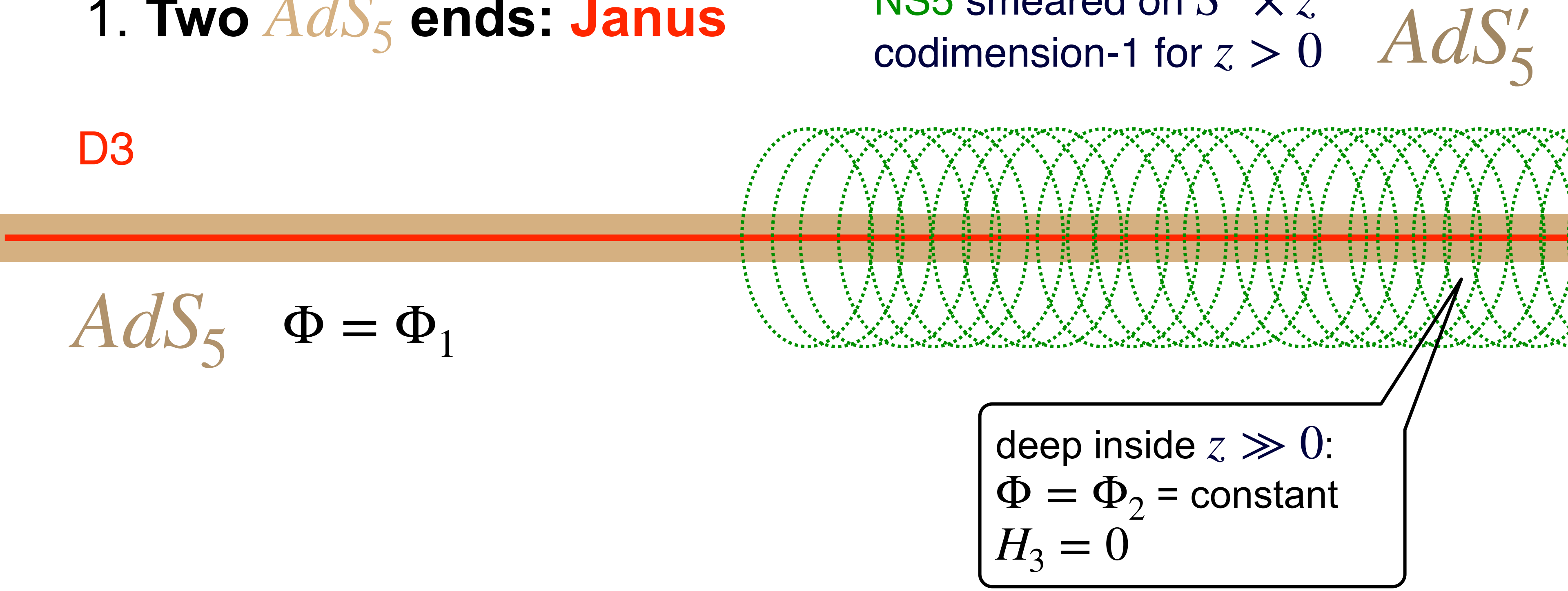

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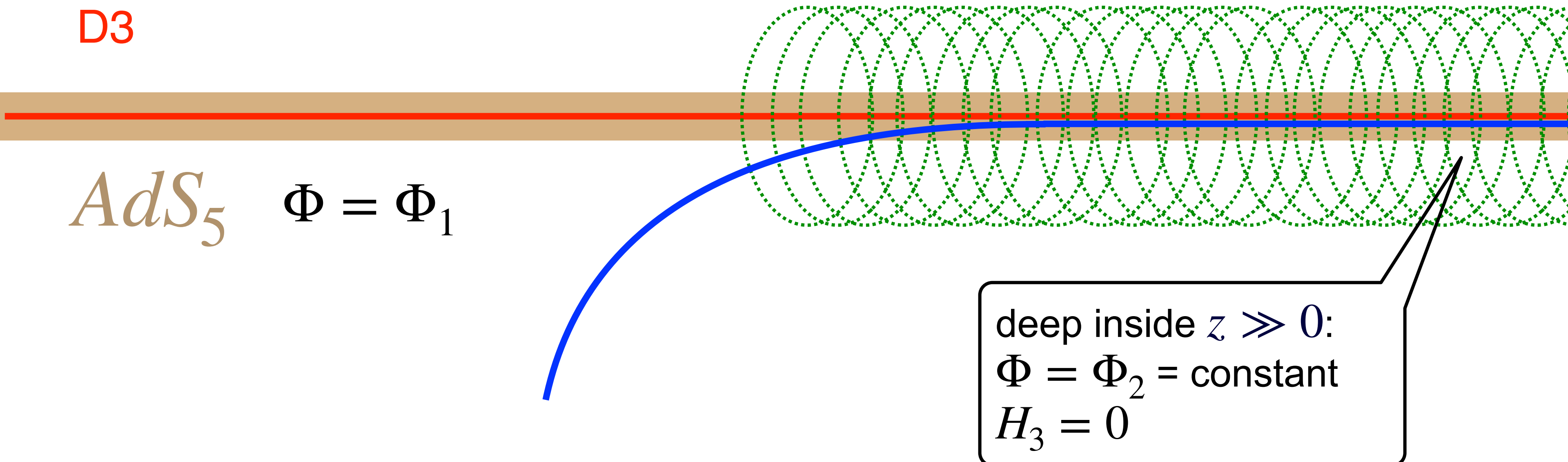
AdS_5'



One can add extra D3 - D5 spike

$\Rightarrow$ AdS_5' can have different N_3

$AdS_4 \times S^2 \times S^2 \times \Sigma$ solutions: 3 classes

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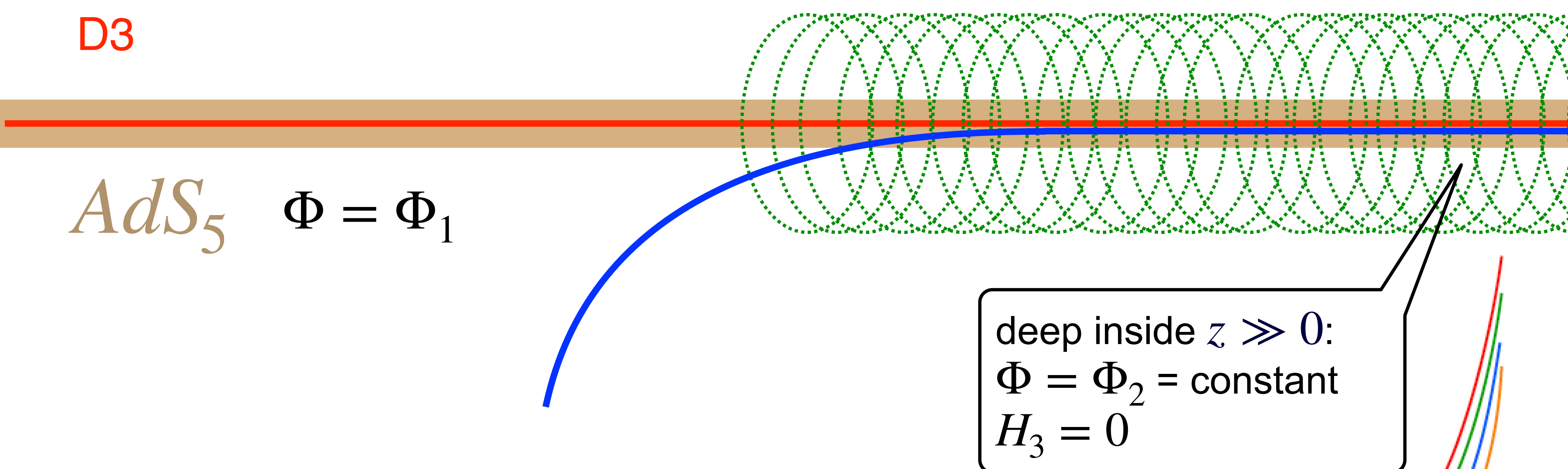
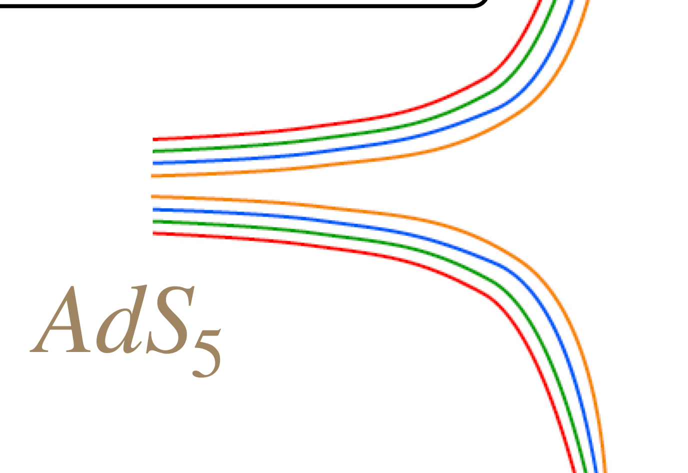


One can add extra D3 - D5 spike

$\Rightarrow$ AdS'_5 can have different N_3

2. One AdS_5 end:

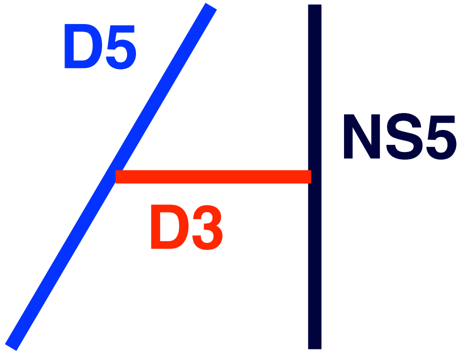
D3 spikes on D5 and NS5 branes:



3. No AdS_5 end

Everybody and their brother is confused

Claim:



Directly ruled out by our mapping

μ direction parameterizes an **infinite spike**

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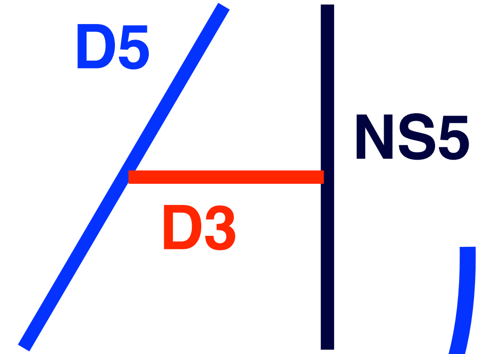

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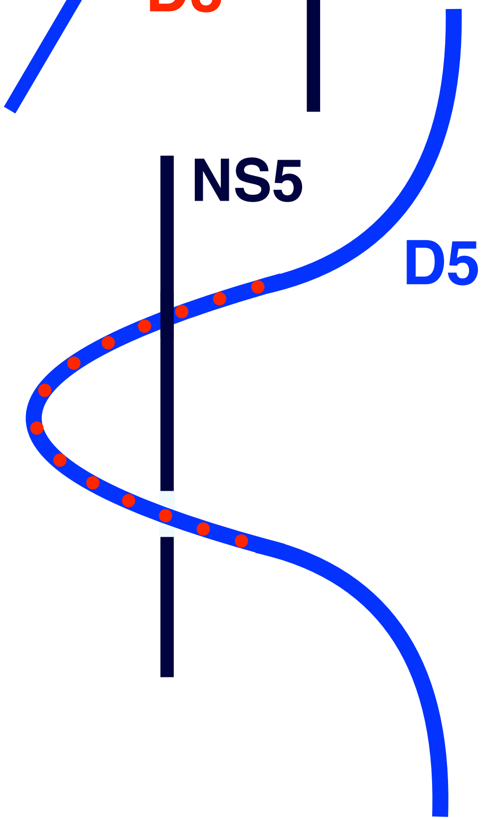
Story much more subtle

NS5 induces D3 charge on D5 worldvolume.

D5 gets a bulge:



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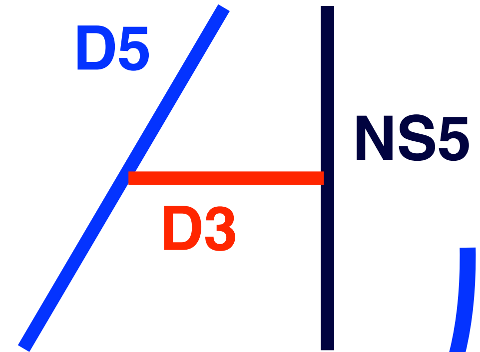

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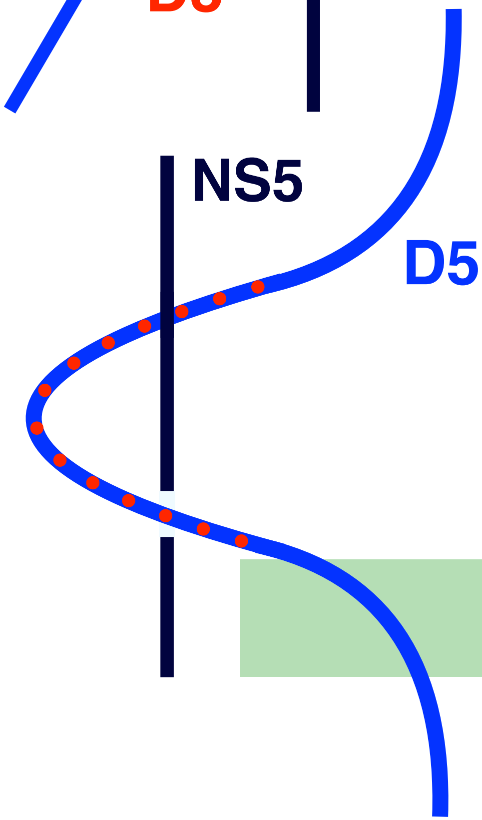

Solution = zoom-in on side of the bulge

looks like a spike

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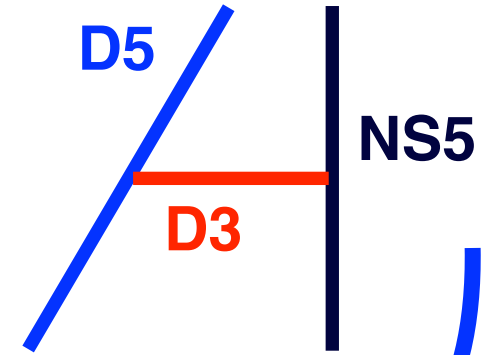

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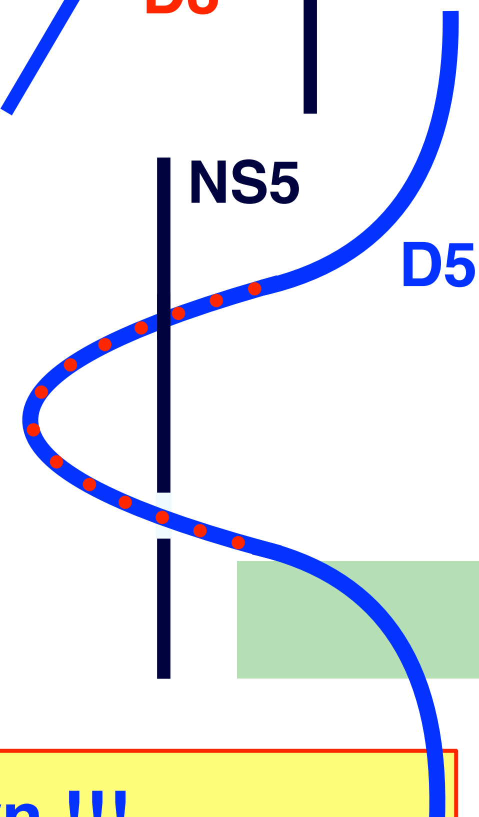

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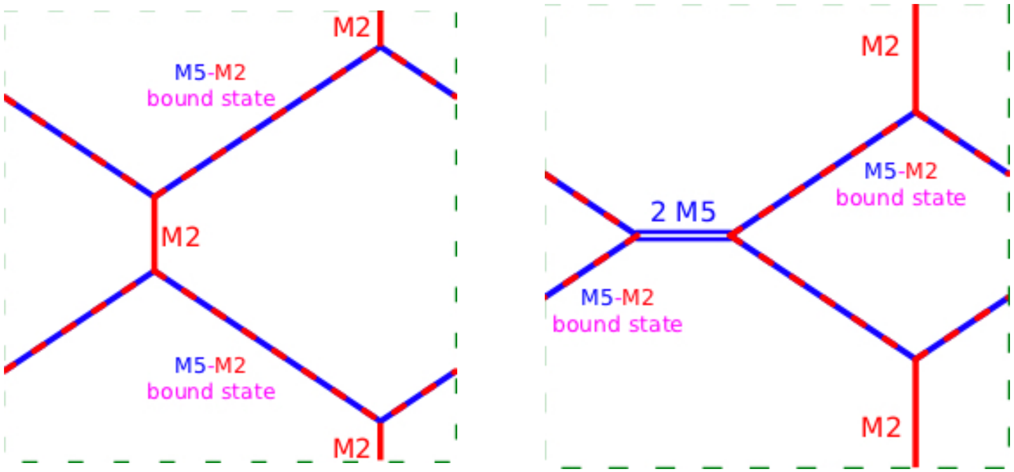
AdS solutions **: It's spikes all the way down !!!**

No chance to describe **D3 sandwiched between 2 D5's**

('t Hooft Polyakov monopole) or **D3 between D5 and NS5**

God makes to the nest of blind bird … but very spiky nest

How will the $SO(4)$-invariant solution look like ?



- *16-susy locally ⇒ no horizon*
- Branes wrapping compact contractible cycles ⇒ Geometric transition ⇒ Bubbles wrapped by fluxes inside the internal dimensions.

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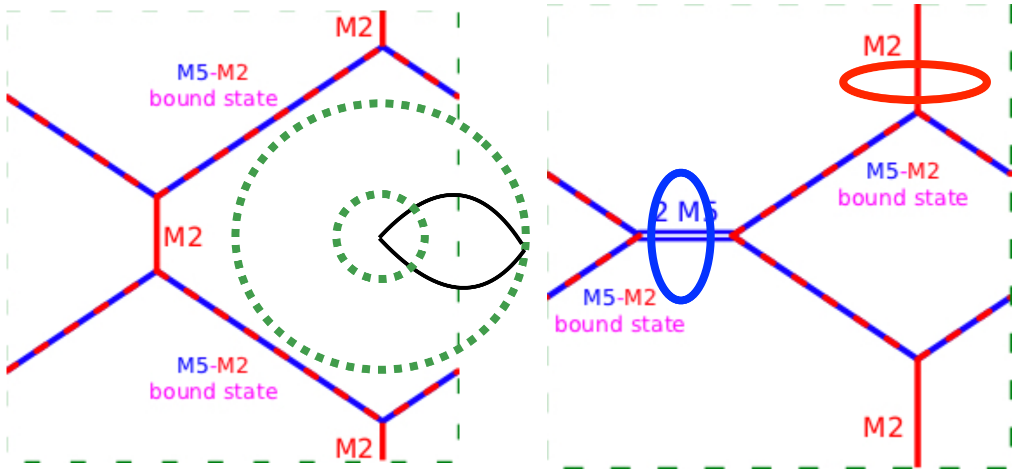

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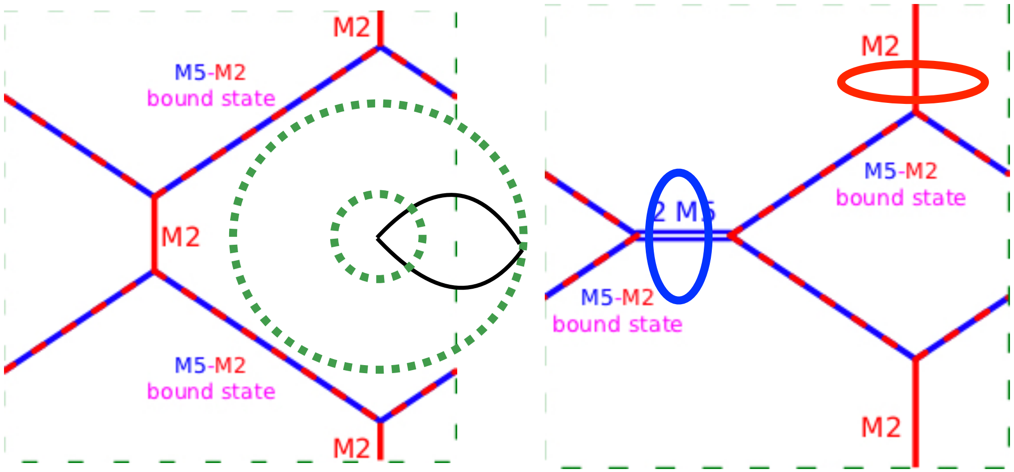
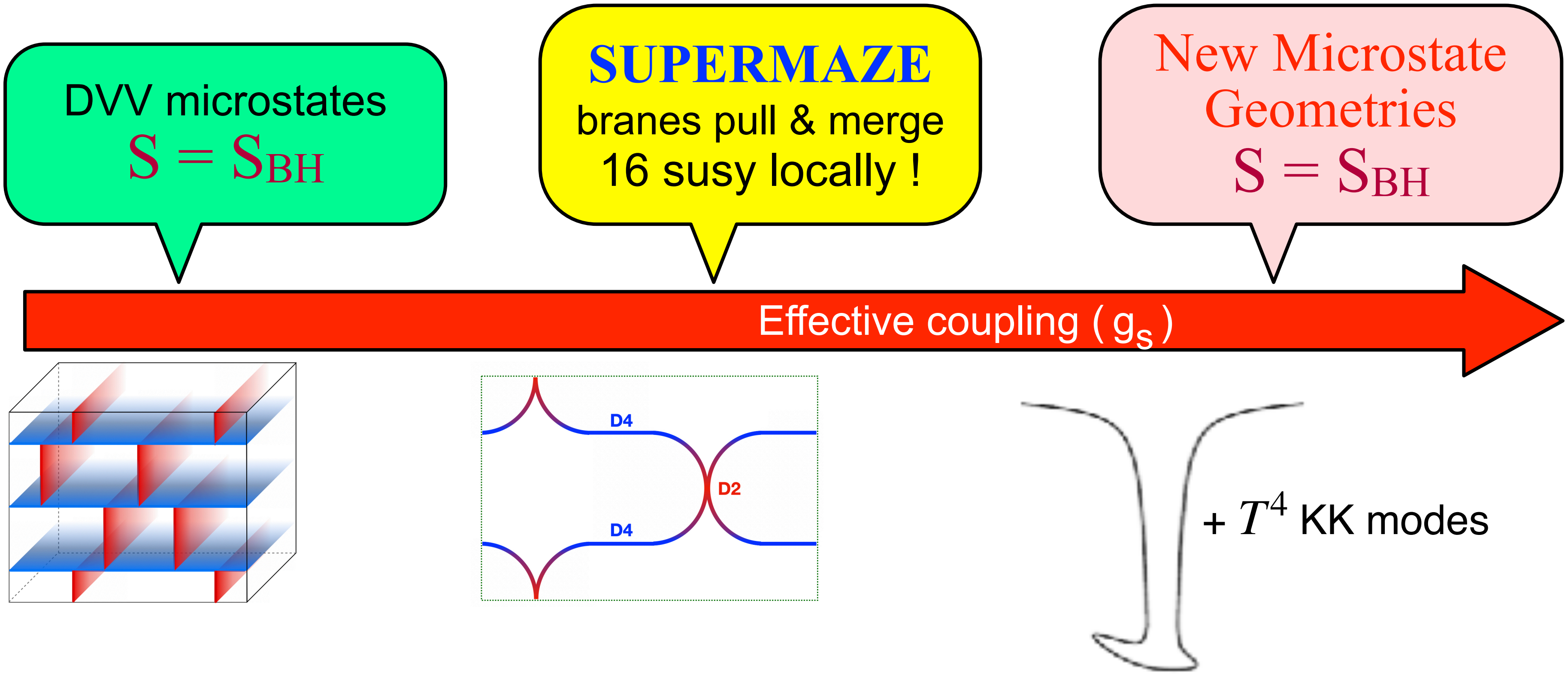


- *16-susy locally ⇒ no horizon*
- Branes wrapping compact contractible cycles ⇒ Geometric transition ⇒ Bubbles wrapped by fluxes inside the internal dimensions.

- Smooth bubbling sources: currently trying to construct
- Expectation based on earlier work:
  - backreaction will make bubbles large
  - *irrespective* of T^4 size at infinity

The big hope: Track **each and every** BH microstate from zero-gravity regime to fully-backreacted solution



- Need to build supergravity solution !
- Most generic beast: is 6D sugra enough? or one needs 10D?
- Flat space: supermaze fields decay exponentially. Universal ?

What about non-extremal (real-world) BH ?

Extremely hard to build generic microstates

– Coupled 2'nd order PDE's. No susy $\Rightarrow$ no factorization

– Numerics, multiple domains, machine learning + Santos

- No susy, no rotation $\Rightarrow$ *factorization !* Bah, Heidmann
- Schwarzschild microstates geometries ! Bah, Heidmann, Weck
- Cycles with positive or negative flux (brane-antibrane)

- No susy, anti-self-dual fluxes $\Rightarrow$ *factorization !*
- Running (Kerr-Taub) Bolt Bena. Giusto, Ruef, Warner 2008
- Non-BPS with rotation. Quadrupole moment $M_2 > 0$
  Bena, Santos, Pani, Witek; Bena, Lochet
- $M_2^{\text{Kerr}} = -\frac{J^2}{M}$. Normal spinning objects pancake $M_2 < 0$
- LIGO data: $+16.0^{+16.7}_{-13.6}$

$$\mathcal{L}_v G_0 \;=\; (\mathcal{L}_u G_0)\,(\partial_z \partial_z G_0) \;-\; (\nabla_{\vec{u}} \partial_z G_0) \cdot (\nabla_{\vec{u}} \partial_z G_0)$$

Conclusions

- Give me a lever… to solve Monge-Ampère, and I will give you the e^S horizonless geometries that replace the susy BH horizon.
- So far - big hopes, but only spikes.
- "*It is hard for you to kick against the spike*"
- Non-extremal microstates: $M_2 > 0$. Universal ?

$$\mathcal{L}_v G_0 = (\mathcal{L}_u G_0)(\partial_z \partial_z G_0) - (\nabla_{\vec{u}} \partial_z G_0) \cdot (\nabla_{\vec{u}} \partial_z G_0)$$

Conclusions

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- So far - big hopes, but only spikes.
- “*It is hard for you to kick against the spike*”
- Non-extremal microstates: $M_2 > 0$. Universal ?
- *KKLT ex nihilo* constraints (talk by Severin)
- Scale separation in AdS solutions is too small for KKLT construction to work
- Swamplanders seem to be right about that one
- What if they are right about inflation as well ?

Waaaait !

- Haven't Saclay people been arguing since 2009 that *antibranes ⇒ instabilities*
- *Yes !* But unlike de Sitter, non-extremal microstate geometries *should* have instabilities
  - JMaRT (+ bubbles) unstable Cardoso, Dias, Hovdebo, Myers
  - D1-D5: BPS left-moving open string + right-moving open string ⇒ emitted closed string
  - Instability time = Hawking Radiation of coherent state ! Chowdhury, Mathur
- Conjectured "swampland" dS instabilities are natural from a BH microscopic perspective.