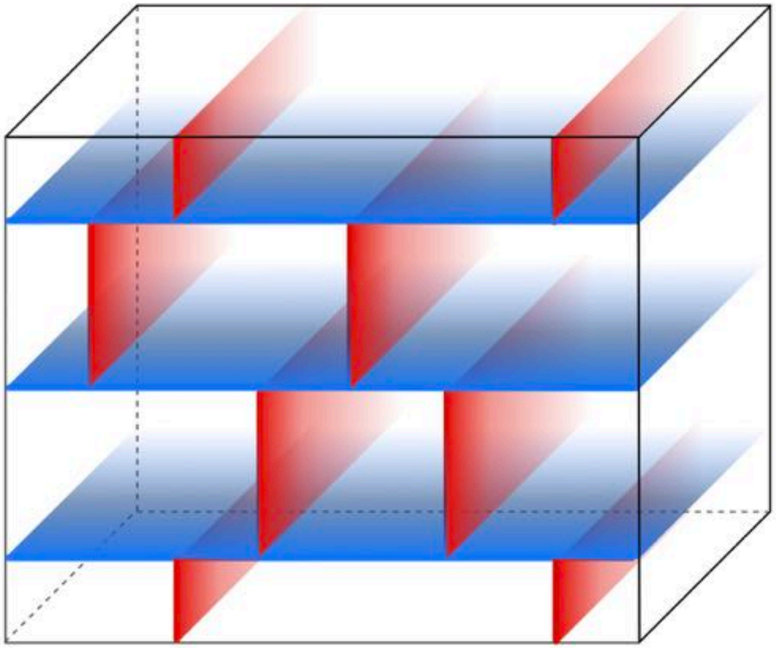
The Amazing Super-Maze

Iosif Bena

IPhT, CEA

Université Paris-Saclay



with Dimitrios Toulikas, Anthony Houppe, Yixuan Li, Nejc Čeplak, Shaun Hampton and Nick Warner

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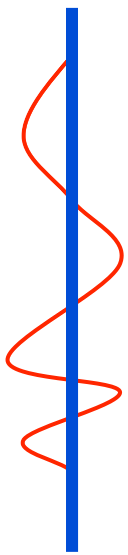
An amazing success of String Theory

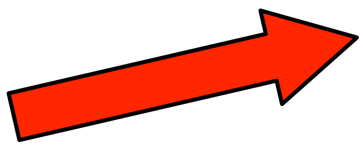
Count Black Hole Microstates (branes + strings)

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

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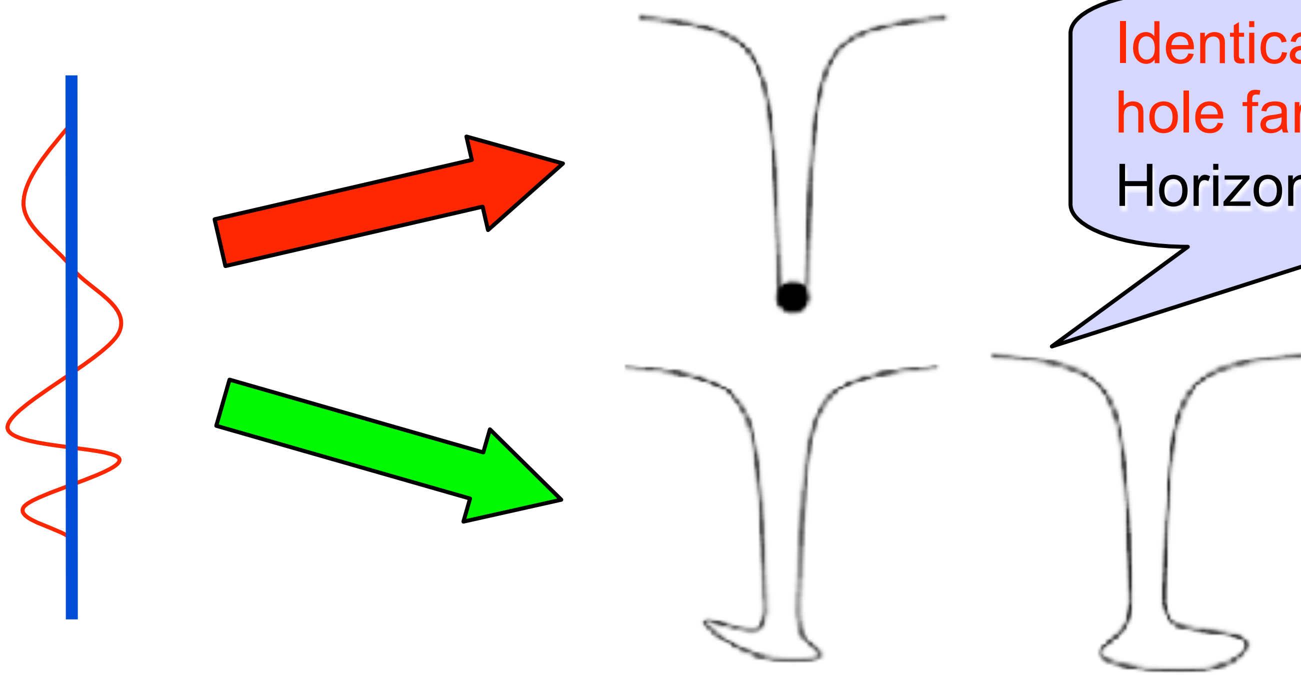


Identical to black hole far away.

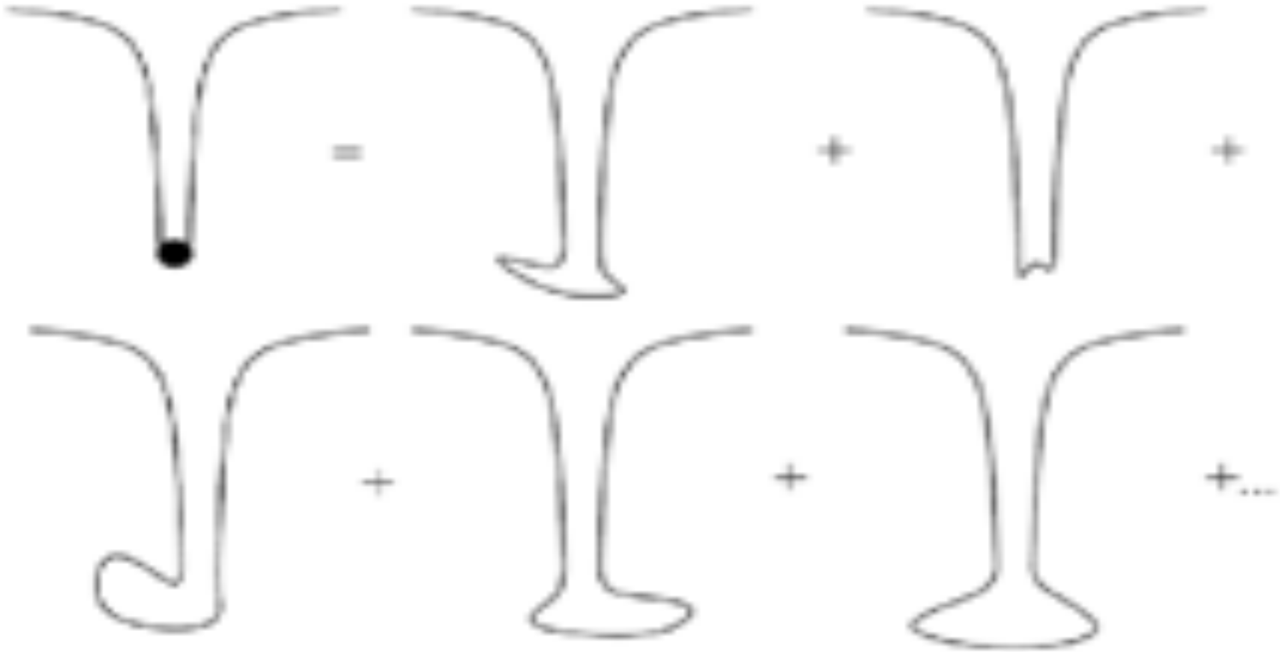
Horizon → Smooth cap

past 20 years

BIG QUESTION: Are ***all*** black hole microstates becoming geometries with no horizon ?

Black hole = ensemble of horizonless microstate configurations

Mathur 2003



(Only?) *reasonable* way to solve the Information Paradox

Mathur 2009, Almheiri, Marolf, Polchinski, Sully 2012

Other options:

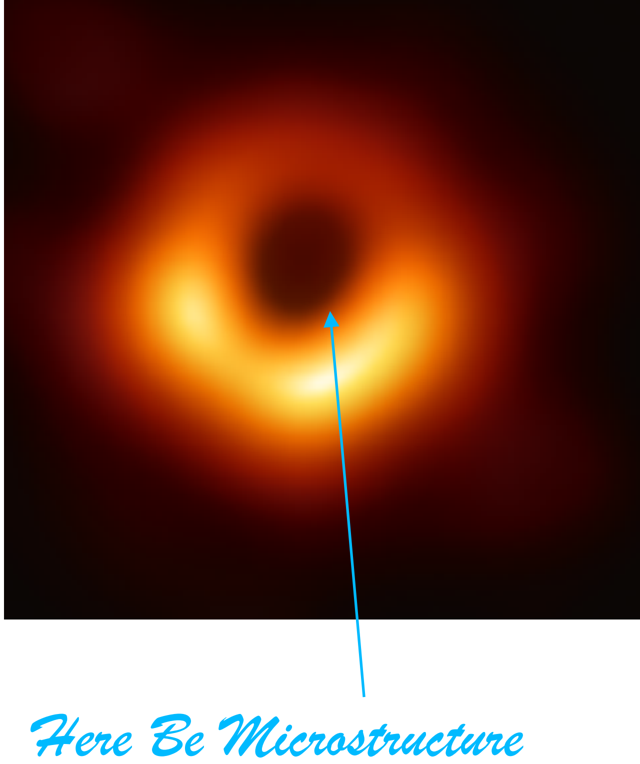
- ER=EPR, Islands $\Rightarrow$ wormholes + nonlocalities at scales M_{BH}^3

(for solar-mass BH this is 10^{80} m = $10^{53} \times$ size of observable universe)

- State-dependent operators (non-Copenhagen) Papadodimas, Raju

Structure@horizon in vogue these days (ECO)

- Gravastars
- Quark-stars
- Boson-stars
- Gas of wormholes (ER=EPR)
- Quantum Black Boxes
- BMS / Soft hair @ horizon
- Mirrors floating on Pixie Dust
- Modified gravity
- Bose-Einstein condensate of gravitons
- Infinite-density firewall hovering just above horizon



But …

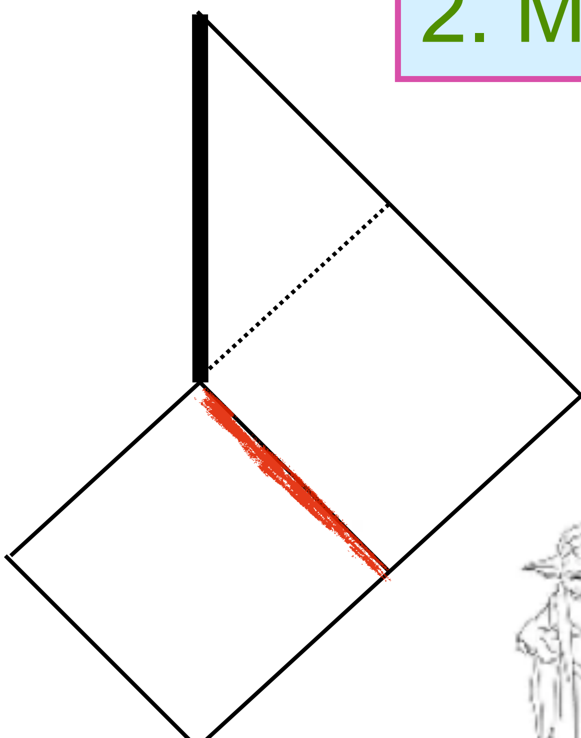
1. Growth with G_N $\leftrightarrow$ BH size for all masses

Horowitz

- Normal objects shrink;   BH horizon grows
- **microstate geometries** have BH size for all masses
- D-branes = solitons, $m \sim 1/g_s$ lighter as $G_N = g_s^2$ increases

To build structure@horizon, non-perturbative degrees of freedom you must use !

2. Mechanism not to fall into BH



GR Dogma:

Thou shalt not put anything at the horizon !!!

- Null ➞ speed of light.
- Normal stuff falls in
- Cannot hide behind *quantum*

If support mechanism have you not, wrong physics are you doing

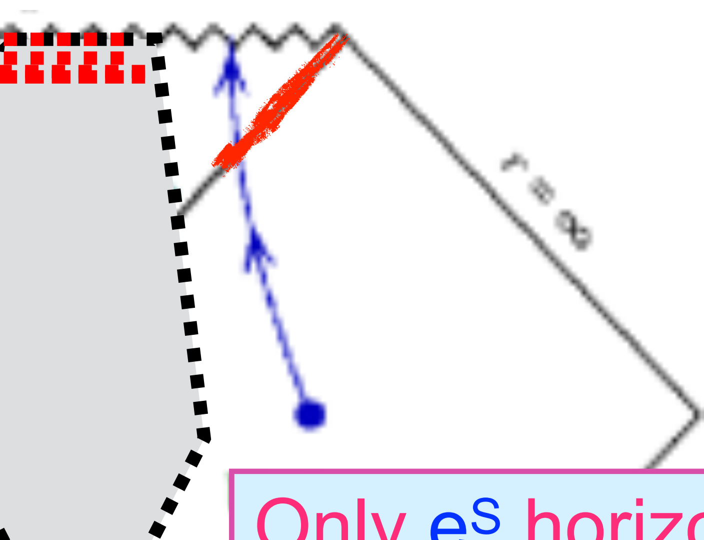
Quantum Coyote Principle

GRAVITY DOES NOT WORK `TILL YOU LOOK DOWN ….

Such is the fate of
Firewalls, quantum black boxes, Mirrors & their brothers

3. Avoid forming a horizon

– Collapsing shell forms horizon @ low curvature
  Oppenheimer and Snyder (1939)
– By the time shell becomes curved-enough for quantum effects to become important, horizon in causal past (180 hours for TON618 BH)



Backwards in time - illegal !

BH has e^S microstates with no horizon

Small tunneling probability = e^{-S}

Shell tunnels with probability **ONE** !!!

Kraus, Mathur; Bena, Mayerson, Puhm, Vercnocke

Only e^S horizon-sized microstates can do it !

Black hole entropy the structure must have

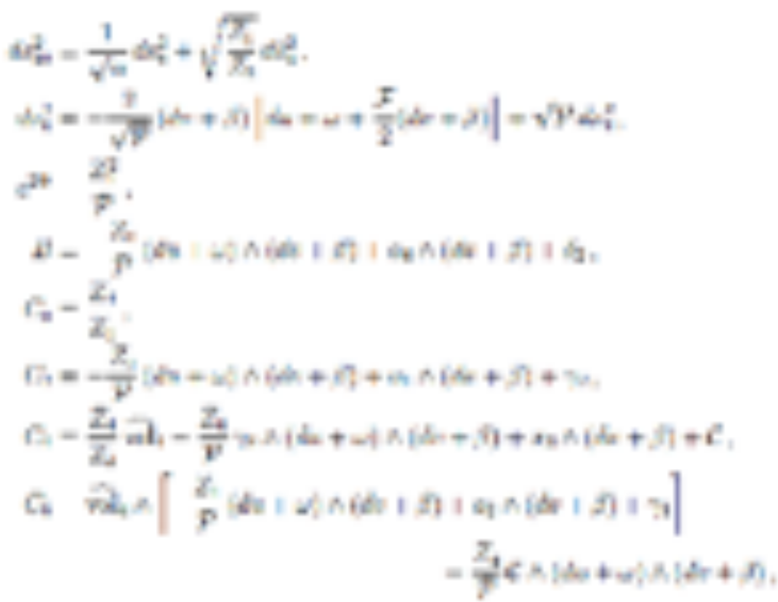
Rules out gravastars & almost everything else

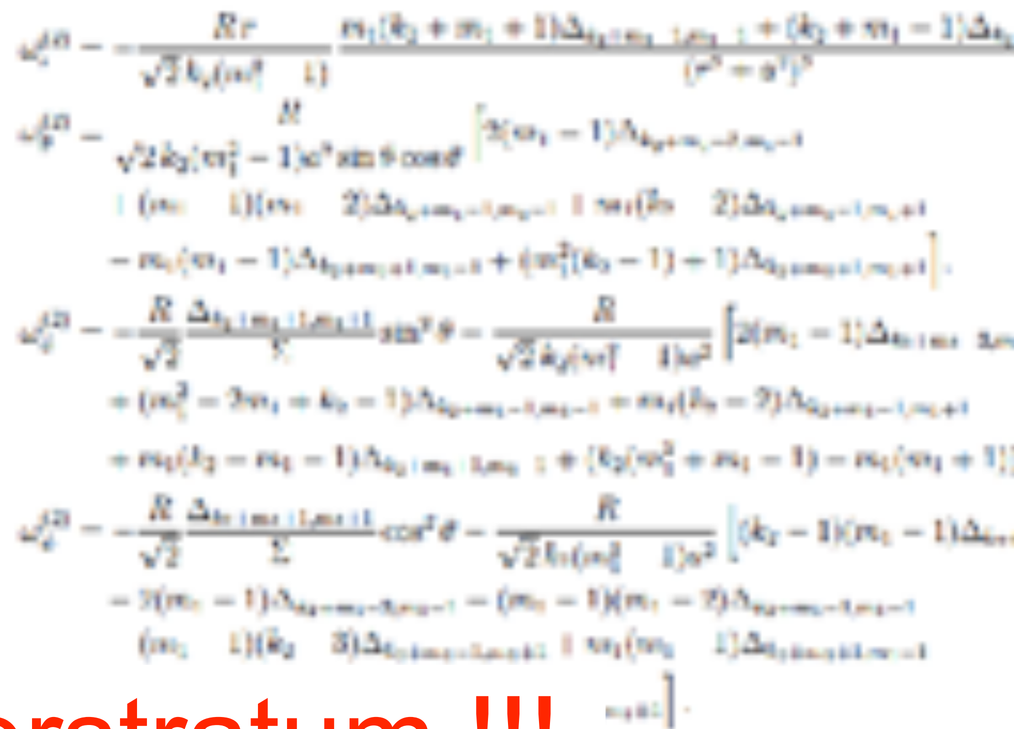
Supersymmetric Microstate Geometries:

- Only construction with 3 properties - 2.5 rather 😀
- Largest family of solutions known to mankind

Arbitrary fns. of **3** variables: ∞ X ∞ X ∞ parameters !

Cohomogeneity-**5** !

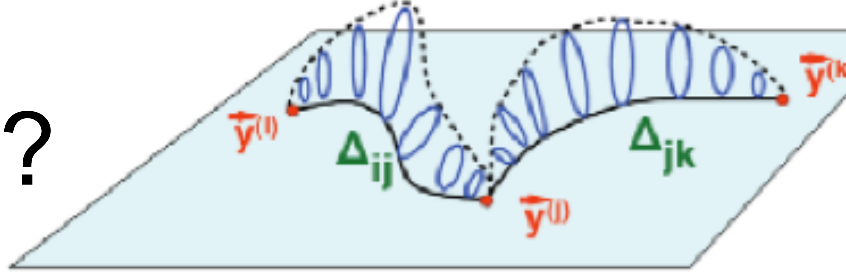




Habemus Superstratum !!!

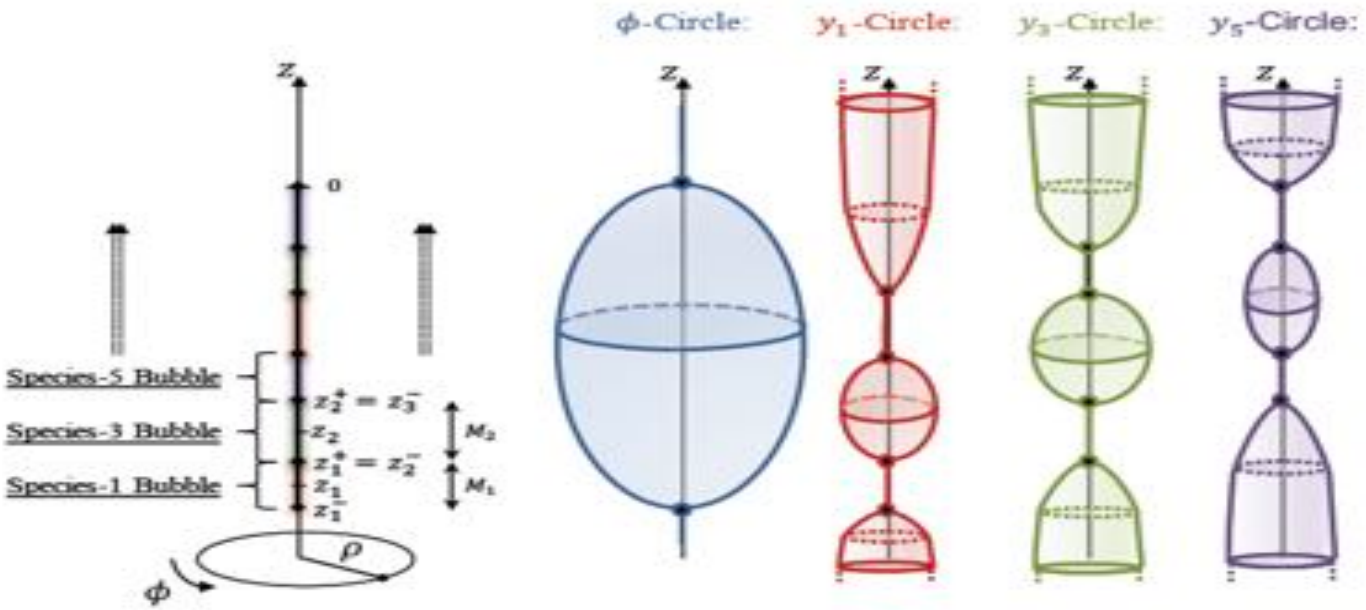
Many features of typical microstates: mass gap = $\frac{1}{N_1 N_5}$

Why not collapsing ?



- 5(+6)d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller ⟶ increases energy
  - bubbling = only mechanism to avoid collapse Gibbons, Warner

Works for nonextremal black holes as well Bah, Heidmann



First Schwarzschild microstates !!!
Bah, Heidmann, Weck ‘22

20 years of microstate geometries

- Huge number of smooth horizonless solutions
  - Bubbling geometries, superstrata
  - Largest known class of solutions to Einstein's equations
  - Many features of typical microstates (mass gap)
  - $S \sim (Q_1 Q_5)^{1/2} (Q_p)^{1/4} < S_{BH} \sim (Q_1 Q_5 Q_p)^{1/2}$ Mayerson, Shigemori *'20*
- Link with D1-D5 states that count BH entropy ?
  - Only known for a few solutions
  - *Needs Elvish Medicine* (precision holography)
  - momentum modes giving D1-D5 BH entropy are quantized in units of $1/R_y N_1 N_5$ - *fractionated*
  - Duals of states with fractionated momentum carriers are very hard to build in supergravity

    Bena, Martinec, Turton, Warner *'16*; Shigemori *'21, '22*

The Painful Reality

- We have not succeeded to track *typical* D1-D5 Strominger-Vafa microstates from the zero-gravity regime to the finite-gravity regime where BH exists
- *Fundamental* limitation or *technical* problem ? we can only build superstrata as fibrations on $\mathbb{R}^4$ base
- Bubbling solutions - more general hyper-Kähler base
  - but no holographic dual
  - superstrata-building techniques fail
  - most generic base - not even hyper-Kähler
  - fractionated modes - missing magical ingredient ?

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

Romanian proverb

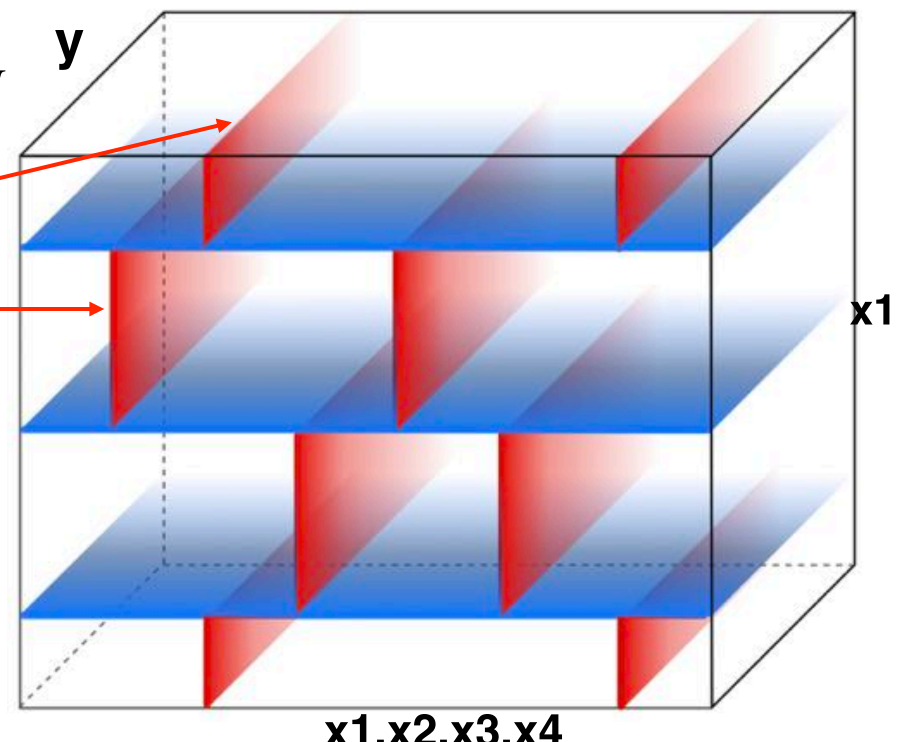
Instead of D1-D5 look at D2-D4 (or F1-NS5 in type IIA)

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

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

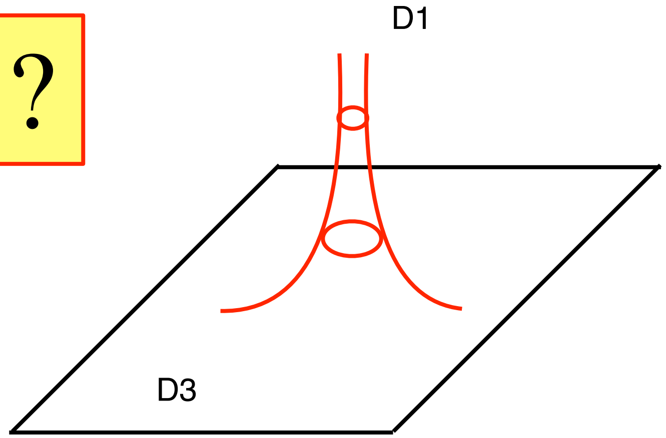


M2 along y,11
M5 along y,1234
P along y

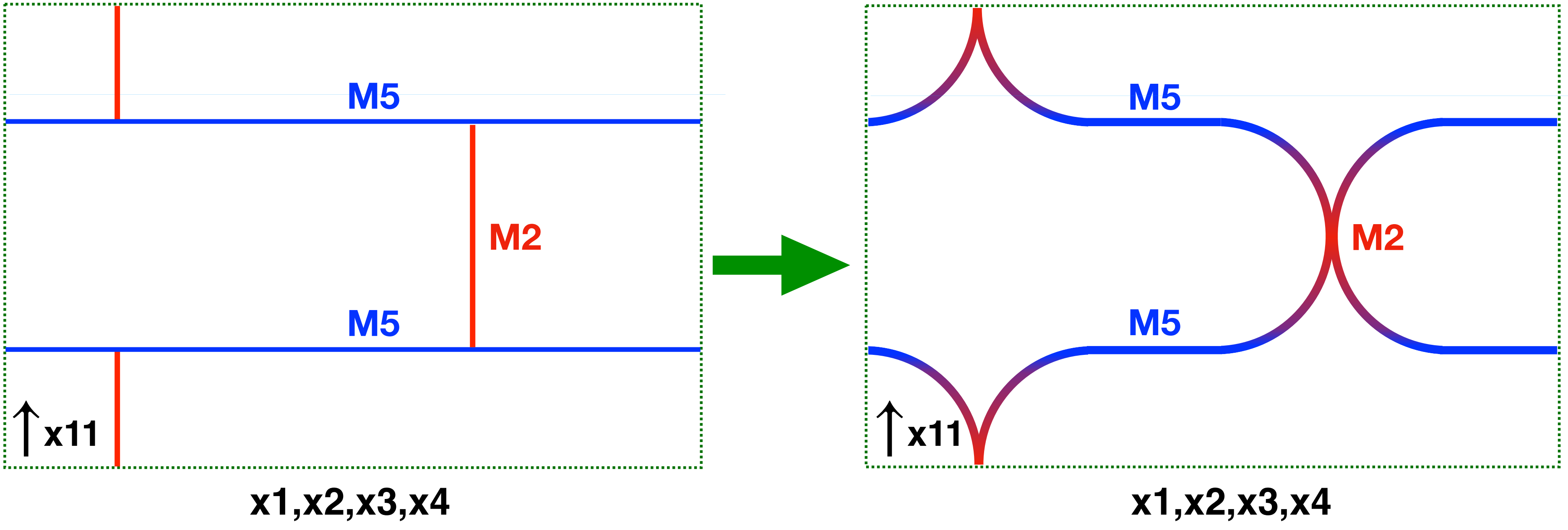
D1-D5: fractionated P
F1-NS5: fractionated F1

zero-coupling picture

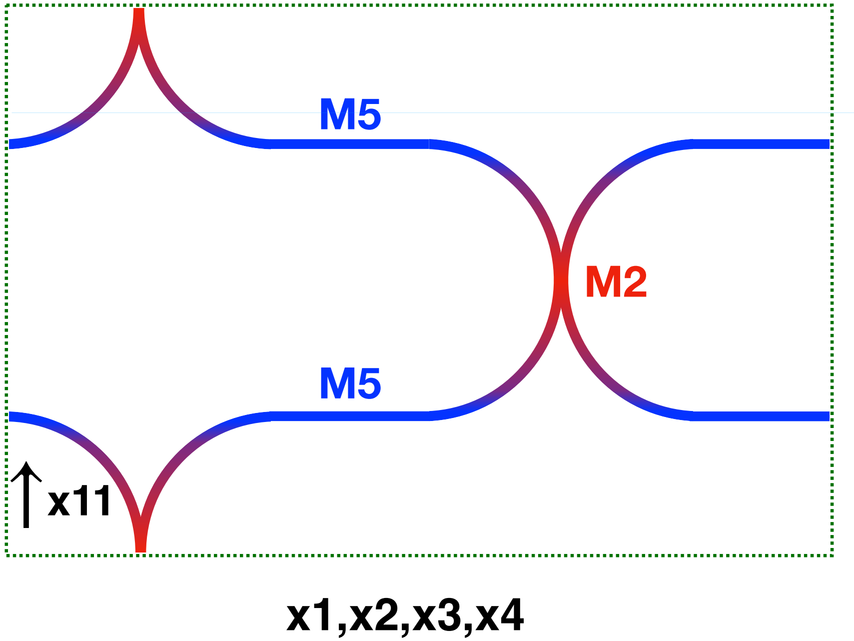
What about finite coupling ?

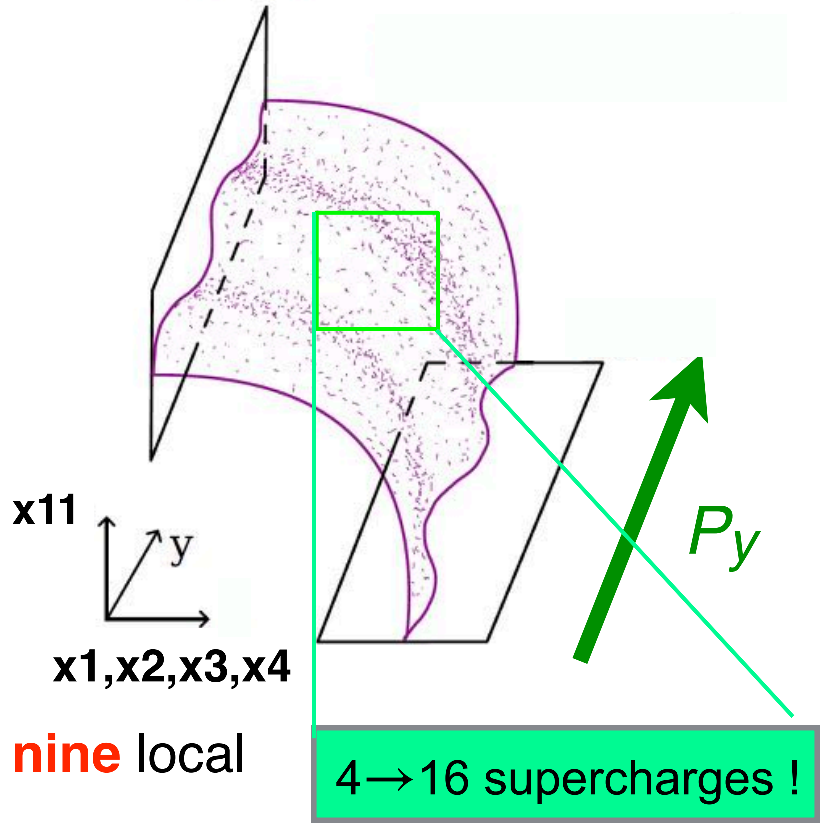


- Reminder:
  Callan-Maldacena spike formed by D1 pulling on an orthogonal D3
- M2 branes also pull on the M5 branes



Except that the spike is a *furrow* carrying momentum waves along y



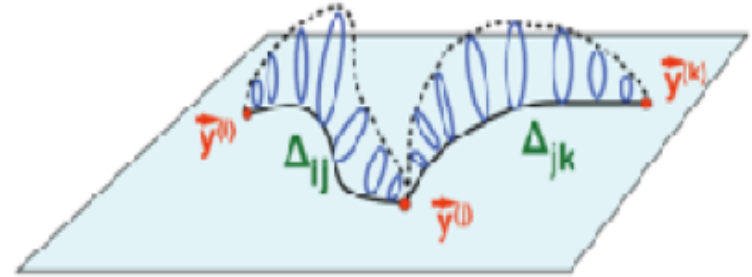


Zoom in on the furrow carrying momentum: **nine** local brane charges: **$M2_{x11,y}$ $M5_{y,x1,x2,x3,x4}$ P_y**

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

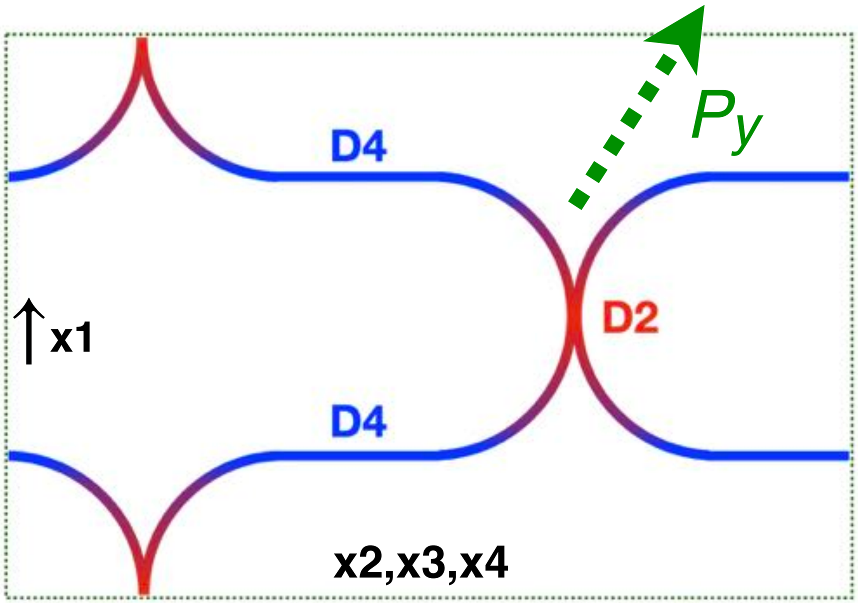
Smoking gun of smooth horizonless solutions

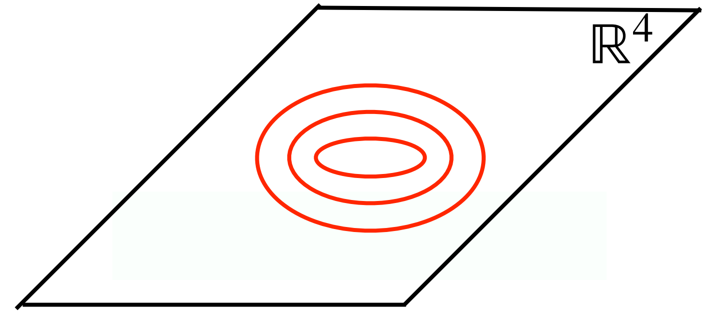
Some history



- First microstate geometries
  - Bubbling solutions with GH centers. Bena, Warner '06
  - Smooth in all duality frames. Horizonless
  - 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
- Pattern: **smooth horizonless sols ⇔ brane configurations: 16 susy locally, 4 globally**

Super-Maze entropy





spherically symmetric in $\mathbb{R}^4$ (x5,x6,x7,x8)
same spacetime $SO(4)$ symmetry as BH

$SO(4)$ invariant solutions:

momentum carried by waves on fractionated strings (inside T^4) =

bosonic d.o.f. : $S_{bosonic} = 2\pi\sqrt{\frac{4}{6}N_1 N_5 N_p}$

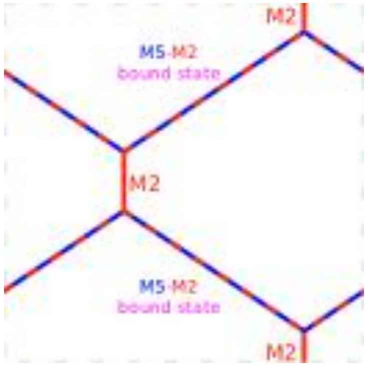
+ 2 *fermionic* d.o.f. preserving $SO(4) \Rightarrow S_{SO(4)\ \text{invariant}} = 2\pi\sqrt{\frac{5}{6}N_1 N_5 N_p}$

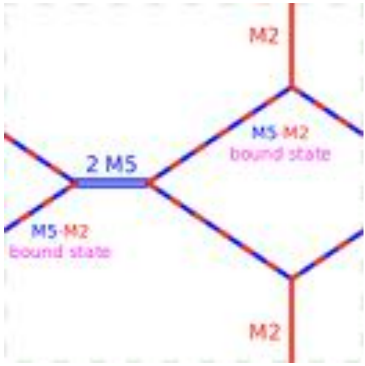
Remaining 2 *fermionic* d.o.f. break $SO(4) \Rightarrow S_{SO(4)\ \text{breaking}} = 2\pi\sqrt{\frac{1}{6}N_1 N_5 N_p}$

Confirms expectations from Bena, Shigemori, Warner 2014

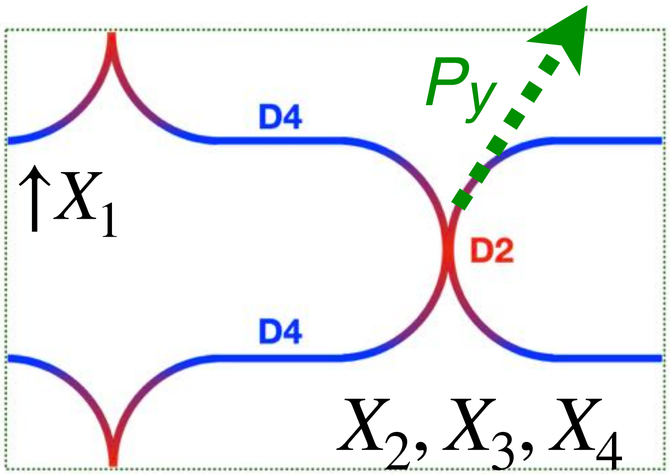
How will the $SO(4)$-invariant solution look like ?

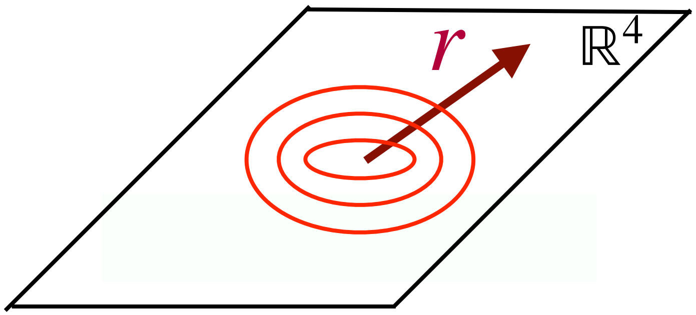
- **Two-charge solutions:**
- Monge-Ampère equation
- solution at least *cohomog-3*
- smeared on $T^3 \Rightarrow$ string web:





- Singular brane sources $\Rightarrow$ solution exists (singular)
  Lunin 07
- **Three-charge solutions** with $\mathrm{D2}_{y1}+\mathrm{D4}_{y234}+\mathrm{P}_y$
  at least *cohomogeneity-4* (X_1, X_2, r, y)





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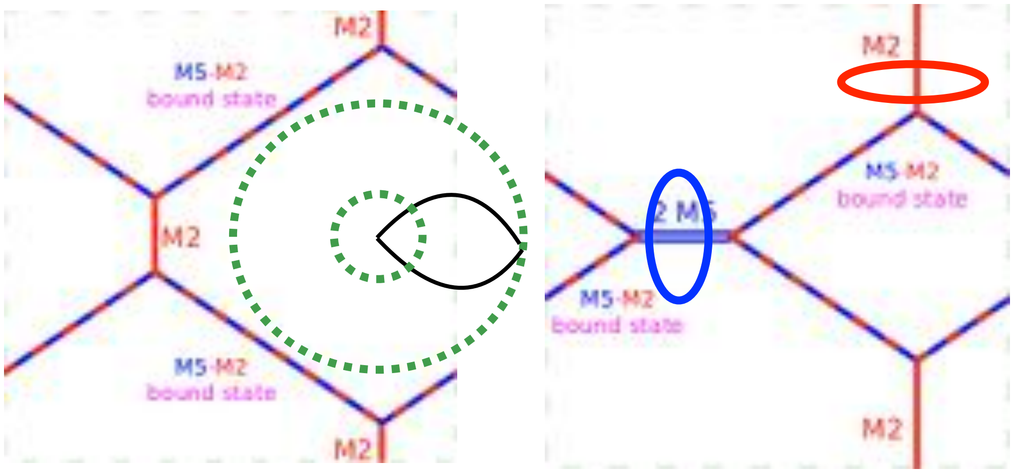


- *16-susy locally ⇒ no horizon*
- Branes wrapping compact contractible cycles ⇒ Geometric transition ⇒ Bubbles wrapped by fluxes on internal dimensions.
- Smooth bubbling sources: can we construct it ?
- can we show in principle that the solution exists ?
- Expectation based on earlier work:
  - backreaction will make bubbles large
  - *irrespective* of T^4 size at infinity

Holography of $SO(4)$-invariant solutions

- Microstate geometry differs from BH by T^4 KK modes:
- Asympt. $\mathbb{R}^{4,1} \times S^1 \times T^4$: *exponentially-decay*
- Asympt. $AdS_3 \times S^3 \times T^4$: *power-law decay*
  - *High-dimension operators:* $\Delta^2 \sim Q_5 n_{\text{mode}}^2 / L_1^2$
  - Official '97 Dogma: *not surviving in decoupling limit*
  - *Νέα θεολογία:* anything asymptotic to $AdS_3 \text{ x } S^3 \text{ x } T^4$ ∈ *CFT* & can tunnel to anything else
  - Operator dimension depends on T^4 moduli. SUSY?
  - Is operator visible at free-orbifold point ?
  - Can CFT distinguish different supermaze solutions ?

How will the generic solution look like ?

- Generic microstates will contain

  $SO(4)$ breaking modes + $SO(4)$ invariant (T^4 modes)

2-charge systems revisited:

- when both T^4 and $SO(4)$ breaking modes are present
- $S_{\text{total}} = 2\pi\sqrt{2\,N_1 N_5}$
- Smearing on T^4 does not lose info. Can get S_{total} from T^4-invariant solutions Kanitscheider, Taylor, Skenderis

- If only T^4 dependent modes present:
- $S_{SO(4)\ \text{invariant}} = 2\pi\sqrt{N_1 N_5}$
- smearing on T^4 erases information $\Rightarrow$ one obtains the naïve D1-D5 solution: singular, small horizon

How will the generic solution look like ?

3-charge story ?

- $SO(4)$-breaking strands: (+,+),(-,-),(+,-),(-,+)
- T^4-dependent strands: $(\dot{a}b + \dot{b}a), \dot{a}a, \dot{b}b, (\dot{a}b - \dot{b}a) = (00)$
- Superstrata = 6D supergravity solutions smeared on T^4
  - When $SO(4)$-breaking (++) strands are present, superstrata can capture T^4 strands: (00)
  - When no (++) strands are present, superstrata collapse into naïve solution with a horizon

We get horizons only when smearing too much

- Q1: Could the presence of $SO(4)$-breaking modes in generic supermaze allow T^4 smearing without info loss ?
- Q2: Would T^4-dependent supermaze information be lost upon smearing, even when $SO(4)$-breaking modes exist ?

How will the generic solution look like ?

Big fat 3-charge generic beast ?

Combination of $SO(4)$-breaking modes and T^4-dependent modes

Themelia:

General idea:

Global charges

dipole charges = ***Glue***

needed for 16 susy

Object	Coefficient	
F1(y)	α_1	x_1 y_1 z_1
NS5(y1234)	α_2	
P(y)	α_3	
KKm(y1234;ψ)	α_4	
D2(y1)	α_9	u_1
D4(y234)	$\alpha_{10} = -\alpha_9$	
D0	α_{13}	v_1
D4(1234)	$\alpha_{14} = -\alpha_{13}$	
F1(1)	α_{17}	w_1
P(1)	$\alpha_{18} = -\alpha_{17}$	

Object	Coefficient	
F1(ψ)	α_5	x_2 y_2 z_2
NS5(ψ1234)	α_6	
P(ψ)	α_7	
KKm(ψ1234;y)	α_8	
D2(ψ1)	α_{11}	u_2
D4(ψ234)	$\alpha_{12} = -\alpha_{11}$	
D2(yψ)	α_{15}	v_2
D6(yψ1234)	$\alpha_{16} = -\alpha_{15}$	
NS5(yψ234)	α_{19}	w_2
KKm(yψ234; 1)	$\alpha_{20} = -\alpha_{19}$	

$$u_1 + i u_2 = s_1 s_2\, e^{i\varphi_1}\,,$$

$$v_1 + i v_2 = s_2 c_2\, e^{i(\varphi_1-\varphi_2-\varphi_3)}\big(e^{-2i\varphi_4} - c_1\big)$$

$$w_1 + i w_2 = s_1 c_2\, e^{i\varphi_2}\,, \quad x_1 + i x_2 = c_1 e^{i\varphi_3}$$

$$y_1 + i y_2 = e^{i(2\varphi_2+\varphi_3)}\,\big(c_1 c_2^2 + s_2^2\, e^{-2i\varphi_4}\big)\,,$$

$$z_1 + i z_2 = e^{i(2\varphi_1-\varphi_3)}\,\big(c_2^2\, e^{2i\varphi_4} + c_1 s_2^2\big)\,,$$

Most generic beast with 16 supercharges locally

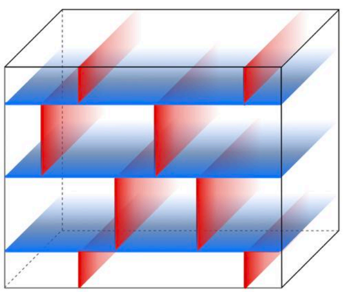
The big hope: Track **each and every** BH microstate from zero-gravity regime to fully-backreacted solution

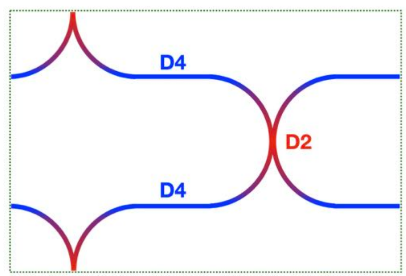
DVV microstates
$S = S_{BH}$

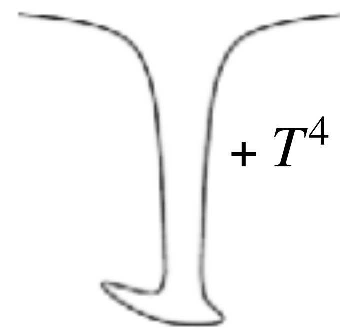
SUPERMAZE
branes pull & merge
16 susy locally !

New Microstate Geometries
$S = S_{BH}$

Effective coupling (g_s)





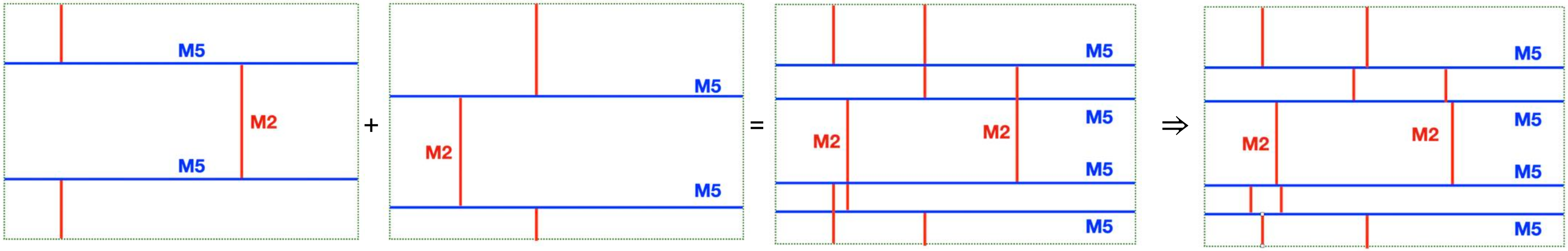


+ T^4 KK modes

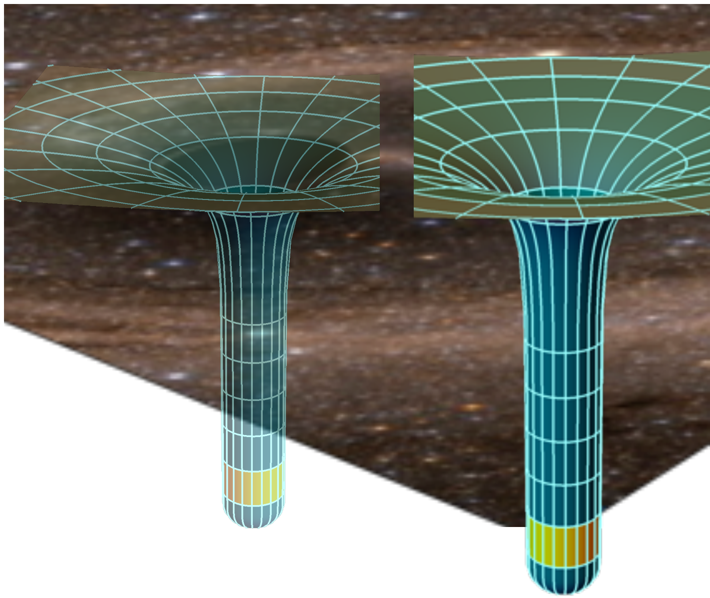
- Need to build supergravity solution !
- Precision holography for supermaze with T^4-dependent modes ?
  $$\langle \Psi_{\text{supermaze}} \,|\, \mathcal{O}_{T^4-\text{dependent}} \,|\, \Psi_{\text{supermaze}} \rangle \neq 0$$
- Most generic beast: is 6D sugra enough? or one needs10D?
- Flat space: supermaze fields decay exponentially. Universal ?

How to black holes merge ?

- GR Dogma: *horizons join*, *new horizon forms*, *irreversible*
- *Νέα θεολογία : microstates* - KK modes/internal directions



- Some of these modes shed off
- KK charge = 0 ⇒ gravity
- KK charge ≠ 0 ⇒Stand. Model
- *Electromagnetic counterpart ?*
- *Experimental constraints?*
- *Calculate for 2-charge*



Stay tuned for the supergravity solution and the new holographic insights