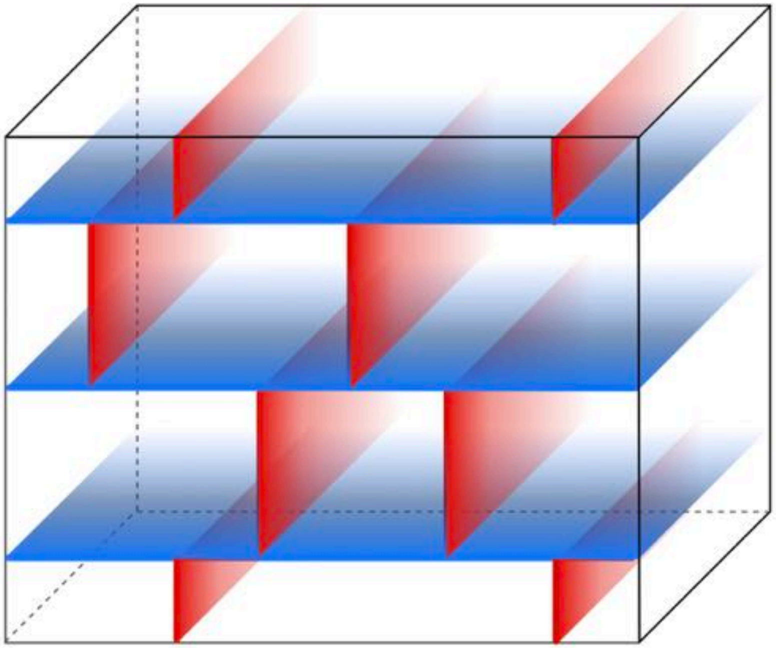
The amazing Super-Maze

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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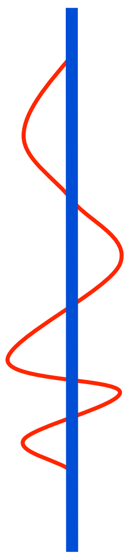
An amazing success of String Theory

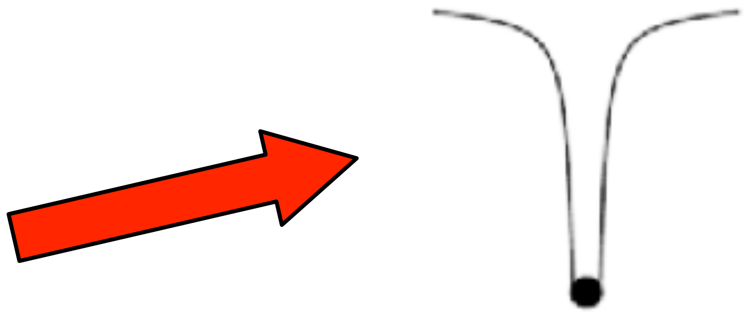
Count Black Hole Microstates (branes + strings)

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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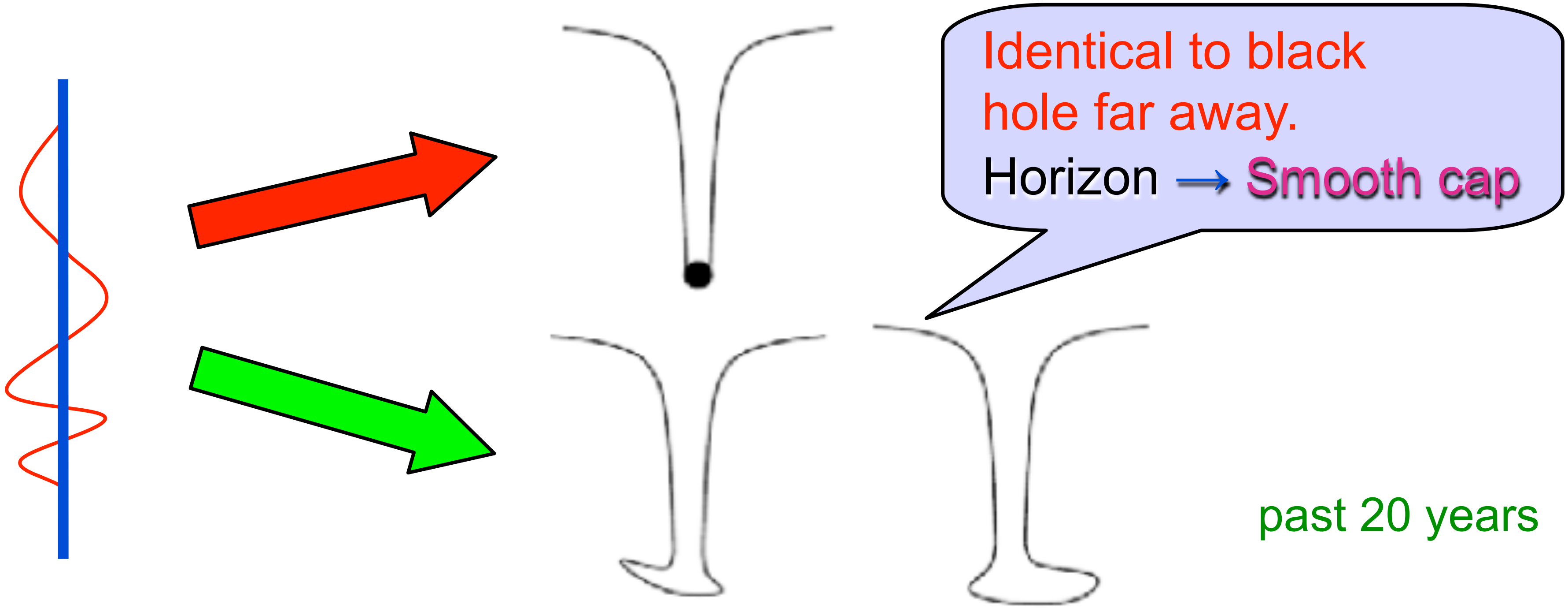


The big hope: Track **each and every** BH microstate from zero-gravity regime to fully-backreacted solution

20 years of microstate geometries

Nick's talk

- Huge number of smooth horizonless solutions
  - Bubbling geometries, superstrata
  - Largest class of solutions to Einstein's equations ever
  - 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*
  - 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.

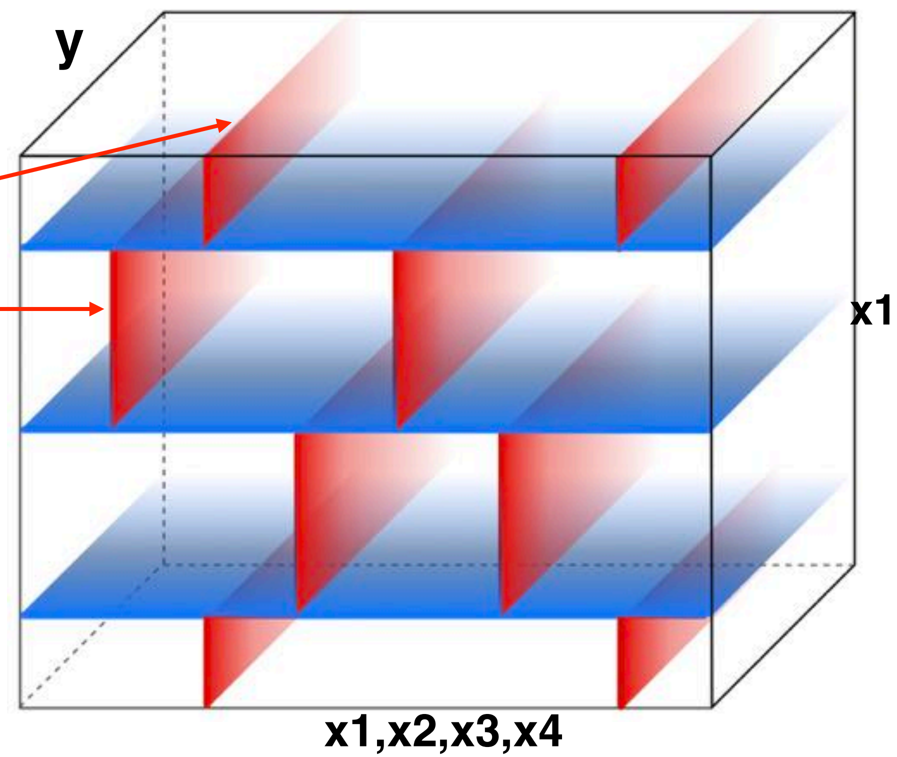
Dijkgraaf, Verlinde, Verlinde

- 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

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

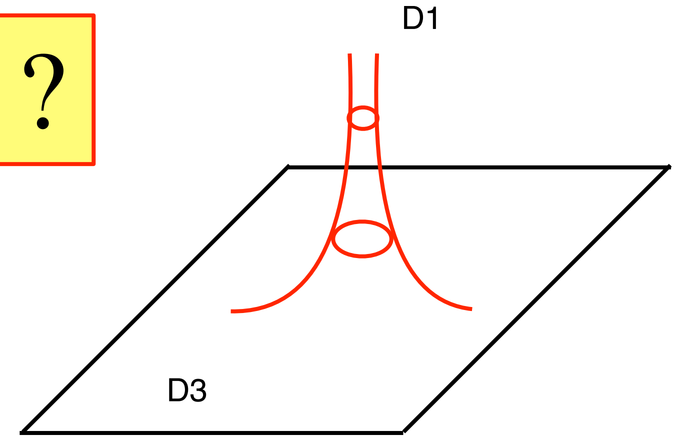
M2 along y,11
M5 along y,1234
P along y

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

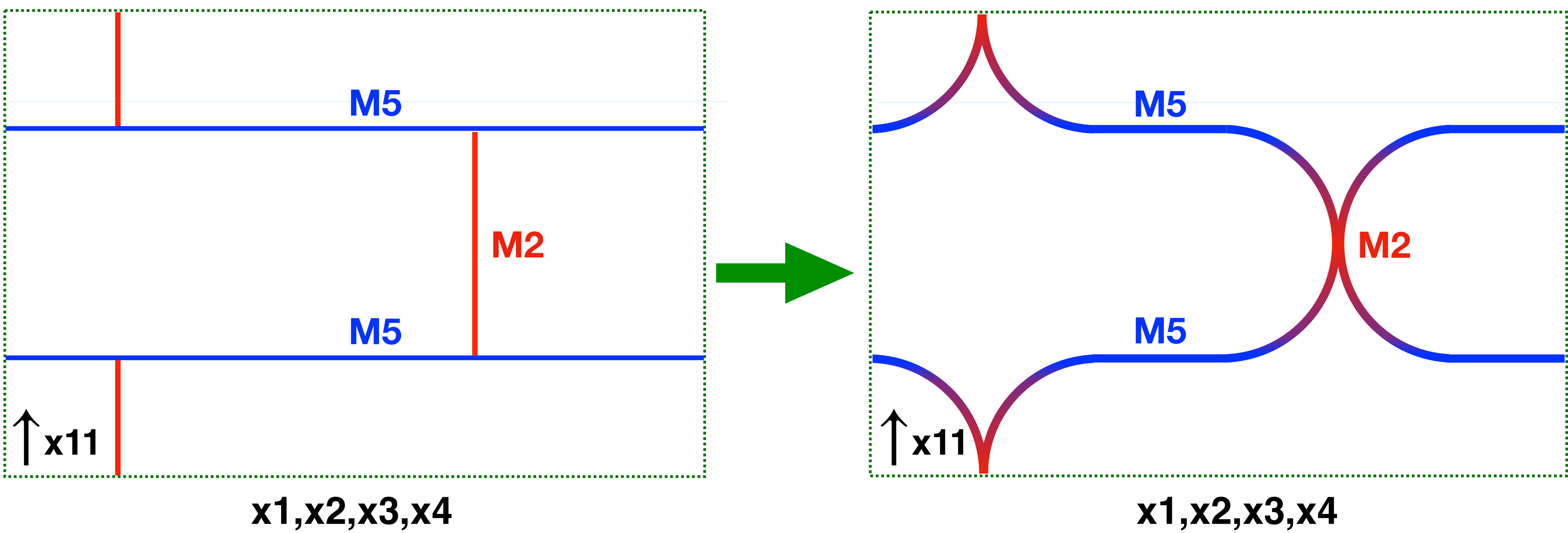


zero-coupling picture

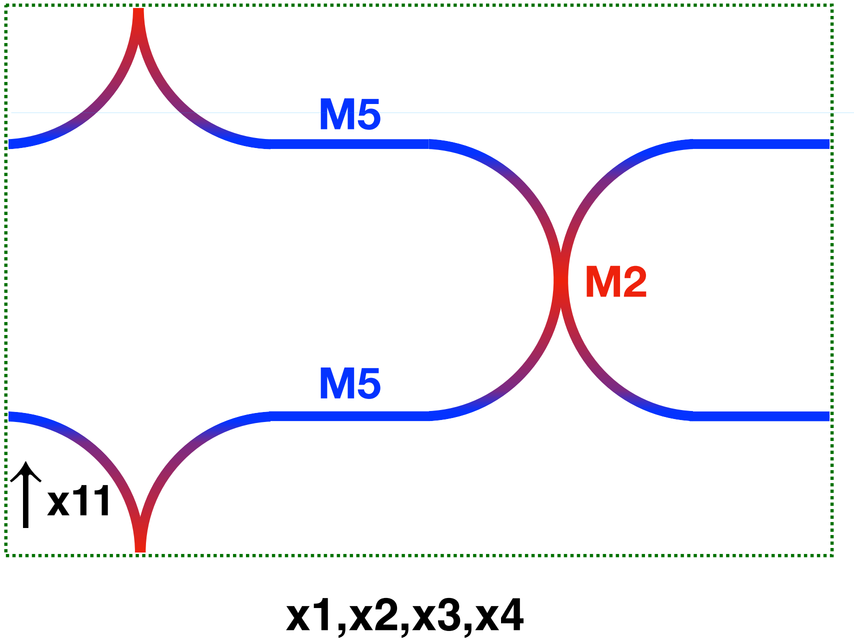
What about finite coupling ?

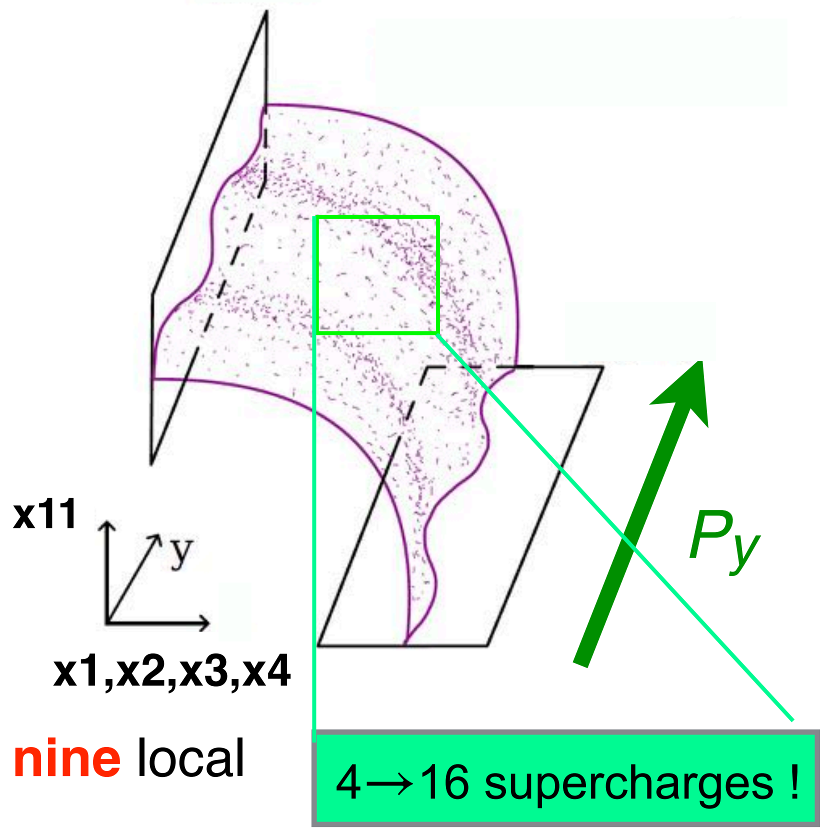


- Reminder:
  Callan-Maldacena spike formed by D1 pulling on an orthogonal D3
- M2 branes also pull on the M5 branes



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



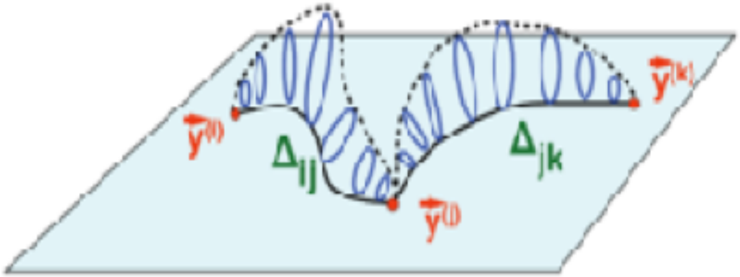


Zoom in on the furrow carrying momentum: **nine** local brane charges: **$M2_{x11,y}$** **$M5_{y,x1,x2,x3,x4}$** **P_y**

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

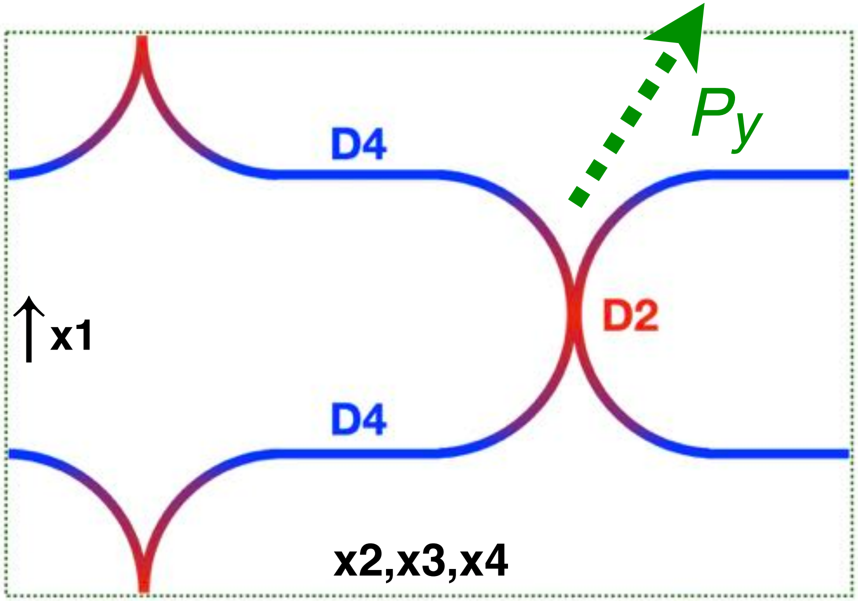
Smoking gun of smooth horizonless solutions

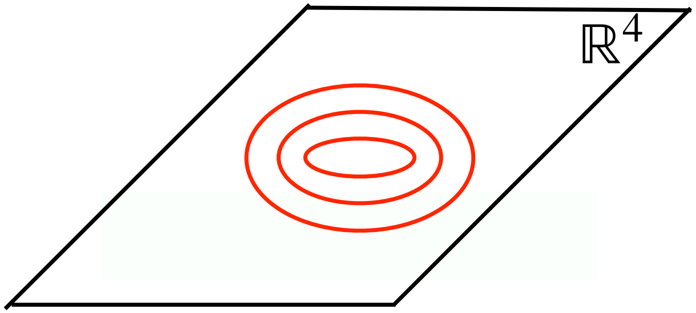
Some history



- 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
- 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 T⁴) =

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

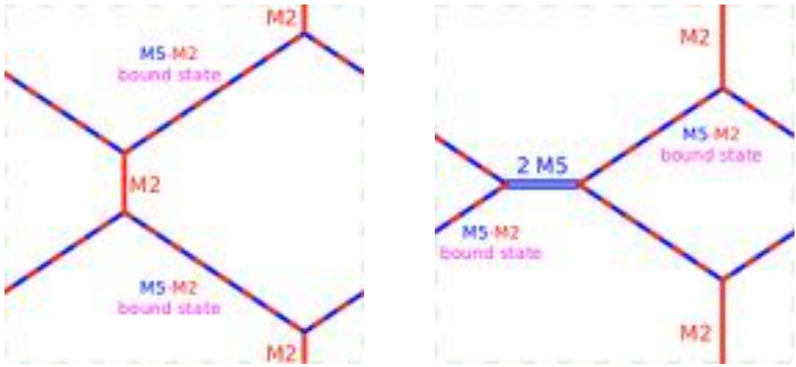
+ 2 *fermionic* d.o.f. preserving $SO(4) \Rightarrow S_{SO(4)\ \text{invariant}} = 2\pi\sqrt{\frac{5}{6}N_1 N_5 N_p}$

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)
- *16-susy locally $\Rightarrow$ no horizon*
- Branes wrapping compact contractible cycles $\Rightarrow$
  Geometric transition $\Rightarrow$ Bubbles wrapped by fluxes on internal dimensions.
  - Smooth bubble sources: can we solve ?
  - can we show solution exists ?

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

- Expectation based on earlier work:
  - backreaction will make bubbles large, *irrespective* of T^4 size at infinity
- 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*
  - *Νέος Θεολόγος: anything asymptotic to* $AdS_3 \text{ x } S^3 \text{ x } T^4$ $\in$ *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 **+** T^4 dependent modes

2-charge systems:

- 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 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

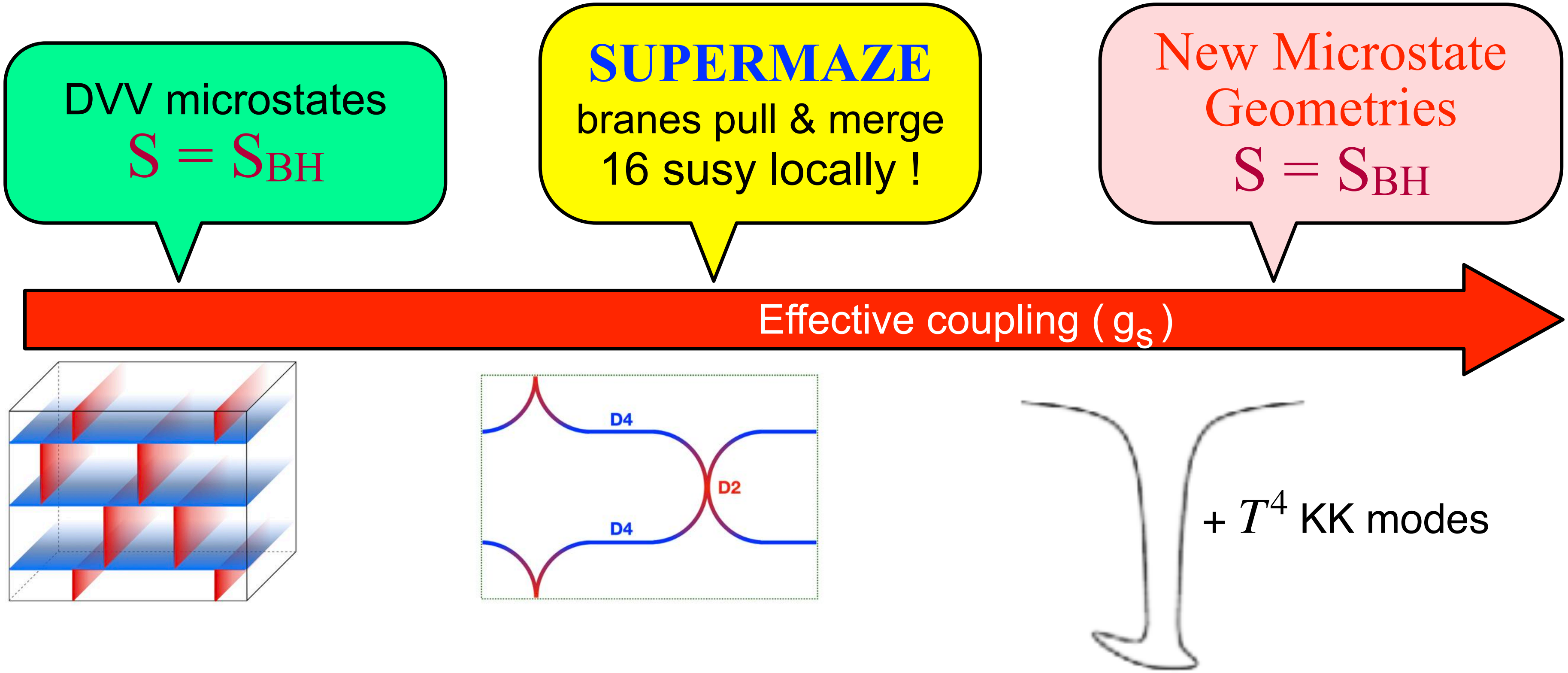
dipole charges = ***Glue***

needed for 16 susy

Object	Coefficient		Object	Coefficient	
F1(y)	α_1	x_1	F1(ψ)	α_5	x_2
NS5(y1234)	α_2	y_1	NS5(ψ1234)	α_6	y_2
P(y)	α_3	z_1	P(ψ)	α_7	z_2
KKm(y1234;ψ)	α_4		KKm(ψ1234;y)	α_8	
D2(y1)	α_9	u_1	D2(ψ1)	α_{11}	u_2
D4(y234)	$\alpha_{10} = -\alpha_9$		D4(ψ234)	$\alpha_{12} = -\alpha_{11}$	
D0	α_{13}	v_1	D2(yψ)	α_{15}	v_2
D4(1234)	$\alpha_{14} = -\alpha_{13}$		D6(yψ1234)	$\alpha_{16} = -\alpha_{15}$	
F1(1)	α_{17}	w_1	NS5(yψ234)	α_{19}	w_2
P(1)	$\alpha_{18} = -\alpha_{17}$		KKm(yψ234; 1)	$\alpha_{20} = -\alpha_{19}$	

$$u_1 + i u_2 = s_1 s_2 \, e^{i\varphi_1} \,,$$
$$v_1 + i v_2 = s_2 c_2 \, e^{i(\varphi_1 - \varphi_2 - \varphi_3)} (e^{-2i\varphi_4} - c_1)$$
$$w_1 + i w_2 = s_1 c_2 \, e^{i\varphi_2} \,, \quad x_1 + i x_2 = c_1 e^{i\varphi_3}$$
$$y_1 + i y_2 = e^{i(2\varphi_2 + \varphi_3)} \, (c_1 c_2^2 + s_2^2 \, e^{-2i\varphi_4}) \,,$$
$$z_1 + i z_2 = e^{i(2\varphi_1 - \varphi_3)} \, (c_2^2 \, e^{2i\varphi_4} + c_1 s_2^2) \,,$$

Most generic beast with 16 supercharges locally



- 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 ?

Generic microstates merging

- Both have KK modes on the internal direction
- Some of these modes may be shed off
- KK modes expected decay to Standard-Model fields
- BH merger should have *Electromagnetic counterpart*
- *Experimental constraints?*
- *Calculate for 2-charge*