Black Holes, Black Rings and their Microstates

Trous Noirs, Anneaux Noirs, et leur Microétats

Iosif Bena

IPhT, CEA Saclay

HABILITATION A DIRIGER DES RECHERCHES

Black Holes

Exist in nature

Information Paradox

Quantum Mechanics ⟷ General Relativity

Sharp Contrast

Black hole thermodynamics $\Rightarrow$ $S = \frac{1}{4}\frac{A}{\ell_p^2}$ ⇨ $e^{10^{90}}$ states

Black hole uniqueness ⇨ 1 state

QUESTION: What are the states of the black hole ?

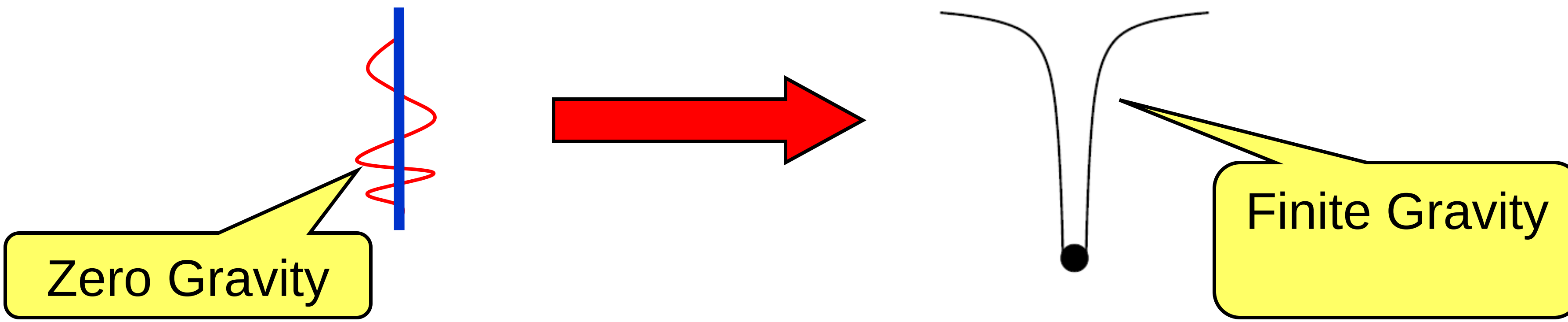
Strominger and Vafa (1996)

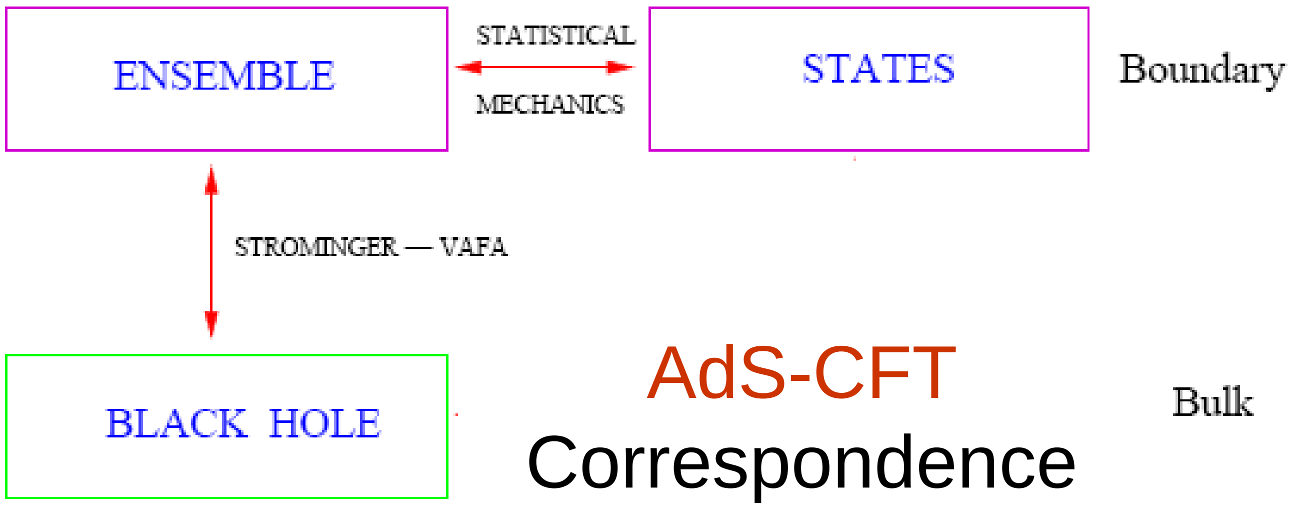
+1000 other articles

Count BH Microstates

Match B.H. entropy !!!

2 ways to understand:





AdS-CFT
Correspondence

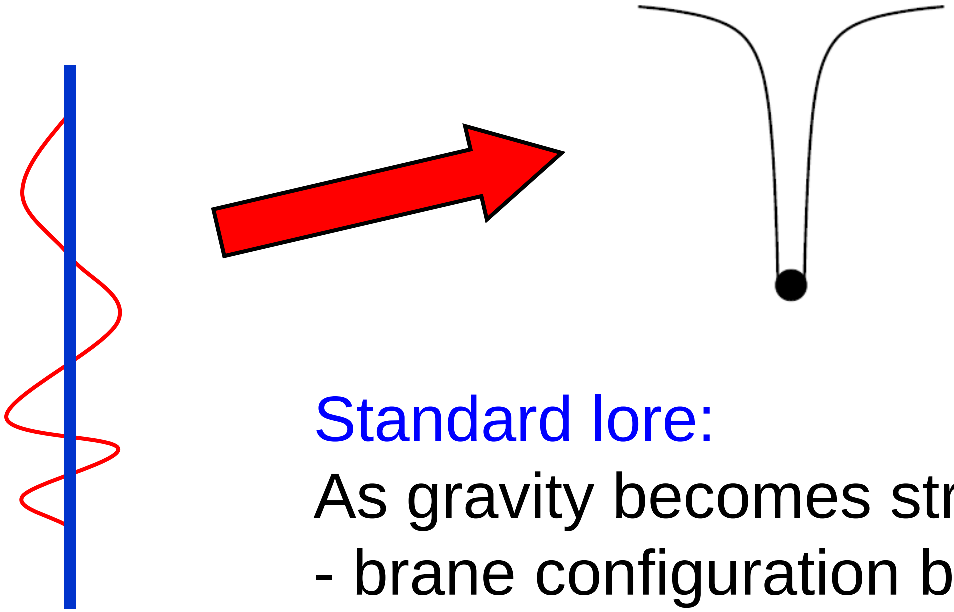
Strominger and Vafa (1996):

Count Black Hole Microstates (branes + strings)

Correctly match BH entropy !!!

Zero Gravity

Black hole regime of parameters:



Standard lore:

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

Susskind
Horowitz, Polchinski
Damour, Veneziano

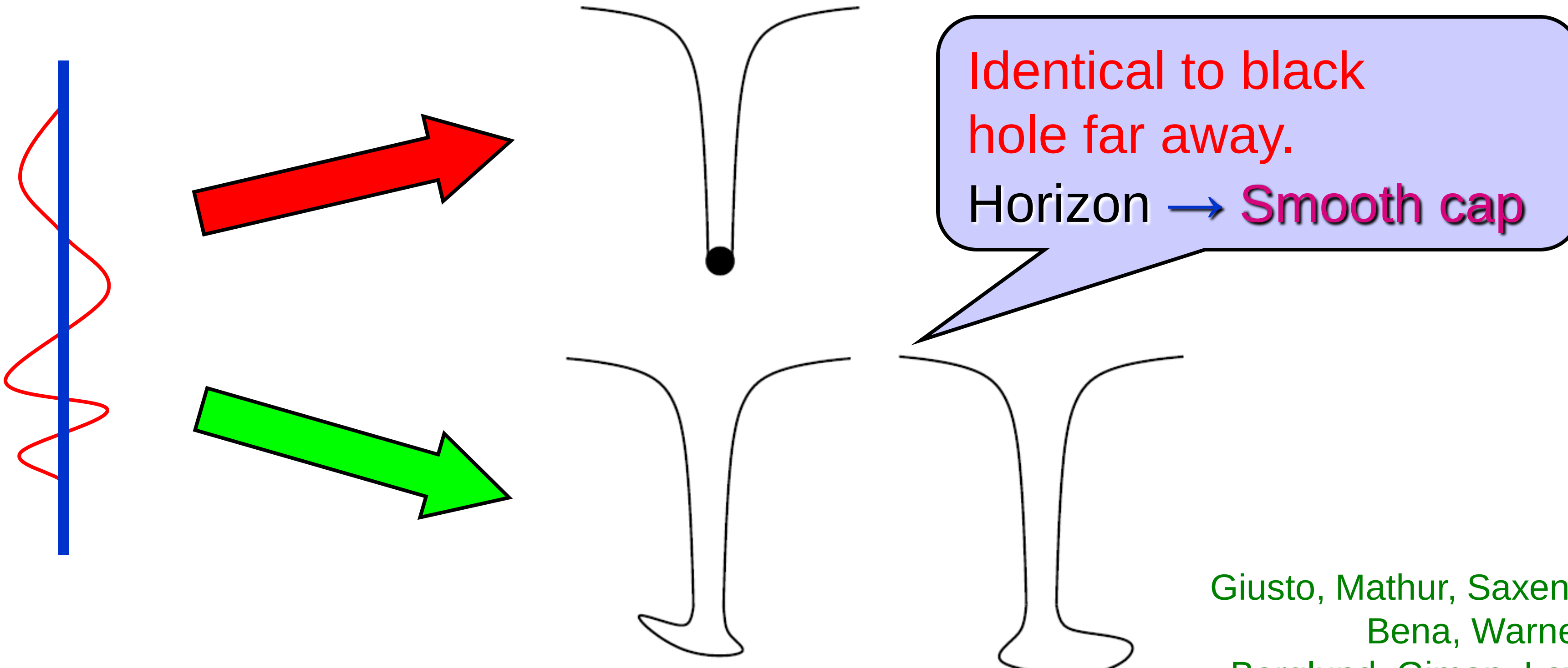
Strominger and Vafa (1996):

Count Black Hole Microstates (branes + strings)

Correctly match BH entropy !!!

Zero Gravity

Black hole regime of parameters:

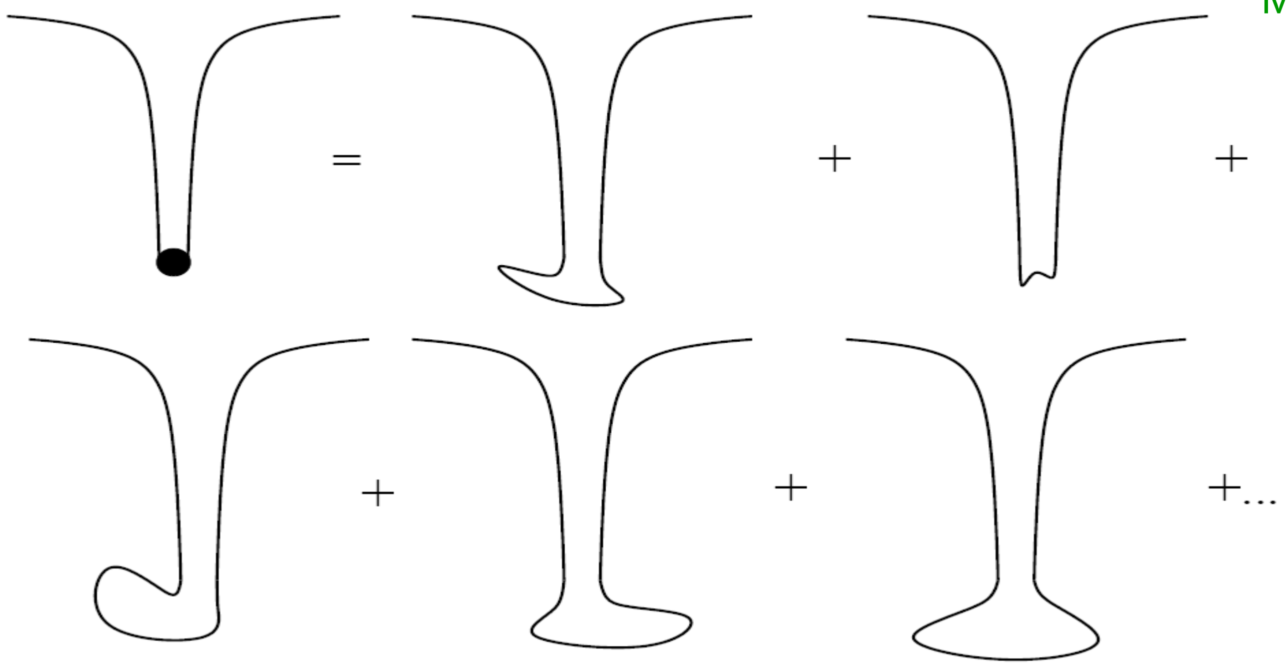


Giusto, Mathur, Saxena
Bena, Warner
Berglund, Gimon, Levi

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

Black hole solution $\overset{?}{=}$ thermodynamic description of horizonless microstates

Mathur & friends



Analogy with ideal gas

Thermodynamics

(Air = ideal gas)

$P V = n R T$

$dE = T\, dS + P\, dV$

Statistical Physics

(Air -- molecules)

e^S microstates

typical

atypical

Thermodynamics

Black Hole Solution

Statistical Physics

Microstate geometries

Long distance physics

Gravitational lensing

Physics at horizon

Information loss

A few corollaries

new low-mass
degrees of freedom

- **Thermodynamics (LQFT)** breaks down at horizon. Nonlocal effects take over.

- No spacetime inside black holes. **Quantum superposition** of microstates geometries.

Can be proved by rigorous calculations:

1. Build most generic microstates + Count
2. Use *AdS*-CFT

∞ parameters
black hole charges

Question

- Can a large blob of stuff replace BH ?

Question

- Can a large blob of stuff replace BH ?
- Sure !!!
- *AdS*-QCD
  - Plasma ball dual to BH in the bulk
- Recover all BH properties
  - Absorption of incoming stuff
  - Hawking radiation
- Key ingredient:
  large number of degrees of freedom (N^2)

Word of caution

- To replace classical BH by BH-sized object
  - Gravastar
  - Quark-star
  - Object in LQG
  - you name it …

satisfy very stringent test: Horowitz

Same growth with G_N !!!

- BH size grows with G_N
- Size of objects in other theories becomes smaller

- BH microstate geometries pass this test
- Highly nontrivial mechanism Bena, Kraus

Microstate geometries

M2	0	1	2				
M2	0			3	4		
M2	0					5	6

3-charge 5D black hole Strominger, Vafa; BMPV

$$S_{BMPV} = 2\pi\sqrt{N_1 N_5 N_P - J^2}$$

$$ds^2 = Z_1^{-2/3} Z_2^{-2/3} Z_3^{-2/3} (dt + \vec{k})^2 + Z_1^{1/3} Z_2^{1/3} Z_3^{1/3} dx_{\mathbb{R}^4}^2 + ds_{T^6}^2$$

$$F_{120i} = \partial_i Z_1^{-1} \qquad F_{340i} = \partial_i Z_2^{-1} \qquad F_{560i} = \partial_i Z_3^{-1} \qquad \text{electric}$$

Want solutions with same asymptotics, but no horizon

Microstate geometries

M2	0	1	2					
M2	0			3	4			
M2	0					5	6	
M5	0			3	4	5	6	θ
M5	0	1	2			5	6	θ
M5	0	1	2	3	4			θ

T^6 (directions 1–6) $\mathbb{R}^4$

CLOSED CURVE (θ)

$$ds^2 = Z_1^{-2/3} Z_2^{-2/3} Z_3^{-2/3} (dt + \vec{k})^2 + Z_1^{1/3} Z_2^{1/3} Z_3^{1/3} dx^2_{\mathbb{R}^4} + ds^2_{T^6}$$

$F_{120i} = \partial_i Z_1^{-1}$ $\quad F_{340i} = \partial_i Z_2^{-1}$ $\quad F_{560i} = \partial_i Z_3^{-1}$ $\quad$ electric

$F_{12ij} = G^1_{ij}$ $\quad F_{56ij} = G^2_{ij}$ $\quad F_{56ij} = G^3_{ij}$ $\quad$ magnetic

Solution depends on G^1 G^2 G^3 Z_1 Z_2 Z_3 $\vec{k}$

Bena, Warner
Gutowski, Reall

Microstate geometries

Linear system
4 layers:

Bena, Warner

$\mathbb{R}^4$ base (4D Hyper Kahler)

$$*G^I = G^I$$

$$d * dZ_1 = G^2 \wedge G^3$$

$$d\vec{k} + *d\vec{k} = G^1 Z_1 + G^2 Z_2 + G^3 Z_3$$

Charge coming from fluxes

Focus on Gibbons-Hawking (Taub-NUT) base:

$$ds^2 = V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2$$

$$\nabla \times \vec{A} = \nabla V$$

$V = \frac{1}{r}$ $\mathbb{R}^4$

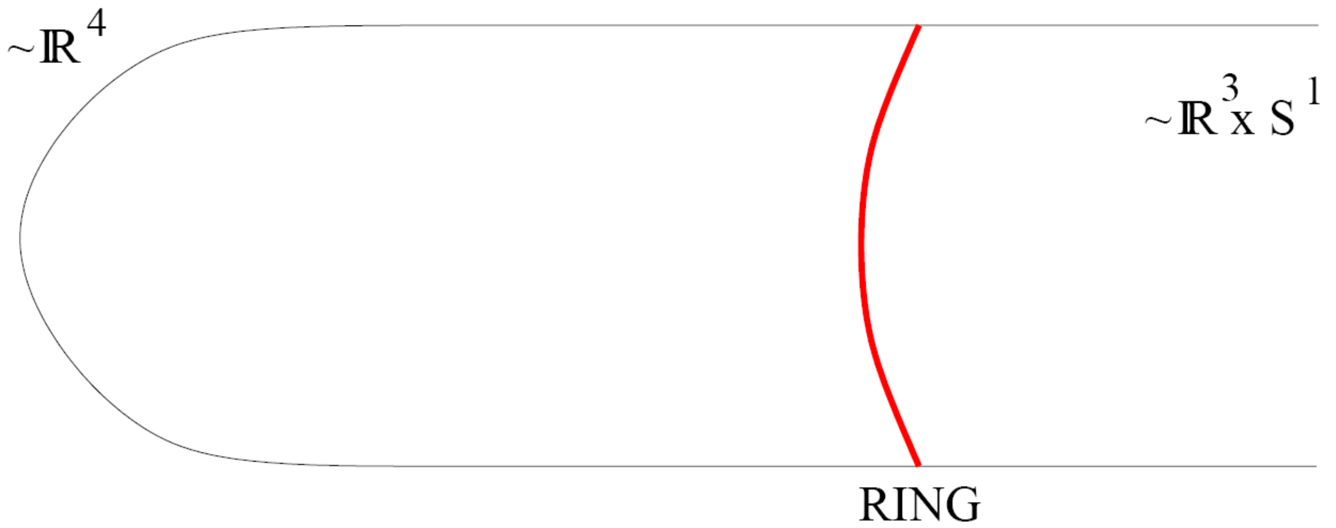
$V = 1 + \frac{1}{r}$ Taub-NUT

8 harmonic functions

Gauntlett, Gutowski,
Bena, Kraus, Warner

Examples: Black Ring in Taub-NUT

Elvang, Emparan, Mateos, Reall; Bena, Kraus, Warner; Gaiotto, Strominger, Yin



$$S = \pi\sqrt{2n_1n_2\bar{N}_1\bar{N}_2 + 2n_1n_3\bar{N}_1\bar{N}_3 + 2n_2n_3\bar{N}_2\bar{N}_3 - n_1^2\bar{N}_1^2 - n_2^2\bar{N}_2^2 - n_3^2\bar{N}_3^2 - 4n_1n_2n_3J_T}$$

4D BH: D2 charges $\bar{N}_1$ $\bar{N}_2$ $\bar{N}_3$, D4 charges n_1 n_2 n_3 and D0 charge J_T

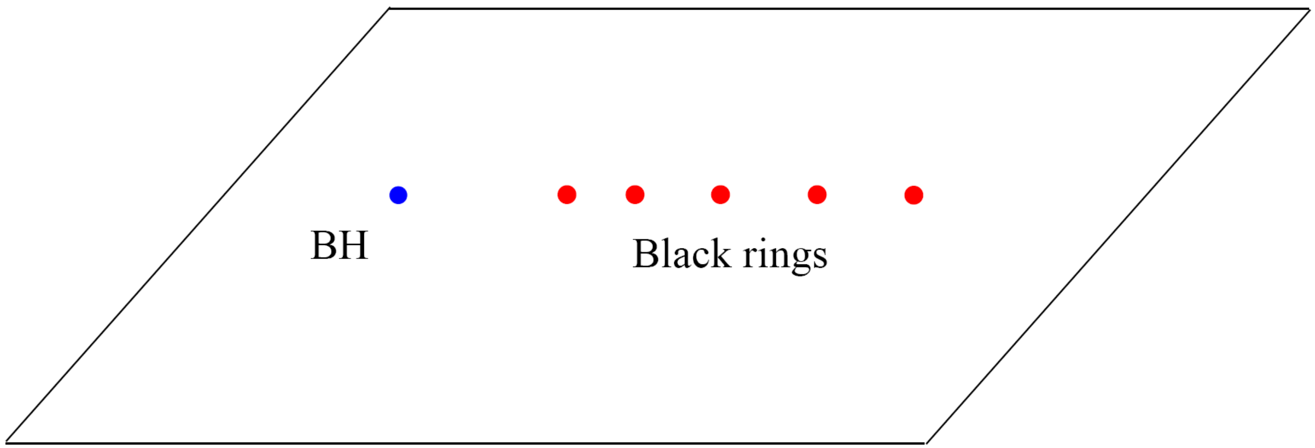
Entropy given by $E_{7(7)}$ quartic invariant Bena, Kraus; Kallosh, Kol

Descends to 4D two-centered solution Denef, Bates, Moore

Examples: Multiple Black Rings

Gauntlett, Gutowski

- 5D BH on tip of Taub-NUT ~ 4D BH with D6 charge
- Black ring with BH in the middle ~ 2-centered 4D BH
- 5 black rings + BH ~ 6-centered 4D BH

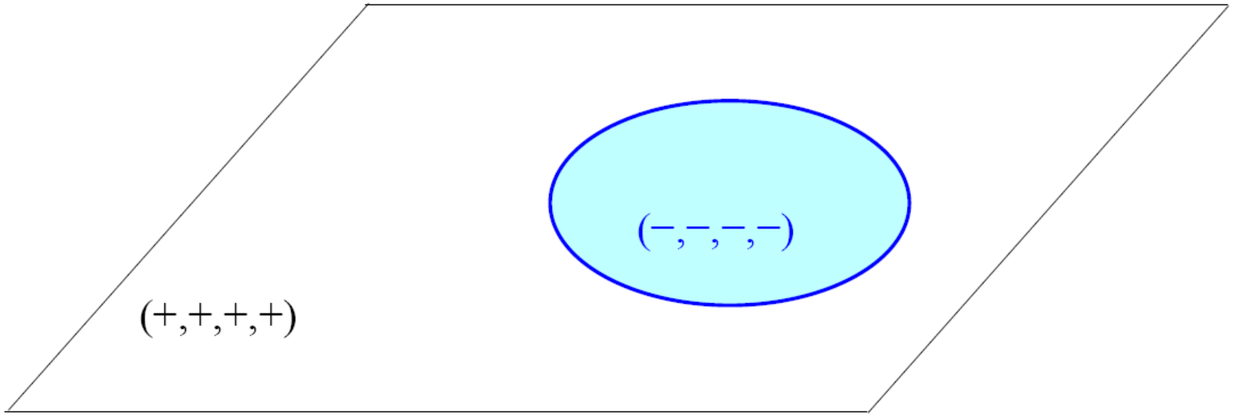


- 4D BH with D6 charge ~ 5D black hole
- 4D BH with no D6 charge ~ 5D black ring
- 5D: ring supported by angular momentum
- 4D: multicenter configuration supported by ***E*** x ***B***

Microstate geometries

$$ds^2 = V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2$$

$$V = \frac{1}{r} - \frac{Q}{|\vec{r} - \vec{a}|} + \frac{Q}{|\vec{r} - \vec{b}|}$$



- Signature of base changes from $(+,+,+,+)$ to $(-,-,-,-)$
- Z_i blow up and change sign at interface:

$$d * d\, Z_1 = G^2 \wedge G^3 \qquad \Rightarrow \qquad Z_i \sim \frac{1}{V}(\ldots)$$

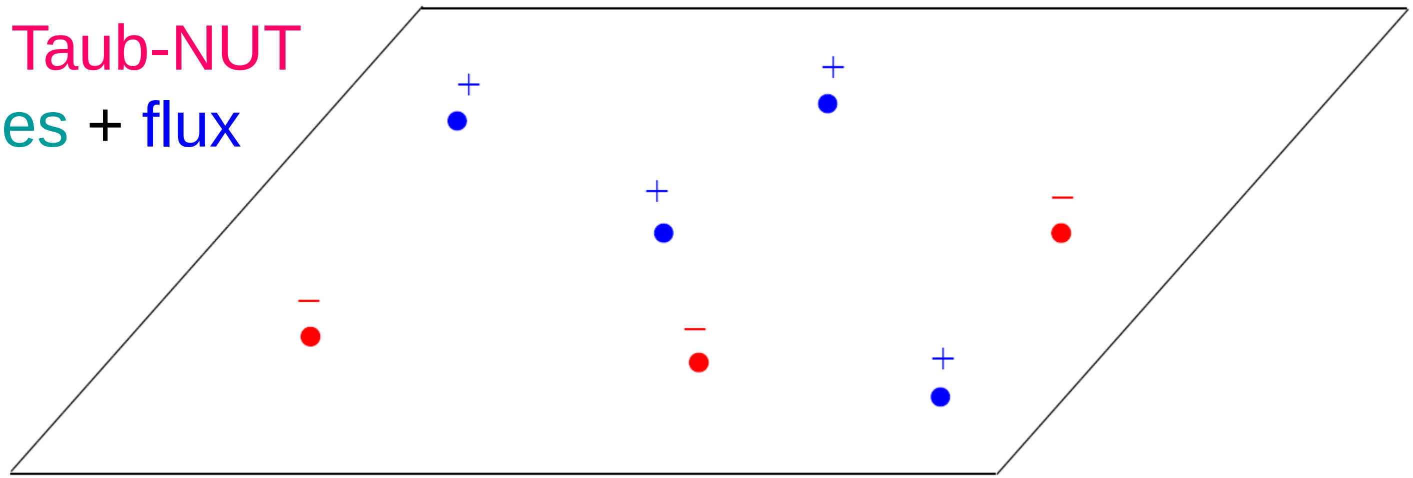
Giusto, Mathur, Saxena
Bena, Warner
Berglund, Gimon, Levi

- Full 11D metric is smooth:

$$ds^2 = -Z^{-2}(dt + \vec{k})^2 + Z\left[V\left(dx_1^2 + dx_2^2 + dx_3^2\right) + V^{-1}(d\psi + \vec{A})^2\right] + ds^2_{T^6}$$

Microstate geometries

Multi-center Taub-NUT
many 2-cycles + flux



Compactified to 4D $\longrightarrow$ multicenter configuration

- $+$ GH center $\Leftrightarrow$ $\mathrm{D6}$ brane
- $-$ GH center $\Leftrightarrow$ $\overline{\mathrm{D6}}$ brane

Abelian worldvolume flux
Each: 16 supercharges
4 common supercharges

Replace 5D black hole by smooth microstate geometry

$\Updownarrow$

Break 4D black hole into primitive multicenter configuration

Microstate geometries

- Where is the BH charge ?

$\mathcal{L} = q\, A_0$

magnetic

$\mathcal{L} = \ldots + A_0\, F_{12}\, F_{23} + \ldots$

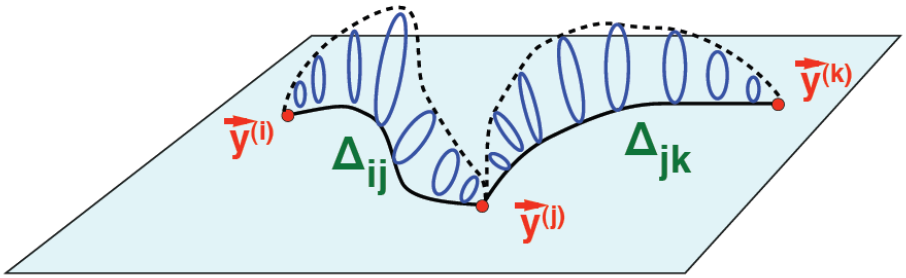
- Where is the BH mass ?

$\mathcal{E} = \ldots + F_{12}\, F^{12} + \ldots$

- BH angular momentum

$\mathcal{J} = E \times B = \ldots + F_{01}\, F_{12} + \ldots$

2-cycles + magnetic flux

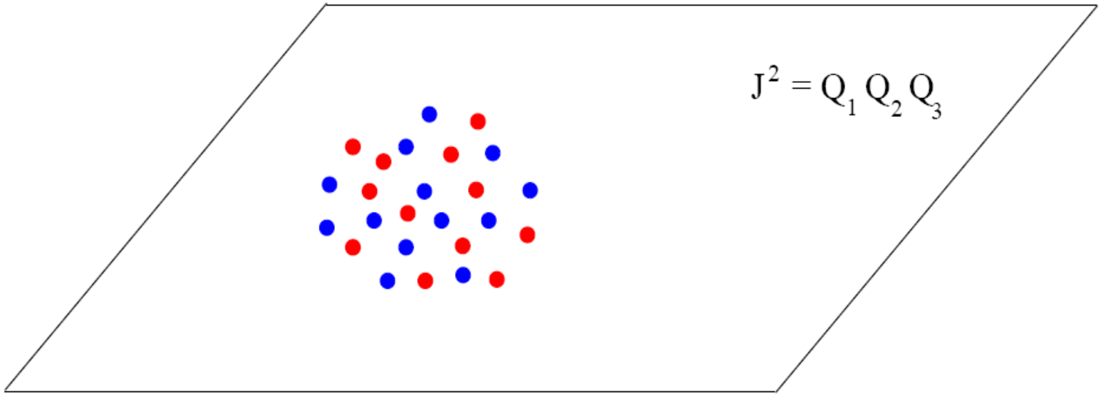


Charge disolved in fluxes

Klebanov-Strassler

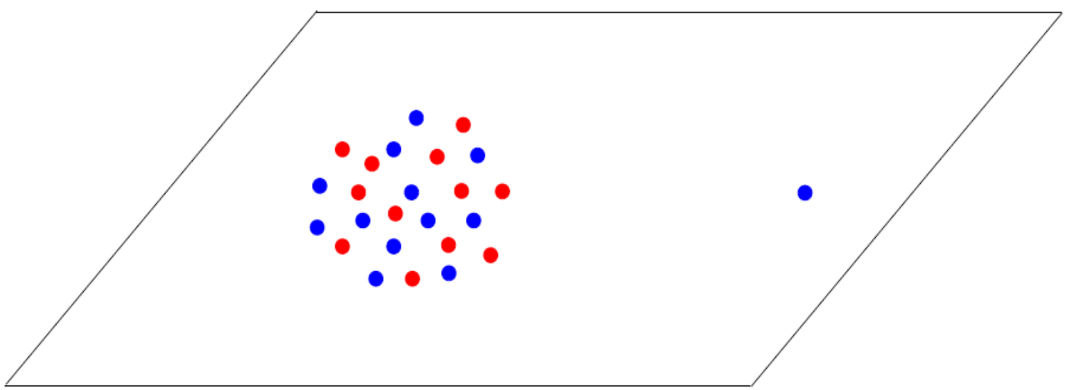
$$\int_{a-b} F_{12ij} = n_1 \qquad \int_{O-a} F_{34ij} = f_2$$

Microstates of many bubbles



microstate of S = 0 black hole

D6 charge = 1



microstate of S = 0 black ring

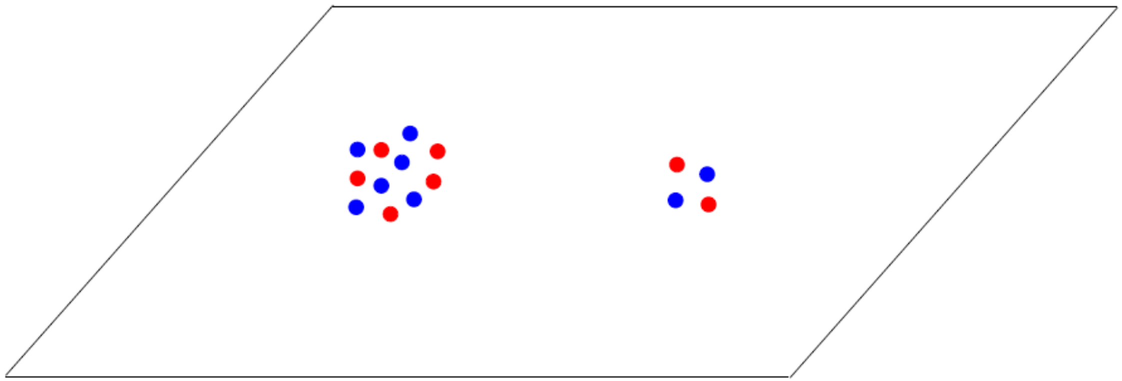
D6 charge = 0

A problem ?

- Hard to get microstates of *real* black holes
- All known solutions
  - D1 D5 system
    Mathur, Lunin, Maldacena, Maoz, Taylor, Skenderis
  - 3-charge (D1 D5 P) microstates in 5D
    Giusto, Mathur, Saxena; Bena, Warner; Berglund, Gimon, Levi
  - 4-charge microstates in 4D
    Bena, Kraus; Saxena Potvin, Giusto, Peet
  - Nonextremal microstates
    Jejjala, Madden, Ross, Titchener (JMaRT); Giusto, Ross, Saxena

did not have charge/mass/J of black hole with classically large event horizon ($S > 0$, $Q_1 Q_2 Q_3 > J^2$)

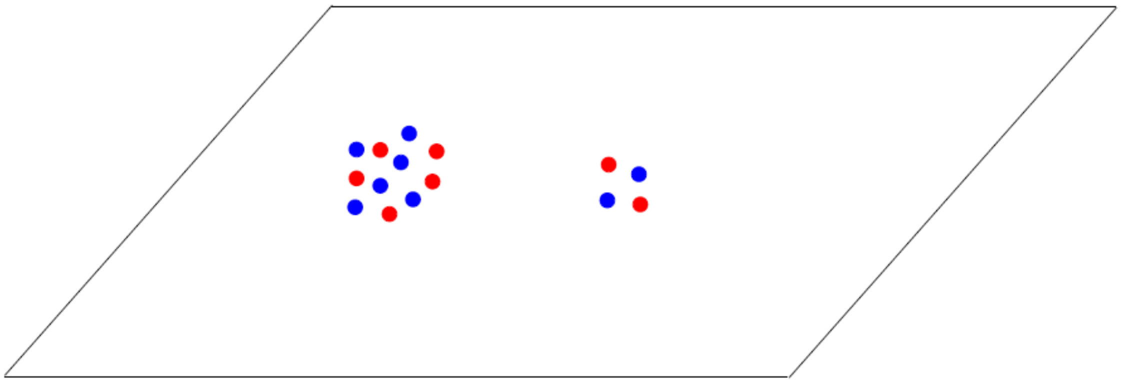
Reversible merger of BH and BR microstates



Reversible merger

S=0 BH + S=0 BR $\longrightarrow$ S=0 BH

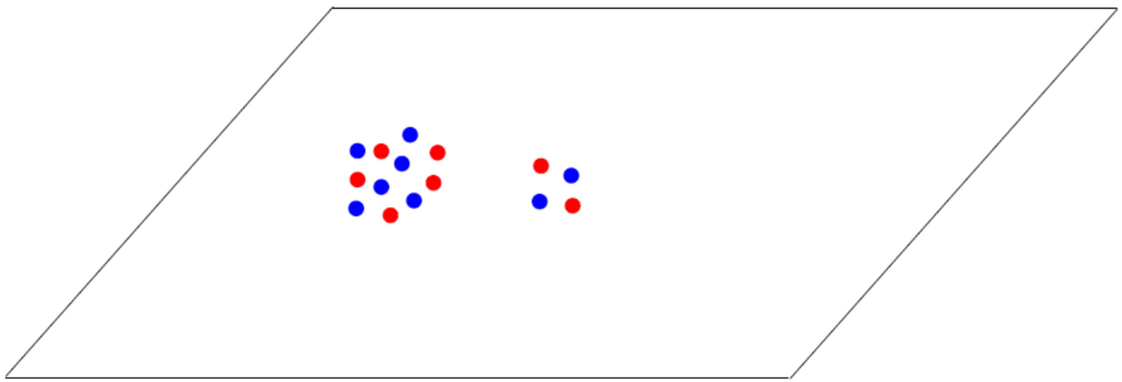
Reversible merger of BH and BR microstates



Reversible merger

S=0 BH + S=0 BR $\longrightarrow$ S=0 BH

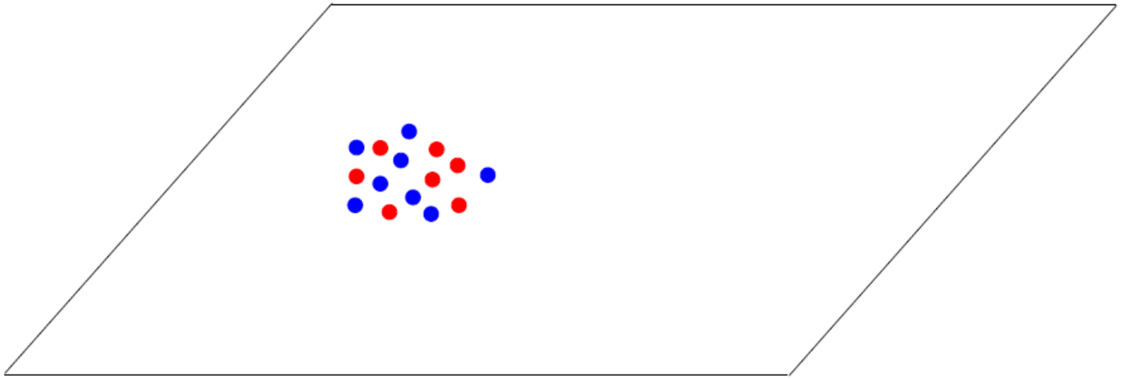
Reversible merger of BH and BR microstates



Reversible merger

S=0 BH + S=0 BR ⟶ S=0 BH

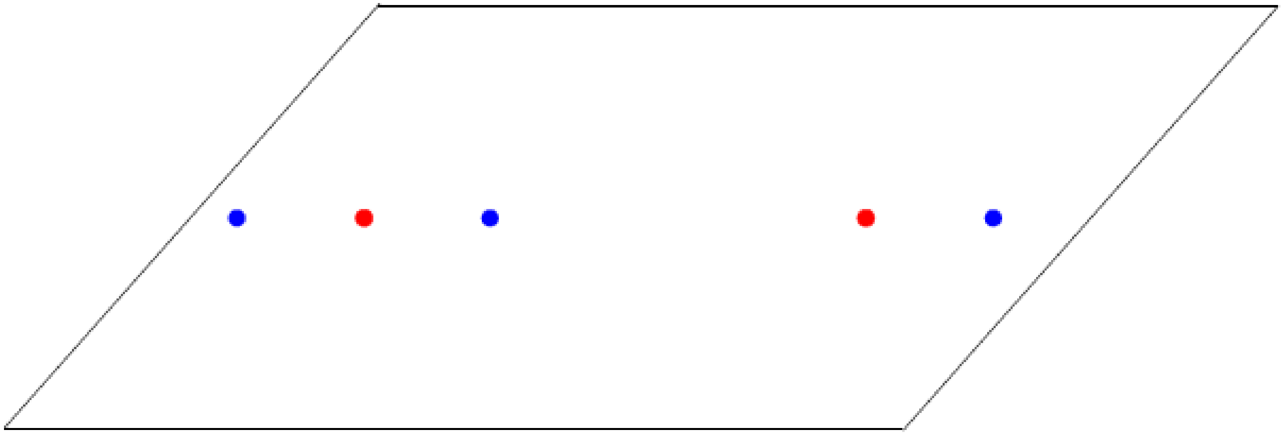
Reversible merger of BH and BR microstates



Reversible merger

S=0 BH + S=0 BR $\longrightarrow$ S=0 BH

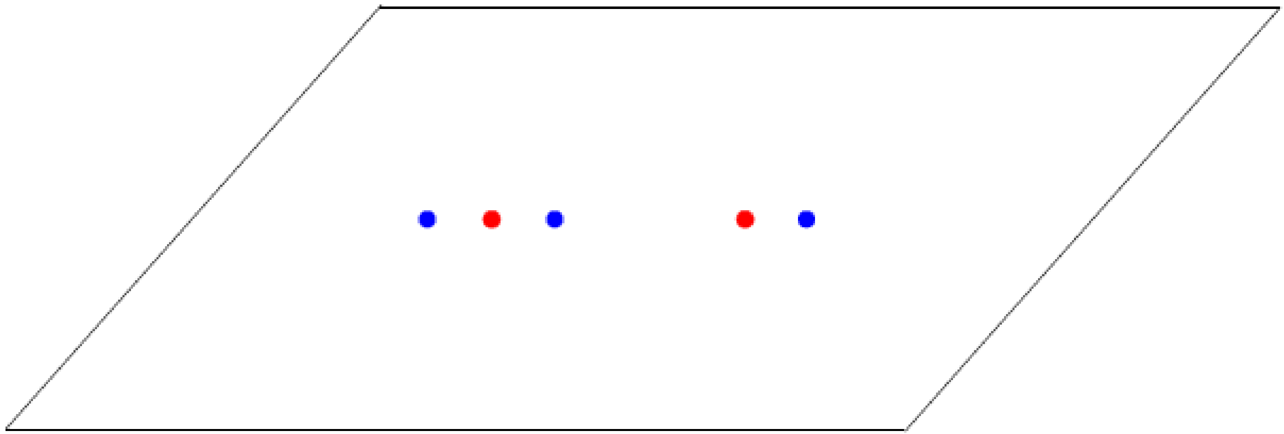
Microstates for S>0 black holes



Irreversible merger

S=0 BH + S=0 BR ⟶ S>0 BH

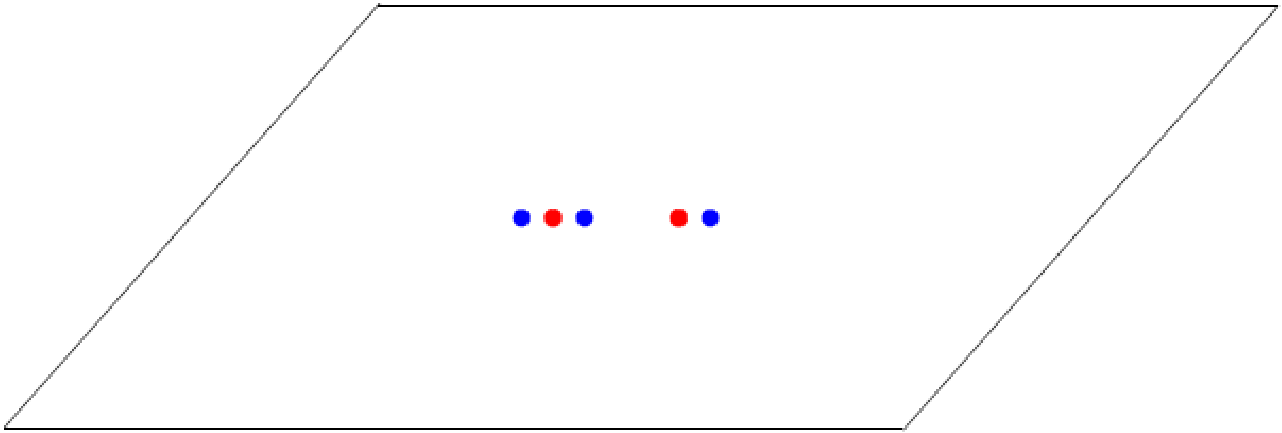
Microstates for S>0 black holes



Irreversible merger

S=0 BH + S=0 BR ⟶ S>0 BH

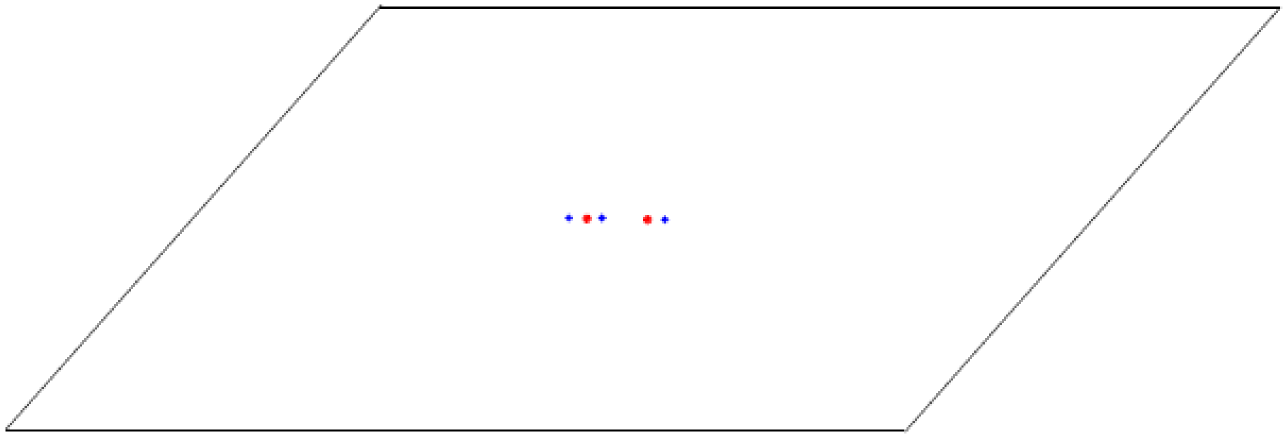
Microstates for S>0 black holes



Irreversible merger

S=0 BH + S=0 BR ⟶ S>0 BH

Microstates for S>0 black holes



Irreversible merger

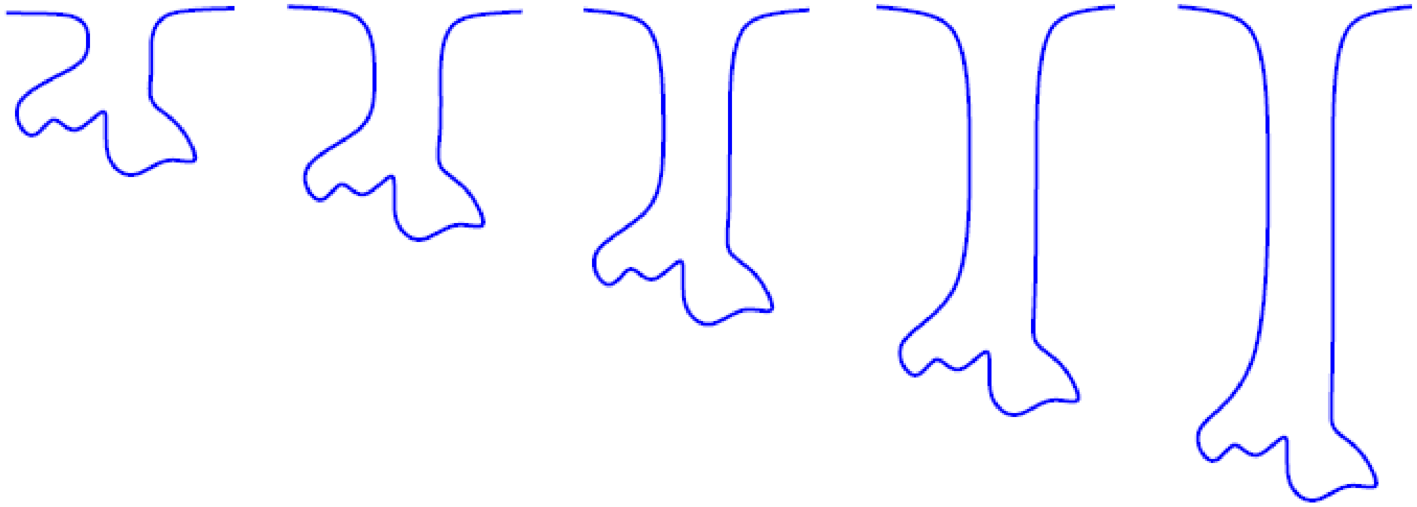
Scaling solution

Points shrinking on the base $\Rightarrow$

Region where solution looks like the black hole is larger

Bena, Wang, Warner

Deep microstates



- 4D perspective: points collapse on top of each other
- 5D perspective: throat becomes deeper and deeper; cap remains similar !
- Solution smooth throughout scaling !
- Scaling goes on forever !!!
  - Can quantum effects stop that ?
  - Can they destroy huge chunk of smooth low-curvature horizonless solution ?

Always asked question:

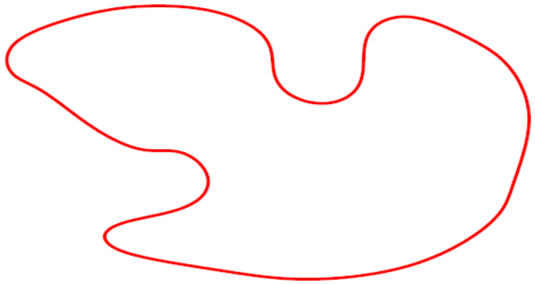
- Why are quantum effects affecting the horizon (low curvature) ?
- Answer: space-time has singularity:
  - low-mass degrees of freedom
  - change the physics on long distances
- This is very common in string theory !!!
  - Polchinski-Strassler
  - Giant Gravitons + LLM
- It can be even worse – quantum effects significant even without horizon
  de Boer, El Showk, Messamah, van den Bleeken

CFT dual of deep microstates

- Microstates with angular momentum J_L have mass gap $J_L / N_1 N_5$
  - Dual CFT - break effective string of length $N_1 N_5$ into J_L components
  - Deepest U(1) x U(1) invariant microstates have J_L=1 – one long component string
- Same CFT sector as typical microstates !
- Holographic anatomy Taylor, Skenderis

More general solutions

- Spectral flow: Ford, Giusto, Saxena; Bena, Bobev, Warner
  GH solution ⇔ solution with 2-charge supertube in GH background
- Supertubes Mateos, Townsend, Emparan
  - supersymmetric brane configurations
  - arbitrary shape:
  - smooth supergravity solutions
    Lunin, Mathur; Lunin, Maldacena, Maoz



- Classical moduli space of microstates solutions has infinite dimension !

More general solutions

Problem: 2-charge supertubes have 2 charges

$$S_{TUBE} = 2\pi\sqrt{2N_1N_2}$$

$$S_{TUBE} << S_{BH}$$

Marolf, Palmer; Rychkov

Solution:

- In deep scaling solutions: Bena, Bobev, Ruef, Warner

$$N_1 \rightarrow N_1^{\text{eff}} \equiv N_1 + d_3 A_2, \quad N_2 \rightarrow N_2^{\text{eff}} \equiv N_2 + d_3 A_1$$

- Entropy enhancement !!!

$$S_{TUBE}^{ENHANCED} \sim S_{BH}$$

smooth sugra solutions

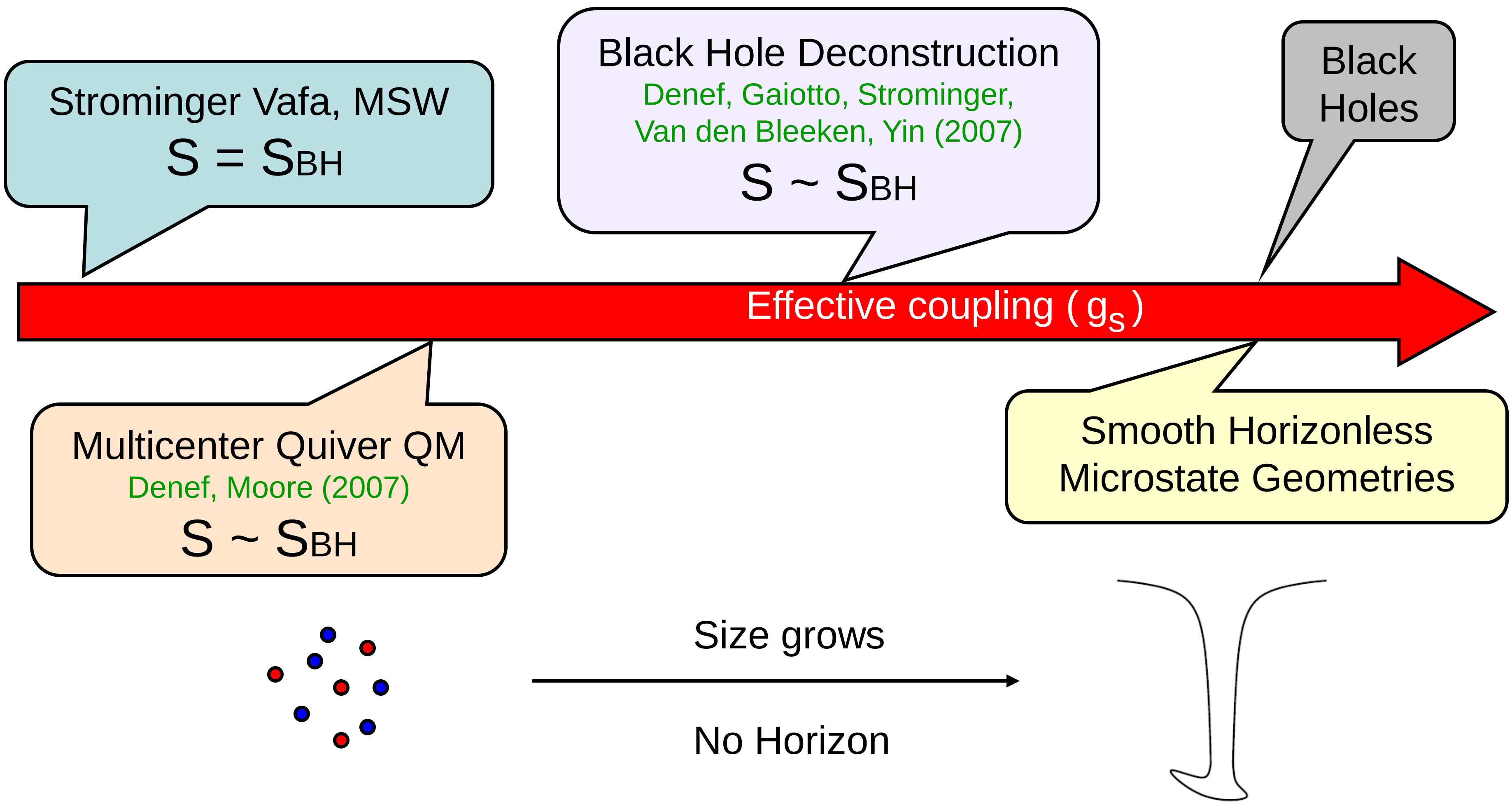
Relation to Denef - Moore

- Take limit of microstates as $g_{\text{eff}} \to 0$
- Multiple $\text{D6} - \overline{\text{D6}}$ branes, with D4, D2 and D0 overall charge.
- At $g_{\text{eff}} = 0$, description à la Maldacena-Strominger-Witten
- At g_{eff} = small $\to$ quiver quantum mechanics.
  - D6 and $\overline{\text{D6}}$ form finite-sized bound state.
  - Black-hole-like entropy if $\text{D6} - \overline{\text{D6}}$ form scaling solution Denef, Moore
- At g_{eff} = large $\to$ supergravity solutions.
  - Same equations as in quiver description Denef, Bates
  - Scaling solutions $\Leftrightarrow$ Deep microstates

Relation to BH deconstruction

Denef, Gaiotto, Strominger, Van den Bleeken, Yin; Gimon, Levi

- D4-D4-D4-D0 4D BH;
- D4's backreact; bubble into D6-$\overline{\text{D6}}$
- D0's treated as probes
- Scaling D0-D6-$\overline{\text{D6}}$ solution
- D0 polarized into D2 branes;
- Landau levels of D2 $\longrightarrow$ BH entropy
- Scaling solution of primitive centers

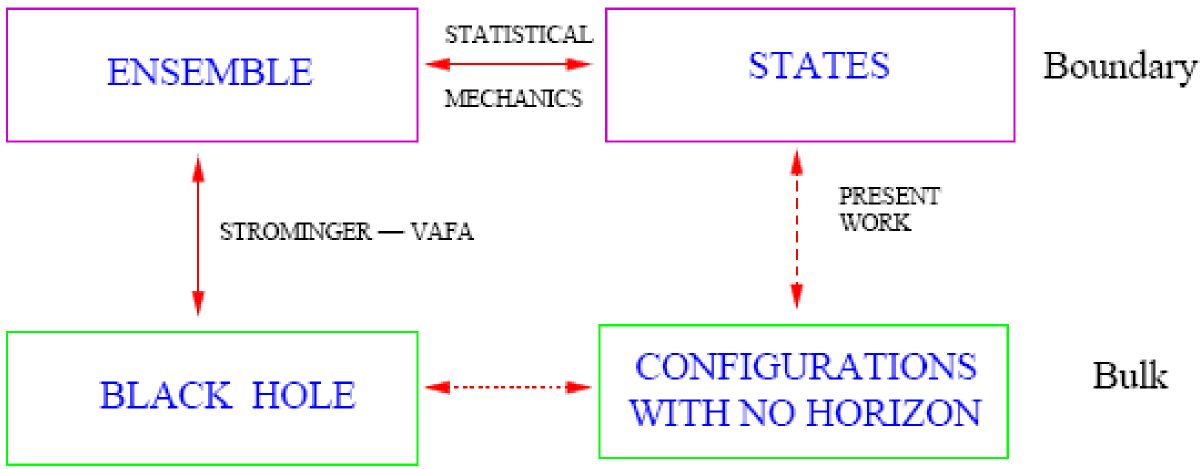


Same ingredients: Scaling solutions of primitive centers

Punchline: Typical states grow as G_N increases.
Horizon never forms.

Black Holes in AdS-CFT: Option 1

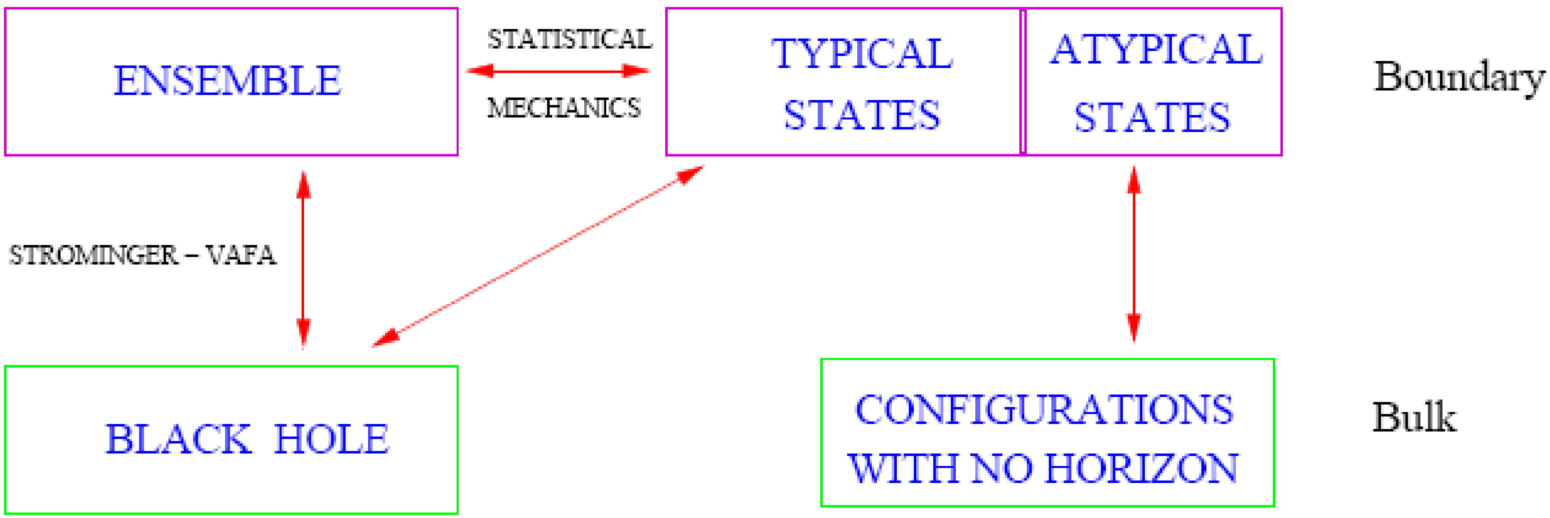
- Each state has horizonless bulk dual Mathur
- Classical BH solution = thermodynamic approximation



- Lots of microstates; dual to CFT states in typical sector
- Size grows with BH horizon
- Finite mass-gap - agrees with CFT expectation Maldacena
- Natural continuation of Denef-Moore, DGSVY

Black Holes in AdS-CFT: Option 2

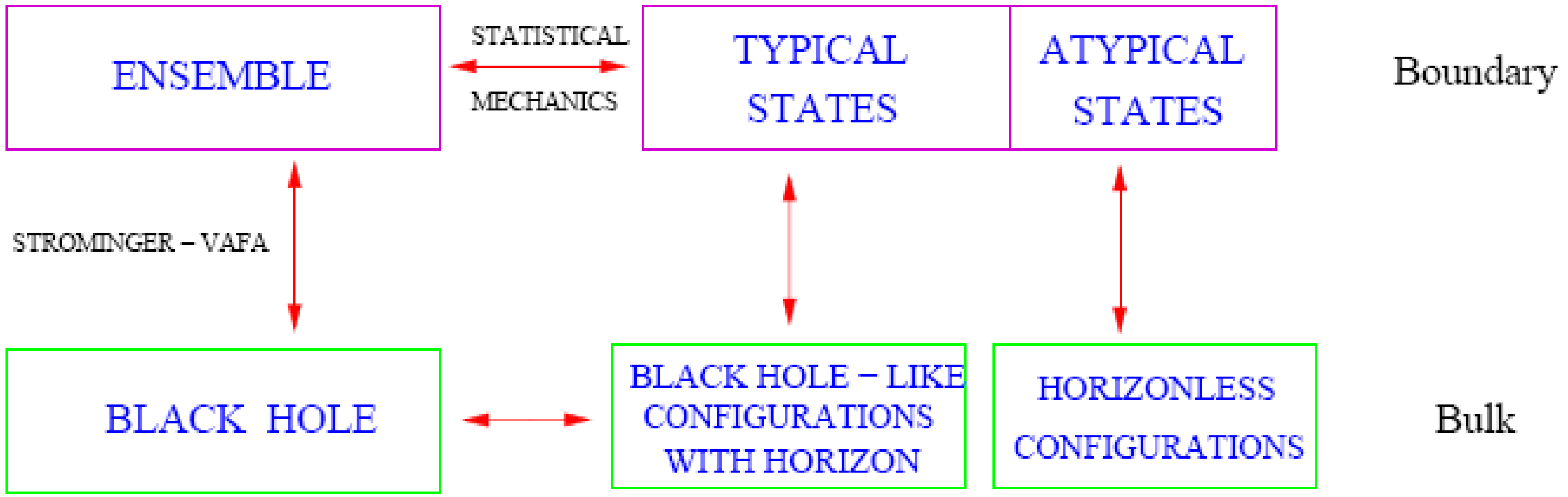
- Typical CFT states have no individual bulk duals.
- Many states mapped into one BH solution



- Some states in typical CFT sector do have bulk duals.
- 1 to 1 map in all other understood systems (D1-D5, LLM, Polchinski-Strassler, GKP). Why different ?

Black Holes in AdS-CFT: Option 3

- Typical states have bulk duals with horizon (~ BH)



- States in the typical sector of CFT have both infinite and finite throats.
- CFT microstates have mass-gap and Heisenberg recurrence. Would-be bulk solutions do not.

Maldacena; Balasubramanian, Kraus, Shigemori

Summary and Future Directions

- Strong evidence that in string theory, BPS extremal black holes = ensembles of microstates
  - One may not care about extremal BH's
  - One may not care about string theory
  - Lesson is generic: QG low-mass modes can change physics on large (horizon) scales
- Extend to extremal non-BPS black holes
  Goldstein, Katmadas; Bena, Dall'Agata, Giusto, Ruef, Warner
- Extend to non-extremal black holes
- New light degrees of freedom. Experiment ?

Extremal Black Hole

- This is not so strange
- Space-like singularity resolved by stringy low-mass modes