AdS_2 holography

Mind the Gap !

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with

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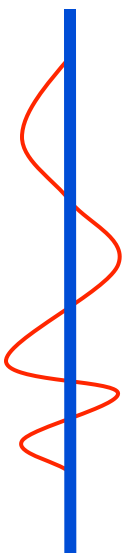
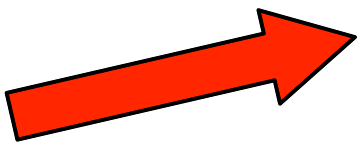
Strominger and Vafa (1996):

Black Hole Microstates at ***Zero Gravity*** (branes + strings)

Correctly match B.H. entropy !!!

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
Damour, Veneziano

Strominger and Vafa (1996):

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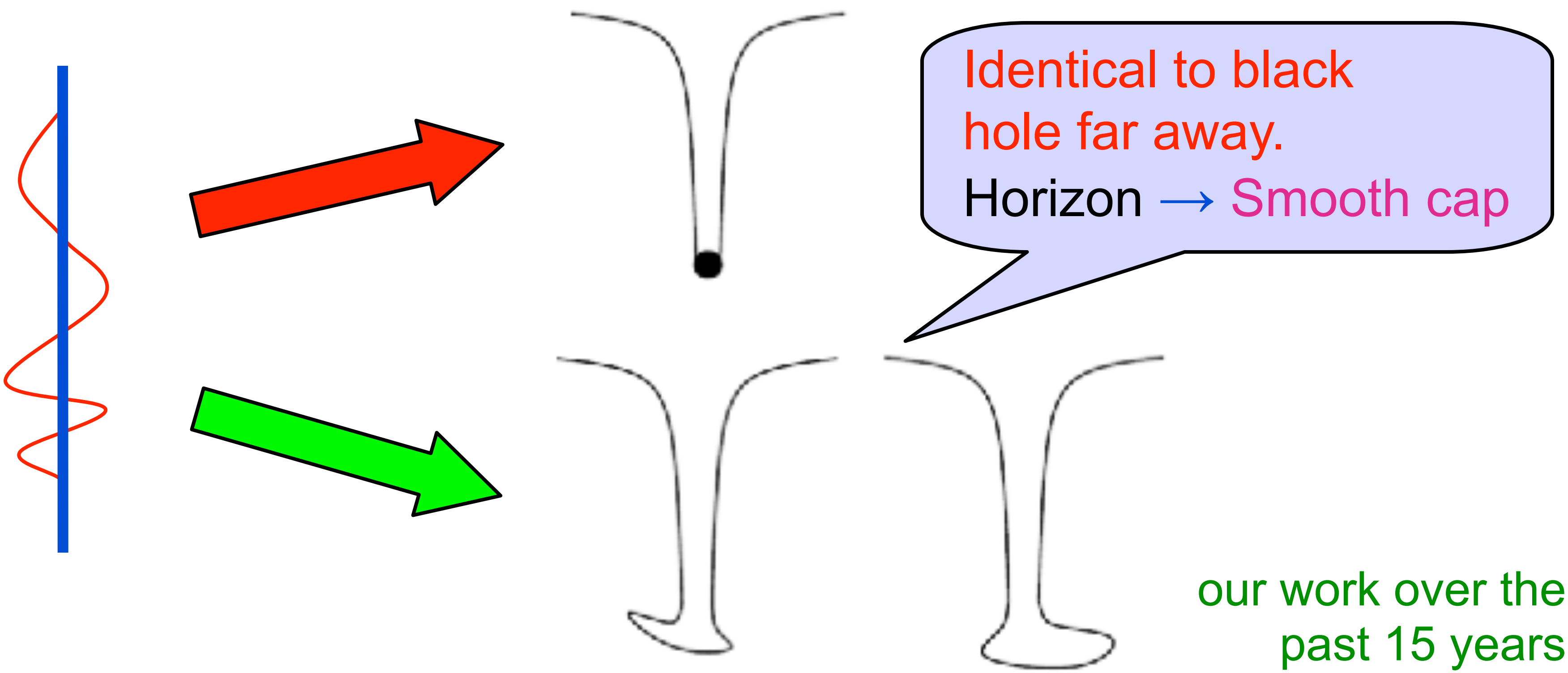
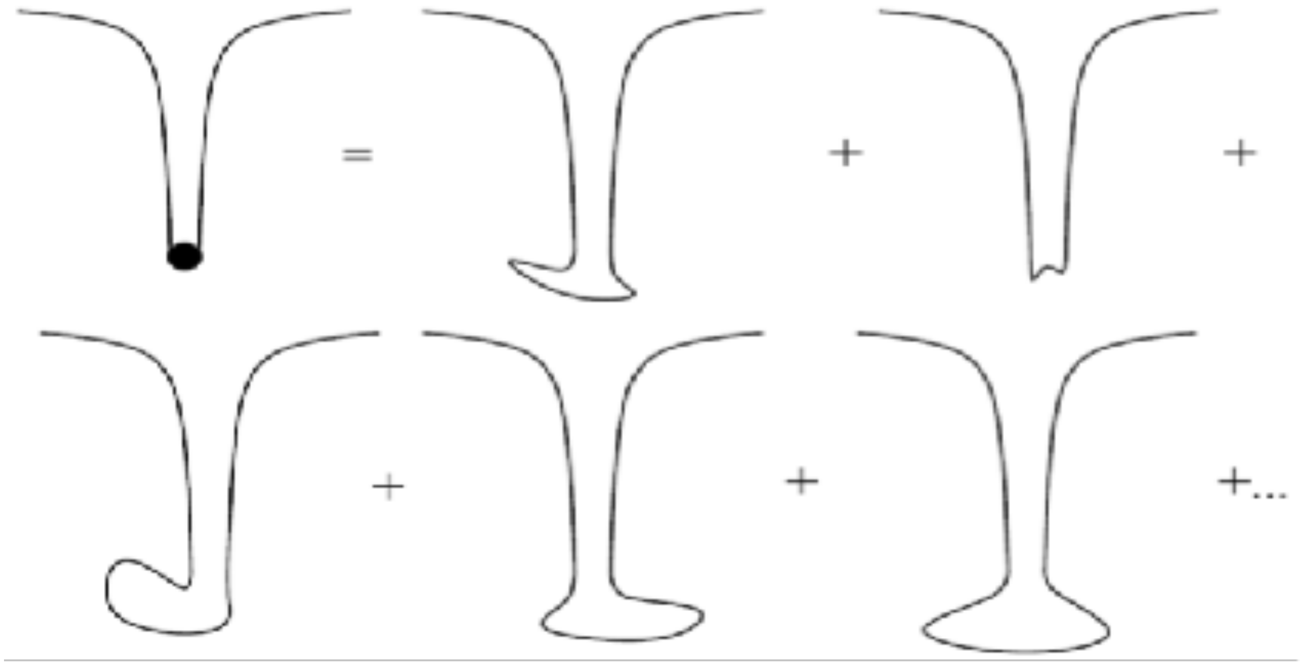


BIG QUESTION: Are ***all*** black hole microstates becoming geometries with no horizon ?

Black hole $\stackrel{?}{=}$ ensemble of horizonless microstate configurations

Mathur 2003



Only way to solve QM-GR conflict

Mathur 2009, Almheiri, Marolf, Polchinski, Sully 2012

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

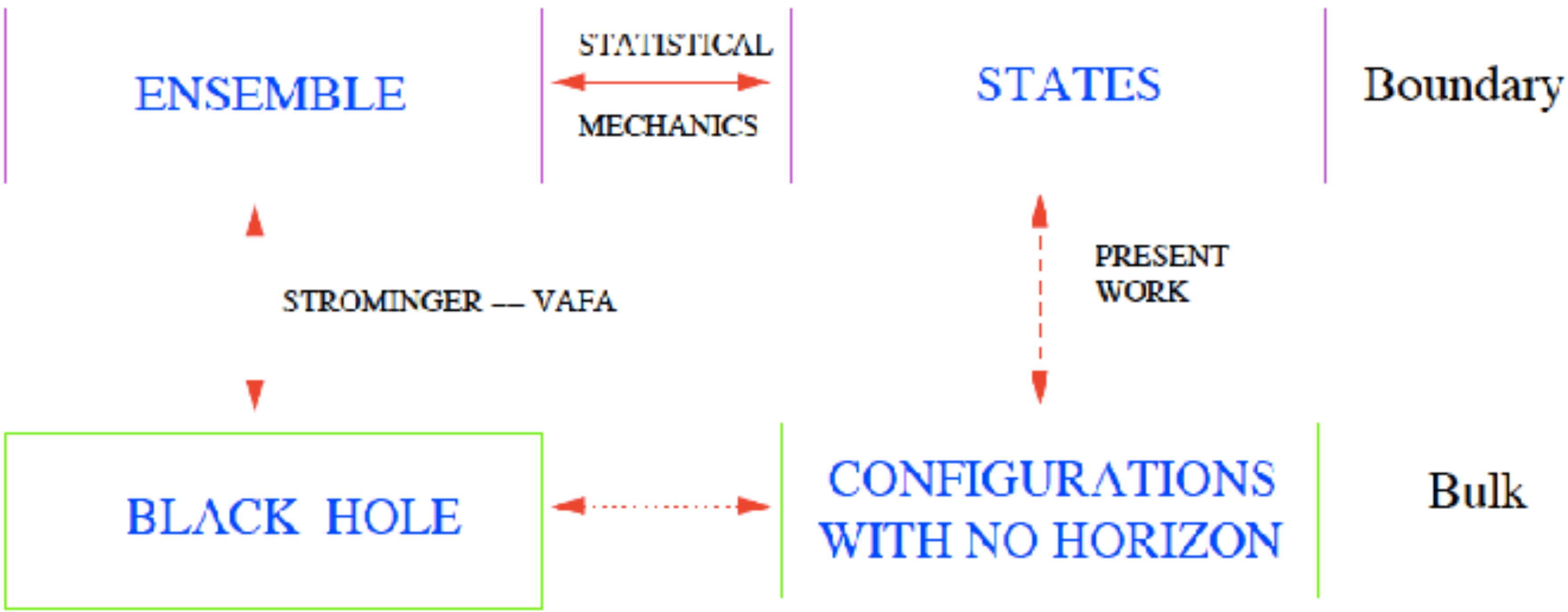
Microstate geometries

Long distance physics
Gravitational lensing

Physics at horizon
Information loss
Gravity waves ?

AdS-CFT formulation:

e.g. Bena, Warner, 2007



Not some hand-waving idea - provable by rigorous calculations in String Theory

Word of caution

- To replace classical BH by BH-sized object
  - Gravastar, quark-star, boson-star
  - Infinite density firewall hovering just above horizon
  - Gas of wormholes
  - Bose-Einstein condensate of gravitons
  - LQG configuration…

3 very stringent tests:

1. Same growth with G_N !!!

Horowitz

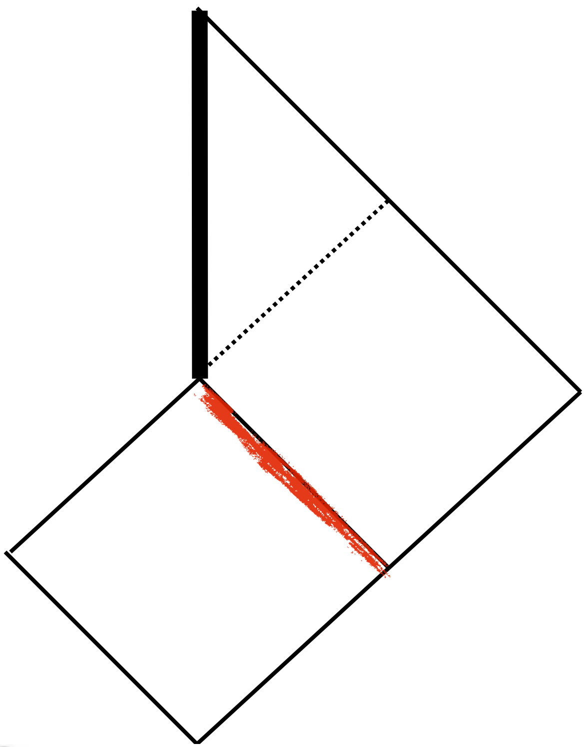
BH size grows with G_N ; "normal objects" shrink

- BH microstate geometries pass this test
- Highly nontrivial mechanism: $G_N = g_s^2$
- D-branes = solitons, tension ~ $1/g_s$ ➞ lighter as G_N increases

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

2. Mechanism not to fall into BH

Very difficult !!!



GR Dogma:

Thou shalt not put anything at the horizon !!!

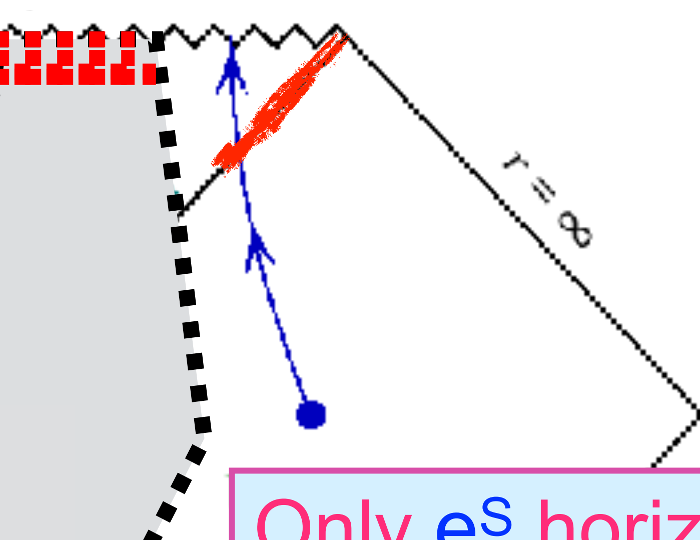
- Null ➔ speed of light.
- If massive: ∞ boost ➔ ∞ energy
- If massless: dilutes with time

- Nothing can live there ! (or carry degrees of freedom)
- No membrane, no spins, no “quantum stuff”
- No (fire)wall

If support mechanism have you not, go home and find one

3. Avoid forming a horizon

- Collapsing shell forms horizon — Oppenheimer and Snyder (1939)
- If curvature is low, no reason not to trust classical GR
- By the time shell becomes curved-enough for quantum effects to become important, horizon in causal past



Backwards in time - illegal !

BH has e^S microstates with no horizon

Small tunneling probability = e^{-S}

Will tunnel with probability **ONE** !!!

Kraus, Mathur; Bena, Mayerson, Puhm, Vercnocke

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

If quantum tunneling you are brushing aside, incorrect physics you are doing

Microstates geometries: M2-M2-M2 frame

- Where is the BH charge ?

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

magnetic

$\mathcal{L} = \ldots + A_0\, F_{12}\, F_{34} + \ldots$

- Where is the BH mass ?

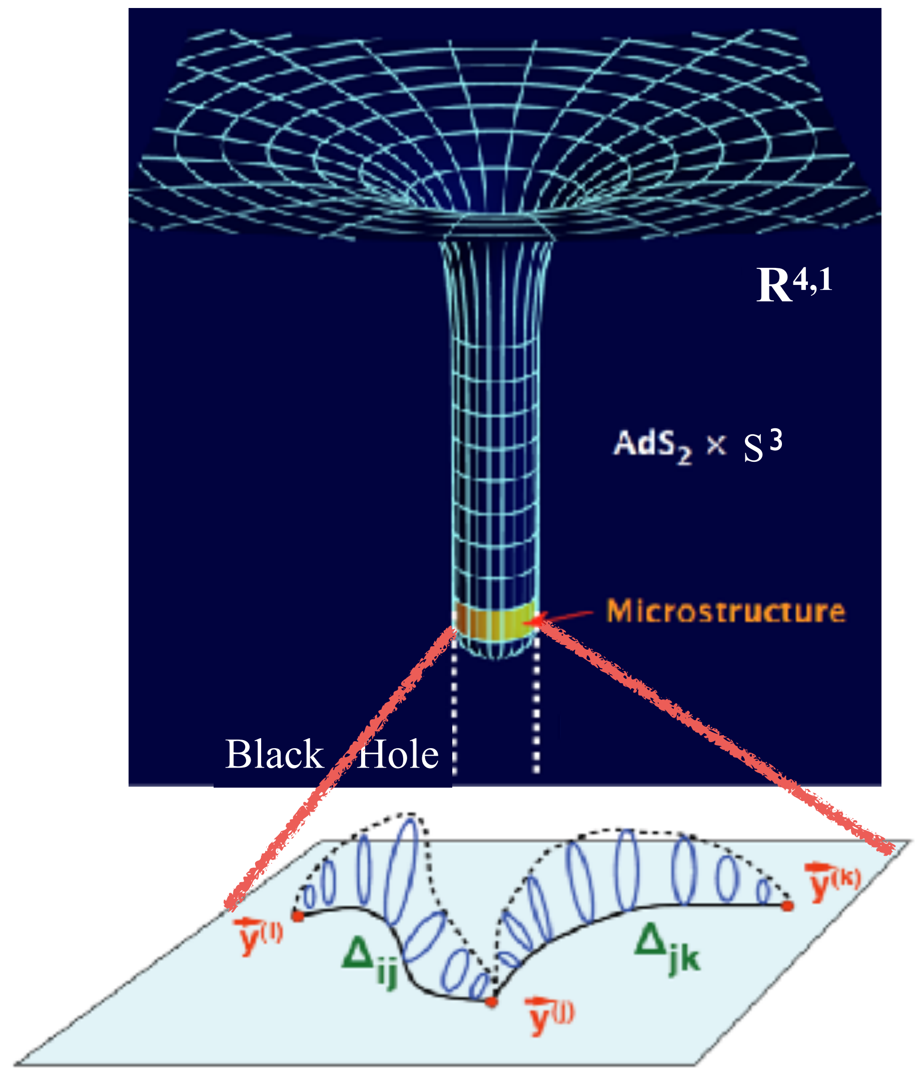
$E = \ldots + F_{12}\, F^{12} + \ldots$

- BH angular momentum

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

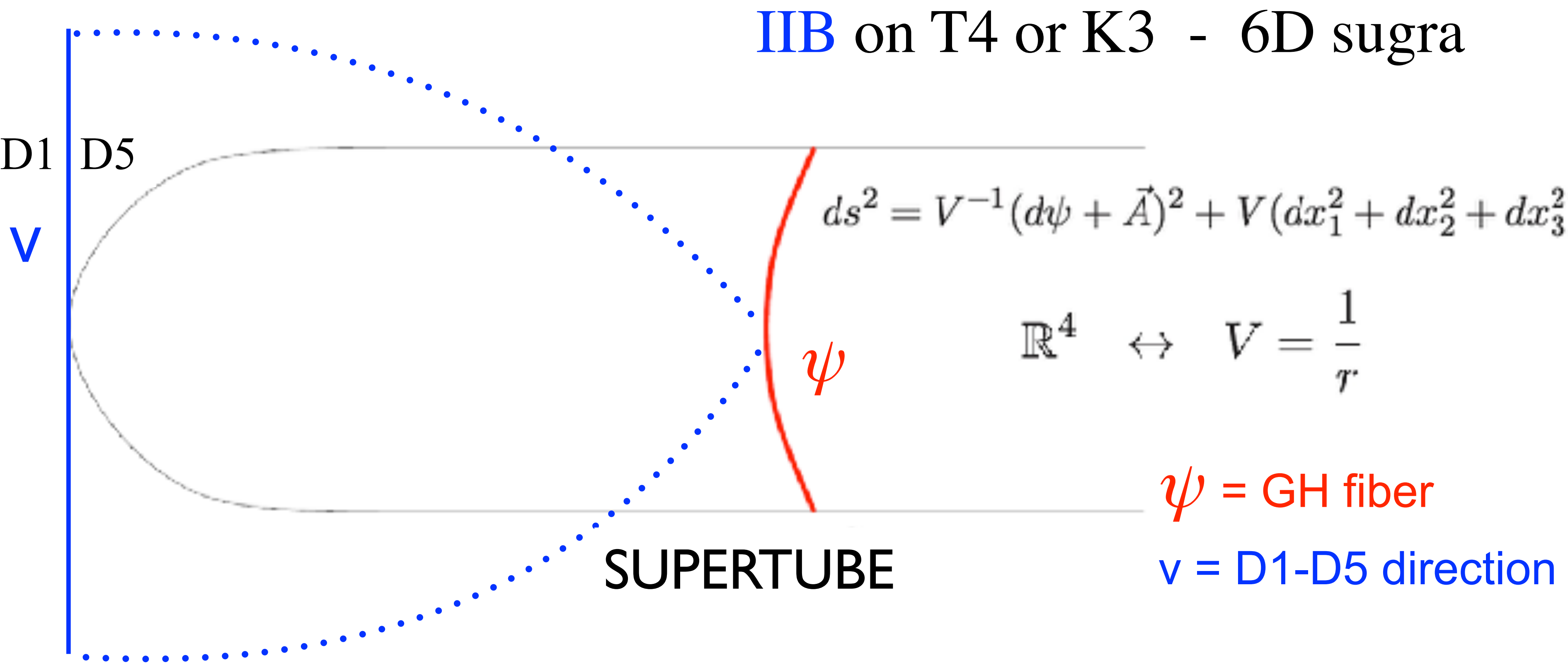
Charge dissolved in fluxes.
No singular sources.
Klebanov-Strassler

11d/CY - black hole in 5d



2-cycles + magnetic flux

Microstates geometries: D1-D5-P frame



- Starting solution: $AdS_3 \times S^3$ **Add wiggles**
- Arbitrary $F(\psi)$ - 8 supercharges - supertube
  Lunin, Mathur; Lunin, Maldacena, Maoz; Taylor, Skenderis
- Arbitrary $F(\psi,v)$ - 4 supercharges - superstratum
  Bena, Giusto, Russo, Shigemori, Warner

Entropy of wiggles

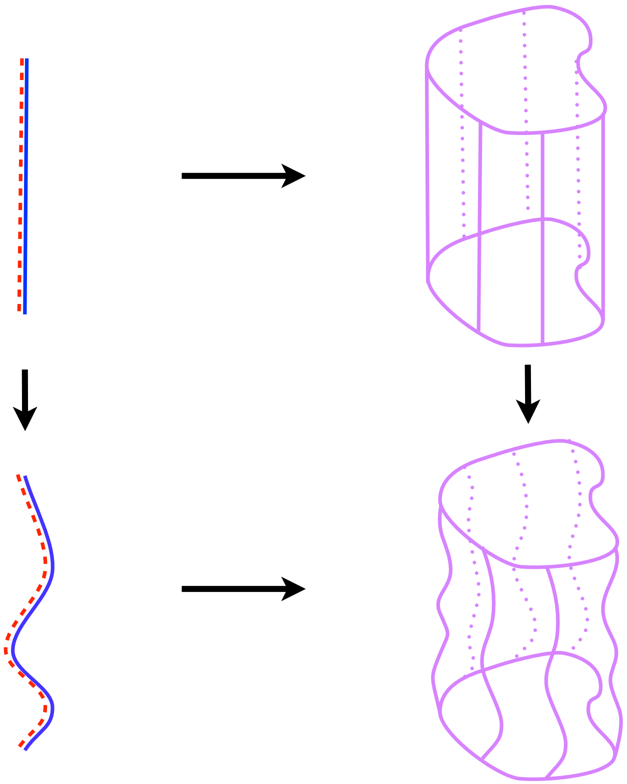
Bena, Shigemori, Warner

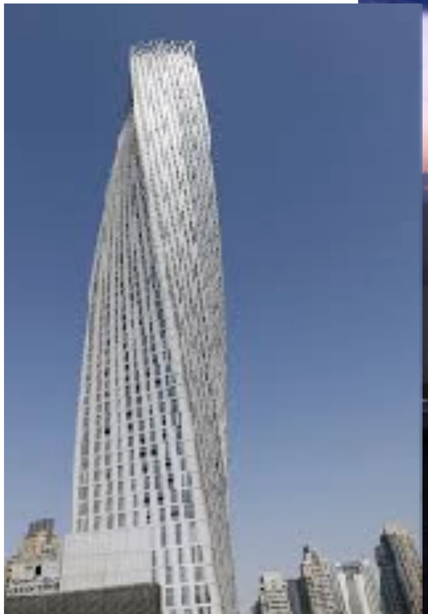
Supertubes - eight $F(\psi)$, (c = 8) $\mathbf{S} \sim (c\, L_0)^{1/2} \sim \mathbf{(Q_1 Q_5)^{1/2}}$

(with massaging $S \sim Q^{5/4}$)

Superstrata - four $F(\psi, v)$, (c = ∞), quantize: $\mathbf{S = 2\pi(Q_1 Q_5 Q_p)^{1/2}}$

Double supertube transition. In general non-geometric.





Largest family of solutions known to mankind

Arbitrary functions of two variables: ∞ X ∞ parameters

Bena, Giusto, Russo, Shigemori, Warner

$$ds^2_{10} = \frac{1}{\sqrt{\alpha}}\, ds^2_6 + \sqrt{\frac{Z_1}{Z_2}}\, d\hat{s}^2_4\,,$$

$$ds^2_6 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\left[du+\omega+\frac{\mathcal{F}}{2}(dv+\beta)\right] + \sqrt{\mathcal{P}}\, ds^2_4\,,$$

$$e^{2\phi} = \frac{Z_1^2}{\mathcal{P}}\,,$$

$$B = -\frac{Z_4}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_4\wedge(dv+\beta) + \delta_2\,,$$

$$C_0 = \frac{Z_4}{Z_1}\,,$$

$$C_2 = -\frac{Z_2}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_1\wedge(dv+\beta) + \gamma_2\,,$$

$$C_4 = \frac{Z_4}{Z_2}\,\widehat{\mathrm{vol}}_4 - \frac{Z_4}{\mathcal{P}}\gamma_2\wedge(du+\omega)\wedge(dv+\beta) + x_3\wedge(dv+\beta) + \mathcal{C}\,,$$

$$C_6 = \widehat{\mathrm{vol}}_4\wedge\left[-\frac{Z_1}{\mathcal{P}}(du+\omega)\wedge(dv+\beta) + a_2\wedge(dv+\beta) + \gamma_1\right] - \frac{Z_4}{\mathcal{P}}\,\mathcal{C}\wedge(du+\omega)\wedge(dv+\beta)\,,$$

$$\alpha \equiv \frac{Z_1 Z_2}{Z_1 Z_2 - Z_4^2}\,, \qquad \mathcal{P} \equiv Z_1 Z_2 - Z_4^2\,.$$

$$-\frac{R\,r}{\sqrt{2}\,k_2(m_1^2-1)}\,\frac{m_1(k_2+m_1+1)\Delta_{k_2+m_1-1,m_1-1} + (k_2+m_1-1)\Delta_{k_2+m_1} \ldots}{(r^2+a^2)^2}$$

$$-\frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2\sin\theta\cos\theta}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1}$$
$$+(m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}$$
$$-m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (m_1^2(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big]\,,$$

$$-\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\sin^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} \ldots$$
$$+(m_1^2-2m_1+k_2-1)\Delta_{k_2+m_1-1,m_1-1} + m_1(k_2-2)\Delta_{k_2+m_1-1,m_1+1}$$
$$+m_1(k_2-m_1-1)\Delta_{k_2+m_1+1,m_1-1} + (k_2(m_1^2+m_1-1) - m_1(m_1+1))\Delta_{k_2} \ldots$$

$$-\frac{R}{\sqrt{2}}\frac{\Delta_{k_2+m_1+1,m_1+1}}{\Sigma}\cos^2\theta - \frac{R}{\sqrt{2}\,k_2(m_1^2-1)a^2}\Big[(k_2-1)(m_1-1)\Delta_{k_2+m_1-} \ldots$$
$$-2(m_1-1)\Delta_{k_2+m_1-3,m_1-1} - (m_1-1)(m_1-2)\Delta_{k_2+m_1-1,m_1-1}$$
$$-(m_1-1)(k_2-3)\Delta_{k_2+m_1-1,m_1+1} + m_1(m_1-1)\Delta_{k_2+m_1+1,m_1-1}$$
$$-(m_1-1)(m_1(k_2-1)+1)\Delta_{k_2+m_1+1,m_1+1}\Big]\,.$$

String theory input crucial

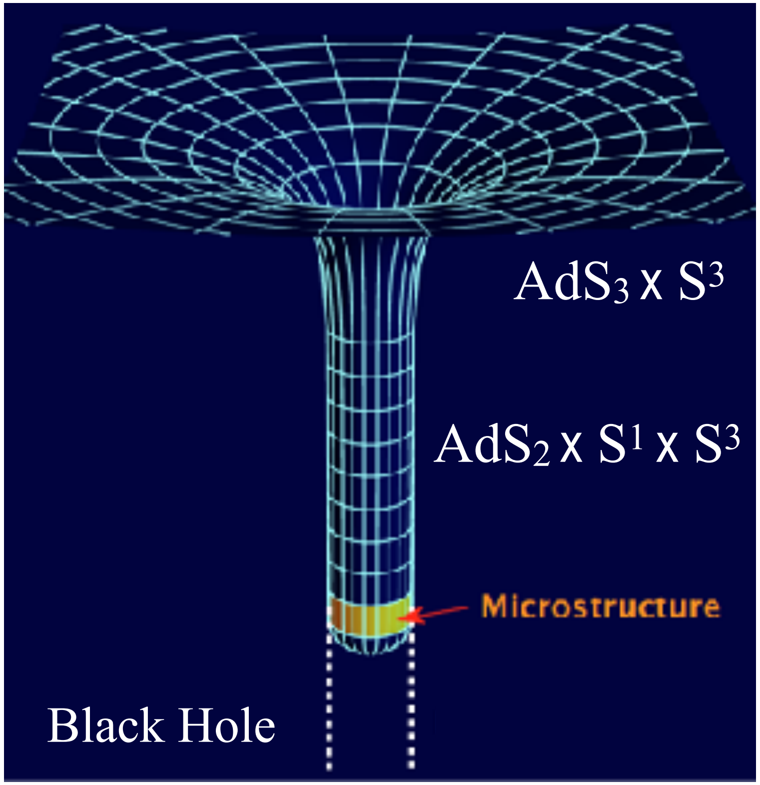
Giusto, Russo, Turton

Habemus Superstratum !!!

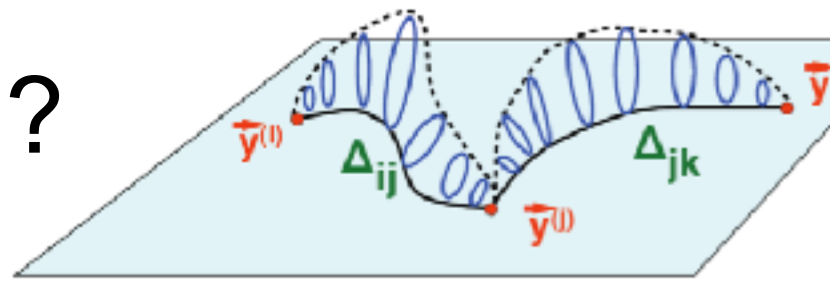
Deep superstrata

- J can be arbitrarily small
  Bena, Giusto, Martinec Russo, Shigemori, Turton, Warner '16 (PRL editor's selection)
- First BTZ microstates
- CFT dual state known
- Certain superstrata (1,0,n)
  Wave equation separable !
  Bena, Turton, Walker, Warner
- Can compute many things:
  Geodesics Tyukov, Walker, Warner
  Mass gaps Bena, Heidmann, Turton
  Wightman functions Raju, Shrivastava
  Green fns, Thermalization, Chaos, dip-ramp-plateau
  Bena, Guica, Heidmann, Monten, Warner (to appear)

D1-D5-P black string in 6D



Why not collapsing ?



- 5(+6)d : smooth solutions + quantized magnetic flux on topologically-nontrivial 2-cycles
  - cycles smaller $\longrightarrow$ increases energy
  - bubbling = only mechanism to avoid collapse in semiclassical limit Gibbons, Warner
  - If any state in the e^S-dimensional BH Hilbert space has a semiclassical limit, it **must** be a microstate geometry !
- 4(+6)d : multicenter solutions Denef
  - smooth GH centers with negative charge $\longrightarrow$ centers with negative D6 charge and negative mass
  - common in String Theory (e.g. orientifolds); nowhere else
  - **Highly unusual** matter from a 4d perspective
  - Usual matter does not hang around, just falls in BH

Quantum Gravity in AdS_2

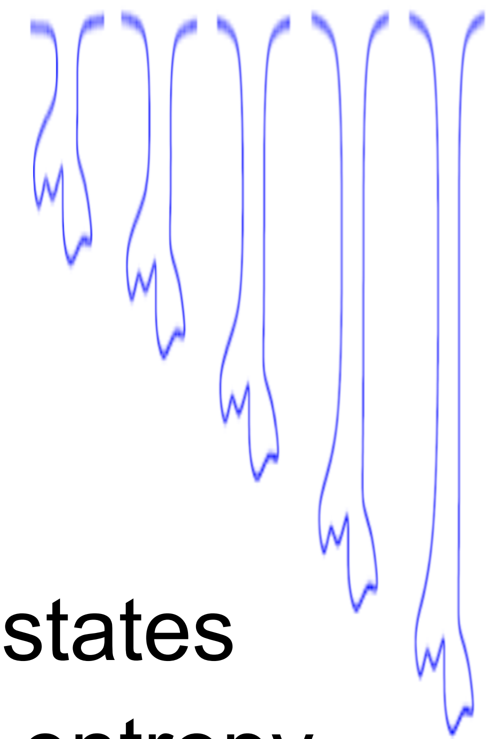
Bena, Heidmann, Turton

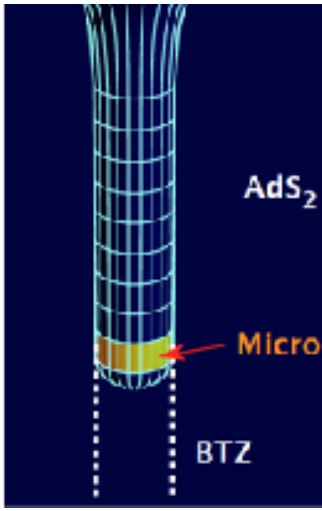
- Everybody & their brother & SYK & JT
- AdS_2 - no finite-energy excitations
  Maldacena, Michelson, Strominger
- backreaction of particle in AdS_2 either
  - destroys UV (work instead with *near-AdS_2*)
  - destroys IR $\rightarrow$ singularity
- Singularities in String Theory and AdS-CFT solved by string and brane dynamics involving extra dimensions 20 years of examples

Quantum Gravity in AdS_2

Bena, Heidmann, Turton

- Typical microstate geometries have long AdS_2 throat
- Limit when length $\rightarrow \infty$
- Disconnect from AdS_3
- Solutions above $\rightarrow$ asymptotically-AdS_2
  Bena, Heidmann, Turton
- Same entropy as microstates
- If superstrata count BH entropy, so do these solutions !





Quantum Gravity in AdS_2

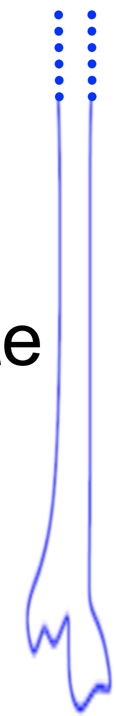
Bena, Heidmann, Turton

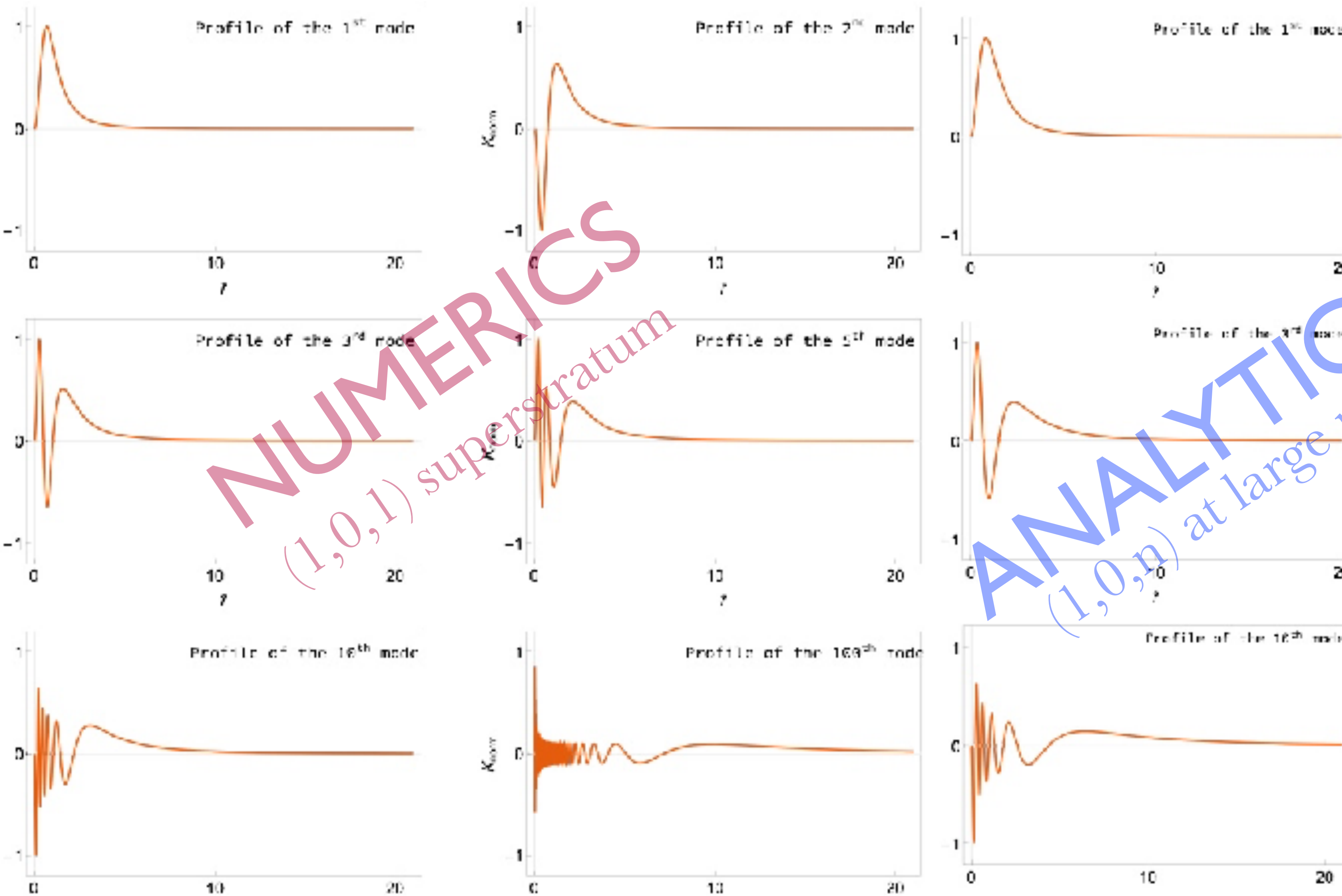
- Lots of geometries with AdS_2 UV and IR cap
- BPS ground states of CFT_1 dual to AdS_2
- finite-energy time-dependent excitations →

Paulos

- CFT_1 has no conf.-invariant ground state !!!
- Empty Poincaré AdS_2 not dual to any ground state of CFT_1 (similar to Poincaré AdS_3)
- All CFT_1 ground states break conf. symmetry
- Tower of finite-energy excitations above each and every one of them
- Microstates of AdS_2 non-extremal black hole

Castro, Grumiller, Larsen, McNees





- Claims that CFT$_1$ does not have such excitations - looking at the wrong ground state

AdS_2/CFT_1 2 options:

Bena, Heidmann, Turton

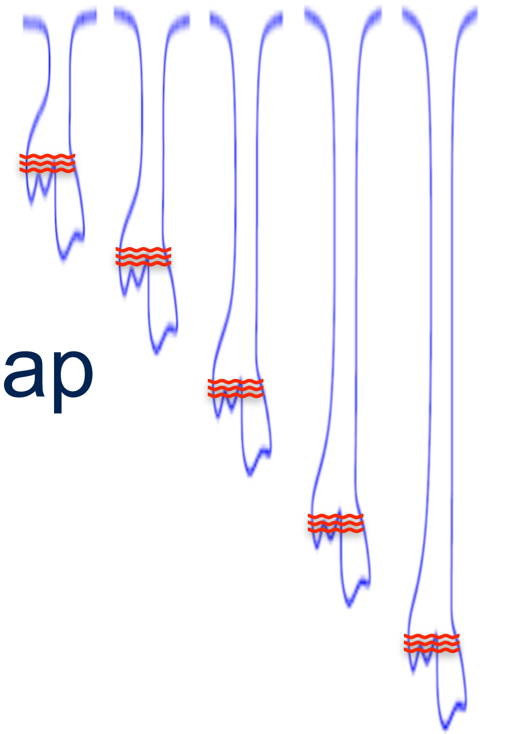
- Keep AdS_2 UV. Work in String Theory
  - Kosher holography
  - All CFT_1 ground states break conf. sym. IR cap
  - Excitations, non-trivial dynamics, entropy
- Destroy AdS_2 UV. Toy models (SYK, J-T)
  - לא כשר: irrelevant ops, IR to UV flows
  - No CFT_1 dynamics. Only nAdS (Singleton-like)
  - Conf. sym. preserved in IR ➡
    Nothing to do with AdS_2/CFT_1 in String Theory

- AdS_2 holography is NOT subtle !
  - Crystal clear if done in String Theory and incorrect assumptions discarded - Mind the Cap !!!

Gluing back to AdS_3

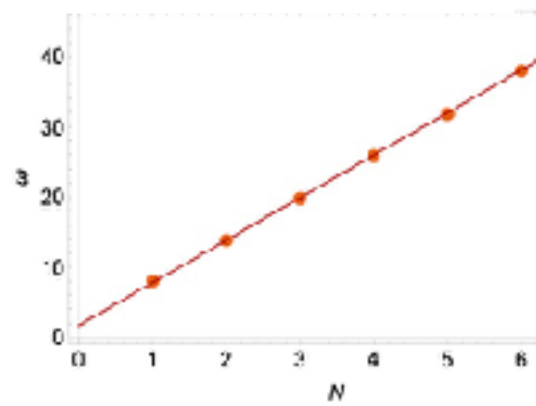
Bena, Heidmann, Turton

- Longer throats with decreasing J
- AdS_3 mass gap depends on length
- smallest gap = 2 J/$N_1 N_5$
- precisely matches smallest CFT_2 gap
- CFT_1 finite-energy excitations → CFT_2 excitations above gap
- Wightman functions also match



Raju, Shrivastava

$$\lambda_{\text{fuzz}} \equiv \lim_{\gamma \to \infty} \frac{\log |G(\omega, \gamma)|}{\gamma} = \lambda_{BH} + \frac{\pi (3n-1) J}{32\, N_1 N_5\, n^{3/2}}$$



Connection with T-branes

Bena, Blåbäck, Savelli, Zoccarato

$$F^{(0,2)} = 0\,, \quad \bar{\partial}_A \Phi = 0\,, \quad \omega \wedge F_2 = [\Phi, \Phi^\dagger]$$

$$A_x = \frac{1}{2}(\Phi_1 + i\Phi_2)$$
$$A_y = \frac{1}{2}(\Phi_3 + i\Phi_4)$$
$$\Phi = \frac{1}{2}(\Phi_5 - i\Phi_6)$$

Constant worldvolume fields T-dualize

$$F^{(0,2)} = -i[A_x, A_y] = 0 \iff \begin{cases} [\Phi_1, \Phi_3] = [\Phi_2, \Phi_4] \\ [\Phi_1, \Phi_4] = [\Phi_3, \Phi_2] \end{cases}$$

$$\bar{\partial}_{\bar{A}_{\bar{x}}} \Phi = 0 = -i[A_{\bar{x}}, \Phi] = 0 \iff \begin{cases} [\Phi_1, \Phi_5] = [\Phi_2, \Phi_6] \\ [\Phi_1, \Phi_6] = [\Phi_5, \Phi_2] \end{cases}$$

$$\bar{\partial}_{\bar{A}_y} \Phi = 0 = -i[A_{\bar{y}}, \Phi] = 0 \iff \begin{cases} [\Phi_3, \Phi_5] = [\Phi_4, \Phi_6] \\ [\Phi_3, \Phi_6] = [\Phi_5, \Phi_4] \end{cases}$$

$$\omega \wedge F_2 - [\Phi, \Phi^\dagger] = [A_x, A_{\bar{x}}] + [A_y, A_{\bar{y}}] - [\Phi, \Phi^\dagger] \iff [\Phi_1, \Phi_2] + [\Phi_3, \Phi_4] + [\Phi_5, \Phi_6]$$

Connection with T-branes

Bena, Blåbäck, Savelli, Zoccarato

Solutions with infinite matrices:

$$D_i = \bigotimes_{j=1}^{6} \left((1-\delta_{ij})\mathbb{I}_M + \delta_{ij} D\right) \ , X_i = \bigotimes_{j=1}^{6} \left((1-\delta_{ij})\mathbb{I}_M + \delta_{ij} X\right) \qquad [D, X] = i\mathbb{I}_M$$

$$\Phi_1 = D_1 - \frac{1}{2}\sqrt{\alpha_1} X_1 X_3$$

$$\Phi_2 = D_2 - \frac{1}{2}\sqrt{\alpha_1} X_1 X_4 - \frac{1}{2}\sqrt{\alpha_2} X_1 X_2$$

$$\Phi_3 = D_3 - \frac{1}{2}\sqrt{\alpha_3} X_3 X_5$$

$$\Phi_4 = D_4 - \frac{1}{2}\sqrt{\alpha_3} X_3 X_6 + \frac{1}{2}\sqrt{\alpha_2} X_3 X_4$$

$$\Phi_5 = D_5 + \frac{1}{2}\sqrt{\alpha_2} X_1 X_5$$

$$\Phi_6 = D_6 + \frac{1}{2}\sqrt{\alpha_2} X_2 X_5 + \frac{1}{2}\sqrt{\alpha_3} X_5 X_6$$

D0	–	–	–	–	–	–
D4	×	×	×	×	–	–
D4	×	×	–	–	×	×
D4	–	–	×	×	×	×

D0 description of 4D susy BH

Only AdS_2 no AdS_3 !

Could give first microscopic counting for such black holes

The take-home story

- Huge number of BH microstate geometries
  - Fns. of 2 variables: ∞ X ∞ dim. moduli space
  - Smooth solutions, low curvature, no horizon
  - Topology and fluxes prevent collapse
  - Black hole entropy
  - Mass gaps, Wightman fns. match typical CFT states
- AdS_2 holography is easy in String Theory
  - IR cap ➡ nontrivial dynamics ➡ CFT_1 NOT topological
  - No conformally-invariant ground state !
  - BH with horizon not dual to any pure CFT state
  - Toy models need to be improved - Mind the Cap !
- T-branes : description BH with only AdS_2 (no AdS_3)
- Extension: extremal non-BPS and non-extremal