Non-Supersymmetric Black Hole Microstates in Supergravity and String Theory

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Based on:
Bossard, Katmadas, DT 1711.04784, JHEP
Martinec, Massai, DT 1803.08505

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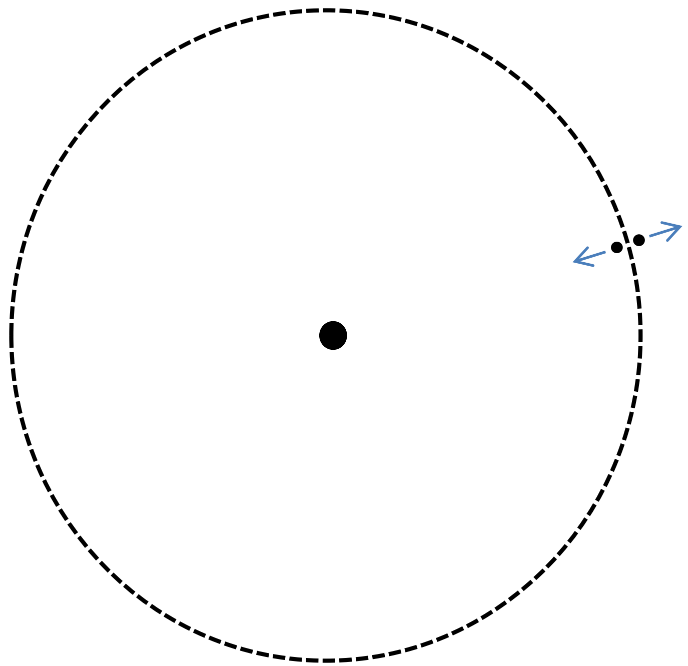
Outline

1. Introduction
2. Non-BPS black hole microstates in supergravity
3. Non-BPS black hole microstates in worldsheet String Theory

The Information Paradox

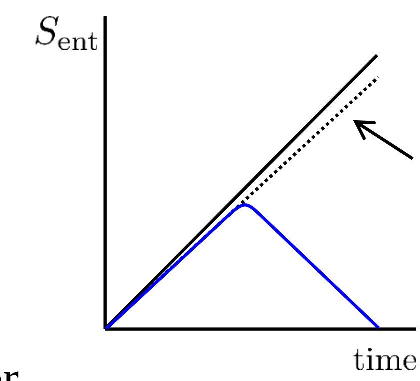
Classical BH horizon:
normal lab physics
(small curvature)



Hawking radiation:
pair creation

$\rightarrow$ entangled pair

$\rightarrow$ Final state not pure?



- Endpoint of process: violation of unitarity or exotic remnants.

  Hawking '75

- Conclusions robust including small local corrections

  Mathur '09

- Much recent interest in implications for physics of infalling observer

  Almheiri, Marolf, Polchinski, Sully '12

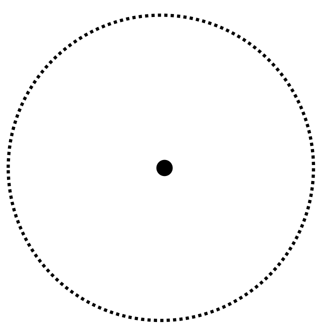
Black Hole Quantum Hair

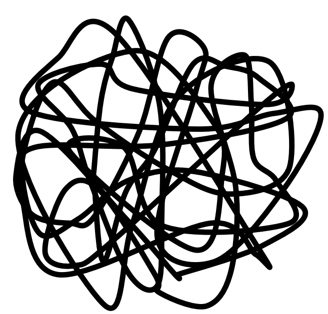
- Bekenstein-Hawking entropy $S \;\rightarrow\; e^{S}$ microstates
- Can physics of individual microstates modify Hawking's calculation?
- Many searches for Black hole 'hair': deformations at the horizon.
- In classical gravity, many 'no-hair' theorems resulted

Israel '67, Carter '71, Price '72…

However, in String Theory, we find examples of Quantum Hair. This suggests that

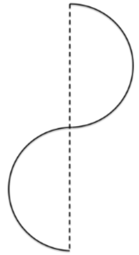
- Quantum effects important at would-be-horizon (fuzz)
- Bound states have non-trivial size (ball)





"Fuzzball"

Two-charge Black hole



Multiwound fundamental string + momentum

- Entropy: exponential degeneracy of microscopic states

Sen '94

- For classical profiles, string sources good supergravity background

  Classical profiles $\leftrightarrow$ coherent states

Dabholkar, Gauntlett, Harvey, Waldram '95
Lunin, Mathur '01

- No horizons; string source
- Transverse vibrations only $\rightarrow$ non-trivial size

F1-P is U-dual to D1-D5 bound state

Lunin, Mathur '01

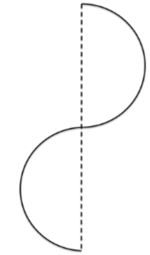
- Configurations are everywhere smooth in D1-D5 frame

Lunin, Maldacena, Maoz '02

- Can study precision holography in this system.

Taylor '05, '07
Skenderis, Taylor '06–'08

Two-charge Black hole



Typical state is highly quantum

- Superposition of profiles including string-scale curvatures

- Supergravity is not a good approximation for typical states.
- However the supergravity solutions give us a comprehensive understanding of this system. (Of course, some details visible only in full String Theory.)
- Original black hole solution is a very good approximation of typical states for many purposes, but microstates have a rich finer quantum structure.
- Typical states are horizon-sized.

Important caveat: two-charge Black hole is string-scale sized.

→ How much of this physics carries over to large black holes?

Large BPS black holes

- D1-D5-P black hole: large BPS black hole in 5D / black string in 6D

- Entropy reproduced from microscopic degrees of freedom

Strominger, Vafa '96

Breckenridge, Myers, Peet, Vafa '96

- Certain microstates admit classical descriptions as supergravity solitons; large classes of three-charge 'microstate geometries' constructed & studied

  (In D1-D5-P as well as other duality frames)

Mathur, Lunin, Bena, Warner, Denef, Moore, de Boer, Ross, Balasubramanian, Gibbons, Giusto, Russo, Shigemori, Martinec, DT,…

- Supergravity solitons are interesting in their own right, for holography, and for the classification of solutions to supergravity theories

Despite much progress, important open questions remain.

1. Can one construct & study (many) solutions which have large near-horizon throats and general values of angular momenta?

2. Can one identify the holographic description of such solutions?

3. What is the gravitational description of non-extremal black hole microstates?

4. How much physics can be captured in supergravity, and to what extent is stringy physics necessary to describe typical states?

Recent progress on each of these; in this talk I will focus on Questions 3 and 4.

The D1-D5 system

D1-D5 system

Consider type IIB string theory on T^4 or K3 (take T^4 for concreteness)

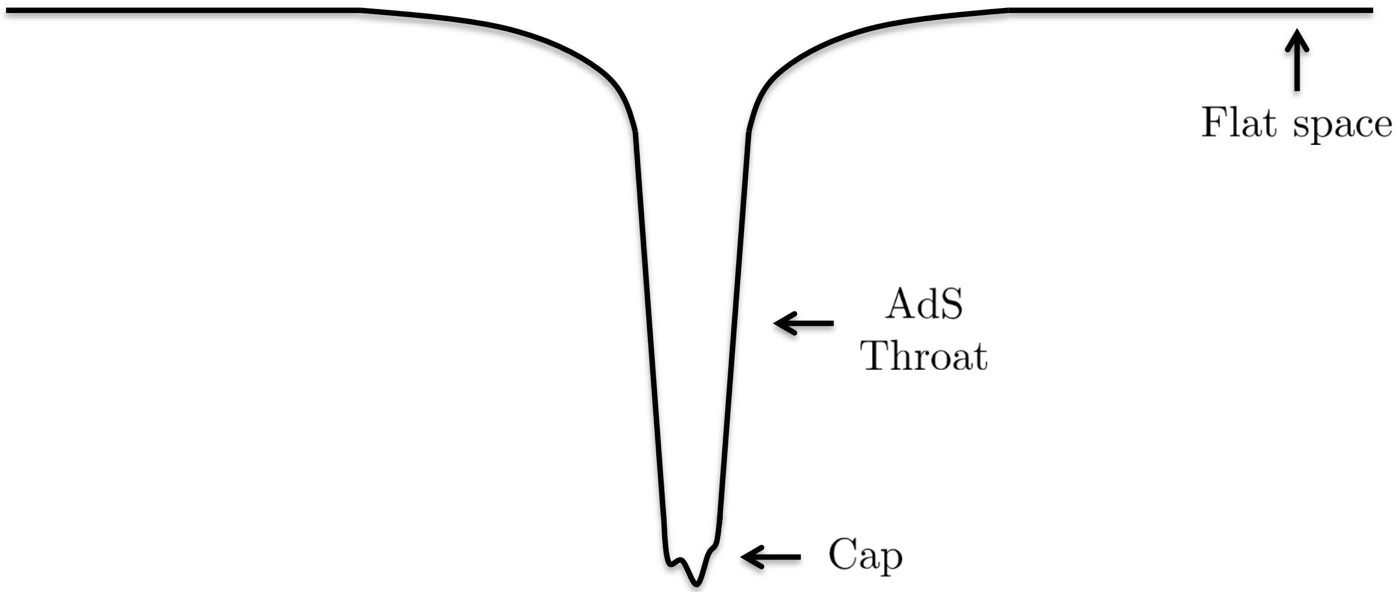
$$\begin{array}{ccccc} \mathbb{R}^{1,4} & \times & S^1 & \times & T^4 \\ t, x^\mu & & y & & z^i \end{array}$$

- Radius of S^1 : R_y
- n_1 D1 branes on S^1
- n_5 D5 branes on $S^1 \times T^4$
- n_P units of momentum along S^1

For states which have geometrical descriptions, the geometry has charges

$$Q_1 = \frac{g_s \alpha'^3}{V} n_1 \,, \qquad Q_5 = g_s \alpha' n_5 \,, \qquad Q_P = g_s^2 \alpha'^4 n_P \,.$$

To get an AdS throat, take $(Q_1 Q_5)^{1/4} \ll R_y$. Structure of geometry is then:



The throat is locally $AdS_3 \times S^3 \times T^4$.

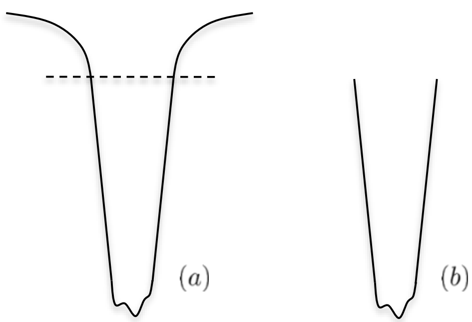
D1-D5 CFT & Holography

- Worldvolume gauge theory on D1-D5 bound state flows in IR to a (1+1)-dimensional $\mathcal{N} = (4,4)$ SCFT.

- Deformation of symmetric product orbifold SCFT with target space $(T^4)^N/S_N$, $N = n_1 n_5$.

Vafa '95, Douglas '95

- Decoupling limit of asymptotically-flat configurations results in asymptotically $AdS_3 \times S^3 \times T^4$ solutions



- One of the original examples of holographic duality.

Maldacena '97

Non-supersymmetric microstates

JMaRT solutions

- The JMaRT solutions are smooth solitons with ergoregions, and they have an associated ergoregion instability

- This can be derived by solving the free massless scalar wave equation, and finding modes which are regular in the cap, outgoing at infinity, and grow with time

Cardoso, Dias, Hobdevo, Myers ’05

- Using AdS/CFT this is interpreted as Hawking radiation from these states, which is enhanced to a classical effect due to the special coherent nature of the states.

Chowdhury, Mathur ’07

JMaRT solutions

- The JMaRT metric is that of the general non-BPS Cvetic-Youm D1-D5-P solution, which includes both black hole solutions and smooth solitons:

$$
\begin{aligned}
\mathrm{d}s^2 \quad = \quad & -\frac{f}{\sqrt{\tilde{H}_1\tilde{H}_5}}(\mathrm{d}t^2-\mathrm{d}y^2)+\frac{M}{\sqrt{\tilde{H}_1\tilde{H}_5}}(s_p\mathrm{d}y-c_p\mathrm{d}t)^2 \\
& +\sqrt{\tilde{H}_1\tilde{H}_5}\left(\frac{r^2\mathrm{d}r^2}{(r^2+a_1^2)(r^2+a_2^2)-Mr^2}+\mathrm{d}\theta^2\right) \\
& +\left(\sqrt{\tilde{H}_1\tilde{H}_5}-(a_2^2-a_1^2)\frac{(\tilde{H}_1+\tilde{H}_5-f)\cos^2\theta}{\sqrt{\tilde{H}_1\tilde{H}_5}}\right)\cos^2\theta\mathrm{d}\psi^2 \\
& +\left(\sqrt{\tilde{H}_1\tilde{H}_5}+(a_2^2-a_1^2)\frac{(\tilde{H}_1+\tilde{H}_5-f)\sin^2\theta}{\sqrt{\tilde{H}_1\tilde{H}_5}}\right)\sin^2\theta\mathrm{d}\phi^2 \\
& +\frac{M}{\sqrt{\tilde{H}_1\tilde{H}_5}}(a_1\cos^2\theta\mathrm{d}\psi+a_2\sin^2\theta\mathrm{d}\phi)^2 \\
& +\frac{2M\cos^2\theta}{\sqrt{\tilde{H}_1\tilde{H}_5}}[(a_1c_1c_5c_p-a_2s_1s_5s_p)\mathrm{d}t+(a_2s_1s_5c_p-a_1c_1c_5s_p)\mathrm{d}y]\mathrm{d}\psi \\
& +\frac{2M\sin^2\theta}{\sqrt{\tilde{H}_1\tilde{H}_5}}[(a_2c_1c_5c_p-a_1s_1s_5s_p)\mathrm{d}t+(a_1s_1s_5c_p-a_2c_1c_5s_p)\mathrm{d}y]\mathrm{d}\phi+\sqrt{\frac{\tilde{H}_1}{\tilde{H}_5}}\sum_{i=1}^{4}\mathrm{d}z_i^2
\end{aligned}
$$

where

$$
\begin{aligned}
\tilde{H}_i \quad &= \quad f+M\sinh^2\delta_i, \qquad f \;=\; r^2+a_1^2\sin^2\theta+a_2^2\cos^2\theta, \\
c_i \quad &= \quad \cosh\delta_i\,, \qquad\quad s_i \;=\; \sinh\delta_i
\end{aligned}
$$

Cvetic, Youm ’96

Jejjala, Madden, Ross, Titchener ’05

Holographic description

- Orbifold CFT on $(T^4)^N/S_N$: N copies of $c=6$ T^4 sigma model, fields:

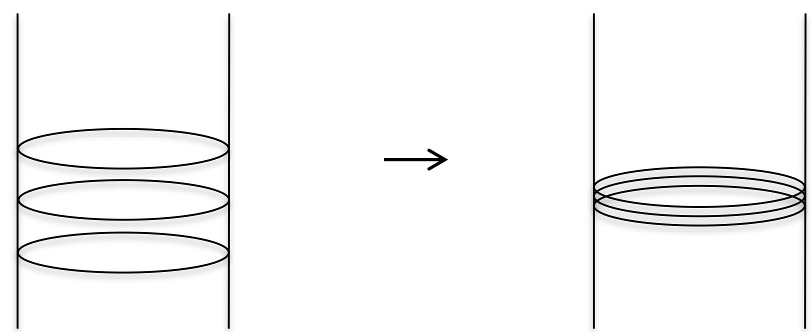
$$X_{A\dot{A}} \qquad \psi^{\alpha A} \qquad \bar{\psi}^{\dot{\alpha} A} \qquad\qquad \mathcal{N}=(4,4)$$

- Twist operators: permute fields, 'link together' different copies:

$$\sigma_k : \qquad \begin{array}{l} X^{(1)} \to X^{(2)} \to \cdots \to X^{(k)} \to X^{(1)} \\ \psi^{(1)} \to \psi^{(2)} \to \cdots \to \psi^{(k)} \to -\psi^{(1)}. \end{array}$$

- The operator σ_k links together k copies of the sigma model to effectively make a single CFT on a circle k times longer.

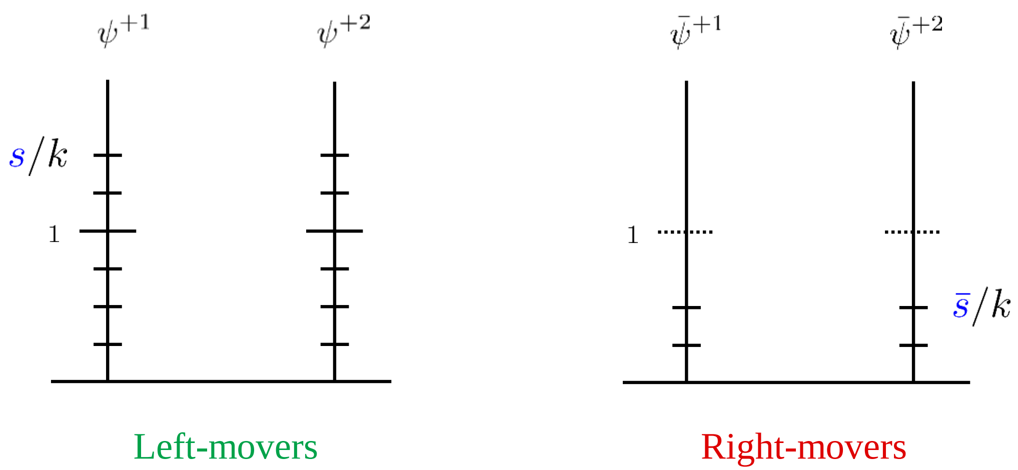
σ_3 :



'Strand' of length k

Holographic description

- Consider Fermi seas filled to fractional level s/k in left-moving sector, and $\bar{s}/k$ in right-moving sector



- These states arise from fractional spectral flow by s/k in left-moving sector, and $\bar{s}/k$ in right-moving sector

Chakrabarty, DT, Virmani, 1508.01231, JHEP

Holographic description

Parameter space of general JMaRT solutions:

- n_1 , n_5 : number of D1 and D5 branes
- R_y : Radius of the y circle at infinity
- $\mathfrak{m}$, $\mathfrak{n}$: integers parameterising the two angular momenta
- k : orbifold parameter

Holographic description: N/k strands of length k in the D1-D5 orbifold CFT, excited by independent L & R fractional spectral flow with parameters

$$\alpha = \frac{s+1/2}{k} , \qquad \bar{\alpha} = \frac{\bar{s}+1/2}{k} .$$

Identification of parameters:

$$\boxed{\mathfrak{m} = s + \bar{s} + 1 , \qquad \mathfrak{n} = s - \bar{s}}$$

Chakrabarty, DT, Virmani 1508.01231, JHEP

see also JMaRT '05; Avery, Chowdhury, Mathur '07-'09

New system containing non-extremal solitons

Open problem for >10 years: How to systematically generalize the JMaRT solutions?

- Spatial slices of JMaRT solutions have topology $\mathbb{R}^2 \times \mathrm{S}^3$
- There are families of BPS solutions that have many topological cycles, or “bubbles”
- Can one construct multi-bubble families that generalize JMaRT solutions?

New system containing non-extremal solitons

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System recently constructed that achieves this

Bossard, Katmadas '14

Bena, Bossard, Katmadas, DT, 1611.03500, JHEP

- Relatively simple basic set of equations,
  although they involve a non-linear first layer that is hard to solve
- Somewhat complicated ansatz built from these quantities
  $\rightarrow$ smoothness analysis is quite involved.
- New two-bubble solutions found

Bena, Bossard, Katmadas, DT, 1511.03669, JHEP

Bossard, Katmadas, DT, 1711.04784, JHEP

We work in 6D $\mathcal{N} = (1,0)$ supergravity coupled to n_T tensor multiplets.

- This section: focus on $n_T = 1$.
- Field content: metric, two-form potential, scalar.

Ansatz is organised as a fibration over a 3D base space, with metric γ_{ij} .

Ansatz functions: $V, \overline{V}, K_I, L^I, M$, $I = 1, 2, \ldots n_T + 2$.

- V, $\overline{V}$ determine γ_{ij} and parameterize an auxiliary 4D gravitational instanton
- K_I, L^I parameterize the matter fields supporting the configuration
- M parameterizes an angular momentum.

- Non-linear first layer:

  data of an auxiliary 4D gravitational instanton (JMaRT: Kerr-NUT)

- Linear layers on top of this build (5+1)-dimensional solutions supported by flux

First Layer: $V, \ \overline{V}$ parameterize an auxiliary 4D Ricci-flat gravitational instanton, with an isometry. Non-linear equations.

$$\Delta V = \frac{2\,\overline{V}}{1+V\overline{V}}\,\nabla V\cdot\nabla V\,, \qquad \Delta\overline{V} \;=\; \frac{2\,V}{1+V\overline{V}}\,\nabla\overline{V}\cdot\nabla\overline{V}\,,$$

$$R(\gamma)_{ij} = -\frac{\partial_{(i}V\,\partial_{j)}\overline{V}}{(1+V\overline{V})^2}\,.$$

Sequentially-Linear Layers: sources are solutions to previous layer(s).

$$\begin{aligned}
\Delta K_I &= \frac{2\,V}{1+V\overline{V}}\,\nabla\overline{V}\cdot\nabla K_I\,,\\
\Delta L^I &= \frac{1}{2}\,\frac{V}{1+V\overline{V}}\,C^{IJK}\,\nabla K_J\cdot\nabla K_K\,,\\
\Delta M &= \nabla\cdot\left(\frac{V}{1+V\overline{V}}\,\left(L_I\nabla K^I - 2\,M\nabla\overline{V}\right)\right)\,.
\end{aligned}$$

Bena, Bossard, Katmadas, DT, 1611.03500, JHEP

6D Einstein-frame metric: fibration over a 3D base. Asymptotics: $\begin{matrix} \mathbb{R}^{1,4} & \times & S^1 \\ t, \psi, x^i & & y \end{matrix}$

$$ds^2 = \frac{H_3}{\sqrt{H_1 H_2}}(dy + A^3)^2 - \frac{W}{H_3\sqrt{H_1 H_2}}(dt + k)^2 + \sqrt{H_1 H_2}\Big(\frac{1}{W}(d\psi + w^0)^2 + \gamma_{ij} dx^i dx^j\Big)$$

$$A^3 \;=\; A^3_t\,(dt + \omega) + \alpha^3\,(d\psi + w^0) + w^3\,, \qquad k \;=\; \frac{\mu}{W}\,(d\psi + w^0) + \omega$$

Dilaton: $$e^{2\phi} = \frac{H_1}{H_2}$$

Two-form potentials: similar fibration structure, satisfying twisted self-duality condition for three-form field strengths:

$$\star_6 G_1 = -e^{-2\phi} G_2$$

Part of ansatz:

$$
\begin{aligned}
W =& \left((1+\overline{V})\, M - \frac{1}{2}\, K_I L^I + \frac{1}{4}\, \frac{V}{1+V\overline{V}}\, K_1\, K_2\, K_3 \right)^2 \\
&+ \frac{1-V}{1+V\overline{V}} \left(K_1\, K_2\, K_3\, M + 2\,(1+\overline{V})\, L^1\, L^2\, L^3 - \frac{1}{4}\, C^{IJK} K_J K_K\, C_{ILM} L^L L^M \right) , \\
H_I =& \frac{1}{2}\, C_{IJK}\, L^J L^K - K_I\, M + \frac{1}{2}\, \frac{V}{1+V\overline{V}} \left((K_J L^J)\, K_I - \frac{1}{2} C_{IJK} L^J\, C^{KLP}\, K_L K_P \right) , \\
\mu =& (1+\overline{V})\, M^2 - \frac{1}{2}\, M\, K_I L^I - \left(1 + 2\, \frac{V-1}{1+V\overline{V}} \right) L^1\, L^2\, L^3 \\
&+ \frac{1}{2}\, \frac{V}{1+V\overline{V}} \left(-\frac{1}{6}\, K_1\, K_2\, K_3\, M + \frac{1}{4}\, C^{IJK} K_J K_K\, C_{ILM} L^L L^M \right) .
\end{aligned}
$$

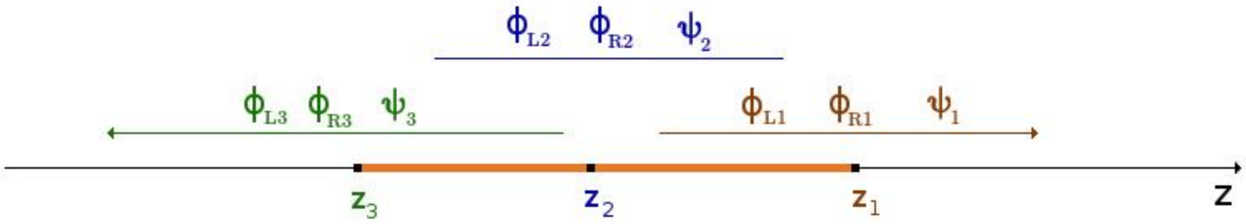
$$
\begin{aligned}
\star d\omega =& dM - \frac{V}{1+V\overline{V}} \left(L^I\, dK_I - 2\, M\, d\overline{V} \right) , \\
\star dw^0 =& -(1+\overline{V})\, dM - \frac{1}{2}\, \frac{1 - V\overline{V} - 2\, V}{1+V\overline{V}} \left(L^I\, dK_I - 2\, M\, d\overline{V} \right) + \frac{1}{2}\, K_I\, dL^I \\
&- \frac{1}{4}\, \frac{V}{1+V\overline{V}}\, d\,(K_1\, K_2\, K_3) + \frac{1}{4}\, \frac{K_1\, K_2\, K_3}{(1+V\overline{V})^2} \left(V^2 d\overline{V} + dV \right) , \\
\star dw^I =& dL^I - \frac{1}{4}\, \frac{V}{1+V\overline{V}}\, d \left(C^{IJK}\, K_J K_K \right) + \frac{1}{4\,(1+V\overline{V})^2}\, C^{IJK}\, K_J K_K \left(V^2 d\overline{V} + dV \right) .
\end{aligned}
$$

State-of-the-art solutions: we take the first layer to be an instanton with two non-trivial topological 2-cycles, known as bolts

- Resulting (5+1)-D sugra solutions have two topologically non-trivial 3-cycles that are naturally thought of as bolts in the five spatial dimensions.

Chen, Teo, ’11, ’15

Smoothness analysed in local coordinates near the special points of the solution.



Bossard, Katmadas, DT, 1711.04784, JHEP

Two-bolt 4D gravitational instanton

$$ds_4^2 = \frac{F}{(x-y)\,H}\left(d\tau + \frac{G}{F}\,d\varphi\right)^2 + \frac{H}{(x-y)^3\,F}\left(\kappa^2 F\left(\frac{dx^2}{X} + \frac{dy^2}{Y}\right) + X\,Y\,d\varphi^2\right),$$

where

$$X = P(x)\,, \quad Y = -P(y)\,.$$

$$P(u) = a_0 + a_1 u + a_2 u^2 + a_3 u^3 + a_4 u^4 = a_4(u-t_1)(u-t_2)(u-t_3)(u-t_4)\,.$$

$$\begin{aligned} F(x,y) &= x^2\,Y + y^2\,X\,, \\ H(x,y) &= (\nu\,x + y)\big[(\nu\,x - y)(a_1 - a_3\,x\,y) - 2\,(1-\nu)\,\big(a_0 - a_4\,x^2\,y^2\big)\big], \\ G(x,y) &= X\left[\nu^2\,a_0 + 2\,\nu\,a_3\,y^3 + (2\,\nu - 1)\,a_4\,y^4\right] - Y\left[(1 - 2\,\nu\ )\,a_0 - 2\,\nu\,a_1\,x - \nu^2\,a_4\,x^4\right] \end{aligned}$$

and where κ and ν are two additional constant parameters.

There is also an unphysical reparametrisation redundancy (1 real parameter),

so the base solution has 6 real parameters overall.

Two-bolt solutions

Two-bolt solutions: rich parameter space.

– 6 integer parameters parameterizing the smooth geometry at the bolts, plus

2 real parameters encoding the charges, subject to polynomial constraints.

Physically interesting features include:

- Near-BPS solutions with large AdS_3 throats
- Far-from-extremal solutions: arbitrarily small charge-to-mass ratio
  - Approaches neutral Myers-Perry regime
- Fluxes on bolts can be both aligned or anti-aligned

Bossard, Katmadas, DT, 1711.04784, JHEP

String Dynamics of Black Hole Microstates

String dynamics in NS5-F1-P geometries

String theory contains much more than supergravity.

To what extent is the physics of strings and branes necessary to describe black hole interior structure?

- On general grounds, expected to be important.

- Example: Microstate geometries contain topological cycles at the bottom of a throat; branes wrapping those cycles are massive, but become light as one increases the length of the throat. Such branes have been dubbed “W-branes”.

Martinec ’14

An S-duality from D1-D5-P to NS5-F1-P results in a background that has pure NS-NS flux – easier to deal with on the worldsheet.

$$Q_1 = \frac{g_s^2 \alpha'^3}{V} n_1 , \qquad Q_5 = \alpha' n_5 , \qquad Q_P = \frac{g_s^2 \alpha'^4}{R_y^2 V} n_P .$$

We work with the JMaRT solutions, and also their supersymmetric limit.

Jejjala, Madden, Ross, Titchener ’05

Giusto, Mathur, Saxena ’04

Giusto, Lunin, Mathur, DT 1211.0306, JHEP

Consider the large R_y supergravity regime, in which we have the hierarchy of scales

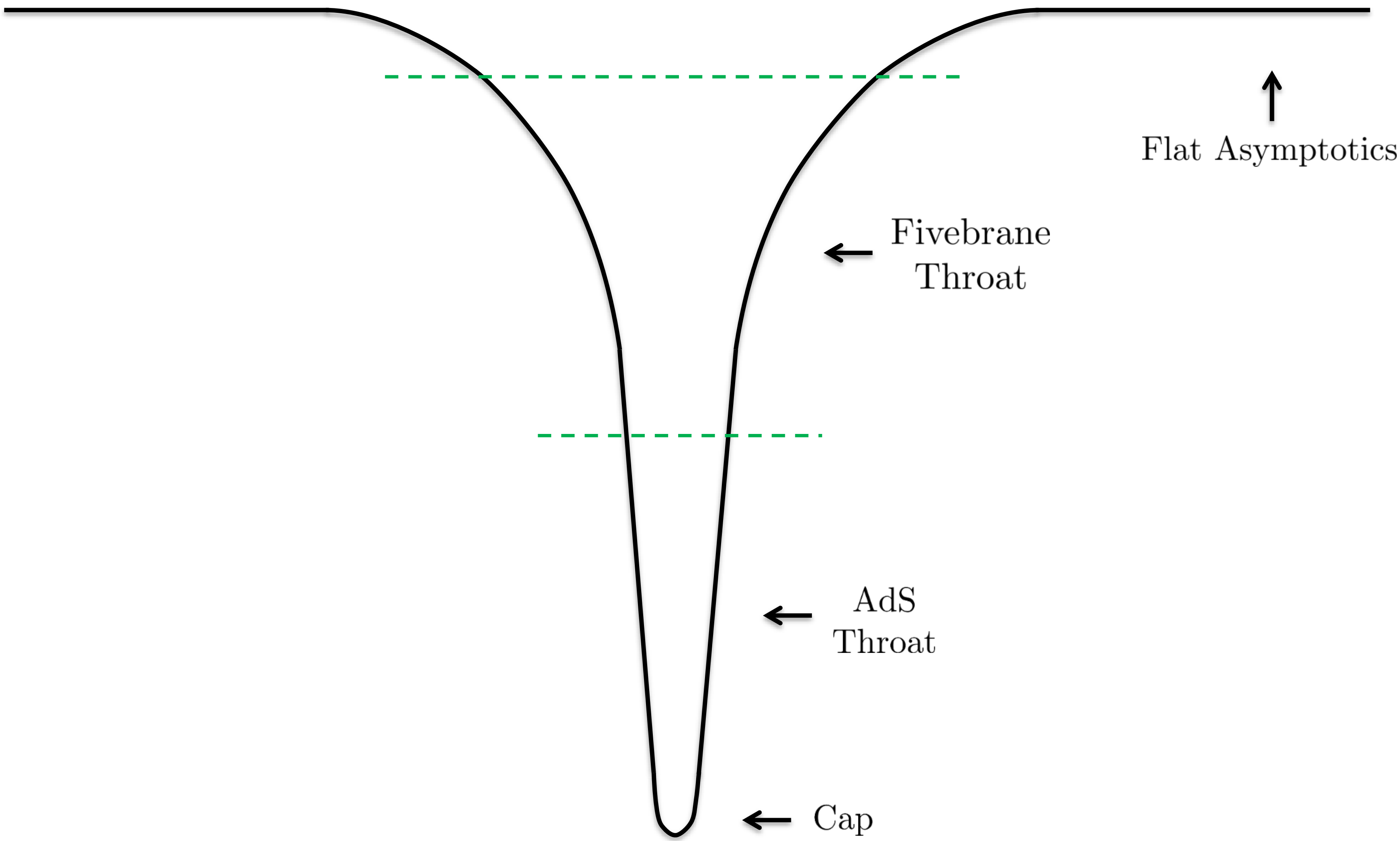
$$Q_5 \gg Q_1 \gg Q_p\,, \qquad\qquad \frac{Q_5}{\alpha'} \equiv n_5 \gg 1\,.$$

Take the NS5 decoupling limit – this results in an asymptotically linear-dilaton background,

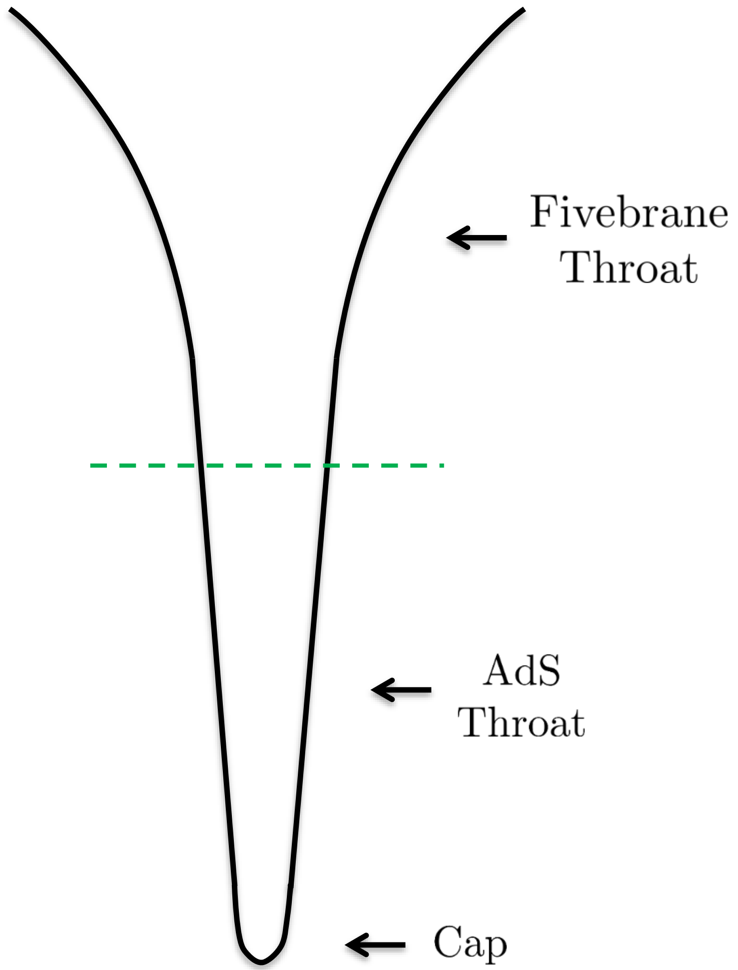
$$ds^2 \;\sim\; -dt^2 + dy^2 + Q_5(d\rho^2 + d\Omega_3^2) + \sum_{a=1}^{4} dz_a^2\,, \qquad\qquad \Phi \;\sim\; -\rho\,.$$

The background has an $\mathrm{AdS}_3 \times \mathrm{S}^3$ region in the IR.

Full geometry:



NS5-brane decoupling limit:



Worldsheet CFT

The worldsheet description of the JMaRT solutions is a particular gauged $\mathcal{N}=1$ supersymmetric Wess-Zumino-Witten model,

$$\mathcal{S}_{WZW}(g,\mathsf{k}) = \frac{\mathsf{k}}{2\pi}\int \mathrm{Tr}\left[(\partial g)g^{-1}(\bar\partial g)g^{-1}\right] + \Gamma_{WZ}(g)\,.$$

WZW model is 10+2-dimensional a priori – null gauging removes 1+1 directions

$$\frac{\mathrm{SL}(2,\mathbb{R})_{n_5}\times \mathrm{SU}(2)_{n_5}\times \mathbb{R}_t\times \mathrm{S}^1_y}{\mathrm{U}(1)_{\mathrm{L}}\times \mathrm{U}(1)_{\mathrm{R}}}\times \mathrm{T}^4$$

- Asymmetric null gauging; null currents $\mathcal{J}\,,\bar{\mathcal{J}}$

$$\mathcal{S}^{\mathcal{G}}_{gWZW} = \mathcal{S}^{\mathcal{G}}_{WZW} + \frac{1}{\pi}\int d^2\hat{z}\left[\mathcal{A}\bar{\mathcal{J}} + \bar{\mathcal{A}}\mathcal{J} - \frac{\Sigma}{2}\bar{\mathcal{A}}\mathcal{A}\right]$$

Worldsheet CFT

Integrating out the gauge field results in a sigma model on various backgrounds of interest, depending on the choice of null currents $\mathcal{J}\,,\bar{\mathcal{J}}$

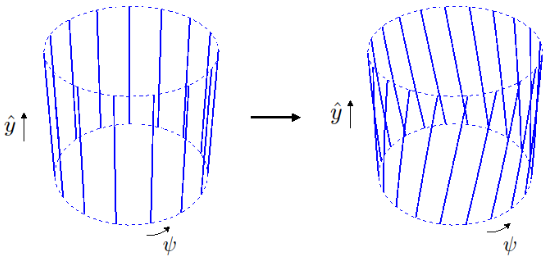
(Dilaton generated at one loop as usual.)

Backgrounds that can be generated in this way include:

- NS5 branes on Coulomb branch, in a circular $\mathbb{Z}_{n_5}$-symmetric configuration

Israel, Kounnas, Pakman, Troost '04

- NS5-P helical supertube
- NS5-F1 helical supertube
- NS5-F1-P spectral flowed BPS solutions
- NS5-F1-P JMaRT – spectral flowed non-BPS solutions.



The gauging procedure leaves gauge constraints that must be respected.

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Null currents:

$$\begin{aligned} \mathrm{U}(1)_{\mathrm{L}}: &\quad \mathcal{J} = l_1 J_3^{\mathrm{sl}} + l_2 J_3^{\mathrm{su}} - l_3 \partial t + l_4 \partial y \,, \\ \mathrm{U}(1)_{\mathrm{R}}: &\quad \bar{\mathcal{J}} = r_1 \bar{J}_3^{\mathrm{sl}} + r_2 \bar{J}_3^{\mathrm{su}} - r_3 \bar{\partial} t + r_4 \bar{\partial} y \,, \end{aligned}$$

where

$$0 = \langle \mathbf{l}, \mathbf{l} \rangle = n_5(-l_1^2 + l_2^2) - l_3^2 + l_4^2 \quad , \qquad 0 = \langle \mathbf{r}, \mathbf{r} \rangle = n_5(-r_1^2 + r_2^2) - r_3^2 + r_4^2$$

NS5-F1-P JMaRT background:

$$\begin{aligned} l_1 &= -\mu \sinh\zeta \,, \quad l_2 = -\mu \cosh\zeta \,, \quad l_3 = \sqrt{n_5}\,\mu \cosh\xi \,, \quad l_4 = -\sqrt{n_5}\,\mu \sinh\xi \,, \\ r_1 &= -\mu \sinh\bar{\zeta} \,, \quad r_2 = -\mu \cosh\bar{\zeta} \,, \quad r_3 = \sqrt{n_5}\,\mu \cosh\bar{\xi} \,, \quad r_4 = +\sqrt{n_5}\,\mu \sinh\bar{\xi} \,. \end{aligned}$$

where

$$\mu^2 = \frac{M}{2n_5} \,, \quad \xi = \delta_1 - \delta_p \,, \quad \bar{\xi} = \delta_1 + \delta_p \,, \quad e^{2\zeta} = \frac{\mathfrak{m} + \mathfrak{n} + 1}{\mathfrak{m} + \mathfrak{n} - 1} \,, \quad e^{2\bar{\zeta}} = \frac{\mathfrak{m} - \mathfrak{n} + 1}{\mathfrak{m} - \mathfrak{n} - 1} \,.$$

BPS limit: can treat at same time – simply set $\mathfrak{m} = s + 1, \, \mathfrak{n} = s$.

Closed string spectrum

- The gauge constraints, together with the Virasoro constraints, determine the spectrum of closed strings on these backgrounds

- Supergravity sector contains bound states in cap as well as scattering states

- Due to the modified asymptotics of the NS5 decoupling limit, we find no instability (unlike in the asymptotically-flat solutions)

- Correspondingly, in the NS5 decoupling limit there is always a globally timelike Killing vector field, so indeed no ergoregion instability is expected.

- We do however identify the modes that become unstable in the asymptotically-flat solutions.

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Closed string spectrum

For generic parameters $\mathfrak{m}\,,\mathfrak{n}\,,k\,,$ the background has non-supersymmetric orbifold singularities: another potential source of instability

- However the worldsheet CFT is not an orbifold CFT, so results from string theory on non-supersymmetric orbifolds do not directly apply
- We find no instability in the worldsheet description.

Worldsheet spectral flow in SL(2,R) & SU(2) generates additional states of interest

- E.g. giant graviton strings winding around AdS_3 & S^3

Strings wound along y can be absorbed or emitted by the background; such processes are conveniently described in terms of large gauge transformations on the worldsheet.

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String-flux transitions

Spectral flow in axial gauge direction is a large gauge symmetry

- This relates y-winding number to worldsheet spectral flow parameters, exchanging one for the other.

The amount of spectral flow is not conserved in correlators, so neither is y-winding.

Correspondingly, in the sugra background, there are no non-contractible cycles.

Strings with non-zero y-winding carry same F1 charge as background H_3 flux.

- Total F1 charge is conserved

  $\rightarrow$ F1 charge can be exchanged between background flux and wound strings.

c.f. Gregory, Harvey, Moore '97,
Tong '02, Giusto, Mathur '10

This physics is nicely encoded via the above large gauge transformations.

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Summary

- New system that allows construction of non-BPS supergravity solutions, and new two-bolt solutions explicitly constructed
- String worldsheet CFT on background of BPS & non-BPS supergravity solutions studied, and rich spectrum analyzed
- Much more to do!