Black Hole Microstates in Supergravity and String Theory

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Black Holes, Quantum Information and Space-time Reconstruction
CERN TH Institute
Aug 28, 2018

Based on:
Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner 1607.03908, PRL
Bossard, Katmadas, DT 1711.04784, JHEP
Martinec, Massai, DT 1803.08505, JHEP
Bena, Heidmann, DT 1806.02834

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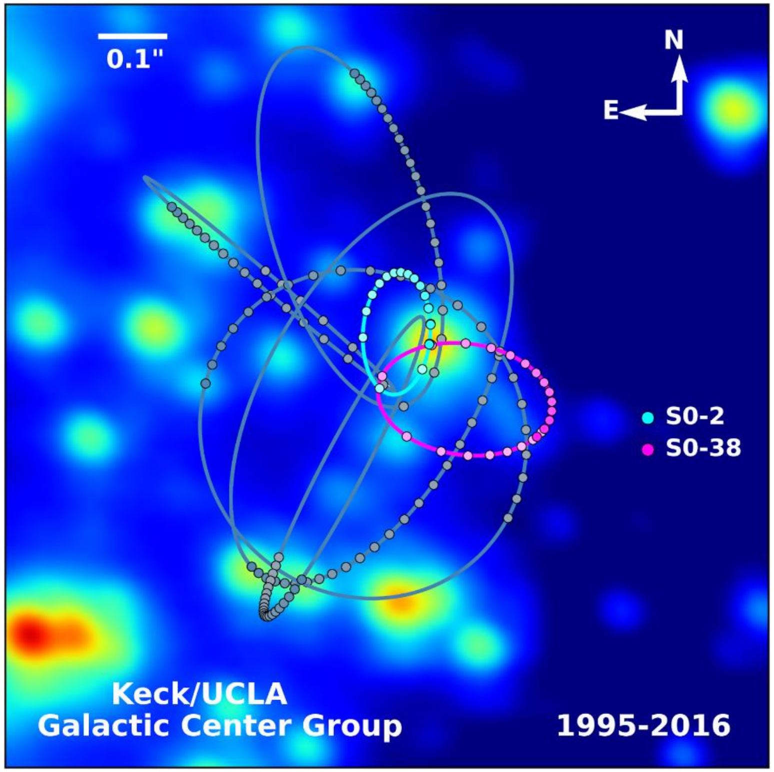
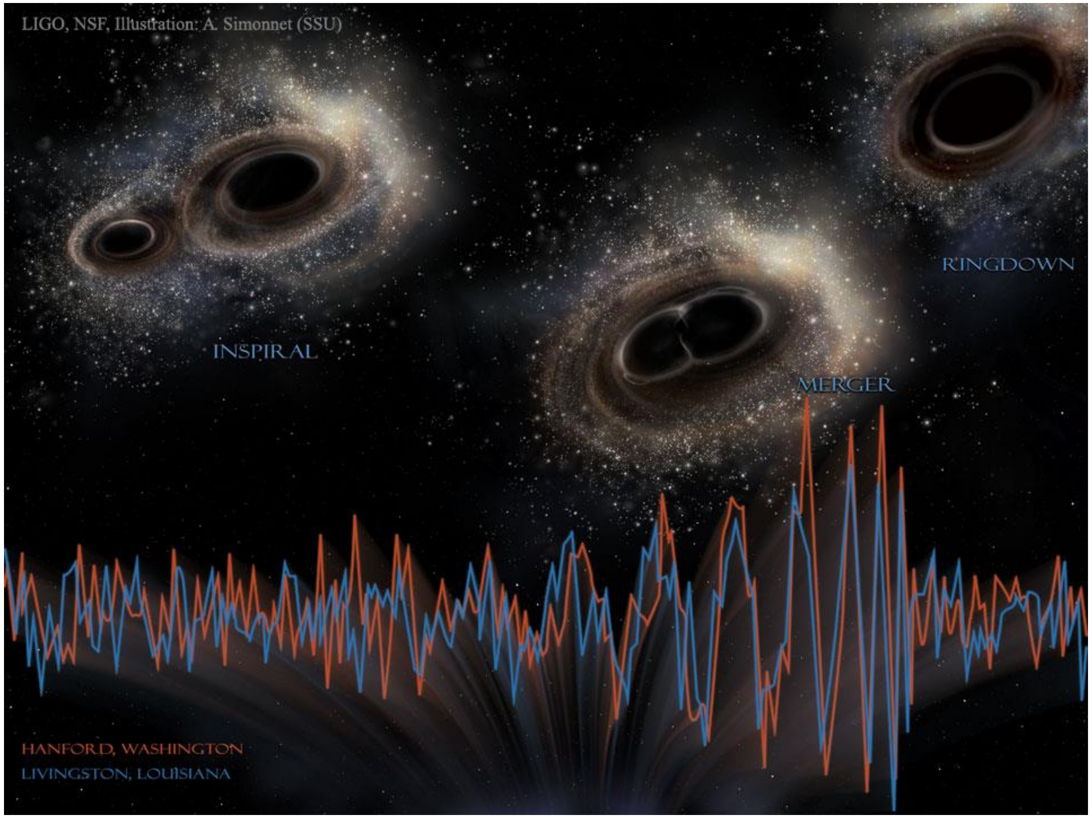
THE ROYAL SOCIETY

Outline

1. Motivations
2. Supersymmetric microstates
3. Non-supersymmetric microstates
4. String dynamics
5. Falling into a black hole

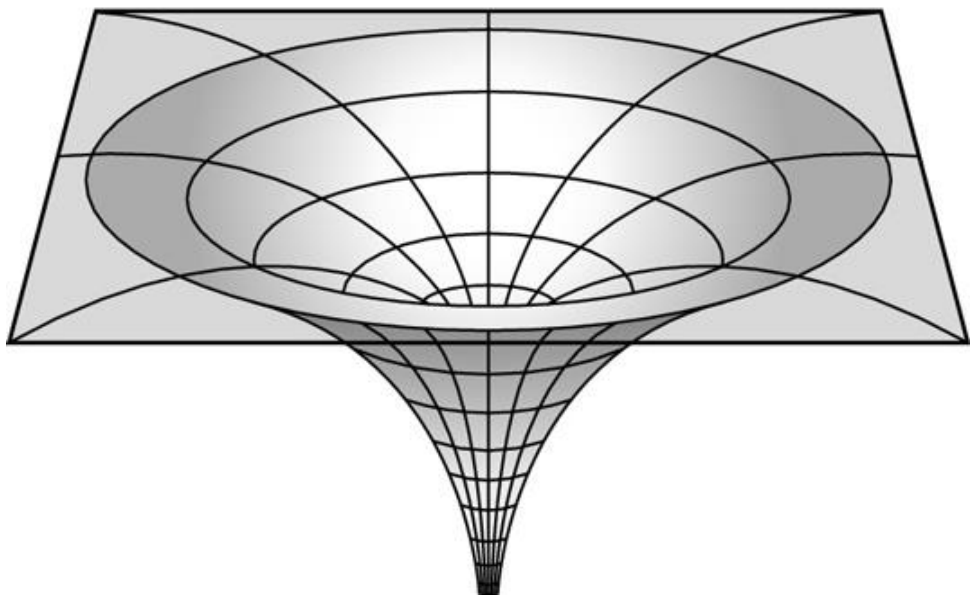
There is now strong evidence for the existence of black holes.





Classically, black holes are solutions to gravitational theories

with horizons and singularities.



Quantum mechanically however, black holes are much more mysterious.

1. Non-extremal black holes have finite temperature, and evaporate.

2. In a complete theory, black hole singularities must be resolved.

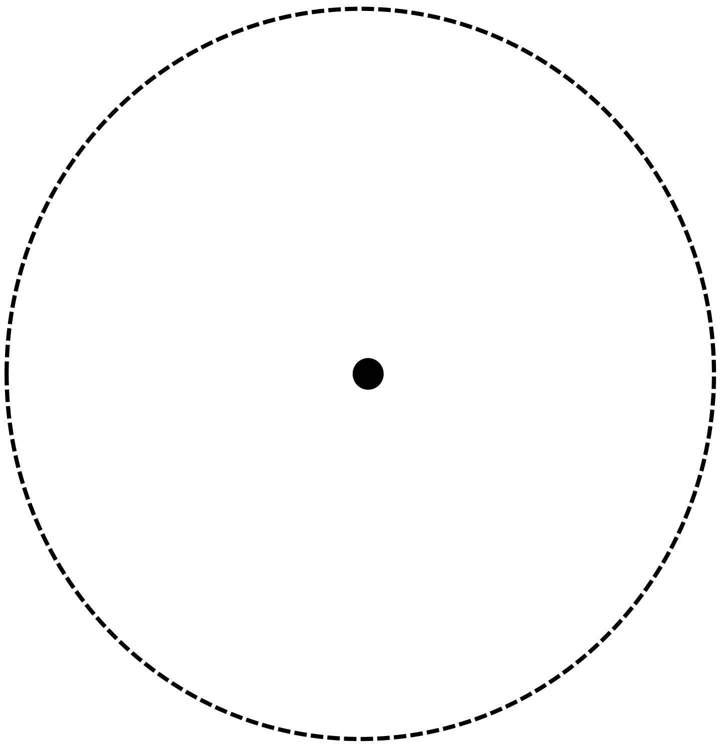
At present, we do not have a complete and consistent description of black hole interiors, nor of black hole evaporation.

This is a challenge for any theory of quantum gravity.

Semi-classical Black Hole

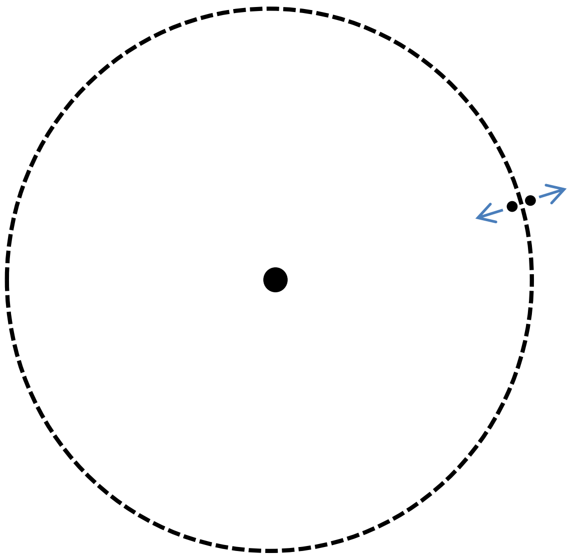
Standard semi-classical model of a black hole formed from collapse:

Once the black hole has settled down to a quasi-stationary state, the region around the horizon is the vacuum of freely infalling observers (Unruh vacuum).



For a large black hole, we have low curvature, so a priori we expect to trust normal lab physics of QFT in curved spacetime.

The Information Paradox



QFT in curved spacetime predicts that black holes evaporate via the production of pairs of entangled particles from the vacuum region around the horizon.

As long as the black hole remains large, the entanglement between the black hole and its surroundings is predicted to increase.

This is in sharp conflict with unitary evolution.

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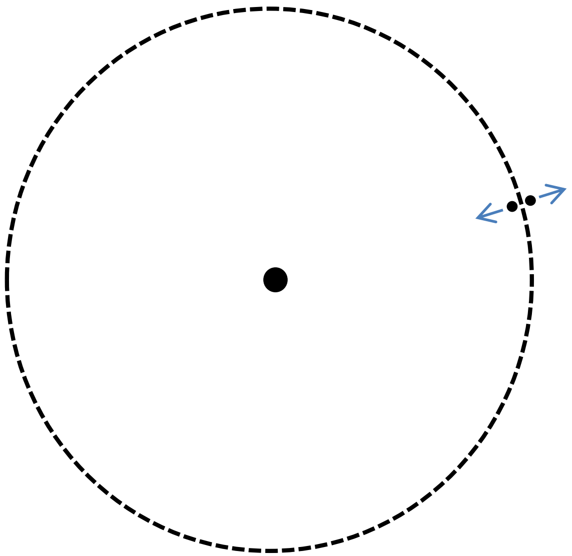

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Endpoint of process: violation of unitarity or exotic remnants.

Hawking '75

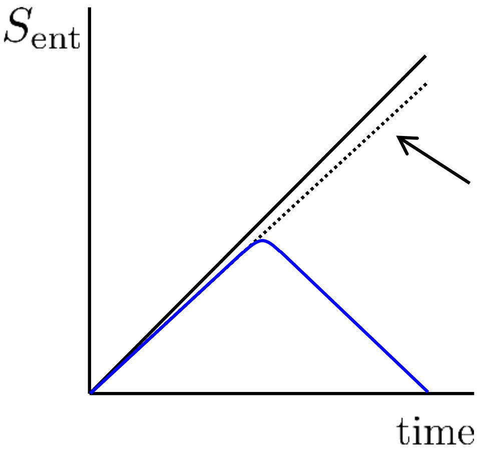
Entanglement entropy in conflict with unitary 'Page curve'.

Page '93

Including small corrections due to arbitrary physics inside

& near the horizon does not solve the problem.

Mathur '09



Black Hole 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, Robinson '75,…

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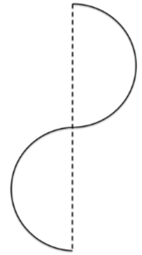
However, in String Theory, we find a much more interesting situation.

Two-charge Black hole



Consider a multi-wound fundamental string F1 carrying momentum P.

- 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

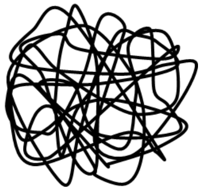
Lunin, Maldacena, Maoz '02

- 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 Planck-scale curvatures

- Supergravity is not a good approximation for typical states.
- However the family of supergravity solutions is useful for entropy counting (upon appropriate quantization) and for estimating the size of typical states
- Supergravity solutions indicate that typical states have size of would-be-horizon.

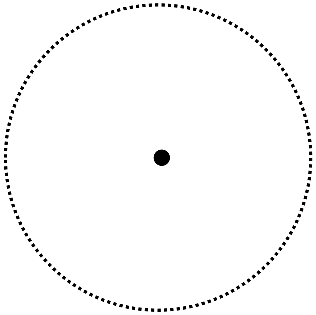
Lunin, Mathur '02

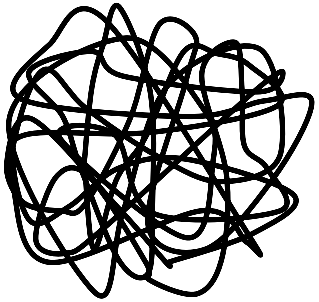
- Original black hole solution is a good approximation of typical states for many purposes, but microstates have a rich finer quantum structure that extends out to the would-be-horizon.

Black Hole Quantum Hair

So in String Theory, we have examples of quantum hair. This suggests the conjecture that:

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





"Fuzzball"

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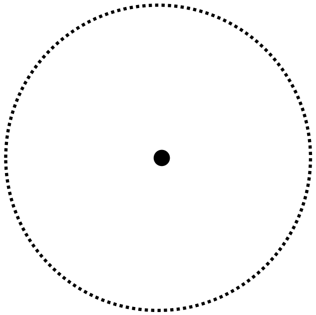
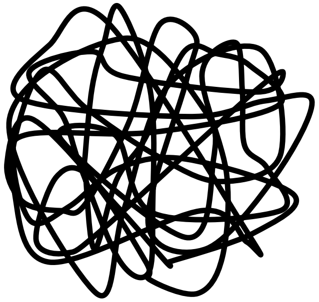




"Fuzzball"

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

$\rightarrow$ How much of this physics carries over to large black holes?

- Note other approaches to BH quantum hair – relation is an open question.

Hawking, Perry, Strominger '16

Large supersymmetric black holes

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

- Entropy reproduced from counting 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, Strominger,
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 and/or quantum physics necessary to describe typical states?

In this talk I will report progress on each of these questions.

The D1-D5 system

D1-D5 system: setup

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

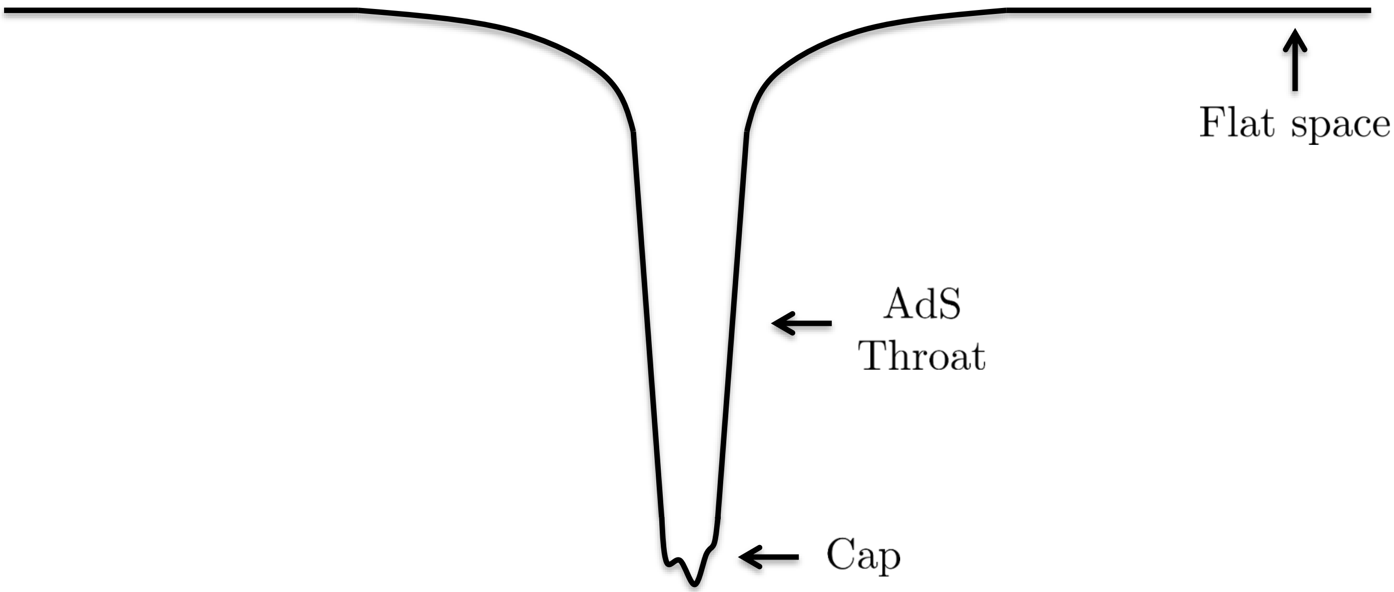
$$\begin{array}{ccccc} \mathbb{R}^{1,4} & \times & S^1 & \times & \mathrm{T}^4 \\ t, x^\mu & & y & & z^i \end{array}$$

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

For states which have geometrical descriptions, the geometry has charges

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

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



The throat is locally $\mathrm{AdS}_3 \times \mathrm{S}^3 \times \mathrm{T}^4$.

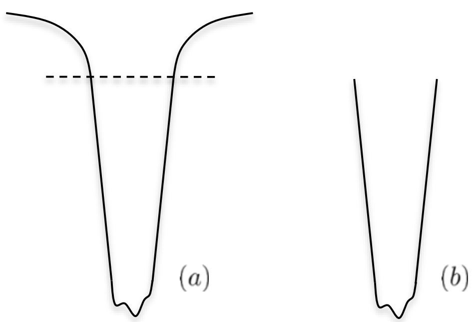
D1-D5 CFT & Holography

- 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

Supersymmetric microstates

Smooth horizonless geometries

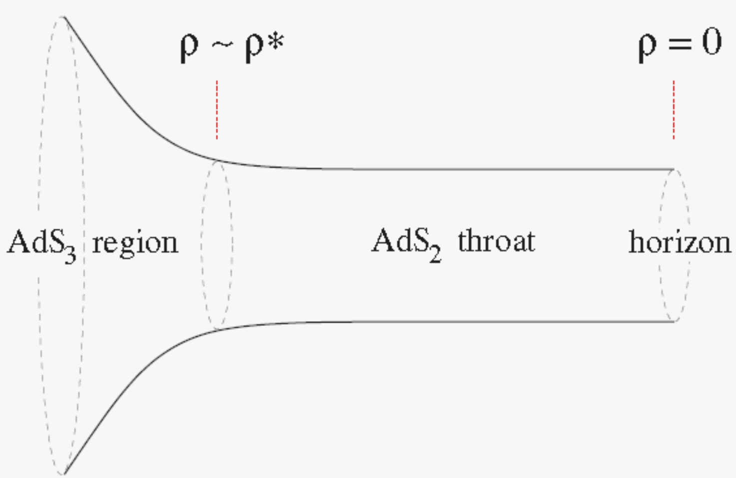
deep inside the black hole regime

D1-D5-P black holes

D1-D5-P BPS black string in 6D: near-horizon geometry is S^3 fibered over extremal BTZ black hole,

$$ds^2_{\mathrm{BTZ}} = \ell^2_{\mathrm{AdS}}\left[\rho^2(-dt^2 + dy^2) + \frac{d\rho^2}{\rho^2} + \rho_*^2(dy + dt)^2\right]$$

$$\ell^2_{\mathrm{AdS}} = \sqrt{Q_1 Q_5}\,, \qquad \rho^2 = \frac{r^2}{Q_1 Q_5}\,, \qquad \rho_*^2 = \frac{Q_{\mathrm{P}}}{Q_1 Q_5}\,.$$



- BTZ solution is locally AdS_3 everywhere, with global identifications
- "Very-near-horizon" throat:
  S^1 fibered over AdS_2

Strominger '98

The black hole regime

- The angular momentum of rotating D1-D5-P black string/BMPV black hole is bounded above by the charges:

$$j_L < \sqrt{n_1 n_5 n_{\mathrm{P}}}$$

- Desire solutions with microstructure inside large AdS_2 throat.

- Until recently, examples (“scaling solutions”) known only in the range

$$0.85 \lesssim \frac{j_L}{\sqrt{n_1 n_5 n_{\mathrm{P}}}} \leq 1$$

Bena, Wang, Warner ’06

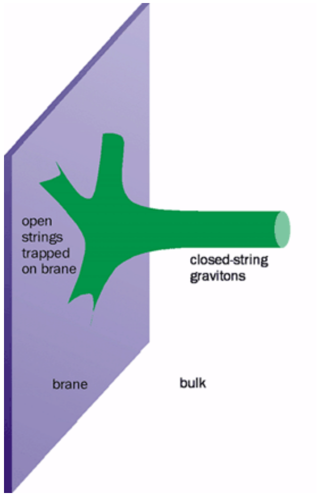
(see more recently Heidmann ’17, Bena, Heidmann, Ramirez ’17)

and CFT description not known.

- New solutions: have large AdS_2 throats, probe the entire range of values of j_{L}, & we give a proposal for the dual CFT states.

BPS D1-D5-P solutions in 6D

- IIB sugra on T^4. 6D theory: minimal sugra coupled to two tensor multiplets
- For configurations invariant on the T^4, this 6D theory contains all fields that arise in worldsheet calculations of the backreaction of D1-D5-P bound states



Giusto, Russo, DT 1108.6331, JHEP

- The general BPS 6D metric takes the form:

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\left[du+\omega-\frac{Z_3}{2}(dv+\beta)\right]+\sqrt{\mathcal{P}}\,ds_4^2$$

Gutowski, Martelli, Reall '03

Giusto, Martucci, Petrini, Russo '13

$$\mathcal{P} = Z_1 Z_2 - Z_4^2 \qquad\qquad v = t+y\,, \quad u = t-y$$

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$$v=t+y\,,\quad u=t-y$$

The BPS eqns have an almost-linear structure: (Layer 1 is non-linear, the rest are linear)

1. Base metric ds_4^2 , one-form β

2. Scalars $Z_1,\, Z_2,\, Z_4$, two-forms $\Theta_1,\, \Theta_2,\, \Theta_4$

3. Scalar Z_3 , one-form ω

Giusto, Martucci, Petrini, Russo '13

Smooth solutions deep inside the black hole regime

Layer 1 solution:

We take ds_4^2 (flat R^4) and β to be those of a seed solution,

$$ds_4^2 = \frac{\Sigma\, dr^2}{r^2+a^2} + \Sigma\, d\theta^2 + (r^2+a^2)\sin^2\theta\, d\phi^2 + r^2\cos^2\theta\, d\psi^2\,,$$

$$\beta \;=\; \frac{R_y}{\sqrt{2}}\frac{a^2}{\Sigma}(\sin^2\theta\, d\phi - \cos^2\theta\, d\psi)\,,$$

where $$\Sigma = r^2 + a^2\cos^2\theta\,.$$

Smooth solutions deep inside the black hole regime

- The solutions depend explicitly on the angular directions, through three positive integer parameters (k, m, n), $m \leq k$, parameterizing the phase

$$\hat{v}_{k,m,n} \equiv \frac{\sqrt{2}}{R_y}(m+n)\,v + (k-m)\phi - m\psi$$

"Superstratum"

- The solutions contain a continuous parameter a/b, where
  - b controls the momentum charge
  - a controls the angular momenta

Smoothness: $\boxed{a^2 + \frac{b^2}{2} = \frac{Q_1 Q_5}{R_y^2}}$

- The asymptotically $AdS_3 \times S^3$ metrics are independent of u, v, ψ, ϕ.
  - Dependence on $\hat{v}_{k,m,n}$ is only through the matter fields.

Layer 2 solution:

$$Z_1 = \frac{Q_1}{\Sigma} + \frac{R_y^2}{2Q_5} b_4^2 \frac{\Delta_{2k,2m,2n}}{\Sigma} \cos \hat{v}_{2k,2m,2n} \,, \qquad Z_2 = \frac{Q_5}{\Sigma} \,,$$

$$Z_4 = b_4 R_y \frac{\Delta_{k,m,n}}{\Sigma} \cos \hat{v}_{k,m,n}$$

$$\mathcal{P} = Z_1 Z_2 - Z_4^2$$

$$\Delta_{k,m,n} \equiv \frac{a^k r^n}{(r^2 + a^2)^{(k+n)/2}} \cos^m \theta \, \sin^{k-m} \theta$$

- Given this solution to Layer 2, the final layer of the BPS equations can then be solved to find Z_3 and ω.

- Smoothness imposes the condition:

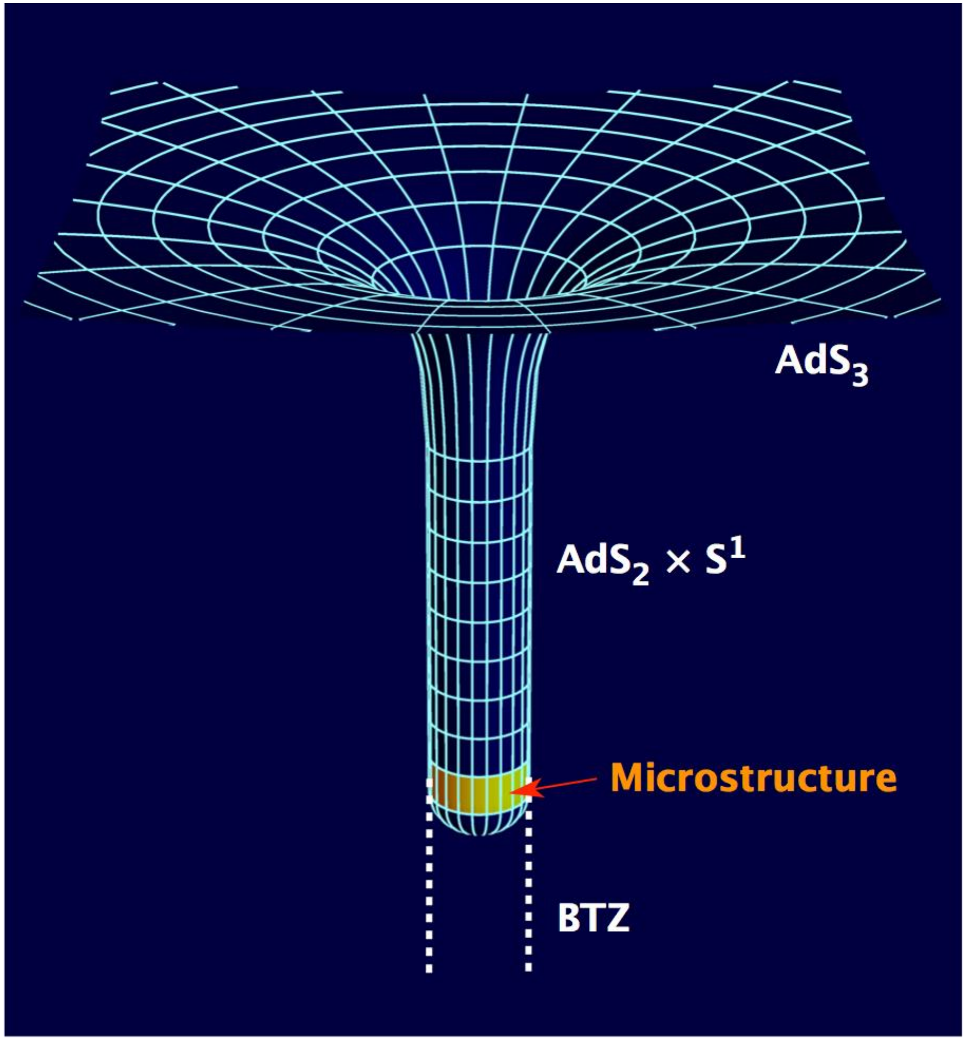
$$\boxed{\frac{Q_1 Q_5}{R_y^2} = a^2 + \frac{b^2}{2} \,,} \qquad b^2 = x_{k,m,n}\, b_4^2 \,, \qquad x_{k,m,n}^{-1} \equiv \binom{k}{m} \binom{k+n-1}{n}$$

Structure of the solutions

- Solutions are asymptotically $AdS_3 \times S^3$.

(Asymptotically flat extensions have also been constructed).

- For $a \ll b$, the geometry has the following structure:



CFT description

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

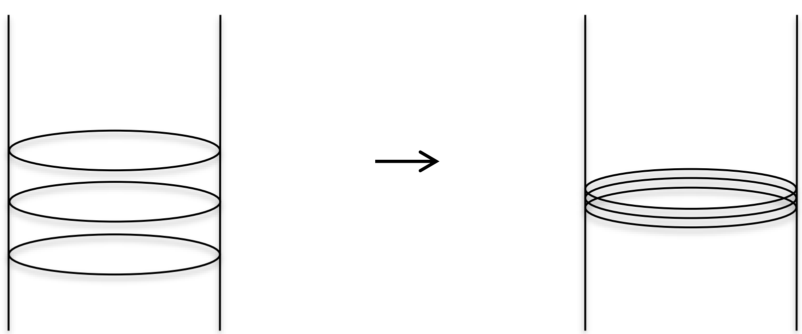
$$X_{A\dot{A}} \qquad \psi^{\alpha A} \qquad \bar{\psi}^{\dot{\alpha} A} \qquad\qquad \mathcal{N}=(4,4)$$

- 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

- There are five T^4-invariant, bosonic R-R ground states in each twist sector

- We label them by their charges under $SU(2)_L \times SU(2)_R$ $\quad (+\frac{1}{2}\,, -\frac{1}{2}\,, \quad \text{or} \quad 0)\,,$

$$|\pm\pm\rangle_k \;, \qquad\qquad |00\rangle_k \;.$$

- On each strand, there are L and R-moving small N = 4 superconformal algebras. L-moving bosonic generators:

  - Virasoro symmetry L_n
  - SU(2) R-symmetry $J_n^{\pm}\,,\; J_n^3$

CFT description

- Our proposed CFT description is a particular family of coherent states:

$$\sum C_{N_1} \Big(|{+}{+}\rangle_1 \Big)^{N_1} \Big((J^+_{-1})^m (L_{-1} - J^3_{-1})^n |00\rangle_k \Big)^{N_{k,m,n}}$$

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where the sum runs over the allowed partitions $\boxed{N_1 + kN_{k,m,n} = N\,.}$

The coefficients $\{C_{N_1}\}$ are determined by the parameter a/b .

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- The conserved charges match precisely between gravity and CFT

Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner 1607.03908, PRL

- Further holographic tests are possible

Kanitscheider, Skenderis, Taylor '06, '07

Giusto, Moscato, Russo '15

Comments

These microstates are atypical, coherent states.

The bulk description of typical microstates is an open question.

However, this is the first family of microstate geometries with large AdS_2 throats, general values of angular momentum, and identified dual CFT_2 states.

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- Certain sub-families display complete integrability of null geodesics

Bena, DT, Walker, Warner arXiv:1709.01107, JHEP

- These solutions have been completed to asymptotically-flat solutions.
  The resulting metric depends explicitly on the phase $\hat{v}_{k,m,n}$.

Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner 1711.10474, JHEP

- Using solution-generating techniques and dualities, one can construct similar solutions describing microstates of the MSW system on T^6

Maldacena, Strominger, Witten '97

Bena, Martinec, DT, Warner 1703.10171, JHEP

AdS_2 Holography: Mind the Cap

One can define a general AdS_2 limit for large classes of smooth horizonless solutions.

- Generalization of "very near-horizon" limit of BTZ / D1-D5-P BPS BH Strominger '98

This limit takes the family of superstrata discussed above to smooth capped AdS_2 superstrata, whose asymptotics are $AdS_2 \times S^1 \times S^3$.

If one forcibly reduces to 2D, these solutions are geometrically singular, since one has reduced on the cycle that shrinks smoothly in the IR to make the smooth cap.

Unlike other approaches to AdS_2 quantum gravity that deform the UV, here the UV is undeformed and we have non-trivial physics in the IR.

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Holography suggests that these solutions should correspond to some pure states in a putative dual CFT_1.

One can solve for excitations of these solutions; the backreaction of these excitations is a very interesting open question, which may have implications for the dual CFT_1.

Bena, Heidmann, DT, arXiv:1806.02834

Non-supersymmetric microstates

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:

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

where

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

Cvetic, Youm '96

Jejjala, Madden, Ross, Titchener '05

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

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?

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- Can one construct multi-bubble families that generalize JMaRT solutions?

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.

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

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

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

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: $\begin{array}{ccc} \mathbb{R}^{1,4} & \times & S^1 \\ t, \psi, x^i & & y \end{array}$

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

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

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:

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

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

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

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

Chen, Teo, ’11, ’15

- 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.

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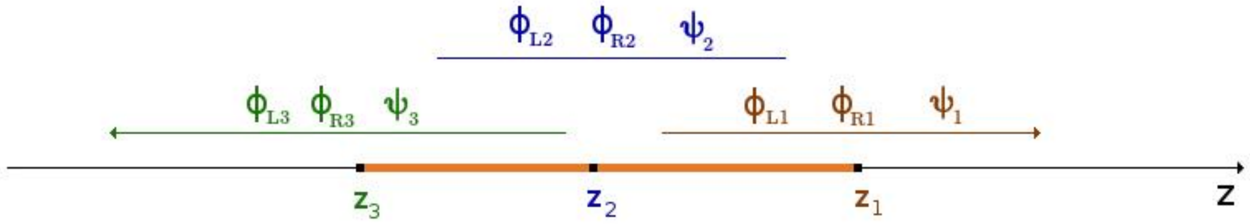
Smoothness analysed in local coordinates near the special points of the solution.



Bossard, Katmadas, DT, 1711.04784, JHEP

Two-bolt solutions

These new smooth two-bolt solutions have a rich parameter space.

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

Beyond supergravity:

Black hole microstates

in string worldsheet CFT

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, may be 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

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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

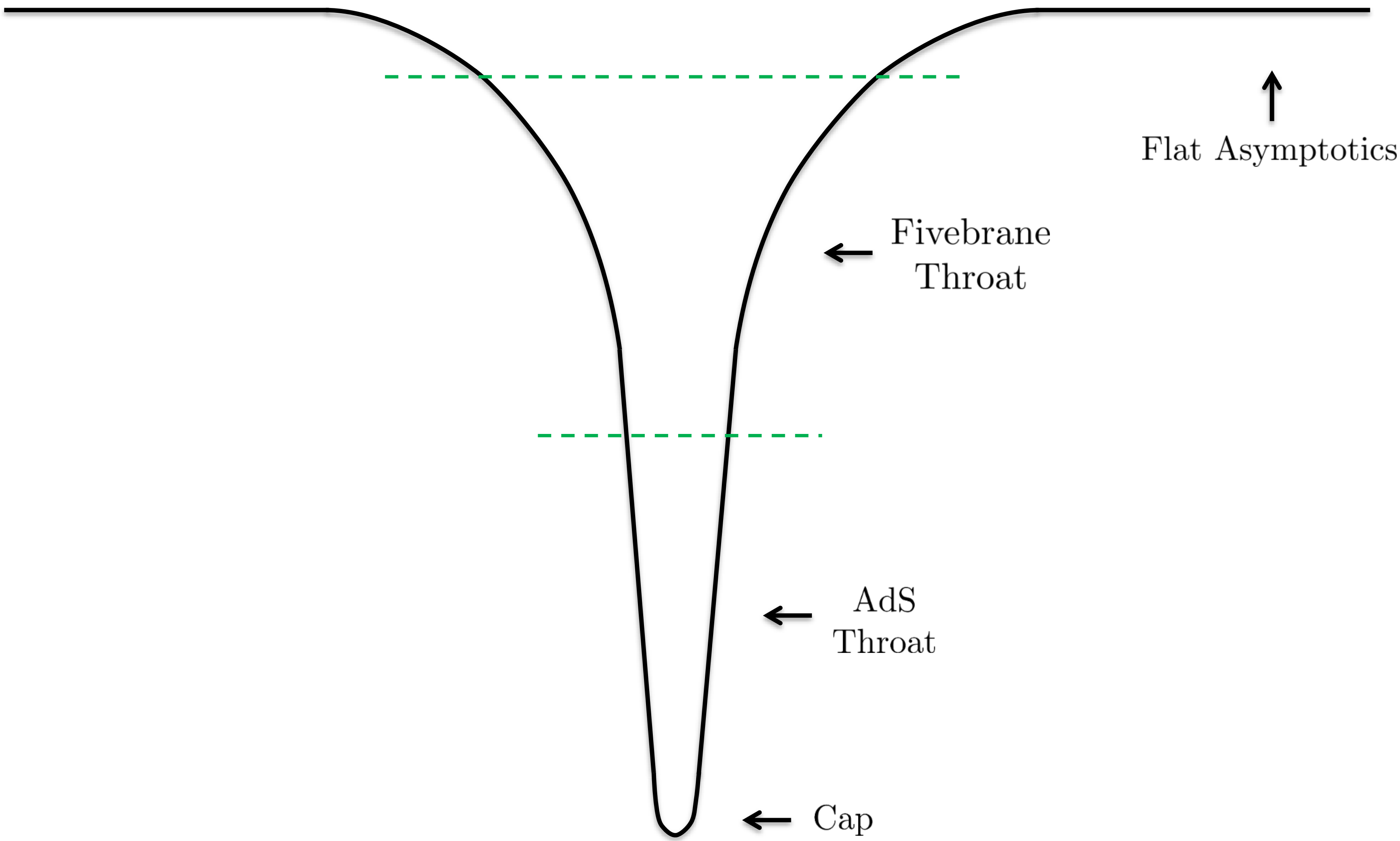
$$Q_5 \gg Q_1 \gg Q_p \,, \qquad\qquad \frac{Q_5}{\alpha'} \equiv n_5 \gg 1 \,.$$

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

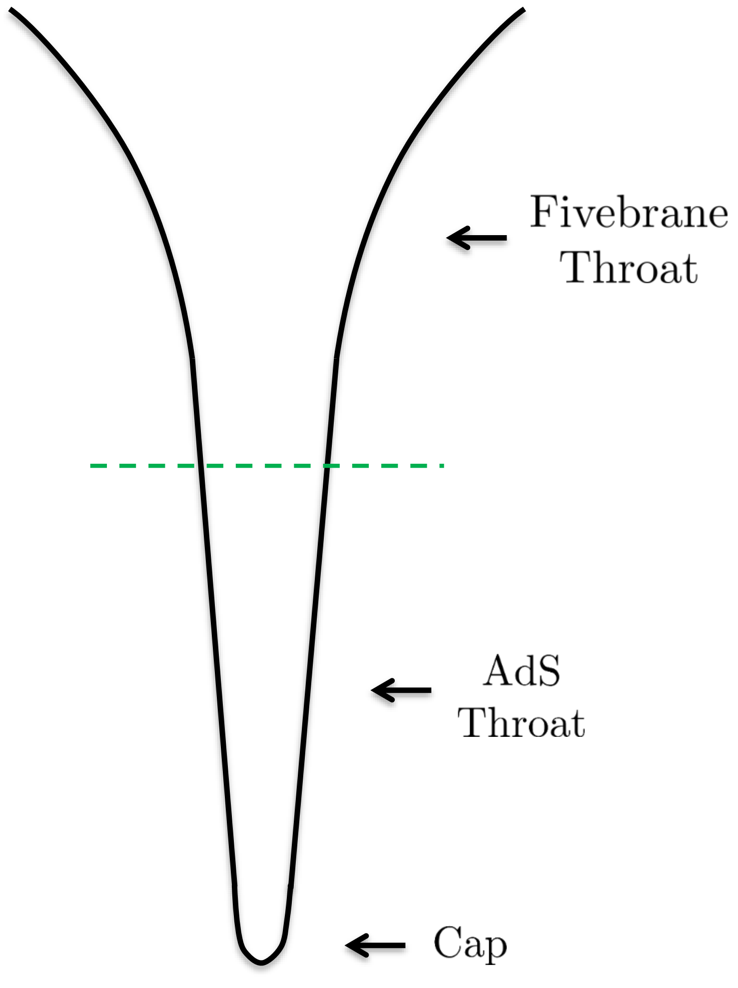
$$ds^2 \;\sim\; -\,dt^2 + dy^2 + Q_5(d\rho^2 + d\Omega_3^2) + \sum_{a=1}^{4} dz_a^2 \,, \qquad\qquad \Phi \;\sim\; -\,\rho \,.$$

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 $\mathcal{J}\,,\bar{\mathcal{J}}$

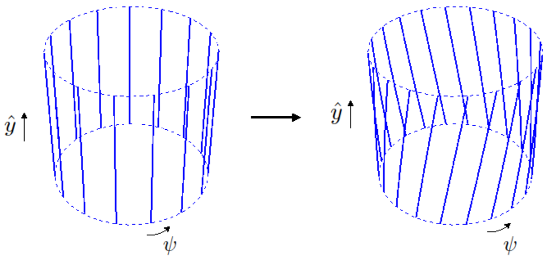
(Dilaton generated at one loop as usual.)

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.

Martinec, Massai '17

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.

Martinec, Massai, DT 1803.08505

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.

Martinec, Massai, DT 1803.08505

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.

Martinec, Massai, DT 1803.08505

Stringy physics beyond the cap

Certain probes acquire an additional time delay when scattering off the d.o.f. in the IR – they are sensitive to the fivebrane physics that is not seen in the supergravity approximation, due to smearing.

- Supergravity modes in the continuous series of SL(2,R)
- Strings winding around y direction.

So there is a wealth of interesting physics beyond what can be seen in supergravity, which can now be accessed in worldsheet CFT.

Martinec, Massai, DT 1803.08505

Falling into a black hole

The Black Hole Interior

- Black hole complementarity: Different observers could have different low-energy EFT descriptions of their observations

Susskind, Thorlacius, Uglum '93

- As originally postulated, this has been argued to be inconsistent
- Suggestion that infalling observer experiences a "Firewall" of Planck-scale radiation at the horizon

Almheiri, Marolf, Polchinski, Sully '12

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Almheiri, Marolf, Polchinski, Sully '12

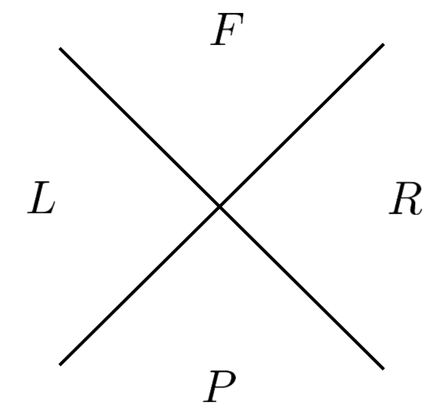
- From a string theory point of view, if Quantum Hair is present, question becomes: what is the interaction of an infalling observer with the hair?

- Fuzzball Complementarity conjecture: for coarse, high energy ($E \gg T$) physics, strong interaction with Quantum Hair has a dual description as infall on the empty black hole interior spacetime.

Mathur, DT 1208.2005, JHEP

Mathur, DT 1306.5488, NPB

Correlators in Rindler space



Rindler space:

- Accelerated observer in Minkowski space
- Near-horizon region of a Schwarzschild BH

- Minkowski space decomposes into four Rindler wedges

- Consider a free scalar field theory
- Minkowski vacuum restricted to right Rindler wedge is a thermal state

$$|0\rangle_M = C \sum_k e^{-\frac{E_k}{2}} |E_k\rangle_L |E_k\rangle_R, \qquad C = \Big(\sum_k e^{-E_k} \Big)^{-\frac{1}{2}}$$

Correlators in Rindler space

- Consider the right Rindler wedge, in a particular typical pure state.
  (Analog of considering the BH exterior in a typical pure state.)

- Some correlators will be well approximated by the canonical ensemble, while others will not.

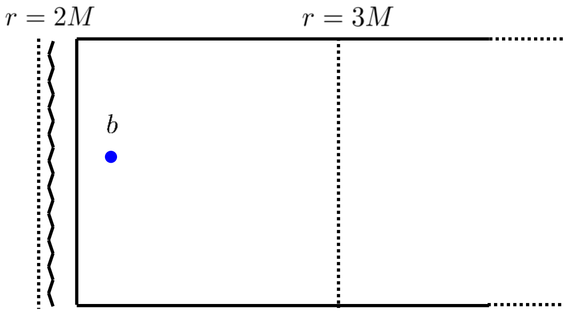
- Minkowski space $\leftrightarrow$ canonical ensemble,
  so it accurately describes those correlators that are well-approximated by the canonical ensemble.

$$ {}_R\langle E_k|\hat{O}_R|E_k\rangle_R \;\approx\; \frac{1}{\sum_l e^{-E_l}} \sum_i e^{-E_i}\, {}_R\langle E_i|\hat{O}_R|E_i\rangle_R \;=\; {}_M\langle 0|\hat{O}_R|0\rangle_M $$

This suggests how one should interpret the classical black hole metric.

Fuzzball Complementarity

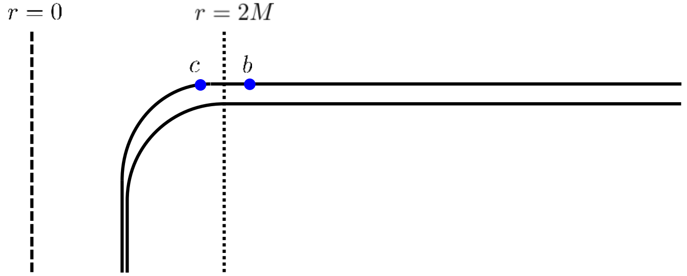
- **Picture 1**: classical black hole solution is good approximation outside the horizon, but this description is cut off at the would-be horizon by the fuzzball; state is a solution of string theory.
  - This description is appropriate for all physical processes.



Stretched horizon model of a typical fuzzball state

Picture 2: Traditional black hole metric.

- This description is appropriate for coarse, high energy ($E \gg T$) processes



Consistent with AMPS thought experiments.

Mathur, DT 1208.2005, JHEP
Mathur, DT 1306.5488, NPB

The traditional black hole solution

More generally, how should one interpret the traditional black hole solution?

- The Euclidean solution is a smooth gravitational soliton and so is a good solution
- The Lorentzian solution has a singularity that is unphysical from a string theory point of view, and so must be resolved.

The Euclidean solution is valid and so one can use Euclidean methods to compute the entropy, as well as thermal correlators.

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The Euclidean solution is valid and so one can use Euclidean methods to compute the entropy, as well as thermal correlators.

The Euclidean solution counts all the states at once, so may be expected to be spherically symmetric.

However one should take great care when continuing to Lorentzian signature: the fuzzball proposal is that the Lorentzian microstates have horizon-scale structure.

- Infalling observers conjectured to experience an approximate effective interior.

Comments

- The fuzzball effect that (at least some) black hole microstates in string theory are horizon-sized appears to be non-local physics from the point of view of the traditional geometry with horizon.

- The fuzzball scenario is that the important non-local physics has its main support in the black hole interior, rather than over cosmological lengthscales.
  - Conservative extent of important non-local effects.

- The lengthscale over which the important nonlocal effects operate appears to be the main distinction between the fuzzball proposal and other ideas such as those of Giddings, Papadodimas-Raju and Maldacena-Susskind.

- The fuzzball effect is established in string theory, in simple situations. It would be very interesting to have a bulk string theory derivation of other possible effects, to better compare and contrast these approaches.

Summary

- Smooth horizonless BPS supergravity solitons constructed, that have large near-horizon AdS_2 throats and general values of angular momentum
- Dual CFT_2 description proposed for the asymptotically AdS_3 solutions
- AdS_2 limit derived
- 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 string spectrum analyzed
- Much more to do!