Title: Black Hole Microstates in String Theory

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Abstract: The presence of a mass term for the scalar field allows for dramatic increases in the radiated gravitational wave signal and may stretch out the signal to last for years or even centuries. There are several potential smoking gun signatures of a departure from general relativity associated with this process. These signatures could show up within existing LIGO-Virgo searches.

Black Hole Microstates in String Theory

David Turton

University of Southampton

"Quantum Black Holes in the Sky?" workshop
Perimeter Institute
Nov 9, 2017

Based on:
Bena, Giusto, Martinec, Russo, Shigemori, DT, Warner arXiv:1607.03908, PRL
Bena, Bossard, Katmadas, DT arXiv:1611.03500, JHEP
Bena, DT, Walker, Warner arXiv:1709.01107, JHEP in press
Bossard, Katmadas, DT in preparation

Outline

1. Motivation & background
2. Supersymmetric microstates
3. Non-supersymmetric microstates
4. Extracting universal features of horizon-scale structure

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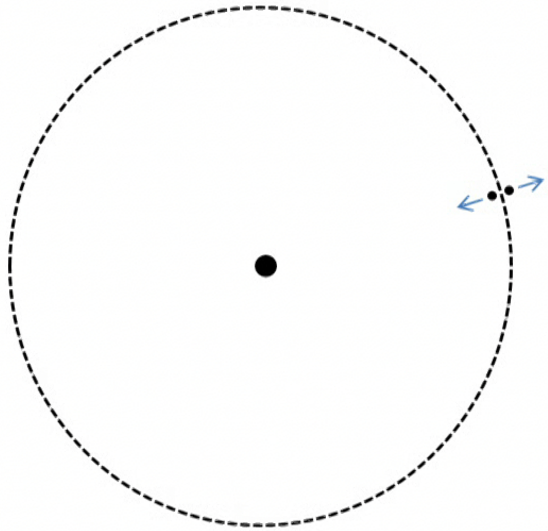
The Information Paradox

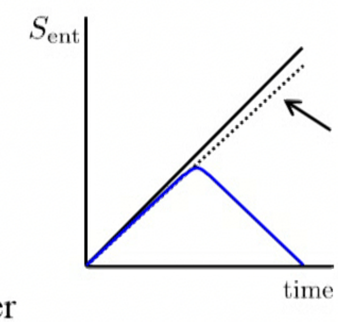
Classical BH horizon:
normal lab physics
(small curvature)



Hawking radiation:
pair creation

→ entangled pair

→ 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…

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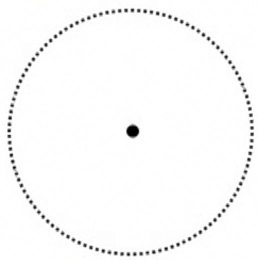
Israel '67, Carter '71, Price '72…

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"

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Overall status

- Small supersymmetric black holes: very strong evidence for string-theoretic structure at horizon scales.
  - However, these black holes are microscopic (string-scale sized).

Lunin, Mathur '01
Lunin, Maldacena, Maoz '02
Kanitscheider, Skenderis, Taylor '07

- Large supersymmetric black holes: evidence of structure on horizon scales, but this is not yet fully established.

Mathur, Giusto, Bena, Warner, de Boer, Martinec, Russo, Shigemori, DT, …

- Large non-extremal black holes: some progress, but early stages. Hard task.

Jejjala, Madden, Ross, Titchener '05,…

Bena, Bossard, Katmadas, DT '15, '16
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- For mergers of neutral rotating black holes, data is ahead of theory.

- However, there is a clear physical mechanism at play, and one can attempt to extract universal features to address phenomenological questions.

Open questions

Despite much progress, important open questions remain:

1. Can one construct & study (many) black hole microstate 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 fraction of black hole microstates are describable in supergravity?

These questions are key to understanding more typical states of large supersymmetric black holes.

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

Much less known; recent progress, however.

5. If there is new physics at the horizon, what does an infalling observer experience?
6. Does string-theoretic horizon-scale structure have observable implications?

Supersymmetric microstates

Smooth horizonless geometries

deep inside the black hole regime

D1-D5 system on T^4

Consider type IIB string theory on T^4.

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

- 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

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

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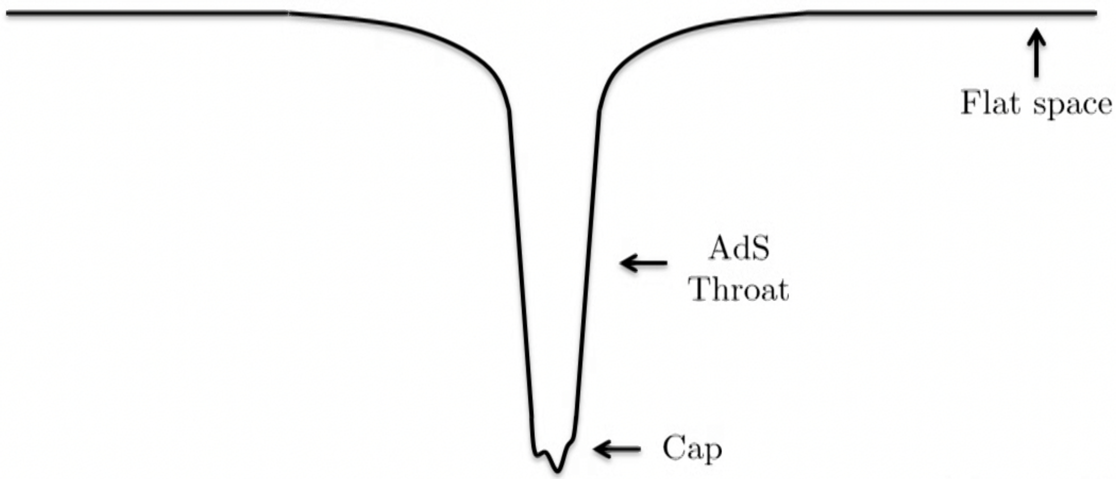
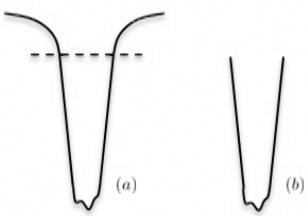
Interesting to consider near-decoupling regime: take $(Q_1 Q_5)^{1/4} \ll R_y$.

Structure of geometry is then:



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

One of the original examples of holographic duality.



Maldacena '97

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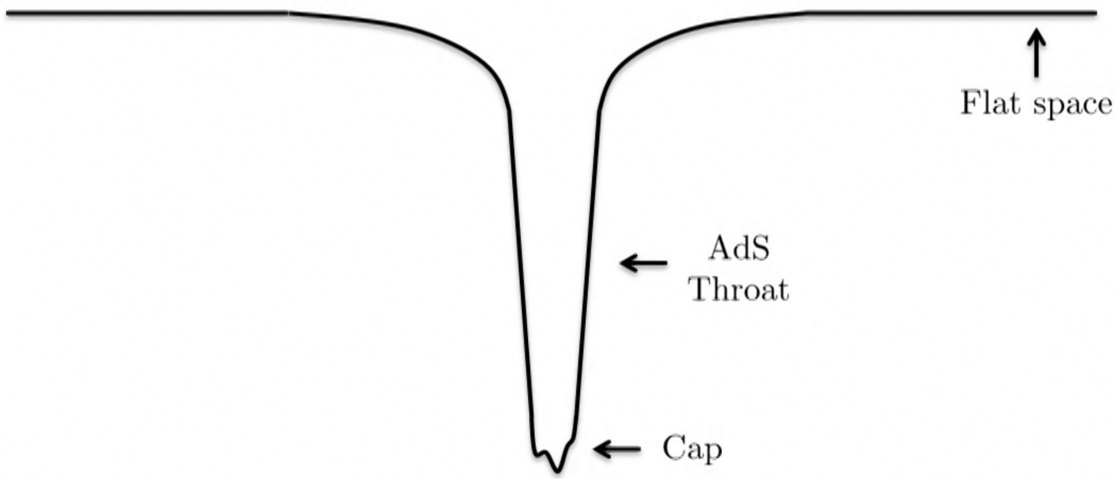

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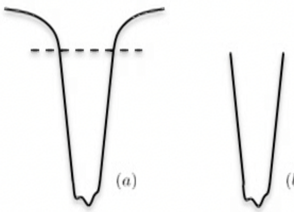


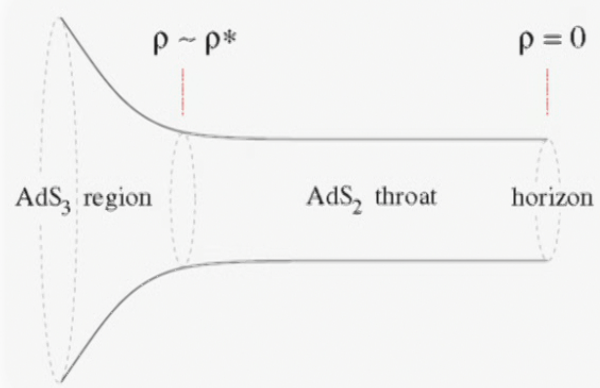
Maldacena '97

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,

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

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



- 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 this black hole is bounded above by the charges:

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

- Desire solutions with microstructure inside large AdS_2 throat.

- Previous such examples ("scaling solutions") known only in the range

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

Bena, Wang, Warner '06

and CFT description not known.

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

- Our 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.

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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"

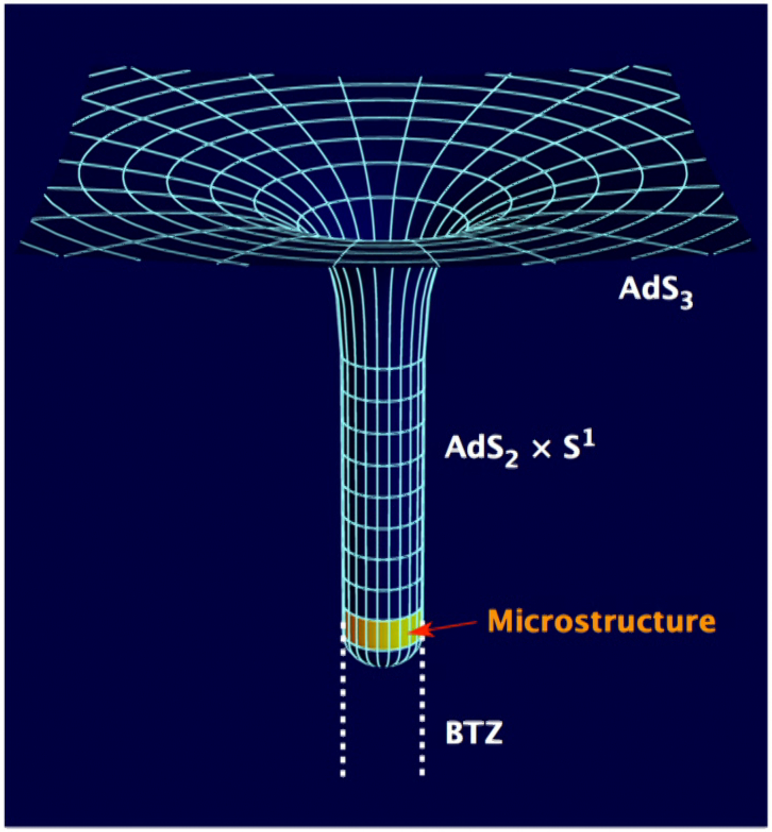
- The solutions contain a continuous parameter b/a, where
  - b controls the momentum charge
  - a controls the angular momenta

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

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

Structure of the solutions

- Solutions are asymptotically $AdS_3 \times S^3$.
- For $b/a \gg 1$, the geometry has the following structure:
- We have an explicit proposal for the corresponding family of states in the holographically-dual CFT.



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


flat
AdS3×S3

Some comments

- These microstates are atypical.
- 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 states.

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

Special properties

Question: can one solve for the geodesic motion on these backgrounds?

- A one-integer-parameter family of the above solutions, $(k, m, n) = (1, 0, n)$, has the special property that null geodesic motion is completely integrable.
- There are four isometries, the standard conserved quantity quadratic in velocities, and a "hidden symmetry" corresponding to an additional quadratic conserved Killing tensor.
- Another family, $(k, m, n) = (2, 1, n)$, has integrability only for massless geodesics that have a specific angular momentum.
- Much to study!

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

JMaRT solutions

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

  Jejjala, Madden, Ross, Titchener '05

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

  Cardoso, Dias, Hobdevo, Myers '05

- Using holography this is interpreted as Hawking radiation from these states, which is enhanced to a classical effect due to the special nature of the states.
  - (Analogous to laser radiation vs thermal radiation)

  Chowdhury, Mathur '07
  Avery, Chowdhury, Mathur '07-'09
  Chakrabarty, DT, Virmani, 1508.01231, JHEP

- Well-understood, but a small and special family.

New system containing non-extremal solitons

- Open problem for >10 years:

  How to construct multi-bubble solutions generalizing the JMaRT family?

- System recently constructed that achieves this

Bossard, Katmadas '14
Bena, Bossard, Katmadas, DT, 1511.03669, JHEP
Bena, Bossard, Katmadas, DT, 1611.03500, JHEP

Novel system of equations:

- First layer is non-linear, following three layers are linear.
- Somewhat complicated ansatz built from these quantities.
- Enables construction of solutions with more general topological structure.

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Nuts and Bolts

In 4D, given a one-parameter isometry, smooth fixed loci are of two types:

- Nut: fixed locus is a point, e.g. self-dual Taub-NUT
- Bolt: fixed locus is two-dimensional surface, e.g. Euclidean Schwarzschild

Gibbons, Hawking, '79

In 5D, fixed loci are one-dimensional or three-dimensional;

we will call them nuts and bolts respectively.

Natural to continue this terminology to spatial slices of (5+1)-dimensional solutions,

whereupon the JMaRT solution has a single bolt.

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Results

- Smooth two-bubble solutions containing one bolt and an additional single nut constructed

  (4D base: Euclidean Kerr)

  Bena, Bossard, Katmadas, DT, 1511.03669, JHEP

- One bolt + multi-nut solutions constructed, local smoothness conditions analyzed

  (Global smoothness under investigation)

  Bena, Bossard, Katmadas, DT, 1611.03500, JHEP

To appear soon: smooth two-bolt solutions, with a large & interesting parameter space:

- Near-BPS solutions with large AdS_3 throats
- Far-from-extremal solutions: arbitrarily small charge-to-mass ratio!
  - Approaches Myers-Perry (5D Kerr) regime
- Fluxes on bolts can be either aligned or anti-aligned

Bossard, Katmadas, DT, in preparation

Extracting universal physics:

Infall & phenomenology

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

- 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

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Correlators in Rindler space

- Consider the right Rindler wedge, in a particular typical pure state.

Divide correlators into those which

1. Are well approximated by the canonical ensemble (coarse)
2. Are not well approximated by the canonical ensemble (fine).
   (sensitive to some details of typical microstates)

- Minkowski space $\leftrightarrow$ canonical ensemble,
  so accurately describes coarse correlators:

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

- Suggests correct role of classical black hole metric.

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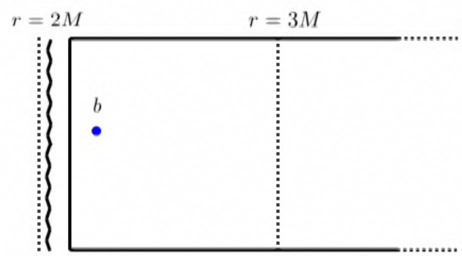
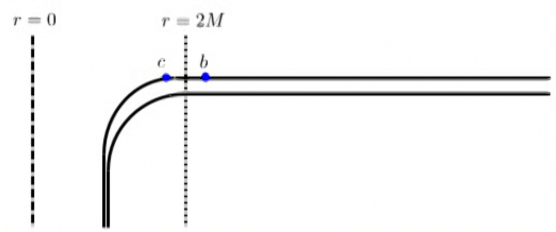
Fuzzball Complementarity

- **Picture 1**: space-time is cut off at the horizon by the Quantum Hair/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

Absorption

- Fuzzball: exponential degeneracy of states at horizon scale

- Entropic arguments strongly suggest that short-wavelength quanta ($E \gg T$) should be effectively near-perfectly absorbed: any reflection likely unobservably small.

$$\frac{N_f}{N_i} \simeq e^{\alpha \frac{E}{T}} \gg 1$$

- For $E \sim T$ or $E \ll T$ quanta, a priori there may be some room for a non-zero reflection coefficient; perhaps natural to expect it to be small. But how small?

- So far unclear whether or not this will be observable by present detectors, or by LISA.

- Hard to compute, important to do so! Work to do.

Summary

- Smooth horizonless D1-D5-P supergravity solitons constructed, that have large near-horizon AdS_2 throats and general values of angular momentum
- Holographic descriptions identified
- Significant progress on constructing non-supersymmetric solutions
- Quantum Hair in String Theory is expected to reproduce the physics of the classical black hole, for coarse $E \gg T$ infall processes.

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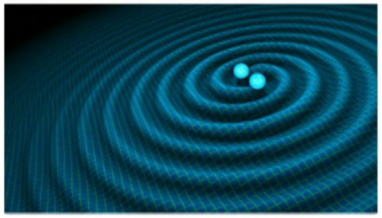
Future

- Construct more general supersymmetric microstate solutions
- Non-extremal black hole microstates: lots to do!
- Role of string & brane degrees of freedom
- Observability of black hole quantum structure?
  - LIGO-VIRGO: late ringdown
  - Event Horizon Telescope: black hole shadow
  - Future ground-based gravitational wave detectors
  - LISA: precision tests



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