Black Holes in String Theory

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Dec 6, 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, JHEP

Outline

1. Motivations
2. String theory & black holes
3. Black hole microstates
4. Falling into a black hole

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

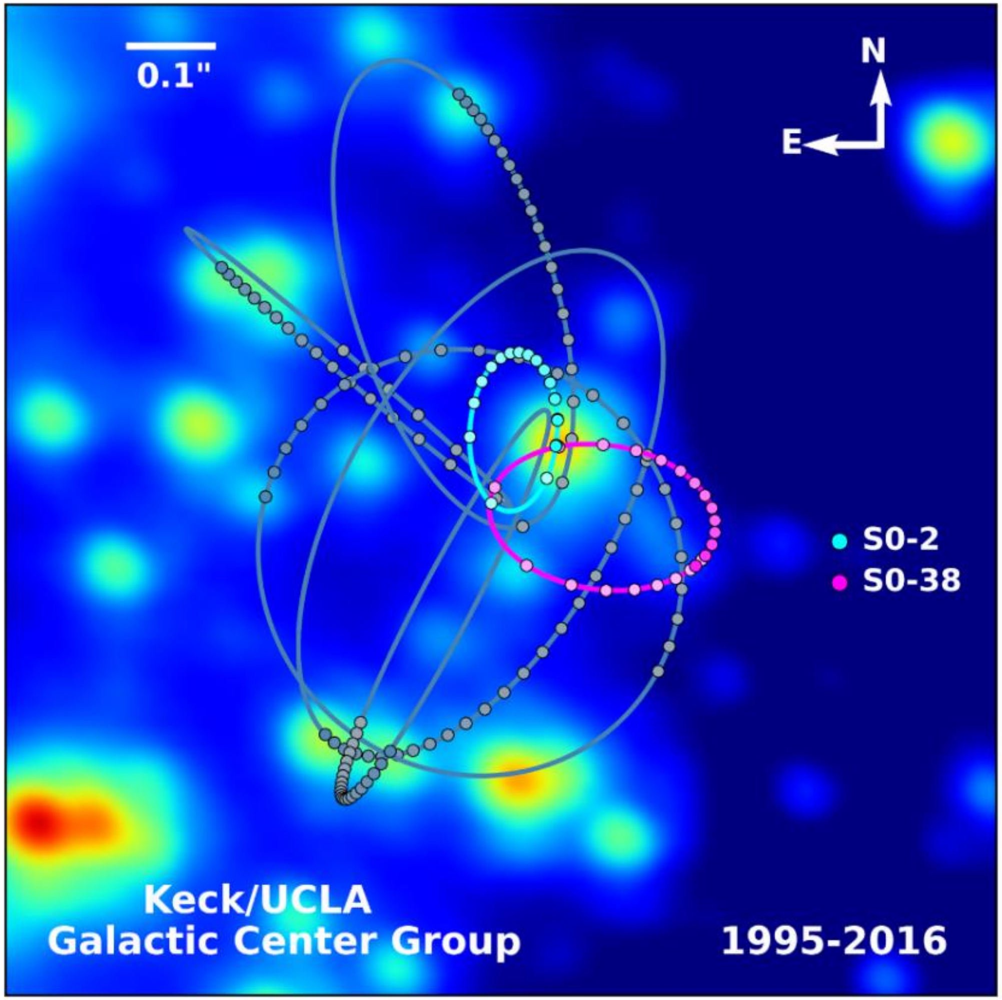
E.g. Sagittarius A* :

– Mass $\simeq 4 \times 10^6 M_\odot$

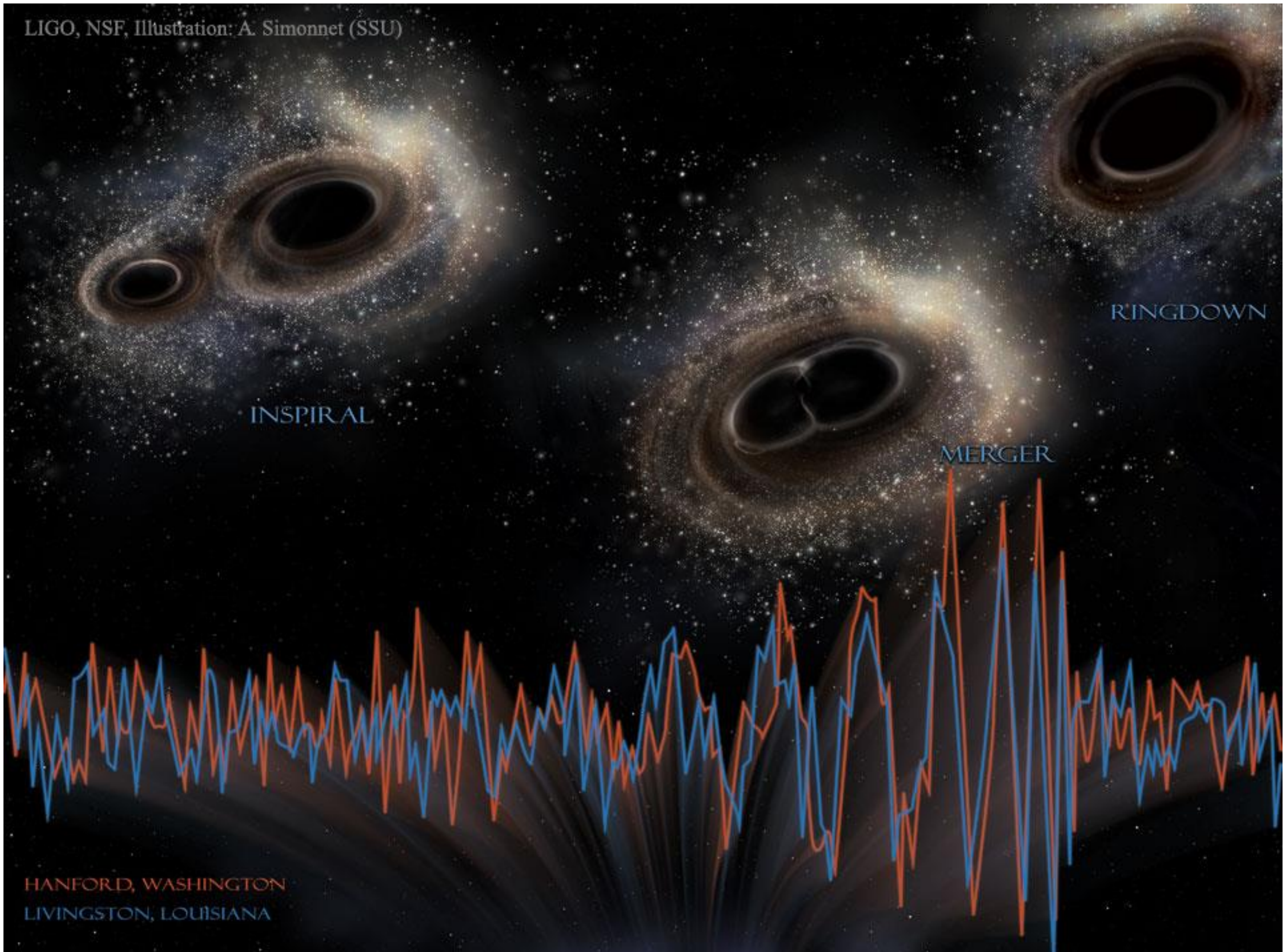
– Dark (no detectable surface emission)

– Angular size comparable to apparent size of a BH horizon

(a few multiples of the size of the BH).



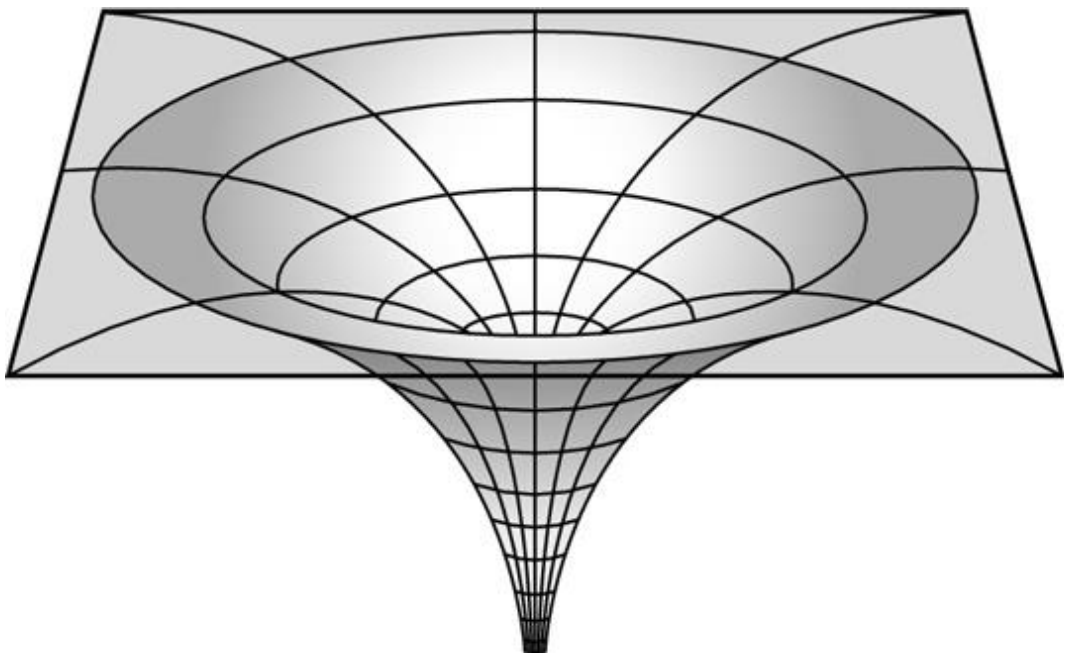
In addition, gravitational waves have recently given us a whole new set of evidence for black holes.



Classically, black holes arise in solutions to gravitational theories

as regions from which nothing can escape.

They have horizons and singularities.



Quantum mechanically however, black holes are much more mysterious.

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

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

At present, we do not have a complete and consistent description of

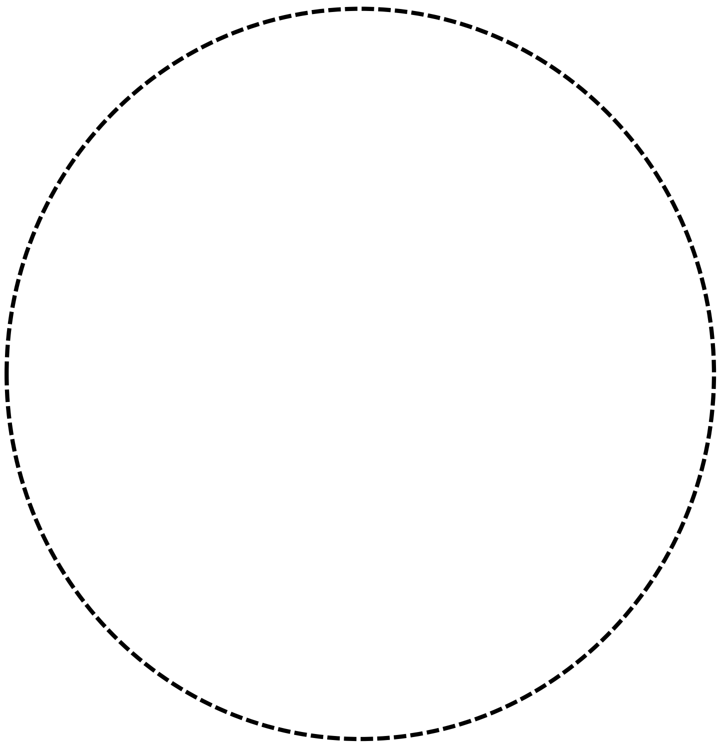
black hole interiors, nor of black hole evaporation.

This is a challenge for any theory of quantum gravity.

Classical Black Holes

Classical model of a black hole formed from collapse:

Once the black hole has settled down to a quasi-stationary state, the gravitational field is characterized by its mass M, angular momentum J, and electric charge Q.



There is an event horizon, from inside which nothing can escape; the black hole absorbs all matter perfectly. The region around the horizon is the vacuum of freely infalling observers (Unruh vacuum).

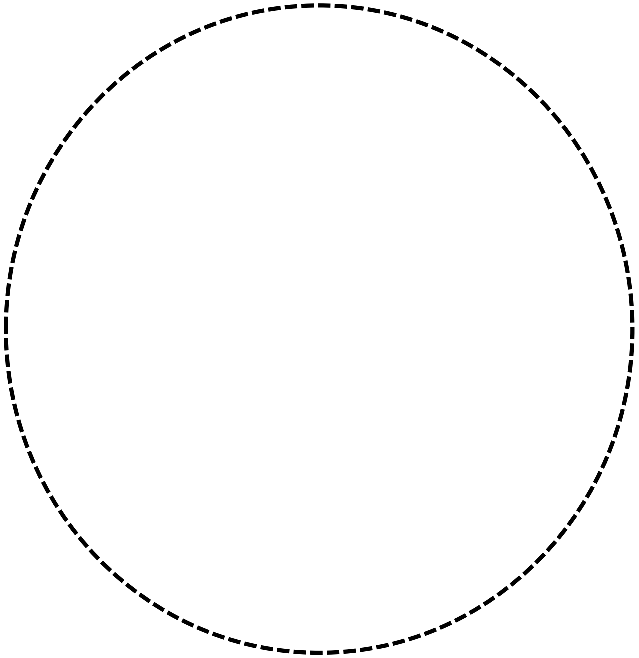
Classical Black Holes

The classical model is in agreement with all observations of black holes, to date.

However there are three major problems with this model, on a theoretical level.

1) There is a singularity in the black hole interior, signifying a breakdown of our description, which is deeply unsatisfactory.

A complete theory of Nature cannot have any singularities; thus black hole singularities must be resolved in any complete theory.



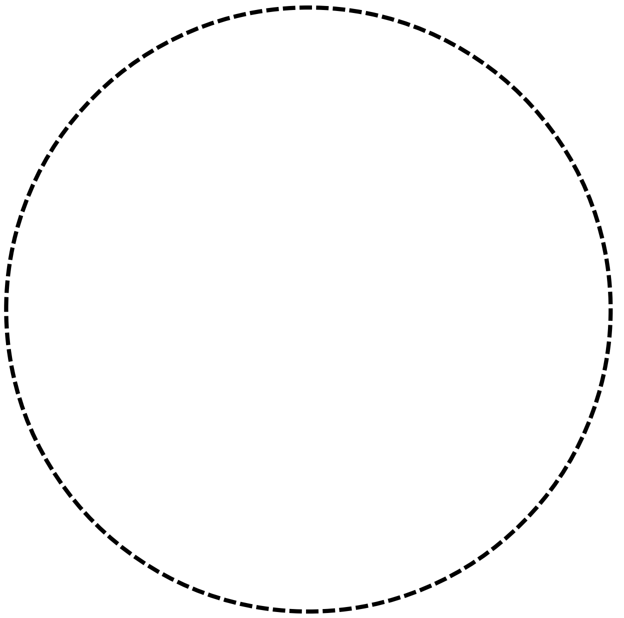
Semiclassical Black Holes

2) Semi-classically, black holes radiate via the Hawking effect; they have (a very low) temperature and (a very large) entropy. They are thermodynamic systems.

Statistical physics: all other thermodynamic systems are understood in terms of an underlying description involving a large degeneracy of quantum microstates.

However the black hole solution is unique for given M, J, Q.

If traditional statistical physics applies to BHs, then at best the semi-classical model is an incomplete description.



Semiclassical Black Holes

3) The Hawking effect gives rise to the Information Paradox:

As long as the black hole remains large, semiclassical theory predicts that the entanglement between the black hole and its surroundings increases.

This is in sharp conflict with unitary evolution, which is the default expectation if we view the formation and evaporation of a black hole as a large scattering experiment.

Semiclassical Black Holes

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Endpoint of process: violation of unitarity or exotic remnants.

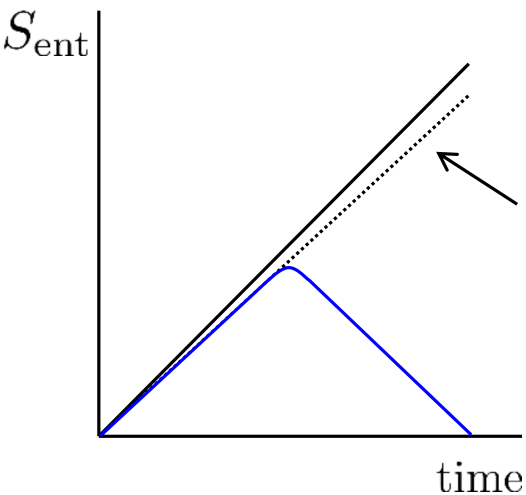
Hawking '75

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 somehow give rise to unitary evaporation?
- 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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Israel ’67, Carter ’71, Price ’72, Robinson ’75,…

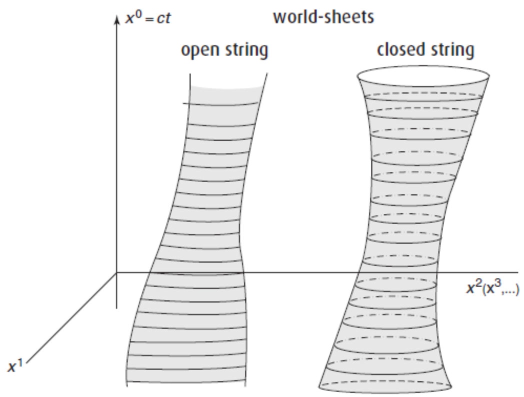
However, in String Theory, we find a much more interesting situation.

String Theory

String Theory is a quantum theory of fundamental strings, and other extended objects.

Postulates:

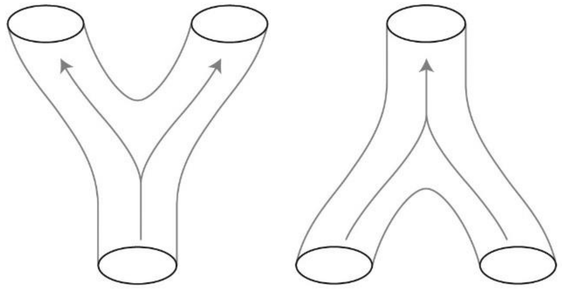
– Fundamental string has tension; action principle to extremize surface area of world-sheet (generalizion of a world-line)



– Strings can be either closed loops,

or open with endpoints

– Interactions: strings can split and join



– Require a consistent theory upon quantization.

String Theory

The fundamental string has many excitations of its oscillating degrees of freedom.

The lowest states are massless, and there is a tower of massive states.

Consistency of quantum string requires supersymmetry (bosons $\longleftrightarrow$ fermions)

and 10 = 9+1 spacetime dimensions.

We must therefore assume that 6 dimensions are small and compact, to obtain

3+1 large spacetime dimensions.

The resulting theory is a well-behaved theory of quantum gravity,

and potentially a unified quantum theory of all fundamental interactions.

D-Branes

String Theory also contains higher-dimensional membranes known as D-branes.

D-branes provide Dirichlet boundary conditions for open string endpoints.

D-branes are dynamical objects, and are heavy at weak string coupling.

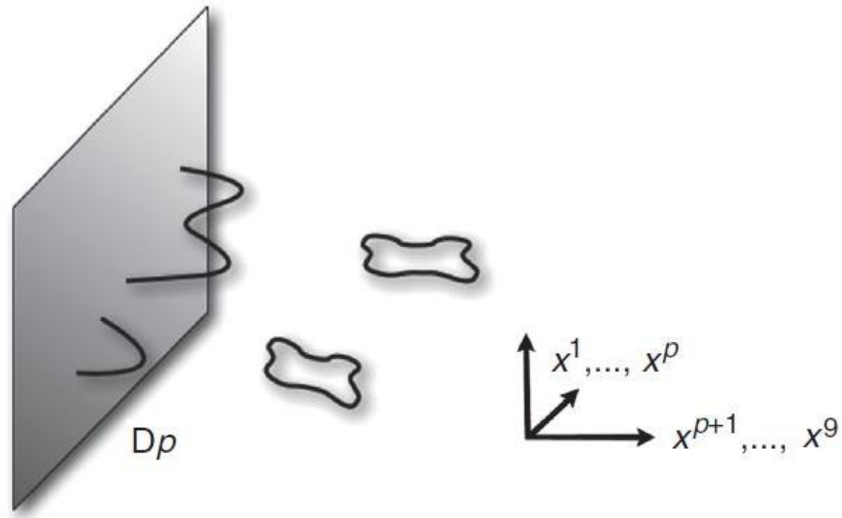
This makes them ideal building-blocks for black holes.

D-branes are labelled

by their dimensionality:

a Dp-brane has

p spatial dimensions.



Supergravity

The massless sector of the closed string is supergravity, which describes gravity coupled to other bosonic and fermionic massless fields, with supersymmetry.

Supergravity has classical black hole solutions that we are interested in.

More generally, supergravity solutions describe the long-range gravitational fields, and other massless fields, sourced by bound states of strings and D-branes.

The other massless bosonic fields are scalars, vectors, and generalizations of Maxwell fields to higher-rank antisymmetric tensor field strengths & potentials

$\rightarrow$ e.g. antisymmetric three-form field strength / two-form potential

$$H_{\mu\nu\rho} = \partial_{[\mu} B_{\nu\rho]} \, .$$

Black Holes in String Theory

A black hole in String Theory is a bound state that is

– massive,

– compact (of order the size of the would-be horizon),

– dark (effectively perfectly absorbing),

– and has an exponential degeneracy of internal quantum states.

The simplest examples are supersymmetric and carry conserved charges.

They are generalizations of extremal Reissner-Nordstrom black holes,

i.e. $J = 0$, $M = Q$.

(Generically we can also have non-zero angular momentum within an allowed range.)

Note that supersymmetric implies extremal but the converse is not true.

Two-charge Black hole

Let's describe the simplest black hole in String Theory, and the best understood.

Let one of the extra dimensions of String Theory be a circle.

Consider a fundamental string (F1) wound many times around this circle. This creates a massive state that is pointlike from the point of view of the other directions.

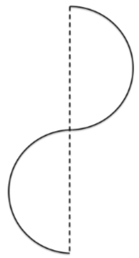
To get an exponential degeneracy of states, we must add a second charge.

We can do so by adding momentum (P) along the compact direction.

The string carries momentum in the form of a transverse travelling wave

(the fundamental string has no longitudinal modes of oscillation).

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

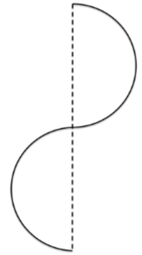
  Classical profiles $\leftrightarrow$ coherent states

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

- No horizons; string source

- Transverse vibrations only $\rightarrow$ non-trivial size

Two-charge Black hole



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String duality maps an F1-P bound state to a D1-D5 bound state

Lunin, Mathur '01

- Configurations are everywhere smooth in D1-D5 frame

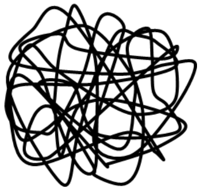
Lunin, Maldacena, Maoz '02

- 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”

Black Hole Quantum Hair

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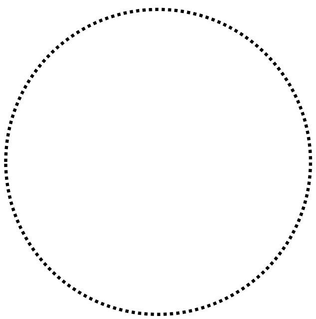
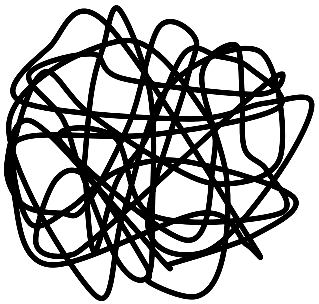




"Fuzzball"

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

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

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 describe recent progress on each of these questions.

D1-D5 system: setup

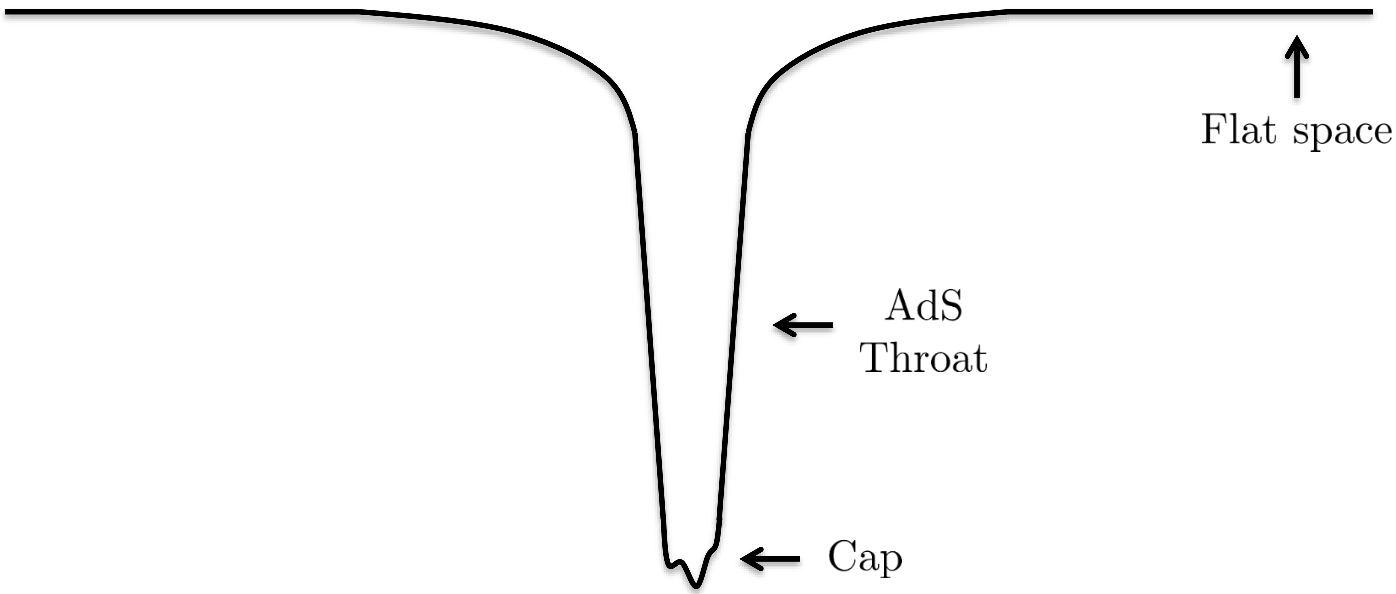
Consider type IIB string theory on T^5.

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

- 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.

To get an AdS throat, we take R_y to be the largest lengthscale in the problem.

Structure of supergravity solutions that describe black hole microstates:



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

Supersymmetric microstates:

Smooth horizonless geometries

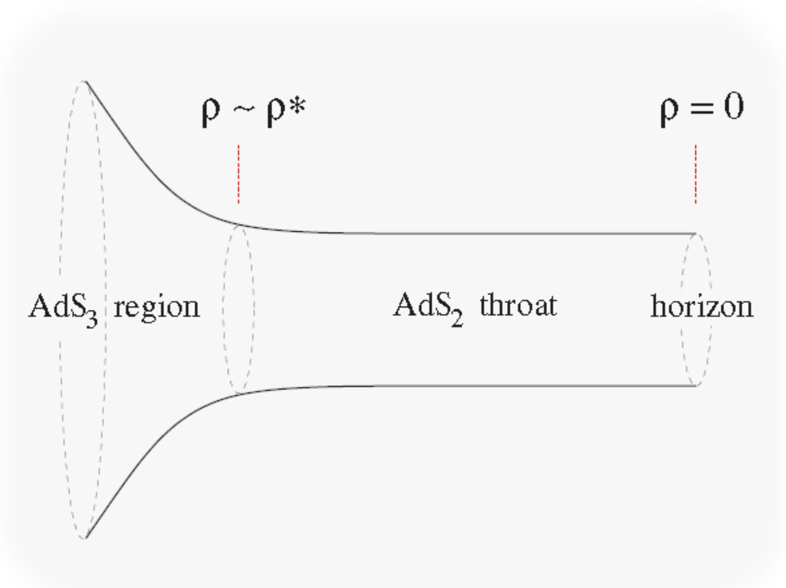
deep inside the black hole regime

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,

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

$$\ell^2_{\mathrm{AdS}} = \sqrt{Q_1Q_5}\,, \qquad \rho^2 = \frac{r^2}{Q_1Q_5}\,, \qquad \rho_*^2 = \frac{Q_\mathrm{P}}{Q_1Q_5}\,.$$



- 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 were 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 holographic description still not known.

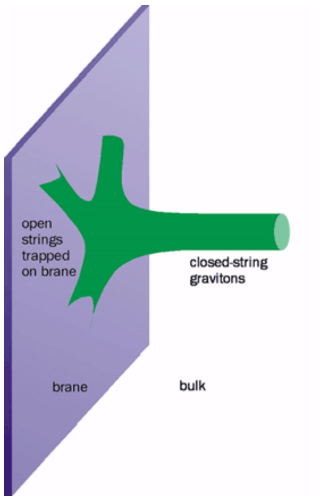
- New solutions: have large AdS_2 throats, probe the entire range of values of j_L, & we have given a proposal for the holographically dual CFT states.

Supersymmetric solutions in 6D

We consider configurations invariant on T^4, and work in the six remaining dimensions.

- We work in a supergravity theory whose bosonic content is the metric, two scalars, and three self-dual antisymmetric two-form tensor potentials

- 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

Supersymmetric solutions in 6D

The 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

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

The equations 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

Solution-constructing technique:

1) We take the 4D base metric and the one-form β to be those of a known seed solution. In particular the base metric is simply flat R^4.

2) In the second layer we introduce an explicit dependence on the angular directions. This breaks the isometries preserved by the black hole.

3) We then integrate the final layer and impose smoothness.

The parameters of the solution are three integers (k, m, n) , $m \leq k$, and a continuous parameter a/b , where

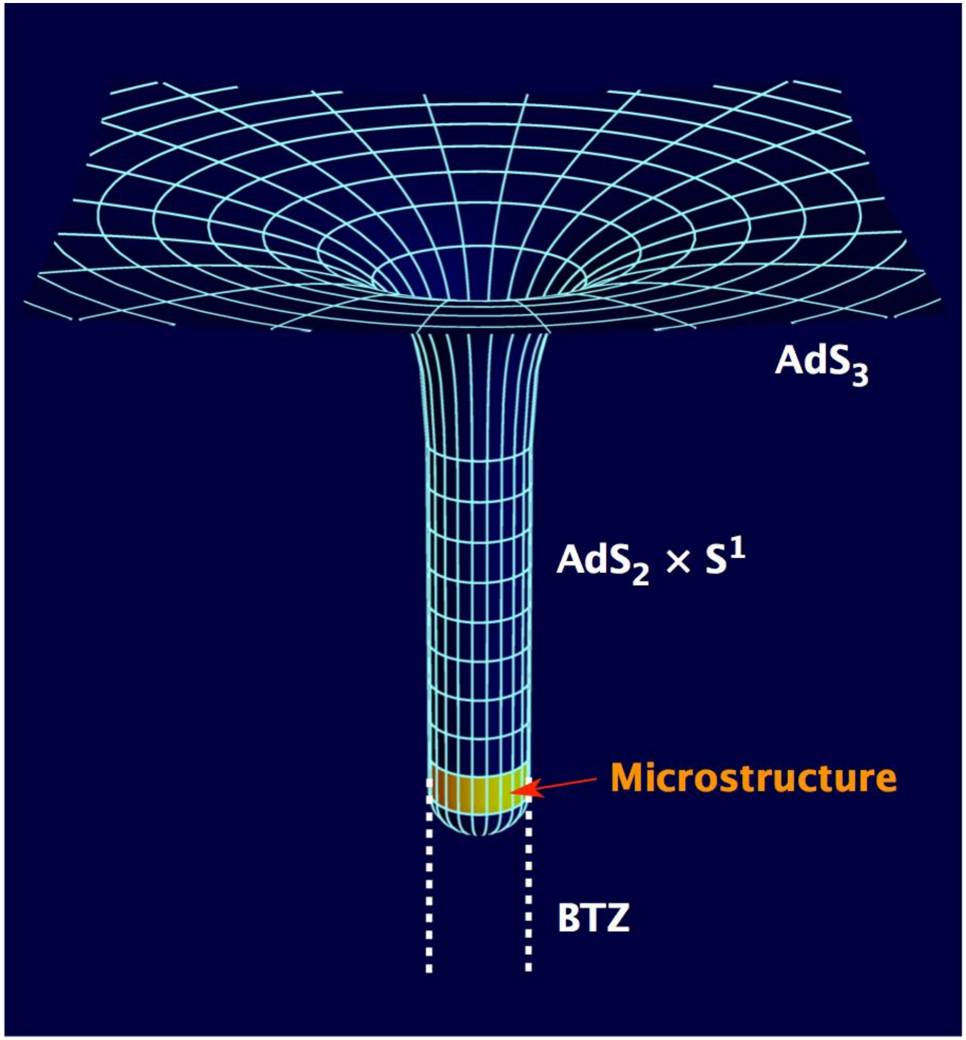
- b controls the momentum charge
- a controls the angular momentum

Smooth solutions deep inside the black hole regime

- 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:



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

Comments

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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.

- 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.

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

- One can take an AdS_2 limit, in which the solutions become smooth capped AdS_2 solutions with $AdS_2 \times S^1 \times S^3$ asymptotics: implications for AdS_2 holography

Bena, Heidmann, DT, arXiv:1806.02834, JHEP

Non-supersymmetric microstates

JMaRT solutions

- The JMaRT solutions are smooth non-supersymmetric supergravity solitons with ergoregions (regions in which any asymptotically timelike Killing vector becomes spacelike).

  Jejjala, Madden, Ross, Titchener '05

- Such solutions generally have an associated ergoregion instability

  Friedman '78

- 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 holography this is interpreted as unitary 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

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 is known explicitly.

Chakrabarty, DT, Virmani 1508.01231, JHEP

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

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

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 $\mathbb{R}^2 \times S^3$ (single 'bolt')
- There are supersymmetric solutions that have many topological cycles, or 'bubbles'
- Can one construct multi-bubble families that generalize JMaRT solutions?

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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

Non-supersymmetric microstates

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

Bena, Bossard, Katmadas, DT, 1511.03669, JHEP

- Multi-center solutions constructed, local smoothness conditions analyzed

Bena, Bossard, Katmadas, DT, 1611.03500, JHEP

State of the art: smooth two-bolt solutions with a large parameter space, including

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

Bossard, Katmadas, DT, 1711.04784, JHEP

Beyond supergravity:

Black hole microstates

in string worldsheet

conformal field theory

String physics of black hole microstates

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.

E.g. 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.

Martinec ’14

Worldsheet Conformal Field Theory

The worldsheet description of the string is a quantum theory of string dynamics, which can be on the "background" of a non-trivial supergravity solution.

This quantum theory is a two-dimensional quantum field theory that is invariant under rescalings of lengths + Poincare transformations + other transformations, making up the conformal group, hence conformal field theory (CFT).

Such a quantum description of string dynamics enables us to study the spectrum and scattering of strings, encoding a wealth of physics beyond what can be described in the supergravity approximation.

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

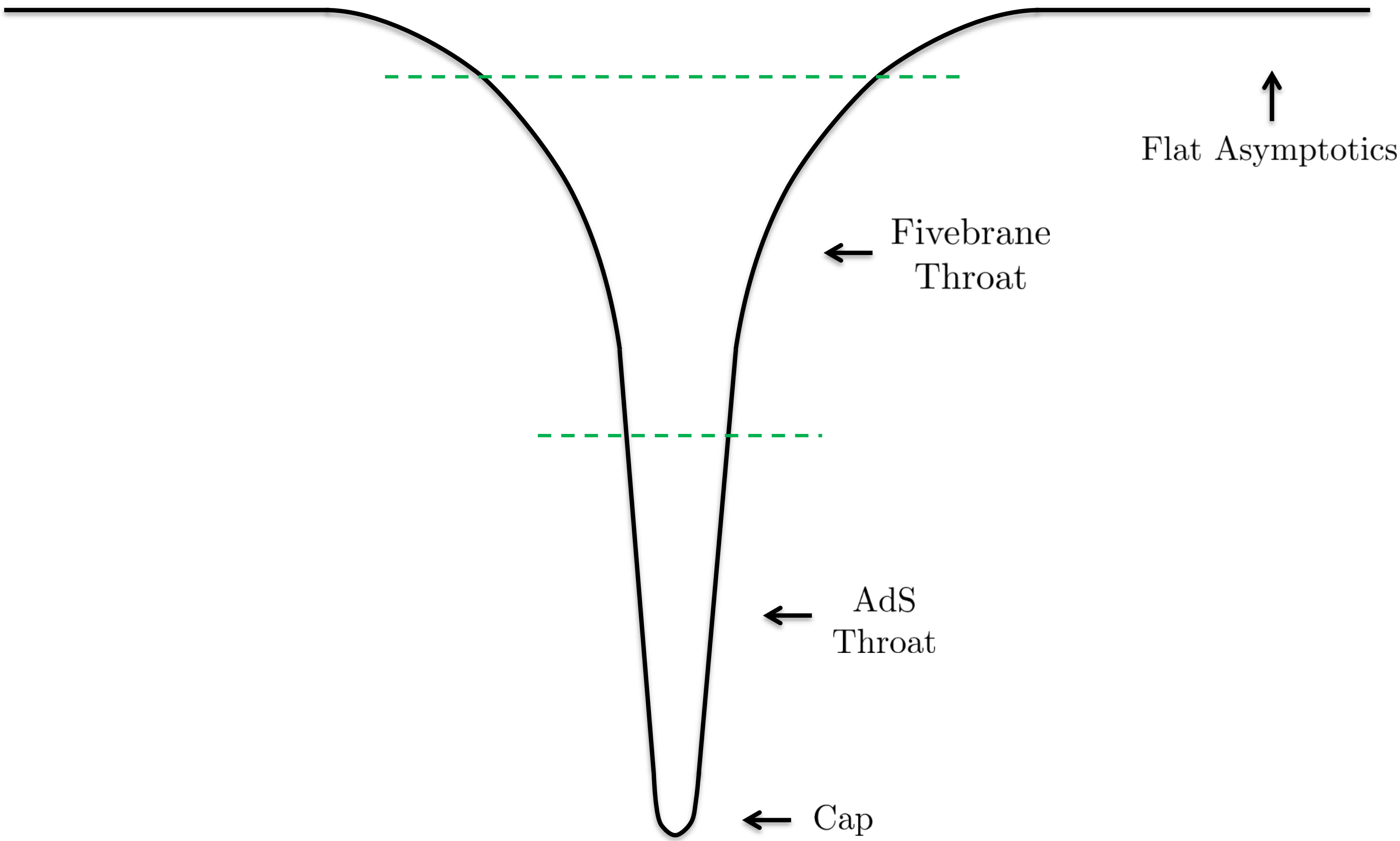
Jejjala, Madden, Ross, Titchener '05
Giusto, Mathur, Saxena '04
Giusto, Lunin, Mathur, DT 1211.0306, JHEP

We S-dualize to the NS5-F1-P duality frame.

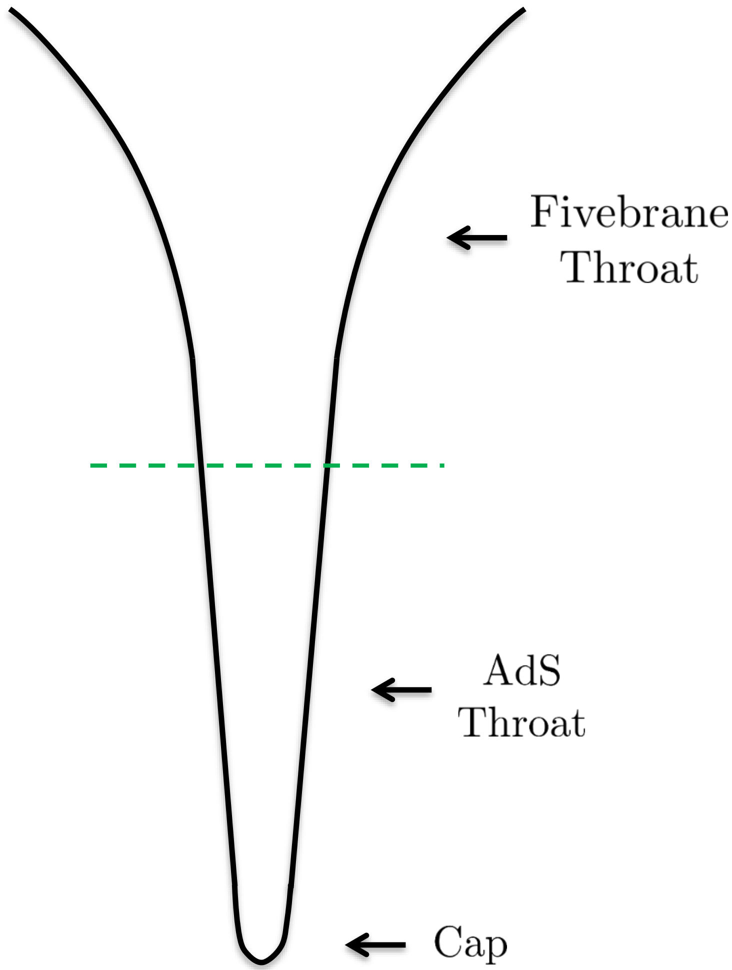
(NS5: solitonic 5-brane, electric-magnetic dual of the fundamental string.)

In this duality frame the background has a particular type of flux (pure NS-NS) that is easier to deal with on the worldsheet.

Again, take R_y to be largest lengthscale in the problem. Full geometry:



Work in NS5-brane decoupling limit:



Worldsheet CFT of JMaRT solutions

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

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

Closed string spectrum

From the worldsheet theory one can compute the spectrum of closed strings

- Supergravity sector plus long strings winding around AdS_3 circle & S^3

We find no instability; in NS5 decoupling limit, there's no ergoregion.

Strings wound along y can be absorbed (or emitted) by the background, by annihilating with the background flux (or emerging from it).

Martinec, Massai, DT 1803.08505, JHEP

Stringy physics beyond the cap

Certain high-energy string probes acquire an additional time delay when scattering off the d.o.f. in the IR – they are sensitive to the NS5-brane physics that is not seen in the supergravity approximation.

SL(2) part of two-point function:

$$\left\langle \Phi^{\mathrm{sl}}_{j_{\mathrm{sl}};m_{\mathrm{sl}},\bar{m}_{\mathrm{sl}}} \Phi^{\mathrm{sl}}_{j_{\mathrm{sl}};-m_{\mathrm{sl}},-\bar{m}_{\mathrm{sl}}} \right\rangle \sim \frac{\Gamma(1-\frac{2j_{\mathrm{sl}}-1}{n_5})}{\Gamma(\frac{2j_{\mathrm{sl}}-1}{n_5})} \times \frac{\Gamma(-2j_{\mathrm{sl}}+1)\Gamma(j_{\mathrm{sl}}-m_{\mathrm{sl}})\Gamma(j_{\mathrm{sl}}+\bar{m}_{\mathrm{sl}})}{\Gamma(2j_{\mathrm{sl}}-1)\Gamma(-j_{\mathrm{sl}}-m_{\mathrm{sl}}+1)\Gamma(-j_{\mathrm{sl}}+\bar{m}_{\mathrm{sl}}+1)} \,.$$

Higher energy probes appear to probe deeper, “beyond” the cap of the geometry: the exact CFT description contains much more physics than the naïve effective geometry describes.

Martinec, Massai, DT 1803.08505, JHEP

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.

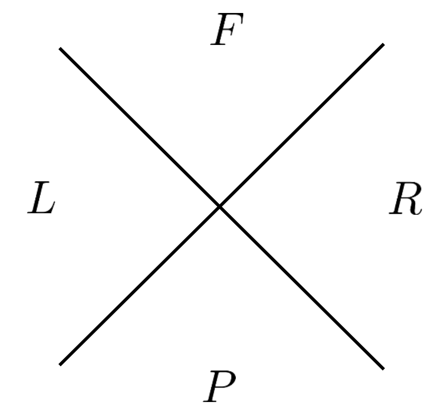
Mathur, DT 1208.2005, JHEP

Mathur, DT 1306.5488, NPB

Analogy 1: 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

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

Analogy 1: 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.

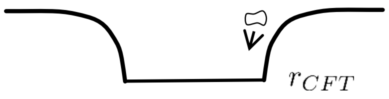
$$ {}_R\langle E_k|\hat{O}_R|E_k\rangle_R \;\approx\; \frac{1}{\sum_l e^{-E_l}} \sum_i e^{-E_i}\, {}_R\langle E_i|\hat{O}_R|E_i\rangle_R \;=\; {}_M\langle 0|\hat{O}_R|0\rangle_M $$

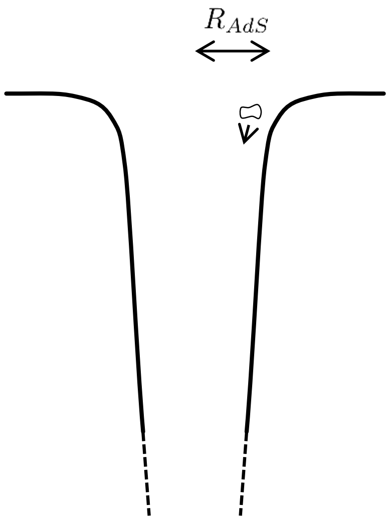
This suggests how one should interpret the classical black hole metric.

Analogy 2: AdS/CFT

Consider a holographic CFT in the regime of parameters where the dual AdS bulk theory is weakly coupled. Work in near-decoupling limit.

- In the CFT description, an incoming graviton impacts the brane bound state and breaks up into excitations of the (strongly coupled) CFT.

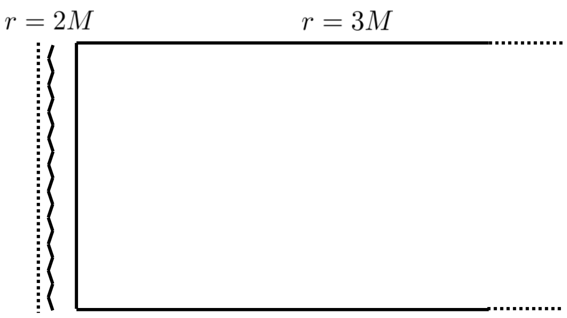




- In the dual gravity description, the graviton experiences a smooth space-time with low curvature through the vicinity of the CFT location.

Fuzzball Complementarity

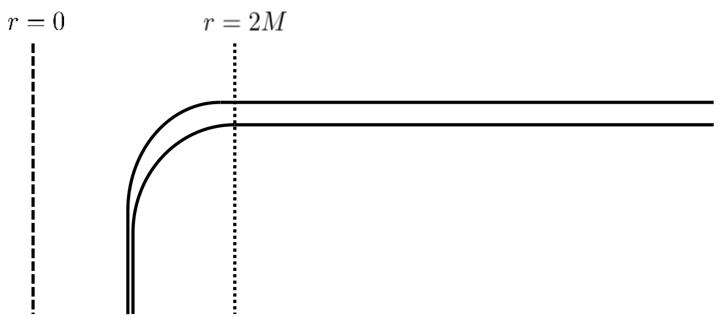
- **Picture 1**: classical black hole solution is good approximation outside the horizon, but this description is cut off at the would-be horizon by the fuzzball; state is a solution of string theory.
  - This description is appropriate for all physical processes.



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

Summary

- String Theory provides a mechanism by which black hole singularities are resolved.
- The resolution involves the extended nature of the bound states, and all results point to the resolution involving quantum effects on the scale of the would-be horizon.
- Hawking radiation becomes ordinary thermal radiation, and black hole formation and evaporation is a unitary process.
- Recent progress in studying supersymmetric & non-supersymmetric black hole microstates in both supergravity and on the string worldsheet.
- If these features could be demonstrated in general, they would give a complete and consistent quantum description of black holes.

Future

- Study more general microstates of supersymmetric black holes, in particular the most entropic sector.
- Non-extremal black hole microstates: lots to do!
- Role of string & brane degrees of freedom
  - New worldsheet CFTs for BH microstates
  - Disk worldsheet amplitudes to derive backreaction of D-brane bound states

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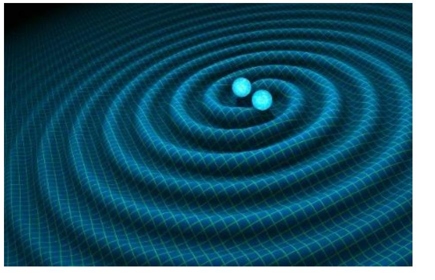

- Can effects of black hole quantum structure be observed?
  - LIGO-VIRGO: late ringdown
  - Event Horizon Telescope: black hole shadow
  - Future ground-based gravitational wave detectors
  - LISA: precision tests