Describing the interior of a black hole using holography

Marika Taylor

Mathematical Sciences and
STAG research centre, Southampton

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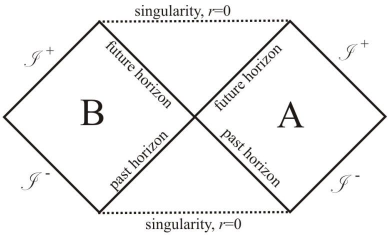
Introduction

- Traditional viewpoint: BH singularity is resolved by quantum gravity effects; these effects are small except close to $r = 0$ but suffice to solve information loss.



- Recent arguments of AMPS and Mathur suggest that significant deviations from the semi-classical picture must arise at the horizon.

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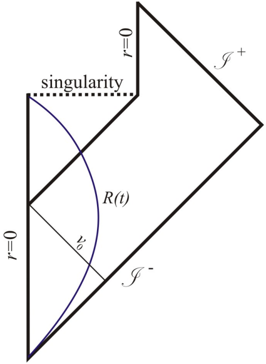
The information loss paradox revisited (AMPS)

The following postulates are inconsistent with each other:



1. Unitary evolution
2. QFT in curved spacetime is valid outside horizon
3. BH entropy is given by area law
4. No drama at the horizon

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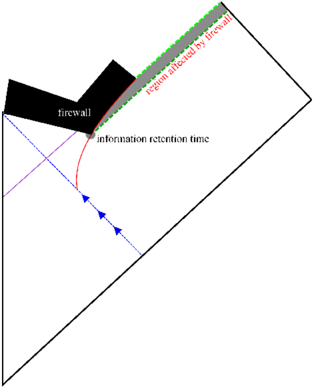
Firewalls (AMPS)

- Consider a correlated Hawking pair A and B such that A crosses the horizon.
- Suppose A encounters high energy quanta (a firewall) just behind the horizon.
- A dramatic horizon gives $S_{AB} \neq 0$ $\rightarrow$ information recovery.

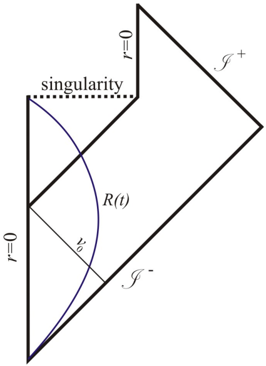


Objections to firewalls

1. Violation of equivalence principle (Bousso et al)
2. CPT violation (Hawking)
3. Black hole complimentarity (Susskind et al)
4. Holographic arguments (Papadodimas et al)

Plus arguments by Giddings, Mathur, Chowdhury, Bena, Warner,...

The hidden postulate



- Why do we insist on trusting this diagram so much?

What if there is **no horizon**?

Black hole microstates

The fuzzball proposal for black holes states that associated with any black hole of entropy S there are $\exp(S)$ horizon-free non-singular geometries* representing individual black hole microstates, with the black hole arising from coarse-graining over these geometries.

* String backgrounds, as most geometries are not describable within classical gravity.

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Basic questions in the microstate scenario

1. What is the "geometry" for a given black hole microstate? I.e. what is the "fuzz"?
2. Can one obtain almost thermal emission from a typical microstate geometry and recover the black hole upon coarse-graining?

Mathur et al; Bena, Warner et al; Giusto et al; Skenderis and MMT; Balasubramanian, de Boer, Ross, Simon et al; Czech, Levi, van Raamsdonk et al. Also Hawking.

Introduction

Aim of this talk:

Use holography to describe internal structure of a black hole (quantitatively!).

- Kostas Skenderis and Marika Taylor
  The fuzzball proposal for black holes,
  Physics Reports 467 (2008) 117.
- Kostas Skenderis and Marika Taylor
  What is quantum superposition for gravity?
- Marika Taylor
  The structure of black hole microstates

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Outline

- **Supersymmetric black holes**
- Holography and black holes
- Describing the interior of a black hole

Supersymmetric extremal black holes

- Supersymmetry is a powerful tool:
  - susy reduces supergravity equations to first order equations;
  - regular susy solutions with appropriate charges are candidate black hole microstates.

Example geometries

- Microstate geometries involve many sugra fields in addition to the metric and break rotational symmetry.
- E.g. 6d black string microstates with metric

$$ds^2 = -\frac{1}{\sqrt{Z_1 Z_2} Z_3}(dt + k)^2 + \frac{Z_3}{\sqrt{Z_1 Z_2}}(dy + \mathcal{A})^2 + \sqrt{Z_1 Z_2} g_{mn} dx^m dx^n$$

  where g_{mn} is a hyper-Kähler 4-space, $(k, \mathcal{A}, Z_a)$ are forms and scalars respectively.
- Other sugra fields are expressible in terms of similar data.

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Example geometries

- In the stationary BMPV black string the 3 functions Z_a are harmonic functions on R^4:

$$Z_a = 1 + \frac{N_a}{r^2}.$$

(This is the D1-D5-P system: D5 wrapped on $T^4/K3$.)

- In $P = 0$ microstate geometries one finds functions such as

$$Z_a = 1 + \int \frac{N_a dv}{|x^m - F^m(v)|^2},$$

i.e. curves $F^m(v)$ in the hyper-Kähler space characterize microstates (supertubes).

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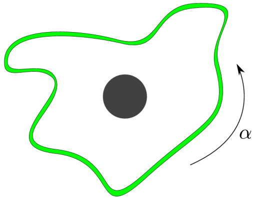
Heuristic picture



- D1-D5 branes along (t, y) directions, located on rotating curve (tube) in transverse 4-space.
- Non-singular, horizon-free.

Limitations of susy approach

Only works for extremal black holes but also:

1. Are constructed geometries dual to typical black hole microstates?
2. Can one even in principle find enough supergravity geometries to account for black hole entropy?

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Holography and black hole microstates

- Holography relates black hole entropy to counting states $\{|\phi_i\rangle\}$ in the CFT.
- The black hole itself is treated as a **mixed state** in the CFT, i.e. as a density matrix $\rho = \sum_i |\phi_i\rangle\langle\phi_i|$.
- A natural question is thus: what is the dual geometric interpretation of the individual CFT microstates $\{|\phi_i\rangle\}$?

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Horizonless dual geometries

The holographic dictionary tells us that each such (pure) state should be mapped to a dual horizonless geometry.

(Skenderis and Taylor, 2008)

- A given state $|\phi\rangle$ is uniquely determined by giving the expectation values of all local gauge invariant operators $\langle\mathcal{O}\rangle_{\phi}$ in that state.
- This set of gauge invariant operators includes single trace chiral operators $\mathcal{O}_c$ dual to supergravity fields (metric) and the remaining operators $\mathcal{O}_s$, dual to other modes.

Holographic matching with black hole microstates

- Given any candidate horizonless microstate geometry, we can extract from its AdS boundary behavior

$$ds^2 = \frac{d\rho^2}{4\rho^2} + \frac{1}{\rho}(g_{(0)ij} + \rho g_{(2)ij} + \cdots)dx^i dx^j$$

  the expectation values of all chiral operators $\langle \mathcal{O}_c \rangle$ dual to supergravity fields.
- Matching all of these to those of CFT black hole microstates provides very strong evidence for the correspondence. (Kanitscheider, Skenderis and M.T.)

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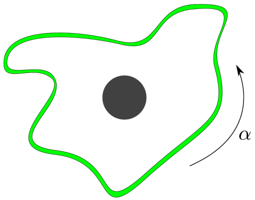
D1-D5 microstates

- Each microstate geometry can be viewed as a spinning supertube.
- Multipole moments of the supertube capture expectation values of dual CFT operators.



Decoupling region

- The decoupled geometry is asymptotic to massless BTZ black hole $\times S^3$.
- As $\rho \to \infty$ the metric can therefore be expressed as

$$ds^2 = -\rho^2 dt^2 + \frac{d\rho^2}{\rho^2} + \rho^2 dy^2 + d\theta^2 + \sin^2\theta d\phi^2 + \cos^2\theta d\psi^2 + \delta g_{ab}(\rho, \theta, \phi, \psi) dx^a dx^b$$

- We can read off from δg_{ab} the expectation values of CFT operators.
- Each spherical harmonic corresponds to an operator of different R charge/dimension.

Precision map

Harmonics of $F^m(v) \leftrightarrow$ Coherent superposition of D1-D5 states

Ellipse: $F^1 = a\cos(2\pi n v)$, $F^2 = b\sin(2\pi n v) \leftrightarrow$ Superposition

$$\sum_{k=0}^{N/n} c_k (a+b)^{\frac{N}{n}-k}(a-b)^k (\mathcal{O}_n^+)^{\frac{N}{n}-k}(\mathcal{O}_n^-)^k$$

with $\mathcal{O}_n^{\pm}$ twist n CFT operators associated with specific cohomology cycles.

Multipole moments of supergravity fields $\leftrightarrow$ Chiral operator one point functions

Exact match (to leading order in N)!

Lesson from the D1-D5 system

Horizonless non-singular black hole microstate geometries exist!

BUT

For $P = 0$ typical scale is comparable to higher derivative corrections to sugra (as expected).

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General (BPS) black hole microstates

- For any state $\mathcal{O}_\phi|0\rangle$,

$$\langle\phi|\mathcal{O}_c(\mu^{-1})|\phi\rangle = \langle 0|(\mathcal{O}_\phi)^\dagger(\infty)\mathcal{O}_c(\mu^{-1})\mathcal{O}_\phi(0)|0\rangle$$

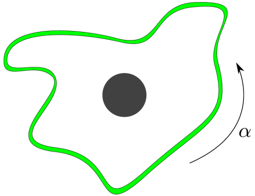
  where μ is the AdS radius.
- Information about the dual microstate geometry inferred from three point functions.
- The latter are well-understood using orbifold CFT results, large N factorisation etc.

Characteristic scale of microstate geometries

- Microstates differ from the black hole at a radius scale r_t set by the lowest dimension operator

$$\langle \mathcal{O}_{\Delta,c} \rangle \sim N r_t^{\Delta}$$

  with $N = N_1 N_5$.
- Generic BPS microstates typically have $r_t \sim \mu N^{-k}$, with μ the AdS radius and $k > 0$.



BMPV rotating black strings

- The decoupled region is asymptotic to an S^3 fibration over the BTZ black hole.
- As $\rho \to \infty$ the microstate metrics are

$$ds^2 = -(\rho - \frac{P}{\rho})^2 dt^2 + (\rho - \frac{P}{\rho})^{-2} d\rho^2 + \rho(dy - \frac{P}{\rho^2} dt)^2$$

$$+ d\theta^2 + \sin^2\theta(d\phi + J(dy - dt))^2$$

$$+ \cos^2\theta(d\psi + J(dt - dy))^2 + \delta g_{ab}(\rho, \theta, \phi, \psi) dx^a dx^b$$

where P is the momentum and J is the R charge (rotation).

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D1-D5-P Strominger-Vafa black hole

- CFT microstates for the Strominger-Vafa black hole ($J = 0$) have zero R charge.
- Almost all supergravity operators have non-zero R charge but $\langle \mathcal{O}_c \rangle = 0$ for all R charged operators.
- $\delta g = 0$ and Strominger-Vafa black hole microstates cannot be seen in supergravity!

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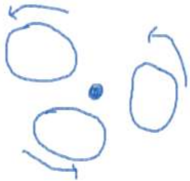
Bubbling microstate geometries

- For $J \neq 0$ candidate microstate geometries exist: (Bena, Warner et al)
- Multipole moments are too large for the known microstate geometries to be typical.
- Most BH microstates are in the long string sector, but only tuned short string microstates produce large multipole moments.



Typical microstates

$$ds^2 = -(\rho - \frac{P}{\rho})^2 dt^2 + (\rho - \frac{P}{\rho})^{-2} d\rho^2 + \rho(dy - \frac{P}{\rho^2} dt)^2$$
$$+ d\theta^2 + \sin^2\theta(d\phi + J(dy - dt))^2$$
$$+ \cos^2\theta(d\psi + J(dt - dy))^2 + \delta g_{ab}(\rho, \theta, \phi, \psi) dx^a dx^b$$

- The scale set by δg is typically $(\rho - \sqrt{P}) \sim \frac{1}{N^k}$.
- For $\rho = \sqrt{P} + \epsilon$, $\frac{1}{N^k} \ll \epsilon \ll 1$ the geometry only has parametrically small corrections!

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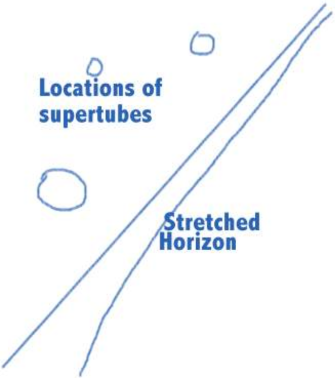
Near horizon behaviour

- Metric and other fields deviate only slightly from BMPV, even very close to horizon scale.
- Yet the deviations remove the horizon!
- Behind the stretched horizon $(\rho - \sqrt{P}) = \epsilon$ there are pockets of high curvature and coupling.



Distinguishability

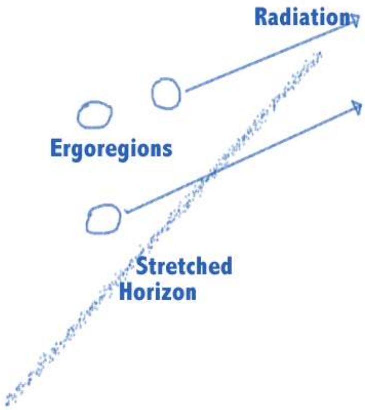
Higher derivative corrections e.g.

$$S = \int dx \sqrt{-g} \left(R + (\alpha')^3 R^4 + \cdots \right)$$

must play an essential role.

- Higher derivative terms are dual to higher dimension CFT operators.
- Their expectation values (normalizable modes) are needed to distinguish different microstates.

Qualitative picture of radiating BH microstates



- Non-extremal microstates must radiate.
- Finding representative geometries within supergravity is very difficult.

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Conclusions

- Information is recovered in horizonless geometries.
- Holography matches known microstate geometries to special BH microstates.
- Generic microstates require higher derivative corrections.
- Construct non-extremal BH microstates numerically from holographic initial and boundary data?