The Black Holes' Information Paradox and String Theory

Based on works by S.Mathur, O.Lunin, K.Skenderis, I.Bena, S.Giusto, J.F.Morales, M.Bianchi

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- The Information Paradox
- Building Black Holes in String Theory
- The Fuzzball Conjecture

The simplest BH anatomy

Schwarzschild metric

$$ds^2 = \left(1 - \frac{R_s}{r}\right) c^2 dt^2 - \left(1 - \frac{R_s}{r}\right)^{-1} dr^2 - r^2 d\Omega_2^2$$

- Completely determined by $R_s \equiv \frac{2MG}{c^2}$
- Horizon at $r = R_s$: light cannot escape to infinity $\Rightarrow$ Trapped region
- Real singularity at $r = 0$

More general cases completely determined by M, Q, J

$\Downarrow$

"Black holes have no hair" (Wheeler)

Entropy puzzle

Throw a box of hot gas inside the BH

$\Downarrow$

It had a definite entropy, now it seems lost

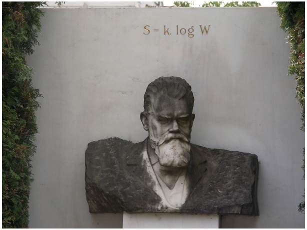
Save the II Law of Thermodynamics: assign an entropy to Black Holes

Bekenstein 1973

$$S_{Bek} = \frac{A}{4G} \Rightarrow \frac{dS_{Bek}}{dt} + \frac{dS_{matter}}{dt} \geq 0$$

Entropy puzzle

Puzzle: entropy has usually a fundamental interpretation



There should be $\mathcal{N} = \exp S \simeq \exp\left[10^{76}\left(\frac{M}{M_\odot}\right)^2\right]$ microstates

However...

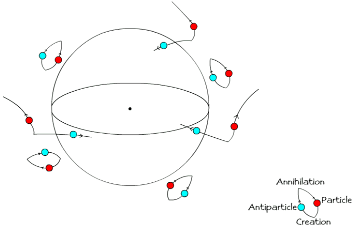
BLACK HOLES HAVE NO HAIR

No real trouble: "hair" may be produced by Quantum Gravity and hidden well beyond the horizon

Hawking Radiation

Semiclassically, Black Holes are no longer stable

Hawking 1974



QFT+gently curved background

Pair creation near the horizon: one falls in the BH, the other escapes to infinity

↓

Seen by a far observer as thermal emission from the BH

Black Hole Thermodynamics

Law	Thermodynamics	Black Holes
Zeroth	T constant over bodies at equilibrium	κ constant over the horizon
First	$dE = TdS - PdV$	$dM = \frac{1}{8\pi}\kappa dA + \Omega dJ$
Second	$\delta S \leq 0$	$\delta A \leq 0$
Third	$T = 0$ not achievable	$\kappa = 0$ not achievable

To complete the duality, we have

Hawking emission $\leftrightarrow$ Blackbody radiation

The Information Paradox

Throw some matter in a BH, wait for complete evaporation through Hawking emission

- Initial matter $\rightarrow$ pure state $|\psi\rangle$
- Final state $\rightarrow$ density matrix ρ_{rad}

The final state carries no information of what fell beyond the horizon

Loss of UNITARY EVOLUTION

Based on very few, reasonable assumptions

- Quantum Gravity effects are confined to ℓ_p
- Vacuum is unique

Details of Quantum Gravity are not relevant

The Information Paradox

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Possible ways around

How can Quantum Gravity work around the paradox?

- Planck sized remnants$\rightarrow$ ugly: size independent from S
- Non-local interactions (singularity $\leftrightarrow$ horizon)
- Unitarity is effectively lost
- Structure modified up to the horizon

String theory points towards the last one

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String Theory in few words

One principle: fundamental objects are 1-dimensional

Consequences

- SUSY to produce fermions
- Spacetime dimension=10 $\Rightarrow$ compact dimensions
- $p-$Branes: extended, charged objects on which strings can end
- In principle: no dimensionless free parameters
- Five theories related by web of dualities $\Rightarrow$ M-Theory?

But the most important

It is a consistent Quantum Gravity (SUGRA as Eff.Th.)

$\Downarrow$

it MUST solve the information paradox somehow

Building Black Holes (Susskind)

How to solve the entropy puzzle:

Take a system of fundamental objects (strings/branes)

- Count degeneracy $\rightarrow$ Microscopic count: easy at small g_s
- Increase g_s until a BH is formed$\rightarrow$ Compute Area of Horizon
- Compare the degeneracy with the Bekenstein entropy: should match (or we throw away string theory)

Inconsistency: levels can shift with changes in g_s

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Focus on BPS states: levels shift together (Thank you SUSY)

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5D Multi charge states

2-Charge state (winding n_y,momentum n_p in N_L)

$$S_{micro} = 2\sqrt{2}\pi\sqrt{n_y n_p}$$

$$ds^2_{naive} = \left(1 + \frac{Q_1}{r^2}\right)^{-1}\left[-dudv + \frac{Q_p}{r^2}dv^2\right] + dx_i dx^i + dz_a dz^a$$

No horizon: if we add higher derivative terms, it develops a horizon at $r = 0$ with

$$S_{Bek} = S_{micro}$$

We called it naive for a fundamental reason

This metric cannot exist in string theory

(datails later, crucial for next section)

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5D Multi charge states

3-Charge state (add n_5 5-Branes)

$$S_{micro} = 2\pi\sqrt{n_y n_p n_5}$$

Construct the corresponding metric, compute the horizon area

$$S_{Bek} = S_{micro}$$

No subtleties, remarkable matching and moreover...

This solution is an extremal BH $\rightarrow$ no Hawking radiation

Perturb this configuration to make it not extremal (add some N_R)

Left and Right moving excitations can collide and escape as massless quanta leaving the Brane configuration

Rate and spin dependence agree with Hawking emission

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Real geometries

The Information Paradox

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Conclusions

Let's go back to the 2-Charge state

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Cannot be produced by any string configuration

WHY?

ds^2_{naive} is spherically symmetric $\Rightarrow$ generated by a pointlike source in transverse space

But the momentum MUST be carried by transverse waves on the string

$\Downarrow$

Cannot be pointlike in transverse space

Should be considered just a valid SUGRA solution far from $r = 0$

Real geometries

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Real geometries

Vibration profile described by $\vec{F}(v \equiv t - y)$ with
$$0 \leq y \leq 2\pi n_y R$$

- Find the corresponding metric
- Make approximations (neighbouring "strands" give the same contribution)
- Use dualities of string theory to move to $D1 - D5$ system

Real geometries

Resulting solution

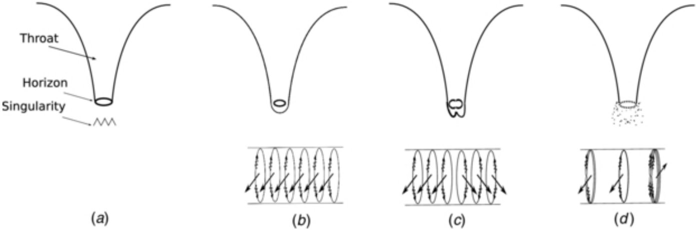
$$ds^2=\sqrt{\frac{H}{1+K}}\left[-(dt-A_i dx^i)^2+(dy+B_i dx^i)^2\right]+\sqrt{\frac{1+K}{H}}dx_i dx^i+\sqrt{H(1+K)}dz_a dz^a$$

$$H^{-1}=1+\frac{\mu Q_1}{L}\int_0^{\mu L}\frac{dv}{|\vec{x}-\mu\vec{F}(v)|^2}$$

$$K=\frac{\mu Q_1}{L}\int_0^{\mu L}\frac{dv(\mu^2\dot{F}_i(v))^2}{|\vec{x}-\mu\vec{F}(v)|^2}$$

$$A_i=\frac{\mu Q_1}{L}\int_0^{\mu L}\frac{dv\mu\dot{F}_i}{|\vec{x}-\mu\vec{F}(v)|^2}\quad ;\quad dB=-\star_4 dA$$

How do they look?



The geometry can be divided in three main regions

- $r \to \infty \Rightarrow$ FLAT SPACE
- Intermediate "throat" $AdS_3 \times S_3 \times T_4 \Rightarrow \approx ds^2_{naive}$
- $r \to 0 \Rightarrow$ ends in a smooth "cap"

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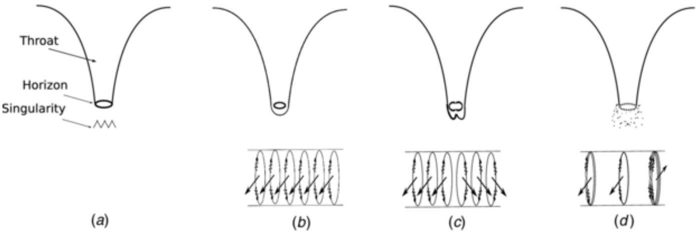


We have found the hair

- Different $\vec{F}(v) \Rightarrow$ Different caps
- From afar, they look like the classical "naive" BH
- Horizonless $\Rightarrow$ Crucial: microstates have no entropy

The classical BH is a coarse-grained description

The size

Last issue

Information of the microstates must reach the horizon scale, or we have not solved the paradox

$$\Delta x = |\dot{\vec{F}}|\Delta y \sim \sqrt{\alpha'} \equiv \ell_s$$

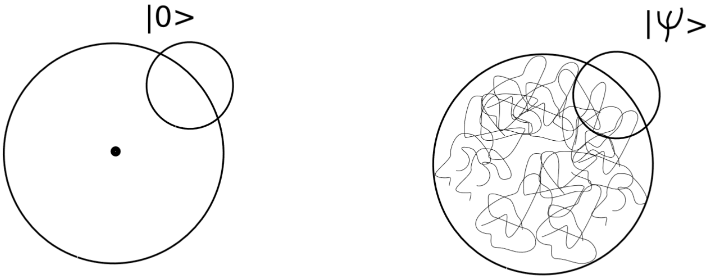
$$\text{For } x \gg \sqrt{\alpha'} \Rightarrow ds^2 \to ds^2_{naive}$$

Compute area at $|\vec{x}| = \sqrt{\alpha'}$ in transverse space

$$\frac{A}{4G_{10}} \sim \sqrt{n_y n_p} = S_{micro}$$

Area reproduces the Bekenstein Entropy!

The size



The state near the horizon is not the vacuum, instead we have

$$\langle 0|\psi\rangle \approx 0$$

On the "would-be" horizon

The "cap" region has a size which satisfies a Bekenstein relation

Does the boundary of this region behave like a horizon?

Simple test: consider a quantum falling in the cap region

The time it takes to cross the generic cap is found to be proportional to $\left(\frac{M}{m_{pl}}\right)^2$

$\Downarrow$

A classical observer for which $\hbar \sim 0$ finds an infinite crossing time

Everything that falls in the cap, can never escape

Conclusions

String theory passes a nontrivial test as a consistent Quantum Gravity

- BHs are coarse-grained descriptions of Fuzzballs
- Entropy comes from coarse-graining of $\mathcal{N} = e^S$ Fuzzball states
- Fuzzball states are horizonless (no information loss)
- Effects from string theory extend to horizon scale $\Rightarrow$ the "would-be horizon" carries hair
- Hawking radiation is no different from that emitted by a burning coal

Thanks for your attention