Quantum Black Holes as Solvents

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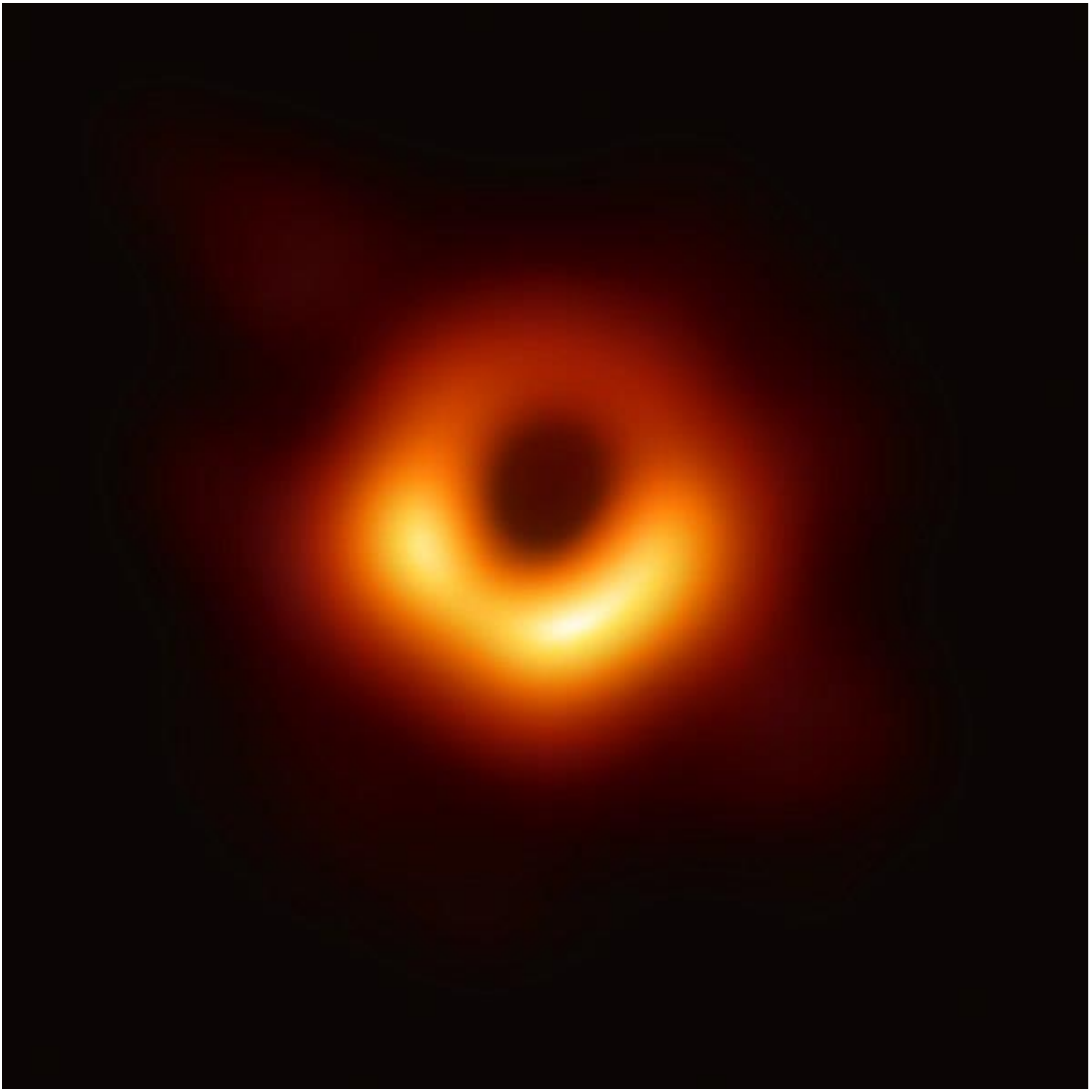

Picture of the black hole M87*

11 April 2017

Event Horizon Telescope (EHT)

European Southern Observatory (ESO)

Wikimedia commons

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Number of outstanding people who have worked on or around quantum black holes is huge

Hawking, Bekenstein, Penrose, Zeldovich, Novikov, Wheeler, Zurek, Susskind, Maldacena, Wald, Unruh, ’t Hooft, Verlinde, Verlinde, Giddings, Horodecki, Horodecki, Aaronson, Page, Strominger, Bousso, Harlow, Sorkin, Smolin, Wilczek, Życzkowski,…

To give appropriate credit is impossible.

KTH VETENSKAP OCH KONST
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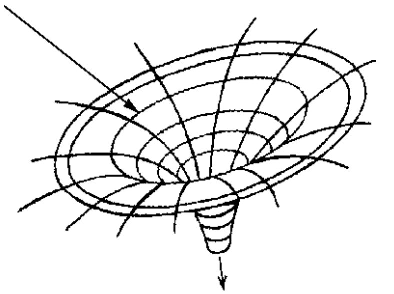
Bekenstein-Hawking (black hole) entropy

Entropy of a black hole of area A: $$S = \frac{A k_B c^3}{4 \hbar G}$$



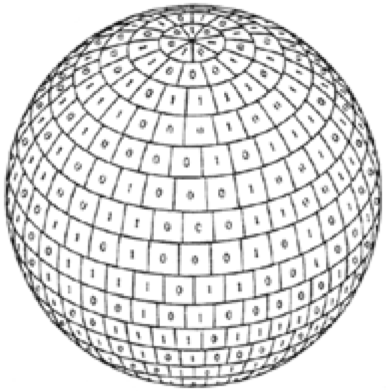
k_B Boltzmann's constant

$\hbar$ Planck's constant

G Newton's constant

c speed of light

$$L_P = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-35} \text{ m}$$



Entropy of a black hole is equal to ¼ the area measured in the units of Planck area.

This entropy is enormously large. More than 99.99999% of all the entropy in the universe today.

Most of the slide courtesy Dave Bacon, U Washington

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Black hole information paradox

Take a large piece of matter in a pure quantum state, and have gravity turned off.

Turn on gravity. The matter collapses in a black hole.

The black hole evaporates through Hawking radiation.

At the end the black hole is gone, and all that remains is thermal radiation.

A pure state has developed into a mixed state. This breaks unitarity.

Ways out?

Fundamental information loss: actually the dynamics of a quantum black hole is not unitary.

Physics at horizon: firewalls or other physics stops the collapse.

Information return in Hawking radiation: entanglement between early and late Hawking radiation.

Remnants: evaporation is not complete, something remains that keeps the information.

The issue is still very actively discussed…

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S_{BH} as function of mass

For a Schwarzschild black hole, such that $R = \frac{2GM}{c^2}$

$$S_{BH} = 4\pi\left(\frac{M}{m_{\mathrm{Pl}}}\right)^2 \quad m_{\mathrm{Pl}} = 2.2 \times 10^{-8}\ \mathrm{kg}$$

Normal thermodynamic entropy is an extensive quantity. It grows linearly with mass. But black hole entropy grows quadratically with mass. The most entropic other object in the universe is a photon gas, which has entropy $\sim M^{\frac{3}{2}}$ ['t Hooft, arXiv:gr-qc/9310026].

The entropy of a black hole is much, much larger than the entropy of anything that could have formed the black hole. Even though the black hole has been compressed to a much smaller volume. Normal entropy does not behave that way.

$S = \log \mathcal{N}$?

For a classical liquid this is so. $\mathcal{N}$ is the volume of phase space accessible to the molecules of the liquid.

Or for the molecules of a salt crystal which dissolves into a liquid like water. The process of solvation proceeds when the dissolving salt molecules gain more entropy in the larger volume than they lose in internal energy by moving away from the salt crystal.

What is $\mathcal{N}$ for the quantum black hole? Is there even such a thing? For a negative answer, see e.g. Hossenfelder & Smolin, *Phys. Rev. D* **81:**064009 (2010).

On the other hand "…thermodynamics is the only physical theory that will never be over-turned…" demands that if black hole entropy is an entropy in the sense of normal entropy, there must be an $\mathcal{N}$.

Entanglement entropy

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$$|\psi\rangle = \sum c_i |S\rangle_i |A\rangle_i \qquad \rho = \mathrm{Tr}_A[|\psi\rangle\langle\psi|]$$

$$S = -\mathrm{Tr}[\rho \log \rho]$$

von Neumann entropy. The quantum version of Shannon entropy.

S cannot increase under local operations and classical communication (LOCC) [Horodecki[4], *Rev Mod Phys* (2009)].

Gravitational collapse is a local process (mostly).

Entanglement entropy between a black hole and the rest of the universe (ancilla) cannot be much larger than the entanglement entropy of the star that gave rise to the black hole.

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Entanglement with gravity

$$|\psi\rangle_{init} = \left(\sum b_i |S\rangle_i |A\rangle_i\right) \otimes |G\rangle$$

Initial state of the star and ancilla and a pure quantum gravity state (if such a thing exists)

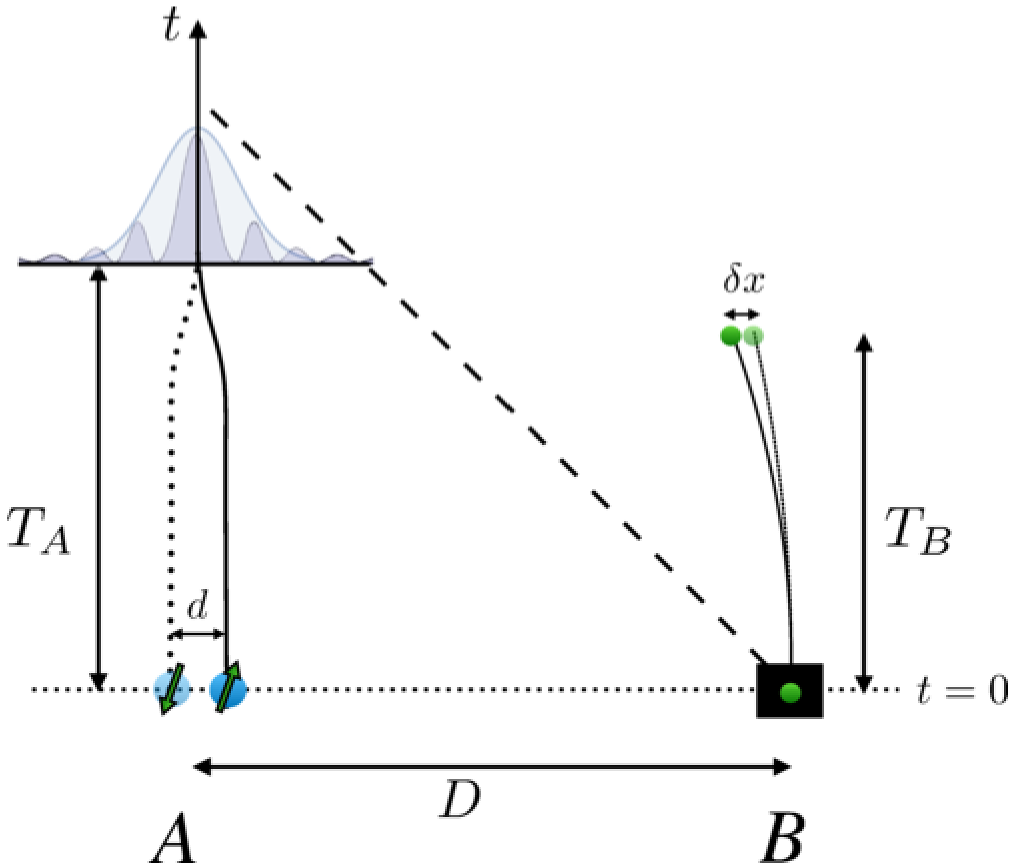
$$|\psi\rangle_{final} = \sum b_i' |A\rangle_i \left(\sum c_i^k \, |B\rangle_k |G\rangle_k\right)$$

Final state of black hole + gravitation with the ancilla

An "entangled entanglement" state [Walther, Resch, Brukner & Zeilinger, *Phys*. *Rev*. *Lett*. **97**:020501 (2006)].

Internal B-G entanglement can be much greater than the one between the joint system B+G and rest of the Universe. This can hence be $\mathcal{N}$.

Table-top experiments



An active field with contributions from Brukner. Aspelmeyer, Pikovski, Vedral, Bose, Millburn and others.

The experts believe that the quantum nature of gravity can be shown (or disproven) in quantum optics experiments, in a few years' time.

Fig 1 in Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner & Aspelmeyer *Phys. Rev. D* **98:**126009 (2018)

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“Reasonable ideas” of a quantum black hole

It is in a maximally mixed state given its macroscopic parameters (mass, charge, angular momentum) [a microcanonical ensemble] (unclear what this actually means if you don’t know what the quantum states are, but it is an often stated assumption…)

A small quantum test particle which is not at the singularity behaves as if it is moving in the background of a classical black hole. Experimentally shown for quantum particles moving in the gravitational field of the Earth [Nesvizhevsky et al, *Nature* **415**:297299 (2002)]

A small quantum test particle also behaves as if moving in the classical background when evolving with a pure quantum state of the black hole picked randomly with respect to the microcanonical ensemble. A kind of typicality argument [Reimann, *Phys. Rev. Lett.* **101**:190403 (2008); Gogolin & Eisert *Rep. Prog. Phys*. **79:**056001 (2016)].

If the “reasonable ideas” are admitted…

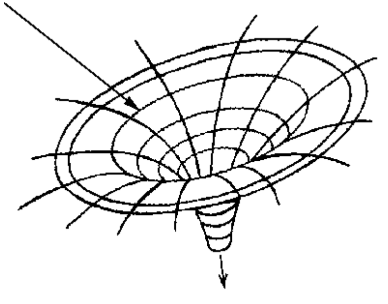
It suffices to consider the evolution of a pure state of the test particle and a pure state of the gravitational field of the black hole.

$$|T\rangle \otimes |G\rangle$$

Let there be some (unknown) basis $|S\rangle_i$ that describes the matter inside the black hole close to singularity, and some (unknown) basis $|G\rangle_i$ for gravitation. Consider two different test particles ***T*** and ***T***’ in the same ***G***.

$$|T\rangle \otimes |G\rangle \rightarrow \sum c_i |S\rangle_i |G\rangle_i$$

$$|T'\rangle \otimes |G\rangle \rightarrow \sum c_i' |S\rangle_i |G\rangle_i$$



?

Model for information

Suppose all the final states close or at the singularity are very similar.

$$|T\rangle \otimes |G\rangle \rightarrow \sum c_i |S\rangle_i |G\rangle_i \dashrightarrow |S^*\rangle |G\rangle$$

$$|T'\rangle \otimes |G\rangle \rightarrow \sum c_i' |S\rangle_i |G\rangle_i \dashrightarrow |S^*\rangle |G'\rangle$$

From this does not follow that the final states of the gravitational field are the same.

The (classical) action of the two paths which will be arbitrarily different when they hit the singularity (infinite tidal forces). There may also be a quantum information argument based on distinguishability of quantum states (this you have to ask Paweł Horodecki and Michał Eckstein).

Model of the aftermath

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Suppose that Hawking radiation is a unitary process. The initial state has no photons in the radiation field:

$$|\Psi\rangle = \left(\sum_i c_i |S\rangle_i \, |G\rangle_i\right) \otimes |R\rangle_0$$

The final state should be an entangled state between radiation and gravitation (the matter of the hole has returned to the vacuum state):

$$|\Psi'\rangle = \sum c'_j |R\rangle_j \, |G\rangle_j$$

In the black hole information paradox context, this is hence a proposal of a remnant, but not of the usual kind.

Bekenstein 1973:2001

Jacob Bekenstein in 1973 proposed that BH entropy is the log of the number of different quantum systems that could have given rise to the black hole, and estimated that quantity. In 2001 he considered a black hole emitting Hawking radiation and at the same time being feeded by a stream of matter so that its mass, angular momentum and charge stays constant:

> *[The black hole then] does not change in time, and neither does its entropy. But surely the inflowing matter is bringing into the black hole fresh quantum states; yet this is not reflected in a growth of SBH! [...] If we continue thinking of the Hawking radiation as originating outside the horizon, this does not sound possible.*

Bekenstein, *Stud. Hist. Philos. Mod. Phys*. **32**:511-524 (2001)

From the point of view of today, the above describes a non-equilibrium stationary state (NESS). It could be possible. Compare Earth atmosphere.

Thanks

Michał Eckstein
Paweł Horodecki

<u>*Pictures / slides from internet*</u>
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