Mapping the Unknown: Inside Black Holes

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Mapping the Unknown: Inside Black Holes

Dr Niloofar Vardian at the SISSA school has advanced our understanding of black hole interiors through precise mathematical modelling. Her recent publication sheds light on previously inaccessible aspects of black hole dynamics, deepening our knowledge of these mysterious and difficult-to-study phenomena.

The Black Hole Information Paradox

To describe our universe, we employ two big theories: general relativity and quantum physics. Unfortunately, the two theories are irreconcilable on many fundamental questions, mostly centred around gravity, where many paradoxes point to the existence of a bigger, complete theory of quantum gravity. This framework unifies the fundamental forces of nature. Among these, the theory of black holes stands out as particularly significant. A black hole is a region of space so dense that the gravitational pull is too strong for even light to escape. This means that we have no means to directly investigate what lies in the interior of a black hole.

At its core, the black hole information paradox revolves around the smoothness of a black hole's boundary, known as the event horizon. According to our understanding of general relativity, once something crosses this boundary, it is forever lost within the black hole. However, quantum mechanics tells us that information is always preserved during physical processes. We may hypothesise that the information is still there, just inaccessible inside the black hole, but quantum mechanics adds another complication, where black holes emit energy via the theoretical Hawking radiation. This means that black holes can evaporate, leaving no trace of their previous existence. When that happens, where did the information go?

Bringing Together Quantum Field Theory, General Relativity, and Information Theory

Dr Niloofar Vardian, a physicist based at SISSA, Italy, works in an area rooted in the complex interplay of quantum field theory, general relativity, and information theory.

Dr Vardian has adopted an approach inspired by the Papadodimas-Raju proposal. This proposal suggests that the interior of a black hole can be described in terms of a conformal field theory (CFT), a type of quantum field theory that describes how fields, representing elementary particles, behave.

The team focuses on a specific subspace within the CFT, known as the code subspace. This subspace is created by acting with a small algebra on a pure state, a quantum state with all its properties perfectly defined. Within this code subspace, they seek to find the CFT description of the interior operator, which can be thought of as a tool that provides a window into the hidden depths of the black hole.

This is achieved through the Petz map (a specific choice of the dual of the universal recovery channel) comes from the quantum error correction technique), a tool that allows the researchers to connect the black hole interior to the CFT, effectively bridging the gap between the macroscopic and microscopic degrees of freedom. In other words, it helps translate the large-scale properties of the black hole (like its mass and spin) to the small-scale quantum behaviours and vice versa, enabling a link between predictions from different theories.

The bath system can be described as essentially the environment that absorbs the Hawking radiation, which is the theoretical prediction that black holes are not completely black but emit small amounts of thermal radiation due to quantum effects.

The interior modes of a black hole refer to the quantum states that exist within the black hole. The interior modes in the island after the Page time (see below) are expected to map to certain operators that only have support on the bath system: this would resolve the black hole information paradox, providing a way to retrieve information from the otherwise inaccessible interior.

Results

In her paper 'Black hole interior Petz map reconstruction and Papadodimas-Raju proposal', Dr Vardian makes significant strides forward in the field of black hole research by successfully constructing the interior operator on the boundary side. She reports how her team found that after a certain time known as Page time, some parts of the interior were encoded in the early Hawking radiation, or in other words, could be reconstructed through the bath.

This prediction aligns with the island conjecture, a recent proposal in the field of quantum gravity. According to this conjecture, the information that falls into a black hole isn't lost but is encoded in a region called an 'island', which can be reconstructed from the Hawking radiation emitted by the black hole. The Petz map, a tool from quantum information theory, serves as the key to this intricate puzzle, enabling the team to decode the hidden information within the Hawking radiation.

The team's findings have led to the discovery of a new Ryu-Takayanagi surface, subtly positioned inside the black hole event horizon. The Ryu-Takayanagi formula, a cornerstone of the holographic principle, relates the area of certain surfaces in a gravitational theory to the entanglement entropy in a dual quantum theory. Beyond a time known as the Page time, portions of the black hole interior begin to emerge in the early radiation. This suggests a deeper connection between the black hole and its surroundings, hinting at a profound link between gravity and quantum mechanics.

This discovery, if confirmed, could help not just by providing new insights into the structure of black holes but also in our general understanding of the fundamental nature of the universe, perhaps shedding light on the unknown, missing general theory that links gravity and quantum mechanics.

The theoretical results reached by Dr Vardian are, of course, suggestive at this stage but consistent with other papers in the literature, including the Papadodimas-Raju proposal. The Papadodimas-Raju proposal is a specific example of the Petz map reconstruction of the black hole interior and the formulation that has been provided in the main article introduces a general approach to go much more through the detail and also studies the most complicated examples as the evaporating black holes as discussed in the paper.

As with most topics in theoretical physics, decades can pass between theoretical breakthroughs and experimental confirmation: after all, black holes are (thankfully!) very far away from us, and, therefore, very hard to study. If confirmed by experimental data, the findings by Dr Vardian could open the way to a new understanding of physics, an elusive quest that has been ongoing for over 80 years, ever since Albert Einstein's famous statement, 'God does not play dice'.

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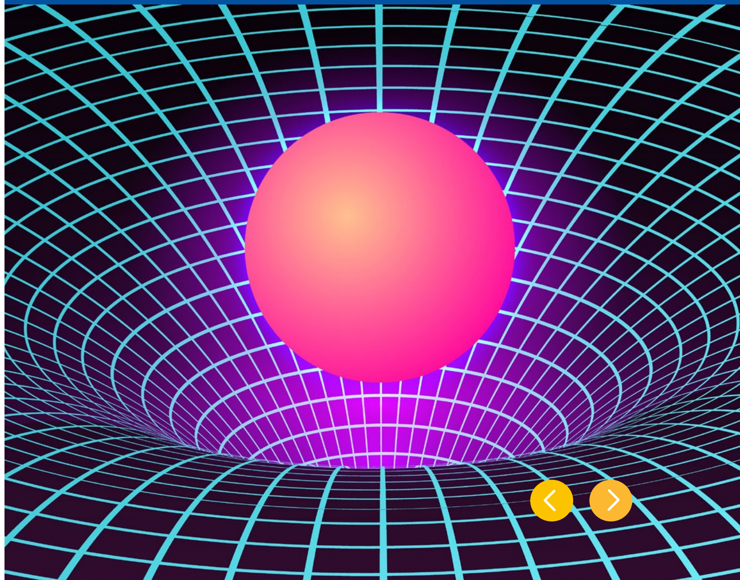

MEET THE RESEARCHER

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Dr Niloofar Vardian is a physicist who recently completed her PhD at Scuola Internazionale Superiore di Studi Avanzati in Trieste under the supervision of Dr Kyriakos Papadodimas. She completed her MSc in Physics in Tehran in 2016, which included a thesis titled 'Continuous Matrix Product Ansatz for studying 1+1 Quantum Field Theory' at the Sharif University of Technology in Tehran. Having an outstanding academic record, Dr Vardian has visited CERN on several occasions and already published in leading journals.

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FURTHER READING

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