

# The Black Hole Information Paradox

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**Abstract** The black hole information paradox remains one of modern physics's most interesting and confounding challenges. It stems from the two wrestling ideas between quantum mechanics and general relativity; mainly surrounding the information that falls into a black hole. This paper investigates the theoretical and observational aspects of the paradox and what may come from its resolution. Firstly, we discuss the quantum mechanical and classical properties of black holes, and we look at the role of Hawking radiation and the resulting information loss paradox. There are many proposed resolutions to this paradox including black hole complementarity and the firewall hypothesis that we examine in detail. Next, we assess the observational constraints on these frameworks and consider the evidence for the information retention of black holes. We also explore the role of quantum gravity and new theories on the paradox's resolution, offering possible bridges between quantum mechanics and general relativity. Finally, we discuss the philosophical implications of the black hole information paradox, touching on concepts like the holographic principle and the nature of reality. This paper aims to shed light on the wild nature of black holes and the questions they pose for a better understanding of our universe.

## 1 Introduction

Black holes have captivated the imagination of scientists and the public alike for decades. Black holes are born from the collapse of massive stars and possess extraordinary properties that challenge our understanding of the fundamental laws of physics. There is a plethora of mysteries surrounding black holes, though none is more interesting than the black hole information paradox.

At the heart of the black hole information paradox lies a fundamental question: what happens to the information encoded in matter that falls into a black hole? According to classical physics, black holes are described solely by their mass, charge, and angular momentum; this leads to the proposition that all information about infalling matter is completely lost once it crosses the event horizon. However, this prediction conflicts with the principles of quantum mechanics, which dictate that the information

cannot be destroyed but must be conserved.

We will explore the possibilities of what this could mean for us through several possible outcomes, all of which will inevitably change the fundamental laws of physics forever. Quantum mechanics tells us that all of the information in the universe must be conserved somehow, such as when a piece of paper is burned, we don't lose its information; it is just mixed up in the pile of ashes it left behind. Because of this, many scientists believe that black holes store the information (mixed particles) on their edge: the event horizon. The issue with this, however, was created when Stephen Hawking discovered radiation coming from black holes of Hawking radiation [Haw74]. This discovery tells us that black holes evaporate and shed particles over time, thus the information stored in the black holes will be lost forever: erasing the universe. So what truly happens to the information of the infalling objects?

## 2 Theoretical Background

To start, I want to explain what a black hole is. A black hole is created when a supermassive star collapses, the outer section of the star explodes and creates a supernova, but the core remains and collapses in on itself to form a ball of incredibly high mass and, thus, high gravity. Through the following theories, we can better explain exactly what happens near and in a black hole.

### 2.1 General Relativity

General relativity was theorized by Einstein in 1915 and is comprised of four physical and geometrical principles: spacetime structure, the equivalence principle, local causality, and preferred local coordinate frames [Ein15]. The spacetime structure is a four-dimensional differentiable manifold of the Lorenz signature and leads to the field equations being generally covariant. The equivalence principle leads to the idea that spacetime has a metric and a pseudo-Riemannian structure. Local causality states that general relativity (GR) subsumes special relativity (SR), in which an important role is the local freely falling reference frames and the fact that gravitational waves travel at the speed of light. From this, we can assume that freely falling test particles follow time-like geodesics and light follows null geodesics of the spacetime geometry. An important thing to note when studying GR is that it cannot be studied on a small scale since that delves more into quantum mechanics [CW17].

Einstein's field equations have three main aspects [CW17]:

1. They are hyperbolic partial differential equations and do not restrict the topology of spacetime.
2. The geometry and matter are dynamic.
3. Energy is not conserved in general. Instead, the energy-momentum tensor is conserved thus

mixing energy, matter, and geometry.

Einstein has ten field equations that are wrapped together in one tensor equation listed below.

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu} \quad (1)$$

In this equation,  $G_{\mu\nu}$  is the Einstein tensor and is determined by the curvature of space and time,  $R_{\mu\nu}$  is the Ricci curvature tensor,  $R$  is the scalar curvature,  $g_{\mu\nu}$  is the metric tensor which specifies spacetime geometry,  $\Lambda$  is the cosmological constant,  $G$  is Newton's gravitational constant,  $c$  is the speed of light, and  $T_{\mu\nu}$  is the stress-energy tensor.

Einstein also stated in this theory that once an object crosses a black hole's event horizon, it will never be known again.

## 2.2 Quantum Mechanics

In quantum mechanics, time is treated classically and space is treated at the quantum level. It explains how extremely small objects have two behavioral characteristics: they can act as both a wave and a particle. This is commonly known to scientists as the "wave-particle duality". On the particle side, we focus on the smallest discrete unit of a natural phenomenon in a bound-state unit, a "quanta". An example of this is a photon, which is the quanta of electromagnetic radiation (light). To be quantized means that the particles in a bound state can only have discrete values for their properties like energy and momentum. This is quite different from most things we see since they never have a fixed or discrete value for their energy or momentum as they can usually be picked up and moved at any speed.

On the other side of the wave-particle duality, we have tiny quantized particles (i.e. electrons) that are often described as waves. Waves, at the quantum level, are always moving. Because a wave is always moving, we use the wave function (found through Schrödinger's equation 2) to determine the possibility of there being a particle at a certain time and location with some momentum.

$$\hat{H}\Psi = E\Psi \quad (2)$$

In this equation,  $\hat{H}$  is the Hamiltonian Operator,  $\Psi$  is the wave function, and  $E$  is the energy. This equation is independent of time.

In the conservation of quantum information, there are three fundamental theorems: the no-cloning theorem, the no-deleting theorem, and the no-hiding theorem. The no-cloning theorem states that it is impossible to make a perfect copy of an unknown quantum state. The no-deleting theorem states that, given two copies of some quantum state, it is impossible to delete one of the copies. Finally, the no-hiding theorem states that if information is missing from one system, the information must be

somewhere else in the universe. These all come together to tell us that information cannot be created or destroyed.

Even though quantum mechanics states that information cannot be deleted, it also states that if an object has a temperature, it must emit radiation, since all thermal bodies do. Hawking showed, in 1974, that because of this, black holes must emit radiation and, therefore, matter as well. This means that as it radiates, it sheds the information it stores [Haw74]. The issue we have yet to solve is where does that information go?

### 3 Resolutions

There are quite a few theorized answers to this problem: the holographic principle, the quantum hair theorem, and the firewall hypothesis.

#### 3.1 The Holographic Principle

The holographic principle was introduced in 1993 by Gerard't Hooft. He stated, "According to general relativity, there should exist a direct mapping that relates physical phenomena in one setting (with a gravitational field present) to another one (freely falling coordinates)" [tH00]. Hooft believed that we could look at the world with one less dimension. The idea is to change the degrees of freedom of a gravitational theory, from using area rather than volume. The principle goes even deeper and states that the information of a whole gravitational field is located at the boundary of the region, leaving it on a two-dimensional, curved plane.

To explain this mathematically, we first need to think of a spherical region with volume  $V$  and entropy  $S_{region}$ . Suppose we add more matter with entropy  $S_{matter}$  to make a black hole. Since entropy grows over time, there must be an upper bound  $S_{region} + S_{matter} \leq S_{Bound}$ . From this, we can find the inequality called the spherical entropy bound.

$$S_{region}(V) \leq S_{Bound} = \frac{A}{4G_N} \quad (3)$$

In this,  $A$  is the Planck area. Continuing on that equation, we can find the holographic bound using the number of Hilbert states  $N$ .

$$N_{region}(V) \leq \frac{A}{4G_N} \quad (4)$$

The holographic principle opposes the quantum field theory as well as locality because of this.

It is called the holographic principle because the information believes it is still in a three-dimensional

space but actually resides on a two-dimensional plane. This tells us that information won't be lost to a black hole, but does not seem to account for Hawking radiation [Ber23].

### 3.2 The Quantum Hair Theorem

The Quantum Hair Theorem states that matter falling into a black hole will leave an imprint in the black hole's gravitational field when taking into account quantum gravity. These imprints are what we call "quantum hair". This entangles the quantum state of the matter inside the black hole to the state of gravitons on the outside. The entanglement would allow us to see the encoded information about the inside of the hole regardless of Hawking radiation [Sta22].

### 3.3 The Firewall Hypothesis

Since the idea of conserved information relies on entanglement between two particles, the firewall hypothesis says that maybe the entanglement is broken upon the infalling particle's impact. This comes from the existence of a large energy-momentum that would break the tie.

The issue with this hypothesis, however, is that it contradicts the equivalence principle and also the quantum field theory on curved spacetime [Rov19].

## 4 Observational Strategies

There are many ways to observe this and possibly get some evidence pointing towards an answer to this paradox. First, we can try to further examine accretion disks that lie outside of black holes. If we study the radiation emitted across different wavelengths, we can infer properties such as temperature, density, and chemical composition. From this, we can put together theoretical models and create constraints that may lead us to find the fate of infalling information. Next, we can observe black hole X-ray emission. Black holes can emit intense X-ray radiation towards the event horizon. By analyzing the spectrum and variability, we can deduce characteristics such as the mass and spin of the black hole as well as the properties of surrounding matter. From this, we can hopefully find out if information is stored in the event horizon. Finally, we can look at gravitational wave signatures. From instruments like LIGO and Virgo, we found that black hole mergers emit gravitational waves. These waves have signals that could hold information about the masses, spins, and orbital parameters of the merging black holes which offer opportunities to test predictions and constraints related to information retention.

## 5 Philosophical Implications

Some key philosophical implications of the black hole information loss paradox include the loss in determinism, the violation of unitarity, and the laws of conservation. The principle of determinism is the idea that the future state of a physical system can be predicted by its current state. It suggests that we can determine the universe's history and its forward evolution. This conflicts with the uncertainty that comes with quantum physics and thus Hawking radiation and the information loss paradox. The conservation of quantum mechanical unitarity is a fundamental principle in quantum mechanics. It states that the total probability of all possible outcomes of a quantum system must sum to one. The idea that information would be lost would mess up the probability and thus violate the principle. If information does truly vanish, we would have to completely reevaluate our knowledge of unitarity. Lastly, it completely violates the laws of conservation, as briefly discussed when we talked about the basics of quantum mechanics. The law of conservation states that information and matter can not be created or destroyed. Once again, such as the unitarity principle, we would have to reevaluate how we see information and its conservation if Hawking radiation forces black holes to lose information.

## 6 Conclusion

The black hole information paradox stands as a troubling intersection between classical and quantum physics, challenging our understanding of fundamental principles and the nature of the universe itself. Throughout this paper, we delved into the theoretical bases, proposed resolutions, and observational constraints surrounding this phenomenon.

We revealed the depth of the theoretical challenges posed by the black hole information paradox. From the clash between general relativity and quantum mechanics to the implications for conservation laws and the principle of unitarity, the paradox forces us to confront fundamental questions about the nature of reality and the limits of our current scientific knowledge.

Proposed resolutions to the paradox, such as the quantum hair theorem or the firewall hypothesis, offer intriguing insights into the nature of black holes and the fate of information within them. Yet, each resolution brings its own set of challenges, highlighting the complexity of the problem at hand.

Observational constraints, derived from studies of black hole accretion disks, X-ray emission, and gravitational wave signatures, provide valuable clues about the behavior of black holes and the retention or loss of information. While indirect, these observations offer valuable insights that can inform and create constraints to theoretical models of black holes.

As we continue to probe the mysteries of black holes and the cosmos, the black hole information paradox serves as a reminder of the questions that lie at the heart of astronomy. The further we

look into these questions, the more information we retrieve, and the smarter we become as a whole; hopefully, eventually, we can solve the secrets of the universe.

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