Hawking Radiation and the Black Hole Information Paradox: A Review of Current Theoretical Perspectives

Maya Dagim

1. Abstract

Hawking radiation is a theoretical prediction proposed by Stephen Hawking in 1974, demonstrating that black holes can emit thermal radiation due to quantum effects near the event horizon. This discovery introduced the Black Hole Information Paradox, a fundamental challenge in theoretical physics that questions whether information is preserved during black hole evaporation, as required by quantum mechanics, or lost through the process of Hawking radiation. Resolving this paradox is essential for reconciling the principles of general relativity and quantum mechanics. This review examines the fundamental properties of black holes, the physics underlying Hawking radiation, the assumptions of semiclassical gravity, and major proposed solutions to the information paradox, including black hole complementarity, the AdS/CFT correspondence, and the Firewall Hypothesis. While no universally accepted resolution currently exists, recent developments in quantum gravity suggest that information may ultimately be preserved through mechanisms that remain an active area of research.

2. Introduction

Modern physics rests on two remarkably useful yet fundamentally incompatible theories: general relativity and quantum mechanics. While general relativity describes gravity and the structure of spacetime at cosmic scales, dealing with macroscopic objects, quantum mechanics focuses on the behavior of matter and energy at microscopic scales with atomic and subatomic particles. Black holes occupy a unique position at the intersection of these two fields of physics, as they exert immense gravitation effects but also exhibit quantum effects, unlike any other existing astronomical body. Hawking's discovery that black holes emit thermal radiation reveals that black holes evaporate over time, meaning that they are constantly losing mass and energy. In other words, black hole radiation and evaporation imply that these celestial bodies can erase unique properties of matter, such as total mass, electric charge, and angular momentum of the initial particle's state [1, 2, 3].

However, this destruction of information conflicts with quantum mechanics, which demands information conservation. Understanding whether and how this paradox can be resolved is essential for the development of a consistent theory of quantum gravity and can fundamentally change how scientists perceive the transfer and loss of energy as well as their understanding of space and time. This paper aims to explain how Hawking radiation arises from quantum field theory in curved spacetime and why it gives rise to the black hole information paradox due to its conflict with Quantum Mechanics, specifically the Heisenberg Uncertainty Principle. It also touches on possible solutions to the paradox, its importance to physics, and future research.

3. Black Holes

Black holes are among the most fascinating and mysterious objects in the universe. They are astronomical bodies in which gravity is so intense that nothing, not even light, can escape their pull. The gravity is so intense, in fact, that if you were to fall into a black hole, your body would experience “spaghettification,” in which your body stretches out and tears into long, thin streams of tiny particles, resembling pieces of spaghetti [5].

Average-sized black holes would spaghettify you so fast your brain would rip apart into separate atoms instantly. No human has ever experienced spaghettification as this process more commonly occurs with stars consumed by black holes.

Black holes form when a celestial object becomes unable to withstand the compressing weight of its own gravity, primarily via a supernova explosion in which a star at least 25 times the mass of our Sun runs out of nuclear fuel. The type of black hole formed through this method is a stellar-mass black hole, but two other types can be formed. In relation to spaghettification, stellar black holes have much higher spacetime curvature—the distortion of space and time due to mass and energy—at their event horizon, which is the “point of no return” within a black hole where gravity is so strong that even light cannot escape. This causes the forces causing spaghettification to stretch and compress the astronaut far before they reached the event horizon [5, 6].

3.1 Types of Black Holes

Supermassive black holes have a mass millions or billions of times that of the Sun and grow by merging with other black holes and accumulating matter from collapsing stars and gas clouds, although their formation is not yet fully understood. They lie at the centers of most galaxies, including our own. An astronaut may cross the event horizon of a supermassive black hole without noticing any squashing and pulling, although it remains only a matter of time before they experience spaghettification, as once inside an event horizon, falling towards the center is inevitable. Intermediate-mass black holes are the rarest type and are considered a “missing link” in black hole evolution, theorized to form in dense star clusters or from the collapse of one extremely massive star. Cosmologists suspect there may be a fourth type called a primordial black hole formed during the universe's birth in extremely dense pockets of subatomic matter [5, 6, 7].

Black holes do not emit or reflect light but create gravitational waves—ripples in the fabric of space-time—that scientists can detect. However, despite their reputation as cosmic vacuums, black holes do not “suck in” everything around them. Objects can orbit a black hole safely if they are far enough away, just as planets orbit stars. As mentioned before, our galaxy, the Milky Way, orbits a black hole Sagittarius A* (shown in Fig. 1) at its center, though we are too far away to be directly affected by its immense gravity [8].

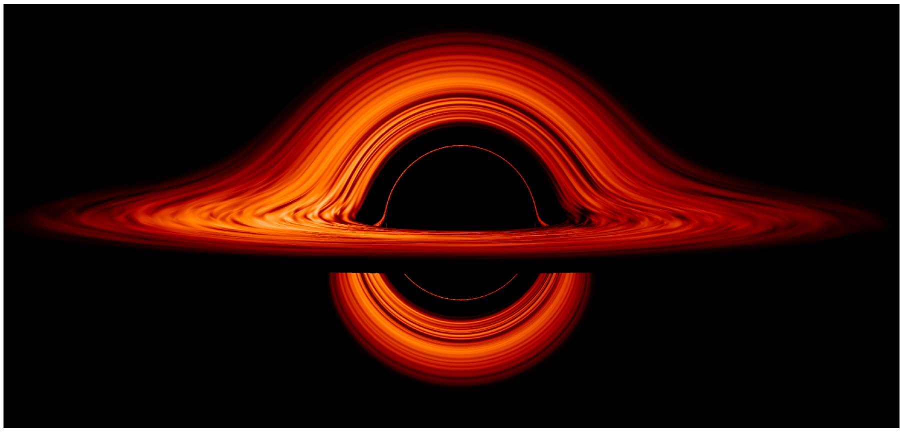

Fig. 1 Sagittarius A*

This is an image of Sagittarius A* taken from the Event Horizon Telescope in submillimeter radio waves. Sgr A* is the supermassive black hole in the center of the Milky Way. The glow surrounding the black hole is called the accretion disk, which is where infalling matter collects into a thin, hot structure, and the area past it is the event horizon. The thin ring in the center is called the photon ring, and inside this ring is the black hole shadow.

Reproduced from [8]

3.2 Black Holes in General Relativity

One of the most important aspects of classical physics is general relativity: Albert Einstein's expansion of special relativity that defined gravity as a property of space and time. In this theory, Einstein also concluded that space and time were intertwined into one continuum called space-time, combining the three dimensions of space with the fourth dimension of time. Close to the black hole, the geometry becomes so warped that all possible future paths an object can take lead deeper inward, making escape impossible past a certain boundary. [10, 11, 12].

Massive objects, such as black holes, warp space-time and mass become so concentrated at a boundary called the event horizon. The event horizon is often described as the point of no return, but its physical nature is far more subtle. It is not a solid surface but a spherical boundary in spacetime where the escape velocity equals the speed of light. Inside this boundary, all paths—even those that would normally move outward—curve inward due to the shape of spacetime itself. To an outside observer, an object falling toward the event horizon appears to slow down indefinitely. Yet the falling object itself experiences nothing unusual as it approaches this invisible threshold, until it reaches the point of spaghettification as mentioned earlier [11].

At the event horizon, gravity becomes inescapable, creating a central singularity of infinite density as shown in Fig. 2. Singularities are the theoretical hearts of black holes, predicted by general relativity to be a point of infinite density and curvature where the known laws of physics break down. In classical theory, all the mass that has collapsed into the black hole is compressed into an infinitely small region, producing gravitational forces so strong that no physical description remains valid. [11]

However, most physicists believe that the singularity is not a literal physical entity but a sign that the mathematical model of general relativity is incomplete at extremely small scales. Quantum gravity is a theoretical framework aimed at reconciling Einstein's general relativity with quantum mechanics that claims at extremely small scales space and time are not continuous but composed of discrete, finite loops or pixels. This theory is expected to replace the singularity with a more realistic description, possibly involving a very dense but finite core or a new state of matter. Although the singularity is forever hidden behind the event horizon and can never be observed directly, its theoretical implications are profound. It challenges fundamental understanding of spacetime and the ultimate behavior of matter under infinite compression [11].

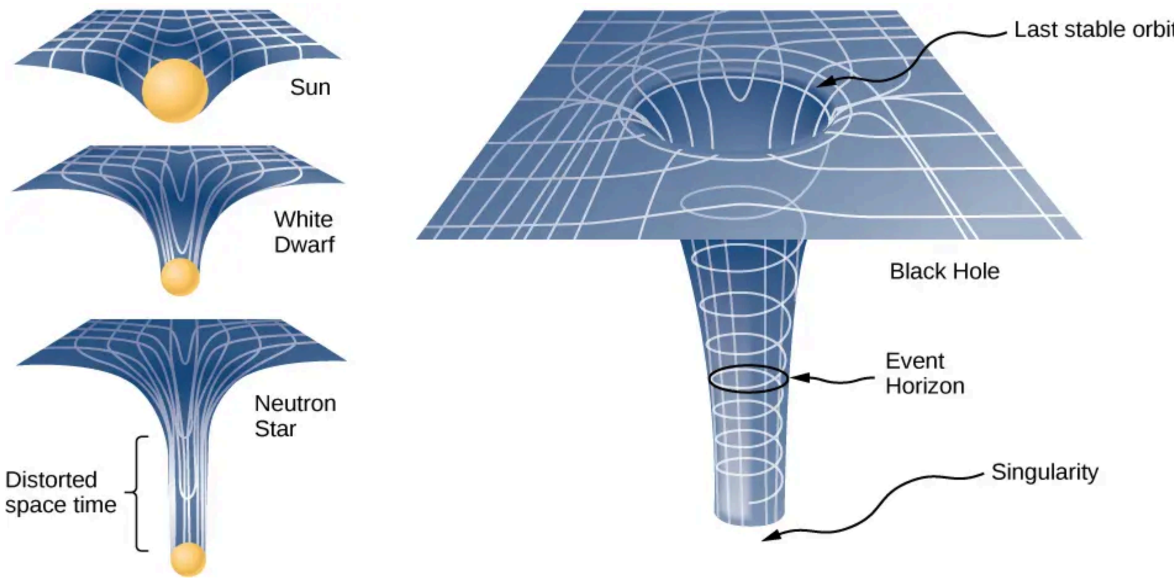

Fig. 2 Black Hole Spacetime

This image demonstrates the extreme curvature caused by black holes. As the mass of a space object increases, the space distortion also increases until it reaches a critical level and a black hole forms, tearing the fabric of space-time. The curvature of a black hole becomes infinite due to its mass, the surface collapses to a singularity, and the cone extends to infinity.

Reproduced from [12]

3.3 Classical vs Quantum Mechanics

As mentioned above, black holes involve both classical and quantum physics. Classical physics is the structure that describes cause and effect relationships in everyday motion, which allows us to make future predictions–determinism–and recall past behavior. For example, using classical physics, astronomers can predict the time of solar and lunar eclipses decades into the future within an accuracy of merely seconds [1, 2].

However, classical physics cannot be used to describe phenomena such as electromagnetic fields, hence the origin of quantum mechanics. Quantum mechanics is the foundational framework that describes the behavior of matter and energy at the smallest scales, where classical physics breaks down. A foundational part of quantum mechanics is the Heisenberg Uncertainty Principle, which asserts that there is a limit to how accurately pairs of physical properties, like energy and time, can be simultaneously known [2, 9].

Black holes deal with the very large and the very small, creating a unique intersection between classical and quantum physics that produces some of the most profound puzzles in modern physics. General relativity predicts that nothing can escape from within a black hole's event horizon. However, quantum field theory in curved spacetime suggests otherwise. Fluctuations near the horizon create a thermal spectrum called Hawking radiation. This radiation causes black holes to lose energy and slowly evaporate, leading to the black hole information paradox. This paradox challenges the compatibility of quantum mechanics' requirement that information be preserved with the apparent loss of information through black hole evaporation. Thus, black hole physics serves as a testing ground for developing a complete theory of quantum gravity [10].

4. Quantum Effects

Quantum mechanics explains the behavior of matter and of light and its odd characteristics, which typically occur at the subatomic scale. Because the scale of quantum effects is so small, matter and light stop behaving like classical objects and instead exhibit wave-like properties [1].

4.1 The Heisenberg Uncertainty Principle

Quantum mechanics departs fundamentally from classical physics in its description of physical observables. In classical mechanics, quantities such as position and momentum can, in principle, be measured simultaneously with arbitrary precision. In contrast, quantum mechanics imposes intrinsic limits on the precision with which certain pairs of observables can be known or even exist [1].

This limitation is formalized by the Heisenberg uncertainty principle, which states that the uncertainties in position and momentum satisfy

$$\sigma_x \sigma_p \geq \frac{\hbar}{2}$$

where σ_x and σ_p denote the standard deviations of position and momentum measurements respectively, and $\hbar$ is the reduced Planck constant ($\frac{h}{2\pi} \approx 1.054571817 \times 10^{-34}$ J*s). The Planck constant describes how a photon's energy is equal to its frequency multiplied by the Planck constant, while the reduced Planck constant relates the energy of a photon–small, massless particles–to its angular frequency [9].

Beyond position and momentum, uncertainty relations exist for other pairs of observables. Of particular relevance in the context of black hole physics is the energy–time uncertainty relation, often expressed as

$$\sigma_E \ \sigma_t \ \geq \frac{\hbar}{2}$$

This principle provides physical intuition for the existence of transient energy fluctuations in the quantum vacuum. In quantum field theory, the vacuum is not an empty state but instead exhibits continual fluctuations due to the uncertainty principle. These fluctuations can be interpreted as the temporary creation of particle-antiparticle pairs, which exist for a limited time before annihilating. While such virtual particles cannot usually be directly observed in flat spacetime–with the exception of the Casimir effect–their effects become significant in the presence of strong gravitational fields [9].

Near a black hole event horizon, extreme spacetime curvature alters the behavior of quantum fluctuations. The uncertainty principle alone does not produce Hawking radiation; however, it provides important intuition for why quantum fields cannot remain in a vacuum state near the horizon. A complete description requires quantum field theory in curved spacetime, in which the definition of particles depegrnds on the spacetime geometry and the observer's frame of reference. This framework forms the foundation for Hawking's prediction that black holes emit thermal radiation [9, 10, 11]

4.2 Hawking Radiation

Hawking radiation is one of the most groundbreaking predictions in modern theoretical physics because it bridges quantum mechanics and general relativity, two frameworks that normally operate in very different domains. The mechanism arises from quantum field theory, which states that even "empty" space is filled with fluctuations that briefly create pairs of virtual particles and antiparticles, which are particles with the same characteristic but the opposite charge. Near the event horizon of a black hole, the gravitational gradient is so steep that these particle pairs can be torn apart before they annihilate. When one particle falls into the black hole and the other escapes to infinity, the escaping one is detected as real radiation. From the perspective of an outside observer, this process causes the black hole to lose mass, effectively converting gravitational energy into emitted thermal energy. Over unimaginable timescales, this slow leakage could cause small black holes to evaporate entirely. The time a black hole takes to dissipate is:

$$t \approx 2.140 \times 10^{67} \text{years} \ \times (\frac{M}{M_{\odot}})^3$$

where M is the mass of the black hole in kilograms and $M_{\odot}$ is the solar mass in terms of the Sun's mass, which is about 1.989×10^{30} kilograms. A black hole with a solar mass of one ($M_{\odot} = 2 \times 10^{30}$ kilograms) would take more than 10^{67} years to evaporate–longer than the current age of the universe at 1.4×10^{10} years old–while much smaller black holes can evaporate within seconds. In conclusion, hawking radiation raises profound questions about the fate of information and behavior of matter in gravitational settings [13].

4.3 Black Hole Evaporation

The prediction of Hawking radiation fundamentally changes the classical picture of black holes. In general relativity, a black hole is a one-way boundary from which nothing can escape. However, when quantum mechanics is applied to the curved spacetime near the event horizon, black holes are no longer completely isolated.

Instead, they emit a faint stream of thermal radiation, as shown in Fig. 3. This emission has a crucial consequence: energy is leaving the black hole. Because mass and energy are equivalent, the loss of energy means the black hole must gradually lose mass. Over time, this process causes the black hole to shrink. This slow decrease in mass due to quantum radiation is known as black hole evaporation. The process is extremely gradual for large black holes. Stellar-mass and supermassive black holes emit radiation so weak that their evaporation times far exceed the current age of the universe. Nevertheless, the theoretical implication is profound: black holes are not eternal. As a black hole becomes smaller, its temperature increases, causing it to radiate more intensely. This creates a feedback effect in which evaporation accelerates as the black hole loses mass. In its final stages, the process is predicted to become rapid and highly energetic, though the exact outcome remains uncertain [14, 15].

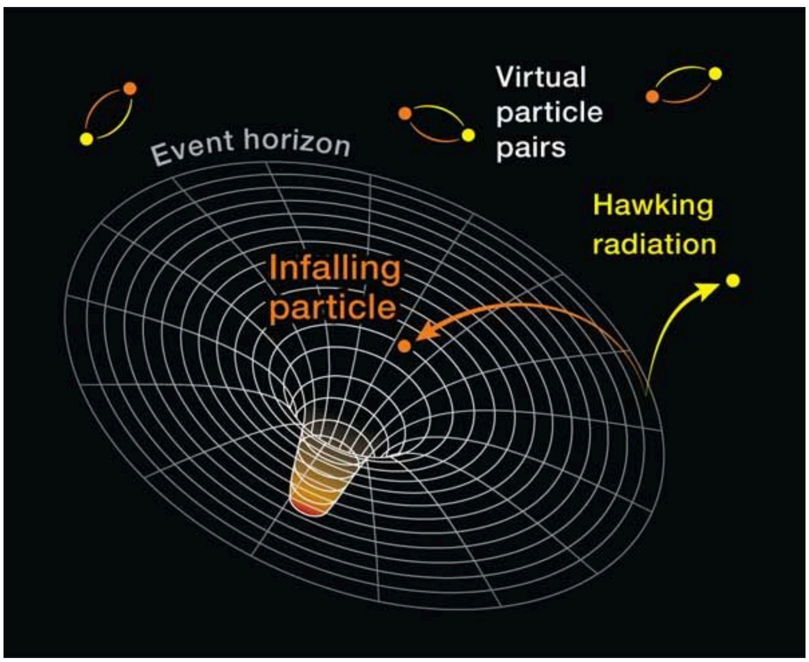

Fig. 3 Hawking Radiation

This image demonstrates Hawking radiation. As the particle and antiparticle pairs approach the event horizon, one particle escapes as radiation (yellow) while the other falls into the black hole (orange).

Reproduced from [14]

The concept of evaporation reveals that black holes are not purely gravitational objects, but thermodynamic systems with temperature and finite lifetimes. The hawking radiation temperature of a black hole is:

$$T_H \approx \frac{10^{23}}{M}$$

The work of Stephen Hawking showed that black holes obey physical laws that connect quantum mechanics, thermodynamics, and general relativity. Evaporation therefore represents more than just mass loss; it demonstrates that black holes sit at the intersection of the fundamental theories of physics. Most significantly, black hole evaporation leads to deep theoretical challenges. If a black hole can completely disappear, what happens to the information about the matter that once fell into it? This question forms the basis of the black hole information paradox and highlights why evaporation remains one of the most important problems in modern theoretical physics [13].

5 Black Hole Information Paradox

The Black Hole Information Paradox arises from a conflict between General Relativity and Quantum Mechanics, the two most successful theories in modern physics. General relativity predicts that anything crossing a black hole's event horizon is lost forever, implying that information about matter that falls into a black hole disappears from the universe. However, quantum mechanics states that information can never be destroyed. The problem became more complicated when Stephen Hawking showed that black holes emit Hawking Radiation, meaning black holes can slowly evaporate over time. If a black hole completely evaporates and the information about everything that fell into it is gone, this would violate quantum mechanics. To resolve this contradiction, physicists have proposed several theories, including the Black Hole Complementarity, the Firewall Hypothesis, and AdS/CFT Correspondence. The information paradox therefore represents more than just a problem about black holes; it reveals that our current understanding of gravity, spacetime, and quantum physics is incomplete and that a new unified theory may be needed to fully explain how the universe works [15].

5.1 Black Hole Complementarity

One proposed solution to the Black Hole Information Paradox is Black Hole Complementarity, which suggests that information behaves differently depending on the observer. To an outside observer, information appears to be stored on the event horizon and slowly released through Hawking Radiation, meaning information is not lost. However, to an observer falling into the black hole, nothing unusual happens at the event horizon, and the information passes inside the black hole as predicted by General Relativity. According to black hole complementarity, both perspectives are correct because no observer can witness both events at the same time. This idea attempts to resolve the conflict between quantum mechanics and general relativity without violating the laws of either theory, although it remains a debated concept in theoretical physics [16].

5.2 Firewall Hypothesis

The Firewall Hypothesis utilizes a unique approach to explaining the black hole information paradox. It claims that the two entangled particles created near the event horizon must immediately become separated, releasing immense amounts of energy and thus creating what is known as a “black hole firewall.” According to quantum mechanics, particles that are entangled must remain connected so that information is not lost. However, near a black hole, one particle falls past the event horizon while the other escapes as Hawking radiation. To prevent information loss, the entanglement would have to break, and the energy released from this break would form a high-energy barrier, or firewall, around the event horizon. This would mean that anything falling into a black hole would be destroyed at the event horizon instead of passing through it normally [17].

Yet, this hypothesis also contradicts General Relativity, which predicts that an observer falling into a black hole should not experience anything unusual at the event horizon due to the principle of equivalence–free-falling is indistinguishable from floating in empty space. The firewall idea instead suggests that the event horizon would be an extremely violent region, which conflicts with relativity’s predictions. This disagreement highlights one of the biggest unsolved problems in physics: the incompatibility between Quantum Mechanics and general relativity. Because both theories are well supported by evidence but cannot both be correct in this situation, the firewall hypothesis demonstrates how black holes remain one of the greatest challenges in modern physics [10, 12, 17].

5.3 AdS/CFT Correspondence

Another proposed solution to the black hole information paradox comes from the AdS/CFT Correspondence, a theory developed in string theory that connects gravity and quantum mechanics. The correspondence suggests that a gravitational system in Anti-de Sitter Space–a negatively curved spacetime in which no point in space and time can be distinguished in any way from another–can be mathematically equivalent to a quantum theory without gravity known as a Conformal Field Theory on the boundary of that space. This idea is often described using the holographic principle, where a three-dimensional space can be fully described by information stored on a two-dimensional surface. Applied to black holes, this means that information that falls into a black hole may not be lost but instead stored on the event horizon and encoded in Hawking radiation. If this theory is correct, it would resolve the black hole information paradox by showing that information is preserved, while also providing a possible connection between quantum mechanics and general relativity. Because of this, AdS/CFT is considered one of the most important theoretical developments in modern physics and may help lead to a unified theory of quantum gravity [18].

5.4 Current Limitations

Despite the progress made in understanding black hole radiation, there are still many limitations to current theories. Hawking Radiation has never been directly observed because the radiation emitted by black holes is extremely weak and difficult to detect with modern instruments. Additionally, the Black Hole Information Paradox remains unresolved, as scientists still do not fully understand how information escapes a black hole.

Proposed solutions such as the Firewall Hypothesis conflict with General Relativity, while the AdS/CFT Correspondence may not fully apply to our universe because it is based on a different spacetime geometry.

6. Conclusion

The idea of black holes arises naturally from Albert Einstein's theory of general relativity, which describes gravity not as a force but as the curvature of spacetime caused by mass and energy. According to this theory, when a massive star exhausts its nuclear fuel, it may collapse under its own gravity. If the remaining mass is large enough, spacetime bends so steeply that all paths curve back toward the center, forming a black hole. The boundary beyond which nothing can return is known as the event horizon, and the center point, where density becomes infinite, is called the singularity. While general relativity explains black holes' large-scale structure and gravitational behavior, quantum mechanics governs the microscopic world—and the two theories conflict when applied together [10].

This tension becomes especially apparent near the singularity, where both gravitational and quantum effects are extreme. In the 1970s, physicist Stephen Hawking made a groundbreaking contribution by showing that quantum effects near the event horizon cause black holes to emit faint radiation, now called Hawking radiation. This discovery bridged the gap between relativity and quantum mechanics, suggesting that black holes are not entirely black—they slowly lose mass and can eventually evaporate over immense timescales. However, this leads to the black hole information paradox, a mystery about whether information that falls into a black hole is truly lost or somehow preserved in the radiation that escapes [10 15].

6.1 Importance of Hawking Radiation to Physics

Hawking radiation is of paramount importance to physics because it is the first major theoretical achievement in the quest for a theory of quantum gravity, bridging the gap between general relativity and quantum mechanics. It reshaped the understanding of black holes from eternal traps to thermodynamic objects that eventually evaporate.

6.2 Outlook and Future Research Directions

Recent work on gamma-ray observations of black hole mergers highlights both the challenges and potential of detecting Hawking radiation. Although no conclusive signal has yet been observed, this approach establishes a promising framework for combining gravitational wave and high-energy data to probe quantum effects in strong gravity.Future research will likely focus on expanding analyses to a larger sample of merger events and improving theoretical models of black hole fragmentation and emission spectra. At the same time, next-generation gamma-ray observatories with greater sensitivity may enable the detection of short-lived evaporation signatures from low-mass black holes [19].

Ultimately, confirming Hawking radiation would provide direct evidence of quantum effects in curved spacetime, offering critical insight into unresolved problems such as the information paradox and moving physics closer to a unified theory of quantum gravity.

7. Appendix

7.1 Gravitational Lensing

Gravitational lensing is one of the most important observable effects produced specifically by black holes. According to Einstein's theory of general relativity, the extreme curvature of spacetime near a black hole causes light from background stars or galaxies to bend dramatically as it passes nearby. In the strongest cases–particularly near supermassive black holes–this bending can produce multiple distorted images, arcs, or even complete rings of light known as Einstein rings In the context of black holes, gravitational lensing does more than confirm general relativity; it provides direct information about the black hole itself. The degree of light deflection depends on the black hole's mass and the geometry of spacetime near its event horizon. By analyzing lensing patterns, astronomers can measure black hole masses, probe their gravitational influence, and study how they shape their surrounding environments. Because black holes emit no light of their own, gravitational lensing serves as a crucial indirect method of detecting and characterizing them [12, 20].

7.2 Black Hole Shadows

A black hole shadow is a direct visual signature of a black hole's event horizon and extreme gravitational field. The shadow forms because the black hole's gravity bends and captures nearby light, preventing some photons from reaching a distant observer. The result is a dark central region, larger than the event horizon itself, surrounded by a bright ring of glowing, orbiting material known as the photon ring as shown in Fig. 4. Black hole shadows are particularly significant for studies of Hawking radiation because they confirm the existence of the event horizon [21].

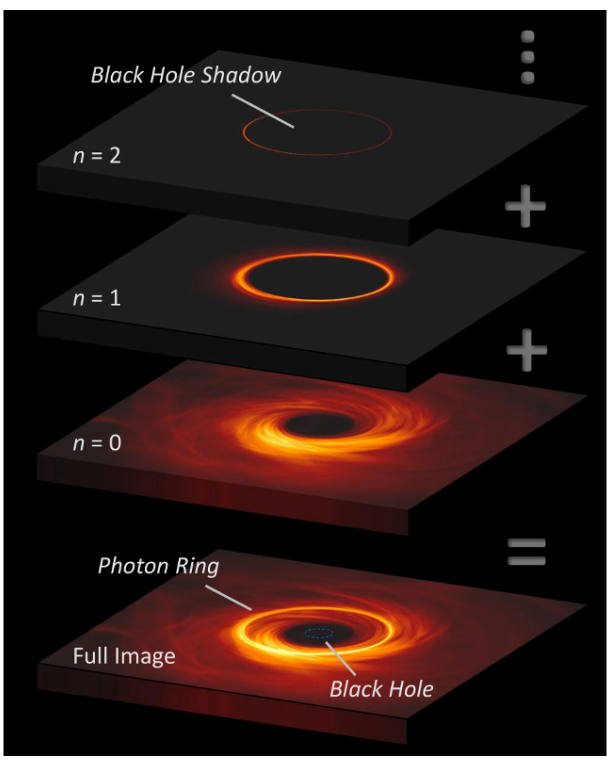

Fig. 4 Black Hole Shadow

This image of a black hole consists of a central shadow surrounded by a bright emission ring composed of a series of increasingly narrow subrings produced by photons.

Reproduced from [21]

8. Works Cited

[1] The Quantum Atlas, “Quantum vs. Classical,” quantumatlas.umd.edu. https://quantumatlas.umd.edu/entry/quantum-classical/

[2] “Classical physics - an overview | sciencedirect topics,” Science Direct, https://www.sciencedirect.com/topics/physics-and-astronomy/classical-physics.

[3] “Quantum mechanics,” Quantum mechanics | Institute of Physics, Jul. 18, 2022. https://www.iop.org/explore-physics/big-ideas-physics/quantum-mechanics

[4] C. Stuart, “What is Hawking radiation?,” www.skyatnightmagazine.com, Jan. 24, 2024. https://www.skyatnightmagazine.com/space-science/hawking-radiation

[5] D. Lincoln, “‘Spaghettification’: How Black Holes Stretch Objects into Oblivion,” JSTOR Daily, Mar. 28, 2024. https://daily.jstor.org/spaghettification-how-black-holes-stretch-objects-into-oblivion/

[6] B. Specktor, “Black holes: Facts, news, features and articles about the darkest objects in the universe,” LiveScience, https://www.livescience.com/space/astronomy/black-holes

[7] “Types - NASA science,” NASA, https://science.nasa.gov/universe/black-holes/types/

[8] E. Howell, “Sagittarius A* in pictures: The 1st photo of the milky way’s monster black hole explained in images,” Space, https://www.space.com/milky-way-black-hole-sagittarius-a-pictures

[9] Wikipedia Contributors, “Uncertainty principle,” Wikipedia, Apr. 30, 2019. https://en.wikipedia.org/wiki/Uncertainty_principle

[10] S. W. Hawking, “Black holes in general relativity,” Communications in Mathematical Physics, vol. 25, no. 2, pp. 152–166, Jun. 1972, doi: https://doi.org/10.1007/bf01877517

[11] NASA, “Black Hole Anatomy - NASA Science,” science.nasa.gov, May 2024. https://science.nasa.gov/universe/black-holes/anatomy/

[12] “13.7 Einstein’s Theory of Gravity | University Physics Volume 1,” courses.lumenlearning.com. https://courses.lumenlearning.com/suny-osuniversityphysics/chapter/13-8-einsteins-theory-of-gravity/

[13] Wikipedia Contributors, “Hawking radiation,” Wikipedia, Apr. 07, 2026. https://en.wikipedia.org/wiki/Hawking_radiation#cite_ref-gubser_pretorius_15-0

[14] D. Maiolo, “Exploring Hawking Radiation: A Key to Black Hole Mysteries - David Maiolo,” David Maiolo, Feb. 17, 2024. https://www.davidmaiolo.com/2024/02/17/exploring-hawking-radiation-black-hole-mysteries/

[15] N. Engelhardt, “THE BLACK HOLE INFORMATION PARADOX A RESOLUTION ON THE HORIZON 2023 MIT PHYSICS ANNUAL 42,” 2023. Available: https://physics.mit.edu/wp-content/uploads/2023/09/PhysicsAtMIT_2023_Engelhardt_Feature.pdf

[16] E. T. Tatum, “Black Hole Complementarity in Terms of the Outsider and Insider Perspectives,” Journal of Modern Physics, vol. 15, no. 02, pp. 184–192, 2024, doi: https://doi.org/10.4236/jmp.2024.152010.

[17] C. Rovelli, “The Subtle Unphysical Hypothesis of the Firewall Theorem,” Entropy, vol. 21, no. 9, p. 839, Aug. 2019, doi: https://doi.org/10.3390/e21090839.

[18] “AdS/CFT correspondence,” Wikipedia, Apr. 22, 2020. https://en.wikipedia.org/wiki/AdS/CFT_correspondence

[19] “Unveiling the Quantum Nature of Black Holes: Towards a Proof of Hawking Radiation through Gamma-Ray Observations,” Arxiv.org, 2025. https://arxiv.org/html/2509.17599v1 (accessed Apr. 16, 2026).

[20] S. L. Stanley, “What Are Gravitational Lenses?,” lettersandsciencemag, Oct. 20, 2025. https://lettersandsciencemag.ucdavis.edu/science-technology/gravitational-lenses-uc-davis-astronomy

[21] M. Luciani, “A possible technique to observe photon rings around a black hole,” Tachyonbeam.com, Mar. 21, 2020. https://english.tachyonbeam.com/2020/03/21/a-possible-technique-to-observe-photon-rings-around-a-black-hole/