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ONTOLOGICAL AND EPISTEMOLOGICAL IMPLICATIONS OF BLACK HOLE EVAPORATION IN MODERN PHYSICAL PHILOSOPHY

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Abstrak

Penelitian dilatarbelakangi oleh perkembangan fisika modern yang menunjukkan bahwa lubang hitam, yang dalam relativitas umum klasik dianggap sebagai entitas paling stabil dan permanen di alam semesta, ternyata mengalami evaporasi melalui radiasi Hawking. Fenomena ini menimbulkan implikasi filosofis mendalam terkait sifat keberadaan fisik, status informasi, struktur ruang-waktu, serta arah waktu kosmologis. Penelitian ini bertujuan untuk menganalisis implikasi ontologis dan epistemologis dari evaporasi lubang hitam dalam konteks hubungan mikro-makro, ontologi relasional, serta konsep waktu sebagai fenomena yang muncul dari proses fisik fundamental. Penelitian ini menggunakan metode kajian kualitatif berbasis studi literatur dan analisis konseptual dengan mengintegrasikan perspektif fisika teoretis, filsafat fisika, dan kosmologi modern. Hasil penelitian menunjukkan bahwa evaporasi lubang hitam menegaskan bahwa tidak ada entitas fisik yang bersifat absolut dan permanen. Keberadaan fisik lebih tepat dipahami sebagai fenomena relasional *yang bergantung pada interaksi antara geometri ruang-waktu, fluktuasi kuantum, dan proses termodinamika kosmik. Selain itu, paradoks informasi lubang hitam dapat dipahami sebagai keterbatasan deskripsi epistemologis manusia, bukan sebagai hilangnya realitas fisik secara ontologis. Penelitian ini juga menegaskan bahwa arah waktu merupakan konsekuensi emergen dari peningkatan entropi alam semesta. Kebaruan penelitian ini terletak pada integrasi fenomena evaporasi lubang hitam dengan pendekatan ontologi struktural-relasional untuk menjelaskan realitas fisik sebagai proses dinamis dan emergen.*

Kata kunci*: evaporasi Lubang Hitam, radiasi Hawking, ontologi relasional, paradoks informasi, panah waktu termodinamika.*

Abstract

The research is motivated by developments in modern physics which show that black holes, which in classical general relativity are considered the most stable and permanent entities in the universe, actually undergo evaporation through Hawking radiation. This phenomenon has profound philosophical implications regarding the nature of physical existence, the status of information, the structure of space-time, and the direction of cosmological time. This research aims to analyse the ontological and epistemological implications of black hole evaporation in the context of micro-macro relationships, relational ontology, and the concept of time as a phenomenon that emerges from fundamental physical processes. This study employs a qualitative research method based on literature review and conceptual analysis, integrating perspectives from theoretical physics, philosophy of physics, and modern cosmology. The findings indicate that black hole evaporation confirms that no physical entity is absolute or permanent. Physical existence is more accurately understood as a relational phenomenon that depends on the interaction between the geometry of space-time, quantum fluctuations, and cosmic thermodynamic processes. In addition, the black hole information paradox can be understood as a limitation of human epistemological description, not as an ontological loss of physical reality. This research also confirms that the direction of time is an emergent consequence of the increase in the entropy of the universe. The novelty of this research lies in the integration of the phenomenon of black hole evaporation with a structural-relational ontological approach to explain physical reality as a dynamic and emergent process.

Keywords*: Black Hole evaporation, Hawking radiation, relational ontology, information paradox, thermodynamic arrow of time.*

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INTRODUCTION

Within the framework of classical general relativity, black holes are understood as highly stable cosmic entities and tend to be perceived as permanent objects (Choquet-Bruhat, 2023; Kakade, 2024). This perspective gives rise to the assumption that there is a physical structure in the universe that remains unchanged throughout cosmic time. However, developments in modern physics, particularly the integration of quantum mechanics into curved space-time, raise new questions about the existence of black holes as physical objects, as well as philosophical questions about reality. To date, there is no conceptual consensus on the changes in the mass and structure of black holes within the ontology of physics, thus requiring studies that combine theoretical physics analysis and philosophical reflection.

In classical metaphysics, reality is understood through the distinction between fixed substance and attributes that can change (Scaltsas, 1994; Singh, 2024). Modern cosmological phenomena challenge the classical separation of physical reality and demand new philosophical interpretations that are consistent with scientific developments. Debates about being and becoming, tensions between general relativity and quantum mechanics, and the ontological status of cosmic information show that the relationship among entropy, the direction of time, and the evolution of the universe remains not fully understood within modern physical ontology (Bittner, 2018; Pauri, 1997). This has led to the emergence of relational and structural ontological approaches in physics as alternative paradigms for understanding reality, although their application to extreme cosmological phenomena still requires more in-depth conceptual study. The ontological status of the event horizon as a causal boundary in space-time also raises philosophical questions about how the existence of a physical object can depend on the geometric structure of space-time. The debate over whether time is a fundamental entity or a phenomenon arising from physical changes shows that there remains conceptual uncertainty in cosmology and the philosophy of physics. In addition, the discourse on the most fundamental entities in physical reality, namely, whether they are particles, information, or microscopic space-time structures, shows that there is still no consensus in modern physics ontology. The complexity of the issues surrounding these extreme cosmic phenomena indicates that their understanding cannot be explained by a single discipline alone. Therefore, research that comprehensively integrates theoretical physics and the philosophy of physics is needed to understand the nature of physical reality in the development of contemporary science.

The philosophical framework of this research departs from the assumption that physical reality is not something that is entirely ontologically fixed, but rather consists of cosmic processes that are constantly changing and undergoing temporal transformation. Physical existence is understood as a process of *"becoming"*, not a static state, so that change becomes the basic character of the universe. In this perspective, physical entities do not stand alone but depend on their interactions with the surrounding space-time structure, quantum fields, and cosmological conditions. Furthermore, information is positioned ambiguously, existing between the possibilities of being an ontological entity and an epistemological construct to represent reality. The direction of time is understood to arise from thermodynamic asymmetry through changes in entropy, while physical reality is formed from the reciprocal relationship between quantum phenomena and cosmological structures. Thus, fundamental reality is more accurately explained through structural realism, which places relational patterns and structures as the ontological basis, while physical entities are understood as manifestations of ever-changing structural configurations.

This study aims primarily to analyze the impermanence of physical entities through the phenomenon of black hole evaporation by integrating insights from general relativity and quantum mechanics within a philosophical framework of cosmological dynamics. In pursuing this primary objective, the study revisits the concept of permanent reality in the ontology of physics and explores how black hole evaporation changes our understanding of existence in the universe. Specifically, the study explores the relationship between the concepts of existence and change in cosmological change and the laws of thermodynamics, as well as the implications of black hole evaporation for relational ontology. In addition, this study analyzes the black hole information paradox from the perspective of the ontology and epistemology of science. This research investigates the relationship between entropy, the direction of time, and cosmic evolution, as well as the reciprocal relationship between micro and macro phenomena. This study examines the ontological status of the event horizon in determining the existence of black holes and discusses the concept of time as a relational and emergent phenomenon. Conceptually, this research is expected to contribute to the development of modern philosophy of physics, expand theoretical understanding of the relationship between general relativity, quantum mechanics, and cosmology, and serve as an academic reference for interdisciplinary studies between theoretical physics and philosophy of science, including in the development of quantum gravity theory and structural ontology. This study has limitations because it still relies on a semi-classical Hawking radiation approach without a complete theory of quantum gravity, while Hawking radiation itself has not been directly observed. Methodologically, this study is conceptual in nature, using idealised mathematical models without detailed quantitative testing. Furthermore, its scope is limited to the study of black hole evaporation and still faces ontological and epistemological limitations between physical reality and scientific representation.

Research on black hole evaporation in modern physics is still dominated by mathematical and predictive approaches, such as Hawking radiation, black hole thermodynamics, and quantum gravity theory. However, ontological and metaphysical studies of the implications of this phenomenon for the concept of physical existence are still limited and unsystematic. To date, few studies have linked the dynamics of black hole evaporation with the redefinition of the concepts of existence, substance, and eternity in the philosophy of reality. Furthermore, in the classical tradition of general relativity, black holes are often viewed as the most stable cosmic entities, even though modern studies show that these entities can undergo evaporation (Choquet-Bruhat, 2023). The philosophical implications of black hole evaporation for the continuity of matter and cosmic structure have rarely been studied. There is no conceptual model that places it as a cosmological principle of universal impermanence, and the relational ontological approach has also not been widely used. Research is still dominated by the paradigm of substantial objects and reductionism, so that the relationship between black hole evaporation, the information paradox, ontological identity, and the direction of time has not been analysed in depth. Therefore, a more comprehensive study integrating theoretical physics, cosmology, and ontological philosophy is needed.

This research offers conceptual novelty by reformulating black hole evaporation not only as a physical phenomenon but as an ontological principle that affirms the impermanence of all physical entities. This study integrates general relativity, quantum mechanics, and relational ontology within a structural realism framework to explain that the existence of cosmic entities is emergent and dependent on the space-time relational network. Furthermore, the black hole information paradox is reinterpreted as an epistemological problem that reveals the limitations of human scientific representation, rather than an ontological conflict in physical reality. This research also develops the concept of relational structural emergence, which demonstrates the interconnection between the macro structure of space-time and local quantum processes. Thus, black hole evaporation is viewed as a philosophical laboratory for cosmology, helping to understand the ontological evolution of reality and the fundamental relationship between cosmology, quantum physics, and metaphysics.

DISCUSSION

1. Impermanence of Physical Entities

In the classical view of general relativity, black holes are solutions to Einstein's equations that are extremely stable and appear to be *"Eternal"* (Choquet-Bruhat, 2023). An object with sufficient mass that collapses beyond the Schwarzschild radius will form a singularity surrounded by an event horizon. In classical theory, there is no physical mechanism to reduce the mass or eliminate the horizon (Ashtekar, 2000; Padmanabhan, 2005). Therefore, black holes are considered the most permanent physical entities in the universe. However, with the discovery of Hawking radiation theory (1974), which incorporates quantum effects within a curved-spacetime framework, it is known that black holes can emit radiation due to vacuum fluctuations near the horizon (Helfer, 2003). This process causes black holes to slowly lose mass until they eventually disappear completely over an extremely long cosmic timescale. Mathematically, this evaporation rate can be described by Hawking's equation:

$$\frac{dM}{dt} \sim -\frac{\hbar c^4}{G^2 M^2}, \qquad (1)$$

where (M) is the mass of the black hole, ($\hbar$) are the reduced Planck constant, (c) the speed of light, and (G) the gravitational constant. This equation confirms that the mass of a black hole decreases over time, so that entities that appear eternal actually have a finite lifespan.

Classical ontology in physics considers certain objects (protons, neutron stars, or black holes) to be part of a fixed structure of reality, a solid *"Cosmic structure"* (Allori, 2013; Quni-Gudzinas, 2025). However, if even black holes can be destroyed, then no physical entity is truly eternal. This challenges the idea of permanent substance in the cosmos. In Western metaphysical tradition, a distinction is made between substance (the permanent core of existence) and accident (changing attributes) (Carriero, 1995; Scaltsas, 1994). The evolution of black holes shows that even physical matter is temporary, subject to the dynamics of the wider cosmos. Physical reality cannot be assumed to be static; rather, it is dynamic and temporary.

The ancient Greek philosopher Heraclitus stated (Syifa et al., 2024); *"Everything flows"* (panta rhei). In modern physics, including the process of black hole evaporation, we see that all physical entities are in a process of continuous change. There is no such thing as an absolute *"Being"*; there is only *"Becoming."* This impermanence is a cosmological principle, not merely a local reality. Even objects with extraordinary density, extreme gravitational pull, and causal isolation, such as black holes, are not immune to time and change.

This process of change can be linked to the laws of thermodynamics, such as the change in black hole entropy (Bekenstein, 1973):

$$S_{BH} = \frac{kc^3 A}{4G\hbar}, \qquad (2)$$

where (A) is the horizon area, (k) is the Boltzmann constant. As evaporation occurs, (A) decreases, but Hawking radiation carries entropy out, indicating that the change in the black hole is irreversible, confirming the *"Becoming"* character of physical existence.

Black hole evaporation emphasizes that the existence of physical entities is not independent, but relational, dependent on the surrounding space-time structure, quantum fluctuations, and the thermal conditions of the universe. In relational ontology (the Rovelli or Whitehead approach), objects are not viewed as *"Absolute blocks,"* but as nodes in a network of interactive processes (Ferrari, 2021). Black holes are not final entities, but rather phases of a broader physical process, which ends through interaction with the quantum field.

Black hole evaporation shows that even extreme entities have an end, confirming that cosmic time is unidirectional, creating conditions of finality for structures previously considered *"Unchanging."* This reinforces the interpretation of time as a thermodynamic arrow, not merely a symmetric parameter in physical equations. In other words, physical existence is always related to processes and interactions, not permanent attributes or fixed substances.

2. Is Information Reality or Representation?

One of the most profound conflicts in modern theoretical physics concerns whether information is lost when black holes evaporate. On the one hand, quantum mechanics, as the basis of all microscopic physics, states that the evolution of physical systems is unitary (Ghirardi et al., 1985; Wallace, 2024). This means that, in principle, information about the initial state of a system can always be reconstructed from its final state. Mathematically, unitary evolution can be written as (Drossel, 2020; Parker, 2025):

$$|\psi(t)\rangle = U(t)|\psi(0)\rangle \qquad (3)$$

Where $(U^{\dagger}U = I)$ and {U(t)} is a unitary evolution operator (Schwinger, 1960). This law guarantees the reversibility of time and the preservation of information in every quantum transformation. Quantum states evolve in a way that does not destroy or create information, but merely redistributes it within the system. Consequently, the principle of unitary evolution becomes a fundamental principle in the discussion of the black hole information paradox, as this principle implies that information must remain encrypted in the total quantum state of the universe even when extreme gravitational processes occur.

On the other hand, general relativity, as a theory of space-time geometry, allows for scenarios that appear to contradict this unitary principle. In the classical description of black holes, as explained by Stephen Hawking, there is the phenomenon of Hawking radiation, a quantum process near the horizon that causes black holes to emit radiation and slowly lose mass until they eventually evaporate completely (Hawking, 1976). In the original version of this theory, the process leaves no trace of information about the matter that previously fell into the black hole. It is as if matter, with its physical identity and complex history, is reduced to random thermal radiation, with no traceable information structure.

The tension between these two views forms what is known as the black hole information paradox (Giddings, 1995; Neukart et al., 2024). This paradox is not merely a matter of physical prediction, but touches on the core of the ontology and epistemology of physics, namely, whether information is truly manifest in a physical entity, or merely a descriptive construct in the language and mathematics we use to understand the universe.

Ontologically, information does not have the same properties as physical quantities such as mass (m), energy (E), or momentum (p). Information has no position in space, no charge, and cannot be measured directly as a physical object. Placing information within the domain of physical entities in the universe's dynamics is a misleading simplification.

From an epistemological perspective, information is better understood as a symbolic structure produced by language, mathematics, and logic systems that enable humans to organise physical experiences and formulate scientific laws. This view is supported by the theory of information introduced by Claude Shannon and the philosophical framework of information developed by Luciano Floridi, both of which emphasise that information functions as a formal and conceptual structure in human knowledge systems rather than merely as a physical entity (Chambert-Loir, 2023; Floridi, 2002). When it is said that *"Information is lost"* from systems such as black holes, what is actually lost is the ability of humans to reconstruct the system's initial state from its final state, not reality itself. This confirms the duality between description and reality, that human language and theory differ from reality, which exists independently of our perception.

Many modern physics arguments assume that because entropy (S) and information (I) have similar mathematical forms, for example, both can be related to the logarithm of the number of microstates:

$$S = k_B ln\ \Omega \qquad (4)$$

$$I = log_2\ \Omega \qquad (5)$$

They are considered physically identical. This view often appears in thermodynamics, statistical mechanics, and quantum information theory, for example, in the Bekenstein-Hawking entropy of black holes in equation (2).

Despite formal similarities, physicist-philosophers such as Carlo Rovelli and Michel Bitbol emphasize that mathematical similarities do not guarantee ontological equivalence (Bitbol, 2024; Rovelli, 2021). In thermodynamics, entropy measures the degree of uncertainty or the number of possible microstates of a macrostate (Touchette, 2015). However, in the black hole debate, a philosophical question arises: does the loss of information mean the loss of substance, or merely the loss of humanity's ability to describe the system completely?

If we accept the philosophical position that information is not a physical entity but rather a symbolic representation, then the information paradox takes on a different character. What is lost is not something ontological or material, but humanity's ability to reconstruct the initial state of the system. This paradox is not a problem of fundamental physics, but rather a limitation of scientific description when faced with extreme conditions at the event horizon or Planck scale.

This phenomenon can be understood as a product of epistemological narrowing, namely the imposition of human categories and concepts, such as *"Information,"* into extreme contexts whose structures differ greatly from classical intuition or current theoretical models. Philosophical reflection emphasizes that not all concepts useful in everyday physics automatically apply at the frontiers of physics; conceptual caution is required in assessing the ontological claims of contemporary physics theories.

3. Entropy and the Direction of Time

From a physics perspective, the second law of thermodynamics states that in a closed system, entropy never decreases; it can only increase or remain constant (Zivieri, 2023). Entropy can be understood as a measure of disorder or the amount of information lost in a system. Stephen Hawking's discovery that black holes can emit radiation, now known as Hawking radiation, shows that black holes are not stationary or *"Lifeless"* entities, but rather objects that interact thermally with their environment and are subject to the laws of thermodynamics. Jacob Bekenstein previously formulated that the entropy of a black hole is proportional to the area of its event horizon, not its volume (Bekenstein, 2003). This formula shows that when a black hole undergoes evaporation, the horizon area shrinks, but Hawking radiation carries away more entropy than is lost by the horizon. Thus, the total entropy of the universe continues to increase.

Philosophically speaking, the direction of time or *"Time's arrow"* is one of the most profound problems in the philosophy of physics (Price, 1996). Fundamental laws of physics, such as Newtonian mechanics, general relativity, and even non-collapsing quantum mechanics, are symmetric with respect to time; they remain valid if time is reversed (Luo, 2025). However, real experience shows that time is experienced asymmetrically, just as ice melts but does not freeze again spontaneously, we age rather than become young, stars emit energy rather than absorb it back.

The philosophical question that arises is, why does this asymmetry occur? The answer comes from the second law of thermodynamics, namely that because entropy increases, natural processes can only proceed in the direction where entropy increases. From this perspective, the direction of time is not a fundamental property of the laws of physics themselves, but rather a phenomenon that arises from thermodynamic asymmetry.

Black holes, as extreme thermodynamic objects, demonstrate this principle clearly. Black hole evaporation is an irreversible process; it cannot be reversed by any classical law (Ashtekar & Bojowald, 2005). Hawking radiation carries energy and entropy out of the horizon, making this process naturally irreversible. Thus, black holes serve as extreme natural experiments, confirming that the direction of time arises from thermodynamic asymmetry, not from fundamental symmetric laws.

On a cosmological scale, a bigger question arises: why was the initial entropy of the universe so low? The universe began in a highly ordered state (low entropy), then evolved toward a more disordered state (high entropy), and black holes are the pinnacle of systems with extreme entropy (Avchenko & Chudnenko, 2020). When a black hole evaporates, it contributes entropy to the universe in the form of radiation. This process occurs very slowly (up to about 10^{66} years), but on a cosmic scale, it becomes the main driver of long-term entropy increase. This phenomenon shows that the direction of time and the evolution of the cosmos are not solely determined by fundamental laws but are emergent consequences of the accumulation of irreversible processes throughout the universe. From the perspective of the philosophy of physics, this confirms that time is a relational and emergent phenomenon, dependent on the processes of change and interaction within physical systems, rather than an absolute entity that stands alone.

4. Micro and Macro Relations

Black hole evaporation begins with quantum fluctuations around the event horizon, where the quantum field in curved spacetime allows for the creation of particle–antiparticle pairs (Builes Canchala, 2025; Traschen, 2000). In the semi-classical approach, one member of the pair falls beyond the horizon, while its partner escapes as Hawking radiation. Physically, this process is often represented by the Hawking temperature:

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}, \quad (6)$$

which shows that the existence of this radiation depends explicitly on the mass of the black hole and, implicitly, on the geometric structure of the horizon itself. On a local scale, this event appears as a very small and probabilistic quantum phenomenon. However, when this process accumulates over a cosmological timescale, it determines the macroscopic fate of the black hole, namely the shrinkage of its mass until it eventually disappears completely.

This phenomenon cannot be adequately understood simply as a reduction from the macro to the micro. If strong ontological reductionism were true, then the entire macroscopic reality of black holes should be fully explainable as a direct result of elementary particle interactions. However, in the case of black hole evaporation, it is precisely the macroscopic structure of space-time, namely the existence of the event horizon, that becomes the condition of possibility for the emergence of the quantum process itself. Without the horizon as a global causal structure, there is no meaningful definition of particles, and thus no Hawking radiation. This shows that the relationship between the micro and the macro is reciprocal and non-hierarchical, not one-way.

The micro and macro are not in a purely reductive relationship, but rather in ontological dependence. Local quantum processes do contribute to changes in global structure, while the global structure of space-time simultaneously determines the types and behaviours of quantum processes that may occur. This perspective is more accurately described as relational structural emergence than Nagel's nomological reduction, a model proposed by Ernest Nagel in which higher-level theories are explained entirely as logical derivations of more fundamental laws. In such a reductionist framework, macroscopic phenomena can be fully explained based on microscopic laws alone. Conversely, in this study, the macroscopic is not *"Erased"* by the microscopic, but rather emerges as a level of reality that has its own causal and ontological significance.

The classic tension between micro and macro, between quantum mechanics and cosmology, thus becomes blurred. Black hole evaporation shows that quantum laws are not only relevant at the scale of elementary particles but also determine the direction of cosmic structure evolution. Conversely, cosmic structures such as event horizons cannot be reduced to mere aggregates of local quantum events, because they function as global causal boundaries that shape the dynamics of the quantum field itself. Space-time can no longer be viewed as a passive framework in which physical events occur, but rather as a dynamic structure that emerges from and simultaneously constrains microscopic processes.

The micro-macro relationship revealed through black hole evaporation also has important implications for the ontology of space-time. If event horizons can shrink and eventually disappear due to the accumulation of quantum fluctuations, then the structure of space-time itself is contingent and historical. It is not an absolute, self-contained backdrop, but rather the result of continuous interaction between geometry and quantum fields. In other words, physical reality is not sharply divided between the *"Quantum world"* and the *"Cosmic world,"* but forms an ontological continuum in which differences in scale are not differences in types of reality, but differences in levels of structure.

Consequently, the long-term evolution of the universe, including its possible final state as a photon gas after all black holes have evaporated, cannot be understood solely through macroscopic laws such as FLRW expansion,

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho, \tag{7}$$

without considering the role of quantum intervention at the most fundamental scale. The laws of cosmology and quantum physics do not stand apart, but complement each other in shaping the ontological history of the universe. Thus, black hole evaporation is an extreme example that shows that physical reality is relational, hierarchical, and emergent, where the micro and macro do not negate each other, but rather shape each other.

5. Ontology of Horizon and Existence

The discussion of the ontology of the horizon in black holes opens up a very fundamental reflection on the nature of existence within the framework of general relativity. One of the most defining characteristics of black holes is the existence of an event horizon, which is a causal boundary in the structure of space-time where no matter, energy, or causal signals can escape to external observers. In The Large Scale Structure of Space-Time by Stephen Hawking and George F. R. Ellis, the event horizon is described as a global geometric boundary defined by the causal structure of space-time rather than a physical surface (Hawking & Ellis, 2023). A similar explanation in General Relativity by Robert M. Wald shows that horizons arise from the behavior of lightlike geodesics in curved space-time within Einstein's theory (Wald, 2010). Mathematically, the event horizon appears when the Schwarzschild or Kerr metric solutions satisfy the condition that the escape velocity of light toward infinity becomes zero, which is classically marked by the Schwarzschild radius:

$$r_s = \frac{2GM}{c^2} \tag{8}$$

The horizon, therefore, is not something that *"Exists"* materially, but something that *"Applies"* structurally in the causal network of space-time.

When quantum effects are taken into account through Hawking radiation, this ontological picture begins to shift. Hawking radiation shows that black holes have a temperature in equation (6) so that they emit energy and slowly lose mass. As mass decreases, the area of the horizon given by:

$$A = 4\pi r_s^2 \qquad (9)$$

also shrinks to the point where, in theory, the horizon disappears. This process raises ontological questions that go far beyond technical physics: Is the existence of a physical entity, in this case a black hole, determined by the existence of a geometric structure such as the event horizon?

This view challenges classical substantialist ontology, which regards physical entities as objects with intrinsic existence independent of space-time relations. In general relativity, especially in the case of black holes, such a framework becomes difficult to maintain. The existence of an entity is not determined by a fixed material substrate, but by the configuration of the space-time metric and the causal relations it generates. Rather than placing relations above substance, this perspective proposes that the two mutually constitute each other, forming an identity in which entities emerge through their integration into the geometric and dynamic structure of spacetime, a position discussed in the work of Giovanni Buonocore (Buonocore, 2017). From this perspective, the loss of the horizon due to evaporation is not merely a reduction in mass, but an ontological transformation, a shift in the relational conditions that support the identity of entities within the causal structure of the cosmos.

This view challenges classical substantialist ontology, which holds that physical entities are objects with intrinsic existence independent of spacetime relations. In general relativity, and particularly in the case of black holes, such an ontology becomes difficult to maintain. The existence of an entity is no longer determined by a fixed material substrate, but rather by the configuration of the spacetime metric and the causal relations it generates. General relativity implicitly promotes a relational ontology, in which physical entities exist to the extent that they are integrated into the geometric structure and dynamics of space-time. The disappearance of the horizon due to evaporation is not merely a reduction in mass, but an ontological transformation: from an entity that is meaningful within the causal structure of the cosmos to something that no longer has the same identity.

This issue becomes even more acute when linked to the ontological status of the horizon itself. The event horizon is not a fundamental entity like an elementary particle, but it is also not merely an epistemic artifact. It has an intermediate ontological status, being physically real because it produces measurable consequences such as Bekenstein–Hawking entropy. Yet it is also emergent because its existence depends on the global structure of spacetime and interactions with the quantum field. Thus, the horizon cannot be reduced to specific microscopic components, but emerges as a collective property of geometric configurations and causal dynamics.

When the horizon disappears through evaporation, it is not only the geometric boundary that collapses, but also the relational structure that supports the identity of the black hole. In this context, the ontology of physics moves away from object realism toward structural realism, in which what truly exists are not *"Objects"* in the classical sense but rather the structures and relations that organize physical phenomena. Black holes, therefore, are better understood as structural phases of spacetime than as objects with independent existence.

The question of whether there is an *"Existential residue"* after the horizon disappears reveals the depth of this problem. If, at the end of evaporation, a Planckian relic with a mass approaching the

Planck scale remains, then that entity cannot be understood as an ontological continuation of the black hole in the classical sense. It no longer has a horizon, no longer forms a causal boundary, and no longer functions as the center of a macroscopic geometric structure. In this sense, what remains is not a black hole in a reduced form, but a new entity with a different ontological status. Alternatively, it can also be understood that what *"Remains"* is not an object, but a structural trace in the fabric of space-time itself, a kind of wound or geometric knot that no longer has an objectual identity.

6. Time as a Relational Phenomenon

Time is one of the most problematic entities in the philosophy of physics because it lies at the intersection of ontological reality, mathematical structure, and phenomenological experience. Since Newtonian mechanics, time has been understood as an absolute entity that flows uniformly, independent of events occurring in the universe (Oh, 2024). In this framework, time is represented as a universal parameter (t) that enters the laws of dynamics, as in classical equations of motion:

$$F = m\frac{d^2x}{dt^2} \qquad (10)$$

In this formulation, time functions as the ontological backdrop against which all change takes place. However, the development of Einstein's general relativity challenges this view by showing that time is not an independent entity, but rather part of a dynamic four-dimensional space-time structure, which is influenced by the distribution of matter and energy (Scano, 2024). This dynamic is mathematically expressed through Einstein's field equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \qquad (11)$$

This equation shows that the geometry of space-time, including its temporal structure, does not stand alone but is determined by the energy-momentum tensor ($T_{\mu\nu}$) (Mallick et al., 2020). Even in general relativity, time begins to exhibit relational properties because it depends on the physical configuration of the universe (Owino, 2025).

Ontological reflections on time become increasingly complex when modern cosmology considers the long-term evolution of the universe. Cosmological models based on Friedmann equations (Sheykhi, 2021):

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{12}$$

describing the dynamics of cosmic expansion through scale factors $\{a(t)\}$. In the very long term, the universe is expected to move toward a state often referred to as heat death, a condition approaching maximum thermodynamic equilibrium, in which energy gradients are nearly eliminated and macroscopic physical processes become extremely rare (Henry, 2021; Zanstra, 1968).

In this phase, complex structures such as stars, galaxies, and even black holes are predicted to disappear through cosmic evolution and Hawking evaporation (Alzerkany, 2025). Hawking radiation itself arises from quantum effects near the event horizon with temperatures as in equation (6), causing black holes to gradually lose mass until they eventually evaporate. When all black holes have evaporated and structured matter has decayed, the universe is expected to be dominated by low-energy radiation and quantum vacuum fluctuations (Preskill, 1992).

At this point, a fundamental philosophical question arises: Does time still have physical meaning when macroscopic changes practically disappear? Mathematically, the parameter (t) can still be used in the solution of cosmological equations, but it may lose its empirical correlation with distinguishable physical processes. This opens up the possibility that time does not have an independent ontological status, but rather emerges as a measure of the relationship between changes in physical states.

This view is consistent with the relationalism of time rooted in the Leibnizian tradition and finds modern expression in approaches such as Rovelli's thermal time hypothesis (Evangelidis, 2018; Prabakaran, 2024). In this approach, time is not assumed to be a fundamental variable, but rather emerges from the statistical structure of the physical system through the density state operator (ρ) , with an effective evolutionary generator defined as:

$$H_\rho = -k_B ln\ \rho \tag{13}$$

This formulation shows that temporal direction and structure can arise from the thermodynamic conditions of the system, rather than from fundamental time parameters. Consequently, the arrow of time does not originate from fundamental dynamic laws that are generally symmetric with respect to transformations $(t \rightarrow -t)$, but rather from initial cosmological boundary conditions that had very low entropy. This principle is often formulated through the low-entropy initial state hypothesis, which explains why the total entropy of the universe tends to increase in accordance with the second law of thermodynamics (Ben-Naim, 2022):

$$\frac{dS}{dt} \geq 0 \tag{14}$$

However, the claim that the absence of macroscopic change implies the absence of time requires philosophical caution. In general relativity, there are vacuum spacetime solutions such as de Sitter space that have a temporal metric structure without requiring matter (Volovik, 2024). This fact is used by supporters of spacetime substantivalism to argue that time may still have ontological status even in the absence of matter. Thus, the debate between substantivalism and relationalism cannot be resolved solely through cosmological analysis, but requires deeper metaphysical reflection on whether the geometric structure of spacetime can be considered an independently existing entity.

On the other hand, the quantum cosmology approach presents new challenges through the Wheeler–DeWitt equation (Basilakos et al., 2025; Znojil, 2022):

$$H^{\wedge}\Psi = 0 \quad (15)$$

which describes the universe as a whole without explicit time parameters. In this context, time is understood as an emergent phenomenon that arises from internal correlations among subsystems, as described in the Page–Wootters approach (Favalli, 2025; Schmitt, 2023). This perspective reinforces the argument that time may not be a fundamental entity, but rather a consequence of the dynamic relationship between physical configurations.

Metaphysically, the relational approach has radical consequences for our understanding of existence. If time arises from change, then change becomes more fundamental than time itself. However, this position faces a circularity dilemma: change is usually defined as a variation in state over time. Therefore, philosophical analysis must consider the possibility that time and change are co-emergent structures within a network of physical relations, rather than a one-way ontological hierarchy.

In cosmology, at the end of the universe, when change becomes minimal, time may not stop ontologically, but rather lose its epistemological and phenomenological relevance. The parameter of time may still appear in mathematical formulations, but no longer represents an observable sequence of events. Thus, time can be understood as a relational construct that has validity when there are measurable differences in physical states.

This interpretation places time as a product of thermodynamic structures and quantum relations in space-time, while also opening up the possibility that fundamental reality is atemporal. From this perspective, cosmic evolution, including black hole evaporation and the increase in universal entropy, suggests that temporal experience may be an emergent phenomenon arising from energy and information imbalances in the universe.

If this approach is accepted, then time is no longer understood as the stage on which reality unfolds, but rather as a relational pattern that emerges from cosmic dynamics. Thus, time is not the ontological foundation of reality, but rather a structural shadow of physical changes occurring in the space-time network. When changes approach total equilibrium, this temporal shadow does not disappear as a mathematical concept, but loses its physical meaning as an indicator of the evolution of reality.

7. Is the Fundamental Entity a Particle or Information?

The question of what constitutes the most fundamental entity in the universe, whether it is particles, information, or microscopic spacetime structures is one of the most profound metaphysical problems in contemporary philosophy of physics. This debate is not only related to theoretical physics, but also touches on the ontological question of reality, namely, what fundamentally exists. The phenomenon of black hole evaporation through Hawking radiation and the possible existence of microscopic relics as the final remnants of this process reopens this discourse in a very radical way, because it places the boundary between matter, information, and the structure of space-time in an increasingly blurred position.

In the paradigm of classical particle physics and quantum field theory, reality is usually understood as being composed of elementary particles or fundamental fields (Carroll, 2022; Nagashima, 2011). Within the framework of quantum field theory, particles are not independent entities, but rather excitations of the underlying quantum field (Kuhlmann, 2006). Mathematically, the state of a particle can be represented by a quantum field operator $\{\phi^{\wedge}(x\})$ acting on the quantum vacuum, so that particles appear as excited states of that field. Even within the modern framework, the ontology of particles has shifted towards the ontology of fields.

However, quantum gravity theory proposes an even more profound shift: the possibility that fields themselves are not the most fundamental entities but rather manifestations of microscopic spacetime structures (Pauri, 1997).

Black hole evaporation provides a very important context in this discussion. According to Hawking's theory, black holes emit thermal radiation with a temperature given by equation (6), where the radiation temperature is inversely proportional to the mass of the black hole. As the black hole's mass decreases due to this radiation, it will become hotter until it eventually reaches the Planck scale (Cheek et al., 2022; Hawking, 1976). At this stage, current physics theories lose their validity because quantum gravity effects become dominant. Some theoretical models propose that the evaporation process does not completely eliminate black holes, but rather leaves behind stable objects with masses close to the Planck mass, namely:

$$M_P = \sqrt{\frac{\hbar c}{G}} \tag{16}$$

If such an object truly exists, then it cannot be understood as a particle in the standard physical sense. It has no internal structure that can be explained by the Standard Model of particle physics, no significant electromagnetic or nuclear interaction spectrum, and can likely only be understood as a geometric or topological configuration of quantum space-time itself (Boi, 2022). In this context, black hole relics become ontological candidates that challenge classical concepts of matter as a fundamental entity.

However, deeper philosophical questions arise when we consider whether the Planck scale is an ontological limit of reality or merely an epistemological limit of human theory. In one realist interpretation, the Planck length:

$$l_P = \sqrt{\frac{\hbar G}{c^3}} \qquad (17)$$

It is regarded as a scale at which the continuous structure of space-time collapses and is replaced by a discrete structure. In this interpretation, physical reality has a fundamental granularity, and all macroscopic entities are emergent manifestations of a microscopic space-time network. However, in the instrumental or epistemological interpretation, the Planck scale only indicates the limits of our theory's ability to describe reality, without asserting that reality itself has a discrete structure at that scale. Thus, the question of Planck fundamentalism is not only a question of physics, but also a question of scientific epistemology.

Another alternative in the discourse of physical ontology is the view that information is the most fundamental entity. This idea is rooted in John Archibald Wheeler's famous proposition, *"It from bits,"* which states that physical reality emerges from the structure of information (Furlan, 2024; Wheeler, 2018). In modern physics, information is often associated with entropy, which can be statistically expressed in equation (4), which (Ω) states the number of possible microstates for a system. In the context of black holes, Bekenstein's equation (2) shows that the entropy of a black hole is directly proportional to the area of its event horizon. This equation implies that information about the contents of a black hole appears to be stored on the surface of the horizon, rather than within its volume. The holographic interpretation of this equation suggests that three-dimensional reality may be a projection of a two-dimensional information structure onto the spacetime boundary. However, philosophically, the view that information is an ontological entity still faces a fundamental problem: whether information exists independently of the physical system that represents it, or is merely an epistemological construct used to describe the regularity of natural phenomena.

Another approach that is gaining attention in the philosophy of physics is structural ontology. In this view, what is fundamental is not objects but the relations and structures that connect them. This approach is supported by quantum gravity theories such as Loop Quantum Gravity, in which space-time is represented as a discrete spin network, as well as Causal Set theory, which views reality as a set of discrete causal relations (Dribus, 2017; Rovelli, 2003). In this framework, particles are no longer understood as material entities, but rather as excitation patterns in the relational fabric of space-time.

If black hole evaporation produces microscopic relics, then these relics can be interpreted not as remnants of matter, but as stable configurations within the relational structure of space-time. These relics can be viewed as *"Topological knots"* in the cosmic network, which preserve the historical traces of black hole evolution without retaining their material identity. This interpretation shifts the ontology of physics from object realism to structural realism, in which what fundamentally exists are patterns of relations, not material entities.

The epistemological consequences of this ontological change are significant. For centuries, physical theories have been built on the assumption that space-time is the setting for physical phenomena, while matter is the main actor in the dynamics of nature. However, if the structure of space-time itself is dynamic and has a fundamental microstructure, then this paradigm must be reversed. Space-time can no longer be understood as a passive stage, but rather as an active entity that determines the existence of particles, fields, and even the concept of information. In this perspective, particles and information are not fundamental entities, but emergent phenomena that arise from the deeper dynamics of the structure of space-time.

This debate shows that there is no single consensus on the fundamental ontology of modern physics. Particle ontology emphasizes the reality of elementary matter, information ontology emphasizes the role of symbolic structures and entropy, while structural and relational ontology places geometric relations as the basis of reality. The phenomenon of black hole evaporation serves as a conceptual laboratory demonstrating that entities previously considered the most stable and permanent can undergo radical ontological transformations. This suggests that physical reality may be better understood as a dynamic and relational process rather than as a collection of fixed and independent objects.

CONCLUSIONS

The phenomenon of black hole evaporation through Hawking radiation shows that even cosmic structures that have long been considered the most stable are, in fact, impermanent. Theoretically, this confirms that physical reality is dynamic, historical, and constantly undergoing transformation. Black holes can no longer be understood as objects with a fixed essence, but rather as configurations of relationships within the space-time network and quantum interactions, in which their identity is determined by the existence of an event horizon. The disappearance of the horizon marks a fundamental ontological change. This study also confirms that the relationship between micro and macro phenomena is interdependent and emergent, while the direction of time is better understood as a consequence of increasing entropy in cosmic processes. Furthermore, the black hole information paradox reflects the limitations of human scientific description rather than the loss of reality itself, so that information is understood as a symbolic representation rather than a fundamental physical entity.

Practically, this research reinforces the importance of integrating theoretical physics and philosophy of science in understanding extreme cosmological phenomena. An interdisciplinary approach helps provide a conceptual framework for the development of quantum gravity theory and clarifies the relationship between general relativity, quantum mechanics, and thermodynamics. In the field of education and science development, this study confirms that philosophical reflection plays an important role in explaining complex modern physics concepts, thereby deepening conceptual understanding and enriching research methodologies in cosmology and fundamental physics.

Further research should be directed toward strengthening the study of black hole evaporation through quantum gravity approaches, such as Loop Quantum Gravity, String Theory, and Causal Set Theory, in order to understand the structure of space-time at the Planck scale and the possible existence of black hole residue. In addition, further studies are important to examine the ontological status of information in physics by comparing the perspectives of information realism, instrumentalism, and structuralism, particularly in the context of the black hole information paradox. The development of numerical simulations is also necessary to dynamically model the evolution of black hole mass, temperature, and entropy so as to produce quantitative predictions about the final stage of evaporation. On the other hand, research on micro and macro relations in cosmology needs to be expanded through a multi-scale approach and complexity theory to explain the emergence mechanism between quantum phenomena and cosmic structures. Philosophical studies of relational time are also important for evaluating the thermal time hypothesis and the Page–Wootters approach in quantum cosmology. In addition, indirect observational research needs to be developed through the search for indications of Hawking radiation or quantum horizon effects through the observation of gravitational waves, cosmic radiation, and analog black hole simulations in laboratory systems.

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