Thermodynamic Stabilization of Gravitational Collapse at Planck-Scale Temperatures

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March 2025

Abstract

The conventional view of gravitational collapse predicts the formation of a classical event horizon (EH), followed by an inevitable singularity. However, this scenario does not fully account for the thermodynamic properties of self-gravitating systems, particularly their negative heat capacity. In this work, we investigate how thermodynamic constraints may influence the late stages of collapse and propose that a non-singular, thermodynamically stabilized intermediate state may emerge at Planck-scale temperatures.

By analyzing the temperature evolution driven by gravitational compression and energy-momentum effects, we show that the system can reach the Planck temperature well before the classical free-fall time completes. This rapid heating phase naturally leads to a transition into a stabilized state supported by an Anti-de Sitter (AdS)-like interior with a negative cosmological constant. While an event horizon still forms as an observer-independent boundary, the singularity is avoided due to this internal stabilization.

We further examine the holographic implications of this scenario. The event horizon acts not as a classical one-way membrane, but as a quantum-classical interface that stores and gradually releases information. This provides a thermodynamically motivated framework for resolving the black hole information paradox.

Rather than contradicting standard black hole physics, this model extends it by incorporating thermodynamic and quantum gravitational principles. The results suggest new avenues for theoretical and observational exploration of non-singular gravitational collapse.

1 Introduction

In classical general relativity (GR), the gravitational collapse of sufficiently dense matter leads to the formation of a black hole, characterized by an event horizon (EH) at the Schwarzschild radius:

$$R_S = \frac{2GM}{c^2}, \tag{1}$$

where G is the gravitational constant, M is the mass, and c is the speed of light. This boundary encloses a singularity—a region of diverging curvature and density—implying a breakdown of the classical theory at its core. For a mass of $10M_\odot$ (ten solar masses), the Schwarzschild radius is approximately $R_S \approx 29.49\,\mathrm{km}$, while for $7M_\odot$, it is $R_S \approx 20.64\,\mathrm{km}$.

The collapse time in an idealized free-fall scenario, starting from an initial radius R_0, is given by:

$$t_{\mathrm{ff}} = \frac{\pi}{2}\sqrt{\frac{R_0^3}{8GM}}. \tag{2}$$

For $R_0 = 100\,\mathrm{km}$, representative of a neutron star's scale, we find $t_{\mathrm{ff}} \approx 4.82 \times 10^{-4}\,\mathrm{s}$ for $10M_\odot$ and $t_{\mathrm{ff}} \approx 5.36 \times 10^{-4}\,\mathrm{s}$ for $7M_\odot$. In realistic scenarios, this timescale may increase due to internal pressure gradients, neutrino emission, or rotation, often reaching the order of seconds [2, 3].

Despite its predictive success, the classical picture neglects essential thermodynamic and quantum aspects. Once the EH forms, all information about the infalling matter is causally disconnected from the external observer, leading to the well-known singularity problem and the black hole information paradox [4]. Crucially, standard GR does not incorporate the thermodynamic behavior of self-gravitating systems—most notably, their negative heat capacity [5]—nor does it account for possible quantum modifications near the Planck scale [6].

In this work, we propose an alternative scenario. We suggest that a non-singular intermediate state, which we term a *Grey Hole* (GH), may form before the EH fully develops. This state emerges due to thermodynamic constraints, stabilizing the collapse and avoiding a curvature singularity, while preserving the formation of an observer-independent boundary. The GH concept is inspired by Rovelli's proposal of white holes within loop quantum gravity [1], but departs from it by emphasizing entropic and holographic mechanisms that operate already during collapse, not through post-bounce dynamics.

Our approach integrates three key ingredients: (i) the role of negative heat capacity in collapse dynamics, (ii) entropic gravity as an emergent mechanism [7], and (iii) an Anti-de Sitter (AdS)-like interior stabilized by an effective negative cosmological constant [8]. These elements jointly suggest that the collapse process may transition into a GH state at finite time and finite radius, before a singularity can form.

The structure of this paper is as follows: In Section 2, we analyze the thermodynamic behavior of gravitational collapse and derive the conditions under which a transition to a Grey Hole (GH) state occurs. Section 3 presents the resulting AdS-like interior geometry and demonstrates its consistency with Einstein's equations. In Section 4, we interpret the physical implications of this framework, particularly its relevance for holography and information conservation. We conclude in Section 5 by summarizing the main contributions and outlining directions for future research.

2 Methods: Thermodynamics of Gravitational Collapse

The collapse of self-gravitating matter involves thermodynamic processes that differ fundamentally from those of conventional systems. In particular, such systems exhibit a negative heat capacity, leading to counterintuitive behavior: as energy is lost, the system heats up rather than cools down. This property, combined with increasing spacetime curvature, accelerates collapse and drives the system toward extreme temperatures.

2.1 Negative Heat Capacity and Energy-Momentum Contributions

Self-gravitating systems are characterized by a negative heat capacity of the form:

$$C = -\frac{GM^2}{Rk_B}, \tag{3}$$

where R is the system's radius and k_B is Boltzmann's constant. Unlike in ordinary thermodynamic systems, energy loss leads to further contraction and an increase in temperature. This behavior, first identified in the context of gravothermal instability [5], is also relevant in black hole thermodynamics [11].

This effect is further amplified by the energy-momentum tensor $T_{\mu\nu}$, which governs the evolution of the spacetime metric via Einstein's field equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{4}$$

For a spherically symmetric distribution, the dominant component is approximated by $T_{00} \approx \rho c^2$, with:

$$\rho = \frac{M}{\frac{4}{3}\pi R^3}. \tag{5}$$

As collapse progresses and R decreases, both the energy density T_{00} and the curvature increase rapidly, enhancing the thermal instability.

At sufficiently high densities, quantum gravitational effects become relevant. In the context of entropic gravity [7], gravity itself may be viewed as an emergent entropic force, suggesting that collapse is thermodynamically constrained rather than necessarily singularity-bound.

2.2 Thermal Energy Growth from Gravitational Collapse

The process of gravitational collapse converts potential energy into kinetic and eventually thermal energy. In self-gravitating systems, this conversion is not only governed by Newtonian dynamics but also exhibits thermodynamic peculiarities, such as negative heat capacity, which leads to counterintuitive behavior: energy loss results in heating [5, **?**]. This property becomes particularly relevant in late-stage collapse, where compression intensifies and the energy-momentum tensor plays an increasing role in spacetime curvature and internal energy distribution [16].

As the collapse proceeds, the gravitational work done on the system increases the internal temperature, especially near the Schwarzschild radius. In this regime, quantum gravitational effects may become significant, triggering a transition to a thermodynamically stabilized state. We now quantify this process by analyzing the rate of temperature change during collapse and its implications for the onset of the Grey Hole (GH) transition.

2.3 Temperature Evolution and the Onset of the GH Transition

To quantify the thermodynamic instabilities during gravitational collapse, we derive the temperature evolution from the energy released by contraction. The rate of temperature change is given by:

$$\frac{dT}{dt} = \frac{\sqrt{G} M^{1/2} k_B}{R^{3/2}} + \frac{3 G k_B M^{3/2}}{c^2 R^{7/2}}, \tag{6}$$

where k_B is Boltzmann's constant, M is the mass of the system, R is its radius, G is the gravitational constant, and c is the speed of light. The first term reflects the gravitational work converted into thermal energy, proportional to the free-fall velocity, while the second term captures the contribution from the increasing energy density $T_{00} \approx \frac{3Mc^2}{4\pi R^3}$. This rate is driven by the negative heat capacity of the self-gravitating system, $C = -\frac{GM^2}{Rk_B}$, which amplifies the temperature increase during collapse [?, 12].

Evaluating this rate at the Schwarzschild radius $R = R_S = \frac{2GM}{c^2}$, we estimate the temperature evolution for astrophysical systems:

- For $M = 10M_\odot$, with $R_S = 29.49\,\text{km}$, the rate is $\frac{dT}{dt} \approx 3.3 \times 10^{20}\,\text{K/s}$,
- For $M = 7M_\odot$, with $R_S = 20.64\,\text{km}$, the rate is $\frac{dT}{dt} \approx 4.5 \times 10^{20}\,\text{K/s}$.

We define t_{GH} as the time required for the system to heat from an initial temperature $T_0 \approx 10^8\,\text{K}$ (typical of a neutron star core) to the Planck temperature $T_P \approx 1.4 \times 10^{32}\,\text{K}$. Approximating the rate as constant at $R \approx R_S$ during the late stages, we compute:

$$t_{\text{GH}} = \frac{T_P - T_0}{\frac{dT}{dt}}, \tag{7}$$

yielding:

- $t_{\text{GH}} \approx 4.2 \times 10^{-7}\,\text{s}$ for $10M_\odot$,
- $t_{\text{GH}} \approx 3.1 \times 10^{-7}\,\text{s}$ for $7M_\odot$.

These timescales are significantly shorter than the classical free-fall times ($t_{\rm ff} \approx 4.82 \times 10^{-4}\,$s for $10M_\odot$ and $5.36 \times 10^{-4}\,$s for $7M_\odot$), confirming that the system reaches Planck-scale temperatures well before the classical collapse completes. This rapid heating marks the onset of the Grey Hole (GH) transition, where thermodynamic stabilization intervenes to prevent singularity formation, as explored in subsequent sections. We now examine how this temperature-driven instability gives rise to an entropic stabilization mechanism that prevents further collapse and the formation of a classical singularity.

2.4 Entropic Stabilization Mechanism

In Verlinde's framework, entropy gradients give rise to effective forces:

$$F_{\rm ent} = T_P \frac{\Delta S}{\Delta R} \approx \frac{8\pi m_P c^5 R}{G\hbar}. \tag{8}$$

As the system approaches T_P, the internal entropy decreases ($\Delta S < 0$), generating an outward entropic force that counteracts further collapse.

This entropic resistance introduces an effective negative pressure, halting the runaway instability and stabilizing the system. The transition to a GH state can thus be interpreted as a thermodynamically favored configuration—supported by entropy dynamics rather than repulsive matter effects. This insight motivates the search for a suitable interior solution, which we address in the next section.

3 Results: Interior Geometry of Grey Holes

The thermodynamic analysis presented in Section 2 suggests that gravitational collapse may stabilize at the Planck temperature T_P, before the formation of a classical singularity. This motivates the search for a non-singular interior geometry consistent with the equations of general relativity and thermodynamic constraints. In this section, we derive such a metric and demonstrate its compatibility with Einstein's field equations.

3.1 Motivation for an AdS-like Interior

Several features of the GH state point toward an Anti-de Sitter (AdS)-like interior:

- **Thermodynamic pressure:** The entropic force derived in the previous section introduces an effective negative pressure opposing further collapse.
- **Avoidance of singularities:** AdS spacetimes allow solutions with bounded curvature, avoiding divergent behavior characteristic of Schwarzschild interiors.
- **Holographic compatibility:** AdS geometries are central to holographic dualities, enabling consistent information encoding on boundary surfaces [10, 15].

Taken together, these aspects suggest that a static, spherically symmetric AdS geometry may serve as a viable interior metric for GHs.

3.2 AdS Interior Metric and Cosmological Constant

We consider the standard AdS metric in static coordinates:

$$ds^2 = -\left(1 + \frac{r^2}{l^2}\right) dt^2 + \left(1 + \frac{r^2}{l^2}\right)^{-1} dr^2 + r^2 d\Omega^2, \tag{9}$$

where l is the AdS curvature radius, related to the effective cosmological constant by:

$$\Lambda = -\frac{3}{l^2}. \tag{10}$$

Assuming stabilization occurs near the Planck scale, we set $l \approx l_P$, yielding energy densities of order ρ_P. This suggests that the GH interior is dominated by quantum gravitational effects while remaining geometrically well-defined.

3.3 Einstein Equations and Stress-Energy Tensor

To verify consistency, we insert the metric (9) into Einstein's field equations:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{11}$$

The resulting stress-energy tensor is isotropic and takes the form:

$$T_{\mu\nu} = -\frac{3c^4}{8\pi G l^2} g_{\mu\nu}, \tag{12}$$

implying an effective energy density:

$$\rho = \frac{3c^2}{8\pi G l^2} \approx \rho_P. \tag{13}$$

This confirms that the AdS-like interior is a self-consistent solution, stabilized at Planckian densities and compatible with the thermodynamic transition proposed in Section 2.

3.4 Physical Interpretation and Holographic Implications

The AdS interior provides a natural framework for avoiding singularity formation. The presence of a negative cosmological constant introduces an inward curvature that balances the outward entropic pressure. Simultaneously, the AdS geometry enables a holographic description of interior degrees of freedom, aligning with the idea that the event horizon acts as a boundary storing information.

This dual role—geometric stabilization and holographic encoding—positions the AdS interior as the natural candidate for modeling the core of GHs.

Key Results:

- The GH interior admits an AdS solution with $\Lambda < 0$, consistent with Planck-scale stabilization.
- The resulting energy-momentum tensor corresponds to a negative vacuum pressure.
- The structure aligns with holographic expectations from AdS/CFT duality.

4 Discussion: Information Preservation and Holography

A central challenge in black hole physics is the tension between general relativity (GR) and quantum mechanics (QM) regarding the fate of information during gravitational collapse. While GR predicts that all matter and information crossing the event horizon (EH) is irretrievably lost to a singularity, QM requires unitary evolution and information conservation. This apparent contradiction gives rise to the well-known black hole information paradox [4, 17].

In the GH framework developed here, this paradox is naturally avoided. The event horizon forms concurrently with a thermodynamic phase transition that halts collapse at the Planck temperature T_P. The interior stabilizes in an AdS-like geometry, preventing singularity formation and allowing for a reversible, information-preserving evolution.

4.1 The Event Horizon as a Quantum-Classical Interface

In contrast to the classical view of the EH as a one-way boundary, GHs reinterpret the EH as a semi-permeable holographic interface. Information falling inward is not destroyed but is dynamically mapped onto the EH surface. This interpretation aligns with the Bekenstein-Hawking entropy relation:

$$S_{\text{EH}} = \frac{k_B c^3 A}{4G\hbar}, \tag{14}$$

where $A = 4\pi R_S^2$ is the surface area of the horizon. In the GH scenario, the entropy of infalling matter is transferred to the EH, rather than being lost to an inaccessible singularity.

The AdS/CFT correspondence [10] further supports this view. The AdS-like interior allows the EH to serve as a dual encoding surface, consistent with holographic principles [14, 15].

4.2 Dynamical Entropy Balance and Reversibility

A key feature of the GH framework is that entropy is not lost but redistributed. The total entropy of the system evolves according to:

$$\frac{dS_{\text{int}}}{dt} + \frac{dS_{\text{EH}}}{dt} = 0, \tag{15}$$

ensuring that as the internal entropy of collapsing matter decreases, the entropy at the horizon increases proportionally. This balance maintains global information conservation, in contrast to the irreversible loss implied by classical singularities.

Such a mechanism is conceptually similar to Rovelli's white hole scenario [1], where information trapped in a collapsing core re-emerges over long timescales. In the GH case, however, this process is continuous and thermodynamically regulated—requiring no bounce or time reversal.

4.3 Hawking Radiation as Entropic Information Release

Within the GH paradigm, Hawking radiation emerges not as a purely quantum field effect but as a manifestation of entropic rebalancing. The entropy carried away by radiation reflects a gradual information release from the horizon:

$$\frac{dS_{\text{rad}}}{dt} = -\frac{dS_{\text{EH}}}{dt}. \tag{16}$$

This process preserves unitarity and provides a physical mechanism for information recovery, addressing long-standing objections to standard Hawking evaporation [25, 19]. It also supports Verlinde's view of gravity as an emergent phenomenon driven by entropy gradients [7].

4.4 GR-QM Duality at the EH

One of the most significant conceptual implications of GHs is the reinterpretation of the EH as a dual interface between GR and QM:

- From the GR perspective: the EH remains a causal boundary, consistent with classical observers' expectations.
- From the QM perspective: the EH functions as a dynamically active holographic surface that stores and emits information.
- From the thermodynamic perspective: the EH reflects the entropic state of the interior, balancing information inflow and outflow.

Rather than being a barrier, the EH in the GH model acts as a regulated information interface—ensuring consistency between classical geometry and quantum unitarity. This resolves the apparent contradiction between EH formation and information preservation without requiring exotic postulates or speculative extensions.

Implications:

- The GH model provides a thermodynamically grounded resolution to the information paradox.
- The EH serves as a unified surface for classical causality and quantum holography.
- Hawking radiation acquires a natural interpretation as entropic information release, not mere thermal noise.

5 Conclusion

This work presents a thermodynamically consistent alternative to the classical picture of gravitational collapse. By incorporating the effects of negative heat capacity, entropic gravity, and holographic principles, we argue that a non-singular intermediate state—the Grey Hole (GH)—may form before the completion of event horizon formation. This GH state is stabilized at Planck-scale temperatures by an AdS-like interior geometry and avoids the formation of a singularity.

Our model offers a coherent mechanism for information preservation. The event horizon functions not as an information sink, but as a dynamic interface where entropy is stored, balanced, and gradually released through Hawking-like radiation. This interpretation aligns with holographic expectations and provides a thermodynamically motivated resolution to the black hole information paradox.

5.1 Implications for Fundamental Physics

The GH framework reframes the role of the event horizon, unifying geometric, thermodynamic, and quantum perspectives:

- It resolves singularities via a pressure-stabilized AdS core.
- It supports unitarity through entropy flow across the EH.
- It reinterprets Hawking radiation as entropic information retrieval.

Together, these elements point toward a deeper connection between thermodynamics and spacetime structure, suggesting that gravitational collapse may be governed by quantum-statistical principles long before classical singularities arise.

5.2 Future Directions

Several open questions emerge from this proposal:

- Can gravitational wave signatures from collapse events distinguish GH formation from classical black holes?

- How does the AdS interior modify the expected spectrum or coherence of Hawking-like radiation?
- Can quantum simulations or analogue gravity systems emulate GH behavior?
- What is the precise role of the cosmological constant in regulating collapse dynamics?

Further theoretical refinement and observational investigation are required to test the GH model and its predictions. If validated, this framework may contribute to resolving one of the deepest tensions in modern physics: the unification of gravity and quantum information.

Declarations

Conflict of Interest: The author declares no conflict of interest.

Funding: This research received no external funding.

Data Availability: No datasets were generated or analyzed during the current study.

Ethics Approval: Not applicable.

Author Contributions: The author is solely responsible for the conceptual development, writing, and revision of the manuscript.

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