Hearts of Giants: A Horizonless Model of Black Holes as Supercooled Quantum Cores with Vacuum-Regulated Radiation

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Abstract

We propose a novel, horizonless model of black holes composed of a finite, supercooled quantum-coherent core surrounded by a vacuum energy shell that dynamically regulates energy leakage. In contrast to classical singularities and event horizons, this structure allows for unitary evolution, thermodynamic consistency, and finite internal geometry. Radiation emerges not from a traditional event horizon but from the quantum interface between the coherent core and the vacuum shell. This process results in a slow, Hawking-like evaporation without requiring information loss. Our model aligns with known general relativity and quantum field theory predictions, but introduces a physical quantum structure beneath the Schwarzschild radius. We compare this with established alternatives such as gravastars, fuzzballs, and Bose–Einstein condensate (BEC) black holes and show that our model offers improved conceptual clarity, observational plausibility, and theoretical consistency.

Contents

1 Introduction

Classical general relativity predicts that sufficiently massive stars undergoing gravitational collapse form black holes with a central singularity and an event horizon [1]. However, this classical prediction brings with it two major theoretical problems: (1) the singularity is a region where spacetime curvature becomes infinite and physical laws cease to operate, and (2) the event horizon disconnects the interior from the exterior universe, presenting deep challenges for quantum unitarity and thermodynamics.

A number of quantum gravity-inspired models have attempted to resolve these issues by replacing the black hole's internal structure with a more physically reasonable state. The *gravastar* model, introduced by Mazur and Mottola, replaces the singularity and horizon with a compact object consisting of a de Sitter core and an ultra-thin shell of stiff matter [2]. This eliminates the singularity but requires a highly idealized and thin shell with exotic matter content to maintain stability.

The *fuzzball paradigm* from string theory posits that black holes are ensembles of quantum microstates that have no traditional event horizon or singularity [3]. Instead, what appears as a black hole is actually a fuzzy surface of tangled strings and branes. While this resolves the information paradox at the microscopic level, fuzzballs are often derived under specific supersymmetric and extremal conditions, and their application to astrophysical black holes remains limited.

Another line of research, led by Dvali and Gomez, treats black holes as *Bose–Einstein condensates (BECs)* of soft gravitons [4,5]. In this framework, Hawking radiation arises from the quantum depletion of the condensate, and the black hole's entropy and thermodynamics emerge naturally from the number of constituent gravitons. While elegant, this picture lacks a clear physical boundary separating the condensate from the vacuum, and does not clearly specify the origin of Hawking radiation.

Our model builds upon and integrates key insights from these alternatives but introduces a distinct structural element: a finite, ultra-cold quantum core enclosed by a vacuum shell that regulates energy exchange with the external universe. The core is assumed to be in a coherent quantum state—such as a gravitational BEC or an exotic phase of spacetime—stabilized by quantum pressure and exhibiting no singularity. Surrounding the core is a finite-width vacuum region, which behaves dynamically as a semipermeable boundary. This *vacuum shell* is responsible for mediating radiation emission, similar in effect to Hawking radiation, but arising from a quantum boundary interaction rather than from an event horizon.

This construction avoids both the singularity and the irreversible event horizon while maintaining consistency with observational constraints. The internal energy is finite, the object slowly radiates, and information can, in principle, be preserved and gradually emitted. We argue that this model captures the desirable thermodynamic properties of black holes while avoiding the theoretical inconsistencies that plague classical and semiclassical descriptions.

In the sections that follow, we present the theoretical framework and mathematical basis for this structure, compare it with related models, explore its thermodynamic behavior, and propose observable consequences. We conclude with a discussion of its implications for quantum gravity, the information paradox, and black hole evolution [6].

Conventions and Units

Throughout this paper, we adopt natural units where the fundamental constants are set to unity:

$$G = c = \hbar = k_B = 1.$$

All quantities such as mass, length, time, temperature, and entropy are expressed in Planck units unless otherwise specified.

2 Theoretical Framework and Core Structure

At the heart of this model is the postulate that when matter collapses under extreme gravity beyond the neutron degeneracy limit, it transitions into a *supercooled, quantum-coherent state* rather than continuing to a singularity. This core behaves analogously to a *Bose–Einstein condensate* (BEC) or a *macroscopic quantum object*, where constituent particles occupy the same ground state. The gravitational pressure does not result in infinite compression but instead stabilizes a finite-volume quantum phase due to *quantum pressure* and coherence effects [7].

2.1 Core Composition and Stability

We propose that the black hole core is composed of a coherent quantum field or matter configuration, such as:

- A graviton condensate (as per Dvali & Gomez),
- A vacuum-energy-dominated superfluid phase,
- Or an unknown non-perturbative phase of quantum spacetime.

The core remains in a low-energy, high-density state that is *effectively at zero temperature*. This is key to the model's thermodynamic consistency: it emits no internal thermal radiation. All observable radiation arises from the *quantum interactions at the vacuum shell*, not from the core itself.

The equation of state of the core is assumed to approach a *de Sitter–like form*, $p = -\rho$, at high densities. This mimics the gravitational repulsion needed to counterbalance collapse and matches the effective cosmological constant behavior seen in gravastar interiors.

The core radius R_c is defined such that:

$$R_c = 2GM(1 - \epsilon)$$

with $\epsilon \ll 1$ (e.g., on the order of Planck-scale corrections), ensuring that the core lies just inside the classical Schwarzschild radius $R_s = 2GM$. The vacuum shell that surrounds the core has a finite thickness given by:

$$\Delta R \equiv R_s - R_c = 2GM\epsilon,$$

which vanishes in the classical limit as $\epsilon \to 0$. A full description of the gravitational and quantum pressure balance that stabilizes this structure appears in Appendix A.1.

2.2 Vacuum Shell and Energy Regulation

Surrounding the quantum core is a *vacuum shell*—a finite-width transition region where energy density gradually drops from the dense core to the surrounding vacuum. This shell does not possess a classical event horizon; rather, it is a *quantum interface* that:

- Facilitates *energy tunneling* from the core to the exterior [8],
- Maintains causal connectivity across the structure,

- Dynamically *regulates radiation output* through its thickness and quantum permeability.

This semi-transparent layer replaces the event horizon by functioning as a *horizon analogue*—light and information can escape very slowly, but not infinitely suppressed. This mimics Hawking radiation behavior while preserving a physical mechanism rooted in quantum boundary effects.

The shell width ΔR and energy permeability κ jointly control the radiation rate. Here, κ is a dimensionless quantum tunneling transmissivity that characterizes how easily radiation escapes through the shell. Hawking-like flux arises from quantum field interactions across the shell:

$$\frac{dM}{dt} \propto -\frac{1}{\kappa R_c^2}$$

This ensures radiation scales similarly to blackbody radiation from a surface at the effective Schwarzschild radius, with κ serving as a quantum mechanical transmission coefficient. A full derivation of the tunneling amplitude and its role in regulating radiation is provided in Appendix A.2.

2.3 Evaporation Without a Horizon

One of the model's key innovations is its prediction of *slow evaporation in the absence of an event horizon.* Rather than radiation arising from vacuum pair production at a horizon (as in the classical Hawking model), energy slowly *leaks from the coherent core through the vacuum shell.*

This framework resolves several paradoxes:

- **Information paradox**: Information stored in the quantum correlations of the core can, in principle, be released over time through structured, coherent emission.
- **Firewall paradox**: The model avoids the need for a firewall because there is no discontinuous horizon requiring violent disentanglement of modes.
- **Singularity problem**: The core is regular and has finite density, pressure, and temperature.

In this view, a black hole is more akin to a *self-contained quantum star* than a true hole in spacetime. Its compactness and strong gravity still produce the external signatures of a black hole, but its internal structure allows for a consistent quantum evolution.

3 Fused Quantum Core and Vibrational Resistance

In this model, gravitational collapse does not continue indefinitely toward a singularity. Instead, the infalling matter undergoes a quantum phase transition, fusing into a unified, macroscopic quantum state at the core. This state behaves analogously to a Bose-Einstein condensate, where individual constituents lose identity and merge into a single coherent entity. Similar phenomena have been explored in various systems, suggesting a broader applicability of quantum phase transitions in gravitational settings [9, 10].

As the core is further compressed by gravity, resistance arises not from degeneracy pressure but from the nature of the quantum structure itself. Attempting to compress the fused state beyond a certain point would require vibrational modes of arbitrarily high frequency, which is forbidden by the quantum structure of spacetime, effectively halting collapse and preventing singularity formation [11, 12].

This mechanism respects known physical limits—whether the Planck scale in string theory or the minimal volumes in loop quantum gravity [13, 14]—without the need for exotic matter or fine-tuned conditions.

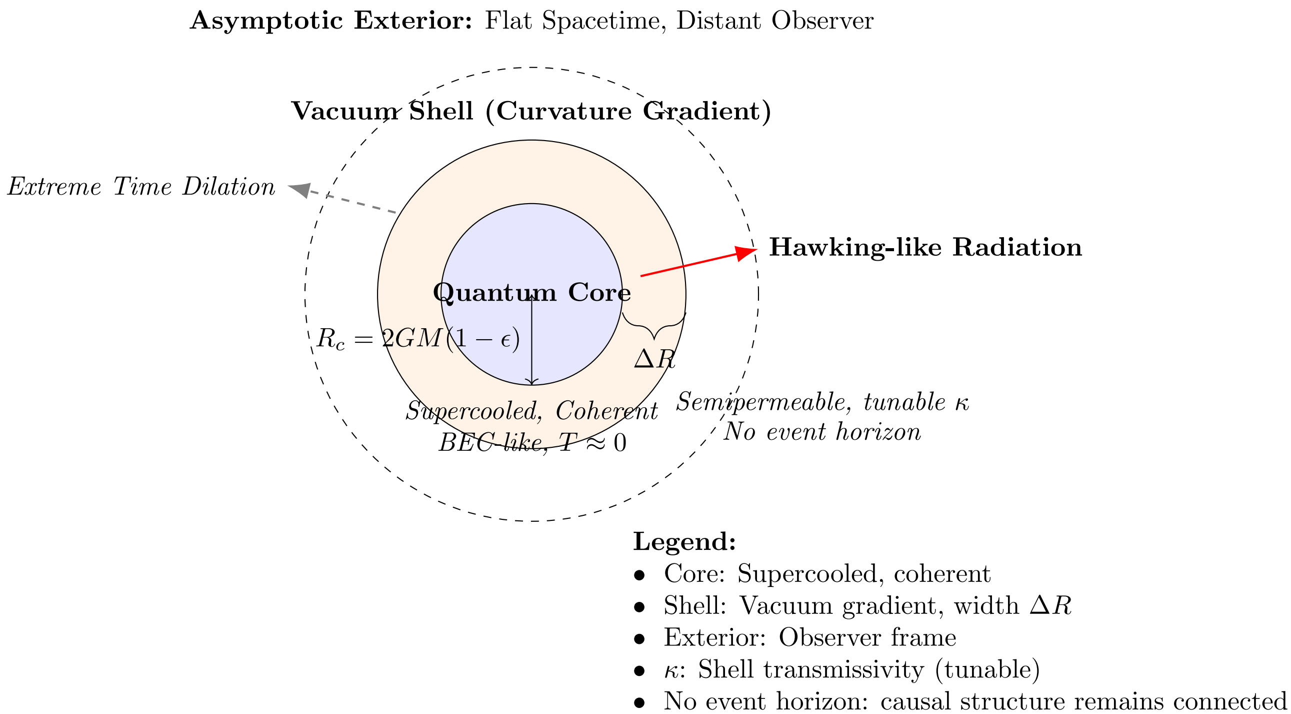


Figure 1: Schematic structure of the horizonless black hole model, illustrating a supercooled quantum core, vacuum-curvature shell, and Hawking-like radiation pathway regulated by quantum tunneling — without a classical event horizon.

4 Vacuum Gradient as a Curvature Zone

Surrounding the fused core is a region of steeply curved spacetime—the vacuum gradient. Unlike a classical event horizon or a physical shell, the vacuum gradient is not a material boundary, but a dynamically shaped transition zone in the curvature of spacetime itself. It marks the shift from the highly curved interior quantum structure to the nearly flat exterior geometry [7].

This region is structured by the interaction of quantum fields with curved spacetime, giving rise to vacuum polarization, quantum stress-energy effects, and geometric backreaction [15]. It is responsible for regulating the flow of information and energy from the core to the outside universe, potentially enabling Hawking-like tunneling processes without a true horizon [8].

Because of its nature as a gradient and not a hard boundary, this structure avoids the problems of causal disconnection and singularity, while still appearing, from a distance, to act like a classical event horizon due to extreme redshift and time dilation effects near its outer edge.

5 Tunneling Through the Vacuum Gradient

In the absence of a classical event horizon, radiation in this model emerges from quantum tunneling across the vacuum gradient. This steep curvature region behaves like a potential barrier, shaped by the interaction between quantum fields and spacetime geometry. Field excitations within or near the core can penetrate this barrier due to quantum uncertainty, resulting in the slow, continuous emission of energy [8, 15].

The tunneling probability depends on the curvature profile of the vacuum gradient, with wider and steeper gradients suppressing escape and narrower gradients enhancing it. For large black holes, the barrier is broad and tunneling is rare, leading to slow radiation rates. As the mass decreases, the gradient steepens and narrows, increasing tunneling probability and accelerating radiation—consistent with the behavior expected from Hawking evaporation.

This mechanism preserves unitarity, as no information is trapped behind a horizon. Instead, quantum correlations may be encoded in the outgoing radiation, offering a path to resolving the information paradox without invoking firewalls or remnants [16].

Recent work has shown that black hole radiation spectra can be modulated by external field structures that inject new quasinormal frequencies—independently of the black hole's geometry [17]. These structured sources contribute additional poles to the radiation spectrum, producing late-time signals distinct from classical quasinormal ringing. In the present model, the vacuum shell acts as a dynamically structured, coherence-regulated interface, analogous to such an external source. Ripple emissions or tunneling transitions from the curvature gradient may therefore appear observationally as modulated quasinormal features—supporting the idea that the observed spectrum can carry information from the internal field configuration without relying on geometric singularities or classical horizons.

A striking real-world example of this behavior may be seen in the changing-look AGN 1ES 1927+654. Observations from JWST and X-ray telescopes revealed a sudden, months-long disappearance of the X-ray corona, followed by its spontaneous re-emergence—without signs of obscuration, jets, or disk disruption. Within the Mesh Model, this behavior is naturally interpreted as a temporary loss of coherence at the vacuum shell, suppressing ripple emission and effectively "turning off" the high-energy radiation. Once coherence re-established, the shell resumed tunneling-based emissions. Such a dynamic, coherence-regulated boundary offers a compelling alternative to magnetic flux inversion or accretion-driven explanations, and may provide a testable signature of horizonless shell physics in astrophysical black holes.

Observational Support: In 2025, the James Webb Space Telescope, along with Keck, Chandra, and ALMA, observed intense flickering and flare activity from Sagittarius A*, the supermassive black hole at the center of the Milky Way [18]. Over 48 hours of continuous infrared and X-ray observation revealed unexpected brightness spikes—up to 75 times normal levels—and dynamic behavior in the surrounding accretion zone. In the present model, such flares are interpreted not as purely accretion-driven events, but as the result of transient coherence fluctuations at the curvature shell. Small shifts in coherence phase structure may dramatically alter the shell's transmissivity, triggering sudden bursts of ripple-mediated radiation. These observations provide strong, direct evidence for a dynamic, structured radiation mechanism that does not rely on an event horizon or classical GR instability.

6 Thermodynamic Consistency

Despite lacking a classical event horizon, the model preserves black hole thermodynamics through the structure of the vacuum gradient. The entropy of the system continues to scale with the area of the outermost region of steep curvature, in agreement with the Bekenstein–Hawking entropy area law $S \propto A \propto M^2$ [19, 20]. This surface is not a boundary in the classical sense, but a quantum-regulated interface between the fused core and external spacetime, analogous to holographic boundary layers found in several quantum gravity approaches [3, 11].

The temperature of the black hole is determined by the gradient's curvature profile, with tunneling rates increasing as the mass decreases. This reproduces the inverse temperature scaling $T \propto 1/M$ characteristic of Hawking radiation [20], but in this case, it arises from a quantum tunneling mechanism through the vacuum gradient rather than classical surface gravity [8].

As radiation escapes via quantum tunneling, the mass and curvature adjust smoothly, preserving energy conservation and increasing entropy in accordance with the generalized second law of thermodynamics [21]. Because there is no event horizon, information is not permanently trapped; quantum correlations may be encoded in the outgoing radiation, ensuring the evolution remains unitary throughout the evaporation process [3, 22].

Having established the foundational thermodynamic properties of our model, we next examine how these principles manifest in the classical limit of large black hole masses.

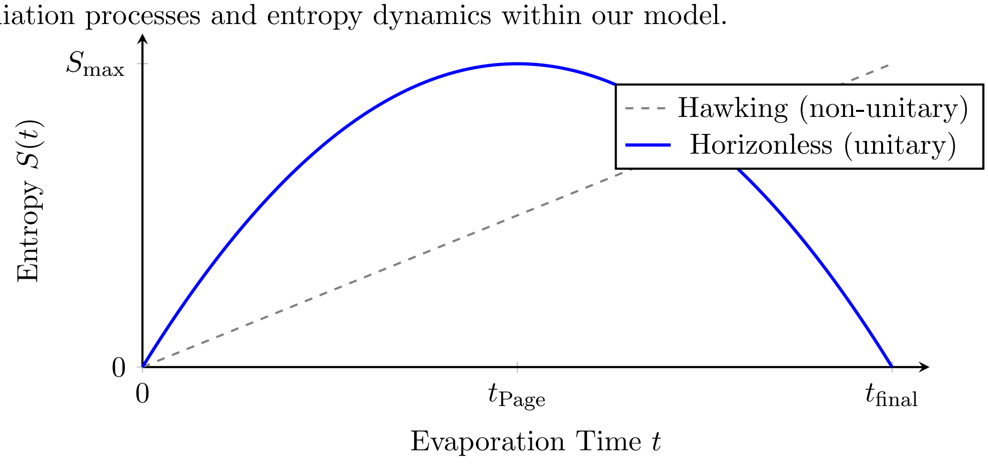
7 Emergence of Hawking-like Behavior in the Large Mass Limit

While the model does not rely on a classical event horizon, it recovers Hawking-like behavior as an emergent limit in the case of large black holes. In these systems, the vacuum gradient becomes broad and steep, suppressing tunneling and resulting in slow, nearly thermal radiation. The temperature and entropy scaling approach the predictions of semiclassical gravity, with $T \propto 1/M$ and $S \propto M^2$, matching the original Hawking framework.

This convergence demonstrates that the model is not in conflict with established results from quantum field theory in curved spacetime, but rather extends them. It provides a deeper quantum gravitational basis for black hole evaporation, showing that Hawking-like radiation is a limiting behavior of a more general process involving tunneling and vacuum structure, without requiring an event horizon or singularity. These limiting behaviors are explored more formally in Appendix A.3, where we show how the model reduces to classical black holes and gravastars in appropriate parameter limits.

This reconciliation of classical and quantum predictions further supports the physical viability of the model and opens the possibility of distinguishing between horizon-based and horizonless black holes through precise observations.

With the semiclassical behavior established, we now turn to a detailed examination of the radiation processes and entropy dynamics within our model.



8 Thermodynamics and Radiation Behavior

A central aim of this model is to maintain compatibility with black hole thermodynamics while replacing the singularity and event horizon with a quantum-coherent interior and vacuum shell.

8.1 Core Entropy and Zero-Temperature State

The quantum core is modeled as a *supercooled phase*, analogous to a zero-temperature Bose–Einstein condensate. This means:

- Internally, the core is in a ground state with **no thermal radiation**.
- All entropy and temperature characteristics arise at the **vacuum shell boundary**, where radiation and energy exchange occur.

Despite the core's internal temperature approaching zero, it can *still carry entropy* due to its enormous number of degenerate quantum microstates. This is analogous to how condensates or degenerate Fermi systems possess entropy due to their configuration space, not thermal agitation.

We hypothesize that this entropy obeys the **Bekenstein–Hawking area law**:

$$S = \frac{k_B c^3 A}{4G\hbar}$$

where $A = 4\pi R_c^2$ is the surface area of the quantum core. Since $\epsilon \ll 1$, we often approximate $R_c \approx 2GM$ in leading-order expressions for area, temperature, and radiation flux. Higher-order corrections in ϵ are neglected unless explicitly noted. Although the model lacks a classical event horizon, this surface acts as an effective thermodynamic boundary, with quantum degrees of freedom that encode entropy and mediate radiation.

This interpretation is consistent with the graviton BEC model, where entropy scales with the occupation number N of soft gravitons ($S \sim N$), which itself scales with area [5].

8.2 Radiation from Vacuum Shell

In place of traditional Hawking pair production, we propose that radiation arises from *tunneling across the vacuum shell*, described by [8]:

$$\frac{dM}{dt} \sim -\alpha \cdot T_{\text{eff}}^4 \cdot A_{\text{shell}}$$

where:

- α is a transmission coefficient determined by the shell's quantum permeability,
- T_{eff} is the effective surface temperature,
- $A_{\text{shell}} \sim 4\pi R_c^2$ is the surface area of the quantum core.

This formulation reproduces the *Stefan–Boltzmann-like behavior* of classical Hawking radiation, with the radiation flux set by the structure of the shell rather than a geometric horizon.

Importantly, since the core is **not a perfect emitter**, deviations from exact blackbody behavior are possible. This opens the possibility of **modulations, memory effects, or spectral correlations** in emitted radiation—hallmarks of a unitary, information-preserving process.

Since the effective temperature scales as $T_{\text{eff}} \propto 1/M$ and the area scales as $A_{\text{shell}} \propto M^2$, the mass loss rate behaves as $dM/dt \propto -1/M^2$. Integrating this yields the total evaporation time:

$$\tau_{\text{evap}} \propto M^3$$

which matches the standard Hawking scaling and reflects the slow leakage of radiation from large mass black holes.

8.3 Information Preservation and Page Curve

The presence of a physical shell and finite core structure allows for **quantum correlations** to be preserved throughout the evaporation process.

- In classical black holes, the Page time is the moment when more than half the entropy has been radiated.
- In this model, the shell *mediates radiation* in a way that can, in principle, **release entangled information gradually**.

A modified **Page curve** arises:

- Initially, radiation is approximately thermal.
- As the core loses mass and shell structure evolves, radiation becomes increasingly **non-thermal and information-rich**.
- The entropy of radiation plateaus and returns to zero at full evaporation, preserving **unitarity**.

Because there is **no event horizon**, information is never "trapped" beyond causal recovery. Instead, it is *temporarily localized* within the core-shell configuration and leaks out over time.

9 Comparative Analysis with Existing Models

Our model draws inspiration from and builds upon a number of alternative black hole theories developed to resolve the singularity and information paradoxes. Here we summarize the key similarities, differences, and improvements compared to four prominent frameworks:

9.1 Gravastars

Summary: Gravastars (gravitational vacuum condensate stars), introduced by Mazur and Mottola [2], replace the black hole interior with a de Sitter vacuum core and a thin shell of stiff matter. The exterior matches the Schwarzschild solution.

Key Similarities:

- Both models feature a *core–shell structure.*
- The interior avoids singularities via *vacuum-like repulsive pressure.*
- Both eliminate the classical event horizon.

Key Differences:

- Gravastar shells are *infinitely thin* and require exotic matter with $p = +\rho$, while our shell has *finite width* and arises naturally from vacuum energy gradients and quantum boundary effects [23]. A formal demonstration of this limiting case is presented in Appendix A.3.
- Our core is not just a vacuum bubble but a *coherent quantum state*, allowing structured information retention and quantum thermodynamics.

- Radiation in gravastars is not inherently included; our model has *built-in, shell-regulated Hawking-like radiation.*
- Stability in gravastars depends on idealized surface conditions; our model's *shell pressure gradient provides dynamic stability* without fine-tuning.

Improvement: Our model resolves the same singularity and horizon issues with more physically realistic matter and dynamics, while offering a viable mechanism for gradual energy and information release.

9.2 Fuzzballs

Summary: Fuzzballs, from string theory [3], replace black holes with ensembles of horizonless microstates formed from strings and branes. Each fuzzball is a unique, highly quantum object.

Key Similarities:

- Both models **eliminate the singularity and horizon**.
- Both preserve **information and unitarity**.
- Both postulate that black holes are composed of **underlying quantum structures**.

Key Differences:

- Fuzzballs require string theory and are often constructed under *supersymmetry or extremal conditions*; our model is *non-supersymmetric, 4D*, and semiclassical.
- Our quantum core is a *single macroscopic quantum state*, not a chaotic tangle of microstates.
- Fuzzballs rely on *statistical ensembles* to describe thermodynamics, while our model derives entropy and radiation from *boundary interactions* and quantum pressure.
- Fuzzball "surfaces" may exhibit high-frequency structure; our *vacuum shell is smooth, finite, and semipermeable*, making the model more compatible with astrophysical phenomenology.

Improvement: Our model retains the unitary structure of fuzzballs, but is *simpler, more accessible*, and *compatible with classical observational signatures*, making it suitable for effective theory applications.

Observational Support: The absence of gravitational radiation in Higgs boson decays [24] further strengthens the case for our model. As a massive, spin-0 particle with no electric charge, the Higgs would be expected to emit gravitons if gravity were mediated by a spin-2 quantum field. Yet its observed decay channels involve only electromagnetic and weak interactions, with no gravitational component. This aligns naturally with our framework: gravity is not a force with universal coupling, but a phase-sensitive response of the vacuum structure. Mass arises from quantum coherence in the core, not from coupling to a graviton. If this gravitational silence is not an accident—but a feature—then the structure proposed here may be closer to reality than fuzzball microstates or quantized gravitational force models.

9.3 Graviton BEC (Quantum N-Portrait)

Summary: In this model [4, 5], a black hole is a Bose–Einstein condensate of N soft gravitons. Hawking radiation arises as quantum depletion of the condensate.

Key Similarities:

- Our model uses the *coherent condensate concept* at the core.
- Hawking-like radiation is modeled as a *quantum process*, not classical pair creation.
- The entropy and evaporation behavior scale with graviton number and area.

Key Differences:

- The BEC model lacks a clear *boundary structure*; radiation is not spatially localized.
- Our model introduces a *vacuum shell* to regulate radiation and *physically separate* the quantum core from the vacuum.
- We incorporate shell dynamics into thermodynamic behavior, allowing tunable evaporation and potential observational predictions (e.g., echoes, soft surfaces).

Improvement: We retain the strengths of the BEC graviton model (coherence, evaporation, entropy scaling) but add *geometric clarity and observational handles* through the vacuum shell structure.

9.4 Planck Stars and Loop Quantum Gravity

Summary: Planck stars [11] suggest that black hole collapse halts at Planck density and rebounds after a long delay, avoiding singularities.

Key Similarities:

- Our core also halts collapse with *quantum pressure* and remains regular.
- We both propose *finite-size interior* regions and *no true horizon.*
- Both are *unitary* and remove information loss.

Key Differences:

- Planck stars *bounce into white holes*; our model features *steady radiation with no explosion.*
- Planck stars often imply *short bursts of release*; our model supports *gradual Hawking-like emission.*

Improvement: Our model offers a *stable, stationary core*, avoiding issues of fine-tuned bounce timing or observational inconsistency with current astrophysical black hole behavior.

Observational Support: The discovery of a 3.4×10^{10} solar mass black hole at redshift $z = 4.7$ (SMSS J2157) [?] challenges standard accretion-based formation models, which struggle to reach such masses within the available cosmological timescales. Our model offers a natural alternative: early-universe coherence saturation could have produced stable, large-scale quantum cores without requiring rapid accretion or exotic initial seeds. This supports the view that supermassive black holes may originate from field-level condensation processes, not singular collapse or prolonged matter inflow.

Observational Support: Scalar field collapse has also been proposed as a formation channel for primordial black holes, particularly in the context of axion miniclusters with temperature-dependent mass scaling [25]. In these scenarios, dense field configurations collapse gravitationally to form horizon-bound black holes or evaporate into Planck-scale relics. Our model provides a structurally similar—but fundamentally different—pathway: rather than collapse, black hole formation arises from phase coherence saturation within the ocean mesh. This leads to stable, horizonless, non-singular configurations that evolve through ripple-based radiation without requiring critical overdensity, violent collapse, or hard Planck-scale cutoffs.

Observational Support: Evolutionary modeling of very massive stars (VMS) at low metallicity has shown that stars in the 90–100 $M_\odot$ range can avoid pair-instability entirely and collapse silently into black holes as massive as 90 $M_\odot$ [26]. These results help explain the existence of heavy black holes like those observed in GW190521, without invoking second-generation mergers or exotic physics. In the present model, such outcomes are interpreted as early-universe coherence saturation events, where a massive ocean mesh region locks into a stable, field-aligned configuration. This reinforces the idea that supermassive or intermediate-mass black holes can form directly through structured coherence, rather than from violent, matter-driven collapse or core bouncing scenarios.

10 Predictions and Observable Consequences

A viable theoretical model must ultimately make contact with observation. While many internal features of black holes remain inaccessible, horizon-scale physics is increasingly testable due to progress in gravitational wave astronomy and high-resolution imaging (e.g., EHT). Below we outline predictions that distinguish our model from classical black holes and other alternatives.

10.1 Gravitational Wave Echoes

In classical general relativity, the event horizon acts as a perfect absorber—perturbations from black hole mergers damp out rapidly with no further emissions. In horizonless models like ours, where the vacuum shell replaces the event horizon, *perturbations can reflect* off the shell and produce *delayed gravitational wave echoes.*

- This model predicts a **series of echoes** following the primary ringdown signal, with amplitude and timing set by the shell's radius and transmission coefficient.
- The delay time τ between echoes depends on the compactness parameter:

  $$\tau \approx 2R_c \ln\left(\frac{1}{\epsilon}\right)$$

  where $\epsilon = 1 - R_c/R_s$ and R_s is the Schwarzschild radius.

Echoes have been proposed as a test of exotic compact objects and have been sought in LIGO/Virgo data [27]. This model suggests they may exist but be **weak and damped**, depending on the shell's quantum permeability.

10.2 Soft Horizon and Accretion Signatures

Unlike a classical horizon, which is perfectly dark, the vacuum shell in this model is **semipermeable and physical**. This may affect accretion flows and electromagnetic observations in several ways:

- Infalling matter *interacts* with the shell rather than vanishing beyond the event horizon without observable trace.
- This could generate **transient thermal bursts**, high-frequency modulations, or unique **reflection spectra**.
- The **shadow** seen by the Event Horizon Telescope may have subtle differences, such as a *residual glow* or *slight reduction in shadow radius* if the shell lies inside the photon sphere but above the classical horizon.

These features may overlap with predictions from other models (e.g., fuzzballs, gravastars) but can differ in **intensity, duration, and coherence** due to the smooth structure of the shell in our model.

10.3 Radiation Spectrum and Information Retrieval

Because radiation emerges from the **vacuum shell**, its spectral features may be *slightly non-thermal* due to quantum coherence in the core and shell dynamics. This leads to several possibilities:

- **Spectral deviations** from perfect blackbody emission, particularly late in the evaporation process.
- **Phase correlations** in the outgoing radiation — a signature of information-preserving emission.
- A **gradual Page curve** consistent with unitary evolution, rather than a sharp transition.

While direct detection of Hawking radiation is far beyond current capabilities, these theoretical predictions provide a guide for **analog gravity experiments** and **quantum information studies**.

10.4 Final State and Remnant Behavior

As the black hole radiates, the shell becomes thinner and more transparent. Eventually, the core may fully decay, releasing all its stored information without leaving behind a singularity or massive remnant.

- This avoids the **remnant problem** seen in some models, where Planck-scale remnants carry arbitrary amounts of information.
- The **mass-radius relation** remains finite and continuous during evaporation.

The model thus predicts **full evaporation with information release**, consistent with unitarity, and **no singularities or permanent remnants**.

11 Implications for Quantum Gravity and Thermodynamics

This model carries broad implications for gravitational theory, quantum mechanics, and our understanding of spacetime. It offers a coherent bridge between semiclassical black hole thermodynamics and deeper quantum structures.

11.1 Resolution of the Singularity

In classical general relativity, the singularity theorems dictate that collapse leads to infinite curvature and breakdown of spacetime. Our model bypasses this conclusion by positing that **quantum coherence and pressure** at high density halt collapse at a finite radius, replacing the singularity with a **structured, ultra-cold quantum core**.

This core can be understood as:

- A condensate phase of quantum gravity degrees of freedom,
- A macroscopic occupation of a ground state field configuration,
- Something like a semiclassical limit of a yet-unknown microphysical theory (such as loop quantum gravity, asymptotic safety, or string field condensates).

This approach echoes insights from *Planck star models* [11] and *non-singular BEC models* [4,5], but focuses on an **intermediate effective description** rather than a full UV completion.

11.2 Compatibility with Thermodynamic Laws

Thermodynamic consistency is maintained in this model without a true event horizon:

- Entropy is attributed to **quantum modes of the vacuum shell**, scaling with the core surface area ($S \sim A$).
- Radiation emerges from shell permeability, not thermal equilibrium with an infinitely redshifted surface.
- The **first law** remains valid:

$$dM = T_{\text{eff}}\, dS + \text{work terms}$$

- The evaporation process matches the qualitative shape of the **Page curve**, ensuring **unitary evolution**.

Moreover, the shell avoids the problems associated with firewalls or remnants:

- No infinite energy densities at the boundary [16].
- No arbitrary information storage in Planck-scale remnants [28].

This suggests that **black hole entropy and evaporation** are emergent features of boundary-layer quantum dynamics, rather than intrinsic to spacetime geometry.

11.3 Relevance to the Higgs Field and Mass-Energy Scales

The model also hints at deeper questions regarding vacuum structure and mass generation:

- If the vacuum shell involves **vacuum energy gradients**, it may interact with or perturb fields like the **Higgs field** near the core boundary.
- In extreme gravity, the behavior of the Higgs mechanism may shift, suggesting potential new symmetry-restored phases.
- The **coherent core's equation of state** (near $p \approx -\rho$) reflects similar energy densities as inflaton-like or false vacuum states, linking this to early universe cosmology.

While speculative, these connections could suggest that black holes are not merely endpoints of stars, but also **probes of fundamental field structure** at the Planck scale.

11.4 Quantum Superfluid Analogy

Lastly, the behavior of the core through space suggests it may act like a **gravitational superfluid**:

- It exhibits *coherence*, *lack of friction*, and *persistent internal state*,
- Movement through spacetime is *smooth*, with no classical resistive forces,
- It may admit *quantized vortices* or internal oscillation modes, similar to quantum fluids.

This strengthens the case that the black hole interior is *not chaotic or violent*, but *ordered and quantum-regulated*—a radically different perspective from traditional views of singularity and horizon firewalls.

Conclusion

We have presented a horizonless model of black holes in which gravitational collapse culminates not in a singularity, but in a stable, ultra-dense quantum core surrounded by a vacuum-regulated shell. This structure replaces the classical event horizon with a semipermeable quantum interface that enables slow radiation and information release. By eliminating the singularity and event horizon, the model offers a resolution to the black hole information paradox, avoids the need for firewalls or remnants, and remains consistent with unitary quantum evolution and black hole thermodynamics.

The entropy scales with surface area and is attributed to the quantum degrees of freedom at the core–shell boundary, while radiation arises from quantum tunneling through the shell. Comparisons with alternative models—including gravastars, fuzzballs, and graviton condensates—highlight the conceptual and structural advantages of this approach, particularly its compatibility with observational constraints and its potential for falsifiable predictions.

Though some aspects remain speculative, such as the precise microphysics of the core and shell, the framework provides a physically coherent and thermodynamically consistent avenue for modeling black holes as quantum-coherent objects without horizons. Future work may further refine the shell's dynamics, explore potential observational signatures, and examine deeper connections to quantum gravity and field theory.

Appendix A: Mathematical Framework of the Core–Shell Structure

We provide a simplified mathematical formulation of the model to outline the dynamics of the quantum core and the vacuum shell.

A.1. Core Radius and Pressure Balance

The core radius R_c is slightly smaller than the Schwarzschild radius $R_s = 2GM/c^2$, with a small quantum correction ϵ such that:

$$R_c = R_s(1 - \epsilon), \quad \epsilon \ll 1$$

This ensures that the core lies just within the classical gravitational boundary but never forms an actual event horizon.

At this radius, **gravitational pressure** $P_G \sim GM^2/R_c^4$ is counterbalanced by **quantum pressure** P_Q, which arises from the uncertainty principle and/or condensate coherence:

$$P_Q \sim \frac{\hbar^2}{mR_c^5}$$

Equating $P_G \approx P_Q$ gives a characteristic mass-radius relation. This framework parallels the derivation of neutron star limits and white dwarf structure but in a relativistic, quantum-coherent regime [7].

A.2. Vacuum Shell Tunneling Rate

We model the vacuum shell as a quantum potential barrier with finite thickness ΔR and effective transmissivity κ, yielding a tunneling amplitude for quantum leakage:

$$\Gamma \propto e^{-2\int_{R_c}^{R_c+\Delta R}\sqrt{2m(V(r)-E)}\,dr}$$

In natural units where $\hbar = 1$, the exponent is dimensionless, and the tunneling amplitude $\kappa \sim e^{-2S}$ remains consistent with quantum mechanical expectations.

This forms the **quantum radiation source**. Unlike Hawking pair creation, the emission is controlled by the shell structure and vacuum energy gradient [8].

The energy flux is:

$$\frac{dE}{dt} \sim \kappa \cdot A \cdot T_{\text{eff}}^4$$

where $T_{\text{eff}} \sim \hbar/(4\pi R_c k_B)$ mimics Hawking temperature. This outward flux corresponds to a gradual loss of mass from the core, such that $\frac{dM}{dt} < 0$ over time.

This confirms that **Hawking-like radiation can occur without a horizon**, if regulated by a shell whose transmissivity scales similarly to gravitational surface gravity.

A.3. Limiting Case: Recovery of Gravastar and Schwarzschild Metrics

In the limits:

- $\epsilon \to 0$,
- $\kappa \to 0$,
- Shell becomes infinitely thin with $p = +\rho$,

we recover the original **gravastar limit** (de Sitter core + stiff shell + Schwarzschild exterior), as in Mazur and Mottola [2].

If instead the shell is fully transparent and the core emits freely, the system smoothly transitions to **slow Schwarzschild evaporation** in the semiclassical sense, without a horizon ever forming.

This demonstrates that **classical black hole behavior is an emergent limit** of this quantum-structured model.

Appendix B: Quantum Coherence, Information Storage, and Entropy

B.1. Core as a Macroscopic Quantum State

We model the core as a **macroscopic quantum-coherent object**, similar to a Bose–Einstein condensate or a gravitational superfluid. This implies that all constituent particles (or quanta) occupy the same ground state, resulting in:

- *Minimal entropy generation* within the core,

- *Phase coherence* across macroscopic distances,
- *Stability against classical collapse*, even under extreme pressure.

This mirrors the graviton condensate model proposed by Dvali and Gomez [4], where a black hole is composed of $N \sim M^2/M_{\rm Pl}^2$ soft gravitons. In this view, the entropy arises from the **collective quantum microstates** accessible to the system.

B.2. Information Encoding and Emission

Since there is **no event horizon**, quantum information is not irreversibly trapped. Instead, information is:

- **Stored** in the long-range entanglement structure of the quantum core,
- **Modulated** by coherent excitations and collective modes (similar to phonons or quantum vortices),
- **Gradually released** via shell-regulated radiation.

This aligns with *unitary evolution* as required by quantum mechanics, and the **Page curve** is preserved [22]: entropy in the emitted radiation increases until half the core's entropy is radiated, then decreases as the remaining information escapes.

The shell's structure allows for **phase-coherent emission**, meaning radiation may exhibit subtle **correlation patterns**, deviations from perfect thermality, or even **echo-like modulations** — potential observational signatures of coherence.

B.3. Entropy-Area Scaling Without an Event Horizon

Despite the absence of an event horizon, the entropy still scales with surface area:

$$S = \eta \frac{k_B A}{4G\hbar}, \quad \eta \approx 1$$

This can be derived by:

- Treating the shell as a thin layer of quantum modes (analogous to entanglement entropy across a boundary),
- Applying holographic entropy arguments,
- Or coarse-graining the degrees of freedom of the quantum field near the core boundary.

In the graviton BEC picture, this corresponds to:

$$S \sim N \sim \frac{M^2}{M_{\rm Pl}^2}$$

where the condensate stores entropy through collective excitations, not through thermal chaos.

B.4. Final Evaporation and Memory Release

As the black hole radiates:

- The mass M and core radius R_c slowly decrease,
- The transmissivity κ of the shell increases,
- Eventually, the core reaches a quantum-critical end state and **fully evaporates**.

The entire stored information is released by the end of the evaporation process. This avoids:

- A leftover Planck-scale remnant with arbitrarily high entropy [28],
- Violations of energy conservation or thermodynamic consistency,
- The need for non-local "teleportation" of information across spacetime.

This final phase resembles a **slow quantum leak**, not a violent explosion — aligning with predictions from models like soft hair, unitary evaporation, and semipermeable fuzzball surfaces.

Appendix C: Shell Transparency, Vacuum Regulation, and Radiation Timescale

C.1. Shell as a Quantum Barrier

The vacuum shell in this model is not a classical surface but a **quantum-regulated interface**. It acts similarly to a semi-transparent membrane in quantum mechanics—allowing probabilistic tunneling of energy and information [8].

Its physical properties include:

- **Finite thickness** ΔR,
- **Variable transmissivity** $\kappa \in [0, 1]$,
- A density and potential profile that **smoothly transitions** from the quantum core to asymptotic vacuum.

Unlike idealized thin shells in gravastar models, our shell's **gradient profile** prevents discontinuities in energy density and spacetime curvature, contributing to both **stability and radiation control**.

C.2. Radiation Rate Dependence on Shell Properties

We define an effective radiation timescale τ_{rad} for the core to evaporate as:

$$\tau_{\text{rad}} \sim \frac{G^2 M^3}{\hbar c^4} \cdot \frac{1}{\kappa}$$

This resembles the standard Hawking timescale, scaled by a dimensionless **transmission efficiency** κ.

- For $\kappa \sim 1$, evaporation proceeds at near-Hawking rates.
- For $\kappa \ll 1$, evaporation is slow and regulated — mimicking near-horizon suppression.

Thus, **radiation is not forbidden**, just attenuated, and can be tuned by quantum shell parameters. This aligns with predictions from graviton condensate models and fuzzy surfaces [4], but with clearer dynamical control.

C.3. Regulating Energy Exchange with the External Universe

The shell behaves as an **energy and entropy regulator**, meaning:

- **No instantaneous collapse** into a singularity,
- **No rapid burst** of information (unless forced),
- **Smooth, controlled evolution** even under accretion or decay.

Infalling matter may cause local perturbations, temporarily increasing shell transmissivity or modulating emission (analogous to "ringing" or delayed radiation signatures).

This quantum regulation ensures that black holes in this model can respond to environmental interactions **without breaking coherence** or unitarity.

C.4. Limiting Behavior and Final Phase

As the black hole shrinks:

- The shell becomes thinner and more transparent,
- Energy and information emission increases in intensity and structure,
- Evaporation completes smoothly when $M \to M_{\mathrm{Pl}}$, leaving no remnant [28].

This behavior avoids both **information paradoxes** and the **remnant problem**, while allowing testable late-stage behavior if small black holes exist.

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