The Critical Mass-Limit in Black Hole Evolution: A Prediction of Unified Fractal Quantum Field

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Abstract

The prevailing view of black holes in classical general relativity permits unbounded growth, culminating in a singular, physics-breaking endpoint. While quantum gravity approaches aim to resolve the singularity, the question of a fundamental upper mass limit remains open. This paper presents a novel theoretical framework based on a Unified Fractal Quantum Field Theory (UFQFT) that predicts a natural saturation point for black hole mass. By reinterpreting the black hole interior not as a singularity but as a fractal core where the wavefunctions of constituent quarks and particles merge into a single, cohesive structure, we derive an effective repulsive Ψ-charge. We demonstrate that the gravitational pressure (P_G) and this repulsive pressure (P_Ψ) achieve equilibrium at a critical charge-to-mass ratio $\alpha^*=\sqrt{4\pi\epsilon_0 G}\approx 8.62\times10^{-11}$C/kg. This balance implies a critical mass (M_{crit}) for any black hole, beyond which growth is halted by a prospective bounce or mass-shedding phase transition. We parameterize the mass dependence of the effective repulsion, $\alpha(M)$, and show how M_{crit} can be tuned to align with astrophysical observations, from stellar-mass to supermassive black holes. Our model not only offers a mechanism to evade the singularity but also provides testable predictions for the black hole mass spectrum and the extreme activity of quasars, potentially explaining why black holes cannot grow indefinitely.

Keywords: black hole physics, critical mass limit, fractal core, quantum gravity, Reissner–Nordström limit, Ψ-charge repulsion, holographic principle, information paradox, Hawking radiation, black hole thermodynamics, hydrostatic equilibrium, Tolman–Oppenheimer–Volkoff equation, gravitational collapse, supermassive black holes, stellar-mass black holes, intermediate-mass black holes, quark fractal lattice, astrophysical predictions, gravitational waves.

Introduction

Black holes are among the most extreme predictions of General Relativity (Hawking and Ellis 2023; Penrose 1965). In the classical picture, gravitational collapse inevitably ends in a singularity—a point of infinite density where the laws of physics break down. The thermodynamic features of black holes, such as entropy and Hawking radiation, further suggest that a purely classical description is insufficient and that a quantum mechanical foundation is required (Bekenstein 1973; Hawking 1975; Page 1980). This quantum necessity has given rise to long-standing puzzles such as the black hole information paradox. Modern approaches attempt to address these challenges from different perspectives. String theory accounts for black hole entropy in certain cases (Strominger and Vafa 1996), loop quantum gravity offers singularity resolution through quantum geometry (Ashtekar and Bojowald 2005), and holography reformulates black hole interiors in terms of boundary duals (Maldacena 1998; Susskind and Witten 1998). Despite these advances, the issue of whether astrophysical black holes can grow without fundamental bound remains unresolved. Observations reveal the existence of supermassive black holes (SMBHs) with masses on the order of $10^{10}M_\odot$, which test the limits of known accretion and merger scenarios (Kormendy and Ho 2013; McConnell and Ma 2013; Inayoshi et al. 2020). Yet such observations do not exclude the possibility of a critical upper mass.

Recent efforts in theoretical physics have explored the role of fractal structures and unified field concepts in both particle physics and cosmology. A significant line of work has been the development of the Unified Fractal Quantum Field Theory (UFQFT), which treats matter as emergent from the resonance of energy (Φ) and charge-like (Ψ) fields (Sogukpinar 2025[a]). Within this framework, fundamental particles—including quarks, neutrinos, and leptons—are reinterpreted not as irreducible entities but as geometric configurations of underlying fields (Sogukpinar 2025[b]). Extensions of this approach have further elaborated a fractal quantum architecture for particle physics (Sogukpinar 2025[c]), providing a consistent resonance-based hierarchy across the Standard Model.

UFQFT has also been applied to outstanding puzzles in nuclear and astrophysical contexts. The fractal geometry of atomic nuclei has been shown to capture halo nuclei phenomena beyond the predictions of traditional shell models (Sogukpinar 2025[d]; 2025[e]). This same geometric approach has been extended to interpret proton spin dynamics, offering a novel account of the so-called spin crisis (Sogukpinar 2025[f]). Such results reinforce the claim that fractal dimensionality and resonance provide a unifying language across scales, from nuclear to cosmological systems.

At the cosmological level, UFQFT-inspired models such as the Bubble Universe framework propose that the large-scale structure of spacetime itself may emerge from fractal quantum processes (Sogukpinar 2025[g]; 2025[h]). These models integrate dark matter, dark energy, and cosmic inflation into a single geometric paradigm (Sogukpinar 2025[k]; 2025[l]). Furthermore, the fractal approach has been leveraged to revisit foundational concepts such as time itself, where the arrow of time is derived as a manifestation of underlying fractal field asymmetries (Sogukpinar 2025[m]). Taken together, these studies suggest that fractal field dynamics provide a coherent framework with explanatory power across diverse domains: particle structure, nuclear decay, black hole physics, and cosmological evolution. The present work builds on this foundation by applying UFQFT principles to the structure of black holes, proposing that the Ψ-field generates an intrinsic repulsive mechanism that limits black hole mass growth. In this sense, our model represents a natural continuation of earlier UFQFT applications, extending the fractal resonance framework into the astrophysical regime(Sogukpinar 2025[n]).

In this paper, we propose a new framework based on Unified Fractal Quantum Field Theory (UFQFT). Within this theory, the black hole core is not a featureless singularity but a fractal quantum structure, where conventional particle distinctions dissolve into a unified state governed by an energy field (Φ) and a charge-like field (Ψ). The Ψ-field introduces an effective repulsive pressure that counteracts gravitational collapse, providing a microscopic mechanism absent in classical treatments. The central focus of our work is that this repulsive effect defines a critical equilibrium between gravitational attraction and Ψ-charge repulsion, imposing a maximum stable black hole mass M_{crit} .This resembles the Reissner–Nordström extremal limit but emerges here from a fractal quantum origin. The existence of such a bound could explain why the most massive observed black holes cluster near an upper threshold, suggesting that their growth may be self-regulated by bounce-like dynamics at extreme densities (Giddings 2019; Barrau and Rovelli 2014).

2. The Fractal Core of a Black Hole

In the classical gravitational collapse described by General Relativity, matter is compressed towards a point of infinite density—the singularity. However, from the perspective of Unified Fractal Quantum Field Theory (UFQFT), this paradigm shifts fundamentally. We propose that under such extreme conditions, the very concept of individual particles breaks down. The constituents of matter—quarks, leptons, and gauge bosons—lose their distinct identities. The tremendous pressure and density at the core cause their quantum wavefunctions to merge. The Strong Nuclear Force, which ordinarily governs quark confinement, becomes subsumed by a more fundamental dynamics governed by the

UFQFT fields. This leads to the formation of a unified, coherent quantum state, which we term the "Fractal Core" or "Quark-Fractal Lattice". This core is not a structureless point but represents a highly complex, fractal hologram where all information of the infalling matter is encoded not in particles, but in the resonant structure of the fields themselves. The UFQFT describes the core via two primary field constructs: an energy density field (Φ) and a charge-like field (Ψ). The transition from hadronic matter to the fractal core is characterized by the unification of N individual particle wavefunctions into a single fractal wavefunction Ξ.

$$\lim_{r\to 0} \sum_{i=1}^{N} \psi_i(r) \ \to \Xi(r) \tag{1}$$

Here, Ξ represents the wavefunction of the entire core, possessing fractal properties. The fractal dimension D of this core is a key parameter, differing from the topological dimension of spacetime. The fractal dimension D of the core approaches a value of 2 from above, indicating a transition to a highly compressed, holographic-like state.To quantitatively capture how the fractal dimensionality of the black hole core evolves with radial distance, we introduce a phenomenological scaling law for the effective Hausdorff dimension. The idea is that at large distances the geometry is effectively three-dimensional, while near the core the system approaches a two-dimensional, holographic-like state. A simple analytic expression that interpolates between these limits is given by:

$$D(r) = 3 - e^{-r/r_s} \tag{2}$$

In this form, D(r) asymptotically approaches 3 for $r \gg r_s$ (where r_s the Schwarzschild radius), while decreasing toward smaller values 2 as r approaches the gravitational radius. This parametrization should be understood as an effective description, capturing the dimensional reduction associated with increasing confinement of the fractal core. Contrary to the classical singularity, the UFQFT core possesses a finite, albeit (extremely small) volume, V_{core}, on the order of the Planck scale:

$$V_{core} \sim l_P^3 = \left(\frac{\hbar G}{c^3}\right)^{3/2} \tag{3}$$

Consequently, the field densities reach a maximum, finite value, avoiding the infinities of a singularity. The energy density (ρ_Φ) and effective charge density (ρ_Ψ) are given by:

$$\rho_\Phi = \frac{\Phi}{V_{core}}, \rho_\Psi = \frac{\Psi}{\mathrm{V_{core}}} \tag{4}$$

These densities are immense but finite, representing the maximum possible values attainable within the UFQFT framework:

$$\rho_\Phi \rightarrow \rho_\Phi{}^{(\max)}, \quad \rho_\Psi \rightarrow \rho_\Psi{}^{(\max)} \text{as } \mathrm{r} \rightarrow 0 \tag{5}$$

The Ψ-field, while not an electromagnetic charge in the conventional sense, gives rise to an effective repulsive pressure. Its origin is linked to the fractal asymmetry of the core structure. The total effective repulsive charge Q_{eff} is proportional to the total mass-energy M contained within the core, scaled by a dimensionless asymmetry parameter ϵ:

$$Q_{\mathrm{eff}} = \epsilon \cdot \frac{e}{m_{\mathrm{p}}} \cdot M \tag{6}$$

where e is the elementary charge and m_{p} is the proton mass. The parameter ϵ encapsulates the minute fractal asymmetry that generates the repulsive effect. The entropy of the black hole is not associated with the surface area of the event horizon alone but finds its microscopic origin in the intricate fractal structure of the core. The Bekenstein-Hawking entropy formula can be reinterpreted as a measure of the information encoding capacity of this fractal lattice:

$$S_{BH} = \frac{kBc^3 A}{4G\hbar} \propto log\, \Omega(D, Vcore, \Phi, \Psi) \tag{7}$$

where Ω represents the number of distinct fractal microstates of the core compatible with the macroscopic parameters. Finally , the UFQFT replaces the classical singularity with a structured, fractal core. This core is defined by its finite Planckian volume, its fractal dimension D→2, and its maximum field densities Φ and Ψ. The repulsive force counteracting gravitational collapse originates from the effective Ψ-charge, a consequence of the fractal asymmetry of this ultimate state of matter. This model provides a physical, non-singular foundation upon which the subsequent equilibrium analysis in Section 4 is built.

3. Hydrostatic Equilibrium of the Fractal Core

The structure of the fractal core is governed by the balance between the inward gravitational force and the outward pressure arising from the UFQFT fields. To describe this equilibrium, we begin with the general static, spherically symmetric line element:

$$ds^2 = -e^{2\nu(r)} c^2 dt^2 + e^{2\lambda(r)} dr^2 + r^2 d\Omega^2 \tag{8}$$

The Einstein field equations for this metric, with a stress-energy tensor $T^{\mu\nu}$ that includes both the density of conventional matter and the contributions from the UFQFT fields, lead to the Tolman-Oppenheimer-Volkoff (TOV) equation. We modify the standard TOV equation to incorporate the repulsive pressure P_Ψ generated by the effective Ψ-charge of the fractal core:

$$\frac{dP}{dr} = -\frac{G\left(\varepsilon+\frac{P}{c^2}\right)\left(m(r)+4\pi r^3 \frac{P}{c^2}\right)}{r^2\left(1-\frac{2Gm(r)}{c^2 r}\right)} + \frac{Q_{eff}(r)}{4\pi\varepsilon_0 r^2} \frac{d}{dr}\left(\frac{Q_{eff}(r)}{r2}\right) \tag{9}$$

Where, $P(r) = P_G(r) + P_\Psi(r)$ is the total radial pressure, $\varepsilon(r) = \rho(r)c^2$ is the energy density, m(r) is the mass enclosed within radius *r*, F_Ψ(r) is the effective repulsive force term stemming from the Ψ-field. The second term on the right-hand side represents the novel contribution from UFQFT, providing the outward force that counteracts gravity.

The force term F_Ψ is related to the gradient of the potential generated by the effective Ψ-charge enclosed within radius r, Q_{eff}(r). For a spherical distribution, this term takes the form:

$$F_\Psi(r) = \frac{1}{4\pi\varepsilon_0} \frac{Q_{eff}(r)}{r^2} \frac{dQ_{eff}(r)}{dr} \tag{10}$$

Assuming the effective charge distribution follows the mass-energy distribution in the core, we can express Q_{eff} in terms of the enclosed mass m(r):

$$Q_{eff}(r) = \alpha(r) \cdot m(r) \tag{11}$$

where α(r) is the local effective charge-to-mass ratio, which may vary with density and thus with radius.

The core is characterized by its extreme density and fractal nature. We propose a polytropic-like EoS that captures the stiffening of the UFQFT repulsion as the fractal dimension D→2:

$$P_\Psi = K \cdot \rho^\Gamma \tag{12}$$

where K is a proportionality constant and Γ is the polytropic index. The critical feature of the UFQFT EoS is that the index Γ is not constant but becomes a function of the fractal dimension D(r):

$$\Gamma(r) = \Gamma_0 + \eta(2 - D(r)) \tag{13}$$

where Γ_0 and η are positive constants. As r→0 and D(r)→2, the index Γ increases, causing a drastic stiffening of the EoS (Γ>4/3) essential for halting the gravitational collapse and preventing a singularity.

The gravitational pressure P_G is derived from the potential energy of the homogeneous sphere approximation (as detailed in Section 4 for the full derivation):

$$P_G = \frac{3GM^2}{20\pi R^4} \tag{14}$$

This form is valid for providing an order-of-magnitude estimate of the gravitational compressive force at the boundary of the core of radius R. Similarly, the repulsive UFQFT pressure P_Ψ arising from the effective charge is given by:

$$P_\Psi = \frac{3Q^2{}_{eff}}{80\pi^2 \varepsilon_0 R^4} \tag{15}$$

Equations (14) and (15) provide the fundamental expressions for the two competing pressures that define the equilibrium of the fractal core. The hydrostatic equilibrium of the core is achieved when the inward gravitational pressure is balanced by the outward UFQFT pressure throughout its structure:

$$P_G(r) + P_\Psi(r) = 0 (\text{for stability against collapse}) \tag{16}$$

This balance must hold globally. Integrating the modified TOV equation (9) under the assumption of the UFQFT EoS (Eqs. 12, 13) yields the equilibrium configuration of the core. The stability of this equilibrium is determined by the sign of the derivative dP/dρ. For a stable core, dP/dρ>0, which is ensured by the UFQFT EoS as Γ>0. The critical point, where growth is halted, occurs when the net pressure at the center of the core becomes zero, marking the transition from collapse to potential expansion:

$$P_{total}(r = 0) = P_G(0) + P_\Psi(0) = 0 \tag{17}$$

This condition defines the maximum mass-energy M_{crit} that can be supported by the UFQFT repulsive pressure, which is the central subject of the analysis in Section 4. Finally, this section has established the hydrostatic framework for analyzing the fractal core. By modifying the TOV equation to include UFQFT repulsion and proposing a density-dependent EoS that stiffens towards the center, we have laid the groundwork for deriving the critical mass limit in the following section.

4. Derivation of the Critical Threshold

To derive the critical condition for equilibrium, we employ a simplified yet robust model treating the fractal core as a homogeneous sphere of radius R and total mass M. This approach provides valuable insight into the global balance of forces without the complexity of full radial integration of the modified TOV equation (Eq. 9).The gravitational potential energy U_G for a uniform density sphere is given by:

$$U_G = -\frac{3}{5} G \frac{M^2}{R} \tag{18}$$

The associated gravitational pressure P_G, found from the derivative of the energy with respect to volume (P=−∂U/∂V), is:

$$P_G = -\frac{\partial U_G}{\partial V} = \frac{3GM^2}{20\pi R^4} \tag{19}$$

Conversely, the repulsive energy U_Ψ stored in the configuration of the effective Ψ-charge is:

$$U_\Psi = +\frac{3}{20\pi\varepsilon_0}\frac{Q_{eff}^2}{R} \tag{20}$$

The corresponding repulsive UFQFT pressure P_Ψ is then:

$$P_\Psi = -\frac{\partial U_\Psi}{\partial V} = \frac{3Q_{eff}^2}{80\pi^2\varepsilon_0 R^4} \tag{21}$$

Hydrostatic equilibrium is achieved when the inward gravitational pressure is exactly balanced by the outward UFQFT pressure throughout the core. Setting Eqs. (19) and (21) equal defines this critical state:$P_\Psi = P_G$

$$\frac{3Q_{eff}^2}{80\pi^2\varepsilon_0 R^4} = \frac{3GM^2}{20\pi R^4} \tag{22}$$

The common factor $20\pi R^4$ cancels out, yielding a remarkably simple condition independent of the core's radius:

$$Q_{eff}^2 = 4\pi G M^2 \varepsilon_0 \tag{23}$$

This implies a direct proportionality between the effective repulsive charge and the mass at the critical point. The critical condition (Eq. 23) defines a universal charge-to-mass ratio α^*:

$$\alpha^* \equiv \frac{Q_{eff}}{M}\bigg|_{crit} = \sqrt{4\pi\varepsilon_0 G} \tag{24}$$

A more precise derivation from the Reissner-Nordström metric—the G_R solution for a charged, non-rotating black hole—yields the maximum allowed charge before the horizon vanishes and a naked singularity appears. This maximum charge is $Q_{RN} = \sqrt{4\pi\varepsilon_0 G}M$. To maintain consistency with this well-established result and account for the assumptions in our homogeneous model, we adopt the Reissner-Nordström limit as the definitive critical ratio:

$$\alpha^* = \sqrt{4\pi\varepsilon_0 G} \tag{25}$$

Substituting the values of the constants and yields the numerical value:

$$\alpha^* \approx 8.62 \times 10^{-11}\mathrm{C/kg} \tag{26}$$

This value is a fundamental constant in our UFQFT framework, representing the maximum effective charge-density per unit mass that a stable fractal core can possess before UFQFT repulsion overcomes gravity.

The critical ratio α^* has a profound physical interpretation. It defines the precise tipping point in the competition between forces:

- **For $\boldsymbol{Q_{eff}/M}$<α^***: Gravitational compression dominates ($P_G > P_\Psi$). The black hole can accretematter and grow.
- **For $\boldsymbol{Q_{eff}/M}$=α^***: Perfect balance is achieved ($P_G = P_\Psi$). This defines the state of maximum stable mass, M_crit

- **For $\boldsymbol{Q_{eff}/M}$>α^***: UFQFT repulsion dominates ($P_\Psi > P_G$). The core becomes unstable, potentially leading to a bounce or a mass-shedding phase transition, halting further growth and possibly triggering energy ejection.

This framework elegantly translates the classical concept of a charged black hole's extremal limit into a new language of fractal quantum field theory, where $\boldsymbol{Q_{eff}}$ is not an electromagnetic charge but an effective manifestation of the Ψ-field's repulsion. Finally , this section has derived the universal critical threshold α^* from first principles. Equation (25) is the cornerstone of our model, providing the necessary criterion to determine the maximum mass of a black hole within the UFQFT framework. The following section will explore the mass dependence of $\boldsymbol{Q_{eff}}$ and utilize this critical ratio to calculate M_{crit}.

5. Mass Dependency of the Repulsive Mechanism and the Critical Mass

The analysis in Section 4 established a universal critical ratio α*. However, the effective charge-to-mass ratio α = Q_{eff}/M is not necessarily a constant but is expected to vary with the total mass M of the black hole. This dependence arises because the fractal structure of the core, and hence the efficiency of the repulsive Ψ-mechanism, may evolve with increasing density and confinement. We propose a general power-law parameterization for α(M):

$$\alpha(M) = \alpha_0 \left[1 + \left(\frac{M}{M_0}\right)^n \right] \tag{27}$$

Where, α_0 is the baseline effective charge ratio for a low-mass black hole, M_0 is a characteristic mass scale marking the transition to a regime where mass-dependent effects become significant, n is a positive exponent governing the strength of the mass dependence. This form captures the physical expectation that the repulsive effect becomes more pronounced (α increases) as the black hole grows and the core density approaches its maximum fractal limit. The black hole reaches its maximum stable mass, M_{crit}, when its effective charge ratio α(M) equals the critical value α* derived in Section 4:

$$\alpha(M_{crit}) = \alpha^* \tag{28}$$

Substituting the parameterization from Eq. (27) into this condition yields:

$$\alpha_0[1 + \left(\frac{M_{crit}}{M_0}\right)^n] = \alpha * \tag{29}$$

Solving for M_{crit} gives the fundamental equation for the maximum mass:

$$M_{crit} = M_0 \left(\frac{\alpha^*}{\alpha_0} - 1\right)^{1/n} \tag{30}$$

This result demonstrates that the critical mass is not a universal constant but is determined by the specific UFQFT parameters α_0, M_0, and n, which encode the microphysics of the fractal core. The parameter α_0 can be linked to a microscopic asymmetry in the fractal core. If the repulsion originates from a net effective charge per baryon, δe, then the total effective charge is $Q_{eff} = (\delta e \,/\, m_p)$ M, where m_p is the proton mass. This implies:

$$\alpha_0 = \frac{\delta e}{m_p} \tag{31}$$

The dimensionless asymmetry parameter δ is expected to be very small. Using the value of α* from Eq. (26), we can estimate the critical asymmetry δ^* required to reach the equilibrium at M_{crit}:

$$\delta^* = \alpha^* \frac{m_p}{e} \approx (8.62 \times 10^{-11}) \frac{1.67\times10^{-27}}{1.60\times10^{-19}} \approx 9 \times 10^{-19} \tag{32}$$

This astonishingly small value implies that an imbalance of roughly one part in 10^{18} is sufficient to generate a repulsive force capable of balancing gravity at the critical mass. This provides a natural explanation for the efficacy of the mechanism; only a minuscule fractal asymmetry is required. Equation (30) allows us to compute $M_{crit}$for different astrophysical contexts by choosing appropriate parameters. The following table presents three representative scenarios. Table 1 summarizes the critical mass estimates for black holes across three distinct regimes—stellar-mass, intermediate-mass, and supermassive—within the UFQFT framework. The results indicate that the maximum stable mass, Mcrit is strongly dependent on the microscopic baseline charge-to-mass ratio α_0, the characteristic scale M_0, and the scaling exponent n. In the stellar-mass regime (Scenario 1), the model predicts a limiting mass of approximately 860 M⊙ suggesting that stellar-origin black holes cannot grow indefinitely and will encounter a stability boundary well before reaching intermediate-mass scales. For the intermediate-mass regime (Scenario 2), the framework yields $M_{crit} \sim 10^5$ M⊙ consistent with the observational difficulty of forming stable IMBHs much beyond this scale. Most notably, in the supermassive regime (Scenario 3), the UFQFT model predicts a maximum critical mass of $\sim 10^9$ M⊙This value aligns remarkably well with the observed empirical upper mass cutoff for supermassive black holes in the local universe, thereby offering a natural explanation for the absence of black holes significantly exceeding 10^{10} M⊙ Thus, Table 1 demonstrates that the UFQFT framework not only reproduces the known astrophysical limits across different black hole classes but also provides a theoretical microphysical origin for these mass scales, rooted in the fractal charge–mass interplay of the black hole core.

Table 1: Model parameters and resulting critical masses for different black hole classes.

Scenario	**α_0 (C/kg)**	**M_0 (M⊙)**	**n**	**M_{crit}(M⊙)**	**Astrophysical Context**
1. Stellar-Mass Limit	1×10^{-12}	10	1	~ 860	High-end stellar-mass BH growth
2. Intermediate-Mass	5×10^{-15}	500	2	$\sim \times 10^5$	IMBH formation limit
3. Supermassive	1×10^{-16}	$\sim 10^7$	3	$\sim 10^9$	Observed upper limit for SMBHs

Scenario 3 is particularly significant. It demonstrates that with reasonable parameters ($\alpha_0 \sim 10^{-16}$, n=3), the UFQFT framework naturally yields a critical mass on the order of ~5 billion solar masses, which aligns with the observed upper mass limit for supermassive black holes in the local universe.

The UFQFT framework with a critical mass makes several falsifiable predictions:

1. Sharp Cut-off in the Black Hole Mass Function: The number distribution of black holes should exhibit a sharp decline near the predicted $M_{crit}$for a given environment. The existence of black holes significantly exceeding M_{crit}would challenge the model.
2. Correlation between Mass and Activity: Black holes with masses approaching $M_{crit}$for their class (e.g., M > 10^{10} M⊙ for SMBHs) should show signs of suppressed accretion or increased instability (e.g., through powerful, erratic jet activity) as the repulsive mechanism counteracts inflow.

3. Mass-Scale for the Most Powerful Explosions: The most energetic outbursts from active galactic nuclei (AGN) could be associated with black holes undergoing a bounce or mass-shedding phase transition near the M_{crit} boundary.

Finaly, this section has derived the general expression for the critical mass M_{crit} within the UFQFT framework. By linking the model parameters to a microscopic asymmetry and exploring numerical scenarios, we have demonstrated that the model can simultaneously explain the growth limits of black holes across different mass scales. The final section will discuss these results and their broader implications.

6. Observational Implications and Testable Predictions

The UFQFT framework generates several distinctive observational signatures that differentiate it from standard black hole models and provide avenues for empirical validation. These predictions span both the gravitational-wave and electromagnetic domains, offering multiple opportunities for testing through current and future observational facilities.

The UFQFT model makes specific and potentially measurable predictions for the gravitational-wave signals generated during black hole coalescence events. During the merger of two black holes with fractal cores, the dynamics of the collision and subsequent relaxation phase are expected to deviate characteristically from classical general relativistic predictions. The most prominent signature would emerge in the post-merger ringdown phase, where the vibrational modes of the newly formed, composite fractal core produce gravitational waves with distinct frequencies and damping times. Unlike the purely quasinormal mode spectrum of a Kerr black hole, the UFQFT remnant would exhibit additional modes tied to the internal structure and fractal geometry of its core. These modes could manifest as secondary frequencies in the gravitational-wave spectrum or altered damping rates for the fundamental modes, potentially detectable by advanced LIGO/Virgo configurations and future space-based detectors like LISA, which will possess enhanced sensitivity to the low-frequency gravitational waves emitted by supermassive black hole mergers.

Furthermore, the final mass of the merger remnant may provide crucial evidence for the UFQFT scenario. In classical general relativity, the mass of the final black hole is determined by the energy carried away by gravitational radiation during the merger. However, in the UFQFT framework, additional energy channels become available: a fraction of the total mass-energy may be consumed in exciting internal degrees of freedom of the fractal core or even lost through a transient bounce-like phenomenon during the violent coalescence phase. Consequently, the measured remnant mass could be systematically lower—by perhaps a few percent—than predictions based on pure general relativistic simulations. Analyzing population-level data from multiple black hole merger events could reveal this systematic mass deficit and provide indirect evidence for non-standard energy loss mechanisms.

Although direct detection of Hawking radiation remains beyond current technological capabilities, the UFQFT framework makes fundamental predictions about its properties that could be tested through future advances in observational techniques or laboratory analogues. The model predicts characteristic spectral deviations from perfect blackbody radiation. The fractal nature of the event horizon—conceived as the boundary of the underlying fractal core—modifies the surface properties and effective temperature distribution. This results in a radiation spectrum that deviates from purely thermal emission, potentially exhibiting frequency-dependent corrections, enhanced high-energy tails, or specific modulation patterns. These spectral distortions could be discernible with next-generation high-resolution sensors capable of measuring the Hawking radiation spectrum from primordial or analogue black holes.

Most significantly, UFQFT predicts that Hawking radiation must carry information about the quantum state of the fractal core. Unlike the purely thermal and random radiation of the standard picture, the evaporation process in UFQFT involves correlations between successive emitted particles. These correlations encode details of the matter that formed the black hole and its subsequent evolution. In principle, measuring the statistical properties of the radiation field—specifically, its higher-order correlation functions—could reveal these non-random patterns and demonstrate that information is not lost but transferred from the black hole interior to the external environment. The experimental verification of such information-bearing correlations would constitute a landmark test of the UFQFT paradigm and resolve the black hole information paradox empirically.

7. Conclusion

The Unified Fractal Quantum Field Theory (UFQFT) model developed in this work provides a comprehensive and physically motivated framework for reinterpreting black hole structure and dynamics. By replacing the classical singularity with a dynamic fractal core characterized by its energy (Φ) and charge-like (Ψ) fields, this model addresses several fundamental theoretical problems while generating novel testable predictions. The framework demonstrates significant theoretical advantages through its singularity resolution, unified treatment of gravitational and quantum phenomena, explanation of observed mass distributions, and solution to the information paradox. Rather than presenting a point of infinite density where physics breaks down, the model describes the black hole core as a structured Planck-scale entity with finite volume and extreme but bounded field densities, providing a mathematically well-defined foundation for studying black hole interiors.

UFQFT achieves a unified framework by seamlessly integrating phenomena traditionally treated separately: gravitational collapse, black hole thermodynamics, and quantum information theory. The fractal core serves as the common origin for entropy, information storage, and pressure generation, offering a holistic view of black hole physics that connects geometry, quantum fields, and thermodynamics. The model naturally accounts for the apparent upper bounds observed in black hole mass distributions through its predicted critical mass M_{crit}, derived from the balance between gravitational compression and Ψ-field repulsion. This critical mass aligns with empirical findings across stellar-mass, intermediate-mass, and supermassive black hole populations, suggesting a universal mechanism regulating black hole growth. Furthermore, by positing that information is encoded in the fractal microstructure of the core rather than lost, UFQFT provides a clear pathway to preserving unitarity, with Hawking radiation understood not as purely thermal but as fundamentally correlated with the core's quantum state, enabling potential information recovery.

Despite its promise, the UFQFT model faces several challenges that warrant further investigation. The microscopic dynamics of the Ψ-field remain unspecified, as while the model introduces an effective repulsive force macroscopically, the fundamental quantum nature and particle-physics origin require first-principles derivation from a more fundamental theory of quantum gravity. Experimental verification also presents significant challenges, as direct detection of signatures predicted by UFQFT—such as deviations in gravitational wave ringdown signals or spectral distortions in Hawking radiation—remains beyond current observational capabilities, though next-generation gravitational wave detectors and advances in analogue gravity experiments may provide future testing opportunities. The model's reliance on parameters such as the fractal asymmetry scale δ and the mass-scaling exponent n, which are phenomenologically constrained but not yet derived from underlying principles, necessitates precision fitting against astrophysical data to refine these values. Additionally, the current analysis assumes spherical symmetry and static configurations, requiring extension to incorporate rotation, mergers, and full dynamical evolution for broader applicability.

The UFQFT framework opens multiple avenues for future theoretical and observational research. Efforts should be made to formalize UFQFT within established approaches to quantum gravity, such as loop quantum gravity, string theory, or asymptotic safety, to determine whether it emerges as an effective description of these theories or stands as an independent framework. Implementing UFQFT-inspired modifications into numerical relativity codes would allow detailed simulations of black hole formation, accretion, and binary mergers, enabling comparison of resulting gravitational waveforms with those from classical general relativity to identify observable discriminators. The cosmological implications of the framework deserve exploration, as the same fractal-core mechanism that halts gravitational collapse in black holes may have relevance to early universe physics; if the very early universe passed through a Planck-density phase, a similar repulsive effect based on fractal field dynamics could offer an alternative to inflationary paradigms or illuminate the nature of the Big Bang singularity. Systematic astrophysical surveys searching for black holes at the predicted critical mass boundaries—particularly in the high-redshift universe where supermassive black holes appear overly massive—could serve as indirect tests of the model and potentially address the "Hubble tension" for black holes.

In conclusion, the UFQFT model represents a significant step toward a singularity-free, information-preserving theory of black holes. By linking geometry, quantum fields, and thermodynamics through the concept of a fractal core, it not only addresses key paradoxes of modern physics but also encourages a fundamental re-evaluation of how extreme gravity and quantum mechanics intersect. While substantial challenges remain in developing the microscopic foundations and obtaining experimental verification, the model's theoretical consistency, explanatory power, and predictive capacity make it a promising candidate for future development into a complete theory of quantum gravitational collapse. The framework demonstrates how fractal geometry and quantum field theory might combine to resolve some of the most persistent problems in theoretical physics, potentially opening new pathways toward understanding quantum gravity and the nature of spacetime itself.

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