Article

Not peer-reviewed version

Black Holes as Vacuum Phase Interfaces: Oscillation, Saturation, and Confinement

André Kamminga *

Posted Date: 13 February 2026

doi: 10.20944/preprints202512.0387.v2

Keywords: black holes; QCD; quark–gluon plasma; bounded vacuum; black-hole thermodynamics; event horizon; entropy; semiclassical gravity; effective interior models

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 February 2026 doi:10.20944/preprints202512.0387.v2

Article

Black Holes as Vacuum Phase Interfaces: Oscillation, Saturation, and Confinement

André J. H. Kamminga

Independent Researcher, The Netherlands; ajhkamminga@gmail.com

Abstract

We propose a phenomenological model for black-hole interiors in which the effective vacuum energy relevant at high densities is bounded by QCD-scale physics. The analysis is formulated as a sector-specific, late-time application of the Spectral Bounded Vacuum (SBV) framework, evaluated at the present epoch. The Spectral Bounded Vacuum description employed here is understood as a sector-specific, phenomenological realization of the more general Quantum Emergent Vacuum (QEV) framework developed in earlier work. In this setting, vacuum fluctuations that couple to gravitational collapse are restricted to a finite energy band associated with QCD confinement and deconfinement thermodynamics. We explore how such a QCD-bounded vacuum structure can modify the interior region of black holes, leading to finite-density interior configurations within the effective regime considered, while leaving the exterior spacetime well approximated by classical general relativity. The resulting interior is described as a thermodynamically stable quark–gluon plasma core whose energy density and temperature remain bounded by QCD physics rather than by Planck-scale effects. The analysis is qualitative and effective in nature. It does not aim to provide a microscopic origin theory for vacuum bounds, but instead focuses on the physical consequences of a spectrally bounded vacuum in the strong-interaction regime. Possible implications for black-hole thermodynamics and information storage are discussed.

Keywords: black holes; QCD; quark–gluon plasma; bounded vacuum; black-hole thermodynamics; event horizon; entropy; semiclassical gravity; effective interior models

1. Introduction

Black holes provide a unique theoretical laboratory in which gravity, quantum field theory, and thermodynamics intersect. While the exterior properties of black holes are well described by classical general relativity and semiclassical quantum effects, their interior structure remains far less understood. In particular, the fate of matter and vacuum degrees of freedom at extreme densities continues to raise fundamental questions, including the role of high-energy physics, the nature of singularities, and the interpretation of black-hole entropy.

Classical singularity theorems imply the breakdown of spacetime descriptions under gravitational collapse, but do not specify the physical mechanisms governing matter and vacuum behavior at ultra-high densities. At the same time, black-hole thermodynamics demonstrates that horizons behave as macroscopic thermodynamic systems, characterized by entropy, temperature, and energy exchange with the exterior universe. These observations suggest that black-hole interiors may admit effective descriptions rooted in known many-body physics, even in the absence of a complete theory of quantum gravity.

Quantum Chromodynamics (QCD) provides a particularly well-established framework for describing matter under extreme conditions. Experimental and theoretical studies of strongly interacting matter indicate that, above characteristic energy densities, QCD transitions to a deconfined quark–gluon plasma state with a rapidly growing density of states and entropy-dominated thermodynamic behavior. These properties motivate the hypothesis that, once QCD energy scales are reached during

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 February 2026 doi:10.20944/preprints202512.0387.v2

gravitational collapse or sustained accretion, the interior of a black hole may be regulated by QCD-scale physics rather than by Planck-scale effects.

In parallel, a series of earlier works introduced the Quantum Emergent Vacuum (QEV) framework, in which vacuum structure is treated as an effective, environment-dependent entity rather than a fixed background. Within this broader conceptual approach, the Spectral Bounded Vacuum (SBV) formulation provides an operational realization in which the vacuum modes relevant to a given physical sector are restricted to a finite spectral band. In the present work, the QEV framework serves as the conceptual foundation, while the SBV description constitutes its effective, sector-specific realization in the QCD-dominated regime relevant for black-hole interiors.

The purpose of this paper is to explore the consequences of applying the SBV/QCD framework to black-hole interiors at late times. We do not modify the Einstein field equations, nor do we introduce new horizon degrees of freedom or microscopic models of quantum gravity. Instead, we adopt a phenomenological approach in which the vacuum energy and thermodynamic response of the interior are regulated by known QCD physics. Within this setting, the interior region is described as a finite-density, high-entropy quark–gluon plasma core, while the exterior spacetime remains well approximated by classical general relativity.

This approach leads naturally to an interpretation of the black-hole horizon as an *effective vacuum phase interface*: a boundary separating regions governed by different effective physical descriptions without implying the existence of a physical membrane or additional dynamical structure. The framework emphasizes thermodynamic stability, saturation of interior variables, and consistency with black-hole entropy, while remaining agnostic about the microscopic origin of vacuum structure.

The paper is organized as follows. In Section 2 we introduce the Spectral Bounded Vacuum framework and its relation to QCD-scale physics. Section 3 develops the effective interior model and discusses characteristic scales. Sections 4–7 analyze the thermodynamic interpretation, stability, information flow, and limitations of the effective description. Speculative implications are briefly discussed in Section 8, and concluding remarks are given in Section 9.

2. Bounded Vacuum and the QCD Scale

In the Spectral Bounded Vacuum (SBV) framework (V3), vacuum "bounds" are treated as effective, late-time constraints on the subset of modes that remain physically relevant for propagation and stress–energy transport in a given environment. In the present paper we specialize this idea to the QCD-dominated regime inside black holes, where strong-interaction physics provides experimentally established scales that can act as natural regulators. Our goal is not to propose a fundamental ultraviolet completion, but to identify a physically motivated, sector-specific band structure that plausibly limits the interior energy density and temperature during gravitational collapse.

Sector-specific and local meaning of the bounds.

Throughout this work, the symbols E_{min} and E_{max} refer to an *effective QCD-sector band* defined in the local rest frame of the interior medium (a QGP-like state). These bounds are not identical to the infrared/ultraviolet bounds that appear in cosmological SBV applications. To avoid confusion, one may read the present notation as $E^{\mathrm{QCD}}_{\mathrm{min}}$ and $E^{\mathrm{QCD}}_{\mathrm{max}}$. The central claim is simply that in a QCD-dominated interior the physically active spectrum relevant to the effective stress–energy tensor does not extend arbitrarily, but is controlled by confinement and finite-temperature QCD thermodynamics.

2.1. Physical Bounds from QCD

The upper edge of the effective band is associated with QCD confinement. Colored excitations do not exist as asymptotic hadronic states below length scales of order the confinement distance,

$$\lambda_{\mathrm{QCD}} \sim 1\ \mathrm{fm}, \tag{1}$$

corresponding to the characteristic energy scale

$$E_{\mathrm{QCD}} \sim \frac{\hbar c}{\lambda_{\mathrm{QCD}}} \approx 200\ \mathrm{MeV}. \tag{2}$$

At finite temperature, lattice QCD and heavy-ion phenomenology indicate a crossover to deconfined quark–gluon matter at temperatures of order

$$T_c \approx 150\text{–}200\ \mathrm{MeV} \quad (\sim 2 \times 10^{12}\ \mathrm{K}), \tag{3}$$

with a strongly non-conformal equation of state in the transition region [2,4,5,8,24]. In this regime, additional energy density predominantly increases entropy and the number of active degrees of freedom rather than producing an unbounded rise in temperature. A convenient schematic representation of the hadronic growth of states is the Hagedorn-like form

$$\rho(E) \propto E^{-a}\, e^{E/T_H}, \tag{4}$$

which implies an effective limiting temperature $T \to T_H$ as E grows [6,9]. In the present phenomenological setting this motivates the identification

$$E_{\mathrm{max}} \simeq E_{\mathrm{QCD}}, \tag{5}$$

as the effective upper scale governing physically active QCD-sector vacuum excitations in the interior environment.

2.2. Finite QCD-Sector Vacuum Band and Effective Vacuum Density

In the QCD-sector SBV picture, the physically active modes relevant for the interior effective stress–energy tensor are restricted to a finite band,

$$E_{\mathrm{min}} \le E \le E_{\mathrm{max}} \simeq E_{\mathrm{QCD}}. \tag{6}$$

The lower edge E_{min} is introduced as an effective freeze-out threshold for hadronic degrees of freedom in the relevant high-density/high-temperature environment. Operationally, this is represented as a thermal threshold scale,

$$E_{\mathrm{min}} \sim k_B T_{\mathrm{freeze}}, \tag{7}$$

signaling that below this scale the contribution of hadronic modes to the effective vacuum response becomes dynamically irrelevant. Importantly, this E_{min} is *not* the cosmological infrared bound used in earlier low-energy applications; here it is a QCD-scale threshold and may be read as $E_{\mathrm{min}}^{\mathrm{QCD}}$.

Using the finite band defined in Equation (6), the effective vacuum energy density can be estimated as the associated vacuum energy density in this effective sector can be written schematically as

$$\rho_{\mathrm{vac}}^{(\mathrm{QCD})} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{QCD}}} g(E)\, E\, dE, \tag{8}$$

which is finite as long as the spectral density $g(E)$ is not singular at the endpoints. This contrasts with the conventional unbounded estimate

$$\rho_{\mathrm{vac}}^{(\mathrm{QFT})} \propto \int_0^\infty E^3\, dE, \tag{9}$$

which diverges quartically. The purpose of Equation (6) is not to impose an ad hoc cutoff, but to encode the physically realized fact that QCD confinement and finite-temperature thermodynamics restrict which excitations can propagate as independent degrees of freedom in a QCD-dominated medium. Figure 1

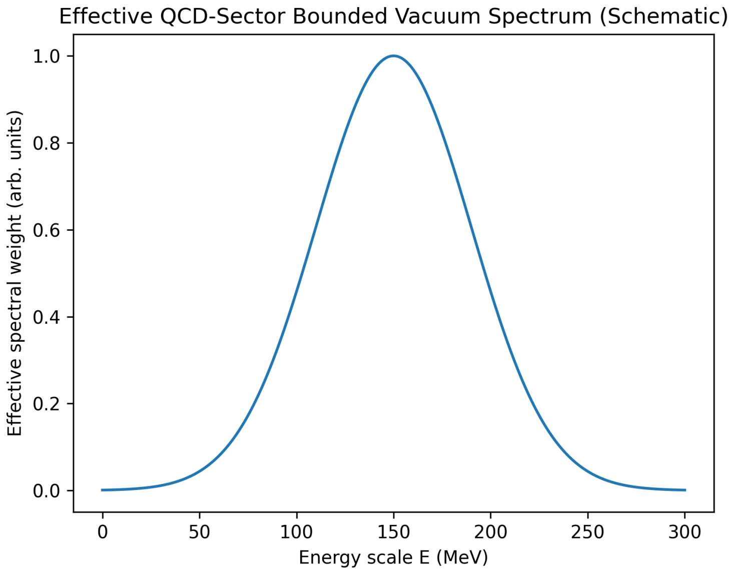

Figure 1. Schematic illustration of an effective, sector-specific vacuum spectrum relevant for QCD-dominated environments. The spectral weight is confined to a finite band associated with QCD-scale physics. The bounds shown are phenomenological and describe a late-time effective response within the Spectral Bounded Vacuum framework, not a fundamental microscopic cutoff.

No double counting of thermal and spectral effects.

Thermal considerations enter here as motivation for the effective equation of state and for the identification of the relevant QCD scales. We do not treat temperature as an additional, independent dynamical suppressor on top of the spectral restriction. This aligns with the baseline SBV logic (V3): the effective band is the primary coarse-grained input, while the thermodynamic behavior determines how the interior medium organizes energy into entropy and pressure.

2.3. *Application to Black-Hole Interiors*

If the interior of a black hole forms a quark–gluon core governed by QCD thermodynamics, then the core temperature and energy density are expected to remain controlled by QCD-scale physics rather than diverging. In particular, the existence of a crossover scale and the entropy-dominated behavior near the transition suggest an effective bound

$$T_{\text{core}} \lesssim T_H \sim 150\text{–}200\ \text{MeV}. \tag{10}$$

in the phenomenological sense that further energy influx increases entropy more efficiently than temperature [2,4,8,24]. This behavior naturally complements black-hole thermodynamics: if accreted energy predominantly feeds entropy, one may write schematically

$$dE \simeq T_H\, dS, \tag{11}$$

and the horizon area responds according to the Bekenstein–Hawking relation [3,10]

$$S_{\text{BH}} = \frac{k_B A}{4L_P^2}, \qquad dA = 4L_P^2\, dS. \tag{12}$$

In this way, the horizon grows while the interior thermodynamic variables remain controlled by QCD. This provides a concrete physical mechanism by which black holes can absorb energy without requiring divergent temperatures or curvature: the interior approaches a finite-density, high-entropy QCD phase, whose effective stress–energy contribution is bounded by the QCD-scale band structure introduced above.

doi:10.20944/preprints202512.0387.v2

3. Black-Hole Interiors in a QCD-Bounded Vacuum

In classical general relativity, the interior of a black hole formed by gravitational collapse is characterized by the development of a spacetime singularity, where curvature invariants diverge and the classical description ceases to be valid [11,22]. The existence of such singularities is often taken as an indication that new physics must intervene at sufficiently high densities. In this section we explore how a QCD-bounded vacuum, formulated within the Spectral Bounded Vacuum (SBV) framework, can qualitatively modify the interior structure of black holes without altering their exterior properties.

3.1. Gravitational Collapse and the QCD Regime

As matter collapses beyond the event horizon, local energy densities and temperatures increase rapidly. Once characteristic energy scales approach those of QCD, hadronic degrees of freedom are expected to dissolve into a deconfined quark–gluon plasma (QGP). Lattice QCD and heavy-ion experiments indicate that this transition occurs at temperatures of order $T_c \sim 150$–200 MeV, beyond which the system exhibits strong interactions and a large effective number of degrees of freedom [2,4,8,24]. In such a regime, the equation of state departs significantly from that of an ideal relativistic gas, and the increase of energy density is largely accommodated by entropy production rather than by a dramatic increase in temperature.

Within the SBV picture, this QCD transition has an important implication: the vacuum modes that remain dynamically relevant for propagation and stress–energy transport are restricted to the finite QCD-sector band discussed in Section 2. As collapse proceeds, additional gravitational energy does not activate arbitrarily high-frequency vacuum modes, but instead feeds into the internal degrees of freedom of the QGP core.

3.2. Formation of a Finite-Density Quark–Gluon Core

We therefore consider the interior of the black hole to approach a configuration in which a central region is occupied by a hot, dense quark–gluon plasma, surrounded by layers of increasingly dilute matter toward the horizon. The core temperature is expected to remain of order the Hagedorn or crossover scale,

$$T_{\text{core}} \lesssim 150\text{–}200\ \text{MeV}, \tag{13}$$

in the phenomenological sense that further energy input increases entropy and the number of accessible states rather than raising the temperature substantially [6,9].

The corresponding energy density is therefore large but finite, set by QCD-scale physics rather than by Planck-scale considerations. Figure 2

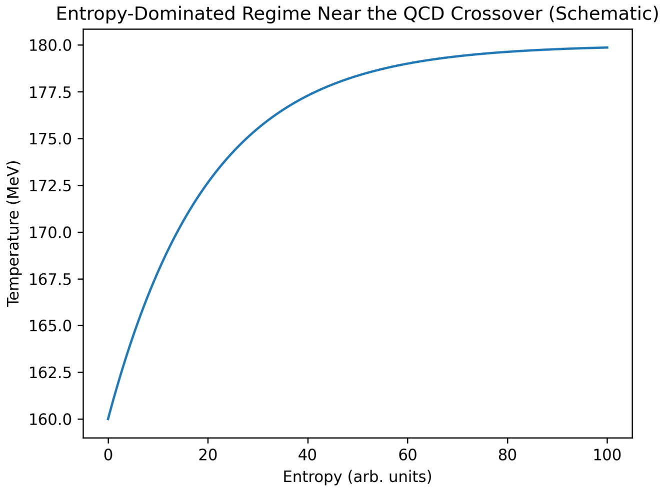

Figure 2. Qualitative behavior of temperature as a function of entropy in the QCD regime. Near the crossover or Hagedorn scale, additional energy input predominantly increases entropy rather than temperature. This thermodynamic behavior complements the effective spectral band structure and does not constitute an independent dynamical suppression.

In this picture, the effective stress–energy tensor inside the core is dominated by QCD matter and by the contribution of vacuum modes restricted to the finite band (6). Because both contributions are bounded, curvature invariants remain finite within the domain of applicability of the effective description. This does not constitute a proof that singularities are eliminated in all possible collapse scenarios, but it demonstrates the existence of physically consistent interior configurations in which the classical divergence is avoided. Figure 3 and Figure 4

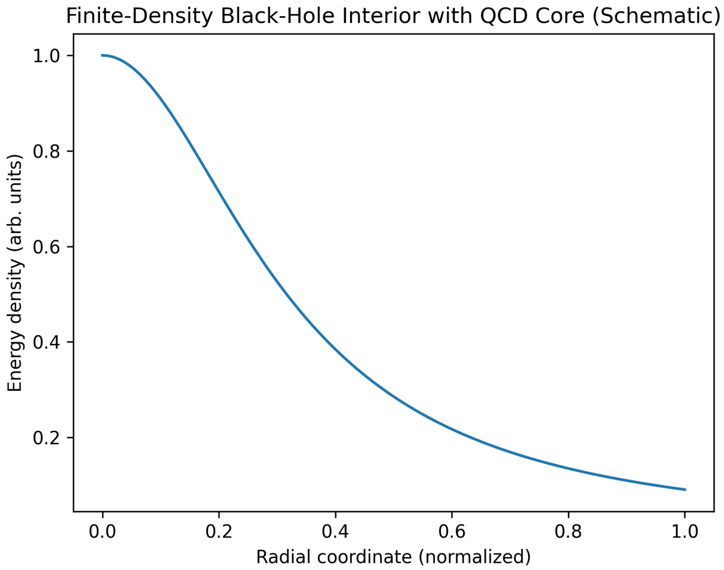

Figure 3. Schematic radial profile of a black-hole interior in a QCD-bounded vacuum scenario. A central high-density quark–gluon plasma core forms once QCD energy scales are reached. Within the effective SBV/QCD description, the interior energy density remains finite, while the exterior geometry is well approximated by classical general relativity.

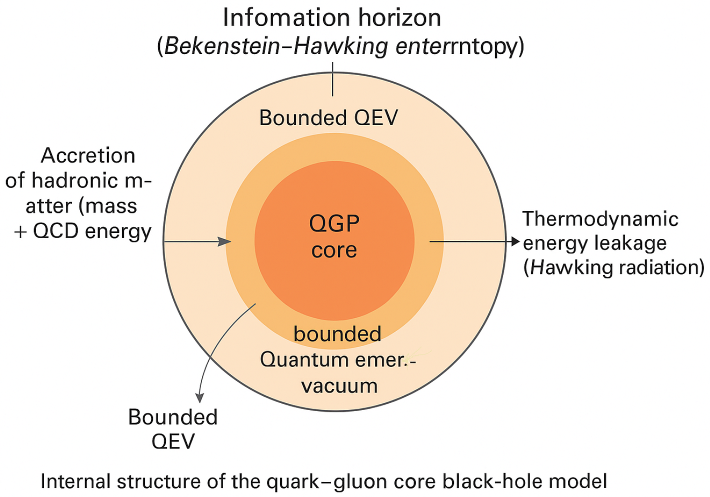

Figure 4. Schematic internal structure of the quark–gluon core black-hole model. A central quark–gluon plasma (QGP) core forms once QCD scales are reached during collapse. The surrounding region represents an effective, sector-specific bounded vacuum response in the QCD regime as described by the Spectral Bounded Vacuum (SBV) framework. Accretion feeds mass and internal QCD energy into the core, while energy leakage is represented phenomenologically by Hawking emission at the horizon. *Note:* the label "QEV" in the diagram refers to the same effective SBV/QCD sector framework used in this paper (v2) and is kept for continuity with earlier terminology.

3.3. Thermodynamics, Entropy, and Horizon Growth

A key feature of this scenario is the role of entropy. In the QCD regime, the density of states grows rapidly, and the system efficiently converts infalling energy into entropy. Schematically, one may write

$$dE \simeq T_{\text{core}}\, dS_{\text{core}}, \tag{14}$$

with T_{core} remaining approximately fixed near T_H. The growth of entropy inside the black hole is naturally accompanied by an increase in horizon area, in accordance with black-hole thermodynamics [3,10,25].

Using the Bekenstein–Hawking relation,

$$S_{\text{BH}} = \frac{k_B A}{4L_P^2}, \tag{15}$$

one finds that additional entropy generated in the interior is reflected in the growth of the horizon, while the interior temperature and curvature remain controlled by QCD-scale physics. Figure 5

This perspective offers a physically intuitive resolution of the tension between continued mass accretion and finite interior variables: the black hole grows primarily through entropy and horizon area, not through unbounded increases in temperature or energy density. The SBV/QCD framework thus complements the thermodynamic interpretation of gravity, in which spacetime dynamics is closely linked to entropy flow and information storage [12,21].

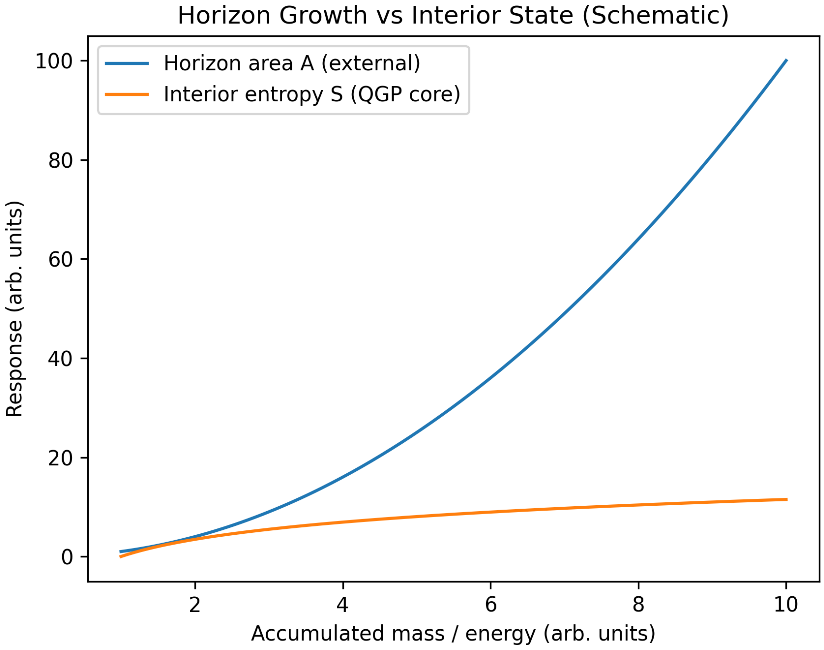

Figure 5. Schematic relation between interior thermodynamic response and horizon growth. As mass or energy is accreted, the black-hole horizon area increases according to black-hole thermodynamics, while the interior QCD-dominated core responds primarily through entropy production rather than unbounded increases in temperature or energy density. Within the effective SBV/QCD framework, horizon growth acts as the dominant macroscopic channel for accommodating additional energy.

3.4. Exterior Geometry and Observational Consistency

Importantly, the modifications described above are confined to the interior of the event horizon. Outside the horizon, spacetime is well described by classical general relativity, and standard results such as the Schwarzschild or Kerr solutions remain valid to excellent approximation. This ensures consistency with observational tests of gravity and with the successful description of astrophysical black holes.

From the exterior point of view, the black hole is characterized by its mass, angular momentum, and charge, while the detailed interior structure remains hidden. Nevertheless, the existence of a finite-density, high-entropy core may have implications for black-hole evaporation, information retention, and late-time dynamics, which will be discussed in Section 4. Figure 6

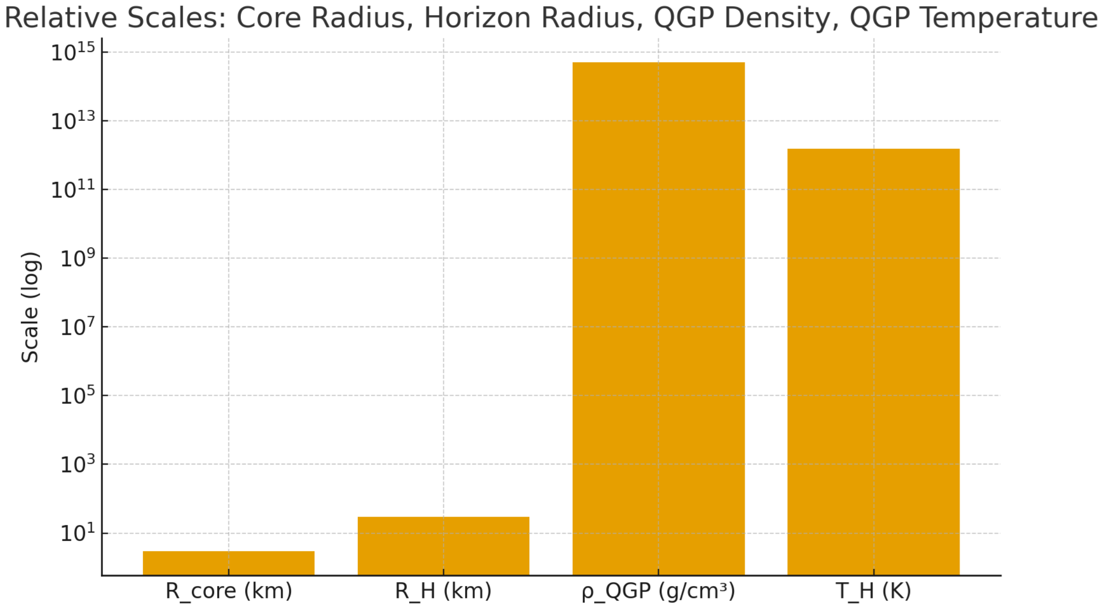

Figure 6. Logarithmic comparison of characteristic scales in the QCD-core interior scenario. Shown are (i) a representative core radius $R_{\rm core}$, (ii) the horizon radius R_H, (iii) the QGP energy density $\rho_{\rm QGP}$, and (iv) a characteristic QCD temperature scale T_H (crossover/Hagedorn scale). The figure emphasizes that interior densities and temperatures remain finite and are controlled by QCD-scale physics within the effective SBV/QCD description, while geometric radii remain macroscopic.

4. Black Holes as Effective Vacuum Phase Interfaces

In the preceding sections we have argued that, once QCD energy scales are reached during gravitational collapse or sustained accretion, the interior of a black hole can be described effectively as a finite-density, high-entropy quark–gluon plasma (QGP) core embedded in a spectrally bounded vacuum. In this section we introduce an interpretative framework that clarifies how such an interior description can coexist with a classical exterior spacetime without modifying the Einstein field equations.

4.1. The horizon as an Effective Interface

In classical general relativity, the event horizon is a global causal boundary rather than a physical surface [11,22]. This geometric interpretation is retained unchanged in the present work. However, when combined with black-hole thermodynamics, the horizon also plays an effective role as the interface through which energy, entropy, and information are exchanged between interior and exterior descriptions [3,10].

Within the Spectral Bounded Vacuum (SBV) framework [17], the interior region is characterized by a QCD-dominated equation of state and a sector-specific bounded vacuum response, while the exterior region remains accurately described by classical general relativity coupled to quantum fields in a standard vacuum state. The event horizon separates these regimes without introducing new dynamical boundary conditions. It is therefore natural to regard the horizon as an *effective vacuum phase interface*: a location where the relevant physical description changes, even though spacetime itself remains continuous.

This notion of an interface is purely phenomenological. It does not imply the existence of a physical membrane, additional horizon degrees of freedom, or a modification of the Einstein equations. Rather, it provides a conceptual framework for organizing the transition between a QCD-bounded interior and a classical exterior spacetime.

4.2. Energy Flow and Phase Separation

Accretion across the horizon injects mass and energy into the black hole. In the effective picture developed here, this energy is absorbed by the QGP core and redistributed into entropy through the large number of strongly interacting degrees of freedom available in finite-temperature QCD [2,4,8,24]. From the exterior point of view, the same process manifests as an increase in the horizon area, consistent with black-hole thermodynamics [3,10].

The language of an effective vacuum phase interface captures this separation of roles: macroscopic growth is encoded geometrically in the exterior solution, while microscopic energy redistribution occurs in the interior. No microscopic model of horizon dynamics is required for this description.

4.3. Compatibility with Black-Hole Thermodynamics

The interface interpretation is fully compatible with the thermodynamic view of gravity, in which spacetime dynamics is closely linked to entropy flow [12,21]. Horizon entropy acts as a bookkeeping device for the information accessible to an external observer, while the large interior entropy of the QGP core accounts for the multiplicity of microscopic interior configurations.

In this view, the SBV/QCD framework complements, rather than replaces, the standard thermodynamic interpretation of black holes.

5. Stability, Saturation, and Interior Response Modes

The presence of a QCD-dominated interior raises natural questions concerning stability and dynamical response under continued accretion. In this section we argue that the combination of a spectrally bounded vacuum response and an entropy-dominated equation of state leads to a stable and saturated interior configuration.

5.1. Thermodynamic Saturation

Finite-temperature QCD exhibits a rapid growth of the density of states near the crossover region, such that additional energy input predominantly increases entropy rather than temperature [2,4,6,9]. Within the SBV/QCD framework, this behavior implies that interior thermodynamic variables approach characteristic QCD scales and remain of that order even as the total mass of the black hole increases.

This saturation mechanism provides a physically motivated alternative to scenarios in which interior energy density or curvature diverges without bound.

5.2. Interior Response Modes

Perturbations induced by accretion events or mergers displace the interior state from equilibrium. The resulting response can be described phenomenologically as damped thermodynamic response modes associated with local adjustments in temperature, density, or composition. These modes are expected to be strongly dissipative due to the large interaction rates of strongly coupled QCD matter.

Crucially, these response modes are thermodynamic rather than geometric in nature. The present framework does not predict new spacetime oscillations, quasi-normal modes, or observable gravitational-wave signatures associated with interior dynamics.

5.3. Role of the Spectral Bound

The effective spectral bound inherent to the SBV framework further contributes to stability by preventing the excitation of arbitrarily high-frequency vacuum modes during perturbations [17]. In this way, both thermodynamics and spectral structure act together to stabilize the interior configuration.

6. Information Flow, Horizon Entropy, and Effective Confinement

Questions of energy flow in black holes are inseparable from issues of entropy and information. The present work does not attempt to resolve the black-hole information paradox. Instead, we examine how information flow can be consistently interpreted within the effective SBV/QCD framework.

6.1. Entropy as a Coarse-Grained Measure

The Bekenstein–Hawking entropy provides a quantitative measure of the information accessible to an exterior observer [3,10]. In the present framework, this entropy is interpreted as a coarse-grained bookkeeping device rather than as a literal count of microscopic horizon states.

As energy crosses the horizon, the interior QGP core converts this energy into entropy, while the horizon area grows accordingly. This parallel growth ensures consistency with black-hole thermodynamics without requiring a direct identification between interior and horizon microstates.

6.2. Effective Confinement of Information

Detailed information about the interior state remains inaccessible to external observers due to the causal structure of spacetime. Within the SBV/QCD framework, this is described as effective confinement: interior information influences the exterior only through aggregate quantities such as mass and angular momentum.

No assumptions are made regarding the microscopic storage or transport of information at the horizon. The framework remains agnostic about the underlying quantum-gravitational mechanism.

6.3. Hawking Radiation

Energy leakage via Hawking radiation is treated phenomenologically and assumed to proceed as in the standard semiclassical picture [10,25]. The existence of a QCD-dominated interior does not modify the leading-order properties of Hawking emission, which are determined by near-horizon quantum field theory in curved spacetime.

7. Limits of the Effective Description

The SBV/QCD framework is intentionally limited in scope. It provides a late-time, sector-specific effective description of black-hole interiors and does not claim fundamental completeness.

The framework applies to astrophysical black holes whose interiors reach QCD-scale conditions and for which strongly interacting matter dominates the interior equation of state. It does not address Planck-scale physics, the microscopic origin of vacuum structure, or the global resolution of spacetime singularities in all regimes.

No new observational signatures are predicted in gravitational-wave spectra or horizon fluctuations. Interior response modes are thermodynamic and dissipative and are not expected to couple directly to external observables.

Within its domain of applicability, however, the framework provides a physically grounded and internally consistent picture of black-hole interiors regulated by known QCD physics.

8. Outlook and Speculative Implications

The effective framework developed in this work provides a coherent description of black-hole interiors in which QCD-scale physics and a spectrally bounded vacuum response regulate thermodynamic behavior without modifying classical spacetime dynamics. While the preceding sections have focused on the validated domain of applicability of this framework, it is natural to ask whether similar ideas might have broader relevance. In this section we briefly outline a number of speculative directions, emphasizing that they lie beyond the established scope of the present analysis.

8.1. Possible Extensions beyond Astrophysical Black Holes

One possible extension concerns black holes formed in non-standard environments, such as those involving unusually high accretion rates or extreme initial conditions. In such cases, QCD-scale physics may still play a regulatory role, but additional effects could become relevant, including electroweak or beyond-Standard-Model degrees of freedom. The present SBV/QCD framework does not address these regimes, but it provides a template for how sector-specific physics might influence interior behavior in a controlled manner.

8.2. Analogies with Cosmological Phase Transitions

The interpretation of black holes as effective vacuum phase interfaces naturally invites analogies with phase transitions in cosmology. In particular, the conversion of infalling energy into entropy within a bounded interior resembles, at a qualitative level, the entropy production associated with early-universe transitions. These analogies should be understood strictly as heuristic. No claim is made that black-hole interiors reproduce cosmological initial conditions or that they constitute localized “Big-Bang-like” events in any literal sense.

8.3. Limitations of Speculative Interpretations

We stress that the ideas discussed in this section are not required for the internal consistency of the framework presented in this paper. They are offered solely as motivating perspectives for future work. Any attempt to elevate these analogies to quantitative models would require new physical input and, most likely, a deeper understanding of quantum gravity and vacuum structure.

8.4. Concluding Outlook

The central result of this work is the demonstration that QCD-scale physics, when combined with an effective spectral bound on vacuum response, provides a physically grounded and thermodynamically consistent description of black-hole interiors. Whether similar principles extend to other extreme environments remains an open question. The present analysis suggests that progress in understanding black holes may benefit from closer attention to experimentally established sectors of high-energy physics, even in regimes traditionally thought to require fundamentally new theories.

9. Conclusion

We have presented an effective description of black-hole interiors in which QCD-scale physics and a spectrally bounded vacuum response regulate thermodynamic behavior without modifying classical general relativity. Once QCD energy scales are reached, the interior can be described as a finite-density, high-entropy quark–gluon plasma core embedded in a sector-specific bounded vacuum.

Within the SBV framework, vacuum bounds arise as effective, late-time constraints on physically relevant modes rather than as fundamental cutoffs. Combined with the thermodynamic properties of QCD matter, this leads naturally to interior saturation, stability, and finite curvature, while continued mass accretion is accommodated through horizon growth in accordance with black-hole thermodynamics.

The framework is deliberately limited in scope and does not claim to resolve the black-hole information paradox or to provide a theory of quantum gravity. Its primary contribution is to demonstrate that known, experimentally grounded physics can play a nontrivial regulatory role in black-hole interiors. This perspective suggests that black holes may be understood not only through fundamentally new theories, but also through a careful reexamination of how established physical sectors behave under extreme gravitational conditions.

Appendix A. Technical Clarifications of the SBV/QCD Band

This appendix provides technical clarification of the effective spectral bounds employed in the main text. It is intended to support the phenomenological arguments presented in Sections 2 and 3 and does not introduce new physical assumptions or claims.

Appendix A.1. Meaning of the Spectral Bounds

Within the Spectral Bounded Vacuum (SBV) framework, spectral bounds are not interpreted as fundamental cutoffs imposed on quantum fields at the microscopic level. Instead, they represent effective, coarse-grained limits on the subset of vacuum modes that remain dynamically relevant for propagation and stress–energy transport in a given physical environment.

In the present work, the relevant environment is a QCD-dominated medium characterized by strong interactions and finite-temperature effects. The effective band,

$$E_{\min}^{\mathrm{QCD}} \leq E \leq E_{\max}^{\mathrm{QCD}} \simeq E_{\mathrm{QCD}}, \tag{A1}$$

should therefore be understood as sector-specific and local, defined with respect to the rest frame of the interior medium.

Appendix A.2. Relation to Confinement and Thermodynamics

The identification of the upper scale $E_{\max}^{\mathrm{QCD}}$ with a characteristic QCD energy reflects the fact that colored excitations do not exist as asymptotic states below the confinement length scale. At finite temperature, the rapid growth of the density of states near the QCD crossover further limits the physical relevance of higher-energy modes, as additional energy is efficiently redistributed into entropy rather than into independent propagating degrees of freedom.

The lower scale $E_{\min}^{\mathrm{QCD}}$ represents an effective freeze-out threshold below which contributions of hadronic modes to the interior vacuum response become dynamically negligible. This scale is introduced phenomenologically and should not be identified with cosmological infrared bounds used in other applications of the SBV framework.

Appendix A.3. Vacuum Energy Estimates

Given a finite effective band, schematic estimates of vacuum energy density take the form

$$\rho_{\mathrm{vac}}^{(\mathrm{QCD})} = \int_{E_{\min}^{\mathrm{QCD}}}^{E_{\max}^{\mathrm{QCD}}} g(E)\, E\, dE, \tag{A2}$$

where $g(E)$ denotes an effective spectral density. The finiteness of this expression follows directly from the bounded integration domain and does not depend on the detailed form of $g(E)$, provided it remains regular within the band.

These estimates are not intended as precise calculations of vacuum energy, but as illustrations of how physically motivated bounds eliminate the formal divergences that arise in unbounded mode sums.

Appendix A.4. No Modification of Quantum Field Theory

Finally, we emphasize that the introduction of effective spectral bounds does not imply a modification of quantum field theory at the fundamental level. Standard quantum field theory in curved spacetime is assumed to hold in the exterior region, and no claims are made regarding the microscopic behavior of fields at arbitrarily high energies. The SBV framework is a phenomenological tool designed to capture the physically realized response of the vacuum in specific environments.

References

1. J. Barbour, *The End of Time: The Next Revolution in Our Understanding of the Universe* (Oxford University Press, Oxford, 1999).
2. A. Bazavov *et al.*, “Equation of state in (2+1)-flavor QCD,” *Phys. Rev. D* **90**, 094503 (2014). doi:10.1103/PhysRevD.90.094503 arXiv:1407.6387 [hep-lat]
3. J. D. Bekenstein, “Black holes and entropy,” *Phys. Rev. D* **7**, 2333–2346 (1973). doi:10.1103/PhysRevD.7.2333

4. S. Borsanyi *et al.*, "Full result for the QCD equation of state with 2+1 flavors," *Phys. Lett. B* **730**, 99–104 (2014), arXiv:1309.5258 [hep-lat].
5. P. Braun-Munzinger and J. Stachel, "The quest for the quark-gluon plasma," *Nature* **448**, 302–309 (2007). doi:10.1038/nature06080
6. N. Cabibbo and G. Parisi, "Exponential Hadronic Spectrum and Quark Liberation," *Phys. Lett. B* **59**, 67–69 (1975).
7. B. J. Carr and S. W. Hawking, "Black holes in the early Universe," *Mon. Not. Roy. Astron. Soc.* **168**, 399–416 (1974).
8. M. Gyulassy and L. McLerran, "New forms of QCD matter discovered at RHIC," *Nucl. Phys. A* **750**, 30–63 (2005). doi:10.1016/j.nuclphysa.2004.10.034
9. R. Hagedorn, "Statistical Thermodynamics of Strong Interactions at High Energies," *Nuovo Cim. Suppl.* **3**, 147–186 (1965).
10. S. W. Hawking, "Particle creation by black holes," *Commun. Math. Phys.* **43**, 199–220 (1975). doi:10.1007/BF02345020
11. S. W. Hawking and G. F. R. Ellis, *The Large Scale Structure of Space-Time*, Cambridge University Press, Cambridge (1973).
12. T. Jacobson, "Thermodynamics of spacetime: The Einstein equation of state," *Phys. Rev. Lett.* **75**, 1260–1263 (1995). doi:10.1103/PhysRevLett.75.1260 arXiv:gr-qc/9504004
13. A. J. H. Kamminga, *"A New Vision of Black Holes"*, doi:10.20944/preprints202512.0387.v1, Preprints.org, 2025.
14. A. J. H. Kamminga, *"The Quantum Emergent Vacuum"*, doi:10.20944/preprints202511.1577.v3, Preprints.org, 2025.
15. A. J. H. Kamminga, *"Photonic Vacuum Windows"*, doi:10.20944/preprints202511.0290.v1, Preprints.org, 2025.
16. A. J. H. Kamminga, *"Vacuum Density and Cosmic Expansion"*, doi:10.20944/preprints202509.0972.v4, Preprints.org, 2025.
17. A. J. H. Kamminga, *"Vacuum Energy with Natural Bounds"*, doi:10.20944/preprints202507.0199.v3, Preprints.org, 2025.
18. P. F. Kolb and U. Heinz, "Hydrodynamic description of ultrarelativistic heavy-ion collisions," in *Quark-Gluon Plasma 3*, ed. R. C. Hwa and X.-N. Wang (World Scientific, Singapore, 2004), pp. 634–714. arXiv:nucl-th/0305084
19. J. M. Maldacena, "The large-N limit of superconformal field theories and supergravity," *Adv. Theor. Math. Phys.* **2**, 231–252 (1998), arXiv:hep-th/9711200.
20. J. Martin, "Everything You Always Wanted To Know About The Cosmological Constant Problem (But Were Afraid To Ask)," *C. R. Phys.* **13**, 566–665 (2012), arXiv:1205.3365 [astro-ph.CO].
21. T. Padmanabhan, "Thermodynamical aspects of gravity: New insights," *Rep. Prog. Phys.* **73**, 046901 (2010). doi:10.1088/0034-4885/73/4/046901 arXiv:0911.5004 [gr-qc]
22. R. Penrose, "Gravitational Collapse and Space-Time Singularities," *Phys. Rev. Lett.* **14**, 57–59 (1965).
23. C. Rovelli, "Time in quantum gravity: An hypothesis," *Phys. Rev. D* **43**, 442–456 (1991). doi:10.1103/PhysRevD.43.442
24. E. V. Shuryak, "What RHIC experiments and theory tell us about properties of quark-gluon plasma?" *Nucl. Phys. A* **750**, 64–83 (2005). doi:10.1016/j.nuclphysa.2004.10.022
25. W. G. Unruh, "Notes on black-hole evaporation," *Phys. Rev. D* **14**, 870–892 (1976). doi:10.1103/PhysRevD.14.870
26. E. P. Verlinde, "On the origin of gravity and the laws of Newton," *JHEP* **04**, 029 (2011). doi:10.1007/JHEP04(2011)029 arXiv:1001.0785 [hep-th]
27. J. F. Wang *et al.*, "A non-stellar Balmer break in a black-hole-dominated system at $z \sim 7$," arXiv:2501.13082 [astro-ph.GA] (2025).
28. S. Weinberg, "The Cosmological Constant Problem," *Rev. Mod. Phys.* **61**, 1–23 (1989).
29. S. Zhang, B. Liu, V. Bromm and F. Kühnel, "Primordial black holes as seeds for extremely overmassive AGN observed by JWST," arXiv:2512.14066 [astro-ph.GA] (2025).