

Communication

A Single-Scale Regular Black-Hole Background for Black-Hole Quantum Information

Lorenzo Albanese 

Institute of Bioeconomy, National Research Council of Italy, Via Madonna del Piano 10, 50019 Florence, Italy;
lorenzo.albanese@cnr.it

Abstract

Regular black-hole models replace the Schwarzschild singularity with a finite inner core, thereby removing the geometric endpoint at which the classical spacetime description breaks down. This issue is relevant to black-hole quantum information, since a singular interior prevents a regular effective description of interior degrees of freedom and horizon correlations. In this work, the regular black-hole geometry introduced by Dymnikova is used as a compact, single-scale effective background for black-hole quantum information considerations. The aim is not to propose a new regular metric but to clarify how an established finite-core geometry can support a nonsingular description of the Schwarzschild interior at the effective level. The geometry preserves the Schwarzschild asymptotic limit while replacing the divergent central region with a finite de Sitter-like core. The curvature invariants remain finite, and the effective source admits an anisotropic-fluid interpretation whose central limit is isotropic and vacuum-like. This use therefore provides a minimal geometric setting, rather than a newly proposed metric solution, for discussing nonsingular black-hole interiors. It does not establish unitary evaporation, information recovery, dynamical stability, or a microscopic quantum-gravity mechanism. Instead, it identifies a finite-curvature spacetime framework in which questions concerning interior quantum degrees of freedom and horizon entanglement can be formulated without encountering a curvature singularity.

Keywords: black-hole quantum information; Dymnikova black hole; regular black holes; Schwarzschild core; horizon entanglement; de Sitter core; mass inflation; quantum gravity phenomenology

1. Introduction

Black holes occupy a central position at the interface between gravity, quantum theory, and information. The black-hole information problem shows that the classical description of gravitational collapse is not only incomplete in the high-curvature regime, but also inadequate for describing the fate of quantum information, correlations and entanglement associated with matter and fields falling into the black hole [1–4]. In the Schwarzschild solution, this limitation is concentrated at the central singularity, where curvature invariants diverge and the classical spacetime description ceases to provide a regular background for quantum degrees of freedom.

The singularity theorems of Penrose and of Hawking and Penrose showed that, under broad and physically reasonable assumptions, gravitational collapse generically leads to geodesic incompleteness and hence to a breakdown of the classical spacetime description [5,6]. In the Schwarzschild solution, this breakdown appears as a curvature singularity



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at the center, where standard geometric invariants diverge and the predictive content of the classical theory is lost. The singular interior of a Schwarzschild black hole is therefore generally regarded not as a physically acceptable endpoint but as an indication that the classical metric must be modified in the high-curvature regime [7].

A natural way to address both the geometric singularity and its associated information-theoretic obstruction is to replace the central singularity with a regular core while preserving the successful large-distance behavior of the Schwarzschild geometry. This idea underlies the broad class of regular black-hole models, beginning with Bardeen's proposal [8] and subsequently developed in many different directions [9].

Representative examples include models with de Sitter-like cores [10,11], noncommutative-geometry-inspired constructions based on smeared matter distributions [12,13], regular black holes supported by nonlinear electrodynamics [14–16], and phenomenological regular metrics such as the Hayward model [17].

Although these approaches differ in technical structure and physical interpretation, they share a common feature: the central region is regularized so that curvature invariants remain finite, while the metric approaches the Schwarzschild form in the weak-field regime.

At the same time, it is well known that singularity resolution alone does not settle all the physical or information-theoretic issues associated with black-hole interiors. The effective source supporting a regular geometry often involves anisotropic stresses together with nontrivial violations or saturations of the standard energy conditions [18,19].

Moreover, many regular metrics possess an inner horizon whose stability is highly problematic because of the mass inflation mechanism first analyzed by Poisson and Israel [20,21], an issue that remains central in more recent analyses [22–24].

Regularity of curvature invariants is therefore a necessary condition for a nonsingular black-hole model but not a sufficient one for full physical viability.

Against this background, the present work addresses a restricted but quantum information-relevant issue: whether the Schwarzschild singularity can be replaced by a finite effective core within an established static and spherically symmetric regular geometry, thereby providing a regular background for discussing interior quantum degrees of freedom. The analysis builds on the regular black-hole geometry introduced by Dymnikova [10], using it as a minimal, single-scale setting in which the Schwarzschild singularity is replaced by a finite de Sitter-like core.

The aim is not to present this metric as a new solution, nor to construct a complete microscopic theory of black-hole evaporation, information recovery, or quantum gravity.

This point is relevant for quantum information-theoretic descriptions of black holes because correlations and entanglement require a regular setting to be meaningfully discussed. A curvature singularity obstructs such a description at the classical level, whereas a finite-curvature core provides an effective setting in which questions about interior quantum information can be formulated. The geometry considered below should therefore be understood as a simple regular background for black-hole quantum information analyses, not as a complete solution of the information paradox.

The main contribution of this work is therefore not the derivation of a new regular metric, but the use of an established single-scale regular geometry as an effective background for black-hole quantum information considerations. Within this scope, the finite-curvature behavior of the geometry is recalled explicitly, together with the effective-source interpretation in which the central region approaches an isotropic vacuum-like state. The quantum information relevance of this regular geometry is then discussed in relation to interior degrees of freedom, horizon entanglement, inner-horizon limitations, and possible remnant-like configurations.

2. Effective Density Profile, Mass Function, and Metric

The regular background used in this work builds on the regular black-hole geometry introduced by Dymnikova [10] and is based on the assumption that, below a characteristic scale r_c , the continuum description of spacetime should be regarded as effective rather than fundamental. Within this perspective, the regularized gravitational core is specified by three ingredients: an effective density profile, the associated mass function, and the corresponding metric function. The aim of adopting this geometry is to describe a regularized Schwarzschild interior in a minimal way, preserving the standard vacuum behavior at large distances while removing the central curvature divergence through a smooth delocalization of the source.

The total mass M is therefore not concentrated at a point but distributed according to the regular profile

$$\rho(r) = \frac{3M}{4\pi r_c^3} e^{-(r/r_c)^3} \quad (1)$$

where r is the radial coordinate and r_c sets the scale of the regular core. This profile has three essential properties: the central density $\rho(0)$ is finite, the total mass is normalized to M , and the distribution decays rapidly for $r \gg r_c$. In this way, short-distance corrections are represented effectively by a delocalization mechanism that prevents the source from remaining point-like at the center.

The enclosed mass within a sphere of radius r is then defined by

$$m(r) = 4\pi \int_0^r \rho(s) s^2 ds \quad (2)$$

Substituting Equation (1) gives

$$m(r) = M(1 - e^{-(r/r_c)^3}) \quad (3)$$

This mass function has the required behavior in the two relevant limits. For $r \rightarrow \infty$,

$$m(r) \rightarrow M \quad (4)$$

so that the total mass coincides with that of the Schwarzschild solution. For $r \rightarrow 0$,

$$m(r) \approx M \frac{r^3}{r_c^3} \quad (5)$$

showing that the enclosed mass grows proportionally to the volume near the center. This r^3 behavior is the basic mechanism responsible for regularizing the geometry and is precisely the behavior associated with a de Sitter-like core. More generally, the near-origin form of $m(r)$ is more important than the detailed functional form of the density profile itself: different smooth profiles lead to the same qualitative result provided they yield $m(r) \propto r^3$ near the center and approach the total mass sufficiently rapidly at large radius.

The associated effective geometry is described by the static and spherically symmetric line element

$$ds^2 = -f(r) dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2 \quad (6)$$

where $d\Omega^2$ is the metric on the unit 2-sphere. The metric function is taken in the Schwarzschild-like form

$$f(r) = 1 - \frac{2Gm(r)}{r} \quad (7)$$

with G denoting Newton's gravitational constant. Using Equation (3), one obtains

$$f(r) = 1 - \frac{2GM}{r}(1 - e^{-(r/r_c)^3}) \quad (8)$$

At large radius, the exponential term is suppressed and the metric reduces to the Schwarzschild form. Near the center, the regular behavior of $m(r)$ replaces the potentially singular $1/r$ contribution with a finite expression. The central geometry is therefore no longer governed by a divergent point source, but by a smooth core of characteristic scale r_c .

Equations (1), (3), and (8) define the essential content of the regular background considered here: the source is delocalized over the scale r_c , the effective mass grows regularly toward the origin, and the metric remains finite in the inner region while recovering Schwarzschild asymptotics at large distance. In the present manuscript, this established geometry is used as an effective setting for black-hole quantum information considerations, rather than being presented as a new metric solution.

3. Asymptotic Behavior and Curvature Regularity

The effective metric introduced above can now be analyzed in the two physically relevant regimes: the large-distance region, where the Schwarzschild behavior must be recovered, and the central region, where the regularization becomes dominant.

For $r \gg r_c$, the exponential term in Equation (8) is negligible, and the metric function reduces to

$$f(r) \approx 1 - \frac{2GM}{r} \quad (9)$$

The geometry therefore coincides asymptotically with the Schwarzschild solution, as required for consistency with the standard weak-field regime.

For $r \ll r_c$, the exponential term can be expanded as

$$e^{-(r/r_c)^3} \approx 1 - \frac{r^3}{r_c^3} \quad (10)$$

Substituting this expression into Equation (3) gives

$$m(r) \approx M \frac{r^3}{r_c^3} \quad (11)$$

and substituting Equation (11) into Equation (7) gives

$$f(r) \approx 1 - \frac{2GM}{r_c^3} r^2 \quad (12)$$

To leading order, this is of de Sitter form. Indeed, the standard metric function for a de Sitter core is

$$f_{dS}(r) = 1 - \frac{\Lambda_{eff}}{3} r^2 \quad (13)$$

so that the effective cosmological constant is identified as

$$\Lambda_{eff} = \frac{6GM}{r_c^3} \quad (14)$$

The central region is therefore replaced by a regular de Sitter-like core. This result is consistent with a broad class of regular black hole models, in which the singular Schwarzschild interior is replaced by a finite vacuum-like region with positive effective energy density [10,17,25].

This behavior implies that the curvature invariants remain finite at the origin. In particular, the Ricci scalar takes the finite value

$$R(0) = 4\Lambda_{eff} = \frac{24GM}{r_c^3} \quad (15)$$

while the Kretschmann scalar has the finite central limit

$$K(0) = \frac{8}{3}\Lambda_{eff}^2 = \frac{96G^2M^2}{r_c^6} \quad (16)$$

consistently with the bounded-curvature behavior expected in regular black hole geometries [26].

Within this regular background, the Schwarzschild singularity is thus replaced by a finite-curvature inner region controlled by the single scale r_c . In this way, the metric remains regular at the center while matching continuously to the Schwarzschild exterior at large radius.

4. Effective Anisotropic Fluid Interpretation

The effective source associated with the regular geometry considered here can be interpreted in terms of a static and spherically symmetric anisotropic fluid [27]. This interpretation is understood in the standard effective sense used in the regular black-hole literature: rather than postulating an ordinary microscopic fluid, one identifies the stress-energy tensor associated with the geometry. The corresponding effective source is then characterized by an energy density together with generally different radial and tangential pressures.

Starting from the mass function, the effective energy density is

$$\rho(r) = \frac{m'(r)}{4\pi r^2} = \frac{3M}{4\pi r_c^3} e^{-(r/r_c)^3} \quad (17)$$

where a prime denotes differentiation with respect to r . Within the Schwarzschild-like ansatz of Equations (6)–(8), the radial and tangential pressures satisfy

$$p_r(r) = -\rho(r) \quad (18)$$

and

$$p_t(r) = -\rho(r) - \frac{r}{2}\rho'(r) \quad (19)$$

From Equation (17), one finds

$$\rho'(r) = -\frac{3r^2}{r_c^3}\rho(r) \quad (20)$$

so that

$$p_t(r) = -\rho(r) + \frac{3}{2}\frac{r^3}{r_c^3}\rho(r) \quad (21)$$

In the limit $r \rightarrow 0$, it follows that

$$p_r(0) = p_t(0) = -\rho(0) \quad (22)$$

The regular core therefore approaches an effective vacuum with isotropic negative pressure at the center, consistently with the de Sitter-like behavior found above. In particular, the equality $p_r(0) = p_t(0)$ shows that the anisotropy disappears in the central limit. It is also useful to examine the strong energy condition.

The relevant combination is

$$\rho + p_r + 2p_t \quad (23)$$

Using Equation (18), this becomes

$$\rho + p_r + 2p_t = 2p_t \quad (24)$$

Taking the central limit of Equation (24) and using Equation (22), one obtains

$$\rho(0) + p_r(0) + 2p_t(0) = -2\rho(0) < 0 \quad (25)$$

since $\rho(0) > 0$. The strong energy condition is therefore violated at the center, and hence in a neighborhood of the core. This behavior is consistent with the regular black-hole literature, where violation of the strong energy condition is commonly associated with the removal of the central singularity [18,28].

5. Quantum Information Interpretation of the Regular Core

The replacement of the Schwarzschild singularity by a finite core can also be interpreted from the viewpoint of black-hole quantum information. In the classical Schwarzschild geometry, the singularity represents a terminal region at which the spacetime description breaks down. Consequently, within the classical Schwarzschild background, quantum degrees of freedom cannot be associated with a regular interior geometry all the way to the center. This obstruction is directly relevant to information-loss discussions, since the interior does not provide a regular geometric setting for describing quantum degrees of freedom once the singular boundary is reached [2–4].

In the regular geometry considered here, this obstruction is removed at the effective metric level. The divergent central region is replaced by a de Sitter-like core with finite curvature invariants controlled by the single scale r_c . As a result, the effective background no longer contains a curvature singularity as the terminal geometric endpoint of the interior. The finite-curvature core can therefore be used, at least phenomenologically, as a regular domain for discussing interior quantum degrees of freedom.

This observation is also relevant for horizon entanglement and for the structure of correlations between exterior Hawking modes and interior partner modes [1,4].

If the interior geometry ends at a singularity, the ultimate status of these correlations is tied to a region where the classical description loses validity. In a nonsingular geometry, by contrast, the background itself does not contain a curvature singularity at which such correlations would be forced to terminate. The present analysis does not specify a microscopic mechanism for information recovery, nor does it define a unitary evaporation dynamics.

It is important to emphasize that regularity alone does not imply information preservation. A complete resolution of the black-hole information problem would require a microscopic Hilbert space description, a unitary evaporation dynamics, and control over possible inner-horizon instabilities [2–4,20–24]. The contribution of the present analysis is more limited: it shows that the established single-scale regular geometry considered here can remove the singular geometric endpoint and thereby provide an effective setting in which quantum information-motivated questions about black-hole interiors can be formulated at the geometric level.

6. Discussion and Physical Limitations

From the quantum information viewpoint, the main limitation of the geometric background considered here is that it does not define a microscopic quantum dynamics or an evaporation process. Therefore, the analysis should not be interpreted as a solution of the

information paradox. Its role is instead preparatory: it replaces the singular interior by a finite-curvature region, thereby allowing information-theoretic questions that are ill-defined in the classical Schwarzschild geometry to be posed at the effective geometric level.

The regularity of the adopted metric and its asymptotic Schwarzschild behavior do not by themselves establish the full physical viability of the spacetime or its suitability for a complete quantum information description.

As widely emphasized in the regular black-hole literature, the removal of the central singularity does not automatically guarantee dynamical stability or provide a complete description of black-hole interiors [22,23]. In particular, many nonsingular black-hole geometries possess an inner horizon, and such a structure may be affected by significant instabilities, most notably the mass inflation mechanism originally analyzed by Poisson and Israel [20,21]. This issue remains central in more recent investigations [22–24].

The present analysis is formulated at the level of an effective metric and source profile and is therefore not intended as a complete dynamical model of collapse or as a fundamentally derived semiclassical solution. Within this scope, the geometry considered here provides a particularly economical realization of a regular de Sitter-like inner core controlled by a single short-distance scale.

A detailed classification of the horizon structure is not the main purpose of the present work, but the basic horizon condition can be stated explicitly. Depending on the relation between M and r_c , the geometry may admit non-extremal, extremal, or horizonless configurations. Horizons are determined by the positive zeros of the metric function, namely

$$f(r) = 1 - \frac{2GM}{r}(1 - e^{-(r/r_c)^3}) = 0 \quad (26)$$

Equivalently, by introducing the dimensionless variable $x = r/r_c$ and the compactness parameter $\alpha = 2GM/r_c$, the horizon equation for $x > 0$ becomes

$$x = \alpha(1 - e^{-x^3}) \quad (27)$$

Depending on α , this equation may admit two positive roots, corresponding to an outer and an inner horizon; a degenerate extremal horizon; or no positive root. This classification is relevant because the inner horizon, when present, is precisely the region where stability issues associated with mass inflation may arise.

This point is also important for the quantum information interpretation. If mass inflation or related inner-horizon instabilities develop, the finite-curvature core cannot automatically be assumed to provide a stable arena for long-lived interior quantum correlations. In particular, the possible survival of correlations between exterior Hawking modes and interior partner modes would depend on the dynamical behavior of the inner-horizon region, which is not determined by the static effective geometry alone. The present analysis should therefore be understood as identifying a nonsingular background on which such questions can be formulated, not as proving that quantum correlations are dynamically preserved throughout evaporation.

A brief thermodynamic comment is also useful in this context. In standard natural units, the Hawking temperature associated with a horizon r_h is proportional to the surface gravity and may be written as

$$T_H = \frac{|f'(r_h)|}{4\pi} \quad (28)$$

In an extremal configuration, where the inner and outer horizons merge, the horizon is degenerate and $f'(r_h) = 0$, corresponding to a zero-temperature limiting state. At the effective geometric level, this may be interpreted as a remnant-like configuration. However, such a possibility should not be understood as a demonstrated resolution of

the information problem. Whether a remnant-like endpoint can store, release, or preserve quantum information requires dynamical and microscopic input beyond the scope of the present analysis.

A further limitation is that the geometry considered here is not derived from a fundamental action, a specific matter Lagrangian, or a complete semiclassical treatment. Stronger claims concerning collapse dynamics, stability, or microscopic origin would therefore require additional physical input. These limitations, however, do not affect the main geometric result: within the adopted single-scale regular background, the classical Schwarzschild singularity is replaced by a finite-curvature inner region while the correct large-distance limit is preserved.

7. Conclusions

A single-scale effective regularization of the Schwarzschild core has been considered within an established regular black-hole geometry. The adopted geometry provides an analytically transparent interpolation between an asymptotically Schwarzschild exterior and a regular de Sitter-like central core. In this way, the Schwarzschild curvature singularity is removed while the correct large-distance vacuum limit is preserved.

The main geometric result is that a static and spherically symmetric spacetime can be regularized in an economical way, yielding finite curvature invariants together with an effective anisotropic-fluid interpretation of the supporting source. The central region approaches an isotropic vacuum-like state, while the strong energy condition is violated in the core, consistently with the general expectations for nonsingular black-hole geometries.

The regular background considered here is also relevant to black-hole quantum information studies in a limited but well-defined sense. It does not establish information recovery, unitary evaporation, or microscopic quantum dynamics. Rather, it provides a simple finite-curvature background in which such questions can be formulated without the obstruction of a singular Schwarzschild endpoint. The contribution of this work is therefore not the derivation of a new regular metric but the use of an established finite-core geometry as a controlled effective background for formulating black-hole quantum information questions. This places the analysis within the foundational and theoretical scope of black-hole quantum information studies.

Several limitations remain. The geometry considered here is formulated at the effective metric level and is not derived from a fundamental action, a specific matter Lagrangian, or a microscopic quantum-gravity model. Moreover, possible inner-horizon instabilities, including mass inflation effects, are not resolved by geometric regularity alone. The possible presence of outer, inner, extremal, or horizonless configurations also shows that the global causal structure remains relevant for the physical interpretation of the model. Similarly, a remnant-like extremal endpoint, if present, should be regarded only as an effective geometric possibility, not as a demonstrated mechanism for information recovery.

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