The astrophysical nature of black holes

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Abstract

Astrophysical black holes have been conventionally interpreted as objects that have already formed event horizons and singular interiors. I show that this interpretation is incompatible with causal structure when applied to black holes presently existing in the observable universe. Using only general relativity and the empirical fact that astrophysical black holes continue to merge and accrete, I prove that any merger or accretion event that is causally accessible to observation must occur while the collapsing object was larger than its associated horizon radius.

This result is consistent with, and reinforced by, the standard modelling of gravitational-wave signals, which identifies observed waveforms with the causal evolution of the exterior spacetime geometry and does not invoke completed horizons or interior dynamics. More generally, each merger or accretion event replaces the exterior spacetime to its causal future, rendering any prior analytic extension of the collapse geometry beyond that event physically unrealized. In a universe with ongoing structure formation, this continual updating of the causal future along a collapsing object's worldline prevents the realization of globally completed event horizons while the black hole's astrophysical evolution remains incomplete.

Present astrophysical black holes are therefore not settled Kerr objects with physically realized event horizons, but perpetually collapsing systems whose collapse remains asymptotic. As a consequence, no closed trapped surface is ever physically realized in the astrophysical domain, so that singularities are not avoided by new physics but rendered physically irrelevant by causal structure. Cosmic censorship is therefore unnecessary; semiclassical Hawking radiation does not arise in the absence of an event horizon, and the information–loss paradox does not apply to the present universe. These conclusions follow from causal structure, observational accessibility, and spacetime event invariance alone, and require no modification of general relativity: methodologically, the analysis treats the astrophysical black hole as an evolving worldtube of generating stress–energy, and identifies the physically realized spacetime with the exterior geometry determined by that worldtube's actual history, rather than by global extensions that suppress its interactions.

Keywords: causal structure, gravitational collapse, event horizons, black hole physics, classical general relativity

1 Introduction

In classical general relativity, astrophysical black holes are traditionally described as the end state of gravitational collapse, in which matter contracts through an event horizon and continues toward a spacetime singularity. The inevitability of collapse under broad conditions, specifically the formation of trapped surfaces, was established by Penrose [1]. Subsequently, Penrose noted that within the Kerr family of solutions [2], formally extending the spin parameter beyond the bound $|a| \leq M$ eliminates the event horizon and yields naked singularities [3]. These considerations motivated the cosmic censorship conjecture, according to which physically realistic gravitational collapse should not result in such horizonless end states.

In semiclassical gravity, Hawking [4, 5] showed that quantum fields evolving on such a spacetime produce thermal radiation at future null infinity, and subsequently argued that evaporation leads to an information paradox [6].

The causal structure relevant to these analyses is conveniently illustrated using idealized spherically symmetric collapse diagrams in Schwarzschild spacetime, which provide a schematic visualization of the causal ordering involved in black hole geometries (see Fig. 1). The Schwarzschild solution, and its generalization to the Kerr family, are exterior vacuum solutions of the Einstein equations. Their formal continuation into the stellar worldtube (shaded in Fig. 1) is purely mathematical and does not represent the physical spacetime of the collapsing matter, where the geometry is determined by nontrivial stress–energy. In the exterior vacuum region, the event horizon is defined as the null

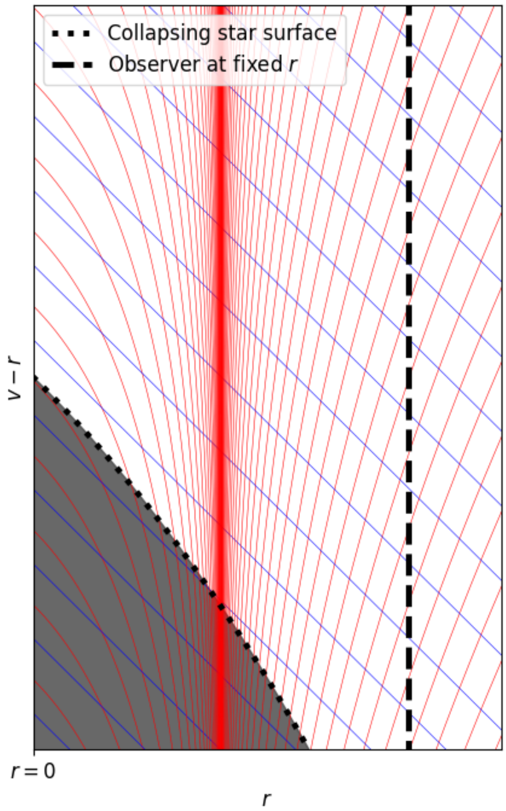

Figure 1. Spacetime diagram of gravitational collapse in ingoing Eddington–Finkelstein coordinates. The dotted curve denotes the worldtube of the collapsing stellar surface, and the dashed vertical line represents the worldline of a distant observer at fixed areal radius. Radial null directions shown with blue (ingoing) and red ("outgoing") lines illustrate the geometry's global causal structure; the greyed region indicates the formal continuation of the exterior vacuum Schwarzschild geometry into the region occupied by the collapsing star. This continuation does not describe the physical interior spacetime, which is matter-filled and governed by nonzero stress–energy.

hypersurface at which nominally "outgoing" null geodesics cease to increase in areal radius and instead propagate inward, marking the boundary beyond which all causal evolution is directed toward decreasing radius.

Recent gravitational-wave observations, beginning with the detection of GW150914 by LIGO in 2015 [7], have established the existence of a cosmic population of merging black holes whose masses and dynamics are consistent with relativistic compact-object coalescences. With the advent of the LIGO–Virgo–KAGRA (LVK) network, the catalog of confidently detected compact-binary mergers now extends beyond the initial observing runs, encompassing O1–O3 [8] and subsequent extensions into O4 [9]. Population analyses based on these catalogs show that the black-hole mass spectrum is structured rather than featureless, with statistically significant overdensities and a steeply declining high-mass tail broadly consistent with expectations from massive-star evolution and pair-instability physics. The local merger rate of stellar-mass binary black holes is $\sim 10\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ and increases with redshift on cosmological scales [9, 10]. The observed population is further characterized by low to moderate effective spins and a mixture of aligned and misaligned spin orientations, consistent with contributions from both isolated binary evolution and dynamical assembly channels [9, 10]. Together, these results provide a statistically robust characterization of the astrophysical black-hole population.

The interpretation of gravitational-wave observations relies on detailed modelling of binary black-hole mergers using numerical relativity [11–15]. In these calculations, Einstein's equations are evolved in a computational domain encompassing the strong-field exterior region, and gravitational radiation is extracted at large radius (and, in characteristic approaches, at future null infinity) using curvature- or gauge-invariant waveform diagnostics such as Ψ_4 or related gauge-invariant variables [16–18]. Accordingly, the waveforms used for comparison are constructed from the exterior spacetime's radiative degrees of freedom and propagated outward to represent what would be measured by distant observers (ideally at infinity) [19].

In practice, numerical relativity simulations do not require the interior region associated with a black-hole horizon to be resolved in order to obtain the correct exterior evolution. Depending on the formulation, simulations either excise regions bounded by apparent horizons, imposing inner boundary conditions to avoid singular behavior, or adopt puncture-based representations in which gauge and variable choices render the evolution regular and stable while accurately evolving the exterior spacetime [20–22]. The inspiral, merger, and ringdown waveforms are therefore modelled entirely as features of the evolving exterior spacetime and extracted from the wave zone, without invoking any physical assumptions about interior geometry or dynamics [23, 24]. This reflects the causal structure of black-hole spacetimes: no influence from within an event horizon can reach future null infinity, so the gravitational-wave signal measured by a distant detector is determined entirely by the region of the spacetime lying in its causal past [25, 26].

In what follows, we adopt a deliberately conservative stance: the physically relevant spacetime is taken to be the domain of dependence of the collapsing matter's worldtube and its interactions with the surrounding universe. The exterior geometry used to describe an astrophysical black hole is therefore treated as generated by the actual, evolving stress–energy distribution along its worldline, rather than by idealized analytic extensions of any particular instantaneous state.

Taken together, causal structure, observational accessibility, and the operational framework used to model gravitational-wave signals impose a sharp constraint on the physical status of astrophysical black holes in the present universe. In a spacetime that continues to evolve through mergers and accretion, objects that remain causally connected to observation cannot be treated as already-formed, dynamically closed event-horizon geometries. As demonstrated in Section 3.1, any merger or accretion event that is observable must occur at a stage when the participating bodies were still larger than their event horizons, and therefore prior to physical completion of horizon formation. The gravitational-wave signals we detect consequently probe interactions between ultra-compact, still-collapsing systems rather than collisions between completed black holes. The standard picture of astrophysical black holes as settled Kerr objects with physically realized event horizons and singularities must therefore be re-evaluated in light of causality and the conditions under which observations are actually made.

2 The present nature of astrophysical black holes

We define a *present astrophysical black hole* as a compact object formed through stellar-core collapse, hierarchical mergers, or sustained mass accretion that is currently embedded in the evolving universe and whose future includes interaction with its environment through the exchange of mass, angular momentum, or energy.

This definition includes the full astrophysical population: stellar-remnant black holes, merger products in dense environments, and supermassive black holes residing in galactic nuclei. It excludes only hypothetical objects existing in an arbitrarily isolated final state at asymptotically late cosmic times.

Although general relativity does not privilege any global notion of simultaneity, the analysis here is explicitly restricted to black holes existing in the empirically accessible universe, as described by standard cosmology. We therefore avoid coordinate-dependent notions of "present existence" based on extreme kinematic constructions and instead use "present" in the physically operational sense: objects whose interactions, radiation, or gravitational influence remain in principle observable.

This restriction is not philosophical but astrophysical. Every black hole currently observed exists within a universe that continues to form structure. Accretion from surrounding matter and mergers with other compact objects are not exceptional possibilities, but generic features of cosmic evolution. The present analysis therefore concerns black holes whose future evolution is neither dynamically closed nor causally isolated.

With this definition in place, the standard picture—according to which astrophysical black holes in the present universe have already formed event horizons and singular interiors—may be evaluated against causal accessibility and invariant features of spacetime geometry.

Throughout this evaluation, a present astrophysical black hole is understood as an evolving worldtube of matter and fields embedded in the cosmological background, together with the exterior spacetime lying in its domain of dependence. The question is therefore not whether an idealized, globally completed spacetime admits an event horizon, but whether such a horizon is generated by the realized history of this worldtube in the physically realized universe.

3 Causal structure, worldlines, and the physical domain of black holes

Classical collapse analyses, most prominently that of Oppenheimer and Snyder [27], emphasized the familiar two-picture structure: in proper time the collapsing matter becomes singular after a finite interval, while for a distant static observer the surface asymptotically approaches its horizon radius without ever crossing it. That framework treats collapse as an isolated process and interprets the resulting spacetime in terms of foliation-dependent descriptions of the same global solution.

The present analysis addresses a different question. Rather than contrasting local proper-time evolution with an external asymptotic slicing, we ask which regions of the analytic collapse geometry are ever *physically realized* in a universe where mergers and accretion continually update the matter worldtube and the external spacetime lying in the domain of dependence of that evolving worldtube. The focus is not on competing observer descriptions, but on the domain of dependence of the evolving worldtube in an astrophysical setting.

3.1 Causal localization of merger radiation

Let q denote a gravitational-wave detection event on an observer's worldline. The detected signal must have propagated to q along a past-directed null geodesic γ.

By construction, in any smooth collapse geometry relevant to astrophysics γ intersects the worldtube of the collapsing object at a unique event p, which is the earliest causally admissible point along γ at which the exterior vacuum geometry gives a valid physical description.

Because no event on or inside an event horizon lies in the past light cone of any external observer, any point of the worldtube that can lie on γ must have occurred *prior to* the horizon-formation event. Thus the intersection event p necessarily belongs to the pre-horizon phase of the collapsing worldtube, with the object's physical radius satisfying $r(p) > r_h$, where r_h is the associated horizon radius of the idealized exterior solution. The physical state of the collapsing object at p is the state that is causally accessible to the observation.

There are only two logical possibilities for the emission event associated with the detected signal:

(A) The signal is emitted at p itself, an event on the still-collapsing object's worldtube.

(B) The signal is emitted at some event X further along the same null ray γ, lying at larger r and later time than p.

In either case, the emission event must lie in the causal past of q. We now examine whether case (B) can support an interpretation of mergers as interactions between already-completed black holes.

Suppose the collapsing object crosses its event horizon at an event h on its worldline, with h lying to the future of p. Then h is necessarily spacelike separated from X. Any event involving horizon formation or later evolution of the black hole occurs outside the past light cone of X. Therefore, no physical process occurring *after* p along the collapsing worldline—including horizon formation or subsequent evolution of the black hole—can causally influence X.

If one nevertheless claims that the signal detected at q was emitted by a completed black hole and not an event p on the still-collapsing worldtube, then one is asserting that X depends on physical conditions at events that do not lie in its causal past. This requires superluminal causal influence and violates locality. Thus case (B) cannot be used to attribute the detected signal to an object that has already collapsed beneath its event horizon.

The remaining possibility is (A): the signal originated on the collapsing object's worldtube at the event p itself. Since p lies on the pre-horizon segment of the worldtube, the emission must have occurred at a stage when the object's physical radius satisfied $r(p) > r_h$.

This conclusion is coordinate-invariant and independent of any global foliation. It follows strictly from: (a) the null structure of spacetime, (b) the causal ordering of events, and (c) locality of physical influence.

Applied to binary coalescences: the gravitational-wave burst we detect from a merger corresponds to strong-field dynamics occurring at the merger event itself. Because that event lies on the relevant worldtubes in our past light cone, each participating object must still satisfy $r > r_h$ at the moment of collision. Therefore every gravitational-wave detection associated with a compact-object merger necessarily informs of a collision between two ultra-compact, still-collapsing bodies. No detected merger can ever involve objects that had already formed event horizons at the time of collision.

In fact, we have established the more general result: **every merger or accretion event that is causally accessible and in principle observable from the external universe must occur at a pre-horizon segment of the collapsing worldtube.**

Having established this causal localization of the emission event, it is instructive to compare the result with how gravitational-wave signals are modelled and identified in practice. In numerical relativity, merger waveforms are not attributed to processes occurring at or beyond event horizons, nor are they constructed by evolving completed black-hole interiors. Instead, the signal is associated with the causal evolution of the exterior spacetime geometry and is extracted from regions that lie entirely within the domain of dependence of the detector. The intersection event p identified above therefore lies within the portion of the spacetime used both to generate the waveform in the models and to support causal propagation to observation.

Consequently, the physical configuration probed by a detected merger signal is not a collision between already-formed black holes understood as causally closed objects, but a dynamical interaction between ultra-compact bodies whose exterior geometry has not yet settled into an isolated-horizon state. More generally, the spacetime region relevant for observation is the exterior domain of dependence of the collapsing worldtubes and their interactions. It is this realized domain, generated by the actual history of the sources, that we identify as the astrophysical black hole, rather than any globally completed extension of an earlier, artificially isolated state. The familiar language of "black-hole mergers" thus functions as a shorthand for the exterior spacetime dynamics inferred from the signal, rather than as a literal description of interactions between completed event-horizon geometries with physically realized singularities. What emerges instead is a single, consistent physical picture of the interaction event, in which basic causal structure, the empirical properties of observed gravitational-wave signals, and the theoretical frameworks used to model those signals all refer to the same dynamical process involving ultra-compact, still-collapsing bodies, rather than to interactions between causally closed, completed black holes.

3.2 Failure of globally completed horizons in a dynamical universe

We now examine the global consequence of the result established in Section 3.1 when the collapsing source is dynamically embedded in a universe containing further interactions.

In textbook treatments, gravitational collapse is idealized as producing a globally completed spacetime containing an event horizon that persists indefinitely. The standard Penrose diagram depicts a single asymptotic exterior region attached to an interior ending at a singular boundary. Subsequent modelling of accretion and mergers is then performed on top of this fixed background, with the horizon treated as a permanent geometric structure.

This idealization implicitly presupposes that no future interaction ever alters the collapsing object's worldline or the causal future of the spacetime. That assumption is violated for every astrophysical black hole in the observed universe.

Consider any collapsing object that later undergoes a merger or sustained accretion. At the spacetime event p of interaction, the exterior geometry to the future of the outgoing null hypersurface generated at p must be replaced by a new solution corresponding to the combined mass, energy, and angular momentum of the system. The pre-interaction exterior solution cannot be physically extended beyond that hypersurface.

This structure is illustrated in Fig. 2. The outgoing null surface $\mathcal{N}_p$ partitions the spacetime into two distinct domains: a realized exterior geometry up to the interaction event, and a future exterior determined by the merger product. Any extension of the pre-merger solution beyond $\mathcal{N}_p$ (shaded in the figure) belongs to a counterfactual spacetime in which the interaction never occurred.

The essential point is that the event horizon is a *global structure*: its location depends on the entire future development of the spacetime. A merger or accretion event is not future boundary data but part of the spacetime's dynamical evolution. Each such interaction alters the future null structure and therefore changes the global horizon definition itself.

It follows that any horizon defined prior to an interaction cannot be the event horizon of the physically realized spacetime. It is instead the horizon of an auxiliary solution that implicitly—and incorrectly—assumes no further interactions occur.

Treating such counterfactual extensions as physically instantiated is no more legitimate than treating the interior of a still-collapsing star as described by the mathematical continuation of its exterior vacuum solution. In both cases, a formally admissible extension is mistaken for a realized physical geometry despite the presence of physical structure—i.e. nontrivial stress–energy, nontrivial interaction—that invalidates it.

Because real astrophysical black holes are observed to merge and accrete, and are expected to continue doing so far into the cosmic future, no object in the present universe possesses a globally completed event horizon as a physical spacetime structure. Each interaction event replaces the exterior geometry to its causal future, requiring the spacetime to be re-extended accordingly. The horizon associated with the prior exterior is not preserved as a global structure.

The standard picture therefore misidentifies contingent global constructions as inevitable physical entities. *Each interaction event updates both the collapsing object's worldline and the causal future of the spacetime.*

In a universe with ongoing structure formation, mergers, and accretion, the collapsing object's worldtube is never completed and therefore cannot be physically extended as an inevitable outcome without imposing unrealized future boundary conditions. Future event horizons are not completed

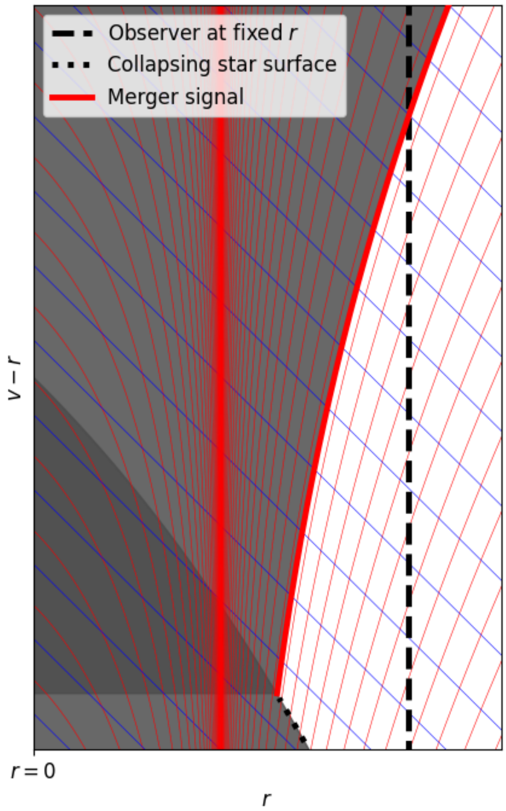

Figure 2. Spacetime diagram of collapse with a merger event at p. An outgoing null ray from p reaches a distant observer at q, defining the null hypersurface $\mathcal{N}_p$. The exterior geometry beyond $\mathcal{N}_p$ is determined by the merger product. Shaded regions indicate extensions of the pre-merger solution that are not part of the physically realized spacetime.

within any finite astrophysical evolution; they remain formal boundary constructs belonging to counterfactual spacetimes and are physically well-defined only in the artificial case of collapse in perfect isolation.

Present astrophysical black holes are therefore not settled Kerr geometries with physically instantiated horizons and singularities, but evolving, still-collapsing matter distributions whose worldlines and exterior spacetime geometries dynamically update before physical horizon formation occurs, for as long as the black hole interacts with its environment.

Ontologically, this means that the physically realized spacetime is generated by the entire evolving worldline of the collapsing source and its interactions, while the globally completed horizons of textbook diagrams belong only to counterfactual extensions that ignore those interactions and therefore do not describe the black hole that actually exists in the universe.

3.3 The asymptotic nature of collapse

Sections 3.1 and 3.2 imply that the formation of a completed event horizon is not a physical process that occurs within the realized spacetime of the external universe, but a boundary structure defined only in an idealized global extension.

This can be stated geometrically. Let $r(\tau)$ denote the areal radius of the collapsing surface as a function of proper time τ along the worldtube. In any exterior solution admitting an event horizon, the horizon radius r_h is defined only with respect to the total future null structure of the spacetime. Because mergers and accretion repeatedly alter that structure, r_h is not fixed by any local collapse process.

Instead, each interaction replaces the exterior geometry before $r(\tau)$ can reach the corresponding horizon radius of that geometry. As illustrated in Fig. 2, the exterior spacetime is redefined across each outgoing null surface $\mathcal{N}_p$, such that the longer the universe evolves, the more frequently auxiliary completions required to define a horizon are invalidated.

Thus collapse in a realistic universe does not terminate at a finite spacetime event but continues indefinitely through a sequence of asymptotically defined exterior solutions.

The surface therefore evolves according to

$$r(\tau) \to r_h(\tau)$$

in the sense of repeated approximation, not attainment. Horizon formation occurs only in the counterfactual limit in which no further interactions take place, in a future that lies beyond observationally grounded astrophysics.

This eliminates any notion of event-horizon formation as a dynamical transition analogous to phase change or instability. No locally definable operation, measurement, or invariant distinguishes the moment "of horizon crossing" in the external geometry, because no such moment exists in the physically instantiated spacetime.

Rather, the event horizon is a null boundary that may be constructed only after the entire future of the spacetime is fixed. In a universe with ongoing structure formation, the future is never fixed at any finite time. Accordingly, event horizons remain purely asymptotic objects belonging to auxiliary completions of the metric, not to realized evolutionary histories.

The gravitational collapse observed in the universe therefore does not produce black holes as completed spacetime objects with physically realized curvature singularities bounded by event horizons, but rather astrophysical black holes: perpetually collapsing ultra-compact bodies whose radii asymptotically approach geometrically defined thresholds that are never physically attained.

Consequently, one may not reasonably conclude that any present astrophysical black hole harbors either a real event horizon or a singularity. Those can appear only as asymptotic or cosmological limits, not as operationally meaningful structures in the present universe.

3.4 Exterior spacetime is generated by pre-horizon collapse

The results of the previous sections may seem surprising only if one tacitly assumes that, once an event horizon forms in an analytic extension, the exterior spacetime thereafter becomes physically grounded in the completed black hole itself. That assumption is widespread in intuition and language, but it is not supported by the causal geometry of gravitational collapse.

To see this, it is useful to return to the structure illustrated in Fig. 1. In ingoing Eddington–Finkelstein coordinates, the exterior spacetime is foliated by ingoing and outgoing null congruences. Every outgoing null generator that reaches future null infinity originates on the worldtube of the collapsing matter prior to the putative event-horizon formation event. There is no outgoing null generator of the physically relevant exterior spacetime that emerges from, intersects, or is causally grounded in a region that lies on or within an already-formed event horizon.

In other words, every null ray that constructs the exterior geometry accessible to observation, and that determines the causal past of any asymptotic observer, terminates not on a completed black hole, but on the *pre-horizon collapsing surface*. The exterior causal structure is therefore generated by the still-collapsing object. Nowhere in the physically realized spacetime does the completed horizon or interior singularity become the generator of the exterior domain of dependence.

This fact is independent of any choice of foliation or coordinate slicing. It reflects an invariant structural feature: the entirety of the exterior geometry that ever participates in causal interaction with the universe traces back to worldtube events that occur strictly prior to horizon completion in any analytic extension.

Thus, the familiar interpretive image in which a black hole "forms," after which the exterior belongs to a completed Kerr solution grounded in a physically realized horizon, does not correspond to what causal structure actually provides. Even in the idealized textbook case, where collapse is treated in isolation of its astrophysical surroundings, the exterior spacetime is always only generated by the pre-horizon phase of the collapsing matter worldtube.

This observation reinforces the conclusions of Sections 3.1–3.3. If the realized exterior geometry is always causally anchored to the pre-horizon collapsing worldtube, then it is neither surprising nor optional that every observable interaction occurs while $r > r_h$, that prior analytic extensions are invalidated by subsequent evolution, and that horizon formation never becomes a physically instantiated transition in the external universe. The exterior spacetime is never "handed over" to a completed event-horizon object. It remains forever generated by an evolving worldtube whose collapse is never completed in the realized universe.

3.5 Absence of Hawking radiation

The semiclassical derivation of Hawking radiation assumes a spacetime containing a globally completed event horizon separating an exterior region from a causally disconnected interior. Quantum field modes are evolved on this fixed background and traced across the horizon, leading to particle creation through a nontrivial Bogoliubov transformation between asymptotic field configurations.

That construction requires three conditions:

1. a globally defined horizon,
2. a completed causal structure joining $\mathcal{I}^-$ to $\mathcal{I}^+$,
3. the permanent loss of causal contact between exterior and interior degrees of freedom.

None of these conditions is met for present astrophysical black holes.

From Sections 3.1–3.4, no merger or accretion event ever occurs inside a completed horizon, and no globally defined horizon is realized in a universe undergoing continued structure formation. Every astrophysical black hole remains in a perpetual pre-horizon collapse phase in which the exterior metric is repeatedly replaced before any horizon can form as a physical boundary.

As a result, the quantum field is defined on a single connected spacetime domain with no permanently inaccessible region. Field modes are never lost behind a horizon, and no mode splitting occurs between causally disconnected sections of the geometry.

Therefore the Bogoliubov transformation between inequivalent asymptotic vacua that produces thermal radiation does not arise. The mathematical horizon that appears in auxiliary idealizations does not belong to the physical spacetime in which the quantum field evolves, and therefore cannot define inequivalent in- and out-vacua. Only a regular exterior metric is ever realized, and the vacuum state remains globally well defined.

No astrophysical spacetime contains the conditions required for horizon-induced radiation. The phenomenon arises only in spacetimes that contain a completed event horizon, which do not occur in a universe with ongoing accretion and mergers.

This conclusion is independent of any ultraviolet completion of gravity. It relies only on causal structure and does not assume modifications to quantum theory or general relativity.

Local particle production mechanisms unrelated to horizons (e.g., strong-field vacuum polarization) are not excluded. The result applies specifically to horizon-induced radiation associated with globally completed black hole geometries, which do not exist in a universe with ongoing astrophysical evolution.

3.6 Absence of the information–loss paradox

Approaches framed within an Oppenheimer–Snyder–style two-picture ontology—including analyses that attempt to recover information using radiation defined with respect to the asymptotic observer's foliation—presuppose that the global collapse spacetime with a completed event horizon is a physically realized structure, even if its causal significance is modified by quantum effects. In such frameworks, one may hope that phenomena such as pre-horizon or "pre-Hawking" radiation reorganize the flow of information so that the apparent loss associated with the classical event horizon does not arise [28].

The results of Sections 3.1–3.5 negate that premise altogether. In a universe where mergers and accretion continually update the collapsing worldtube and replace the exterior geometry that ever becomes causally realized, the globally completed horizon required for those analyses never exists. The very spacetime object that these approaches analyze—a globally completed collapse geometry with a physically realized event horizon—is never instantiated in the actual universe.

The information–loss paradox arises only if a completed event horizon forms and subsequently evaporates, forcing quantum evolution to be defined on a spacetime that contains a permanently inaccessible interior region. From Sections 3.1–3.5, no astrophysical black hole in the present universe ever attains such a horizon, and no evaporation process occurs. The spacetime remains globally connected, with no hidden sector to trace over and no obstruction to unitary evolution.

Accordingly, because the spacetime never becomes causally partitioned, the domain of quantum evolution always admits a global Cauchy surface, and no quantum information is discarded. The paradox does not arise for any astrophysical black hole embedded in a dynamical universe.

This conclusion does not depend on singularity resolution, quantum gravity, or speculative microphysics. It follows directly from causal structure and the absence of physically realized event horizons.

4 Conclusion

We have shown that astrophysical black holes presently existing in the observable universe cannot be consistently interpreted as objects that have already formed event horizons.

Using only general relativity and the empirical fact that black holes continue to merge and accrete, we proved that every merger or accretion event that is causally accessible to observation must occur while the collapsing matter remains outside its associated horizon radius. No interaction observable from the external universe can therefore involve a completed event-horizon geometry.

This causal constraint is reinforced by the operational framework used to model and interpret gravitational-wave observations. In numerical relativity, detected merger signals are identified with the causal evolution of the exterior spacetime geometry and are constructed entirely from regions that remain in the domain of dependence of the detector. Completed horizons and interior regions play no operational role in the generation or identification of the observed signal. Gravitational-wave observations thus probe interactions between ultra-compact, still-collapsing systems rather than collisions between dynamically closed black holes.

More generally, event horizons are global structures whose definition depends on the full future development of spacetime. In a universe with ongoing mergers and accretion, each interaction replaces the exterior spacetime to its causal future, invalidating any prior analytic extension of the collapse geometry beyond that event. Horizons defined prior to such interactions therefore belong to auxiliary spacetimes in which all future interactions are artificially suppressed, rather than to the physically realized spacetime.

As a result, gravitational collapse in the observed universe is necessarily asymptotic. Astrophysical black holes are not globally settled Kerr geometries with physically realized horizons and singular interiors, but perpetually collapsing systems whose exterior spacetimes are repeatedly replaced before any horizon can form as a physical boundary. The appropriate object of astrophysical black-hole physics is therefore not a timeless Kerr manifold with a completed event horizon, but the evolving worldtube of collapsing matter and fields, together with the exterior region it generates in its domain of dependence.

This reflects not merely an astrophysical contingency, but a structural feature of relativistic causal geometry: the exterior spacetime that ever becomes physically realized is generated entirely by the pre-horizon phase of collapse, and is never causally anchored to a completed horizon or singular interior. Once this worldline-first perspective is adopted, the familiar global extensions with completed horizons are revealed as auxiliary mathematical constructions that do not correspond to the physically instantiated spacetime of the present universe.

It follows that semiclassical Hawking radiation does not arise for any astrophysical black hole whose interactions are in principle accessible to observation, and that the information–loss paradox does not apply to the present universe. These conclusions require no modification of general relativity and no appeal to speculative quantum-gravity effects. The conventional picture of astrophysical black holes as already completed event-horizon objects is thus not merely an idealization, but an extrapolation beyond the domain of causal and observational validity, that assigns physical reality to global extensions which never become the generators of the exterior spacetime geometry actually realized in the universe. A consistent physical description must instead treat astrophysical black holes as dynamical systems whose collapse remains asymptotic and never physically completed.

It follows immediately that in a universe with ongoing mergers and accretion, no closed trapped surface is ever physically realized. Penrose's singularity theorem [1] therefore remains a correct mathematical result, but its physical preconditions are never satisfied by astrophysical black holes. Singularities are not avoided by new physics; they are rendered physically irrelevant by causal structure.

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