Firewall or smooth horizon?

Amos Ori*

Department of Physics
Technion-Israel Institute of Technology
Haifa 3200, Israel

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Abstract

Recently, Almheiri, Marolf, Polchinski, and Sully found that for a sufficiently old black hole (BH), the set of assumptions known as the complementarity postulates appears to be inconsistent with the assumption of local regularity at the horizon. They concluded that the horizon of an old BH is likely to be the locus of local irregularity, a “firewall”. Here I point out that if one adopts a different assumption, namely that semiclassical physics holds throughout its anticipated domain of validity, then no inconsistency seems to arise, and the horizon retains its regularity. In this alternative view-point, the vast portion of the original BH information remains trapped inside the BH throughout the semiclassical domain of evaporation, and possibly leaks out later on. This appears to be an inevitable outcome of semiclassical gravity.

1 Introduction

Almheiri, Marolf, Polchinski, and Sully [1] recently analyzed the evaporation of black holes (BHS) via Hawking radiation [2], from the view-point of information theory. They concluded that, if one accepts a set of postulates concerning evaporating BHs (the so-called complementarity postulates), including the assumption that local physics is regular at the horizon, one is led to a contradiction. Based on this contradiction, AMPS proposed that for a sufficiently old evaporating BH, the horizon’s local regularity predicted by classical (and semiclassical) theory is actually replaced by a pathological local behavior at the horizon—a firewall. This conclusion was subsequently confirmed by several authors [3, 4], though several other authors disagree [5, 6, 7]. (See also [8, 9].)

It must be noted that no mechanism was proposed in [1] for explaining how the irregularity actually develops: It is merely the alleged contradiction found

*amos@physics.technion.ac.il
in the set of “complementarity postulates” (combined with the assumption of regular horizon) that led AMPS to the firewall proposal.

One should also bear in mind that the analysis and discussion in [1, 3] rely on a certain assumption, which is so commonly used that the authors do not even bother to spell it out in their set of postulates: Namely, that most of the BH information is carried out with the Hawking radiation, already in the semiclassical phase of evaporation. We may refer to this additional assumption as the “zeroth complementarity postulate.”

The main goal of this manuscript is to discuss this problem from a different view-point. Instead of the complementarity postulates, I will simply assume that the semiclassical theory of gravity (augmented by the equivalence principle) holds throughout its anticipated domain of validity—that is, as long as curvature is small compared to Planckian value. I will argue that this assumption naturally leads to a different scenario, in which most of the information is actually stored inside the shrinking BH throughout the semiclassical stage of evaporation, and may possibly be released later on (after the BH approaches a small mass, of order the Planck mass \( m_p \)). The contradiction pointed out by AMPS does not arise in this scenario, hence there is no reason to assume a firewall: Instead, the horizon is regular throughout the semiclassical domain—that is, as long as the BH is macroscopic (\( m \gg m_p \)); and seemingly no inconsistency is encountered.

Throughout the manuscript I will consider an uncharged, non-spinning, spherical BH, and use the Planck units \( c = G = \hbar = 1 \).

A key ingredient in this discussion is Bekenstein’s BH entropy, \( S = 4\pi m^2 \) (in Planck units). It may be tempting to interpret this \( S \) as characterizing the number of different micro-states associated with a macroscopic BH of given mass \( m \)—or, stated in other words, as a measure of the overall “amount of information” carried by the BH. We shall later demonstrate, however, that this interpretation becomes very problematic when applied to an evaporating BH with remaining mass \( m \) (as long as the validity of semiclassical physics is assumed). This is in fact a fairly well-known observation, though seemingly it is often overlooked in current literature.

Over the last two decades it became widely accepted that (unlike Hawking’s original claim) information is actually conserved in the process of BH evaporation—and more specifically, that an initial pure state remains pure. Various approaches have been proposed as for how the information is encoded in the BH, and at what form (and at what timing and rate) is it released to the external world.

Consider now an evaporating BH with initial mass \( M_0 \). According to semiclassical theory the remaining BH mass \( m \) evolves according to

\[
m(v) = c(t_0 - v)^{1/3}
\]

where \( c \) is a certain constant, \( v \) is the Eddington outgoing coordinate (parametrizing the BH horizon, and set to zero at the moment of collapse), and \( t_0 \) is a

\[1\] One may contend that this additional assumption is implicitly contained in the first complementary postulate. (However, this is not necessarily the most natural interpretation of that postulate, as usually formulated.)
constant characterizing the BH’s life-time, from collapse to full (semiclassical) evaporation: \( t_0 = (M_0/c)^3 \). This law presumably applies as long as the remaining BH mass is macroscopic, that is, \( m(v) \gg m_p \).

The various proposals as for how information is stored in the evaporating BH, and at what time (and rate) is it released out, may be crudely divided into two categories:

(A) The BH entropy \( S(v) = 4\pi m(v)^2 \) properly represents the (steadily shrinking) information capacity of the evaporating BH. Accordingly, assuming that no information loss occurs, we must assert that while the BH evaporates, the decrease in \( S(v) \) is directly translated into increase (by the same amount) of the information contained in the Hawking-radiation field (this information is encoded in inter-correlations between emitted particles, as well as correlations with the BH near-horizon and/or internal state). Stated in other words, the amount of information contained in the Hawking radiation up to an “advanced moment” \( u \) is

\[
I(u) \equiv S(M_0) - S(m_b(u)) = 4\pi \left[ M_0^2 - m_b(u)^2 \right] = 4\pi c^2 \left[ t_0^{1/3} - (t_0 - u)^{1/3} \right]^2,
\]

where \( u \) denotes the ingoing Eddington coordinate (given by \( u = v - 2r_+ \)), and \( m_b(u) \) is the Bondi mass (namely, the remaining mass, as observed by a far observer as a function of \( u \)). Thus, \( I \) vanishes at \( u = 0 \) (the advanced moment of collapse), and grows monotonically with \( u \) until it gets the maximal value \( I_{\text{max}} = 4\pi M_0^2 \) at the end of evaporation, \( u = t_0 \). (Note that when the remaining Bondi mass becomes small, \( m_b(u) \ll M_0 \), \( I \) is approximately \( I_{\text{max}} \)— even though \( m_b \) is still macroscopic.) We may refer to this scenario as prompt information release.

(B) The information encoded in an evaporating BH with remaining mass \( m \) may be much larger than \( S(m) \), and in fact it is by no means bounded by the current value of \( m \). According to this view, the Hawking radiation may encode (throughout the semiclassical phase of evolution) very little information about the initial state of the system. Most of the information thus remains trapped inside the shrinking BH. This scenario, to which I will refer as confined information, comes in several variants, differing by the final fate of the information (and of the internal BH geometry):

(B1) The information may be trapped for a long time in a small-mass (say, \( m \sim m_p \)) remnant of finite life-time, and be released during a long period of time, after the completion of (the semiclassical stage of) the BH evaporation. I will refer to this variant as delayed information release; or

(B2) it may be trapped forever in a stable small-mass (\( m \sim m_p \)) remnant,

\footnote{A simple intuitive way to conceive this quantitative notion of “information” (and its relation to \( I \)) is to count the number of binary bits required for encoding all possible micro-states of the system in consideration. This is of course closely related to the notion of Entropy, which is the log of the number of micro-states. Thus, \( I \) (as defined in Eq. (1)) may be interpreted here as the number of required bits, multiplied by \( \ln 2 \).}
or (B3) perhaps it may migrate to a “baby universe” (created when the internal part of the small-\(m\) BH pinches off our parent universe).

Over the last two decades, the first viewpoint (A) became the most dominant one. An important boost emerged from analyses by Bekenstein [10] and Page [11], showing that, despite of the approximate thermal character of the Hawking radiation, its potential information capacity is large enough to carry the entire BH information. Later this idea was further boosted due to the analysis by Hayden and PresKil [12]. One should bear in mind, however, that none of these works provided any concrete indication that information is actually carried out by the emitted radiation (namely, that the state of the radiation field is actually correlated with the BH’s initial micro-state).

The analysis in Ref. [1], and similarly the discussion in [3], rely on this assumption of prompt information release (scenario A) — and so is their conclusion concerning the existence of firewalls.

On the contrary, the discussion in this manuscript will instead rely on one key assumption, to which I will refer as the **semiclassicality postulate**:

- The semiclassical theory of gravity holds as long as curvature is much smaller than Planckian. (That is, along the horizon semiclassical theory should apply as long as \(m \gg m_p\), and inside the BH it should apply in all regions which are not too close to the \(r = 0\) singularity.)

Stated in other words, we postulate that no mysterious unexpected phenomena are to be expected to occur at the macroscopic level. In particular this postulate would forbid non-local macroscopic phenomena — and obviously non-causal ones. This is surely a rather conservative assumption.

In particular, it will be assumed that in the semiclassical domain there is a well-defined notion of (classical) geometry, with a well-defined causal structure, and this geometry satisfies the Einstein equations with the usual semiclassical source term \(\hat{T}_{\alpha\beta}\), the renormalized stress-Energy tensor. Below I will argue that once this postulate is adopted, one is naturally led to the second viewpoint (B). The consequence is that no mysterious firewall is needed, and the horizon may still be viewed as a regular place — as suggested by the equivalence principle (and by semiclassical gravity).

I should emphasize that this picture (B) is by no means new: Some variants of it were proposed several decades ago, for example by Banks and collaborators [13]. It was also proposed by Parentani and Piran [14]. More recently this scenario was re-considered by Hossenfelder and Smolin [15]. Yet, for some reasons (probably due to some objections which I’ll mention below), this viewpoint never gained much popularity. My feeling, however, is that the very recent dramatic developments — the recognition that the complementarity postulates are not contradiction-free (and the resultant firewall argument) call for a re-consideration of this alternative viewpoint (B). I find this viewpoint quite compelling.
2 Semiclassical spacetime of evaporating black hole

Consider the gravitational collapse of an uncharged, spherically-symmetric, compact object with large initial mass \( M_0 \). The resulting BH then evaporates during a very long time, \( \propto M_0^3 \). Figure 1 displays the corresponding spacetime diagram.

Figure 1: Spacetime diagram of an (uncharged) evaporating spherical BH. The horizontal red line denotes the \( r = 0 \) singularity, the dashed blue line \( S \) is the worldline of the collapsing thin shell, and the bold diagonal black line marked by \( H \) is the event horizon. The point “\( p \)”, the intersection of the horizon and the \( r = 0 \) singularity, is the “end of evaporation” point, which is actually a (naked) singularity of the semiclassical spacetime. The diagonal dashed line marked by “\( (CH) \)” (which extends the horizon in the upper-right direction) is in fact a Cauchy horizon of the semiclassical spacetime, beyond which the extension of geometry is not really predictable by the semiclassical theory. The green dashed line denotes the spacelike hypersurface \( \Sigma \) (see text). The points marked by \( c, x, \) and \( m \) respectively denote the intersection points of \( \Sigma \) with the regular center, with the collapsing shell, and with the horizon (at a “moment” \( v \) where the remaining mass is \( m \), much smaller than the initial mass \( M_0 \)).

To simplify the discussion, we shall consider the case of a thin-shell collapse; however, our main conclusions will as well apply to the more general and more realistic case of e.g. a collapsing star.

Upon evaporation, the BH mass \( m(v) \) monotonically shrinks from \( M_0 \) toward smaller values. Let us discuss the situation at a fairly late advance time \( v = v_m \), where most of the mass has already been evaporated, yet the remaining BH mass is still macroscopic: \( m_p \ll m \ll M_0 \). To this end we choose a typical spacelike hypersurface \( \Sigma \) which intersects the horizon at \( v = v_m \) (the point denoted “\( m \)” in
Fig. 1). One can easily construct such a spherically-symmetric hypersurface $\Sigma$ which is asymptotically-flat, smooth everywhere (except, technically speaking, at the thin shell), and with (intrinsic as well as extrinsic) curvature which is nowhere larger than $\sim 1/m^2$. Such a hypersurface $\Sigma$ is depicted in Fig. 2, by plotting the corresponding area coordinate $r$ as a function of proper length $L$ (in the radial direction). An embedding diagram of the hypersurface $\Sigma$ is shown in Fig. 3.

Figure 2: The geometry of the spacelike hypersurface $\Sigma$, represented here by the corresponding function $r(L)$, where $r$ is the area coordinate and $L$ is the proper length along the hypersurface $\Sigma$ (in the radial direction). The points $c$, $x$, and $m$ (see caption of Fig. 1) are marked.

Figure 3: Embedding diagram for the hypersurface $\Sigma$. Note the narrow throat (at the horizon-crossing point “m”) and the large internal volume.

Here is a sketch of a simple construction of such a hypersurface $\Sigma$: (i) Inside the shell, take it to be a hypersurface $t_m = \text{const}$, where $t_m$ denotes the Minkowski time inside the shell—that is, take $r(L) = L$. (ii) Along the long section of $\Sigma$ from point “x” to point “m”, take $r = \gamma m_e(L)$, where $0 < \gamma < 2$ is a constant that may take any value which is not too close to zero or 2 (we may take for example $\gamma \sim 1$), and $m_e$ denotes the (L-dependent) effective BH mass. (Due to the BH evaporation $m_e$ varies monotonically from $M_0$ at point “x” to $m$ at point “m”.) (iii) In the neighborhood of the horizon-crossing point “m”, take the curve $r(L)$ to be a radial spacelike geodesic (in the Schwarzschild geometry
with mass-parameter $m$). It is described by the solution of the equation

$$\frac{dr}{dL} = \left[ \frac{2}{\gamma} - \frac{2m}{r} \right]^{1/2}.$$  \hspace{1cm} (2)

In such a solution $r(L)$ grows monotonically from $r = \gamma m$ at a certain $L$ (inside the BH) up to the asymptotic external region $r \gg 2m$ where it takes a constant-slope asymptotic form, $r \cong (2/\gamma)^{1/2}L + \text{const}$. (iv) Beyond a certain $r \gg 2m$, pick a linear function $r = L + \text{const}$. It is not difficult to smoothly glue these four different functions $r(L)$ to each other, by slightly deforming them near their respective boundaries.

Notice the fairly unusual geometric shape of $\Sigma$: It has a narrow throat of radius $r \approx 2m$ (located at point “m” in Figs. 2,3). However, “inside”, to the left of the throat, there is a much larger, elongated, “balloon” of typical width $\sim M_0$ (and typical length $\sim M_0^3$). It thus admits a huge 3-volume. It resembles the “horned” configurations previously considered by Banks and collaborators [13] in some respects, although there are several important differences.

We point out that no exact solutions are known for the semiclassical field equations describing the spacetime of a 4D evaporating BH. Furthermore, even the form of $\hat{T}_{\alpha\beta}$ is not known explicitly in 4D (for a prescribed time-dependent metric). The picture portrayed if Figs. 1-3 relies on several inputs: (i) Qualitative considerations taking into account some known key features of $\hat{T}_{\alpha\beta}$ in 4D (and using the adiabatic approximation, applicable to macroscopic BHs, for constructing the semiclassical geometry); (ii) Detailed numerical analysis of spherical collapse and evaporation in 4D, carried out by Parentani and Piran [14] (who assumed a specific form of $\hat{T}_{\alpha\beta}$); and (iii) Numerical [16] as well as approximate-analytical [17] investigation of the analogous problem in 2D gravity, based on the CGHS model [18]. (Note that in 2D, $\hat{T}_{\alpha\beta}$ is known explicitly for any prescribed metric [18].) These three pieces of information all lead to the same qualitative structure of spacetime — a large-scale region located inside the BH, beyond a narrow throat — as depicted in Fig. 3. 3

### 2.1 The hard-disc thought experiment

How much information can be stored in the remaining BH when it is so old that its remaining mass $m$ is $\ll M_0$? It might be tempting to postulate that this amount is of order $S(m) = 4\pi m^2$, and indeed, such statements often appear in the literature. However, at least according to our conservative semiclassicality postulate, this cannot be the case! In fact, a spacelike hypersurface like $\Sigma$ admits a huge 3-volume—regardless of how small $m$ is, and it may therefore harbor a huge amount of information.

To verify the last point, let us carry the following thought experiment: Recall that our model assumes a collapsing thin shell, with (approximately) Minkowski

3Yet, there are certain differences between the 2D and 4D semiclassical spacetimes. Most notably, in 4D $\Sigma$ admits a regular center, i.e. the point c. Instead, in 2D $\Sigma$ extends to the left up to a second spacelike infinity (disconnected from the one at the right edge).
interior. Suppose we place a 10-Terabyte hard-disc inside the shell—say, in its central region, the region marked by gray in Fig. 1 (near its left boundary). As long as this hard-disc is still intact, we are assured that the BH information capacity is at least 10-Terabyte (multiplied by \( \ln 2 \)). For, the hard disc can be in \( 2^{10^{13}} \) different states, all with same mass.

(Of course, the BH’s information storage is much larger than this: Any prescribed state of the system of \( 10^{13} \) “mesoscopic” bits can be represented by many different micro-states. However, for the sake of the present discussion, the derivation of a lower bound on the amount of information capacity, it will be sufficient to recall that the system now has at least 10-Terabyte information capacity.)

The spacelike hypersurface \( \Sigma \) intersects the center of symmetry at the point \( c \) in Fig. 1. The hard disc, with its \( 10^{13} \)-bits information capacity, is thus registered at the “moment” \( \Sigma \). The disc is still intact (and hence the stored information is still safe), because virtually no tidal forces are present in the (almost) flat interior of the shell. Thus, even when the evaporating BH remains with arbitrarily small (though still macroscopic) mass \( m \), it still enjoys this information capacity of the hard disc.

Obviously, we can actually store inside the hollow collapsing shell many hard discs of this type. We are only restricted by the overall mass of the discs, which will be limited by the initial BH’s mass \( M_0 \). One thus finds that the amount of information that may be stored in hard-discs and survive up to \( \Sigma \) is bounded below by

\[ I_{\text{disc}} = \beta M_0 \]

where \( \beta \) is some constant.

We therefore conclude that the information stored in an evaporating BH is by no means restricted by its remaining mass \( m \)! It may only be restricted by its initial mass \( M_0 \).

Of course, we do not really need a hard disc to store the information concerning the initial state. We can replace the thin shell and the hard disc altogether by e.g. a collapsing star. The matter composing the star should carry (almost) all the information concerning the system’s initial state, encoded in its (time-evolving) micro-state — at least until it gets very close to the singularity. (Later I’ll briefly discuss the fate of information when the hard disc hits the \( r = 0 \) singularity.) I chose to establish the toy model on a “hard-disc” device because it has several simplifying ingredients: The information is stored in a

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4What I actually have in mind, when saying “hard disc”, is a disc of hard metal, on which the information is scratched, encoded in a certain binary code (so in a sense it is reminiscent of an optical “compact disc”, or a gramophone disc). So one can actually think of this “hard disc” as a static device, which does not need to consume energy — which simplifies the considerations below.

5To be more pragmatic, we demand that the total mass of the hard discs will be bounded by \( \alpha M_0 \), where \( \alpha \) is a certain fixed parameter, \(<1\).

(One can also show that for fixed \( \alpha \), the “hydrostatic pressure” emerging from the self-gravity of the system of hard-discs, if distributed homogeneously inside the shell, will decrease with \( M_0 \) like \( M_0^{-2} \).)
robust and durable manner, scratched on a hard metal disc. It is well-localized, and hence well protected from damage as long as the disc is still inside the hollow shell. Also the information may be accessed in a direct, non-intricate manner (as opposed to e.g. subtle correlations between photons or atoms), so no fine subtleties are involved in an attempt to access the stored information. Furthermore, since the scratches are in fact macroscopic, avoiding the above conclusion would require violations of the principles of locality and causality already at the macroscopic level (see discussion below)\(^6\).

We must emphasize that this simple observation (namely that the information carried inside the BH is not sensitive to the remaining mass \(m\)) is not new. It was already pointed out, for example, by Preskill\(^{19}\) and several others, several decades ago. In fact it was this observation of the non-shrinking internal information capacity which led Susskind and collaborators\(^{20}\) to introduce the logically-subtle concept of “complementarity”: If for some reason one is willing to insist that the information concerning the BH’s initial state is released out of the BH along with its entropy \(S(m)\), then, by the time the remaining mass \(m\) is \(< \ll M_0\), one faces the difficulty of holding (on \(\Sigma\)) two copies of the information: One deep inside the BH (e.g. our hard disc), and the other one in the emitted radiation field. This would conflict with the quantum-mechanical “no-cloning” principle. The complementarity concept was aimed to resolve this conflict. But of course there is a logically simpler way out of this conflict: There is no need to assume in the first place that the bulk of BH information is emitted together with the BH entropy.

What will happen to the information stored in the hard disc (or alternatively in the collapsing star) at later stages, when the disc heads towards the \(r = 0\) singularity? At some stage, the collapsing shell will presumably crash on the disc, and the latter will ultimately be destroyed (as a mechanical device) — due to this clash, and also due to the growing tidal forces. This does not mean that information is really destroyed at this stage: rather, it should merely take a more subtle and intricate form. This assertion, which is based on standard rules of local physics (augmented by the equivalence principle) should presumably hold as long as curvature is not too large. But it is less clear what will happen to the matter debris afterward, e.g. when curvature grows to Planckian values and even beyond (formally the curvature will diverge at some stage, when the debris’ worldlines approach the \(r = 0\) singularity). One might suppose that perhaps information will truly be destroyed at this stage. But this is still not necessarily the case: It has been suggested by various authors that Quantum Gravity will somehow cure the classical singularity, hence avoiding true information destruction. An especially interesting scenario demonstrating this idea was proposed several years ago by Ashtekar, Tavera and Varadarajan\(^{21}\), based on quantization of the CGHS\(^{18}\) semiclassical model.

Is there any reasonable way to evade the above conclusion, the \(m\)-independence

\(^{6}\) The hard-disc toy model yielded an information lower bound \(I_{\text{disc}}\) proportional to \(M_0\). A more realistic physical system (e.g. a collapsing star) should probably yield a significantly larger information capacity. For example, considering a gas of photons enclosed in the collapsing shell, one obtains a lower bound \(\propto M_0^{3/2}\).
of the information capacity? As Preskill [19] noted, this would require the existence of a strange “bleaching” mechanism that “strips away (nearly) all information about the collapsing body as the body falls through the apparent horizon (and long before the body reaches the singularity)”. Our collapsing-shell model makes it clear, however, that this “bleaching” must take place way before the disc arrives at the apparent horizon (which coincides in this region with the shell’s hypersurface; see Fig. 1). Such a mysterious “bleaching” phenomenon conflicts with the equivalence principle, and represents a macroscopic violation of locality [19]. Moreover, one can deform $\Sigma$ slightly toward the past at its left side, such that the point $c$ will no longer be in the causal future of $h$. In other words, the hard disc now intersects $\Sigma$ before it can get any causal signal from any point on the apparent horizon. Therefore, the “bleaching” phenomenon would also require a violation of causality, already at the macroscopic level.

2.2 Conclusion: Information content of the shrinking BH

Summarizing, the discussion in the previous subsection led to a simple conclusion (based on the semiclassicality postulate):

- The information enclosed inside an evaporating BH is not restricted in any way by the current value of $m$ (the remaining BH mass). This seems to be an inevitable result—unless one is willing to postulate the existence of a mysterious “bleaching” mechanism (which, as noted above, involves a violation of causality at the macroscopic level, well within the semiclassical domain; and ultimately it would violate our semiclassicality postulate).

Once this conclusion is accepted, it has a direct logical consequence:

- There is no need to assume that a significant amount of information is emitted through Hawking radiation. Instead, we may contend (as Hawking did originally) that during the semiclassical stage of evaporation, the radiation field carries very little information—much smaller than the original capacity $4\pi M_0^2$.

Thus, the semiclassicality postulate naturally leads to option B in the discussion: Namely, the original BH information stays trapped inside the BH throughout the semiclassical phase of evaporation.

This viewpoint B has obvious advantages: It is no longer necessary to introduce the logically-complex concept of “complementarity”. Furthermore, the apparent contradiction which led AMPS to introduce the firewall concept is now avoided.

3 What is the final fate of information?

Assuming that the vast of BH information is not emitted during the (semiclassical phase of) Hawking evaporation, there may be several options concerning its final fate:
(i) Information is stored in a small-mass \((m \sim m_p)\) remnant of finite life-time.

(ii) Information is stored in a small-mass stable remnant;

(iii) Information may leak to a “baby universe”.

Each of these options has its own advantages and difficulties. An excellent discussion of these scenarios may be found in Ref. [19].

I find option (i) to be the most compelling one. Information is stored for a long time in a temporary \(m \sim m_p\) remnant. The latter’s (time-evolving) internal geometry resembles that of \(\Sigma\) (depicted in Figs. 2,3): It has a rather narrow throat (presumably of order the Planck size), but to the left of it there is a large, macroscopic, internal “balloon”, inside which the information is stored. This internal balloon presumably shrinks with time slowly, “pouring out” its information content to the external universe, through massless particles of extremely low frequency (typically \(\omega \sim M_{\text{Pl}}^{-2}\) in Planck units, or possibly even smaller). The system’s end-state will then be just radiation field. Note that in this scenario the radiation field is composed of two components: The standard Hawking radiation (emitted in the semiclassical phase of evaporation), and the subsequent, “post-evaporation” component. Overall, the radiation field will presumably be in pure state — just like in the more popular scenario of “prompt information release” (scenario A in the Introduction).

It is sometimes argued [22], based on the approach of effective field theory, that if small-mass remnant configurations are allowed, then spontaneous pair-production of such remnants must occur with unbounded rate. Several authors pointed out, however, that the applicability of effective field theory to this problem is in question, due to the large-scale, macroscopic nature of the remnant’s internal geometry [13, 15, 23].

In this regards one should also bear in mind that the formation of “balloon”-like configurations like \(\Sigma\) is in fact guaranteed by the semiclassical laws of evolution, and these laws also guarantee that the throat will continue to shrink, presumably up to Planck scale (at least). So small-mass balloon-like configurations admitting narrow (Planck-scale) throat and large macroscopic interior are not only legitimate elements in superspace, but also real physical states that must form in black-hole evaporation (provided that we accept semiclassical gravity throughout the domain of sub-Planckian curvature). The only question is the final fate of these configurations: Stable remnant, or a temporary one, or perhaps a baby universe.

4 Discussion

Our discussion throughout this manuscript was based on one key assumption, the “semiclassicality postulate”: Namely, that semiclassical physics (along with the equivalence principle) applies throughout its anticipated domain of validity. In particular, no causality violation is to be anticipated (especially at the macroscopic level) in the semiclassical domain. Using this assumption, and focusing
attention on the state of matter inside the BH, we have arrived at the following conclusion: The information content of an evaporating BH with a (macroscopic) remaining mass \( m \) cannot be bounded by the value of \( m \) in any way (though it may be bounded by the BH’s initial mass \( M_0 \)). In turn, this observation naturally leads us to option B in the Introduction: Namely, that the Hawking radiation does not carry out a significant amount of information (throughout the semiclassical domain of evaporation).

As a consequence, no firewalls are expected to develop at the horizons of old evaporating BHs: The contradiction that led AMPS to propose the firewall scenario was based on a set of assumptions, including the presumption that the BH information is efficiently carried out by the Hawking radiation, along with the BH mass. This presumption is now avoided. Instead we assume that the semiclassical theory of gravity holds (which in particular implies regularity of the horizon), and no inconsistency seems to arise.

In the scenario which emerges here, most of the original BH information is stored in the BH interior (instead of being Hawking-radiated out). This view is also motivated by the geometric properties of a typical hypersurface \( \Sigma \) that intersects the horizon at a moment \( v \) of small remaining mass \( m \). The 3-geometry of \( \Sigma \) is characterized by a narrow throat (\( \sim m \)) but a large internal volume (essentially independent of \( m \)), with typical radius \( \sim M_0 \) and typical length \( \sim M_0^3 \), so the volume is huge, of order \( (M_0/m_p)^2 M_0^3 \).

There may be several options concerning the fate of this information after the BH completes its evaporation \[19\] (see previous section). A compelling option is that of a finite-lifetime remnant (scenario B1 in the Introduction): The information is temporarily stored in a finite-lifetime, small-mass (\( m_{\text{rem}} \sim m_p \)) remnant, and slowly released through massless particles of very small frequency, of order \( M_0^{-2} \). The end state should thus be a radiation field in pure state (assuming that the system’s initial state was pure).

The small-mass remnant scenario was discussed by several authors previously, but it never gained popularity. This is probably due to several reasons: (i) For “esthetic” reasons, it may be tempting to assume that the information capacity of an evaporating BH with remaining mass \( m \) is just \( S(m) \approx 4\pi m^2 \) — which (for small \( m \)) is too small to store all the initial information; (ii) As was already mentioned in the previous section, it is often argued \[22\] that if small-mass remnant configurations are allowed, then spontaneous pair-production of such remnants must occur in unbounded rate; and (iii) Insights emerging from the AdS/CFT correspondence seem to support the standard picture (A) of prompt information release via Hawking radiation. \[1\]

How convincing are these points of objection? The claim (i) was actually shown here to be invalid (provided that one accepts the semiclassicality postulate). As for point (ii), the argument based on effective field theory appears to be inconclusive (as briefly discussed in the previous section).

Point (iii) appears to be the most worrisome one. There appears to be a deep conflict between the insights emerging from the AdS/CFT correspondence, and the standard picture emerging from the equivalence principle and the semiclassical theory of gravity. \[1\] We may hope that further investigations will clarify the
roots of this conflict, hopefully retaining causality (at least at the macroscopic level) to the AdS/CFT framework.

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