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Publication Date

2016-10-01

DOI

10.1016/j.physletb.2016.08.003

Peer reviewed



Why firewalls need not exist

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ARTICLE INFO

Article history:

Received 1 March 2016

Received in revised form 31 July 2016

Accepted 1 August 2016

Available online 4 August 2016

Editor: M. Cvetič

ABSTRACT

The firewall paradox for black holes is often viewed as indicating a conflict between unitarity and the equivalence principle. We elucidate how the paradox manifests as a limitation of semiclassical theory, rather than presents a conflict between fundamental principles. Two principal features of the fundamental and semiclassical theories address two versions of the paradox: the entanglement and typicality arguments. First, the physical Hilbert space describing excitations on a fixed black hole background in the semiclassical theory is exponentially smaller than the number of physical states in the fundamental theory of quantum gravity. Second, in addition to the Hilbert space for physical excitations, the semiclassical theory possesses an unphysically large Fock space built by creation and annihilation operators on the fixed black hole background. Understanding these features not only eliminates the necessity of firewalls but also leads to a new picture of Hawking emission contrasting pair creation at the horizon.

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1. Introduction

Ever since the discovery of the thermodynamic behavior of black holes [1–3], we have been searching for a deeper structure of spacetime and gravity beyond that described by general relativity. Its exploration, however, has repeatedly led to confusions involving fundamental principles such as unitarity of black hole evolution and smoothness of their horizons [4–7]; see, e.g., Refs. [8,9] for reviews. In this regard, the latest major puzzle is the firewall paradox [7,10,11], which asserts that unitarity of black hole evolution as viewed from the exterior is inconsistent with smoothness of the horizon, assuming that the semiclassical theory is valid away from the stretched horizon. It has been argued that the most likely implication of this is that an infalling observer encounters drama at the horizon, so that there is no such thing as the interior spacetime, at least for an old black hole in which the information retrieval process is operative [12].

In this paper, we elucidate how the firewall paradox may manifest as a limitation of the semiclassical theory, rather than presents a conflict between fundamental principles. We do this by illustrating how an interpretation of the semiclassical theory undermines some of the assumptions that went into the arguments of Refs. [7,10,11]. In fact, by using this understanding of the paradox

we can explore the Hilbert space structure of matter and spacetime in the fundamental theory of quantum gravity. While the picture we present is already implicit in more complete treatments of evaporating black holes in Refs. [13–15], we find it useful to explicitly extract the features responsible for avoiding the existence of firewalls. In particular, the following aspects of the fundamental and semiclassical theories play key roles:

- The number of physical configurations representing semiclassical excitations, i.e. the configurations that are physically realized and which the operators in the semiclassical theory can discriminate, is much (exponentially) smaller than the number of physical states in the fundamental theory of quantum gravity. This implies that in the fundamental theory, or the “dual field theory,” the same semiclassical operators can be realized in exponentially many different ways. In other words, the actions of these operators are defined only on a subset of the whole degrees of freedom in the fundamental theory.
- The semiclassical theory possesses a (formally infinitely) large Hilbert space constructed as the Fock space associated with the creation and annihilation operators on a fixed black hole background. This is because the effect of the excitations on the spacetime background is ignored in the semiclassical theory. The finite number of independent configurations for the physical semiclassical excitations are mapped into this Hilbert space. In other words, the elements of the Hilbert space out-

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side the image of this map are unphysical, and as such, they do not exist in the corresponding dual field theory.

We argue that these two features are responsible for addressing the two representative arguments for firewalls: the entropy and typicality arguments. After reviewing the firewall paradox in Section 2 and presenting our view on the semiclassical approximation in Section 3, we refute the typicality and entanglement arguments in Sections 4 and 5, respectively. In Section 6, we present the picture of Hawking emission [13,14] implied by these analyses.

For simplicity, we present our analysis for a Schwarzschild black hole in 4-dimensional spacetime, although we do not expect difficulty in extending to other cases. Throughout the paper, we do not discriminate the Planck length, l_p , and the string length, but they can be straightforwardly separated if needed. We use natural units in which $\hbar = c = l_p = 1$, unless otherwise stated.

2. The firewall paradox

Recall that the firewall arguments asserted that the complementarity picture [6] was not enough to answer the black hole information problem. What is the complementarity picture? Despite what Hawking considered long ago [4], we now do not think that the black hole formation and evaporation process violates unitarity, at least from the viewpoint of a distant observer (based mainly on gauge/gravity duality [16]). This, however, raises the black hole “information cloning paradox” [8]: the complete information about an object fallen into a black hole seems to reside *both* in late Hawking radiation *and* in the interior region, violating the no-cloning theorem in quantum mechanics. The complementarity picture was proposed to address this paradox. The basic idea was that no one can be distant and infalling observers *at the same time*, physically obtaining the information both from Hawking radiation and the fallen object. The hope was that when one restricts the application of the classical spacetime picture to a causal patch (i.e. the spacetime region which a single observer, represented by a timelike geodesic, can access), semiclassical field theory still gives a good local description of physics.

A key point of the firewall arguments was that a paradox similar to the information cloning one could be formulated within a single causal patch. The argument presented originally in Ref. [7] goes as follows. Consider an outgoing mode B localized in the black hole zone region, $r < r_z \simeq 3M$, which corresponds to Hawking radiation just emitted from the stretched horizon at $r = r_s = 2M + O(1/M)$. Here, r is the Schwarzschild radial coordinate. For a sufficiently old black hole, unitarity requires this mode to be entangled with a mode representing Hawking radiation emitted earlier [12]. On the other hand, according to semiclassical field theory, the smoothness of the horizon requires that any mode in the zone region, including B , must be entangled (almost maximally) with the pair mode inside the horizon [17]. These two statements cannot be reconciled. A single mode B cannot be entangled with two different modes, i.e. the earlier Hawking radiation mode (at $r > r_z$) and the interior mode (at $r < r_s$), since it would violate strong sub-additivity of the entropy, entailing the information cloning. We call this argument for firewalls the *entropy argument*.

Another argument was subsequently put forward using a putative map between a mode in semiclassical field theory (e.g. B above) and an operator in the dual field theory. The most sophisticated version [11] calculates the average of the number operator, $\hat{a}^\dagger \hat{a}$, in the dual field theory over states having energies in a chosen range, with \hat{a} corresponding to an infalling mode a in the bulk. It was claimed that the resulting number is at least of order unity, $\bar{N}'_a \gtrsim O(1)$, because one can choose a basis for these states such that they are all eigenstates of the number operator $\hat{b}^\dagger \hat{b}$ with \hat{b}

corresponding to an exterior mode localized in the zone region (and because the expectation value of $\hat{a}^\dagger \hat{a}$ in any eigenstate of $\hat{b}^\dagger \hat{b}$ is at least of order unity). This would imply that the expectation value of $\hat{a}^\dagger \hat{a}$ is of order unity or larger in a typical black hole state, i.e. most black hole states have firewalls. We call this argument the *typicality argument*.

The firewall paradox refers to a set of arguments indicating a conflict between unitarity of black hole evolution and smoothness of the horizon implied by the equivalence principle, formulated within a single causal patch. The two arguments described above represent the most well developed among those formulated so far.

3. Semiclassical approximation

What is the semiclassical approximation? Answering this question accurately is a key to resolving the firewall paradox. Here we present a picture focusing on the relation between the Hilbert spaces of fundamental quantum gravity and semiclassical theory. This picture builds on earlier work of one of the authors (Y.N.) with Sanches and Weinberg [13–15,18,19].

Consider a set of quantum states representing a dynamical black hole of mass M and its zone region, $r < r_z$. Here, we have adopted the Schrödinger picture; in the Heisenberg picture this corresponds to considering a set of quantum states which have a black hole of mass M at a fixed location at a fixed time, with the region outside the zone being unexcited. The first step toward constructing the semiclassical approximation is to split the degrees of freedom represented by this set into those associated with the black hole “itself” and excitations around it. According to the standard entropy argument, the number of independent black hole states without an excitation is

$$\mathcal{N}_{\text{vac}} \sim e^{\frac{1}{4}\mathcal{A} + O(\mathcal{A}^p; p < 1)}, \quad (1)$$

where $\mathcal{A} = 16\pi M^2 \gg 1$ is the area of the black hole, and from now on we suppress possible higher order corrections in $1/\mathcal{A}$ in the exponents in analogous expressions. The number of possible configurations for the excitations is expected to be

$$\mathcal{N}_{\text{exc}} \sim e^{\gamma \mathcal{A}}, \quad (2)$$

see, e.g., Ref. [20]. Here, the coefficient γ satisfies the holographic bound [21], $\gamma < (r_z/4M)^2 - 1/4$.¹ Since the total number of quantum states is

$$\mathcal{N} \approx \mathcal{N}_{\text{exc}} \mathcal{N}_{\text{vac}}, \quad (3)$$

the physical Hilbert space describing excitations around a fixed black hole background is exponentially smaller than that of the whole quantum gravitational degrees of freedom, $\mathcal{N}_{\text{exc}} \ll \mathcal{N}$.² This first step is depicted as (a) \rightarrow (b) in Fig. 1.

The next step is to “classicalize” the degrees of freedom corresponding to \mathcal{N}_{vac} , which were called the vacuum degrees of freedom in Refs. [13,14,19] because they are associated with the black hole vacuum state in semiclassical theory. This step consists of two processes. First, we must formally make the number of black hole degrees of freedom infinite as depicted as (b) \rightarrow (c) in Fig. 1 (although we will see later how semiclassical theory “corrects” this

¹ In Refs. [13–15], it was stated that the number of physical configurations for the excitations around the black hole is $\ln \mathcal{N}_{\text{exc}} \sim \mathcal{A}^q$ with $q < 1$, ignoring the effect of the redshift of the Schwarzschild geometry. Including this effect, the number of possible configurations is rather $\ln \mathcal{N}_{\text{exc}} \sim \mathcal{A}$. This does not affect the basic conclusion. Important points are that $\ln \mathcal{N}_{\text{exc}}$ is finite and that there are large number of degrees of freedom, $\ln \mathcal{N}_{\text{vac}}$, that cannot be probed by operators in the semiclassical theory.

² A similar conclusion has also been reached in Ref. [22] in the context of the AdS/CFT correspondence.

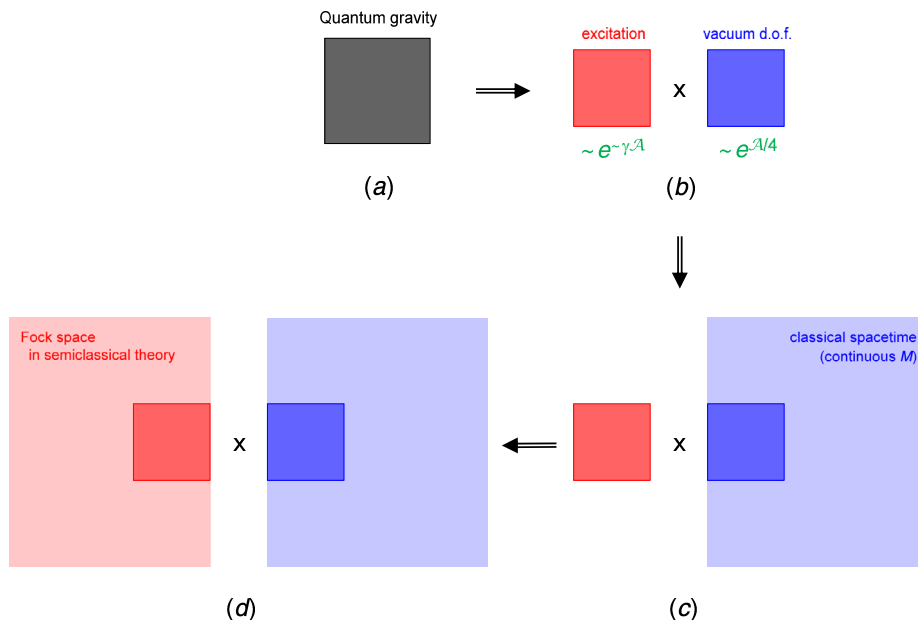


Fig. 1. Construction of the semiclassical approximation requires splitting the physical degrees of freedom in quantum gravity, (a), into the degrees of freedom associated with the black hole vacuum (vacuum degrees of freedom) and excitations around it, (b). The vacuum degrees of freedom are then classically approximated, (c), which creates a large (fictitious) Hilbert space: the Fock space of creation and annihilation operators on the resulting classical background, (d). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

to represent phenomena associated with finite \mathcal{N}_{vac}). This can be understood by analyzing the origin of the Bekenstein–Hawking entropy, $\ln \mathcal{N}_{\text{vac}} = \mathcal{A}/4$. The quantum uncertainty principle implies that a dynamical black hole of mass M has an energy uncertainty of $\Delta E \approx \Delta M \approx O(1/M)$ and, with the position uncertainty of order the quantum stretching of the horizon $\Delta r \approx O(1/M)$, a momentum uncertainty of $\Delta p \approx O(1/M)$.³ The finiteness of the Bekenstein–Hawking entropy means that there are only a finite number of independent quantum states, $e^{\mathcal{A}/4}$, within these uncertainties. On the other hand, classically, the number of independent states in this range is infinite, labeled by a *continuous* number M (even ignoring the momentum uncertainty).⁴ Regarding the background spacetime as classical, therefore, amounts to enlarging the number of possible vacuum states to infinity. This can also be seen from the fact that $\ln \mathcal{N}_{\text{vac}}$ is written as $\mathcal{A}^3/4l_p^2\hbar$ when \hbar , c , and l_p are restored, which becomes infinite for $\hbar \rightarrow 0$.⁵

The second process is to ignore the backreaction, i.e. the effect of excitations on the (now classical) spacetime. This comes with a major “side effect”: since the effect of excitation degrees of freedom on the vacuum degrees of freedom is ignored, the resulting theory—semiclassical theory—allows for having a much larger (formally infinite) number of excitations on a fixed spacetime background. In semiclassical field theory, this manifests itself as the fact that the Fock space built by creation and annihilation operators on

the background is much larger than the actual Hilbert space for physical excitations; see (d) in Fig. 1. In other words, the physical Hilbert space for the excitations is much smaller than what is naively implied by the Fock space in semiclassical field theory; by design, the semiclassical approximation is valid only for a very “small” number of excitations, of order $\ln \mathcal{N}_{\text{exc}}$ or smaller.

At this point of the construction, the resulting theory seems fairly “superficial.” The effect of excitations (matter and radiation) on spacetime is not automatically included—the only way to incorporate it is to solve the classical Einstein equation with a given configuration of the excitations (often taken as the quantum expectation value of the energy-momentum tensor) and adopt the resulting spacetime as the background. The entropy of the black hole is formally infinite, so its temperature is zero—the black hole background exists eternally. However, the semiclassical approximation is actually more clever. It inherits some features reflecting the basic structure of the true physical degrees of freedom and their interactions, which allowed Hawking to discover the renowned black hole emission effect.

Suppose we describe the system from the viewpoint of an external observer. If we want to describe the entire history of black hole evolution, we need to consider the whole time-dependent background from formation to evaporation, but if we are interested only in the black hole emission process, then we may consider a black hole background of mass M , which may be viewed as eternal at the semiclassical level [17]. As we have discussed, the fact that the static approximation for the black hole is valid only for $\Delta t \lesssim M$ implies that the state must have an uncertainty $\Delta E \gtrsim 1/M$, so when we say a black hole of mass M we are actually considering an ensemble of black holes of masses in the range $M \pm O(1/M)$. Semiclassical field theory encodes this fact such that the black hole vacuum state is a mixed (thermal) state. While this state is unique for a given M , the von Neumann entropy of the state is nonzero, reflecting the fact that the black hole microstate in the fundamental theory is not unique (so with this procedure, black holes of slightly different masses in the range $M \pm O(1/M)$ need no longer be regarded as different). This is depicted in Fig. 2. Note that by

³ The energy and momentum here refer to those as measured in the asymptotic region. The energy uncertainty, therefore, is given by $\Delta E \approx 1/\Delta t$, where Δt is the characteristic timescale for the change of the black hole state in Schwarzschild time. Assuming that the relevant timescale is the Planck time as measured locally at the stretched horizon, we obtain $\Delta t \approx O(M)$. This is indeed the timescale for Hawking emission.

⁴ This is a standard phenomenon in the relation between quantum and classical mechanics. For example, the number of independent states of a harmonic oscillator in a fixed energy interval is finite in quantum mechanics (labeled by a discrete number for the levels) while it is infinite in classical mechanics (labeled by a continuous amplitude).

⁵ This implies that it is inaccurate to say that a classical black hole loses exponentially many quantum hairs of a quantum black hole. The corresponding “hairs” for a classical black hole is the mass parameter M .

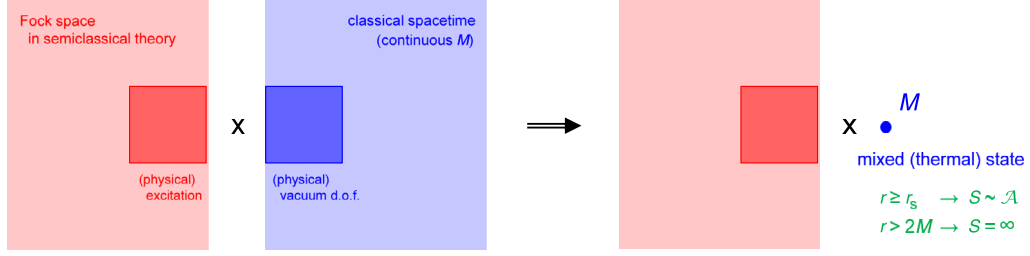


Fig. 2. Semiclassical theory as viewed from an external observer encodes possible black hole microstates as the von Neumann entropy associated with the mixed black hole vacuum state. By integrating the entropy density associated with the local temperature from the stretched horizon (Schwarzschild horizon) to the edge of the zone, we obtain an entropy that scales as the area of the black hole (infinity), which corresponds to the number of black hole microstates in the quantum (classical) theory. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

integrating the thermal entropy density calculated using the local temperature

$$T(r) = \frac{1}{8\pi M} \frac{1}{\sqrt{1 - 2M/r}}, \quad (4)$$

from the stretched horizon, $r = r_s$, to the edge of the zone, $r = r_z$, we indeed obtain an entropy that scales as the area of the black hole, $S \sim \mathcal{A}$. If we do not take into account the quantum stretching and integrate the entropy density from the Schwarzschild horizon, $r = 2M$, to the edge of the zone, $r = r_z$, then we obtain $S = \infty$ consistently with the fact that the black hole entropy is infinite in the classical theory.

As we will discuss in more detail later, the thermal nature of the black hole vacuum state not only reflects the number of independent black hole microstates in the fundamental theory, but also encodes interactions of the black hole vacuum degrees of freedom with the rest of the degrees of freedom, e.g. field theory modes outside the zone, $r \gtrsim r_z$. Another important point here is that the number of physical excitations one can have on the black hole background is finite, of order $\ln \mathcal{N}_{\text{exc}} \sim \mathcal{A}$. The Hilbert space representing these excitations must be embedded into the infinitely large Fock space that one can formally build on the fixed black hole background.

4. Refutation—the typicality argument

The picture in the previous section tells us how the typicality argument for firewalls can be flawed. An important point is that the “map” from the physical Hilbert space of the fundamental theory to the Fock space of the semiclassical theory with a fixed black hole background is not one-to-one. In particular, all the unexcited black hole microstates look exactly the same as probed by the operators in the semiclassical theory. This occurs because these operators do not probe the vacuum degrees of freedom, i.e. the degrees of freedom in the right half in (c) and (d) of Fig. 1 and the left panel of Fig. 2. This implies that in the dual field theory, there are exponentially many different ways to represent the bulk semiclassical operators, which differ in actions on the degrees of freedom other than the excitation degrees of freedom. Said differently, the actions of these operators are defined only on a subset (excitation) of the whole degrees of freedom (excitation + vacuum). In Refs. [13,14,18,19], this fact was referred to as that the semiclassical picture is obtained after coarse-graining the degrees of freedom associated with the Bekenstein–Hawking entropy.

Consider the creation and annihilation operators, b^\dagger and b , corresponding to a mode localized outside the stretched horizon. In terms of these operators, all the black hole vacuum states appear as a unique, thermal state. The situation is analogous in the dual field theory. In terms of the dual field theory operators \hat{b}^\dagger and \hat{b} , which are the images of b^\dagger and b , all the black hole vacuum states

appear as the unique thermal state. It is then clear that the average over all the $\hat{b}^\dagger \hat{b}$ eigenstates considered in Ref. [11] is irrelevant to the discussion on the smoothness of the horizon for the black hole vacuum states—all the states in the average are the same thermal state in terms of \hat{b}^\dagger and \hat{b} even with a finite width of energy range of order ΔM in which the average is taken. We stress that the thermal state in question should not be viewed as a statistical ensemble of states that look different as probed by the \hat{b}^\dagger and \hat{b} operators, as would be the case if the system were in thermal equilibrium in the usual sense. This state is intrinsically mixed from the perspective of the semiclassical operators, and has the correct entanglement structure when the state is purified using the “mirror” modes \tilde{b} [17,23] at the semiclassical level.

What about the excited states? One might think that if we take the average of Ref. [11] over all the black hole (not necessarily vacuum) states, one can take the basis of the states to be eigenstates of the number operator for one of the exterior modes, b , leading to the conclusion that a typical state must have firewalls. This is, however, not necessarily the case because the number of physical states is finite, $\sim \mathcal{N}$, so that the map from the physical states to the Fock space of the semiclassical theory may not be onto. In particular, one may assume that the physical states correspond to states in which *infalling* modes a (and/or excitations on the “horizon” as viewed from an infalling reference frame [14]) are excited. In the distant description, this corresponds to states in which, when the vacuum state is purified using the mirror modes \tilde{b} , excitations preserve entanglement between b and \tilde{b} necessary to ensure the smoothness of the horizon. For example, a state in which an a mode is excited is described effectively as a state in which the thermal state is modulated by a linear combination of the b , b^\dagger , \tilde{b} , and \tilde{b}^\dagger operators as implied by the Bogoliubov transformation between the a and b, \tilde{b} operators (although the full description may require intrinsically stringy effects because of a large boost between the infalling and distant reference frames [14,24]). While we have not proved the assumption made here, we do not find a reason why it is impossible.

The picture described above implies that the average considered in Ref. [11] over the eigenstates of $b^\dagger b$ —or its putative map $\hat{b}^\dagger \hat{b}$ —corresponds to taking the average over an unphysically large Hilbert space, depicted as the light shaded (pink) region in the left half in (d) of Fig. 1 and the two panels of Fig. 2. One might think that if we impose a simple ultraviolet cutoff, e.g., the upper bound on the local energy of a b quantum, then (the logarithm of) the number of states involved in the average becomes the right order, keeping the firewall argument. This is, however, not the correct way to implement the cutoff. The set of the physical states, i.e. the states that actually exist in the dual field theory, does not agree with the set kept by such a simple ultraviolet cutoff. In other words, firewalls may reside only outside the dark shaded (red) box in the figures, and hence may be unphysical.

We note that many of the physical states considered here do have high energy quanta near the horizon. This is, however, different from the firewall phenomenon. These states have many *physical* excitations near the horizon which will either fall into the black hole or fly into the asymptotic space within the timescale of $O(M \ln M)$; in particular, they cannot be obtained in the course of the standard black hole evaporation process. In fact, the first two paragraphs of this section are sufficient to address the typicality argument for firewalls presented in Ref. [11], which concerns old, near vacuum black holes.

5. Refutation—the entanglement argument

We now address the entropy argument for firewalls. An implicit assumption of the argument is that in the Hawking emission (or the black hole mining [25]) process, the microscopic information about the black hole is carried from the stretched horizon to the edge of the zone (or where the mining apparatus is located) by an excitation of a semiclassical mode: B in Section 2. If this were indeed the case, then it would lead to a contradiction between unitarity and smoothness of the horizon.

The information transfer, however, does not occur in this manner [13,14]. Recall that the microscopic information of the black hole is represented by the configuration of the vacuum degrees of freedom, the dark shaded (blue) box in the right side in the left panel of Fig. 2. The question is how the black hole vacuum degrees of freedom interact with the other degrees of freedom: the modes outside the zone, $r > r_z$, in the case of Hawking emission and excitation modes within the zone, $r_s < r < r_z$, in the case of mining. The answer given in Refs. [13,14] is that they interact as if they are distributed according to the gravitational thermal entropy density. This distribution is reference frame dependent, reflecting the fact that the vacuum degrees of freedom are not standard radiation, and its precise forms are not known in general. In a distant reference frame, however, the quasi-static nature of the system allows us to infer the correct distribution—the relevant entropy density is that obtained from the blueshifted Hawking temperature in Eq. (4).

Since the amount of integrated entropy contained around the edge of the zone is of $O(1)$, outgoing field theory modes can extract the information *directly* from the vacuum degrees of freedom there, without involving a semiclassical mode deep in the zone. To quantify this statement, we may introduce the tortoise coordinate $r^* = r + 2M \ln(r/2M - 1)$, in terms of which the stretched horizon is at $r_s^* \equiv r^*|_{r=r_s} \simeq -4M \ln M$ and the edge region is $|r^*| \approx O(M)$. We then find

$$\int_{|r^*| \lesssim O(M)} T^3(r(r^*)) dr^* \approx O(1), \quad (5)$$

where $T(r)$ is given by Eq. (4). This implies that the microscopic information about the black hole is delocalized over the entire zone region.⁶ Note, however, that the distribution is not uniform and is strongly peaked toward the stretched horizon; we obtain the full degrees of freedom only if we integrate the entropy density down to the stretched horizon

$$\int_{r_s^*}^{O(M)} T^3(r(r^*)) dr^* \approx O(A). \quad (6)$$

Since entropy indicates how much information one can extract from a system in the characteristic timescale, in this case $t \approx$

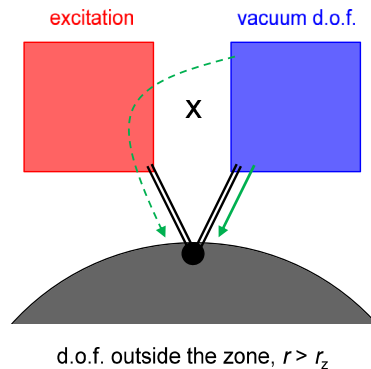


Fig. 3. Semiclassical degrees of freedom outside the zone, $r > r_z$, not only interact with semiclassical excitations inside the zone through usual kinetic terms (the left bond) but also with the vacuum degrees of freedom (the right bond). The information transfer associated with Hawking emission occurs through the latter interaction (the solid arrow), rather than through semiclassical excitations in the zone (the dashed arrow).

$O(M)$, the amount of delocalization in Eq. (5) is enough for outgoing field theory modes to extract an $O(1)$ amount of information from the vacuum degrees of freedom in each Hawking emission, which occurs in the timescale of $t \approx O(M)$ around the edge of the zone, where t is the Schwarzschild time. This is how Hawking emission must be viewed at the semiclassical level. (A similar analysis can also be performed for the mining process.)

One might wonder what is the relation between this picture and the original calculation by Hawking [3], which seems to involve modes deep in the zone in the semiclassical theory. It is not uncommon in physics that calculation of some quantity involves “unphysical” entities in the intermediate step of the calculation. For example, density fluctuations generated by cosmic inflation [26] are calculated by imposing the Bunch–Davies vacuum condition for all modes, including those that are super-Planckian at early times. We do not interpret this to mean that the spacetime is indeed classical in sub-Planckian distances. Likewise, a Casimir force can be calculated by summing up an infinite tower of modes (with an arbitrary large ultraviolet cutoff), and the electron anomalous magnetic moment can be computed by performing the momentum integral to infinity (with suitable counterterms). We do not interpret these to mean that the theories under consideration, e.g. QED, are valid up to arbitrary high energies. In some cases, we can indeed find explicit regularizations which make it clear that the results do not depend on entities that appear in the intermediate steps of calculations. In other cases, finding such explicit regularizations are difficult, but even in these cases, one can often be convinced (by various arguments) that the most naive extrapolations of the theories are giving the correct answers for certain “inclusive,” or “low energy,” quantities, despite the fact that these extrapolations cannot be taken literally. This can happen because such extrapolations often capture the essential features of the (unknown) fundamental theories which are sufficient to guarantee the correct answers. (For a discussion on an illustrative example of this phenomenon, see Ref. [27].) We consider Hawking’s original calculation to be of this kind—it gives the correct answers for the emission rate and spectrum as viewed from a distance, but we should not take all the intermediate steps too seriously, especially the part involving modes deep in the zone.

A schematic picture representing interactions between semiclassical degrees of freedom outside the zone and the black hole degrees of freedom (both vacuum and excitation) is given in Fig. 3. The portion of the outside degrees of freedom located around $r = r_z$ interact with the semiclassical degrees of freedom inside and near the edge of the zone through usual kinetic terms, as rep-

⁶ This is consonant with the intuition that different microstates of the black hole correspond, in some sense, to black holes with slightly different masses. It is natural to expect that the information about the mass is stored nonlocally, as is indeed the case classically (in the form of the metric).

resented by the left bond in the figure. They also interact, however, with an $O(1/\mathcal{A})$ fraction of the vacuum degrees of freedom directly, as indicated by the right bond. This is where one of the assumptions in Ref. [7]—the “literal” validity of the semiclassical theory outside the stretched horizon—breaks down.⁷ The information transfer associated with Hawking emission occurs through direct interactions of the outside modes with the vacuum degrees of freedom (indicated by the solid arrow), rather than through semiclassical excitations in the zone as envisioned in the firewall argument (the dashed arrow).

6. Hawking emission: a spacetime view

An intuitive picture of the Hawking emission process can be obtained if we choose the vacuum on which excitations are defined to be the (hypothetical) static black hole background (the so-called Hartle–Hawking vacuum [29]), rather than the evolving black hole background as we have been doing so far. Creation of Hawking quanta around the edge of the zone in this description is associated with that of an ingoing negative energy flux which carries *negative entropy* [13,14]. Here, the energy and entropy is defined with respect to the static background. We can understand this phenomenon by the following simple qubit model.

Let $|\psi_k(M)\rangle$ ($k = 1, \dots, e^{S_0(M)}$) be the vacuum microstates (in the sense of the static vacuum) of the black hole of mass M . Suppose that a black hole, in a superposition state of $|\psi_k(M)\rangle$'s, releases 1 qubit of information through Hawking emission. This occurs in the timescale of $t \approx O(M)$, and the energy of the emitted quantum is $E \simeq (\ln 2)/8\pi M$, so that $e^{S_0(M-E)} = e^{S_0(M)}/2$. We can model this process by saying that the emitted Hawking quantum is in states $|r_1\rangle$ and $|r_2\rangle$ if k is odd and even, respectively. Due to energy-momentum conservation, the process is accompanied by the creation of an ingoing negative energy excitation on the black hole (static) vacuum, which we denote by a star; namely, $|\psi_k^*(M)\rangle$ represents black hole microstates with the negative energy excitation.

What would this emission process look like at the microscopic level? Can it simply be

$$|\psi_k(M)\rangle \rightarrow \begin{cases} |\psi_k^*(M)\rangle|r_1\rangle & \text{if } k \text{ is odd,} \\ |\psi_k^*(M)\rangle|r_2\rangle & \text{if } k \text{ is even,} \end{cases} \quad (7)$$

as one might naively imagine? If this were the case, we would find a problem. Remember that $|\psi_k^*(M)\rangle$ have energy $M - E$, and we expect that they will relax into vacuum states of the black hole of mass $M - E$:

$$|\psi_k^*(M)\rangle \rightarrow |\psi_{k'}(M-E)\rangle. \quad (8)$$

However, since k' runs only over $k' = 1, \dots, e^{S_0(M-E)} = e^{S_0(M)}/2$, such a relaxation cannot occur unitarily. Instead, what actually happens in the emission process is

$$|\psi_k(M)\rangle \rightarrow \begin{cases} |\psi_{\frac{k+1}{2}}^*(M)\rangle|r_1\rangle & \text{if } k \text{ is odd,} \\ |\psi_{\frac{k}{2}}^*(M)\rangle|r_2\rangle & \text{if } k \text{ is even,} \end{cases} \quad (9)$$

i.e. the index for the black hole microstates with the negative energy excitation runs only from 1 to $e^{S_0(M)}/2$. This allows for these

states to relax unitarily into the black hole vacuum states of mass $M - E$, as in Eq. (8). Note that the process in Eq. (9) is also unitary by itself if we consider the whole quantum state, including both the black hole and the exterior of the zone.

The above analysis implies that a negative energy excitation over the black hole static vacuum carries a negative entropy; i.e., in the existence of a negative energy excitation, the range over which the black hole microstate index runs is smaller than that without. Specifically, the excitation of energy $-E$ carries entropy $-8\pi ME$. This picture is rather comfortable, since entropy is usually associated with energy, $S \sim E$, and we are saying that this is also the case even if these quantities are measured with respect to the static black hole background. We find that the information transfer from an evaporating black hole occurs through an ingoing negative entropy flux, at least from this viewpoint.

A comment is in order. Since the creation of a Hawking quantum, and hence of a negative energy excitation, occurs in the timescale of $O(M)$, and the relaxation time of a negative excitation is expected to be of $O(M \ln M)$, the amount of negative energy excitations we have on the static black hole background is of order $\ln M$ at any time. Here, the relaxation timescale can be estimated from the time it takes for the excitation to propagate from the edge of the zone to the stretched horizon and the time it takes for the information to be scrambled [30], both of which give $O(M \ln M)$. We may therefore view that an evaporating black hole has steady negative energy and entropy *fluxes* and redefine the black hole vacuum to include them. The resulting vacuum then has entropy $S(M)$, given by $S(M) - S_0(M) \approx -\ln M$. This redefined vacuum corresponds, very roughly, to the Unruh vacuum [17] in the semiclassical theory, and the corresponding geometry is that of an evaporating black hole, which is well described by the advanced/ingoing Vaidya metric near the horizon [31]. In this picture, the change in the local gravitational field supplies the energy of outgoing Hawking quanta created at $r \approx r_z$. The dark shaded (blue) boxes in the right side in (b), (c), (d) of Fig. 1 and in the left panel of Fig. 2 represent the microscopic degrees of freedom associated with this redefined vacuum.

The picture of Hawking emission resulting from the above analysis [13,14] is different from what was imagined in Refs. [7,10,11,32], which implicitly assumed that some information transportation mechanism is in operation from the stretched horizon to the edge of the zone on *the semiclassical background*; see the left panel of Fig. 4. Our picture says that the information transfer from an evaporating black hole cannot be understood in this manner—it is the *spacetime itself* that carries the microscopic information about the black hole, and this information must be viewed as delocalized throughout the zone in the semiclassical picture. With respect to the static background, the transfer occurs through an ingoing flux of negative energy-entropy excitations created around the edge of the zone, as depicted in the right panel of Fig. 4 (although these excitations can be incorporated as a part of the evolving black hole vacuum). The absence of the problem found in the entanglement argument is now obvious: there is no outgoing mode that is entangled with both early radiation and the mirror mode. While late Hawking quanta are certainly entangled with early ones for an old black hole, these quanta exist only outside the zone, where the near horizon approximation is not applicable (and hence there is no such thing as the mirror modes).

Comparing this picture [13,14] with the old, heuristic picture of Hawking's pair creation [3,4], we find two key features which we reiterate here:

- From the semiclassical viewpoint, the location in which pairs of a positive energy Hawking quantum and a negative energy excitation are created is *not* at the (stretched) horizon

⁷ This does not necessarily mean that generic soft quanta sent to an evaporating black hole must see violation of the semiclassical theory because such processes are not the same as the time reversal of the Hawking emission process [13,14]. To see the violation certainly, we need to send finely-tuned soft quanta to an *anti-evaporating* black hole. This is a process in which the coarse-grained entropy decreases, since usual Hawking emission is a process in which the coarse-grained entropy increases [28].

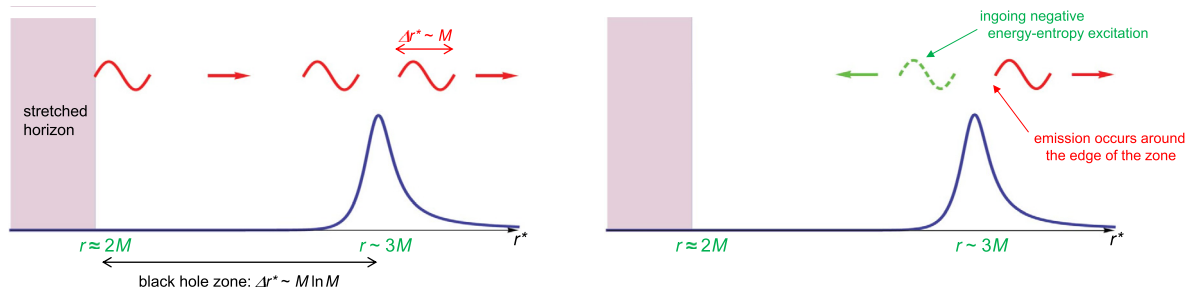


Fig. 4. The information transfer from an evaporating black hole does not occur through outgoing positive energy-entropy excitations (left panel) but through ingoing negative energy-entropy excitations in the zone (right panel). This is possible because the microscopic information about the black hole is carried by the “spacetime itself” (the vacuum degrees of freedom), which at the semiclassical level must be viewed as delocalized over the zone according to the thermal entropy density associated with the blueshifted Hawking temperature.

but around the edge of the zone, which is *macroscopically* away from the horizon.⁸ Microscopic information about the black hole is transferred there to field theory quanta, as in Eq. (9), which is possible because the information is carried by the spacetime itself and so is delocalized over the entire zone region. Note that it is not unnatural for such special dynamics to occur in this particular region, since it is where the near horizon, Rindler-like space is “patched” to the asymptotic, Minkowski-like space.

- The creation of a positive energy Hawking quantum and a negative energy excitation takes a form very different from the standard “pair creation” of particles. In the standard pair creation picture, the final states associated with the positive and negative energy excitations are assumed to be maximally entangled with each other, which is *not* the case here as one can see by writing explicitly the expression in Eq. (9) for the first few k 's. For example, the black hole states after the emission are the same for $k = 1$ and 2, despite the fact that the states for the emitted quanta are different. In fact, it is this lack of entanglement that allows for the emission process to transfer the information from the black hole to the radiation.

The calculation by Hawking “bypasses” these points while still giving the correct answers for the rate and spectrum of the emitted quanta as viewed from a distance. This must be because it captures an essential feature(s) of the fundamental theory, which is ultimately responsible for this energy-information transfer process between spacetime and particles.

What is the essential feature Hawking’s calculation is capturing? We suspect that it may exactly be the smoothness of the horizon, i.e. the ability of erecting a reference frame in which physics looks approximately Minkowskian locally there. Hawking’s (or other related) calculation provides an effective way of incorporating this information into the derivation of the rate and spectrum of the emitted particles. As we have argued, while we may trust these quantities as viewed from a distance (or from “high energy” excitations such as a mining detector in the zone) since the black hole physics is already “integrated out,” it does not mean that all the intermediate steps of the calculation can necessarily be trusted. To diagnose if we can in analogous cases, we usually analyze if the naive interpretation of the theory leads to pathological conclusions. In some cases these pathologies are readily evident, but in general not all sicknesses of effective theories are straightforward to see (cf. Ref. [35]). The firewall arguments may be viewed as such a pathology, indicating the limitation of the semiclassical theory interpreted naively.

Acknowledgements

This work was supported in part by the Director, Office of Science, Office of High Energy and Nuclear Physics, of the U.S. Department of Energy under Contract DE-AC02-05CH11231, the National Science Foundation under grant PHY-1521446, and MEXT KAKENHI Grant Number 15H05895.

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⁸ Similar points have also been discussed more recently in Refs. [33,34].

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