Oscillations for Equivalence Preservation and Information Retrieval from Young Black Holes

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Abstract: We follow the prevailing view that black holes do not destroy but rather process and release information in the form of Hawking radiation. By making certain conservative assumptions regarding the interior dynamics of the quantum system we suggest an outside observer could, in principle, recover the initial quantum state $|\psi>$ before the black hole has evaporated half of its entropy. In the current framework the retention time is associated with the time scale for a local perturbation to become effectively undetectable (scrambling time). Also, we provide a scenario for storing the information about an infalling matter in the near-horizon region in a layered fashion. Later we present a generic phenomena which provides a set of boundary conditions for breaking the trans-horizon vacuum entanglement between in- and out-modes, and thus preserve the effective field theory after Page time $O(R^3)$. The scenario follows from black hole perturbation theory. We further argue the proposed Planckian-amplitude horizon oscillations can account for the physical membrane which an observer at future null infinity $\mathcal{L}^+$ measures in the complementarity conjecture.
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1 Introduction

Hawking argued in his semiclassical calculations [1] that the radiated to infinity out-modes were of almost thermal spectrum. Particle dependence solely on the mass of the black hole would imply lack of correlations with the internal degrees of freedom (limited by causality) for an outside observer. As a result, the emitted quanta will

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carry no information and large amount of entropy $S = M^2 / M_p^2$, where M_p is the Planck mass. In his model the lack of unitary S-matrix and the geodesic divergence as r $\to$ 0 lead to loss of information. Ever since Hawking's proposal [1] that a pure quantum state $\rho = |\psi><\psi|$ evolves into a mixed one $\rho = \sum\limits_{n=1}^{N} \rho_n|\psi_n><\psi_n|$ there has been a tremendous amount of work done to both falsify and back-up his claims [2-6]. Although many proposals regarding the fate of information as it falls inside a black hole have been made a consensus has still not been reached.

Recent developments [7-12] strongly suggest the processes of black hole formation/evaporation are described by unitary S-matrix. In the current paper we build upon a model which, to my knowledge, was proposed by Page [13] and advocate a scenario which suggests steady monotonic information release throughout the black hole's evolution. For now this seems like a physically reasonable and less radical approach.

We present a model assuming no remnants are left behind and the system is described by unitary S-matrix. Namely, we suggest monotonic information release begins soon after the in-modes have crossed the horizon. By making certain reasonable (conservative) assumptions regarding the interior dynamics of the black hole, we suggest an outside observer does not have to wait for half of the entropy of the hole to evaporate in order to be able to recover the initial quantum state $|\psi>$ of an ingoing matter. Further, the advocated dynamics is such that it associates the retrieval with the scrambling time scales. Moreover, we conjecture a method for storing the information regarding infalling matter onto the degenerate vacuum surrounding the hole in a layered-like manner as an alternative to the conventional storing onto the horizon. We find relations between the alternative information storing method and black hole complementarity which further support the notion of a physical membrane (stretched horizon) as far as a distant observer is concerned. The reference-based complementarity descriptions establish a time-symmetric map between past and future null infinity. Later in the paper we use black hole perturbation theory to derive a quasi-stable behavior of the horizon. As a result, under plausible assumptions regarding black hole mechanics we have found that unitary interior dynamics can cause Planckian-amplitude horizon oscillations. The conjectured horizon oscillations may account for the stretched horizon reported by an observer at future null infinity. The paper is organized as follows.

In Sec. II, by making certain assumptions, we examine a scenario for information retrieval from a black hole which has evaporated less than half of its mass. In Sec. III we present an alternative model for storing information regarding the quantum state of an ingoing matter onto the degenerate vacuum in the near-horizon region. The model we present is identical to the one given by Susskind concerning a relation between complexity and proper distance to the horizon. Section IV contains a brief formulation of the firewall paradox as given by AMPS. In Sec. V we describe the quasi-stable nature of the horizon, and further make the case for how the conjectured

oscillations may account for the stretched horizon in complementarity.

2   Partial Information Reflection

In the current Section we put forward a model motivated by an argument made by Page [13], certain generic assumptions regarding the fate of information as it crosses the horizon, and the internal unitary dynamics of the hole to make the case that "young" black holes act as partiallyreflectingmirrors. Until the end of the Section we will consider the more conservative approach that infalling information experiences no drama as it crosses the horizon and shortly after that gets embedded onto it. Alternative proposal will be given in Sec. III.

We define a "young" black hole to be one which has evaporated less than half of its coarse-grained entropy. As a result we argue an observer outside a black hole before Page time can, in principle, recover some information regarding infallen perturbation.

Consider the following gedanken experiment. Suppose we have matter in a box and an observer, Alice, who can freely manipulate it. Just as it has been argued by Preskill and Hayden [14] let us assume that Alice has studied thoroughly the matter and possesses complete knowledge of its state. Suppose now that Alice collapses the matter to produce a Schwarzschild black hole given by the metric

$$ds^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \left(\frac{1}{1 - \frac{2M}{r}}\right)dr^2 + r^2(d\Theta^2 + sin^2\Theta d\phi^2) \qquad (1)$$

where the singularity is at $r = 0$ and the global horizon is at $r = 2M$. The black hole is described by a Hilbert space H_{BH} with dimensionality of

$$dim(H_{BH}) = e^{A/4} \qquad (2)$$

in Planck units. Following the argument we further suggest Alice has complete knowledge not only of the initial quantum state of the newly formed hole but of its dynamics, too. Imagine now that Alice decides to throw inside the black hole k bits whose states she has also studied. Note that no additional perturbations have been added to the system. By assuming that Alice performs decoding once every k bits are emitted, we are interested in two questions.

- When will Alice be able to recover the first of the tossed k bits?
- How long will it take Alice to recover all of the bits?

For addressing the questions we will begin by using an argument presented by Page [13] concerning gradual information escape in the form of Hawking radiation and will then describe the internal black hole dynamics. A general estimate in [13] shows that information in young black holes may, in fact, be released adiabatically. For that reason we consider the black hole and the Hawking cloud to be subsystems of a composite system in random pure state. The information content in the emitted

photons would be barely noticeable in a perturbative analysis. Straightforwardly the emission will be low for a massive black hole. In the particular model we are interested in estimating the information content in the early radiation of a black hole which has evaporated much less than half of its entropy. Suppose that the two subsystems, the black hole and the Hawking emission, are described by Hilbert spaces of dimensions B and A, respectively. Together they compose a larger system AB. The Hilbert space dimensions will be then given by

$$dim(H_{whole}) = AB \tag{3}$$

$$dim(H_{BH}) = B \tag{4}$$

$$dim(H_{radiation}) = A \tag{5}$$

The average information content I can be approximated to be

$$I_{AB} = A/2B \tag{6}$$

where A denotes the dimensionality of the Hilbert space of the Hawking cloud $H_{radiation}$ and B denotes the dimensionality of the subsystem of the black hole where $dim(H_{BH}) = A/4$. The initial emission of information has been calculated [13] to be

$$\frac{dI}{dt} \sim e^{-4\pi/y^2} \tag{7}$$

where $y = M_p/E$ and E is radiation energy.

The smaller subsystem of a larger system in pure state is expected to be in nearly maximally mixed state. For a young black hole we expect $B > A$. As the hole evolves, however, due to the effects of the strong gravitational field onto the quantum vacuum, the black hole will monotonically lose mass. Based on the assumption we made in the gedanken experiment that no matter is further tossed into the hole (except for the initial k bits where $k \ll H_{BH}$), as it radiates we should see the following inversed proportionality between the subsystems $dim(H_{BH}) = -dim(H_{radiation})$. As a result in the case of a young black hole we expect to find little information in the smaller subsystem. In fact most of the information is found in the correlations between the subsystems A and B. Detailed calculations have been carried out in [13].

Based on the provided argument and a few generic assumptions given below we address the questions regarding information retrieval time.

The notion that black holes scramble information very rapidly rather than destroy it is embraced throughout the paper. They are conjectured to be the fastest scramblers in nature [15]. We define a system to be scrambled when a subsystem, smaller than half of the larger system, reaches maximum entanglement entropy. We take the scrambling to be a strong form of thermalization. In the context of black hole physics, the scrambling time t_s is the smallest possible time scale for localized

perturbation to become scrambled, (strongly thermalized) and hence effectively undetectable

$$t_s = R \ln\left(\frac{R}{l_p}\right) \qquad (8)$$

where R is the Schwarzschild radius and l_p is the Planck length. In other words, that is the time it takes for a state to become maximally mixed with the degrees of freedom of a system. Preskill and Hayden have recently made the case [14] that for a sufficiently old black hole (after Page time), the scrambling time is of order the retrieval time $t_s \sim t_{retrieval}$. The retrieval time in this context should be regarded as the time it takes an outside observer to recover initially tossed information from a black hole in the form of Hawking radiation. For instance, suppose we throw a bit of classical information into an already scrambled system. As a result the system will be briefly taken out of its present state, and of order t_s later will return to its initial strongly thermalized state. Based on the provided example one might argue the scrambling time is the time period for which the inner dynamics of an already scrambled system "deals" with the additionally introduced perturbation (which has, in a way, partially unscrambled it), and thus returns to its initial scrambled state.

Moreover we suppose infalling matter experiences no drama as it crosses the horizon $r = 2M$. Further we believe in the presence of a strong gravitational field (like the interior of a black hole as $r \to 0$) the strong energy condition (SEC) $(T_{\mu\nu} - \frac{1}{2}T g_{\mu\nu})X^\mu X^\nu \geq 0$ may be violated. Therefore as infalling matter reaches $r = 0$ the unitary dynamics transform the coarse-grained into fine-grained entropy. Thus information is not destroyed but rather processed. It is strongly thermalized (scrambled), and by the repulsive gravity features of the $r = 0$ region, embedded onto the horizon. The Bekenstein-Hawking bound $S = A/4$ is satisfied as far as an outside observer is concerned. We argue the distribution of the scrambled information across the horizon is an exclusively stochastic process. Hence the strongly thermalized information is not embedded onto the horizon in a perfectly uniform manner. Homogeneous distribution would imply that each of radiated Hawking particles carries a bit which would be problematic. In that case the retrieval time would be of order $logR$ which is less than $R \ln\left(\frac{R}{l_p}\right)$. Information retention in a time scale smaller than the scrambling time, Eq.(8), would allow an outside observer to verify quantum cloning. Moreover, it is hard to come up with a physically reasonable scenario for storing the information onto the horizon in a specific pattern.

As a result of Page's argument and the generic assumptions we have put forward regarding the unitary interior dynamics of a black hole which has evaporated less than half of its coarse-grained entropy we argue the required time for an outside observer, Alice, to recover the first of the initially tossed k bits cannot be known a priori. Regardless of Alice's complete knowledge about the black hole's state, dynamics and the state of the k bits, there are no measurements she can perform in order to derive a time scale for the retrieval. The inability of determining $t_{retrieval}$ is rooted in the completely probabilistic nature of the distribution of fine-grained

entropy across the horizon. Also, nonuniformity is necessary for deriving a value for $t_{retrieval}$ which obeys the no-cloning bound $t_{retrieval} \geq t_s$, and thus preserves the linearity of quantum mechanics. As we have already made the case, if we assume that the thermalized matter is effectively "stretched out" throughout the horizon (perfectly uniform distribution, as one would naively expect) we allow quantum xeroxing to be verified. Following the same line of reasoning and expanding the argument we arrive at the same conclusion for the case of retrieving all of the thrown k bits. Namely, Alice cannot a priori derive a time scale. It should be noted there is nothing, in principle, which forbids the first k bits emitted from a young black hole to be that same k bits that Alice had tossed an order of t_s earlier. However, due to the random nature of the involved processes (scrambling and distribution across the horizon) the probability of that occurring is exponentially small.

We now derive several generic relations which follow from classical black hole mechanics and thermodynamics regarding the evolution of the information content in the Hawking radiation as a young black hole evaporates. Let us substitute the information content I from Eq.(6) with Δt , where Δt is the typical retention time. We get

$$\Delta t = A/2B \tag{9}$$

One can easily derive a relation between the typical retention time Δ t and black hole's mass/area

$$\Delta t = -dim(H_{radiation}) \tag{10}$$

$$dim\,(H_{radiation}) = \frac{1}{16\pi M^2 G^2} \tag{11}$$

where M is the mass of the hole and G is the Newton constant. As the black hole evaporates, the dimensionality of the Hilbert space describing the emitted Hawking radiation cloud $dim\,(H_{radiation})$ grows. Hence the usual time it would take Δt for initially thrown k bits inside the hole to be retrieved by an outside observer (Alice) decreases. This implies the information content in the radiation I is associated with the retrieval time

$$\Delta t = -I \tag{12}$$

However, Δt is not unbounded. As the black hole evaporates half of its entropy, we assume we get into the realm of the argument given by Preskill and Hayden [14], Figure 1. Namely, as the hole passes its "half-way" point (Page time) Δt reaches its lower bound

$$\Delta t \sim R \ln\left(\frac{R}{l_p}\right) \tag{13}$$

as $dim\,(H_{radiation}) \geq dim\,(H_{whole})$

The provided relations Eqs. (9-12) are simple tools for more robust illustration of the given gedanken experiment and the overall model. This further justifies our claim that black holes which have evaporated less than half of their entropy can be regarded as partially-reflecting mirrors. Before Page time, an observer, Alice, staying
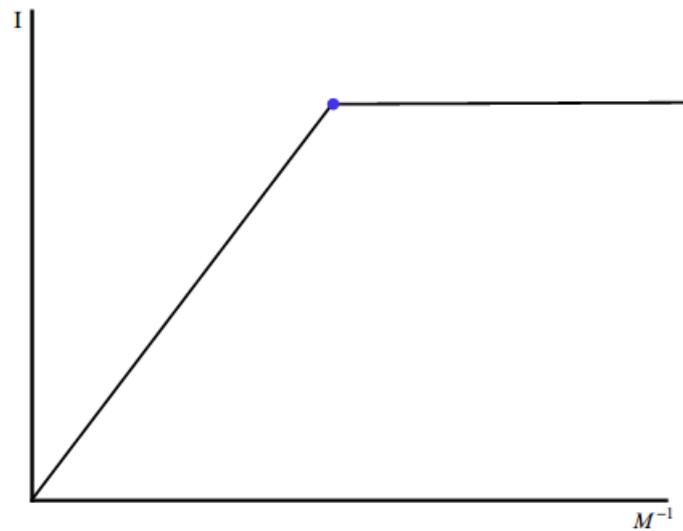
Fig. 1 Depiction of the information content of the emitted radiation by a young black hole I as a function of black hole's mass M. The blue dot denotes the Page time at which $\Delta t \sim t_s$.

outside a black hole, collecting and decoding radiation would expect to receive a bit every once in a while, so to speak. We argue Alice can expect to get a complete and rapid "reflection" of the thrown k bits only after the "half-way" point has been passed.

3   Alternative Information Storing

In this Section we consider an alternative scenario for storing information about infalling matter. In the past, attempts have been made to falsify the hypothesis of a complete (remnant-free) evaporation with gradual release of information [21,22] by stating that locality has to be violated in order for information to escape from $r < 2M$. However, it was proposed in [21,22] that one can preserve locality by assuming no information enters the interior of the black hole. The current Section provides such a mechanism.

It has been recently argued [16,17] that an observer outside a black hole should see slight deviations from the unique Minkowski vacuum. Hence implying the apparent uniqueness of the quantum vacuum is an effective field theory. As a result the near-horizon black hole region should be surrounded by energetically indistinguishable states. Following the postulates of black hole complementarity [18] we suppose the degenerate vacuum should be able to store information about infalling matter and not get physically excited. Thus an infalling observer will not feel anything out of the ordinary (no drama). It has been suggested the number of the different vacua $|\psi_n >$ is the exponential of the Bekenstein-Hawking area/entropy bound; namely

$$|\psi_n > \; = \mathrm{e}^{\mathrm{A}/4} \tag{14}$$

where A is the area of the black hole.

Spherically symmetric solutions to Einstein field equations (EFE) describe generic collapse with the horizon region being a flat plane with no special dynamics. Quantum vacuum in asymptotically flat spacetime with a boundary surface leads to a certain ambiguity (Casimir effect). In this case the number of measured eigenstates $a_i^\dagger a_i$, will be observer-dependent. Here $a_i^\dagger$ is a creation operator, and a_i is an annihilation operator.

Suppose we have a pair of observers, Alice and Bob, each carrying a measuring apparatus, where Alice is close to the event horizon, and Bob is far away. We expect Alice and Bob to disagree on the number of the produced eigenstates in the near-horizon region

$$\phi = \sum_i (a_i^\dagger f_i^* + a_i f_i) \tag{15}$$

$$\phi = \sum_i (b_i^\dagger f_i^* + b_i f_i) \tag{16}$$

Hence they measure different number of particles, $N_A \neq N_B$.

In [19] Susskind introduced a duality which connects the distance from the horizon to the computational complexity in order to study the relation between black holes and complexity. To do so he conjectured an onion-like (layered) structure in the near-horizon region. Each layer carries different degrees of freedom. We believe similar method can be used for storing information onto the degenerate vacuum. Suppose we embrace the same layered structure,
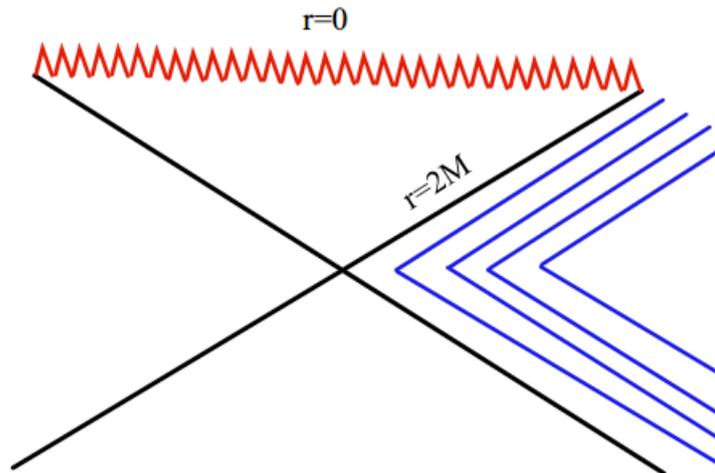
Fig. 2 Penrose diagram for the layered (onion-like) structure of the degenerate vacuum in the near-horizon region. The blue lines indicate the different layers. The singularity is given by the red wave-like line.

Let's assume the thickness of each layer is of order l_p and that they extend in outward direction of order R, where R is the Schwarzschild radius. It seems reason-

able to make that assumptions since at that scale the geometry of the spacetime is flat (Minkowski vacuum)

$$\frac{R}{l_p} = S_{BH} \qquad (17)$$

In this case the layered degenerate vacuum is sufficient to effectively reproduce the degrees of freedom of the black hole. As a result, ingoing matter should encode the information about its initial quantum state onto the degenerate vacuum. We further wish to extend the assumption we made about the random embedding of scrambled information onto the event horizon. Namely, we suggest even for the case of layered-structured degenerate vacuum one should regard the storing of information as a completely random process. In this case the emitted thermal Hawking photons will periodically "pick up" information from the vacuum. We suspect the exact mechanism for that requires insights from quantum gravity which we do not yet possess. Thus not every single Hawking particle will carry information. Addressing the questions raised in Sec. II in the context of the current framework yields identical results. This could be easily seen by the similarities between the stochastic information encoding onto the horizon and the degenerate vacuum. Although it may not sound as straightforward as the scenario for encoding onto the horizon given in Sec. II, the current alternative should not be ignored altogether as it succeeds to achieve similar results.

4   Postulates Inconsistency

In the present Section we examine AMPS argument regarding an inconsistency between the postulates of complementarity.

Recently, it has been argued by AMPS [23] there is an inconsistency between the postulates of black hole complementarity [18] which causes drama for an infalling observer after half of the mass has been evaporated. The three postulates are given as follows. The absence of drama for an ingoing observer is also mentioned in [18], and has been established in the literature as a fourth postulate.

Postulate 1: The process of formation and evaporation of a black hole, as viewed by a distant observer, can be described entirely within the context of standard quantum theory. In particular, there exists a unitary S−matrix which describes the evolution from infalling matter to outgoing Hawking-like radiation.

Postulate 2: Outside the stretched horizon of a massive black hole, physics can be described to good approximation by a set of semiclassical field equations.

Postulate 3: To a distant observer, a black hole appears to be a quantum system with discrete energy levels. The dimension of the subspace of states describing a black hole of mass M is the exponential of the Bekenstein entropy $S(M)$.

Postulate 4: A freely falling observer experiences nothing out of the ordinary when crossing the horizon.

We wish to preserve unitarity in accordance with Postulate 1

$$\rho = |\psi><\psi| \tag{18}$$

Following the semiclassical approximation, stated in Postulate 2, combined with the desired information preservation in Postulate 1, we see that an infalling observer should encounter high-energy quanta at the horizon,
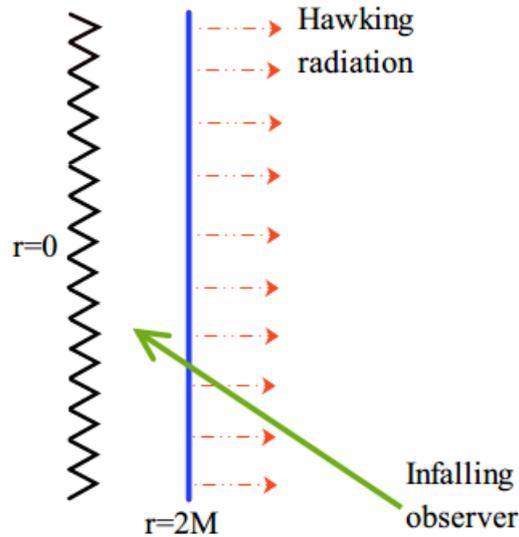
Fig. 3 Black hole in Eddington-Finkelstein coordinates. The wave-like line ($r = 0$) is the singularity. The event horizon is depicted by the solid blue line. The solid green line depicts an infalling observer, and the Hawking radiation is shown by the red arrows.

However, according to Postulate 4, there should be absence of drama for an infalling observer. Hence she should measure the ground state with no deviations from the classical Unruh vacuum. Suppose an infalling observer is counting the high-energy modes with a measuring apparatus. Following Postulate 4, the expectation value should be zero, $N_i = 0$, where $N_i = a_i^\dagger a_i$. As AMPS have pointed out, this statement appears to be in contradiction with our nomenclature regarding quantum field theory in curved spacetime (Postulate 2). As Hawking has explicitly shown in his semiclassical calculations [24] the strong gravitational field acts on the quantum vacuum and polarizes the virtual particle pairs. The number of the produced particles which are radiated away to infinity is thus given by

$$< 0 \left| a_i^\dagger a_i \right| 0 > = \sum_i |\beta_i|^2 \tag{19}$$

By finding the value of β we approximate the number of the emitted quanta. As it follows from black hole perturbation theory [25,26] as the hole evaporates it loses mass which leads to an increase of the temperature, and thus faster evaporation rate. Although the value of β is generally negligible, the effects of the black hole's mass on the matter fields add up during the course of evaporation, and should be significant after Page time.

Therefore, after half of the black hole has evaporated the number of out-modes, that an infalling observer carrying measuring apparatus will count, should be non-zero, hence causing drama and contradicting Postulate 4.

Because of the contradiction between the postulates of complementarity, AMPS argue the following three statements cannot all be true:

(i) Purity of the emitted Hawking quanta.

(ii) Absence of drama for an infalling observer.

(iii) Semiclassical physics in the vicinity of the black hole.

5 Oscillations as Stretched Horizon

We now address the question of what boundary conditions need to be present at the vicinity of the event horizon in order to avoid formation of a firewall for a sufficiently old black hole. We then put forward the quasi-stable behavior of the horizon which can account for the conjectured in complementarity stretched horizon.

As it has been argued in Sec. IV AMPS' argument leads to violation of the no-drama principle after Page time if there is an entanglement (maximal correlation) between early- and late-time Hawking radiation. It has been shown in [27] that dis-entangling the quantum vacuum in the near-horizon region by introducing certain boundary conditions preserves the effective field theory for old black holes. The imposed boundary conditions have to meet certain requirements, namely to change the correlation between the in- and out-modes without affecting the thermal spectrum of the radiation emitted to $\mathcal{L}^+$, and preserve the conservation of momentum. Even small deviations from the purely thermal spectrum of the Hawking particles will lead to stress-energy divergence due to the large blueshift which occurs when an observer at $\mathcal{L}^+$ traces the particles to the origin. In that case, $T_{\mu\nu} \to \infty$ as $r \to 2M$.

Following [18,27] as far as a far away observer is concerned there is a stretched horizon (physical membrane) located l_p away from the global horizon ($r = 2M$) in outward direction. The proposed membrane acts as a partially-reflecting mirror with the following characteristic

$$\Phi_{out} - \Phi_{in} = 0 \tag{20}$$

where *in* and *out* stand for coming from $\mathcal{L}^-$ and radiated to $\mathcal{L}^+$, respectively. Thus an observer at $\mathcal{L}^+$ can obtain all of the information from $\mathcal{L}^-$ and vice versa. The reflective property Eq.(20) implies we preserve the unitary evolution of the S-matrix and establish a complete time-symmetric map between past and future null infinity. As a result the stress-energy tensor is normalized. That being said, the conditions imposed in [27] lead to polarization of the particle pairs solely on one side of the horizon, either $r < 2M$ or $r > 2M$, and hence break the trans-horizon correlations.

We argue the Planckian-amplitude horizon oscillations [20] can generically account for the suggested boundary conditions. The conjectured oscillations arise

naturally from perturbation theory. The effect is argued to be caused by transformation of coarse-grained degrees of freedom into fine-grained degrees of freedom which is an integral part of the black hole formation/evaporation process. We assume the frequency of the horizon oscillations are related to the mass of the hole following trivial principles from black hole thermodynamics. That being said, the oscillations frequency should be gradually increasing for a monotonically evaporating isolated black hole with no ingoing matter present. Hence the frequency of the oscillations solely depends on the mass of the hole

$$\omega = \sqrt{\frac{-T_{\mu\nu}}{M}} \tag{21}$$

where $T_{\mu\nu}$ is the emitted Hawking radiation and M is the mass of the black hole. We assume the conjectured oscillations can account for the vacuum disentanglement.

Suppose we have a spherically symmetric collapse given by the Schwarzschild metric, Eq.(1). In the context of complementarity an observer at $\mathcal{L}^+$ would measure the entropy of the black hole to emerge from the fine-grained degrees of freedom outside the global horizon (stretched horizon). As it has been argued in [18] each point from the global horizon ($r = 2M$) is projected onto a physical membrane located a l_p away. Hence the whole horizon surface is shifted by order of , where δ is a small positive constant. Therefore the entropy of the event horizon equals the entropy of the stretched horizon which obey the Bekenstein bound in Planck units

$$S_{horizon} = S_{stretched} = A/4 \tag{22}$$

Because of the established equality we argue the oscillations can account for the physical membrane as far as an observer at $\mathcal{L}^+$ is concerned.

Since the black hole polarizes the quantum vacuum in the vicinity of its horizon, we suppose the proposed oscillations are sufficient to produce the desired effect, namely the particle pairs remain in either the interior or exterior region. Thus breaking up the vacuum entanglement. Suppose we have a collapse in initially pure state

$$|\psi> = \sum_i |\psi> |\bigotimes i> \tag{23}$$

where $|\psi> \in H_{out}$ and $|i> \in H_{in}$. Here H_{out} and H_{in} stand for radiation emitted to infinity and radiation close to the horizon, respectively. For a black hole after Page time we assume $|\psi> >> |i>$. If we interpret the radiated Hawking particles in terms of Hilbert spaces, we get $dim(H_{out}) > dim(H_{in})$ [28]. That being said, when an observer at $\mathcal{L}^+$ traces the Hawking quanta back to the origin no deviations will be observed due to the purely thermal spectrum of the emission. Moreover, when the out-modes are traced back no membrane will be present. As far as a close-by observer is concerned infalling matter is not reflected by a stretched horizon, and crosses the $r = 2M$ region with no drama. We argue there will be discrepancy between the reference-based descriptions of order the scrambling time t_s , Eq.(8),

due to the lack of perturbation to the background metric caused by ingoing matter. Hence a close-by observer should see matter being radiated away from the global horizon, which would imply it has been reflected by the singularity region (dS core) [20] of order t_s later.

So far we have provided a complementary description of the physical membrane, and have shown how the conjectured horizon oscillations can account for it. However, we still have not addressed the question of what causes the infalling matter reflection, as reported by an observer at $\mathcal{L}^+$.

In Sec. III we have argued the near-horizon region is surrounded by numerous energetically-identical vacua. Later on in Sec. V we have shown the number of the indistinguishable vacua, Eq.(14) equals the entropy of the global, and hence stretched horizon of the black hole, Eq.(22). That being said, we argue a distant observer (Bob) can falsely interpret the information stored onto the degenerate vacuum as a partially-reflective surface. As far as Bob is concerned, infalling matter gets thermalized, and reflected back by the stretched horizon. Moreover, the out-modes emitted to infinity are also seen to originate from the physical membrane, from the perspective of an observer at $\mathcal{L}^+$. For Alice, however, who is at proper distance r from the black hole nothing unusual happens. Infalling matter experiences no drama, and the Hawking particles are emitted from the global horizon ($r = 2M$).

We have been able to show that by starting from different principles one might derive a complementary description similar to the one given in [18].

6 Conclusions

Section II was built on the premise that black hole are objects which process information. By using mathematical framework given by Page [13] and making certain generic assumptions regarding the unitary interior dynamics of a black hole which has evaporated less than half of the its coarse-grained entropy, we made the case that one does not have to wait for Page time in order to recover information concerning in-modes. In fact, what we have shown is that an outside observer, having complete knowledge regarding the initial quantum state of the black hole and the tossed matter, can, in principle, retrieve information in the form of Hawking particles. Hence establishing young black holes as partially-reflecting mirrors. Also, we presented several relations which further explain the connection between the information content in the Hawking radiation I and black hole's mass . As it turns out, once the "half-way" point (Page time) is reached the typical retention time reaches its lower bound $t_s \sim t_{retrieval}$. Furthermore, in Sec. III we described an onion-like layered behavior of the degenerate vacuum in the near-horizon region that can record information about ingoing matter. In both cases, conventional (horizon) and alternative (degenerate vacuum) we managed to obtain similar results for the typical time scale for information retention. Thus in both cases CPT symmetry is respected. We have then shown (Sec.V) that the generic phenomena of Planckian-amplitude

horizon oscillations can account for the stretched horizon proposed in black hole complementarity, and also provide the necessary conditions for breaking up the entanglement between early- and late-time Hawking particles. Thus preventing the formation of a firewall after Page time. The conjectured oscillations follow from classical black hole perturbation theory. The model builds on the complementary picture given by Susskind by providing natural explanation of its basic features.

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