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Is Alice burning or fuzzing?

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Abstract: Recently, Almheiri, Marolf, Polchinski and Sully have suggested a Gedanken experiment to test black hole complementarity. They claim that the postulates of black hole complimentarily are mutually inconsistent and choose to give up the "absence of drama" for an in-falling observer. According to them, at least after Page time, the black hole is shielded by a firewall. This has generated some controversy. In our opinion a lot of this is caused by confusions stemming from an observer-centric language. In this letter we formulate the AMPS's Gedanken experiment in the decoherence picture of quantum mechanics without invoking any sentient beings. While we find that the objections raised by advocates of observer complimentarily are irrelevant, an interesting picture emerges when we take into account objections from the advocates of fuzzballs. We find that low energy wave packets "burn up" like AMPS claim while high energy wavepackets do not. This is consistent with Mathur's recent proposal of *approximate complementarity* for high energy quanta. *Within* the fuzzball proposal AMPS's firewall fits in nicely as the thermal bath that low energy in-coming quanta perceive.

Contents

1 Introduction

Recently Almheiri, Marolf, Polchinski and Sully (AMPS) have argued that if a black hole formed by a collapse of a pure state is to evaporate away to a pure state, then an observer falling into the black hole at sufficiently late times will encounter high energy quanta and burn up at a *firewall* [1].

To many people this is a surprising result because of the lore that the horizon of black holes formed by collapse of a pure state, is in the vacuum state for the in-falling observer. However, previous papers of Mathur [2, 3] have shown that if information is to come out, the state at the horizon has to be *very* different from an information-free vacuum state for the in-falling observer. The recent Gedanken experiment by AMPS has incorporated this result and provided a testing ground for black hole complementarity. They conclude that these degrees of freedom at the horizon are a firewall that leads to a "drama" for the in-falling observer.

There have been several responses to AMPS's firewall result. In [4] Mathur and Turton claim that a macroscopic detector cannot detect the difference between the thermal and a typical state. In [5, 6] Bousso and Harlow even argue for the persistence of an information-free horizon using observer complementarity saying the various subsystems are entangled differently for different observers.[1] In our opinion these issues can be settled from not focusing too much on an observer-centric language. Our purpose in this letter is to explicate AMPS's analysis in the language of decoherence and ask what is the "fate" of an in-falling

[1]We would like to point out a confusing use of the term equivalence principle in [5] where the notion of observer complementarity is introduced as a response to AMPS's result in order to "save" the equivalence principle. AMPS found that there is a stress tensor at the horizon and therefore concluded an in-falling person does not fall freely. This is no more a violation of the equivalence principle than an astronaut's not feeling weightless upon re-entry into the Earth's atmosphere is. We thank David Turton for this analogy.

wave packet. When phrased in the decoherence language we find the main result of Mathur and AMPS, that there is information at the horizon, stands validated and the results of [5, 6] are irrelevant.

We then comment on the realization of the degrees of freedom as fuzzballs - singularity and horizon less configurations with some very complicated structure in the vicinity of the would-be horizon. We advocate, by the application of *Occam's razor*, that fuzzballs are the *most conservative* resolution of the information loss paradox.

Finally, we address the most interesting issue of what happens to an in-falling observer. Since measurement is just decoherence by entanglement we can ask this question by looking at the fate of the in-falling wave packet. We find that depending on the width of the in-falling wave-packet its interaction with early and late radiation is different. While it seems unlikely that for narrow wave packet ($E \gg kT_{BH}$) the interaction with early and late radiation is consistent with the picture AMPS advocate[2], for wide wave packets ($E \sim kT_{BH}$) AMPS's picture seems correct: the firewalls seem to be the thermal bath that low energy in-coming quanta perceive. In the context of fuzzballs this can be seen as a macroscopic probe being able to see only the coarse grained description while a microscopic probe can perceive the structure of the fuzzballs.

2 The Gedanken experiment of AMPS

AMPS start with three postulates as put forth in [8] based on the assumption that black hole evolution is consistent with quantum mechanics:

- 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 a good approximation by a set of semi-classical 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).

and add one more postulate to this set which states:

- Postulate 4 (AMPS): A freely falling observer experiences nothing out of the ordinary when crossing the horizon[3].

[2] AMPS's argument of burning is based on an in-falling observer's measurement of early radiation projecting the entangled late radiation in the number operator basis as pointed out by Nomura et. al. [7]. For narrow wave packets it is not clear how such a "measurement", which is governed by local, unitary evolution, can be performed.

[3] It is worth noting that the word "experiences" might leave room for different interpretations. In addition the observer-centric language can cause confusions, like the Schrodinger cat paradox has already taught us. Below we review the main points of AMPS's argument and in section 3 we reformulate their argument without observers and measurements, just in terms of local interactions of wave packets.

They go on to argue citing results of [9] that if a body in a pure state is radiating unitarily, the entanglement entropy in the radiation initially rises but at some point has to start decreasing and eventually reaches zero when the body has radiated away completely. Moreover, there is an upper bound, known as the Page time, when the entropy has to start decreasing: namely when half the entropy has been radiated away. Imagine a pure state collapsing into a black hole and emitting half its entropy in early Hawking radiation A. Unitary black hole evaporation now requires that any further outgoing quantum of radiation B has to be maximally entangled with A so that the entropy of the combined system of early and later Hawking radiation starts decreasing. Let us introduce an in-falling observer, called Alice, who encounters these outgoing Hawking quanta B close to the stretched horizon and later their partner quanta C behind the horizon. Since B is already maximally entangled with A it cannot be maximally entangled with C, the latter is however a necessary requirement for the BC system to be the vacuum state for Alice. AMPS claim that this implies Alice encounters high energy quanta and "burns up", hence the name *firewall*.

In summary, the postulates 1), 2) and 4) - purity of the Hawking radiation, semiclassical behavior outside the horizon and absence of infalling drama, are mutually inconsistent and they decide to give up the last one. That an information-free horizon cannot lead to a unitarity evolution of black hole evaporation has already been shown by Mathur [2, 3]. But while he proposes [10, 11] that the interaction of Alice with the state at the horizon may have an *approximate and short lived* description as continuing past that region[4], AMPS propose that the black hole is protected by a Planck-scale firewall at which an in-falling observer burns up.

3 The rephrased Gedanken experiment

We wish to rephrase the "observer-centric" language of the previous section 2 in favor of decoherence [12] because such a language can cause a lot of confusion, as is well known in the case of Schrödingers cat. As we will see in later see this exercise will turn out to be quite fruitful.

Therefore, we replace the "observers" Alice and Bob by wave packets. While we will continue to use the names Alice and Bob, they should not be understood as some sentient beings but as wave packets with the usual properties of large density of states etc. to make them classical enough[5]. In this picture wave packets interact when they overlap via a local, unitary evolution and get entangled.

3.1 Non observer-centric Black hole complementarity

We want to understand the fate of a wave packet that is moving towards the black hole horizon in the black hole complementarily picture. Far from the black hole Alice is described by semi-classical evolution (figure 1). When it gets close to the horizon there are two

[4] We will have more to comment on Mathur's proposal within the fuzzball proposal in section 4.

[5] Since we view Alice and Bob as wave packets we will use the word *it* to refer to them. We apologize to them for this rudeness.

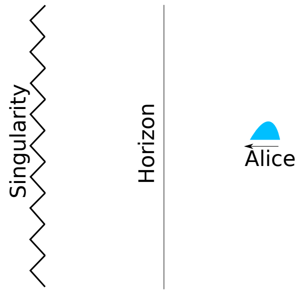


Figure 1. A wave packet far away from the horizon evolves semi-classically.

complementary descriptions: one where it passes through and then hits the singularity (figure 2) and another where it hits a "membrane", scrambles, and with its information being finally re-emitted unitarily, escapes to infinity (figure 3).

(a) (b)

Figure 2. One of the complementary descriptions is the wave packet passes through the horizon and hits a singularity.

(a) (b)

Figure 3. The other complimentary description is that the wave packet gets mapped onto the degrees of freedom on a membrane. This wave packet is now scrambled, looses any semblance of itself, but the information leaks out of the membrane unitarily.

While discussing in a non-observer centric language we realize that the crucial feature in black hole complemenarity is that when the wave packet reaches the stretched horizon it evolves in two distinct ways. In *some sense*, its state gets mapped onto *two copies* in separate Hilbert spaces which then evolve with different Hamiltonians[6].

This remarkable proposal was forwarded in [8, 13] to reconcile a pair of otherwise incompatible statements, that there is nothing from which a wave packet can *bounce off* at the horizon and yet *somehow* information must be recovered.

In normal situations such an ad hoc prescription is not allowed as it leads to many inconsistencies and - in trying to fix them - unnecessary postulates. Copying of quantum states e.g. leads to *cloning*. While this does not evoke problems if the copies cannot interact as is in the case of black hole complimentarily, one might still ask what it means to have two copies of a state?

This prescription is consistent if the complementary pictures are *dual* descriptions. For example, the state of a closed string heading towards a stack of D-branes gets mapped onto them as open string states in one picture, while in the dual description the close string continues to move on into an AdS space[7]. For such dual descriptions there is no issue with cloning. However, the hamiltonian evolutions of the states need to be consistent since, at the end of the day, in one description, the closed string emerges out of the AdS as a closed string in flat space and in the other description the open strings leave the D-brane as a closed string. They must be in the *same state*.

However, black hole complementarity is not a duality. This conclusion can be drawn from the completely different outcomes in the two complementary pictures. If it is not a duality then one can ask *what* it is and what is this operation that makes two copies of the states[8]? We will comment on a recent proposal of Mathur to view black hole complimentarily as an *approximate complementarity* in the context of fuzzballs in section 4.[9] For now we continue with our non observer-centric description.

3.2 Non observer-centric AMPS

Now let us look at the AMPS Gedanken experiment in terms of these wave packets. We begin with the unitary evolution process of Alice away from the black hole in the causal future of early radiation A. While for clarity we have drawn only one wave packet A in figures 4, it should be thought of as many wave packets: when Alice interacts with A, it interacts in fact with many such wave packets successively. How strong the interaction is and how much entanglement will be generated between Alice and A in the process is governed by local unitary dynamics and the properties of the wave packet Alice, e.g. what frequencies is the wave packet supported on. This will cause the crucial difference in Alice's "experience" which we alluded to in section 2. We will come back to this issue in section 5. Regardless of this, in each encounter there is some mixing between Alice and wave packets in A.

[6]For discussion why this is consistent with no quantum cloning see [13, 14] and our comments below.

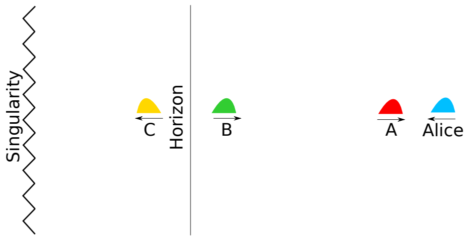
[7]We thank Samir Mathur for pointing this out to us.

[8]If one is uncomfortable with the language of making two copies of the states one can say it is two descriptions of the same state which evolve differently.

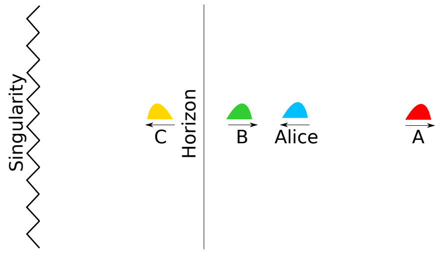
[9]We note in passing that AdS/CFT does not provide a solution to the information paradox: this duality requires the same evolution of two copies of information but in the presence of a black hole in the infra-red the evolution of these two copies is different and there is no duality.

When Alice gets closer to the horizon it interacts with wave packet B. Since B is just a blue shifted version of A and Alice is also blue shifted, this interaction is stronger than any of the Alice-A interactions.

After these interactions Alice heads towards the stretched horizon. At this point, it is worth observing that Alice's interactions with A and B are encoded in Alice and in the AB system. We have not talked about any measurements or observations. We will have something to say about this in section 5. When Alice reaches the (stretched) horizon



(a)



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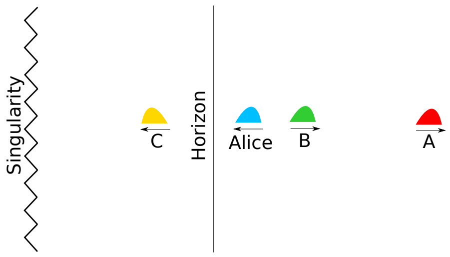


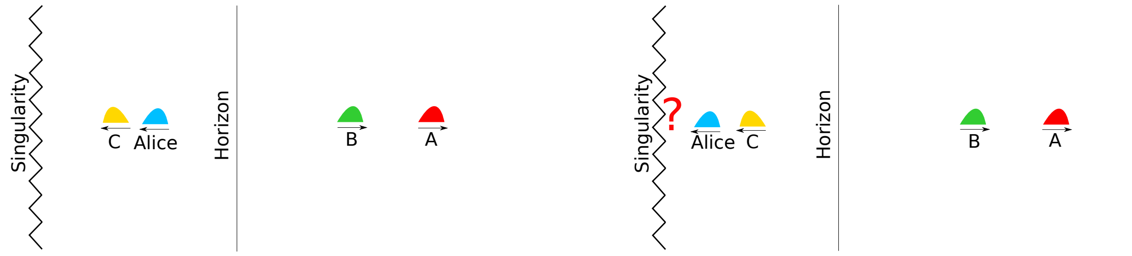
(c)

Figure 4. Away from the horizon postulate 2 tells us that the usual rules of quantum mechanics work. When wave packet 'Alice' crosses the wave packets 'A' and 'B' they will get entangled successively.

we make use of black hole complementarity: According to one picture Alice (entangled with AB) goes through the horizon and encounters wave packet C, the in-falling Hawking pair of B, with which it interacts and mixes and eventually hits the singularity (figure 5).[10] In the complementary picture Alice's (entangled with AB) state gets mapped onto the thermal membrane at the stretched horizon where it gets scrambled and eventually re-emitted unitarily as radiation to infinity (figure 6).

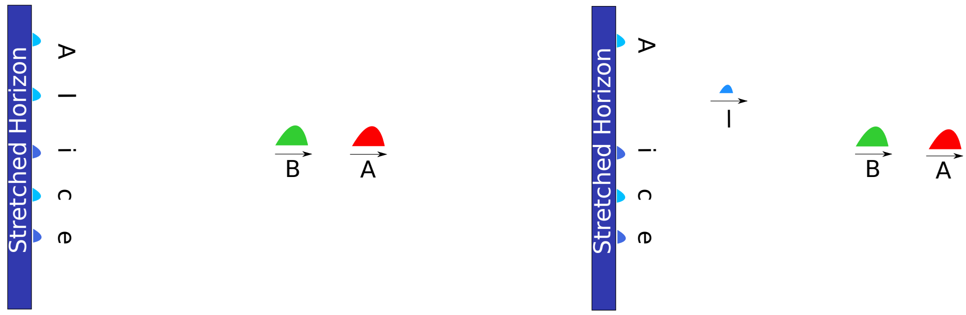
Unitarity of black hole evaporation requires B to be maximally entangled with A while free infall requires B to be maximally entangled with C. A system cannot be maximally entangled with two distinct systems. Alice interacting with system AB will have different evolutions depending on whether B was maximally entangled with A or C to begin with. The state of this wave packet will then be recorded on the stretched horizon in one of the black hole complementarity pictures. In the other complementary picture it and fall

[10]While one may argue that the singularity will get resolved at Planck scale it is not clear how this picture can be modified to make black hole complementarity an actual duality.



(a) (b)

Figure 5. In one complementary picture Alice having interacted with A and B falls through the horizon. Its interaction with C will depend on whether B was entangled with A or C. It then falls into the singularity.



(a) (b)

Figure 6. In the other complementary picture Alice's state after having interacted with AB is registered on the membrane. It gets scrambled but eventually leaks out unitarily.

through the horizon, and interacts with C. The interaction of Alice with C will have a different evolution depending on wether B was maximally entangled with A or C to begin with. Eventually in this complementary picture Alice hits the singularity.

AMPS argue that since B is maximally entangled with A, Alice's encounter with B is fatal for it (which in our language should be read as its wave packet changes so much that it does not resemble its former self). Thus they advocate that black hole complementarily has to be given up. However, while it is clear that Alice's state will be different than previously thought, it is not immediately clear by how much. The answer to this will depend on the properties of the wave packet Alice. Thus we see the possibility of some kind of approximate complementarity. Such an idea was recently proposed by Mathur and we will talk about this more in section 4 and section 5.

3.3 Observer Complementarity: Alice in Wonderland?

In follow-up papers to the AMPS argument Bousso [5] and Harlow [6] have argued, using *observer complimentarily*[11], that the interpretation of strong sub-additivity by AMPS is

[11]Observer complimentarily is different from black hole complementarity as discussed in [5].

incorrect. They say different observers can find different answers to the question of whether B is maximally entangled with A or C. We find this claim somewhat like the Schrödinger cat paradox. In our opinion it is best to phrase all quantum mechanics in terms of decoherence without invoking observers. We try understand their arguments in light of this and find some fantastic outcomes.

In order to analyze their claims we try to gather the postulates used in [5, 6]. In [6] the postulates used are stated explicitly. Postulates 1,2 and 4 appear to be the same as the ones in section 4 but the Postulate 3 is replaced by:

- Postulate 3 (Harlow): If two observers can causally communicate the results of their experiments, they must agree on the results of those experiments.

The third postulate in section 2 was needed to say that from the outside observer's point of view there is a membrane at the stretched horizon which can hold the information. Without the same, it is not clear how Harlow assumes unitarity. Since he does seem to assume unitarity for the outside observer, we will assume he also uses postulate 3 of section 2. The postulates in [5] are not stated explicitly but the membrane is used so it seems they are the same five.

We now review their argument. In [5] it is argued that since different observers have different causal diamonds they have their 'own theory'. Although an outside and an in-falling observer, both, need to find the early Hawking radiation A to be consistent with unitary evolution, the in-falling observer can *relinquish* the possibility of measuring B and is therefore *free to claim* that A is not entangled with B. After crossing the horizon the in-falling observer then concludes that B and C are entangled and is safe. While, in [5] the possibility of a communication between the two observers spoiling the argument is raised, [6] follows through with a calculation arguing that this possibility is not realized. An in-falling observer who has an upper bound on what temperatures are "unhealthy" i.e. will burn him/her, cannot process the information of the encounter with such an unhealthy quanta B and send it to an asymptotic observer before getting to the stretched horizon.

In order to carefully analyze these arguments we abandon this observer-centric language and talk about wave packets. For the picture where Alice hits the membrane, the story goes along the same lines as in the previous section: It moves towards the stretched horizon, crosses and entangles with B, then gets thermalized at the membrane and returns in the form of scrambled radiation. In this language what [6] is really stating above is that the information of the encounter of Alice and B cannot be sent as a small wave packet *before* it hits the membrane. While his calculations seem to be correct the answer is moot because the state of Alice is mapped onto the membrane and will eventually *be communicated* to Bob. Bob *will* know what the result of Alice's encounter with B was. Thus, while postulate 3 above seems reasonable it is not relevant in this situation.

Next, let us try to see if we can understand what it would mean, as stated in [5], that different observers have their 'own theory' and "the in-falling observer is free to claim that B is not entangled with A" in terms of Alice and Bob (and other) wave packets. Alice crosses wave packet B without a choice. In order for it to 'claim' B is not entangled with A but with C, *somehow* it's interaction with B must be different in this case. Since in the two pictures it has to interact with B in two different ways we are therefore led to the conclusion that the interaction is governed by *two different Hamiltonians even before the stretched horizon*. Furthermore, one is supposed to be more Alice-centric and the other Bob-centric even though both of them evolve wave packet Alice and wave packet Bob and there are no sentient beings in the setup.

Our attempts have led us to conclude that this picture suggests infinite universes (one for each causal diamond) with different Hamiltonians governing them even outside the stretched horizon. While each such universe might be consistent on its own (having a wave packet Alice and a wave packet Bob and anybody else), it would be inconsistent to describe the experiences of Alice in one such universe and those of Bob in a different one. We also do not see any meaning in saying that they should be similar in the past when the causal diamonds overlap. Since these are independent universes which do not communicate, in what sense are these supposed to be similar? Even if they are somehow similar at time t_0, different Hamiltonians will evolve them differently in past so they will become very dissimilar. For a time independent Hamiltonian it would seem the universe in which Alice hits a singularity in the future will also have Alice hit a singularity in the past.

Finally we want to stress that out of all these universes it is *only in one of them* that we have unitarity and in this one an in-falling wave packet's interaction with B is consistent with AMPS's claim and it can communicate this to an asymptotic wave-packet. Talking about other universes and experiences of observers in them does not seem necessary for the black hole information problem.

4 Fuzzballs

Black hole complementarity tried to reconcile the two opposing ideas of unitarity and free infall at the horizon. Mathur and AMPS have shown that *at least* after page time it is not possible to reconcile the two pictures. Furthermore, AMPS have proposed a Gedanken experiment to argue that the horizon will not be a vacuum state for an in-falling observer after the Page time. We wish to observe that the Page time is a upper bound and it is possible the results of Mathur and AMPS might be relevant even before that time. Furthermore, enforcing an information-free horizon via black hole or observer complementarity seems to require a very strange picture involving evolutions by different Hamiltonians etc.

Given the state of affairs, in our opinion the most conservative thing to do, using Occam's razor, is to depart once and for all from the traditional black hole picture. History has shown us that attempts to reconcile contradicting fundamental notions on the black hole solution cannot be forced upon without leading ad absurdum.

As pointed out earlier, the infallible technical lesson of what Mathur [2, 3] and more recently AMPS [1] say is that to be able to describe black hole evaporation by a unitary S-matrix for an asymptotic observer the traditional picture has to give way to one where the state at the horizon is not the vacuum state for an in-falling observer. This picture was long ago proposed by Mathur [15, 16] and incorporated in the fuzzball community. According to the fuzzball conjecture the true microstates of quantum gravity are singularity and horizon free solution that are either smooth *geometries* or solutions which in the core region are truly stringy and cannot be described by supergravity. In either case, since there is no horizon and no singularity there is no information loss. The exterior black hole geometry together with the membrane at the stretched horizon should be viewed as an effective coarse grained description of these fuzzballs. For reviews on fuzzballs we can refer the reader to [16–20].

Since these fuzzballs have no horizon and therefore no spacetime *behind* the horizon what meaning, if any, can be ascribed to such 'space time'? Why does a classical solution of general relativity have such a region of 'space time'? Recently, a family of near-extremal black hole microstate geometries has been constructed and one can hope to use such solutions to probe what the scale is at which an in-falling observer stops experiencing spacetime [21].

Interestingly, Mathur has recently proposed an approximate complementary picture [10, 11] based on [22, 23]. According to this proposal when a high energy wave packet ($E \gg kT$) hits a typical fuzzball, it excites the collective modes of the latter. This process has an approximate dual description where the wave packet just continues in some auxiliary spacetime. The wave packet hitting the singularity is interpreted as a breakdown of this approximate duality. Mathur refers to this as approximate complementarity because unlike black hole complementarity this picture only works for $E \gg kT$. A realization of fuzzballs, inherently stringy objects, giving a complimentary description of black holes would be a fulfillment of the prediction made in [13]: *It is our view that black hole complementarity is not derivable from a conventional local quantum field theory. It seems more likely that it requires a radically different kinematical description of physics at very high energy, such as string theory.*

5 Is Alice burning or fuzzing?

Up till this point we have not commented on AMPS's interpretation of their result that an in-falling observer would "burn up" before reaching the stretched horizon. While we agree with AMPS in that an in-falling wave packet will have an unexpected encounter with an outgoing Hawking-like quanta after Page time (and maybe even earlier), we do not think that the issue of how much the structure of the in-falling wave packet will change (i.e. weather it will "burn" or not) is settled yet.

For example, in [4] Mathur and Turton argue that the response of a detector falling into a typical state (for which $S_{BC} \neq 0$) cannot be distinguished from a thermal state (for which $S_{BC} = 0$) and thus argue for Mathur's approximate complementarity picture (as discussed in section 4) .

Furthermore, Nomura et al claim in [7] that AMPS's conclusion that an in-falling observer sees a firewall is incorrect based on the following very interesting reasoning. AMPS claim that since the state of the final Hawking radiation is pure it can be written as an early and late part

$$|\Psi\rangle = \sum_i |\psi_i\rangle_E \otimes |i\rangle_L \,, \tag{5.1}$$

where $|i\rangle_L$ is an arbitrary complete basis for late radiation and $|\psi_i\rangle_E$ is a state in the early Hawking radiation. After Page time the Hilbert space of the early radiation will be much larger than that of the late radiation and so, for typical states $|\Psi\rangle$, the reduced density matrix describing the late-time radiation is close to the identity. Thus one can construct operators acting on early radiation whose action on $|\Psi\rangle$ is

$$P_i|\Psi\rangle \propto |\psi_i\rangle_E \otimes |i\rangle_L \,. \tag{5.2}$$

While this is true, AMPS claim that Alice can make measurements on early radiation tantamount to projection into the eigenvector of the number operator. In [7] an objection is raised to this stating that "the existence of the projection operator for an arbitrary i does not imply that a measurement in a sense that it leads to a classical world can occur to pick up the corresponding state". In other words measurement is a dynamical process dictated by unitary evolution of the state.

Translated in our wave packet language this means that when Alice passes through early radiation A it can not *choose* which basis it projects onto. This is because the interaction of Alice and A is governed by a local hamiltonian. Let the typical energy of quanta in A be kT which of the order of the Hawking temperature. Then we have two different kind of scenarios

- Alice is a wave packet with support on energies $E \gg kT$ and is thus smaller than typical wave packets in A. In this case Alice interaction with A does not project onto the number operator basis in any typical interaction and it cannot 'predict' the number of quanta in a mode of B.
- Alice is a wave packet with support on energies $E \sim kT$ and thus is of the same size as wave packets in A. In this case a typical interaction of them will project A onto the number operator basis. When Alice falls in, it will encounter B and will be able to 'predict' the number of quanta in a mode of B.

The remaining case of $E \ll kT$ is not so interesting as for such wave packets the wavelength is bigger than the black hole.

We see that we clearly have two different scenarios but what is also very interesting is that we also have two different expectations on what happens to in-falling wave packets.

- Mathur claims that for quanta of energy $E \gg kT$ there is approximate complimentarily (approximate in that this does not work for for $E \sim kT$) as explained in the previous section.
- AMPS claim that an in-falling observer encounters high energy quanta in the number basis near the horizon. While this seems not to be true for $E \gg kT$[12] it is true for $E \sim kT$.

[12] It is not immediately clear that a local wave packet Alice cannot sample all of A on the sphere in some coherent way and then fall in and encounter B projected on a number basis. However typical interaction will not have this effect

Based on these observation we seem to have the following interesting picture of fuzzballs. For high energy observers it seems, based on [22, 23], that the interaction of the observers with the typical fuzzballs is more like Mathur's approximate complimentarily as stated in section 4. However, low energy observers start seeing the microscopic structure of the fuzzballs even when they are a macroscopic distance away from the bottom of the fuzzball. We expect intermediate wave packets to have experience ranging between these two extremes.

So finally, in response to the question Is Alice burning or fuzzing? one should ask back what Alice is made of or sing in the song "Alice, Alice, Who the **** is Alice?" [24].

Acknowledgments

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References

[1] A. Almheiri, D. Marolf, J. Polchinski and J. Sully, *Black Holes: Complementarity or Firewalls?*, 1207.3123

[2] S. D. Mathur, *The Information paradox: A Pedagogical introduction*, Class.Quant.Grav. **26** (2009) 224001, 0909.1038

[3] S. D. Mathur, *What the information paradox is not*, 1108.0302

[4] S. D. Mathur and D. Turton, *Comments on black holes I: The possibility of complementarity*, - to appear

[5] R. Bousso, *Observer Complementarity Upholds the Equivalence Principle*, 1207.5192

[6] D. Harlow, *Complementarity, not Firewalls*, 1207.6243

[7] Y. Nomura, J. Varela and S. J. Weinberg, *Complementarity Endures: No Firewall for an Infalling Observer*, 1207.6626

[8] L. Susskind, L. Thorlacius and J. Uglum, *The Stretched horizon and black hole complementarity*, Phys.Rev. **D48** (1993) 3743–3761, hep-th/9306069

[9] D. N. Page, *Average entropy of a subsystem*, Phys.Rev.Lett. **71** (1993) 1291–1294, gr-qc/9305007

[10] S. D. Mathur, *Black holes and holography*, 1207.5431

[11] S. D. Mathur, *Black Holes and Beyond*, 1205.0776

[12] M. Schlosshauer, *Decoherence, the measurement problem, and interpretations of quantum mechanics*, Rev.Mod.Phys. **76** (2004) 1267–1305, quant-ph/0312059

[13] L. Susskind and L. Thorlacius, *Gedanken experiments involving black holes*, Phys.Rev. **D49** (1994) 966–974, hep-th/9308100

[14] P. Hayden and J. Preskill, *Black holes as mirrors: Quantum information in random subsystems*, JHEP **0709** (2007) 120, 0708.4025

[15] O. Lunin and S. D. Mathur, *Statistical interpretation of Bekenstein entropy for systems with a stretched horizon*, Phys.Rev.Lett. **88** (2002) 211303, hep-th/0202072

[16] S. D. Mathur, *The Fuzzball proposal for black holes: An Elementary review*, Fortsch.Phys. **53** (2005) 793–827, hep-th/0502050

[17] I. Bena and N. P. Warner, *One ring to rule them all ... and in the darkness bind them?*, Adv.Theor.Math.Phys. **9** (2005) 667–701, hep-th/0408106

[18] K. Skenderis and M. Taylor, *The fuzzball proposal for black holes*, Phys.Rept. **467** (2008) 117–171, 0804.0552

[19] S. D. Mathur, *Fuzzballs and the information paradox: A Summary and conjectures*, 0810.4525

[20] B. D. Chowdhury and A. Virmani, *Modave Lectures on Fuzzballs and Emission from the D1-D5 System*, 1001.1444

[21] I. Bena, A. Puhm and B. Vercnocke, *Non-extremal Black Hole Microstates: Fuzzballs of Fire or Fuzzballs of Fuzz?*, - to appear

[22] B. Czech, J. L. Karczmarek, F. Nogueira and M. Van Raamsdonk, *The Gravity Dual of a Density Matrix*, Class.Quant.Grav. **29** (2012) 155009, 1204.1330

[23] B. Czech, J. L. Karczmarek, F. Nogueira and M. Van Raamsdonk, *Rindler Quantum Gravity*, 1206.1323

[24] Smokie, *Living next door to Alice*,