The end of the firewall story?

In 2012 a group of physicists (Almheiri, Marolf, Polchinski and Sully) from the University of California, Santa Barbara, made a startling claim: in any theory where black holes do not lose information, a person falling towards the hole will get 'burnt' by a 'firewall' of radiation as he approaches the horizon of the black hole [1].

This claim flew in the face of earlier theories where information was *not* lost and where an infalling observer *could* maintain a sense of 'falling freely through empty space' as he reached the horizon. In 2014, Mathur and Turton pointed out the flaw in the firewall argument: an assumption in the argument implied that information travels faster than light to escape the hole [2]. With the offending assumption removed, an explicit model of the black hole could be made which bypassed the firewall argument.

There remained, however, a last piece of the firewall story, which was closed in a paper by Guo, Hampton and Mathur, due to appear shortly in the Journal of High Energy Physics. In considering the behavior of black holes, it is normally assumed that the holes are *large*; i.e., their mass is much larger than Planck mass, the microscopic mass scale where quantum gravity effects begin to take over. Marolf (one of the authors of the firewall argument) had agreed that Mathur and Turton's suggested process provided a way around the firewall claim for sufficiently large holes. But he questioned if the astrophysical holes we observe around us are large enough for the scenario to work.

This may sound odd, since a solar mass hole is about 10^{38} times heavier than Planck mass. But the arguments of Mathur and Turton assumed that the firewall would burn infalling objects by gravitational interactions, and for holes that are not too large, *electromagnetic* interactions might be more important than gravitational ones. The electrostatic repulsion between two electrons is about 10^{42} times stronger than the gravitational attraction between the electrons. For sufficiently large holes gravitational effects would have to dominate in any firewall, but perhaps astrophysical holes were small enough that electromagnetic effects would create the conjectured firewall. In that case there might be a window for the firewall argument; i.e., a range where the black hole is large enough to be interesting but small enough for the Mathur-Turton scenario to not apply.

In their new paper, Guo, Hampton and Mathur explored the possibility of firewalls for astrophysical holes, now including interactions from all four fundamental forces: gravitational, electromagnetic, strong and weak. They found that the earlier Mathur-Turton argument against firewalls continued to hold, unless the hole was smaller than one-hundredth the size of an atom. This ruled out firewalls for holes of astrophysical interest, closing the last loophole in the argument of Mathur and Turton against firewalls.

Black holes

To understand the latest result, one must first understand the remarkable physics of black holes. In standard general relativity, the gravitational attraction in a black hole is so large that everything inside its horizon gets sucked into a central singularity,

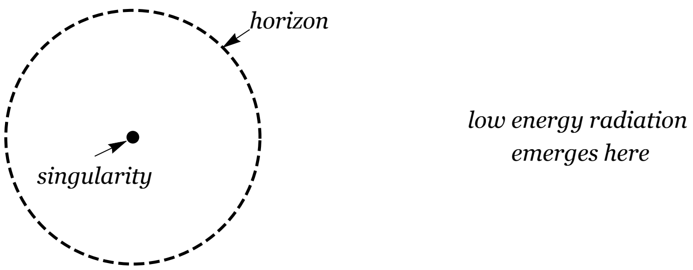

Figure 1: The traditional black hole arising in Einstein's general relativity: All the matter gets sucked into a central singularity. The region around the horizon is a vacuum. Low energy Hawking radiation materializes far from the horizon; there is no high energy radiation anywhere.

leaving the rest of the hole a vacuum (fig.1). In 1975, Stephen Hawking found that this vacuum was unstable: it slowly leaked energy in the form of 'Hawking radiation'. But this radiation was pulled out of the vacuum, so it carried no information about the star which collapsed to make the hole. When the hole evaporated away to Hawking radiation, the information of that star was 'lost'. This is the 'black hole information paradox' [3].

Mathur and his group had found several years ago that in *string theory* black holes had a completely different structure: instead of a vacuum region with a central singularity, there was a tangle of strings, branes and other objects spread throughout a horizon sized region, making the hole conceptually no different from a planet (fig.2). Such an object is called a *fuzzball.* This fuzzball radiates at the same temperature as Hawking's black hole. But the radiation emerges from its surface just like it would for any other normal body, and so the radiation carries the information present on this surface. This resolves the information paradox.

What is a firewall?

The firewall argument expressed a worry with any theory where the vacuum hole was replaced by a planet-like body like a fuzzball. The radiation from the surface of such a body is extremely hot. In the process of escaping the strong gravity near the surface, the radiation loses energy and cools down, so that its final temperature is very low (fig.2). But if a person was falling towards the hole, he would encounter the radiation when it was at hotter and hotter temperatures. So it would seem that he would get 'burnt' by this firewall of radiation before he ever reaches the surface of the fuzzball.

By contrast, in the traditional picture of a vacuum hole used by Hawking, there is no surface from where the radiation could emerge. Instead, the radiation materializes out of the vacuum, *with a very low temperature*, in a region far outside the horizon. Thus there is no region where an infalling observer could get burnt by this radiation; in particular, there is nothing at the horizon which would impede his infall.

Thus the firewall claim looks like a simple statement about the behavior of black holes in *any* theory where the vacuum hole was replaced by a planet-like body.

But as Mathur and Turton pointed out, there is a flaw in this argument. A crucial assumption in the argument was that *the object falling towards the hole encounter no*

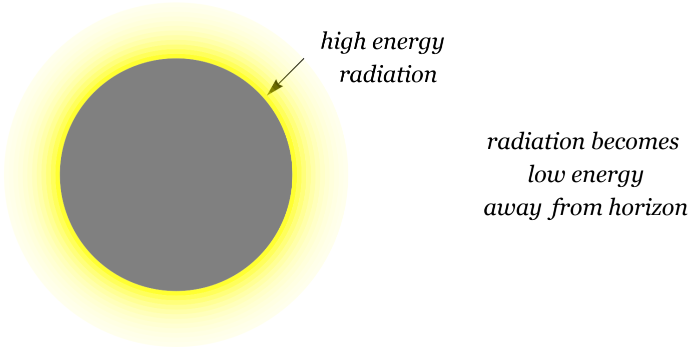

Figure 2: In the fuzzball paradigm the interior of the horizon is not the vacuum; instead it is a very quantum region with high curvature and string/brane sources. The fuzzball radiates from its surface, and the radiation carries the information of the fuzzball. Thus there is no information paradox. The radiation is very hot near the surface, but cools as it moves away from the horizon.

novel physics – like quantum gravitational effects arising from string theory – before it reaches the surface of the fuzzball. The reason for this assumption is clear. We do have to assume that novel physics dominates in the interior of the hole, since we wish to replace the vacuum hole with a planet like object. But if this novel physics could alter physics in the exterior as well, then we cannot know for sure what happens in the exterior, and in particular we cannot argue that an infalling object gets burnt.

It is this innocuous sounding assumption which causes a problem, as we will now see.

The flaw in the firewall argument

Consider a black hole of solar mass; the horizon radius of such a hole is 3 Km. In string theory this horizon and its vacuum interior would be replaced by a fuzzball of radius 3 Km. Now imagine that a shell carrying some extra mass falls onto this fuzzball. With this larger mass, the horizon would be at a larger radius, say 3.1 Km.

If the shell encounters no novel physics to impede its progress, it will get trapped inside a horizon when it crosses the radius 3.1 Km. This is exactly what would happen in the firewall argument, since it was assumed that no novel physics can intervene outside the 3 Km radius of the initial hole, and so classical general relativity would apply here.

But once the shell is trapped inside a horizon at 3.1 Km, the information in the shell cannot escape without traveling faster than light. Note that the firewall argument starts with the assumption that the radiation from the hole carries out the information of the hole. So the assumptions of the firewall argument require that information be transported faster than the speed of light.

Why can't we allow faster-than-light travel? In well studied theories like string theory, we have never found a situation where anything traveled faster than light. Interestingly, if we allow faster-than-light travel, then there is no information paradox in the first place. The only reason that information was 'trapped' in the hole was that in classical general relativity signals could not escape from inside a horizon without traveling faster than light. If there was no limitation on how information could travel, then we could imagine that some process just takes the information from the center of the hole to a point outside the horizon, and then this information could freely float away from the hole.

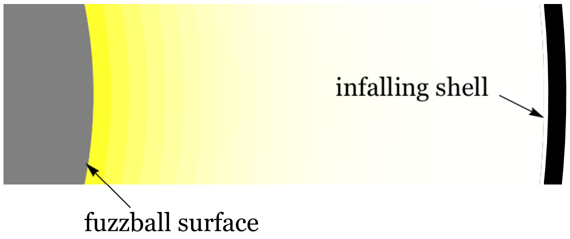

Figure 3: A shell with some energy E falls onto the fuzzball. In the firewall argument, no novel effects are allowed before the shell reaches the fuzzball surface. The hot radiation near the fuzzball surface is then argued to burn the shell.

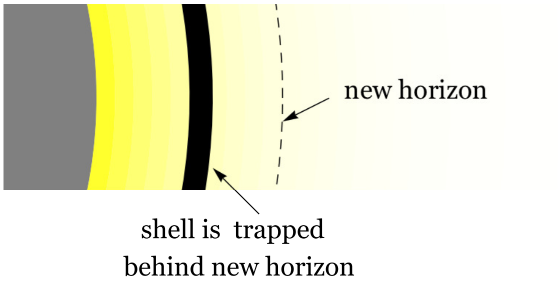

Figure 4: But if no novel effects are allowed outside the fuzzfall surface, then the shell will get trapped behind a new horizon, *before* reaching the fuzzball surface. The information in the shell cannot then come out without traveling faster than light.

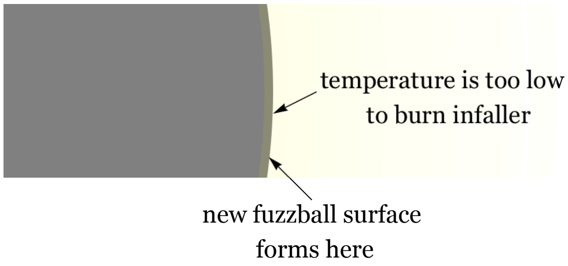

Figure 5: In the fuzzball paradigm the novel physics which created the fuzzball in the first place now causes new fuzzballs to form at the location where the *new* horizon would have appeared. The temperature is too low at this location to burn anything.

Let us return to the shell falling into the solar mass hole. To avoid having the shell trapped inside a horizon, we must conjecture that the novel effects start not at the 3 Km radius of the original horizon, but at the 3.1 Km radius of the *new* horizon. In the fuzzball paradigm, it is indeed conjectured that fuzzballs will form at the new horizon of radius 3.1 Km. (More generally, fuzzballs are conjectured to form whenever there is enough energy in a region so that classical general relativity would predict the formation of a horizon.)

For firewalls, we now see that the question is not whether radiation from the fuzzball can burn the shell at the radius 3 Km, *but whether the radiation is hot enough to burn the shell at the radius 3.1 Km.* This is the case because inside the radius 3.1 Km novel physics must already have taken hold.

Now we come to the crucial point. The temperature of the radiation falls off very quickly as we recede from the horizon. At a distance 1 millimeter from the horizon it is already colder than outer space, which is filled with microwave radiation at 3 degrees Kelvin. What Mathur and Turton argued was that the temperature at the new horizon is so low that the infalling shell does *not* get burnt by the radiation emerging from the fuzzball. They assumed that the infalling object starts off with an energy which is larger than the energy of one photon emitted by the hole (when this photon has reached infinity). For any such infalling object, the new horizon is far enough outside the original horizon that the probability of interaction with the radiation becomes negligible. In fact the larger the hole, the more energy the infalling object gathers as it falls towards the horizon; thus the larger the radius of the new horizon, and thus the lower the temperature of the radiation it encounters.

The new result

The Mathur-Turton argument result said that *gravitational* interactions between infalling objects and the emerging radiation will never become important unless than black hole had a radius smaller than Planck length which is about $10^{-33}\,cm$. Marolf's question was: what is this radius if we consider electromagnetic interactions?

In their recent paper, Guo, Hampton and Mathur computed the relevant radius, now including all four fundamental forces: gravitational, electromagnetic, strong and weak. They found that there was no firewall effect as long as the black hole radius was less than $10^{-10}\,cm$. This is very much smaller than the radius of astrophysical holes, which tend to range in radius from a few Km to several hundred million Km. For a solar mass hole, the probability that an infalling electron will interact with a photon of this radiation outside the *new* horizon was one part in 10^{19}; i.e., completely negligible.

Thus Guo et. al. conclude that the firewall argument does not have an interesting window where it could apply: from a conceptual viewpoint, it anyway does not apply when a black hole is sufficiently large, and from a practical viewpoint the range where the hole is *not* sufficiently large does not cover typical holes of astrophysical interest.

Next steps?

We have noted that novel quantum gravity effects – like the formation of fuzzballs – must be encountered where the new horizon forms, and not where the infalling object reaches the hot radiation near the old horizon. But what actually happens when these novel effects are encountered? Will the inaflling object still burn, or can it have a sense of 'free fall through empty space'?

We do not know enough about quantum gravity to give a definite answer to this question. In the fuzzball paradigm, it is possible to make a model for the behavior of fuzzballs, where the infalling observer does *not* burn. His infall energy creates *new* fuzzballs, and his motion gets encoded in the evolution of these new fuzzballs. This encoding describes an approximate and effective 'free fall through the horizon'. Having such effective behaviors is not new: in the AdS/CFT correspondence [10] we can have an observer fall on a stack of D-branes, and instead of feeling 'shattered' the observer feels he is falling through gently curved anti-de-Sitter spacetime.

What we do learn, from all these results is the following. Many people had the feeling that the firewall argument looked too simple to enable a conclusion about the dynamics of black holes. We see that it was indeed too naive; one actually needs a detailed understanding of quantum gravity to decide what an infalling observer feels as he reaches the horizon.

1 Notes

1. The first computations showing that black holes in string theory swelled up into horizon sized fuzzballs were done in [4]. The fuzzball states for the simplest holes were made in [5].
2. Other fuzzball states for these simplest holes were made by Lunin, Maldacena and Maoz, and by Skenderis and Taylor [6].
3. More complicated fuzzballs were made in [7]. A general program to make fuzzballs was initiated by Bena and Warner and their students/collaborators. Other techniques were added by Giusto Russo, Shigemori, Turton, Martinec, and others.
4. The question raised by Marolf can be found on the 'Fuzz or Fire' conference (2014) Website

   http://fuzzorfire-m13.wikispaces.com/Notes
5. The ideas about how and where fuzzballs will form were discussed in [8].
6. A model for how an infalling object can feel it is in free fall once it reaches the fuzzball surface was given in [9]. We do not know if this is a good model for how fuzzballs behave. But the existence of such a model shows that we cannot use a firewall type logic to argue that a sense of free fall is impossible.

References

[1] A. Almheiri, D. Marolf, J. Polchinski and J. Sully, JHEP **1302**, 062 (2013) [arXiv:1207.3123 [hep-th]].

[2] S. D. Mathur and D. Turton, Nucl. Phys. B **884**, 566 (2014) doi:10.1016/j.nuclphysb.2014.05.012 [arXiv:1306.5488 [hep-th]].

[3] S. W. Hawking, Commun. Math. Phys. **43**, 199 (1975) [Erratum-ibid. **46**, 206 (1976)]; S. W. Hawking, Phys. Rev. D **14**, 2460 (1976).

[4] S. D. Mathur, "Emission rates, the correspondence principle and the information paradox," Nucl. Phys. B **529**, 295 (1998) [arXiv:hep-th/9706151].

[5] O. Lunin and S. D. Mathur, "AdS/CFT duality and the black hole information paradox," Nucl. Phys. B **623**, 342 (2002) [arXiv:hep-th/0109154];

[6] O. Lunin, J. Maldacena and L. Maoz, arXiv:hep-th/0212210; I. Kanitscheider, K. Skenderis and M. Taylor, arXiv:0704.0690 [hep-th];

[7] I. Bena and N. P. Warner, "Black holes, black rings and their microstates," Lect. Notes Phys. **755**, 1 (2008) [arXiv:hep-th/0701216]; B. D. Chowdhury and A. Virmani, "Modave Lectures on Fuzzballs and Emission from the D1-D5 System," arXiv:1001.1444 [hep-th].

[8] S. D. Mathur, arXiv:0805.3716 [hep-th]; S. D. Mathur, Int. J. Mod. Phys. D **18**, 2215 (2009) [arXiv:0905.4483 [hep-th]]; P. Kraus and S. D. Mathur, Int. J. Mod. Phys. D **24**, no. 12, 1543003 (2015) doi:10.1142/S0218271815430038 [arXiv:1505.05078 [hep-th]]; I. Bena, D. R. Mayerson, A. Puhm and B. Vercnocke, JHEP **1607**, 031 (2016) doi:10.1007/JHEP07(2016)031 [arXiv:1512.05376 [hep-th]]; S. D. Mathur, arXiv:1703.03042 [hep-th].

[9] S. D. Mathur, arXiv:1506.04342 [hep-th].

[10] J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998) [Int. J. Theor. Phys. **38**, 1113 (1999)] [arXiv:hep-th/9711200]; S. S. Gubser, I. R. Klebanov and A. M. Polyakov, Phys. Lett. B **428**, 105 (1998) [arXiv:hep-th/9802109]; E. Witten, Adv. Theor. Math. Phys. **2**, 253 (1998) [arXiv:hep-th/9802150].