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Black Hole Paradoxes

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Abstract. We propose here that the well-known black hole paradoxes such as the information loss and teleological nature of the event horizon are restricted to a particular idealized case, which is the homogeneous dust collapse model. In this case, the event horizon, which defines the boundary of the black hole, forms initially, and the singularity in the interior of the black hole at a later time. We show that, in contrast, gravitational collapse from physically more realistic initial conditions typically leads to the scenario in which the event horizon and space-time singularity form simultaneously. We point out that this apparently simple modification can mitigate the causality and teleological paradoxes, and also lends support to two recently suggested solutions to the information paradox, namely, the 'firewall' and 'classical chaos' proposals.

One of the most spectacular predictions of the general theory of relativity is the black hole, an object that plays a central role in modern physics [1,2,3] and astrophysics [4,5]. Black holes are, however, plagued by fundamental paradoxes that remain unresolved to this day. First, the black hole event horizon is teleological in nature [6] which means that we need to know the entire future space-time of the universe to determine the current location of the horizon. This is essentially impossible. Second, any information carried by infalling matter is lost once the material falls through the event horizon. Even though the black hole may later evaporate by emitting Hawking radiation [7], the lost information does not reappear, which has the rather serious and disturbing consequence that quantum unitarity is violated [8]. Here we propose that the above paradoxes are restricted to a particular idealized model of collapse first studied in the 1930s [9, 10] in which the event horizon, which defines the boundary of the black hole, forms initially, and the singularity in the interior of the black hole forms at a later time. In contrast, gravitational collapse from more reasonable and/or physically more realistic initial conditions often leads to models in which the event horizon and the singularity form simultaneously. We show that this apparently simple modification mitigates the causality and teleological paradoxes and at the same time lends support to two recently proposed solutions to the information paradox, namely, the "firewall" [11] and "classical chaos" [12].

A black hole is expected to form naturally in the universe whenever a massive star runs out of nuclear fuel at the end of its life and collapses under its own self-gravity. As a result, the infalling mass is compressed to a space-time singularity of infinite curvature and density. This singularity is, however, hidden from view because it is covered by an event horizon, a one way membrane through which particles, light rays and signals can enter but from which nothing can escape.

The above standard picture of black hole formation is motivated by the classic work of Oppenheimer & Snyder [9] and Datt [10], who studied the collapse of a "dust" cloud (fluid with mass density but no pressure) of uniform density. As the space-time diagram in Figure 1 shows, the key feature of this idealized collapse model is that the event horizon forms already at the space-time point A, where local conditions in the infalling dust cloud are perfectly normal, and the density and curvature are finite. The singularity, where the curvature diverges, forms at the point S, which lies in the future of A; indeed, S lies in the future for all worldlines within the dust cloud when they cross the horizon, e.g., the point B. In addition, the location of the horizon at points A and B depends on the entire future history of infalling matter, including shells such as C which fall in later and whose very existence is unknown to the gas falling through A or B.

This illustrates the teleological nature of the event horizon: the location of the event horizon is determined by the entire future history of space-time, a profoundly paradoxical situation.

Another problem is that black holes run into a major conflict with quantum theory. A black hole swallows all information carried by matter falling in through the event horizon. When the hole subsequently evaporates by emitting Hawking radiation [7], the mass energy that was swallowed is returned to the external universe, but in an uncorrelated mixed form that carries no information. Thus, a black hole takes in pure quantum states and converts them to mixed states [8]. This violates quantum unitarity, which is a very disturbing prospect and is dubbed the black hole information paradox.

The above paradoxes have attracted considerable attention over the years and various solutions have been proposed. A rather radical solution was suggested recently [11] in which the event horizon is replaced by a firewall. According to this proposal, an infalling observer encounters a firewall of outgoing bolts of radiation at the horizon and is destroyed. Thus, the event horizon is replaced by a curvature singularity — the firewall — associated with outgoing radiation at the horizon. The information carried in by the observer is absorbed at the firewall and is presumably returned via pure quantum states when the singularity radiates or the hole evaporates, thus solving the information paradox. Proponents of the firewall hypothesis present it as "the most conservative resolution" [11] of the information paradox.

The firewall proposal, however, faces several objections, including the fact that CPT invariance of quantum gravity rules out the model [12]. In our view, the most serious problem is the fact that the firewall is by construction located at the event horizon, but the location of the horizon is determined teleologically. Somehow, the firewall singularity must sense the future space-time and thereby decide where it ought to be located. There is no information, either in local conditions of the collapsing matter or in signals received from the past, that provides any indication that a firewall must form.

There are also other models proposed to resolve these issues, such as the 'fuzzball' scenario (see e.g. [13], and also [14]). Yet another alternative to the firewall model was suggested by Hawking [12] proposing that gravitational collapse produces only an apparent horizon and not a true event horizon, and that therefore no information needs to be lost in the collapse. In order to avoid the horizon, Hawking suggests that the region of the collapsed object inside the event horizon develops a chaotic metric and matter fields. Such a chaotic collapsed object would radiate chaotically but deterministically, so quantum unitarity is preserved. However, the chaos model again suffers from the teleological problem. Chaos must be generated at and inside the horizon, but how does the infalling material know that it should become chaotic when local conditions are perfectly normal and when the location of the horizon must be determined by all of the future? Moreover, for near-spherically symmetric collapse models such as those considered here, any chaos is likely to be restricted to regions close to the singularity, and the causal structure of the solution does not permit signals to propagate from this region out to the

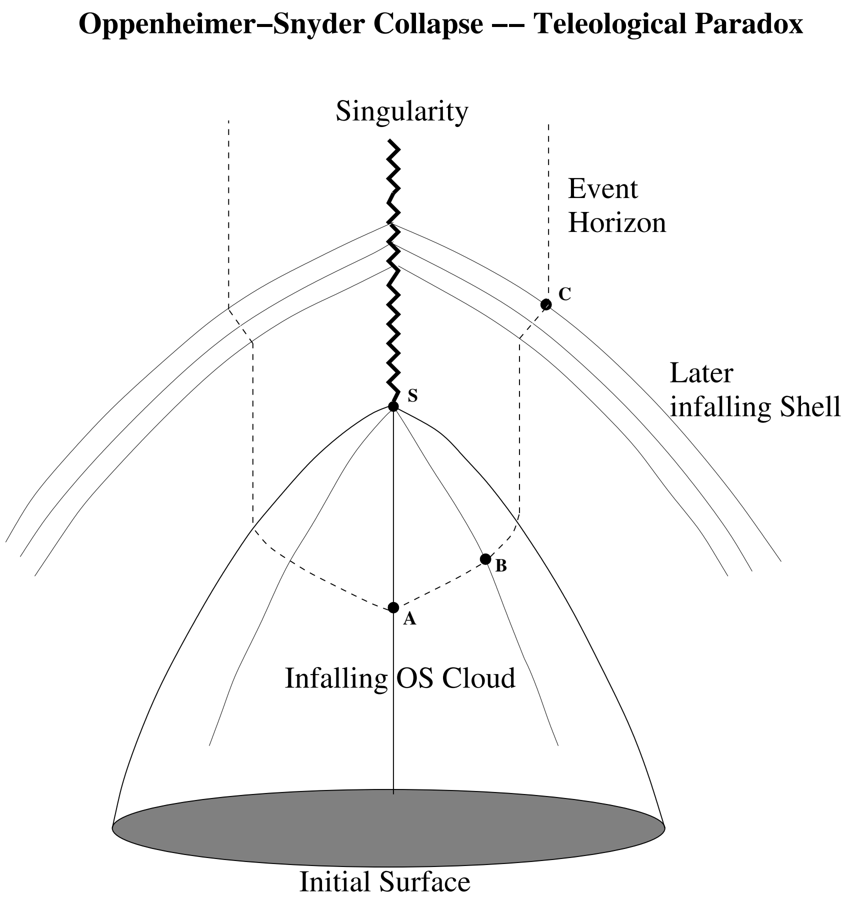

Figure 1. Gravitational collapse of a spherical pressureless matter cloud (dust cloud) of uniform density whose initial state is shown by the shaded region at the bottom. Time increases in the vertical direction, and space is represented by the horizontal directions. The thin solid lines show worldlines of infalling matter. The event horizon (dashed line) first forms on the worldline of the center of the cloud, at the space-time point A, where conditions are very non-singular. Even point B, on the worldline of matter farther out in the cloud, is at an earlier time than the epoch corresponding to S, where the singularity (thick jagged line) first forms. Although the point C, on a subsequently infalling shell of matter, is at a later time than S, no signals can reach this point from the singularity. Therefore, if any new physics, e.g. firewall or chaos, is to be triggered at A or B or C, it has to be via information traveling back from the future, either along the horizon from future infinity or along worldlines of matter backward from the singularity. This is the teleological paradox, which is caused by the fact that the event horizon is causally cutoff from the singularity, a consequence of cosmic censorship.

horizon.

The problems described above arise as a result of assuming a foundational principle of black hole theory, namely, the so-called cosmic censorship conjecture [15]. This conjecture, which is motivated by the space-time diagram shown in Figure 1, suggests that, generically, every singularity that forms as a result of collapse is hidden from view behind an event horizon. That is, the singularity is always cutoff from the external universe. This has the profound consequence that it rules out any signals or communication from the singularity (or its vicinity) to the event horizon. In other words, no worldline at the horizon ever receives any information from the past about the singularity; the only way it can find out about the existence of the singularity is by receiving information from the future (teleological nature of the horizon). We propose that this is the root cause of the black hole paradoxes that we are facing today.

A reasonable alternative emerges if we agree or assume that any solution to the information paradox, such as firewall or chaos, requires information to be received at the horizon about the existence of a singularity in the space-time, and moreover, that this information should be received via signals from the past. If such signals are able to reach the event horizon, they could carry information related to "new physics" that might emerge in the vicinity of the singularity due to the extreme nature of all physical quantities there, and this information could potentially provide a causal trigger to generate either a firewall or chaos. By this reasoning, cosmic censorship and firewalls/chaos are mutually incompatible, since cosmic censorship requires the future of a worldline to determine its present behaviour (teleological communication).

Fortunately, it is now known that the cosmic censorship conjecture is not fully correct since large classes of physically reasonable gravitational collapse models have been worked out within Einstein gravity and been shown to transcend cosmic censorship [16]. In these solutions, the event horizon either is delayed or does not form at all [17], allowing a naked space-time singularity to be visible to the external universe. Moreover, such solutions are by no means fine-tuned. They occur for a wide range of physically reasonable initial conditions.

To illustrate the last point, we note that the (OSD) collapse shown in Figure 1 corresponds to an initial density distribution of the dust cloud of the form

$$\rho(r) = \rho_0, \qquad r \leq r_c. \tag{1}$$

This model is physically rather unlikely since it requires a finite density at the cloud boundary. A homogeneous density sphere is not a good approximation for a massive star. Consider instead the following centrally-peaked model of the initial density, which has the same radius and mass as the constant density model, but is arguably more reasonable,

$$\rho(r) = \frac{5}{2}\,\rho_0 \left[1 - \left(\frac{r}{r_c}\right)^2\right], \qquad r \leq r_c. \tag{2}$$

The collapse of this centrally-peaked cloud, starting from dilute initial conditions ($r_c \gg GM_c/c^2$ where M_c is the total mass of the cloud), gives the causal structure shown in Figure 2 [18,19]. The key difference from Figure 1 is that the two distinct points A and S in the former have collapsed to a single point. As a result, the event horizon originates at the singularity itself, and the singularity becomes naked. Signals emitted at or near the singularity can have different histories. An infinite family of rays escapes to infinity (making the singularity at least partially visible), some rays are trapped and fall back on the singularity, and a select few rays travel along the horizon, connecting the singularity to points on the horizon. The existence of these last rays — null geodesics that emerge from the singularity and travel along the event horizon — is the key result we highlight here.

Before exploring the consequences, we note that a wide range of spherically-symmetric dust collapse models with different initial density and velocity structure have the same qualitative causal structure as that shown in Figure 2. Furthermore, models that include pressure with reasonable equations of state also behave similarly [20], as does at least one non-spherically symmetric model [21]. The general conclusion is that the causal structure shown in Figure 2 is as plausible as the standard OSD solution (Figure 1), and possibly more realizable in realistic physical situations. One caveat is that models with rotation have not so far been explored, so their collapse properties are not known.

The model illustrated in Figure 2 produces a radically different scenario compared to the OSD picture of collapse (Figure 1) which has formed the basis of all discussions so far on the

Physically More Plausible Collapse –– No Paradox

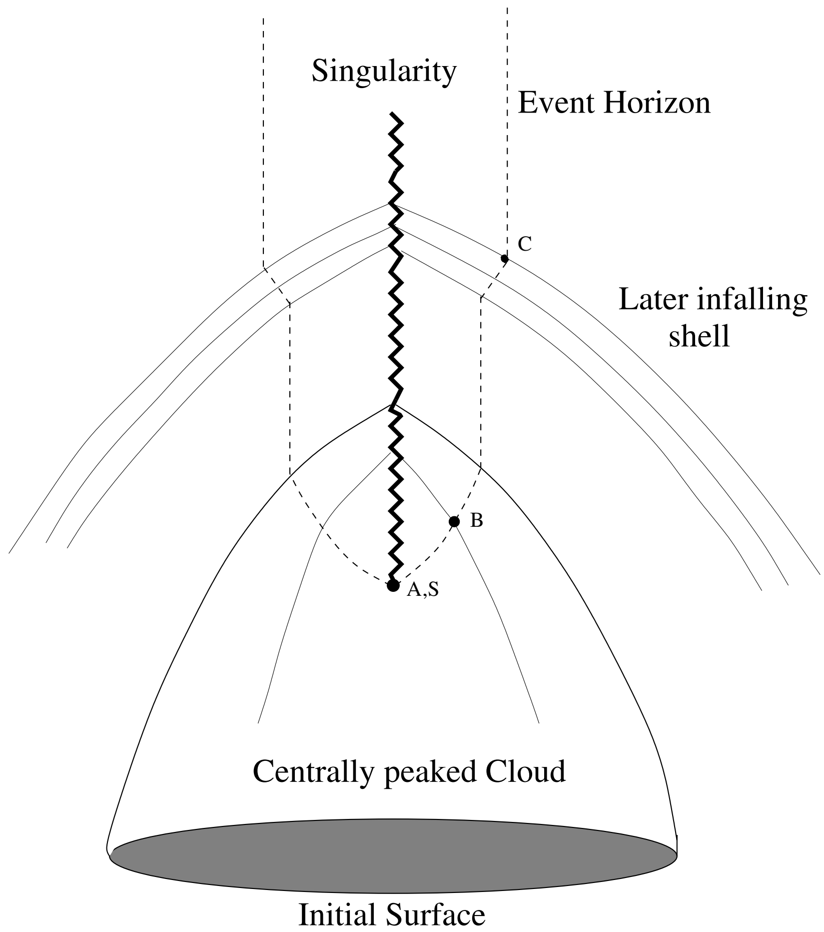

Figure 2. Gravitational collapse of a spherical dust cloud with a density maximum at the center (equation 2). A naked singularity S forms at A, and the event horizon (dashed line) also originates at A. As a result, the singularity can communicate with the entire event horizon, including points such as B and C. New physics, e.g., firewall or chaos, could thus be triggered on the horizon by signals from S, i.e., from the past. Because of the presence of a naked singularity, this model violates cosmic censorship, which is rather restrictive and is confined to special models such as in Figure 1. Correspondingly, there is no teleological paradox. A wide range of physically reasonable initial conditions of the cloud gives collapse with the causal structure shown here.

causal structure of black holes, the information paradox, cosmic censorship. etc. Fluid at the center of the cloud (initial density peak) no longer enters the horizon when it is physically very regular with modest density and curvature. Instead, by the time this matter reaches the horizon, it has already attained extremely high densities and has an arbitrarily large space-time curvature. We expect the matter to behave very much like the hot big bang in reverse, and to become arbitrarily hot and radiation-dominated. Moreover, as the curvature approaches the Planck scale (or other appropriate scale), new physical phenomena associated with quantum gravity should emerge. Most importantly, signals from this ultra-dense region in the quantum gravity regime will flow out along the horizon, conceivably modifying physics throughout the

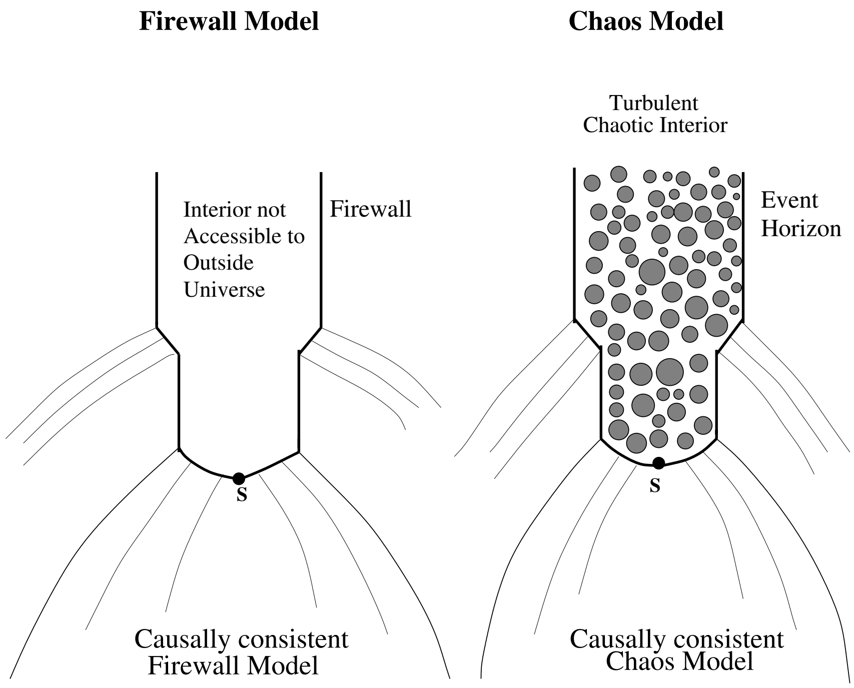

Figure 3. A causally consistent version of the firewall (left) and chaos (right) models. Both models require some exotic phenomenon — a singular firewall or chaotic dynamics — to switch on suddenly at the horizon (thick solid lines). To trigger this behaviour, a warning of some sort must reach fluid that is about to cross the horizon. Because of cosmic censorship, no such warning from the past is possible if the collapse behaves as in Figure 1. In contrast, when the event horizon connects to the singularity in the past, as in the case of the naked singularity scenario shown in Figure 2, signals from the singularity travel to all points on the horizon. Since the singularity is a region of extreme physical conditions corresponding to the quantum gravity regime, signals originating from here could, in principle, trigger the necessary behaviour for the firewall and chaos models. (No specific trigger mechanism is described here since the focus is on establishing causality.)

horizon. Two ways in which this might happen are illustrated in Figure 3.

In one scenario, the quantum matter at the singularity in Figure 2 is radiated away along outgoing rays. The maximum burst of radiation will arguably be along the event horizon because close to that surface and below the singularity the densities, pressures and all other physical quantities attain their maximum and unbounded values. The firewall could then originate at the naked singularity and propagate as a singular wall of outgoing radiation. As material farther out in the cloud approaches the firewall, e.g., point B, even though its own local properties may be quite regular, when it hits the singularity at the firewall, it will be absorbed and will add to the firewall (Figure 3 left). We do not have any explanation of how the latter might happen, but neither was an explanation offered with the original firewall hypothesis. Our contribution here is to show that it is possible to have a firewall originate at a singular point and then evolve causally, without any need for a teleological connection to the future.

Another interesting point is that the null and timelike paths in the vicinity of the naked singularity have been examined in earlier work [22,23] and found to have a complex structure that might well give rise to chaotic behaviour in the interior of the horizon. If this chaos, which will originate in the naked singularity, is able to expand and fill the interior of the horizon, then it is conceivable that the entire interior of the black hole could become chaotic, thereby resembling the classical chaos model [12] (Figure 3 right). Once again, we do not attempt to explain the detailed dynamics of such a model. What we show is that a chaos model could potentially be causally consistent without having to invoke teleological properties.

With reference to chaos from gravitational collapse, we know that the inner region of Kerr geometry is unstable and might be chaotic. If the collapse of a massive rotating star results in a configuration described by the Kerr metric on the outside, this may offer a way to produce chaos in the interior, as suggested by Hawking [12]. However, we note that the unstable region does not extend outside the inner horizon and so chaos cannot propagate all the way to the outer horizon as needed to solve the information paradox. Thus the chaos model requires some other trigger to generate the necessary turbulence. Our proposal in Figure 3 is a possible solution.

In summary, we suggest that some of the problems that have plagued black hole physics might be the result of (i) relying on the classical OSD picture of gravitational collapse of a constant density cloud (Figure 1), in which the event horizon forms much earlier than the singularity, and (ii) assuming that this model and its associated cosmic censorship describes the generic behaviour of collapse. By making use of physically more realistic gravitational collapse models, e.g., those with initial density higher at the center (Figure 2), a very different picture of black hole formation through collapse emerges in which the horizon and the singularity generically form at the same epoch. Such models violate cosmic censorship and can potentially resolve the event horizon and information paradoxes.

Finally, a number of astronomical observations indicate that astrophysical black holes have dark surfaces, and this has been used to argue that they possess event horizons [4,24,25]. In actual fact, the evidence indicates only that the objects possess apparent horizons, so the observations are in principle consistent with the chaos model [12]. The situation is less clear in the case of the firewall model [11], since there has been little discussion of the radiative properties of the firewall.

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