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The absence of horizon in black-hole formation

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Abstract

With the back-reaction of Hawking radiation taken into consideration, the work of Kawai, Matsuo and Yokokura [1] has shown that, under a few assumptions, the collapse of matter does not lead to event horizon nor apparent horizon. In this paper, we relax their assumptions and elaborate on the space-time geometry of a generic collapsing body with spherical symmetry. The geometry outside the collapsing sphere is found to be approximated by the geometry outside the white-hole horizon, hence the collapsing matter remains outside the Schwarzschild radius. As particles in Hawking radiation are created in the vicinity of the collapsing matter, the information loss paradox is alleviated. Assuming that the collapsing body evaporates within finite time, there is no event horizon.

1. Introduction

The information loss paradox [2] has been one of the most interesting and controversial problems in theoretical physics for decades. It is a crucial test of our understanding of black holes when quantum effects are taken into account.

The paradox presents a conflict between the unitarity of quantum mechanics and other basic notions in physics. A major part of the puzzle is how to transfer information from the collapsed matter deep inside the horizon to the Hawking radiation. All proposals of resolution seem to be in conflict with some of our understandings in theoretical physics, e.g. the no-cloning theorem,

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the monogamy of entanglement, as well as the causality and locality of semiclassical effective theories. In particular, it was recently proven [3] that the information loss can be avoided only if there is order-one correction at the horizon (for instance, a firewall [4]). The possibility we would like to focus on in this paper is that the event horizon never forms as long as the collapsing body completely evaporates within finite time.

For a static black hole, from the viewpoint of a distant observer, it takes an infinite amount of time for her to see an infalling observer to cross the horizon. On the other hand, an infalling observer can pass through the horizon within finite proper time. This is related to the fact that the Eddington advanced time v (which is more relevant to an infalling observer [5]) is related to the Schwarzschild coordinates t and r (which is more relevant to a distant observer) via the relations

$$v = t + r^*, \qquad r^* \equiv r + a \log \left| \frac{r}{a} - 1 \right|. \tag{1}$$

Because $r^* \to -\infty$ when $r \to a$, it is possible that an infinite time $t = \infty$ at $r = a$ corresponds to a finite value of v, say $v = v_1$. However, one should be alerted when we take the Schwarzschild radius $a(t)$ to be time-dependent. If the black hole is completely evaporated at $t = t^*$ ($a(t) = 0$ for $t \geq t^*$), it is no longer possible to say that v_1 corresponds to $t = \infty$, because $v_1 = t_1 + r^* = t + r$ for $t > t^*$, assuming that eq. (1) still makes sense for time-varying $a(t)$. A more careful analysis [5] shows that if we modify the formula (1) to properly incorporate a time-dependent $a(t)$, it would indeed take infinitely long in his proper time for the infalling observer to pass through the apparent horizon, if $a(t) \to 0$ within finite time. This is in contradiction with the common belief that an infalling observer can pass through the horizon in finite time even if the horizon evaporates completely in finite time. In fact, this common belief typically necessitates a negative energy flux near the horizon.

Classically, the appearance of a horizon also takes infinite time for a distant observer, who sees the collapse of a star getting slower and slower as it gets closer and closer to the point where the horizon emerges. When Hawking radiation is turned on, it is assumed in the conventional model of a black hole [6] that the (apparent) horizon appears in finite time for a distant observer, although it is unclear how Hawking radiation can speed up the formation of horizon. (This is another way to see that a negative energy flux is needed in the conventional model.) Conventionally, it is also believed to be a good approximation to ignore Hawking radiation during the formation of a black hole, and consider Hawking radiation only after the horizon appears. By patching the Penrose diagram of black-hole formation in the absence of Hawking radiation with that of black-hole evaporation, one finds the Penrose diagram in Fig. 1 [6], which represents the conventional model of a black hole.

One of the most important features of this diagram is that, the trajectories of the collapsing matter, as well as that of an infalling observer, are terminated at the event horizon at finite Eddington retarded time u^* for a distant observer. Another feature is that the space-time is geodesically complete (Minkowskian) for a distant observer after $u = u^*$, when the black hole completely evaporates. Intriguingly, according to Fig. 1, a distant observer would see (through signals at the speed of light) at the same instant ($u = u^*$) the images of all infalling objects disappearing into the event horizon, and at the same moment the black hole evaporates completely with the horizon shrunk to zero size.

There has been suspicion that the conventional model of black holes is incorrect. Some argued that the event horizon should be replaced by a trapping horizon [7]. In the context of string theory, the picture of the fuzzball was proposed to replace the black hole and its horizon [8]. In the collapse of a scalar-field domain wall, there is no horizon either [9]. More recently, through