



Black hole complementarity: The inside view



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ABSTRACT

Within the framework of black hole complementarity, a proposal is made for an approximate interior effective field theory description. For generic correlators of local operators on generic black hole states, it agrees with the exact exterior description in a region of overlapping validity, up to corrections that are too small to be measured by typical infalling observers.

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1. Introduction

Black hole complementarity posits that a unitary and local description of physics exists outside a stretched horizon, a timelike surface a short distance from the event horizon of a black hole. The postulates of [1] leave open the question of how to describe the physics inside the horizon but based on the equivalence principle it is reasonable to expect that a freely falling observer experiences nothing out of the ordinary when crossing the horizon of a sufficiently large black hole. If this expectation is indeed borne out, it also seems reasonable that observations made inside a laboratory that enters a black hole in free fall should be described, to within achievable experimental precision, by a more or less conventional effective field theory. It was already observed in [1] that this effective description cannot be a local quantum field theory that is simultaneously valid for distant observers and observers who have entered the black hole in free fall. The problems that arise when one attempts to implement unitary black hole evolution from the point of view of distant observers in the context of a local effective field theory that extends into the black hole interior were stated more sharply in [2], where it was pointed out that observations made on the outgoing Hawking radiation would project the quantum state of the black hole and in effect burn up the inside observer. In fact, no explicit measurements are needed – the effect follows from decoherence due to the local coupling between the Hawking radiation and degrees of freedom far from the black hole. More recently similar conclusions were reached in [3,4] by considering the entanglement between outgoing Hawking modes at different times during the evaporation. An alternative conclusion

is that there is no firewall but that the problem lies with applying local effective field theory across the horizon [2,5].

In the present work we construct an approximate effective field theory for an observer who passes through the black hole horizon in free fall. The construction follows up on our recent work in [6] where the evolution of a black hole formed in a generic pure state was considered and it was argued that a typical infalling observer would not see any drama on their way towards the stretched horizon. While this is a satisfying conclusion it does not answer the key question of what happens to such an observer in the interior region, which we take to include both the black hole region inside the event horizon and the region between the event horizon and the stretched horizon. In order to address that question we need to have a model for the interior quantum evolution and the answer turns out to depend on the model. If we, for instance, choose to use a local quantum field theory on a set of time slices that cover the exterior region during much of the black hole lifetime and also extend smoothly into the black hole region, staying away from the strong curvature near the black hole singularity, then we would conclude that either there is no information about the black hole state carried in the Hawking radiation, as was indeed concluded by Hawking [7], or that the equivalence principle is violated, as was concluded by the authors of [3,4]. Our construction gets around this by patching together effective field theories on either side of the stretched horizon in such a way that a typical infalling observer will not see any drama until near the black hole singularity. A prescription for the interior initial data is provided which is formally non-unitary, but we argue this non-unitarity is unobservable, and akin to the harmless non-unitarity introduced by a finite proper distance cutoff in effective field theory around an expanding cosmological background. This non-unitary step in constructing an effective field theory description for an infalling observer does not affect the unitarity of the evaporation process

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from the exterior viewpoint, and is perhaps the key new element that allows us to evade the arguments of [3,4].

The construction only applies to a restricted class of observers and it is restricted to a set of time slices that only cover a relatively short period of time before and after the observer enters the black hole. Our main claim is that, even with these restrictions imposed, the resulting effective field theory can describe observations made by a typical infalling observer to sufficient accuracy to conclude that no drama is encountered until deep inside the black hole.

An alternative approach to describing the interior physics, inspired by the non-locality of string field theory [8], is to look for a non-local formulation of quantum field theory on a continuous background geometry. For recent work along those lines see [9, 10]. Another approach is that of fuzzball complementarity [11,12] which uses string theory degrees of freedom to build an interior description. Fuzzball complementarity shares some features of our effective field theory construction but there are important differences which we comment on at the end of Section 5 below.

2. Black hole geometry and infalling observers

A black hole of mass M formed in the gravitational collapse of non-rotating neutral matter in $3 + 1$ dimensional asymptotically flat spacetime will settle down to a metastable state in a time of order M as measured by distant observers and then slowly evaporate due to Hawking emission in a time of order M^3 . During the evaporation, on time scales that are short compared to the black hole lifetime, the geometry is well approximated by the static Schwarzschild solution

$$ds^2 = -\frac{32M^3}{r} e^{-\frac{r}{2M}} dUdV + r^2 d\Omega^2$$

written here in Kruskal coordinates, related to the familiar Schwarzschild coordinates r, t by

$$V = \left(1 - \frac{r}{2M}\right)^{1/2} e^{\frac{r+t}{4M}}$$

$$U = \left(1 - \frac{r}{2M}\right)^{1/2} e^{\frac{r-t}{4M}}$$

inside the horizon and

$$V = \left(\frac{r}{2M} - 1\right)^{1/2} e^{\frac{r+t}{4M}}$$

$$U = -\left(\frac{r}{2M} - 1\right)^{1/2} e^{\frac{r-t}{4M}}$$

outside the horizon. In these coordinates, the future event horizon is at $U = 0$ and the curvature singularity on the hyperboloid $UV = 1$. Time translations in Schwarzschild time act as opposite rescalings of U and V .

According to the second postulate of [1], physics outside the so-called stretched horizon is well described by a local effective field theory, which we'll take to have a UV cutoff Λ . The stretched horizon is a timelike surface just outside the event horizon, located where fiducial observers at rest with respect to the black hole would measure a local temperature of order the cutoff scale. In Kruskal coordinates this corresponds to a hyperboloid $UV = -a^2$, where a is a cutoff dependent constant $a \sim (M\Lambda)^{-1/2}$. The effective field theory of the second postulate is only valid outside the stretched horizon and is intended for describing observations made by outside observers. For unitary black hole evolution, it needs to be supplemented by non-trivial quantum dynamics on

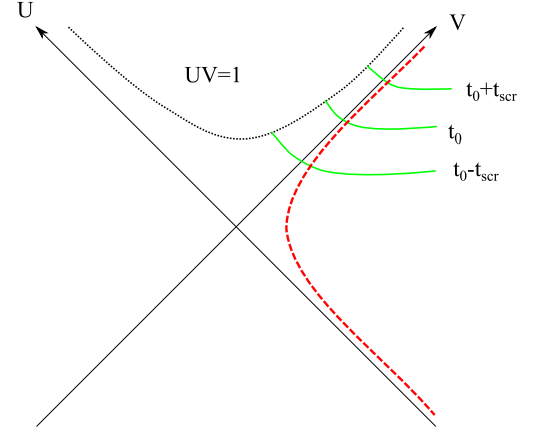


Fig. 1. Schematic figure of time slices labelled by Schwarzschild time t outside the stretched horizon and which approach light sheets inside the black hole.

the stretched horizon that serves to absorb, thermalize and re-emit the information in infalling matter. This outside effective field theory is not well suited for modeling observations made by infalling observers who enter the black hole, since, in this description, no reference is made to the interior geometry of the black hole. Below, we provide an alternative low-energy effective description, suitable for typical infalling observers, i.e. ones who do not carry with them detailed information about the quantum state of the black hole. We refer to the Hamiltonian of the outside effective field theory plus stretched horizon dynamics as the exact Hamiltonian as it generates the exact S-matrix between the initial and final states of the system.

In order to describe infalling observers, we need to introduce a foliation of the spacetime that covers the black hole interior. Following [13], we adopt a set of time-slices, labelled by Schwarzschild time t , that enter the region inside the horizon of the black hole as shown in Fig. 1. Far outside the black hole the time-slices follow the usual Schwarzschild coordinate system but within a distance of order M from the stretched horizon the slices turn over and join smoothly onto surfaces of constant V inside the stretched horizon.

Consider an observer on the $t = t_0$ time-slice, who enters the black hole in radial free fall at $V = V_0 \gg 1$. At the event horizon the equation for the corresponding radial geodesic simplifies to

$$\frac{dU}{d\tau} = \frac{\alpha}{4MV_0}, \quad \frac{dV}{d\tau} = \frac{eV_0}{4M\alpha},$$

where $\alpha > 0$ parametrizes the instantaneous velocity and low energy corresponds to $\alpha \sim O(1)$. The worldline is timelike so $dU/d\tau > 0$ everywhere inside the black hole. Assuming the observer stays in free fall for at least a one Planck unit of proper time after passing through the horizon, but allowing for arbitrary timelike motion after that, it follows that the worldline will intersect the singularity at Kruskal retarded time $U > \frac{\alpha}{4MV_0}$. This in turn implies an upper bound on the advanced Kruskal time when the observer runs into the singularity given by $V < \frac{4M}{\alpha} V_0$.

Now consider a signal sent into the black hole at Schwarzschild time $t_0 + t_{scr}$. The advanced Kruskal time at the point, where the signal passes through the event horizon, satisfies $V = e^{\frac{t_{scr}}{4M}} V_0$ and only the region in the forward light-cone of this point on the horizon can be influenced by the signal. Therefore, we see that as long as

$$t_{scr} > 4M \log \frac{4M}{\alpha}$$

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