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On the interior of (quantum) black holes

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ABSTRACT

Different approaches to quantum gravity conclude that black holes may possess an inner horizon, in addition to the (quantum corrected) outer 'Schwarzschild' horizon. In this Letter we assume the existence of this inner horizon and explain the physical process that might lead to the tunneling of particles through it. It is shown that the tunneling would produce a flux of particles with a spectrum that deviates from the pure thermal one. Under the appropriate approximation the extremely high temperature of this horizon is calculated for an improved quantum black hole. It is argued that the flux of particles tunneled through the horizons affects the dynamics of the black hole interior leading to an endogenous instability.

1. Introduction

The discovery that black holes emit radiation had a big impact on the scientific community. The celebrated pioneering work on this subject was performed by Hawking in 1975 [1] who showed, based on results of quantum field theory on a fixed curved background (Schwarzschild's solution), that black holes emit a thermal spectrum of particles from their event horizon. The heuristic picture most commonly proposed as an explanation of this effect is that of pair creation near the horizon of the black hole and the corresponding tunneling of particles in which one of the components of the pair is swallowed by the black hole and the other escapes. This picture led Parikh and Wilczek [2] to propose a method for studying Hawking radiation from the Schwarzschild horizon by explicitly considering the tunneling of particles through it. Furthermore, their method took into account the back-reaction effect of the radiation on the black hole thanks to the requirement of energy conservation and showed that new terms appear in the distribution function which deviate it from pure thermal emission, i.e., the standard Boltzmann distribution.

Of course, this picture is incomplete since, in order to describe the last stages of black hole evaporation, one should take into account quantum gravity effects. The possibility of studying the radiation from the outer horizon of quantum corrected black holes is now feasible from different approaches to Quantum Gravity [3–6]. Sometimes a strict thermal evolution has been imposed on the quantum black hole by estimating Hawking's energy flux directly from Stefan–Boltzmann's law. However, it is also possible to study more accurately the radiation from quantum black holes by following the approach of Parikh and Wilczek. For example, in [7] the tunneling of particles through the outer horizon has been studied by using an effective quantum spacetime [3] based on the Quantum Einstein Gravity approach.

On the other hand, the possibility that black holes could have an inner horizon seems nowadays plausible since the results from different frameworks [3–6] point in this direction. However, while there exists a vast amount of work devoted to the properties of the outer horizon, the properties of this inner horizon remain, in comparison, relatively unknown. It seems, therefore, natural at this moment to speculate about the properties of this horizon and its consequences on the inner dynamics of the black hole. This is the aim of this Letter in which the possibility of tunneling from the inner horizon is studied (specifically for the solution found in [3]) and the physical process behind it is explained. Moreover, guided by the well-known existence of classical solutions possessing an inner horizon instability under the perturbation of external fields (from which, the Reissner–Nordström solution is the paramount example), the stability of the inner horizon of a quantum corrected solution is checked. In particular, we are interested not only in the influence of external fields, but in whether the flux of energy tunneled through the black hole horizons could have consequences on its own stability.

The Letter has been divided as follows. Section 2 introduces the solution for the quantum black hole (the *improved Schwarzschild spacetime*) and its main properties. In Section 3 the stability of the solution is checked under the action of a test distribution of noninteracting massless particles. Section 4 analyzes the tunneling of particles through the inner horizon of the improved black hole. This allows us, in Section 5, to evaluate the spectral

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distribution and temperature of the emitted particles. The flow of energy through the inner horizon is found in Section 6 and a model for the evolution of an evaporating quantum black hole is then treated in Section 7. The stability of the evaporating model under the flow of energy from its horizons is analyzed in Section 8. Finally, the results are discussed in Section 9.

2. Improved Schwarzschild solution

In [3] Bonanno and Reuter found an effective spacetime for a quantum black hole by using the idea of the Wilsonian renormalization group [8] in order to study quantum effects in the Schwarzschild spacetime. Specifically, they obtained a *renormalization group improvement* of the Schwarzschild metric based upon a scale dependent Newton constant G obtained from the exact renormalization group equation for gravity [9] describing the scale dependence of the effective average action [10,11]. The solution can be written as

$$ds^2 = -f(R)\,dt_S^2 + f(R)^{-1}\,dR^2 + R^2\,d\Omega^2. \tag{2.1}$$

where

$$f(R) = 1 - \frac{2G(R)M}{R} \tag{2.2}$$

with

$$G(R) = \frac{G_0 R^3}{R^3 + \tilde{\omega} G_0 (R + \gamma G_0 M)} \tag{2.3}$$

and where G_0 is Newton's universal gravitational constant, M is the mass measured by an observer at infinity and $\tilde{\omega}$ and γ are constants coming from the non-perturbative renormalization group theory and from an appropriate cutoff identification, respectively. In [3,12] it is argued that the preferred value for γ is $\gamma = 9/2$. On the other hand, $\tilde{\omega}$ can be found by comparison with the standard perturbative quantization of Einstein's gravity (see [13] and references therein). It can be deduced that its precise value is $\tilde{\omega} = 167/(30\pi)$, but the properties of the solution do not rely on its precise value as long as it is strictly positive.

The horizons in this solution can be found by solving $f(R) = 0$. The number of positive real solutions to this equation correspond to the positive real solutions of a cubic equation and depends on the sign of its discriminant or, equivalently, on whether the mass is bigger, equal or smaller than a critical value M_{cr}. In general, the critical value takes the form

$$M_{cr} = a(\gamma)\sqrt{\frac{\tilde{\omega}}{G_0}} = a(\gamma)\sqrt{\tilde{\omega}}m_p \sim \sqrt{\tilde{\omega}}m_p, \tag{2.4}$$

where m_p is Planck's mass and the function $a(\gamma)$ has, in general, an involved expression that, for reasonable values of γ satisfies $a(\gamma) \sim 1$. In particular, the preferred value $\gamma = 9/2$ provide us with

$$M_{cr} = \frac{1}{24}\sqrt{\frac{1}{2}\left(2819 + 85\sqrt{1105}\right)}\sqrt{\frac{\tilde{\omega}}{G_0}} \simeq 2.21\sqrt{\tilde{\omega}}m_p \simeq 2.94 m_p.$$

If $M < M_{cr}$ the equation has not positive real solutions, so that there are not horizons. If $M = M_{cr}$ there is only one positive real solution to the cubic equation. Finally, if $M > M_{cr}$ then the equation has two positive real solutions $\{R_-, R_+\}$ satisfying $R_- < R_+$. The outer solution R_+ can be considered as the *improved Schwarzschild horizon*, i.e., the Schwarzschild horizon when quantum modifications are taken into account. On the other hand, the inner solution R_- represents a novelty with regard to the classical solution. It is a monotonically decreasing function of M defined for

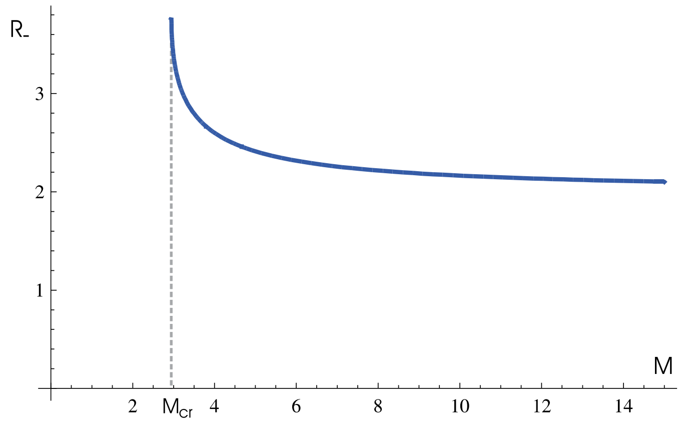

Fig. 1. $R_-(M)$ is plotted in Planck units for masses around the critical mass. A calculation shows that $R_-(M = M_{cr}) \simeq 3.772$ while $R_-(M \to \infty) \simeq 1.997$.

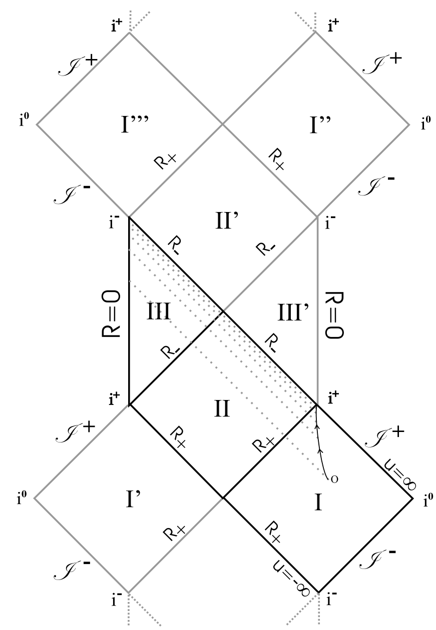

Fig. 2. A Penrose diagram corresponding to the case $M > M_{cr}$. The region drawn using a solid black line (I–II–III) correspond to the zone defined by the solution in Eddington–Finkelstein-like coordinates (3.1) with the null coordinate going from $u = -\infty$ to $u = \infty$. The regions drawn in grey correspond to extensions of this solution. Penrose's classical instability argument [14] is schematically shown: An eternal observer 'O' emits radiation (dashed lines) at equal intervals from the asymptotically flat region I towards $R = 0$. As it approaches its timelike infinite i^+ the radiation piles up at the inner horizon R_- ($u = \infty$), which is an instable surface of infinite blueshift.

masses non-smaller than the critical mass (see Fig. 1) that from its maximum value $R_+(M_{cr})$ ($\simeq 3.772\sqrt{G_0}$) tends asymptotically towards the value $R_{-min} = \sqrt{G_0 \gamma \tilde{\omega}/2}$.

The maximally extended spacetime for this solution in the case $M > M_{cr}$ resembles the Reissner–Nordström maximally extended spacetime in the case $M > |Q|$. A Penrose diagram of the improved black hole for this case has been depicted in Fig. 2. Note that the usual $R = 0$ singularity in the classical Schwarzschild solution does not exist in the improved solution [3,15]. It is also important to remark for later purposes that, from a classical point of view and as can be directly checked from Fig. 2, a photon in region II that follows the ingoing direction towards region III must reach $R = 0$.

In order to interpret the physical meaning of this solution let us suppose that it has been generated by an effective matter fluid in such a way that the coupled gravity-matter system satisfies