PROCEEDINGS OF SCIENCE

Hawking radiation of non-standard black holes

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Black Holes of primordial origin (PBHs) can constitute a large fraction of dark matter (DM) in the Universe. If light enough, they can emit a sizeable amount of Hawking radiation, which may be detected by dark matter experiments and be used to set constraints on the fraction of PBHs as DM components. Lately, these constraints have been extended to spinning PBHs, and it is very important to extend such analyses to other black hole metrics, in particular in the perspective of a signal detection. Recent works on black holes modification by quantum gravity effects have resulted in metrics that are regular at the black hole center, solving the singularity problem. We will present a generalization of the existing formalism to the generic class of spherically symmetric and static black holes, determining the short-range potentials for the equations of motion for these metrics. Using the public code BlackHawk, we will show how the Hawking radiation is modified for such black holes, and we will in particular focus on the case of polymerized black holes, which are black hole solutions arising from loop quantum gravity.

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1. Introduction

The nature of dark matter is still an unresolved question, and many dark matter models are currently under scrutiny [1]. In particular, dark matter may be constituted of primordial black holes (PBHs) created in the early Universe. If light enough, such PBHs vanish and emit Hawking radiation (HR), and the flux of emitted particles might be detected by dark matter indirect detection experiments (see e.g. [2, 3]). The emission rates of HR is related to the geometry of the black hole (BH) metric, and in [4, 5] we investigated the consequences of the geometry for spherically symmetric static BHs on the emission rates. In the following, after reviewing the equations related to HR, we will discuss the case of polymerized BHs.

2. Emission rates of spherically symmetric black holes

We consider here spherically-symmetric and static metrics of the form

$$\mathrm{d}s^2 = -G(r)\mathrm{d}t^2 + \frac{1}{F(r)}\mathrm{d}r^2 + H(r)\mathrm{d}\Omega^2\,, \tag{1}$$

where $\mathrm{d}\Omega^2 = \mathrm{d}\theta^2 + \sin(\theta)\mathrm{d}\varphi^2$, that are asymptotically flat and present a horizon at some radius r_H which is a pole of F. We have shown in [4] that for these metrics the equations of motion of spin 0, 1, 2 and 1/2 massless particles can be transformed into one-dimensional Schrödinger-like wave equations

$$\partial^2_{r^*} Z + \left(\omega^2 - V\big(r(r^*)\big)\right) Z = 0\,, \tag{2}$$

where $\mathrm{d}r^*/\mathrm{d}r \equiv 1/\sqrt{FG}$ and the spin-dependent potentials V are given in [4].

The rate of emission of one degree of freedom i per unit time t and energy E is given by

$$\frac{\mathrm{d}^2 N_i}{\mathrm{d}t\,\mathrm{d}E} = \sum_{l,m} \frac{1}{2\pi} \frac{\Gamma_i(E, M, x_j)}{e^{E/T} - (-1)^{2s_i}}\,, \tag{3}$$

where s_i is the spin of the particle i and T is its Hawking temperature given by

$$T = \frac{1}{4\pi} \left.\frac{F^{1/2} G'}{G^{1/2}}\right|_\mathrm{hor} \tag{4}$$

where "hor" denotes the horizon $r = r_\mathrm{H}$. The greybody factor Γ_i is the probability that a particle generated by thermal fluctuations at the horizon escapes to spatial infinity, which can be obtained by solving Eq. (2).

3. Polymerized black holes

Polymerized BHs have emerged as an effective template for black holes in loop quantum gravity [6]. We consider here the polymerized BH metric derived in [7, 8] and given by

$$G = \frac{(r-r_+)(r-r_-)(r+\sqrt{r_+ r_-})^2}{r^4 + a_0^2}\,, \quad F = \frac{(r-r_+)(r-r_-)r^4}{(r+\sqrt{r_+ r_-})^2 (r^4 + a_0^2)}\,, \quad H = r^2 + \frac{a_0^2}{r^2}\,. \tag{5}$$

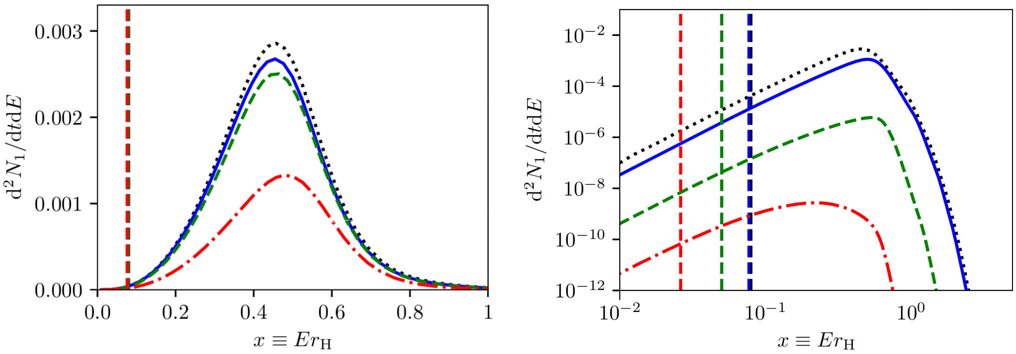

Figure 1: Hawking radiation of photon from polymerized BHs (left) with $\varepsilon = \{10^{-1}, 10^{-0.6}, 10^{-0.1}\}$ (solid blue, dashed green and dot-dashed red respectively) and $a_0 = \sqrt{3}\gamma/2$ where $\gamma \equiv \ln(2)/\sqrt{3}\pi$, and (right) with $\varepsilon = \{1, 4, 10\}$ (solid blue, dashed green and dot-dashed red respectively) and $a_0 = 0$. The Schwarzschild BH is in dotted black. The vertical lines represent the temperature of the BH.

The metric components have two roots $r_+ = 2M/(1+P)^2$ and $r_- = 2MP(\varepsilon)^2/(1+P)^2$, where M is the ADM mass and $P = (\sqrt{1+\varepsilon^2} - 1)/(\sqrt{1+\varepsilon^2} + 1)$ is the polymerization factor, so that a polymerized BH acquires a Cauchy horizon at $r = r_-$ in addition to the event horizon at $r = r_+$. Here the parameter a_0 is the minimal area in loop quantum gravity, typically of the Planck scale, and the deformation parameter $\varepsilon \geq 0$ is an *a priori* independent parameter indicating the typical scale of the geometry fluctuations.

The temperature is $T_{\rm LQG} = (r_+^2(r_+ - r_-))/(4\pi(r_+^4 + a_0^2))$. When $\varepsilon \ll 1$, the change in the temperature is quite negligible compared to the Schwarzschild case, however, in the limit $\varepsilon \to +\infty$, the radii collapse $r_- \to r_+$ and the temperature goes to $T_{\rm LQG} \to 0$, cancelling HR.

The full HR spectra for photons in the case of a polymerized BH described by the metric (5) has been obtained with the BlackHawk code [9, 10] and is shown in Fig. 1 and compared to the Schwarzschild case. One can observe large decreases of the emission rate in comparison to the Schwarzschild case.

4. Observational consequences

We discuss Hawking radiation constraints on polymerized primordial black holes. We know that an increase in ε results in a decrease of the Hawking temperature and emission rates, giving in a longer lifetime, shifting the (time-dependent) constraints towards smaller PBH masses. In addition, this decrease will also lead to weaker (instantaneous) constraints. Thus, the most striking result is that we expect the window for light PBHs to represent all DM to be reopened in the case of high values of ε, down to smaller PBH masses than in the Schwarzschild case.

To illustrate this, we computed the prospective evaporation constraints from MeV to GeV photons as will be measured by AMEGO, whose expected sensitivity can be found in [11]. The results are shown in Fig. 2 where we plot the constraints for $\varepsilon = \{1, 5, 10\}$ as well as the fiducial constraint for the classical case.

As expected, the constraints for the classical Schwarzschild BH and the polymerized BH with $\varepsilon = 1$ are similar, as their Hawking radiation rates are very close . Then, as we increase ε to 5 and then 10, we observe that the constraints get weaker in the high mass range $M_{\rm PBH} \gtrsim 10^{15}$ g, allowing

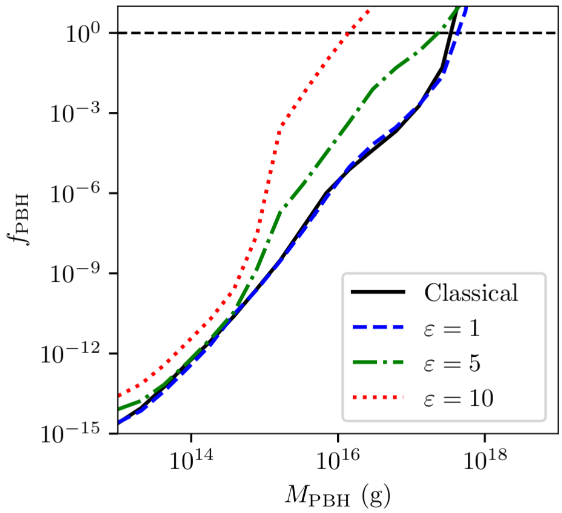

Figure 2: Constraints on the PBH fraction in DM from the measurement of MeV-GeV photons in the galactic center by AMEGO. The constraints derived for a classical Schwarzschild BH case are in solid black. We show the constraints computed for increasing values of $\varepsilon = \{1, 5, 10\}$ (dashed blue, dot dashed green and dotted red, from right to left). The horizontal dashed line denotes the limit $f_{\rm PBH} = 1$.

the DM fraction $f_{\rm PBH}$ of PBHs to be 1 for $M_{\rm PBH} \gtrsim 10^{16}$ g with $\varepsilon = 10$. Also, the mass range down to masses $M_{\rm PBH} = 10^{13}$ g is reopened, which is 2 orders of magnitude below the usual evaporation limit $M_{\rm PBH} \lesssim 10^{15}$ g set by the lifetime of the PBHs, because the decreased emission rates result in an increased PBH lifetime at the same initial mass, thus allowing smaller PBHs to contribute to DM today

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