Effect of the memory burden on primordial black hole hot spots

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When primordial black holes (PBHs) evaporate, they deposit energy in the surrounding plasma, leading to temperature gradients, or *hot spots*, which evolve during the evaporation process. Motivated by recent studies suggesting that a memory burden may slow down PBH evaporation, we explore how a suppression of the evaporation rate affects the morphology of such hot spots. We include such a suppression in the form of transfer functions and derive general formulas for the hot-spot core temperature and radius. Applying our results to illustrative scenarios, we find that, in the vanilla memory burden scenario in which the evaporation rate and Hawking temperature are exactly constant, the hot-spot temperature is substantially lowered. Nonetheless, we show that alternative scenarios may lead to sizable hot spots with morphologies that differ significantly from the semiclassical case.

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I. INTRODUCTION

Primordial black holes (PBHs) that formed in the early universe, besides providing an alternative candidate to the dark matter of our Universe [1,2], constitute some of the very few remnants that could have survived across cosmological time and left imprints in cosmological data that might be measurable today. PBHs form from the collapse of primordial curvature overdensities [3], which can originate from various physical mechanisms [4–50]. As such, they may also constitute unique probes of very-high energy particle physics phenomena. Nevertheless, PBHs with masses less than 10^{15} g evaporate on timescales smaller than the age of the Universe, due to Hawking radiation, which makes hunting for their existence in cosmology very challenging.

So far, studies searching for the signatures of evaporating PBHs in cosmological data (see, e.g., [51] for a review) assumed that their evaporation is a homogeneous process. However, it was suggested in Refs. [52–54] that the dynamics of energy deposition onto the plasma around PBHs when they evaporate can lead to the formation of *hot spots* with large local temperature gradients. Since then, such gradients were revealed to be extremely important when assessing the effect of PBH evaporation on particle physics phenomenology [55–57].

One crucial ingredient in obtaining the temperature profile time evolution around PBHs is the PBH evaporation rate, that was derived by Hawking in the semiclassical (SC) approximation [58,59]. In Refs. [52–54], this evaporation rate was used to obtain the time evolution of PBH hot spots during their evaporation. Recently, it was proposed that this evaporation rate is affected by the *memory burden* (MB) effect, a property of high-entropy storage quantum systems that may be featured by black holes, affecting their evaporation dynamics [60–62]. Remarkably, this effect—which can be thought of as the backreaction of the metric evolution on the particle production rate—can significantly prolong the life of a black hole, resulting in a markedly different PBH phenomenology and corresponding strategies to search for their existence in the cosmos [63–87].

In this work, we investigate how this memory burden effect—or, more generally, a modification of the SC rate derived by Hawking—may lead to a different morphology and dynamics for PBH hot spots. The paper is organized as follows: In Sec. II we introduce the definition of the semiclassical evaporation and its memory-burden modification and parametrize the effect using appropriate transfer functions. In Sec. III, we review the results of Refs. [52–54] in the SC case and generalize them to the case of the memory burden using these transfer functions. Finally, in Sec. IV, we present numerical results in the presence of the standard memory burden effect, and study how the PBH hot-spot morphology is affected by this modified PBH dynamics, before concluding in Sec. V.

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II. PBH EVAPORATION

We start by reviewing standard results regarding the evaporation of primordial black holes in the early universe. We then report how the memory burden effect was proposed to be accounted for in the literature, so we set the scene and basic ingredients that we will then use in the next section when studying the dynamics of PBH hot spots.

A. Semiclassical approximation

Assuming that Hawking radiation takes place on top of a classical background that is uniquely determined by the total mass of the black hole—the SC approach—Hawking [88] showed that all available degrees of freedom evaporated by a PBH of mass M follow a blackbody spectrum distribution with temperature,

$$T_H = \frac{1}{8\pi GM} \sim 10^3\ \mathrm{TeV}\left(\frac{10^7 g}{M}\right), \tag{1}$$

where G denotes the Newton constant. The differential emission rate per unit energy E, time t, of a particle species i with mass m_i is given by

$$\frac{d^2N_i}{dtdE} = \frac{g_i}{2\pi}\frac{\vartheta(M,E)}{e^{E/T_H} - (-1)^{2s_i}}, \tag{2}$$

where s_i denotes the spin of the particle species i and g_i its number of internal degrees of freedom, and the absorption cross section $\vartheta(M,E)$ represents the likelihood that a particle reaches spatial infinity, accounting for the curvature-induced potential barrier acting on particles around the black hole. The PBH mass loss rate in the SC case can then be estimated as [88–90]

$$\left.\frac{dM}{dt}\right|_{\mathrm{SC}} = -\sum_i \int_{m_i}^{\infty} \frac{d^2N_i}{dtdE} EdE = -\varepsilon(M)\frac{m_p^4}{M^2}, \tag{3}$$

where $m_p \approx 1.22 \times 10^{22}$ GeV denotes the Planck mass and $\varepsilon(M)$ is the evaporation function that accounts for the degrees of freedom that can be produced at a given time, i.e., for an instantaneous mass. Although, in principle, this evaporation function is a function of the mass whose variation needs to be tracked numerically (see, for instance, Ref. [91]), at high energy this evaporation function is constant $\varepsilon \approx 4.2 \times 10^{-3}$, which we will assume throughout this work.

B. Memory burden effect

When accounting for the memory burden [62,92], one usually considers that the evaporation rate follows Eq. (3) from the time of PBH formation, when $M = M_{\mathrm{ini}}$, to the point when the memory burden kicks in, usually assumed to be an order one fraction of the initial mass at $M = qM_{\mathrm{ini}}$, where $q \lesssim 1$. After that, the effect is typically parametrized as

$$\left.\frac{dM}{dt}\right|_{\mathrm{MB}} = \frac{1}{\tilde{S}^k}\left.\frac{dM}{dt}\right|_{\mathrm{SC}}, \tag{4}$$

where $k \geq 0$ (with $k = 0$ reproducing the SC result) and the suppression factor is directly inferred from the Hawking-Bekenstein entropy of the PBH,

$$\tilde{S}(M) \equiv \frac{S}{k_{\mathrm{B}}} = \frac{4\pi GM^2}{\hbar k_{\mathrm{B}}} \simeq 2.6 \times 10^{30}\left(\frac{M}{10^{10}\ \mathrm{g}}\right)^2, \tag{5}$$

where k_{B} is the Boltzmann constant.

Although it was argued in Ref. [65] that in Eq. (4) the rate should be understood as being constant across the rest of the evaporation, its interpretation in the literature has been diverse, with some considering this expression as holding true at any time, such that $S(M)$ and $dM/dt|_{\mathrm{SC}}$ both vary over time with $M(t)$ [93–96] and some considering the rate to be constant [63,71,95,96].

To account for this diversity of interpretations, and the fact that the exact evolution of the Hawking temperature and the evaporation rate might deviate from these extreme cases when using a more sophisticated approach, we encapsulate the MB effect by considering that these two crucial quantities evolve as

$$\left.\frac{dM}{dt}\right|_{\mathrm{MB}} \equiv \eta_M \times \left.\frac{dM}{dt}\right|_{\mathrm{SC}} \quad \text{and} \quad T_H \equiv \eta_T \times T_{H,\mathrm{SC}}, \tag{6}$$

where $T_{H,\mathrm{SC}}$ refers to the semiclassical Hawking temperature formula used in Eq. (1).

In the true MB scenario where both the evaporation rate and Hawking temperature freeze at $M = qM_{\mathrm{ini}}$, these functions correspond to

$$\eta_M = \begin{cases} 1, & qM_{\mathrm{ini}} < M \leq M_{\mathrm{ini}}, \\ \frac{1}{\tilde{S}(qM_{\mathrm{ini}})^k}\left(\frac{M}{qM_{\mathrm{ini}}}\right)^2, & M \leq qM_{\mathrm{ini}}, \end{cases} \tag{7}$$

and

$$\eta_T = \begin{cases} 1, & qM_{\mathrm{ini}} < M \leq M_{\mathrm{ini}}, \\ \frac{M}{qM_{\mathrm{ini}}}, & M \leq qM_{\mathrm{ini}}. \end{cases} \tag{8}$$

In scenarios incorporating a smooth transition between the SC and MB rate, but maintaining a sharp transition for the Hawking temperature, such as in Refs. [63,65], η_T would remain the same, but η_M would typically be a smoother function of the PBH mass, or of time, depending on how it is parametrized.

Before we continue, let us emphasize at this stage that, in the standard memory burden case, $\eta_M \ll \eta_T \lesssim 1$ and that we generally expect this ordering to remain true throughout this paper.

III. PBH HOT SPOTS

During their evaporation, PBHs inject energy in the surrounding plasma, creating temperature gradients and supporting the evolution of hot spots with a characteristic temperature profile around them. The existence of such hot spots was first suggested in Ref. [54] and refined—accounting for the Landau-Pomeranchuk-Migdal (LPM) effect in the calculation of the Hawking radiation energy deposition rate in Ref. [52]—before it was supported by a Boltzmann-improved numerical treatment [53]. In these references, the plasma is assumed to be in local thermal equilibrium, such that it can be uniquely described at every radius r by a scalar function $T(r)$. The rate of energy deposition of high-energy Hawking radiation particles with momentum $k \approx T_H$ onto a much lower-energy plasma of temperature $T \ll T_H$ is given by the LPM rate [52]

$$\Gamma_{\rm dep}(T, T_H) \approx \alpha^2 T \sqrt{\frac{T}{T_H}}. \tag{9}$$

The diffusion rate that encodes the radial cooling of the profile is of the Bethe-Heitler form

$$\Gamma_{\rm diff}(T) \approx \alpha^2 T, \tag{10}$$

where, in these two expressions, the coupling constant $\alpha \sim 0.1$ is assumed to be universal, which is a good approximation at high energy when the evaporation is dominated by hard gluons [52,97]. In what follows, we will consider these equations to hold throughout PBH evaporation, such that they can be used to evaluate distance and timescales characteristic to the physical problem studied in this work.

A. Hot-spot morphology

To obtain the temperature gradient profile within the hot spot, one first needs to determine, at a given time, under which radius the thermal plasma is able to thermalize faster than it is being heated by PBH evaporation. To do so, one can proceed in three steps: First, consider that Hawking radiation deposits energy onto a plasma of temperature T at the distance $\Gamma_{\rm dep}(T, T_H)^{-1}$ away from the BH. Then, estimate the time $t_{\rm diff}$ it takes within a plasma of temperature T for a plasma particle interacting with a diffusion rate $\Gamma_{\rm diff}(T)$ to propagate over a similar distance. Using that $r_{\rm diff} \sim \sqrt{t_{\rm diff}/\Gamma_{\rm diff}}$, this gives [52–54]

$$r_{\rm diff} = \Gamma_{\rm dep}^{-1} \Rightarrow t_{\rm diff} = \alpha^{-2} T^{-2} \frac{m_p^2}{8\pi M}. \tag{11}$$

Finally, demanding that, within that time, the energy contained in a sphere of radius $\Gamma_{\rm dep}(T, T_H)^{-1}$ equals the energy deposited by Hawking radiation provides an expression for the hot-spot core temperature [52–54]

$$\frac{\pi^2}{30} g_\star(T_c) T_c^4 \times \frac{4\pi}{3} \Gamma_{\rm dep}(T_c, T_H)^{-3} = -t_{\rm diff} \frac{dM}{dt}. \tag{12}$$

Using the expression of the Hawking temperature and evaporation rate in the presence of MB in Eq. (6), we obtain the core temperature, as well as the corresponding radius of the core $r_c \equiv r_{\rm diff}|_{T=T_c}$,

$$T_c = \left(\frac{\eta_M^2}{\eta_T}\right)^{1/3} T_{c,\rm SC}, \qquad r_c = \left(\frac{\eta_T}{\eta_M}\right) r_{c,\rm SC}, \tag{13}$$

where the semiclassical results were derived in Ref. [52]:

$$T_{c,\rm SC} = 24 \left(\frac{150}{\pi^2}\right)^{1/3} \alpha^{8/3} \left(\frac{\varepsilon}{g_\star}\right)^{2/3} T_{H,\rm SC} \tag{14}$$

$$\approx 1.5 \times 10^{-4} \left(\frac{\alpha}{0.1}\right)^{8/3} \times \left(\frac{\varepsilon}{4.2 \times 10^{-3}}\right)^{2/3} \left(\frac{g_\star}{106.75}\right)^{-2/3} T_{H,\rm SC}, \tag{15}$$

and

$$r_{c,\rm SC} = \frac{\pi^2 g_\star}{360 \alpha^6 \varepsilon} r_H, \approx 7.0 \times 10^8 \left(\frac{\alpha}{0.1}\right)^{-6} \left(\frac{\varepsilon}{4.2 \times 10^{-3}}\right)^{-1} \left(\frac{g_\star}{106.75}\right) r_H, \tag{16}$$

in which $r_H = 2M/m_p^2$ denotes the classical Schwarzchild radius of the BH and $g_\star$ needs, in principle, to be evaluated at the true hot-spot core temperature T_c. In practice, like we did for the evaporation function ε, we will assume this number of relativistic degrees of freedom to be constant throughout this work. Note that, according to these equations and the typical ordering of the transfer functions, one obtains that $r_c \gg r_{c,\rm SC}$ and $T_c \ll T_{c,\rm SC}$, which is expected: the evaporation flux being suppressed by the memory burden effect, so is its capacity to deposit energy efficiently around the black hole, leading to a colder and larger homogeneous core at the center of the hot spot.

Outside this homogeneous core, a local thermal equilibrium persists, but diffusion is at play, with a temperature evolving as $\propto r^{-1/3}$ [52], which remains the case in the presence of memory burden. During the evaporation timescale[1]

[1]Note that this timescale differs with an $\mathcal{O}(1)$ prefactor from the total evaporation time of the PBH.

$$\tau_{\rm ev} \equiv \left(\frac{1}{M}\frac{dM}{dt}\right)^{-1}, \tag{17}$$

such diffusion can only propagate until the maximum *decoupling* radius, defined as the radius $r_{\rm dec}$ matching the distance it takes for the Brownian motion of particles to propagate them in the plasma on the same distance

$$r_{\rm dec} \equiv \sqrt{\frac{\tau_{\rm ev}}{\alpha^2 T(r_{\rm dec})}}, \qquad T(r_{\rm dec}) = T_c (r_c/r_{\rm dec})^{-1/3}, \tag{18}$$

giving

$$r_{\rm dec} = \eta_M^{-4/5} r_{\rm dec,SC}, \tag{19}$$

where [52]

$$r_{\rm dec,SC} = \frac{\pi^{3/5} g_\star^{1/5}}{720^{1/5}\alpha^{8/5}\varepsilon^{4/5}}\left(\frac{M}{m_p}\right)^{6/5} r_H, \tag{20}$$

$$= 1.1\times 10^{20}\left(\frac{\alpha}{0.1}\right)^{-8/5}\left(\frac{\varepsilon}{4.2\times 10^{-3}}\right)^{-4/5} \times \left(\frac{g_\star}{106.75}\right)^{1/5}\left(\frac{M}{10^9\ {\rm g}}\right)^{6/5} r_H. \tag{21}$$

For $r_{\rm dec}(M) < r < r_{\rm dec}(M_{\rm ini})$, though diffusion still contributes, it is no longer efficient due to the increasingly short timescales. Consequently, in Ref. [52], it was shown that the temperature decreases like $\propto r^{-7/11}$, such that the overall temperature profile is

$$T = \begin{cases} T_c, & r_H < r \le r_c, \\ T_c\left(\frac{r}{r_c}\right)^{-1/3}, & r_c < r \le r_{\rm dec}, \\ T_c\left(\frac{r_{\rm dec}}{r_c}\right)^{-1/3}\left(\frac{r}{r_{\rm dec}}\right)^{-7/11}, & r_{\rm dec} < r \le r_{\rm dec}(qM_{\rm ini}). \end{cases} \tag{22}$$

Note that these equations remain valid unless $r_c \ge r_{\rm dec}$, after which diffusion is no longer able to establish a local thermal equilibrium on scales smaller than the core. This happens when the mass decreases below a critical mass,

$$M_\star = \eta_M^{-1/6}\eta_T^{5/6} M_{\star,\rm SC}, \tag{23}$$

where η_M and η_T need to be evaluated at $M_\star$ and the semiclassical value is[2] [52]

$$M_{\star,\rm SC} = \frac{\pi^{7/6}}{(64800\sqrt{2})^{1/3}}\frac{g_\star^{2/3} m_p}{\alpha^{11/3}\varepsilon^{1/6}}, \approx 0.58 g\left(\frac{\alpha}{0.1}\right)^{-11/3}\left(\frac{\varepsilon}{4.2\times 10^{-3}}\right)^{-1/6}\left(\frac{g_\star}{106.75}\right)^{2/3}. \tag{24}$$

Once the PBH mass drops below this critical mass, it was argued in Ref. [52] that the hot spot does not vary by much since the remaining energy evaporated by the black hole is subdominant in comparison to total energy of the hot-spot core. This energy does not efficiently diffuse within the hot spot, and we will assume this to be true in this study.

At $M = M_\star$, the PBH has thus reached its maximum core temperature, equal to

$$T_{\rm max} = \eta_M^{5/6}\eta_T^{-7/6} T_{\rm max,SC}, \tag{25}$$

where the semiclassical reference value is given by[3] [52]

$$T_{\rm max,SC} = \frac{(262440000\sqrt{2})^{1/3}}{\pi^{17/6}}\frac{m_p \alpha^{19/3}\varepsilon^{5/6}}{g_\star^{4/3}}, \approx 3.2\times 10^9\ {\rm GeV} \times\left(\frac{\alpha}{0.1}\right)^{19/3}\left(\frac{\varepsilon}{4.2\times 10^{-3}}\right)^{5/6}\left(\frac{g_\star}{106.75}\right)^{-4/3}. \tag{26}$$

Again, we note that, as expected, the memory burden tends to increase the critical mass $M_\star$ and suppress the maximum temperature reached in the hot-spot core as compared to the semiclassical case.

IV. RESULTS

We will now study specific examples of memory-burden-like transfer functions η_M and η_T and describe their effect on the hot-spot evolution and maximum temperature.

To do so, we will consider the two extreme cases mentioned above: first, the case where the MB kicks in and leads to constant rates and Hawking temperature, and second, the case of a memory-burden rate that remains self-similar. We stress that, although the second case might not be well motivated from a theoretical point of view (see Ref. [65]), it constitutes a good illustrative example of an evaporation rate that would be significantly suppressed compared to the semiclassical case, while still evolving in time. We emphasize that other cases, such as the smooth transition between the SC and MB regimes [63,65], could easily be studied using the formulas above and lead to

[2]Note that there is a factor of $3^{5/12}$ of difference between this result and the result obtained in [52], as we have used $\tau_{\rm ev}$ in the evaluation of $r_{\rm dec}$ as opposed to the integrated PBH lifetime.

[3]Note again the difference of prefactor, which is again given by $3^{5/12}$ as compared to [52] due to the same (but inverse) prefactor appearing in $M_{\star,\rm SC}$.

substantial variations of the results presented here. Before continuing, we stress that the hot spot that forms during the semiclassical phase of evaporation is not relevant to the present discussion, though a hot spot would indeed be supported during this period. This is because the semiclassical evaporation rate is large enough to deposit energy rapidly into the surrounding plasma, enabling thermalization and diffusion. Indeed, during the semiclassical phase, the evaporated energy was sufficiently large to deposit energy quickly into the surrounding plasma due to rapid thermalization and diffusion thus supporting the formation of a hot spot. Once the MB becomes active, the timescales are significantly lengthened. Evaporation takes longer, the flux of particles emitted by the black hole is drastically lowered, and the black hole is unable to maintain any hot spot formed in the semiclassical era. Therefore, it is sensible to think of a hot spot formed during the memory burden era as a PBH of initial mass $M \approx qM_{\mathrm{ini}}$.

A. Rigid memory burden

We now consider the original MB scenario, in which, after the mass passes the threshold $M < qM_{\mathrm{ini}}$, the evaporation rate and Hawking temperature become exactly constant. This corresponds to the choice of transfer functions exhibited in Eqs. (7) and (8).

After the MB kicks in, all of the time and energy scales involved in the problem freeze. The shape of the hot spot is thus established while $M \approx qM_{\mathrm{ini}}$ and does not evolve further, until the evaporation is over and diffusion dissipates the hot spot. Because of the large MB suppression of the rate, the core of the hot spot is significantly colder compared to the SC case. In Fig. 1, we represent the value of this maximum temperature for $q = 0.5$ and various values of the parameter k. From the figure, one can see that the hot-spot temperature drops rapidly below the electron's mass (cyan-shaded region). This is the threshold at which electrons decouple from the plasma surrounding the black hole. Beyond this threshold, it is unclear if any hot spot could form at all since the derivations in this paper depend on established results that assume local thermal equilibrium. Therefore, it seems that the effect of a substantial memory burden is to prevent the formation of a hot spot in that regime. In Fig. 1, the gray area corresponds to the region of parameter space where the temperature in the ambient universe is greater than the hypothetical hot-spot temperature. Consequently, no temperature gradient can form in this region either. The tan region also excludes parameters for which the PBH is longer lived than the Universe. In that case, it thus appears that the vanilla memory-burden scenario does not lead to the formation of a hot spot unless the mass of the black hole is between $10^5\ \mathrm{g} \lesssim qM_{\mathrm{ini}} \lesssim 5 \times 10^{12}$ g and the MB exponent $k \lesssim 0.3$. This excludes, in particular, hot-spot formation in cases with nonzero integer values of k.

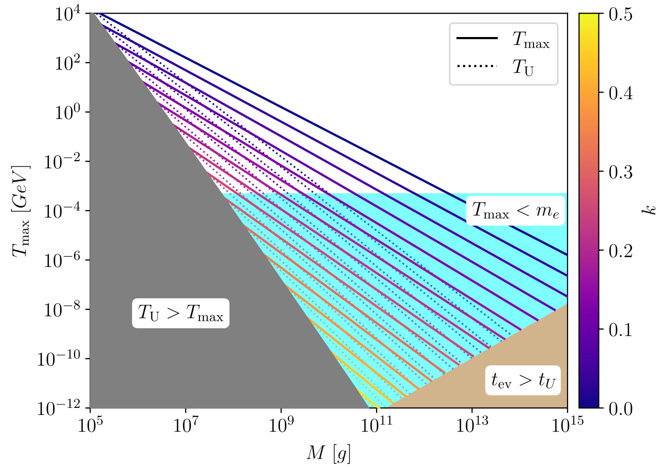

FIG. 1. Hot-spot core temperature (plain colored lines) compared to the Universe's temperature at the time of evaporation (dotted lines) for different values of k, and as a function of $M = qM_{\mathrm{ini}}$. Regions where the hot-spot core is colder than the ambient Universe, and where the PBH is stable on cosmological timescales, are shaded in gray and brown, respectively.

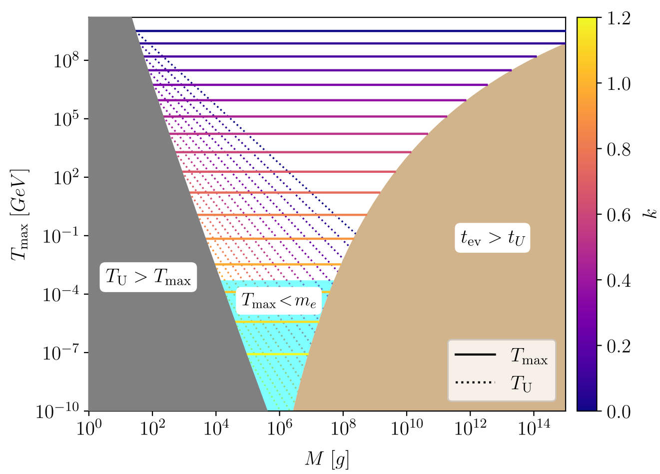

FIG. 2. Same as in Fig. 1, but in the case of *self-similar* MB rate and Hawking temperature.

B. Self-similar memory burden

If one considers the memory burden suppression to evolve in a self-similar manner with the black hole mass (while the Hawking temperature evolves in an SC manner), one obtains a suppression of the rate that does suppress the hot-spot core temperature, but still allows it to grow over time. This corresponds to setting $qM_{\mathrm{ini}} \to M(t)$ in Eqs. (7) and (8). In that case, the evolution of the maximum temperature is presented in Fig. 2. As expected, as the mass of the PBH decreases, the rate suppression also decreases, and the Hawking temperature is still increasing in a SC manner, leading to a hot spot that can still be much hotter than the ambient universe at the time of evaporation. Notably, the maximum temperature of the hot-spot core is independent of the mass, as in the SC case, as the rate has recovered its self-similarity property. In that case, a hot spot is able to form for masses 50 g $\lesssim qM_{\rm ini} \lesssim 5 \times 10^{15}$ g and the MB exponent $k \lesssim 1$.

V. SUMMARY AND DISCUSSION

In this paper, we explored the effect of a modification of the PBH evaporation rate and Hawking temperature evolution on the formation of hot spots, as compared to results established in the semiclassical limit. We introduced general transfer functions η_M and η_T that encapsulate this modification and derived expressions for the temperature radial profile of the thermal plasma around an evaporating PBH, as a function of these transfer functions and the semiclassical results derived in Ref. [52]. As expected, we find that, due to the memory burden, corresponding to a slowing down of the evaporation process and energy injection, the hot spots predicted are substantially colder than in the semiclassical case. Furthermore, from Eqs. (13) and (19), it is also easy to see that the overall size of the hot-spot core and outer envelope is also much larger, which is also expected as a colder plasma leads to a smaller energy deposition rate, and therefore a longer mean-free path for the particles emitted by the BH. For illustrative purposes, we considered the case of a rigid memory burden kicking in at about half the initial mass of the black hole, and showed that a vanilla memory-burden scenario does not lead to the formation of a hot spot unless the mass of the black hole is between 10^5 g $\lesssim qM_{\rm ini} \lesssim 5 \times 10^{12}$ g and the MB exponent $k \lesssim 0.3$. This excludes in particular hot-spot formation in cases with nonzero integer values of k. For further comparison, we also considered the case where the memory-burden modified evaporation rate would be self-similar, with its expression varying with the PBH mass, while its Hawking temperature would follow the SC evolution. In that case, despite the large suppression of the PBH evaporation rate, the formation of a hot spot is possible as long as the power-law exponent used in the MB suppression factors is smaller than unity.

As shown in numerous studies [55–57,98], precise knowledge of the PBH hot-spot evolution is crucial for understanding the imprint of evaporating PBHs in cosmological data. Thanks to the generality of our derivation, we expect that any future derivation of the evaporation rate and Hawking temperature that may be intermediate between the cases we considered in this paper could easily be studied in the future. One such possibility could be the case of a smooth transition between the SC and MB regimes studied in Refs. [63,65]. As future research uncovers a more comprehensive understanding of the memory burden and its quantitative effect on the PBH evaporation rate and Hawking emission spectrum, these results will thus allow the community to refine our knowledge of the thermal plasma morphology during the evaporation.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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