

Primordial rotating black holes

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Primordial black holes formed in an early postinflation matter-dominated epoch during preheating provide a novel pathway for a source of the dark matter that utilizes known physics in combination with plausible speculations about the role of quantum gravity. Two cases are considered here: survival of Planck-scale relics and an early universe accretion scenario for the formation of primordial black holes of asteroid-scale masses.

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I. INTRODUCTION

Standard Model relics do not have adequate abundances to explain the existence of dark matter in the universe, apart from (sterile) neutrinos which erase small-scale fluctuations because of their free streaming. To avoid excessive power suppression, investigations have generally focused on particles generated via extensions of the Standard Model and, in particular, from minimal supersymmetric theories. So far, no signal of supersymmetry has been found in experiments performed with the Large Hadron Collider [1] and results from direct search experiments are unconfirmed [2,3]. Negative results have also been obtained via indirect searches related to the detection of high energy neutrinos photons, leptons, and hadrons that could have been produced by the annihilation of dark matter particles predicted in diverse environments [4], including the sun [5], in the Galactic Center [6] and in nearby dwarf galaxies [7,8].

Confronted with these difficulties, a revival of the idea that primordial black holes (PBHs) could be dark matter particles has flourished in the recent literature. Although early investigations on the formation of PBHs have focused on the radiation-dominated phase just after reheating, some studies raised the possibility that the scalar fields that drive inflation may be affected by gravitational instabilities (similar to the Jeans instability) that may lead to black hole formation [9–11] at the end of inflation when the fields (or field) driving the expansion oscillate(s) around a local minimum of the potential before decaying

into matter/radiation. During this short oscillatory phase, the energy density varies approximately as $\rho_\phi \propto a^{-3}$, i.e., it behaves like a “dust” fluid. This short matter era is advantageous for black hole formation since pressure gradients are practically absent in density fluctuations, contrary to the situation in the postreheating phase. The formation of these PBHs depends not only on the amplitude of the perturbations but also on the form of the field potential. Moreover, as discussed below, a broad mass spectrum of PBHs is produced that results in substantial growth of the most massive PBHs by accretion of small PBHs before they have time to Hawking evaporate.

Two principal scenarios have been envisaged: in the first, only one field is responsible for driving the inflation, while in the second, an additional “spectator” field (or several such fields) may be also present. In the former scenario, the scalar field can fragment into lumps via gravitational instability and form black holes under certain conditions [12]. In the second picture, one or more spectator fields are present. These fields are characterized by the fact that their energy densities are never dominant in comparison with that of the main field. However, their curvature power spectra dominate at small scales, favoring black hole formation [13]. PBHs originating from these mechanisms may form before the end of reheating [14], have, in general, masses larger than 10^{15} g and hence survive the Hawking evaporation process.

Here we are concerned with smaller mass PBHs that would evaporate on short timescales, potentially leaving a Planck-sized remnant. The possible existence of these relics and their possible stability are the main purpose of the present investigation. It is worth mentioning that PBHs of

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small masses ($M \sim 10^6 g$) are expected to be formed in a hybrid inflationary scenario as discussed by [15,16]. Also, in a single field scenario, small mass black holes form via a resonant instability that develops during the oscillatory phase for wavelengths that exit the Hubble radius near the end of inflation [17]. This mechanism is able to produce PBHs with masses around $\sim 10^3 g$.

We envisage two alternative scenarios for these PBHs. They may evaporate but leave stable Planck mass remnants, accounting for a substantial part of dark matter [17]. Alternatively, if the mass range is broad, accretion of many low mass PBHs by the most massive PBHs will produce long-lived PBHs that can equally account for most of the dark matter by populating the only available PBH window, in the mass range $10^{17}-10^{22} g$.

Here we consider a scenario in which PBHs formed by the aforementioned mechanisms, leaving extremal rotating remnants. Our motivation is based on recent investigations suggesting that PBHs formed in such a particular phase of the universe might have acquired significant angular momentum [18,19].

Surviving Planck-scale objects can be described by a particlelike formalism [20,21] that permits the existence of an extremal configuration associated with the ground state. The PBHs formed by accretion must lie above the accretion limit imposed by the diffuse gamma ray background.

Our paper is organized as follows: Planck-sized relics and their stability are discussed in Sec. II and the particlelike formalism describing the black hole will be presented in Sec. III. It will be shown that the resulting horizon area is equally spaced in agreement with the early findings by Bekenstein [22] and that the Bohr correspondence principle is verified or, in other words, general relativity is recovered at large quantum numbers. A following section describes the PBH accretion scenario. Our main conclusions are given in Sec. V.

II. PLANCK REMNANTS

The Hawking evaporation process has always been an obstacle for explaining the survival of PBHs with masses smaller than $\sim 10^{15} g$. To avoid such a difficulty, MacGibbon [23] postulated that Planck-sized black holes could be surviving remnants of such a process and could eventually constitute a substantial fraction of the dark matter. The existence of relics of the Hawking process is still a matter of debate since it is related not only to the possibility of having Planck-scale black holes as dark matter but also to the disappearance of the singularity [24,25].

A possible resolution derived from string theory leads to a generalization of the Heisenberg uncertainty principle (or simply GUP). This suggests that Hawking evaporation ends when the black hole mass attains a minimal value of the order of the Planck mass [16,26,27]. Such remnants are expected to not emit radiation/particles despite having an extremely high horizon temperature. Black holes with an

inner Cauchy horizon could be a possible resolution of this problem, especially since in the extremal case, i.e., when the two horizons coincide, the associated temperature is zero and Hawking emission is suppressed.

In this situation, extremal regular black holes described either by the Bardeen or the Hayward metrics [28,29] are able to produce Planck-sized objects if their Riemann curvature invariant is comparable to that derived in terms of the volume operator in loop quantum gravity [30,31]. A similar approach was adopted by Chamseddine *et al.* [32] who assumed that general relativity is modified at curvatures near the Planck scale. As a result, they have obtained stable (zero Hawking temperature) remnants with masses determined by the inverse limiting curvature.

We note that in loop gravity the Hawking evaporation timescales as $m_b h^2$, as opposed to $m_b h^3$ in Einstein gravity. This potentially affects the mass range of PBHs that survive evaporation.

Extremal singular charged or rotating black holes described, respectively, by the Reissner-Nordstrom or the Kerr metrics have been also considered in the literature. In the former case, debate about discharge by spontaneous pair production remains open. This process affects large black holes ($M \sim 10^{17} g$) while other processes also affect the charge evolution of smaller ones as emphasized by [33,34]. The main difficulty in describing the discharge mechanism is to find an adequate transition from a space-time with a Cauchy horizon to another in which the inner horizon is absent [35,36]. More recently, Lehmann *et al.* [37], searching for detectable effects of primordial Planck mass black holes, explored the idea that a fraction of them could be charged, regardless of their origin and stability.

III. QUANTUM BLACK HOLES

A quantum description of a black hole necessarily requires a complete quantum theory of gravitation, still nonexistent. In the meantime, it is possible to adopt an approach in which either the mass-energy spectrum or the horizon surface of the black hole may assume discrete values. In fact, in a seminal paper, Bekenstein [22] considered that the horizon area of nonextremal black holes behaves as a classical adiabatic invariant, corresponding to a quantum operator with a discrete spectrum, according to the Ehrenfest principle. His point of departure was the squared-irreducible mass relation for a Kerr-Newman black hole with which quantum mechanical operators are associated. Another point of view was developed by Carr [38], who assumed a smooth transition between the Schwarzschild and Compton scales associated with a black hole of mass M . To some extent, these approaches suggest that BHs can be assimilated into elementary particles with Planck masses. Although these ideas can be pushed a little further, one would expect that any formal quantum particle description of a black hole should permit the recovery of general relativity at larger quantum numbers. More recently, a particlelike black hole formalism

was adopted [21] to describe a Reissner-Nordstrom black hole. This approach permits the existence of extremal configurations that correspond to a minimal mass below which no horizon forms. The Hawking temperature in this extremal state is zero, and objects deviating from extremal configurations radiate well-defined quanta of energy in the form of radiation and particles. Thus, one should expect that a quantum rotating black hole in an excited state will also spontaneously decay into lower spin states since the asymmetric emission of neutrino quanta will carry away angular momentum according to Leahy and Unruh [39].

Here we will focus our interest in the Kerr space-time since it includes a Cauchy horizon permitting extremal solutions, stable from a thermodynamic point of view. However, for the moment, the question concerning the existence of a ground-state solution that at the same time coincides with the extremal case remains open. It should be emphasized that black holes must also be considered as relativistic objects in the sense that they are subject to strong gravitational fields. Contrary to the approach by [22], who adopted the squared irreducible mass of a Kerr-Newman black hole as the departure point, here the relation defining the inner (“−”) and outer (“+”) horizons of a Kerr black hole will be used, that is,

$$r_{\pm}(M, J) = \frac{GM}{c^2} \left[1 \pm \sqrt{1 - \left(\frac{Jc}{GM^2} \right)^2} \right]. \quad (1)$$

In the above equation, M and J are, respectively, the mass and the spin of the black hole and the other symbols have their usual meaning. In a second step, it is assumed that the black hole spin is quantized by the usual rules, i.e., $J = m\hbar$, where $m = 0, 1, 2, \dots$. In the particlelike description, the size of the black hole (or its outer horizon) should never be smaller than the associated Compton wavelength. Hence, following [21,40], one assumes that

$$r_+(M, J) = n \frac{\hbar}{Mc}, \quad (2)$$

where $n = 1, 2, 3, \dots$. Notice that up to this point, nothing is imposed concerning the mass of the black hole, but as we shall see, the adopted quantum conditions will lead naturally to Planckian values. Replacing the horizon radius given by Eq. (2) into Eq. (1) permits us to obtain an equation defining the possible values for the black hole masses, that is,

$$\frac{M}{M_P} = \sqrt{\frac{(n^2 + m^2)}{2n}}, \quad (3)$$

where M_P is the Planck mass. It is interesting to remark that the equation above, which gives discrete values for the black hole mass, coincides with that derived by Bekenstein [22] if the electric charge in his relation is put equal to

zero. Now, insert this result into Eq. (1) and after some straightforward algebra, one obtains

$$r_{\pm} = \ell_P \sqrt{\frac{(n^2 + m^2)}{2n}} \left[1 \pm \sqrt{1 - \frac{4m^2 n^2}{(n^2 + m^2)^2}} \right], \quad (4)$$

where ℓ_P is the Planck length.

It can be shown trivially from Eq. (4) that extremal black holes can be obtained if both quantum numbers are equal, i.e., $n = m$. In this case, the horizon radius and the mass are, respectively,

$$r_H = \sqrt{n} \ell_P \quad \text{and} \quad M = \sqrt{n} M_P. \quad (5)$$

If such an extremal rotating black hole is in the “ground” state ($n = 1$), then the degenerate horizon r_H and the mass correspond precisely to the Planck length and mass with a spin equal to \hbar . Equation (4) can be expanded and explicit relations for the Cauchy and the event horizons obtained, that is,

$$r_- = \sqrt{\frac{2m^4}{n(n^2 + m^2)}} \ell_P \quad (6)$$

and

$$r_+ = \sqrt{\frac{2n^3}{(n^2 + m^2)}} \ell_P. \quad (7)$$

Notice also that the condition $r_+ \geq r_-$ implies necessarily that $n \geq m$.

General relativity imposes no restrictions on the mass spectrum of black holes, contrary to the discrete values resulting from Eq. (3). If Bohr’s correspondence principle is applicable, one should expect to recover general relativity in the limit of large quantum numbers. Performing the ratio between Eqs. (7) and (3), one obtains after some algebra

$$\frac{c^2 r_+}{2GM} = \frac{n^2}{(n^2 + m^2)}. \quad (8)$$

It can be easily verified that when $n > m$ and $n \gg 1$, the right side of the above equation goes to unity and general relativity is recovered since the event horizon goes to $2GM/c^2$ as expected.

Another important aspect of the particlelike picture concerns the horizon area or the black hole entropy. Bekenstein, in his pioneering work [22], suggested that the black hole area should be discrete and equally spaced with a spectrum $A_n = \alpha \ell_P^2 n$ with $n = 1, 2, \dots$. He estimated the proportionality constant as $\alpha = 8\pi$ by assuming that the squared irreducible mass of the black hole is the analog of an adiabatic invariant action integral. Based on Bohr’s correspondence principle, Hod [41] reached a different result for the proportionality constant, i.e., $\alpha = 4 \ln 3$. This has been contested by other authors

(see, for instance, [42,43]), who confirmed the value $\alpha = 8\pi$ by independent analyses.

It is interesting to verify if the present description of a quantum black hole is consistent with such a discretization of the black hole area and to ascertain the expected value of the constant α . For a Kerr black hole, the horizon area is given by

$$A = 4\pi \left[r_+^2 + \left(\frac{J}{Mc} \right)^2 \right]. \quad (9)$$

Inserting into the above equation the horizon radius given by Eq. (7), the quantization condition for the spin and the black hole mass given by Eq. (3), one finally obtains

$$A = 4\pi \ell_P^2 \left[\frac{2n^3}{(n^2 + m^2)} + \frac{2m^2 n}{(n^2 + m^2)} \right] = 8\pi \ell_P^2 n. \quad (10)$$

Thus, the quantization conditions imposed in the present description of a quantum rotating black hole are consistent with the discrete area spectrum first proposed by Bekenstein. It worth mentioning that Medved [44], adopting a perturbative approach of the adiabatic invariant method, reached a similar result but included a fourth order spin correction term. Moreover, for a Kerr black hole family of solutions, the Cauchy horizon is the future boundary of the domain of dependence of the event horizon and the product of the areas of both horizons depends only on the squared angular momentum [45]. The area product $A_+ A_-$ of both horizons can be simply written as

$$A_+ A_- = (8\pi)^2 \left(\frac{GM}{c^2} \right)^2 r_+ r_-. \quad (11)$$

Inserting into this equation the expression for the mass and those for the inner and outer horizons, one obtains

$$A_+ A_- = (8\pi \ell_P^2)^2 m^2 = \left(\frac{8\pi G}{c^3} \right)^2 J^2. \quad (12)$$

The last term on the right side of the above equation coincides with the relation given in [45] when the electrical charge is put equal to zero, being an additional test for the consistency of the particle-like model.

As we have seen previously, the ground state of the present quantum black hole model corresponds to $n = m = 1$, which also represents an extremal case. A further step is to examine the energy spectrum. For a Kerr black hole as well as for the Schwarzschild case, the total energy inside the horizon depends only on the black hole mass [46]. In this case, using the preceding results,

$$E_{n,m} = M_P c^2 \sqrt{\frac{(n^2 + m^2)}{2n}}. \quad (13)$$

Hence, the ground state corresponds to an energy $E_{1,1} = M_P c^2$, the Planck energy. A larger black hole (with $n \neq m$)

will be in an excited state that can decay to a lower state by emitting an amount of energy $\Delta E = E_{n',m'} - E_{n,m}$. Such an energy quantum ΔE does not correspond to a single particle (or photon) but should be imagined as a ‘‘bunch’’ of radiation/particles with a well-defined total energy. If we appeal again to Bohr’s correspondence principle, one should expect that at large quantum numbers, the equivalent transition frequency between two consecutive levels, i.e., $\omega = \Delta E/\hbar$ should approach the ‘‘classical’’ frequency representing a quasinormal mode [41,42]. In fact, when $n > m \gg 1$, the energy gap between two consecutive levels is

$$\Delta E_{n,m} = (E_{n+1,m+1} - E_{n,m}) \approx \frac{M_P c^2}{\sqrt{2}} \left[\frac{1}{\sqrt{2n}} + \frac{m}{n^{3/2}} \right]. \quad (14)$$

In order to interpret the terms in the above equation, we recall that when $n > m \gg 1$, the black hole mass is given by $M \approx M_P \sqrt{n/2}$. Thus, the first term on the right side of Eq. (14) can be written $\hbar c^3/4GM$ or, equivalently, $2\pi k T_H$ where T_H is the Hawking temperature. The second term requires a little extra work with the expression defining the angular rotational velocity of a Kerr black hole (in geometric units), that is,

$$\Omega = \frac{4\pi a}{(r_+^2 + a^2)}, \quad (15)$$

where a is the spin parameter. Performing the quantization as before and recovering the physical constants, the angular velocity can be recast as

$$\Omega_{n,m} = \frac{c}{2\ell_P} \frac{\sqrt{2}m}{\sqrt{n(n^2 + m^2)}}. \quad (16)$$

For large values of the quantum numbers ($n > m$), one obtains $\Omega_{n,m} \approx (c/\ell_P)(m/\sqrt{2}n^3)$. Using these results, Eq. (14) can be rewritten as

$$\Delta E_{n,m} = \hbar \omega_{n,m} = 2\pi k T_H + \hbar \Omega_{n,m}. \quad (17)$$

This expression is consistent with the limit at large quantum numbers for the real part of quasinormal modes found by Hod [41] in the case of rotating black holes. On the other hand, for a black hole in a given state (n, m) , there is a limit for the energy that can be extracted from the ergosphere [47], which corresponds to the total utilization of the rotational energy leaving the black hole in a state $(n, 0)$ or with an energy

$$E_{n,0} = M_P c^2 \sqrt{\frac{n}{2}}. \quad (18)$$

For consistency, the above energy must coincide with that corresponding to the irreducible mass given by

$$E_{\text{ir}} = \frac{c^4}{G} \sqrt{\frac{A_+}{16\pi}} = M_p c^2 \sqrt{\frac{n}{2}}, \quad (19)$$

where Eq. (10) was used to replace the area of the horizon. Despite this mathematical consistency, one should expect that this result would be valid only for large black holes ($M > 10^{15} g$) since for small ones the state $(n, 0)$ does not correspond to the ground state and the stability against the Hawking process disappears. Hence, for small black holes, one should expect that the extraction of rotational energy stops when $m = 1$. In this case, the irreducible mass becomes

$$M_{\text{ir}}^2 = \frac{A_+ c^4}{16\pi G^2} + \frac{4\pi \hbar^2}{A_+ c^2}. \quad (20)$$

In the equation above, the second term on the right represents a ‘‘quantum correction’’ to the irreducible mass that permits the black hole to decay to the ground state. Notice that for large black holes, such a correction term is completely negligible.

IV. ACCRETION OF PBHS BY PBHS

Most discussions of PBH production argue that an extended mass function is fairly generic. Early production during an extended reheating phase boosts the PBH mass scale because of accretion by the rarer more massive PBHS of the many smaller ones hovering near the ground state. The generated mass function should peak near a mass limit determined by accretion over the time available before reheating is completed. Using the spherical thin shell approximation to accretion in an Einstein-de Sitter universe (Bertschinger, 1985), we estimate that the PBH masses increase by a factor $\sim(1 + z_{\text{inf}})/(1 + z_{\text{rh}})$, where z_{inf} is the inflationary scale, estimated to be $\sim 3 \cdot 10^{16}$ GeV for a weakly interacting and slowly rolling scalar field that yields the observed low level of scalar density fluctuations. Also, z_{rh} is the reheat scale at a temperature estimated to be anywhere from $\sim 10^{16}$ GeV down to the QCD scale ~ 100 MeV, or even as low as ~ 10 MeV from BBN constraints.

Detection of primordial B-mode cosmic microwave background (CMB) polarization offers our best way of determining the reheat temperature, but is constrained by restriction to the experimentally feasible regime of $r \gtrsim 0.0001$, while $r \lesssim T_{\text{rh}}^2$ allows a much larger but unmeasurable range. Hence, accretion allows PBHS produced during preheating to survive to the present epoch and to populate the window accessible today by microlensing, provided they make up all or most of the dark matter of the universe. There need be no adverse effects of early evaporation, e.g., during the epoch of nucleosynthesis, since PBHS mostly evaporate later and are also very subdominant deep into the radiation era. Spectral μ distortions of the CMB produced via evaporation and energy

injection into the thermal bath of the CMB may provide a possible signature of their existence.

V. CONCLUDING REMARKS

Formation of PBHS in the very early universe, in particular during the short matter-dominated regime prevailing during the oscillatory phase of the inflaton field, has recently been the subject of extensive investigations. Small mass black holes can be formed in a hybrid inflation scenario first proposed by Linde [48] (see also [16]) as a consequence of a resonant instability affecting perturbations with wavelengths exiting the Hubble radius at the end of inflation [17]. More recently [49], it was shown that PBHS with masses as small as $10^3 g$ can be formed in a warm inflation scenario since the associated curvature power spectrum has a blue tilt that favors small-scale perturbations.

In these different scenarios, PBHS of small masses ($10^3 g$ of up to $10^5 g$) can be formed. Since these objects evaporate in a short timescale, the key question to be answered is whether or not a remnant will be left. Many authors have simply postulated the existence of Planck-sized relics without any consideration about their nature or stability. If such relics are Planck-sized black holes, their stability, at least from the thermodynamic point of view, is guaranteed if they are extremal black holes. Regular or nonsingular black holes described either by the Bardeen or the Hayward metrics are one possibility [30]. However, these objects have a particular mass (or charge) distribution leading to a tenuous ‘‘outer’’ atmosphere, which is one reason to classify them more appropriately as ‘‘Planck stars’’ [50]. Moreover, instabilities appear in the core during the evaporation process that complicates the analysis of the last stages of the process leading to remnant formation [51]. Extremal singular charged or rotating black holes are an alternative possibility. While the former include, for instance, difficulties concerning the discharge by the Schwinger mechanism, the latter option is favored by recent studies on the spin distribution of PBHS, suggesting that a substantial fraction has spin parameters near the maximum value [18]. Moreover, other studies [52] indicate that rotating PBHS are not constrained by the so-called Thorne limit [53] and might have spin parameters in excess of $a \sim 0.998$.

If remnants of the evaporation process are Planck-sized black holes, one would expect that quantum effects become important. In fact, a possible quantum approach was first proposed by [22], who considered that the horizon surface of a charged, rotating black hole behaves as a classical adiabatic invariant having a discrete spectrum. Another quantum picture was adopted by [21] to describe charged black holes. In such a particlelike formalism, it is possible to find extremal configurations associated with the ground state. Here the particlelike formalism is adopted to describe rotating black holes. The ground state of such a particlelike Kerr black hole corresponds to a mass and a horizon having Planck-sized values and a spin equal to \hbar . This state

corresponds also to an extremal case. Excited states satisfying the condition $n = m$ are also extremal but are expected to decay following excitation by mass accretion $n, m \rightarrow n', m$ with $n' > n$ and subsequent decay according to $n', m \rightarrow n'', m'$ with $n'', m' < n, m$. Similarly, the ground state population may oscillate due to these processes.

Using the derived expressions for the horizon radius and mass, the resulting area is also quantized and equally spaced according to the original result first derived by Bekenstein [22]. The energy spectrum is not equally spaced but satisfies Bohr's correspondence principle, since the equivalent frequencies due to transitions between two consecutive levels at large quantum numbers approach the frequencies of quasinormal modes. Moreover, the product between the inner and the outer horizon surfaces

is proportional to the squared angular momentum showing that the quantum picture reproduces the main properties expected for macroscopic black holes.

Accretion during reheating by the largest surviving but rare PBHs of the far more numerous but small, down to Planck mass, relic PBHs allows a substantial boost in PBH mass especially if reheating is late. This means that there are potentially observable signatures. These include late evaporation into the diffuse gamma-ray and x-ray backgrounds [54], cosmic ray signature in the (very) local interstellar medium [55], gravitational microlensing of deep stellar fields [56], and spectral distortions of the CMB, from evaporation in the radiation era (μ -type) and in the matter era (γ -type), as well as the intermediate hybrid (μ - γ) variety [57].

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