X-ray and gamma-ray limits on the primordial black hole abundance from Hawking radiation

Guillermo Ballesteros1,2, Javier Coronado-Blázquez1,2,† and Daniele Gaggero1‡

1Instituto de Física Teórica UAM/CSIC, Calle Nicolás Cabrera 13-15, Cantoblanco E-28049 Madrid, Spain and
2Departamento de Física Teórica, Universidad Autónoma de Madrid (UAM) Campus de Cantoblanco, 28049 Madrid, Spain

The non-observation of Hawking radiation from primordial black holes of 10^{16} g sets a conservative strong bound on their cosmological abundance. We revisit this bound and show how it can be improved (both in mass reach and strength) by an adequate modeling of the combined AGN and blazar emission in the MeV range. We also estimate the sensitivity to the primordial black hole abundance of a future X-ray experiment capable of identifying a significantly larger number of astrophysical sources contributing to the diffuse background in this energy range.

I. INTRODUCTION

The isotropic background radiation that fills the Universe and extends over more than 16 orders of magnitude in frequency—from radio waves all the way up to high-energy gamma rays [1]—carries information on the emission mechanisms of different astrophysical and cosmological sources over the history of the Universe, and can possibly shed further light on the nature of the elusive dark matter (DM) that constitutes the largest fraction of its mass.

In this work we consider the hypothesis that the bulk of the DM is made up of black holes of primordial origin (PBHs), formed from the collapse of large density fluctuations prior to the big-bang nucleosynthesis epoch [2, 3]. We focus on the PBH mass window ranging from 10^{16} g to 10^{19} g, revisiting the Hawking radiation constraints on their abundance from gamma-ray data obtained in [4] and showing how future gamma- and X-ray data allowing an increased sensitivity will have the potential for discovery of a population comprising the totality of the DM.

The PBH mass range from 10^{16} g to 10^{19} g is indeed particulary relevant for DM, given that previously claimed femtolensing bounds [5] are marred by an inadequate treatment of the involved optics, leaving much of that window open [6]. Besides, it had been argued in [7] that the observed distribution of white dwarfs constrains the PBH abundance to at most ~10% of the DM at 10^{19} g. However, a more detailed analysis [8] has recently challenged this conclusion, opening the possibility that even PBHs as heavy as ~5 \times 10^{22} g—which are constrained by microlensing [9]—could explain all the DM. The lower mass bound at ~10^{17} g comes instead from the non-observation of gamma-ray Hawking radiation [4].

Hawking radiation [10–14] is an approximately thermal particle emission expected to be emitted by black holes with temperature \( T = (8\pi k_B)^{-1}c^2 m_p^2/M \approx 6 \times 10^{-8}M_\odot/M_\text{K} \), being \( M \) the mass of the black hole, \( M_\odot = 3 \times 10^{33} \text{g} \) the mass of the Sun and \( m_p = \sqrt{\hbar c/G} \) the Planck Mass. In Ref. [4], a conservative (but nonetheless stringent) upper bound on the cosmological PBH abundance was set for \( M \lesssim 10^{17} \text{g} \) by comparing the predicted Hawking gamma-ray emission with the isotropic gamma-ray background in the approximate energy range 0.1 MeV — 10 GeV that was measured by EGRET [15], Fermi-LAT [16] and COMPTEL [17]. This bound has recently been updated in [18] (with the data from the same experiments), finding a good agreement with [4].

The main focus of our analysis is on the isotropic gamma- and X-ray background in the 10 keV – MeV domain. Using a power-law modeling of such background—motivated by the assumption that a population of unresolved extra-Galactic sources (mainly AGNs and blazars) represent the main contribution to it—we place an upper limit on the abundance of PBHs (as a function of their mass) by considering an array of datasets acquired by a variety of instruments over the latest decades. We also estimate the expected improvement in the bounds from a putative future experiment. We do so by assuming that such a future, more sensitive, experiment will resolve a significantly larger number of individual AGNs and blazars and will therefore provide a lower isotropic unresolved background for energies above ~200 keV.

II. HAWKING RADIATION FROM PBHS

The X-ray emission from a population of PBHs of mass \( M \) accounting for a fraction \( f = \Omega_{PBH}/\Omega_{DM} \) of the total DM density in the Universe is

\[
\Phi_M = \frac{dN}{dE dt} = f \frac{c \rho}{4\pi M} \int dz \frac{e^{-\tau(z)}}{H(z)} \Psi_M[(1+z)E],
\]

\( \text{(1)} \)
where \(\rho = 2.17 \times 10^{-30} \text{g/cm}^3\) is the current DM density of the Universe [19], and \(H(z)\) is the Hubble rate of expansion as a function of redshift. The function \(\Phi_M(E)\) denotes the differential flux emitted by a single PBH, as a function of the energy \(E\), per unit of energy and time. For PBHs of masses above \(10^{16} \text{g}\) is well approximated by the primary [20] Hawking emission:

\[
\Phi_M(E) = (2\pi h)^{-1}\Gamma_s/(\exp(E/k_B T) - 1),
\]

where the so-called grey factor \(\Gamma_s\) is a function of \(M\) and \(E\). In the high-energy limit \(E \gg k_B T\), the grey factor approximately satisfies \(\Gamma_s \propto (M/m_p)^2(E/m_p c^2)^2\); whereas for \(E \ll k_B T\), \(\Gamma_s \propto (M/m_p)^3(E/m_p c^2)^3\) [13]. These expressions are insufficient to render adequately the peak height and position of \(\Phi_M(E)\), which is best computed numerically. To do so we use the public code BlackHawk [21], which also allows to include the (sub-dominant) secondary emission. The differential flux for BHs of mass between \(10^{16} \text{g}\) and \(10^{20} \text{g}\) can be approximated by

\[
\Psi_M(E) \simeq \frac{2.5 \times 10^{21} \text{GeV}^{-1}\text{s}^{-1}}{(M_{18} E/E_0)^{2.7} + (M_{18} E/E_0)^{6.7}}, \tag{3}
\]

where \(E_0 = 6.54 \times 10^{-5} \text{GeV}\) and \(M_{18} \equiv M/10^{18} \text{g}\). This approximation is accurate to better than \(\sim 1\%\) around the emission’s peak (until \(\Psi_M(E)\) decreases an order of magnitude), which is enough for our purposes. Nevertheless, we obtain the bounds on the PBH abundance from the instantaneous spectra given by BlackHawk.

The factor \((1+z)^{-1}\) inside \(\Phi_M([1+z]E)\) accounts for the Doppler shift from the time of emission to the time of arrival to the detector. The optical depth \(\tau(z)\) describes the attenuation due to the propagation of the signal over the relevant cosmological redshifts. Unlike for hard gamma rays, this is negligible for soft gamma-rays and X-rays. The integrand in (1) decreases very rapidly with \(z\) and accurate results are obtained integrating up to \(z \sim \mathcal{O}(100)\).

III. THE X-RAY AND GAMMA-RAY AGN BACKGROUND

There has been a considerable effort dedicated to interpret the measurements of the X-ray and gamma-ray background from keV energies all the way up to \(\sim 100 \text{ GeV}\) in terms of a superposition of a large number of unresolved extra-Galactic sources. In particular, the data in the range \(\sim 5-200 \text{ keV}\) observed by Swift/BAT [22], MAXI [23], ASCA [24], XMM-Newton [25], Chandra [26] and ROSAT [27] are well reproduced by a population synthesis model of active galactic nuclei (AGNs) developed by Ueda et al. in [28] (see the blue dotted line in Figure 1). AGNs are powered by gas accretion onto a supermassive black hole and are very efficient X-ray emitters. The model of [28] is based on the extrapolations of the luminosity functions of AGNs in different redshift ranges inferred by a sample of 4039 AGNs in soft (up to 2 keV) and/or hard X-ray bands (>2 keV). The objects in the sample include both Compton-thin and Compton-thick AGNs (with the latter being heavily obscured by dust). As can be seen if Figure 1, this AGN modeling fails to describe adequately the SMM data.

Indeed, for energies above \(50 - 100 \text{ keV}\) the contribution from blazars is expected to become progressively more important. These objects correspond to the AGNs that are detected at a small angle between the accretion disk axis and the observer line of sight [29]; together with star-forming galaxies and radio galaxies, they are thought to dominate the GeV-TeV gamma-ray isotropic background measured by Fermi-LAT.

Although the details of the intermediate MeV – GeV domain are still not clearly understood (see in particular the discussion in [30]), the previous considerations lead us to employ the working assumption that a combination of different classes of extra-Galactic emitters explain the X-ray and gamma-ray unresolved diffuse background in a wide energy range, and that the emission from these populations of sources can be modeled as a superposition of featureless power-laws.

Therefore, in the approximate energy range going from 20 keV to 3000 keV, which corresponds to the region where the Hawking emission from BHs in the mass range \(10^{16} \text{g} - 10^{19} \text{g}\) can contribute importantly to the Universe’s diffuse spectrum, we model the astrophysical background as a double power-law fit to the data from the SMM [31], Nagoya balloon [32], HEAO-1 and HEAO-A4 [33, 34] experiments. Concretely, we will use the following proxy for the combined AGN and blazar emission:

\[
\Phi_{\text{AGN}} = \frac{dN}{dE dt} = \frac{0.0642 \text{keV}^{-1}\text{s}^{-1}\text{cm}^{-2}\text{sr}^{-1}}{(E/E_b)^{1.4199} + (E/E_b)^{2.8956}}, \tag{4}
\]

where \(E_b = 35.6966 \text{keV}\) (black dashed line in Figure 1).
IV. CONSTRAINTS AND PROSPECTS ON $f$

We present now our results on the current upper limits on the PBH abundance $f = \Omega_{\text{PBH}}/\Omega_{\text{DM}}$, in the mass window of interest, and estimate the prospects for a future MeV mission.

**Current bound: Conservative approach.** We start by deriving the present bound on $f$ under the most conservative approach, i.e. without assuming any astrophysical modeling of the data, as done in [4] and also very recently in [18]. We compute the estimator (under the assumption that the data are Gaussian distributed)

$$\hat{\chi}^2 = \sum (D - E^2 \Phi_M)^2 / \Delta^2$$

(5)

over the energy bins for which the PBH emission $\Phi_M$ is larger than the X-ray data $D$ shown in Figure 1 and whose errors are denoted $\Delta$ in (5). The allowed PBH fraction $f$ for a given PBH mass $M$ at 95% c.l. corresponds to values of $\hat{\chi}^2$ smaller than the threshold

$$\hat{\chi}^2 \leq \chi^2_{0.05}(N - 1),$$

(6)

where $N$ –which depends on $f$– is the number of bins in which the model overshoots the data. The threshold and the estimator are computed as functions of $f$ by adopting $N - 1$ as the number of degrees of freedom for the $\chi^2$ distribution. The bound is shown in Figure 2 as a black continuous line. Our result is in good agreement with those of [4] (see blue dotted line) and [18] in the PBH mass region ($M \geq 10^{16}g$) that we consider, even though in the (relevant) region between 1 MeV and 20 MeV those works used COMPTEL data whereas we use SMM, which has a much smaller error and a broader range.

**Sensitivity reach with the current data.** We now use the the power-law fit of the background described by Eq. (4) and consider the following estimator, evaluated over all energy bins (of the data we have used to obtain the fit):

$$\hat{\chi}^2 = \sum (D - E^2 \Phi_M - E^2 \Phi_{\text{AGN}})^2 / \Delta^2.$$  

(7)

The upper limit on the PBH abundance is set at the value of $f$ above which $\hat{\chi}^2$ worsens beyond the threshold for the 95% c.l. with respect to the minimum: i.e. the threshold is set as

$$\hat{\chi}^2 - \hat{\chi}^2_{\text{min}} \leq \chi^2_{0.05}(1) \simeq 3.84$$

(8)

In Figure 2 we show the results of both approaches to obtain 95% c.l. upper limits on $f$. Regarding the conservative approach (black solid line), our constraints are in good agreement with those from [4] (blue dotted line), while the bound assuming the power-law AGN model (blue solid line) is a factor $\sim 10$ stronger for the same $M$ and reaches larger PBH masses (up to about $7 \times 10^{17}g$).

**Future prospects.** In the forthcoming years the X-ray sky will be probed with increasing accuracy by several planned space observatories. In particular, the e-ASTROGAM mission [30] will explore a wide photon energy range from $\simeq 300$ keV to $\simeq 3$ GeV, and the hard X-ray instrument onboard the ASTRO-H mission [35] will focus on X-rays up to 80 keV. Both instruments are expected to provide a significant increase in sensitivity, and will identify a larger number of individual point sources. They will therefore provide a lower and better characterized isotropic background due to unresolved point sources. Given this expected increase in performance, a hypothetical PBH signal will be easier to detect. It is thus useful to provide a quantitative estimate of the potential of a generic future experiment in either setting a stronger upper limit on the PBH abundance in the mass range under investigation, or identifying a PBH signal with sufficient significance. To this aim, we assume here that the expected order-of-magnitude increase in sensitivity results in a larger number of individual sources detected, and hence a factor of 10 reduction in the diffuse, unresolved background, accompanied by a reduction by the same factor of its uncertainty. We generate mock data according to this prescription, and adopt the same procedure we applied to the current data in the sensitivity reach approach described previously. The result is shown in Figure 2 (red dashed line), which indicates a significant improvement of the current upper limits, together with a notable extension towards larger masses. For illustrative purposes, we show in the same figure (green dashed line) the results expected for an (optimistic) reduction by a factor of 100.

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**FIG. 2. 95% c.l. upper limits on the PBH abundance versus the PBH mass assuming a monochromatic mass population. The black line is the result of the present work neglecting the background contribution from AGNs. The light blue-dotted line is the analogous result of [4], see also [21]. The blue continuous line is the bound obtained assuming a power-law modeling of the AGN and blazar contribution to the observed spectrum. The red and blue dashed curves indicate the sensitivity achievable with an experiment capable of reducing the astrophysical background by factors of 10 and 100, respectively.**

V. DISCUSSION AND CONCLUSIONS

In this paper we have studied the upper limits on the abundance of primordial black holes from X-ray and gamma-ray Hawking radiation, as a function of mass and assuming a monochromatic distribution in the \(10^{16}\) g – \(10^{19}\) g mass range. This approximate mass window is particularly interesting from the model-building point of view. The known examples of the conceptually simplest mechanism capable of producing PBHs from single-field inflation –based on an approximate inflection point in the potential [36], see e.g. [37–41]– tend to do so in this range, once a reasonable fit to the CMB data at cosmological scales is imposed, see e.g. the related discussion in [39]. As discussed in the introduction, this mass range is within the currently most promising region for the existence of a significant contribution of PBHs to the DM.

We have first computed the upper limit with a conservative approach, by requiring that the expected signal from PBHs does not overshoot the diffuse X-ray background. The bound we have obtained is mostly driven by SMM data and agrees with the results presented in [4, 18], which instead used COMPTEL data in the relevant energy range. This bound is competitive with the recently derived upper limits based on the Voyager e\(\pm\) data [42] and extends to larger masses.

Then, we have considered a less conservative approach, which attempts to take into account in a simple way the expected effect of known classes of unresolved astrophysical sources –AGNs and blazars in particular– that are thought to provide the dominant contribution to the X-ray and gamma-ray diffuse isotropic background. Under the well-motivated assumption that the current data are consistently reproduced by such sources, we derive a stronger upper limit based on a power-law fit of the X-ray and gamma-ray data in the MeV domain. This (sensitivity reach) bound is about an order of magnitude stronger than the conservative upper limit described above.

We have also considered the potential of a future, more sensitive, experiment in the MeV domain that could resolve a larger number of individual sources, therefore providing a lower and more accurate estimate of the diffuse unresolved background. The prospects in case of a significant reduction of the background are very promising: We remark in particular that masses as large as \(10^{18}\) g are within reach under the assumption of a background reduction by a factor of 10.

The exploration of the low-energy gamma-ray channel (or upper X-ray range) is therefore a promising avenue towards a possible future detection of a signal associated to a population of PBHs that may constitute a significant part –perhaps even all– the dark matter in the Universe. In order to obtain further progress in this PBH mass region, a more sensitive experiment is needed in the MeV domain, and a more detailed understanding of the population of astrophysical sources that contribute to the bulk of the diffuse background is essential. Such a modeling of the MeV background should potentially include not only the contributions from sources (AGNs and blazars) that are known to be dominant in the sub- and sup-Mev bands, but also possible currently subdominant sources.

We also remark that there exist other channels for PBH detection in this window. In particular, the energy injection associated to Hawking emission around or just after recombination can be probed with CMB data [43]. Also, if the effect occurs during the reionization epoch it can be potentially detectable in the 21 cm absorption line of neutral Hydrogen [44]. Moreover, the positron emission by PBHs of mass around \(10^{17}\) g has been recently used to set a bound on \(f\) using the keV line, which can improve over the gamma-ray bound, depending on the assumed Galactic density profile [45]. All these channels are complementary and their further exploration could help to identify or rule out a significant population of PBHs in this promising mass window.

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