Ruling out QCD phase transition as a PBH origin of LIGO/Virgo events

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Abstract

The best-motivated scenario for a sizable primordial black hole (PBH) contribution to the LIGO/Virgo binary black hole mergers invokes the QCD phase transition, which naturally enhances the probability to form PBH with masses of stellar scale. We reconsider the expected mass function associated not only to the QCD phase transition proper, but also the e^+e^- annihilation process, and analyze the constraints on this scenario from a number of observations. We find that the scenario is not viable, unless an ad hoc mass evolution for the PBH mass function and a cutoff in power-spectrum very close to the QCD scale are introduced by hand.

Contents

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1 Introduction

The detection of heavy black hole merger events, see for instance [1], provides a strong motivation for primordial black holes (PBHs) as the candidates responsible for the bulk of these events (see e.g. [2, 3, 4, 5]). PBHs are theoretical objects that were firstly discussed in the

60s and 70s by Zeldovich & Novikov [6] and Hawking [7] and are typically assumed to be formed in the early universe from the collapse of large overdensities. PBHs are a well-studied non-particle dark matter (DM) candidate. Indeed, while there is no shortage of DM particle candidates in extensions of the SM, there is no guarantee nor observational indication that DM is made of microscopic fundamental particles. For a review of PBHs as DM and current bounds see [8]. In addition, PBHs also are very interesting objects in the context of supermassive black holes (SMBHs), LIGO/Virgo coalescing events, inflation etc.

In this work, we will focus on PBHs in the mass range $M_{\rm PBH} \sim 10^{-2} M_{\odot} - 10^{9} M_{\odot}$. This mass window is interesting at least for a couple of reasons. On the heavy end, PBHs whose mass is above $M_{\rm PBH} \sim 10^{6} M_{\odot}$ provide a possible explanation for the most massive BHs observed in the universe and, in particular, those at high redshift, which are difficult to explain through standard astrophysical processes otherwise (REF). On the light end, PBHs falling within the stellar mass range, namely $M_{\rm PBH} \sim 1 M_{\odot} - 10^{2} M_{\odot}$, are particularly interesting in light of LIGO/Virgo merger events observations. Even if the abundance of PBHs in the the stellar mass range is pretty constrained, some authors explored the possibility of PBHs constituting a large fraction of the events detected by LIGO/Virgo. In particular, as reported in [9], PBHs with masses $M_{\rm PBH} \sim \mathcal{O}(10) M_{\odot}$ contributing a fraction $f_{\rm PBH} \simeq \mathcal{O}(10^{-3})$ could explain a significant fraction of the events, improving fits to the inferred mass distribution with respect to the simplest astrophysical source templates.

The question now is: do we have any PBH production model that can yield such abundance in this specific mass range? Generally speaking, PBH models are hardly predictive on its mass distribution. However, it turns out that there is at least one physically motivated model amenable to observational tests based on physics in the early universe, in particular the QCD phase transition. Such model [10, 11, 12, 13, 14, 15, 16], when including other early universe phenomena (like e^+e^- annihilation) yields a peculiar mass function with physically motivated features extending up to $M_{\rm PBH} \sim 10^{7} M_{\odot}$.

In this work, we revisit this "best motivated" scenario to assess its viability in the light of current constraints from cosmic microwave background (CMB) anisotropies associated to accretion onto PBH [17], from CMB spectral distortions [18], as well as null searches of subsolar PBHs [19] and a stochastic gravitational wave background [20] in LIGO/Virgo. To do so, we compute the expected mass function associated not only to the QCD phase transition proper, but also the following particle antiparticle annihilation processes, down to the electron-positron annihilation.

The material included in this paper summarizes the work presented in the 14th conference on the identification of dark matter (IDM2022) organized by HEPHY in Vienna and closely follows reference [21], where we will constantly refer the reader to for more detailed calculations and further discussion.

2 Physics in the early universe

The PBH mass distribution adopts a very characteristic shape due to physical phenomena occurring in the early universe, namely the QCD phase transition and electron-positron annihilation. In particular, an enhancement of PBH production is induced at those particular times which, as we will see, are associated to a specific mass scale. A simple picture to understand how the mass function is shaped is the following: essentially it all boils down to the decrease of relativistic degrees of freedom which take place as a consequence of the drop of the temperature of the primordial plasma due to the expansion of the universe and the disappearance of species from it when the temperature falls roughly below its mass. This phenomena induces a decrease of the equation of state parameter which can be translated into a decrease of the

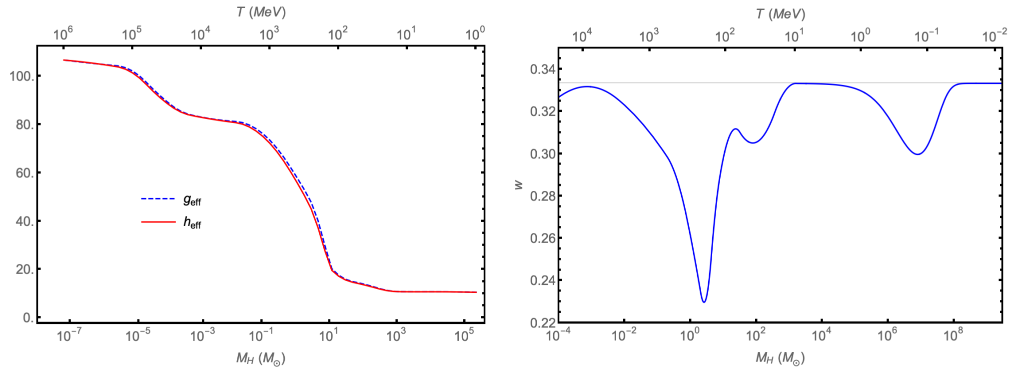

Figure 1: (Left) Effective number of relativistic degrees of freedom,$g_{\rm eff}$ and $h_{\rm eff}$,$g_{\rm eff}$ and $h_{\rm eff}$ as a function of the temperature (upper x-axis) and amount of mass enclosed in a Hubble patch (lower x-axis).(Right) Equation of state parameter w as a function of the temperature of the universe (top scale) or Hubble mass M_H (bottom scale). The gray horizontal line corresponds to the value during radiation domination $w = 1/3$.

overdensity threshold above which a PBH is formed. Therefore, whenever this drop of degrees of freedom happens, the value an overdensity has to reach in order to collapse decreases and as a result PBH production is enhanced. In order to have a more quantitative sense of how much the mass function is enhanced, we start by introducing the following definition for the effective number of relativistic degrees of freedom in terms of the energy density ρ, entropy density s and temperature T [22]

$$\begin{aligned} g_{\rm eff}(T) &\equiv \frac{30\rho}{\pi^2 T^4}, \\ h_{\rm eff}(T) &\equiv \frac{45s}{2\pi^2 T^3}. \end{aligned} \tag{1}$$

In the left plot of Figure 1 we plot $g_{\rm eff}$ and $h_{\rm eff}$ as a function of the temperature. One can easily see the several drops in value taking place at different temperatures or, equivalently, different Hubble masses.

From Eq. 1 and using thermodynamical relation $P = sT - \rho$ and the definition of the equation of state parameter $w \equiv P/\rho$, we can express w as an implicit function of the temperature through $g_{\rm eff}$ and $h_{\rm eff}$ as follows:

$$w(T) = \frac{4h_{\rm eff}(T)}{3g_{\rm eff}(T)} - 1. \tag{2}$$

Now, with the tabulated values of $g_{\rm eff}$ and $h_{\rm eff}$ [23,24] used to obtain the left plot in Fig. 1, we can easily plot w as a function of the temperature (Hubble mass) as shown in the right one.

Indeed, as we explained before, a decrease in the number of degrees of freedom induces the dip structure one can observe in the right plot in Fig. 1. In particular, the most prominent dip at around $\sim 1M_\odot$ is due to the QCD phase transition proper, the one at $\sim 100M_\odot$ to the pion and muon annihilation and the third one at $\sim 10^7 M_\odot$ is caused by the electron-positron annihilation. At this point, bringing back the definition $w \equiv P/\rho$ and recalling that the collapse of an overdensity depends on the balance between gravity and the internal pressure gradients, one can easily see that a decrease in w is indicating a decrease in pressure (so a more matter-like behavior) so it will be easier for the gravitational force to induce the collapse of the overdensity into a black hole.

3 The power spectrum

The early universe phenomena we just revisited in the previous section turns out to not be enough to obtain a significant production of PBHs. There is a second ingredient we need to deal with in order to account for a non-negligible amount of PBHs: the power spectrum. This object is well constrained at large scales, namely at CMB scales REF. However, PBHs are associated to the smallest scales, where constraints on the power spectrum still allow for a large variety of options (see REF). Naively, a first attempt to provide an expression for the power spectrum at such small scales would be to extrapolate it from the CMB scale. Nonetheless, one quickly realizes that such scenario leads to negligible production of PBHs. Therefore, in order to derive interesting scenarios, we need to introduce an enhancement of the power spectrum to larger values at the scales relevant for PBH production.

A couple of considerations regarding the scale of enhancement are in order. Firstly, it should not be placed too close to CMB scales since the power spectrum is already well constrained in this range and we don't want to mess it up. And secondly, it should not be placed too close to the QCD scale either, since we are trying to evaluate the scenario where the QCD phase transition is shaping the mass function in a very characteristic way and we don't want to spoil the natural appeal of it. All in all, the power spectrum should ideally be enhanced at a given scaled fulfilling condition 3.

$$k_{QCD} \gg k_{cut} \gg k_{CMB} \quad \Longleftrightarrow \quad M_{QCD} \ll M_{cut} \ll M_{CMB}, \tag{3}$$

where $M_{\rm cut} = (\frac{k_{cut}}{10^6 {\rm Mpc}^{-1}}(\frac{g_*}{10.75})^{1/12} 17^{-1/2})^{-2} M_\odot$. For a particular parametrization of the power spectrum fulfilling condition 3, we refer the reader to **??**, where one can see a phenomenological expression used to obtain some of the results in the next section.

4 Results and Conclusion

We first derive a mass distribution by requiring that the fraction of PBHs in the stellar mass range amounts to 10^{-3}, as this is the value that seems to be preferred from the statistical fits of LIGO/Virgo data. Therefore, we impose condition 4

$$f_{GW} \equiv \int_{5M_\odot}^{160M_\odot} \psi_p(M) dM \sim 10^{-3}, \tag{4}$$

where ψ_p is the mass function that ultimately depends on the power spectrum and all its parameters p. For a more detailed definition of the mass function and its derivation we again refer the reader to **??**. For the moment, we will not study any particular parametrization of the power spectrum in the whole wavenumber range (from CMB to PBHs) so we just assume condition 3 is implicitly fulfilled and take a CMB-like expression valid on CMB scales only of the form

$$\sigma^2 = 0.0033 \left(\frac{M}{10 M_\odot} \right)^{n_M}, \tag{5}$$

where $n_M = 0.025$ ($n_M = 0$ corresponds to the scale invariant limit) and the numerical factor is obtained from 4. The resulting mass distribution is displayed in the left plot of Figure 2.

Before making any assessment on the validity of such scenario let us note the following remark. In Fig. 2 we are overplotting an extended mass distribution on top of a set of monochromatic bounds. In order check the agreement among them, one cannot compare them directly as it is shown in the plot but instead one should first translate the monochromatic bounds

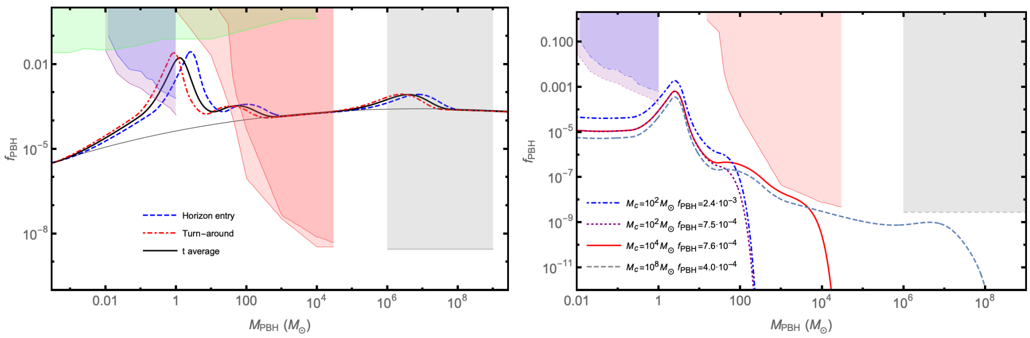

Figure 2: (Left) PBH mass distribution for a quasi-flat spectrum with a spectral index $n_M = 0.025$. The thin black line corresponds to the scenario without QCD/e^+e^- enhancement. It corresponds to Figure 5 in [13]. We also plot excluded regions from microlensing [25] [26] [27] in light green, GW production [19] for two different two-point delta mass distributions in blue and purple, accretion effects on CMB anisotropies [17] in pink/red and inferred SMBH population at high redshift [17] in gray.(Right) Mass functions consistent with three different sets of bounds for fixed values of M_c. We show the results for $M_c = 10^8 M_\odot$ and SMBH counting (gray), $M_c = 10^4 M_\odot$ and spherical accretion (red) and $M_c = 10^2 M_\odot$ and GW production (blue and purple).

into their extended version. Under some linear assumptions, one can derive the constraints imposed by a monochromatic bound $f_{\rm mono}^{\rm max}$ on an extended mass function by imposing equation 6 as discussed in [28].

$$\int_{M_{\rm min}}^{M_{\rm max}} {\rm d}M \frac{\psi_p(M)}{f_{\rm mono}^{\rm max}(M)} = 1, \tag{6}$$

where $M_{\rm min}$ ($M_{\rm max}$) is taken as the minimum (maximum) value for which the monochromatic bound has support.

With this in mind, one can easily check that this particular scenario is in tension with most of the upper bounds. Is there a way to still get a considerable amount of PBHs in the stellar range and avoid the upper bounds at the same time? One option is to play with the enhancement scale. Clearly, depending on where we set this scale, we can easily avoid some of the bounds. Some allowed models for different values of the enhancement scale (M_{cut}) are shown in the right plot of Figure 2. For scales such that $M_{cut} \gtrsim 10^4 M_\odot$, the mass function gets in tension with the CMB anisotropies bound and even for the SMBH counting bound at larger values. On the other hand, for $M_{cut} \lesssim \mathcal{O}(10^2 M_\odot)$, the cut is just above the QCD scale and, as discussed, cutting below means renouncing the idea of a QCD-inspired scenario.

The last issue we need to assess now is whether any of the models in the right plot of Fig. 2 can actually account for a fraction of $f_{GW} \sim 10^{-3}$. As it can be seen in Figure 3, current bounds on f_{PBH} lead to an upper limit of $f_{GW} \lesssim 10^{-5}$, which is well below (about two orders of magnitude!) the amount required in phenomenological fits. Therefore, in QCD-inspired scenarios, PBHs have at most a tiny contribution to LIGO/Virgo events.

Clearly, the results displayed in the previous plots are only valid under certain assumptions. In particular, we implicitly assumed a fixed mass function, that is the primordial mass distribution of PBHs at formation time is the same as the one today. This assumption might seem quite strong since we expect a significant evolution of the mass function, most notably due to accretion phenomena and PBH mergers. However, as discussed in [21], it does not seem plausible that such phenomena can modify the mass function in such a way that $f_{GW} \sim 10^{-3}$ is attained and all the bounds avoided.

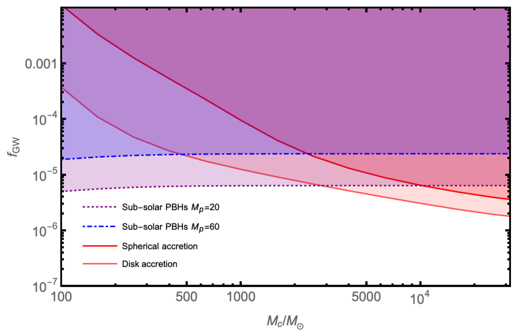

Figure 3: Upper bounds on $f_{\rm GW}$ vs the cutoff mass M_c from CMB anisotropies (pink/red excluded regions) and non-observations of mergers with a BH whose mass is sub-solar; these bounds mildly depend on the heavier partner mass M_p, and the two blue bands in the plot bracket the extremes; see [19] for more details.

In conclusion, the most appealing scenario to explain the required mass function to significantly contribute to LIGO/Virgo merger events, invoking the physics of the early universe between the QCD phase transition and the $e^{\pm}$ annihilation era does not appear viable. Of course, one could always tailor an alternative model leading to a prominent enough peak in the stellar mass range amounting to $f_{GW} \sim 10^{-3}$ and avoiding all the bounds, although that would be at the expense of its predictability power.

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