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Constraints from microlensing experiments on clustered primordial black holes

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ABSTRACT

It has recently been proposed that massive primordial black holes (PBH) could constitute all of the dark matter, providing a novel scenario of structure formation, with early reionization and a rapid growth of the massive black holes at the center of galaxies and dark matter halos. The scenario arises from broad peaks in the primordial power spectrum that give both a spatially clustered and an extended mass distribution of PBH. The constraints from the observed microlensing events on the extended mass function have already been addressed. Here we study the impact of spatial clustering on the microlensing constraints. We find that the bounds can be relaxed significantly for relatively broad mass distributions if the number of primordial black holes within each cluster is typically above one hundred. On the other hand, even if they arise from individual black holes within the cluster, the bounds from CMB anisotropies are less stringent due to the enhanced black hole velocity in such dense clusters. This way, the window between a few and ten solar masses has opened up for PBH to comprise the totality of the dark matter.

1. Introduction

Since the detection of gravitational waves from the merging of five massive black hole binaries by the Advanced LIGO/VIRGO interferometers [1–5] a lot of attention has been given to the possibility that these massive black holes could actually be of primordial origin and that they could constitute all of the dark matter [6–8]. Scenarios of PBH production from large peaks in the matter power spectrum that could provide the totality of the dark matter date back several decades [9], and more recently it has been suggested that the distribution of PBH is a lognormal in mass and that PBH are spatially clustered [10], as one would expect from a broad peak in the primordial power spectrum [11].

The scenario we are considering here [12] is that of cold dark matter comprised of compact clusters of several hundreds to thousands of PBH in a small volume, with a very massive black hole at the center that has grown due to merging from dynamical friction, and a swarm of smaller but still massive black holes orbiting closely around it, sometimes colliding and merging [13–16], others simply scattering off each other, emitting gravitational waves in the process [17]. Such compact clusters behave like collisionless cold dark matter "particles" falling in the potential wells left by curvature fluctuations generated during inflation, giving rise to the present large scale structures observed in deep galaxy surveys like SDSS and DES [18].

The most stringent constraints on PBH in the range of a few solar masses[1] come from microlensing experiments [20], like MACHOS, EROS [21,22] and OGLE [23], and from dwarf spheroidals, like Eridanus II [24–26], and less strongly from CMB anisotropies [27,28]. Interestingly, some massive compact objects have been detected by microlensing experiments [23,29], as well as by their radio emission in dense molecular clouds [30]. Other clues for PBH Dark Matter include the spatial correlation in the cosmic infrared background and soft X-ray backgrounds [31,32] and the detection of a huge population of super-massive black holes at high redshifts in the Chandra deep field [33]. PBH could also provide natural mechanisms to resolve the small scale crisis of large scale structure [34]. In the future, more results will come from GAIA astrometry [35] as well as from a follow up of the Fermi-LAT point source catalog [36].

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[1] High-cadence microlensing surveys in M31 also set constraints on sub-stellar PBH [19].

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The wide mass and low spin distributions of the observed LIGO Black Hole Binaries (BHB) [4] come naturally from early universe models of PBH formation from large peaks in the matter power spectrum, arising both in single (e.g. [37,38]) and multi-field (e.g. [39,40]) models of inflation. These models predict in general a broad peak in the power spectrum of fluctuations, which leads to a wide mass distribution as well as to significant clustering of those primordial black holes.

The effect of wide mass distributions on the general PBH constraints has already been addressed in Refs. [41,42]. In this paper we leave out most of the discussion on future prospects of detectability of PBH [34], and concentrate on the modification of the PBH constraints due to their clustering. These can be very different if BH are uniformly distributed or, on the contrary, if they are hierarchically clustered, with the more massive black hole at the center of the cluster and the less massive ones orbiting around them. In the latter case, the spatial distribution is more like a complicated and the probability of one given PBH cluster being in the line of sight of a particular star, in say the Large Magellanic Cloud, is significantly reduced.

In the next section we will study the lognormal distribution of black hole masses reconstructed from the *known* AdvLIGO events and will discuss the effect that such a broad distribution has on synthetic microlensing constraints. Next we will study the effect of clustering on the microlensing and CMB constraints and will apply the formalism to the present PBH constraints. Finally, we will present our conclusions.

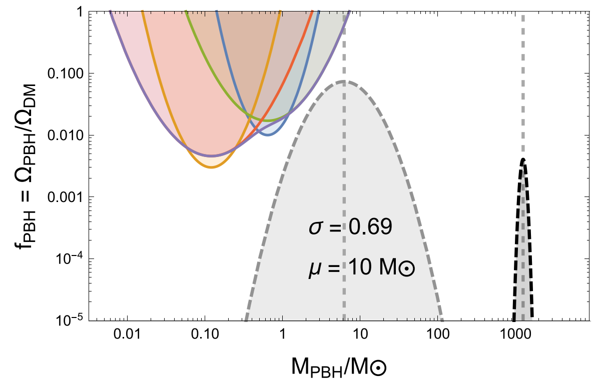

Fig. 1. Synthetic microlensing constraints for an extended lognormal mass distribution of parameters $\mu = 10\,M_\odot$ and $\sigma = 0.69$, assuming PBH spatial uniformity. The blue and orange contours correspond to the expected constraints for a *monochromatic* distribution ($\sigma \simeq 0$). The green and red lines are the *modified* constraints when taking into account the width of the PBH distribution [41]. The purple line is the overall microlensing constraint. The (light gray) curve shows the distribution for $\mu = 10\,M_\odot$ and $\sigma = 0.69$, excluded by the microlensing constraints if PBH have a *uniform* spatial distribution and $f_{PBH} = 1$ (note that the vertical line crosses the purple constraint). The narrow (dashed black) distribution on the right is the *equivalent* distribution for the same extended-mass model but clustered PBH with $N_{cl} = 100$ members per cluster. It is a lognormal with $\bar{\mu} = 1266\,M_\odot$ and $\bar{\sigma} = 0.08$ which passes all microlensing constraints. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. The mass distribution of PBH

The five BHB mergers detected by Advanced LIGO and recently also by the Virgo Collaboration are distributed in masses in the range from 8 to 40 $M_\odot$. The final black holes after merger have masses between 20 and 70 $M_\odot$. We will assume, for simplicity, that the PBH mass distribution is lognormal[2] with parameters $(\mu,\ \sigma)$,

$$P(M) = \frac{d\,n_{PBH}}{d\ln M} = \frac{f_{PBH}}{\sqrt{2\pi}\,\sigma}\,\exp\left[-\frac{\ln^2(M/\mu)}{2\sigma^2}\right], \tag{1}$$

where $f_{PBH} = \Omega_{PBH}/\Omega_{CDM}$ is the *total* fraction of PBH in cold dark matter, and we have chosen $P(M)$ to be normalized to that fraction, $\int_0^\infty P(M)\,dM/M = f_{PBH}$. Note that the mean mass for this distribution is given by

$$\bar{M} = f_{PBH}^{-1}\int_0^\infty \frac{dM}{M}\,P(M)\,M = \mu\, e^{\frac{1}{2}\sigma^2}, \tag{2}$$

which can be significantly larger than μ. One can wonder what are the most likely values of μ and σ, given the LIGO observations. This has been recently investigated in [43], by using a Markov-Chain-Monte-Carlo method to reconstruct their posterior likelihood distributions, given the detected black hole masses and their uncertainties, the inferred merging rate, and the detectability of BH merger events by LIGO, scaling with the chirp mass and the inverse distance of the binary. It results that the most likely value of μ and σ range between a few and 20 $M_\odot$ and between 0.2 and 1.5, respectively. We considered as a benchmark $\mu = 10\,M_\odot$ and $\sigma = 0.69$, consistent with the best fit from the MCMC reconstruction.

Let us consider now a potential constraint from a specific microlensing experiment. It is typically presented as a bound on the fraction of PBH in a given infinitesimal interval $(M,\ M + dM)$ around mass M, i.e. the bounds are shown as constraints $C(M)$ on a *monochromatic* mass distribution. Those coming from microlensing experiments $(i = 1, \ldots, N)$ are typically of the form

$$C_i(M) = A_i\,\exp\left(\frac{\ln^2(M/m_i)}{2s_i^2}\right), \tag{3}$$

where $(A_i,\ m_i,\ s_i)$ are the amplitude, central mass and width parameters that characterize the constraint. Note, however, that most PBH scenarios have a wide mass distribution [10,39,44], rather than monochromatic, and therefore the actual constraint can be written as [41]

$$\int_0^\infty \frac{dM}{M}\,\frac{P(M)}{C(M)} \le 1\,. \tag{4}$$

For a lognormal distribution of PBH, see Eq. (1), the individual $(i = 1, \ldots, N)$ integral constraint becomes

$$\frac{f_{PBH}\,s_i}{A_i\sqrt{s_i^2+\sigma^2}}\,\exp\left(-\frac{\ln^2(\mu/m_i)}{2(s_i^2+\sigma^2)}\right) \le 1\,. \tag{5}$$

In the case of multiple constraints one finds

$$f_{PBH}(M) \le \left[\sum_{i=1}^{N}\frac{s_i^2}{A_i^2(s_i^2+\sigma^2)}\,\exp\left(-\frac{\ln^2(M/m_i)}{(s_i^2+\sigma^2)}\right)\right]^{-1/2}, \tag{6}$$

where we have assumed that each constraint is statistically independent and we have summed them in quadrature. We have plotted in Fig. 1 the enhanced constraints for the case of a wide lognormal distribution with $\sigma = 0.69$. Note that the PBH model in the example (light gray contour) would then be barely acceptable, and future improvements on long duration microlensing experiments (colored curves on the left) would be able to rule out a large fraction of that PBH mass distribution.

2.1. Clustering of PBH

While a reanalysis of the effect of extended mass distributions on the microlensing constraints has been done recently [25,41], there is no consideration yet of the fact that those PBH distributions not only cover a wide mass range, but also that PBH are spatially clustered. The origin of PBH from high and broad peaks in the primordial power spectrum suggest that PBH are highly clustered in space [11], as successive fluctuations reenter the horizon during

[2] A different convention is to replace ln by $\log_{10}$ in Eq. (1), which is equivalent to a rescaling of σ into $\ln 10\,\sigma$.