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The clustering of massive Primordial Black Holes as Dark Matter: Measuring their mass distribution with advanced LIGO

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ABSTRACT

The recent detection by Advanced LIGO of gravitational waves (GW) from the merging of a binary black hole system sets new limits on the merging rates of massive primordial black holes (PBH) that could be a significant fraction or even the totality of the dark matter in the Universe. aLIGO opens the way to the determination of the distribution and clustering of such massive PBH. If PBH clusters have a similar density to the one observed in ultra-faint dwarf galaxies, we find merging rates comparable to aLIGO expectations. Massive PBH dark matter predicts the existence of thousands of those dwarf galaxies where star formation is unlikely because of gas accretion onto PBH, which would possibly provide a solution to the missing satellite and too-big-to-fail problems. Finally, we study the possibility of using aLIGO and future GW antennas to measure the abundance and mass distribution of PBH in the range [5–200] $M_\odot$ to 10% accuracy.

Understanding the nature of Dark Matter (DM), accounting for about one third of the energy density of the Universe, is one of the most important challenges in cosmology nowadays (for a review, see e.g. [1]). A popular hypothesis is that DM is composed of Weakly Interacting Massive Particles (WIMP's). However, in the absence of a clear signal from direct or indirect WIMP interactions, possible alternatives should be considered.

For instance, DM could be composed partially or totally in the form of Primordial Black Holes (PBH) [2–9]. These could have formed in the early universe due to the collapse of large density fluctuations, e.g. induced by a waterfall phase during inflation [6,10–12] , by a first-order phase transition [13] or in some curvaton scenarios [14–16]. Like a WIMP, a PBH is non-relativistic and effectively collisionless and is thus a perfect DM candidate. PBHs must be heavy enough not to evaporate in a time shorter than the age of the Universe, which is fulfilled if their mass is $m_{\rm PBH} \gtrsim 5\times10^{11}$ kg [3,17]. A noticeable exception is the possibility that PBH form stable relics with Planck-like mass [18] after their evaporation. Very stringent constraints have been set on their abundances, from various observations: if $m_{\rm PBH} \lesssim 7\times10^{12}$ kg, the gamma-ray radiation due to PBH evaporation should have been detected by EGRET and FERMI [17]; within the range $5 \times 10^{14} - 10^{17}$ kg, they should have been detected by FERMI through the gravitational femto-lensing of gamma-ray bursts [19]; for $10^{15} < m_{\rm PBH} < 10^{21}$ kg PBHs should have destroyed neutron stars in globular clusters [20]; the absence of microlensing events of stars in the Magellanic clouds exclude large abundances of PBHs within the range 10^{23}–10^{31} kg [21–23], although such constraints are model dependent [24,25]. Their abundance in the early Universe is also well constrained by the absence of important spectral distortions of the CMB black-body spectrum, which excludes PBH as dark matter if $m_{\rm PBH} \gtrsim 1M_\odot$ [26]. This last constraint closes the range of possible PBH masses, therefore most people often considers the model as ruled out.

However, as was pointed out recently in Ref. [10], the merging of PBHs could have been very efficient in the early Universe, such that initially substellar mass black holes, passing the CMB distortion constraints, could have grown by several orders of magnitude, enough to evade the most stringent microlensing constraints. In this way, the galactic halo would be populated by a large number of massive PBHs, which is consistent with the recent observation of numerous BH candidates in the central region of Andromeda and nearby galaxies [27–31]. Moreover, recent analysis of the gamma-ray excess seen by Fermi-LAT towards the Galactic Center finds evidence for a population of unresolved point sources [32,33] which could be, together with the 30% unidentified point sources of the 3FGL catalog [34], the tip of the iceberg of the PBH distribution of Dark Matter.

In addition, in the case of a broad PBH mass spectrum, covering a few orders of magnitude, the high-mass tail of the distribution provides a subdominant number of very massive PBHs, which could quick-start structure formation and, in particular, are good

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candidates for the seeds of the Super-Massive Black Holes (SMBH) observed at the center of galaxies,[1] as well as for the Intermediate Mass Black Holes (IMBH) in Globular Clusters [36]. The recent observation of one of those IMBH in the central region of the Milky-Way [37] could be a hint in favor of abundant IMBHs, beyond what is expected via stellar evolution. Moreover, massive PBH could be responsible for the observed ultra-luminous X-ray sources [38–42].

In this *letter*, we examine the possibility that the $\sim 30 M_\odot$ BH merger at the origin of the first direct detection of gravitational waves by Advanced LIGO [43] has a Dark Matter origin in the form of PBHs. More generally, we explore how the new bounds set by aLIGO on the rate of massive BH merging [44] can be satisfied by a massive PBH–DM model. Two cases are distinguished: first, the PBHs are uniformly distributed in galactic halos and follow Einasto or Navarro–Frenk–White (NFW) profiles; second, PBHs are clustered in compact sub-halos. In both cases we compute the merger rate and evaluate the typical size and density of those PBH sub-halos leading to a rate within the range of 2–400 $\text{yr}^{-1}\,\text{Gpc}^{-3}$ inferred from aLIGO observations [44].

Upon completion of our work, S. Bird et al. released a similar analysis [45].[2] Here we extend their claim that aLIGO could have detected PBH–DM to the case that black holes are clustered: (i) rather than a scale-invariant spectrum we use the predicted peak in the matter power spectrum on small scales and assume that PBH could have already clustered in the early Universe; (ii) we consider the case of a broad mass distribution of the PBH spectrum, rather than a single-mass "monochromatic" spectrum; (iii) we provide a mechanism for generating such initially clustered PBH in the context of inflation with a mild-waterfall phase; (iv) we discuss the implications of our results for the missing-satellites and too-big-to-fail problems [1], which could be solved naturally if PBH–DM are mostly concentrated in faint dwarf galaxies with high mass-to-light ratios.

Uniform distribution in the Milky-Way Halo: We have assumed that the galactic DM density follows an Einasto profile [46],

$$\rho(r) = \frac{\rho_{-2}}{e^{2n\left[(r/r_{-2})^{1/n}-1\right]}} \tag{1}$$

where r_{-2} is the radius at which the logarithmic slope of the profile equals -2, and the density parameter $\rho_{-2} \equiv \rho(r_{-2})$. These are equivalent to the radius R_s and density $\rho_s/4$ of the common NFW profile, respectively. Typical values from DM simulations for massive halos, like the Milky-Way halo for which $r_{-2} \approx 20$ kpc, give $4 \lesssim n \lesssim 7$. The case $n = 4$ is considered below, but it has been checked that different values only affect marginally the results. We also assume that PBHs follow a Maxwellian distribution with average velocity $\bar{v} = 200$ km/s. Varying those parameters in a reasonable way would have a rather limited impact on the merging rate, so for simplicity they are kept constant throughout the paper. If PBH are uniformly distributed within the galactic halo, i.e. they are not clustered, the typical distance between two BHs goes from a few to tens of parsecs, for PBH masses in the range $1 \lesssim m_{\text{PBH}}/M_\odot \lesssim 100$.

In order to calculate the merging rate, we have referred to Refs. [47,48] where the capture cross-section σ^{capt} of two black-holes in dense clusters has been calculated. Two encountering BHs become bounded to each other if the energy lost in the form of gravitational waves is of the order of the kinetic energy. Once gravitationally bounded to each other, the two BH quickly merge in less than a million years. In the Newtonian approximation, this capture rate $\tau_{\text{PBH}}^{\text{capt}} \equiv n_{\text{PBH}}\,\bar{v}\,\sigma_{\text{PBH}}^{\text{capt}}$ of a BH of mass m_A by a BH of mass m_B is given by [48]

$$\tau_{\text{PBH}}^{\text{capt}} = (2\pi)\, n_{\text{PBH}}(m_A)\bar{v}\left(\frac{85\pi}{6\sqrt{2}}\right)^{2/7} \times \frac{G^2 (m_A+m_B)^{10/7}(m_A m_B)^{2/7} c^{18/7}}{c^4 v_{\text{rel}}^{18/7}} \tag{2}$$

where n_{PBH} is the PBH number density and v_{rel} is the relative velocity of the two BHs, which we take equal to $\bar{v}$. Since the cross-section is much larger than the BH surface area, the Newtonian approximation is valid. The capture rate can be compared to the direct merging rate $\tau_{\text{PBH}}^{\text{merg}}$, which was derived in the Newtonian approximation in Refs. [49,20] in the context of WIMP–neutron star and PBH–neutron star collisions respectively, assuming that two PBH merge if the closest distance between them is smaller than the Schwarzschild radius $R_{\text{PBH}} = 2Gm_{\text{PBH}}/c^2$. This rate is given by

$$\tau_{\text{PBH}}^{\text{merg}} = n_{\text{PBH}}(m_A)\left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2}\frac{8\pi^2 G}{3} m_B R_B \bar{v}^2 \,. \tag{3}$$

The direct merging and capture rates have the same mass dependence and are represented on Fig. 1 as a function of the radial distance to the galactic center, for $m_A = m_B = 30 M_\odot$. The capture rate is ~ 170 times larger than the direct merging rate. General relativistic corrections could enhance the direct merging rate by a factor of a few, as noticed in Ref. [49], but merging through direct collisions can be considered as a subdominant process. Individual capture rates are found to be lower than $10^{-19}\ \text{yr}^{-1}$. Integrating over all the PBHs inside the galactic halo, one gets the total rate in our galaxy, $\tau_{\text{gal}} \approx 5\times 10^{-12}\ \text{yr}^{-1}$. This rate is comparable to the probability of star collisions within the galactic disk. It is very low, and is found to be independent of the mass of PBHs. The exact shape of the density profile is of little importance, similar results being obtained for the common NFW profile, with variations in the merging rate not exceeding a few percent. Therefore, one can conclude that if PBH are uniformly distributed in the halos of galaxies, the model passes all the present and future constraints from gravitational wave experiments. This also confirms that PBHs are effectively collisionless, as expected for a good dark matter candidate. We have considered above the merging rate within our galaxy and extrapolated it to all possible galaxies in our local Universe up to 450 Mpc. It is clear that the rate of mergers from a uniformly distributed PBH population in the local universe is not enough to account for the LIGO observations. These could only come from high density regions with large mass-to-light ratios where PBH could be highly concentrated, like Dwarf Spheroidals or Globular clusters in our local cosmological neighborhood up to $z \sim 0.12$.

Clustering in sub-halos: Depending on the process of formation, as well as on the evolution of cosmic inhomogeneities, it is possible that nowadays massive PBHs are regrouped in dense clusters, whose size could range from a few parsecs to a few hundreds. Early clustering of PBHs is expected e.g. in the scenario proposed in Ref. [10], in which quantum diffusion close to a tachyonic instability in hybrid inflation leads to different perturbation dynamics during the subsequent mild-waterfall phase [50,51]. As a result, the formation of PBHs is expected to occur in localized regions during the radiation era, whereas on CMB scales, the primordial spectrum is unchanged and the level of non-gaussianity and isocurvature modes as expected for a slow-roll single-field model, thus evading the constraints of [32,52].[3] Another possibility is that PBH have

[1] Such a scenario is well-constrained by the absence of CMB distortions [35] but is allowed if the power spectrum of curvature perturbations is only enhanced on smaller scales than the ones relevant for μ-type distortions, as in the model proposed in Ref. [10].

[2] Soon after the first version of the present letter, another similar analysis was released by Sasaki et al. [25] with similar conclusions.

[3] Another PBH clustering scenario was considered in [53,54] but only applies to abundances less than the dark matter [32,52].