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Solving puzzles of GW150914 by primordial black holes

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Abstract. The black hole binary properties inferred from the LIGO gravitational wave signal GW150914 posed several serious problems. The high masses and low effective spin of black hole binary can be explained if they are primordial (PBH) rather than the products of the stellar binary evolution. Such PBH properties are postulated ad hoc but not derived from fundamental theory. We show that the necessary features of PBHs naturally follow from the slightly modified Affleck-Dine (AD) mechanism of baryogenesis. The log-normal distribution of PBHs, predicted within the AD paradigm, is adjusted to provide an abundant population of low-spin stellar mass black holes. The same distribution gives a sufficient number of quickly growing seeds of supermassive black holes observed at high redshifts and may comprise an appreciable fraction of Dark Matter which does not contradict any existing observational limits. Testable predictions of this scenario are discussed.

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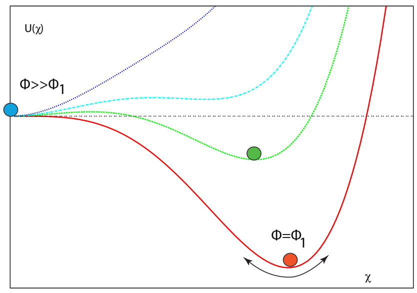
Contents

1 Introduction

The recent discovery of gravitational waves (GWs) by LIGO [1] not only opened a new window into high redshift universe but simultaneously presented several problems. The first observed signal GW150914 nicely fits the hypothesis of the coalescence of two heavy black holes (BHs) which form a binary system with masses $M_1 = 36^{+5}_{-4} M_\odot$ and $M_2 = 29^{+4}_{-4} M_\odot$. While the individual spins of coalescing BH components are poorly constrained, the effective spin $\chi_{\rm eff}$ turns out to be close to zero, suggesting either low spins of the components or their opposite direction, which is difficult to explain by the standard evolution from a massive binary system. The parameter $\chi_{\rm eff}$ has been determined to be within $[0.19, 0.17]$ from its effect on the inspiral rate of the binary [2]. The final BH mass is $M = 62^{+4}_{-4} M_\odot$ and its spin is substantial, $a = 0.65^{+0.05}_{-0.07}$, as expected from the orbital angular momentum of the colliding BHs.

The first problem with GW150914 is a possible origin of so heavy BHs. One of the proposed mechanisms involves highly rotating massive (from $50M_\odot$ up to $100M_\odot$) stars in close binary systems [3–5]. The rapid rotation of the stars, achieved due to strong tidal interaction, provides effective mixing of nuclear burning products, thus avoiding significant post-main-sequence expansion and subsequent mass exchange between the components. To form so heavy BHs within this mechanism, the progenitors should have low metal abundance to avoid heavy mass loss during the evolution. Unfortunately, due to poor observational statistics, there is no strong observational confirmation of the rates of binary systems, undergoing such chemically homogeneous evolution [3]. Moreover, the LIGO collaboration [2] has shown that if both spins need to be aligned with orbital momentum, the individual spins with 90% probability have quite low values $a < 0.3$. The second reliable LIGO detection, GW151226, turned out to be closer to the standard binary BH system [6], which can be explained by classical binary system evolution.

The misaligned BH spins and low values of effective inspiral spin parameter $\chi_{\rm eff}$ detected in GW150914 may strongly constrain astrophysical formation from close binary systems [7]. However, the dynamical formation of double massive BHs with misaligned spins in dense stellar clusters is still possible [8, 9].



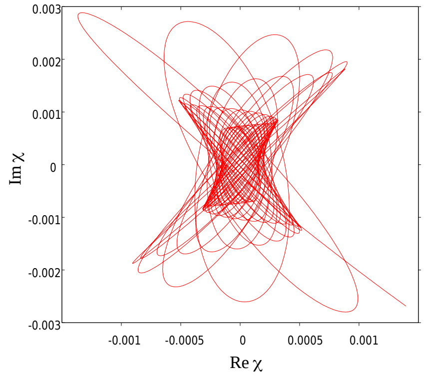


Figure 1. Left: behavior of the effective potential of χ for different values of the inflaton field Φ. The upper blue curve corresponds to $\Phi \gg \Phi_1$ which gradually decreases to $\Phi = \Phi_1$, the red curve. Then the potential returns back to an almost initial shape, as $\Phi \to 0$. The evolution of χ in such a potential is similar to the motion of a point-like particle (shown as the colored ball) in Newtonian mechanics. First, due to quantum initial fluctuations, χ left the unstable extremum of the potential at $\chi = 0$ and "tried" to keep pace with the moving potential minimum and later starts oscillating around it with decreasing amplitude. The decrease of the oscillation amplitude is due to the cosmological expansion. In mechanical analogy, the effect of the expansion is equivalent to the liquid friction term, $3H\dot{\chi}$. When $\Phi < \Phi_1$, the potential recovers its original form with the minimum at $\chi = 0$, and χ ultimately returns to zero, but before that it could give rise to a large baryon asymmetry [20]. Right: The evolution of χ in the complex $[\mathrm{Re}\chi, \mathrm{Im}\chi]$-plane [20]. One can see that χ "rotates" in this plane with a large angular momentum, which exactly corresponds to the baryonic number density of χ. Later χ decays into quarks and other particles creating a large cosmological baryon asymmetry.

Mechanisms of BH formation from PopIII stars and subsequent formation of BH binaries are analyzed in [10]. The scenario proposed in [11] is found to be the most appropriate. However, the contribution of PopIII stars to the formation of BH binaries with masses $\sim 30 + 30 M_\odot$ can be negligible, contradicting the population synthesis results [12, 13].

A binary system of massive BHs like LIGO GW150914 could be formed from primordial black holes (PBH) [14–16]. Here we propose a specific model of PBH formation which both naturally reproduce the extreme properties of GW150914, the rate of binary BH merging events as inferred from the first LIGO science run 9-240 Gpc^{-3} yr^{-1} [17], and provide seeds for early supermassive BH formation in galaxies. The model is based on the modified Affleck-Dine [18] scenario for baryogenesis. It was suggested in 1994 [19], discussed in more details in ref. [20], applied to an explanation of the early supermassive BH (SMBH) observations at high redshifts [21], and to a prediction and study of the properties of possible antimatter stellar-like objects in the Galaxy [22, 23].

2 The model: Affleck-Dine scenario

Our model of early formation of heavy primordial black holes is based on the supersymmetric scenario of baryogenesis (Affleck and Dine mechanism) [18] slightly modified by an addition of general renormalizable coupling of the scalar baryon field χ to the inflaton field Φ, see figure 1. The potential of the interacting fields Φ and χ are taken in the form:

$$U(\chi, \Phi) = U_\Phi(\Phi) + U_\chi(\chi) + \lambda_1(\Phi - \Phi_1)^2|\chi|^2, \tag{2.1}$$

where the first term $U_\Phi(\Phi)$ is the potential of the inflaton field which ensures sufficient inflation, $U_\chi(\chi)$ is the potential of the scalar field with non-zero baryonic number. According to the suggestion of ref. [18], this potential possesses flat directions along which the χ could travel away from the origin accumulating a large baryonic number density. The last term in eq. (2.1), introduced in ref. [19], closes the flat directions when the inflaton field Φ is away from some constant value Φ_1. The latter is chosen such that Φ passes through Φ_1 during inflation, close to its end when the remaining number of e- foldings was about 30-40. This number depends upon the model can can be adjusted if necessary to comply with specific observational requirements.

The potential (2.1) allows for an open window to the flat directions only during a relatively short period of time. Correspondingly, the probability of the scalar baryon, χ, to reach a large value is small because the initial evolution of χ from the unstable minimum at $\chi = 0$ is a slow stochastic one, similar to the Brownian motion. Most of χ would remain small, and in these regions of the universe the baryon asymmetry would have its normal value, $\beta = 6 \times 10^{-10}$. However, there would be some small bubbles where the asymmetry might be huge, even of order unity. With properly chosen parameters of the model these bubbles would have astrophysically interesting sizes but occupy a relatively small fraction of the whole volume of the universe. Despite that, due to large baryonic number, they could make a noticeable contribution to the total cosmological energy density. The shape of the mass distribution of these high-B bubbles is determined by inflation and thus it is virtually model independent (except for the unknown values of the parameters) and has the log-normal form:

$$\frac{dn}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_0)\right], \tag{2.2}$$

where μ, γ, and M_0 are some unknown, model dependent constant parameters. An interesting feature of this distribution is that a power-of-mass, M^q, factor instead of μ^2 does not change the log-normal shape after the redefinition of parameters.

Originally, the induced small scale fluctuations of the baryonic number lead predominantly to isocurvature fluctuations, but after the QCD phase transition at the temperature $T = 100 - 200$ MeV, when the massless quarks turn into heavy nucleons, the isocurvature fluctuations transformed into large density perturbations at astrophysically large but cosmologically small scales.

Depending upon the history of their formation, the high-B bubbles could be either primordial black holes, compact stellar-like objects, or even rather dense primordial gas clouds. In particular at the high mass tail of the distribution superheavy PBHs might be created. Their emergence at redshifts of order 10 is highly mysterious and even their existence in each large galaxy is in serious tension with the conventional mechanisms of their formation. An early formation of superheavy black holes which later serve as seeds for galaxy formation looks more probable. For a review of the problems with rich evolved population in the early universe see sec. 5 of ref. [24] or more recent review in the lecture [25]. The accumulated data of the last few years suggest an early SMBH formation.

We can fit the parameters of the distribution (2.2) using the following three sets of data and/or assumptions:

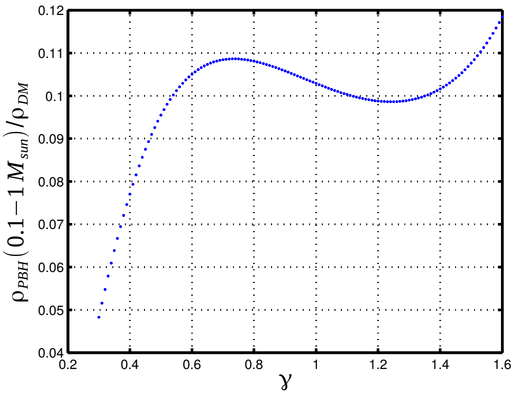


Figure 2. Fraction of PBH density $\rho(0.1-1)/\rho_{DM}$ in the mass range $0.1-1M_\odot$ as a function of parameter γ. See Eq. (2.2).

A The fraction of dark matter in MACHOs is $f \approx 0.1$ for the mass range $(0.1-1)M_\odot$ (see, e.g. [26]).

B All primordial black holes make the whole cosmological dark matter

C The number density of the primordial black holes with masses above $10^3 M_\odot$ is equal to the number density of the observed large galaxies.

(A) The MACHO group has concluded that compact objects with masses $0.15M_\odot < M < 0.9M_\odot$ have a fraction f in the Galactic halo in the range $0.08 < f < 0.50$ (95% CL). Therefore, based on the results of MACHO group, it is recognized that a population of compact lensing objects really exists [26]. There were some contradicting results based on microlensing observations of Andromeda galaxy M31, see reviews in [23, 27]. A recent study of M31 [28] has discovered 10 new microlensing events and the authors conclude: "statistical studies and individual microlensing events point to a non-negligible MACHO population, though the fraction in the halo mass remains uncertain". To fit this constraint, the parameter M_0 and γ of the distribution 2.2 should be related as $M_0 = M_\odot(\gamma + 0.1\gamma^2 - 0.2\gamma^3)$ (see figure 2).

(B) Condition B is not obligatory and can (must) be diminished in accordance with the bound on the BH dark matter. Condition C should be fulfilled if all large galaxies were seeded by a superheavy PBH. The initially formed superheavy PBH might have much smaller masses (around $10^3 - 10^5 M_\odot$) which subsequently grow to $10^9 M_\odot$ because of an efficient accretion of matter and mergings. This mass enhancement factor is much stronger for heavier BH and thus their mass distribution may be different from (2.2). However, we assume that the original BHs were created with the distribution (2.2). Note that the accepted lower mass limit $M > 10^3 M_\odot$ is rather arbitrary and is used here only for the sake of simple parameter estimates.

Conditions A,B, and C can be crudely satisfied if the parameters in the initial PBH mass distribution (2.2) are $\gamma = 0.5$, $M_{\max} = M_\odot$, and $\mu = 10^{-43}$ Mpc^{-1} in the natural system of units $\hbar = c = 1$. Here the value of μ is fixed by the condition that all Dark Matter is described by objects with the distribution (2.2). The energy density of black holes with masses above $10M_\odot$ in this case would be close to the energy density of the cosmological dark matter.

Let us note that the B-bubbles are formed predominantly spherically symmetric because such configurations minimizes the bubble energy. Their angular momentum should be zero because they are formed as a result of phase transition in cosmological matter with vanishing angular momentum due to absence of the cosmological vorticity perturbations. This is in striking contrast to BHs formed through the matter accretion, when the angular momentum must be substantial.

3 An upper limit on ADBD PBH.

Let us discuss what could be the maximum mass of PBH in the AD scenario. The mass of the bubbles with high baryonic number density, or High B Bubbles (HBB), after their formation at the inflationary stage was equal to:

$$M_{\text{infl}} = \frac{4\pi}{3}\rho l^3, \tag{3.1}$$

where $l \sim (1/H)\exp(H(t - t_{in}))$, H is the Hubble parameter during inflation, t_{in} is the moment when the window to the flat direction became open, i.e. the inflaton filed Φ started to approach Φ_1 from above.

The cosmological energy density at this stage was

$$\rho = \frac{3H^2 m_{Pl}^2}{8\pi} = \text{const}\,. \tag{3.2}$$

Thus we obtain for the maximum value of the HBB mass at the end of inflation at $t = t_e$:

$$M_{\text{infl}}^{(\text{max})} = \frac{m_{Pl}^2}{2H} e^{3H(t_e - t_1)}\,. \tag{3.3}$$

In the instant heating approximation, when the universe was heated up to temperature T_h, one finds

$$\rho = \frac{\pi^2}{30} g_* T_h^4, \tag{3.4}$$

where $g_* \sim 100$ is the number of particle species in thermal equilibrium plasma after the inflaton decay.

Taking all factors together, we find for the maximum value of the HBB mass at the end of inflation:

$$M_{\text{infl}}^{(\text{max})} = \left(\frac{90}{32\pi^3 g_*}\right)^{1/2} \frac{m_{Pl}^3}{T_h^2}\, e^{3H(t_e - t_1)}\,. \tag{3.5}$$

After the end of inflation the HBBs were filled by relativistic matter and thus their masses dropped down as T/T_h because the density of relativistic matter decreased as $1/a^4$, while the HBB size rose as a, i.e. its volume grew up as a^3, where a is the cosmological scale factor. After the QCD phase transition at $T_{MD} \sim 100$ MeV the matter inside HBBs turns into nonrelativistic one, and the total mass of HBB becomes constant. A reasonable value of T_h is about 10^{14} GeV, but the exact magnitude is of minor importance because the necessary duration of inflation to create HBB with the present day value of the mass M_{today} depends only logarithmically on the temperature. So we find for the maximum value of the HBB mass today:

$$M_{\rm today} = \left(\frac{90}{32\pi^3 g_*}\right)^{1/2} \frac{m_{Pl}^3}{T_h^2}\frac{T_{\rm MD}}{T_h}\, e^{3H(t_e - t_1)}\,. \tag{3.6}$$

Therefore, for the duration of inflation after the HBB formation which is necessary to create PBH with the mass $M_{BH}^{(\rm max)}$ we find:

$$e^{3H(t_e-t_1)} = 10^{37+5-10+15}\left(\frac{T_h}{10^{14}{\rm GeV}}\right)^3 \frac{M_{\rm BH}^{(\rm max)}}{10^4 M_\odot}\frac{100\ {\rm MeV}}{T_{\rm MD}}\,. \tag{3.7}$$

Thus, finally we need $H(t_e - t_1) = 36$ to create a PBH distribution with the mass cut-off of $10^4 M_\odot$, if all other factors are taken to be unity. Such a duration of inflation after $\Phi = \Phi_1$ looks very reasonable. In these estimates the Planck mass was taken to be $m_{Pl} = 10^{-5}{\rm g} = 10^{19}$ GeV.

In principle, we can turn equation (3.6) another way around to find the high mass cut-off for fixed duration of inflation after the HBB formation.

4 Black hole growth.

The very first estimations of the accretion growth of PBHs in radiation-dominated epoch were done by Zel'dovich and Novikov [29]. Using non-relativistic Bondi-Hoyle accretion analysis the authors have shown that the masses of the formed at $t = t_0$ BHs change as

$$M = \frac{M_0}{1 - \frac{KM_0}{t_0}(1 - \frac{t_0}{t})}, \tag{4.1}$$

where $K = 9\sqrt{3}G/2c^3$. According to this formula, a PBH grows at the same rate as the Universe if its initial size is comparable to the cosmological horizon, and at the end of radiation-dominated epoch the predicted masses of the resultant BHs would become unrealistically high. Zel'dovich & Novikov method was generalized for the relativistic case in [30], [31]. However, while accounting for cosmological decrease of the density of the accreted substance, the previous simplified analyses ignored the influence of cosmological expansion on the dynamics of accretion itself. This effect can be significant in the case of massive PBHs in the early Universe when the BHs' radius can approach the Universe horizon. In our case, the mass of PBH is

$$M_0 \approx 10^5 M_\odot t \tag{4.2}$$

for t in seconds, that is the Schwarzschild radius of PBH

$$r_g \simeq ct = 3\times 10^{10}\frac{t}{\rm s}\,{\rm cm} \tag{4.3}$$

is comparable to the size of horizon $r_{\rm H} \simeq 2ct = 6\times 10^{10}(t/{\rm s})\,{\rm cm}$. Carr and Hawking [32] were the first who had drawn attention to downsides of estimations based on the Bondi-Hoyle formula. Their results were analytically confirmed in [33], [34]. According to Carr-Hawking mechanism of accretion, the growth of very massive PBHs in Zel'dovich & Novikov analysis is significantly overestimated [35]. However, Lora-Clavijo et al [36] numerically showed substantial growth of relatively smal$M_0 = M_\odot(\gamma + 0.1\gamma^2 - 0.2\gamma^3)$l PBHs ($r_g \ll r_{\rm H}$) during the leptonic era (up to 100 sec).

5 Massive PBH as galaxy seeds.

The state-of-the-art SMBH growth paradigm, see e.g. resent EAGLE results [37], assumes a delta-like initial BH seed masses of about $10^5 M_\odot$, which formed in DM halos at $z \sim 15$ and rapidly grow through gas accretion and host galaxy mergings by $z \sim 5$. In the DM halos less massive than $\sim 10^{12} M_\odot$, virtually no growth of the seed BH mass is observed, while at larger halo masses the BH mass increases rapidly until a self-regulating BH mass – DM halo mass relation ($M_{\rm BH} - M_{200}$) is established. The seed SMBH masses increase up to $10^8 M_\odot$, after which their growth is linearly proportional to the surrounding DM halo mass. Importantly, the shape of the SMBH mass function almost does not change after $z \sim 5$, exhibiting only the normalization increase by an order of magnitude by $z = 0$. These finding are independent on the assumed seed BH mass for $M_{\rm seed} \gtrsim 10^4 M_\odot$.

However, if there is a population of primordial SMBHs, they can serve as seeds for galaxy formation. Guided by analogy with numerical simulations discussed above, we can assume that

1) seed BH masses $\lesssim 10^5 M_\odot$ do not substantially evolve, i.e. in the low mass interval the observed SMBH mass function has the primordial shape;

2) seed BH masses in the range $10^5 - 10^8 M_\odot$ rapidly grow up to $\sim 10^8 M_\odot$;

3) seed BH masses exceeding $10^8 M_\odot$ at $z = 0$ scale linearly with DM halo mass;

4) the rapid SMBH growth is completed by $z = 5$ after which the SMBH mass function (for $M > 10^6$) linearly increases up to the present-day values.

Points (2) and (3) imply that the actual shape of the primordial SMBH mass function is not very important for seed BH masses $\gtrsim 10^5 M_\odot$, since these BHs rapidly grow to reach self-regulation in the surrounding DM halos.

Therefore, fitting the PBH mass function normalization in the $10 - 100$ $\mathrm{M}_\odot$ range to the BH+BH merging rate derived from the LIGO BH+BH detections ($9 - 240$ events a year per cubic Gpc), we should only take care that the mass density of primordial SMBHs does not contradict the existing SMBH mass function as inferred from observations of galaxies, $dN/(d\log M dV) \simeq 10^{-2} - 10^{-3}$ Mpc^{-3} (see figure 3).

6 LIGO GW150914 as ADBD PBH event.

Fixing the parameters μ, γ, and M_0 in (7.1) we can satisfy all existing constraints, understand the origin and properties of the merging BBHs, and explain other exciting puzzles. We have found that the model parameters $\mu = (2-3)\cdot 10^{-43}$ Mpc^{-1}, $\gamma = 0.4 - 1.0$, and $M_0 = M_\odot(\gamma + 0.1\gamma^2 - 0.2\gamma^3)$ are suitable to explain most of DM as ADBD BHs, do not contradict all existing constraints on PBHs [38] and give sufficient amount of massive PBHs as seeds for early galaxy formation (see figure 4). Note that CMB constraints from early accretion onto PBH shown in the analogous plot [39] are model-dependent and should be treated with caution.

Assuming the fraction of binaries among the PBH to be 10^{-3}, the present-day merging rate of binary BPH can be estimated as the space density divided by the Hubble time (10^{10} years) (see figure 5). Clearly, this can be easily made compatible with the binary BH merging rate as inferred from LIGO observations (the purple rectangle in figure 5) by assuming the parameters of the initial ADBD PBH distribution which are consistent with MACHO and SMBH constraints discussed above.

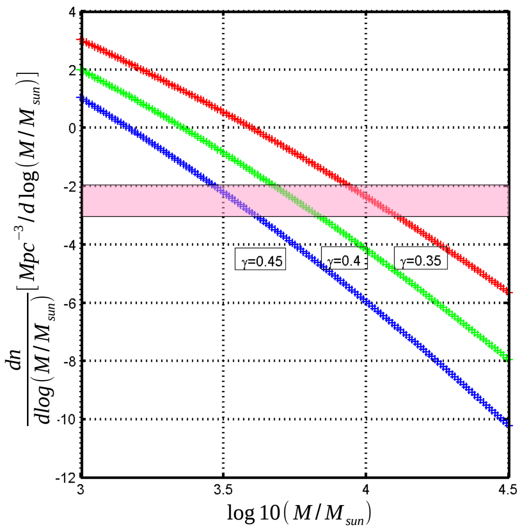


Figure 3. Space density of PBH (per Mpc^{-3} per $d\log M$), to be compared to those derived from observations of SMBH in large galaxies (purple rectangle).

Binary systems from PBHs started forming already at the radiation-dominated epoch [41]. Assuming the population of PBHs with the same mass $M_{\rm BH}$, on the stage of matter-radiation equality with radiation density $\rho_{\rm eq}$ the average distance between BHs can be defined as:

$$\bar{x} = \left(\frac{M_{\rm BH}}{f\rho_{\rm eq}}\right)^{\frac{1}{3}}, \tag{6.1}$$

where f is the fraction of DM in MACHOs. Two PBHs separated by the co-moving distance x form a binary system and decouple from cosmological expansion when the absolute value of mean gravitational energy of the PBH binary becomes higher than the energy of the universe within horizon:

$$a > \frac{L_{\rm eq}}{f}\left(\frac{x}{\bar{x}}\right)^3, \tag{6.2}$$

where a is the scale factor, and $L_{\rm eq} \sim (3c^2/8\pi G\rho_{\rm eq})^{1/2}$ is the horizon scale at matter-radiation equality [41]. Along with mean fluctuation field and angle dependence of the tidal force, the authors of [42], have accounted for an important mechanism of 3-body interaction. The tidal interactions with neighboring PBHs provide the almost born binary system with sufficient angular momentum to prevent the two components of the binary from merging even if PBHs are assumed to be born with negligibly small relative velocities. All these effects should be accurately taken into consideration, since ignoring them leads to a 50% uncertainty in the PBH binary merging rate estimates [42].

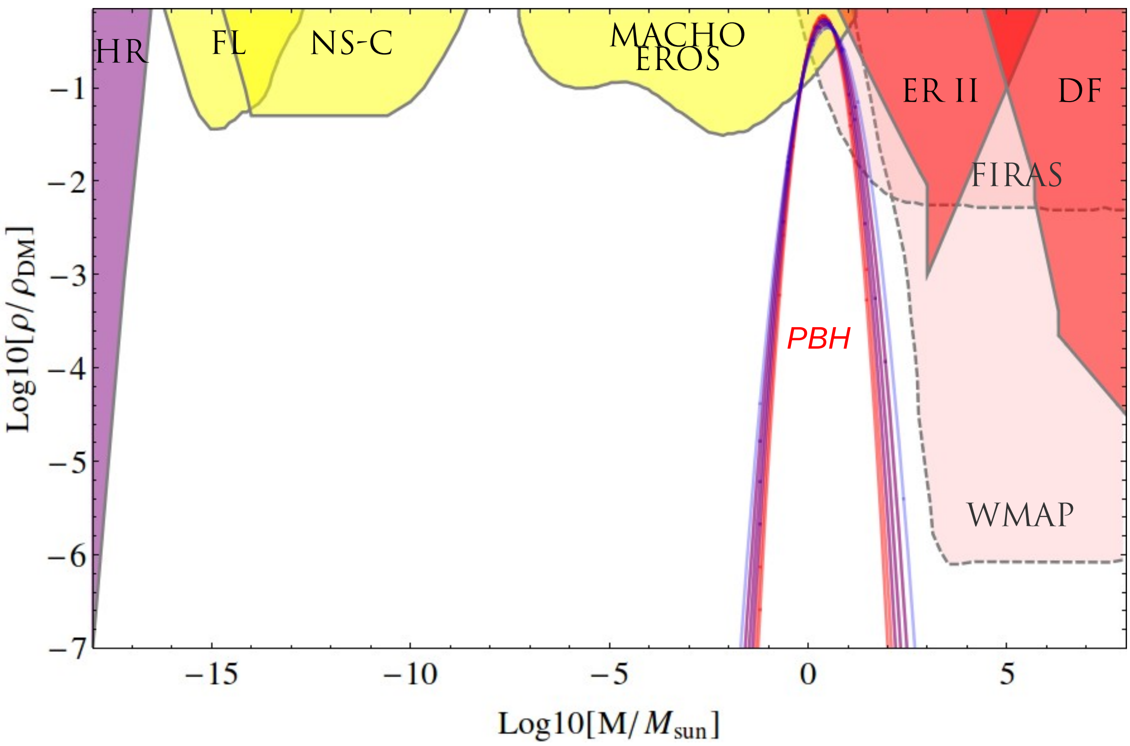


Figure 4. Constraints on PBH fraction in DM, $f = \rho_{\rm PBH}/\rho_{\rm DM}$, where the PBH mass distribution is taken as $\rho_{\rm PBH}(M) = M^2 dN/dM$ (see [38]). The existing constraints (extragalactic γ-rays from evaporation (HR), femtolensing of γ-ray bursts (F), neutron-star capture constraints (NS-C), MACHO, EROS, OGLE microlensing (MACHO, EROS) survival of star cluster in Eridanus II (E), dynamical friction on halo objects (DF), and accretion effects (WMAP, FIRAS)) are taken from [38] and reference therein. The PBH distribution is shown for ADBD parameters $\mu = 10^{-43}$ Mpc^{-1}, $M_0 = \gamma + 0.1 \times \gamma^2 - 0.2 \times \gamma^3$ with $\gamma = 0.75 - 1.1$ (red solid lines), and $\gamma = 0.6 - 0.9$ (blue solid lines).

These estimates can be easily generalized for the non-monochromatic mass spectrum of PBHs presented in (2.2). For PBHs with the mass $30 M_\odot$ the predicted event rate of GW bursts [15] matches the one observed by LIGO only for $f \simeq 7 \times 10^{-4} - 7 \times 10^{-3}$. Taking into account the tidal forces from adiabatic density perturbation of dark matter [43], the valid range of f shifts to $f \simeq 2 \times 10^{-3} - 2 \times 10^{-2}$. These limits on f can be satisfied assuming different ranges of parameter γ of log-normal distribution: $\gamma \simeq 0.75 - 1.1$ and $\gamma \simeq 0.6 - 0.9$ in the first and second case, respectively (see figures 3 and 5).

Binary PBHs can also form later in the matter-dominated epoch. Driven by dynamical friction with collisionless particles, PBHs can form gravitationally bounded pair in the centers of DM halos. However, the effectiveness of this mechanism is poorly known and considerably model dependent [44].

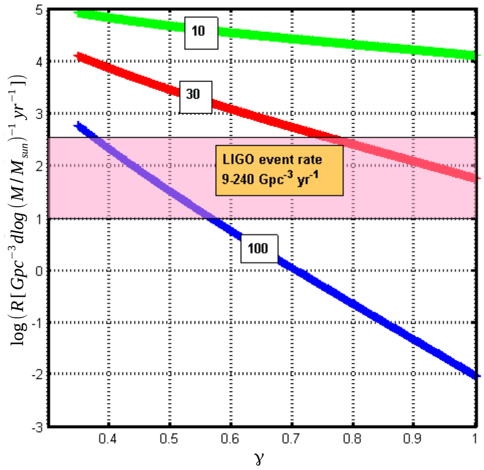


Figure 5. Merging rate of binary BH R (1/Gpc^3/yr) per logarithmic mass interval over the universe age. The observed LIGO event rate is shown by the purple rectangle [40].

7 Discussion and conclusions.

We have summarized the basic features of the HBB formation mechanism in figure 1. In this scenario [19, 20] cosmologically small, but possibly astronomically large, bubbles with high baryon density β could be created in the early universe, occupying a small fraction of the universe volume, while the rest of the universe has the standard $\beta \approx 6 \cdot 10^{-10}$.

The mass distribution of the high baryon density bubbles has the log-normal form:

$$\frac{dN}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_0)\right], \tag{7.1}$$

where μ, γ, and M_0 are constant parameters.[1] The shape of the spectrum is practically model-independent, it is determined by inflation. There is an intrinsic high-mass cut-off in the spectrum set by duration of inflation that can be $\sim 10^4$ $M_\odot$ or even higher (see Section 4). The constants in Eq. (7.1) are not predicted by the theory, they can be fixed from comparison with observations. For example, the parameter μ can be determined by the normalization to the total number of high-B bubbles (i.e. BD-stars and black holes) per comoving volume.

The formation of PBHs from the high-B bubbles proceeded in the following way. After the QCD phase transition in the early universe at $T = 100$ - 200 MeV and $t \sim 10^{-5} - 10^{-4}$ seconds, quarks combined forming nonrelativistic baryons (protons and neutrons), thus large density contrast arose between the bubble filled by heavy baryons and the relativistic plasma in the bulk of the universe. When the bubble radius reenters the cosmological horizon, the density contrast could easily be large, $\delta\rho/\rho \gtrsim 1$, and thus the bubble would turn into a BH. This mechanism is strongly different from those traditionally considered in the literature (e.g. [45] and references therein).

[1]Though the log-normal mass distribution is quite common for the usual stars, the considered here mechanism is the only one known to us for creation of such mass distribution of primordial black holes.

The promising constraints on PBHs density in several tens of solar masses range can be made with pulsar timing arrays through investigation of third-order Shapiro delay [46]. However, upper limit based on today's timing sensitivity will be within Eridanus and Firas estimates (figure 4).

Thus, the PBHs formed in the AD-BD scenario possess the following properties:
1. They have negligible angular momenta (vorticity perturbations are practically absent).
2. They have tiny peculiar velocities in the cosmological frame.
3. They could be easily captured, forming binaries, due to dynamical friction in the dense early universe.
4. Their number density can be high enough to create an avalanche of GW observations, especially with the higher sensitivity of the advanced LIGO and new GW detectors.
5. At the high-mass end of the universal log-normal PBH spectrum, they can seed an early SMBH formation in galaxies and even seed the galaxy formation.

Measurement of BH mass and spin distribution from LIGO GW observations can be used to check the prediction of the ADBD model presented here.

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