Massive primordial black holes in contemporary universe

Alexander.D. Dolgov[1], Shiladitya Porey[1]
Novosibirsk State University
Pirogova ul., 2, 630090 Novosibirsk, Russia
dolgov@fe.infn.it
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Abstract. The parameters of the original log-normal mass spectrum of primordial black holes (PBH) are approximately adjusted on the basis of existing observational data on supermassive black holes in the galactic centers and the mass distribution of the near-solar mass black holes in the Galaxy. Together with the assumption that PBHs make all or a noticeable mass fraction of the cosmological dark matter, it allows to fix the parameters of the original mass spectrum. The predicted, in this way, number density of MACHOs is found to be about an order of magnitude below the observed value. A possible resolution of this controversy may be prescribed to the non-isotropic and inhomogeneous distribution of MACHOs or to the modification of the original spectrum, e.g. assuming a superposition of two-maximum log-normal spectra of PBHs. A competing possibility is that MACHOs are not PBHs but dead primordial compact stars.
Key words: primordial black holes, mass spectrum

1 Introduction

The idea of the primordial black hole (PBH) formation was first put forward by Zeldovich and Novikov, 1966, Zeldovich and Novikov, 1967 and later was elaborated by Carr and Hawking Hawking, 1971, Carr and Hawking, 1974, Carr, 1975. According to their ideas, the density excess in the early universe might accidentally happen to be large, $\delta\rho/\rho \sim 1$ at the cosmological horizon scale, and then that piece of volume would be inside its gravitational radius i.e. it became a PBH, which decoupled from the cosmological expansion. In a subsequent paper Chapline Chapline, 1975 suggested that PBH with masses below the solar mass might be abundant in the present-day universe with the density comparable to the density of dark matter[1].

A different mechanism of PBH formation was suggested in refs. Dolgov and Silk, 1993, Dolgov et al., 2009. A quarter of century-old idea of these works that massive and very massive primordial black holes are abundant in the present-day universe, is gaining more and more popularity. According to the mechanism of PBH production proposed in refs. Dolgov and Silk, 1993, Dolgov et al., 2009, the mass spectrum of PBHs at the moment of creation had the simple log-normal form:

$$\frac{dN}{dM} = \mu^2 \exp\left[-\gamma \ln^2\left(\frac{M}{M_m}\right)\right], \tag{1}$$

where N is the number density of black holes, γ is dimensionless constant and parameters μ and M_m have the dimension of mass or, what is the same, of inverse length (here the natural system of units is used with speed of light, Boltzmann constant, and reduced Planck constant

[1] We thank P. Frampton for indicating this reference

all equal to unity: $c = k = \hbar = 1$ is used). Probably log-normal spectrum is a general feature of inflationary production of PBH or, to be more precise, is a consequence of the creation of appropriate conditions for the PBH formation during the inflationary cosmological stage, while the PBHs themselves might be formed long after inflation. In the mentioned above model, black holes were formed after the QCD phase transition (QCD PT) at the temperature of about 100 MeV. Some other forms of the spectrum were postulated in the literature, in particular, the delta-function one and a power-law spectrum. In this work, we confine ourselves to the log-normal spectrum which has a rigorous theoretical justification. Such spectrum is an example of the so-called extended mass spectrum which has come to life recently, see e.g. ref. Clesse and García-Bellido, 2015a, instead of narrow (monochromatic) mass spectra assumed in earlier works. As it was envisaged in ref. Dolgov and Silk, 1993, cosmological dark matter could consist entirely of PBHs (see also ref. Ivanov et al., 1994). It was even claimed recently that practically all black holes in the contemporary universe, with masses starting from a fraction of the solar mass, $M_\odot$, up to supermassive black holes of billions of solar masses, and intermediate-mass black holes with $M = (10^3 - 10^6)\, M_\odot$ are predominantly primordial Dolgov, 2017, Dolgov, 2018a, Dolgov, 2018b. A recent review on the bounds on the contemporary density of PBHs for different masses can be found in refs. Carr et al., 2020, Carr and Kühnel, 2020a.

The analysis of the chirp mass distribution of the coalescing BH binaries Dolgov et al., 2020 agreed very well with the log-normal mass distribution of the individual black holes and nicely fits the hypothesis that they are primordial.

It is argued in the paper Dolgov and Postnov, 2020 that the PBH mass distribution has maximum near $M_{BH} = 10 M_\odot$, because it is the mass inside the cosmological horizon at the QCD PT.

The recent analysis of the situation with PBH based on the LIGO/Virgo data was performed in ref. De Luca et al., 2020. According to the author's conclusion, the current data in the absence of accretion seems to exclude that all the sources of the observed gravitational waves are primordial. However, the possible effects of accretion can relax this constraint.

In this work, we will use available observational data to fix the parameters of distribution (1). This task is highly non-trivial and the results can be trusted only approximately because the original mass spectrum of PBHs was surely distorted through the matter accretion by PBHs during the course of the cosmological evolution. This problem was addressed in two works by one of us (with collaborators)
Blinnikov et al., 2015, Dolgov and Postnov, 2017. Here we use a different set of observational data and somewhat change the assumptions about the evolution of the original mass spectrum.

In ref. Blinnikov et al., 2016 we assumed that:
1. MACHOs are primordial black holes and their cosmological mass density makes the fraction $f = 0.1$ of the cosmological mass density of dark matter.
2. All primordial black holes constitute the whole cosmological dark matter,
3. 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.

The basic assumptions which are relied upon in this work are the fol-

lowing:
1. The total cosmological mass density of primordial black holes in the universe makes the fraction f of the dark matter density with f being a free parameter. The most interesting case is of course $f = 1$. We also consider the case $f = 0.1$.
2. The observed number density of large galaxies is equal to the number density of the heavy black holes with masses exceeding some boundary value, M_b. While M_b is supposed to be much smaller than the masses of the supermassive black holes (SMBH) observed in the centers of large galaxies, they could serve as appropriate seeds for the SMBH creation not only in the present-day universe but also in the young universe at the redshifts $z \sim 10$ Blinnikov et al., 2016, Dolgov and Postnov, 2020, Arbey et al., 2020
3. The value of M_m, at which the distribution (1) reaches the maximum, is taken from the data on the mass spectrum of black holes in the Galaxy. In the papers Blinnikov et al., 2015, Dolgov and Postnov, 2017, it was taken to be equal to one solar mass. However, in this work, we assume that M_m is in the interval $(6-8)M_\odot$ as dictated by the observations of the mass spectrum of the black holes in the Galaxy, see Section III. Maybe it is more proper to take M_m higher, closer to $10M_\odot$, as it is argued in ref. Dolgov and Postnov, 2020.
With this choice of the three basic sets of the observational data the mass density of MACHOs derived here is about $f \leq 10^{-3}$. The apparent contradiction of the observations can be resolved if the MACHOs are non-homogeneously distributed in space, see discussion below, or the mass spectrum (1) is generalized to a more complicated form having two or several maxima, as is envisaged in ref. Dolgov et al., 2009. Another possibility is that MACHOs are not PBH but compact primordial stars which were mostly destroyed after formation Dolgov and Postnov, 2020.

We want to stress that our work is not the final truth but a discussion of the hypothesis about PBH distribution which can be compared with observational data and verified in this way to check if it is valid or not.

2 Total mass density of black holes

The total cosmological mass density of the primordial black holes at the present time is given by the integral

$$\rho_{BH} = \mu^2 \int_0^{M_{max}} dM M \exp\left[-\gamma \ln^2\left(\frac{M}{M_m}\right)\right] \tag{2}$$

under the assumption that the spectrum (1) is weakly distorted by accretion in the essential mass range where M is close to M_m. As shown in ref. Blinnikov et al., 2015, the spectrum has a cutoff at large mass, M_{max}. The maximum value of PBH mass is estimated in ref. Blinnikov et al., 2015 as a function of the model parameters. According to this work, a reasonable value of M_{max} may lay in the range $M_{max} = (10^5 - 10^6)M_\odot$. Since M_m is below $10M_\odot$, see the next section, integral (2) can be safely extended to infinity.

Assuming that ρ_{BH} makes a fraction f of the mass density of dark matter, $\rho_{BH}/\rho_{DM} = f$, where

$$\rho_{DM} \approx 2.5\ 10^{-30}\,\mathrm{g/cm^3} \approx 3.7 \cdot 10^{10} M_\odot/\mathrm{Mpc}^3 \tag{3}$$

we find the first equation for the fixation of the parameters of the distribution:

$$\mu^2 \int_0^{M_{max}} dMM \exp\left[-\gamma \ln^2\left(\frac{M}{M_m}\right)\right] = f\rho_{DM}. \tag{4}$$

For the numerical estimates, it is convenient to present the solar mass in different units, not only in grams but in inverse megaparsec as well:

$$M_\odot = 2 \cdot 10^{33}\,\mathrm{g} = 1.75 \cdot 10^{95}/\mathrm{Mpc}. \tag{5}$$

There is no agreement on the value of f in the literature. According to the recent work Manshanden et al., 2019a, the mass fraction of black holes should be rather small, $f < 0.1$. However, this result is valid for a high value of the median mass $M_m \geq 20 M_\odot$. On the other hand, the data on the mass spectrum of Galactic black holes indicate that $M_m = (6-9)M_\odot$, see the next section. For M_m in this interval, the limits are much weaker. In what follows, we allow for the extreme case $f = 1$, which might not be excluded.

3 Mass spectrum of black holes in the Galaxy

The mass spectrum of black holes in the Galaxy shows striking features which are not expected in the standard picture of stellar-mass BH formation through stellar collapse after a star exhausted its nuclear fuel and if it had a sufficiently large mass. The observed picture strongly disagrees with the natural expectation from this scenario. According to ref. Özel et al., 2010 the masses of the observed black holes are surprisingly high and are concentrated in a narrow interval $(7.8 \pm 1.2)M_\odot$. This result is supported by another work 5, according to which the spectrum maximum is situated at $M \sim 8M_\odot$ and sharply drops above $M \sim 10M_\odot$ and below $5M_\odot$.

It is also observed Farr et al., 2011 that black holes in the Galaxy have a two-peak mass distribution with the second peak situated above the maximum mass of neutron star but below the lower limit of the BH masses found in the quoted above papers Özel et al., 2010, 5. The lower mass BHs are presumably produced by the usual mechanism of stellar collapse. So we expect that galactic black holes have log-normal distribution of heavier BHs, but lower mass BHs have a replica of stellar mass distribution of stars exceeding the Chandrasekhar limit.

Matter accretion in the course of galactic evolution may lead to some increase of the galactic black hole masses. Bearing this in mind, we take as the test values $M_m/M_\odot = 6, 7$, and 8.

4 Supermassive PBH in the centers of large galaxies

Astronomical observations strongly indicate that in each large galaxy there resides a supermassive black hole (SMBH) Cherepaschuk, 2016. Moreover, SMBHs are also observed in some small galaxies and even in practically empty-space; for a review, see Dolgov, 2018a, Dolgov, 2018b.

The origin of such black holes is mysterious. According to conventional understanding, SMBHs in galactic centers appeared as a result of matter accretion on a massive seed. However, the estimates of the necessary accretion rate to create such giants demand it to be much larger than any reasonable value. These facts create serious doubts about the traditional picture of the galaxy and SMBH formation, according to which the galaxy was created first and later an SMBH was formed in the center by the accumulation of the galactic matter. The data certainly indicates to invert picture that SMBHs were formed first and they served as a seed for the galaxy formation Dolgov and Silk, 1993, Dolgov et al., 2009, van den Bosch et al., 2012. Recent observations of high red-shift, $z \sim 10$ SMBHs Dolgov, 2018a, Dolgov, 2018b, strongly support this assertion.

Accordingly, we assume that the number density of supermassive primordial black holes is equal to the number density of galaxies. As it is assumed in ref. Blinnikov et al., 2015, the initially formed superheavy PBH might have much smaller masses, roughly speaking in the range $(10^3 - 10^5) M_\odot$ which could subsequently grow up to $10^9 M_\odot$ because of an efficient accretion of matter on the preexisting very massive seeds and mergings. A similar statement is done in ref. Rosas-Guevara et al., 2016, namely that the PBHs with masses around $(10^4 - 10^5) M_\odot$ may subsequently grow to $10^9 M_\odot$

This mass enhancement factor is much stronger for heavier BH and thus their mass distribution may be different from (1). We assume the simplified picture that the original PBHs were created with the distribution (1) but a PBH with the mass larger than a certain boundary value M_b became a supermassive seed for galaxy formation. Correspondingly the number density of PBH with masses larger than M_b should be equal to the present-day number density of (large) galaxies:

$$N_b = \mu^2 \int_{M_b}^{M_{max}} dM \exp\left[-\gamma \ln^2 \left(\frac{M}{M_m} \right) \right] = N_{gal} \tag{6}$$

In what follows, we take the following two sampling values

$$M_b = [10^4, \, 10^5] \, M_\odot. \tag{7}$$

Evidently, we must choose $M_{max} > M_b$. If $M_{max} \gg M_b$, the upper limit in eq. (6) maybe extended to infinity. If accidentally M_{max} is close by magnitude to M_b, the integral in Eq. (6) would be strongly diminished.

Determinations of the number density of galaxies by different groups give rather dispersed results.
According to refs Shinkai et al., 2017, Conselice et al., 2016 this density is in the interval.

$$N_{gal} = (0.01 - 0.1)/\mathrm{Mpc}^3. \tag{8}$$

This relation presents the third and the last necessary condition for the determination of the parameters of distribution (1).

5 Determination of the parameters

Using the presented above conditions, we can determine the parameters: γ and μ. The value of the median mass M_m is fixed in the interval $6M_\odot \le M_m \le 8M_\odot$ by the mass spectrum of the Galactic black holes, see Sec. III.

From equations (4,6,8) we find:

$$\frac{\rho_{DM}}{M_{odot} N_{gal}} = 3.7 \times 10^{10} f/K = \frac{I_1(0, x_{max}, x_m, \gamma)}{I_0(x_b, x_{max}, x_m, \gamma))}, \tag{9}$$

where

$$I_n(x_{min}, x_{max}, x_m, \gamma) = \int_{x_{min}}^{x_{max}} dx x^n \exp\left[-\gamma \ln^2\left(\frac{x}{x_m}\right)\right] \tag{10}$$

with $x_{min} = M_{min}/M_\odot$, $x_{max} = M_{max}/M_\odot$, $x_b = M_b/M_\odot$, and $x_m = M_m/M_\odot$

We calculate the ratio in the r.h.s. of eq. (9) as a function of γ for $f = 1, 0.1$; $K = 0.1$; $x_b = 10^4, 10^5$ and $x_{max} = 10^5, 10^6$. According to the definition, M_b should be smaller than M_{max} in each sample of the parameters. The results are not significantly different except for the case when M_b closely approaches M_{max} from below.

The calculated values of the parameters γ and μ are presented in Table I in the appendix for $M_b = 10^4, 10^5$. In that table μ_1 is the value of parameter μ calculated from the condition $N_{gal} = 0.1/\text{Mpc}^3$ and μ_2 is the value of the same parameter calculated from the condition $\rho_{PBH} = 2.5\ 10^{-30} f\ \text{g/cm}^3$. As mentioned in Introduction, we have taken two sample values of f, 1 and 0.1.

According to ref. Dolgov and Postnov, 2017 fitting the PBH mass function normalization in the $10 - 100$ 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}. The density of PBHs with the masses in the interval observed by LIGO, i.e. $20M_\odot - 50M_\odot$ with the chosen values of our parameters, see the left columns of the Table, is equal to a few times 10^9 per galaxy, if we take the density of galaxies equal to $Ngal = 0.1/\text{Mpc}^3$. It is a large number, however such BHs are not all in a galaxy but dispersed in the dark matter halo with the radius an order of magnitude larger than the galactic one. Correspondingly the number of such BHs in a galaxy would be 2-3 orders of magnitude smaller. Presumably, with so many black holes in disposal, the sufficient number of binaries can be formed to explain the observed LIGO rate.

The initially formed superheavy PBHs could have much smaller masses (around $(10^4 - 10^5)M_\odot$ but still grow up to $10^9 M_\odot$ because of an efficient accretion of matter and mergings, see the state-of-the-art SMBH growth calculations in Rosas-Guevara et al., 2016.

There is a tremendous activity during several recent years in attempts to derive upper limits on the BH density in different mass intervals, see Table II. These bounds, however, should be taken with a grain of salt, since the limits are model-dependent and usually derived with the most favorable assumptions to get the strongest possible bound.

6 Problems with MACHOs

As we have found in the previous section, γ is typically about 0.5. If we choose $M_m = (6-8)\,M_\odot$, then the calculated mass density of MACHOs would be several orders of magnitude lower than most results on the measured MACHO density for all reasonable values of γ.

The data presented by different groups are rather controversial. The present date situation is reviewed and summarized in refs. Moniez, 2010, Blinnikov, 2014, Blinnikov et al., 2015, Blinnikov et al., 2016. Briefly, the situation is the following.

MACHO group Alcock et al., 2000 reported the registration of 13 - 17 microlensing events towards the Large Magellanic Cloud (LMC), which is significantly higher than the number which could originate from the known low luminosity stars. On the other hand this amount is not sufficient to explain all dark matter in the halo. The fraction of the mass density of the observed objects, which created the microlensing effects, with respect to the energy density of the dark matter in the galactic halo, f, according to the observations Alcock et al., 2000 is in the interval:

$$0.08 < f < 0.50, \tag{11}$$

at 95% CL for the mass range $0.15M_\odot < M < 0.9M_\odot$.

EROS collaboration Beaulieu et al., 1995 has placed the upper limit on the halo fraction, $f < 0.2$ (95% CL) for the objects in the specified above MACHO mass range, while EROS-2 Tisserand et al., 2007 gives $f < 0.1$ for $0.6 \times 10^{-7} M_\odot < M < 15M_\odot$ for the survey of Large Magellanic Clouds. It is considerably less than that measured by the MACHO collaboration in the central region of the LMC.

The new analysis of 2013 by EROS-2, OGLE-II, and OGLE-III collaborations Calchi Novati et al., 2013 towards the Small Magellanic Cloud (SMC). revealed five microlensing events towards the SMC (one by EROS and four by OGLE), which lead to the upper limits $f < 0.1$ obtained at 95% confidence level for MACHO's with the mass $10^{-2}M_\odot$ and $f < 0.2$ for MACHOs with the mass $0.5M_\odot$.

Search for microlensing in the direction of Andromeda galaxy (M31) demonstrated some contradicting results Moniez, 2010, Blinnikov, 2014 with an uncertain conclusion. E.g. AGAPE collaboration Riffeser et al., 2008, finds the halo MACHO fraction in the range $0.2 < f < 0.9$. while the MEGA group presented the upper limit $f < 0.3$ Nucita et al., 2008. On the other hand, the recent discovery of 10 new microlensing events Lee et al., 2015 is very much in favor of MACHO existence. 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”.

Some more recent observational data and the other aspects of the microlensing are discussed in ref. Mao, 2012.

It would be exciting if all DM were constituted by old stars and black holes made from the high-density baryon bubbles as suggested in refs. Dolgov and Silk, 1993, Dolgov et al., 2009 with masses in still allowed intervals, but a more detailed analysis of this possibility has to be done.

There is a series of papers claiming the end of MACHO era. For example, in ref. Yoo et al., 2004 the authors stated ”we exclude MACHOs with masses $M > 43 M_\odot$ at the standard local halo density. This removes the last permitted window for a full MACHO halo for masses $M > 10^{-7.5} M_\odot$.

In addition to the criticism raised in the paper Yoo et al., 2004, some more arguments against the abundant galactic population of MACHOs are also presented in ref. Belokurov et al., 2003, Belokurov et al., 2004. However, according to the paper Griest and Thomas, 2005, the approach of the mentioned works have serious flaws and so their results are questionable. A reply to this criticism is presented in the subsequent paper Evans and Belokurov, 2005.

The data in support of smaller density of MACHOs in the direction to SMC is presented in ref. Tisserand et al., 2007

Later, however, another paper of the Cambridge group Quinn et al., 2009 was published where on the basis of studies of binary stars, arguments in favor of real existence of MACHOs and against the pessimistic conclusions of ref. Yoo et al., 2004 were presented.

The latest investigation on the ”end of MACHO era” was presented in ref. Monroy-Rodríguez and Allen, 2014, where it is concluded that ”the upper bound of the MACHO mass tends to less than $5M_\odot$ does not differ much from the previous one. Together with microlensing studies that provide lower limits on the MACHO mass, our results essentially exclude the existence of such objects in the galactic halo”.

A nice review of the state of the art and some new data is presented in ref. Lee et al., 2015 with the conclusion that some statistical studies and individual microlensing events point to a non-negligible MACHO population, though the fraction in the halo mass remains uncertain.

According to the results of different groups, the fraction of MACHO mass density with respect to the total mass density of dark matter varies in a rather wide range:

$$f_{MACHO} = \frac{\rho_{MACHO}}{\rho_{DM}} \sim (0.01 - 0.1) \tag{12}$$

Notice a large variance of the results by different groups. Reasonable agreement between the data and the mass spectrum considered here can be achieved only if $M_m \sim M_\odot$ Dolgov and Postnov, 2017, Blinnikov et al., 2016. So we either have to reject the possibility that practically all galactic black holes are primordial with masses around $(6-8)M_\odot$ or to search for another explanation of the discrepancy between the observed and the predicted density of MACHOs with a log-normal mass spectrum of PBHs.

An interesting option is that the spatial distribution of MACHOs may be very inhomogeneous and non-isotropic. Due to the selection effect, MACHOs are observed only in over-dense clumps where their density is much higher than the average one. For a review and the list of references on dark matter clumping see e.g. Berezinsky et al., 2014. Clumping of primordial back holes, due to dynamical friction, may be much stronger than the clumping of dark matter consisting of elementary particles. This hypothesis would allow to avoid contradiction between the observed high density of MACHOs and the predicted much smaller density of them based on the log-normal mass spectrum with $M_m = (7-9)M_\odot$.

Another possibility to adjust theory to the observations is to assume multi-maximum log-normal spectrum i.e. the superposition of the log-normal spectra with maxima at several different values of M_m:

$$\frac{dN}{dM} = \sum_j \mu_j^2 \exp\left[-\gamma_j \ln^2\left(\frac{M}{M_m^j}\right)\right]. \tag{13}$$

Such spectrum may originate from inflationary stage if the coupling of the inflaton field χ to the scalar with non-zero baryonic number has more complicated polynomial form Dolgov et al., 2009, than that postulated in the original paper Dolgov and Silk, 1993:

$$U_{int} = |\chi|^2 \prod_j \lambda_j (\Phi - \Phi_j)^2 / m_{Pl}^{(2j-2)}. \tag{14}$$

In our case the two-maxima mass spectrum, with j running from 1 to 2, is sufficient to describe all observational data with reasonable accuracy. It allows also to avoid many existing bounds on primordial black holes Carr and Kühnel, 2020b, Ali-Haïmoud and Kamionkowski, 2017, Sasaki et al., 2018, Carr et al., 2017, Murgia et al., 2019. Such two-maximum log-normal spectrum is introduced ad hoc in ref. Celoria et al., 2018 with the same purpose to satisfy the demands of astronomical observations.

On the other hand, according to ref. Dolgov and Postnov, 2020 bubbles with high density of baryons with masses smaller than the mass inside cosmological horizon at the QCD phase transition mostly formed compact stellar-like objects, which could explode in the process of evolution, leading to a considerably smaller density of MACHOs, than predicted by the log-normal mass spectrum.

7 Black holes with intermediate mass

Black holes with masses from $10^3 M_\odot$ up to $10^6 M_\odot$ are rather arbitrarily called Intermediate Mass Black Holes (IMBH). They were observed during the recent few years and now about 10^3 of them are known Mezcua et al., 2018.

It remains unclear if they can be created by the conventional astrophysical processes, such as stellar collapse or matter accretion to some massive seeds. The hypothesis that they are all primordial looks much more attractive.

Having the parameters fixed, we can calculate the number density of the intermediate black holes in each galaxy, N_{IMBH}. We find that for each large galaxy there is $\sim 10^3 - 10^4$ number of IMBHs (see appendix). According to ref. Dolgov and Postnov, 2017 such IMBH can seed the formation of globular clusters and dwarf galaxies. At the moment only in one globular cluster, a black hole with mass about $2000 M_{\odot}$ is detected. It is predicted Dolgov and Postnov, 2017 that in every globular cluster there must be an intermediate-mass primordial black hole, which was a seed of this cluster.

8 Conclusion

Massive primordial black holes with extended mass spectrum became viable candidates for the constituents of the cosmological dark matter. Formation of such PBHs is possible due to inflationary expansion of the very early universe because inflation could create physically connected super-horizon scales. In this sense, the existence of supermassive PBHs can be considered as extra proof of inflation.

In this work, we relied on the log-normal mass spectrum for the following reasons. First, it was historically first extended mass spectrum derived rigorously in a consistent scenario based on a simple modification of the Affleck-Dine baryogenesis Affleck and Dine, 1985 by the introduction of general renormalizable coupling of the scalar baryon to the inflaton field. Nowadays it is the very popular form of the mass spectrum of PBHs.

Moreover, the chirp-mass distribution of the LIGO events analyzed in ref. Dolgov and Postnov, 2020 demonstrates excellent agreement with log-normal mass distribution of PBHs.

The other reason that we confined ourselves to this particular form of the spectrum is that the consideration of several different spectra would make the paper too cumbersome to follow.

Later, there appeared quite a few other models leading to the formation of very massive PBH with extended mass spectrum. All of them are essentially based on the assumption that the conditions for the PBH formation were prepared during inflation, as it was pioneered in ref. Dolgov and Silk, 1993. Indeed, if one does not invoke inflation, the PBH mass cannot reach huge values of $(10^4 - 10^5) M_{\odot}$. There are several papers where inflationary PBH formation is studied and extended mass spectrum is obtained, see e.g., Ivanov et al., 1994, García-Bellido et al., 1996,
Clesse and García-Bellidoo, 2015b. In ref. Ivanov et al., 1994an extended but quite complicated mass spectrum was obtained and the possibility of very massive PBH formation was mentioned.
In the paper García-Bellido et al., 1996 relatively light PBHs with masses $10^{15} - 10^{30}$ g are considered. An extension of the previous work
Clesse and García-Bellidoo, 2015b allows for significantly higher masses but no clear statement about the mass spectrum is made.
In ref. Clesse and García-Bellido, 2017 the log-normal mass spectrum was

exploited but without any justification or reference.
The paper Carr et al., 2019 to a large extend repeats main features of ref. Dolgov and Silk, 1993 but with essentially different kinetics.

There are several relatively recent papers dedicated to the consideration of general conditions for PBH formation see e.g. [Musco et al., 2009, Young et al., 2019, but the bounds derived there are not applicable to the model of refs. Dolgov and Silk, 1993, Dolgov et al., 2009, because these general conditions are valid for the traditional mechanism of PBH formation, while the mechanism of the works Dolgov and Silk, 1993, Dolgov et al., 2009 and of some other quoted-above-papers is significantly different since PBNs were formed very late, after QCD phase transition and prior to it the perturbations were isocurvature ones, which transformed to density perturbations after massless quarks turned into massive nucleons in bubbles with very high baryonic number.

Recent observations of abundant supermassive black holes in the early universe lead to a natural conclusion that they are primordial, see e.g. Dolgov, 2018a. If they indeed have log-normal or some other extended mass distribution, then it is tempting to conclude that the contribution of PBH to the cosmological dark matter is at least non-negligible.

In principle, there could be two, or even several, comparable forms of dark matter: PBHs and different elementary particles species, though such a conspiracy is surely at odds with the Occam's razor. On the other hand, there are impressive examples of similar cosmic conspiracies of near equality of energy densities of baryons, dark matter, and dark energy. Detailed comparison of the observational data with the predicted mass spectrum of black holes at different redshifts could help to solve this deep mystery.

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Appendix:

Table 1.

		$M_b = 10^4 M_\odot, M_{max} = 10^5 M_\odot$	$M_b = 10^5 M_\odot, M_{max} = 10^6 M_\odot$
$M_m = 8M_\odot$	$f = 1$	$\gamma = 0.53$ $\mu_1 = 2.4 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 4.4 \times 10^{-69} \mathrm{cm}^{-1}$ $N_{IMBH} = 3.4 \times 10^5$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$) $\mu_2 = 2.5 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 4.6 \times 10^{-69} \mathrm{cm}^{-1}$ $N_{IMBH} = 3.6 \times 10^5$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)	$\gamma = 0.31$ $\mu_1 = 8.98 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 1.6 \times 10^{-69} \mathrm{cm}^{-1}$ $N_{IMBH} = 1.9 \times 10^4$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$) $\mu_2 = 1.1 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 2 \times 10^{-69} \mathrm{cm}^{-1}$ $N_{IMBH} = 2.8 \times 10^4$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)
	$f = 0.1$	$\gamma = 0.48$ $\mu_1 = 6.4 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 1.2 \times 10^{-69} \mathrm{cm}^{-1}$ $N_{IMBH} = 8.6 \times 10^4$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$) $\mu_2 = 6.9 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 1.3 \times 10^{-69} \mathrm{cm}^{-1}$ $N_{IMBH} = 10^5$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)	$\gamma = 0.29$ $\mu_1 = 3.5 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 6.4 \times 10^{-70} \mathrm{cm}^{-1}$ $N_{IMBH} = 8.6 \times 10^3$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$) $\mu_2 = 3.1 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 5.7 \times 10^{-70} \mathrm{cm}^{-1}$ $N_{IMBH} = 6.8 \times 10^3$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)

<table>
<tr><td></td><td></td><td>$M_b = 10^4 M_\odot, M_{max} = 10^5 M_\odot$</td><td>$M_b = 10^5 M_\odot, M_{max} = 10^6 M_\odot$</td></tr>
<tr><td rowspan="2">$M_m = 7M_\odot$</td><td>$f = 1$</td><td>$\gamma = 0.51$

$\mu_1 = 2.3 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 4.2 \times 10^{-69} \mathrm{cm}^{-1}$

$N_{IMBH} = 2.6 \times 10^5$
(for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)

$\mu_2 = 2.7 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 4.9 \times 10^{-69} \mathrm{cm}^{-1}$

$N_{IMBH} = 3.5 \times 10^5$
(for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)</td><td>$\gamma = 0.31$

$\mu_1 = 1.3 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 2.4 \times 10^{-69} \mathrm{cm}^{-1}$

$N_{IMBH} = 2.1 \times 10^4$
(for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)

$\mu_2 = 1.3 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 2.4 \times 10^{-69} \mathrm{cm}^{-1}$

$N_{IMBH} = 2.1 \times 10^4$
(for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)</td></tr>
<tr><td>$f = 0.1$</td><td>$\gamma = 0.47$

$\mu_1 = 7.7 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 1.4 \times 10^{-69} \mathrm{cm}^{-1}$

$N_{IMBH} = 8.5 \times 10^4$
(for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)

$\mu_2 = 7.7 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 1.4 \times 10^{-69} \mathrm{cm}^{-1}$

$N_{IMBH} = 8.5 \times 10^4$
(for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)</td><td>$\gamma = 0.28$

$\mu_1 = 3.2 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 5.8 \times 10^{-70} \mathrm{cm}^{-1}$

$N_{IMBH} = 7.1 \times 10^3$
(for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)

$\mu_2 = 3.3 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$
$= 6.0 \times 10^{-70} \mathrm{cm}^{-1}$

$N_{IMBH} = 7.6 \times 10^3$
(for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)</td></tr>
</table>

		$M_b = 10^4 M_\odot, M_{max} = 10^5 M_\odot$	$M_b = 10^5 M_\odot, M_{max} = 10^6 M_\odot$
$M_m = 6M_\odot$	$f = 1$	$\gamma = 0.5$	$\gamma = 0.3$
		$\mu_1 = 3.2 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 5.8 \times 10^{-69} \mathrm{cm}^{-1}$	$\mu_1 = 1.3 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 2.4 \times 10^{-69} \mathrm{cm}^{-1}$
		$N_{IMBH} = 2.9 \times 10^5$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)	$N_{IMBH} = 1.9 \times 10^4$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)
		$\mu_2 = 3.1 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 5.7 \times 10^{-69} \mathrm{cm}^{-1}$	$\mu_2 = 1.4 \times 10^{-50} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 2.6 \times 10^{-69} \mathrm{cm}^{-1}$
		$N_{IMBH} = 2.7 \times 10^5$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)	$N_{IMBH} = 2.2 \times 10^4$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)
	$f = 0.1$	$\gamma = 0.45$	$\gamma = 0.27$
		$\mu_1 = 7.5 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 1.4 \times 10^{-69} \mathrm{cm}^{-1}$	$\mu_1 = 3.0 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 5.5 \times 10^{-70} \mathrm{cm}^{-1}$
		$N_{IMBH} = 6.7 \times 10^4$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)	$N_{IMBH} = 5.9 \times 10^3$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)
		$\mu_2 = 8.4 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 1.5 \times 10^{-69} \mathrm{cm}^{-1}$	$\mu_2 = 3.5 \times 10^{-51} (\mathrm{gm\,cm}^3)^{-1/2}$ $= 6.4 \times 10^{-70} \mathrm{cm}^{-1}$
		$N_{IMBH} = 8.3 \times 10^4$ (for $10^3 \lesssim M_{IMBH}/M_\odot \lesssim 10^4$)	$N_{IMBH} = 8 \times 10^3$ (for $10^4 \lesssim M_{IMBH}/M_\odot \lesssim 10^5$)

Table 2.

Eridanus II star cluster	$(10-100)M_\odot$	$f_{\mathrm{PBH,max}} > 0.02$	Fig.[3] of Brandt, 2016
EROS-2 and MACHO (milky way)	$10^{-2} \le M/M_\odot \le 100$	$f_{\mathrm{PBH}} > 2\times10^{-2}$	Fig.[8] of Calcino et al., 2018
GW simulations	$(2-160)M_\odot$	$f_{\mathrm{PBH}} \approx 0.002$	Raidal et al., 2019
Radio and x-ray emission and simulations	$(1-100)M_\odot$	$f_{\mathrm{PBH}} > 2\times10^{-4}$	Fig.[5] of Manshanden et al., 2019a
OGLE concluding paper (towards Magellanic clouds)	$M < 0.1M_\odot$ $(0.1-0.4)M_\odot$ $M_\odot$ $20M_\odot$	$f_{\mathrm{PBH}} < 4\%$ $f_{\mathrm{PBH}} \sim 6\%$ $f_{\mathrm{PBH}} < 9\%$ $f_{\mathrm{PBH}} < 20\%$	Wyrzykowski et al., 2011
PBH and LIGO first run conclusion (Monochromatic mass distribution)	$0.2M_\odot$ $M_\odot$	$f_{\mathrm{PBH}} < 5\%$ $f_{\mathrm{PBH}} < 5\%$	(LIGO colla.)Abbott et al., 2018
New analysis of EROS-2, and OGLE-II, and OGLE-III towards SMC	$10^{-2} < M/M_\odot < 10^{-1}$ $M/M_\odot = 1, 10^{-3}$ $10^{-3} < M/M_\odot < 10^{-1}$ $M/M_\odot = 10^{-2}$ $M/M_\odot = 1$	$f_{\mathrm{PBH}} \le 0.11-0.13$ $f_{\mathrm{PBH}} \le 0.3$ $f_{\mathrm{PBH}} \le 0.10$ $f_{\mathrm{PBH}} \le 0.07$ $f_{\mathrm{PBH}} \le 0.35$	Fig.[6] of Calchi Novati et al., 2013
New analysis of OGLE-II and Ogle-III towards LMC	$10^{-2} < M/M_\odot < 0.5$ $M/M_\odot = 1$ $10^{-2} < M/M_\odot < 0.1$ $M/M_\odot = 100$	$f_{\mathrm{PBH}} \le 0.1-0.2$ $f_{\mathrm{PBH}} = 0.24$ $f_{\mathrm{PBH}} \le 0.5$ $f_{\mathrm{PBH}} \sim 0.5$	Calchi Novati and Mancini, 2011
Planck data	$0.2 \le M/M_\odot \le 100$	$f_{\mathrm{PBH}} > 10^{-6}$	Fig.[4] of Chen et al., 2016
EROS-2 (towards Magellonic clouds))	$10^{-3} < M/M_\odot < 10^{-1}$ $10^{-6} < M/M_\odot < 1$	$f_{\mathrm{PBH}} < 0.04$ $f_{\mathrm{PBH}} < 0.1$	Tisserand et al., 2007
GW obsevations	$10 \le M/M_\odot \le 200$	$f_{\mathrm{PBH}} < 0.008$	Fig.[17] ofSasaki et al., 2018
Wide binary	$20 < M/M_\odot \le 100$	$f_{\mathrm{PBH}} \ge 0.4$	Fig.[3] of Quinn et al., 2009
CMB limits on accreting PBHs	$10 \le M/M_\odot \le 100$	$f_{\mathrm{PBH}} \ge 60$	Fig.[14] of Ali-Haïmoud and Kamionkowski, 2017
CMB bounds on disk-accreting PBHs	$0.1 < M/M_\odot \ge 100$	$f_{\mathrm{PBH}} > 6\times10^{-5}$	Fig.[4] of Poulin et al., 2017
Radio and X-ray bound	$20 < M/M_\odot < 100$	$f_{\mathrm{PBH}} > 2\times10^{-2}$	Fig[1] of Gaggero et al., 2017
WMAP	$1 \le M/M_\odot \le 100$	$f_{\mathrm{PBH}} > 4\times10^{-3}$	Fig.[2] of Inoue and Kusenko, 2017 (original Fig.[9] of Ricotti et al., 2008)