Primordial Black Holes and Modification of Zeldovich–Novikov Mechanism

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Abstract—Bulk of various astronomical observations of black holes suggest that virtually all observed black holes can be of primordial origin. A modified mechanism of the primordial black hole formation is described. A universal log-normal mass spectrum with a mean mass of around  predicted by this mechanism is strongly confirmed by the LIGO/Virgo observations of gravitational waves from coalescing binary black holes.

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1. INTRODUCTION

The idea of primordial black holes (PBHs), i.e., of black holes which could be created in the early universe during pre-stellar epoch, was first put forward by Ya. Zeldovich and I. Novikov in 1966 in the seminal paper entitled “The Hypothesis of Cores Retarded during Expansion and the Hot Cosmological Model” [1]. According to their idea, the density contrast in the early universe inside a bubble with radius equal to the cosmological horizon might accidentally happen to be large, \( \delta \rho / \rho \approx 1 \). In this case, that piece of volume turns out inside its own gravitational radius, i.e. it forms a PBH that decouples from the cosmological expansion. This idea was elaborated later by S. Hawking in his paper “Gravitationally collapsed objects of very low mass” [2] and by B. Carr and S. Hawking in “Black holes in the early Universe” [3].

The mass inside the horizon in the early universe at the radiation dominated stage (RD) stage, \( r_\text{hor} = 2t \), is equal to \( M_\text{hor} = m_\text{pl}^2 \). If \( \delta \rho / \rho = 1 \), then \( M_\text{BH} = M_\text{hor} \), and the gravitational radius is indeed equal to the horizon, \( r_\text{g} = 2M/m_\text{pl}^2 = r_\text{hor} \).

In [4], the mechanism of PBH formation was modified in several essential features. This paper was the first to suggest cosmological inflation for the PBH formation. The proposed mechanism allowed the creation of PBHs with very high masses exceeding millions solar masses. According to this mechanism, large isocurvature density perturbations had been generated during inflationary stage. Later on, at the QCD phase transition, these perturbations turned into density perturbations. The mechanism of [4], see also [5], predicts a simple log-normal mass spectrum of PBHs:

\[
\frac{dN}{dM} = \mu^2 \exp\left[ -\gamma \ln^2 \left( \frac{M}{M_0} \right) \right].
\]

The parameters \( \mu \) and \( \gamma \) are determined by physics at very high energies and are unknown, but \( M_0 \) should be equal to the mass inside the cosmological horizon at the QCD phase transition [6]:

\[
M_\text{hor} = 8M_\odot \left( \frac{100 \text{ MeV}}{T} \right)^2,
\]

where \( M_\odot = 2 \times 10^{33} \text{ g} \) is the solar mass. According to the lattice calculations, \( T_{\text{QCD}} = 100–150 \text{ MeV} \) but with large chemical potential of quarks \( T_{\text{QCD}} \) may be noticeably smaller, so we expect \( M_0 \) somewhat larger than \( 10M_\odot \), which happens to be in very good agreement with observations, see below.

Another mechanism of inflationary creation of PBHs was proposed about two years later in [7]. It is based on suggestion of [8] on the generation of the inflaton field perturbations in a model with double field inflation. The PBH mass spectrum calculated in [7] has a rather complicated analytical structure and to the best of our knowledge has not been applied to the analysis of observational data.
Presently, there is a lot of inflationary mechanisms of PBH creation predicting different mass spectra.

2. MODIFIED MECHANISM OF PBH CREATION

As suggested in [4], conditions of PBH formation were prepared during inflation by dynamical generation of perturbations with large baryonic number on astrophysical scales. It is based on the popular baryogenesis model of Affleck and Dine (AD) [9] enabling the creation of a baryon asymmetry of order of unity, much larger than the observed conventional number, $\beta \approx 6 \times 10^{-10}$.

Due to the interaction between the inflaton and a scalar Affleck–Dine field with non-zero baryon number, the creation of domains with high $\beta$ could take place only during a relatively short time. Thus, cosmologically small but possibly astronomically large bubbles with high $\beta$ could be created. By construction, they occupy a small fraction of the universe volume, while the rest of the universe has the ordinary small baryon asymmetry $\beta \simeq 6 \times 10^{-10}$.

Therefore, during inflation huge isocurvature perturbations of the baryonic number could emerge which transformed into high density perturbations at the QCD phase transition when massless quarks turned into heavy baryons. The inflationary prehistory allows for the creation of huge PBH with masses up to $(10^5-10^5)M_\odot$ and possibly even higher [10].

Note that the possible outcome of this mechanism is the creation of early compact star-like objects which might consist of both matter and antimatter.

3. THE LOG-NORMAL PBH SPECTRUM, COMPARISON WITH OBSERVATIONS

LIGO/Virgo observations of gravitational wave emission from coalescing black hole binaries offer a very powerful tool to probe the PBH mass spectrum.

As is well known, a binary system of orbiting gravitationally bound massive bodies emits gravitational waves. In a quasi-stationary Newtonian inspiral stage, the radius of the circular orbit and the orbital frequency gradually change, with the GW frequency being equal to the double orbital frequency:

$$\omega^2 = \frac{M_1 + M_2}{m_{\text{pl}}^2 R^3}. \quad (3)$$

The GW luminosity of this stage is

$$L = \frac{32}{5} m_{\text{pl}}^2 \left( \frac{M \omega_{\text{orb}}}{m_{\text{pl}}^2} \right)^{10/3}, \quad (4)$$

where $M_1$, $M_2$ are the masses of two bodies and $m_{\text{pl}}$ is the so called chirp mass:

$$m_{\text{chirp}} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}. \quad (5)$$

In [11], the cumulative chirp mass distribution of coalescing binary BH is calculated using the publicly available LIGO data:

$$F_{\text{PBH}}(<M) = \int \mathcal{P}_{\text{PBH}}(M) \, dM = \frac{\int_0^M dM \mathcal{D}(M)}{\int_0^M dM \mathcal{D}(M)}, \quad (6)$$

where $\mathcal{D}(M)$ is the detection rate by the LIGO/Virgo interferometers per year determined by the sensitivity of the detectors. Importantly, this ratio does not depend upon the unknown normalization factor $\mu$ of the distribution (1) which determines the total cosmological density of PBHs. The comparison of the LIGO/Virgo data with theoretical expectation for $F_{\text{PBH}}(<M)$ according to [11] for the best-fit PBH mass spectrum parameters $M_0$ and $\gamma$ is presented in Fig. 1. Figure 1 suggests that the log-normal mass spectrum of PBHs with the central mass $M_0 = 17 M_\odot$ perfectly agrees with the data. On the other hand, a similar comparison with the best-fit of several astrophysical models of BH origin, shown in Fig. 2, demonstrates a much worse agreement. An analysis of the recently released LIGO/Virgo GWTC-2 data leads to a similar value of $M_0 = 13 M_\odot$ with a slightly smaller $\gamma \approx 0.7$.

To conclude this section, the available LIGO/Virgo data on the coalescing binary BHs strongly evidence in favor of their primordial origin. A log-normal mass spectrum of PBHs is clearly confirmed by observations. To the best of our knowledge, no other mass spectrum has not been checked by the data, to say nothing of confirmation. The puzzle of a hundred solar mass black hole in GW190521 [12] can be naturally explained if one assumes that it is primordial, and no exotic mechanism of its formation is necessary. The discovery of such an “astrophysically impossible” BH can be taken as an impressive confirmation of our model.

More arguments in favor of the primordial formation of LIGO/Virgo sources can be also found in [10].

With the parameters of the log-normal mass spectrum of PBHs determined here (see also [13]), one may conclude that universe should be filled with PBHs with different masses, from supermassive BHs in galactic nuclei with masses up to 100 billion solar masses, down to intermediate mass BHs, with $M = (10^5-10^7)M_\odot$, and, of course, with a plenty of stellar-mass BHs.
Fig. 1. Comparison of the empirical cumulative distribution function (EDF) of chirp masses of the LIGO/Virgo coalescing binary black holes with the calculated distribution $F_{\text{PBH}} (<\mathcal{M})$ assuming a log-normal PBH mass spectrum with the best-fit parameters $M_0$ and $\gamma$; left panel: model distribution $F_{\text{PBH}} (<\mathcal{M})$ for two best Kolmogorov–Smirnov tests; right panel: model distribution $F_{\text{PBH}} (<\mathcal{M})$ for two best Van der Waerden tests (figures from [11]).

Fig. 2. Cumulative distributions $F(<\mathcal{M})$ for several astrophysical models of binary BH coalescences, see [11] for more detail.
It could not be an exaggeration to say that (almost) all BHs in the universe are primordial. These black holes may naturally solve many cosmological problems in the present-day and early universe [14, 15], as we discuss in the following section.

4. COSMIC CONUNDRUMS AND PBHS

PBHs, which for many years have been taken as strange exotic creatures, now force their place among respectable members of the establishment, as one can see by the number of publications on PBHs per year, which rises faster than exponentially. Now PBHs are serious candidates for dark matter carriers, though the original suggestions [16] (very light PBH, \( M < 10^{22} \) g) and [4] (masses up to millions solar masses, and even higher) were not taken seriously at that time.

Presently PBHs not only may help to solve the problem of dark matter but also are able to disentangle many other striking problems of modern cosmology and astrophysics [14, 15], which are very difficult to resolve in other way.

Discoveries of the last decade indeed demonstrate the contemporary and even the early (\( z = 5–10 \)) universe is indeed unexpectedly rich with supermassive black holes (SMBH), \( M = (10^6 – 10^{10})M_\odot \) and intermediate mass black holes (IMBH), \( M = (10^3 – 10^5)M_\odot \).

4.1. Contemporary Universe

Every large galaxy contains a central supermassive BH with the mass of billions solar masses in giant elliptical and compact lenticular galaxies and with a few million solar masses in spiral galaxies, like Milky Way. The origin of these BHs is poorly understood. The commonly accepted faith is that these BHs are created by matter accretion onto a central seed with an initial mass of \( -10^4 – 10^5 M_\odot \). However, the standard accretion efficiency is insufficient by two orders of magnitude to grow them during the Universe lifetime, \( t_U = 14 \) Gyr [17].

Moreover, SMHBs are discovered in small diffuse galaxies and even in almost empty space, where is not enough material to create such huge monsters through accretion, see [14] for more detail and references.

These observations indicate a possible upside-down change of the galaxy formation paradigm. Instead of creation of SMBH by accretion to the galactic center, galaxies are formed by matter attraction by a preexisting primordial massive black hole, as suggested in [4, 5, 18]. It is tempting to make the next step and to speculate that the type of any large galaxy is determined by the mass of the BH seed.

Another, but possibly far-fetched, piece of evidence favoring the primordial formation of SMBHs is their clumping. There are at least four binaries of SMBH, one triple system and one quartet (see references in [14]). According to the conventional approach, a SMBH binary may be formed in the process of merging of two galaxies each having a SMBH in the center. It is almost infinitely more problematic to create a triple system of SMBHs along this way, to say nothing of a quartet. It appears much easier to create a close binary system of SMBHs in the early universe, should they be primordial.

Coming to less massive but still huge BHs, note that about a thousand of black holes with masses \( 10^5 M_\odot \) and a few with much smaller but still huge masses, \( M \sim 2000 M_\odot \) have been now discovered. It is hard to imagine that such BHs have been created as a result of stellar collapse. On the other hand, the early universe can easily provide them in the necessary amount. According to our prediction [19], if the parameters of the mass distribution of PBHs, \( M_\gamma \) and \( \gamma \), are chosen to fit the LIGO data and the normalization factor \( \mu \) is chosen to provide the density the PBH with masses exceeding \( 10^4 M_\odot \), which could seed the observed SMBH in the galaxies, then the number of PBH with masses \( 2–3 \times 10^5 M_\odot \) would be about \( 10^5 – 10^6 \) per one SMBH. This allows all large galaxies to host their own SMBH, seeded by a primordial single or maybe even double black hole. The predicted density of IMBHs is sufficient to seed the formation of all globular clusters and dwarf galaxies. Up to now only one or two IMBHs are observed in globular clusters, while there could be an IMBH in each of them.

4.2. Anti Dark Matter

In a recent publication, already after the Conference was over, an interesting idea was put forward that dark matter may consist of compact anti-stars [20]. It is noteworthy that the creation of compact stellar-like antimatter objects was envisaged in [4, 5]. As argued in [21–23], an abundant number density of compact anti-stars in the universe and even in the Galaxy does not violate existing observational limits. Such anti-DM may be easier to spot than other forms of macroscopic DM.

4.3. High-\( z \) Universe

Astronomical observations of the last decade led to the striking discovery that the early universe at \( z \sim 10 \) is grossly overpopulated with bright quasars or, what is presumably the same, by SMBHs, with masses up to \( M \sim 10^{10} M_\odot \), by superluminous young galaxies, by supernovae and gamma-bursters. Moreover, the universe at this young age proved to be very dusty and full of heavy elements.

According to [24], the number density of galaxies at \( z \approx 11 \) is \( 10^{-6} \) Mpc\(^{-3} \), an order of magnitude higher
than estimated from the data at lower \( z \). It is difficult to understand how these galaxies can be formed using the standard lore. However, having in our disposal supermassive seeds in the form of PBHs, we can allow for their existence. So, again, first black holes and then galaxies.

Presently, about a hundred quasars at redshift \( z > 6 \) are known. The record one, ULAS J134208.10+092838.61 at redshift \( z = 7.54 \) when the universe was only 690 mln yrs old, has a mass of about billion solar masses [25]. The known accretion rate is not sufficiently strong to ensure their creation. As is shown in [26], a massive BH could accrete only about 2200 \( M_\odot \) during 320 Myr in the halo with a mass of \( 3 \times 10^{10} M_\odot \) at \( z = 7.5 \). There is general agreement that ultra-massive seeds are necessary for the QSO creation, which could be easily presented by PBHs with masses of about \( 10^4 M_\odot \).

One more argument against sufficiently efficient accretion is neutrality of the medium around QSO [25], because otherwise strong accretion should strongly ionize the surrounding medium.

A few months ago, a remarkable statement was presented in [27] that quasars at \( z = 6 \) had remained active only during \( 10^3 \)–\( 10^4 \) yr. This striking observation implies that we see only a minor fraction of SMBHs which “lives” in the early universe, not more than \( 10^{-4} \). It is hardly possible to create so many SMBHs by the conventional accretion mechanism in about 500 million years. PBHs are badly needed.

5. CONCLUSIONS

We have determined the mass spectrum of PBHs from the comparison with the chimp mass distribution of coalescing binary BHs extracted from the LIGO/Virgo data. The best-fit PBH mass spectrum is perfectly well described by a log-normal form, confirming the 1993 prediction of [4].

The extracted value of the central mass of the PBH mass spectrum is found around 13–17 solar masses, which very well agrees with our earlier prediction [6]. Some astrophysical models of binary black hole formation and evolution poorly describe the LIGO/Virgo data, signaling the need for much improvement of the theory of astrophysical black hole formation.

Based on the extracted PBH mass spectrum parameters, one may suggest that virtually all black holes in the contemporary and early universe can be primordial. This assumption allows us to solve quite naturally many of cosmic conundrums.

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