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Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics

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Contents

Abstract. We discuss recent astronomical data showing that the role of massive primordial black holes in the Universe is much more significant than previously thought, both for the present Universe and for redshifts of the order of 10. We consider the model proposed in 1993 accounting for the primordial creation of heavy and superheavy black holes with a log-normal mass spectrum, which naturally explains some facts about the Universe that are unaccounted for in standard cosmology and astrophysics.

Keywords: black holes, massive and supermassive black holes, gravitational waves, globular clusters, formation of galaxies, the Universe at redshifts of about 10

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1. Introduction

In recent years, a significant increase in the sensitivity of telescopes (at all wavelengths) has led to many amazing astronomical discoveries, especially in the Universe at high redshifts $z = 5-10$ corresponding to the cosmological age from about 400 mln to one billion years. Such a young Universe was found to be densely populated by objects that could not be formed over such a short time according to current knowledge.

This young Universe was found to host quasars with supermassive black holes (SMBHs) (with a mass of a few billion solar masses $M_{\odot}$), very bright and very large galaxies, supernovae, and gamma-ray bursts. A significant number of metals were discovered in the chemical composition of matter, and finally, the Universe was found to be very dusty.

Similar problems are also pertinent to the modern Universe. They have been especially well recognized after recent discoveries at high redshifts. Each large elliptical or lenticular galaxy hosts an SMBH with a mass of one billion $M_{\odot}$. In spiral galaxies, for example, in the Milky Way, the mass of the central black hole (BH) is much smaller, about 5 mln $M_{\odot}$. A theory of the formation of such BHs, especially SMBHs, due to the accretion of ambient matter onto the galactic center encounters significant difficulties, and hence their mere presence is a serious astrophysical problem.

It is tempting to think that it is not BHs that grow inside the already formed galaxies, but vice versa, galaxies form around pre-existing (primordial?) BHs. Moreover, the galaxy type is determined by the seed BH, rather than the BH mass being determined by the galaxy properties, as is posited in the standard scenario. The new astronomical data presented below compellingly favor such an inverted picture.

What remains unclear is the mass spectrum of galactic BHs and the origin of MACHOs (Massive Astrophysical Halo Objects) — faint or fully dark objects with a mass somewhat below the solar mass, which have been discovered in the Galaxy and its halo using gravitational microlensing — as well as a number of other not so grave but still significant problems that do not fit traditional cosmology and astrophysics.

Recent evidence of the presence of BHs with masses around 2000 $M_{\odot}$ inside globular clusters does not contradict the globular cluster formation around the already existing primordial massive BHs.

The most recent methods for determining the stellar age have led to the unexpected discovery of a few 'patriarchs', with the age of one of the stars having been found to even exceed the age of the Universe. Of course, observational errors cannot be fully ruled out, but such stars are still older than the Galaxy.

The last, but not the least is the recent detection of gravitational waves by LIGO (Laser Interferometer Gravitational-wave Observatory) (GW150914, GW170104), which are uniquely interpreted as coalescences of binary BHs with masses around 30 $M_{\odot}$ and low proper angular momenta; this can hardly be explained by the BH formation mechanism due to stellar collapses.

All the surprising discoveries listed above (and some others) can be straightforwardly explained by one hypothesis of massive primordial BH (PBH) formation far before $z = 10$. Such a mechanism was elaborated in [1]. There, in particular, a log-normal BH mass distribution was predicted, which has become popular in the last couple of years in connection with the LIGO discoveries and the possibility of describing cosmological dark matter by primordial BHs. However, this 'new' statement that BHs with such a mass spectrum can constitute all or a significant fraction of cosmological dark matter was first put forward as early as 1993 in [1] (see also [2]).

This review has the following structure. In Section 2, we present recent observational data on the high-redshift Universe at $z \sim 10$. In particular, we discuss the discovery of bright young galaxies, quasars (hosting SMBHs), the dusty early Universe, young supernovae, and gamma-ray bursts. In Section 3, we discuss recently discovered 'facts of life' of the modern Universe that cannot be easily explained by the Standard Model or which simply contradict it. Section 4 is devoted to problems of the formation of the LIGO binary BHs. The proposed solution to the problems considered there is based on paper [3]. Section 5 describes the theoretical model [1] of the formation of massive and supermassive PBHs and compact stellar-like objects and presents the predicted mass spectrum, as well as observational consequences of the theory. In Section 6, we consider the evolution of the mass spectrum of PBHs and associated compact astrophysical objects due to the accretion of matter at later stages. In Section 7, based on paper [4], we discuss the relation between globular clusters and PBHs with masses $\gtrsim 2000 M_{\odot}$. The effect of compact astrophysical objects born in the early Universe on primordial nucleosynthesis and the cosmic microwave background (CMB) is discussed in Section 8. In Section 9, we consider the hypothesis of the transformation of intense gravitational waves into electromagnetic radiation. In Section 10, we discuss predictions of our model, briefly describing alternative theories of heavy PBH formation, and make final conclusions.

This review is based on papers [5–9], in which the reader can find references to earlier astronomical observations.

Below, we use the natural system of units in which the speed of light c, the Planck constant $\hbar$, and the Boltzmann constant $k_{\rm B}$ are set to unity: $c = \hbar = k_{\rm B} = 1$. The only dimensional value is length, which has the same dimension as time, while mass, energy, and temperature have the dimension of inverse length. For the reader's convenience, we present Table 1 from [10, 11] that can be used to convert ordinary units into natural ones.

In particular, the proton mass is $m_{\rm p} \approx 940$ MeV, and in seconds and centimeters, it is $1/m_{\rm p} \approx 2 \times 10^{-14}$ cm or 0.7×10^{-24} s. The gravitational constant in these units has the dimension of inverse mass squared: $G_{\rm N} = 1/m_{\rm Pl}^2$, where $m_{\rm Pl} = 1.221 \times 10^{19}$ GeV is the Planck mass. Temperature has the same dimension as energy, and 1 K is equal to about 10^{-4} eV. More precise values of the transformation coefficients can be obtained from Table 1.

2. Population of the Universe at redshift $z \sim 10$

In this section, we present and briefly discuss data from recent astronomical observations of the Universe at redshifts $z = 5 - 10$. We consider giant galaxies, quasars, gamma-ray bursts, supernovae, and the chemical composition of the interstellar medium. To understand the characteristic time scales, it is worthwhile to start with the age of the Universe as a function of the redshift and cosmological parameters.

Table 1. Transformation coefficients for the natural units.

	s^{-1}	cm^{-1}	K	eV	a.m.u.	erg	years
s^{-1}	1	0.334×10^{-10}	0.764×10^{-11}	0.658×10^{-15}	0.707×10^{-24}	1.055×10^{-27}	1.173×10^{-48}
cm^{-1}	2.998×10^{10}	1	0.229	1.973×10^{-5}	2.118×10^{-14}	3.161×10^{-17}	0.352×10^{-37}
K	1.310×10^{11}	4.369	1	0.862×10^{-4}	0.962×10^{-13}	1.381×10^{-16}	1.537×10^{-37}
eV	1.519×10^{15}	0.507×10^{5}	1.160×10^{4}	1	1.074×10^{-9}	1.602×10^{-12}	1.783×10^{-33}
a.m.u.	1.415×10^{24}	0.472×10^{14}	1.081×10^{13}	0.931×10^{9}	1	1.492×10^{-3}	1.661×10^{-24}
erg	0.948×10^{27}	0.316×10^{17}	0.724×10^{16}	0.624×10^{12}	0.670×10^{3}	1	1.113×10^{-21}
g	0.852×10^{48}	2.843×10^{37}	0.651×10^{37}	0.561×10^{33}	0.602×10^{24}	0.899×10^{21}	1

2.1 Age of the Universe as a function of the redshift

The age of the Universe is known to be expressible through the redshift z and fundamental cosmological parameters:

$$t(z) = \frac{1}{H} \int_0^{1/(z+1)} \frac{\mathrm{d}x}{\sqrt{1 - \Omega_{\mathrm{tot}} + (\Omega_{\mathrm{m}}/x) + x^2 \Omega_{\mathrm{v}}}}\,, \tag{1}$$

where H is the present-day value of the Hubble parameter and Ω_i are dimensionless densities of the mass/energy normalized to the critical energy density $\rho_{\mathrm{c}} = 3H^2 m_{\mathrm{Pl}}^2/(8\pi)$. Values of all quantities are taken at the present time. According to the bulk of astronomical data (see, e.g., review [12]), the total energy density is close to the critical one, $\Omega_{\mathrm{tot}} = 1$. The mass density of nonrelativistic matter is $\Omega_{\mathrm{m}} = 0.317$ (including ordinary baryonic and dark matter of an unknown nature as yet). The remaining energy density $\Omega_{\mathrm{v}} = 0.683$ is due to enigmatic dark energy, which is responsible for the present-day accelerated expansion of the Universe. The subscript 'v' here means 'vacuum-like'. The accuracy of these values is at a level of a few percent.

The Hubble parameter was quite precisely measured by detectors aboard the Planck space mission [13] from the analysis of angular fluctuations of the cosmic microwave background: $H = 67.3$ km (s Mpc)$^{-1}$. However, recently, accurate measurements of H by traditional astronomical means have been reported [14–16], which lead to significantly higher values, up to $H = 74$ km (s Mpc)$^{-1}$. Depending on the value of H, the age of the Universe varies significantly (Table 2).

The origin of the disagreement between the two types of measurements of H remains unclear. If this discrepancy is not a result of some systematic error or other measurement problem, this could be a strong indication of a new physics, for example, the existence of a new long-lived dark matter particle [17] with a lifetime exceeding the age of the Universe with the hydrogen recombination time $t_{\mathrm{rec}} \sim$ 400,000 years.

It is likely that the discrepancy in the measurements of H is due to the deviation of the Universe expansion law from the canonical form when the scale factor at the early stage, during which the dark energy effect was insignificant (at $z > 1.3$), increased faster than the first power of time. It was shown in [18] that the present expansion of the Universe and in the recent epoch is well described by the law $a(t) \sim t^{3/2}$ (see also [19]). The hypothesis of the linear scale factor increase with time, $a(t) \sim t$, was discussed in [20–22] with the aim to increase the age of the Universe. However, according to [18], this time behavior of $a(t)$ does not satisfactorily describe observations.

Although a change in the cosmological expansion law could facilitate resolving the problem of the early formation of galaxies and quasars, it does not solve many other issues related to populations in the early and present-day Universe.

Table 2. Age of the Universe t_{U} as a function of the redshift z for two values of the Hubble parameter H.

z	t_{U}, bln years	
	$H = 67.3$ km (s Mpc)$^{-1}$	$H = 74.0$ km (s Mpc)$^{-1}$
0	13.8	12.5
3.0	5.0	4.5
6.0	0.93	0.84
8.0	0.64	0.58
10	0.47	0.43

Therefore, we do not discuss it further and focus on the hypothesis of the early formation of PBHs.

2.2 Bright galaxies in the early Universe

Gravitational lensing made it possible to discover several very remote (and young) galaxies that 'luckily' proved to be in the line of sight between Earth and a gravitational lens. Such lenses operate as natural telescopes.

Among the detected galaxies is one with $z \approx 9.6$, which formed when the age of the Universe was less than 500 mln years. The corresponding paper is entitled "A highly magnified candidate for a young galaxy seen when the Universe was 500 Myrs old" [23]. Somewhat later, a galaxy at $z \approx 11$ was discovered [24], which formed when the age of the Universe was less than 410 mln years, or even 380 mln yrs for the higher value of the Hubble parameter.

Recently, the galaxy GN-z11 was discovered with a higher redshift $z = 11.1$ [25]. Despite the young age, GN-z11 has (had) a very high luminosity. As noted in [25], the ultraviolet emission from this galaxy is about a factor of three higher than the emission from galaxies at $z = 6-8$. It is also noted in [25] that about 800 galaxies with $z = 7-8$ have been found by the present time. References to earlier publications can also be found in that paper.

The discovery of a galaxy with the currently record high redshift $z = 13.2^{+1.9}_{-1.6}$, corresponding to an age of less than 300 mln years, even for the lower value of the Hubble constant, is reported in [26]. In addition, the discovery of a significant number of galaxies with redshifts greater than seven is reported in [26].

Thus, we can conclude that the Universe was very densely populated at $z > 6$, although we observe only the brightest galaxies, which constitute a small fraction of the total number. In the Standard Model, such an intensive early galaxy formation is not expected.

In 2015, the discovery of a not very young but extremely luminous galaxy was reported [27]. According to estimates in [27], the age of this galaxy is about 1.3 bln years, and its luminosity $L = 3 \times 10^{14} L_{\odot}$ is almost a factor of 10^4 higher than that of the Milky Way. To provide such a huge luminosity, an active galactic nucleus is required that is fed by an SMBH which, as the authors of [27] conclude, was very massive from the very beginning or experienced a very rapid mass growth. The authors of [27] write: "The existence of AGNs with $L_{\mathrm{bol}} > 10^{14} L_{\odot}$ suggests that these supermassive black holes are born with large mass, or have very rapid mass assembly. For black hole seed masses $\sim 10^3 M_{\odot}$, either sustained super-Eddington accretion is needed, or the radiative efficiency must be $< 15\%$, implying a black hole with slow spin, possibly due to chaotic accretion." Nevertheless, the authors of [27] conclude that the seed galaxy of the BH embryo around which the galaxy formed must be much heavier than thought possible.

During a talk with journalists, one of the authors of [27], P Eisenhardt, spoke in images [28]: "How do you get an elephant? One way is to start with a baby elephant." However, it remains unclear how this 'baby elephant' could be born when the age of the Universe was only one-tenth of its present age.

As another author of [27], Chao-Wei Tsai, said, "Another way for a black hole to grow this big is for it to have gone on a sustained binge, consuming food faster than typically thought possible. This can happen if the black hole isn't spinning that fast" [28].

In the last sentence and above, we draw attention to the need for a low BH spin. According to the LIGO results mentioned in the Introduction (to be discussed in detail in Section 4), binary BHs (GW150914 and GW170104) have an almost zero spin, which is quite unusual for BHs formed due to accretion, but quite natural for the PMBHs we consider in this review.

According to the analysis in paper [29], which is remarkably entitled "Monsters in the dark," the existence of the galaxy GN-z11 [25] suggests that the density of galaxies in the early Universe at $z \sim 11$ should be around 10^{-6} Mpc^{-3}. This is about an order of magnitude higher than the expected galaxy density at lower redshifts inferred from observational data. According to estimates in [29] based on existing observations, the new WFIRST telescope (Wide-Field Infrared Survey Telescope) will be able to discover around 1000 galaxies in the redshift range from $z = 11$ to $z = 13.5$. However, the origin of these galaxies is unclear.

We conclude this section with a quotation from [21]: "Rapid emergence of high-z galaxies so soon after the Big Bang may actually be in conflict with current understanding of how they came to be."

Another, but also very surprising, observation was made in [30], where the discovery of a not-so-young galaxy with an age of two to three billion years, which lacks dark matter, was reported. The conclusion about the absence of dark matter was made from measurements of rotation curves, which do not go to a constant value with the distance from the galaxy, as is usually the case in dark matter halos, but decrease. It is commonly believed that galaxies are formed inside potential wells formed earlier by dark matter clumps. If our hypothesis that SMBHs serve as seeds for galaxy formation is valid, the presence of additional dark matter may not be so essential.

2.3 Quasars and supermassive black holes at $z > 6$

Another much more striking example of astrophysical objects formed early is high-redshift quasars. Presently, around 40 quasars with $z > 6$ are known, each containing a massive BH with a mass of about one billion $M_\odot$. The existence of such BHs formed at the time when the Universe was much younger than one billion years is in drastic contradiction to standard models of their formation and growth. The discovery of six (possibly, nine) new high-redshift quasars was recently reported in [31].

The record high measured quasar redshift is $z = 7.085$ [32], which means that this quasar emerged when the Universe was younger than 770 mln years. The luminosity of this quasar is $L = 6.3 \times 10^{13} L_\odot$ and its mass is $M = 2 \times 10^9 M_\odot$. Such a rapid growth of an SMBH is at least problematic in the framework of the canonical theory.

In 2015, an even more massive 'monster' at the redshift $z = 6.3$ with a huge mass of 12 bln $M_\odot$ was discovered [33]. Its optical and near-infrared luminosity is higher than those of quasars at $z > 6$ discovered earlier by a factor of a few. As noted above, there are serious problems in explaining even lighter and less powerful quasars. However, the existence of this monster aggravates the disagreement with the standard theory. An analysis of traditional mechanisms of SMBH formation and references to earlier literature can be found in recent papers [34–39].

Here, we would like to continue the quotation from [21] given at the end of Section 2.2: "This problem [of early formed galaxies] is very reminiscent of the better known (and probably related) premature appearance of supermassive black holes at $z \sim 6$. It is difficult to understand how $10^9 M_\odot$ black holes appeared so quickly after the Big Bang without invoking nonstandard accretion physics and the formation of massive seeds, neither of which is seen in the local Universe."

The cited paper appeared before the discovery of the most massive quasar [33] with a mass much higher than others.

The flow of discoveries of early galaxies and quasars is not abating. In [40], the discovery of eight new quasars with the redshift from 6 to 6.5 and the estimated age from 1 to 10 mln years was announced, which are possibly excluded from PBH candidates in the early Universe. However, the accuracy of the age estimate is unclear, and these quasars could initially be much lighter and could acquire mass by the late accretion of matter (see Section 6).

The discovery of another 32 quasars with $5.7 < z < 6.6$ by the Subaru telescope was reported in [41], increasing the total number of high-redshift quasars discovered by this group to 33. In addition, 14 high-redshift luminous galaxies were found in the Subaru deep sky survey [41]. The discovered quasars have lower luminosity than other quasars found by other groups. On the other hand, the galaxies found in [41] turned out to be much more powerful. According to the authors, they represent a new type of objects, different from those known earlier.

The discovery of a quasar with the redshift 7.1 located inside a very compact galaxy 1 kpc in diameter was reported in [42], which additionally puts in doubt the standard formation mechanism of quasars (SMBHs) due to the accretion of galactic matter.

The authors of [43] analyzed the possibility of the birth of quasars at $z = 6-7$ and concluded that their existence challenges the commonly accepted paradigm of cosmic structure formation. As an alternative, they proposed a mechanism in which SMBH growth is due to accretion of cold dense flows, likely providing rapid assembling of some galaxies in later epochs. We note that this rapid growth could be due to the presence of SMBH seeds, as we suggest below in this review.

The situation in the Universe at $z > 6$ was discussed in [44], raising the same questions as in this review and earlier publications by the author [5–9].

The arguments given above suggest almost straightforwardly that SMBHs are primordial objects born in the prestellar epoch of the Universe. In particular, this hypothesis can imply that they are seeds for galaxy formation and not products of accretion onto the galactic center. This is supported by recent observations of both the early and present-day Universe discussed in Section 3.

2.4 Dust, supernovae, and gamma-ray bursts

The Universe at $z > 6$ was found to be highly dusty, which is also rather unexpected. To produce dust, a long chain of different processes is needed. First, supernovae should explode to enrich the interstellar medium with heavy elements, so-called metals (in astronomy, any chemical elements heavier than helium are called metals). Later on, atoms of metals cool to become bound in molecules, and only after that molecules form macroscopic particles — dust grains.

Dust is observed in some young galaxies, for example, in HLFS3 at the redshift $z = 6.34$ [45] and A1689-zD1 at $z = 7.55$ [46]. The galaxy A1680-zD1, discovered by gravitational lensing, is the earliest of known galaxies in which interstellar matter is observed. The age of the Universe at this redshift is 500 mln years. These results are confirmed by observations [47]. These and other observations were used in the catalogue of 'dusty' high-redshift galaxies [48]. The conclusion was reached that the number of these dusty sources is about one order of magnitude higher than predicted by canonical galaxy evolution models.

As noted above, stellar explosions are needed to produce the interstellar dust. However, according to [49], even assuming a maximum contribution of supernovae to dust production, the observed amount of dust in the galaxy A1689-zD1 requires an unusually powerful growth of seed grains. This in turn requires that the density of both hot and cold gas in which dust seeds grow in this galaxy be comparable to the gas density in galaxies hosting central quasars. Although not impossible, the upper bounds on the continuum dust emission from galaxies at $6.5 < z < 7.5$ show that these conditions are not met for most galaxies. Interestingly, could this suggest that the galaxy A1689-zD1 also hosts a central dormant quasar?

Another possible source of dust in addition to supernovae, AGB (Asymptotic Giant Branch) stars was considered in [50]. The result also proved to be pessimistic: such stars are not numerous enough to provide the required amount of dust at $z = 4-7.5$. The authors conclude that supernovae could produce the needed amount of dust only if their efficiency reached the theoretical maximum efficiency. The most likely possibility, in this case, is the rapid growth of dust seeds in the interstellar medium. We note in advance that the mechanism of heavy BH formation discussed in Section 5 could lead to a significant number of dense stellar-like objects — seeds of future supernovae at $z \sim 10$ and even earlier.

In addition, it cannot be ruled out that the number of supernovae in the early Universe was much higher than expected. This idea is supported by observations of significant metal abundance around early quasars. According to standard cosmology, only light elements up to ^{4}He are produced in the primordial nucleosynthesis, with a tiny addition of Li, Be, and B, while heavier elements are generated in stars and are ejected into the interstellar medium during stellar explosions. According to this picture, intensive star formation must have occurred before or simultaneously with quasar formation. Furthermore, it is required that many of the stars explode as supernovae and enrich the interstellar medium with metals that later formed molecules and dust. (It is well known that all of us are the dust from a supernova exploded not too far away from the Sun, but in a much later epoch.)

Another possibility of enriching the interstellar medium by metals is offered by nonstandard nucleosynthesis with a high initial baryon density [51–54] (see Section 5).

Observations of gamma-ray bursts also suggest an unexpectedly large number of high-redshift supernovae. The record high gamma-ray burst redshift is 9.4. Additionally, several gamma-ray bursts were observed at smaller but still very high z. The star formation rate required to explain the observations does not fit the canonical theory. Nevertheless, while being unexplained by the theory, gamma-ray bursts and generally supernovae are observed at high redshifts, implying a high star formation rate above the expected values. These stars must have been created simultaneously with or even earlier than quasars. Then they would have been able to produce many supernovae, which would in turn enrich the interstellar space with the required high metal abundance. The possible formation mechanism of high-redshift gamma-ray bursts from collapses of these early stars is considered in [55].

We stress that the mechanism we discuss in Section 5 naturally leads to the formation of a large number of compact stars or stellar-like objects long before $z = 10$.

3. Puzzles of the modern and almost modern Universe

The Universe has surprised us recently not only by events from its youth that do not fit the canonical picture but also by the enigmatic properties of astrophysical objects we observe today.

3.1 Old stars in the Milky Way

Recently, the accuracy of stellar age determination using nuclear chronology has greatly increased. Thanks to this, the age of some stars in the Galaxy has been estimated much more accurately than previously. Below, we consider the most impressive results.

Using old nuclear chronometers uranium and thorium, and comparing the corresponding elemental abundance, the age of the star BD + 17° (a metal-deficient halo star) was estimated to be $t = (13.8 \pm 4)$ bln years [57]. (For comparison, the age of the inner galactic halo is (11.4 ± 0.7) bln years [57]). Errors in the age measurements are still large, but the discrepancy between central values raises trouble or great interest.

Similar results were obtained for the age of the star HE 1523-0901 in the galactic halo, which turned out to be 13.2 bln years [58]. These measurements for the first time used a number of nuclear chronometers, including the ratios U/Th, U/Ir, Th/Eu, and Th/Os. The uncertainty in the age determination is about 2 bln years.

The most striking result is the one in [59], according to which the age of HD 140283 (a metal-deficient subgiant with *high velocity*) is (14.46 ± 0.31) bln years. The central value exceeds the age of the Universe by two standard deviations if we assume that $H = 67.3$ km (s Mpc)$^{-1}$ and the age of the Universe is 13.8 bln years, and even by 10 standard deviations if $H = 74$ km (s Mpc)$^{-1}$ and $t_U = 12.5$ bln years. The high velocity of this subgiant possibly suggests its early pregalactic origin.

Clearly, a star cannot be older than the Universe, and the unusual chemical composition of this and other old stars could be the possible explanation for this contradiction. It is commonly accepted that the first stars consist of 25% He and 75% H in accordance with primordial nucleosynthesis and observational data of the light element abundance. However, in the scenario we discuss below, in a relatively small spatial volume, the primordial nucleosynthesis can generate a significant number of nuclei much heavier than helium, as we noted in Section 2.4. In addition, the early supernovae that enriched the interstellar medium with metals could also alter the chemical composition of later stars in such a way that they could reach the present-day state much more rapidly. Clearly, this hypothesis requires numerical calculation of stellar nucleosynthesis with nonstandard initial chemical abundance.

In conclusion, we note that in addition to these old stars in the Milky Way, a planet with an age of $10.6^{+1.5}_{-1.3}$ bln years was discovered [60]. (For comparison, the age of Earth is only 4.5 bln years.) The formation of such an old planet (two times older than Earth) must have been preceded by a supernova explosion and formation of molecules, which also requires a long time.

3.2 Supermassive black holes at present

Astronomical observations give compelling evidence that each galaxy hosts a central SMBH (see review [61]). In giant elliptical and compact lenticular galaxies, the central BH mass can exceed one billion $M_{\odot}$. In spiral galaxies, such as the Milky Way, the BH masses are much smaller, of the order of a few million solar masses.

The central BHs in galaxies are thought to arise due to accretion onto some massive seed. However, estimates of the BH mass grown in this process show that the accretion efficiency is insufficient to create these giants. This problem resembles that of the SMBH formation in the early Universe considered in Section 2, but is not so highly pronounced because the available time is longer. Nevertheless, below, we provide spectacular examples that do not fit the accretion mechanism.

As a rule, the central BH mass is about 0.1% of the bulge mass [62, 63], but in some galaxies, for example, in NGC 1277, the BH mass is fantastically high, $1.7 \times 10^{10} M_{\odot}$, or 60% of the bulge mass [64]. The origin of such a BH is utterly unclear.

Several similar examples are presented in [65]. These authors argue that despite a good correlation between the SMBH mass and the host galaxy mass, an increasing number of outliers emerge. These include the galaxies Henize 2-10, NGC 4889, and NGC 1277, in which the masses of SMBHs are at least an order of magnitude higher than could be expected from their host galaxy masses.

The discovery of a supercompact dwarf galaxy [66] also disagrees with the standard model. This galaxy has an age of 10 bln years and is enriched with metals. It possibly hosts a central massive BH. The dynamical mass of the galaxy is $2 \times 10^8 M_{\odot}$ and its radius is only 24 pc, and hence its density is very high. According to Chandra X-ray satellite data, there is a variable X-ray source with the luminosity $L_X \sim 10^{38}$ erg s^{-1} in the galactic center. This can be an active galactic nucleus related to a massive BH or a low-mass X-ray binary. Analysis of the optical spectrum suggests that the system must be very old, 10 bln years or older. The chemical composition is close to the solar one, but with an increased abundance of [Mg/Fe] and greatly increased [N/Fe]. This suggests a possible self-enrichment with light elements, which could arise in close binary systems. On the other hand, it could result from nonstandard primordial nucleosynthesis for a very high baryon-to-photon ratio.

The discovery of another over-heavy BH in a moderate-mass galaxy was reported in [67]. The BH mass in the active galactic nucleus was estimated to be $M_{\rm BH} = (3.5 \pm 0.8) \times 10^8 M_{\odot}$ with the accretion luminosity $L_{\rm AGN} = (5.3 \pm 0.4) \times 10^{45}$ erg s$^{-1} \approx 10^{12} L_{\odot}$, which is 12% of the Eddington value. This is much higher than one could expect in such a modest-size galaxy. The results contradict the commonly accepted picture according to which this galaxy was recently transformed from a disk star-forming galaxy into a passively evolving early-type galaxy.

The most striking example of an SMBH emerging from nowhere is the BH discovered in [68], which resides in an almost empty space.

Recently, a large dark-matter-dominated galaxy was discovered [68]. The total mass of the galaxy is estimated to be $\sim 10^{12} M_{\odot}$ with a very low luminosity. The mass-to-luminosity ratio suggests that the fraction of unseen (dark) matter in this galaxy can be very high, about 98%. The origin of such a dark galaxy is unclear. It would be interesting to understand whether the SMBH in its center is not accreting matter due to the absence of ordinary baryonic matter. Or has this matter already been consumed by the quasar?

The observations discussed above question the standard scenario of SMBH formation in galactic centers due to the accretion of matter onto the central galactic region. The reversed scheme, in which the SMBH appears earlier than the galaxy and serves as a seed for later galaxy assembling seems to be much more compelling [1, 2, 64]. It would be interesting if it could be shown whether the galaxy type (spiral or elliptical) is determined by the initial BH mass.

The discovery of a 'quasar quartet' [70] at the redshift $z \approx 2$, i.e., not in the present-day Universe but not too early, as for $z = 5-10$, provided an unexpected argument favoring the primordial origin of SMBHs. According to the authors of [70], all galaxies have presumably gone through the quasar phase, during which their luminosity was sustained by accretion onto the SMBH. But because quasars are rare objects at cosmological distances, the probability of finding a quadruple quasar is very low, $\sim 10^{-7}$. This in turn requires that the dominant portion of massive structures in the distant Universe acquired a huge amount of cold gas with a density of about 1 cm^{-3}, which substantially contradicts cosmological simulations.

It is commonly accepted that SMBHs in galactic centers have grown due to accretion, but new observational data apparently contradict this classical model.

Recently, interesting observations of an SMBH at the redshift $z = 0.3504$, i.e., at a distance of about one Gpc, were published in [71]. The BH mass is about 180 mln $M_{\odot}$ ($\log M_{\rm BH} = (8.21 \pm 0.02) M_{\odot}$ as stated in [71]). This BH is offset from the galactic nucleus by a distance of 1.260 ± 0.05 kpc and moves away from the center with a velocity of 175 ± 25 km s^{-1}. The authors of [72] hypothesize that the runaway BH resulted from the coalescence of two lighter BHs in the galactic center. This process could give rise to a significant recall momentum, leading to the observed runaway BH.

A much more natural scenario could be one in which a primordial SMBH that did not acquire a proper galaxy (as we have seen above, such BHs exist), like an insomniac bear on an astronomical scale, simply moves through another galaxy that does have a proper BH in the center.

3.3 Solar-mass black holes

The mass distribution of BHs observed in the Milky Way has a strange shape from the standpoint of standard theory. According to [72], the BH masses are unexpectedly high and concentrated in the narrow range $(7.8 \pm 1.2) M_{\odot}$. This result is in agreement with other observations [73], which also find a mass distribution peaking at $M \sim 8 M_{\odot}$, while there are virtually no BHs with masses below $5 M_{\odot}$, and their number greatly decreases above $10 M_{\odot}$.

Such a behavior is unusual if BHs are formed in stellar collapses.

As noted in [74], astronomical data apparently also suggest a double-peaked mass distribution with a minimum between the maximum neutron star mass and the lower limit of BH masses found in papers cited above. In the standard model, this distribution is unexplained, but complies with the hypothesis of the primordial massive BH formation if there are two BH populations in the Galaxy: 'our' primordial (dominating?) one and a 'normal' one resulting from collapses of very massive stars. The mass distribution for these two populations should be different: in the first case, it is a log-normal mass distribution, and in the second case it should repeat the mass distribution of stars with masses above 20–30 $M_\odot$.

3.4 MACHO problem

The MACHO (Massive Astrophysical Compact Halo Object) problem also possibly relates to the BH problem. MACHOs are invisible or very faint objects with masses of about half the solar mass, which were discovered by the MACHO and EROS (Expérience de Recherche d'Objets Sombres) collaborations by gravitational microlensing. MACHOs have been discovered in the galactic halo in the direction of the galactic center and recently in the Andromeda galaxy (M31). The density of these objects greatly exceeds the expected one if they are low-luminosity stars. However, it is insufficiently high to explain all dark matter in the galactic halo. A brief review of the MACHO problem can be found in [75], which we follow below (see also [76]).

The MACHO collaboration [77, 78] reported the discovery of 13–17 microlensing events in the direction of the Large Magellanic Cloud, which is much higher than the microlensing events due to low-luminosity stars. According to [77, 78], the ratio of the density of the discovered microlenses to the matter density in the halo, which is in fact the density of dark matter, falls within the range $0.08 < f < 0.50$ at a 95% CL (confidence level) for $0.15 M_\odot < M < 0.9 M_\odot$.

The EROS collaboration reported only the upper bound for the mass fraction of the registered lenses, $f < 0.2$ (95% CL) in the same mass interval as shown above for the MACHO data. The subsequent EROS-2 observations [79] led to a stronger bound $f < 0.1$ in the mass range $10^{-6} M_\odot < M < M_\odot$.

The AGAPE (Andromeda Gravitational Amplification Pixel Experiment) collaboration [80], which searches for MACHOs in the direction to the Andromeda galaxy, reports $0.2 < f < 0.9$, whereas the MEGA (Microlensing Exploration of the Galaxy and Andromeda) [81] gives a tighter upper bound $f < 0.3$.

An analysis of this contradictory situation is carried out in [82]. Later searches [83] by EROS-2 and OGLE (Optical Gravitational Lensing Experiment) in the direction of the Small Magellanic Cloud give $f < 0.1$ (95% CL) for masses $\sim 10^{-2} M_\odot$ and $f < 0.2$ for masses $\sim 0.5 M_\odot$.

Undoubtedly, MACHOs exist. Their density is comparable to that of dark matter in the galactic halo, but their nature is unclear. In principle, MACHOs could be brown dwarfs, dead stars, or PBHs. However, brown dwarfs or dead stars could not be produced from normal stellar evolution in the required amount, while PBHs or compact stellar-like objects formed in the early Universe could well exist.

3.5 Intermediate-mass black holes in the contemporary Universe

In the contemporary Universe, so-called intermediate-mass BHs with masses of several dozen, hundred, and thousand solar masses have been discovered. Their canonical astrophysical formation raises many serious questions (see, e.g., review [84]).

For example, unusual properties of the recently discovered supernova iPTF13bvn [85] in the nearby galaxy NGC 5806 can be explained by assuming a heavy BH companion of the supernova progenitor, which could result from the collapse of a 70 $M_\odot$ star [86]. As an alternative, heavy PBHs, whose formation is discussed in Section 5, could be plausible companions.

Recently, evidence appeared that intermediate-mass BHs (thousands of solar masses) can reside in the centers of globular stellar clusters. It is not easy to explain the formation of these heavy BHs in the commonly accepted models, but in our approach they appear exactly in the required numbers (see Section 7).

All these data fit the inverse galaxy formation model well, assuming that central BHs do not result from the collapse of matter in galactic centers but instead are seeds for the formation of different stellar clusters. Small BHs with masses of $(10^3 - 10^4)\, M_\odot$ acquire small 'galaxilets'. Heavier BHs serve as centers for dwarf galaxies, and giant galaxies 'condense' around SMBHs. In spiral galaxies, BHs are not very big and their mass is not more than several million solar masses (as in the Milky Way), while in elliptical and lenticular galaxies, BH masses can be as high as several billion solar masses. Interestingly, which is the cause and which is the effect here?

A similar standpoint was discussed in [4, 87], in relation to the question as to whether intermediate-mass BHs can be present in virtually all old dwarf galaxies. According to the authors of [4, 87], this hypothesis explains all enigmatic properties of dwarf galaxies.

4. Problems with LIGO gravitational-wave sources

On February 11, 2016, the LIGO gravitational wave observatory announced the discovery of gravitational waves emitted in a coalescence of two heavy BHs (GW150914) [88].[1] The initial masses of the BHs were $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$. The mass of the resulting BH was $62^{+4}_{-4} M_\odot$. The proper angular momentum of the resultant BH (its spin) was close to the maximum possible one: $s = 0.67^{+0.05}_{-0.07}$, while the spins of the initial BHs were small (consistent with zero). The results of measurements for the GW150914 event are listed in Table I in [88].

On January 4, 2017, LIGO registered the event GW170104 with very similar properties [96]. The masses of the coalescing BHs where $31.2^{+8.4}_{-6.0} M_\odot$ and $19.4^{+5.3}_{-5.9} M_\odot$. The mass of the final BH was $M_{\text{fin}} = 48.7^{+5.7}_{-4.6} M_\odot$, and the emitted energy was $\Delta E = 2.0^{+0.6}_{-0.7} M_\odot$. The spins of the coalescing BHs were consistent with zero, whereas the spin of the final BH was high, $s = 0.64^{+0.09}_{-0.20}$.

The signal waveform in GW 150914 and GW1 170104 is in remarkable agreement with the prediction of General Relativity (GR) for the coalescence of two Schwarzschild BHs. Therefore, these results not only are the first direct detections of gravitational waves but also provide the first GR tests in the strong-field regime, where the spacetime metric is significantly different from flat, as is the case for the Schwarzschild field near the event horizon. Presently, several other, but perhaps not so bright, events have been discovered.

But the proof of GR for strong fields gave rise to new problems related to the surprising properties of coalescing

[1] See papers [89–95] in *Physics–Uspekhi* devoted to different aspects of gravitational wave detection.

BHs, which were especially pronounced in the first event GW150914. The essence of these problems, which arise in the standard astrophysical origin of BHs discovered by LIGO, is described in detail in our paper [3], which we follow here (see also [97, 98]). The following three problems of the standard theory are to be addressed.

(1) What is the origin of such heavy BHs with masses $\sim 30 M_{\odot}$?

(2) Is it possible to explain the low spins of coalescing BHs?

(3) How could a BH binary arise from a binary star system?

The classical BH formation model meets with significant difficulties in explaining these observations. Below, we answer the above questions in the early heavy BH formation model.

The problem of heavy BH formation. Black holes are usually assumed to result from stellar collapses, although there is no self-consistent theory of this process as yet. To form a heavy BH with a mass of, say, $30\,M_{\odot}$, the progenitor star must have a very big mass, $M > 100 M_{\odot}$, and low metal abundance to avoid too heavy a mass loss in the course of its evolution. These massive stars can be present in young galaxies with active star formation, but an appreciable number of such galaxies have not been discovered in the nearby Universe.

Low spins of coalescing BHs in the first (GW150914) *and third* (GW170104) LIGO events. The low spins of coalescing BHs greatly constrain the possible astrophysical formation mechanisms of such BHs in stellar collapses (see, e.g., recent paper [99]). However, the dynamical formation of a massive BH binary system in dense stellar clusters is not ruled out. The second reliable LIGO event (GW151226) does not contradict the standard astrophysical scenario.

Finally, the problem of gravitationally bound binary BHs. Binary stars are frequently observed in galaxies. They are thought to be formed in a common gravitationally bound interstellar gas cloud. If a BH emerges from a stellar collapse, as is usually assumed, a tiny collapse anisotropy results in a large recoil, high BH velocity, and possible destruction of the binary system. Indirect evidence of this process is the high velocities of Galactic pulsars, up to 1000 km s^{-1}, while the average velocities of stars do not exceed 200–300 km s^{-1}. The direct formation of BHs from Population III stars with the subsequent formation of a binary BH system ($\sim (30+30) M_{\odot}$) was considered in the literature, and was found to be unlikely.

All these problems can be solved in an elegant and economical way if the observed gravitational-wave sources are PBHs formed by the mechanism presented in Section 5. This mechanism enables easy production of a sufficient number of BHs with masses of several dozen solar masses. These BHs are born with zero velocity in the comoving frame. Therefore, the probability of their capture is not suppressed by a large relative velocity, especially after BHs lose it, for example, due to dynamical friction in the dense primordial plasma, as suggested, in particular, in [100], albeit for another physical situation. The spin of these BHs is close to zero because there are no rotational perturbations in the early Universe.

The mass spectrum of these BHs is predicted almost independently of the model. Only the fact that the formation of such BHs comes from conditions during the inflation stage is essential.

The hypothesis that the LIGO binary BHs are not ordinary products of stellar evolution but represent primordial objects from the early Universe was proposed in several papers [101–108], but only our paper [3] offers a specific dynamical formation model for these BHs [1, 2] and predicts their mass spectrum.

A model of PBH formation embodying these properties is considered in Section 5.

5. Early formation of massive and supermassive black holes and compact star-like objects

The formation mechanism of massive BHs and compact stellar-like objects used in this review was proposed in [1] and detailed in [2]. The main idea of this mechanism is a slight modification of the Affleck and Dine baryogenesis (ADB) model [109], a unique mechanism that naturally leads to a very large baryonic asymmetry up to $\beta_{\rm AD} = n_B/n_\gamma \sim 1$, whereas its observed value is many orders of magnitude smaller, $\beta_{\rm obs} = n_B/n_\gamma = 6 \times 10^{-10}$. Here, n_B and n_γ are the number densities of baryons and microwave background photons. Usually, theoreticians try to maximally increase the efficiency of the matter over antimatter domination generation mechanism, but in the ADB mechanism this efficiency has to be suppressed.

An important ingredient of the ADB model is the existence of a hypothetical complex scalar field χ with a nonzero baryon number. It is also assumed that the mass of this field m_χ is small compared to the Hubble parameter at the relevant evolutionary stage (below, we specify exactly when). In addition, the χ field potential has so-called flat directions along which the field energy does not change. All these conditions, as well as the baryon number nonconservation, are naturally realized in supersymmetric models; however, full supersymmetry is not a necessary condition.

As an example realizing this mechanism, we consider a model with the potential

$$U_\chi = m_\chi^2 \chi^2 + m_\chi^{*2} \chi^{*2} + \lambda_\chi (\chi^4 + \chi^{*4} + 2|\chi|^4) = 2|m_\chi|^2 |\chi|^2 \cos(2\theta + 2\alpha) + 2\lambda|\chi|^4 \cos(4\theta)\,, \qquad (2)$$

where $\chi = |\chi| \exp(i\theta)$, $m_\chi = |m_\chi| \exp(i\alpha)$, and $\lambda > 0$. We assume λ to be real, because its phase can be made zero by the transformation $\chi \to \exp(i\theta_0)\,\chi$ with a constant phase.

The baryon current is determined by the expression

$$J_\mu(\chi) = iB_\chi (\chi^* \partial_\mu \chi - \partial_\mu \chi^* \chi) = 2B_\chi\, \partial_\mu \theta |\chi|^2\,, \qquad (3)$$

where B_χ is the baryon number of the χ field quantum.

If $\alpha \neq 0$, the charge conjugation invariance, i.e., invariance under the particle–antiparticle mapping, is violated. If the potential U_χ is not invariant under the phase rotation $\chi \to \exp(i\theta_0)\,\chi$, the baryon number is not conserved. Thus, two of Sakharov's three conditions [110] are satisfied. As we show below, the third condition (deviation from thermodynamic equilibrium) is not necessary for the ADB mechanism.

A homogeneous field $\chi = \chi(t)$ in the Friedmann metric satisfies the equation

$$\ddot{\chi} + 3H\dot{\chi} + \frac{dU}{d\chi^*} = 0, \qquad (4)$$

where U is the χ field potential, for example, Eqn (2), and $H = \dot{a}/a$ is the Hubble parameter, where a is the cosmological scale factor. Equation (4) formally coincides with the Newtonian equation of motion for a point-like particle in the two-dimensional space ($\mathrm{Re}\,\chi$, $\mathrm{Im}\,\chi$) under the action of the force $F = -U'$ in a medium with liquid friction $\sim \dot{\chi}$. If the potential U is symmetric under rotations, the angular momentum is conserved, which in this setup coincides with the baryon number density $n_B = J_0(\chi)$, where $J_0(\chi)$ is determined by Eqn (3). This analogy enables us to easily imagine the evolution of $\chi(t)$ and the baryon number in a given potential.

At the cosmological inflationary stage, when the scale factor increases almost exponentially, $a(t) \sim \exp(Ht)$, and the potential slope is small compared to the world expansion rate, i.e., $U'' \ll H^2$, quantum fluctuations of the field χ turn out to be stronger than the classical force returning χ to mechanical equilibrium, and the mean field square increases with time, $\chi^2 = H^3 t/(2\pi)^2$ [111–113].[2] This means that the field χ with a very high probability has a large amplitude along the valley with a weakly growing (or constant if the mass of χ remains zero) potential.

When inflation ends and the Hubble parameter starts decreasing with time as $H \sim 1/t$, the quantum fluctuation effect decreases, and the field χ returns to the potential minimum in accordance with equation of motion (4). If, in rolling down, χ for some reason acquires a nonzero angular momentum, then the baryon number of χ becomes nonzero. Later on, in decays of the χ field, this accumulated baryon number leads to an asymmetry between the number of quarks and antiquarks, and the asymmetry can be very significant.

The reason for the appearance of a nonzero n_B [see Eqn (3)] can be quantum fluctuations across the valley or a difference in the directions of the quartic, $\sim \chi^4$, and quadratic, $\sim \chi^2$, valleys. At high amplitudes, the motion of χ is governed by the quartic valley and is directed down along it. With decreasing $|\chi|$, the quadratic potential becomes dominating, and the field χ transits into this valley. If the directions of the valleys are different, then, when moving from one valley into another, a motion across χ appears, i.e., $\dot{\theta}$ becomes nonzero, and therefore a nonzero baryon number density emerges.

This is the essence of the classical ADB mechanism. Full supersymmetry is not necessary for it to operate: what is needed is only the presence of a scalar field with a relatively low mass $m_\chi < H$ with a nonzero and nonconserved baryon number. The accumulated baryon number of the field χ transits into the baryon number of quarks via decays of χ, which can, however, preserve the baryon number.

We modify the ADB mechanism [1] by introducing an additional interaction of the field χ with the inflaton field Φ in the form

$$U_{\chi\Phi} = g|\chi|^2(\Phi - \Phi_1)^2 , \tag{5}$$

where g is a dimensionless coupling constant and Φ_1 is the value of the inflaton field reached during inflation. At first glance, this interaction looks rather artificial; however, this is the general form of a renormalizable interaction of two scalar fields. The only condition required is the choice of Φ_1 such that, after the inflation field Φ passes through Φ_1, inflation lasts sufficiently long for objects of an astrophysically significant size with high a baryonic density to be formed.

[2] See, however, [114], where the same result but with the opposite sign is obtained.

Interaction (5) radically changes the evolution of the field $\chi(t)$. When Φ was far from Φ_1, the effective mass of χ was high and the field was kept near the potential minimum at $\chi = 0$. However, at $\Phi \approx \Phi_1$, the gate to larger values of χ opens, and the field can run away fairly far from zero. After Φ passes through Φ_1 and the difference $|\Phi - \Phi_1|$ exceeds H, the field χ must return to zero, but in returning it acquires a significant angular momentum and hence the baryon number in accordance with the picture depicted above.

If the gate to the 'flat direction' opens for a short time, the probability of breaking forth to higher values of χ is low, and objects with high baryon density occupy an insignificant volume in the Universe, whereas another, much bulkier, part of the Universe acquires the usual baryon asymmetry $\beta \approx 6 \times 10^{-10}$ produced by a small χ field that had no time to take large values. This process has an intermediate character between the first- and second-order phase transitions. It could be called a 3/2-order phase transition. When the inflaton Φ passes through the value Φ_1, the effective mass of χ becomes large again, and the field gradually returns to zero at the potential minimum by creating a huge baryon asymmetry on its way.

At first, this process results only in inhomogeneities of the chemical composition of the primordial matter (isocurvature fluctuations), because quarks are massless in the very early Universe. However, after the QCD phase transition from free quarks to confinement, when quarks form massive nucleons, the fluctuations in the baryon number transform into energy/mass density perturbations. As a result, at a temperature of 100–200 MeV in the Universe at an age above $10^{-5} - 10^{-4}$ s, either stellar-like compact objects or PBHs should appear. Which of the objects should form depends on the ratio of the object mass and the Jeans mass. These objects can be called High Baryon Bubbles (HBBs).

The HBB mass distribution can be calculated using the Starobinsky diffusion equation [115, 116] generalized to the case of a complex field χ [1, 2]. The form of the distribution is almost model independent; it is determined by the bubbles having been formed at the inflationary stage and has the log-normal shape [1, 2]:

$$\frac{\mathrm{d}N}{\mathrm{d}M} = \mu^2 \exp\left(-\gamma \ln^2 \frac{M}{M_0}\right) , \tag{6}$$

where the parameters μ and M_0 have the dimension of mass or, equivalently, of inverse length, and the parameter γ is dimensionless.

It is known that this distribution can arise during star formation, but at a much later stage and due to quite different physics. There are no *a priori* grounds to expect that PBHs formed much earlier would have a log-normal mass distribution, unless a nontrivial dynamical model like the one in [1, 2] is proposed.

The high-mass cutoff of distribution (6) is determined by the duration of inflation after Φ passes through the value Φ_1. Following [3], the maximum HBB mass can be estimated as follows. The mass of matter inside the region with a large χ is equal, by the order of magnitude, to

$$M_{\mathrm{infl}} = \frac{4\pi}{3}\,\rho l^3 , \tag{7}$$

where l is the size of the volume with high χ and the initial size of the order of $1/H$, which, during the time after Φ crossing Φ_1 to the inflation end, inflates to $l \sim (1/H)\exp[H(t_{\mathrm{end}} - t_{\mathrm{in}})]$.

Here, H is the Hubble parameter during inflation, $t_{\rm in}$ is the instant at which the window to the flat direction opened, i.e., when the inflaton amplitude Φ approached Φ_1 from above, and $t_{\rm end}$ is the effective inflation end time.

The energy density during inflation stays approximately constant:

$$\rho = \frac{3H^2 m_{\rm pl}^2}{8\pi} = {\rm const}\,. \tag{8}$$

Hence, the maximum HBB mass toward the end of inflation at $t = t_{\rm end}$ is

$$M_{\rm infl}^{\rm max} = \frac{m_{\rm Pl}^2}{2H} \exp\left[3H(t_{\rm end} - t_{\rm in})\right]. \tag{9}$$

In the approximation of instantaneous reheating, when the Universe rapidly reaches the temperature $T_{\rm h}$, energy density (8) can be expressed in terms of $T_{\rm h}$ as

$$\rho = \frac{\pi^2}{30}\, g_* T_{\rm h}^4\,, \tag{10}$$

where $g_* \sim 100$ is the number of relativistic degrees of freedom in the primeval plasma. Taking all factors into account, we obtain an estimate of the maximum mass of a BH formed during the QCD phase transition:

$$M_{\rm infl}^{\rm max} = \left(\frac{90}{32\pi^3 g_*}\right)^{1/2} \frac{m_{\rm Pl}^3}{T_{\rm h}^2} \exp\left[3H(t_{\rm end} - t_{\rm in})\right]. \tag{11}$$

Assuming that HBBs are filled with relativistic matter after inflation, it is possible to see that their mass should decrease as $T/T_{\rm h}$, because the relativistic matter density decreases as $1/a^4$, while the HBB size increases linearly with the scale factor a, and therefore the volume of these bubbles grows as a^3. A reasonable reheating temperature is about 10^{14} GeV, and the temperature at which nonrelativistic matter starts dominating inside the HBBs is equal to the QCD phase transition temperature $T_{\rm MD} \sim 100$ MeV. The precise value is not very important because of the logarithmic dependence of the result. Therefore, the maximum HBB mass at present is

$$M_{\rm today} = \left(\frac{90}{32\pi^3 g_*}\right)^{1/2} \frac{m_{\rm Pl}^3}{T_{\rm h}^2}\, \frac{T_{\rm MD}}{T_{\rm h}} \exp\left[3H(t_{\rm end} - t_{\rm in})\right]. \tag{12}$$

This result was obtained by ignoring accretion onto PBHs, which we discuss below.

It follows that the necessary duration of inflation to form a PBH of a mass $M_{\rm BH}^{\rm max}$ is expressed as

$$\exp\left[3H(t_{\rm end} - t_{\rm in})\right] = 10^{37+5-10+15}\left(\frac{T_{\rm h}}{10^{14}\ {\rm GeV}}\right)^3 \frac{M_{\rm BH}^{\rm max}}{10^4 M_\odot}\, \frac{100\ {\rm MeV}}{T_{\rm MD}}\,. \tag{13}$$

This implies that to create a PBH with a mass $\gtrsim 10^4 M_\odot$, the condition $H(t_{\rm end} - t_{\rm in}) \gtrsim 36$ must be satisfied, if we assume all other factors in the right-hand side of (13) to be of the order of unity. We recall for comparison that the minimum duration of inflation needed to create our Universe is about $H\Delta t_{\rm infl} \sim 70$. Equation (12) can be inverted to find the maximum BH mass for a given inflation duration.

Usually, interaction potentials (2) and (5) are added to the so-called Coleman–Weinberg correction [117]

$$U = \lambda_{\rm CW} |\chi|^4 \ln \frac{|\chi|^2}{\sigma^2}\,, \tag{14}$$

which arises when summing over one-loop diagrams describing the interaction of the field χ with other fields, including its self-interaction. As a result, the total potential of χ includes three terms: those in Eqns (2), (5), and (14). The numerical calculations in our papers [1, 2] were carried out just for such a potential. The evolution of the total potential with changing $\Phi(t)$ is shown in Fig. 1. Figure 2 presents the behavior of the modulus of the amplitude χ when the second minimum of the potential appears and disappears. Figure 3 demonstrates the emergence of rotation of $\chi(t)$ when moving from one potential valley to another.

As noted above, in the subsequent decay of the χ meson into quarks with B conservation, a large baryon asymmetry emerges, but only in small-size, approximately stellar-like,

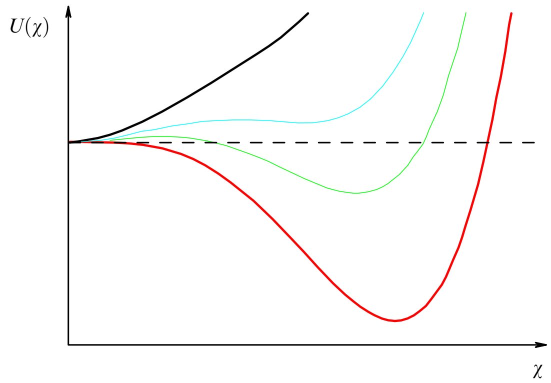

Figure 1. Potential U of the field χ for various amplitudes of the inflaton field Φ. The upper curve corresponds to the condition $\Phi \gg \Phi_1$, for which there is only one minimum at $\chi = 0$. As Φ approaches Φ_1, a second gradually deepening minimum arises. The bottom curve and the deepest minimum correspond to the equality $\Phi = \Phi_1$. With a further increase in Φ, the reverse shift of the potential curve begins by returning to one minimum at $\chi = 0$.

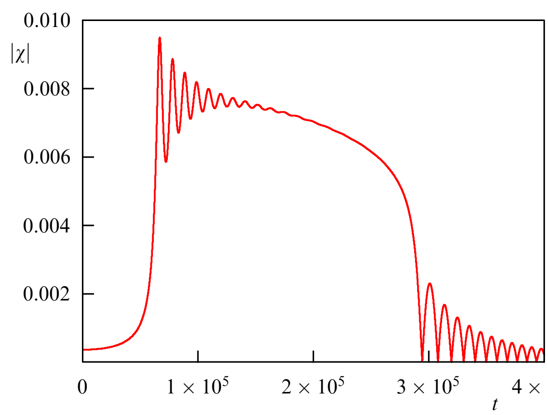

Figure 2. Amplitude $|\chi|$ in the course of potential deepening. The time t is in units of the inverse inflaton mass. At the beginning, $|\chi|$ monotonically increases following the potential minimum and then starts overtaking the minimum and oscillating such that it decays away from the minimum. As the second, deeper, minimum disappears, χ rolls down to the zero amplitude by acquiring a nonzero angular momentum in passing, as shown in Fig. 3.

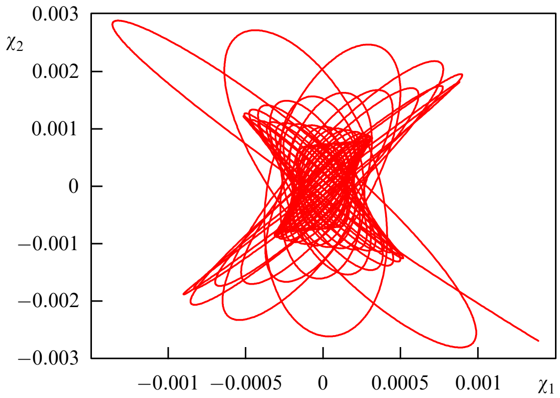

Figure 3. Evolution of the field $\chi(t) = \chi_1 + i\chi_2$ on the complex plane. It is seen that a nonzero phase of $\chi(t)$ changing with time appears, and hence, according to Eqn (3), a nonzero baryon number density of the field $\chi(t)$ arises.

objects. Interestingly, in this model, it is possible to expect the natural (although not obligatory) appearance of compact objects consisting of antimatter, comparable in number to baryonic objects, which could copiously populate our Galaxy halo. The number of antibaryons can be comparable to that of commonly observed baryons and even exceed it, but this does not contradict the existing antimatter constraints because the antimatter is then in the form of compact stellar-like objects, not to mention BHs. The constraints on the number of compact antistars in the Galaxy and possible related effects were analyzed in [118–120]. An analysis of the search for antimatter in the Universe was carried out in [121].

The mechanism considered in this section naturally explains a wealth of amazing observations obtained in the last few years as described in Section 2–4 and (for suitable parameters) predicts the presence of a sufficient number of heavy BH binaries, which are the sources of the observed gravitational waves. With such a broad mass spectrum, notably different from the one assumed earlier, all (or at least a sizeable portion of) dark matter could be formed by heavy PBHs, as proposed in our early papers [1, 2]. This hypothesis has recently been revisited and became popular again in relation to the LIGO discoveries (see Section 4 for further references).

The log-normal mass spectrum was later reproduced in [122] based on other considerations and postulated in [123] without any justifications.

6. Accretion mass growth of primordial black holes

6.1 Traditional approach

Expression (6) describes the mass distribution of PBHs immediately after their birth. Later, BH masses increase by accretion of the surrounding matter, with the accretion efficiency being dependent on both the matter equation of state and the BH mass. Therefore, the mass spectrum is deformed and its form deviates from the simple log-normal form. We follow paper [3] in the discussion below.

The first analysis of PBHs and an estimate of their accretion mass growth was carried out by Zeldovich and Novikov [124]. According to [124], BHs arise when the relative density fluctuations on the cosmological horizon scale $r_h = 2t$ reach unity, $\delta\rho/\rho \approx 1$, where ρ is the energy density of matter at the radiation-dominated stage:

$$\rho = \frac{3m_{Pl}^2}{32t^2} \,. \tag{15}$$

The mass of the region inside the radius $r = r_h$ is

$$M_h = \frac{4\pi r_h^3}{3}\,\rho = m_{Pl}^2 t \,. \tag{16}$$

Here, the gravitational radius corresponding to M_h is exactly equal to the cosmological horizon, i.e., all the fluctuations are inside the volume bounded by the gravitational radius and hence form a BH of the initial mass

$$M_0 = m_{Pl}^2\, t_0 \approx 10^5\, M_\odot t_0 \,, \tag{17}$$

where the time t_0 is expressed in seconds.

Using the nonrelativistic Bondi–Hoyle approximation, the authors of [124] showed that a BH with an initial mass M_0 formed at a time t_0 grows as

$$M = \frac{M_0}{1 - (KM_0/t_0)\,(1 - t_0/t)} \,, \tag{18}$$

where $K = 9\sqrt{3}/(2m_{Pl}^2)$. According to Eqn (18), the BH mass increases to infinity in a short time; this result clearly requires an improvement. Carr and Hawking [125] were the first to point out the shortcomings of estimates based on the Bondi–Hoyle formula. Their results were analytically confirmed in [126, 127]. The Carr–Hawking model shows that the growth rate of very massive PBHs is greatly overestimated in the Zeldovich–Novikov mechanism [128]. However, numerical simulations in [129] demonstrate a significant mass increase in relatively small BHs with $r_g \ll r_h$ in the leptonic era during a time up to 100 s.

The Zeldovich–Novikov approximation was generalized for the relativistic case in [130, 131] (see also [132]). The cosmological decrease in the accreting matter density was also taken into account. However, the cosmological expansion effect on the accretion dynamics was ignored in the early simplified calculations. That effect can be very significant for massive BHs whose radius is close to the cosmological horizon in the early Universe.

6.2 Growth of baryon bubbles

In our model, the formation and evolution of PBHs with high baryon density proceeds differently. After the QCD phase transition in the early Universe at the temperature $T = 100-200$ MeV and $t \sim 10^{-5}-10^{-4}$ s, quarks form nonrelativistic protons and neutrons. This results in the appearance of a large density contrast between bubbles filled with heavy baryons and the relativistic cosmological plasma filling almost all the remaining volume of the Universe, in which the baryon contribution is insignificant at this stage. When the bubble radius goes under the cosmological horizon, the density contrast with high probability can be large, $\delta\rho/\rho \gtrsim 1$, and this bubble turns into a BH. We note that this mechanism is significantly different from the traditional scheme discussed in the literature (see, e.g., [133] and the references therein).

The modern state of seed (parent) BH growth in the galactic centers is described in recent paper [134] for an assumed delta-like initial mass function centered at $M \gtrsim 10^4 - 10^5 M_\odot$. These BHs are assumed to have formed in dark matter halos at $z \gtrsim 15$ and then to rapidly grow due to gas accretion. If the halo mass were less than $\sim 10^{12} M_\odot$, the BH mass would barely increase, whereas in a more massive halo the BH mass would grow very rapidly. The ultimate BH mass is determined by a self-consistent relation between the dark matter halo mass and the central BH mass. In this process, the SMBH mass could grow up to $10^8 M_\odot$, after which the BH mass would grow linearly in proportion to the surrounding halo mass. It is essential that the form of the BH mass function does not change significantly at redshifts smaller than $z \sim 5$. Only the normalization changes, by about an order of magnitude, when reaching $z = 0$. These results are insensitive to the initial mass of the seed BH if $M_{\rm seed} \gtrsim 10^4 M_\odot$. The BH masses rapidly increase until the self-consistent regime sets in due to the reaction on the halo mass. The seed BH mass can reach $10^8 M_\odot$, after which its growth slows down and it increases proportionally to the halo mass.

However, if there is a population of PMBs, they could serve as natural seeds for galaxy formation. By analogy with the numerical simulation described above, we can conclude that

1) BH seed masses $\lesssim 10^5 M_\odot$ barely evolve, i.e., in the range of low masses of the observed PBHs, their mass spectrum has the original form (6);

2) BHs with initial masses $10^5 - 10^8 M_\odot$ rapidly grow to $\sim 10^8 M_\odot$ and, possibly, above this value;

3) masses of seed BHs for galaxy formation exceeding $10^8 M_\odot$ at $z \sim 0$ increase proportionally to the dark matter halo mass;

4) the rapid growth of supermassive PBHs is completed by $z \approx 5$, after which their mass function (for $M > 10^6$) linearly increases to the present-day values.

According to items 2 and 3, the initial form of the PBH mass function is of minor importance for large masses, $\gtrsim 10^5 M_\odot$, because BHs with these masses have time to rapidly grow until the self-consistent regime sets in the surrounding dark matter halo. Therefore, by fitting the normalization of the mass spectrum in the mass range $(10-100)\, M_\odot$ to the merger rate of binary BHs, as inferred from the LIGO observations (9–240 events per year per Gpc^3), we should only take care that the mass density of primordial SMBHs be consistent with the SMBH mass function inferred from galaxy observations, $\mathrm{d}N/(\mathrm{d}\log M \mathrm{d}V) \simeq 10^{-2}$–$10^{-3}$ Mpc^{-3}.

By adjusting the parameters μ, γ, and M_0 in formula (6), we can satisfy all the existing constraints [135], understand the origin and properties of coalescing BHs, and explain other exotic discoveries described above. According to our estimates (see below), the choice of the mass distribution parameters $\mu = (2-3) \times 10^{-43}$ Mpc^{-1}, $\gamma = 0.4-1.0$, and $M_0 = M_\odot(\gamma + 0.1\gamma^2 - 0.2\gamma^3)$ allows satisfying the conditions formulated above, creating a sufficient number of BHs to seed galaxy formation, and, additionally, describing all (or a significant fraction of) dark matter by PBHs generated by the mechanism described in Section 6.1. Constraints on the BH density as a function of the BH mass are presented in Fig. 4. We note that the constraints shown on a similar plot in [136] as inferred from the analysis of early accretion onto PBHs and are highly model-dependent, and should therefore be treated with caution.

Constraints on the BH abundance inferred in recent papers [137, 138] from the microwave background observations do not rule out populating the Universe by PBHs with the chosen parameters. It is asserted in [137] that BHs with masses $\gtrsim 10^2 M_\odot$ cannot be the major dark matter component. A stronger statement in [138] is that PBHs with masses $\gtrsim 5 M_\odot$ can hardly exist in a significant amount. However, as those authors note themselves, this constraint is based on the poorly known accretion processes onto BHs.

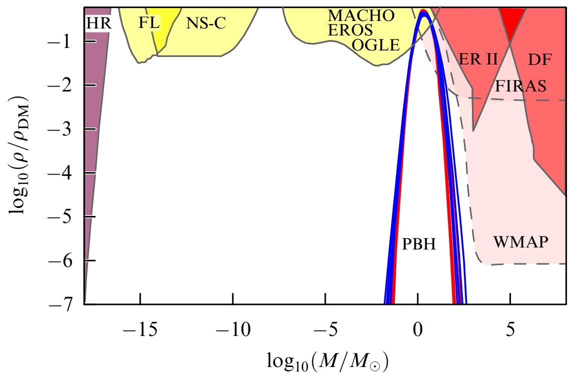

Figure 4. (Color online.) Bounds on the fraction of PBHs in the dark matter density, $f = \rho_{\rm PBH}/\rho_{\rm DM}$, where the PBH density is $\rho_{\rm PBH}(M) = M^2\, \mathrm{d}N/\mathrm{d}M$. The constraints were obtained from the following data: extragalactic gamma-ray background from evaporating BHs (HR); the femtolensing of gamma-ray bursts (F); PBH capture by neutron stars (NC-C); microlensing observations by MACHO, EROS, and OGLE; the survival of several star clusters in the ultra-faint galaxy Eridanus II (ER II); the dynamical friction (DF) of objects in the galactic halo; and accretion effects on the CMB as derived from WMAP (Wilkinson Microwave Anisotropy Probe) and FIRAS (Far-InfraRed Absolute Spectrophotometer) observations. The predicted PBH mass distribution is shown for $\mu = 10^{-43}$ Mpc^{-1} and $M_0 = \gamma + 0.1\gamma^2 - 0.2\gamma^3$ with $\gamma = 0.75 - 1.1$ (red solid line) and $\gamma = 0.6 - 0.9$ (blue solid line).

A new constraint on the dark matter fraction consisting of BHs was recently presented in [135] based on X-ray data. However, the conclusion of the authors is based on not very reliable assumptions about the velocity dispersion of PBHs, which in fact could be weaker than the authors argue.

We resume the discussion of the parameters M_0 and γ of the universal mass distribution (6) of PBHs and compact stellar-like objects that appeared from high baryon density bubbles. We call them the Affleck–Dine primordial black holes (ADPBHs). In the natural system of units with $\hbar = c = 1$, the solar mass is $M_\odot \approx 1.75 \times 10^{95}$ Mpc^{-1} and the normalization constant is $\mu = 10^{-43}$ Mpc^{-1}. With this μ, setting $\gamma = 0.5$ and $M_0 = M_\odot$, we conclude that the total mass density of such objects is several times smaller than the total (baryonic and dark) cosmological matter density, $\rho_{\rm m} \approx 4 \times 10^{10} M_\odot$ Mpc^{-3}. For convenience, we introduce dimensionless variables $x = M/M_\odot$ and $y = M_0/M_\odot$. As shown in [3], the condition that the fraction of the cosmological density of PBHs and compact stellar-like objects in the mass range $(0.1-1)\, M_\odot$ is $f = \rho_{\rm BH}/\rho_{\rm m} = 0.1$ for γ in the range $0.4-1.6$ leads to the relation

$$y \approx \gamma + 0.1\gamma^2 - 0.2\gamma^3 \,. \tag{19}$$

For such PBH parameters, the fraction of ADPBHs in the logarithmic mass range from M_1 to M_2 is

$$r = \frac{x_1}{x_2} \exp\left\{\gamma\left[\ln\left(\frac{x_2}{y}\right)^2 - \ln\left(\frac{x_1}{y}\right)^2\right]\right\} = \left(\frac{x_2}{x_1}\right)^{-1+\gamma\,\ln(x_1 x_2/y^2)} . \tag{20}$$

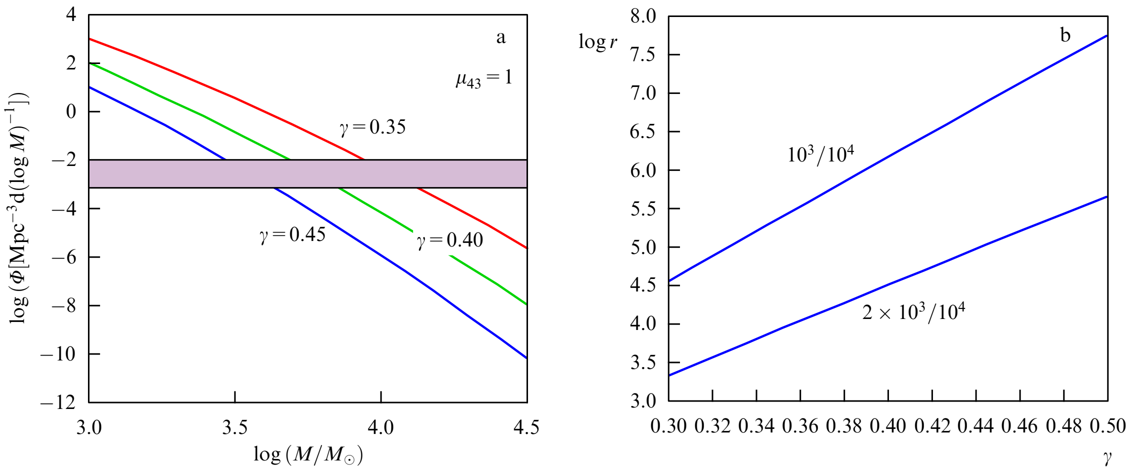

Figure 5. (Color online.) (a) Spatial density of ADPBHs per cubic Mpc per logarithmic mass interval d log M as a function of the parameter γ; the purple rectangle shows the observed interval of masses and the number density of SMBHs in large galaxies. (b) The ratio of the ADPBH number density per logarithmic mass interval for masses near $10^3 M_\odot$ and $2 \times 10^3 M_\odot$ to that for masses $M > 10^4 M_\odot$ as a function of γ.

We consider so-called intermediate BHs with masses $M \approx 2 \times 10^3 M_\odot$, which are likely to reside in globular cluster centers. In accordance with the arguments given below, we assume that all ADPBHs with $M > 10^4 M_\odot$ have become seeds for SMBHs in galactic centers, which have by now grown to several billion solar masses. In this case, $x_2 = 10^4 > x_1 = 2 \times 10^3 \gg 1$, whence

$$r \approx \left(\frac{x_1 x_2}{y^2}\right)^{\gamma \ln (x_2/x_1)}, \tag{21}$$

or

$$\log r \approx \gamma \log \mathrm{e} \log \frac{x_2}{x_1} \log \frac{x_1 x_2}{y^2}. \tag{22}$$

If $\gamma < 1$, Eqn (20) implies that $y \approx \gamma$. Therefore, for example, to obtain $r = 10^5$, the value $\gamma \approx 0.4$ is required, which seems quite reasonable, as can be seen from Fig. 5a. The value $\log r$ as a function of γ determined by formula (20) is presented in Fig. 5b. We see that for $\gamma \sim 0.35-0.45$, there is about one ADPBH with the mass $(2-3) \times 10^3 M_\odot$ per 10^4-10^5 ADPBHs with masses $> 10^4 M_\odot$. If all ADPBHs with the initial mass exceeding $10^4 M_\odot$ in the course of the evolution of the Universe turned into SMBHs in galactic centers, their number density would be $10^{-2}-10^{-3}$ per cubic Mpc, as shown by the purple rectangle in Fig. 5a. In this case, the number density of the intermediate-mass BHs mentioned above would fall in the range $\sim 10^2-10^3$ per cubic Mpc. This ADBPH number density is sufficient for them to serve as seeds of globular clusters in galaxies [4] (see Section 7).

7. Globular clusters

Primordial black holes with a mass of about $2000\, M_\odot$ can play an important role in the formation and evolution of globular star clusters, as noted in our paper [4], which we closely follow here.

According to the model discussed in Section 5, the number density of intermediate-mass PBHs, $M \sim 2000\, M_\odot$, can be 10^5-10^6 per SMBH. This means that in each galaxy there can be about 10^5-10^6 such intermediate-mass BHs. This prediction can have a bearing on globular clusters (GCs), which for a long time have been thought to be the oldest stellar systems in the Universe [140]. Presently, it is recognized that GCs do not have extended dark matter halos [141]. Globular cluster formation and evolution were considered in recent papers [142, 143] (see also the references therein).

The modern number density of intermediate-mass BHs is about 10^2-10^3 Mpc^{-3}. Therefore, in the epoch of the first star formation at $z \sim 15$, it was $n_{\mathrm{IMBH}} \sim 10^6-10^7$ Mpc^{-3}. Taking into account that the Jeans wavelength at $z \sim 15$ was $\lambda_{\mathrm{J}} \sim 3$ kpc, we find that there were about $N_{\mathrm{J}} \sim 10^7$ Jeans volumes in one cubic Mpc at that time. The closeness of this number to the space density of PBHs with a mass $\sim (2-3) \times 10^3 M_\odot$ suggests that such BHs could be the seeds for the first GCs. In this scenario, each GC should contain a central intermediate-mass BH. According to [144], an $M = 2200 M_\odot$ BH can indeed reside in the center of a GC. Recently, data appeared in [145] suggesting the presence of a putative BH with a mass of several tens of thousand solar masses in another GC.

The formation of BHs of several thousand solar masses by the canonical mechanism is also possible. They could result from Population III stars [146] in stellar collisions in young stellar clusters [147]. A brief review of the possible formation channels of intermediate-mass BHs can be found in [148].

The presence of intermediate-mass BHs in GC centers should greatly affect the GC evolution [149]. We note in this connection that the universal relation between the central BH mass and the galactic bulge mass [150] can also be applied to the central BHs in GCs with an account for the GC mass decreasing in the course of evolution [151]. However, as we have seen in Section 3.2, this relation for galaxies is frequently violated for PBHs formed in the early Universe.

In addition to GCs with intermediate-mass BHs, dark stellar clusters with a high mass-to-luminosity ratio have recently been discovered. They are also thought to contain a central intermediate-mass BH [152, 153]. These stellar clusters can be the remnants of dwarf spheroids with a mass intermediate between that of GCs and large galaxies.

Intermediate-mass BHs of several thousand solar masses are an interesting alternative (or addition) to the standard theory of early hierarchical structure formation [154]. In our scenario, all BHs with masses above $\sim 10^4 M_\odot$ were turned into the SMBHs presently observed in galactic centers, while lighter BHs became centers of GCs and were possibly seeds for their formation [4]. In this connection, it would be interesting to study the formation of GCs at high redshifts $z \sim 5$ [155]. According to the authors of [155], "The formation of globular clusters... remains a puzzling, unsolved problem in astrophysics."

If intermediate-mass BHs indeed seeded GCs, each GC should contain such a BH, which can be tested in future astronomical observations. If these BHs are primordial, GC progenitors should be found already at high redshifts z. To date, the presence or absence of intermediate BHs in GCs remains an open issue [156].

8. Effect of primordial black holes on Big Bang nucleosynthesis and cosmic microwave background

Data on the cosmic abundance of the light elements deuterium, helium-3, helium-4, and, to some extent, lithium-7, beryllium, and boron created in the early Universe agree with the theory of primordial nucleosynthesis with a very small baryon-to-CMB-photon density ratio $\beta_{\text{obs}} = n_B/n_\gamma \approx 6 \times 10^{-10}$. A similar value of β is inferred from the analysis of angular CMB fluctuations. This value is much smaller than the values of β in the high-baryon-density compact objects discussed here.

A natural question arises as to whether the existence of high-β regions contradicts observations of light element abundance. Clearly, those high-β bubbles that collapsed into BHs are not dangerous from this standpoint; however, 'not all are so lucky', and in the sky there should be gas clouds or stellar-like objects with anomalous chemical abundance. The yield of light elements in the primordial nucleosynthesis with $\beta \gg \beta_{\text{obs}}$ was calculated in [51–54], but only for $\beta \ll 1$ due to numerical difficulties. Nevertheless, it is evident that in regions with $\beta \gtrsim 1$, primordial nucleosynthesis does not terminate at lithium-7 and proceeds until much heavier elements are created. However, the discovery of such regions has a low probability because they occupy a minor volume in the Universe. In this connection, the search for stars or clouds overabundant with heavy elements seems to be very interesting. In particular, a star older than the Universe (see Section 3.1) could be such an object created in the early Universe from a high-baryon-density 'bubble', which appears to be older due to the anomalous chemical composition.

As noted above, the discussed mechanism of high-β object formation, although not obligatory, leads to a noticeable amount of antimatter. In this case, stars consisting of antimatter could exist even in our Galaxy. Estimates in [118–120] show that the annihilation of galactic gas on the surface of antistars gives rise to gamma-radiation that can be registered if the emitting object is known. Suspicious from this standpoint are stars with an anomalous chemical composition, which could be an indication that they consist of antimatter.

As we noted above, the baryon-to-photon ratio can be calculated from the analysis of CMB angular fluctuations, which yields a result consistent with the value inferred from observations of light element abundances. The reason for this coincidence is that the fluctuation spectrum shape is sensitive to the number of baryons only on very large scales exceeding ~ 10 Mpc, while our high-β bubbles have a much smaller characteristic size and do not affect the form of the CMB angular fluctuation spectrum. Their role in spectrum formation is the same as the role of dark matter and does not show up on small scales.

9. Electromagnetic radiation from gravitational waves

In addition to the facts discussed in Sections 1–8 that poorly (if at all) fit the canonical formation theory of galaxies and SMBHs, there can be other, as yet not discovered phenomena related to BHs with masses ranging from fractions of $M_\odot$ to several billion $M_\odot$. This is quite interesting because such PBHs apparently could be much more abundant in the Universe than thought before.

It is now very important to understand whether the gravitational burst during BH coalescence can be accompanied by electromagnetic radiation. If a tiny fraction of the powerful gravitational wave pulse can be transformed into photons, the effect can be very significant. In this respect, studying the mechanisms of this radiation, in particular, the conversion of gravitons into photons in an external magnetic field, is of interest [157–162]. Modern calculations of this effect are carried out in Refs [163, 164]. However, in all papers except [165], the conversion of gravitons into photons has been considered at rather high frequencies exceeding the plasma frequency of the surrounding medium. The last condition seems to be obligatory because, as is well known, photons with frequencies below the plasma frequency cannot propagate. However, this is not fully the case. A gravitational wave propagating in any medium with a magnetic field constantly converts some energy into plasma waves [166], which can significantly heat the plasma, which in turn can generate a powerful electromagnetic (radio?) pulse.

The conversion of a plane ($\sim \exp(-\mathrm{i}\omega t + \mathrm{i}\mathbf{kx})$) gravitational wave into an electromagnetic wave in an external magnetic field is described by the equations (see, e.g., [163])

$$(\omega^2 - k^2)\, h_j(\mathbf{k}) = \kappa k A_j(\mathbf{k})\, B_{\text{t}}\,, \tag{23}$$

$$(\omega^2 - k^2 - m^2)\, A_j(\mathbf{k}) = \kappa k h_j(\mathbf{k})\, B_{\text{t}}\,, \tag{24}$$

where B_{t} is the external magnetic field component transverse to the graviton or photon propagation direction (B_{t} is assumed to be virtually homogeneous). The spatial index j determines the polarization state of the graviton or photon, and h_j is the canonically normalized gravitational wave field, such that the kinetic term in the Lagrangian has the form $(\partial_\mu h_j)^2$. In other words, h_j is related to the metric $g_{\mu\nu} = \eta_{\mu\nu} + \tilde{h}_{\mu\nu}$ by a dimensional factor,

$$h_j = \frac{\tilde{h}_j}{\kappa}\,, \tag{25}$$

with $\kappa^2 = 16\pi/m_{\text{Pl}}^2$.

The last term in the left-hand side of (24) is the effective mass of a photon in the medium, which includes the plasma frequency and the Heisenberg–Euler correction due to interaction with the external field:

$$m^2 = \Omega^2 - \frac{2\alpha C\omega^2}{45\pi}\left(\frac{B}{B_{\text{c}}}\right)^2 \approx \Omega^2\,, \tag{26}$$

where C is a numerical constant of the order of unity, depending on the relative direction of the magnetic field and wave polarization, $B_c = m_e^2/e$, $e^2 = 4\pi\alpha = 4\pi/137$, and

$$\Omega^2 = \frac{n_e e^2}{m_e} \tag{27}$$

is the plasma frequency, where n_e is the electron number density. The contribution of ions is ignored here.

The frequency of gravitational waves detected by LIGO is small compared to the plasma frequency in the interstellar medium; therefore, we disregard the second term in (26). However, for high frequencies and external magnetic fields, resonant graviton-to-photon conversion is possible, which significantly enhances the probability of the transformation.

The eigenvalues k for system (23), (24) are

$$k_1 = \pm\omega\sqrt{1+\zeta^2}\,, \quad k_2 = \pm i m\sqrt{(1-\zeta^2)(1-\eta^2)}\,, \tag{28}$$

where

$$\zeta^2 = \frac{(\kappa B)^2}{m^2} \ll 1\,, \quad \eta^2 = \frac{\omega^2}{m^2}\,. \tag{29}$$

Correspondingly,

$$A_1 = \eta\,\zeta h_1\,, \quad h_2 = i\zeta A_2\,. \tag{30}$$

The first solution describes a graviton entering into a magnetic field and generating some photons, and the second solution, conversely, describes a photon generating some gravitons in a magnetic field. In the second case, k_2 is purely imaginary, corresponding to the decay of an electromagnetic field in plasma when the frequency is below the plasma. In the first case, k_1 is real, and the electromagnetic wave does not decay and is 'happy' to run together with the gravitational wave, despite the low frequency. The gravitational wave 'pulls' the electromagnetic wave by preventing it from decaying.

The interaction with the medium is described by introducing the dielectric permeability, which describes the relation between the wave frequency and its wave vector: $k^2 = \epsilon\omega^2$. For the first solution, $k \approx \omega$ plus small corrections of the order of ζ^2. However, this is not all, because it is also necessary to take the imaginary part of ϵ into account, which appears due to the interaction of the electric field of photons with electrons in the plasma. This imaginary part leads to the energy transformation from the electromagnetic wave into plasma. For a transverse wave, the imaginary part is calculated, for example, in textbook [167, p. 165]:

$$\mathrm{Im}\,\epsilon = \sqrt{\frac{\pi}{2}}\,\frac{\Omega}{\omega k a_e} \approx \sqrt{\frac{\pi}{2}}\,\frac{\Omega}{\omega^2 a_e}\,, \tag{31}$$

where $a_e = \sqrt{T_e/(4\pi e^2 n_e)}$ is the Debye length for electrons and T_e is the electron temperature. In the last equality, we have used Eqn (28), $k = k_2 = \omega$.

In a collisionless plasma, this absorbed energy can be transferred from the wave to the plasma and back. However, accounting for collisions leads to part of the gravitational wave energy being converted into photons that heat the plasma, and if the heating turns out to be significant, the additional electromagnetic radiation from the heated plasma can be detected.

In the interstellar medium with $n_e = 0.1$ cm^{-3} and a temperature of 1 eV, the Debye length is $a_e \approx 10^3$ cm = 3×10^{-8} s, and the plasma frequency is $\Omega \sim 3\times10^4$ s^{-1}, whereas the frequency of the first LIGO event was $\omega \approx 2000$ s^{-1}. Hence, $\Omega a_e \approx 10^{-3}$, and the value $\omega^2 \mathrm{Im}\,\epsilon \sim \Omega/a_e$ significantly exceeds Ω^2, and therefore the amplitude of the electromagnetic wave dragged by the gravitational wave is

$$A_j \approx \frac{\omega a_e \kappa B}{\Omega}\,h_j\,. \tag{32}$$

The frequency of these photons is about 10^3 Hz, which is much smaller than the temperature of the interstellar or intergalactic plasma and even smaller than the CMB temperature. Therefore, although quite a large amount of energy can be injected into plasma, plasma heating due to this additional energy is not effective. However, this is not wholly true because electrons are accelerated by the electric field of the wave and thus acquire a high energy. Indeed, electrons in the electric field E of an electromagnetic wave are accelerated in accordance with

$$m_e \ddot{x}_e = eE = eE_0 \cos(\omega t) \tag{33}$$

and acquire the velocity

$$V_e \sim \frac{\ddot{x}_e}{\omega} \sim \frac{eE_0}{m_e\omega}\,, \tag{34}$$

where ω is equal, by an order of magnitude, to the frequency of the incident gravitational wave. Therefore, the acquitted kinetic energy of electrons is

$$\mathcal{E}_e = \frac{m_e V_e^2}{2} \sim \frac{e^2 E_0^2}{m_e \omega^2}\,. \tag{35}$$

The electric field amplitude can be calculated if the ratio of energy fluxes of the electromagnetic and gravitational waves is known:

$$E_0^2 = 8\pi Q \rho_{GW} = \frac{8\pi Q E_{GW}^{tot}}{4\pi R^2 \Delta t}\,, \tag{36}$$

where E_{GW}^{tot} is the total energy emitted in the form of gravitational waves during the binary BH coalescence, $Q = \rho_\gamma/\rho_{GW} = (\omega a_e \kappa/\Omega)^2$, R is the distance from the BH source to the cosmic plasma cloud in which the transformation of the gravitational to electromagnetic wave occurs, and $\Delta t \sim 1/\omega$ is the duration of the gravitational wave pulse. For the first LIGO event, $E_{GW}^{tot} \approx 3M_\odot$.

Using these formulas, we can estimate the electric field of the wave. For example, for $\omega = 2000$ s^{-1}, $\Omega = 2\times10^4$ s^{-1}, $a_e = 100$ cm, we obtain

$$\mathcal{E}_e = 4\times10^{-22}\left(\frac{B}{1\,\mathrm{G}}\right)^2\left(\frac{1\ \mathrm{yr}}{R}\right)^2\ [\mathrm{eV}]\,. \tag{37}$$

For the distance $R = r_g = 10^7$ cm (i.e., for the gravitational radius of a 30 $M_\odot$ BH), we find the energy of electrons to be $\mathcal{E}_e = 4B^2$ [eV] (here, B is expressed in gauss), which means that the electrons are already relativistic for moderate magnetic fields $B = 10^3$ G. Moreover, electron–positron pairs can be created in a relativistic plasma. Their presence significantly changes the plasma frequency and Debye radius estimates, but the qualitative picture should be the same.

The idea to identify the energy injected into cosmic plasma by a gravitational wave and re-emitted in the radio band as fast radio bursts (FRBs) appears to be very interesting. These bursts have a huge power and appear in the sky at a rate of several thousand events per day. To make this possible, the presence of a very strongly magnetized plasma near coalescing BHs is needed. This seems rather improbable, but if the binary BH itself generates a strong magnetic field, the probability becomes of the order of unity. A strong and even superstrong magnetic field could be generated due to entraining surrounding protons and electrons into circular motion by the BH binary. If the interaction with the medium is ignored, nonrelativistic electrons and protons would be equally entrained into motion by the gravitational field, which would lead to a difference between their angular velocities and that of photons. Just as plasma photons markedly interact with electrons by dragging them, a difference between angular velocities of electrons and protons emerges, leading to the appearance of currents and magnetic field generation. These fields could be as high as $10^{14}-10^{15}$ G.

This mechanism is known as the Biermann battery effect [168]. A similar idea was used to explain the generation of the large-scale galactic magnetic field in [169, 170]. It was shown in these papers that for a sufficiently strong field to appear, the energy density of the radiation 'bath' should be very high, at the limit or even higher than the observed values. Difficulties with this and other mechanisms of magnetic field generation around binary BHs are discussed in [166], which we have closely followed here.

Perhaps the above estimate is too optimistic. In addition, in this mechanism, it is unclear how to explain repetitive FRBs unless a cluster of magnetars is present near the BH coalescence site or there are many coalescing BHs in one site at one time, which is even more unrealistic.

Independently of the application of this mechanism to FRBs, it seems interesting to understand whether such a transformation of gravitational waves into electromagnetic ones could have caused planetary catastrophes on Earth in the past and whether it is possible in the future.

Recently, electromagnetic radiation was detected from a gravitational wave source associated with the coalescence of two compact objects of $1.5\,M_{\odot}$ each [151], presumably neutron stars. We note that such radiation was predicted long before this discovery in [172]. Also, we note that the mechanism of gravitational wave production from nonspherical collapses in the Universe was studied in [173].

10. Conclusion

Recent astronomical observations compellingly suggest the possibility that the Universe is densely populated by BHs with masses ranging from a fraction of the solar mass to several billion $M_{\odot}$. The evidence comes from ever-increasing observations of the early Universe at redshifts of the order of 10. Already in the process of writing this review, it was necessary to take new publications of recent months into account.[3] The young Universe turns out to be much more densely populated than thought quite recently. Especially impressive is the existence of SMBHs with masses up to 10 bln $M_{\odot}$ and ages less than 0.5 bln years. Their formation mechanism in the Standard Model is uncertain. The presence of young luminous galaxies, supernovae, gamma-ray bursts, and heavy dustiness of the early Universe only aggravates the problem.

In the modern Universe, we also encounter many similar problems. It is not easy to create SMBHs in the nuclei of large galaxies by accretion of the surrounding medium even over the entire lifetime of the Universe, i.e., 14 bln years, although this is perhaps easier to do than in 0.5 bln years. But on the other hand, SMBHs are observed inside some pauper galaxies and even in almost empty space. Moreover, in the Universe (in fact, in our close vicinity), there are many invisible solar-mass objects. Nobody understands how they have appeared or what they are. Another puzzle is the mass distribution of BHs observed in our Galaxy. Their spectrum cuts off at about 7–8 $M_{\odot}$, at variance with the standard hypothesis of BH formation in stellar collapses.

These and other phenomena discussed in this review cannot be easily (if at all) explained in the framework of standard cosmology/astrophysics, but they are in perfect agreement with the hypothesis of the primordial creation of massive BHs in the very early Universe. Their possible formation model, first proposed in 1993 and presented in this review, by adjusting only three free parameters of the log-normal mass spectrum, describes the observed picture very well and predicts some new phenomena. In particular, our hypothesis explains the unusual properties of the LIGO BHs, describes the observed evolution of GCs and dwarf galaxies, and predicts the detection rate and frequencies of gravitational waves by the present and future detectors. The broad mass spectrum of PBHs predicted in [1] offers an intriguing possibility that all dark matter in the Universe consists of massive BHs. In the last couple of years, this possibility was rediscovered and has become quite popular. (See [174] for a review of dark matter in galaxies and its properties.)

The proposed theory definitely favors the reversed formation of small and large galaxies, in which first a heavy seed is formed and then a galaxy is assembled around it. The recent discovery of a galaxy free of dark matter can evidence the correctness of this mechanism. That galaxy would be difficult to form without a seed. Meanwhile, in the usual scenario, first the galaxy is formed and then the SMBH grows in its center by accretion of matter.

In addition to the statement that a significant fraction (or even all) of dark matter could consist of PBHs with masses of a few solar masses [1, 2], a prominent, possible, but not obligatory prediction of the model is an abundant number of compact objects made of antimatter in our very vicinity in the Galaxy.

Possibly, a conservative explanation of these puzzling discoveries will be found, but diverse mechanisms will most likely be invoked to solve different problems, whereas the PBH concept allows solving all these problems in a unique and economical way.

Many PBH formation models have been discussed in the literature (see, e.g., the recent review [135]). For completeness, we also refer to the relevant papers [175–190], in addition to those mentioned in Section 6.1. The predictions of these models are not identical, and there are hopes that in the not so remote future we can understand exactly which mechanism is realized in the Universe.

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[3] In particular, when this review was in press, the discovery of a new quasar with a record high redshift was reported in [192]. It is remarkable that the matter surrounding this quasar is neutral. This excludes the accretion mechanism of central BH formation, i.e., the BH should be primordial. (Note added in proof.)

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