Primordial Black Holes Around Us Now, Long Before, and Far Away

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Abstract. Recent astronomical data on Black hole observations are reviewed. The arguments in favor that the observed black holes are predominantly primordial (PBH) are presented. The mass spectrum of PBH is best fit to the log-normal one. A model of PBH formation with log-normal spectrum is briefly described.

1. Introduction
Astronomical observations of the last decade present very strong evidence that the universe is filled with unexpectedly high amount of different kinds of black holes. Moreover these black holes are seen not only in the contemporary, almost 15 billion year old universe, but also in the quite young one which was only 500 million year old.

The black holes are observed in all imaginable mass ranges: supermassive black holes (SMBH), \( M = (10^{10} - 10^6)M_\odot \), intermediate mass black holes (IMBH), \( M = (10^2 - 10^5)M_\odot \), black holes with masses of tens solar masses \( M \sim 10M_\odot \), and maybe black holes (BHs) even with a fraction of the solar mass.

These BHs live just next door in our Galaxy and in not so distant galaxies, as well as rather far-away but still in the present day universe, and, what was a striking surprise, they were already formed during the first hundred million years after big bang, which is by far too short time according to the conventional scenario of their creation.

The observed black holes may make all or a weighty fraction of the cosmological dark matter, have seed galaxy formation, and create binaries emitting gravitational waves observed at LIGO/Virgo interferometers.

Most probably all, or almost all, those BHs are primordial (PBH). In this case the tension with the conventional cosmology and astrophysics, created by their high abundance, smoothly disappears. These problems are reviewed in two-year old paper [1], but a lot of new data since that time are accumulated indicating the same direction towards PBH.

Recently a torrent of new abundant BHs, has been observed presumably primordial. In any single case an alternative interpretation might be possible but the overall picture is very much in favor of massive \textit{primordial black holes}.

2. Black holes by the formation mechanisms
Three types of BH: astrophysical, accreting, primordial

\textit{I. Astrophysical BHs}: created by stellar collapse after star exhausted its nuclear fuel. Expected
masses are just above the neutron star masses, \( \sim 3M_\odot \), and naively expected they should quite close to this value. Instead, the mass spectrum of BH in the Galaxy has maximum at \( M \approx 8M_\odot \) with the width: \( \sim (1 - 2)M_\odot \). For the discussion of this problem and the list of references see e.g. [1]. Bearing in mind that there are strong arguments that the sources of the LIGO/Virgo observed gravitational waves are binaries of RBHs (see below sec. 4), it is natural to accept that the black holes observed in the Galaxy are (mostly) primordial as well.

II. BH created by matter accretion to excessive density regions.

There is a supermassive BH (SMBH) in any large galaxy with \( M \geq 10^9M_\odot \) in elliptic and lenticular galaxies and \( M \sim (10^6 - 10^7)M_\odot \) in elliptic galaxies, as Milky Way. However, the known mechanisms of accretion are not efficient enough to create such monsters during the universe age \( t_U \approx 15 \text{ Gyr} \). Very massive seeds are necessary, but their origin is mysterious. Moreover SMBH are found in very small galaxies and one SMBH lives even in almost empty space.

SMBH are also observed recently with surprisingly large amount in quite young universe with the age about (1 - 0.5) Gyr. Probably SMBH are primordial or created by the accretion to supermassive primordial seeds, see the next point.

III. Primordial black holes (PBH) created in the very early universe during pre-stellar epoch.

The idea of the primordial black hole (PBH) i.e. of black holes which could be formed the early universe prior to star formation was pioneered by Zeldovich and Novikov [2]. According to their idea, the density contrast in the early universe inside the piece of volume with the radius equal to the cosmological horizon might accidentally happen to be large, \( \delta \rho/\rho \approx 1 \), then that piece of volume would be inside its gravitational radius i.e. it became a PBH, which decoupled from the cosmological expansion.

The mechanism was elaborated and developed later by Hawking [3] and by Carr and Hawking [4].

3. Modified mechanism of PBH formation

An essentially different mechanism for creation of primordial black holes was suggested in our work of 1993 [5], see also an extension and more detail in ref. [6]. The mechanism is based on the popular Affleck-Dine (AD) scenario of baryogenesis [7] realized at inflationary epoch and immediately after. The AD baryogenesis is stimulated by supersymmetry (SUSY) at high energy scale. In such a theory must exist a scalar field with non-zero baryonic number, we call it \( \chi \). The potential of \( \chi \) possesses the so called flat directions, along which the potential does not rise but remains constant. Due to quantum fluctuations during inflation field \( \chi \) may “travel” far along one or other flat direction and acquire a large amplitude.

After inflation was over and SUSY broke, so that \( \chi \)-field acquired non-zero mass, the flat directions became curved, and \( \chi \) started to roll down towards the origin, \( \chi = 0 \). On the way down field \( \chi \) gained huge baryonic number, which finally led to even large baryon asymmetry of the universe which may be even of order unity, much larger than the observed one \( \beta = 6 \cdot 10^{-10} \). So theorists have to invent some clever ways to suppress the asymmetry down to the proper value.

The new PBH creation mechanism could be realized if \( \beta \) reached large values only in cosmologically small but possibly astronomically large bubbles, while in the bulk of the universe it has normal value. \( \beta \approx 6 \cdot 10^{-10} \). This may be achieved by introduction of the general renormalizable coupling of the AD baryonic scalar field with inflaton, see below eq. (10).

The fundament of PBH creation is set on at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations. The huge perturbations in baryonic number transformed later into density perturbations at the QCD phase transition when massless quarks turned into heavy baryons.
The emerging universe looks like a piece of Swiss cheese, where holes are high baryonic density bubbles (HBB) occupying a minor fraction of the universe volume. Inflationary prehistory allows for creation of huge PBH with masses up to \((10^4 - 10^5)M_\odot\), or even higher depending on the model. The mass spectrum of the created PBHs has very simple log-normal form with only 3 constant parameters: \(\mu, \gamma, M_0\):

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

The values of \(\gamma\) and \(\mu\) depend upon unknown high energy physics at the AD baryogenesis, but the central mass, \(M_0\), is equal to the known mass inside horizon at the QCD phase transition [8].

The mass inside horizon at RD stage, \(r_{\text{hor}} = 2t\) is

\[
M_{\text{hor}} = m^2_{\text{Pl}}t.
\]

If \(\delta \rho/\rho = \kappa\), then \(M_{BH} = \kappa M_{\text{hor}}\) and the gravitational radius is

\[
r_{g} = \frac{2M}{m^2_{\text{Pl}}} = 2\kappa r_{\text{hor}}.
\]

For PBHs formed at the QCD phase transition at \(T \sim 100\) MeV, and the universe age equal to \(t = 4 \cdot 10^{-5} (100\text{ MeV}/T)^2\) sec we find

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

According to lattice calculations \(T_{QCD} = 100 - 150\) MeV but if quark chemical potential is large, \(T_{QCD}\) may be smaller and \(M_0\) be bigger.

So the central mass of PBH log-normal mass spectrum is predicted to be close to \(10M_\odot\) [8]. As we see in what follows, this result is in good agreement with observations, see figures 1 and 2 below.

Such form of the mass spectrum and similar ones, the so called extended spectra, became quite popular nowadays. The suggested scenario of PBH formation [5] pioneered in implementation of inflation to PBH formation. It allows for PBH huge masses, much larger than horizon mass in the very early universe. To the present time a long list of works on inflationary formation of PBH came to life.

Let us describe a toy model which has the desired properties. The quartic potential of \(\chi\) with flat directions can be presented as:

\[
U_\lambda(\chi) = \lambda |\chi|^4 (1 - \cos 4\theta)
\]

and of the mass term, i.e. quadratic potential may have the form:

\[
U_m(\chi) = m^2 |\chi|^2 [1 - \cos(2\theta + 2\alpha)],
\]

where \(\chi = |\chi| \exp(i\theta)\) and \(m = |m| e^{i\alpha}\). If \(\alpha \neq 0\), C and CP symmetries would be explicitly broken.

In grand unified (GUT) SUSY models baryonic number is naturally non-conserved. In our toy model the non-conservation of baryons is enforced by non-invariance of potential \(U(\chi)\) with respect to the phase rotation, \(\chi \rightarrow \chi \exp(i\phi)\). Deviation form thermal equilibrium is practically evident. So all three Sakharov’s conditions for baryogenesis are fulfilled.
Initially (after inflation) $\chi$ could be away from origin and, when inflation is over, started to evolve down to equilibrium point, $\chi = 0$ according to the equation similar to that of the Newtonian mechanics:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0.$$  \hspace{1cm} (7)

Baryonic number of $\chi$:

$$B_\chi = \dot{\theta}|\chi|^2$$  \hspace{1cm} (8)

is analogous to mechanical angular momentum. $\chi$ decays transferred baryonic charge to that of quarks in B-conserving process.

If $m \neq 0$, the angular momentum, or $B$ \hspace{1cm} (8), is generated by a different direction of the quartic and quadratic valleys at low $\chi$. If CP-odd phase $\alpha$ is small but non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of one of them.

Matter and antimatter domains may exist but globally cosmological excess of baryons over antibaryons (or vise versa) is more probable than globally B-symmetric universe.

Our new input to the model is an introduction of the Affleck-Dine field $\chi$ coupling to inflaton $\Phi$, the first term in the equation below:

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln \left(\frac{|\chi|^2}{\sigma^2}\right) + \lambda_1(\chi^4 + h.c.) + (m^2\chi^2 + h.c.).$$  \hspace{1cm} (9)

As we have already mentioned, C and CP would be broken, if the relative phase of $\lambda_1$ and $m$ is non-zero, otherwise one can ”phase rotate” $\chi$ and come to real coefficients in the potential above.

The introduced above interaction between $\Phi$ and $\chi$ is quite natural. An interaction between two scalar fields $\Phi$ and $\chi$ in one or other form must exist. This coupling is a general renormalizable one. The only mild tuning is that $\Phi$ reached and passed $\Phi_1$ during inflation. Duration of inflation after that is a free parameter.

When $\Phi$ is close to $\Phi_1$, the window to flat direction is open but presumably only during a short period, cosmologically small but possibly astronomically large bubbles with high $\beta$ could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$, created by small $\chi$. The formed in this way HBBs would turn in massive black holes after the QCD phase transition. However, HBBs with considerably smaller masses may not form black holes but some dense stellar-like objects.

This mechanism of massive PBH formation is quite different from all others. The fundament of PBH creation is build at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations. The initial isocurvature perturbations are created by the large variation of chemical potential of massless quarks and antiquarks. Density perturbations are generated rather late after the QCD phase transition when quarks turn into massive baryons. The emerging universe may be full of massive and supermassive black holes.

The outcome of the discussed mechanism, depending on $\beta = n_B/n_\gamma$ could be:

- **PBHs** with log-normal mass spectrum.
- **Compact stellar-like objects**, similar e.g. to cores of red giants.
- **Disperse hydrogen and helium clouds** with (much) higher than average $n_B$ density.
- **$\beta$** may be negative leading to compact antistars which could survive annihilation with the homogeneous baryonic background.
A modification of inflaton interaction with scalar baryons as e.g.
\[ U \sim |\chi|^2(\Phi - \Phi_1)^2((\Phi - \Phi_2)^2 \tag{10} \]
gives rise to a superposition of two log-normal spectra or multi-log. The consequences of this modification are not yet explored.

4. Gravitational waves and PBHs
Two rotating gravitationally bound massive bodies are known to emit gravitational waves. In quasi-stationary inspiral regime, the radius of the orbit and the rotation frequency slowly change and the GW frequency is approximately twice the Newtonian rotation frequency:
\[ \omega_{orb}^2 = \frac{M_1 + M_2}{m_{Pl}^2 R^3} . \tag{11} \]

The luminosity of the GW radiation during this stage is:
\[ L = \frac{32}{5} m_{Pl}^2 \left( \frac{M_c \omega_{orb}}{m_{Pl}} \right)^{10/3} , \tag{12} \]
where \( M_1, M_2 \) are the masses of two bodies in the binary system and \( M_c \) is the so called chirp mass:
\[ M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} . \tag{13} \]

Discovery of gravitational waves (GW) by LIGO strongly indicate that the sources of GW are primordial black holes, see e.g. [9]. The conventional astrophysical black holes are much less favorable by the following reasons:
1. An astrophysical formation of very massive BHs, \( M \sim 30 M_\odot \), demands much more massive progenitors with \( M > 100 M_\odot \), but they are not observed in sufficient amount. Recently the problem of stellar origin of the LIGO sources became multifold more pronounced after observation of the event GW190521, see fig. 3. On other hand, possible existence of so heavy progenitors can be explained by an extra energy source due to annihilation of DM inside stars [10].
2. Difficulties with formation of BH binaries from the original stellar binaries. If BH is created through stellar collapse, a small non-sphericity results in a huge recoil momentum of the BH and the binary would be destroyed. The problem of the binary formation is simply solved if the observed sources of GWs are the binaries of primordial black holes. They were at rest in the comoving volume, when inside horizon they are gravitationally attracted and may loose energy due to dynamical friction in the early universe. The probability to become gravitationally bound for PBHs is non-negligible. The conventional scenario is not completely excluded but seems much less probable.
3. The low value of the angular momenta of the original BHs in the coalescing binaries is difficult to understand if they are the usual astrophysical BHs formed in the process of stellar collapse. Still, individual non-rotating PBHs forming a binary initially rotating on elliptic orbit could gain collinear spins about 0.1 - 0.3, rising with the PBH masses and eccentricity [11, 12]. This result is in agreement with the most massive events GW170729 LIGO produced by the binary with masses 50M_\odot and 30M_\odot and GW190521 produced by BHs with 85M_\odot and 65M_\odot.

To summarize: each of the mentioned problems might be solved in the conventional frameworks but it looks much simpler to assume that the LIGO sources are primordial.
A very strong argument in favor of PBH sources of the registered gravitational waves is presented in ref. [13] on the basis of the analysis of the chirp mass distribution found from all publicly available LIGO events, namely, the available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum. The inferred best-fit mass spectrum parameters, $M_0 = 17M_\odot$ and $\gamma = 0.9$, fall within the theoretically expected range and shows excellent agreement with observations as is presented in figs. 1 and 2. In fig. 3 the data on the masses of the LIGO observed binaries, both the masses of the initial members of the binaries and on the mass of the resulting BH are presented. With the last event, GW190521, not included into figs. 1 and 2, the agreement becomes noticeably better.

On the opposite, binary black hole models based on massive binary star evolution require serious additional adjustments to reproduce the observed chirp mass distribution, see fig. 4.

**Figure 1.** Model distribution $F_{PBH}(< M)$ with parameters $M_0$ and $\gamma$ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.

**Figure 2.** Model distribution $F_{PBH}(< M)$ with parameters $M_0$ and $\gamma$ for two best Van der Waerden tests.
5. SMBH in contemporary universe

Every large galaxy available to the proper study contains a central SMBH with mass \((10^6 - 10^7)M_\odot\) in spiral galaxies like Milky Way and larger than \(10^9 M_\odot\) in giant elliptical and compact lenticular galaxies, up to the record 66 billions solar masses, TON 618 [14]. The origin of these BHs is mysterious. The accepted faith is that these BHs are created by matter accretion to a central seed. But, the usual accretion efficiency is insufficient to create them during the Universe lifetime, 14.6 Gyr.

According to ref. [15] building up SMBH SgrA* with the mass \(\sim 4 \times 10^6 M_\odot\) residing at the centre of our galaxy, within 14.6 billion year lifetime of our galaxy would require a mean accretion rate of \(4 \times 10^{-4} M_\odot\) per year. At present, X-ray observations constrain the rate of hot gas accretion to \(\dot{M} \sim 3 \times 10^{-6} M_\odot\) per year and polarization measurements constrain it near the event horizon to \(\dot{M}_{\text{hor}} \sim 10^{-8} M_\odot/\text{yr}\). The universe age is short by two orders of magnitude.

Even more puzzling is that SMHBs are observed in very small galaxies and even in almost empty space, where no material to make a SMBH can be found [16].

The mass of BH is typically 0.1% of the mass of the stellar bulge of galaxy but some galaxies may have huge BH: e.g. NGC 1277 has the central BH of \(1.7 \times 10^{10} M_\odot\), or 60% of its bulge mass. This creates serious problems for the scenario of formation of central supermassive BHs by accretion of matter in the central part of a galaxy [17].
A few more examples of SMBH which are at least an order of magnitude more massive than their host galaxy suggests are Henize 2-10, NGC 4889, and NGC1277.

An inverted picture seems to be much more plausible, when first a supermassive BH was formed and attracted matter seeding the galaxy formation, as advocated in refs [5, 6, 18].

Another possible piece of evidence in favor of primordial formation of SMBHs is their clumping. There are at least four binaries of SMBH, one triple system and one quartet. A list of references can be found in the review [1].

An orthodox point of view which might explain the SMBH binary existence is merging of two spiral galaxies creating an elliptical galaxy, leaving two or more SMBHs in the center of the merged elliptical. The traditional way of formation of a triple systems of SMBHs to say nothing of the quartet is much more difficult. Heretic but simpler possibility is that primordial SMBHs formed binaries, triple systems, and quartet in the very early universe.

6. SMBH in young universe

In the early universe at high redshifts \( z > 6 \) about 100 QSO are known, corresponding to billion solar mass SMBH. The QSO with maximum redshift: \( z=7.54 \) with 800 million solar masses is observed by the group [19]. Note that this QSO is situated in the neutral universe, in other words the interstellar medium was not ionized. This means that the accretion was absent or insignificant.

Another very interesting observation is that of the second largest QSO which is powered by 1.5 billion of solar masses [20]. According to the author’s statement, models indicate it must have formed not later than 100 million years after the Big Bang, extremely short time for its creation.

In addition to that another monster of 12 billion solar mass was discovered [21] The problem with formation of lighter quasars multifold deepens with this new fantastically massive "creature". On the other hand the accretion rate according to the conventional estimates [22] is extremely low, a halo with the mass of \( 3 \times 10^{10} M_{\odot} \) at \( z = 7.5 \); accretes only about 2200 \( M_{\odot} \) during 320 Myr.

Recently a striking observation has been done [23] that the life-time of activity of QSO at \( z \approx 6 \) is only \( 10^3 - 10^4 \) years. It means that only a minor fraction of QSO, and thus of SMBH, is observed, about \( 10^{-4} \) or even less. So the early universe is really overpopulated by SMBH.

The universe at redshifts \( z = 5 - 10 \) is also unexpectedly rich of massive and luminous galaxies, with the luminosity up to \( L = 3 \times 10^{14} L_{\odot} \). The corresponding list of references can be found in [1] According to ref. [24] the density of galaxies at \( z \approx 11 \) is \( 10^{-6} \) Mpc\(^{-3} \), an order of magnitude higher than estimated from the data at lower \( z \). The origin of these galaxies is unclear. So, again the conclusion is almost unavoidable that the inverted picture of galaxy formation can solve the problem: primordial SMBHs seeded galaxies but not vice versa, and not only in young universe but also today.

To conclude on QSO/SMBH, the quasars are supposed to be supermassive black holes and their formation in such short time by conventional mechanisms looks problematic. Such black holes, when the Universe was less than one billion years old, present substantial challenges to theories of the formation and growth of black holes and the coevolution of black holes and galaxies. Even the formation of SMBH in contemporary universe during 14 Gyr is hard to explain. Non-standard accretion physics and the formation of massive seeds seem to be necessary. Neither of them is observed in the present day universe.

It is difficult to understand how \( 10^9 M_{\odot} \) black holes (to say nothing about \( 10^{10} M_{\odot} \)) appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe.

There are more problems in contemporary universe and in the universe 14 billion years ago. Because of lack of space and time they are simply enumerated here:
• MACHOS: invisible stellar type objects with $M \sim 0.5M_\odot$
• IMBH unexpected but quite abundant, thousands of them.
• Peculiar stars” too old, too fast, with strange chemistry.
• Globular clusters seeding by $(10^3 - 10^4)M_\odot$ BHs, and dwarfs by $(10^4 - 10^5)M_\odot$ BHs [25].
• Overpopulation of the young, $z \sim 10$ universe with early created gamma-bursters and supernovae, early bright galaxies, evolved chemistry including huge amount of dust.

7. Conclusion
Here we summarize the basic features of the model of refs. [5, 6], preiditons, postdictions, and development in subsequent papers.
• 1. Natural model based on AD-baryogenesis scenario leads to abundant formation of PBHs and compact stellar-like objects in the early universe after QCD phase transition, $t \geq 10^{-5}$ sec.
• 2. Thess compact objects have simple log-normal mass spectrum.
• 3. PBHs formed at this scenario can explain the peculiar features of the sources of GWs observed by LIGO.
• 4. The considered mechanism solves the numerous mysteries of $z \sim 10$ universe: abundant population of supermassive black holes, early created gamma-bursters and supernovae, early bright galaxies,and evolved chemistry including dust.
• 5. There is persuasive data in favor of the inverted picture of galaxy formation, when first a supermassive BH seeds are formed and later they accrete matter forming galaxies.
• 6. An existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is naturally explained.
• 7. ”Older than $t_U$” stars may exist; the large age is mimicked by the unusual initial chemistry.
• 8. Explanation of the origin of BHs with $2000 M_\odot$ in the core of globular cluster (GC) and the observed density of GC is presented.
• 9. A large number of the recently observed IMBH was predicted.
• 10. A large fraction of dark matter or even 100% can be made of massive PBHs.
• 11. Clouds of matter with high baryon-to-photon ratio and unusual chemkistry can exist.
• 12. A possible by-product: plenty of (compact) anti-stars, even in the Galaxy, not yet excluded by observations. Extreme point of view: Black holes in the universe are mostly primordial (PBH).
• Primordial BHs make all or dominant part of dark matter (DM).

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