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REPORT

ON THE PASSAGE OF THE COURSE WORK

# Primordial Black Holes



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**Abstract**

A black hole is a region of spacetime exhibiting such strong gravitational effects that nothing - including particles and electromagnetic radiation such as light – can escape from inside it. The black holes are formed by the collapse of massive stars whose mass is $\sim 10\ M_\odot$ or more, or as a result of the collapse of a dense cluster of stars in the centre of the galaxy, their mass is in the range of $\sim 10^6$ -$10^8\ M_\odot$. However, there are models in which black holes are formed in the early stages of the Universe before the formation of large-scale structures.

It was suggested by Zeldovich and Novikov in 1966 and by Hawking in 1971. These black holes are called primordial black holes (PBH). PBHs are of particular interest in cosmology. At first, they are among the candidates for dark matter, at the same time they manage to explain all its density. At second, simple estimates show that PBHs could cause reionization. Also, PBH model can be used as a theoretical instrument for Cosmo archaeological analysis.

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# 1. Introduction:

The history of primordial black hole (PBH) study dates back to sixties, when Zeldovich and Novikov pointed out that Black Holes (BHs) in the early Universe might grow catastrophically by accreting the surrounding radiation [1]. In 1971, Hawking proposed [2] that a highly over dense region of inhomogeneities in the primordial Universe could directly undergo gravitational collapse to form BHs; this initiated the modern theory of the mechanism of PBH formation. In contrast to astrophysical processes (i.e., collapse of stars), which can only form BHs heavier than a particular mass (around three solar masses [3]), extremely strong gravitational forces inside the highly compressed radiation/matter existing in the early Universe allows formation of not only stellar/super-massive BHs but also small BHs that could in principle be as light as the Planck mass $\sim 10^{-5}$ g (see e.g. [4] and references therein). After the advent of inflationary cosmology, formation of PBHs and their properties—such as mass and abundance—had been studied in close connection with inflation models. Conversely, knowledge of observational information about PBHs provides important clues to build inflation models. In particular, it is worth mentioning that even the non-detection of PBHs gives us useful information about the early Universe i.e., in the form of restrictions on the primordial perturbations and on physical conditions at different epochs [5].

There are several models of PBHs formation. PBHs can be formed during the collapses of adiabatic (curvature) density perturbations in relativistic fluid. They can be formed also at the early dust-like stages and rather effectively on stages of a dominance of dissipative superheavy metastable particles owing to a rapid evolution of star-like objects that such particles form. There is also an exciting model of PBHs formation from the baryon charge fluctuations [5].

One of the hypotheses is that the PBHs might be individual pieces of matter, or cores, in an expanding Friedmann universe, which have been retarded in their expansion for an external observer, are located inside their Schwarzschild spheres of radius $R=R_g=2\ GM/c^2$, and emerge from these spheres only after a long period has passed since the beginning of the general expansion [6].

Search for PBHs is going on for several decades now. Depending on the mass, PBHs trigger different observational signals. PBHs lighter than a certain mass $M_c$, given by [7]:

$$M_C \sim 10^{15} g \left(\frac{\alpha_0}{4\times10^{-4}}\right)^{1/3} \left(\frac{t_0}{13.8Gyr}\right)^{1/3}, \quad (1)$$

have already evaporated by the cosmic age $t_0$ due to the Hawking radiation. Thus, PBHs lighter than $\simeq 10^{15}$ g does not exist in the present Universe. Nevertheless, they leave some traces by which we can investigate how many PBHs could have existed in the early Universe. For instance, PBHs in the mass range $10^9$–$10^{13}$ g changes the abundance of light elements produced by the Big Bang nucleosynthesis, due to high energy particles emitted by the evaporating PBHs [8]. Comparison between the observed light elements and the theoretical prediction tightly constrains the abundance of such PBHs [9].

PBHs heavier than $10^{15}$ g have not yet lost mass significantly by evaporation, and remain in the present Universe. They not only imprint observational traces in the early Universe (such as by accretion, and indirect effects by the primordial density perturbations that seed PBHs) but also produce various distinct signals at the present time, such as gravitational lensing, dynamical effects on baryonic matter, radiation emanating from the matter accreting into PBHs, etc. Accretion, and dynamical effects on baryonic matter become more important for heavier PBHs. One of the important questions regarding non-evaporating PBHs is whether they comprise all dark matter or not. Thanks to the achievements of many different types of cosmological and astrophysical observation over decades, a stringent upper limit on PBH abundance has been obtained for a vast PBH mass range [10]. Currently, it appears that PBHs do not explain all dark matter, constituting at most a fraction thereof [11].

The discovery at LIGO of the merger event (GW150914) of binary BHs [12] triggered a renewed interest of PBHs, especially in the stellar mass range (10-100 $M_{\odot}$) [5]. The unexpectedly large mass of the detected BHs (around 30 $M_{\odot}$) brought us a new mystery about this component of the Universe [13]. Many research groups [14–16] independently pointed out that the inferred merger rate can be explained by the merger of PBHs without violating the trivial bound that the PBH abundance is equal to or less than the total dark matter abundance. In [14, 15], binary formation via accidental encounters of PBHs in a dense environment, which works in the low-redshift Universe, has been considered, while a different mechanism of binary formation via the tidal perturbation caused by distant PBHs, which works in the radiation-dominated epoch in the early Universe and was originally proposed earlier in [17], has been investigated in [16]. These studies demonstrate that gravitational waves (GWs)—a brand new observable—provide a powerful and useful tool to probe parameters of PBHs (mass, abundance etc) in ways that had not been possible through electromagnetic waves alone. In other words, the roles of GWs are complementary to those of electromagnetic waves.

# 2. Formation of PBH

There are several mechanisms of PBH formation in the early Universe. As examples, [18, 19] recently discussed the possibility of PBH formation by domain walls, and [18, 20] also proposed a scenario in which PBHs are formed by vacuum bubbles which nucleate during inflation. There have also been several works about PBH formation from cosmic string loops [21-23]. However, the most frequently studied PBH formation scenario must be the gravitational collapse of overdense regions in the early Universe. Here, we briefly review understanding of the latter PBH formation process, and also the inflationary models which could produce such an overdense region.

The characteristics of the black hole are its mass $M$, charge $Q$ and angular momentum $L$.

A black hole is a solution of Einstein's equations:

$$R_{\mu\nu} - (1/2)^* g_{\mu\nu} R = 8\pi G T_{\mu\nu} - g_{\mu\nu}\Lambda \qquad (2.1)$$

where $R_{\mu\nu}$ is the Ricci curvature tensor, $R$ is the Ricci scalar, $g_{\mu\nu}$ is the metric tensor, $G$ is the gravitational constant, $T_{\mu\nu}$ is the stress-energy tensor, $\Lambda$ is the cosmological constant.

In general case, the solution of equation (2.1) is described by the Kerr-Newman-de Sitter metric [24]

$$ds^2 = -\rho^2 \left( dr^2/\Delta_r + d\theta^2/\Delta_\theta \right) - \sin^2\theta /(1+\alpha)^2\rho^2[a dt - (r^2 + a^2)d\phi] + [\Delta_r /(1 + \alpha)^2\rho^2](dt - a\sin^2\theta d\phi)^2 \qquad (2.2)$$

where,

$$\Delta r = (r^2 + a^2)(1 - \alpha r^2 /a^2) - 2Mr + Q^2, \Delta\theta = 1 + \alpha\cos^2\theta$$

$$\rho^2 = \rho \cdot \rho^*, \rho = r + iQ\cos\theta$$

$$\alpha = \Lambda a^2/3, a = L/\mathrm{M}$$

Usually, however, the cosmological constant is neglected and in this case the solution of the equation (2.1) is the Kerr-Newman black hole [25].

$$\mathrm{d}s^2 = -\{ 1 - (2Mr - Q^2)/\Sigma \}\, dt^2 - 2(2Mr - Q^2)[a(\sin^2\theta)/\Sigma]\, dt d\phi + (r^2 + a^2 + \{(2Mr - Q^2)/\Sigma\} a^2\sin^2(\theta))\sin^2(\theta) d\phi^2 + (\Sigma/\Delta)\, dr^2 + \Sigma d\theta^2 \qquad (2.3)$$

where $\Sigma = r^2 + a^2\cos^2\theta, \Delta = r^2 - 2Mr + a^2 + Q^2$ .

Th event horizon is given by

$$r_\mathrm{g} = M + \sqrt{\{ (M^2 - a^2 - Q^2) /M^2_{\mathrm{Pl}}\}} \qquad (2.4)$$

where $M_{Pl}$ is the Planck mass. The Kerr-Newman metric defines a black hole with an event horizon only when the following relation is satisfied,

$$\mathrm{a}^2 + Q^2 \leq M^2 \qquad (2.5)$$

If this relation is violated, the event horizon disappears, and we have the so-called naked singularity, which doesn't exist according to the cosmic censorship principle. In the case of a non-charged rotating black hole solution of the equation (2.1) is the Kerr metric, in the case of a non-rotating charged black hole solution is the Reissner-Nordström metric, and in the case of a non-charged non-rotating black hole solution is the Schwarzschild metric. A feature of PBHs is that their formation isn't due to the collapse of large stars. There are several theoretical ways to describe the formation of PBHs.

## *2.1 PBHs as a manifestation of the dust-like stages in the early Universe*

On the dust-like stage gravitational instability evolves within the cosmological horizon. At this stage the growth of small perturbations can cause to the formation of homogeneities, which can collapse and form PBHs. The probability of such a formation is given by [26]

$$\omega \approx e^{-(\gamma 2)/2\langle\delta 2\rangle} \tag{2.6}$$

where $0 < \gamma < 1$ is a numerical factor which determines the equation of state, $\langle\delta^2\rangle \ll 1$ is the variance of the Gaussian distribution that describes the perturbation of the metric. Formally, on the dust-like stage of evolution of the Universe, when $\gamma = 0$, $\omega \to 1$, but in fact this isn't true. However, detailed analysis shows that there is not exponential suppression and the probability of formation of PBHs is greatly enhanced compared to the RD-stage.

In the modern Universe stars and galaxies formed from the baryonic matter, wherein their evolution is characterized by energy loss due to radiation. This causes a rapid evolution of such an object. By the same analogy the formation of PBHs in the dust-like stage of the Universe can be considered.

Stage of dominance of non-relativistic matter (MD-stage) starts when the density of the non-relativistic matter $\rho$m becomes greater than the density of relativistic matter $\rho\gamma$. The equation of state at this stage is given by $p = 0$, where $p$ is the pressure. With the MD-stage beginning (when $t = t_0$) density fluctuations in the non-relativistic matter are growing within the cosmological horizon like

$$\delta\rho/\rho \propto t^{2/3} \tag{2.7}$$

If the initial perturbation amplitude density was equal to $[\delta\rho/\rho]\ (t_0) = \delta$, then at time $t \sim t_f = t_0\delta^{-3/2}$ the perturbation grows to $\delta\rho/\rho \sim 1$ and will form inhomogeneities that separated from the general cosmological expansion, which are gravitationally bound systems of non-relativistic matter.

Evolution of gravitationally bound system of weakly interacting particles is similar to the galactic evolution, so the dissipation of energy in such a system is a slow process [27], and it is determined by the process of evaporation of particles whose velocity exceeds the parabolic velocity of a gravitationally bound system, so the time of evolution of such systems in the black hole is much higher than the cosmological time [26].

Nonrelativistic matter that interacts with relativistic particles and radiation, forms a gravitationally-bound systems, the evolution of which is determined by the energy loss due to radiation, as in the case of stars from ordinary matter. The time of evolution of these systems is comparable to the cosmological time, or even less, which makes possible the formation of PBHs in relatively short periods of time on the MD-stage.

## *2.2 Direct formation of PBHs*

The idea of direct formation of PBHs due to the fact that the inhomogeneities are formed in the early Universe, and the growth of their fluctuations entail the formation of sufficiently homogeneous and isotropic configurations.

Direct formation means that after the density fluctuation $\delta\rho/\rho$ becomes about 1, inhomogeneities are separated from the general cosmological expansion, and they contract within own gravitational radius. By the time compression begins, these configurations are characterized by:

1) an average density $\rho_{\text{conf}}$
2) an inhomogeneity of density $u \sim \delta\rho_{\text{conf}}/\rho_{\text{conf}}$
3) a size $r_{\text{conf}}$
4) a deviation from sphericity $s_{\text{conf}}$.

The formation of a BH as a result of compression corresponding to the average density,

$$\rho_{\text{BH}} \sim M/r^3_{\text{g}} \sim \rho_{\text{conf}} \,/\, x^3 \tag{2.8}$$

here $x = r_{\text{g}}/r_{\text{conf}}$. On the other hand, when compressing a non-spherical configuration, the maximum achievable density is,

$$\rho_{\text{max}} \sim \rho_{\text{conf}} \,/s^3_{\text{conf}} \tag{2.9}$$

From (2.8), (2.9) it follows that for the formation of a BH configuration should be close to the spherically symmetric,

$$s_{\text{conf}} \leq x \leq 1 \tag{2.10}$$

Restriction on the configuration of the inhomogeneity has the form [28]

$$u \leq x^{3/2} \leq 1 \tag{2.11}$$

Conditions (2.10), (2.11) are enough to direct the formation of PBH.

When normal distribution of inhomogeneity with variance order 1 probability of realization of the configuration with abnormally low inhomogeneity is determined by the phase volume, by appropriate configurations for which the condition (2.11) is satisfied, and this probability is $\omega_u \sim u \sim x^{3/2}$. Assuming that the probability of realization of the configuration that satisfies the condition (2.10) determined by the appropriate phase space, we get $\omega_s \sim x^5$. Hence, we obtain the minimum probability of direct formation of a BH in the dust-like stage,

$$\omega_{\text{BH}} \geq \omega_s \cdot \omega_u \sim x^{13/2} \tag{2.12}$$

Direct mechanism of formation of PBHs is effective in $M_{\text{min}} < M < M_{\text{max}}$, where $M_{\text{min}} \sim M_{\text{Pl}}\, t_0 \,/\, t_{\text{Pl}}$ is defined as the mass contained under the cosmological horizon at the beginning of the dust-like stage $t_0$ ($t_{\text{Pl}}$ - Planck time), and $M_{\text{max}}$ is determined from the condition that the amplitude of the perturbation of the $M$, which "getting out of the horizon" with initial amplitude $\delta(M)$ becomes to 1 at the end of a dust-like stage. Hence, in this mass range can receive the minimum probability of the formation of a PBH, which is determined by the amplitude of the perturbation of its mass,

$$\omega_{\text{BH}} \geq [\delta(M)]^{-3/2} \tag{2.13}$$

This mechanism provides a universal model-independent check for inhomogeneities on the dust-like stages in the early Universe, it does not depend on the form of non-relativistic matter and period of its dominance.

## *2.3 The formation of PBHs in the first-order phase transitions*

In the process of the first-order phase transitions collisions of bubble walls can concentrate the kinetic energy of the walls within its gravitational radius, thereby forming a PBHs [29, 30]. For example, it may be a scalar field with two non-degenerate vacua where vacuum with less energy is true, and the second is false.

The false vacuum decays, it gives rise to its true vacuum bubbles and their subsequent expansion, and the potential energy of the false vacuum is converted into kinetic energy of the walls between them. This bubble will expand to a collision with another bubble, and a PBH can be form at the collision bubbles walls [29, 30]. Immediately after the collision penetration of walls is accompanied by an additional increase in potential energy [31]. Then the walls are reflected and move in the opposite direction to the true vacuum region, their kinetic energy is converted back into potential energy of the false vacuum, and the outer share of the wall still expands and absorbs the false vacuum, and at some moment the central region of false vacuum is separated and forms a detached false vacuum bag. It is shown in figure 2.1.

In the papers [29, 32], vacuum bag will grow as long as the kinetic energy of its walls will not be equal to zero, after that the bag shrinks to a size comparable to the thickness of the wall and then expanded again. So, the compression and expansion processes follow each other, and the bag loses its energy, which is converted into energy of oscillations of the scalar field. The number of these oscillations is a finite [32]. If the bag is compressed under its gravitational radius, the BH is formed.

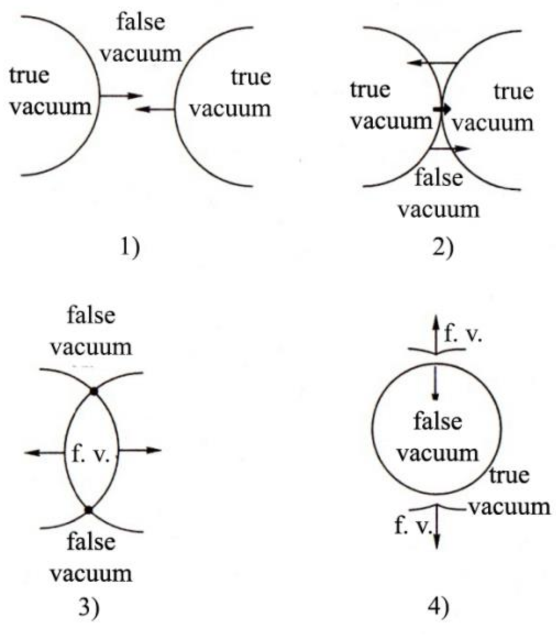



*Figure 2.1. Formation of the false vacuum bag in a collision of two walls of the bubbles.*

## *2.4 The formation of PBHs in the collapse of the closed walls*

Consider a scalar field $\phi = r \cdot e^{i\theta}$, whose potential has U(1)-symmetry and has the form

$$(\phi) = \lambda_1(|\phi|^2 - f^2/2)^2 + \delta V\,(\theta) \quad (2.14)$$

where $\delta V(\theta) = \lambda^4_2(1 - \cos\theta)$, $f$, $\lambda_1$ and $\lambda_2$ are some model parameters. Term $\delta V(\theta)$ can be neglected at the stage of inflation, it makes a significant contribution when $m_\theta = 2f^2/\lambda_2 \sim H$ [33], where $H$ is the Hubble constant. In this case, there is a clear violation of the symmetry, and the potential that describes by (2.14), eventually has a number of degenerate minima $\theta$min = $Z \cdot 2\pi$, where $Z$ is integer number.

During inflation causally disconnected regions will be formed with different initial phases $\theta$. When $m_\theta$ becomes $\sim H$, in some regions, oscillations of the field $\phi$ will occur near the minimum of the potential $V$ . For example, in the region where $\pi < \theta < 2\pi$ oscillations will occur near $\theta_{\min} = 2\pi$, while the phase in the surrounding region of this space, as a rule, tends to $\theta_{\min} = 0$. Since the phase varies continuously while driving from the region with $\theta_{\min} = 0$ in the region with $\theta_{\min} = 2\pi$ we get to $\theta_{\text{wall}} = \pi$, i.e., there is a closed surface, which is characterized by this value, and its size depends on the formation of regions during inflation, but the shape can be of any form. Since there may be a solution of the form of the kink [34], closed wall is formed with $\theta_{\text{wall}} = \pi$, corresponding to the transition from vacuum $\theta_{\text{vac}} = 0$ to vacuum $\theta_{\text{vac}} = 2\pi$.

After the inflation, border of regions, where $\theta_{\text{vac}} > 2\pi$, significantly larger than the cosmological horizon. The walls of these regions continue to expand as long as they are causally disconnected that is, when the size of the wall becomes equal to the horizon size. Internal stress arising in the wall after the horizon intersection initiates processes that seek to reduce to a minimum wall surface. The wall energy is proportional to its region at the time of crossing the horizon. At the maximum compression, this energy is almost completely converted into kinetic energy [35]. If the wall at some moment is localized under the gravitational radius, PBH is formed, and its range of the masses is limited by the parameters $f$ and $\lambda_2$ [33]

$$M_{\max} = (M_{\text{Pl}}/f)\, M_{\text{Pl}}\, (M_{\text{Pl}}/\lambda_2)^2\,, \quad M_{\min} = f\,(M_{\text{Pl}}/\lambda_2)^2$$

# 3. The evaporation of primordial black holes and the reionization of the Universe

It is believed that the black hole is completely absorbing object. However, quantum mechanics predicts that a particle can tunnel through the potential barrier, whose height is greater than its total energy, and it makes Hawking radiation to be possible (i.e., the process of emission of various elementary particles out of BHs) [36]. This process is interpreted as follows: the gravitational field of a black hole polarizes the vacuum, resulting in the formation not only virtual, but also real pairs particle and antiparticle. One of the particles, which is below the event horizon, falls into the BH, while the other, which is above the horizon, go away, carrying away its energy (i.e., the part of the mass BH).

Near the BH event horizon, its radiation can associate a certain temperature

$$T_{\mathrm{BH}} = (T_{\mathrm{Pl}} * M_{\mathrm{Pl}})/(8*\pi*M) \qquad (3.1)$$

where $T_{\mathrm{BH}}$ is BH radiation temperature, $T_{\mathrm{Pl}}$ is Planck temperature. The rate of evaporation of PBH is given by

$$dM/dt \sim M^4_{\mathrm{Pl}} / M^2 \qquad (3.2)$$

It is easy to get the time in which PBH with a certain mass will evaporate. Evaporation time is equal to [36-38]

$$t_e = 10^{-27}\mathrm{c}(M/1\ \mathrm{g})^3 \qquad (3.3)$$

Thus, if the initial mass of PBHs no more than $10^{15}$ g, then they disappeared to date and can't be observed.

BHs with masses $M < 10^{13}$ g have evaporating temperature $T_{\mathrm{BH}} \gg 1$ GeV, which makes it possible the birth of nucleons and antinucleons. At the same time the eq. (3.3) shows that the PBHs with the masses $M \leq 10^9$ g evaporate by the end of the first second of the Universe. It follows that such PBHs can greatly influence the process of primordial nucleosynthesis and the number of extragalactic protons and antiprotons, and on the basis of observational data, we can get some restrictions [26, 9].

As noted earlier, due to Hawking radiation of PBHs could lead to the reionization of the Universe, which had the place to be between 550 million years and 800 million years after the Big Bang.

In the papers [39, 40] PBHs are considered, whose masses are in the range of $10^{16} < M < 10^{17}$g with their relative density in accordance with the upper limit [9], which may be represented in form

$$\Omega_{\mathrm{PBH}} = \begin{cases} 0.25, & M > M_{\mathrm{peak}} \\ 0.25\left(\frac{M}{M_{\mathrm{peak}}}\right)^{3.36}, & M < M_{\mathrm{peak}} \end{cases} \qquad (3.4)$$

where $M_{\mathrm{peak}} = 0.78*10^{17}$ g. Evaporation temperature for this PBHs is $T_{\mathrm{BH}} \approx (0.1*10^{17}\ g\ /M\ )$MeV, the average evaporation energy of photon $\approx 6T_{\mathrm{BH}}$, the average evaporation energy of electrons and neutrinos $\approx 4T_{\mathrm{BH}}$ [9].

In this temperature range evaporating PBHs emit gravitons, photons, three kinds of neutrinos, electrons and positrons.

Photons from evaporation of PBH with energy in the range of $\omega \sim$ 0.5-5 MeV lose energy due to the red shift and Compton scattering, which provides transfer energy baryonic matter.

Electrons and positrons from evaporation of PBH should experience energy losses due to scattering of cosmic microwave background (CMB) photons, ionization and red shift. Effects of interaction with low-density plasma is not considered here. Losses on the CMB is much greater than the ionization losses for most of the period that interests us. At the end of this period (redshift $z \sim$ 10) the rate of ionization losses approaches rate of losses on the CMB, but both are comparable with the rate of expansion. The rate of absorption of the radiation energy baryonic matter from the PBH in the form of electrons and positrons is determined by the ionization process.

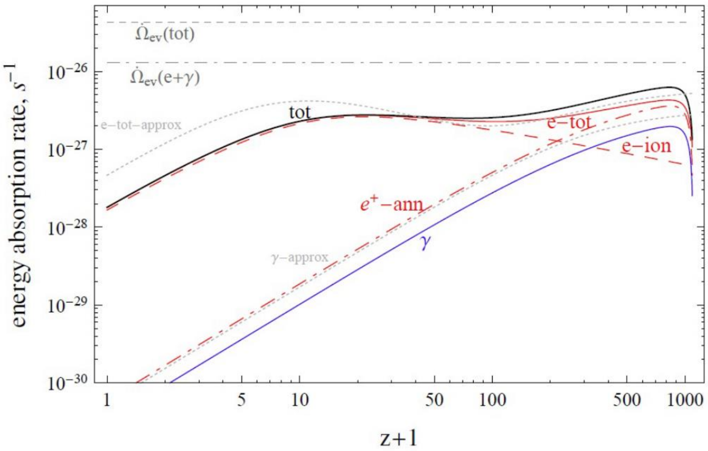



*Figure 3.1. The rates of absorption of energy baryonic matter from the evaporation of PBHs, depending on the redshift.*

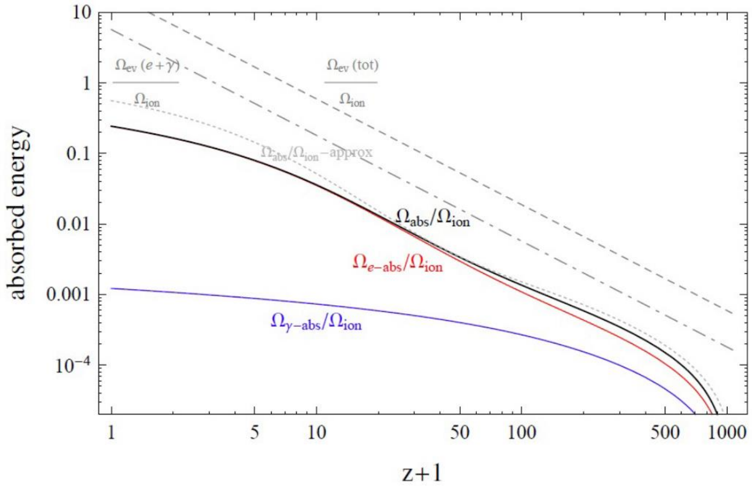



*Figure 3.2. The total absorbed energy from evaporation in the critical energy density of the units, depending on the redshift.*

As can be seen, the ionization losses of electrons and positrons from the evaporation of PBHs are suppressed by the scattering on the CMB and redshift, however, are the most effective mechanism of energy transfer from the radiation of PBHs to the baryonic matter.

When $z \sim$ 5-10 the absorbed by baryonic matter energy is 1-2 eV per atom. That would not be enough to ionize the atom, if this energy is not accounted for each atom. For its consideration of the effect in this case, we must go to thermodynamic consideration. From the first law of thermodynamics can obtain an equation that determines the degree of ionization of matter in the universe, which is shown in Fig. 3.3.

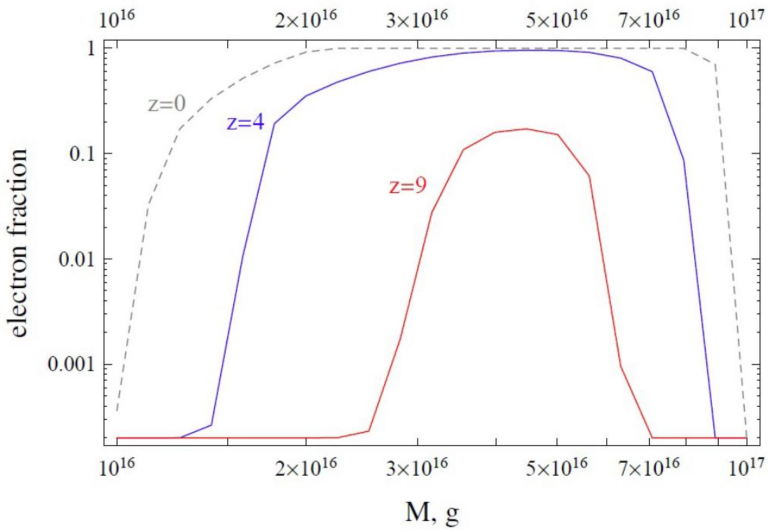



*Figure 3.3. The degree of ionization of the matter depending on the mass of PBHs at different redshifts.*

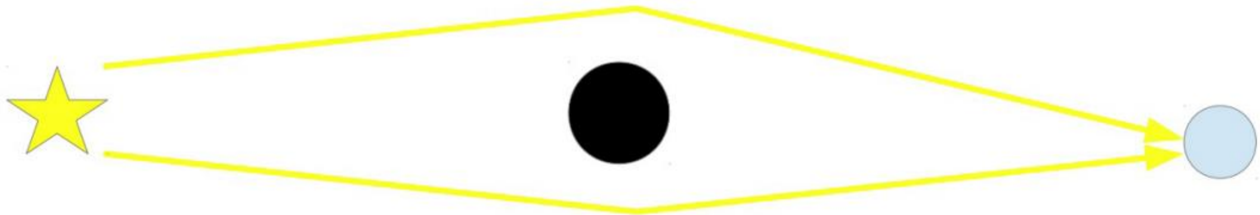
As you can see, this rough estimate indicates that PBHs with masses $3*10^{16} – 8*10^{16}$ could provide reionization of the Universe.

# 4. Restrictions on PBHs

The presence of PBHs in the Universe can significantly affect the dynamics of its development, so we can get some restrictions from observational data. One part of such restrictions is related with the emission of Hawking and the other is related to the gravitational effects.

As noted earlier, the PBHs with $M < 10^{15}$ g should evaporate during the lifetime of the Universe that is, if they were formed in the early Universe, they have disappeared to the present time, while the more massive the BHs must be present. It is generally considered that the evaporation leads to the complete disappearance of PBHs [41], however, there are arguments in favour of the existence of stable evaporation residue [42-46]. If this is true, then we can evaluate the current density of these residues, and such an analysis shows that this theory is poorly compatible with the model of the formation of PBHs in the first-order phase transitions [26].

The massive body can bend the direction of propagation of electromagnetic radiation its gravitational field, just like a normal lens bends the light beam. Such objects are called gravitational lenses. Schematically, the lensing effect is as follows:



The PBH, acting as a gravitational lens, creates two images, the delay time between them can be estimated as $\tau \sim r_g/c$, and we can expect some spectral features associated with the interference [47]. In paper [48] the restriction on the PBHs with masses $5 * 10^{17}$-$10^{20}$ g obtained from data of the Fermi GMB.

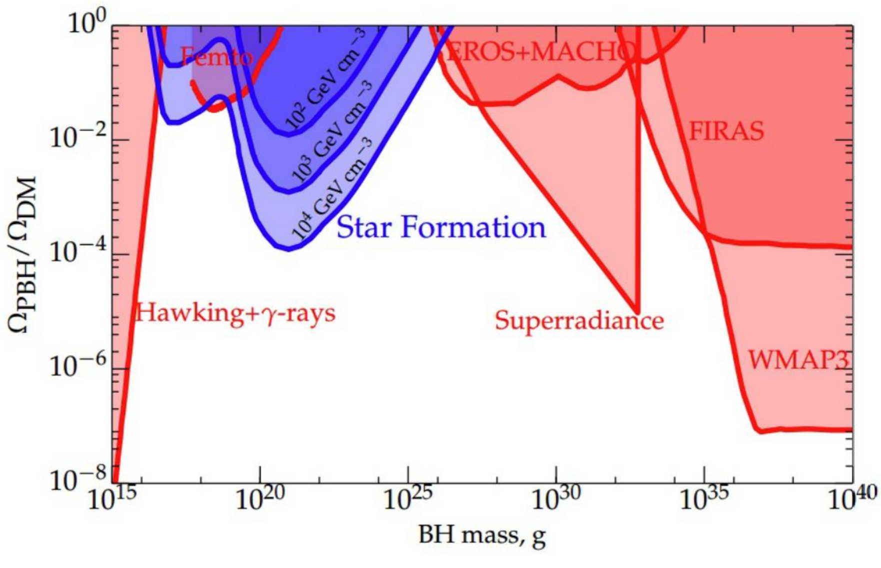



*Figure 4.1. Restricting the proportion of PBHs in the dark matter fractions. The shaded regions are excluded. The blue region corresponds to the restrictions obtained in [28], [29], the red region obtained from other observational data.*

Also, it is possible to put some constraints from observations of stellar evolution: BHs can be captured protostar and due to dynamic friction, they may fall into the central oblate stars. After some time, the compact object (white dwarf or a neutron star) will be formed, and the PBH will absorb it quickly. Thus, from the observation of neutron stars and white dwarfs manage to impose a restriction on the number of PBHs with certain masses [49], [50].

# 5. Conclusion

PBHs are a very convenient to study the evolution of the Universe. Their possible mass quantity and formation mechanisms can be verified observation. In addition, with the help of PBHs we can explain some phenomena, such as the onset of the era of reionization, positron line in the centre of the galaxy, the presence of point gamma-ray sources, dark matter. Currently, this topic is relevant and interesting for further study.

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