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Review

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Review

Primordial Black Hole Messenger of Dark Universe

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Abstract: Primordial black holes (PBH), if survive to the present time, can be a fraction, or even the dominant form of dark matter of the Universe. If PBH evaporate before the present time, rare forms of dark matter like superweakly interacting or supermassive particles can be produced in the course of their evaporation. Stable remnants of PBH evaporation can also play the role of dark matter candidates. In the context of the modern standard cosmology, based on inflationary models with baryosynthesis and dark matter, which find their physical grounds beyond the Standard models of elementary particles (BSM), primordial black holes acquire the important role of sensitive probes for BSM models and their parameters. It makes PBHs a profound messenger of physics of Dark Universe.

Keywords: elementary particles; universe; cosmology; inflation; dark matter; early universe; symmetry breaking; phase transitions; early matter domination; primordial black holes; axion-like particles

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1. Introduction

Black holes may be the final state of evolution of any gravitationally bound system, provided that its mass M can be put within its gravitational radius $r_g = 2GM/c^2$ (where G is the Newton gravitational constant and c is the speed of light). Such conditions should naturally take place at the end of the evolution of massive stars or, possibly, the evolution of dense star clusters [1,2]. It can make natural astrophysical mechanisms responsible for the origin of black holes with mass, exceeding few Solar masses. In the expanding homogeneous and isotropic Big Bang Universe [3,4] formation of black hole of any mass is possible, if expansion can stop within the cosmological horizon [5] and Primordial Black Hole (PBH) is formed [6–9]. Formation of PBH assumes very strong inhomogeneity of early Universe. In the framework of modern paradigm of inflationary cosmology with baryosynthesis and dark matter/energy (see References [10–28] for review and reference), such inhomogeneity can be predicted in cosmological scenarios based on the particular models of particle theory at specific choice of their parameters. It means that the absence of PBHs can put constraints on some specific cosmological scenarios, while evidence of their existence favor such scenarios and their underlying particle models.

The now-standard cosmological paradigm [10,24–27,29,30] involves physics beyond the Standard model (BSM). The energy scale of this physics V can be reached in the combination of probes by cosmological, astrophysical and experimental physical means, as shown in Figure 1.

In the context of BSM models, Dark Universe is related to their fundamental structure [12–16,29–31]. New strict (or approximate) BSM symmetry leads to new conserved charges. The lightest particle, which possess such charge, should be stable (metastable) and play the role of a dark matter (DM) candidate. BSM symmetry breaking leads to cosmological phase transitions, which can leave topological defects, primordial objects and structures, as well as gravitational wave background [29,30]. These predictions are inevitably accompanied by other specific model-dependent signatures. Their combination can provide verification of the considered BSM model [29,30].

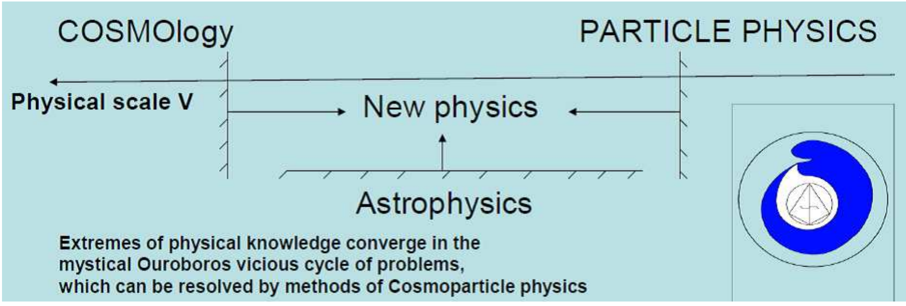

Figure 1. Cosmoparticle physics explores new physics at the energy scale V in the proper combination of its cosmological astrophysical and experimental physical signatures. The original author's figure published in [11,30].

We discuss in the present review various aspects of the physics of Dark Universe, putting PBH formation and effects (see References [32–37]) in the context of its probes.

As was shown in [11,30], physically well-motivated SM extensions predict along with DM candidates additional model dependent phenomena. DM candidates as well as their accompanying model dependent signatures can be called messengers of BSM physics. Such signatures can include set of additional particles and/or new interactions accompanying prediction of a DM candidate. Mechanisms of BSM symmetry breaking can lead to cosmological phase transitions, which can result in formation of various topological defects and structures. BSM model can predict superheavy metastable particles and fields. It can lead to their dominance in very early Universe. By choosing the BSM model and specific parameters, PBH formation may accompany these effects.

Cosmological scenarios, predicting PBH formation, inevitably contain additional model dependent consequences. They can involve PBH clustering and/or creation of some other forms of primordial macroscopic nonlinear structures. In particular, the mechanism of PBH formation can be accompanied by appearance of primordial macroscopic antimatter domains in baryon asymmetrical Universe. The account for various accompanying messengers in the BSM models, predicting PBH formation, puts PBHs in the framework of multimessenger cosmology of the corresponding BSM physics.

Black holes originate from gravitational collapse. This means that any substance that is present in our space–time, and thus, possesses gravitational interaction, can form black hole. Formation of PBHs and their evolution is accompanied by gravitational perturbations, being the source of gravitational wave (GW) signal. Current discussion of GW effects of formation and evolution of PBH in the framework of various BSM models can be found in References [38–46].

Effects of gravitational interaction are sensitive probe for extensive hidden sector of particle theory decoupled from the SM interactions of ordinary matter, as is the case for mirror or shadow matter [47–58]. Cosmological evolution of such an extensive self-interacting dark sector can be traced by the observable consequences of its gravitational effects, in which formation of PBH or various forms of primordial gravitational wave signals play a very important role.

PBHs represent a nonrelativistic form of matter and thus contribute to the dark matter density. If this contribution is dominant, they can play the leading dynamical role in formation of the large-scale structure of the Universe. However, in a rather wide (if not full) range of PBH mass, observational constraints make their abundance not sufficient for this role. Even in this case, the existence of PBHs leads to important astrophysical consequences. In fact, the choice of BSM physics parameters at the edge of any observational constraint on PBHs can provide explanation of the considered phenomenon in the terms of PBH.

BSM models predicting PBH formation deeply involve fundamental particle symmetry and mechanisms of its breaking at a superhigh energy scale. Even approximate particle symmetry makes sufficiently long-living superheavy particles lightweight. The scale of symmetry breaking determines their masses, while the symmetry breaking mechanism can result in phase transitions, which can lead to formation of topological defects, both stable and metastable. Therefore, metastable superheavy particle and fields, phase transitions, and topological defects, involved in the mechanisms of PBH formation, provide reflection of the BSM symmetry and patterns of its breaking in the spectrum of primordial black holes.

Some features of Dark Universe, including PBH formation and effects, may find nontrivial origin in physics of extra dimensions or modified gravity. Multimessenger probes as well as other methods of cosmoparticle physics are completely appropriate for analysis of these extensions of the Standard model. However, these topics are beyond the scope of the present review. Some reviews of theories of modified gravity and their aspects in studies of BSM physics involving mechanisms of formation and evolution of PBHs may be found in References [59–70].

PBHs are the profound signature of the strong nonhomogeneity of the early Universe. In Section 2, we consider origin of such nonhomogeneity and its possible macroscopic forms on the example of axion-like particle (ALP) models (Sections 2.1.1 and 2.1.2). On the example of ALP models and model of spontaneous baryosynthesis, we discuss the possible relationship of the mechanism of PBH formation with the creation of antimatter domains in the baryon asymmetrical Universe and even the existence of antimatter objects in our Galaxy (Section 2.2). In Section 3, we consider mechanisms of PBH formation as cosmological reflection of BSM symmetry and pattern of its breaking. BSM physics at superhigh energy scale can lead to the prediction of superheavy metastable particles, which can dominate in the very early Universe. PBH formation at such early-matter-dominated stages plays the role of messenger of these stages and their underlying physics (Section 3.1). Symmetry breaking at the inflationary stage leads to strong enhancement of the corresponding parts of the spectrum density fluctuations. It creates PBHs at the corresponding scales messenger of such phase transitions (Section 3.2). If inflation ends by the first-order phase transition, copious mini-PBH formation is possible (Section 3.3). Such PBHs cannot survive to the present time and become a component of dark matter, but products of their evaporation can provide a sensitive tool to probe the possibility of the existence of mini-PBH. Both PBHs that have survived to the present time and evaporating PBHs are important messengers of BSM physics.

2. BSM Messengers in Primordial Nonlinear Structures

Phase transitions reflect BSM symmetry breaking pattern in the early Universe. Depending on this pattern, various stable topological defects can be formed [71–77]. Prediction of a stable defect provides a sensitive cosmological probe for the corresponding model [30]. However, even if a defect is unstable, being formed and then washed out in the succession of phase transitions, its temporary existence can lead to an observable effect, if it can leave a trace in primordial nonlinear structures. In the present section, we discuss the formation of such structures and their accompanying cosmological messengers using the example of Axion-Like-Particle (ALP) models.

2.1. Cosmological Messengers of Axion-like Particle Models

To solve the problem of strong CP violation in QCD, an additional global U(1) symmetry (Peccei–Quinn (PQ) symmetry) was proposed by R. Peccei and H. Quinn [78]. Spontaneous breaking of this global symmetry led to prediction of a pseudo-Nambu–Goldstone boson, called axion [79,80]. Constraints on QCD axions imply rather high energy scale of the spontaneous breaking of PQ symmetry. It makes axions invisible, but currently very attractive as a cold dark matter candidate (see Refs. [81,82] for review and references).

Axion-like particle (ALP) models extend axion models beyond the solution of the QCD problem. Pseudo-scalar nature of axion is not involved in such ALP models, which are effectively described by a complex pseudo-Nambu–Goldstone field:

$$\Psi = \psi \exp(i\theta),$$

whose potential leads to a two-step breaking of the global U(1) symmetry. Spontaneous U(1) symmetry breaking is determined by the vacuum expectation value $\langle \psi \rangle = f$ of the amplitude of the field Ψ. The explicit symmetry breaking is induced by the potential:

$$V_{eb} = \Lambda^4 (1 - \cos\theta). \tag{1}$$

In the model of the QCD axion, this term is generated by QCD instanton transitions, but in general, it can be initially present in the Lagrangian of an ALP model.

Spontaneous symmetry breaking at scale f results in continuous degeneracy of vacua, corresponding to any value of the phase θ. The explicit symmetry breaking takes place at smaller energy scale $\Lambda \ll f$. It changes this continuous degeneracy by discrete degeneracy of vacua, corresponding to $\theta_v = 0, 2\pi, ...$ These steps of symmetry breaking lead to phase transitions, in which unstable topological defects are formed. The character of structures, reflecting the creation and washing out of these defects, depends on the conditions in which the first phase transition with spontaneous symmetry breaking takes place; namely, whether it happens at the post-inflationary or at the inflationary stage. In both cases, the ALP field is spectator at the inflationary stage, driven by a specific inflaton field.

2.1.1. Large-Scale Correlations of the Axion Field

If the first phase, the transition proceeds at the post-inflationary stage; at high temperature after reheating, the correlation radius is small and the continuous degeneracy of vacua leads to a small local change of phase θ, which results in a close circle along which θ changes by 2π. Contraction of such a circle leads to singularity. The geometrical place of these singular points is an axion–string network. As a result, an axion–string network is formed. At the second phase transition, the initial local phase value θ acquires a dynamical meaning of the amplitude of the oscillations of the ALP field. This happens when the Hubble parameter H becomes equal to the ALP mass $m = \Lambda^2/f$ and ALP field oscillations are switched on. In the course of the second phase, the transition domain wall along the surface $\theta = \pi$ separates vacua $\theta_v = 0$ and $\theta_v = 2\pi$. The wall is formed along the surface $\theta = \pi$ and its edges coincide with the lines of strings. In this way, the axion–string network transforms into the structure of walls surrounded by strings. The structure of this topological defect is unstable, but it is reflected in the space distribution of energy density of ALP field oscillations and its large-scale inhomogeneity [11].

Local energy density of ALP field oscillation is determined by the amplitude of the field, given by the initial value of θ relative to its local vacuum value θ_v. It makes the energy density of ALP field oscillations strongly nonhomogeneous, ranging from 0 to the maximal value, corresponding to the value of θ close to π. Usually, it is assumed (see References [83,84] and references therein) that such nonhomogeneity is not essential at large distances and can be important only within the cosmological horizon in the period when oscillations start. However, the corresponding large-scale distribution of the ALP energy density reproduces the unstable topological defect pattern of the wall surrounded by string networks. The commonly accepted approach misses such correlations in the ALP large-scale distribution.

Such large-scale correlations persist at large distances, since the numerical analysis (see the review in [85]) indicates that about 80% of the string length corresponds to 'infinite' strings, which go beyond the considered volume. Therefore, if the first phase transition took place after reheating, ALP cosmology should inevitably predict large-scale correlations in the ALP energy density distribution (see Reference [11] and references therein for a review). The evolution and impact of these structures, as well as their correspondence to axion mini-clusters and Bose stars [86] need special study. Such primordial nonlinear structures should contribute to the CMB anisotropy. It puts severe constraints on the possible fraction of the ALP dark matter, if these structures persist to the period large-scale structure formation. In particular, this constraint can exclude axions as the dominant form of Cold Dark Matter [11].

Inflation provides identical initial conditions for phase transitions in causally disconnected regions. It supports large-scale correlation of inhomogeneities, formed within cosmological horizon in the very early Universe, when ALP field oscillations started.

2.1.2. Primordial Seeds for Active Galactic Nuclei

If spontaneous U(1) symmetry breaking takes place at the inflational stage, in all parts of the universe within the modern cosmological horizon, the phase is fixed by the value of θ_{60}, which the phase had in the period of inflation with e-folding $N = 60$, when the initial conditions for the observed part of the Universe were created. At successive steps of inflation, the phase θ fluctuations are of the order of:

$$\delta\theta \sim H_i/(2\pi f),$$

where H_i is the Hubble parameter at the inflational stage [11]. In the course of inflation, these fluctuations change the initial value of phase within the regions of smaller size, corresponding to $N < 60$. If $\theta_{60} < \pi$, in some regions of the universe fluctuations can move at next steps of inflation with $N < 60$ the value of θ_N to $\theta_N > \pi$.

After reheating, when the Hubble parameter decreases down to the value of ALP mass $m = \Lambda^2/f$, ALP field oscillations start, reflecting the explicit symmetry breaking and the phase transition to the discrete vacuum states. They correspond to the minima of V_{eb}, given by Equation (1). For $\theta_N < \pi$, V_{eb} has its minimum at $\theta_v = 0$. In the regions with $\theta_N > \pi$, the vacuum state corresponds to $\theta_v = 2\pi$.

If $\theta_{60} < \pi$, the true vacuum state within the dominant part of the volume of the now-observed Universe corresponds to $\theta_v = 0$. However, phase fluctuations within this volume can lead to the appearance of compact regions with $\theta_v = 2\pi$. At the border of these regions, massive domain walls are formed, separating the two vacua. These walls are closed owing to the compactness of regions with $\theta_v = 2\pi$. When closed walls enter horizon, their collapse into PBHs can take place, if the following conditions are valid.

The mass range of the formed PBHs is determined by the parameters of the ALP model, i.e., f and Λ.

The principally maximal mass of black hole is determined by the condition that the wall does not dominate locally before it enters the cosmological horizon. Otherwise, local wall dominance leads to separation of the corresponding region from the general cosmological expansion, making it a wormhole or baby Universe, and thus, elusive for the other part of the universe. This condition corresponds to the mass [87]:

$$M_{max} = \frac{m_{pl}}{f} m_{pl} (\frac{m_{pl}}{\Lambda})^2 \tag{2}$$

The condition that the gravitational radius of the wall exceeds its width defines the minimal mass of PBHs, which is equal to [87]:

$$M_{min} = f(\frac{m_{pl}}{\Lambda})^2 \tag{3}$$

Closed wall collapse leads to primordial Gravitational Wave (GW) background, peaked at [11,30]:

$$\nu_0 = 3 \times 10^{11} (\Lambda/f)\,\mathrm{Hz} \tag{4}$$

with energy density up to:

$$\Omega_{GW} \approx 10^{-4} (f/m_{pl}) \tag{5}$$

At $f \sim 10^{14}$ GeV, this primordial GW background can reach $\Omega_{GW} \approx 10^{-9}$. For the physically reasonable values of:

$$1 < \Lambda < 10^8\,\mathrm{GeV} \tag{6}$$

the maximum of the spectrum corresponds to:

$$3 \times 10^{-3} < \nu_0 < 3 \times 10^5\,\text{Hz} \tag{7}$$

Such a background may be a challenge for the experimental GW search, ranging from tens to thousands of Hz.

After the first crossing of π, a series of such crossings can take place at the successive stages of inflation, corresponding to smaller scales. It makes the largest closed wall to be accompanied by smaller walls. Their collapse can lead to the formation of PBH clusters [88]. Merging of PBHs in such cluster leads to GW signals, being another profound signature of the considered scenario. Directional detection of correlation of black hole merging in GW experiments may verify this prediction.

At the proper choice of ALP model, PBH parameters of a stellar and superstellar mass can be formed in the closed wall collapse. Their mass can be sufficient to become seeds of active galactic nuclei (AGNs) (see for a review References [11,31,88]). It can offer new solution for the problem of AGN formation [87,89]. Pending on the value of Λ, massive and even supermassive PBHs can form even after Big Bang Nucleosynthesis and avoid observational constraints, if the ALP field belongs to the hidden sector of particle theory and its interaction with SM particles is strongly suppressed.

GW signals from massive black hole merging can find interpretation in terms of massive PBHs and their clustering. Catalogs of GW signals continuously grow [90–92]. They contain the detected signals from the coalescence of massive black hole binaries (BBH). Astrophysical models of the evolution of the first stars have difficulty to explain the origin of massive black holes, if their mass exceeds the "pair instability" threshold about 50 $M_\odot$. This difficulty may be resolved, if massive and supermassive black holes have a primordial origin (see, e.g., [93] for review and references), while massive PBH clustering can facilitate BBH formation [11]. LIGO and Virgo collaborations detected GW signal from a BBH coalescence with total mass 150 $M_\odot$ [94]. This event was interpreted as possible evidence for its primordial origin [95].

Stellar evolution cannot result in formation of black holes of sub-Solar mass. Therefore, observational evidence for their existence would definitely favor their primordial origin [34].

Repeating events of BBH coalescence can provide an observational test for PBH clustering [88,96]. Confirmation of such events would strongly favor BSM models, which predict PBH cluster formation, specifying their parameters with "astronomical accuracy" [11].

Recent discovery of Stochastic Gravitational Wave Background (SGWB) by Pulsar Timing Arrays (PTA) [97] can be another messenger of ALP physics [98,99]. Large closed domain walls with mass $M > M_{max}$ start to dominate within cosmological horizon before the wall enters it as a whole. It separates this region from the surrounding Universe so that a wormhole or baby Universe is formed. The process of this separation causes strong perturbation of surrounding plasma and radiation and is accompanied by gravitational wave background radiation [98,99]. It can reproduce the PTA data.

To reach the value of π at some stage of inflation, fluctuations of phase should move θ towards π at the stages, preceding the stage, when π is crossed. Since $\theta_{60} < \pi$, fluctuations in the course of inflation towards π to the stage, at which the contour of the future domain wall is created, are accompanied by approach to π, making $\theta > \theta_{60}$ in the regions surrounding this contour. As a result, since the energy density of future ALP field oscillations are proportional to θ^2, formation of wall is accompanied in the surrounding regions by larger energy density than the average one of the ALP field in the whole observed part of the Universe. The latter is determined by θ_{60}^2. This leads to the enhanced ALP energy density in the regions, surrounding the wall. Even if the wall disappears in the baby Universe, the ALP density in the surrounding region, which remains in our Universe, is much higher than the average ALP density in the Universe. It strongly facilitates galaxy formation at the redshifts $z > 10$, indicated by the data of JWST [100]. In that way, ALP physics can simultaneously explain the PTA and JWST data [99]. The possibilities to probe such ALP physics are illustrated in Figure 2. The open question in this scenario is the evolution of the regions of the enhanced ALP density, and, in particular, whether black hole formation is possible in their central part, or if the enhanced ALP density itself plays the role of AGN seeds of early galaxies.

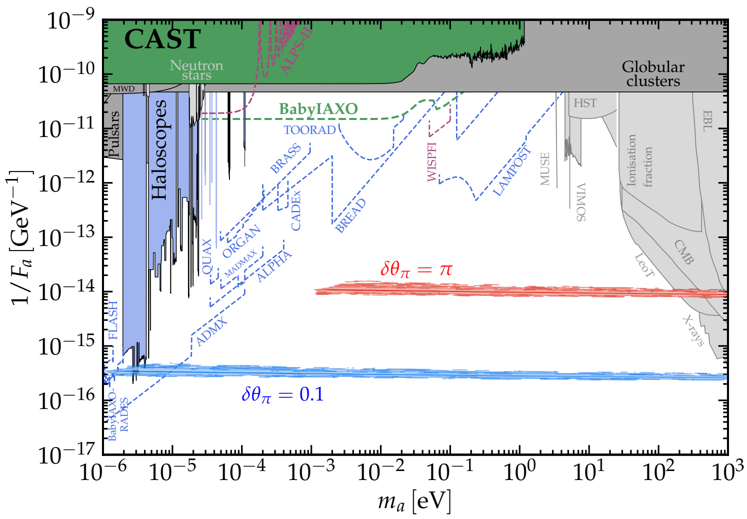

Figure 2. The possibility to explain SGWB and JWST data in the ALP model (taken from [99]).

2.2. Macroscopic Antimatter from BSM Physics

A profound signature of the strong inhomogeneity of baryosynthesis is the appearance of regions with opposite signs of baryon excess generated in the same process of creation of the observed baryon excess. Such strong inhomogeneity of baryon excess can lead antibaryon domains in the baryon asymmetrical universe [87]. To survive to the present time, the annihilation with the surrounding matter domain of antimatter should be sufficiently large. This implies proper combination of nonhomogeneous baryosynthesis and inflation. In early approaches, the combination of strong first-order phase transitions and temporary spontaneous CP violation [87] or large-scale correlation in axion distribution, involving axion as CP violating phase in baryosynthesis, were considered in [101,102].

In the ALP model of spontaneous baryosynthesis (see Reference [103] for review), as was shown in [104], proper combination of inflation and nonhomogeneous baryosynthesis can provide quantitative prediction for distribution of surviving antimatter domains.

Antimatter Domains in Baryon Asymmetrical Universe

Spontaneous baryogenesis [103,105,106] involves a complex scalar field:

$$\chi = (f/\sqrt{2})\exp(\theta),$$

which carries baryonic charge. It represents a specific type of ALP with spontaneous and explicit breaking of global U(1) symmetry of the baryon charge. The explicit breakdown of U(1) symmetry is caused by the similar phase-dependent term as the potential (1):

$$V(\theta) = \Lambda^4(1-\cos\theta) \tag{8}$$

The field χ interacts with matter fields with violation of baryon and lepton numbers [103]:

$$\mathcal{L} = g\chi\bar{Q}L + \text{h.c.}, \tag{9}$$

where heavy quark Q and heavy lepton L are coupled to the ordinary matter fields.

In the course of the post inflational stage, the rate of expansion H slows down and becomes comparable with the mass $m_\theta = \frac{\Lambda^2}{f}$. Then, the phase θ acquires dynamical meaning. It starts to oscillate around the minimum of its potential (8) and decay to matter fields, generating baryon and lepton excess. It creates the baryon excess, when the phase rolls down in the clockwise direction [103]. If it rolls down in the opposite anticlockwise direction, the antibaryon excess is generated. It makes the sign of the baryon excess to be determined by the initial value of θ, given at the inflational stage.

This mechanism of baryon excess generation is illustrated in Figure 3. The value of phase θ_{60} at the e–fold $N = 60$ corresponds to the observed part of the modern Universe. If it is in the range $[\pi, 0]$, the baryon excess, corresponding to the observed baryon asymmetry, is generated. However, at each successive e–fold, corresponding to smaller scales, this value fluctuates and experiences Brownian steps

$$\delta\theta = H_i/(2\pi f).$$

Here H_i is the Hubble parameter at the inflational stage. In the course of inflation the e-fold N decreases from 60 to 0. The region, containing phase θ_N at the e–fold N is divided at e–fold $N-1$ into e^3 causally disconnected domains. Each new domain contains almost homogeneous phase value:

$$\theta_{N-1} = \theta_N \pm \delta\theta.$$

Such phase fluctuations continue in every domain with each successive step of inflation. At some e–fold N, the phase θ_N can cross the value of π. In such a domain with $\theta_N > \pi$, the minimum of potential (8) is 2π. The rolling down to it is anticlockwise and antibaryon excess is generated in this region. Such region of antibaryon excess is surrounded by baryon excess outside it.

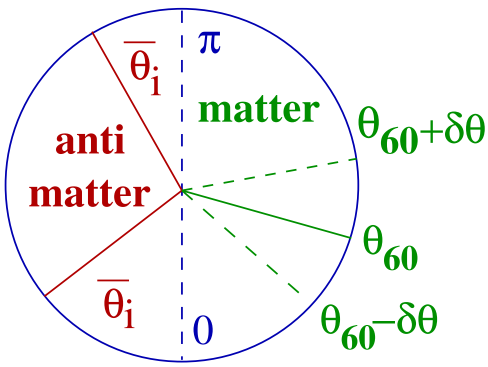

Figure 3. The evolution of the phase at the inflational stage. This original author's figure was published in Reference [11].

Evolution of antimatter domains depends on their size and antibaryon density. To survive annihilation with surrounding matter their size must exceed the critical surviving scale $L_c = 8h^2$ kpc [87]. Then, diffusion to the borders of domain cannot lead to their complete dissipation. If antibaryon density is low, diffused antimatter regions can be formed. Neither nucleosynthesis nor recombination are possible in such domains with low antibaryon density. They should appear as regions of low-density antiproton–positron plasma [87].

Sufficiently dense antimatter domains can evolve in antibaryon objects. Such objects can be present in our Galaxy. Assuming similarity of antimatter evolution with the one of the baryonic matter, a hypothesis of antimatter globular cluster in our Galaxy was put forward [87]. This idea looked rather attractive. Such a cluster in the halo of our Galaxy cannot be a bright gamma-ray source. Density of matter gas in halo is low, and annihilation can take place only on the surface of antimatter stars. Antimatter, lost by such a cluster and annihilating with matter gas in the Galaxy, can contribute to the observed galactic gamma background. The data on this background are in the range of tens–hundreds MeV [87], which puts an upper limit on the total mass of antimatter of about $10^5 M_\odot$ [87]. Together with minimal estimation of the mass of surviving antimatter domain (about $10^3 M_\odot$ [87]) the total mass M of antimatter in our Galaxy was obtained as $10^3 M_\odot < M < 10^5 M_\odot$ [87]. This mass interval is typical for galactic globular clusters and appealed to search for a candidate of a cluster of antimatter stars among them. Assuming that the expected antihelium component of cosmic rays is proportional to the ratio of the total masses of antimatter and matter in our Galaxy the predicted flux of cosmic ray antihelium was shown to be accessible for its search in the AMS02 experiment [87]. If the existence of such component is confirmed, such antinuclei can hardly have a secondary origin [107].

Symmetry of matter and antimatter celestial objects seemed to make possible to consider antimatter meteorites [87] for direct experimental test of macroscopic antimatter in our Galaxy. However, the basic problem of such consideration, as well as of the hypothesis of antimatter globular cluster as a whole, is the principal difference in chemical evolution of matter in Galaxy and antimatter, localized in domain. Chemical evolution of matter in our Galaxy strongly involves mixture of products of stellar nucleosynthesis and existence of giant molecular clouds, giving rise to creation of molecules, dust, planetesimals, etc., which cannot be formed in the localized region of antimatter. Products of nuclear reactions in antimatter stars cannot come to this region from surrounding matter, while these products are easily lost and annihilate in the interstellar matter gas. Antimatter stars should contain only primordial antinuclear abundance (in the wide range of antibaryon densities, it is antihydrogen and antihelium-4) and it makes hardly possible their enrichment in metallicity from products of antistellar nucleosynthesis. Proper description of possible forms of celestial antimatter objects needs special study, but the presence of primordial antihelium in them makes antihelium-4 component of cosmic rays a stable signature of macroscopic antimatter in our Galaxy.

The value $\theta_{60} \ll \pi$ determines the averaged density of baryonic matter in the Universe. If fluctuations move the phase to $\theta > \pi$, antimatter domain may have much higher antibaryon density than baryon density in the Universe. Then, very dense self-gravitating antibaryon systems can form. Their evolution can differ substantially from ordinary baryonic matter [11]. It can lead to formation of superdense antibaryonic objects in our Galaxy. The possibility of such dense antimatter objects as well as the strategy of their search was discussed in [108].

To survive, antimatter domain should be sufficiently large. Crossing π leads to formation of domain wall on its border. If the wall starts to dominate, before it enters the horizon as a whole, such a domain can escape from our Universe in a self-closed world of a baby Universe. This condition can put an upper limit on the possible size of the dense antimatter domain, unless there is a mechanism of wall dissipation.

To conclude, the list of cosmological messengers of the Dark Universe is enriched by the strong primordial inhomogeneities. Primordial black holes play special role in this list. In the next section we consider the variety of PBH probes for physics of Dark Universe.

3. Physics of Dark Universe in Primordial Black Hole Formation

3.1. PBH Messenger of Early Matter Domination

For the cosmological equation of state given by:

$$p = \gamma\epsilon, \tag{10}$$

with γ in the range:

$$0 \leq \gamma \leq 1 \tag{11}$$

formation of a black hole from a fluctuation with dispersion:

$$\left\langle \delta^2 \right\rangle \ll 1 \tag{12}$$

has the probability given by [8]:

$$W_{PBH} \propto \exp\left(-\frac{\gamma^2}{2\langle\delta^2\rangle}\right). \tag{13}$$

As can be seen from Equation (13), the PBH spectrum is exponentially sensitive to the parameter γ of the equation of state and amplitude $\langle\delta^2\rangle$ of fluctuations. The exponential suppression can be relaxed, if the equation of state is soft, ($\gamma \to 0$) or the amplitude of fluctuations is enhanced ($\langle\delta^2\rangle \to 1$).

Such enhancement can be a signature of BSM physics [31]. Softening of the cosmological equation of state takes place at early matter-dominated stage, implemented by superheavy metastable particles and fields predicted by BSM models. BSM symmetry breaking leads to strong nonhomogeneity of the very early Universe. We discuss these aspects of PBH formation in their relationship with BSM physics in the present section.

3.1.1. PBHs from Dominance of Superheavy Particles

BSM symmetry breaking at very high energy scale can lead to the existence of superheavy metastable particles and fields with lifetime $\tau \ll 1\,\mathrm{s}$. Such predictions cannot be directly probed by in the astrophysical means. However, at the stage of dominance of such particles or fields before their decay at $t \leq \tau$ PBHs can be formed. The spectrum of these PBHs keeps information on properties of such particles and fields after their decay [109]. Comparison of the predicted effect of these PBHs with the astrophysical data provides a multi-step probe for the existence of such particles and fields.

After reheating, the Universe can be radiation dominated, but at the following temperature:

$$T < T_0 = rm \tag{14}$$

particles with mass m and relative abundance $r = n/n_r$ can start to dominate. Here, n is the particle number density and n_r that of relativistic species. At the matter dominance of nonrelativistic particles at $t > t_0$ density fluctuations grow. Here:

$$t_0 = \frac{m_{pl}}{T_0^2} \tag{15}$$

and density fluctuations grow with time as:

$$\delta(t) = \frac{\delta\rho}{\rho} \propto t^{2/3}. \tag{16}$$

In the course of development of gravitational instability, fluctuations, which enter the horizon with amplitude $\delta(t_i)$ at $t = t_i > t_0$, grow to $\delta(t_f) \sim 1$. This leads to the formation of gravitationally bound systems. These systems decouple from general cosmological expansion at:

$$t \sim t_f \approx t_i \delta(t_i)^{-3/2}, \tag{17}$$

Here, we discuss possible mechanisms of black hole formation at the matter-dominated stage in the context of the reflection of BSM features in this spectrum. They can be formed directly after the system decouples from expansion (Section 3.1.2) and this mechanism is universal and independent of the nature of superheavy particles or fields. The formation of a black hole can be the result of the evolution of the gravitationally bound systems (Section 3.1.3). Such an evolution strongly depends on the particle properties.

3.1.2. Direct PBH Formation

After the gravitationally bound configuration decouples from the expansion, it starts to contract. If it can manage to contract within its gravitational radius, it collapses in a black hole. Such a direct collapse is possible if the configuration is especially Homogeneous and isotropic. Probability of this direct collapse is determined by the probability of the appearance of such a specially homogeneous and isotropic configuration. It gives the minimal universal estimation of a black hole formation at the matter-dominated stage, being independent of the nature of the dominating form of the nonrelativistic matter.

This probability was calculated in Reference [109]. It is reduced to evaluation of a probability for the configuration to have such a high sphericity and homogeneity that it can contract within its gravitational radius. It is sufficient that configuration can contract within the size, which it had, when it entered the horizon, corresponding to its gravitational radius. These conditions deal with the geometrical properties of the fluctuation. They turn to be independent of the physical nature of the dominating matter. It was shown that the same probability is valid for both the collisionless and self-interacting nonrelativistic matter [31].

The configuration should be sufficiently spherical to provide its isotropic contraction within the size, which it had, when it entered horizon at $t - t_i$. If $\delta(t_i)$ is the amplitude of fluctuation at $t - t_i$, such sufficient sphericity has the probability [31,109]:

$$W_s \sim \delta(t_i)^5. \tag{18}$$

In addition to isotropic, the contraction should be sufficiently homogeneous to allow entering of the whole configuration within its gravitational radius. Nonhomogeneous isotropic collapse of collisionless gas leads to escape of the part of the mass from this region, after passing caustics. In the case of a dissipational matter, nonhomogeneus collapse leads to a shock wave, preventing contraction of the whole mass within its gravitational radius. It was shown in [31,109] that the probability of sufficient homogeneity is the same in the both cases and is equal to:

$$W_u \sim \delta(t_i)^{3/2}. \tag{19}$$

The product of these two probabilities results in the strong power-law suppression of probability for the considered mechanism of direct black hole formation:

$$W_{PBH} = W_s \cdot W_u \sim \delta(t_i)^{13/2} \tag{20}$$

The calculation [31,109] does not involve any specific form of Gaussian distribution for fluctuations. Therefore, it can be also appropriate in a case of non-Gaussian fluctuations [110].

The mechanism [10,31,109] provides formation of PBHs with mass in an interval:

$$M_0 \leq M \leq M_{bhmax} \tag{21}$$

In Equation (21), the minimal mass corresponds to the mass within the cosmological horizon at $t \sim t_0$, when matter dominance began. This minimal mass is equal to [10,109]

$$M_0 = \frac{4\pi}{3}\rho t_0^3 \approx m_{pl}(\frac{m_{pl}}{rm})^2. \tag{22}$$

The maximal mass is determined by the condition:

$$\tau = t(M_{bhmax})\delta(M_{bhmax})^{-3/2}. \tag{23}$$

The condition (23) means that the fluctuation can manage to grow, separate from the cosmological expansion and collapse before particles decay at $t = \tau$. It assumes that the mass M_{bhmax} enters horizon at $t(M_{bhmax})$ and has an amplitude $\delta(M_{bhmax}) \ll 1$. If spectrum is scale-invariant $\delta(M) = \delta_0$, the maximal mass is equal to [87]:

$$M_{bhmax} = m_{pl}\frac{\tau}{t_{Pl}}\delta_0^{-3/2} = m_{pl}^2 \tau \delta_0^{-3/2} \tag{24}$$

The probability, given by Equation (20), is independent on the nature of the dominating matter. Therefore, it is also appropriate for the PBH formation, if the preheating stage after inflation is matter dominated [10,111].

At a small amplitude of fluctuations $\delta(M) \ll 1$, the fraction of total density corresponding to PBHs with mass M is small, being determined by the probability $W_{PBH}(M)$:

$$\beta(M) = \frac{\rho_{PBH}(M)}{\rho_{tot}} \approx W_{PBH}(M). \tag{25}$$

It means that the dominant fraction of particles does not collapse directly into PBHs. They form nonrelativistic gravitationally bound systems. The evolution of these systems strongly depends on particle properties. The account for such evolution can substantially enhance the fraction of nonrelativistic matter forming PBHs at early matter-dominated stages.

3.1.3. Evolutionary Formation of PBHs

Depending on particle properties, gravitationally bound systems can be compared with modern galaxies with collisionless gas of stars or with stars, in which evolution is determined by radiative energy loss. Though any gravitationally bound systems is unstable relative to collapse to a black hole, the evolution timescale strongly depends on the mechanisms of dissipation, which differ in these two cases.

In the gravitationally bound system of collisionless gas dissipation is a very slow process. It is determined by evaporation of particles, whose velocity exceeds the escape velocity [10,112]. If such particles appear in gravitational binary collisions, the evolution timescale [10,112] is given by:

$$t_{ev} = \frac{N}{\ln N} t_{ff}. \tag{26}$$

where N is the total number of massive particles in the system and t_{ff} is the free fall time. This evolution timescale may be shorter with the account for collective effects in collisionless gas [113]. At large N, it can be in the order of:

$$t_{ev} \sim N^{2/3}.t_{ff} \tag{27}$$

For a system with density ρ, the free fall time is given by:

$$t_{ff} \approx (4\pi G\rho)^{-1/2}.$$

It is in the order of cosmological time t_f corresponding to the period when gravitationally bound systems of collisionless gas are formed at the matter-dominated stage. Therefore, even with the account for collective effects, the timescale of black hole formation in the evolutionary process is very long $t_{ev} \gg t_f$. The collisionless particles should be very long-living ($\tau \gg t_f$) to form black holes in the evolution of their gravitationally bound systems.

The evolutionary time scale is much smaller, if superheavy particles interact with light relativistic particles and radiation. Such star-like systems could be formed by superheavy color octet fermions, which were predicted in asymptotically free SU(5) model (see Reference [11] for a review and references). Color interaction of these fermions makes their gas dissipative. Another example would give matter dominance of magnetic monopoles of GUT models. If the initial abundance of such monopoles with mass 10^{16} GeV is not suppressed by inflation, their frozen out abundance had to be $r \sim 10^{-9}$ [73,74]. It made inevitable the magnetic-monopole-dominated stage at $T < 10^7$ GeV. The hope was that monopoles and antimonopoles can annihilate in gravitationally bound systems, formed at this stage, and their abundance can be reduced in this way. However, as shown in detailed numerical simulation (see Reference [11] for review and references), the dominant fraction of mass of these systems can collapse in a black hole and the annihilation cannot prevent the collapse. Instead of magnetic monopole overproduction, PBH overproduction had to take place in this case.

The timescale of PBH formation in the evolution of star-like objects is comparable with the cosmological time, when these objects are formed. The PBH spectrum is peaked at the value, given by Equation (22). It corresponds to the mass within the cosmological horizon in the period, when early matter dominance started.

3.2. PBHs from Phase Transitions in the Inflationary Stage

The data of the precision cosmology favor a slight decrease of the amplitude of density fluctuations to smaller scales. Such a red spectrum follows the prediction of single-field inflation. However, this trend is observed on the large scales. It is based on observations of Cosmic Microwave Background (CMB) and Large-Scale Structure (LSS). On scales smaller than clusters of galaxies, matter is distributed nonhomogeneously. Its observed strong inhomogeneity can easily mask strong deviations from the red spectrum at smaller scales. These deviations can reflect the symmetry-breaking pattern of BSM models.

The symmetry-breaking pattern can involve other scalar fields to be present in the period of inflation. It can lead to spikes in the spectrum of density fluctuations, reflecting parameters of the scalar fields and their interaction with inflaton. This possibility was first revealed in the chaotic inflation scenario [114]. Spikes strongly enhance the amplitude of fluctuations and, correspondingly, increase the probability of PBH formation on these scales. It makes the PBH spectrum a sensitive probe for the prediction of such fields.

This sensitivity can be illustrated by the example of a phase transition in the chaotic inflation scenario. The phase transition is induced by interaction of a Higgs field ϕ with inflaton η (see [11] for review and references). Such an interaction can induce positive mass term $+\frac{\nu^2}{2}\eta^2\phi^2$. The amplitude of the inflaton field decreases in the model of chaotic inflation. As a result, at a certain value $\eta_c = m/\nu$, the mass term in Higgs potential changes sign:

$$V(\phi, \eta) = -\frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\nu^2}{2}\eta^2\phi^2 \tag{28}$$

At this stage of the inflaton phase, a transition takes place. It results in a characteristic spike in the spectrum of fluctuations. These spike-like features are generated at a e–fold ($60 \geq N \geq 1$). They strongly enhance PBH formation at the corresponding scale.

The amplitude δ of a spike is given by [11]:

$$\delta \approx \frac{4}{9s} \tag{29}$$

with:

$$s = \sqrt{\frac{4}{9} + \kappa 10^5 \left(\frac{v}{m_{pl}}\right)^2} - \frac{3}{2}, \tag{30}$$

where the vacuum expectation value of a Higgs field is taken as:

$$\langle \phi \rangle = \frac{m}{\lambda} = v, \tag{31}$$

where $\lambda \sim 10^{-3}$ and $\kappa \sim 1$.

The spikes, reentering horizon at the radiation dominated (RD) stage, enhance formation of PBHs with the mass

$$M \approx \frac{m_{Pl}^2}{H_i} \exp\{2N\}, \tag{32}$$

where H_i is the Hubble parameter in the period of inflation.

The spikes, which reenter horizon in the matter-dominated (MD) stage, induce formation of PBHs with the mass:

$$M \approx \frac{m_{Pl}^2}{H_0} \exp\{3N\}. \tag{33}$$

The model of horizontal unification [10] predicts several steps of family symmetry breaking. It leads to succession of phase transitions. Such phase transitions should take place in the inflationary stage, if the energy scale of this is high. It leads to the enhancement of PBH formation by the corresponding spikes. Upper limits on PBHs in the corresponding mass range put severe constraints on the scale of family symmetry breaking [11].

3.3. PBHs Formation in First-Order Phase Transitions

If cosmological phase transition is of the first order, it goes through nucleation of bubbles of true vacuum. The bubbles expand in the false vacuum [115]. In the course of this expansion, energy of the false vacuum converts into the kinetic energy of bubble walls. The bubble expands until it collides with another bubble. Collision of several bubbles can create a black hole [116,117]. The probability of a collision of only two bubbles is much higher. PBH formation in such processes seemed to be forbidden by the strict conservation of the O(2,1) symmetry. However, the mechanisms of breaking of this symmetry was revealed (see Reference [87] for review and references). It makes possible PBH formation with probability of order unity in collisions of only two bubbles. This mechanism of PBH formation provides a sensitive probe for the pattern of BSM symmetry breaking, reflected in first-order phase transitions in the early Universe.

Inflation can end by a first-order phase transition [118–125]. Such a phase transition is completed when the true vacuum percolation regime is established. Percolation means that at least one bubble per unit Hubble volume is nucleated. This corresponds to the following condition [125]:

$$Q \equiv \frac{4\pi}{9}\left(\frac{\Gamma}{H^4}\right)_{t_{end}} = 1, \tag{34}$$

where Γ is the bubble nucleation rate. In (34), H is the Hubble constant in the period of transition. If PBH is formed in the collision of two bubbles, the mass of such PBH is given by [87]:

$$M_{BH} = \gamma_1 M_{bub}, \tag{35}$$

where $\gamma_1 \simeq 10^{-2}$ and M_{bub} is the mass within the bubble volume in the period of collision. Then, the collision of bubbles would lead to copious formation of PBHs with masses:

$$M_0 = \gamma_1 M_{end}^{hor} = \frac{\gamma_1}{2}\frac{m_{pl}^2}{H_{end}}. \tag{36}$$

Here M_{end}^{hor} is the mass within the Hubble horizon at the end of inflation. This mass coincides with M_{bub} in Equation (35). Then, the mass fraction of these PBHs is given by [87] $\beta_0 \approx \gamma_1/e \approx 6\times 10^{-3}$. If the Hubble parameter in the end of inflation $H_{end} \approx 4\times 10^{-6}\, m_{pl}$, PBHs with mass $M_0 \approx 1$ g are formed in the first-order phase transition with the mass fraction β. Such mini PBHs experience Hawking evaporation [126,127] at $t \sim 10^{-27}$ s. However, products of their evaporation must lead to observable effects, discussed in the next subsection.

Physics of Dark Universe can involve first-order phase transitions in the dark sectors. The underlying symmetry breaking pattern can find cosmological messengers in PBHs and the accompanying gravitational wave background. It makes necessary a detailed analysis of these messengers. In particular, lattice calculations did not confirm PBH formation in bubble wall collisions [128]. However, these calculations did not take into account formation and evolution of false vacuum bag, studied in [129]. On the other hand, studies of formation and evolution of a false vacuum bag found rather probable formation of oscillons. Their evolution does not lead to collapse in PBHs. Physics of Dark Universe in the relationship between oscillons, PBHs, and the gravitational wave background remains an open question, which deserves special study.

4. Dark Matter from PBHs

4.1. PBHs as the Form of Dark Matter

PBHs with mass $M > 10^{15}$ g should survive to the present time. This nonrelativistic form of matter should be a component of dark matter in this case. Assumption of a monochromatic PBH spectrum seems to exclude PBH as the dominant form of cosmological dark matter (see Figure 4). The constraints presented on this figure may be relaxed with the account for PBH clustering, nonmonochromatic spectrum of PBHs, or critical analysis of the observational constraints [88,130]. It may admit PBHs in the mass interval:

$$10^{18} < M < 10^{22}\ \mathrm{g} \tag{37}$$

as the dominant form of the cosmological dark matter [33,88,130]. It was recently claimed that a major portion of this logarithmic window can be closed by the Solar system ephemeris [131]. It is argued that the external mass enclosed within 50 astronomical units from the Sun did not change in recent decades by more than $\sim 5 \cdot 10^{-14} M_\odot\ \mathrm{yr}^{-1}$. However, stability of these data and the validity of this conclusion was questioned in [132], leaving room for PBHs in the mass interval (37) to dominate in the cosmological dark matter.

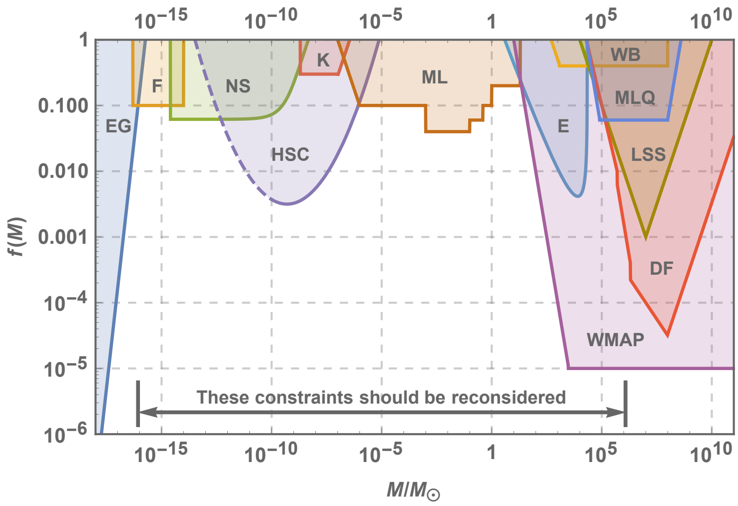

Figure 4. Existing constraints on PBH dark matter taken from [88]. The relative contribution into the dark matter density is constrained for monochromatic PBH mass distribution. The strongest constraints in the corresponding PBH mass ranges are obtained from: EG—extragalactic gamma-ray background observation, F—femtolensing, NS—neutron star destruction, HSC—searches for gravitational microlensing events by Subaru Hyper Suprime-Cam, K—Kepler satellite, ML—MACHO searches, MLQ—quasars millilensing, WB—wide binary destruction, E—star cluster destruction in Eridanus dwarf galaxy, WMAP—CMB distortion due to accretion effects, DF—effects of dynamical friction in our Galaxy and LSS—large-scale structure. As was stated in Reference [88], these constraints should be reconsidered to account for PBH clustering in the mass range, as indicated by the double-headed arrow.

Even if the observational constraints are strengthened and PBHs cannot explain the dominant form of dark matter, their existence would add a new aspect in the cosmological evolution. In this case, the edges of observational constraints convert into the PBH-based explanation of the corresponding phenomenon. The same is valid for small mass PBHs, which do not survive to the present time, but can leave observational evidence for their presence in the early Universe.

4.2. PBH Evaporation as Universal Particle Accelerator

Though PBH evaporation [126,127] makes it impossible for PBHs of small mass to survive to the present time, its effects strongly increase the sensitivity of the astrophysical data to the presence of such PBHs in the early Universe. It can strengthen observational probes for the mechanisms of PBH formation, related to physics of Dark Universe [10,11,31]. Analysis of effects of PBH evaporation has led to stringent upper limits for PBHs with initial masses between $\sim 10^9$ g and $\sim 10^{16}$ g (see References [31,133–135]). The observational constraints follow either from the direct effects of the products of evaporation (for PBHs with masses between 10^{14} g and 10^{16} g) or from indirect effects of the interaction of such products with matter and radiation (for PBH masses between 10^9 g and 10^{14} g). Evaporated nonequilibrium particles can influence the entropy per baryon, the deuterium destruction, the ^{4}He destruction, and the ^{3}He production, lead to distortions of the black body CMB spectrum, and put contributions to the cosmic-rays, gamma rays, and high energy neutrino backgrounds. It makes evaporating PBHs a specific source of nonequilibrium particles, constrained by the abovementioned data, as shown in Figure 5.

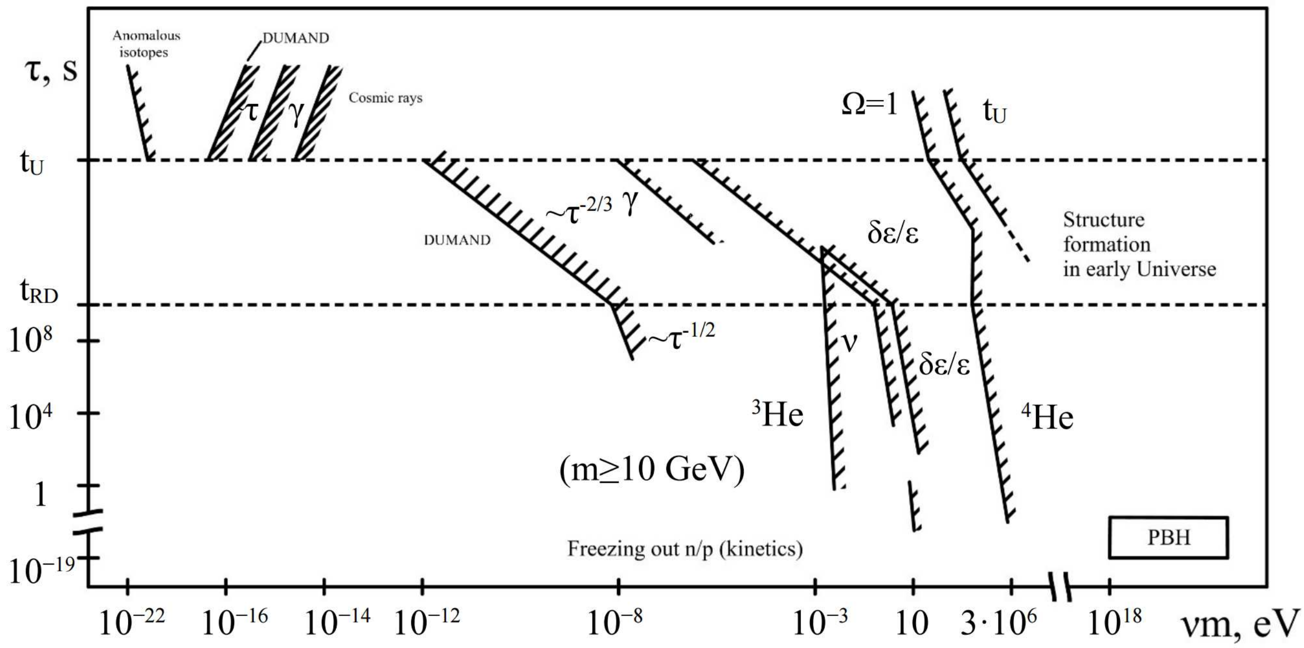

Figure 5. Constraints on nonequilibrium particles, originated from decays of particles with mass m and relative concentration $\nu = n/n_\gamma$ at different periods τ of cosmological evolution. The original author's figure is published in [10].

However, evaporation is originated by the gravitational field. Therefore, any particle which exists in our space-time possesses gravitational interaction and can be among the products of evaporation, if the particle mass does not exceed significantly the black hole temperature, T_{PBH}. In the course of evaporation, PBH mass decreases with corresponding growth of T_{PBH}. It makes possible copious production of supermassive particles at the last stages of evaporation.

If PBH vanishes completely [127], the effects of nonequilibrium particles—products of evaporation—can provide the test for their existence. If PBH evaporation can leave a stable relic (see References [133,136–138]) with a mass of order $m_{rel} = km_{pl}$ $(1 \leq k \leq 10^2)$, the constraints on such PBHs may be strengthened [11,87]. Taking into account the observational constraints on PBHs [11,31,139–144], the coexistence of stable remnants of PBH evaporation with the first-order phase transitions at the end of inflation can be excluded. The mechanism of PBH formation in the first-order phase transitions, described in Section 3.3, results in formation of nonsingular black holes, in which vacuum-like false vacuum dark energy is concentrated within its gravitational radius. Specific features of evaporation of such nonsingular black holes may strongly influence the rate of evaporation and the corresponding constraints [145,146].

PBH evaporation can provide copious production of superweakly interacting particles. Owing to their superweak interaction, such particles cannot be frozen out, since they have never been in equilibrium with the hot plasma and radiation. The source of such particles in the early universe is their freeze-in due to the rare superweak processes of their production. Mini-PBH evaporation strongly enhances their frozen-in abundance.

In particular, superweakly interacting gravitino can be copiously produced in PBH evaporation [10,11,87,147] (see also [148,149]). Mini-PBHs with a mass $M \leq 10^9$ g evaporate before BBN. Their evaporation can only influence entropy production. Production of gravitino in the evaporation of such PBHs increases the sensitivity of astrophysical data to their existence and presence in the early Universe. Astrophysical constraints on gravitino provide in this case the probe for the mechanisms of mini-PBH formation [147]. It makes possible to study the BSM physics, underlying these mechanisms.

Metastable Gravitino

Local supersymmetry as well as supergravity predict the supersymmetric partner of graviton-gravitino. Gravitino coupling is suppressed by the factor $1/m_{Pl}$ leading to its superweak semi-gravitational interaction. If gravitino is not the Lightest Supersymmetric Particles (LSP), it is unstable, but the lifetime determined by this semi-gravitational coupling can be long, given by:

$$\tau \propto \frac{m_{Pl}^2}{m_G^3}. \tag{38}$$

If the the mass of gravitino $m_G \leq 10^4$ GeV, gravitino decays after BBN. Then, products of gravitino decay change light element abundance due to interaction with nuclei. It makes primordial chemical abundance a sensitive tool for testing gravitino existence and effects. Constraints on gravitino put restrictions on mechanisms of its production. It provides constraints on important features of inflationary cosmology, such as reheating temperature [10,150–152] or mini-PBH formation [11,30,147–149,153].

5. Discussion

For a long time, primordial black holes seemed a rather exotic and improbable phenomenon in the homogeneous and isotropic Universe. However, the development of the cosmological consequences of particle theory revealed fundamental reasons for strong nonhomogeneity of the early Universe, reflecting BSM symmetry and a symmetry breaking pattern. It made PBHs a profound signature of such inhomogeneity, and their existence would lead beyond the standard paradigm of the Big Bang Universe.

If PBHs exist and their mass exceeds 10^{15} g, they contribute into the dark matter density. They can be the dominant DM component, but even if their contribution is small, their existence would shed new light on the nature of many astrophysical phenomena. Mini-PBHs evaporate and do not survive to the present time, but their evaporation is the unique source of supermassive and/or superweakly interacting particles, which cannot be easily produced in the equilibrium of the hot plasma. In this case, PBHs cannot play role of dark matter, but their evaporation can be the source for dark matter particles. On the other hand, mechanisms of PBH formation involve physics of axion-like particle models or mechanisms of neutrino mass generation. They can reflect phase transitions, and thus, reflect the pattern of the BSM symmetry breaking as well as the extensive hidden sector of particle theory.

PBH formation can imply specific models of inflation and baryosynthesis. It may be accompanied by the generation of gravitational waves or nonhomogeneity of the baryon excess, reflected in the appearance of antimatter macroscopic objects in the baryon asymmetrical Universe. It involves PBH in the complex of multimessenger probes for the BSM physics, governing cosmological evolution.

To conclude, the exploration of the physical nature of the Dark Universe would inevitably lead beyond the standard physical and cosmological models. It implies model-dependent multimessenger probes, in which BSM physics of PBH origin plays unique and important role. We tried to give a brief review of BSM physics with an emphasis on its possible cosmological messengers, which may have already appeared in the data of gravitational wave signals, detected by LIGO–Virgo–KAGRA, accounted for in the discovery of the Stochastic Gravitational Wave Background by PTA, indicated in early galaxy and AGN formation at $z > 10$, claimed by JWST, accounted for during researching the possibility of the existence of an antihelium component of cosmic rays, and thoroughly studied by AMS02. These possible signatures of the Dark Universe, in which the physics of the origin of PBH and its effects play an important role, may be considered as the harbinger of a major discovery of new physics, on which the cosmology of Dark Universe is based.

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