FUNDAMENTAL PARTICLE STRUCTURE IN THE
COSMOLOGICAL DARK MATTER

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The nonbaryonic dark matter of the Universe is assumed to consist of new stable forms of matter. Their stability reflects symmetry of micro world and mechanisms of its symmetry breaking. Particle candidates for cosmological dark matter are lightest particles that bear new conserved quantum numbers. Dark matter particles may represent ideal gas of non-interacting particles. Self-interacting dark matter weakly or superweakly coupled to ordinary matter is also possible, reflecting nontrivial pattern of particle symmetry in the hidden sector of particle theory. In the early Universe the structure of particle symmetry breaking gives rise to cosmological phase transitions, from which macroscopic cosmological defects or primordial nonlinear structures can be originated. Primordial black holes (PBHs) can be not only a candidate for dark matter, but also represent a universal probe for super-high energy physics in the early Universe. Evaporating PBHs turn to be a source of even superweakly interacting particles, while clouds of massive PBHs can serve as a nonlinear seeds for galaxy formation. The observed broken symmetry of the three known families may provide a simultaneous solution for the problems of the mass of neutrino and strong CP violation in the unique framework of models of horizontal unification. Dark matter candidates can also appear in the new families of quarks and leptons and the existence of new stable charged leptons and quarks is possible, hidden in elusive “dark atoms”. Such possibility, strongly restricted by the constraints on anomalous isotopes of light elements, is not excluded in scenarios that predict stable double charged particles. The excessive -2 charged particles are bound in these scenarios with primordial helium in O-helium “atoms”, maintaining specific nuclear-interacting form of the dark matter, which may provide an interesting solution for the puzzles of the direct dark matter searches. In the context of cosmoparticle physics, studying fundamental relationship of micro- and macro- worlds, the problem of cosmological dark matter implies cross disciplinary theoretical, experimental and observational studies for its solution.

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1. Introduction

The convergence of the frontiers of our knowledge in micro- and macro worlds leads to the wrong circle of problems, illustrated by the mystical Ouroboros (self-eating-snake). The Ouroboros puzzle may be formulated as follows: *The theory of the Universe is based on the predictions of particle theory, that need cosmology for their test.* Cosmoparticle physics offers the way out of this wrong circle. It studies the fundamental basis and mutual relationship between micro-and macro-worlds in the proper combination of physical, astrophysical and cosmological signatures. Some aspects of this relationship, which arise in the problem of cosmological Dark Matter (DM), is the subject of this review.

Extensions of the standard model imply new symmetries and new particle states. The respective symmetry breaking induces new fundamental physical scales in particle theory. In particle theory Noether’s theorem relates the exact symmetry to conservation of respective charge. If the symmetry is strict, the charge is strictly conserved. The lightest particle, bearing this charge, is stable. It gives rise to the fundamental relationship between dark matter candidates and particle symmetry beyond the Standard model.

If the symmetry is broken, the mechanism of the symmetry breaking implies restoration of the symmetry at high temperatures and densities. Such high temperatures and densities should have naturally arisen at the early stages of cosmological evolution. It makes Big Bang Universe natural laboratory of particle physics, not only due to possibility of creation of hypothetical particles in the early Universe, but also owing to reflection of the hierarchy of particle symmetry breaking in cosmological phase transitions.

In the old Big Bang scenario cosmological expansion and its initial conditions were given *a priori*. In the modern cosmology expansion of Universe and its initial conditions are related to inflation, baryosynthesis and nonbaryonic dark matter (see review in Refs. 18–21). The global properties of the Universe as well as the origin of its large scale structure are considered as the result of the process of inflation. The matter content of the modern Universe is also originated from the physical processes: the baryon density is the result of baryosynthesis and the nonbaryonic dark matter represents the relic species of physics beyond the Standard model. Here we would like to outline some nontrivial forms of relationship between the cosmological problem of dark matter with the fundamental symmetry of particle world.

According to the modern cosmology, the dark matter, corresponding to $\sim 25\%$ of the total cosmological density, is nonbaryonic and consists of new stable forms of matter. These forms of matter (see e.g. Refs. 3, 5, 7, 22–24 for review and reference) should be stable, saturate the measured dark matter density and decouple from plasma and radiation at least before the beginning of matter dominated stage. The easiest way to satisfy these conditions is to involve neutral elementary weakly interacting particles. However it is not the only particle physics solution for the dark
matter problem and more evolved models of the physical nature of dark matter are possible.

Formation of the Large Scale Structure of the Universe from small initial density fluctuations is one of the most important reasons for the nonbaryonic nature of the dark matter that is decoupled from matter and radiation and provides the effective growth of these fluctuations before recombination. It implies dark matter candidates from the physics beyond the Standard model (see Refs. 24–28 for recent review). On the other hand, the initial density fluctuations, coming from the very early Universe are also originated from physics beyond the Standard model. In the present review we give some examples, linking the primordial seeds of galaxy formation to effects of particle symmetry breaking at very high energies.

Here we don’t touch the exciting problems of the possible nature of dark matter related with extra dimensions and brane cosmology, but even in the case of our 1+3 dimensional space-time we find a lot of examples of nontrivial cosmological reflection of fundamental particle structure.

In the Section 2 we present examples of cosmological pattern of fundamental particle symmetry: from various types of stable particle candidates for dark matter to primordial nonlinear structures, relics of phase transitions in the very early Universe. We then pay special attention to primordial black holes as a universal theoretical probe for new physics in the very early Universe (Section 3). We give an example of a possibility to incorporate various types of dark matter within a unique framework of broken gauge symmetry of the three known families as well as discuss a possibility for stable charged species of new quarks and leptons to form dark matter, hidden in neutral dark atoms. In Section 5 we consider specific form of O-helium (OHe) dark atoms that consist of heavy -2 charged heavy lepton-like particle surrounded by helium nuclear shell. The proof of qualitative advantages of this OHe scenario implies strict quantum mechanical solution of the problem of OHe interaction with nuclei. The conclusive Section 6 considers cosmological probes of fundamental particle structure in the context of cosmoparticle physics, studying fundamental relationship of micro- and macro- worlds.

2. Cosmological pattern of particle physics

Let’s specify in more details the set of links between fundamental particle properties and their cosmological effects.

Most of the known particles are unstable. For a particle with the mass $m$ the particle physics time scale is $t \sim 1/m$, so in particle world we refer to particles with lifetime $\tau \gg 1/m$ as to metastable. To be of cosmological significance in the Big Bang Universe metastable particle should survive after the temperature of the Universe $T$ fell down below $T \sim m$, what means that the particle lifetime should exceed $t \sim (m_{Pl}/m) \cdot (1/m)$. Such a long lifetime should find reason in the existence

*Here and further, if it isn’t specified otherwise we use the units $\hbar = c = k = 1$
of an (approximate) symmetry. From this viewpoint, cosmology is sensitive to the most fundamental properties of microworld, to the conservation laws reflecting strict or nearly strict symmetries of particle theory.

So, electron is absolutely stable owing to the conservation of electric charge, while the stability of proton is conditioned by the conservation of baryon charge. The stability of ordinary matter is thus protected by the conservation of electric and baryon charges, and its properties reflect the fundamental physical scales of electroweak and strong interactions. Indeed, the mass of electron is related to the scale of the electroweak symmetry breaking, whereas the mass of proton reflects the scale of QCD confinement.

The set of new fundamental particles, corresponding to the new strict symmetry, is then reflected in the existence of new stable particles, which should be present in the Universe and taken into account in the total energy density.

However, there is no strict symmetry between various quarks and leptons. The symmetry breaking implies the difference in particle masses. The particle mass spectrum reflects the hierarchy of symmetry breaking.

The mechanism of spontaneous breaking of particle symmetry also has cosmological impact. Heating of the condensed matter leads to restoration of its symmetry. When the heated matter cools down, phase transition to the phase of broken symmetry takes place. In the course of the phase transitions, corresponding to given type of symmetry breaking, topological defects can form. One can directly observe formation of such defects in liquid crystals or in superfluid He. In the same manner the mechanism of spontaneous breaking of particle symmetry implies restoration of the underlying symmetry in the early Universe at high temperatures. When temperature decreases in the course of cosmological expansion, transitions to the phase of broken symmetry can lead, depending on the symmetry breaking pattern, to formation of topological defects in very early Universe. Defects can represent new forms of stable particles (as it is in the case of magnetic monopoles\textsuperscript{29–34}, or extended structures, such as cosmic strings\textsuperscript{35, 36} or cosmic walls.\textsuperscript{37}

2.1. Cosmoarcheology of new physics

Physics, underlying inflation, baryosynthesis and dark matter, is referred to the extensions of the standard model, and the variety of such extensions makes the whole picture in general ambiguous. However, in the framework of each particular physical realization of inflationary model with baryosynthesis and dark matter the corresponding model dependent cosmological scenario can be specified in all the details. In such scenario the main stages of cosmological evolution, the structure and the physical content of the Universe reflect the structure of the underlying physical model. The latter should include with necessity the standard model, describing the properties of baryonic matter, and its extensions, responsible for inflation, baryosynthesis and dark matter. In no case the cosmological impact of such extensions is reduced to reproduction of these three phenomena only. The nontrivial path of cos-
mological evolution, specific for each particular implementation of inflational model with baryosynthesis and nonbaryonic dark matter, always contains some additional model dependent cosmologically viable predictions, which can be confronted with astrophysical data. The part of cosmo-particle physics, called cosmoarcheology, offers the set of methods and tools probing such predictions.

Cosmoarcheology considers the results of observational cosmology as the sample of the experimental data on the possible existence and features of hypothetical phenomena predicted by particle theory. To undertake the Gedanken Experiment with these phenomena some theoretical framework to treat their origin and evolution in the Universe should be assumed. As it was pointed out in Ref. 22 the choice of such framework is a nontrivial problem in the modern cosmology.

Indeed, in the old Big Bang scenario any new phenomenon, predicted by particle theory was considered in the course of the thermal history of the Universe, starting from Planck times. The problem is that the bedrock of the modern cosmology, namely, inflation, baryosynthesis and dark matter, is also based on experimentally unproven part of particle theory, so that the test for possible effects of new physics implies the necessity to choose the physical basis for such test. There are two possible solutions for this problem:

- a) crude model independent comparison of the predicted effect with the observational data and
- b) model dependent treatment of considered effect, provided that the model, predicting it, contains physical mechanism of inflation, baryosynthesis and dark matter.

The basis for the approach (a) is that whatever happened in the early Universe its results should not contradict the observed properties of the modern Universe. The set of observational data and, especially, the light element abundance and thermal spectrum of microwave background radiation put severe constraint on the deviation from thermal evolution after 1 s of expansion, what strengthens the model independent conjectures of approach (a).

One can specify the new phenomena by their net contribution into the cosmological density and by forms of their possible influence on parameters of matter and radiation. In the first aspect we can consider strong and weak phenomena. Strong phenomena can put dominant contribution into the density of the Universe, thus defining the dynamics of expansion in that period, whereas the contribution of weak phenomena into the total density is always subdominant. The phenomena are time dependent, being characterized by their time-scale, so that permanent (stable) and temporary (unstable) phenomena can take place. They can have homogeneous and inhomogeneous distribution in space. The amplitude of density fluctuations $\delta \equiv \delta \rho / \rho$ measures the level of inhomogeneity relative to the total density, $\rho$. The partial amplitude $\delta_i \equiv \delta \rho_i / \rho_i$ measures the level of fluctuations within a particular component with density $\rho_i$, contributing into the total density $\rho = \sum_i \rho_i$. The case $\delta_i \geq 1$ within the considered $i$-th component corresponds to its strong inho-
mogeneity. Strong inhomogeneity is compatible with the smallness of total density fluctuations, if the contribution of inhomogeneous component into the total density is small: \( g_i \ll g \), so that \( \delta \ll 1 \) (see for review Ref. 38).

The phenomena can influence the properties of matter and radiation either indirectly, say, changing of the cosmological equation of state, or via direct interaction with matter and radiation. In the first case only strong phenomena are relevant, in the second case even weak phenomena are accessible to observational data. The detailed analysis of sensitivity of cosmological data to various phenomena of new physics are presented in Ref. 3.

The basis for the approach (b) is provided by a particle model, in which inflation, baryosynthesis and nonbaryonic dark matter is reproduced. Any realization of such physically complete basis for models of the modern cosmology contains with necessity additional model dependent predictions, accessible to cosmoarcheological means. Here the scenario should contain all the details, specific to the considered model, and the confrontation with the observational data should be undertaken in its framework. In this approach complete cosmoparticle physics models may be realized, where all the parameters of particle model can be fixed from the set of astrophysical, cosmological and physical constraints. Even the details, related to cosmologically irrelevant predictions, such as the parameters of unstable particles, can find the cosmologically important meaning in these models. So, in the model of horizontal unification,\(^{39-42}\) the top quark or B-meson physics fixes the parameters, describing the dark matter, forming the large scale structure of the Universe, while in supersymmetric models experimental searches for unstable SUSY particles fix the parameters of SUSY dark matter candidates.\(^{10}\)

2.2. Cosmophenomenology of new physics

To study the imprints of new physics in astrophysical data cosmoarcheology implies the forms and means in which new physics leaves such imprints. So, the important tool of cosmoarcheology in linking the cosmological predictions of particle theory to observational data is the Cosmophenomenology of new physics. It studies the possible hypothetical forms of new physics, which may appear as cosmological consequences of particle theory, and their properties, which can result in observable effects.

2.2.1. Stable relics. Freezing out. Charge symmetric case

The simplest primordial form of new physics is the gas of new stable massive particles, originated from early Universe. For particles with the mass \( m \), at high temperature \( T > m \) the equilibrium condition,

\[
n \cdot \sigma v \cdot t > 1
\]

is valid, if their annihilation cross section \( \sigma > 1/(mmPl) \) is sufficiently large to establish the equilibrium. At \( T < m \) such particles go out of equilibrium and their
relative concentration freezes out. This is the main idea of calculation of primordial abundance for Weakly Interacting Massive Particles (WIMPs, see e.g. Refs. 3, 4, 22 for details).

If ordinary particles are among the products of WIMP annihilation, even their small fraction can annihilate in the Galaxy causing significant effect in cosmic rays and gamma background. This effect, first revealed in Ref. 8 and then proved for even subdominant fraction of annihilating dark matter in Ref. 9, is now in the basis of indirect dark matter searches in cosmic rays.

The process of WIMP annihilation to ordinary particles, considered in t-channel, determines their scattering cross section on ordinary particles and thus relates the primordial abundance of WIMPs to their scattering rate in the ordinary matter. Forming nonluminous massive halo of our Galaxy, WIMPs can penetrate the terrestrial matter and scatter on nuclei in underground detectors. The strategy of direct WIMP searches implies detection of recoil nuclei from this scattering.

The process inverse to annihilation of WIMPs corresponds to their production in collisions of ordinary particles. It should lead to effects of missing mass and energy-momentum, being the challenge for experimental search for production of dark matter candidates at accelerators, e.g. at LHC.

2.2.2. Stable relics. Decoupling

More weakly interacting and/or more light species decouple from plasma and radiation being relativistic at $T \gg m$, when

$$n \cdot \sigma v \cdot t \sim 1,$$

i.e. at

$$T_{\text{dec}} \sim (\sigma m_{Pl})^{-1} \gg m.$$  

After decoupling these species retain their equilibrium distribution until they become non-relativistic at $T < m$. Conservation of partial entropy in the cosmological expansion links the modern abundance of these species to number density of relic photons with the account for the increase of the photon number density due to the contribution of heavier ordinary particles, which were in equilibrium in the period of decoupling.

For example, primordial neutrino decouple in the period, when relativistic electron-positron plasma was present in the equilibrium. The account for increase of the number density of relic photons due to electron-positron annihilation at $T < m_e$, where $m_e$ is the mass of electron, results in the well known prediction of the Big Bang cosmology

$$n_{\nu \bar{\nu}} = \frac{3}{11} n_\gamma,$$

where $n_{\nu \bar{\nu}}$ is the modern number density of a one species of primordial left-handed neutrinos (and the corresponding antineutrinos) and $n_\gamma = 400 \text{ cm}^{-3}$ is the number
density of CMB photons at the modern CMB temperature $T = 2.7\,\text{K}$. Multiplying the predicted modern concentration of neutrinos by their mass, we obtain their contribution into the total density. This contribution should not exceed the total density, what gave early cosmological upper limits on neutrino mass. For the long time, it seemed possible that relic neutrinos can be the dominant form of cosmological dark matter and the corresponding neutrino-dominated Universe was considered as physical ground of Hot Dark Matter scenario of Large scale structure formation. Experimental discovery of neutrino oscillations together with stringent upper limits on the mass of electron neutrino exclude this possibility. Moreover, even neutrino masses in the range of 1eV lead to features in the spectrum of density fluctuations that are excluded by the observational data of CMB.

Right handed neutrinos and left handed antineutrinos, involved in the seesaw mechanism of neutrino mass generation, are sterile relative to ordinary weak interaction. If these species were in thermal equilibrium in the early Universe, they should decouple much earlier, than ordinary neutrinos, in the period, when there were much more particle species (leptons, quarks, gluons,...) in the equilibrium, what leads to the primordial abundance of sterile neutrinos much smaller, than of the ordinary ones. Therefore cosmological constraints admit sterile neutrinos with the mass in the keV range. We refer to the Ref. 43 for the recent review of models of sterile neutrinos and their possible effects.

2.2.3. Stable relics. SuperWIMPs

The maximal temperature, which is reached in inflationary Universe, is the reheating temperature, $T_r$, after inflation. So, the very weakly interacting particles with the annihilation cross section

$$\sigma < 1/(T_r m_{Pl}),$$

as well as very heavy particles with the mass

$$m \gg T_r$$

can not be in thermal equilibrium, and the detailed mechanism of their production should be considered to calculate their primordial abundance.

In particular, thermal production of gravitino in very early Universe is proportional to the reheating temperature $T_r$, what puts upper limit on this temperature from constraints on primordial gravitino abundance.\textsuperscript{44–50}

2.2.4. Self interacting dark matter

Extensive hidden sector of particle theory can provide the existence of new interactions, which only new particles possess. Historically one of the first examples of such self-interacting dark matter was presented by the model of mirror matter. Mirror particles, first proposed by T. D. Lee and C. N. Yang in Ref. 51 to restore equivalence of left- and right-handed co-ordinate systems in the presence of P- and
C-violation in weak interactions, should be strictly symmetric by their properties to their ordinary twins. After discovery of CP-violation it was shown by I. Yu. Kobzarev, L. B. Okun and I. Ya. Pomeranchuk in Ref. 52 that mirror partners cannot be associated with antiparticles and should represent a new set of symmetric partners for ordinary quarks and leptons with their own strong, electromagnetic and weak mirror interactions. It means that there should exist mirror quarks, bound in mirror nucleons by mirror QCD forces and mirror atoms, in which mirror nuclei are bound with mirror electrons by mirror electromagnetic interaction.\(^{53,54}\) If gravity is the only common interaction for ordinary and mirror particles, mirror matter can be present in the Universe in the form of elusive mirror objects, having symmetric properties with ordinary astronomical objects (gas, plasma, stars, planets...), but causing only gravitational effects on the ordinary matter.\(^ {55,56}\)

Even in the absence of any other common interaction except for gravity, the observational data on primordial helium abundance and upper limits on the local dark matter seem to exclude mirror matter, evolving in the Universe in a fully symmetric way in parallel with the ordinary baryonic matter.\(^ {57,58}\) The symmetry in cosmological evolution of mirror matter can be broken either by initial conditions,\(^ {59,60}\) or by breaking mirror symmetry in the sets of particles and their interactions as it takes place in the shadow world,\(^ {61,62}\) arising in the heterotic string model. We refer to Refs. 5, 63, 64 for current review of mirror matter and its cosmology.

If new particles possess new y-charge, interacting with massless bosons or intermediate bosons with sufficiently small mass (y-interaction), for slow y-charged particles Coulomb-like factor of "Gamov-Sommerfeld-Sakharov enhancement"\(^ {65–67}\) should be added in the annihilation cross section

\[
C_y = \frac{2\pi \alpha_y/v}{1 - \exp(-2\pi \alpha_y/v)},
\]

where \(v\) is relative velocity and \(\alpha_y\) is the running gauge constant of y-interaction. This factor may not be essential in the period of particle freezing out in the early Universe (when \(v\) was only few times smaller than \(c\)), but can cause strong enhancement in the effect of annihilation of nonrelativistic dark matter particles in the Galaxy.

2.2.5. Subdominant dark matter

If charge symmetric stable particles (and their antiparticles) represent only subdominant fraction of the cosmological dark matter, more detailed analysis of their distribution in space, of their condensation in galaxies, of their capture by stars, Sun and Earth, as well as effects of their interaction with matter and of their annihilation provides more sensitive probes for their existence.

In particular, hypothetical stable neutrinos of 4th generation with mass about 50 GeV should be the subdominant form of modern dark matter, contributing less than 0.1 % to the total density.\(^ {8,9}\) However, direct experimental search for cosmic fluxes of weakly interacting massive particles (WIMPs) may be sensitive to existence
of such component (see Refs. 68–76 and references therein). It was shown in Refs. 77–80 that annihilation of 4th neutrinos and their antineutrinos in the Galaxy is severely constrained by the measurements of gamma-background, cosmic positrons and antiprotons. 4th neutrino annihilation inside the Earth should lead to the flux of underground monochromatic neutrinos of known types, which can be traced in the analysis of the already existing and future data of underground neutrino detectors.78,81–83

2.2.6. Decaying dark matter

Decaying particles with lifetime \( \tau \), exceeding the age of the Universe, \( t_U, \tau > t_U \), can be treated as stable. By definition, primordial stable particles survive to the present time and should be present in the modern Universe. The net effect of their existence is given by their contribution into the total cosmological density. However, even small effect of their decay can lead to significant contribution to cosmic rays and gamma background.84 Leptonic decays of dark matter are considered as possible explanation of the cosmic positron excess, measured in the range above 10 GeV by PAMELA,85 FERMI/LAT86 and AMS0287 (see Ref. 88 for the review of AMS02 experiment).

2.2.7. Charge asymmetry of dark matter

The fact that particles are not absolutely stable means that the corresponding charge is not strictly conserved and generation particle charge asymmetry is possible, as it is assumed for ordinary baryonic matter. At sufficiently strong particle annihilation cross section excessive particles (antiparticles) can dominate in the relic density, leaving exponentially small admixture of their antiparticles (particles) in the same way as primordial excessive baryons dominate over antibaryons in baryon asymmetric Universe. In this case Asymmetric dark matter doesn’t lead to significant effect of particle annihilation in the modern Universe and can be searched for either directly in underground detectors or indirectly by effects of decay or condensation and structural transformations of e.g. neutron stars (see Ref. 89 for recent review and references). If particle annihilation isn’t strong enough, primordial pairs of particles and antiparticles dominate over excessive particles (or antiparticles) and this case has no principle difference from the charge symmetric case. In particular, for very heavy charged leptons (with the mass above 1 TeV), like ”tera electrons”,90 discussed in 4.2, their annihilation due to electromagnetic interaction is too weak to provide effective suppression of primordial tera electron-positron pairs relative to primordial asymmetric excess.91

2.2.8. Charged stable relics. Dark atoms

New particles with electric charge and/or strong interaction can form anomalous atoms and contain in the ordinary matter as anomalous isotopes. For example, if the
lightest quark of 4th generation is stable, it can form stable charged hadrons, serving as nuclei of anomalous atoms of e.g. anomalous helium. Therefore, stringent upper limits on anomalous isotopes, especially, on anomalous hydrogen put severe constraints on the existence of new stable charged particles. However, as we discuss in Section 4, stable doubly charged particles can not only exist, but even dominate in the cosmological dark matter, being effectively hidden in neutral "dark atoms".

2.2.9. Unstable particles

Primordial unstable particles with the lifetime, less than the age of the Universe, $\tau < t_U$, can not survive to the present time. But, if their lifetime is sufficiently large to satisfy the condition $\tau \gg (m_{Pl}/m) \cdot (1/m)$, their existence in early Universe can lead to direct or indirect traces.

Weakly interacting particles, decaying to invisible modes, can influence Large Scale Structure formation. Such decays prevent formation of the structure, if they take place before the structure is formed. Invisible products of decays after the structure is formed should contribute in the cosmological dark energy. The Unstable Dark matter scenarios implied weakly interacting particles that form the structure on the matter dominated stage and then decay to invisible modes after the structure is formed.

Cosmological flux of decay products contributing into the cosmic and gamma ray backgrounds represents the direct trace of unstable particles. If the decay products do not survive to the present time their interaction with matter and radiation can cause indirect trace in the light element abundance or in the fluctuations of thermal radiation.

If the particle lifetime is much less than 1s the multi-step indirect traces are possible, provided that particles dominate in the Universe before their decay. On the dust-like stage of their dominance black hole formation takes place, and the spectrum of such primordial black holes traces the particle properties (mass, frozen concentration, lifetime). The particle decay in the end of dust like stage influences the baryon asymmetry of the Universe. In any way cosmophysical chains link the predicted properties of even unstable new particles to the effects accessible in astronomical observations. Such effects may be important in the analysis of the observational data.

2.2.10. Phase transitions

Parameters of new stable and metastable particles are also determined by a pattern of particle symmetry breaking. This pattern is reflected in a succession of phase transitions in the early Universe. First order phase transitions proceed through bubble nucleation, which can result in black hole formation (see e.g. Refs. 113 and 114 for review and references). Phase transitions of the second order can lead to formation of topological defects, such as walls, string or monopoles. The observational
data put severe constraints on magnetic monopole\textsuperscript{31} and cosmic wall production,\textsuperscript{37} as well as on the parameters of cosmic strings.\textsuperscript{35, 36} Structure of cosmological defects can be changed in succession of phase transitions. More complicated forms like walls-surrounded-by-strings can appear. Such structures can be unstable, but their existence can leave a trace in nonhomogeneous distribution of dark matter and give rise to large scale structures of nonhomogeneous dark matter like \textit{archioles}.\textsuperscript{115–117} This effect should be taken into account in the analysis of cosmological effects of weakly interacting slim particles (WISPs) (see Ref. 118 for current review) that can play the role of cold dark matter in spite of their small mass.

\subsection*{2.3. Structures from succession of U(1) phase transitions}

A wide class of particle models possesses a symmetry breaking pattern, which can be effectively described by pseudo-Nambu–Goldstone (PNG) field and which corresponds to formation of unstable topological defect structure in the early Universe (see Ref. 114 for review and references). The Nambu–Goldstone nature in such an effective description reflects the spontaneous breaking of global U(1) symmetry, resulting in continuous degeneracy of vacua. The explicit symmetry breaking at smaller energy scale changes this continuous degeneracy by discrete vacuum degeneracy. The character of formed structures is different for phase transitions, taking place on post-inflationary and inflationary stages.

\subsubsection*{2.3.1. Large scale correlations of axion field}

At high temperatures such a symmetry breaking pattern implies the succession of second order phase transitions. In the first transition, continuous degeneracy of vacua leads, at scales exceeding the correlation length, to the formation of topological defects in the form of a string network; in the second phase transition, continuous transitions in space between degenerated vacua form surfaces: domain walls surrounded by strings. This last structure is unstable, but, as was shown in the example of the invisible axion,\textsuperscript{115–117} it is reflected in the large scale inhomogeneity of distribution of energy density of coherent PNG (axion) field oscillations. This energy density is proportional to the initial value of phase, which acquires dynamical meaning of amplitude of axion field, when axion mass is switched on in the result of the second phase transition.

The value of phase changes by $2\pi$ around string. This strong nonhomogeneity of phase leads to corresponding nonhomogeneity of energy density of coherent PNG (axion) field oscillations. Usual argument (see e.g. Ref. 119 and references therein) is essential only on scales, corresponding to mean distance between strings. This distance is small, being of the order of the scale of cosmological horizon in the period, when PNG field oscillations start. However, since the nonhomogeneity of phase follows the pattern of axion string network this argument misses large scale correlations in the distribution of oscillations’ energy density.
Indeed, numerical analysis of string network (see review in the Ref. 120) indicates that large string loops are strongly suppressed and the fraction of about 80% of string length, corresponding to long loops, remains virtually the same in all large scales. This property is the other side of the well known scale invariant character of string network. Therefore the correlations of energy density should persist on large scales, as it was revealed in Refs. 115–117.

The large scale correlations in topological defects and their imprints in primordial inhomogeneities is the indirect effect of inflation, if phase transitions take place after reheating of the Universe. Inflation provides in this case the equal conditions of phase transition, taking place in causally disconnected regions.

2.3.2. Primordial seeds for Active Galactic Nuclei

If the phase transitions take place on inflational stage new forms of primordial large scale correlations appear. The example of global U(1) symmetry, broken spontaneously in the period of inflation and successively broken explicitly after reheating, was considered in Ref. 122. In this model, spontaneous U(1) symmetry breaking at inflational stage is induced by the vacuum expectation value \( \langle \psi \rangle = f \) of a complex scalar field \( \Psi = \psi \exp(i\theta) \), having also explicit symmetry breaking term in its potential \( V_{eb} = \Lambda^4 (1 - \cos \theta) \). The latter is negligible in the period of inflation, if \( f \gg \Lambda \), so that there appears a valley relative to values of phase in the field potential in this period. Fluctuations of the phase \( \theta \) along this valley, being of the order of \( \Delta \theta \sim H/(2\pi f) \) (here \( H \) is the Hubble parameter at inflational stage) change in the course of inflation its initial value within the regions of smaller size. Owing to such fluctuations, for the fixed value of \( \theta_{90} \) in the period of inflation with \( e\)-folding \( N = 60 \) corresponding to the part of the Universe within the modern cosmological horizon, strong deviations from this value appear at smaller scales, corresponding to later periods of inflation with \( N < 60 \). If \( \theta_{90} < \pi \), the fluctuations can move the value of \( \theta_N \) to \( \theta_N > \pi \) in some regions of the Universe. After reheating, when the Universe cools down to temperature \( T = \Lambda \) the phase transition to the true vacuum states, corresponding to the minima of \( V_{eb} \) takes place. For \( \theta_N \leq \pi \) the minimum of \( V_{eb} \) is reached at \( \theta_{vac} = 0 \), whereas in the regions with \( \theta_N > \pi \) the true vacuum state corresponds to \( \theta_{vac} = 2\pi \). For \( \theta_{90} < \pi \) in the bulk of the volume within the modern cosmological horizon \( \theta_{vac} = 0 \). However, within this volume there appear regions with \( \theta_{vac} = 2\pi \). These regions are surrounded by massive domain walls, formed at the border between the two vacua. Since regions with \( \theta_{vac} = 2\pi \) are confined, the domain walls are closed. After their size equals the horizon, closed walls can collapse into black holes. The minimal mass of such black hole is determined by the condition that it’s Schwarzschild radius, \( r_g = 2GM/c^2 \) exceeds the width of the wall, \( l \sim f/\Lambda^2 \), and it is given by \( M_{min} \sim f(m_{Pl}/\Lambda)^2 \). The maximal mass is determined by the mass of the wall, corresponding to the earliest region \( \theta_N > \pi \), appeared at inflational stage.

This mechanism can lead to formation of primordial black holes of a whatever
Fig. 1. The inflational evolution of the phase (taken from the Ref. 126). The phase \( \theta_{60} \) sits in the range \([\pi, 0]\) at the beginning of inflation and makes Brownian step \( \delta \theta_{\text{eff}} = H_{\text{inf}}/(2\pi f_{\text{eff}}) \) at each e-fold. The typical wavelength of the fluctuation \( \delta \theta \) is equal to \( H^{-1}_{\text{inf}} \). The whole domain \( H_{\text{inf}}^{-1} \), containing phase \( \theta_N \) gets divided, after one e-fold, into \( e^3 \) causally disconnected domains of radius \( H_{\text{inf}}^{-1} \). Each new domain contains almost homogeneous phase value \( \theta_{N-1} = \theta_N \pm \delta \theta_{\text{eff}} \). Every successive e-fold this process repeats in every domain.

large mass (up to the mass of AGNs, see for latest review Ref. 38). Such black holes appear in the form of primordial black hole clusters, exhibiting fractal distribution in space. It can shed new light on the problem of galaxy formation.

2.3.3. Antimatter in Baryon asymmetric Universe?

Primordial strong inhomogeneities can also appear in the baryon charge distribution. The appearance of antibaryon domains in the baryon asymmetrical Universe, reflecting the inhomogeneity of baryosynthesis, is the profound signature of such strong inhomogeneity. On the example of the model of spontaneous baryosynthesis (see Ref. 128 for review) the possibility for existence of antimatter domains, surviving to the present time in inflationary Universe with inhomogeneous baryosynthesis was revealed in.

The mechanism of spontaneous baryogenesis implies the existence of a complex scalar field \( \chi = (f/\sqrt{2}) \exp(\theta) \) carrying the baryonic charge. The \( U(1) \) symmetry, which corresponds to the baryon charge, is broken spontaneously and explicitly. The explicit breakdown of \( U(1) \) symmetry is caused by the phase-dependent term

\[
V(\theta) = \Lambda^4(1 - \cos \theta).
\]

(1)

The possible baryon and lepton number violating interaction of the field \( \chi \) with matter fields can have the following structure

\[
\mathcal{L} = g \chi \bar{Q}L + \text{h.c.},
\]

(2)

where fields \( Q \) and \( L \) represent a heavy quark and lepton, coupled to the ordinary matter fields.
In the early Universe, at a time when the friction term, induced by the Hubble constant, becomes comparable with the angular mass $m_\theta = \frac{\Lambda^2}{f}$, the phase $\theta$ starts to oscillate around the minima of the PNG potential and decays into matter fields according to (2). The coupling (2) gives rise to the following: as the phase starts to roll down in the clockwise direction (Fig. 1), it preferentially creates excess of baryons over antibaryons, while the opposite is true as it starts to roll down in the opposite direction.

The fate of such antimatter regions depends on their size. If the physical size of some of them is larger than the critical surviving size $L_c = 8h^2$ kpc, they survive annihilation with surrounding matter. Evolution of sufficiently dense antimatter domains can lead to formation of antimatter globular clusters. The existence of such cluster in the halo of our Galaxy should lead to the pollution of the galactic halo by antiprotons. Their annihilation can reproduce the observed galactic gamma background in the range tens-hundreds MeV. The prediction of antihelium component of cosmic rays, accessible to future searches for cosmic ray antinuclei in PAMELA and AMS II experiments, as well as of antimatter meteorites provides the direct experimental test for this hypothesis.

So the primordial strong inhomogeneities in the distribution of total, dark matter and baryon density in the Universe is the new important phenomenon of cosmological models, based on particle models with hierarchy of symmetry breaking.

3. Primordial Black Holes as cosmological reflection of particle structure

It was probably Pierre-Simon Laplace in the beginning of XIX century, who noted first that in very massive stars escape velocity can exceed the speed of light and light can not come from such stars. This conclusion made in the framework of Newton mechanics and Newton corpuscular theory of light has further transformed into the notion of "black hole" in the framework of general relativity and electromagnetic theory. Any object of mass $M$ can become a black hole, being put within its gravitational radius $r_g = \frac{2GM}{c^2}$. At present time black holes (BH) can be created only by a gravitational collapse of compact objects with mass more than about three Solar mass. It can be a natural end of massive stars or can result from evolution of dense stellar clusters. However in the early Universe there were no limits on the mass of BH. Ya.B. Zeldovich and I.D. Novikov (see Ref. 137) noticed that if cosmological expansion stops in some region, black hole can be formed in this region within the cosmological horizon. It corresponds to strong deviation from general expansion and reflects strong inhomogeneity in the early Universe. There are several mechanisms for such strong inhomogeneity and we’ll trace their links to cosmological consequences of particle theory.

Primordial Black Holes (PBHs) are a very sensitive cosmological probe for physics phenomena occurring in the early Universe. They could be formed by many different mechanisms, e.g., initial density inhomogeneities and non-
linear metric perturbations, blue spectra of density fluctuations, a softening of the equation of state, development of gravitational instability on early dust-like stages of dominance of supermassive particles and scalar fields and evolution of gravitationally bound objects formed at these stages, collapse of cosmic strings and necklaces, a double inflation scenario, first order phase transitions, a step in the power spectrum, etc. (see Refs. 3, 4, 110, 114, 167 for a review).

Being formed, PBHs should retain in the Universe and, if survive to the present time, represent a specific form of dark matter. Effect of PBH evaporation by S.W. Hawking makes evaporating PBHs a source of fluxes of products of evaporation, particularly of $\gamma$ radiation. MiniPBHs with mass below $10^{14}\text{g}$ evaporate completely and do not survive to the present time. However, effect of their evaporation should cause influence on physical processes in the early Universe, thus providing a test for their existence by methods of cosmoarcheology, studying cosmological imprints of new physics in astrophysical data. In a wide range of parameters the predicted effect of PBHs contradicts the data and it puts restrictions on mechanism of PBH formation and the underlying physics of very early Universe. On the other hand, at some fixed values of parameters, PBHs or effects of their evaporation can provide a nontrivial solution for astrophysical problems.

Various aspects of PBH physics, mechanisms of their formation, evolution and effects are discussed in Refs. 110, 175–214 particularly specifying PBH formation and effects in braneworld cosmology, on inflationary preheating, formation of PBHs in QCD phase transition, properties of superhorizon BHs, role of PBHs in baryosynthesis, effects of PBH evaporation in the early Universe and in modern cosmic ray, neutrino and gamma fluxes, in creation of hypothetical particles, PBH clustering and creation of supermassive BHs, effects in cosmic rays and colliders from PBHs in low scale gravity models. Here we outline the role of PBHs as a link in cosmoarcheological chain, connecting cosmological predictions of particle theory with observational data. We discuss the way, in which spectrum of PBHs reflects properties of superheavy metastable particles and of phase transitions on inflationary and post-inflationary stages. We illustrate in subsection 3.1 some mechanisms of PBH formation on stage of dominance of superheavy particles and fields and from second order phase transition on inflationary stage. Effective mechanism of BH formation during bubble nucleation provides a sensitive tool to probe existence of cosmological first order phase transitions by PBHs. Existence of stable remnants of PBH evaporation can strongly increase the sensitivity of such probe and we demonstrate this possibility in subsection 3.4 on an example of gravitino production in PBH evaporation. Being formed within cosmological horizon, PBHs seem to have masses much less than the mass of stars, constrained by small size of horizon in very early Universe. However, if phase transition takes place on inflationary stage, closed walls of practically any size can be formed and their successive col-
lapse can give rise to clouds of massive black holes, which can play the role of seeds for galaxies (subsection 3.3).

### 3.1. **PBHs from early dust-like stages**

A possibility to form a black hole is highly improbable in homogeneous expanding Universe, since it implies metric fluctuations of order 1. For metric fluctuations distributed according to Gaussian law with dispersion

\[ \langle \delta^2 \rangle \ll 1 \]  

(3)

a probability for fluctuation of order 1 is determined by exponentially small tail of high amplitude part of this distribution. This probability can be even more suppressed in a case of non-Gaussian fluctuations.140

In the Universe with equation of state

\[ p = \gamma \epsilon, \]  

(4)

with numerical factor \( \gamma \) being in the range

\[ 0 \leq \gamma \leq 1 \]  

(5)

a probability to form black hole from fluctuation within cosmological horizon is given by (see e.g.3,4 for review and references)

\[ W_{PBH} \propto \exp \left( -\frac{\gamma^2}{2 \langle \delta^2 \rangle} \right), \]  

(6)

It provides exponential sensitivity of PBH spectrum to softening of equation of state in early Universe (\( \gamma \to 0 \)) or to increase of ultraviolet part of spectrum of density fluctuations (\( \langle \delta^2 \rangle \to 1 \)). These phenomena can appear as cosmological consequence of particle theory.

#### 3.1.1. **Dominance of superheavy particles in early Universe**

Superheavy particles can not be studied at accelerators directly. If they are stable, their existence can be probed by cosmological tests, but there is no direct link between astrophysical data and existence of superheavy metastable particles with lifetime \( \tau \ll 1 \text{s} \). It was first noticed in Ref. 111 that dominance of such particles in the Universe before their decay at \( t \leq \tau \) can result in formation of PBHs, retaining in Universe after the particles decay and keeping some information on particle properties in their spectrum. It provided though indirect but still a possibility to probe existence of such particles in astrophysical observations. Even the absence of observational evidences for PBHs is important. It puts restrictions on allowed properties of superheavy metastable particles, which might form such PBHs on a stage of particle dominance, and thus constrains parameters of models, predicting these particles.
After reheating, at
\[ T < T_0 = r m \] (7)
particles with mass \( m \) and relative abundance \( r = n/n_r \) (where \( n \) is frozen out concentration of particles and \( n_r \) is concentration of relativistic species) must dominate in the Universe before their decay. Dominance of these nonrelativistic particles at \( t > t_0 \), where
\[ t_0 = \frac{m_{pl}}{T_0^2}. \] (8)
corresponds to dust like stage with equation of state \( p = 0 \), at which particle density fluctuations grow as
\[ \delta(t) = \frac{\delta \rho}{\rho} \propto t^{2/3} \] (9)
and development of gravitational instability results in formation of gravitationally bound systems, which decouple at
\[ t \sim t_f \approx t_i \delta(t_i)^{-3/2} \] (10)
from general cosmological expansion, when \( \delta(t_f) \sim 1 \) for fluctuations, entering horizon at \( t = t_i > t_0 \) with amplitude \( \delta(t_i) \).

Formation of these systems can result in black hole formation either immediately after the system decouples from expansion or in result of evolution of initially formed nonrelativistic gravitationally bound system.

### 3.1.2. Direct PBH formation

If density fluctuation is especially homogeneous and isotropic, it directly collapses to BH as soon as the amplitude of fluctuation grows to 1 and the system decouples from expansion. A probability for direct BH formation in collapse of such homogeneous and isotropic configurations gives minimal estimation of BH formation on dust-like stage.

This probability was calculated in Ref. 111 with the use of the following arguments. In the period \( t \sim t_f \), when fluctuation decouples from expansion, its configuration is defined by averaged density \( \rho_1 \), size \( r_1 \), deviation from sphericity \( s \) and by inhomogeneity \( u \) of internal density distribution within the fluctuation. Having decoupled from expansion, the configuration contracts and the minimal size to which it can contract is
\[ r_{\text{min}} \sim s r_1, \] (11)
being determined by a deviation from sphericity
\[ s = \max\{|\gamma_1 - \gamma_2|, |\gamma_1 - \gamma_2|, |\gamma_1 - \gamma_2|\}; \] (12)
where $\gamma_1$, $\gamma_2$ and $\gamma_3$ define a deformation of configuration along its three main orthogonal axes. It was first noticed in Ref. 111 that to form a black hole in result of such contraction it is sufficient that configuration returns to the size
\[
r_{\text{min}} \sim r_g \sim t_i \sim \delta(t_i)r_1,
\]
which had the initial fluctuation $\delta(t_i)$, when it entered horizon at cosmological time $t_i$. If
\[
s \leq \delta(t_i),
\]
configuration is sufficiently isotropic to concentrate its mass in the course of collapse within its gravitational radius, but such concentration also implies sufficient homogeneity of configuration. Density gradients can result in gradients of pressure, which can prevent collapse to BH. This effect does not take place for contracting collisionless gas of weakly interacting massive particles, but due to inhomogeneity of collapse the particles, which have already passed the caustics can free stream beyond the gravitational radius, before the whole mass is concentrated within it. Collapse of nearly spherically symmetric dust configuration is described by Tolmen solution. It’s analysis\textsuperscript{110,112,148,266} has provided a constraint on the inhomogeneity $u = \delta \rho_1 / \rho_1$ within the configuration. It was shown that both for collisionless and interacting particles the condition
\[
u < \delta(t_i)^{3/2}
\]
is sufficient for configuration to contract within its gravitational radius.

A probability for direct BH formation is then determined by a product of probability for sufficient initial sphericity $W_s$ and homogeneity $W_u$ of configuration, which is determined by the phase space for such configurations. In a calculation of $W_s$ one should take into account that the condition\textsuperscript{14} implies 5 conditions for independent components of tensor of deformation before its diagonalization (2 conditions for three diagonal components to be close to each other and 3 conditions for nondiagonal components to be small). Therefore, the probability of sufficient sphericity is given by\textsuperscript{110–112,148,266}
\[
W_s \sim \delta(t_i)^5
\]
and together with the probability for sufficient homogeneity
\[
W_u \sim \delta(t_i)^{3/2}
\]
results in the strong power-law suppression of probability for direct BH formation
\[
W_{PBH} = W_s \cdot W_u \sim \delta(t_i)^{13/2}.
\]
Though this calculation was originally done in Refs. 110–112,148,266 for Gaussian distribution of fluctuations, it does not imply specific form of high amplitude tail of this distribution and thus should not change strongly in a case of non-Gaussian fluctuations.\textsuperscript{140}
The mechanism\textsuperscript{3, 4, 110–112, 148, 266} is effective for formation of PBHs with mass in an interval

\[ M_0 \leq M \leq M_{bhmax}. \]  \hfill (19)

The minimal mass corresponds to the mass within cosmological horizon in the period \( t \sim t_0 \), when particles start to dominate in the Universe and it is equal to

\[ M_0 = \frac{4\pi}{3} \rho t_0^3 \approx m_{pl} \left( \frac{m_{pl}}{m} \right)^2. \]  \hfill (20)

The maximal mass is indirectly determined by the condition

\[ \tau = t(M_{bhmax})\delta(M_{bhmax})^{-3/2} \]  \hfill (21)

that fluctuation in the considered scale \( M_{bhmax} \), entering the horizon at \( t(M_{bhmax}) \) with an amplitude \( \delta(M_{bhmax}) \) can manage to grow up to nonlinear stage, decouple and collapse before particles decay at \( t = \tau \). For scale invariant spectrum \( \delta(M) = \delta_0 \) the maximal mass is given by\textsuperscript{114}

\[ M_{bhmax} = m_{pl} \frac{\tau}{t_{Pl}} \delta_0^{-3/2} = m_{pl}^2 \tau \delta_0^{-3/2}. \]  \hfill (22)

The probability, given by Eq. (18), is also appropriate for formation of PBHs on dust-like preheating stage after inflation.\textsuperscript{3, 4, 149} The simplest example of such stage can be given with the use of a model of homogeneous massive scalar field.\textsuperscript{3, 4} Slow rolling of the field in the period \( t \ll 1/m \) (where \( m \) is the mass of field) provides chaotic inflation scenario, while at \( t > 1/m \) the field oscillates with period \( 1/m \). Coherent oscillations of the field correspond to an averaged over period of oscillations dust-like equation of state \( p = 0 \), at which gravitational instability can develop. The minimal mass in this case corresponds to the Jeans mass of scalar field, while the maximal mass is also determined by a condition that fluctuation grows and collapses before the scalar field decays and reheats the Universe.

The probability \( W_{PBH}(M) \) determines the fraction of total density

\[ \beta(M) = \frac{\rho_{PBH}(M)}{\rho_{tot}} \approx W_{PBH}(M), \]  \hfill (23)

corresponding to PBHs with mass \( M \). For \( \delta(M) \ll 1 \) this fraction, given by Eq. (18), is small. It means that the bulk of particles do not collapse directly in black holes, but form gravitationally bound systems. Evolution of these systems can give much larger amount of PBHs, but it strongly depends on particle properties.

3.1.3. \textit{Evolutional formation of PBHs}

Superweakly interacting particles form gravitationally bound systems of collisionless gas, which remind modern galaxies with collisionless gas of stars. Such system can finally collapse to black hole, but energy dissipation in it and consequently its
evolution is a relatively slow process.\textsuperscript{3,4,267} The evolution of these systems is dominantly determined by evaporation of particles, which gain velocities, exceeding the parabolic velocity of system. In the case of binary collisions the evolution timescale can be roughly estimated\textsuperscript{3,4,267} as

\[ t_{ev} = \frac{N}{\ln N} t_{ff} \]

for gravitationally bound system of \( N \) particles, where the free fall time \( t_{ff} \) for system with density \( \rho \) is \( t_{ff} \approx (4\pi G \rho)^{-1/2} \). This time scale can be shorter due to collective effects in collisionless gas\textsuperscript{268} and be at large \( N \) of the order of

\[ t_{ev} \sim N^{2/3} t_{ff}. \]

However, since the free fall time scale for gravitationally bound systems of collisionless gas is of the order of cosmological time \( t_f \) for the period, when these systems are formed, even in the latter case the particles should be very long living \( \tau \ll t_f \) to form black holes in such slow evolutional process.

The evolutional time scale is much smaller for gravitationally bound systems of superheavy particles, interacting with light relativistic particles and radiation. Such systems have analogy with stars, in which evolution time scale is defined by energy loss by radiation. An example of such particles give superheavy color octet fermions of asymptotically free SU(5) model\textsuperscript{150} or magnetic monopoles of GUT models. Having decoupled from expansion, frozen out particles and antiparticles can annihilate in gravitationally bound systems, but detailed numerical simulation\textsuperscript{151} has shown that annihilation can not prevent collapse of the most of mass and the timescale of collapse does not exceed the cosmological time of the period, when the systems are formed.

### 3.2. Spikes from phase transitions on inflationary stage

Scale non-invariant spectrum of fluctuations, in which amplitude of small scale fluctuations is enhanced, can be another factor, increasing the probability of PBH formation. The simplest functional form of such spectrum is represented by a blue spectrum with a power law dispersion

\[ \langle \delta^2(M) \rangle \propto M^{-k}, \]

with amplitude of fluctuations growing at \( k > 0 \) to small \( M \). The realistic account for existence of other scalar fields together with inflaton in the period of inflation can give rise to spectra with distinguished scales, determined by parameters of considered fields and their interaction.

In chaotic inflation scenario interaction of a Higgs field \( \phi \) with inflaton \( \eta \) can give rise to phase transitions on inflationary stage, if this interaction induces positive mass term \( + \frac{\nu^2}{2} \eta^2 \phi^2 \). When in the course of slow rolling the amplitude of inflaton decreases below a certain critical value \( \eta_c = m/\nu \) the mass term in Higgs potential

\[ V(\phi, \eta) = -\frac{m_\phi^2}{2} \phi^2 + \frac{\lambda_\phi}{4} \phi^4 + \frac{\nu^2}{2} \eta^2 \phi^2 \]
changes sign and phase transition takes place. Such phase transitions on inflationary stage lead to the appearance of a characteristic spikes in the spectrum of initial density perturbations. These spike–like perturbations, on scales that cross the horizon \((60 \geq N \geq 1)\) e–folds before the end of inflation reenter the horizon during the radiation or dust like era and could in principle collapse to form primordial black holes. The possibility of such spikes in chaotic inflation scenario was first pointed out in Ref. 269 and realized in Ref. 165 as a mechanism of PBH formation for the model of horizontal unification.

For vacuum expectation value of a Higgs field
\[
\langle \phi \rangle = \frac{m}{\lambda} = v
\]  

and \(\lambda \sim 10^{-3}\) the amplitude \(\delta\) of spike in spectrum of density fluctuations, generated in phase transition on inflationary stage is given by \(^{165}\)
\[
\delta \approx \frac{4}{9s}
\]  

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

where \(\kappa \sim 1\).

If phase transition takes place at \(e\)–folding \(N\) before the end of inflation, the spike re-enters horizon on radiation dominance (RD) stage and forms Black hole of mass
\[
M \approx \frac{m_{pl}^2}{H_0} \exp\{2N\},
\]  

where \(H_0\) is the Hubble constant in the period of inflation.

If the spike re-enters horizon on matter dominance (MD) stage it should form black holes of mass
\[
M \approx \frac{m_{pl}^2}{H_0} \exp\{3N\}.
\]  

### 3.3. First order phase transitions as a source of black holes in the early Universe

First order phase transition go through bubble nucleation. Remind the common example of boiling water. The simplest way to describe first order phase transitions with bubble creation in early Universe is based on a scalar field theory with two non degenerated vacuum states. Being stable at a classical level, the false vacuum state decays due to quantum effects, leading to a nucleation of bubbles of true vacuum and their subsequent expansion.\(^{270}\) The potential energy of the false vacuum is converted into a kinetic energy of bubble walls thus making them highly relativistic in a short time. The bubble expands till it collides with another one. As it was
shown in Refs. 161,271 a black hole may be created in a collision of several bubbles. The probability for collision of two bubbles is much higher. The opinion of the BH absence in such processes was based on strict conservation of the original O(2,1) symmetry. As it was shown in Refs. 113,163,164 there are ways to break it. Firstly, radiation of scalar waves indicates the entropy increasing and hence the permanent breaking of the symmetry during the bubble collision. Secondly, the vacuum decay due to thermal fluctuation does not possess this symmetry from the beginning. The investigations113, 163, 164 have shown that BH can be created as well with a probability of order unity in collisions of only two bubbles. It initiates an enormous production of BH that leads to essential cosmological consequences discussed below.

Inflation models ended by a first order phase transition hold a dignified position in the modern cosmology of early Universe (see for example272–278). The interest to these models is due to, that such models are able to generate the observed large-scale voids as remnants of the primordial bubbles for which the characteristic wavelengths are several tens of Mpc.277, 278 A detailed analysis of a first order phase transition in the context of extended inflation can be found in Ref.279. Hereafter we will be interested only in a final stage of inflation when the phase transition is completed. Remind that a first order phase transition is considered as completed immediately after establishing of true vacuum percolation regime. Such regime is established approximately when at least one bubble per unit Hubble volume is nucleated. Accurate computation279 shows that first order phase transition is successful if the following condition is valid:

\[ Q \equiv \frac{4\pi}{9} \left( \frac{\Gamma}{H^2} \right)_{t_{\text{end}}} = 1. \]

(33)

Here \( \Gamma \) is the bubble nucleation rate. In the framework of first order inflation models the filling of all space by true vacuum takes place due to bubble collisions, nucleated at the final moment of exponential expansion. The collisions between such bubbles occur when they have comoving spatial dimension less or equal to the effective Hubble horizon \( H_{\text{end}}^{-1} \) at the transition epoch. If we take \( H_0 = 100hKm/\text{sec}/Mpc \) in \( \Omega = 1 \) Universe the comoving size of these bubbles is approximately \( 10^{-21}h^{-1}Mpc \). In the standard approach it believes that such bubbles are rapidly thermalized without leaving a trace in the distribution of matter and radiation. However, in the previous subsection it has been shown that for any realistic parameters of theory, the collision between only two bubble leads to BH creation with the probability closely to 100%. The mass of this BH is given by113,163,164

\[ M_{\text{BH}} = \gamma_1 M_{\text{bub}} \]

(34)

where \( \gamma_1 \simeq 10^{-2} \) and \( M_{\text{bub}} \) is the mass that could be contained in the bubble volume at the epoch of collision in the condition of a full thermalization of bubbles. The discovered mechanism leads to a new direct possibility of PBH creation at the epoch of reheating in first order inflation models. In standard picture PBHs are formed in the early Universe if density perturbations are sufficiently large, and the
probability of PBHs formation from small post-inflation initial perturbations is suppressed (see subsection 3.1). Completely different situation takes place at final epoch of first order inflation stage; namely collision between bubbles of Hubble size in percolation regime leads to copious PBH formation with masses

\[ M_0 = \gamma_1 M_{\text{hor}}^{\text{end}} = \frac{\gamma_1 m_{\text{pl}}^2}{2 H_{\text{end}}}, \]  

where \( M_{\text{hor}}^{\text{end}} \) is the mass of Hubble horizon at the end of inflation. According to (34), the initial mass fraction of this PBHs is given by

\[ \beta_0 \approx \frac{\gamma_1}{e} \approx 6 \times 10^{-3}. \]

For example, for typical value of \( H_{\text{end}} \approx 4 \times 10^{-6} m_{\text{pl}} \), the initial mass fraction \( \beta_0 \) is contained in PBHs with mass \( M_0 \approx 1 \text{ g} \).

In general the Hawking evaporation of mini BHs could give rise to a variety of possible end states. It is generally assumed, that evaporation proceeds until the PBH vanishes completely, but there are various arguments against this proposal (see e.g. Refs. 175, 281–283). If one supposes that BH evaporation leaves a stable relic, then it is naturally to assume that it has a mass of order \( m_{\text{rel}} = k m_{\text{pl}} \), where \( 1 \leq k \leq 10^2 \). We can investigate the consequences of PBH forming at the percolation epoch after first order inflation, supposing that the stable relic is a result of its evaporation. As it follows from the above consideration the PBHs are preferentially formed with a typical mass \( M_0 \) at a single time \( t_1 \). Hence the total density \( \rho \) at this time is

\[ \rho(t_1) = \rho_\gamma(t_1) + \rho_{\text{PBH}}(t_1) = \frac{3(1 - \beta_0)}{32 \pi t_1^2} m_{\text{pl}}^2 + \frac{3 \beta_0}{32 \pi t_1^2} m_{\text{pl}}^2, \]

where \( \beta_0 \) denotes the fraction of the total density, corresponding to PBHs in the period of their formation \( t_1 \). The evaporation time scale can be written in the following form

\[ \tau_{\text{BH}} = \frac{M_0^3}{g_* m_{\text{pl}}}, \]

where \( g_* \) is the number of effective massless degrees of freedom.

Let us derive the density of PBH relics. There are two distinct possibilities to consider.

The Universe is still radiation dominated (RD) at \( \tau_{\text{BH}} \). This situation will be hold if the following condition is valid \( \rho_{\text{BH}}(\tau_{\text{BH}}) < \rho_\gamma(\tau_{\text{BH}}) \). It is possible to rewrite this condition in terms of Hubble constant at the end of inflation

\[ \frac{H_{\text{end}}}{m_{\text{pl}}} > \frac{\beta_0^{5/2}}{g_*} \rho_\gamma^{-1/2} \approx 10^{-6} \]

Taking the present radiation density fraction of the Universe to be \( \Omega_{\gamma_0} = 2.5 \cdot 10^{-5} h^{-2} \) (\( h \) being the Hubble constant in the units of 100 km s\(^{-1}\) Mpc\(^{-1}\)), and using the standard values for the present time and time when the density of matter
and radiation become equal, we find the contemporary densities fraction of relics

\[ \Omega_{rel} \approx 10^{26} h^{-2} k \left( \frac{H_{end}}{m_{pl}} \right)^{3/2} \]  

(39)

It is easily to see that relics overclose the Universe (\( \Omega_{rel} \gg 1 \)) for any reasonable \( k \) and \( H_{end} > 10^{-6} m_{pl} \).

The second case takes place if the Universe becomes PBHs dominated at period \( t_1 < t_2 < \tau_{BH} \). This situation is realized under the condition \( \rho_{BH}(t_2) < \rho_{\gamma}(t_2) \), which can be rewritten in the form

\[ \frac{H_{end}}{m_{pl}} < 10^{-6}. \]  

(40)

The present day relics density fraction takes the form

\[ \Omega_{rel} \approx 10^{28} h^{-2} k \left( \frac{H_{end}}{m_{pl}} \right)^{3/2} \]  

(41)

Thus the Universe is not overclosed by relics only if the following condition is valid

\[ \frac{H_{end}}{m_{pl}} \leq 2 \cdot 10^{-19} h^{4/3} k^{2/3}. \]  

(42)

This condition implies that the masses of PBHs created at the end of inflation have to be larger then

\[ M_0 \geq 10^{11} g \cdot h^{-4/3} \cdot k^{2/3}. \]  

(43)

From the other hand there are a number of well–known cosmological and astrophysical limits\(^{228, 284–289}\) which prohibit the creation of PBHs in the mass range \( (43) \) with initial fraction of mass density close to \( \beta_0 \approx 10^{-2} \).

So one have to conclude that the effect of the false vacuum bag mechanism of PBH formation makes impossible the coexistence of stable remnants of PBH evaporation with the first order phase transitions at the end of inflation.

### 3.4. PBH evaporation as universal particle accelerator

Presently there are no observational evidences, proving existence of PBHs. However, even the absence of PBHs provides a very sensitive theoretical tool to study physics of early Universe. PBHs represent nonrelativistic form of matter and their density decreases with scale factor \( a \) as \( \propto a^{-3} \propto T^3 \), while the total density is \( \propto a^{-4} \propto T^4 \) in the period of radiation dominance (RD). Being formed within horizon, PBH of mass \( M \), can be formed not earlier than at

\[ t(M) = \frac{M}{m_{pl}} t_{pl} = \frac{M}{m_{pl}^2}. \]  

(44)

If they are formed on RD stage, the smaller are the masses of PBHs, the larger becomes their relative contribution to the total density on the modern MD stage.
Therefore, even the modest constraint for PBHs of mass $M$ on their density
\[ \Omega_{PBH}(M) = \frac{\rho_{PBH}(M)}{\rho_c} \] (45)
in units of critical density $\rho_c = 3H^2/(8\pi G)$ from the condition that their contribution $\alpha(M)$ into the total density
\[ \alpha(M) = \frac{\rho_{PBH}(M)}{\rho_{tot}} = \Omega_{PBH}(M) \] (46)
for $\rho_{tot} = \rho_c$ does not exceed the density of dark matter
\[ \alpha(M) = \Omega_{PBH}(M) \leq \Omega_{DM} = 0.23 \] (47)
converts into a severe constraint on this contribution
\[ \beta = \frac{\rho_{PBH}(M,t_f)}{\rho_{tot}(t_f)} \] (48)
in the period $t_f$ of their formation. If formed on RD stage at $t_f = t(M)$, given by (44), which corresponds to the temperature $T_f = m_{pl} \sqrt{m_{pl}/M}$, PBHs contribute into the total density in the end of RD stage at $t_{eq}$, corresponding to $T_{eq} \approx 1\text{eV}$, by factor $a(t_{eq})/a(t_f) = T_f/T_{eq} = m_{pl}/T_{eq} \sqrt{m_{pl}/M}$ larger, than in the period of their formation. The constraint on $\beta(M)$, following from Eq.(47) is then given by
\[ \beta(M) = \alpha(M) \frac{T_{eq} \sqrt{M}}{m_{pl} \sqrt{m_{pl}}} \leq 0.23 \frac{T_{eq} \sqrt{M}}{m_{pl}}. \] (49)

The possibility of PBH evaporation, revealed by S. Hawking, strongly influences effects of PBHs. In the strong gravitational field near gravitational radius $r_g$ of PBH quantum effect of creation of particles with momentum $p \sim 1/r_g$ is possible. Due to this effect PBH turns to be a black body source of particles with temperature (in the units $\hbar = c = k = 1$)
\[ T = \frac{1}{8\pi GM} \approx 10^{13}\text{GeV} \frac{1\text{g}}{M}. \] (50)
The evaporation timescale BH is $\tau_{BH} \sim M^3/m_{pl}^4$ (see Eq.(37) and discussion in previous section) and at $M \leq 10^{14}$ g is less, than the age of the Universe. Such PBHs can not survive to the present time and the magnitude Eq.(47) for them should be re-defined and has the meaning of contribution to the total density in the moment of PBH evaporation. For PBHs formed on RD stage and evaporated on RD stage at $t < t_{eq}$ the relationship Eq.(49) between $\beta(M)$ and $\alpha(M)$ is given by
\[ \beta(M) = \alpha(M) \frac{m_{pl}}{M}. \] (51)
The relationship between $\beta(M)$ and $\alpha(M)$ has more complicated form, if PBHs are formed on early dust-like stages or such stages take place after PBH formation. Relative contribution of PBHs to total density does not grow on
dust-like stage and the relationship between $\beta(M)$ and $\alpha(M)$ depends on details of a considered model. Minimal model independent factor $\alpha(M)/\beta(M)$ follows from the account for enhancement, taking place only during RD stage between the first second of expansion and the end of RD stage at $t_{eq}$, since radiation dominance in this period is supported by observations of light element abundance and spectrum of CMB.\textsuperscript{3,110,148,178}

Effects of PBH evaporation make astrophysical data much more sensitive to existence of PBHs. Constraining the abundance of primordial black holes can lead to invaluable information on cosmological processes, particularly as they are probably the only viable probe for the power spectrum on very small scales which remain far from the Cosmological Microwave Background (CMB) and Large Scale Structures (LSS) sensitivity ranges. To date, only PBHs with initial masses between $\sim 10^9$ g and $\sim 10^{16}$ g have led to stringent limits (see e.g. Refs. 110,175–177) from consideration of the entropy per baryon, the deuterium destruction, the $^4$He destruction and the cosmic-rays currently emitted by the Hawking process.\textsuperscript{173} The existence of light PBHs should lead to important observable constraints, either through the direct effects of the evaporated particles (for initial masses between $10^{14}$ g and $10^{16}$ g) or through the indirect effects of their interaction with matter and radiation in the early Universe (for PBH masses between $10^9$ g and $10^{14}$ g). In these constraints, the effects taken into account are those related with known particles. However, since the evaporation products are created by the gravitational field, any quantum with a mass lower than the black hole temperature should be emitted, independently of the strength of its interaction. This could provide a copious production of superweakly interacting particles that cannot be in equilibrium with the hot plasma of the very early Universe. It makes evaporating PBHs a unique source of all the species, which can exist in the Universe.

Following Refs. 3,4,98,178 and 258,259 (but in a different framework and using more stringent constraints), limits on the mass fraction of black holes at the time of their formation ($\beta \equiv \rho_{PBH}/\rho_{tot}$) were derived in Ref. 291 using the production of gravitinos during the evaporation process. Depending on whether gravitinos are expected to be stable or metastable, the limits are obtained using the requirement that they do not overclose the Universe and that the formation of light nuclei by the interactions of $^4$He nuclei with nonequilibrium flux of D,T,$^3$He and $^4$He does not contradict the observations. This approach is more constraining than the usual study of photo-dissociation induced by photons-photinos pairs emitted by decaying gravitinos. It opened a new window for the upper limits on $\beta$ below $10^9$ g and correspondingly on various mechanisms of PBH formation.\textsuperscript{291}

3.5. Massive Primordial Black Holes - seeds for galaxy formation

3.5.1. Formation of closed walls in inflationary Universe

To describe a mechanism for the appearance of massive walls of a size essentially greater than the horizon at the end of inflation, let us consider a complex scalar
field with the potential\textsuperscript{114,121,123,125}

\[ V(\varphi) = \lambda (|\varphi|^2 - f^2/2)^2 + \delta V(\theta), \]

(52)

where \( \varphi = re^{i\theta} \). This field coexists with an inflaton field which drives the Hubble constant \( H \) during the inflational stage. The term

\[ \delta V(\theta) = \Lambda^4 (1 - \cos \theta), \]

(53)

reflecting the contribution of instanton effects to the Lagrangian renormalization (see for example Ref. 292), is negligible on the inflational stage and during some period in the FRW expansion. The omitted term becomes significant, when temperature falls down the values \( T \sim \Lambda \). The mass of radial field component \( r \) is assumed to be sufficiently large with respect to \( H \), which means that the complex field is in the ground state even before the end of inflation. Since the term is negligible during inflation, the field has the form \( \varphi \approx f/\sqrt{2} \cdot e^{i\theta} \), the quantity \( f\theta \) acquiring the meaning of a massless field.

At the same time, the well established behavior of quantum field fluctuations on the de Sitter background\textsuperscript{13} implies that the wavelength of a vacuum fluctuation of every scalar field grows exponentially, having a fixed amplitude. Namely, when the wavelength of a particular fluctuation, in the inflating Universe, becomes greater than \( H^{-1} \), the average amplitude of this fluctuation freezes out at some non-zero value because of the large friction term in the equation of motion of the scalar field, whereas its wavelength grows exponentially. Such a frozen fluctuation is equivalent to the appearance of a classical field that does not vanish after averaging over macroscopic space intervals. Because the vacuum must contain fluctuations of every wavelength, inflation leads to the creation of more and more new regions containing a classical field of different amplitudes with scale greater than \( H^{-1} \). In the case of an effectively massless Nambu–Goldstone field considered here, the averaged amplitude of phase fluctuations generated during each e-fold (time interval \( H^{-1} \)) is given by

\[ \delta \theta = H/2\pi f. \]

(54)

Let us assume that the part of the Universe observed inside the contemporary horizon \( H_0^{-1} = 3000h^{-1}\text{Mpc} \) was inflating, over \( N_U \approx 60 \) e-folds, out of a single causally connected domain of size \( H^{-1} \), which contains some average value of phase \( \theta_0 \) over it. When inflation begins in this region, after one e-fold, the volume of the Universe increases by a factor \( e^3 \). The typical wavelength of the fluctuation \( \delta \theta \) generated during every e-fold is equal to \( H^{-1} \). Thus, the whole domain \( H^{-1} \), containing \( \theta_0 \), after the first e-fold effectively becomes divided into \( e^3 \) separate, causally disconnected domains of size \( H^{-1} \). Each domain contains almost homogeneous phase value \( \theta_0 \pm \delta \theta \). Thereby, more and more domains appear with time, in which the phase differs significantly from the initial value \( \theta_0 \). A principally important point is the appearance of domains with phase \( \theta > \pi \). Appearing only after a certain period of time during which the Universe exhibited exponential expansion, these domains turn out to be surrounded by a space with phase \( \theta < \pi \). The coexistence of domains

\[ \text{November 12, 2013 1:24 WSPC/INSTRUCTION FILE KhlopovDMRevCor} \]
with phases $\theta < \pi$ and $\theta > \pi$ leads, in the following, to formation of a large-scale structure of topological defects.

The potential (52) possesses a $U(1)$ symmetry, which is spontaneously broken, at least, after some period of inflation. Note that the phase fluctuations during the first e-folds may, generally speaking, transform eventually into fluctuations of the cosmic microwave radiation, which will lead to imposing restrictions on the scaling parameter $f$. This difficulty can be avoided by taking into account the interaction of the field $\varphi$ with the inflaton field (i.e. by making parameter $f$ a variable). This spontaneous breakdown is holding by the condition of smallness of the radial mass, $m_r = \sqrt{\lambda} \varphi > H$. At the same time the condition (55)

$$m_\theta = \frac{2f^2}{\Lambda} \ll H$$

on the angular mass provides the freezing out of the phase distribution until some moment of the FRW epoch. After the violation of condition (55) the term contributes significantly to the potential (52) and explicitly breaks the continuous symmetry along the angular direction. Thus, potential (52) eventually has a number of discrete degenerate minima in the angular direction at the points $\theta_{\text{min}} = 0, \pm 2\pi, \pm 4\pi, \ldots$.

As soon as the angular mass $m_\theta$ is of the order of the Hubble rate, the phase starts oscillating about the potential minimum, initial values being different in various space domains. Moreover, in the domains with the initial phase $\pi < \theta < 2\pi$, the oscillations proceed around the potential minimum at $\theta_{\text{min}} = 2\pi$, whereas the phase in the surrounding space tends to a minimum at the point $\theta_{\text{min}} = 0$. Upon ceasing of the decaying phase oscillations, the system contains domains characterized by the phase $\theta_{\text{min}} = 2\pi$ surrounded by space with $\theta_{\text{min}} = 0$. Apparently, on moving in any direction from inside to outside of the domain, we will unavoidably pass through a point where $\theta = \pi$ because the phase varies continuously. This implies that a closed surface characterized by the phase $\theta_{\text{wall}} = \pi$ must exist. The size of this surface depends on the moment of domain formation in the inflation period, while the shape of the surface may be arbitrary. The principal point for the subsequent considerations is that the surface is closed. After reheating of the Universe, the evolution of domains with the phase $\theta > \pi$ proceeds on the background of the Friedman expansion and is described by the relativistic equation of state. When the temperature falls down to $T_* \sim \Lambda$, an equilibrium state between the "vacuum" phase $\theta_{\text{vac}} = 2\pi$ inside the domain and the $\theta_{\text{vac}} = 0$ phase outside it is established. Since the equation of motion corresponding to potential (53) admits a kink-like solution (see Ref. 120 and references therein), which interpolates between two adjacent vacua $\theta_{\text{vac}} = 0$ and $\theta_{\text{vac}} = 2\pi$, a closed wall corresponding to the transition region at $\theta = \pi$ is formed. The surface energy density of a wall of width $\sim 1/m \sim f/\Lambda^2$ is of the order of $\sim f\Lambda^2$.

\footnote{The existence of such domain walls in theory of the invisible axion was first pointed out in Ref.}
Note that if the coherent phase oscillations do not decay for a long time, their energy density can play the role of CDM. This is the case, for example, in the cosmology of the invisible axion (see [119] and references therein).

It is clear that immediately after the end of inflation, the size of domains which contains a phase $\theta_{\text{vac}} > 2\pi$ essentially exceeds the horizon size. This situation is replicated in the size distribution of vacuum walls, which appear at the temperature $T_* \sim \Lambda$ whence the angular mass $m_\theta$ starts to build up. Those walls, which are larger than the cosmological horizon, still follow the general FRW expansion until the moment when they get causally connected as a whole; this happens as soon as the size of a wall becomes equal to the horizon size $R_h$. Evidently, internal stresses developed in the wall after crossing the horizon initiate processes tending to minimize the wall surface. This implies that the wall tends, first, to acquire a spherical shape and, second, to contract toward the centre. For simplicity, we will consider below the motion of closed spherical walls.

The wall energy is proportional to its area at the instant of crossing the horizon. At the moment of maximum contraction, this energy is almost completely converted into kinetic energy. Should the wall at the same moment be localized within the gravitational radius, a PBH is formed.

Detailed consideration of BH formation was performed in Ref. 123. The results of these calculations are sensitive to changes in the parameter $\Lambda$ and the initial phase $\theta_U$. As the $\Lambda$ value decreases to $\approx 1\text{GeV}$, still greater PBHs appear with masses of up to $\sim 10^{40}$ g. A change in the initial phase leads to sharp variations in the total number of black holes. As was shown above, each domain generates a family of subdomains in the close vicinity. The total mass of such a cluster is only 1.5–2 times that of the largest initial black hole in this space region. Thus, the calculations confirm the possibility of formation of clusters of massive PBHs ($\sim 100M_\odot$ and above) in the earliest stages of the evolution of the Universe at a temperature of $\sim 1 - 10\text{GeV}$. These clusters represent stable energy density fluctuations around which increased baryonic (and cold dark matter) density may concentrate in the subsequent stages, followed by the evolution into galaxies.

It should be noted that additional energy density is supplied by closed walls of small sizes. Indeed, because the smallness of their gravitational radius, they do not collapse into BHs. After several oscillations such walls disappear, leaving coherent fluctuations of the PNG field. These fluctuations contribute to a local energy density excess, thus facilitating the formation of galaxies.

The mass range of formed BHs is constrained by fundamental parameters of the model $f$ and $\Lambda$. The maximal BH mass is determined by the condition that the wall does not dominate locally before it enters the cosmological horizon. Otherwise, local wall dominance leads to a superluminal $a \propto t^2$ expansion for the corresponding region, separating it from the other part of the Universe. This condition corresponds...
to the mass

\[ M_{\text{max}} = \frac{m_{\text{pl}}}{f m_{\text{pl}}} (\frac{m_{\text{pl}}}{\Lambda})^2. \] (56)

The minimal mass follows from the condition that the gravitational radius of BH exceeds the width of wall and it is equal to

\[ M_{\text{min}} = f (\frac{m_{\text{pl}}}{\Lambda})^2. \] (57)

Closed wall collapse leads to primordial GW spectrum, peaked at

\[ \nu_0 = 3 \cdot 10^{11} (\Lambda/f) \text{Hz} \] (58)

with energy density up to

\[ \Omega_{\text{GW}} \approx 10^{-4} (f/m_{\text{pl}}). \] (59)

At \( f \sim 10^{14} \text{GeV} \) this primordial gravitational wave background can reach \( \Omega_{\text{GW}} \approx 10^{-9} \). For the physically reasonable values of

\[ 1 < \Lambda < 10^8 \text{GeV} \] (60)

the maximum of spectrum corresponds to

\[ 3 \cdot 10^{-3} < \nu_0 < 3 \cdot 10^5 \text{Hz}. \] (61)

Another profound signature of the considered scenario are gravitational wave signals from merging of BHs in PBH cluster. These effects can provide test of the considered approach in LISA experiment.

4. Dark matter from flavor symmetry

4.1. Symmetry of known families

The existence and observed properties of the three known quark-lepton families appeal to the broken \( SU(3)_H \) family symmetry,\(^{39-41} \) which should be involved in the extension of the Standard model. It provides the possibility of the Horizontal unification in the “bottom-up” approach to the unified theory.\(^{42} \) Even in its minimal implementation the model of Horizontal unification can reproduce the main necessary elements of the modern cosmology. It provides the physical mechanisms for inflation and baryosynthesis as well as it offers unified description of candidates for Cold, Warm, Hot and Unstable Dark Matter. Methods of cosmoparticle physics\(^3,5 \) have provided the complete test of this model. Here we discuss the possibilities to link physical basis of modern cosmology to the parameters of broken family symmetry.
4.1.1. Horizontal hierarchy

The approach of Refs. 39–42 (and its revival in Refs. 297–299) follows the concept of local gauge symmetry $SU(3)_H$, first proposed by Chkareuli. Under the action of this symmetry the left-handed quarks and leptons transform as $SU(3)_H$ triplets and the right-handed as antitriplets. Their mass term transforms as $3 \otimes 3 = 6 \otimes \bar{3}$ and, therefore, can only form as a result of horizontal symmetry breaking.

This approach can be trivially extended to the case of $n$ generations, assuming the proper $SU(n)$ symmetry. For three generations, the choice of horizontal symmetry $SU(3)_H$ is the only possible choice because the orthogonal and vector-like gauge groups can not provide different representations for the left- and right-handed fermion states.

In the considered approach, the hypothesis that the structure of the mass matrix is determined by the structure of horizontal symmetry breaking, i.e., the structure of the vacuum expectation values of horizontal scalars carrying the $SU(3)_H$ breaking is justified.

The mass hierarchy between generations is related to the hypothesis of a hierarchy of such symmetry breaking. This hypothesis is called - the hypothesis of horizontal hierarchy (HHH).

The model is based on the gauge $SU(3)_H$ flavor symmetry, which is additional to the symmetry of the Standard model. It means that there exist 8 heavy horizontal gauge bosons and there are three multiplets of heavy Higgs fields $\xi^{(n)}_{ij}$ ($i,j$ - family indexes, $n = 1, 2, 3$) in nontrivial (sextet or triplet) representations of $SU(3)_H$. These heavy Higgs bosons are singlets relative to electroweak symmetry and don’t have Yukawa couplings with ordinary light fermions. They have direct coupling to heavy fermions. The latter are singlets relative to electroweak symmetry. Ordinary Higgs $\phi$ of the Standard model is singlet relative to $SU(3)_H$. It couples left-handed light fermions $f^L_i$ to their heavy right-handed partners $F^R_i$, which are coupled by heavy Higgses $\xi_{ij}$ with heavy left handed states $F^L_{ij}$. Heavy left-handed states $F^L_{ij}$ are coupled to right handed light states $f^L_k$ by a singlet scalar Higgs field $\eta$, which is singlet both relative to $SU(3)_H$ and electroweak group of symmetry. The described succession of transitions realizes Dirac seesaw mechanism, which reproduces the mass matrix $m_{ij}$ of ordinary light quarks and charged leptons $f$ due to mixing with their heavy partners $F$. It fixes the ratio of vacuum expectation values of heavy Higgs fields, leaving their absolute value as the only main free parameter, which is determined from analysis of physical, astrophysical and cosmological consequences.

The $SU(3)_H$ flavor symmetry should be chiral to eliminate the flavor symmetric mass term. The condition of absence of anomalies implies heavy partners of light neutrinos, and the latter acquire mass by Majorana seesaw mechanism. The natural absence in the heavy Higgs potentials of triple couplings, which do not appear as radiative effects of any other (gauge or Yukawa) interaction, supports additional global U(1) symmetry, which can be associated with Peccei-Quinn symmetry and whose breaking results in the Nambu-Goldstone scalar filed, which shares the prop-
erties of axion, Majoron and singlet familon.

4.1.2. *Horizontal unification*

The model provides complete test (in which its simplest implementation is already ruled out) in a combination of laboratory tests and analysis of cosmological and astrophysical effects. The latter include the study of the effect of radiation of axions on the processes of stellar evolution, the study of the impact of the effects of primordial axion fields and massive unstable neutrino on the dynamics of formation of the large-scale structure of the Universe, as well as analysis of the mechanisms of inflation and baryosynthesis based on the physics of the hidden sector of the model.

The model results in physically self-consistent inflationary scenarios with dark matter in the baryon-asymmetric Universe. In these scenarios, all steps of the cosmological evolution correspond quantitatively to the parameters of particle theory. The physics of the inflaton corresponds to the Dirac seesaw mechanism of generation of the mass of the quarks and charged leptons, leptogenesis of baryon asymmetry is based on the physics of Majorana neutrino masses. The parameters of axion CDM, as well as the masses and lifetimes of neutrinos correspond to the hierarchy of breaking of the $SU(3)_H$ symmetry of families.

4.2. *Stable charged constituents of Dark Atoms*

New stable particles may possess new U(1) gauge charges and bind by Coulomb-like forces in composite dark matter species. Such dark atoms would look nonluminous, since they radiate invisible light of U(1) photons. Historically mirror matter (see subsubsection 2.2.4 and Refs. 3, 63 for review and references) seems to be the first example of such a nonluminous atomic dark matter.

However, it turned out that the possibility of new stable charged leptons and quarks is not completely excluded and Glashow’s tera-helium\(^{90}\) has offered a new solution for dark atoms of dark matter. Tera-U-quarks with electric charge +2/3 formed stable (UUU) +2 charged ”clusters” that formed with two -1 charged tera-electrons E neutral [(UUU)EE] tera-helium ”atoms” that behaved like Weakly Interacting Massive Particles (WIMPs). The main problem for this solution was to suppress the abundance of positively charged species bound with ordinary electrons, which behave as anomalous isotopes of hydrogen or helium. This problem turned to be unresolvable,\(^{91}\) since the model\(^{90}\) predicted stable tera-electrons $E^-$ with charge -1. As soon as primordial helium is formed in the Standard Big Bang Nucleosynthesis (SBBN) it captures all the free $E^-$ in positively charged $(HeE)^+$ ion, preventing any further suppression of positively charged species. Therefore, in order to avoid anomalous isotopes overproduction, stable particles with charge -1 (and corresponding antiparticles) should be absent, so that stable negatively charged particles should have charge -2 only.

Elementary particle frames for heavy stable -2 charged species are provided by: (a) stable ”antibaryons” $\bar{U}U\bar{U}$ formed by anti-U quark of fourth gener-
(b) AC-leptons, predicted in the extension of standard model, based on the approach of almost-commutative geometry. (c) Technileptons and anti-technibaryons in the framework of walking technicolor models (WTC). (d) Finally, stable charged clusters of (anti)quarks of 5th family can follow from the approach, unifying spins and charges. Since all these models also predict corresponding +2 charge antiparticles, cosmological scenario should provide mechanism of their suppression, what can naturally take place in the asymmetric case, corresponding to excess of -2 charge species, $O^{- -}$. Then their positively charged antiparticles can effectively annihilate in the early Universe.

If new stable species belong to non-trivial representations of electroweak SU(2) group, sphaleron transitions at high temperatures can provide the relationship between baryon asymmetry and excess of -2 charge stable species, as it was demonstrated in the case of WTC in Refs. 307, 319–323.

4.2.1. Problem of tera-fermion composite dark matter

Glashow’s Tera-helium Universe was first inspiring example of the composite dark matter scenario. $SU(3)_c \times SU(2) \times SU(2)' \times U(1)$ gauge model aimed to explain the origin of the neutrino mass and to solve the problem of strong CP-violation in QCD. New extra $SU(2)'$ symmetry acts on three heavy generations of tera-fermions linked with the light fermions by $CP'$ transformation. $SU(2)'$ symmetry breaking at TeV scale makes tera-fermions much heavier than their light partners. Tera-fermion mass spectrum is the same as for light generations, but all the masses are scaled by the same factor of about $10^6$. Thus the masses of lightest heavy particles are in tera-eV (TeV) range, explaining their name.

Glashow’s model takes into account that very heavy quarks $Q$ (or antiquarks $\bar{Q}$) can form bound states with other heavy quarks (or antiquarks) due to their Coulomb-like QCD attraction, and the binding energy of these states substantially exceeds the binding energy of QCD confinement. Then stable $(QQq)$ and $(QQQ)$ baryons can exist.

According to Ref. 90 primordial heavy quark $U$ and heavy electron $E$ are stable and may form a neutral $(UUUEE)$ ”atom” with $(UUU)$ hadron as nucleus and two $E$'s as ”electrons”. The gas of such ”tera-helium atoms” was proposed in Ref. 90 as a candidate for a WIMP-like dark matter.

The problem of such scenario is an inevitable presence of ”products of incomplete combustion” and the necessity to decrease their abundance.

Unfortunately, as it was shown in Ref. 91, this picture of Tera-helium Universe can not be realized.

When ordinary $^4$He is formed in Big Bang Nucleosynthesis, it binds all the free $E^-$ into positively charged ($^4HeE^-)^+$ ”ions”. This puts Coulomb barrier for any successive $E^-E^+$ annihilation or any effective $EU$ binding. It removes a possibility to suppress the abundance of unwanted tera-particle species (like $(eE^+)$, $(^4HeEe)$
etc). For instance the remaining abundance of \((eE^+)\) and \((^4HeE^-e)\) exceeds the terrestrial upper limit for anomalous hydrogen by 27 orders of magnitude.91

4.2.2. Composite dark matter from almost commutative geometry

The AC-model is based on the specific mathematical approach of unifying general relativity, quantum mechanics and gauge symmetry.94,306 This realization naturally embeds the Standard model, both reproducing its gauge symmetry and Higgs mechanism with prediction of a Higgs boson mass. AC model is in some sense alternative to SUSY, GUT and superstring extension of Standard model. The AC-model94 extends the fermion content of the Standard model by two heavy particles, \(SU(2)\) electro-weak singlets, with opposite electromagnetic charges. Each of them has its own antiparticle. Having no other gauge charges of Standard model, these particles (AC-fermions) behave as heavy stable leptons with charges \(-2e\) and \(+2e\), called \(A^{--}\) and \(C^{++}\), respectively.

Similar to the Tera-helium Universe, AC-lepton relics from intermediate stages of a multi-step process towards a final (AC) atom formation must survive in the present Universe. In spite of the assumed excess of particles \((A^{--}+C^{++})\) the abundance of relic antiparticles \((\bar{A}^{++}+\bar{C}^{--})\) is not negligible. There may be also a significant fraction of \(A^{--}\) and \(C^{++}\), which remains unbound after recombination process of these particles into (AC) atoms took place. As soon as \(^4He\) is formed in Big Bang nucleosynthesis, the primordial component of free anion-like AC-leptons \((A^{--})\) is mostly trapped in the first three minutes into a neutral O-helium atom \(^4He^{++}A^{--}\). O-helium is able to capture free \(C^{++}\) creating (AC) atoms and releasing \(^4He\) back. In the same way the annihilation of antiparticles speeds up. \(C^{++}\)-O-helium reactions stop, when their timescale exceeds a cosmological time, leaving O-helium and \(C^{++}\) relics in the Universe. The catalytic reaction of O-helium with \(C^{++}\) in the dense matter bodies provides successive (AC) binding that suppresses terrestrial anomalous isotope abundance below the experimental upper limit. Due to screened charge of AC-atoms they have WIMP-like interaction with the ordinary matter. Such WIMPs are inevitably accompanied by a tiny component of nuclear interacting O-helium.

4.2.3. Stable charged techniparticles in Walking Technicolor

The minimal walking technicolor model308–313 has two techniquarks, i.e. up \(U\) and down \(D\), that transform under the adjoint representation of an \(SU(2)\) technicolor gauge group. The six Goldstone bosons \(UU, UD, DD\) and their corresponding antiparticles carry technibaryon number since they are made of two techniquarks or two anti-techniquarks. This means that if there is no processes violating the technibaryon number the lightest technibaryon will be stable.

The electric charges of \(UU, UD\), and \(DD\) are given in general by \(q+1, q\), and \(q-1\) respectively, where \(q\) is an arbitrary real number. The model requires in
addition the existence of a fourth family of leptons, i.e. a “new neutrino” $\nu'$ and a “new electron” $\zeta$. Their electric charges are in terms of $q$ respectively $(1 - 3q)/2$ and $(-1 - 3q)/2$.

There are three possibilities for a scenario of dark atoms of dark matter. The first one is to have an excess of $\bar{U}U$ (charge $-2$). The technibaryon number $TB$ is conserved and therefore $UU$ (or $\bar{U}\bar{U}$) is stable. The second possibility is to have excess of $\zeta$ that also has $-2$ charge and is stable, if $\zeta$ is lighter than $\nu'$ and technilepton number $L'$ is conserved. In the both cases stable particles with $-2$ electric charge have substantial relic densities and can capture $^4He^{++}$ nuclei to form a neutral techni-O-helium atom. Finally there is a possibility to have both $L'$ and $TB$ conserved. In this case, the dark matter would be composed of bound atoms $(^4He^{++}\zeta^{--})$ and $(\zeta^{--}(UU)^{++})$. In the latter case the excess of $\zeta^{--}$ should be larger, than the excess of $(UU)^{++}$, so that WIMP-like $(\zeta^{--}(UU)^{++})$ is subdominant at the dominance of nuclear interacting techni-O-helium.

The technicolor and the Standard Model particles are in thermal equilibrium as long as the timescale of the weak (and color) interactions is smaller than the cosmological time. The sphalerons allow violation of $TB$, of baryon number $B$, of lepton number $L$ and $L'$ as long as the temperature of the Universe exceeds the electroweak scale. It was shown in Ref. 307 that there is a balance between the excess of techni(anti)baryons, $(\bar{U}\bar{U})^{--}$, technileptons $\zeta^{--}$ or of the both over the corresponding particles $(UU$ and/or $\zeta^{++})$ and the observed baryon asymmetry of the Universe. It was also shown the there are parameters of the model, at which this asymmetry has proper sign and value, explaining the dark matter density.

### 4.2.4. Stable particles of 4th generation matter

Modern precision data on the parameters of the Standard model do not exclude the existence of the 4th generation of quarks and leptons. The 4th generation follows from heterotic string phenomenology and its difference from the three known light generations can be explained by a new conserved charge, possessed only by its quarks and leptons.\(^{95,304,325-327}\) Strict conservation of this charge makes the lightest particle of 4th family (neutrino) absolutely stable, but it was shown in Refs. 325–327 that this neutrino cannot be the dominant form of the dark matter. The same conservation law requires the lightest quark to be long living.\(^{95,304}\) In principle the lifetime of $U$ can exceed the age of the Universe, if $m_U < m_D$.\(^{95,304}\) Provided that sphaleron transitions establish excess of $\bar{U}$ antiquarks at the observed baryon asymmetry $(\bar{U}\bar{U})$ can be formed and bound with $^4He$ in atom-like state of O-helium.\(^{95}\)

In the successive discussion of OHe dark matter we generally don’t specify the type of $-2$ charged particle, denoting it as $O^{--}$. However, one should note that the AC model doesn’t provide OHe as the dominant form of dark matter, so that the quantitative features of OHe dominated Universe are not related to this case.
5. Dark atoms with helium shell

Here we concentrate on the properties of OHe atoms, their interaction with matter and qualitative picture of OHe cosmological evolution\(^{94,95,307,321,328–330}\) and observable effects. We show following Refs. 97,331 that interaction of OHe with nuclei in underground detectors can explain positive results of dark matter searches in DAMA/NaI (see for review Ref. 69) and DAMA/LIBRA\(^70\) experiments by annual modulations of radiative capture of O-helium, resolving the controversy between these results and the results of other experimental groups.

After it is formed in the Standard Big Bang Nucleosynthesis (SBBN), \(^4\)He screens the excessive \(O^-\) charged particles in composite \((^4\text{He}^{++}O^-)\) O-helium (OHe) “atoms”.\(^95\)

In all the considered forms of O-helium, \(O^-\) behaves either as lepton or as specific ”heavy quark cluster” with strongly suppressed hadronic interaction. Therefore O-helium interaction with matter is determined by nuclear interaction of \(^4\)He. These neutral primordial nuclear interacting species can play the role of a nontrivial form of strongly interacting dark matter,\(^332–340\) giving rise to a Warmer than Cold dark matter scenario.\(^319,320,328\)

5.1. OHe atoms and their interaction with nuclei

The structure of OHe atom follows from the general analysis of the bound states of \(O^-\) with nuclei.

Consider a simple model,\(^341–343\) in which the nucleus is regarded as a sphere with uniform charge density and in which the mass of the \(O^-\) is assumed to be much larger than that of the nucleus. Spin dependence is also not taken into account so that both the particle and nucleus are considered as scalars. Then the Hamiltonian is given by

\[
H = \frac{p^2}{2Am_p} - \frac{ZZ_x\alpha}{2R} + \frac{ZZ_x\alpha}{2R} \cdot \left(\frac{r}{R}\right)^2, \tag{62}
\]

for short distances \(r < R\) and

\[
H = \frac{p^2}{2Am_p} - \frac{ZZ_x\alpha}{R}, \tag{63}
\]

for long distances \(r > R\), where \(\alpha\) is the fine structure constant, \(R = d_oA^{1/3} \sim 1.2A^{1/3}/(200MeV)\) is the nuclear radius, \(Z\) is the electric charge of nucleus and \(Z_x = 2\) is the electric charge of negatively charged particle \(X^-\). Since \(Am_p < M_X\) the reduced mass is \(1/m = (Am_p)/M_X \approx 1/(Am_p)\).

For small nuclei the Coulomb binding energy is like in hydrogen atom and is given by

\[
E_b = \frac{1}{2}Z^2Z_x^2\alpha^2 Am_p. \tag{64}
\]
For large nuclei $X^{-}$ is inside nuclear radius and the harmonic oscillator approximation is valid for the estimation of the binding energy

$$E_b = \frac{3}{2} \left( \frac{Z Z_x \alpha}{R} \right) - \frac{1}{R} \left( \frac{Z Z_x \alpha}{A m_p R} \right)^{1/2}.$$

(65)

For the intermediate regions between these two cases with the use of trial function of the form $\psi \sim e^{-\gamma r/R}$ variational treatment of the problem\textsuperscript{341–343} gives

$$E_b = \frac{1}{A m_p R^2} F(Z Z_x \alpha A m_p R),$$

(66)

where the function $F(a)$ has limits

$$F(a \to 0) \to \frac{1}{2} a^2 - \frac{2}{5} a^4$$

(67)

and

$$F(a \to \infty) \to \frac{3}{2} a - (3a)^{1/2},$$

(68)

where $a = Z Z_x \alpha A m_p R$. For $0 < a < 1$ the Coulomb model gives a good approximation, while at $2 < a < \infty$ the harmonic oscillator approximation is appropriate.

In the case of OHe $a = Z Z_x \alpha A m_p R \leq 1$, what proves its Bohr-atom-like structure, assumed in Refs. 95, 307, 321–323. The radius of Bohr orbit in these “atoms”\textsuperscript{95,328} $r_o \sim 1/(Z_o Z_{He} \alpha A m_{He}) \approx 2 \cdot 10^{-13}$ cm. However, the size of He nucleus, rotating around $O^{-}$ in this Bohr atom, turns out to be of the order and even a bit larger than the radius $r_o$ of its Bohr orbit, and the corresponding correction to the binding energy due to non-point-like charge distribution in He is significant.

Bohr atom like structure of OHe seems to provide a possibility to use the results of atomic physics for description of OHe interaction with matter. However, the situation is much more complicated. OHe atom is similar to the hydrogen, in which electron is hundreds times heavier, than proton, so that it is proton shell that surrounds ”electron nucleus”. Nuclei that interact with such ”hydrogen” would interact first with strongly interacting ”protonic” shell and such interaction can hardly be treated in the framework of perturbation theory. Moreover in the description of OHe interaction the account for the finite size of He, which is even larger than the radius of Bohr orbit, is important. One should consider, therefore, the analysis, presented below, as only a first step approaching true nuclear physics of OHe.

The approach of Refs. 319,328 assumes the following picture of OHe interaction with nuclei: OHe is a neutral atom in the ground state, perturbed by Coulomb and nuclear forces of the approaching nucleus. The sign of OHe polarization changes with the distance: at larger distances Stark-like effect takes place - nuclear Coulomb force polarizes OHe so that nucleus is attracted by the induced dipole moment of OHe, while as soon as the perturbation by nuclear force starts to dominate the nucleus polarizes OHe in the opposite way so that He is situated more close to the nucleus, resulting in the repulsive effect of the helium shell of OHe. When helium
is completely merged with the nucleus the interaction is reduced to the oscillatory potential of $O^{- -}$ with homogeneously charged merged nucleus with the charge $Z + 2$.

Therefore OHe-nucleus potential can have qualitative feature, presented on Fig. 2: the potential well at large distances (regions III-IV) is changed by a potential wall in region II. The existence of this potential barrier is crucial for all the qualitative features of OHe scenario: it causes suppression of reactions with transition of OHe-nucleus system to levels in the potential well of the region I, provides the dominance of elastic scattering while transitions to levels in the shallow well (regions III-IV) should dominate in reactions of OHe-nucleus capture. The proof of this picture implies accurate and detailed quantum-mechanical treatment, which was started in Ref. 344. With the use of perturbation theory it was shown that OHe polarization changes sign, as the nucleus approaches OHe (as it is given on Fig. 3), but the perturbation approach was not valid for the description at smaller distances, while the estimations indicated that this change of polarization may not be sufficient for creation of the potential, given by Fig. 2. If the picture of Fig. 2 is not proved, one may need more sophisticated models retaining the ideas of OHe scenario, which involve more elements of new physics, as proposed in Ref. 345.

On the other hand, O-helium, being an $\alpha$-particle with screened electric charge, can catalyze nuclear transformations, which can influence primordial light element abundance and cause primordial heavy element formation. It is especially important for quantitative estimation of role of OHe in Big Bang Nucleosynthesis and in stellar evolution. These effects need a special detailed and complicated study of OHe nuclear physics and this work is under way.

The qualitative picture of OHe cosmological evolution is presented below following Refs. 94, 95, 97, 307, 319, 321, 328, 329 and is based on the idea of the dominant
Fig. 3. Polarization $< z > (\text{fm})$ of OHe as a function of the distance $R \ (\text{fm})$ of an external sodium nucleus, calculated in Ref. 344 in the framework of perturbation theory.

role of elastic collisions in OHe interaction with baryonic matter.

5.2. Large Scale structure formation by OHe dark matter

Due to elastic nuclear interactions of its helium constituent with nuclei in the cosmic plasma, the O-helium gas is in thermal equilibrium with plasma and radiation on the Radiation Dominance (RD) stage, while the energy and momentum transfer from plasma is effective. The radiation pressure acting on the plasma is then transferred to density fluctuations of the O-helium gas and transforms them in acoustic waves at scales up to the size of the horizon.

At temperature $T < T_{od} \approx 1 S_3^{2/3} \text{eV}$ the energy and momentum transfer from baryons to O-helium is not effective$^{95,307}$ because

$$n_B \langle \sigma v \rangle (m_p/m_o)t < 1,$$

where $m_o$ is the mass of the $OHe$ atom and $S_3 = m_o/(1 \text{TeV})$. Here

$$\sigma \approx \sigma_o \approx \pi r_o^2 \approx 10^{-25} \text{cm}^2,$$

and $v = \sqrt{2T/m_p}$ is the baryon thermal velocity. Then O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12} \text{s}$ at $T \leq T_{RM} \approx 1 \text{eV}$ and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding dark matter scenario.

At $T > T_{RM}$ the total mass of the $OHe$ gas with density $\rho_d = (T_{RM}/T)\rho_{od}$ is equal to

$$M = \frac{4\pi}{3} \rho_d t^3 = \frac{4\pi}{3} \frac{T_{RM}}{T} m_p\left(\frac{m_p}{T}\right)^2,$$
within the cosmological horizon $l_h = t$. In the period of decoupling $T = T_{od}$, this mass depends strongly on the O-helium mass $S_3$ and is given by\(^\text{307}\)

$$M_{od} = \frac{T_{RM}}{T_{od}} m_p \left(\frac{m_{pl}}{T_{od}}\right)^2 \approx 2 \cdot 10^{44} S_3^{-2} \text{g} = 10^{11} S_3^{-2} M_\odot, \tag{70}$$

where $M_\odot$ is the solar mass. O-helium is formed only at $T_o$ and its total mass within the cosmological horizon in the period of its creation is $M_o = M_{od}(T_{od}/T_o)^3 = 10^{37} \text{g}$.

On the RD stage before decoupling, the Jeans length $\lambda_J$ of the OHe gas was restricted from below by the propagation of sound waves in plasma with a relativistic equation of state $p = \epsilon/3$, being of the order of the cosmological horizon and equal to $\lambda_J = l_h/\sqrt{3} = t/\sqrt{3}$. After decoupling at $T = T_{od}$, it falls down to $\lambda_J \sim v_o t$, where $v_o = \sqrt{2T_{od}/m_o}$. Though after decoupling the Jeans mass in the OHe gas correspondingly falls down

$$M_J \sim v_o^3 M_{od} \sim 3 \cdot 10^{-14} M_{od},$$

one should expect a strong suppression of fluctuations on scales $M < M_o$, as well as adiabatic damping of sound waves in the RD plasma for scales $M_o < M < M_{od}$. It can provide some suppression of small scale structure in the considered model for all reasonable masses of O-helium. The significance of this suppression and its effect on the structure formation needs a special study in detailed numerical simulations. In any case, it can not be as strong as the free streaming suppression in ordinary Warm Dark Matter (WDM) scenarios, but one can expect that qualitatively we deal with Warmer Than Cold Dark Matter model.

At temperature $T < T_{od} \approx 1 S_3^{2/3} \text{keV}$ the energy and momentum transfer from baryons to O-helium is not effective\(^{305,319,328}\) and O-helium gas decouples from plasma. It starts to dominate in the Universe after $t \sim 10^{12} \text{s}$ at $T \leq T_{RM} \approx 1 \text{eV}$ and O-helium “atoms” play the main dynamical role in the development of gravitational instability, triggering the large scale structure formation. The composite nature of O-helium determines the specifics of the corresponding warmer than cold dark matter scenario.

Being decoupled from baryonic matter, the $OHe$ gas does not follow the formation of baryonic astrophysical objects (stars, planets, molecular clouds...) and forms dark matter halos of galaxies. It can be easily seen that O-helium gas is collisionless for its number density, saturating galactic dark matter. Taking the average density of baryonic matter one can also find that the Galaxy as a whole is transparent for O-helium in spite of its nuclear interaction. Only individual baryonic objects like stars and planets are opaque for it.

### 5.3. Anomalous component of cosmic rays

O-helium atoms can be destroyed in astrophysical processes, giving rise to acceleration of free $O^{-}$ in the Galaxy.
O-helium can be ionized due to nuclear interaction with cosmic rays.\(^{95,323}\) Estimations\(^{95,346}\) show that for the number density of cosmic rays \(n_{CR} = 10^{-9} \text{ cm}^{-3}\) during the age of Galaxy a fraction of about \(10^{-6}\) of total amount of OHe is disrupted irreversibly, since the inverse effect of recombination of free \(O^-\) is negligible. Near the Solar system it leads to concentration of free \(O^-\) \(n_O = 3 \cdot 10^{-10} S_3^{-1} \text{ cm}^{-3}\). After OHe destruction free \(O^-\) have momentum of order \(p_O \approx \sqrt{2 \cdot m_o \cdot I_o} \approx 2 \text{ GeV} S_3^{1/2}\) and velocity \(v/c \approx 2 \cdot 10^{-3} S_3^{-1/2}\) and due to effect of Solar modulation these particles initially can hardly reach Earth.\(^{320,346}\) Their acceleration by Fermi mechanism or by the collective acceleration forms power spectrum of \(O^-\) component at the level of \(O/p \sim n_O/n_g = 3 \cdot 10^{-10} S_3^{-1}\), where \(n_g \sim 1 \text{ cm}^{-3}\) is the density of baryonic matter gas.

At the stage of red supergiant stars have the size \(\sim 10^{15} \text{ cm}\) and during the period of this stage \(\sim 3 \cdot 10^{15} \text{ s}\), up to \(\sim 10^{-9} S_3^{-1}\) of O-helium atoms per nucleon can be captured.\(^{320,346}\) In the Supernova explosion these OHe atoms are disrupted in collisions with particles in the front of shock wave and acceleration of free \(O^-\) by regular mechanism gives the corresponding fraction in cosmic rays. However, this picture needs detailed analysis, based on the development of OHe nuclear physics and numerical studies of OHe evolution in the stellar matter.

If these mechanisms of \(O^-\) acceleration are effective, the anomalous low \(Z/A\) component of \(-2\) charged \(O^-\) can be present in cosmic rays at the level \(O/p \sim n_O/n_g = 3 \cdot 10^{-10} S_3^{-1}\), and be within the reach for PAMELA and AMS02 cosmic ray experiments.

In the framework of Walking Technicolor model the excess of both stable \(\zeta^-\) and \((UU)^{++}\) is possible,\(^{320}\) the latter being two-three orders of magnitude smaller, than the former. It leads to the two-component composite dark matter scenario with the dominant OHe accompanied by a subdominant WIMP-like component of \((\zeta^- (UU)^{++}\) bound systems. Technibaryons can be metastable and decays of \((UU)^{++}\) can provide explanation for anomalies, observed in high energy cosmic positron spectrum by PAMELA, FERMI-LAT and AMS02.

### 5.4. Positron annihilation and gamma lines in galactic bulge

Inelastic interaction of O-helium with the matter in the interstellar space and its de-excitation can give rise to radiation in the range from few keV to few MeV. In the galactic bulge with radius \(r_b \sim 1 \text{ kpc}\) the number density of O-helium can reach the value \(n_o \approx 3 \cdot 10^{-3} S_3 \text{ cm}^{-3}\) and the collision rate of O-helium in this central region was estimated in: \(^{323}\) \(dN/dt = n_o^2 a r_b^2 \sqrt{\pi} / 3 \approx 3 \cdot 10^{42} S_3^{-2} \text{ s}^{-1}\). At the velocity of \(v_b \sim 3 \cdot 10^7 \text{ cm/s}\) energy transfer in such collisions is \(\Delta E \sim 1 \text{ MeV} S_3\). These collisions can lead to excitation of O-helium. If 2S level is excited, pair production dominates over two-photon channel in the de-excitation by \(E_0\) transition and positron production with the rate \(3 \cdot 10^{42} S_3^{-2} \text{ s}^{-1}\) is not accompanied by strong gamma signal. According to Ref. 347 this rate of positron production for \(S_3 \sim 1\) is sufficient to explain the excess in positron annihilation line from bulge, measured by INTEGRAL (see
Ref. 348 for review and references). If OHe levels with nonzero orbital momentum are excited, gamma lines should be observed from transitions \( (n > m) \) 
\[
E_{nm} = 1.598 \text{ MeV}(1/m^2 - 1/n^2)
\]
(or from the similar transitions corresponding to the case \( I_o = 1.287 \text{ MeV} \)) at the level \( 3 \cdot 10^{-4}S^{-2}_3 (\text{cm}^2 \text{s MeV ster})^{-1} \).

### 5.5. O-helium solution for dark matter puzzles

It should be noted that the nuclear cross section of the O-helium interaction with matter escapes the severe constraints\(^{338-340}\) on strongly interacting dark matter particles (SIMPs)\(^{332-340}\) imposed by the XQC experiment.\(^{349, 350}\) Therefore, a special strategy of direct O-helium search is needed, as it was proposed in.\(^{351}\)

#### 5.5.1. O-helium in the terrestrial matter

The evident consequence of the O-helium dark matter is its inevitable presence in the terrestrial matter, which appears opaque to O-helium and stores all its in-falling flux.

After they fall down terrestrial surface, the in-falling OHe particles are effectively slowed down due to elastic collisions with matter. Then they drift, sinking down towards the center of the Earth with velocity

\[
V = \frac{g}{n\sigma v} \approx 80S_3 A_{med}^{1/2} \text{ cm/s}. \tag{71}
\]

Here \( A_{med} \sim 30 \) is the average atomic weight in terrestrial surface matter, \( n = 2.4 \cdot 10^{24}/A \) is the number of terrestrial atomic nuclei, \( \sigma v \) is the rate of nuclear collisions and \( g = 980 \text{ cm/s}^2 \).

Near the Earth’s surface, the O-helium abundance is determined by the equilibrium between the in-falling and down-drifting fluxes.

At a depth \( L \) below the Earth’s surface, the drift timescale is \( t_{dr} \sim L/V \), where \( V \sim 400S_3 \text{ cm/s} \) is the drift velocity and \( m_o = S_3 \text{ TeV} \) is the mass of O-helium. It means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth \( L \sim 10^5 \text{ cm} \) to the corresponding change in the equilibrium underground concentration of OHe on the timescale \( t_{dr} \approx 2.5 \cdot 10^2 S_3^{-1} \text{ s} \).

The equilibrium concentration, which is established in the matter of underground detectors at this timescale, is given by

\[
n_{oE} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot \sin(\omega(t - t_0)) \tag{72}
\]

with \( \omega = 2\pi/T \), \( T = 1\text{yr} \) and \( t_0 \) the phase. So, there is a averaged concentration given by

\[
n_{oE}^{(1)} = \frac{n_o}{320S_3 A_{med}^{1/2}} V_h \tag{73}
\]

and the annual modulation of concentration characterized by the amplitude

\[
n_{oE}^{(2)} = \frac{n_o}{640S_3 A_{med}^{1/2}} V_E. \tag{74}
\]
Here $V_h$-speed of Solar System (220 km/s), $V_E$-speed of Earth (29.5 km/s) and $n_0 = 3 \times 10^{-4} S_3^{-1}$ cm$^{-3}$ is the local density of O-helium dark matter.

5.5.2. OHe in the underground detectors

The explanation$^97, 328, 331$ of the results of DAMA/NaI$^69$ and DAMA/LIBRA$^70$ (see Ref. 71 for the latest review of these results) experiments is based on the idea that OHe, slowed down in the matter of detector, can form a few keV bound state with nucleus, in which OHe is situated beyond the nucleus. Therefore the positive result of these experiments is explained by annual modulation in reaction of radiative capture of OHe

$$A + (^4 He^{++} O^{-}) \rightarrow [A(^4 He^{++} O^{-})] + \gamma$$

by nuclei in DAMA detector.

To simplify the solution of Schrödinger equation the potential was approximated in Refs. 319, 328 by a rectangular potential, presented on Fig. 2. Solution of Schrödinger equation determines the condition, under which a low-energy OHe-nucleus bound state appears in the shallow well of the region III and the range of nuclear parameters was found, at which OHe-sodium binding energy is in the interval 2-4 keV.

The rate of radiative capture of OHe by nuclei can be calculated$^{328, 331}$ with the use of the analogy with the radiative capture of neutron by proton with the account for: i) absence of M1 transition that follows from conservation of orbital momentum and ii) suppression of E1 transition in the case of OHe. Since OHe is isoscalar, isovector E1 transition can take place in OHe-nucleus system only due to effect of isospin nonconservation, which can be measured by the factor

$$f = (m_n - m_p)/m_N \approx 1.4 \times 10^{-3},$$

corresponding to the difference of mass of neutron, $m_n$, and proton, $m_p$, relative to the mass of nucleon, $m_N$. In the result the rate of OHe radiative capture by nucleus with atomic number $A$ and charge $Z$ to the energy level $E$ in the medium with temperature $T$ is given by

$$\sigma v = \frac{f \pi \alpha}{m_p^2} \frac{3}{\sqrt{2}} \frac{Z^2}{A^2} \frac{T}{\sqrt{A m_p E}}.$$  

(76)

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of our approach the existence of annual modulations of this signal in the range 2-6 keV and absence of such effect at energies above 6 keV means that binding energy $E_{Na}$ of Na-OHe system in DAMA experiment should not exceed 6 keV, being in the range 2-4 keV. The amplitude of annual modulation of ionization signal can reproduce the result of DAMA/NaI and DAMA/LIBRA experiments for $E_{Na} = 3$ keV. The account for energy resolution in DAMA experiments$^{354}$ can explain the observed energy distribution of the signal from monochromatic photon (with $E_{Na} = 3$ keV) emitted in OHe radiative capture.

At the corresponding nuclear parameters there is no binding of OHe with iodine and thallium.$^{328}$
It should be noted that the results of DAMA experiment exhibit also absence of annual modulations at the energy of MeV-tens MeV. Energy release in this range should take place, if OHe-nucleus system comes to the deep level inside the nucleus. This transition implies tunneling through dipole Coulomb barrier and is suppressed below the experimental limits.

For the chosen range of nuclear parameters, reproducing the results of DAMA/NaI and DAMA/LIBRA, the results of Ref. 328 indicate that there are no levels in the OHe-nucleus systems for heavy nuclei. In particular, there are no such levels in Xe, what seem to prevent direct comparison with DAMA results in XENON100 experiment. The existence of such level in Ge and the comparison with the results of CDMS\textsuperscript{72–74} and CoGeNT\textsuperscript{76} experiments need special study.

According to Ref. 328 OHe should bind with O and Ca, what is of interest for interpretation of the signal, observed in CRESST-II experiment.\textsuperscript{352}

In the thermal equilibrium OHe capture rate is proportional to the temperature. Therefore it looks like it is suppressed in cryogenic detectors by a factor of order $10^{-4}$. However, for the size of cryogenic devices less, than few tens meters, OHe gas in them has the thermal velocity of the surrounding matter and this velocity dominates in the relative velocity of OHe-nucleus system. It gives the suppression relative to room temperature only $\sim m_A/m_o$. Then the rate of OHe radiative capture in cryogenic detectors is given by Eq.(76), in which room temperature $T$ is multiplied by factor $m_A/m_o$. Note that in the case of $T = 70$ K in CoGeNT experiment relative velocity is determined by the thermal velocity of germanium nuclei, what leads to enhancement relative to cryogenic germanium detectors.

### 5.6. Conclusions

The existence of heavy stable particles is one of the popular solutions for the dark matter problem. Usually they are considered to be electrically neutral. But potentially dark matter can be formed by stable heavy charged particles bound in neutral atom-like states by Coulomb attraction. Analysis of the cosmological data and atomic composition of the Universe gives the constrains on the particle charge showing that only $-2$ charged constituents, being trapped by primordial helium in neutral O-helium states, can avoid the problem of overproduction of the anomalous isotopes of chemical elements, which are severely constrained by observations. Cosmological model of O-helium dark matter can even explain puzzles of direct dark matter searches.

The proposed explanation is based on the mechanism of low energy binding of OHe with nuclei. Within the uncertainty of nuclear physics parameters there exists a range at which OHe binding energy with sodium is in the interval 2-4 keV. Annual modulation in radiative capture of OHe to this bound state leads to the corresponding energy release observed as an ionization signal in DAMA/NaI and DAMA/LIBRA experiments.

With the account for high sensitivity of the numerical results to the values of
nuclear parameters and for the approximations, made in the calculations, the presented results can be considered only as an illustration of the possibility to explain puzzles of dark matter search in the framework of composite dark matter scenario. An interesting feature of this explanation is a conclusion that the ionization signal may be absent in detectors containing light (e.g. $^3\text{He}$) or heavy (e.g. Xe) elements. Therefore test of results of DAMA/NaI and DAMA/LIBRA experiments by other experimental groups can become a very nontrivial task. Recent indications to positive result in the matter of CRESST detector,\textsuperscript{352} in which OHe binding is expected together with absence of signal in xenon detector,\textsuperscript{75} may qualitatively favor the presented approach. For the same chemical content an order of magnitude suppression in cryogenic detectors can explain why indications to positive effect in CoGeNT experiment\textsuperscript{76} can be compatible with the constraints of CDMS experiment.

The present explanation contains distinct features, by which it can be distinguished from other recent approaches to this problem\textsuperscript{355–372}.

An inevitable consequence of the proposed explanation is appearance in the matter of underground detectors anomalous superheavy isotopes, having the mass roughly by $m_o$ larger, than ordinary isotopes of the corresponding elements.

It is interesting to note that in the framework of the presented approach positive result of experimental search for WIMPs by effect of their nuclear recoil would be a signature for a multicomponent nature of dark matter. Such OHe+WIMPs multicomponent dark matter scenarios naturally follow from AC model\textsuperscript{94} and can be realized in models of Walking technicolor\textsuperscript{320}. Stable $\text{−2}$ charge states ($O^{−−}$) can be elementary like AC-leptons or technileptons, or look like technibaryons. The latter, composed of techniquarks, reveal their structure at much higher energy scale and should be produced at LHC as elementary species. The signature for AC leptons and techniparticles is unique and distinctive what allows to separate them from other hypothetical exotic particles.

Since simultaneous production of three $\bar{U}U$ pairs and their conversion in two doubly charged quark clusters $UUU$ is suppressed, the only possibility to test the models of composite dark matter from 4th generation in the collider experiments is a search for production of stable hadrons containing single $U$ or $\bar{U}$ like $Uud$ and $\bar{U}u/\bar{U}d$.

The presented approach sheds new light on the physical nature of dark matter. Specific properties of dark atoms and their constituents are challenging for the experimental search. The development of quantitative description of OHe interaction with matter confronted with the experimental data will provide the complete test of the composite dark matter model. It challenges search for stable double charged particles at accelerators and cosmic rays as direct experimental probe for charged constituents of dark atoms of dark matter.
6. Discussion

Observational cosmology offers strong evidences favoring the existence of processes, determined by new physics, and the experimental physics approaches to their investigation. Cosmoparticle physics,\textsuperscript{1–4} studying the physical, astrophysical and cosmological impact of new laws of Nature, explores the new forms of matter and their physical properties. Its development offers the great challenge for theoretical and experimental research. Physics of dark matter in all its aspects plays important role in this process.

The new physics follows from the necessity to extend the Standard model. The white spots in the representations of symmetry groups, considered in the extensions of the Standard model, correspond to new unknown particles. The extension of the symmetry of gauge group puts into consideration new gauge fields, mediating new interactions. Global symmetry breaking results in the existence of Goldstone boson fields.

For a long time the necessity to extend the Standard model had purely theoretical reasons. Aesthetically, because full unification is not achieved in the Standard model; practically, because it contains some internal inconsistencies. It does not seem complete for cosmology. One has to go beyond the Standard model to explain inflation, baryosynthesis and nonbaryonic dark matter. The discovery of neutrino oscillations (see for review e.g. Ref. 373) and the experimental evidences for the existence of dark matter particles\textsuperscript{69} indicate that the experimental searches may have already crossed the border of new physics.

In particle physics direct experimental probes for the predictions of particle theory are most attractive. The predictions of new charged particles, such as supersymmetric particles or quarks and leptons of new generation, are accessible to experimental search at accelerators of new generation, if their masses are in 100GeV-1TeV range. However, the predictions related to higher energy scale need non-accelerator or indirect means for their test.

The search for rare processes, such as proton decay, neutrino oscillations, neutrinoless beta decay, precise measurements of parameters of known particles, experimental searches for dark matter represent the widely known forms of such means. Cosmoparticle physics offers the nontrivial extensions of indirect and non-accelerator searches for new physics and its possible properties. In experimental cosmochronology the data is to be obtained, necessary to link the cosmophenomenology of new physics with astrophysical observations (See Ref. 22). In experimental cosmoparticle physics the parameters, fixed from the consitency of cosmological models and observations, define the level, at which the new types of particle processes should be searched for (see Ref. 374).

The theories of everything should provide the complete physical basis for cosmology. The problem is that the string theory\textsuperscript{375} is now in the form of ”theoretical theory”, for which the experimental probes are widely doubted to exist. The development of cosmoparticle physics can remove these doubts. In its framework there
are two directions to approach the test of theories of everything.

One of them is related with the search for the experimentally accessible effects of heterotic string phenomenology. The mechanism of compactification and symmetry breaking leads to the prediction of homotopically stable objects and shadow matter, accessible to cosmoarcheological means of cosmoparticle physics. The condition to reproduce the Standard model naturally leads in the heterotic string phenomenology to the prediction of fourth generation of quarks and leptons with a stable massive 4th neutrino, what can be the subject of complete experimental test in the near future. The comparison between the rank of the unifying group $E_6$ ($r = 6$) and the rank of the Standard model ($r = 4$) implies the existence of new conserved charges and new (possibly strict) gauge symmetries. New strict gauge U(1) symmetry (similar to U(1) symmetry of electrodynamics) is possible, if it is ascribed to the fermions of 4th generation. This hypothesis explains the difference between the three known types of neutrinos and neutrino of 4th generation. The latter possesses new gauge charge and, being Dirac particle, can not have small Majorana mass due to sea saw mechanism. If the 4th neutrino is the lightest particle of the 4th quark-lepton family, strict conservation of the new charge makes massive 4th neutrino to be absolutely stable. Following this hypothesis quarks and leptons of 4th generation are the source of new long range interaction ($y$-electromagnetism), similar to the electromagnetic interaction of ordinary charged particles. If proved, the practical importance of this property could be hardly overestimated.

It is interesting, that heterotic string phenomenology embeds even in its simplest implementation both supersymmetric particles and the 4th family of quarks and leptons, in particular, the two types of WIMP candidates: neutralinos and massive stable 4th neutrinos, as well as nuclear interacting OHe dark atoms, built up by stable (anti-)U quarks of 4th generation. So in the framework of this phenomenology the multicomponent analysis of WIMP effects is favorable.

In the above approach some particular phenomenological features of simplest variants of string theory are studied. The other direction is to elaborate the extensive phenomenology of theories of everything by adding to the symmetry of the Standard model the (broken) symmetries, which have serious reasons to exist. The existence of (broken) symmetry between quark-lepton families, the necessity in the solution of strong CP-violation problem with the use of broken Peccei-Quinn symmetry, as well as the practical necessity in supersymmetry to eliminate the quadratic divergence of Higgs boson mass in electroweak theory is the example of appealing additions to the symmetry of the Standard model. The horizontal unification and its cosmology represent the first step on this way, illustrating the approach of cosmoparticle physics to the elaboration of the proper phenomenology for theories of everything.

For long time scenarios with Primordial Black holes belonged dominantly to cosmological anti-Utopias, to "fantasies", which provided restrictions on physics of very early Universe from contradiction of their predictions with observational data. Even this "negative" type of information makes PBHs an important theoretical
tool. Being formed in the very early Universe as initially nonrelativistic form of matter, PBHs should have increased their contribution to the total density during RD stage of expansion, while effect of PBH evaporation should have strongly increased the sensitivity of astrophysical data to their presence. It links astrophysical constraints on hypothetical sources of cosmic rays or gamma background, on hypothetical factors, causing influence on light element abundance and spectrum of CMB, to restrictions on superheavy particles in early Universe and on first and second order phase transitions, thus making a sensitive astrophysical probe to particle symmetry structure and pattern of its breaking at superhigh energy scales.

Gravitational mechanism of particle creation in PBH evaporation makes evaporating PBH an unique source of any species of particles, which can exist in our space-time. At least theoretically, PBHs can be treated as source of such particles, which are strongly suppressed in any other astrophysical mechanism of particle production, either due to a very large mass of these species, or owing to their superweak interaction with ordinary matter.

By construction astrophysical constraint excludes effect, predicted to be larger, than observed. At the edge such constraint converts into an alternative mechanism for the observed phenomenon. At some fixed values of parameters, PBH spectrum can play a positive role and shed new light on the old astrophysical problems.

The common sense is to think that PBHs should have small sub-stellar mass. Formation of PBHs within cosmological horizon, which was very small in very early Universe, seem to argue for this viewpoint. However, phase transitions on inflationary stage can provide spikes in spectrum of fluctuations at any scale, or provide formation of closed massive domain walls of any size.

In the latter case primordial clouds of massive black holes around intermediate mass or supermassive black hole is possible. Such clouds have a fractal spatial distribution. A development of this approach gives ground for a principally new scenario of the galaxy formation in the model of the Big Bang Universe. Traditionally, Big Bang model assumes a homogeneous distribution of matter on all scales, whereas the appearance of observed inhomogeneities is related to the growth of small initial density perturbations. However, the analysis of the cosmological consequences of the particle theory indicates the possible existence of strongly inhomogeneous primordial structures in the distribution of both the dark matter and baryons. These primordial structures represent a new factor in galaxy formation theory. Topological defects such as the cosmological walls and filaments, primordial black holes, archioles in the models of axionic CDM, and essentially inhomogeneous baryosynthesis (leading to the formation of antimatter domains in the baryon-asymmetric Universe\cite{3,4,114,131–133,379–388}) offer by no means a complete list of possible primary inhomogeneities inferred from the existing elementary particle models.

We can conclude that from the very beginning to the modern stage, the evolution of Universe is governed by the forms of matter, different from those we are built of and observe around us. From the very beginning to the present time, the evolution of the Universe was governed by physical laws, which we still don’t know. These
laws follow from the fundamental particle symmetry beyond the Standard model. Observational cosmology offers strong evidences favoring the existence of processes, determined by such laws of new physics, and the experimental physics approaches to their investigation.

Cosmoparticle physics originates from the well established relationship between microscopic and macroscopic descriptions in theoretical physics. Remind the links between statistical physics and thermodynamics, or between electrodynamics and theory of electron. To the end of the XX Century the new level of this relationship was realized. It followed both from the cosmological necessity to go beyond the world of known elementary particles in the physical grounds for inflationary cosmology with baryosynthesis and dark matter as well as from the necessity for particle theory to use cosmological tests as the important and in many cases unique way to probe its predictions.

Cosmoparticle physics\textsuperscript{1,2} studying the physical, astrophysical and cosmological impact of new laws of Nature, explores the new forms of matter and their physical properties, what opens the way to use the corresponding new sources of energy and new means of energy transfer. It offers the great challenge for the new Millennium.

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