

Article

Multimessenger Probes for New Physics in Light of A. Sakharov's Legacy in Cosmoparticle Physics [†]

Maxim Khlopov ^{1,2,3} 
¹ Institute of Physics, Southern Federal University, Stachki 194, 344090 Rostov on Don, Russia; khlopov@apc.univ-paris7.fr; Tel.: +33-676-380-567

² Virtual Institute of Adtparticle Physics, Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France

³ Center for Cosmoaprticle Physics Cosmion, Moscow State Engineering Physics Institute, National Research Nuclear University "MEPHI", 31 Kashirskoe Chaussee, 115409 Moscow, Russia

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Abstract: A.D. Sakharov's legacy in now standard model of the Universe is not reduced to baryosynthesis but extends to the foundation of cosmoparticle physics, which studies the fundamental relationship of cosmology and particle physics. Development of cosmoparticle physics involves cross-disciplinary physical, astrophysical and cosmological studies of physics Beyond the Standard model (BSM) of elementary particles. To probe physical models for inflation, baryosynthesis and dark matter cosmoparticle physics pays special attention to model dependent messengers of the corresponding models, making their tests possible. Positive evidence for such exotic phenomena as nuclear interacting dark atoms, primordial black holes or antimatter globular cluster in our galaxy would provide the selection of viable BSM models determination of their parameters.

Keywords: cosmology; particle physics; cosmoparticle physics; inflation; baryosynthesis; dark matter; antimatter; primordial black holes



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1. Introduction

Cosmoparticle physics has appeared as a natural stage in the development of both cosmology, involving predictions of particle theory, and particle physics, turning to cosmological probes for its predictions. This mutual relationship led to a vicious circle in which new physics, predicted by particle theory, was involved in cosmology, which in its turn was used for probes of this new physics. Cosmoparticle physics proposed a way out of this circle of problems in cross-disciplinary studies of indirect astrophysical, cosmological and physical signatures of this relationship. In the mid-1980s, the idea of such studies involved experimental and theoretical physicists, astronomers, cosmologists and astrophysicists of the USSR, and the term "cosmoparticle physics", which first appeared in a paper by A.D. Sakharov [1], served as the preface to the extensive program of these studies. The direct reproduction of the beginning and end of Sakharov's handwritten original of [1] published with their English translation in [2] is presented on Figure 1.

In 2021, we commemorate the 100th anniversary of the birth of Andrei D. Sakharov, and UNESCO has nominated this year A.D. Sakharov Year. The paper "Cosmoparticle Physics as Cross-Disciplinary Science" [1] was the last in the list of Sakharov's publications, attributing to the studies of the fundamental relationship between cosmology and particle physics the significance of development of their scientific legacy.

Sakharov conditions in baryosynthesis, Sakharov oscillations in Cosmic Microwave Background radiation and Sakharov enhancement in dark matter annihilation are but a few examples of A.D. Sakharov's contribution to the modern theory of the Universe [3–6].

This theory is heavily based on the development of Sakharov's legacy in studies of the mutual relationship of the foundations of modern particle physics and cosmology, as well as of the nontrivial features of its indirect physical, cosmological and astrophysical probes. Such features involve models of the very early Universe and their observational signatures, physics of dark matter, and its direct and indirect probes, as well as a wide range of models beyond the standard models of particle physics and cosmology and their experimental and observational effects (see for review and references, e.g., [7–21]).

ON COSMOPARTICLE PHYSICS

Cosmoparticle physics (the name is not yet finally fixed) is the new fundamental science formed at the joint of particle physics and cosmology. It has great scientific and general philosophical significance.

О космомикрофизике

Космомикрофизика (название еще не вполне установившееся) — новая фундаментальная наука, возникающая на стыке физики элементарных частиц и космологии. Она имеет огромное научное и общеполитическое значение.

The present paper should draw attention of astronomers, physicists, engineers and mathematicians to the extremely important set of problems, to give the draft prospect of development in this field of knowledge.

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A. Sakharov

Нужно указать, что эта статья должна привлечь внимание астрономов, физиков, инженеров и математиков к чрезвычайно важному кругу проблем, дать наглядное представление о развитии этой отрасли знания. 3/X-88 А. Сахаров



Figure 1. The direct reproduction of the beginning and end of the handwritten original of Sakharov's article [1] and of its English translation taken with the corresponding permission from the Preface to the Proceedings 1 International conference on Cosmoparticle physics "Cosmion-94" [2].

Extensive discussion of development of Sakharov's legacy in various aspects of cosmoparticle physics is the subject of practically all the conferences on cosmology and particle physics, and here we can only give a brief sketch of some aspects of this development with the focus on the nontrivial features and important role of cosmological messengers of new physics on which modern cosmology is based.

The paradox of the current situation is that new physics, on which the modern theory of the Universe is based, still finds no direct experimental evidence. Though the nonzero mass of the neutrino is beyond the Standard model (BSM), the corresponding new physics related with its nature (whether the neutrino mass is Majorana or Dirac, or whether it reflects the existence of new, sterile neutrino states) is still not known, as nor is the mass of the known neutrino states, due to the the combination of direct measurements of beta spectra and parameters of neutrino oscillations being so small that the observed dark matter density cannot be explained. This implies the necessity to involve a combination of astrophysical and cosmological probes for studies of new physics underlying the modern cosmology.

The approach that we discuss here is based on the idea that any BSM model that provides physical mechanism for inflation and baryosynthesis or predicts some candidate for dark matter contains additional model-dependent predictions, which can lead to deviations of the now standard scenario of the inflationary Universe with baryosynthesis and Λ CDM model of large-scale structure formation. We refer to such specific model-dependent predictions as cosmological messengers of new physics, which provide a sensitive probe for the considered BSM model [11]. Here, we discuss such probes for physics of particle dark matter candidates (Section 2) and for the physics of the very early Universe (Sections 3 and 4). We briefly review the basic ideas of cosmoparticle physics and its prospects in Section 5.

2. Cosmoparticle Physics of Dark Matter

To explain the observed dark matter (DM), particle candidates should be stable, or sufficiently long living with the lifetime $\tau \gg t_U$, where t_U is the age of the Universe. From a particle physics viewpoint, such stability implies a new law of conservation, reflecting new strict (or approximate) symmetry of the BSM model, which DM particles possess. To dominate at the matter-dominated stage and trigger large-scale structure formation, these particles should be nonrelativistic and decoupled from plasma and radiation in the beginning of the matter-dominated stage. The simplest solution satisfying these conditions involves the gas of Weakly Interacting Massive Particles (WIMPs). If new particles have mass in the range of tens to hundreds of GeV and a cross-section in the order of the SM weak interaction, their frozen-out abundance in the early Universe leads to a *WIMP miracle*: their contribution to the modern density corresponds to the observed dark matter density.

Physical motivation for WIMPs was supported by the predictions of supersymmetry (SUSY). If supersymmetric partners of known particles bear a specific conserved property (R-Parity), the Lightest Supersymmetric Particle (LSP) should be stable. It turned out that LSP candidates have WIMP properties.

The practical advantage of SUSY to solve SM problems and its support for WIMP as a candidate for dark matter made the search for SUSY at the LHC and the direct search for WIMPs in underground detectors mainstream in dark matter studies and the experimental probes for its physical nature.

2.1. From WIMP Miracle to DM Reality

The important practical role of SUSY was to provide solutions to the internal theoretical problems of the Standard model: divergence of the Higgs boson mass and the origin of the form of the Higgs field potential, whose minimum determines the scale of the electroweak symmetry breaking.

If the SUSY scale, which determines the mass of supersymmetric particles, is in the range of several hundred GeV, freezing out of LSP gas in the early Universe would lead to their modern density, which can explain dark matter, and their interaction with SM particles would have a cross-section typical for weak interactions, such that LSP could play the role of WIMP dark matter. In SUSY, such a form of WIMP was associated with a set of supersymmetric partners of SM particles, challenging the search for SUSY at the LHC and the direct search for WIMPs in underground experiments.

However, the controversial results of direct dark matter searches and the absence of direct positive evidence on the creation of SUSY particles at the LHC encouraged scientists to turn to possible non-supersymmetric solutions to SM problems. This extends the possible set of dark matter candidates and can lead to nontrivial solutions concerning the nature of the dark matter (see, e.g., [12] for review and reference). Here, we turn to one of such nontrivial solution, linking the dark atom nature of dark matter with the models of the composite Higgs boson.

2.2. Multiple Charged Constituents of Composite Higgs Boson

In the context of a lack of cancellation of divergent contributions to the Higgs boson mass and of a SUSY explanation for the form of the Higgs potential, an alternative idea of composite nature of Higgs boson can provide the solutions for the SM problems [22–28].

If the Higgs boson is composite, its constituents can be charged and form additional exotic charged composite particles [12,28–30]. Such a situation can take place in Walking Technicolor models (WTC) [12,31–36], in which techniquarks compose not only a Higgs boson but also technibaryons and their antiparticles. The condition of anomaly cancellation implies with necessity the existence of technileptons and the corresponding charge assignment of technileptons and technibaryons. If technibaryon and/or technilepton charge is conserved, the lightest technibaryon and/or technilepton is stable and depending on the charge assignment not only can be neutral [35,36] but also can bear an electric charge [37,38]. In the latter case, stable charged particles can be hidden in dark atoms and play the role of constituents of composite dark matter [12]. Such particles do not possess QCD interaction and thus behave as multiple charged heavy leptons.

2.3. Messengers of Dark Atom Physics

2.3.1. Dark Atoms and Their Charged Constituents

Dark atoms are composite systems in which stable charged constituents are bound by the Coulomb force. These constituents can be in a free state, and the main problem for the prediction of such stable charged particles is their inevitable existence around us in the form of exotic charged species. The case of fractional charged particles is severely constrained by the search for free quarks in the terrestrial and lunar matter, as well as at accelerators [39]. Stable integer-positive charged particles bind with electrons to form anomalous isotopes, whose abundance is restricted by the observational data, especially for anomalous hydrogen formed by particles with a charge +1. Negatively charged particles with a charge $-(2n - 1)$ can bind with n nuclei of primordial helium, as soon as it is formed in the Big Bang Nucleosynthesis (BBN) (see [40] for recent review and references). Therefore, only negatively charged stable particles with charge $-2n$ can avoid immediate contradiction with the observational constraints, being bound with n nuclei of primordial helium in dark atoms of dark matter. These particles are produced in excess over their positively charged antiparticles, and the latter become strongly suppressed, as discussed in Section 2.3.3. The dominance of elastic scattering of dark atoms with nuclei prevents their merging and formation of anomalous isotopes at the successive stages of evolution.

2.3.2. Structure of Dark Atoms

Depending on the charge of stable techniparticles, there can be two possible types of dark atoms.

At $n = 1$, double-charged O^{--} particles are bound with an α -particle (He nucleus) in a Bohr-like atom, which is called OHe (or O-helium [40–42]). In the approximation of point-like distribution of electric charge in an α -particle, the OHe binding energy is given by [40–42]

$$E_b = \frac{1}{2} Z^2 Z_o^2 \alpha^2 A m_p \quad (1)$$

with the radius of Bohr orbit [10,37,41]

$$r_o = \frac{1}{Z_o Z_{He} \alpha A m_p} = 2 \cdot 10^{-13} \text{ cm}. \quad (2)$$

Bohr radius (2) is equal and even a bit smaller than the size of an α -particle. Therefore, non-point-like charge distribution in He should be taken into account, leading to a significant correction to the OHe binding energy given by Equation (1).

At $n > 1$, multiple charged X^{-2n} leptons form Thomson-like atoms (called XHe or X-helium), which are situated within an n - α -particle nucleus. According to the harmonic oscillator approximation, the binding energy of XHe was estimated as [10,40,42–45]

$$E_b = \frac{3}{2} \left(\frac{ZZ_0\alpha}{R} - \frac{1}{R} \left(\frac{ZZ_0\alpha}{Am_p R} \right)^{1/2} \right), \quad (3)$$

where Z_0 is the charge of X and R is the radius of nucleus with electric charge Z . With the the assumption that $R_{He} \approx r_0$, Equation (3) gives the binding energy of helium with X -particle with charge Z_0 of [42]

$$E_{He} = 2.4 \text{ MeV} \left(1 - \frac{1}{Z_0^{1/2}} \right) Z_0. \quad (4)$$

where $E_{He} = 4.8 \text{ MeV}$ for X -beryllium, 8.6 MeV for X -carbon and 12.8 MeV for X -oxygen [42]. However, this estimation does not take into account the nuclear binding of an α -particle within the $n - \alpha$ -particle nucleus.

OHe and XHe “atoms” strongly differ from usual atomic objects, and their description cannot use the usual approximation of the atomic physics: small radius of nuclear interacting core as compared with the size of an electroweakly interacting electronic shell. A dark atom consists of multiple charged heavy leptons surrounded by a nuclear interacting shell, and the usual approximations of atomic physics are not appropriate in its description.

The advantage of the dark atom cosmology is the involvement of only one parameter of new physics—the mass of the stable charged particle—while the main features of dark atom evolution and interaction with SM particles are determined by the dark atom’s helium shell. It seems to involve only known physics in the description of dark atom effects, but the nontrivial structure of dark atoms makes the problem very complicated, such that the correct quantum mechanical treatment of dark atom nuclear physics is still in the process of elaboration. In particular, such treatment involves the self-consistent account for nuclear attraction and Coulomb repulsion in dark atom interaction with nuclei, and the approach to numerical solution of this problem is proposed in [46].

2.3.3. Cosmological Evolution of Dark Atoms

The important feature of the dark atom scenario, based on WTC, is the balance of baryon asymmetry and the excess of stable techniparticles regulated in the early Universe by sphaleron transitions. It was shown in [37,38] that such a balance provides, under the natural choice of the WTC model parameters, the relationship between the excess of $-2n$ charged stable techniparticles and baryon asymmetry, leading the mass of techniparticles in the TeV range to contribute to the modern cosmological density, which corresponds to the observed dark matter density [11].

The excess of $-2n$ charged techniparticles over their antiparticles supports the suppression of these positively charged species, which is strongly enhanced after BBN. Due to the high excess of primordial He nuclei, all the $-2n$ charged particles are bound with n helium nuclei in dark atoms, while $+2n$ charged particles are captured by these atoms, bound with $-2n$ charged particles and annihilated.

The annihilation cross section of particles with a charge of Z possess, at low relative velocities v , *Sommerfeld-Gamov-Sakharov enhancement* [47–51], which is characterized by an additional factor C in cross section, given by

$$C = \frac{2\pi Z^2 \alpha / v}{1 - \exp(-2\pi Z^2 \alpha / v)}, \quad (5)$$

where α is the fine structure constant. This factor is usually not essential in the period of single-charge particles freezing out in the early Universe, when v was only few times smaller than c , but can cause strong enhancement at $Z \gg 1$ and $v \ll c$.

Dark atoms decouple from plasma and radiation at $T \sim 1 \text{ keV}$ and start to dominate at the matter dominated stage, triggering large-scale structure formation as warmer than

cold asymmetric dark matter. In spite of their nuclear interactions, baryonic matter is transparent for dark atoms unless sufficiently dense baryonic objects of the size R and density n are formed, in which the condition $n\sigma R \gg 1$ holds. Here,

$$\sigma = \pi r^2,$$

where, for OHe, $r = r_0$ is determined by Equation (2) and gives $\sigma \approx 2 \cdot 10^{-25} \text{ cm}^2$, while for XHe with $n > 1$,

$$r \approx (4n)^{1/3} r_0.$$

It makes dark atom gas collisionless at the scale of the galaxy, but dense baryonic objects like stars and planets are opaque for dark atoms and capture them.

2.3.4. Indirect Effects of Dark Atoms

In the charge-symmetric case, frozen-out particles and their antiparticles can be annihilated in the galaxy [52], and although this process involves a negligible fraction of dark matter, the SM products of annihilation can provide a significant contribution as cosmic rays and gamma radiation, even in the case of subdominant component of dark matter [53]. Indirect searches for dark matter are based on this principle [54–57] and should take into account correlations in predicted contribution to cosmic rays and gamma ray background [58].

OHe and XHe dark atoms correspond to asymmetric dark matter, which does not provide effects of annihilation in galaxies. Rare collisions of OHe atoms, more frequent in the regions with higher dark matter density, can lead to OHe excitation. If 2S level is excited, its de-excitation should lead to electron–positron pair production. This makes possible to explain the excess in the positronium annihilation line, observed by INTEGRAL in the galactic bulge by pair de-excitation of OHe, excited in OHe collisions in the center of Galaxy [59]. This explanation is effective for the mass of O^{--} in a narrow range of 1.25 TeV, requiring the search for stable double charge particles at the LHC experimental test for this explanation [60,61].

Captured in stars, dark atoms can be ionized in their interiors, and free O or X particles can be accelerated together with other charged particles, forming anomalous component of cosmic rays. The estimation of this fraction strongly depends on the details of the mechanisms of cosmic ray production. Rough estimation can assume that all the dark atoms captured by a star during its evolution are ionized and accelerated in the SNI explosion (during which no compact remnant is formed). Then the fraction is given by the ratio of total number of captured dark atoms and total number of baryons in the star. Since the number of captured dark atoms depends on the size of the star surface, their dominant part is captured by the star at the stage of a red giant (when the star radius can be of order of 10^{13} cm) or supergiant, where it can reach 10^{15} cm [62]. Taking the duration of this stage of order 10^{15} s , one obtains the estimated fraction of order 10^{-12} – 10^{-8} , which can be a challenge in the search for the anomalous multiple charged lepton component of cosmic rays.

2.3.5. Dark Atom Effects in Underground Detectors

Dark atoms represent a specific type of Strongly Interacting Massive Particles (SIMPs) [63–73] and avoid the constraints on this form of dark matter particles [40,42]. Cosmic dark atoms are slowed down in terrestrial matter and are elusive for direct WIMP searches in underground detectors, in which dark atom collisions with nuclei do not lead to the noticeable effect of nuclear recoil.

However, dark atom concentration in underground detectors is determined by the equilibrium of incoming cosmic flux and diffusion to the center of the Earth. Therefore, this concentration is adjusted to the cosmic flux, which experiences annual modulations due to Earth’s orbital motion around the Sun. This makes possible to explain the annual modulation signal, detected with high statistical significance by DAMA/NaI and DAMA/LIBRA experiments [74–78] by annual modulations in low energy binding of OHe with sodium

nuclei in DAMA detector [79]. In the simple square well and wall approximation, it was shown in [79] that such binding is possible for intermediate mass nuclei, and there is no such binding with heavy and light nuclei.

If such binding of a dark atom with sodium exists, radiative capture to the corresponding few keV level can be calculated by the analogy with the radiative capture of neutron by proton [80]. Conservation of orbital momentum makes M1 transition in OHe nucleus capture impossible, while E1 transition is suppressed since OHe is isoscalar and isovector E1 transition can take place only with the violation of isospin conservation. In [79], the suppression factor due to the isospin nonconservation was taken as relative difference of neutron, m_n , and proton, m_p , masses to the nucleon mass, m_N : $f = (m_n - m_p)/m_N \approx 1.4 \cdot 10^{-3}$.

Under these conditions, the rate of OHe radiative capture to the energy level E by nucleus with atomic number A and charge Z in the medium with temperature T is given by [80]

$$\sigma v = \frac{f \pi \alpha}{m_p^2} \frac{3}{\sqrt{2}} \left(\frac{Z}{A}\right)^2 \frac{T}{\sqrt{A m_p E}}. \quad (6)$$

and the signal, measured in DAMA/NaI and DAMA/LIBRA experiments, can be reproduced [79].

The negative results of other experiments like CDMS, XENON or LUX [81–85] are explained either by suppression of such transitions in cryogenic detectors or by the absence of a low energy bound state in OHe interaction with heavy nuclei.

The existence of a low energy level is crucial in the dark atom explanation of the puzzles of direct dark matter searches and is now under thorough investigation [46].

2.4. Cosmophenomenology of Dark Matter Physics

Physical models, predicting stable particle candidates of dark matter, contain various additional model-dependent physical, astrophysical and cosmological signatures. Metastable particles, predicted in such models with lifetime smaller than the age of the Universe, $\tau < t_U$, may provide a cosmological probe for these models. If particle lifetime is sufficiently large $\tau \gg (M_{Pl}/m) \cdot (1/m)$, where m is the mass of particle and M_{Pl} is the Planck mass, the presence of such particles in the Universe and effects of their decay at $t = \tau$ can lead to observable consequences. These consequences strongly depend on the contribution to the cosmological density and modes of their decay [9,12,13].

Super-weakly interacting decay products contribute to the number of relativistic species in Big Bang Nucleosynthesis, which is restricted by the data on primordial chemical composition. Dark radiation from such decays hinders development of gravitational instability and growth of density fluctuations, being constrained by the condition of the cosmological structure formation.

SM particles (photons or charged particles) from decays contribute to the cosmic ray fluxes and gamma-ray background, and such decay modes can be restricted by the corresponding measurements. This constraint is not appropriate for early decays, since the decay products interact with matter and radiation and do not survive. However, this interaction can change the abundance of primordial light element or distort the CMB spectrum (see, e.g., [13,16,86] and references therein). SM products of decay of superheavy particles interact with thermal neutrino background, producing Ultra High Energy (UHE) neutrino background, to which large UHE neutrino detectors such DUMAND or IceCube [86] can be sensitive. The set of these astrophysical probes for new particles with relative concentration ν and mass m , decaying or present in the Universe at cosmological time $t = \tau$, is shown in Figure 2. This set of probes provides a direct astrophysical test of the existence of particles with lifetime $\tau \geq 1$ s. The sensitivity of astrophysical data strongly increases if particle decay products interact with a subdominant component. Therefore, distortions of CMB spectrum due to electromagnetic energy release from decays are more sensitive at the matter-dominated stage, while the abundance of the light element provide more sensitive probe interaction with baryonic matter at the stage of radiation domination (RD).

Particles with a lifetime $\tau \ll 1$ s cannot provide a direct influence on CMB or BBN. However, if they are supermassive and dominate in the Universe before decay, they can form gravitationally bound systems, evolving into black holes. The spectrum of such Primordial Black Holes (PBH) contains information on particle properties such as their mass, abundance and lifetime [87]. Particle decay to SM particles, by which this early matter dominated stage ends, leads to reheating and increase of entropy and thus influences the dark matter particle abundance if it was created before this stage.

Extensions of SM symmetry involve the pattern of symmetry breaking, which can be reflected in cosmological phase transitions. If the phase transition is first-order, the collision of bubbles created in it can produce PBH [88] (see [89,90] for a review). Phase transitions of the second-order change the vacuum symmetry and lead to formation of topological defects. This creates primordial non-homogeneous structures, which we discuss in the following sections: messengers of not only extension of SM symmetry but also of mechanisms of its breaking.

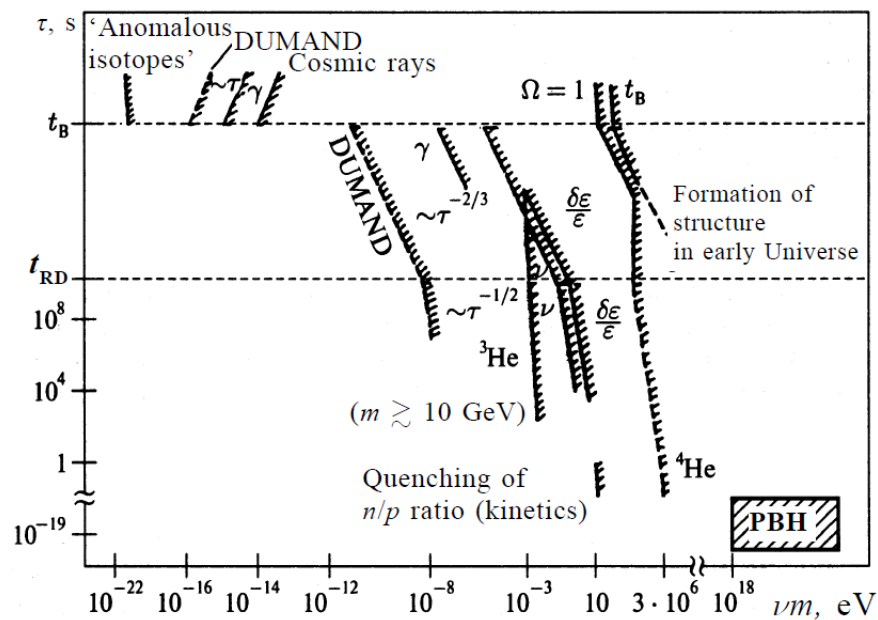


Figure 2. The constraints [9] on the possible effects of particles with relative concentration ν and mass m at the cosmological time τ .

3. PBH Messengers of BSM Models

Primordial Black Holes (PBHs) [91] are an important cosmological messenger of new physics.

PBHs with mass exceeding 10^{14} g can play the role of dark matter (see, e.g., [92]). PBHs of smaller mass evaporate by a Hawking mechanism [93], and products of their evaporation can leave observable effects.

To form a black hole, a strong inhomogeneity is needed. In the expanding homogeneous and isotropic Universe, this corresponds to decoupling from the general expansion of a region within a cosmological horizon. For the the dispersion of amplitude of density fluctuations $\langle \delta^2 \rangle \ll 1$, the probability of PBH formation from a high amplitude δ fluctuation is given by [94]

$$W_{PBH} \propto \exp\left(-\frac{\gamma^2 \delta^2}{2\langle \delta^2 \rangle}\right) \quad (7)$$

for the equation of state $p = \gamma\epsilon$, with $0 \leq \gamma \leq 1$, making it exponentially small at $\gamma > 0$ for a fluctuation with the amplitude $\delta \sim 1$. Therefore, the PBH spectrum is exponentially sensitive to nonstandard cosmological scenarios with early matter domination ($\gamma \rightarrow 0$)

or strong small-scale nonhomogeneity of the early Universe ($\langle \delta^2 \rangle \rightarrow 1$). BSM models predicting such scenarios make PBHs messengers of the corresponding new physics.

Let us consider, following [13–16,92], some examples of PBH messengers of BSM physics.

3.1. PBHs from Superheavy Metastable Particles

The early matter-dominated stage can take place after reheating at the temperature $T < T_0 = rm$ corresponding to $t_0 = M_{\text{Pl}}/T_0^2$ for particles with a mass m and relative concentration $r = n/n_r$, where n is the frozen-in or frozen-out concentration of particles and n_r is the concentration of relativistic species. This stage should end by particle decay before BBN (to satisfy the observational constraints on primordial chemical composition), so that the particles can have lifetime $\tau \ll 1$ s. If the duration of this stage $t_0 < t < \tau$ is sufficiently long, the growth of density fluctuations can lead to the formation of gravitationally bound systems of these particles and, as it was first noticed in [95], it should be accompanied by PBH formation. Such PBHs remain in the Universe after particle decay, and their spectrum contains information on particle mass, concentration and lifetime.

The minimal probability of PBH formation at the early matter-dominated stage is determined by the probability of direct collapse in black holes of especially homogeneous and isotropic configurations, which contract within their gravitational radius after separation from the cosmological expansion [95]. Though this probability does not contain exponential suppression (7), this probability $W \propto \langle \delta^2 \rangle^{13/2}$ has a strong power-law suppression for small density fluctuations with $\langle \delta^2 \rangle \ll 1$ [15,95].

A direct mechanism gives rise to the formation of spectrum PBH masses within the interval

$$M_0 \leq M \leq M_{bhmax}.$$

The minimal mass M_0 of PBHs formed by a direct mechanism is equal to the mass within the cosmological horizon at the beginning of matter dominance at $t \sim t_0$, given by [15,95]

$$M_0 = \frac{4\pi}{3} \rho t_0^3 \approx M_{\text{Pl}} \left(\frac{M_{\text{Pl}}}{rm} \right)^2. \quad (8)$$

The maximal mass M_{bhmax} corresponds to fluctuation, which separates from expansion and collapses just before the particle decay at $t = \tau$. For the scale-invariant spectrum $\delta(M) = \delta_0$, it is given by [15]

$$M_{bhmax} = M_{\text{Pl}} \frac{\tau}{t_{\text{Pl}}} \delta_0^{-3/2} = M_{\text{Pl}}^2 \tau \delta_0^{-3/2}. \quad (9)$$

Being independent of the form of the nonrelativistic matter, the direct mechanism is also appropriate at the dust-like preheating stage of inflaton field oscillations [96].

The direct mechanism of PBH formation involves a tiny fraction of gravitationally bound systems formed at the early matter-dominated stage. The dominant fraction of such systems do not collapse in black holes directly but can evolve into PBHs as a result of their evolution. The rate of such evolution strongly depends on particle properties. If particles are collisionless, the minimal timescale of evolution of their gravitationally bound system into a black hole is determined by the total number of particles N and can be estimated as $N^{2/3} t_0 \delta_0^{-3/2}$. If particles couple to relativistic species and their matter is dissipative, radiative energy loss makes the evolution of the gravitationally bound object much more rapid within a stimescale the order of $t_0 \delta_0^{-3/2}$ [97,98].

3.2. PBHs from Phase Transitions during Inflation

Models of inflation, supported by the data on CMB and Large Scale Structure (LSS), predict a spectrum of density fluctuations slightly decreasing to smaller scales. However, the extrapolation of the amplitude, deduced from the CMB and LSS data, cannot be proven below galactic scales, at which the observed Universe is strongly nonhomogeneous. BSM models of inflation, involving additional parameters, can predict higher amplitude of

density fluctuations at small scales, enhancing the probability of PBH formation and making the PBH spectrum a messenger of the corresponding models.

Realistic BSM models of inflaton inevitably predict a set of scalar fields accompanying inflation, and their effect can lead to specific model-dependent features in the density fluctuations.

The example of such features was proposed in [99]. It was shown that the interaction of a Higgs field ϕ with inflaton η causes phase transitions during inflation. Owing to this interaction Higgs potential acquires a positive mass term $+\frac{v^2}{2}\eta^2\phi^2$, modifying the form of this potential, as given by

$$V(\phi, \eta) = -\frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{v^2}{2}\eta^2\phi^2 \quad (10)$$

In the course of slow rolling, the mass term changes sign at the critical value of the inflaton amplitude $\eta_c = m_\phi/v$. It leads to peaks in the spectrum of density perturbations, which increase the probability of PBH formation [13,16,100], when perturbations on the corresponding scale re-enter the horizon. The mass of PBH is determined by the e-folding, at which the phase transition takes place at the inflationary stage. This makes PBHs produced by this mechanism a sensitive probe for phase transitions at the inflationary stage [15,16,92].

3.3. PBHs from Bubble Collisions in First-Order Phase Transitions

If the phase transition is of the first order going through true vacuum bubble nucleation, black holes can form bubble collisions (see [15,16] for review and reference). At the collision, the energy of expanding bubble walls converts into the energy of false vacuum restored in the region of collision, forming a false vacuum bag [101]. If this bag according to the negative pressure equation of state inside it contracts within the gravitational radius, a black hole can be formed [89]. It should be noted that the formation of PBH in bubble wall collisions was not found in lattice calculations [102], but these calculations did not take into account the evolution of false vacuum bag, studied in [101].

The mass of PBH formed in the bubble collision is determined by the false vacuum energy released within the bubble volume in the course of the phase transition [89]. This makes PBHs formed by this mechanism a sensitive probe for the cosmological first-order phase transitions.

If inflation ends by a first-order phase transition, the size of bubbles in the percolation regime is of the order of the Hubble horizon at the end of inflation H_{end} and the mass within the bubble volume is of the order of $M_{bub} \approx M_{Pl}^2/H_{end}$. The mass of PBHs formed in these bubble collisions is of the order of $M_0 \approx 1$ g, and the contribution of such PBHs into the total density could be as high as $6 \cdot 10^{-3}$ [89]. Although such PBHs should evaporate by the Hawking mechanism at $t \sim 10^{-27}$ s, an effect of their evaporation, discussed in Section 3.5, can provide a sensitive probe for the end of inflation by the first-order phase transition.

3.4. PBH Formation in Succession of U(1) Phase Transitions

Axion-like models involve global U(1) symmetry, which is broken spontaneously and then explicitly. It leads to two steps of symmetry breaking: spontaneous at the energy scale f and explicit at scale $\Lambda \ll f$. The succession of the corresponding phase transitions changes the symmetry of vacuum and gives rise to the formation of topological defects.

If the first phase transition takes place during inflation and the second one after reheating, closed domain walls are formed. Collapse of such walls can lead to PBH formation in the range of masses determined by the parameters f and Λ . Depending on these parameters, this range of masses can reach the stellar, super-stellar and even Active Galactic Nuclei (AGN) mass values of [15,16,103]. The mechanism of closed wall formation provides clustering of smaller walls near the locally most massive one, so their collapse leads to PBH cluster formation [90,104–106].

The maximal mass of a wall that can in principle collapse into black hole is determined by the condition that the wall does not start to dominate locally before it enters as a whole the cosmological horizon. This principally maximal mass is given by [90]:

$$M_{max} = \frac{M_{Pl}}{f} M_{Pl} \left(\frac{M_{Pl}}{\Lambda} \right)^2. \quad (11)$$

The locally most massive PBHs with $M < M_{max}$ host a cluster of PBHs with smaller masses. The minimal mass of a PBH, which can be formed in the collapse of closed wall, follows from the condition that the width of the wall does not exceed its gravitational radius and is given by [90,104]

$$M_{min} = f \left(\frac{M_{Pl}}{\Lambda} \right)^2. \quad (12)$$

The gravitational wave (GW) signal accompanying the collapse of walls and its specific features need special thorough investigation. Qualitative estimation of the expected GW background [15] indicates that it should be peaked at the frequency ν_p

$$\nu_p = 3 \cdot 10^{11} (\Lambda/f) \text{ Hz}, \quad (13)$$

and the estimated contribution of this background in the total modern energy density can be in the order of

$$\Omega_{GW} \approx 10^{-4} (f/M_{Pl}). \quad (14)$$

For $f \sim 10^{14} \text{ GeV}$, this contribution can reach $\Omega_{GW} \approx 10^{-9}$. The peak frequency ν_p , given by Equation (13), also depends on the value Λ , which can be, depending on the BSM model, in the range [15]

$$1 < \Lambda < 10^8 \text{ GeV}, \quad (15)$$

so the maximum of the spectrum at the chosen value of f may be in the interval

$$3 \times 10^{-3} < \nu_p < 3 \times 10^5 \text{ Hz}. \quad (16)$$

GW background in this range may be accessible for searching at LIGO-VIRGO and future LISA GW detectors. The results of the NANOGrav Collaboration [107] measurement of pulsar timing may find interpretation in the detailed analysis of this prediction.

Formation of PBH binaries and their coalescence in clusters can be another source of observable GW signals [13,16,106], which we discuss in Section 3.6.

3.5. Cosmoarchaeology of PBH Evaporation

The effect of SM products of evaporation of PBHs with the mass $M < 10^{14} \text{ g}$ by the mechanism of S. Hawking [93] can be confronted with the constraints on the effect of decay products of unstable particles (see Figure 2).

However, this analogy is not complete, since evaporation is due to the PBH gravitational field, so it involves all the particles that exist in our space-time, provided that their mass $m \leq T_{eva}$, where T_{eva} is the Hawking temperature of evaporation. In particular, PBH evaporation provides the mechanism of freeze-in for superweakly interacting particles.

The contribution of PBHs to the total density grows at the RD stage makes the astrophysical constraints very sensitive to even the small probability of PBH formation in the early Universe [87,108]. However, there is no such relative growth at the matter-dominated (MD) stage, so self-consistent treatment of observational constraints should take into account the specific cosmological scenario, based on the BSM model, predicting PBH formation (see [13,109,110] for details). A multi-step analysis makes it possible to probe effect of PBH formation even if their evaporation does not lead to observable effect directly, as is the case for PBHs evaporating before the 1 s of expansion. Evaporation of such PBHs is the source of superweakly interacting particles, such as the gravitino [111], and analysis of effect of gravitino production can be a sensitive probe for existence of low-mass PBHs [112].

3.6. PBH Dark Matter

PBHs with the mass $M > 10^{14}$ g, which should be retained, if formed, in the Universe, should contribute to modern DM density. It was noted in [106] that severe constraints [113] (see also [114]) may be relaxed with the account of PBH clustering, so the PBH-dominant contribution to dark matter may not be excluded.

However, just the existence of massive PBH and their clustering can shed new light on the interpretation of GW signals from massive black hole merging. Catalogs of GW signals continuously grow [115,116], and the latest [117] catalog now contains 57 events, with only two events of the merging of neutron stars. In the detected signals from the coalescence of black hole binaries (BBH), the measured mass is larger than $10\text{--}20 M_{\odot}$. Astrophysical models cannot easily explain the formation of such massive black holes in the evolution of the first stars, especially if the mass exceeds the value above $50 M_{\odot}$. On the other hand, massive and supermassive black holes may have primordial origins (see, e.g., [118] for review and references), as well as massive PBH clustering, facilitating binary formation. GW signal from a BBH coalescence with total mass $150 M_{\odot}$, detected by LIGO and VIRGO collaborations [119], was recently considered as possible evidence for primordial origin of massive BHs [120]. Clustering of massive PBHs may lead to repeating events of BBH coalescence in the cluster and can be an observable signature for PBH clusters [106,121]. The growing data set of GW signals will soon help to come to a definite conclusion on this possibility, and if confirmed, it will strongly favor BSM models, predicting the formation of massive PBH clusters in the early Universe.

4. Anti-Matter Stars as the Probe for Baryosynthesis in Inflationary Universe

A.D. Sakharov's idea of baryosynthesis generation of baryon excess in a baryon-symmetrical Universe [122] (see also [123]) is the cornerstone of the modern theory of the Universe.

However, any mechanism of baryosynthesis can lead to nonhomogeneity in excess baryon production. If this nonhomogeneity is strong, the baryon excess changes not only its magnitude, but also its sign, producing antibaryon excess in some regions of the baryon-asymmetrical Universe [124]. Such antibaryon domains are surrounded by baryonic matter, and diffusion to their border can result in complete annihilation of domain, if its size is not sufficiently large to survive. In the mass units, this minimal surviving size corresponds to $10^3 M_{\odot}$.

Creation of sufficiently large antibaryon domains assumes a specific combination of nonhomogeneous baryosynthesis and inflation. Such a combination can be illustrated by the model of spontaneous baryosynthesis [125] (see review in Reference [126]), in which the appearance of sufficiently large domains can be predicted, and their mass distribution can lead under a reasonable choice of parameters to the number of antibaryon domains with masses of several thousand M_{\odot} as the number of observed galaxies. The estimated number of larger domains (of galactic scale and higher) is suppressed. This makes it possible to avoid constraints on annihilation at their borders by the observed gamma ray background [13,127].

In the considered approach, the typical mass of antibaryon domains is of the order of the mass of globular clusters, and such a domain can evolve in antimatter globular cluster in our galaxy [128]. If formed, such a globular cluster can survive in the galactic halo and should be a rather faint gamma ray source, since annihilation with matter gas, which has a rather low density in halo, should take place only on the surfaces of antimatter stars. Antimatter stellar winds, anti-stellar flares or anti-supernova explosions expel antimatter from a globular cluster, which annihilate with interstellar matter gas and should contribute to the galactic gamma ray background [129]. It provides the constraint on the total mass of antimatter stars in our galaxy on the order of $10^5 M_{\odot}$. Macroscopic pieces of antimatter, if they can reach the solar system, can provide rather bright events of their annihilation, but the analysis of this possibility does not lead to any stronger constraint [130].

Accelerated antinuclei should be detected as the exotic component of cosmic rays, and the prediction of antihelium component of cosmic rays [131] is of special interest for

experimental tests of the existence of antimatter stars in our galaxy [128]. The specific role of antihelium is that it should be the second element in abundance (after anti-hydrogen) produced in Big Bang Nucleosynthesis in the antibaryon domain, while successive evolution of antimatter stars can increase its abundance, similar to helium enrichment in baryonic matter. Moreover, the interaction of heavier antimatter nuclei from the antimatter globular cluster with interstellar gas in the course of their propagation in the galaxy should lead to destruction of these nuclei accompanied by production of antihelium fragments.

In the rough estimation of the ratio of cosmic antihelium to helium fluxes presented on Figure 3, this ratio is taken as proportional to the ratio of the estimated mass of antihelium globular cluster to the baryonic mass of Galaxy and the minimal and maximal estimations of the expected signal are shown.

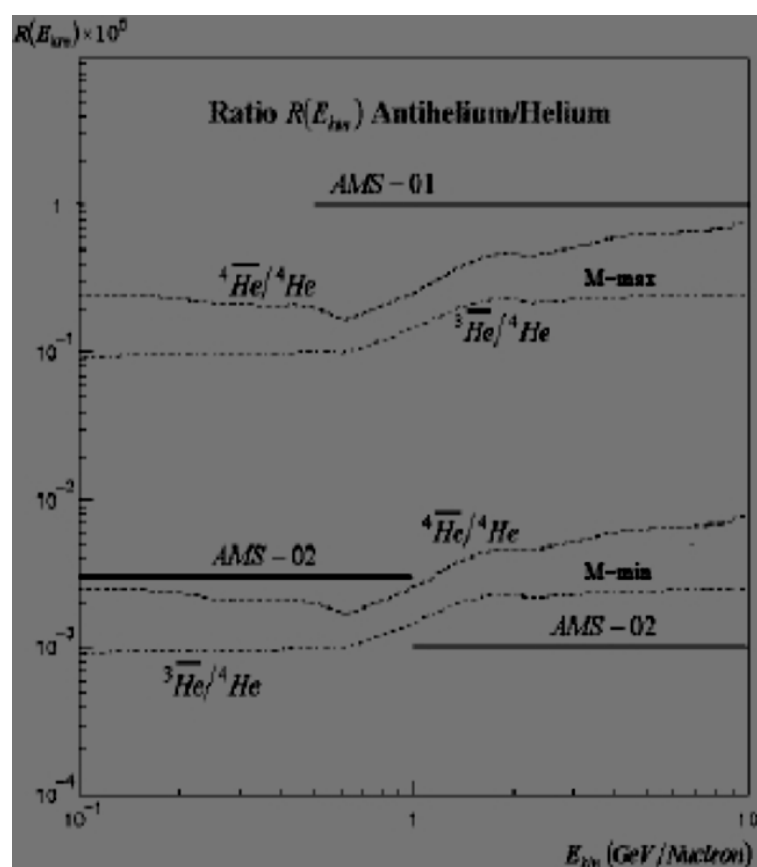


Figure 3. The minimal and maximal estimation of the ratio of fluxes of antiHe-3 and antiHe-4 and the flux of cosmic He nuclei [90] for the minimal and maximal estimation of mass of antimatter globular cluster in comparison with possible sensitivity of AMS01 and AMS02 experiments.

This estimation is challenging for the antihelium search in the AMS02 experiment, making the result of this search a decisive experimental probe for the existence of antimatter globular cluster and BSM physics underlying this hypothesis.

The first results of such a search by AMS collaboration are presented at some conferences and meetings with the demonstration of events that may look like antihelium candidates [132, 133]. However, these results still remain unpublished, since the collaboration expects more statistics, together with effective background rejection to, present a statistically significant status of such events by 2024. The estimated secondary antihelium flux from cosmic ray interactions with matter is several orders of magnitude below the sensitivity of AMS02 [134]. Therefore the confirmation of antihelium detection would inevitably involve interpretation in terms of BSM physics like the antimatter globular cluster hypothesis.

To confront the expected results of the AMS02 experiment with theoretical predictions, the numerical simulation of production and propagation of antinuclei from antimatter

globular cluster is being developed now. This approach assumes that antimatter objects are similar to the corresponding matter objects [135]. However, pending the parameters of nonhomogeneous baryosynthesis, antimatter objects can strongly differ from matter objects and evolve into much denser antistars, as was proposed in [136].

Positive evidence of the existence of antimatter stars in our galaxy would strongly tighten the choice of baryosynthesis models and their parameters, being the sensitive probe of new physics underlying the modern cosmology.

5. Conclusions

The basis of cosmoparticle physics is cross-disciplinary studies of the fundamental relationship of micro- and macro-worlds. This traditional mutual relationship between microscopic and macroscopic descriptions reaches a new level in the case of the two extremes of our knowledge: the Universe and elementary particles, making cosmoparticle physics the mainstream of the exploration of the frontiers of fundamental physics.

Physical, astrophysical and cosmological effects of new physics, underlying the modern cosmology, involve the *messengers*-model-dependent predictions accompanying physical mechanisms of inflation, baryosynthesis and dark matter candidates. The combination of messenger probes provides an overdetermined system of equations for model parameters, making it principally possible to evolve a multimessenger probe of the considered model. However, positive results in search of exotic messengers, such supermassive PBHs or antimatter stars, strongly reduce the number of possible types of models and range of their parameters.

Methods of cosmoparticle physics are appropriate not only for BSM physics of elementary particles but also for extensions of GR as a standard model of gravity. In particular, indications to some problems of simple CDM model in the observational data on the structure and evolution of galaxies, interpreted as evidence for modified gravity [137,138], may stimulate extensions of the cosmoparticle physics approach to BSM models of gravity.

In commemorating 100th Anniversary of A.D. Sakharov, we see the wide prospects of development of their legacy in cosmoparticle physics in fundamental knowledge of the Universe, which is, by 95% of its energy density, full of new physics.

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Abbreviations

The following abbreviations are used in this manuscript:

SM	Standard Model
BSM	Beyond the Standard Model
BBN	Big Bang Nucleosynthesis
AGN	Active Galactic Nucleus
BH	Black Hole
PBH	Primordial Black Hole
DM	Dark Matter
CDM	Cold Dark Matter
MACHO	Massive Astrophysical Compact Halo Object
GW	Gravitational Wave
SUSY	Supersymmetry
LSP	Lightest Supersymmetric Particle
SUGRA	Supergravity
WTC	Walking TechniColor

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