Physics and Cosmology Beyond the Standard Models
Физика и Космология вне рамок Стандартных Моделей

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Современная космология обретает свои физические основания вне рамок стандартных моделей (ВСМ) фундаментальных взаимодействий, привлекая для описания структуры и эволюции Вселенной механизмы инфляции и бариосинтеза, а также гипотетических кандидатов на роль частиц скрытой массы. В то же время, любая последовательная реализация инфляционных космологических моделей с бариосинтезом и скрытой массой на основе физических моделей ВСМ неизбежно содержит модельно-зависимые предсказания, выходящие за рамки ныне стандарной космологической модели. При этом подтвеждение существования таких экзотических объектов и явлений, как темные атомы, первичные черные дыры или макроскопические объекты антивещества в нашей Галактике может обеспечить как выбор моделей ВСМ, так и определение их допустимых параметров. Космомикрофизический подход к исследованию фундаментальной взаимосвязи микро- и макро- мира в комплексном сочетании ее физических, астрофизических и космологических проявлений способствует изучению как физики ВСМ, и основанной на ней картины структуры и эволюции Вселенной.

Modern cosmology acquires its physical foundations Beyond the Standard Models (BSMs) of fundamental interactions, involving the mechanisms of inflation and baryosynthesis, as well as hypothetical candidates for the role of dark matter particles, to describe the structure and evolution of the Universe. However, any consistent implementation of inflationary cosmological models with baryosynthesis and dark matter based on BSM physical models inevitably contains model-dependent predictions that go beyond the now standard cosmological model. At the same time, confirmation of the existence of such exotic objects and phenomena as dark atoms, primordial black holes, or macroscopic antimatter objects in our Galaxy can provide both the choice of BSM models and the determination of their admissible parameters. The approach of cosmoparticle physics to study the fundamental relationship of the micro- and macro-world in a proper combination of its physical, astrophysical and cosmological manifestations explores both the BSM physics and the picture of the structure and evolution of the Universe based on it.

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Introduction

The modern standard cosmological paradigm involves inflationary cosmological scenario with baryosynthesis and dark matter/energy, which imply physics beyond the standard model (BSM) of fundamental interactions. It makes the origin of the observed Universe and its structure and evolution to be determined by the dark sector of particle physics and we need special methods to shed light on it. The basic idea of the approach presented here is to pay special attention to the nontrivial effects of the BSM models, which should inevitably result in observable cosmological consequences. Such model dependent set of model dependent predictions, accompanying BSM models, which underlie the now standard cosmology, and leading to deviations from the standard cosmological paradigm, maintain multimessenger cosmological probes for new physics. Observational restrictions on such predictions put constraints on the parameters of the BSM physics. However, observational signatures for such exotic and nontrivial phenomena would provide the sensitive probe for the BSM physics and its allowed parameters.

Dark atoms and their multiple charged constituents

The last decades, the mainstream of studies of physical nature of the cosmological dark matter was related with the WIMP miracle. The frozen out abundance of primordial gas of Weakly Interacting Massive Particles (WIMPs) can explain the observed density of dark matter if these particles have masses in the range of hundreds GeV and the annihilation cross section in the range of weak interaction. From the theoretical viewpoint the existence of WIMPs had strong motivation in supersymmetric (SUSY) models predicting stable Lightest Supersymmetric Particles, which can play role of WIMPs and should be accompanied with the set of supersymmetric partners of ordinary particles, which could be detected at the LHC.

However, the results of direct dark matter searches are controversial and there is no evidence for SUSY particles at the LHC. The latter can reflect a very high energy scale of SUSY particles, which can be sub-Planckean, so that supersymmetry can provide unification of all the fundamental forces including gravity in the framework of Supergravity, but then the practical advantage of supersymmetry to solve the problem of divergence of the Higgs boson mass and to explain the origin of the Higgs mechanism of electroweak symmetry breaking is lost and the solution of these problems of the Standard Model (SM) should involve some other approach (see [1] for review and references).

Composite nature of the SM Higgs boson can solve the problem of the divergence of its mass and of the origin of the electroweak energy scale. Such solution involves Higgs boson constituents, which can have electromagnetic charge and bind in exotic non-single charged states. If such states are stable they had to be produced in the early Universe and be present in the surrounding matter. Severe upper limits on the abundance of anomalous isotopes exclude fractionally, positively or odd negatively charged species, but, if such states have charge $-2n$, they can be stable and their existence doesn't contradict these constraints since they can be bound with n nuclei of primordial helium in neutral dark atoms.

In Walking TechniColor (WTC) models of composite electroweak Higgs boson the charge of techniquarks and technileptons is not fixed and their charge assignment is regulated by the cancellation of anomalies. Any integer value of n is possible in this case. Techniparticles have no QCD charges and behave like leptons. If $n = 1$, the -2 charged particle binds with helium nucleus in OHe atom - a Bohr like system with leptonic massive techniparticle core and helium nucleus on a Bohr orbit with radius of the order of the size of α-particle. If $n > 1$, the $-2n$ charged techniparticle is situated inside the $n - \alpha$-particle nucleus, being a Thomson like atom.

The nontrivial $SU(2)$ charges of multiple charged stable constituents of dark atoms provide their participation in the electroweak sphaleron transitions, which can balance the excess of these constituents with baryon asymmetry. It turns out that at reasonable parameters of sphaleron transitions baryon excess is balanced with the excess of $-2n$ particles over their positively charged antiparticles. Due to this charge asymmetry primordial abundance of $+2n$ charged particles is suppressed below the upper limits on the abundance of the corresponding anomalous isotopes. The excess of $-2n$ charged stable particles, corresponding to the observed baryon asymmetry can provide their contribution into the modern density explaining the observed dark matter density by dark atoms.

The balance between the excess of even-negatively charged particles and baryon asymmetry can also take place in the case of new stable U-quark of a new successive family of quarks and leptons, which possess same electroweak $SU(2)$ charges as quarks and leptons of the three known families. Then excessive $\bar{U}$ form -2 charged heavy quark cluster $(\bar{U}\bar{U}\bar{U})$. Such clusters are bound by chromo-Coulomb interaction and their QCD interaction is strongly suppressed relative to ordinary hadrons bound by QCD confinement.

Dark atoms represent the minimal possible extension of the Standard model, since this hypothesis involves only one element of BSM physics - existence of stable multiple charged particles. The properties of dark atom interaction with matter are determined by their nuclear interacting helium shell. It makes this form of dark matter strongly interacting and elusive for direct WIMP searches. Owing to their nuclear interaction with the terrestrial matter dark atoms slow down and cannot cause detectable nuclear recoil in the underground detectors, on which the strategy of WIMP searches is based.

Dark atom hypothesis explains positive results of dark matter searches in DAMA/NaI and DAMA/LIBRA experiments by annual modulation of low energy binding of dark atoms with sodium nuclei in DAMA detector. The idea of this explanation is based on the adjustment of the local concentration of dark atoms in the matter of underground detectors to the cosmic dark atom flux, which possess annual modulations due to orbital motion of Earth around Sun. If there is a 3 keV level in the dark atom-nucleus system, radiative transitions to this level can reproduce the observed DAMA effect. The hypothesis on the existence of such a level implies rigorous quantum mechanical prove, which is now under way.

Dark atom cosmological scenario leads to a Warmer than Cold Dark Matter model of Large Scale Structure formation and can lead to nontrivial role of dark atoms in the Big Bang Nucleosynthesis, appearance of new multiple charged heavy components of cosmic rays and dark atom effects in stars. Thorough exploration of these aspects of dark atom astrophysics inevitably involves development dark atom nuclear physics, which still remains the open problem of this approach. In any case, the basic assumption of the dark atom model is the existence of multiple charged stable particles challenging their search at the LHC and the wide set of possible physical, astrophysical and cosmological signatures of dark atoms and their constituents make this hypothesis falsifiable and thus realistic.

Primordial nonlinear structures

Formation of gravitationally bound objects in the expanding homogeneous and isotropic Universe is related in the standard cosmology with growth of initially small density fluctuations at the Matter Dominated stage. However the observational data on the homogeneity and isotropy of the Universe at large scales doesn't exclude existence of a strongly nonhomogeneous but strongly subdominant forms of matter, distributed up to the largest observed distances. One cannot also exclude strong primordial nonhomogeneities at the scales, smaller than the scales of galaxies, at which the primordial nature is masked by the nonlinear evolution of the cosmological structure.

The origin of such forms of primordial nonhomogeneities can be illustrated in Axion-Like Particle (ALP) model, which can be reduced to a simple model of a complex field $\Psi = \psi \exp i\theta$ with broken global $U(1)$ symmetry [1,2]. The potential

$$V = V_0 + \delta V$$

contains the term

$$V_0 = \frac{\lambda}{2}(\Psi^*\Psi - f^2)^2 \tag{1}$$

that leads to spontaneous breaking of the $U(1)$ symmetry with continuous degeneracy of the asymmetric ground state

$$\Psi_{vac} = f\exp(i\theta) \tag{2}$$

and the term

$$\delta V(\theta) = \Lambda^4(1 - \cos\theta) \tag{3}$$

with $\Lambda \ll f$ that leads to manifest breaking of the residual symmetry, leading to a discrete set of degenerated ground states, corresponding to

$$\theta_{vac} = 0, 2\pi, 4\pi, ...$$

The term (3) can be present in the theory initially, or generated by instanton transitions, as it is the case in the axion models. In the result of the second step of symmetry breaking an ALP field $\phi = f\theta$ is generated with the mass

$$m_\phi = \Lambda^2/f. \tag{4}$$

This pattern of global $U(1)$ symmetry breaking leads to succession of phase transitions in the early Universe.

If the first (spontaneous) symmetry breaking takes place at the temperature $T \sim f$ after reheating, the correlation radius is small and the continuous degeneracy of the asymmetric ground state is reflected in continuous change of the phase θ. Closed paths, along which the phase changes from 0 to 2π, lead to singularities at their contraction, in which the phase is not defined and the symmetric ground state is restored. Geometrical place for these singularities is the cosmic string - topological defect arising due to continuous degeneracy of the asymmetric ground state. At $T \sim \Lambda \ll f$ continuous degeneracy is changed by discrete symmetry and simultaneously string network transforms into unstable walls-surrounded-by-strings structure of topological defects. Though this structure is unstable, it provides initial conditions for amplitude of ALP field, which determines the energy density of ALP field oscillations. In that way the initial wall-surrounded -by-string structure is reflected in the large scale correlations of the energy density of ALP field oscillations, called *archioles* in the case of QCD axion [3, 4]. Evolution of these large scale correlations in their relationship with distribution of axion stars [5] needs special studies.

If spontaneous symmetry breaking takes place at the inflationary stage, the value of phase θ has a fixed value θ_o at e-folding, corresponding to observed part of the modern Universe, and fluctuates at successive steps of inflation in smaller scales with the amplitude $\delta\theta = H_i/(2\pi f)$, where H_i is the Hubble parameter at inflation. If $\theta_o < \pi$ such fluctuations can lead to $\theta > \pi$ in some regions, so that these initial conditions lead to the ground state $\theta_{vac} = 0$ everywhere, except for the regions with $\theta > \pi$, where $\theta_{vac} = 2\pi$. At the phase transition at $T \sim \Lambda \ll f$ after reheating such regions should be separated from the surrounding part of the Universe by a topological defect - closed domain wall with the surface mass density $\sigma \sim f\Lambda^2$.

After the first crossing of π fluctuations can continue such crossings at smaller scales, so that at the second phase transition the locally larger closed wall should be surrounded by a set of smaller closed walls. Collapse of closed walls results in formation of Primordial Black Hole (PBH) cluster [1, 2].

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 [2]

$$M_{max} = \frac{m_{pl}}{f} m_{pl} (\frac{m_{pl}}{\Lambda})^2 \tag{5}$$

The minimal mass follows from the condition that the gravitational radius of BH exceeds the width of wall, and it is equal to [2]

$$M_{min} = f(\frac{m_{pl}}{\Lambda})^2 \tag{6}$$

Closed wall collapse leads to primordial gravitational wave (GW) spectrum, peaked at

$$\nu_0 = 3 \times 10^{11} (\Lambda/f)\,\mathrm{Hz} \tag{7}$$

with energy density up to

$$\Omega_{GW} \approx 10^{-4} (f/m_{pl}) \tag{8}$$

th

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

$$1 < \Lambda < 10^8\,\mathrm{GeV} \tag{9}$$

the maximum of the spectrum corresponds toci

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

In the range from tens to thousands of Hz, such background may be a challenge for LIGO-VIRGO-KARGO experiment.

The account for PBH formation in clusters [1] can influence the severe constraints, excluding PBH dominance in dark matter [6] and even open this possibility.

Another profound signature of the primordial origin of stellar mass black holes are gravitational wave (GV) signals from their merging, if the masses of BH companions in the binary exceed the pair instability limit of $50 M_{\odot}$. Then such BH binaries can be hardly prodiuced in the evolution of the first generation stars. In this aspect detection of signals from binary BH coalescence with total mass $150 M_{\odot}$ in the LIGO-VIRGO GW experiment [7] may be considered as a positive evidence for their PBH nature [8].

PBH clustering facilitates formation of BH binaries as compared with the case of their random distribution. It should lead to repeating events of BH coalescence and localization of the corresponding sources of GW signals within the same PBH cluster [9]. With the growth of statistics of GW signals and improvement of localization of their sources this feature of scenario of PBH clustering can get experimental verification [1].

Antimatter probe for the origin of matter

Any mechanism of generation of baryon excess in baryosynthesis may be nonhomogeneous and lead to creation of domains with antibaryon excess in the baryon asymmetrical Universe [1,2,10,11]. To survive in the baryon surrounding, antibaryon domain should be sufficiently large. It implies proper

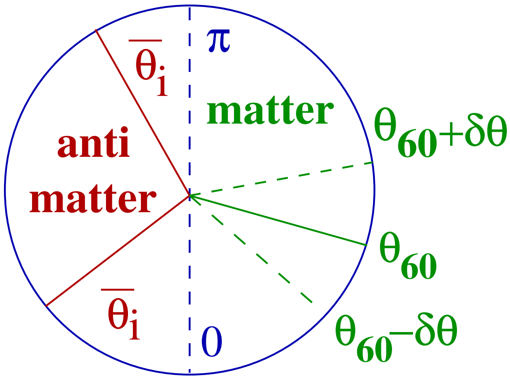

Fig. 1. Fluctuations of phase θ at the inflationary stage move its value from θ_{60}, corresponding to the scale of the modern cosmological horizon, to various local values at smaller scales. Crossing 0 and π leads to generation of antibaryon excess in the corresponding regions. This original author's figure was published in [1].

combination of nonhomogeneous baryosynthesis and inflation. The model of spontaneous baryosynthesis [12] combines these two features and can be reduced to the ALP field, given by Eq.(2), which has in addition to the potential terms Eq.(1) and Eq.(3) a Yukawa interaction with fermions, violating baryon and lepton number conservation. Owing to this Yukawa interaction the field decays and generates baryon excess. The amplitude of the ALP field acquires its vacuum expectation value f at the inflationary stage and the phase θ has the value θ_{60} at the stage of inflation, corresponding to the modern cosmological horizon. Fluctuations of θ at the successive stages of inflation change its value in some regions within the modern cosmological horizon and may cross $\theta = 0$ or $\theta = \pi$, as shown on Fig.1. Decays of ALP field after the second phase transition lead to generation of baryon excess in the course of θ motion to its ground state. At $0 < \theta < \pi$ baryon excess is generated, while in the regions with $\pi < \theta < 2\pi$ is generated an antibaryon excess. The average value of baryon density is proportional to θ_{60} in the observed Universe, while local baryon and antibaryon density can be larger or smaller, pending on the local value of θ, which determines the generated excess (see Fig.1). The measured CMB anisotropy puts constraints on the amplitude of baryon density fluctuations at large scales, but doesn't exclude strong fluctuations at the galaxy scales and smaller [1, 2, 13].

If local amplitude of the ALP phase field $\bar{\theta}_i$ in antibaryon domain is much smaller than θ_{60}, corresponding to the average baryon density, a low antimatter density region forms, in which neither nucleosynthesis;, nor recombination can take place. Such domains of diffused antiworld cannot take part in galaxy formation and can appear in the intergalactic space as low density clouds of antiproton-positron plasma [14].

Domains, originated from the value of phase amplitude $\bar{\theta}_i$ much larger than θ_{60}, contain antibaryon density much higher than the average baryon density and their rapid evolution can lead to formation of antimatter globular cluster in our Galaxy [15]. Such cluster can be the source of antihelium component of cosmic rays accessible to detection in AMS02 experiment [16]. In this scenario antimatter stars are localized in the region of antimatter globular cluster and antistellar winds and products of anti-Supernova leave this region, so that products of anti-stellar nucleosynthesis cannot stay in this region and form dust, planetisimals and other antimatter rigid bodies, making highly improbable formation of antimatter meteorites, which can reach Earth [17]. Localization of antinulei, heavier than antihelium, and their binding in antiatoms and antimolecules (with successive formation of anti-dust, antimeteorites and other rigid antibodies) can be only possible, if such heavy nuclei were created in the antimatter domain at Big Bang Nucleosynthesis owing to much higher antibaryon density as compared to the average cosmological baryon density.

As it looks like from the Fig. 1 fluctuations crossing π may lead to the antibaryon density much higher than the average baryon density and it can lead to formation of very dense antiquark bodies, as considered in [18]. However, to reach values above π the fluctuations should first reach large values below π, so that antibaryon domain with high density should appear within the region of the enhanced baryon density. Moreover, fluctuations inside future antibaryon domain may move the phase back to values below π, leading finally to a nontrivial 'Chinese boxes' structure in which antimatter domain contains matter domains, which in their turn contain smaller antimatter domains etc [14]. Evolution of such structure with the account for matter-antimatter annihilation at the borders can reduce the initial very high antibaryon density down to the conditions similar to the average baryonic matter evolution, which results in generation of antimatter stars and their evolution similar to the ones of the ordinary baryonic stars. Then antihelium flux from antimatter globular cluster becomes the profound signature for macroscopic antimatter in our Galaxy.

Cosmoparticle physics of multimessenger BSM cosmology

We discussed some examples of new physics phenomena, which may be already observed and can lead to determination with "astronomical precision" of parameters of BSM models. We considered dark atom solution for the puzzles of direct dark matter searches and linked the existence of new stable multiple charged constituents of dark atoms to the solution of the the problems of the electroweak sector of the Standard model (SM) by the composite nature of the electroweak Higgs boson. We link Primordial origin of the merging BH binaries, observed in gravitational wave experiments, to the mechanisms of PBH formation in the inflationary Universe, reflecting the symmetry breaking pattern of the ALP models. We extended the discussion of the possible forms of primordial nonhomogeneities in homogeneous and isotropic Universe by discussion of possible existence of macroscopic antimatter domains in baryon asymmetrical Universe. Evolution of such domains to the macroscopic antimatter objects can result in an antimatter globular

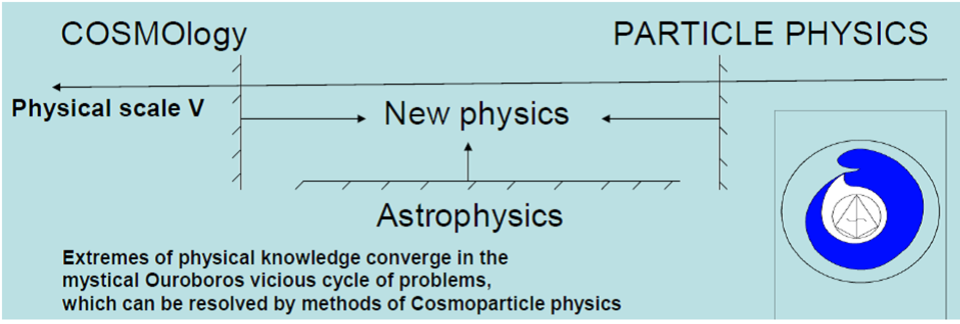

Fig. 2. Cosmoparticle physics probes the scale V of new physics by proper combination of its cosmological astrophysical and experimental physical signatures. This original author's figure was published in [1].

cluster in our Galaxy;, which can be the source of antihelium component of cosmic rays accessible to the experimental detection in the AMS02 experiment. These examples of cosmological messengers of new physics can be put in the context of cosmoparticle physics, studying the fundamental relationship of cosmology and particle physics in the proper combination of its physical, astrophysical and cosmological signatures. Such combination can provide the effective probe for new physics, as it is illustrated on Fig 2.

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