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Cosmoparticle physics: The enlightening voyage to the Dark Universe

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Abstract: Physics of the dominant part of the energy-density of the modern Universe - dark matter and dark energy - lies beyond the Standard model (BSM) of elementary particles. The now standard cosmological model involves BSM physics to describe the cornerstones of the structure and evolution of the Universe: inflation, baryosynthesis and dark matter/energy. It makes Dark the whole story of the Universe: from the origin of its basic initial conditions to the modern structure and evolution. It implies existence of BSM physics, which still finds no experimental evidence, since search for it at the LHC only tightens constraints on its effects. We show that the challenge to shed light on the physics of the Dark Universe can be related to development of cosmoparticle physics, studying fundamental relationship of micro- and macro worlds in cross disciplinary studies of its physical, cosmological and astrophysical signatures.

Keywords: Cosmology; Particle physics; Cosmoparticle physics; inflation; baryosynthesis; Dark matter; Beyond the Standard models

1. Introduction

The paradox of the current situation in cosmology and particle physics can be characterized as *conspiracy* of physics and cosmology beyond the corresponding Standard models [1,2]. Except for the nonzero mass of neutrino there is no experimental evidence for effects of physics Beyond the Standard model (BSM) of elementary particles. Search for such effects at the LHC only tightens the constraints on deviations from the predictions of the standard model (SM) of elementary particles. On the other hand BSM physics is not only needed to solve the internal theoretical problems of the SM like divergence of Higgs boson mass in the electroweak theory or CP violation in QCD, but becomes necessary theoretical basis for the now standard model of the structure and evolution of the Universe - inflationary cosmology with baryosynthesis and dark matter/energy. Astronomical data of the precision cosmology confirm this standard cosmological model, putting more and more stringent constraints on possible deviations from its predictions.

The standards of the modern cosmology mean that the we live in Dark Universe not only because it is dominated now by dark matter and dark energy, but also because its basic parameters are determined by the mechanisms of inflation and baryosynthesis related to the dark (unknown) part of the fundamental physics.

Mutual relationship of cosmology and particle physics is developed in the cosmoparticle physics, studying this relationship in the cross disciplinary search for its physical, astrophysical and cosmological signatures. Here we briefly discuss the motivation for genesis and basic principles of cosmoparticle physics and pay special attention to the reflection of the BSM physics of the modern cosmology in the nonstandard features in astrophysical and cosmological phenomena. The evidences for such features will enlighten the true history of the Universe and the laws of new physics, which governed it.

2. Unification of the frontiers of the fundamental knowledge

The modern picture of the so called Standard model of elementary particle physics finds strong support in the experiments at particle accelerators and colliders. The last missed element in the set of fundamental particles of the Standard model (SM), the Higgs boson was discovered at the Large Hadron Collider (LHC) in 2012.

However it is not the end of discoveries in particle physics, since the wide field of physics Beyond the Standard model is badly needed and waits for its exploration.

Theoretical and practical need to extend the SM follows from its internal problems, some of which can be solved by supersymmetry symmetry between bosons and fermions. Since we do not observe supersymmetry in the mass spectra of known fermions and bosons, then it must be broken, and the search for supersymmetric partners heavier than the corresponding particles was one of the greatest challenges for the Large Hadron Collider and/or the next generation of accelerators. The idea of unifying all the fundamental forces of Nature is the aesthetically appealing reason for the extension of the SM. The similarity of the description of the fundamental particle interactions (electromagnetism, strong and weak interactions), achieved in the SM, is embedded deeply in a grand unified theory (GUT), which extends the fundamental symmetry of elementary particles.

By placing the set of known particles in such theory, we see that there remain white spots which should be occupied to complete it.

The wider the theory, the larger is the number of additional particles and fields, corresponding to the total symmetry. These particles and fields correspond to the hidden sector of the relevant theory, since they are hidden from direct experimental verification or because of their large mass, or because of the extremely weak interaction with the known particles.

In both cases, the (super-weak interaction, or very super-large mass) verification of the predictions requires the use of indirect methods. That is why the expanding Universe, as a possible source of information about elementary particles, attracts the most attention of people involved in elementary particle physics.

Modern cosmology is based on two observational facts. On the fact that the Universe is expanding, and that the modern Universe is filled with the thermal background of electromagnetic radiation. Combining these facts leads to the ideas of Big Bang expanding Universe. Big Bang theory leads to very high temperatures at the very early stages of expansion. We can never build an accelerator of elementary particles to energies of the GUT which are naturally realized in the early stages of cosmological evolution. Thus, the internal development of particle physics leads to the theory of a hot expanding Universe, called Big Bang Universe, as a natural landfill of its fundamental ideas.

However, to resolve the quantitative inconsistencies, which at a deeper examination became more pronounced, it has been necessary to add new fundamental elements to the basics of its theoretical constructions. The theory of the Big

Bang Universe is now supplemented by at least four additional elements inflation, baryosynthesis, non-baryonic dark matter and dark energy, based on physical laws predicted by the theory of elementary particles which, however, have not been experimentally verified.

The inflation gives the principal answer for the questions why is the Universe expanding? Why the expansion makes the Universe so homogeneous and isotropic? and Why the evolution in causally disconnected regions is identical? It suggests that in the past there was a phase of superluminal (in the simplest case of exponential) expansion in the early Universe. This stage could not form if matter, radiation or relativistic plasma was dominant but it could, under certain conditions, form under the effect of various cosmological implications of the theory of elementary particles,

The question: Why does the Universe not contain an equal amount of matter and antimatter? finds its answer in the process of baryosynthesis, linking this observed baryon asymmetry of the Universe with the physical mechanism of generation of an excess of baryons and leptons over their antiparticles in the early Universe.

To explain the difference in the amount of baryonic matter and the total amount of matter in the Universe the dark matter is needed, the physical basis of which relates to the hidden sector of particle physics.

There are many different physical mechanisms pretending to describe inflation and baryosynthesis. There are also many different candidates for the role of dark matter particles. Unfortunately, the early Universe, when there were inflation and baryosynthesis as well as dark matter was created, cannot be observed directly by astronomical means. It is therefore necessary to develop a system of indirect methods of correct choices of variants associated with different cosmological scenarios and models of elementary particles on which they are based. The set of elementary particles and quanta of their interaction represent the Lego of the Universe for different sets we come to different pictures of the Universe, its evolution and structure [3].

Thus the internal development of elementary particle physics requires cosmological verification of the principles of particle physics. On the other hand, this approach which lies in the area inaccessible by direct modern experimental methods, was used to construct the physical principles of modern cosmology. The natural result of this internal development of the frontiers of our knowledge at the largest and smallest physical scales was their unification in the framework of cosmoparticle physics, studying fundamental relationship of micro- and macro world.

3. Cosmophenomenology of very early Universe: from BSM physics to BSM cosmology

The now standard cosmological model reproduces the main features of the observed Universe - its global homogeneity, isotropy, baryon asymmetry, accelerated expansion, formation of the large scale structure from small density fluctuations, reflected in the observed anisotropy of the cosmic microwave background radiation (CMB). In this picture BSM physics, supporting its necessary elements, can lead to specific, model dependent features and one of such possibilities is related with strong primordial inhomogeneities.

3.1. *Primordial Black holes*

The standard model of cosmology assumes homogeneous and isotropic Universe, in which the observed structure of inhomogeneities arises from growth of small primordial density fluctuations. It makes strong primordial inhomogeneities a prominent tracer of BSM physics of very early Universe. Primordial Black Holes (PBH) are the most popular example of this kind (see e.g. [4,5] for review and references).

To form a black hole in the homogeneously expanding Universe the expansion should stop in some region. It corresponds to a very strong inhomogeneity of the cosmological expansion [6–8]. In the universe with equation of state

$$p = \gamma\epsilon, \tag{1}$$

where the numerical factor γ is in the range

$$0 \leq \gamma \leq 1, \tag{2}$$

the probability to form a black hole is given by [9]

$$W_{PBH} \propto \exp\left(-\frac{\gamma^2}{2\left\langle\delta^2\right\rangle}\right), \tag{3}$$

where $\left\langle\delta^2\right\rangle \ll 1$ is the amplitude of density fluctuations.

For relativistic equation of state ($\gamma = 1/3$) the probability (3) is exponentially small. It can be enhanced, if in the early Universe the amplitude of density fluctuations was much larger, than in the period of galaxy formation. Another possibility corresponds to much softer equation of state, corresponding to matter dominated stage with $\gamma = 0$.

Therefore PBH origin represents strong deviation from the Standard cosmological scenario. It may be related with early matter dominated stages, phase transitions in the early Universe or non-flat features in the spectrum of primordial density fluctuations. All these phenomena can be originated from BSM physics.

PBHs with mass $M \leq 10^{15}$ g evaporate by the mechanism of Hawking [12,13]. This process is the universal process of production of any type of particles with mass

$$m \leq T_{evap} \approx 10^{13}\,\mathrm{GeV}\frac{1\,\mathrm{g}}{M}.$$

It can be the source of superweakly interacting particles, like gravitino [14] as well as of fluxes of particles with energy much larger, than the thermal energy of particles in the surrounding medium. It causes non equilibrium processes in the hot Big Bang Universe, nonequilibrium cosmological nucleosynthesis [15], in particular.

PBHs with mass $M \geq 10^{15}$ g should survive to the present time and represent a specific form of dark matter. The existing constraints on PBH contribution into the total density [17] seem to exclude PBH dominance in the dark matter density. However, as it was noticed in [16], PBH formation in clusters can strongly influence these constraints and even the possibility of PBH dominant dark matter is not excluded. It would make primordial nonhomogeneities in the form of PBHs the dominant matter content of the modern nonhomogeneities.

Mechanism of PBH cluster formation can be illustrated with the use of the axion-like model, in which the first step of symmetry breaking at scale f takes place on the inflationary stage [10,5]. Then at the second stage of the symmetry breaking at $T \sim \Lambda$ closed massive walls are formed so that the larger wall is accompanied by a set of smaller walls. Their collapse form a PBH cluster, in which the range of PBH masses M is determined by the model parameters f and Λ [10,11]

$$f(\frac{m_{pl}}{\Lambda})^2 \leq M \leq \frac{m_{pl}}{f} m_{pl} (\frac{m_{pl}}{\Lambda})^2. \quad (4)$$

Here the minimal mass is determined by the condition that the width of wall doesn't exceed its gravitational radius, while the upper limit comes from the condition that the wall enters horizon, before it starts to dominate within it [11]. At $\Lambda < 100\,\mathrm{MeV}(m_{pl}/f)^{1/2}$ the maximal mass exceeds $100 M_{odot}$. Collapse of massive walls to such black holes takes place at [10]

$$t > \frac{m_{pl}}{f} \frac{m_{pl}}{\Lambda^2}. \quad (5)$$

At $\Lambda < 1\,\mathrm{GeV}$ and $f = 10^{14}\,\mathrm{GeV}$ it happens at $t > 0.1\,\mathrm{s}$, what can lead to interesting observable consequences.

Closed wall collapse leads to primordial gravitational wave (GW) spectrum, estimated as peaked at [1,2,10]

$$\nu_0 = 3 \times 10^{11} (\Lambda/f) \mathrm{Hz}. \quad (6)$$

Their predicted contribution to the total density can reach

$$\Omega_{GW} \approx 10^{-4} (f/m_{pl}), \quad (7)$$

being at $f \sim 10^{14}$ GeV $\Omega_{GW} \approx 10^{-9}$. For $1 < \Lambda < 10^8\,\mathrm{GeV}$ the maximum of the spectrum corresponds to

$$3 \times 10^{-3} < \nu_0 < 3 \times 10^5\,\mathrm{Hz}, \quad (8)$$

being in the range from tens to thousands of Hz a challenge for LIGO/VIRGO grvitational wave searches and at smaller frequencies for future eLISA experiment.

Predictions for Gravitational wave signals from PBH coalescence in cluster involve study of cluster evolution, which appears to be a rather nontrivial problem [16] and strongly depends on the period, when cluster separates from the general expansion. If such separation takes place on the RD stage, cluster evolution can lead to rapid coalescence of PBHs within the cluster, accompanied with evaporation of some of PBHs. Separation of cluster on MD stage would lead to much slower evolution of the gravitationally bound system of PBHs, in which formation of binaries of BH (BBH) and their coalescence would lead to observable effects in gravitational wave (GW) detectors.

Being in cluster, PBHs with the masses of tens $M_{\odot}$ form binaries much easier, than in the case of their random distribution, as well as formation of such PBHs in collapse of first stars is rather problematic. In this aspect detection of signals from binary BH coalescence in the gravitational wave experiments [18–22] may be considered as a positive evidence for this scenario [1,2,10]. Repeatedly detected signals localized in the same place would provide successive support in its favor or exclusion [1,2,10,16,23]. The existing statistics is evidently not sufficient to make any definite conclusion on this possibility. However, repeating detection of four GW signals in the August of 2017 noted in GWTC catalog [24] may be an interesting hint to such a possibility [1,2,10].

Primordial black holes reflect strong inhomogeneity of the energy density in very early Universe. Their production is not a necessary consequence of all the models of very early Universe and this model dependence provides a very sensitive probe for BSM physics. On the other hand, the confirmation of PBH existence will not only tighten the class of possible realistic BSM physics models, but will be an inevitable evidence for BSM cosmology.

The same is true for the existence of antimatter objects in baryon asymmetric Universe, which can reflect strong nonhomogeneity of the baryosynthesis.

3.2. Antimatter and Baryon Asymmetry

The baryon asymmetry of the Universe reflects the evident dominance of matter over antimatter in the visible part of the Universe. The set of astrophysical data exclude completely equal amounts of matter and antimatter, however large is the separation of matter and antimatter domains within the observed part of the Universe. Indeed, at the border of such domains annihilation of nuclei and antinuclei should lead to gamma radiation, which is severely constrained by the observed gamma ray background.

However, these constraints still don't exclude completely the existence of antimatter objects, which can be formed in antimatter domains in baryon asymmetric Universe originated from the strongly nonhomogeneous baryosynthesis [25–31] (see [11,4,30] for review and references).

If created, antimatter domains should survive in the surrounding matter to the present time. It puts a lower limit on its size being in terms of its mass about $10^3 M_{odot}$ [27–29] that corresponds to a minimal mass of globular clusters. If antimatter object is formed in our Galaxy, it should be the source of cosmic ray antinuclei.

There are two principal possibilities for an antimatter object in our Galaxy.

The approach of [26,30–32] predicts compact dense objects with exotic properties, being dominantly the source of heavy antinuclei.

In the approach of [27–29] antimatter forms an antimatter globular cluster, whose structure and evolution is similar to the globular cluster of matter stars.

However exotic, the hypothesis on antimatter globular cluster in our Galaxy [27] doesn't contradict observations, if the mass of the cluster doesn't exceed the limit

$$M \leq 10^5 M_{odot}. \tag{9}$$

Indeed, globular clusters belong to an old population of the Galaxy. They are dominantly situated in halo, where matter gas density is low. Their gravitational potentials are not sufficient to hold matter, lost by stars by stellar winds or supernova explosions.

In the case of antimatter cluster, it means that there is no antimatter gas within it and matter gas that enters the cluster annihilates only on the surface of antimatter stars. Taking into account low density of matter gas in halo and relatively small surface on which it can annihilate, one can find with surprise that antimatter globular cluster should be a rather faint gamma ray source. The upper limit (9) follows from the condition that the antimatter lost by antimatter stars and polluting the Galaxy doesn't cause overproduction of gamma ray background from annihilation with the matter gas [27–29].

It was noted in [27–29] that cosmic antihelium flux may be a profound signature for an antimatter globular cluster in our Galaxy. Symmetry in physics of matter and antimatter would make antihelium-4 the second by abundance element of antimatter. In addition to antihelium lost by antimatter stars its cosmic fluxes can increase due to destruction of heavier antinuclei in their annihilation with matter. Rough estimation of the expected antihelium flux as simply proportional to the ratio of the mass of antimatter cluster to the total mass of the Galaxy predicts that it should be within the reach by AMS02 experiment to 2024.

This prospect makes necessary to specify the predictions for the cosmic antihelium flux in more details and such analysis can be based on our knowledge of properties of globular clusters. The nontrivial problem, which arises in this case, is the prediction for the spectrum of cosmic ray flux originated from a single (antimatter GC) source, as well as proper treatment of formation of this flux and of its propagation in the Galaxy.

There is some evidence for possible detection of cosmic antihelium-3 nuclei as well as for some detected events that may correspond to antihelium-4 in AMS02 experiment. Such events can hardly find natural astrophysical explanation [33] and their confirmation would provide a strong evidence for existence of macroscopic forms of antimatter in our Galaxy.

4. From WIMP miracle to Dark Matter reality

4.1 WIMP miracle and beyond

According to the now standard cosmological model, the dark matter, corresponding to $\sim 25\%$ of the total cosmological density, is a new stable form of nonbaryonic matter (see, e.g. Refs. [34–39] for review and reference). To support development of gravitational instability from small initial density fluctuations, dark matter should decouple from plasma and radiation at least before the beginning of matter dominated stage. To satisfy these conditions, one can assume some neutral sufficiently weakly interacting form of nonrelativistic matter. Here sufficiently weak interaction should be considered in the cosmological sense. It should provide decoupling of dark matter and in the conditions of a low density cosmological plasma even nuclear strong interaction cannot prevent decoupling from plasma and radiation.

During the last three decades Weakly Interacting Massive Particle (WIMP, see for details, e.g. Refs. [34,35,39]) were most popular dark matter candidate owing to its *miraculous* feature: if the mass of this particle is in the 100 GeV - 1 TeV range, freezing out of primordial gas of these particles in early Universe naturally leads to prediction of their modern density, explaining the dark matter.

The WIMP miracle was accompanied by the expectations of new physics phenomena to be found at the LHC in this energy range. Such expectations were dominantly related with necessity to explain the origin of the electroweak symmetry breaking scale and to solve the problem of divergence of the Higgs boson mass. Supersymmetry (SUSY) with the scale about 100 GeV - 1 could naturally provide solution for these problems and predicted existence of supersymmetric partners of known particles with the mass, corresponding to this scale. accessible for their search at the LHC. The lightest SUSY particle could be stable,neutral and have the interaction cross section, typical for WIMPs.

SUSY WIMPs should 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 (see for review e.g. [40]).

Production of WIMPS in collisions of ordinary particles 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 the LHC. WIMPs of the supersymmetric origin were expected to be associated with the Lightest Supersymmetric particle (LSP) and their production at the LHC should have been accompanied by discovery of the supersymmetric partners of ordinary particles.

However, in the lack of positive evidence for SUSY at the LHC and controversial results of WIMP searches in the underground detectors a particle physics solution for the dark matter problem can involve much wider class of models.

The list of dark matter candidates in these models extends to both strongly and superweakly interacting particles with masses ranging from super low to super high energy scales. Their list involves: axions and axion-like particles, sterile neutrinos, new stable hadrons, mirror particles and many other examples of new forms of matter, whose stability is supported by extension of SM symmetry (see, e.g. [39] for review and references). Dark matter candidates can be macroscopic, like PBH dark matter [16]. These candidates are elusive for direct or indirect methods of WIMP searches. It implies more nontrivial methods to study their properties, which involve all the possible aspects of dark matter physics.

In the case of SUSY scale, which is too high for direct experimental search, its cosmological impact provides important indirect probes, in which effects of supersymmetric partner of graviton, gravitino, are of special interest [41]. Gravitinos are expected to be present in all local supersymmetric models. If gravitino is not LSS, it is *metastable* and at the mass of few TeV decays after nucleosynthesis. It leads to important modifications of the nucleosynthesis paradigm. High energy products of gravitino decays interact with nuclei of the primordial plasma and give rise to cascades of nonequilibrium nuclear processes. In particular, the antiprotons produced by the fragmentation of gluons emitted by decaying gravitinos are a source of nonequilibrium light nuclei resulting from collisions of those antiprotons on equilibrium nuclei [42–45, 15]. Then, ^{6}Li, ^{7}Li and ^{7}Be nuclei are produced by the interactions of the non-equilibrium nuclear flux with ^{4}He equilibrium nuclei. To compare these predictions with the observational data on the light element abundance the precise information on the particle and nuclear interactions with nuclei is needed. Therefore this approach, supported by its successive development [46, 47], reveals the importance of obtaining these nuclear data as the completion of the missed link in the logical chain, by which cosmological consequences of particle theory are related to their astrophysical probes.

In the extreme case Supersymmetry energy scale may be very high and superweakly interacting superheavy gravitino can become a viable candidate for dark matter (see, e.g. [4] for review and references). The corresponding Supergavity can provide physical framework for unification of all the four fundamental forces of Nature, including gravity, as well as the physical basis for Starobinsky inflation, but in this case the supersymmetry loses a possibility to solve the problems of divergence of Higgs boson mass and of the origin of the electroweak symmetry breaking scale.

4.2 Cosmoparticle physics of composite dark matter

Direct searches for dark matter give puzzling results. The dark matter signal detected by DAMA collaboration at high significance level is not confirmed by other experiments that differ by strategy of searches and the content of detectors. A review of the current experimental situation may be found in [48]. This apparent contradiction comes from the analysis of the data in the terms of WIMPs and under the assumption that nuclear recoils are the source of the signal in DAMA detector.

Starting from 2006 it was proposed [39, 40, 49–51] that the signal may be due to a different source: if dark matter can bind to normal matter, the observations could come from radiative capture of thermalized dark matter, and could depend on the detector composition and temperature. This scenario naturally comes from the consideration of composite dark matter. Indeed, one can imagine that dark matter is the result of the existence of heavy negatively charged particles that bind to primordial nuclei.

New particles with electric charge and/or strong interaction can form anomalous atoms and be present in the ordinary matter as anomalous isotopes. Therefore, stringent upper limits on anomalous isotopes, especially, on anomalous hydrogen put severe constraints on the existence of new stable charged particles. In order to avoid anomalous isotopes overproduction, stable particles with charge ± 1 (and corresponding antiparticles), as well as with the odd charge $\pm(2n-1)$ (where n is integer) should be absent, so that stable negatively charged particles should have even charge $-2n$ only.

Indeed, positively charged particles form atoms of anomalous isotopes with ordinary electrons, while negatively charged particles with even charge $-(2n-1)$ can capture n nuclei of primordial helium after Big Bang Nucleosynthesis and form $+1$ charged ion. Particles with even negative charge $-2n$, created in excess over their antiparticles, bind with n nuclei of primordial helium in neutral strongly interacting dark atoms.

Elementary particle frames for heavy stable $-2n$ charged species are provided by several models (see e.g. [39] for review and references). There are principally two types of such species:

(a) They have no QCD interaction, i.e. are lepton like particles with no fixed absolute value of the charge, which is constrained only by the condition of the absence of anomalies [1, 10, 39, 40, 50].
(b) They are $\bar{\Delta}$ like $(\bar{U}\bar{U}\bar{U})$ clusters of new stable heavy $\bar{U}$ (anti)quarks with strongly suppressed hadronic interaction [39, 40, 49, 51].

In the models (a) any value of $-2n$ charge is possible, while only double charged O^{--} are predicted in models (b).

The models (a) draw special attention due to their possible relationship with composite Higgs models, proposed as the solutions for the SM problems of divergence of Higgs boson mass and origin of electroweak symmetry breaking scale. In such models, like in Walking Technicolor model (see, e.g. [1, 10, 50], the constituents of composite Higgs are linked existence of exotic multiple-charged particles and in the context of dark atom model search for such particles acquires the meaning of experimental probe for physics of Dark Universe.

Just after Big Bang Nucleosynthesis, when primordial helium is produced, these particles are bound with helium nuclei. In the case (a) at $n > 1$ particles with charge $-2n$ bind with n helium nuclei in X-helium Thompson-like atoms. In the case (b) all the O^{--} are bound with helium nuclei in a Bohr atom-like O-helium state, in which heavy lepton-like negatively charged core is surrounded by a nuclear interacting helium shell.

Dark atoms can play the role of dark matter and explain the observed dark matter density. Specifics of their nuclear interaction can explain positive results of DAMA/NaI and DAMA/LIBRA experiments and negative results of other groups [1,10]. Collisions of dark atoms in the center of Galaxy can lead to their excitation with successive de-excitation by emission of electron-positron pairs. It can explain the observed excess in positronium annihilation line in the galactic bulge [1,57]. Such explanation is possible only for a limited range of mass of dark atom constituents. In the case of O^{--} this mass is in a narrow window around 1.3 TeV, challenging verification of this hypothesis in searches for stable double charged particles at the LHC.

O-helium, being an α-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 dark atoms in Big Bang Nucleosynthesis and in stellar evolution. Their constituents can form exotic isotopes and components of cosmic rays. These effects need a special detailed and complicated study of dark atom nuclear physics [10,58].

Combination of physical, astrophysical and cosmological effects of dark atoms illustrates methods of cosmoparticle physics of Dark Universe.

4. Conclusion

The convergence of the frontiers of our knowledge in micro- and macro worlds leads to the following wrong circle of problems: *The theory of the Universe is based on the predictions of particle theory, that need cosmology for their test.* Cosmoparticle physics [34,35,59,60] 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.

The important aspects of this relationship arise in the problem of physics of Dark Universe, which involves BSM particle models and is inevitably associated with observable features, beyond the now standard cosmological paradigm.

Here we have concentrated on the extension of the SM of electroweak and strong interactions of elementary particles. However, BSM physics can hardly avoid modification of the general relativistic description of gravity. Such modifications may be related with extra dimensions of space-time or additional types of space-time symmetries, leading to new types of gravitational phenomena, reflected in astrophysical objects (see [61–66]).

To conclude, even a brief sketch of possible links of cosmology and particle physics shows how large may be the field of such studies. Our voyage to the physics and cosmology of Dark Universe involved nontrivial features of new physics like Primordial black holes, antimatter stars or dark atoms. It was aimed to give some

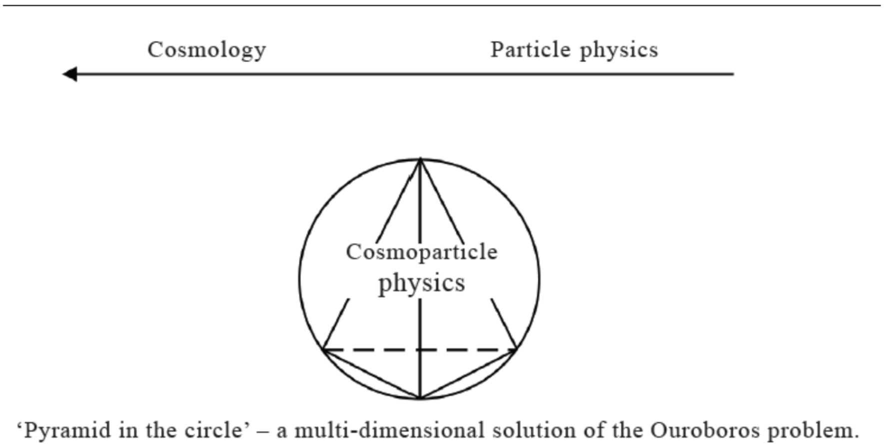

Fig. 1 Cosmoparticle physics provides nontrivial solution for the Ouroboros puzzle

flavor of methods of cosmoparticle physics, appealing to extensive and through investigation of nontrivial aspects of the links that follow from fundamental relationship of micro- and macro-worlds.

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References

1. M.Yu. Khlopov, *Int. J. Mod. Phys. D* **28** (2) (019) 1941012.
2. M. Khlopov, *Bled Workshops in Physics* **20** (2) (019) 21.
3. M. Khlopov, *Res. Rev.: J. Pure and Appl. Phys.* **3** (2015) 9.
4. S. Ketov and M.Yu. Khlopov, *Symmetry* **11** (2019) 511 .
5. M.Y. Khlopov, *Res. Astron. Astrophys* **10** (2010) 495.
6. Y.B. Zeldovich and I.D. Novikov, *Sov. Astron.* **10** (1967) 602.
7. S.W. Hawking, *Mon. Not. R. Astron. Soc.* **152** (1971) 75.
8. B.J. Carr and S.W. Hawking, *Mon. Not. R. Astron. Soc.* **168** (1974) 399.
9. B.J. Carr, *Astroph. J.* **201** (1975) 1.
10. M. Khlopov, *EPJ Web of Conferences* **222** (2019) 01006.
11. M.Y. Khlopov and S.G. Rubin, *Cosmological Pattern of Microphysics in Inflationary Universe* (Springer Science Business Media: Kluwer, Dordrecht, The Netherlands, 2004).
12. S.W. Hawking, *Comm. Math. Phys.* **43** (1975) 199.
13. S.W. Hawking, *Nature* **248** (1974) 30.
14. M.Y. Khlopov, A. Barrau and J. Grain, *Class. Quantum Gravit.* **23** (2006) 1875.
15. E.V. Sedel'nikov, S.S. Filippov and M.Y. Khlopov, *Phys. Atom. Nucl.* **58** (1995) 235.
16. K.M. Belotsky, V.I. Dokuchaev, Yu.N. Eroshenko, E.A. Esipova, M.Yu. Khlopov, L.A. Khromykh, A.A. Kirillov, V.V. Nikulin, S.G. Rubin and I.V. Svadkovsky, *Eur. Phys. J. C* **79** (2019) 246.
17. B. Carr, F. Kuehnel and M. Sandstad, *Phys. Rev. D* **94** (2016) 083504.
18. B.P. Abbott et al., *Phys. Rev. Lett.* **116** (2016) 061102.
19. B.P. Abbott et al., *Phys. Rev. Lett.* **116** (2016) 241103.

20. B.P. Abbott et al., *Phys. Rev. Lett.* **118** (2017) 221101.
21. B.P. Abbott et al., *Phys. Rev. Lett.* **119** (2017) 141101.
22. B.P. Abbott et al., *Astrophys. J. Lett.* **851** (2017) L35.
23. T. Bringmann, P.F. Depta, V. Domcke and K. Schmidt-Hoberg, *Phys. Rev. D* **99** (2019) 063532.
24. The LIGO Scientific Collaboration (The Virgo Collaboration), B.P. Abbott et al., arXiv:1811.12907 (2018).
25. V.M. Chechetkin, M.Y. Khlopov, M.G. Sapozhnikov and Y.B. Zeldovich, *Phys. Lett. B* **118** (1982) 329.
26. A. Dolgov and J. Silk, *Phys. Rev. D* **47** (1993) 4244.
27. M.Y. Khlopov, *Gravit. Cosmol.* **4** (1998) 69.
28. K.M. Belotsky, Y.A. Golubkov, M.Y. Khlopov, R.V. Konoplich and A.S. Sakharov, *Phys. Atom. Nucl.* **63** (2000) 233.
29. M.Y. Khlopov, S.G. Rubin and A.S. Sakharov, *Phys. Rev. D* **62** (2000) 083505.
30. A.D. Dolgov, *Nucl. Phys. Proc. Suppl.* **113** (2002) 40.
31. A.D. Dolgov, M. Kawasaki and N. Kevlishvili, *Nucl. Phys. B* **807** (2009) 229.
32. S.I. Blinnikov, A.D. Dolgov and K.A. Postnov, *Phys. Rev. D* **92** (2015) 023516.
33. V. Poulin, P. Salati, I. Cholis, M. Kamionkowski and J. Silk, *Phys. Rev. D* **99** (2019) 023016.
34. M. Yu. Khlopov, *Cosmoparticle physics* (World Scientific, New York-London-Hong Kong-Singapore, 1999)
35. M. Khlopov, *Fundamentals of Cosmic Particle physics* (CISP-SPRINGER, Cambridge 2012).
36. G. Bertone, *Particle dark matter: Observations, models and searches* (Cambridge Univ. Pr., UK, 2010)
37. E. Aprile and S. Profumo, *New J. of Phys.* **11** (2) (009) 105002.
38. J.L. Feng, *Ann. Rev. Astron. Astrophys.* **48** (2) (010) 495.
39. M.Yu. Khlopov, *Int. J. Mod. Phys. A* **28** (2) (013) 1330042.
40. M.Yu. Khlopov, *Int. J. Mod. Phys. A* **29** (2) (014) 1443002.
41. M.Yu. Khlopov, *Symmetry* **7** (2015) 815.
42. M.Yu. Khlopov and A.D. Linde, *Phys. Lett. B* **138** (1984) 265.
43. F. Balestra, G. Piragino, D.B. Pontecorvo, M.G. Sapozhnikov, I.V. Falomkin and M.Yu. Khlopov, *Sov. J. Nucl. Phys.* **39** (1984) 626.
44. Yu.L. Levitan, I.M. Sobol, M.Yu. Khlopov and V.M. Chechetkin, *Sov. J. Nucl. Phys.* **47** (1988) 109.
45. M.Yu. Khlopov, Yu.L. Levitan, E.V. Sedelnikov and I.M. Sobol, *Phys. Atom. Nucl.* **57** (1994) 1393.
46. K. Jedamzik, *Phys. Rev. D* **70** (2004) 063524.
47. M. Kawasaki, K. Kohri and T. Moroi, *Phys. Lett. B* **625** (2005) 7.
48. R. Bernabei, *Bled Workshops in Physics* **15** (2) (014) 10.
49. M.Yu. Khlopov, *JETP Lett.* **83** (2) (006) 1.
50. M.Y. Khlopov and C. Kouvaris, *Phys. Rev. D* **77** (2) (008) 065002.
51. D. Fargion, M. Khlopov and C.A. Stephan, *Class. Quantum Grav.* **23** (2) (006) 7305.
52. K.M. Belotsky et al., *Gravitation and Cosmology* **11** (2) (005) 3.
53. K. Belotsky, M. Khlopov and K. Shibaev, arXiv:astro-ph/0602261.
54. K. Belotsky, M. Khlopov and K. Shibaev, *Gravitation and Cosmology* **12** (2) (006) 1.
55. K. Belotsky, M.Yu. Khlopov, K.I. Shibaev, Stable quarks of the 4th family? in Eds. N.L. Watson and T.M. Grant: "The Physics of Quarks: New Research." (Horizons in World Physics, Vol. 265), NOVA Publishers, Hauppauge NY, 2009, PP. 19-47; arXiv:0806.1067 [astro-ph].
56. M.Y. Khlopov and C. Kouvaris, *Phys. Rev. D* **78** (2) (008) 065040.
57. J.-R. Cudell, M.Yu. Khlopov and Q. Wallemacq, *Adv. High Energy Phys.* **2014** (2014) 869425.
58. J.-R. Cudell, M.Yu. Khlopov and Q. Wallemacq, *Bled Workshops in Physics* **13** (2) (012) 10.
59. A.D. Sakharov, *Vestnik AN SSSR* **4** (1989) 39.
60. M.Yu. Khlopov, *Vest. Russ. Acad. Sci.* **71** (2001) 1133.
61. G. Abbas, M. Zubair, and G. Mustafa, *Astrophys. Space Sci.* **358** (2015) 26.
62. G. Abbas, A. Kanwal, and M. Zubair, *Astrophys. Space Sci.* **357** (2015) 109.
63. G. Abbas, S. Nazeer and M.A. Meraj, *Astrophys. Space Sci.* **354** (2014) 449.
64. G. Abbas, D. Momeni, M.A. Ali, R. Myrzakulov and S. Qaisar, *Astrophys. Space Sci.* **357** (2015) 158.
65. D. Deb, S. Ghosh, S.K. Maurya, M. Khlopov and S. Ray, *Tech Vistas* **1** (2018) 1.
66. A. Das, S. Ghosh, D. Deb, F. Rahaman and S. Ray, *Nucl. Phys. B* **954** (2020) 114986.
67. S. Nojiri and S.D. Odintsov, *Phys. Lett. B* **631** (2005) 1.