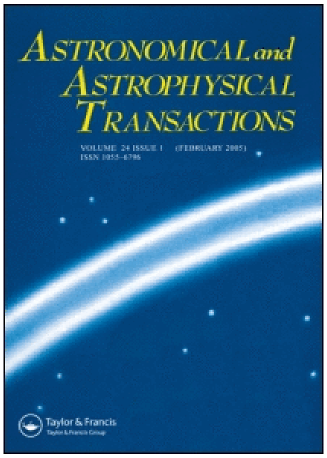

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M. Yu. Khlopov [a]
[a] Centre for Cosmo Particle Physics 'Cosmion' 125047, Moscow, Russia

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COSMOPARTICLE PHYSICS AS THE PHYSICAL BASIS FOR MODERN COSMOLOGY

M. Yu. KHLOPOV

Centre for CosmoParticle Physics 'Cosmion'
125047, Moscow, Russia,
E-mail mkhlopov@orc.ru

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Cosmoparticle physics has appeared as a natural result of the internal development of cosmology, looking for physical grounds for inflation, baryosynthesis and nonbaryonic dark matter, and of particle physics, going beyond the standard model of particle interactions. Its aim is to study the physical basis of modern cosmology in the combination of indirect cosmological, astrophysical and physical effects. The ideas of new particles and fields, predicted by particle theory, and on their cosmological impact are discussed, as well as the methods of cosmoparticle physics to probe these ideas are considered with special analysis of physical mechanisms for inflation, baryosynthesis and nonbaryonic dark matter. These mechanisms are shown to reflect the main principle of modern cosmology, putting instead of formal parameters of cosmological models physical processes governing the evolution of Big Bang Universe. Their realization on the basis of particle theory induces additional model-dependent predictions, accessible to various methods of cosmoparticle physics. The power of these methods is illustrated in the example of a gauge model with broken family symmetry, on which the horizontal unification is based, possessing quantitatively definite physical grounds for inflation, baryosynthesis and effectively multicomponent dark matter scenarios.

KEY WORDS Cosmology, cosmoparticle physics, Big Bang Universe, evolution

1 INTRODUCTION

Modern cosmology is based on two observational facts, namely, that the Universe expands and that the Universe contains the electromagnetic black body background radiation. Putting them together one comes to the ideas of Gamow's Big Bang Universe. Extrapolating, or more precisely interpolating, the law of cosmological expansion to the past, one finds that at much earlier stages of cosmological expansion the energy density of radiation exceeded the matter density, so that the radiation dominated stage should have taken place. One can easily check that matter and radiation were in equilibrium, that there were no galaxies or stars, but that matter was in the form of a nearly homogeneous plasma. Gamow's Big Bang scenario was a self-consistent combination of general relativity, thermodynamics and laws of atomic and nuclear physics, which have been well proven in laboratories, successively applied to the evolution of the Universe as a whole, under the assumption that only baryonic matter and electromagnetic radiation (and neutrinos) make up its content (Zeldovich and Novikov, 1975). According to Gamow's scenario, in the first three minutes nuclear reactions should have taken place, leading to the primordial chemical composition. This picture found qualitative confirmation in the comparison of predictions of Big Bang nucleosynthesis with the observed light element abundance (see references in Schramm and Copi (1996) for a review). It gave a qualitative explanation to the observed structure of inhomogeneities as a result of the gravitational instability in nearly homogeneous matter. However, quantitative disagreements which turned to be more and more profound made the whole picture controversial, unless some additional fundamental elements are added to the basis of the whole construction. The physical nature of these additional cosmological phenomena was related to the new physics, predicted by particle theory.

Gamow's picture seemed to be well supported from the side of physics of the known elementary particles. Hundreds of particles, discovered in accelerators, – all these numerous baryons, mesons and resonances – are unstable, which makes their cosmological significance elusive. Only stable and very long-living metastable particles can play a cosmological role. That is why the list of particles important for cosmology was reduced to the electron, nucleon, neutrinos and photon.

Modern particle theory assumes an underlying symmetry between particles. If the symmetry is strict, following Noether's theorem it corresponds to the existence of strictly conserved charge. The lightest particle having such a charge should be stable. If the symmetry is not strict, the charge is not strictly conserved and the particle is unstable. Thus the existence of stable particles, which are of cosmological importance, reflects the fundamental symmetry of the microworld.

The standard model of particle interactions is based on the $SU(2) \times U(1)$ local gauge symmetry of the electroweak interaction and the $SU(3)_c$ symmetry of quantum chromodynamics (QCD, the gauge theory of strong interactions). Electric charge is strictly conserved in this model and baryon charge is approximately conserved with very high precision. That is why the lightest charged particle (electron) and the lightest baryon (proton) are sufficiently stable to be of cosmological importance.

At present the standard model does not find any direct contradiction with the experimental data. But the internal theoretical inconsistencies and aesthetic challenges to unify all the fundamental forces of Nature makes theory want to go beyond the standard model. It implies new symmetries, corresponding to new strictly or approximately conserved charges, which results in the prediction of new cosmologically important phenomena. In this way particle theory loses the possibilities of direct experimental proofs. It considers the Big Bang Universe as a natural source of information on the possible particle properties. On the other hand, modern cosmology is based on the physical mechanisms, implying the experimentally unproven predictions of particle theory. The resolution of the wrong circle of problems, following from this mutual relationship between cosmology and particle physics, is related with cosmoparticle physics, which is the subject of the present paper.

2 EXTENSIONS OF GAMOW'S BIG BANG MODEL

The principal questions: why does the Universe expand? why were its initial conditions so close to a flat Universe? why were they so similar in causally disconnected regions? why does it contains matter and no antimatter? had no fundamental answers in the Gamow's cosmological picture.

The first three questions found a basic solution in inflationary cosmological models (Guth, 1981), assuming the existence of a stage of superluminous (in the simplest case exponential) expansion in the very early Universe. Such a stage cannot be provided by matter, radiation or relativistic plasma dominancy, but can be realized under some conditions as a cosmological consequence of particle theory, for example in a strong first-order phase transition or by the slow rolling down of a scalar field to its true vacuum state. Most of these effects are related to experimentally inaccessible parts of particle theory, in particular, to the mechanisms of symmetry breaking at superhigh energy scales. One can also find, that different inflationary models follow from different theoretical grounds and in general may coexist in the complete cosmological scenario.

A. Sakharov (1967) and then V. Kuzmin (1970) were the first people, who related the observed baryon asymmetry of the Universe to the generation of baryon excess due to out-of-equilibrium CP violating effects in hypothetical baryon nonconserving processes at very early stages of the initially baryon symmetric Universe. Grand unified models have provided a physical basis for these original ideas of baryogenesis, having the existence of baryon non-conserving interactions among their predictions. The mechanisms of baryosynthesis then found some other grounds in supersymmetric models, where a primordial condensate of scalar quarks is possible, resulting in baryon excess after scalar quarks decay into ordinary quarks, and even in the standard model, leading to baryon non-conservation at very high temperatures, provided that it is extended by a larger Higgs sector and/or by inclusion of lepton number violating processes, related to neutrino Majorna mass generation mechanism.

The necessity to extend Gamow's picture also followed from the quantitative inconsistency of the theory of large scale structure formation. Namely, the level of initial fluctuations, needed in Gamow's Big Bang scenario to provide the formation of the observed large scale structure of the Universe, turned to correspond to an expected effect in anisotropy of thermal electromagnetic background which is inconsistent with the observed level of its isotropy. On the other hand, the low baryonic density one needs to reproduce the observed light element abundance as a result of Big Bang nucleosynthesis (Schramm and Copi, 1996) was inconsistent with the much higher density one needs to provide the formation of the large scale structure as a result of the development of gravitational instability in the matter-dominated stage.

Both problems seemed to find a laboratory based solution within the old Big Bang scenario when in 1980 it was claimed, that the electron neutrino has a mass of about 30 eV. A neutrino thermal background as abundant as the thermal photon background was one of the stable predictions of the old Big Bang scenario. Multiplying this abundance by the mass of neutrino, claimed to be measured in the ITEP experiment, one found that the modern density of massive neutrinos should exceed the density of the baryonic matter by one to two orders of magnitude. One came to the scenario of a neutrino dominated Universe, in which massive neutrinos, weakly interacting with the matter and radiation, has driven the cosmological large scale structure formation with thermal background radiation anisotropy consistent with the observational data and dominate in the modern cosmological density. But successive experimental studies did not confirm the indication of the mass of the electron neutrino as high as it was claimed, and cosmological analysis, proving the necessity for dark matter, dominating in the Universe in the period of large scale structure formation, found serious problems in the neutrino dominated Universe scenario. It lead the physics of dark matter beyond the experimentally proven standard model of elementary particles. This made it necessary to modify the old Big Bang scenario by an additional fundamental element – dark matter, finding physical grounds for it in the hidden sector of particle theory. The problem of the true physical nature of the cosmological dark matter is accomplished by the fact, that however different from the cosmological viewpoint are the models of large scale structure formation by hot, cold, unstable dark matter, or more sophisticated models, implying cosmic strings plus hot dark matter, late phase transitions etc, they are not alternatives from the viewpoint of particle physics, having grounds in different and in general complementary parts of the hidden sector of particle theory. So, in principle, the mixture of all of them should be considered as the general case.

Another important initial condition for large scale structure formation is the spectrum of initial fluctuations. It could be easily checked that statistical fluctuations only cannot grow to form the structure of inhomogeneities in the expanding Universe. One has to assume the existence of small initial inhomogeneities, which originated in the very early stages of cosmological evolution. The old Big Bang scenario had no physical mechanism for their origin. The physical mechanisms for generation of the spectrum of initial fluctuations found their basis in the framework of inflationary models.

So the modern cosmological paradigm reflects the fundamental change in our understanding of what Big Bang cosmology is. From the self-consistent but basically controversial and incomplete old Big Bang scenario we come to the picture of inflationary cosmology with baryosynthesis and (multicomponent?) nonbaryonic dark matter. Thus, directly or indirectly, the old Big Bang theory is supplemented in the modern standard Big Bang Universe by at least three necessary elements (inflation, baryosynthesis and non-baryonic dark matter), based on the physical laws, predicted by particle theory but having no experimental proofs. There is a wide variety of different physical mechanisms for inflation and baryosynthesis and various candidates for the role of dark matter particles and, since both the early Universe, when inflation and baryosynthesis should have taken place, and dark matter cannot be observed directly by astronomical means, one should elaborate the system of indirect means to make the proper choice between these variants corresponding to various cosmological scenarios and particle models underlying them.

The problem is that the space of cosmological and physical parameters is, in general, multidimensional, since physical grounds for different mechanisms of inflation, baryosynthesis and different candidates for dark matter follow from different physical motivations and are not in general alternative but complementary. On the other hand, cosmological tests for particle models should, in general, account both for the particular realization of inflation, baryosynthesis and dark matter and for the additional modifications of cosmological scenarios corresponding to the chosen realization.

Cosmoarcheology, searching in the astrophysical data for the footprints of new physical phenomena in the Universe, may be viewed as already existing branch of proper CosmoParticle Physics (Sakharov, 1989; Khlopov, 1989, 1996, 1999), in which all its components are mixed up in a nontrivial manner, resulting in a set of astrophysical probes for the existence and possible properties of hypothetical particles, fields, objects and phenomena predicted as cosmological consequences of particle theory. Cosmoarcheology treats the Universe as an unique natural accelerator laboratory, so that the astrophysical data play here the role of specific experimental sample in *Gedanken Experiments*, Cosmoarcheology undertakes. As in any experiment, to achieve a meaningful result one should have a precise understanding of the experimental device used, as well as to develop methods of data sampling and analysis. The problem is that in the Universal particle laboratory both the source and detectors are out of control. Astrophysical processes cannot be directly reproduced in laboratories, but however complicated the combination of effects is, theoretical astrophysics uses, as a rule, in its analysis natural laws, proven in experiment. The trouble is, that in the theoretical treatment of the Universe and its evolution the basic physical laws are not known. It makes a self-consistent formulation of cosmoarcheological approach to be, in general, model-dependent. One should account for the relationship between the hypothetical particle or field, probed by the astrophysical data, and the physics, underlying inflation, baryosynthesis and nonbaryonic dark matter. And, since the latter is model-dependent, one should consider cosmological consequences of the considered hypothesis referred to the picture of cosmological evolution, based on the chosen particle model, underlying these necessary elements of the modern cosmology. It means that the cosmological trace of hypothetical particle or field may be multi-step, following the nontrivial cosmological path, the model implies. On the other hand, one should expect, provided that inflationary baryon asymmetrical cosmology with nonbaryonic dark matter is really the proper basis of the Universe, the real picture of its evolution *should* be much more complicated, than Gamow's original Big Bang Universe scenario, and generally more sophisticated, than the simple addition of inflation, baryosynthesis and nonbaryonic dark matter dominance to the Big Bang scenario. The reason is that any physically reasonable theoretical framework, giving rise to the necessary elements of cosmology, is generally much more extensive, supplementing these elements by a number of additional cosmologically relevant details. Testing these details, cosmoarcheology extends the power of observational cosmology relating the true theory of the Universe to observations.

3 EXTENSIONS OF THE STANDARD MODEL OF ELEMENTARY PARTICLES

The practical theoretical necessity of extending the standard model of elementary particles follows from such internal problems of the standard model as the quadratic divergence of loop radiative corrections to the mass of Higgs field or strong CP violation in QCD. The solution of the former problem implies supersymmetry – symmetry between bosons and fermions, giving rise to the cancellation of boson and fermion loop contributions into the Higgs mass due to the difference in Bose–Einstem and Fermi–Dirac statistics. Supersymmetry should be broken, since we do not observe it in fermion and boson mass spectra, and the search for supersymmetric partners of known particles is one of the strongest challenges for the next generation of particle accelerators. But there is no hope to search for the gravitino (the supersymmetric partner of the graviton), predicted in local supersymmetric models, even in accelerators of the far future, due to its very weak, semigravitational coupling to other particles. The solution of the problem of strong CP violation in QCD implies the existence of an invisible axion, pseudoGoldstone boson, the 'smaller brother' of π^0, with superweak interaction, being very elusive for a direct search in accelerators.

The aesthetic motivation to extend the standard model is an attractive idea of unification of the fundamental forces. The similarity in description of the electromagnetic, weak and strong interactions, achieved in the standard model, finds deeper grounds in grand unified theories (GUT), extending the fundamental gauge symmetry and putting the $\mathrm{SU}(2) \times \mathrm{U}(1) \times \mathrm{SU}(3)_c$ group of symmetry of the standard model into a unique group G. Arranging the set of known particles into the representation of the group G, one finds 'white spots' to be occupied to make the representation complete. The larger is G the greater is the number of new particles and fields, which should be introduced to complete the basic particle and field content to the set corresponding to the full symmetry. Such particles and fields correspond to the 'hidden sector' of the respective theory, since they are hidden from the direct experimental probes either due to their large mass or owing to a very weak interaction with the known particles. In the both cases (of weakly interacting and of superheavy particles) one needs some indirect means to test the respective predictions. The same is true for the parts of hidden sector, such as 'invisible axion', gravitino etc invoked due to practical needs to make the standard model self-consistent.

There are a very few indirect effects of superheavy and/or superweakly interacting particles and fields, feasible for laboratory probes. They are the mass of neutrino, CP violation, lepton and baryon number nonconservation (reflected in neutrino oscillations, double neutrinoless beta decay, flavour changing neutral currents, proton decay, neutron–antineutron and hydrogen–antihydrogen oscillations). However rare, these effects may be discriminated due to the manifest violation of conservation laws, held in the standard model. Relatively small amount of such effects appeals for additional probes of hidden sector of particle theory.

The problem of the proper choice for the extensive hidden sector turns to increase in the models of theory of everything (TOE), putting into a unique theoretical framework the foundations for all the four fundamental natural forces, including gravity. Such a framework may follow from successive extension of gauge symmetry, say, from the combination of local gauge models and supersymmetry, as occurs in supergravity. Here unification follows from the extension of internal symmetries to the symmetries of space-time. The alternative approach is based on the extension of the geometry of space-time to include the description of particle interactions. The geometrical approach ascribes fundamental forces to effects of additional compactified dimensions and extends symmetries of space-time to include symmetries of elementary particles. Both trends are incorporated in superstring theories on the basis of fundamentally new fundamental concepts of string theories. In the heterotic string theory one combines the $d = 10$ heterotic string theory with $\mathrm{E}_8 \times \mathrm{E}'_8$ gauge symmetry. So its hidden sector should contain, in principle, all the zoo of particles, fields and new phenomena, arising in various extensions of the standard model, a direct experimental search for which is either very hard or impossible in principle.

That is why the Universe as the possible source of information on elementary particles has drawn the most serious attention of particle physicists. Ya. Zeldovich called the Universe a 'poor man's accelerator', but, as A. Linde followed, even the richest man cannot build an accelerator, reaching GUT or TOE physics, to be naturally released at the earliest stages of cosmological evolution. So the internal development of particle physics has lead its theory to the Big Bang Universe probing its fundamental ideas.

4 TRACERS FOR THE PHYSICS OF THE VERY EARLY UNIVERSE

Assuming that the inflationary baryon asymmetrical cosmology with nonbaryonic dark matter is closer to reality than Gamow's original Big Bang scenario, one should face the problem of observational evidence, specifying the choice for the inflationary model, the mechanism of baryosynthesis and for the proper form of nonbaryonic dark matter. In cosmoarheology it is the problem of the specification of the Universe as a natural accelerator.

4.1 Tracers for the Mechanisms of Inflation

One considers inflation as a necessary element of the cosmological picture. Inflationary models explain why the Universe expands. They provide a solution for the horizon, flatness, magnetic monopole etc problems (Guth, 1981; see review in Khlopov, 1999). The solution is based on superluminous expansion, which occurs for the equation of state $p < -1/3\varepsilon$. Neither matter, nor radiation dominance can provide such an equation of state. One needs some hypothetical phenomena to occur in the very early Universe, inducing an unstable negative pressure stage of cosmological evolution. Such hypothetical processes may be related to R^2 effects in gravity, to strong first-order phase transitions, or to the slow rolling down of the effective potential to the true vacuum state. To make the proper choice between these possibilities, or, at least, to make some reduction in their wide variety, additional tracers of the inflationary mechanism should be considered.

- Fluctuations in the inflationary stage induce the spectrum of initial density fluctuation, giving rise to galaxy and large scale structure formation in respective scales. The amplitude of these fluctuations is constrained by the observed isotropy of the thermal electromagnetic background. It rules out all the inflationary models with a high amplitude of predicted fluctuations, in particular most of the GUT induced phase transition scenarios. In the simplest models with quasi-De Sitter close to the $p = -\varepsilon$ equation of state phase a flat Harrison–Zeldovich form of the spectrum is predicted. Then the estimated amplitude of initial fluctuations at the modern LSS scale provides some information on the possible inflaton properties, i.e. on the form and parameters of the scalar field potential.

- For more complicated inflationary models, i.e. multicomponent inflation, the form of the predicted spectrum of fluctuations may differ from a simple flat one. Phase transitions in the inflationary stage lead to specific peaks or plateaus in the spectrum with the position and amplitude defined by the parameters of the model. One should also account of phase transitions after the global inflational stage, in which the initial spectrum may be modified.

- Both in R^2 and scalar field driven (i.e. chaotic) inflationary scenarios a long dust-like post-inflationary stage appears, induced by coherent inflation field oscillations. The duration of such stages defines the maximal temperature of the Universe after reheating, when the radiation domination stage starts. It also defines the specific entropy of the Universe after re-heating.

- Initial density fluctuations grow in a post-inflationary dust-like stage, following the general law of development of a gravitational instability in the matter-dominated stage in an expanding Universe $\delta\rho/\rho \sim t^{2/3}$. If the ratio of cosmological timescales, corresponding to the end, t_1, and the beginning, t_0, of the dust-like stage exceeds $\delta^{-3/2}$, where δ is the amplitude of fluctuations, in the respective scale an inhomogeneity is formed. The evolution of such inhomogeneities may lead to primordial black hole (PBH) formation. The spectrum of PBHs reflects the scales, at which inhomogeneities are formed as well as the mechanism of PBH formation. The minimal probability $W_{\rm PBH}$ of PBH formation is $\sim \delta^{3/2}$, estimated for direct formation of PBHs in contraction of a very small fraction of configurations, evolved from specifically isotropic and homogeneous fluctuations. The account of PBH formation as a result of evolution of the bulk of inhomogeneities strongly increases the amount of expected PBHs.

- Peaks in the spectrum of density fluctuations, produced at the inflationary stage, may also induce PBH formation even in the radiation domination stage with the probability $W_{\mathrm{PBH}} \sim \exp(1 - /18\delta^2)$.

4.2 Inhomogeneous Baryosynthesis and Antimatter in a Baryon Asymmetric Universe

The generally accepted motivation for a baryon asymmetric Universe is the observed absence of antimatter at macroscopic scales up to the scales of clusters of galaxies. In a baryon asymmetric Universe the observed baryonic matter originated from an initial baryon excess, surviving after local nucleon–antinucleon annihillation, taking place at the first millisecond of cosmological evolution. The baryon excess is assumed to be generated in the process of baryogenesis (Sakharov, 1967; Kuzmin, 1970) see the review in Khlopov (1999), resulting in the baryon asymmetry of an initially baryon-symmetrical Universe.

It turned out that almost all the existing mechanisms of baryogenesis may under some conditions lead to inhomogeneous baryosynthesis and even to generation of antibaryon excess in some places. So inhomogeneities of baryon excess distribution and even domains of antimatter in a baryon asymmetric Universe can provide a probe for the mechanism of baryogenesis. In Sakharov's original scenario of baryosynthesis CP violating effects in out-of-equilibrium B-non-conserving processes, say decays of some particles X, generated in a charge symmetric Universe with equal amount of X and their antiparticles baryon excess proportional to n_{X} and $\mathrm{Im}\,\phi$, ϕ being a CP violating phase. If the sign and magnitude of $\phi(x)$ varies in space, the same out-of-equilibrium B-non-conserving processes, leading to baryon asymmetry, result in $B(x)$ and in $B(x) < 0$ in the regions, where $\mathrm{Im}\,\phi(x) < 0$. The spatial dependence of ϕ is predicted in models of spontaneous CP violation or in models, where a CP violating phase is associated with the amplitude of invisible axion field. The size and amount of antimatter in domains, generated in this case, is related to the parameters of models of CP violation and/or the invisible axion (see review in Khlopov, 1987, 1992, 1999; Chechetkin *et al.*, 1982). SUSY GUT motivated mechanisms of baryon asymmetry imply flatness of the superpotential relative to the existence of a squark condensate. Such a condensate, being formed with $B > 0$, induces baryon asymmetry, after squarks decay on quarks and gluinos. However the mechanism does not fix the value and sign of B in the condensate, opening the possibilities for inhomogeneous baryon charge distribution and antibaryon domains (Khlopov, 1987, 1992; Chechetkin *et al.*, 1982).

A new approach to baryosynthesis, based on electroweak baryon charge nonconservation at high temperatures, also implies the possibility of antimatter domains, e.g. due to spontaneous CP violation (Comelli *et al.*, 1994).

So antimatter domains may appear in a baryon asymmetric Universe and may be related to almost all the mechanisms of baryosynthesis, to mechanisms of CP violation and to possible mechanisms for primordial baryon charge inhomogeneity. The size of domains depends on the details of the respective phase transitions and the initial distributions of spatial variable CP violating phase, whose accounting for inflation may be as large as the modern horizon, being the case for the models of an 'island Universe' (Dolgov *et al.*, 1987) with very large scale inhomogeneity of baryon charge distribution. The general parameters of the averaged effect of the domain structure are the relative amount of antimatter $\Omega_a = \rho_a/\rho_{crit}$, where ρ_a is the averaged over large scales cosmological density of antimatter and $\rho_{crit} = 3H^2/(8\pi G)$ is the critical density, and the mean size of domains, l, (the characteristic scale in their distribution on sizes) or for small domains, t_{an}, the timescale of their annihilation with the surrounding matter. One can estimate the survival scale – the minimal size of domain, surviving in the Universe up to the present time. A dense antimatter domain with a size exceeding the survival scale can form an antimatter globular cluster in our Galaxy. It was recently shown (Khlopov,1998, Belotsky *et al.*, 1999) that the minimal mass of such cluster is determined by the survival scale and the maximal total mass of antimatter stars in our Galaxy is constrained by the galactic gamma ray background. Such a cluster should be the galactic source of an antinuclear component of cosmic rays, which is accessible in all the allowed range to search for antimatter in AMS experiment on Alpha station (Battiston, 1999).

4.3 Arguments for Multicomponent Nonbaryonic Dark Matter

The main arguments favouring the nonbaryonic nature of dark matter in the Universe are Big Bang nucleosynthesis (BBN) in inflationary cosmology and the formation of the large scale structure of the Universe at the observed isotropy of relic radiation. The first line of arguments accounts for the reasonable fits of BBN predictions to the observed light element abundances at $\Omega_b < 0.15$–0.20 and $\Omega_{tot} = 1$ predicted by inflationary cosmology, ascribing the difference to nonbaryonic dark matter. The second type of argument is that one cannot accommodate both the formation of the large scale structure and the observed isotropy of the thermal electromagnetic background without some weakly interacting form of matter triggering structure formation with a minor effect in relic radiation angular distribution (see review in Khlopov, 1999).

There are several scenarios of structure formation by hot (HDM), cold (CDM), unstable (UDM), mixed hot+cold (H+CDM), hierarchical decaying (HDS) etc. dark matter. These scenarios physically differ by the ways and succession in which the elements of structure are formed, as well as by the number of model parameters. But having in mind the general independence of the motivations for each type of dark matter candidates, one finds, from the particle physics viewpoint, hot, cold, unstable etc. dark matter not as alternatives but as supplementary options to be taken together, accounting for the whole set of reasonable physical arguments.

Indeed, one considers the would-be eV-(10 eV)-neutrino mass as a physical motivation for the hot dark matter scenario. But massive neutralinos, predicted in supersymmetric models, or invisible axions, following from Peccei–Quinn solution of the strong CP violation problem in QCD, being cold dark matter candidates, are based on physical grounds, which are in no case an alternative to the physics of neutrino mass. So mixed hot+cold dark matter scenarios seem to be physically more reasonable than simple one-parameter HDM or CDM models. However, all these motivations do not correlate with the problem of quark–lepton families, of the existence of three types of neutrinos. Physical mechanisms of family symmetry breaking lead to new interactions, causing massive neutrino instability relative to decay into lighter neutrinos and a light Goldstone boson, familon or singlet Majoron. Neutrino instability, intimately related to family symmetry breaking, provides physical grounds for unstable dark matter (UDM) scenarios (Khlopov, 1999). At the expense of an additional parameter (the lifetime of unstable particles) UDM models remove the contradiction between the data on the total density within the inhomogeneities, $\Omega_{\rm inhom} < 1$, and the prediction of inflational cosmology, $\Omega = 1$, ascribing the difference in Ω to a homogeneous background of unstable particles decay products. UDM models also recover the disadvantages of HDM scenarios, related to too rapid evolution of the structure after its formation. Owing to neutrino instability, large scale structure, which is formed at redshifts corresponding to observed distant objects, survives after the major part of dark matter, having formed the structure, decayed. The actual multicomponent content of dark matter may be very much richer, if one takes into account the hypothesis of shadow matter, following from the need to recover the equivalence of left- and right-handed coordinate systems in Kaluga–Klein and superstring models. One meets the problem of accounting for the whole set of matter fields and interactions, arising from E'_8 sector of the heterotic string $E_8 \times E'_8$ model. Even the above list of options, which is far from complete, poses a serious problem of the proper choice of the true combination of various dark matter candidates in physically motivated multicomponent dark matter scenarios.

Thus, since physical grounds for all the nonbaryonic dark matter candidates are outside the standard model and lose the proper experimentally proven basis, we either have to take into account all the possible ways to extend the standard model, treating all the candidates as independent, or find a quantitatively definite way to estimate their relative contribution.

5 COSMOLOGICAL TRACERS OF NEW PHYSICS

Cosmologically important consequences of both the aesthetically and pragmatically motivated extensions of the standard model are generally related to stable or sufficiently metastable particles or objects predicted in them. So since (meta)stability is based in particle theory on some (approximate) conservation law, reflecting the respective fundamental symmetry and/or the mechanism of symmetry breaking, cosmoarcheology probes the most fundamental new laws of Nature, assumed by the respective extension of the standard model.

Indeed, new symmetries, extending the symmetry of the standard model, imply new charges, conserved exactly or approximately, and the lightest particle posessing respective charge should be either stable or metastable. New charges may be related to a local or global, continuous or discrete symmetry. They may be topological, induced by the topology of the respective symmetry group. In most cases the mass of hypothetical particles and objects reflects the scale at which the assumed symmetry is broken. So (see e.g. Khlopov, 1999 for details)

- in all the GUT models, unifying electromagnetism with other forces within a compact group of symmetry, the magnetic monopole solutions appear as a topological point object bearing the Dirac magnetic charge $g = hc/e$ and having a mass of the order Λ/e, where Λ is the scale, at which the U(1) symmetry, corresponding to electromagnetism, separates from the rest of interactions.
- in some specific GUT models imply topology of the symmetry group leading to the existence of a domain wall (spontaneously broken discrete symmetry), a cosmic string (spontaneously broken U(1) symmetry), wall-surrounded-by-strings etc, topological solutions. The respective unit surface (unit length) energy density is of the order of the respective power of the scale Λ of symmetry breaking, i.e. Λ^2 for walls and Λ for strings.
- R symmetry (exact or approximate) protects, in the supersymmetric models (meta)stability of the lightest supersymmetric particle (LSSP). Its mass is generally related to the scale of supersymmetry breaking. In the local supersymmetric models this scale also defines the mass of the gravitino – a supersymmetric partner of the graviton having semigravitational coupling to other particles inversely proportional to the Planck scale m_{Pl}.
- the see-saw mechanism of neutrino mass generation implies a heavy right-handed neutrino with the Majorana mass M_{R} related to the scale of lepton number nonconservation, the Majorana mass of the ordinary left-handed neutrino being $m_{\mathrm{D}}^2/M_{\mathrm{R}}$, where m_{D} is the Dirac mass of fermions (typically related to the mass of respective charged lepton). The lifetime of the heavy right-handed neutrino, determined by its mixing with the left-handed one ($\sim m_{\mathrm{D}}/M_{\mathrm{R}}$), turns out to be inversely proportional to the mass of the light left-handed neutrino.
- the spontaneous breaking of Peccei–Quinn symmetry used to remove the problem of strong CP violation in QCD, results in the existence of a (pseudo)Goldstone boson, axion with the mass $m_{\mathrm{a}} \sim \Box m_\pi f_\pi/F$, where F is the scale of Peccei–Quinn symmetry breaking. The axion couplings to fermions are inversely proportional to F, and its lifetime relative to the decay into 2γ is of the order of $64\pi F^2/m_{\mathrm{a}}^3 \sim F^5$.
- equivalence of right- and left-handed coordinate systems implies the existence of mirror partners of ordinary particles. The mirror particles should not have ordinary gauge interactions and their own mirror interactions should be symmetric to the respective interactions of the respective ordinary partners. Then the mirror particles, having the same mass spectrum and the same internal mirror couplings as their ordinary partners, are coupled to the ordinary matter by gravity only.
- inclusion of the mirror particles together with the ordinary particles into the unifying GUT leads, after the GUT symmetry is broken and the ordinary and mirror sectors, retaining a discrete symmetry between them, are separated, to

the existence of Alice strings, cosmic strings, changing the relative mirrority of objects along closed paths around them.

- in superstring models the initial mirror symmetry is broken due to a combined action of compactification and gauge symmetry breaking, so that shadow matter appears, loosing the discrete symmetry with the ordinary partners. In the heterotic string model the initial $E_8 \times E_8'$ gauge symmetry, assuming an exact symmetry between the ordinary (E_8) and mirror (E_8') worlds in the 10 space-time dimensional string model, is reduced after compactification and gauge symmetry breaking to the (broken)$E_6 \times$ (broken?)E_8' 4-dimensional effective field model with the ordinary matter embraced by the (broken)E_6 symmetry and the enormously extensive world of shadow particles and their interactions corresponding to the (broken?)E_8' gauge group.
- the mechanism of gauge symmetry breaking in compactification onto Callaby–Yao manifolds or orbifolds, used in superstring models, implies homotopically stable solutions with the mass $\sim r_c/\alpha'$, where r_c is the radius of compactification and α' is the string tension. These objects are sterile relative to gauge interactions and may act on the ordinary matter by gravity only.

These and many other examples of the particle zoo, induced by the extensions of the standard model of electroweak and strong interactions, are related to the new phenomena, direct experimental search for which is either very hard or principally impossible.

So the cosmological effects are important or even unique sources of information on their possible existence.

6 THE UNIVERSE AS A PARTICLE LABORATORY

One may reduce the effect of new particles and fields in the Universe to two principal possibilities: 1, general dynamical influence on the cosmological expansion and 2, specific influence on particular astrophysical processes. In the first case the very presence of hypothetical particles and fields in the Universe, independent of their specific properties, causes some observational effect. In the second case, to estimate the expected result, some properties of the considered particles and fields should be specified. In the Universe, viewed as a particle laboratory, these two types of effects may be compared with integral and differential detectors used in particle experiment. One can refer to two widely known cosmological probes of new particles

- age of the Universe (the modern total density is restricted by the observational lower bounds on the age of the Universe) and
- ^{4}He primordial abundance (the total density of the Universe in the period of Big Bang nucleosynthesis is restricted by the observational upper limit on the primordial He abundance, or in more refined approaches by a set of the primordial light element abundance constraints)

as to the integral detectors, probing the contribution to the cosmological density of any form of matter, irrespective to its particular properties. In both cases the only thing we assume on the hypothetical forms of matter is their existence in our space-time, resulting in their contribution to the total density of the Universe. The same holds true for

- the condition of a sufficient growth of density fluctuations, following from the existence of the observed large scale structure of the Universe and the observed isotropy of the thermal radiation background. This condition leads to the existence of the dust-like stage of (dark) matter dominance sufficiently long to provide formation of the large scale structure from the initial density fluctuations small enough to satisfy the observed level of isotropy of the relic radiation. It excludes the range of parameters of unstable particles (or objects) leading to the dominance of their relativistic decay products in the period of the large scale structure formation.
- In the latter case one also does not specify the properties or decay modes of unstable matter. All these methods, being universal, have rather a rude sensitivity to the parameters of the hypothetical matter. Only the amount of such matter, comparative to or dominating in the total cosmological density, may be definitely excluded by integral detectors. More refined and sensitive tools are available, once specific tracers of hypothetical matter are specified.

For stable charge-symmetric species, present in the halo of Galaxy, their weak annihilation, resulting in neutrino–antineutrino, gamma-ray, electron–positron or proton–antiproton production, provides the possibility of excluding the range of respective parameters from

- the observed nonthermal electromagnetic backgrounds or the observational upper limits on them
- the observed gamma ray background
- the observed electron–positron background
- the data on cosmic ray fluxes
- the restrictions on high energy neutrino cosmic backgrounds

which may be viewed as 'experimental' data from differential detectors for the hypothetical particle processes.

For unstable species with the lifetime, smaller than the age of the Universe, the same types of data trace the respective decay modes, if the Universe is transparent for the products of decay. For each type of decay product one may fix the redshift starting from which the Universe is opaque for respective fluxes. Then the data on

- the thermal background spectrum distortions
- the light element abundance from nonequilibrium cosmological nucleosynthesis

provides indirect information on the effects of interaction of the fluxes with plasma and radiation in the early Universe. The spectrum of relic radiation may be viewed as an 'electromagnetic calorimeter' of the early Universe, since any electromagnetic energy release, starting from 10^5 s, induces distortions of the Planck form of the thermal microwave radiation background spectrum. Light element abundance turns out to be even a more sensitive probe for inequilibrium processes on the radiation dominance stage, owing to a strong possible change in the concentration for the less abundant light elements (D, ^{3}He, Li, Be, B,...) in the nuclear reactions induced by energetic particle fluxes from the hypothetical sources with a comparatively small electromagnetic energy release.

Almost all the above-mentioned differential detectors may probe the products of PBH evaporation, so that the restrictions on the sources of the respective particle fluxes or effects may be recalculated in the terms of the constraints on the concentration of PBHs with the mass 10^9–10^{15} g, evaporating from the 1 s to the present time. Accounting for the possible mechanisms of PBH formation, one may use the data, sensitive to PBH evaporation effects, to probe the hypothetical processes in the very early Universe.

The relative sensitivity of the integral and differential detectors, discussed above, to the hypothetical particles with the relative abundance $\nu = n/n_\gamma$ (n – concentration of particles and n_γ – concentration of relic photons) and the mass m, causing the respective effects in the period τ, is presented in the review Khlopov (1987), (see also Khlopov, 1999), where a more detailed discussion of various detectors of the Universe and extensive bibliography may be found.

To compare the immediate cosmological impact of the particle theory with the set of restrictions following from the astrophysical data, one generally has to evolve a multistep logical chain, linking the hypothetical processes in the early Universe to the effects, accessible to the astrophysical observations.

In the old Big Bang scenario, assuming the simple picture of relativistic dominancy from The Plankian times followed by the modern stage of the matter dominancy, such a link was established by the analysis of freezing out or decoupling the respective hypothetical species with the use of the Boltzmann equations and tracing the successive evolution of the frozen out or decoupled species on the 'smooth' cosmological background up to the period of their decay or to the modern Universe. The picture assumed the physical conditions at all the stages well known, so that the only laboratory unproven element was related to the hypothetical species studied.

The new Big Bang paradigm of inflational cosmology with baryosynthesis and nonbaryonic dark matter makes the linking much more complicated, since the initial or some successive stages of cosmological evolution of hypothetical species may, in general, differ strongly from the 'smooth' thermodynamical picture of the hot Universe, and, moreover, the complete story of the new standard cosmology is not well defined. One may use two ways to resolve this puzzle. The selfconsistent approach is to consider the physical grounds for inflation, baryosynthesis and dark matter in the same class of particle models to which the considered phenomenon belongs. Say, if we study some hypothetical cosmological consequences of supersymmetric models, we should use the SUSY based cosmological scenario etc. Or, at the expense of self-consistency, we may treat inflation, baryosynthesis and dark matter phenomenologically, not specifying their physical relevance, and apply the approaches used in the framework of the old Big Bang scenario. Provided that light element abundance (primordial ^{4}He, especially) and Planckian shape of the spectrum of relic radiation make the true cosmological evolution on the radiation dominance stage after 1 s to be effectively very close to the old Big Bang scenario, such an approach may not cause much errors in many cases of interest.

7 COSMOLOGY OF HORIZONTAL UNIFICATION

To combine methods of cosmoparticle physics, one can consider the approach, trying to incorporate the main properties of elementary particles and the cosmologically relevant parameters, corresponding to the physical mechanisms of inflation, baryosynthesis and dark matter, into the unique quantitatively definite theoretical framework.

Such an approach may be illustrated by the model of horizontal unification (see Khlopov and Sakharov, 1996 and Refs wherein). It was shown in these studies that the extension of the standard $SU(2) \times U(1) \times SU(3)_c$ model of electroweak and strong (QCD) interactions of elementary particles to the gauge symmetry $SU(3)_H$ of quark and lepton families provides not only a reasonable theoretical description of the established existence of three families of quarks and leptons (ν_e, e, u, d); (ν_μ, μ, c, s); (ν_τ, τ, t, b), but in its realization turns out to be the theoretical framework, incorporating, in an unique scheme, the physical grounds for inflation, baryosynthesis and dark matter. Even at the present level of 'minimal' horizontal unification the quantitatively definite choice of the parameters of the model, as a result of a combined analysis of its physical, astrophysical and cosmological predictions, has lead to reasonable dark matter models of the cosmological large scale structure formation, as well as to the quantitatively definite scenario of the cosmological evolution from the Planck times – to the period of galaxy formation and a set of predictions, open for experimental and observational tests.

This model, offering the alternative (horizontal) way to unification, is in no case an alternative to the more popular GUT or supersymmetric extensions of the standard model. The internal problems of the minimal horizontal unification imply its further supersymmetric and GUT extensions, which are expected to give a better consistency with the observations for its astrophysical and cosmological predictions. But even in the present form the model reflects the main cosmoparticle principles. On the basis of the local gauge model with spontaneous symmetry breaking it provides a phenomenology of the world system, putting together almost all the main known particle properties and the main necessary cosmological parameters related to the hidden sector of particle theory. It offers a quantitatively definite correspondence between the fundamental cosmological parameters (the form of inflaton potential, lepton number violation, mass, spectrum and lifetime of dark matter particles and fields), astrophysical effects (the rate of stellar archion emission, contributing significantly stellar energy losses and dynamics of stellar collapse) and particle properties (the see-saw mechanism of mass generation, hierachy of masses and mixings of quark and lepton families, Majorana mass ratio of neutrinos, rates of archion decays, double neutrinoless beta decays). Finally, the amount of free parameters of the model turns out to be much less than the amount of its signatures in particle processes, astrophysics and cosmology, thus providing its definite test and exhibiting its completeness.

So, the model illustrates the power of cosmoparticle approach. Its fundamental scale of the horizontal symmetry breaking is *a priori* unknown and corresponds to the hidden sector of particle theory, but a complex analysis of the set of its physical, astrophysical and cosmological predictions makes it possible to fix the value of this scale in two rather narrow windows (around 10^6 and around 10^{10} GeV). The second solution, corresponding to higher energy scale, seems to reproduce all the main features of widely assumed as the standard cosmological scenario with inflation, baryosynthesis and cold (axionic) dark matter. The practical realization of such a scenario, which in no case reflects the complete physical basis, shows that even the most simple reduced cosmological scenario does contain some additional elements (cf. post inflational dust-like stage, on which primordial black hole (PBH) formation is possible with a successive PBH evaporation at the RD stage after primordial nucleosyntheis, formation of the primordial percollational structure of archioles etc). This example favours the conclusion that in *no* cases new cosmological elements, based on the hypothetical effects of particle physics, are reduced to inflation, baryosynthesis and dark matter *only*. It also resembles the system of nontrivial cross-disciplinary links which should be used to probe the true world system with the use of the methods of cosmoparticle physics. Astronomy plays an important, and in many cases unique, role in this development.

One can conclude that modern cosmology follows the basic principle of Gamow's approach – to consider the Universe as a physical process. However, the physical laws governing this process turn out to be much more complicated than it could seem in Gamow's times. Cosmoparticle physics offers a nontrivial way to study both the true picture of the Universe and fundamental physics underlying it. On the basis of these studies exciting new phenomena are predicted in the Universe, and we can foresee great astronomical discoveries in the forthcoming century, may be even in the next decade.

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