symmetry

Editorial

Special Issue: Symmetry beyond the Standard Models of Cosmology, High Energy Physics and Quantum Field Theory

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1. Introduction

Research into the nature of matter is gradually advancing to a scale that is still energetically inaccessible at ground-based colliders. Of course, unique and strategic studies of the structural components of matter at high interaction energies (that are achievable in experiments) have now allowed us to confirm the main foundations of the standard model (except for some "minor details", like dark matter and/or dark energy). The entire framework of analytical and experimental research is based on two "pillars"—quantum field theory, QFT, as the theoretical basis for the analysis of matter structure, and high-energy physics—the latter extends the QFT arsenal not only due to a variety of experimental methods and results, but also due to considerations of specific channels of high-energy scattering or annihilation, new types of convenient variables, extra particles in extension to the standard model, etc. [1–4].

However, these powerful tools of cognitive process do not allow us to advance to the high-energy scale at which the physical processes characteristic of New Physics are expected to occur. A natural laboratory for studying phenomena at energies unattainable under terrestrial conditions is the space populated by stars, nebulae, galaxies, black holes, etc. All these objects (just like the scenario in which they evolve, i.e., the space-time) are dynamic; various processes occur within them at the macro- and micro-scale, generating fluxes of ultra-high- and high-energy particles. These cosmic rays propagate at galactic and intergalactic scales, interacting with matter and containing a wealth of information about NPs, dynamics and symmetries of fundamental fields and their evolution at different stages of the Universe [5,6]. Thus, three interdependent paths being paved by cosmology, high-energy physics and quantum field theory lead to an understanding of the phenomena beyond the SM. Using methods and instruments from high-energy physics, it is possible to quantitatively analyze events and signals generated on a cosmological scale (times, energies and distances). More accurately, from cosmology, we can obtain information on the CMB, its fluctuations, the distribution of large-scale objects and baryon acoustic oscillations, which are also dependent on DM features. Then, comparing these data with QFT (perturbative) predictions, we can, in principle, deduce the key elements of the fundamental theory of matter: a type of dynamical symmetry for a system of interacting fields (including gravity) at various scales of space-time as well as a set of particles and non-perturbative dynamics that form the basis of bound-states physics.

Thus, the complex study of the phenomena at the border of the standard model and beyond offers new ways of understanding the nature of matter at various scales, from quantum fields to galaxies and the universe.

Citation: Beylin, V.; Khlopov, M. Special Issue: Symmetry beyond the Standard Models of Cosmology, High Energy Physics and Quantum Field Theory. *Symmetry* **2024**, *16*, 66. https://doi.org/10.3390/sym16010066

Received: 15 December 2023
Accepted: 20 December 2023
Published: 4 January 2024

2. Contributions

In a series of papers in this Special Issue, a number of important fundamental problems have been discussed both qualitatively and quantitatively. In particular, it has been demonstrated that the spin-charge-family theory with massless fermions interacting with gravity only offers an explanation for all assumed properties of the second quantized fermion and boson fields in the standard model. It is assumed that there is a simple starting action in an even-dimensional space with $d \geq (13+1)$, and this is justified by a description of the internal spaces of the fermion and boson fields by odd and even Clifford objects, respectively. An analysis of the internal spaces of fermion and boson fields in odd-dimensional spaces, $d = (2n+1)$, shows that fermion and boson field properties in this space fundamentally differ from their properties in spaces with even dimensions. Some interesting predictions and explanations for several of the observed phenomena are also discussed in detail [7].

A possible mechanism of gravitational baryogenesis (GBG) stabilization via the modification of gravity is suggested by introducing an R^2 term into the canonical action of general relativity. In this scheme, the coupling of the baryonic current to the derivative of the curvature scalar, R, leads to a fourth-order (unstable) differential equation of motion instead of the algebraic equation in general relativity. It is shown that this mechanism allows for the stabilization of GBG with bosonic and fermionic baryon currents, establishing a corresponding region of the model parameters where standard cosmology is noticeably modified.

Studying the evolution of the universe from the sub-Planckian scale to present times also shows that the requirement of an exponential expansion of the space with the observed metric as a final stage leads to significant restrictions in the parameter values of a function of curvature, $f(R)$. In this research, an initial metric of the universe is supposed to be maximally symmetric with the positive curvature.

An interesting model combining a near-inflection point, small-field, slow roll inflationary scenario (driven by single-scalar inflatons) and the production of non-thermal vector-like fermionic dark matter, X, during the reheating era should be noted. Here, two different polynomial forms of the potential have been analyzed: symmetric and asymmetric about the origin. The parameters of the potentials are fixed by agreement with modern Planck–BICEP data. The permissible ranges of y_X and m_X which provide the density of dark matter necessary for the present universe are calculated. All other cosmological bounds, including Cosmic Background Radiation, were also taken into account.

Note that in some models with broken symmetry of the inflation Lagrangian, a binary system consisting of two primordial black hole clusters arises; such clusters can include a large central black hole which is surrounded by many smaller black holes. The orbital evolution of such gravitationally bound binary systems is also considered in [8]. Replacement of single black holes with such clusters significantly changes the merging process and the final rate of gravitational wave bursts in some parameter ranges (for sufficiently large cluster radii). An account of the tidal gravitational interaction of the clusters allows for the description of an additional dissipation of the orbital energy as it transfers into the internal energy of the clusters or is carried away by black holes flying out of the clusters. Comparison with the data from gravitational wave telescopes allows one to constrain the fractions of primordial black holes in the clusters, depending on their mass and compactness. Even the primordial black hole fraction in the composition of dark matter of $\approx$1 turns out to be compatible with LIGO/Virgo observational data.

Some hypothetical hot regions that may be formed by primordial density inhomogeneities could be a source of primordial nucleosynthesis; such a process is studied in reference [9]. It is shown that regions that have survived up to the present time acquire an abnormally high metallicity. This conclusion holds in a wide range of initial parameters of such regions. The thermonuclear reaction rates and estimated abundances of deuterium and helium-3 and -4 inside these areas were analyzed; it was also found that all baryons tend to form helium-4, which is the thermonuclear link in the chain of the formation of heavier elements.

The new stable fermion family, including new superheavy U, D quarks and new E, N leptons with standard model electroweak charges, is likely to participate in sphaleron transitions in the early universe before the breaking of electroweak symmetry. Specific conditions for balance between the excess of new fermions and baryon asymmetry were considered. This analysis was carried out at temperatures above and below the phase transition using a system of equations for chemical potentials.

Additional heavy quarks can form new heavy hadrons with standard quarks. In such scenarios of hadronic dark matter, the structure of the excited states of new heavy hadrons was studied. Fine mass-splitting in a doublet of new mesons stipulates the existence of charged metastable heavy mesons. The structure of new meson excited states was studied in the framework of heavy quark effective theory. Furthermore, some phenomenological consequences of such fine and hyperfine splitting are considered in the hadronic dark matter scenario.

The dipole cosmological principle, i.e., the notion that the universe is a Copernican cosmology that agrees with cosmic flow, is also presented in this Special Issue. In fact, this is the most symmetric paradigm which generalizes the Friedmann–Lemaître–Robertson–Walker ansatz; it is inspired by numerous suggestions for non-kinematic components in the cosmic microwave background dipole. Note that in this scheme of "dipole cosmology", four Friedmann equations arise, and the two extra functions can be regarded as additional scale factors breaking the isotropic group from $SO(3)$ to $U(1)$ and a "tilt" that reflects the cosmic flow. As a result, an axially isotropic universe occurs. The dynamics of the expansion rate, anisotropic shear and tilt in some cases are studied. It was shown that the cosmic flow (tilt) can increase while the anisotropy (shear) is reduced.

3. Conclusions

Theoretical studies of micro- and macro-scale phenomena based on data from both ground-based accelerators and measuring complexes and modern space telescopes have significantly extended the scope of problems under consideration at the forefront of fundamental physics. The papers presented in this Special Issue demonstrate exciting advances in the study of symmetry groups and new types of interacting quantum field algebraic structures, as well as in studies of the origin, evolution and symmetry of macroscopic structures and the Universe as a whole. Options for modifying gravity, the consequences of such modifications in particle physics in gravitational fields, and new types of black hole systems are considered in detail. Much attention has been paid to investigation of the dark matter physical characteristics in various models, the equilibrium of dark matter and the baryonic subsystem of the universe and extensions of the standard model involving new heavy quarks and nucleosynthesis in the early stages. Important details of all these perspectives, ideas and results can be extracted from all the above-mentioned papers.

Author Contributions: Editorial by V.B. and M.K. The authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: The research by M.K. was carried out at Southern Federal University with financial support from the Ministry of Science and Higher Education of the Russian Federation (state contract GZ0110/23-10-IF).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts in any areas of interest.

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