

Nonequilibrium Processes in the Early Universe. Cosmological Constraints

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Abstract. The monograph "Nonequilibrium Processes in the Early Universe. Cosmological Constraints" written by Daniela P. Kirilova, issued in 2017 by Lambert Academic Publishing, ISBN 978-3-330-00900-4, is presented.

Key words: Cosmology, Neutrino Physics, Astroparticle Physics, Beyond Standard Model Physics, Cosmological Constraints

Introduction

To reveal the Universe secrets and find the Physics laws for its proper description is the ultimate goal of Contemporary Physics and Cosmology. The monograph is dedicated to processes, related to the origin, chemical composition and structure of the Universe matter.

Cosmology provides unique physical information relevant at extreme conditions unreachable by physics experiments. It also tests new physics - physics beyond the Standard Model (SM), i.e. beyond Electro Weak Model and beyond Standard Cosmological Model (SCM). Physics beyond SM (BSM) is required for the explanation of the experimental physics data, astrophysical and cosmological observational data. At present the detection of neutrino oscillations and the measured value of the baryon density (unnaturally big to be explained without new physics) are the only robust experimental detection of BSMs physics. The book is dedicated to studies of neutrino oscillations, baryogenesis and leptogenesis, which are among the most actual problems of contemporary Physics, Neutrino Physics, Astrophysics and Cosmology.

The book's main topics include processes at the early Universe stage important for the Universe matter content, namely: *processes important for baryogenesis*, determining the baryonic content and matter-antimatter asymmetry, leptogenesis and constraints on lepton content of the Universe, and to *processes involving neutrino oscillations* during nucleosynthesis epoch, defining the chemical composition of the Universe, processes with chiral tensor particles, presenting extension of the Standard Model matter content, which belongs to the fundamental representation of SU(2) group.

In the first 3 chapters the processes connected with neutrino oscillations and their interplay with lepton asymmetry in the neutrino sector and their BBN effects and constraints are discussed. The following two chapters are dedicated to baryogenesis and antimatter in the Universe. The seventh chapter is dedicated to the investigation of the cosmological influence of chiral tensor particles, presenting a natural extension of the SM. Their search is now conducted at ATLAS experiment of the Large Hadron Collider (LHC) at CERN. LHC works at the highest energies reached till now at terrestrial

experiments and presents the biggest hopes for an experimental discovery of new physics.

In the following section we present the content of the chapters in more detail.

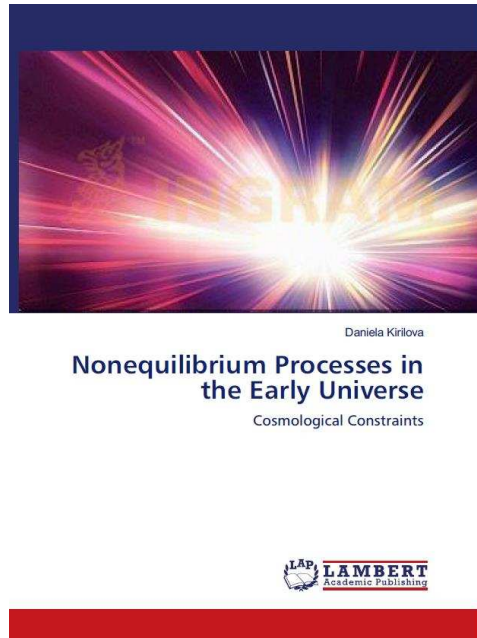


Fig. 1. Front cover of the book.

1 Structure and Content of the Book

The book contains 261 pages structured in 7 chapters, a bibliography of 244 references (consisting of original publications, review papers and textbooks), 45 figures, a list of abbreviations, and an acknowledgments sections.

1.1 The introductory chapter

The first chapter of the book discusses the tremendous progress of Cosmology, which in the last two decades has become a precision science, providing information about Universe characteristics at different epochs of its evolution, and about Nature's physical laws. It presents an introduction to the topics discussed, their actuality, originality, the main objectives and goals of the research presented in the monograph.

In the next chapter of the book we discuss the established and hypothetical beyond SM neutrino characteristics.

1.2 BSMs processes involving neutrino and their cosmological effects and constraints

In the introductory part of **the second chapter** of the book the main established and predicted by Standard Models neutrino characteristics are discussed. A review of the main experimental and theoretical results of neutrino physics and its role in Astrophysics and Cosmology is presented.

Studies involving neutrino are very actual because of neutrino importance in fundamental physics theory, as well as because of neutrino important astrophysical and cosmological role, namely in solar physics, stellar evolution, supernovas physics, nucleosynthesis, Cosmic Microwave Background (CMB), structure formation in the Universe, Dark Matter (DM) problem, etc.

In this chapter the role of neutrino ν in the early Universe is reviewed, relic ν characteristics and the formation of the cosmic neutrino background and its evolution from the early universe stages till today are described. The influence of flavor and sterile neutrino on the Universe expansion rate and on BBN are discussed and cosmological constraints on neutrino are reviewed.

The introductory part of the chapter describes the progress of Neutrino Physics and Astrophysics since Pauli's theoretical ideas about the neutrino in 1930 and the progress of neutrino experimental studies since its detection in 1953. Neutrinos characteristics studied at earth reactors and accelerators: neutrino helicity, the participation in weak neutral currents, and 3 light flavor neutrino types by Large Electron-Positron Collider experiments at CERN, are described. Neutrinos detected from astrophysical sources: from the Sun, the atmosphere, the supernova SN1987, extra-galactic and geo-neutrinos, are discussed, as well. The experimental establishment of the BSMs physics in the ν sector - ν oscillations 40 years after ν oscillations, were proposed as a solution for the solar neutrino problem, is described.¹

Experimental data on neutrino oscillations firmly determined three neutrino mixing angles and two mass differences, pointing to the existence of at least two non-zero ν masses.² The dominant oscillation channels have been proved to be flavor neutrino oscillations. The role of subdominant active-sterile neutrino oscillation channels is studied now. Particularly detailed review is provided on neutrino oscillations influence in the early Universe and cosmological constraints on ν oscillations in chapters 2.1, 2.2, 3.1 and 3.2. Cosmological BBN considerations, including the original works of the author, were the first to exclude two of the possible sterile solutions to the

¹ Solar neutrino experiments found an energy dependent deficit of electron neutrinos coming from the Sun, compared to the predictions of the standard solar model. SNO proved that solar neutrino deficit is not due to the imperfect astrophysical knowledge about the Sun. Atmospheric neutrino anomaly was found by atmospheric neutrino experiments. In 1998 Super-Kamiokande obtained evidence of atmospheric flavor neutrino oscillations. Neutrino oscillations suggested by solar and atmospheric neutrino experiments, were studied by terrestrial experiments, K2K, Minos, T2K, OPERA, KamLAND, which confirmed their existence. Thus, in the period 1998-2003 neutrino oscillations have been definitely experimentally established.

² The question of neutrino mass is of fundamental importance, it is closely related to the search of the mechanism for fermions mass generation, with the structure of the particles generations and GUT models. Besides, non-zero neutrino mass has important astrophysical and cosmological applications.

solar neutrino problem - large mixing angle solution and low mixing angle solution, years before the solar neutrino oscillations experiments.

Cosmology provides valuable information about the properties of the very elusive particles - the neutrinos and beyond SM physics in the ν sector due to the influence of ν on the processes during different epochs of the universe evolution, which have observable relics. Though the predicted cosmic ν background (CNB) from the ν decoupling epoch of the early universe, corresponding to cosmic times ≤ 1 s, has not been detected yet, strong observational evidence for CNB and stringent cosmological constraints on relic ν characteristics exist from BBN, CMB and LSS data.

In the book the role of ν in Cosmology is presented, in particular the ν considerable role during the early radiation dominated (RD) stage of the Universe, when light ν were essential ingredients in the Universe density, determined the dynamics of the Universe, and played an essential role in different processes as for example in BBN, leptogenesis and baryogenesis, the formation of CMB, etc.

At later stages of the Universe ($T \leq \text{eV}$) massive relic neutrinos, contributed to the matter density, influenced the formation of galaxies and their structures, and influenced CMB anisotropies.

Sterile neutrino (right-handed ν), presenting the simplest extension of SM particle content and proposed by many beyond SM theories, has many important cosmological applications: it may provide neutrino mass generation, KeV sterile neutrino present warm DM candidate, eV sterile neutrinos may explain the DR problem in Cosmology and is required by the experimental data of short base line experiments, sterile ν provides the possibility of baryogenesis through leptogenesis, etc.

Thus, possible future detection of relic ν and sterile ν will provide precious cosmological information.

Present CMB and LSS data constraints on ν masses, number of ν species and ν number density during the CMB and the LSS formation epochs, are reviewed. Light elements abundances and BBN put stringent constraints on ν characteristics: ν number density, effective number of relativistic ν types, lepton asymmetry in neutrino sector, sterile neutrino characteristics, ν mass differences and mixing, deviations from thermal equilibrium, ν decay parameters, etc.

Chapters 2, 3 and 4 are dedicated to our studies of the cosmological role of ν and the cosmological constraints on ν characteristics.

The major part of **chapter 2** is dedicated to our original results on the cosmological role of light non-thermalized sterile neutrino, non-equilibrium active-sterile neutrino oscillations, ν non-equilibrium decays and possible tiny lepton asymmetry in the neutrino sector. In previous literature mainly equilibrium case was studied (fast oscillations, thermalized sterile neutrino, fast thermalization of ν decay products, chemical potentials for the account of lepton asymmetry, etc.). Kinetic equations for the density matrix of ν in momentum space describing the evolution of the non-equilibrium oscillating ν in the early Universe are derived and used to study the cosmological influence of nonequilibrium neutrino oscillations during BBN epoch. This approach allows simultaneous account for the Universe expansion, ν oscillations and ν interactions with the hot plasma at the radiation dominated stage of the Universe evolution.

As a result of the precise analysis we manage to provide a precise description of the depletion of the active neutrino number densities and the increase of the effective number of the relativistic degrees of freedom due to active-sterile neutrino oscillations and to reveal two *qualitatively new effects of active-sterile neutrino oscillations*, namely: (i) production of a considerable distortion in the active neutrino energy spectrum due to non-equilibrium neutrino oscillations and (ii) possibility for neutrino-antineutrino asymmetry growth in resonant active sterile neutrino oscillations.

Contemporary cosmological constraints on ν properties, on the basis of astrophysical and cosmological data, are obtained, in particular: cosmological constraints on the number of ν families, neutrino mass differences and mixing, lepton asymmetry hidden in the ν sector, sterile neutrino possible characteristics, deviations of equilibrium in the neutrino sector, and neutrino decay parameters. Most of the cosmological constraints presented are derived on the basis of BBN considerations and are discussed in detail in the 3rd and 4th chapter.

1.3 Processes influencing Big Bang Nucleosynthesis and their BBN constraints

The origin of the chemical content of the Universe and its evolution is one of the basic cosmological and astrophysical questions. BBN explains the observed light element abundances in the Universe. According to the standard BBN in an early period of our Universe, at energies 1 – 0.1 MeV, the conditions were favorable for a nuclear synthesis of light elements, deuterium D, the isotopes of helium, ^3He and ^4He , and ^7Li , to proceed. As a result of BBN the composition of the baryon matter of our Universe is mainly hydrogen-helium one, with tiny traces of D and ^7Li .

The third chapter of the book is dedicated to modified models of BBN. First a review of the contemporary standard BBN model and the observational data on light elements abundances are presented.

BBN today is a very precise quantitative theory of cosmological nucleosynthesis. It is an experimentally confirmed theory: at the corresponding energies the cross sections of the reactions are studied at laboratories. It explains with remarkable precision the observational data on the light elements. Thanks to that good accordance between BBN theory and observations, we know the physical conditions of the Universe, corresponding to the period from the first seconds to the first 30 minutes of the Universe evolution.

BBN is the most precise cosmological test of fundamental Physics and beyond SM Physics. Among the light elements produced primordially helium-4 is the most sensitive to the relativistic density and to the pre-BBN nucleons kinetics. It is the most exactly measured element, precisely calculated and with a simple post-BBN evolution. Therefore, it is appropriate for a precision probe of the conditions of the universe in the BBN epoch. BBN produced He-4 is the best speedometer and leptometer.

In particular, the production of He-4 is sensitive to the speed of the Universe expansion, is very sensitive to the interactions of nucleons involving neutrino. It tests ν properties beyond SM like number of neutrino

types, spectrum distortions of neutrinos, asymmetry in ν sector, etc. BBN provides the most stringent constraints on the lepton asymmetry L of the Universe.

Chapters 3 and 4 of the book are dedicated to BBN, L and processes in modified BBN models (with additional particles, with active-sterile neutrino oscillations, with lepton asymmetry).

In chapter 3 first the main predictions and constraints of standard BBN are discussed. Then the results of original papers of the author concerning modified BBN models are presented. In the major part of the third chapter of the book we investigate the effect of nonequilibrium ν oscillations on the expansion rate of the Universe, and on the pre-BBN kinetics of nucleons, the production of helium-4 in modified BBN models with nonequilibrium electron sterile ν oscillations. The production of helium is numerically studied in non-resonant and resonant neutrino oscillations cases and for the whole parameters range of the models parameters and for different levels of initial population of the sterile neutrino state. Contemporary BBN constraints on neutrino degrees of freedom in case of ν oscillations are presented.

Enormous overproduction of helium (up to 32% in the case of the resonant ν oscillations and up to 12.8% in the non-resonant one) is found possible, due to the precise kinetic approach we have used for the description of the ν oscillations. The possibility for big overproduction of helium allowed, correspondingly, considerable strengthening of the cosmological constraints on ν oscillation parameters. On the basis of the observational data on primordially produced helium-4, coming from BBN light elements data analysis and CMB data on the baryon and photon density, stringent cosmological constraints on electron-sterile neutrino mixing and squared mass differences are obtained, which exclude the electron-sterile channel as dominant for the solution of the solar neutrino anomaly. The dependence of these cosmological constraints on the initial population of the sterile state is studied, as well. Qualitatively new conclusions concerning this dependence were obtained.

In this chapter also the possibilities of relaxation of the BBN constraint on ν oscillations and on the baryon density in modified models of BBN containing Physics beyond SM, are discussed.

The light elements abundances produced in the standard BBN depend on one parameter - the baryon-to-photon ratio. BBN allows us to define the density of baryons during BBN epoch, particularly on the basis of Deuterium, which is the best baryometer among the light elements produced primordially. This value is in remarkable agreement with the measured by CMB value. We have studied the baryon density in modified BBN model with neutrino oscillations. The possibility of relaxation of the BBN constraint on the baryon density in modified models of BBN, containing Physics beyond SM, especially ν oscillations is discussed.

Although the baryon density is measured with high precision, the exact baryogenesis and leptogenesis mechanisms are not known and appropriate B-violation and CP-violation processes are not detected. Many different types of baryogenesis and leptogenesis models exist in literature. In chapter 4 and 5 lepton and baryon asymmetry of the Universe are discussed.

1.4 Processes with lepton asymmetry and its cosmological effect and constraints. Asymmetry–neutrino oscillations interplay

The fourth chapter is dedicated to lepton asymmetry L , its cosmological effect and constraints and asymmetry–neutrino oscillations interplay.

The chapter starts with an extensive review of the lepton asymmetry important role in physical theories and in Cosmology, in particular in baryogenesis models, in primordial nucleosynthesis, for structure formation in the Universe, etc.

At present direct measurements of L have not been done, therefore constraints on L on the basis of its effect on different processes, which have left observable traces in the Universe, are valuable. The known cosmological effects of $L > 0.01$ on processes in the Universe are reviewed. The contemporary cosmological constraints on L from the standard BBN model are discussed.

In the book original results concerning the cosmological effects of tiny lepton asymmetries $|L| \ll 0.01$ are presented. The interplay between L and neutrino oscillations is analyzed. Indirect kinetic effect of such tiny L on BBN via neutrino electron-sterile neutrino oscillations is found considerable.

Different possibilities for the origin of big L , proposed by different models beyond SM exist: GUT, leptogenesis due to out of equilibrium decays of heavy Majorana neutrinos, scenario of baryogenesis with baryonic charge condensate, leptogenesis in fast resonant neutrino oscillations. The possibility for considerable L growth in resonant electron-sterile ν oscillations at small neutrino mixings and small mass differences, found in the original works of the author, is discussed.

The results of our analysis of the interplay between lepton asymmetry and $\nu_e \leftrightarrow \nu_s$ neutrino oscillations are presented. The possibilities of small L to enhance, suppress or stop neutrino oscillations, have been analyzed. The qualitatively new type of resonant oscillations transfer in the presence of small lepton asymmetry - "spectrum wave resonance", proposed in our works, is discussed as well as an explanation of possibility of $\bar{L}$ to enhance neutrino oscillations.

Modified BBN model with $\nu_e \leftrightarrow \nu_s$ oscillations and with tiny lepton asymmetries $|L| \leq 10^{-4}$ is considered and the indirect kinetic effect of lepton asymmetries (relic or oscillations generated) on the production of helium-4 is studied. Such small L are shown to be capable to effect BBN bounds: they can be strengthened, relaxed or evaded. Empirical relations, between the values of oscillations parameters and the lepton asymmetry, obtained on the basis of the exact numerical analysis corresponding to the different cases, are presented. For big enough L , that can suppress oscillations, new cosmological constraints on oscillation parameters are found.

On the basis of indirect kinetic effect of lepton asymmetry via active-sterile neutrino oscillations stringent BBN cosmological bound on the value of the lepton asymmetry was proposed.

A principal solution of DR problem is described – relaxation of the BBN constraints on eV sterile neutrino by preventing its thermalization in neutrino oscillations due to the presence of relic lepton asymmetry, which is large enough to suppress neutrino oscillations.

The fifth and the sixth chapters of the book are dedicated to the processes important for the baryogenesis and evolution of the structures of the baryonic component of the Universe.

1.5 Processes important for baryogenesis.

The fifth chapter discusses the baryon asymmetry and its generation.

The introductory part of the chapter presents a contemporary review of the problem of the baryon asymmetry, its observational and theoretical status.

The baryon number density of the Universe is measured with high precision by CMB and BBN. The baryonic component constitutes around 5% of the total energy density of the Universe. Antibaryons, except the secondaries, have not been detected in astronomically considerable quantities in our Galaxy. The reason for the observed baryon asymmetry its value and sign is not known. Though the baryon component is a small part of the total energy density of the Universe, baryon excess is unexpectedly big - it does not follow naturally from the initial baryon-antibaryon symmetric state of the Universe.

Usually it is assumed that the locally observed asymmetry is a global feature. Unlike the case with BBN, for which precision theory and observational data exist, there is not yet an accepted theory of baryogenesis. It is known that baryogenesis should have occurred at higher energies and, correspondingly, higher temperatures in the early universe in the period after the inflation and before BBN. Different types of baryogenesis mechanisms, like GUT baryogenesis, electroweak baryogenesis, baryo-through-lepto-genesis, Affleck-Dine baryogenesis, etc. are discussed. The most promising of today's baryogenesis scenarios, baryogenesis-through-leptogenesis and AD baryogenesis scenario, compatible with inflation and the low reheating temperature of the Universe, are discussed in more detail in the book.

The major part of the 5th chapter contains original results concerning the scalar field condensate baryogenesis model (SFC), which is among the preferred today baryogenesis models, based on the Affleck-Dine scenario. The results of analytical and numerical analysis of the generated baryon charge and its dependence on the parameters of the model (the characteristics of the baryon charge carrying scalar field – its mass, decay time, self coupling constants, as well as the Hubble constant at the inflationary stage and the gauge coupling) are presented. The importance of the particle creation processes by the time-varying scalar field for the value of the baryon charge is analyzed analytically and numerically. It is proved that for the natural range of model parameters it is possible to generate the observed value of the baryon asymmetry in the SFC baryogenesis model.

1.6 Baryon-antibaryon asymmetry of the Universe and LSS periodicity

In the sixth chapter we discuss the possibility of baryon inhomogeneities at a large scale and their explanation in the framework of an inhomogeneous SFC baryogenesis models.

Inhomogeneous SFC baryogenesis and antimatter in the Universe Search for antimatter in Cosmic ray and gamma-ray data by ground based detectors, balloons and spacecraft found that small quantities of antimatter are allowed within our Milky Way galaxy (anti-stars, a globular anti-cluster), i.e. in our vicinity there exist enormous asymmetry between matter and antimatter. However, neither observational data nor theory exclude categorically the existence of large quantities of antimatter at distances higher than 10-20 Mpc, corresponding to nearby clusters of galaxies. Therefore, it is important to find possible separation mechanisms between matter and antimatter domains. There are known different inhomogeneous baryogenesis models in literature that can predict the existence of astrophysically considerable quantities of antimatter. The detection of ${}^3\bar{H}e$ and ${}^4\bar{H}e$ nuclei by AMS-2 requires the existence of an anti-star - the nuclear engine producing these nuclei.

In the the sixth chapter an inhomogeneous Scalar Field Condensate baryogenesis model, able to explain the locally observed asymmetry and at the same time to predict existence of antimatter domains in the Universe providing sufficient separation between regions of matter and antimatter, is discussed. Different possibilities of CP-violation are analyzed corresponding to different sizes of the predicted domains of matter and antimatter and different distance between them. Observational constraints on inhomogeneous models from CMB, LSS, BBN, CR and gamma ray data are discussed and applied to obtain an indication about the size of the predicted by the model antimatter domains and the distances to them.

Inhomogeneous SFC baryogenesis and very large-scale structure of the Universe

According to the contemporary theory of structure formation in the Universe, based on the standard cosmological model with cold dark matter, a purely gravitational mechanism is not sufficient to explain the formation of giant voids and giant shells, as well as their possible spatial periodicity. A principal possibility for the formation of the quasi-periodicity of the baryonic matter and the very large scale of the Universe of $\sim 120 - 130h^{-1}$ Mpc has been analyzed within the inhomogeneous SFC baryogenesis scenario. Inhomogeneous SFC baryogenesis is shown capable to explain the observed quasi-periodicity in the distribution of the visible matter in the Universe and the generation of super-structures.

1.7 Processes with new chiral tensor particles

The seventh chapter is dedicated to an extended BSMs model with new chiral tensor particles (ChT) and their cosmological influence. These heavy bosons were predicted to be the carriers of new interaction, however in contrast to the gauge bosons, they have only chiral interactions with light fermions, through tensor anomalous coupling.

Today it is known that the existence of particles of this type does not contradict the contemporary experimental data and their presence is able to explain several anomalies in Particle Physics. The experimental search for new chiral bosons continues to be of great interest and at present it is conducted by the international collaboration ATLAS at the Large Hadron Collider at CERN.

In the book the cosmological role and place of the chiral tensor particles in the Universe history have been discussed. The influence of these particles on the early Universe history and evolution is revealed. It is shown that ChT particles slightly speed up the Hubble expansion. Their characteristic processes with the particles of the hot Universe plasma are calculated and the cosmic time of their scattering, creation, annihilation and decay is defined. The time interval of efficiency of these particles in the Universe evolution is determined for assumed values for their masses and couplings. Cosmological BBN constraint on the strength of their interaction is obtained, namely centi-weak interactions, which is in accordance with other theoretical and experimental findings.

2 Conclusions

The book is dedicated to the cosmological influence of beyond standard model processes, related to the origin, chemical composition and structure of the Universe matter, especially its fermionic components. Cosmological and astrophysical investigation of such processes and the obtained cosmological constraints on their characteristics on the basis of observational astrophysical and cosmological data and experimental physical data provide precious and unique information about New Physics and about the physical conditions in the early Universe. The generation of the baryon component of the Universe, its structure and possible antimatter domains, its chemical composition, generation of leptonic asymmetry, neutrino oscillations in the early Universe, Big Bang Nucleosynthesis, particle creation, reheating, processes with chiral tensor particles are among the fascinating themes discussed.

The book is intended for all interested in natural sciences, and is especially useful for specialists in the field of Astrophysics, Astroparticle Physics, Neutrino Physics and Cosmology. It is based on the dissertation for Doctor of Sciences of the author.

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