ФІЗИКО-МАТЕМАТИЧНІ НАУКИ

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COSMOLOGICAL INFLATION IN THE EARLY UNIVERSE AND SUPERSYMMETRIC GRAND UNIFIED THEORY

Summary. The evolution of ideas about the Universe from ancient times to the present is considered. Attention is paid to the current situation in high energy physics. The discovery of the acceleration of the Universe has changed our ideas about vacuum energy: it is necessary to understand why it is small. Recent cosmological observations have shown that the Universe is flat or almost flat, and has confirmed many other predictions of inflation theory. The latest data on our Universe are considered and the question of the early stage of the Universe evolution is raised. Particular attention is paid to the theoretical ideas about new physics beyond the Standard Model: extention of the Standard Model symmetry group, increasing the space-time dimension, adding new scalar supersymmetric particles. The inclusion of these directions in a unified theory – string and D-brane theory leads to the possibility of solving the problem of vacuum stability and the problem of the hierarchy of interactions. Within this theory it is possible to solve the issue of dark matter, and to include the gravity for construction a unified theory of all four interactions – supergravity or M-theory. There are different dualities between string theories within the framework of M-theory. An example of this duality is the AdS/CFT correspondence, which implies that a number of characteristics of the theory can be described both within the framework of four-dimensional field theory and gravity in a five-dimensional de Sitter space. In the framework of the inflationary model, M-theory and supersymmetry, the mechanism of transition between spaces of different configurations from false to true vacuum due to the quantum excitation of the Higgs field are considered. The solution to the problem of experimental confirmation of theories of grand unification is the ability to combine physics at submillimeter ranges and distances of the size of the Universe, since cosmological observations of the properties of relict radiation lead to conclusions about the expediency of theories beyond the SM. SM's successes and efforts which aimed at testing it as well as the search for new physics, both at the LHC accelerators and in non-accelerating experiments, determine the development of high energy physics in the coming years.

Keywords: inflation of the Universe, M-theory, anti-de Sitter space, supersymmetry, Higgs boson.

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КОСМОЛОГІЧНА ІНФЛЯЦІЯ В РАННЬОМУ ВСЕСВІТІ І СУПЕРСИМЕТРИЧНА ТЕОРІЯ ВЕЛИКОГО ОБ'ЄДНАННЯ

Анотація. Розглянуто еволюцію уявлень про Всесвіт від найдавніших часів до сьогодення. Приділено увагу сучасній ситуації в фізиці високих енергій. Відкриття прискорення Всесвіту змінило наші уявлення про енергію вакууму: необхідно зрозуміти, чому ця енергія є малою величиною. Останні космологічні спостереження показали, що Всесвіт плоский або майже рівний, що є підтвердженням теорії інфляції. Представлені останні космологічні дані щодо вимірювання реліктового випромінювання і прискореного розширення Всесвіту, які з'ясовують питання про ранню стадію еволюції Всесвіту. Особливу увагу приділено теоретичним ідеям щодо нової фізики за межами Стандартної моделі (СМ): розширенню групи симетрії СМ, збільшенню розмірності простору-часу, додаванню нових скалярних суперсиметричних частинок. Включення цих напрямків у єдину теорію – теорію струн та D-бран призводить до можливості вирішення проблеми стабільності вакууму та проблеми ієрархії взаємодій. В рамках цієї теорії можна вирішити питання щодо темної матерії і включити до розгляду гравітацію для побудови єдиної теорії всіх чотирьох взаємодій – супергравітації або М-теорії. Наведено різні дуальності між струнними теоріями в рамках М-теорії. Прикладом такої дуальності є AdS/CFT-відповідність, яка передбачає, що ряд характеристик теорії може бути описаний як в рамках чотиривимірної теорії поля так за допомогою гравітації в п'ятивимірному просторі де-Ситтера. В рамках інфляційної моделі, М-теорії та суперсиметрії розглянуто механізм переходу між просторами різних конфігурацій від хибного до справжнього вакууму через скалярні поля типу бозона Хіггса. Вирішення проблеми експериментального підтвердження теорій великого об'єднання полягає в можливості поєднати фізику на субміліметрових діапазонах і на відстанях розміру Всесвіту, оскільки космологічні спостереження властивостей реліктового випромінювання призводять до висновків щодо властивостей теорій за межами СМ. Успіхи СМ і зусилля, які спрямовані на її перевірку, також як і пошуки нової фізики як на прискорювачах типу ВАК, так і в неприскорювальних експериментах визначають розвиток фізики високих енергій на найближчі роки.

Ключові слова: інфляція Всесвіту, М-теорія, простір анти-де-Сіттера, суперсиметрія, бозон Хіггса.

Problem statement. The relationship between the cosmic scales and the scales of elementary particles is the most relevant today for both physicists and astronomers. The discovery of relict radiation and the study of its characteristics that affect our ideas about elementary particles in cosmic space, as well as our ideas about the picture of the early evolution of the Universe, are the most impressive and vividly demonstrate the relationship of sciences at different scales of distances. However, the question remains open about the mechanism of the early stage of the emergence and evolution of the Universe, to which this article is devoted.

Analysis of the latest research and publications. The questions of the evolution of the early universe, as well as the possibility of combining all types of interactions, occupied the minds of many scientists, among which the following can be especially distinguished: Bagger [1], West [2], Wess [1], Polyakov [3], Weinberg [4], Linde [5], etc.

The aim of the article is to explain the inflation model of the Universe through the tunneling mechanism from anti-de Sitter to de Sitter space within M-theory with the help of Higgs field.

The principal material statement. The question of the origin and evolution of the Universe has occupied humanity for almost its entire existence. Even the Babylonians and Egyptians knew something about the laws of the orbits of celestial bodies, and especially about eclipses. The teachings of the ancient Greeks, the most striking of which is represented by the Pythagoreans (VI century BC), were interested in the secret cause of everything.

The basic teaching of the Pythagoreans, as we know, was that things are numbers. The Pythagoreans knew that the Earth is a sphere. Their planetary model is shown in Figure 1.

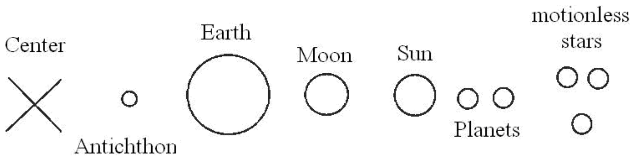

Figure 1. Model of the planetary system and stars of the Pythagoreans, from [6]

The model consists of a fixed center, nine spheres (earth, moon, sun, planets, fixed stars) that rotate around it and an antichthon or counter-earth. The four elements (fire, water, earth, air), apparently, were thought of as consisting of four of the existing five geometrically regular bodies, while the fifth, twelve-sided, was saved as a container for the entire Universe. One of the first Pythagoreans, Peter, claimed that there were also 183 worlds.

Representatives of the Milesian school (Thales, Anaximander and Anaximenes (VII-VI century BC)) suggested considering the only material (water at Thales, air at Anaximenes), of which everything consists which was a step on the path to atomism.

Xenophanes and Heraclitus (VI century BC) believed that this world was created by none of the gods and none of the people; it has always been, and is, and will be forever a living fire that flares up with measures and goes out with measures.

Ancient atomistic theory, which is associated with the names of Leucippus and Democritus (V century BC) is the forerunner of modern one:

– Atoms are invisibly small.
– Atoms are in perpetual motion.

Democritus expressed clearly and meaningfully the most advanced epistemological position of antiquity. He believed in the reduction of an inexpressibly rich variety of behavior to purely geometric images.

Where did the "Cosmos" ("κόσμος"), the Universe come from? Did the Universe have a start? Even in antiquity, people proposed models of the Universe. Aristarchus of Samos and Ptolemy proposed the heliocentric system of the world. The cosmological system, which was of great importance in the Middle Ages, was created by Aristotle. Later Copernicus, Kepler, Galileo, Newton, Lemeter, Friedman, Einstein proposed their models of the Universe. Kepler represented the Universe in the form of a ball of finite radius with a cavity in the middle where the Solar system was located. On the basis of the "Mathematical Principles of Natural Philosophy" in the XVIII century Newton is building his model of the Universe. To overcome the problem of merging gravitating bodies, he believes that the space of the Universe is infinite. In 1916, A. Einstein wrote the equations of the general theory of relativity, describing the "stationary" Universe and in the years 1922-1924. A. Friedman receives non-stationary solutions of the entire Universe [7]. This general solution provides a "special world", a "new type of Universe" – a Universe that changes over time. The periodic increase and decrease in the curvature of the Universe leads to the conclusion that it is unsteady. Friedman proved that Einstein's equations include the possibility of not only a Universe of positive curvature (sphere, de Sitter (dS) space) but also a Universe with negative curvature (anti de Sitter space, AdS) with zero density of matter. Different types of geometries are presented in Figure 2.

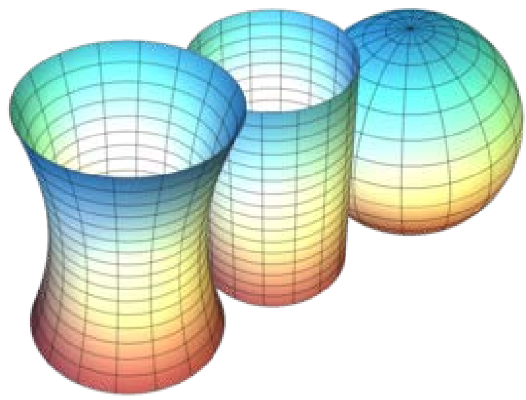

Figure 2. Riemann geometry with different curvatures (from left to right: negative zero, positive)

The further development of physical ideas about the Universe is connected both with the development of observational space technology (terrestrial and space telescopes) and with theoretical constructions. Hubble's discovery (1929) of the expansion of the Universe, later proposed by Gamov (1946-1949) and the discovery of isotropic relic radiation in 1965, together with the impressive cosmic experiments of COBE, WMAP, Planck, were milestones in predicting the Big Bang theory and creating a picture of a homogeneous isotropic unsteady hot expanding Universe [8].

At present, physicists are faced with the problem of coordinating the picture of the observed Universe and the Big Bang theory, which is associated with the initial stage of the first explosion. At the initial stage of the emergence of the Universe, it was assumed that matter compressed to a point had an infinitely high density, temperature and pressure. However, this is impossible, since at high density the particles could not have a high temperature when repelled. So, Alan Gut [9] suggested that the early Universe could go through a period of very rapid expansion at an increasing rate – a period of "inflation", Figure 3.

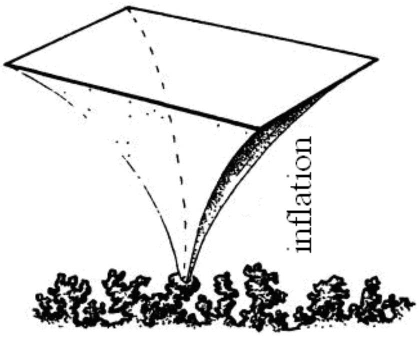

Figure 3. Scheme of inflationary theory: exponential expansion leads to a homogeneous, spatially flat Universe

To solve these issues, it must be assumed that at small (Planck) distances, the true physical space has a complex structure. This structure is modeled by spaces of the Kaluza-Klein type.

One of the greatest advances in physics over the past two millennia is the definition of the four types of interaction that rule the Universe:

– Gravity

– Electromagnetism

– Strong and weak nuclear interactions.

Albert Einstein throughout his life tried to create a "theory of everything", to find a simple equation that combines all physical interactions and describes all the laws of the Universe. Since the Universe is described in terms of two basic theories: the general theory of relativity (on a scale of several kilometers to one with twenty-four zeros of kilometers) and quantum mechanics (scale is a millionth of a millionth of a centimeter), the main task of physics is to search for the quantum theory of gravity, which will include both theories. Such theory was proposed by E. Witten (1995) and called M-theory – a unified theory of all of the fundamental forces of nature and all consistent versions of superstring theory [10]. There are five superstring theories built in ten-dimensional space (3D regular space + 1 time + 6D space of extra dimensions) for explanation of the particles and fundamental forces. They incorporate bosons and fermions into supersymmetric theory (SUSY) and due to S- and T-dualities these five theories are included into supergravity theory – M-theory, Figure 4.

With M-theory is associated AdS/CFT correspondence [11], when the geometry of space-time is described in terms of a vacuum solution of Einstein's equation called AdS space, presented in Figure 5.

AdS/CFT correspondence states that conformal field theory on the boundary of AdS space is equivalent to the gravitational theory on the bulk of AdS space. It means that a particle in the gravitational theory correspond to some collection of particles in the boundary of AdS space. Since we are dealing with M-theory,

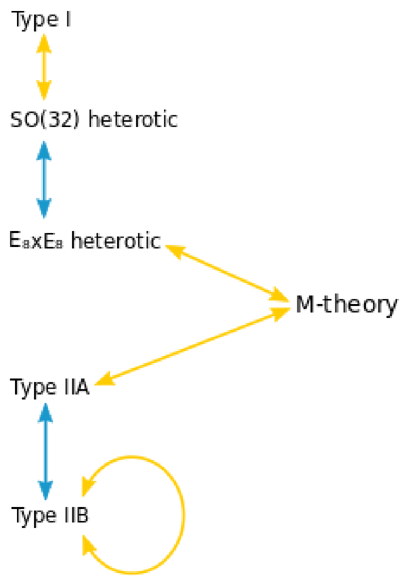

Figure 4. String theory dualities to obtain equivalences of any of the five theories within M-theory

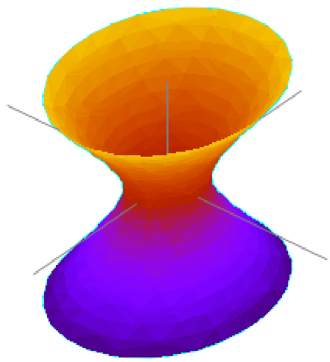

Figure 5. Two (1+1)-dimensional AdS space embedded in three (2+1)-dimensional space

the Einstein equation cannot be used in its pure form, therefore, the question of the connection of the Richey tensor with the cosmological constant does not exist.

To achieve inflation, it is necessary to add a new scalar field φ to the set of known physical particles and fields. The effective energy density in the early Universe, according to the inflationary model, is determined mainly by the effective potential $V(\varphi)$, presented in Figure 6.

Figure 6. Expected function type V(φ) with false vacuum on the left and true on the right from [12]

A Universe of negative curvature could not be stationary according to A. Friedman. Therefore, it can move from the false vacuum of AdS space to the true vacuum of dS space in which we live. At the same time, problems with a zero vacuum density corresponding to the solution of an unsteady Universe are being solved. Here, the AdS/CFT correspondence plays a role, when all particles are on the boundary of space, and not inside it.

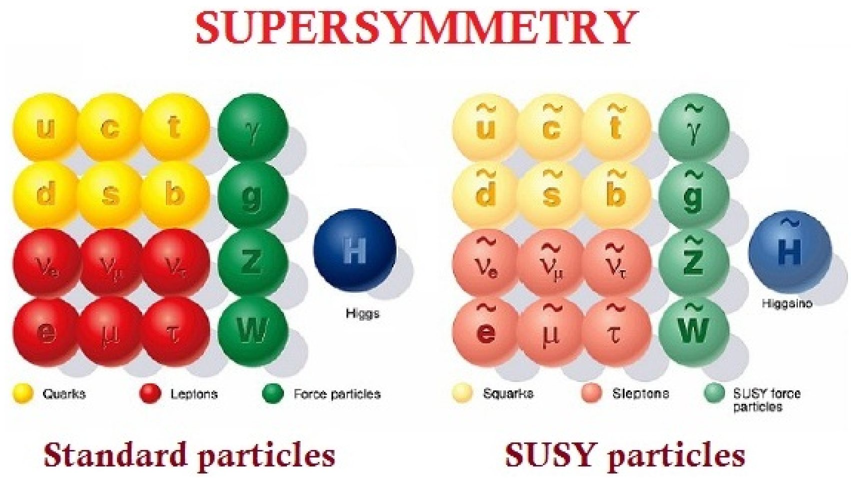

Figure 7. Three generations of quarks and leptons, gauge particles, Higgs bosons (left) and their superpartners (right)

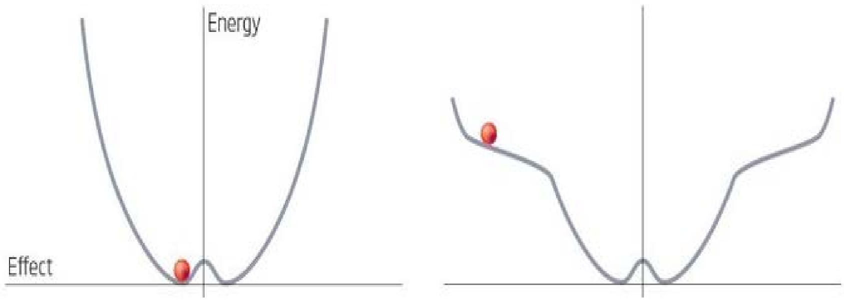

Figure 8. Higgs potential curve for low background energy (left) and large background energy (right) for supercharged field during the early Universe

As for the scalar particle it is necessary to say that SUSY as the theory with additional scalar particles may be a suitable theory [13]. SUSY – a theory linking bosons and fermions into one theory, where each particle with an half-integer spin corresponds to its superpartner with a integer spin and and vice versa, (Gauge-coupling unification Figure 7), solves a number of Standard Model problems:

– the hierarchy problem;
– dark matter candidate problem;
– realizes gauge-coupling unification;
– is part of superstring theory, a string theory of quantum gravity;
– CP-symmetry problem.

Among these particles, the Higgs boson is of most interest, since it is associated with the acquisition of mass from particles. Their clearest description is presented on the CERN website [14]: "Just after the big bang, the Higgs field was zero, but as the universe cooled and the temperature fell below a critical value, the field grew spontaneously so that any particle interacting with it acquired a mass. The more a particle interacts with this field, the heavier it is. Particles like the photon that do not interact with it are left with no mass at all. Like all fundamental fields, the Higgs field has an associated particle – the Higgs boson. The Higgs boson is the visible manifestation of the Higgs field, rather like a wave at the surface of the sea". On 4 July 2012, at the LHC CERN (ATLAS and CMS Collaborations) was observed Higgs boson in the mass region around 125 GeV [15]. Higgs potential curve which describes the energy of the field is presented in Figure 8.

Predicted by SUSY additional Higgs bosons (scalar (h, H, A) and charged (H)), are searched at the LHC. The latest experimental data are explained within Two Higgs Doublet Model (2HDM) and presented in the paper [16]. The scope of the searches for new Higgs bosons is impressive. I can only submit a table with Higgs search channels for ATLAS and CMS Collaborations.

The latest experimental data on the searches for additional Higgs bosons with a statistical significance of 3 sigma and 4 sigma at masses of about 93 GeV and 400 GeV are presented in papers of CMS and ATLAS Collaborations [17; 18], some of which are in Figure 9.

Conclusions. We examined the evolution of ideas about the cosmos, the nature of things and about the Universe since the era of antiquity. Thanks to the development of observational techniques and theoretical models, a modern picture of the Universe was presented. Of greatest interest is the moment of the emergence and evolution of the Universe, the theory of construction of which is under development. We have presented an inflationary scenario for the development of the Universe, which includes the M-theory as a theory of supergravity on the one hand, and on the other as a theory for which AdS/CFT correspondence is performed. A set of supersymmetric theories involving the existence of additional charged and neutral scalar Higgs fields, the active search for which was successfully carried out at the LHC (ATLAS, CMS) experiment, presents a model of the early development of the Universe from the AdS to the dS (our) space, overcoming the contradictions of modern high-energy theoretical physics.

Table 1

Higgs search decay channels for ATLAS and CMS Collaborations

channel	channel		
$A / H \to \mu\mu$	$h \to AA \to bbbb$		
$A / H \to bb$	$h \to AA \to bb\tau\tau$	**channel**	**channel**
$A / H \to \tau\tau$	$h \to AA \to bb\mu\mu$	$A \to hZ \to bbll$	$A / H \to HZ / AZ \to bbll$
$A / H \to \gamma\gamma$	$h \to AA \to \tau\tau\tau\tau$	$A \to hZ \to \tau\tau ll$	$A / H \to HZ / AZ \to \tau\tau ll$
$A / H \to tt$	$h \to AA \to \tau\tau\mu\mu$	$H \to hh$	
$H \to ZZ$	$h \to AA \to \mu\mu\mu\mu$		
$H \to WW$			

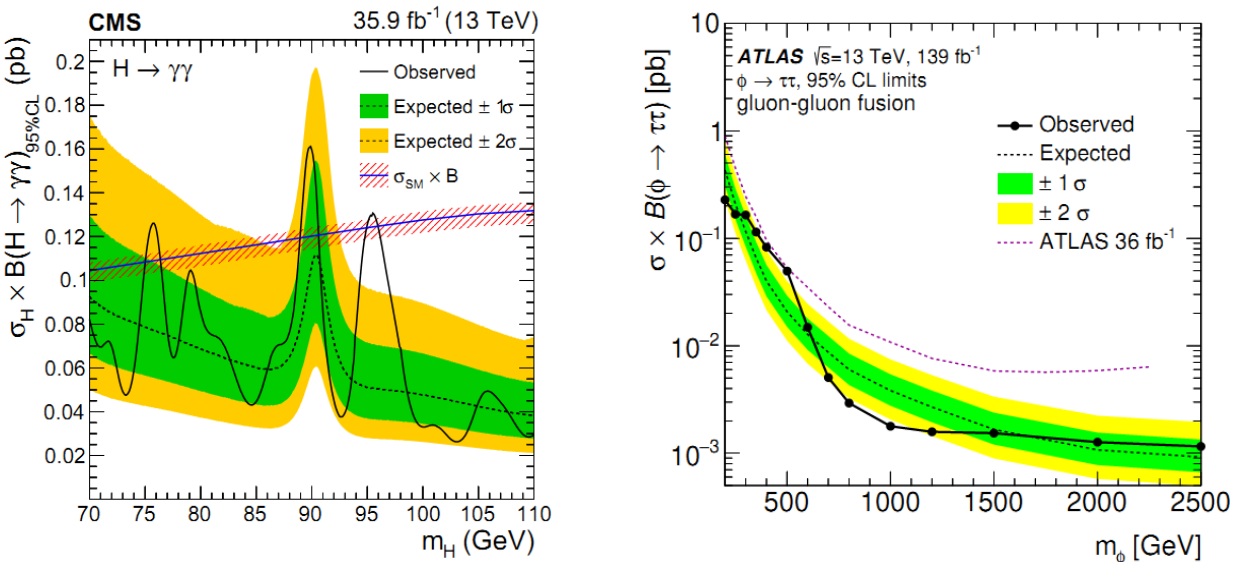

Figure 9. Expected and observed exclusion limits (95% CL) on the product of the production cross section and branching fraction for an additional SM-like Higgs boson, from the analysis of the 13 TeV for mass of about 90 GeV (left) and 350 GeV (right)

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