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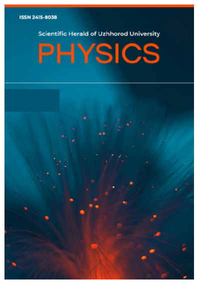

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String theory and theory of everything: Review research

Abdimitalip Satybaldyev*
PhD in Technical Sciences, Associate Professor
Osh Technological University named after M. Adysheva
714018, 81 Isanov Str., Osh, Kyrgyzstan
https://orcid.org/0009-0006-2226-069X

Syrga Berdibekova
PhD in Pedagogical Sciences
Osh Technological University named after M. Adysheva
714018, 81 Isanov Str., Osh, Kyrgyzstan
https://orcid.org/0009-0004-1619-3537

Anarbek Attokurov
Postgraduate Student
Osh Technological University named after M. Adysheva
714018, 81 Isanov Str., Osh, Kyrgyzstan
https://orcid.org/0009-0009-0012-2271

Zhanargyl Igamberdieva
Postgraduate Student
Osh Technological University named after M. Adysheva
714018, 81 Isanov Str., Osh, Kyrgyzstan
https://orcid.org/0009-0000-3795-9408

Abstract

Relevance. Modeling is the primary tool for understanding the surrounding world, processes, and phenomena. The models currently used by humanity are essentially fragmentary (discrete) with certain variations of correlative generalizations. Therefore, humanity is constantly seeking mathematical formulations that can encompass the full picture of the Universe.

Purpose. The aim of the research is to analyze the evolution of the theoretical and modeling foundation of the physical picture of the world with the identification of promising research vectors that have the potential to form broad generalized models of the Universe, in other words, the theory of Everything.

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*Corresponding author

Methodology. To achieve this goal, methods of systematization and generalization, meta-analysis, and meta-synthesis were employed. Since this study is a review and is intended to systematize and deepen knowledge, its structure is unconventional.

Results. The current model of the scientific landscape is described, based on which the dynamic vectors of development of the theoretical foundation of the Universe theory were determined. This allowed us to conclude the current state of the system of physical modeling as the main tool for the civilizational development of mankind. The research suggests that at the current stage of development of ideas about the physical picture of the world, M-theory is a potential model of the theory of Everything.

Conclusions. The practical significance of the research results indicates a potential mathematical and theoretical concept (among existing theories and models) that is relevant and adequate to modern ideas about cosmogony, phenomena, and the structure of the Universe. This can attract more attention to a certain direction of scientific research, not only among the professional community but also among the general public.

Keywords: standard model, quantum chromodynamics, quantum electrodynamics, quantum gravity, grand unified theory, M-theory

Introduction

The development and introduction of new technologies at the present stage of civilisational chronometry depend on the theoretical and modelling basis, which is equipped with an appropriate mathematical apparatus that allows to obtain forecasts of the dynamics of physical systems with a satisfactory level of correlation concerning natural and empirical observations of the real world. In this case, the most adequate models are those mathematical formulations that form the theoretical basis for a wider range of physical phenomena in a generalised, non-local form that allows obtaining local solutions for specific initial conditions. The problem that has been relevant throughout the development of modelling and constantly requires an appropriate solution is the deprivation of discreteness of individual models in terms of their application to the generalised landscape of the theory of the Universe.

Modelling, as the main tool for studying processes, phenomena, and objects, is based on the formation of concepts of certain algorithmic sequences that correlate to the conditions of regularities revealed by natural-empirical or logical-observational methods from the real world. The formation and study of models based on the relevant mathematical apparatuses allow to establish the level of adequacy of perception of the surrounding reality, as reported in the study by S. Raczynski [1].

As noted by S. Hawking and L. Mlodinov (as interpreted by A.F. van Biezen [2]), theoretical models, as the main scientific tool for studying the world and reality, to meet the criteria of completeness and efficiency, must meet three main requirements: first, to have an appropriate mathematical apparatus, second, to describe natural phenomena and processes in the widest possible application with the possibility of obtaining individual solutions for specific initial conditions of the modelled systems and processes, and (third requirement) must generate forecast and model results that should correlate with empirical data. Given the significant influence of the processes and results of modelling on scientific thought and the development of civilisation, it is reasonable to recognise that humanity is currently in the paradigm of model-dependent realism.

In the current state, humanity operates with theoretical models that are discrete in nature, as they describe individual processes and phenomena of external natural reality, and therefore, scientific thought is constantly in the process of searching for a single theory of Everything that can fully describe the essence and manifestations of the Universe. After the revolution in the scientific world (with far-reaching consequences in all spheres and branches of human activity and essence), which was caused by the fundamental works of A. Einstein, humanity, at the present stage, has not received scientific concepts that could explain the universal nature. Many theoretical statements and formulations have been created, but no scientific concepts have been formulated that satisfy the three conditions of completeness outlined above. However, in the landscape of scientific works, a concept has been formulated that currently has significant potential and claims to be a theory of Everything - the string theory and the *M*-theory (following S. Parekh [3]).

As T.A. Mohaupt [4] notes, the basic concepts of string theory were formed in 1914 and went through three iterations: zero - the creation of basic theoretical foundations and two string revolutions, which eventually led to the creation of a generalising concept – *M*-theory.

At the present stage, string theory is in the process of developing its mathematical apparatus and waiting for empirical confirmation (or refutation) of the hypotheses. Among the latest studies of string theory, it is worth highlighting the studies of J. Gomis [5] (on the study of the limitations of bosonic string theory), S.P. De Alwis [6] (on the combination of string theory with Wilsonian effective field theory), S. Raucci [7] (on studies of non-super-symmetric strings, in particular, their vacuum states), S. Brahma [8] (on studies of the matrix model of the cosmogony of the Universe), S. Fumeron [9] (on studies of the topology of compactification spaces of additional dimensions of string theory), etc. Many studies and layers of hypotheses require systematisation and building a chronological vertical containing ordered and mutually consistent concepts, which in the future becomes a potential support structure for the development of the investigated sector of physics.

Thus, it can be stated that string theory is currently well developed and has a thorough mathematical apparatus, so the logical goal of the study is to assess the potential possibility of positioning string theory as a general mathematical model of the Universe – the theory of Everything. To achieve this goal, the Scopus database was searched for scientific sources using the keywords "Particle physics", "Theory of Everything", "Universe models", "Quantum gravity", "Extra-dimension", "Compactification", "Supersymmetry", "Gauge fields". Among the sources found, 35 were selected for meta-analysis, meta-synthesis, systematisation and generalisation [10]. Using the method of generalisation, the following conclusions were formulated.

String theory, M-Theory,and the quest for a unified theory of Everything

Currently, the scientific world has a generalised concept of the interaction of four fundamental forces (Fig. 1).

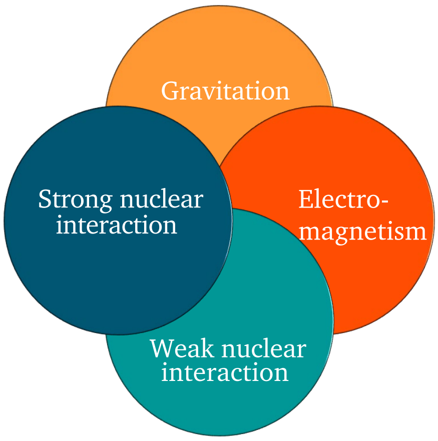

Figure 1. Conceptual diagram of fundamental interactions of the Universe

Source: [11]

Each of the fundamental interactions has a particle of the general class "gauge bosons", which transmits these forces (Fig. 2) [11]. The particle that provides the inert mass of the gauge bosons and the mechanism of spontaneous electroweak symmetry breaking was discovered by P.W. Higgs. This elementary particle is named after the inventor – the Higgs boson, which is de facto a quantum of the Higgs field [12].

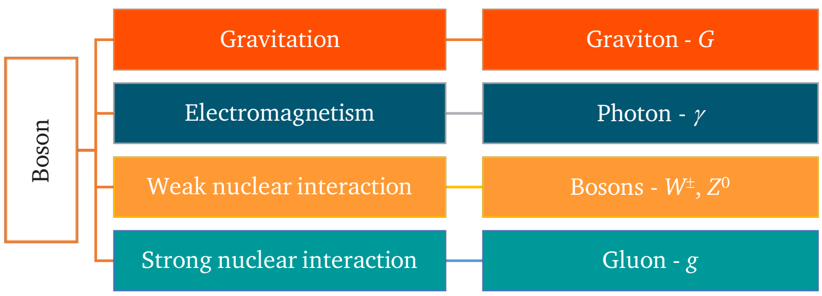

Figure 2. Conceptual diagram of gauge bosons for fundamental force transfer

Source: [11]

Matter also has corresponding elementary particles, which are part of the general class of fermions, consisting of three generations of quarks and leptons (Fig. 3).

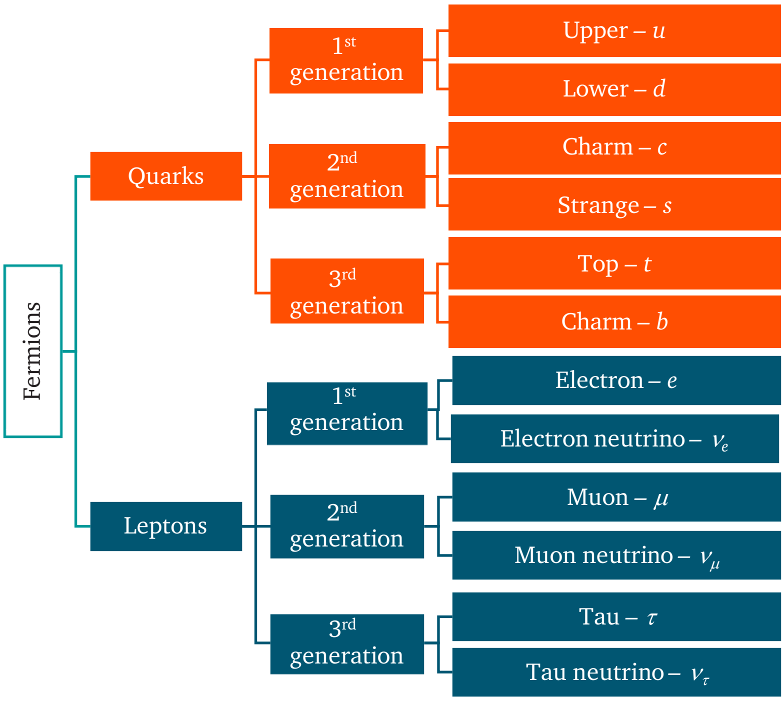

Figure 3. Conceptual diagram of matter fermions

Source: [13]

Classical physical theories are categorically limited in describing the interaction of fermions and bosons on the Planck scale, hence the introduction of quantum physics modelling, which adapts the corresponding fundamental interactions to the quantum level.

Thus, the very first fundamental interaction adapted to the quantum level was quantum electrodynamics (QED), a quantum field (relativistic) theory (formed in the 1940s) that was the first to harmonise quantum mechanics and A. Einstein's special theory of relativity. QED describes the mechanism of electromagnetic force transmission via bosons (in particular, the photon) between charged fermions (reacting to electromagnetic interaction: electrons and quarks). The QED model satisfies three conditions of conformity at once (with a very high level of correlation between empirical and model-predictive data) and has become a template for adapting other fundamental interactions to the quantum level [14].

The peculiarity of the first quantum field adaptation is the development by R.F. Feynman of a special mathematical apparatus based on a convenient graphical representation [15]. Feynman's mathematical apparatus greatly simplified the calculations and was used in other relativistic quantum field adaptations of classical force fields with the account of the boson-fermionic diversity (Fig. 4).

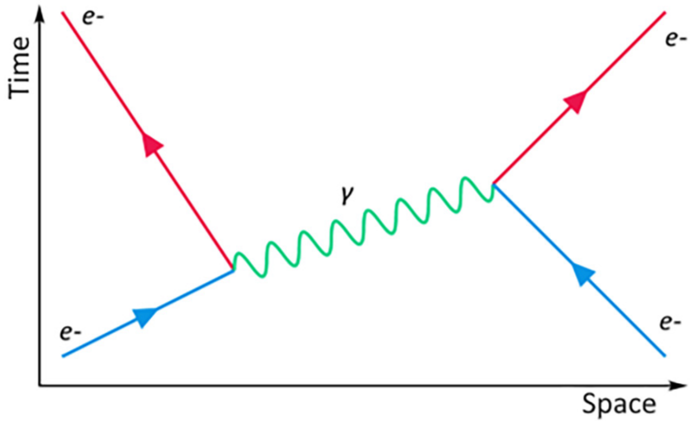

Figure 4. A simple computational case of Feynman's mathematical apparatus demonstrating the electromagnetic interaction between electrons via photon

Source: [15]

The graphically supplemented Feynmanian mathematical apparatus is more informative than the usual mathematical notation given for the calculated case (Fig. 4) - formula :

$$\bar{e}+\bar{e}\xrightarrow{\gamma}\bar{e}+\bar{e}. \qquad (1)$$

The quantum principles underlying quantum field theories (in particular, the principles of quantum uncertainty by W.K. Heisenberg) allow to establish a single chronometry for tracing the motion of a particle, so R.F. Feyman formulated the principle of statistical summation of the contributions of all possible histories of particle motion [16] (Fig. 5).

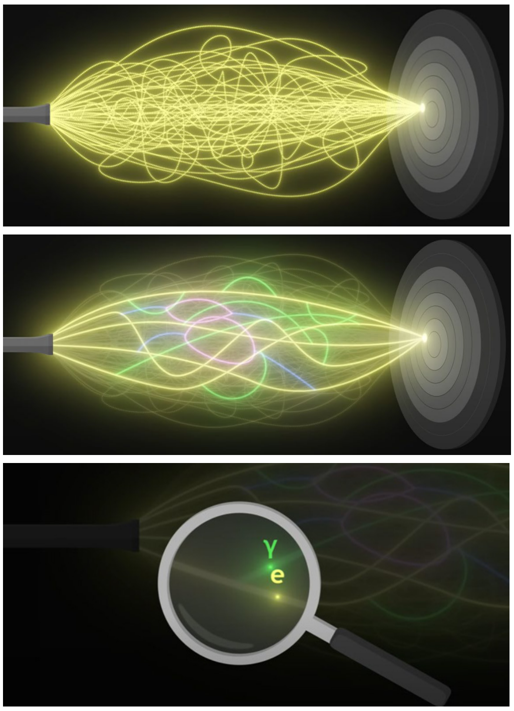

Figure 5. Visualisation of quantum variability based on the uncertainty principle
Source: [15]

Therefore, the summation of contributions from an infinite number of different chronometric trajectories of particles leads to an infinite result, which in turn requires the introduction of a new mathematical method – renormalisation. The renormalisation process involves subtracting values that are assumed to be equal to infinity and negative, so that, with careful mathematical calculation, the sum of the negative infinite values and the positive infinite values that appear in the theory almost balances out, excluding a small residual – the final observed values of mass and charge. Although this method is questionable from a mathematical point of view, the model predictions have a significant correlation with the empirical data [17].

The success of QED prompted further quantum adaptation of other fundamental interactions. Thus, in the 1960s, based on the studies of S.L. Glashow, S. Weinsberg, and M.A. Salam, the electroweak quantum theory was developed, combining QED with weak nuclear interaction. The electroweak interaction model predicted the existence of gauge bosons $W\pm$, Z_0, which are quanta of massless fields, gaining mass according to the Higgs mechanism. This model was empirically confirmed in 1973 at CERN – Conseil Européen pour la Recherche Nucléaire (neutral currents were detected) and in 1983 (based on the results of the international *UA1* and *UA2* experiments) [18].

The next quantum adaptation was made for the strong nuclear interaction, which resulted in the formation of the quantum field theory – quantum chromodynamics (QFT) in 1973, whose creators are D.D. Gross, F. Wilczek, and H.D. Politzer. Within the framework of QCD, thanks to the studies of S.L. Glashow, D. Iliopoulos, and L. Mayan, the concept of the structure of generations of quarks of matter fermions (Fig. 3) was formed. Quantum chromodynamics forms a model of the strong interaction between quarks (hadrons) via gluon fields [19]. The principle of interaction within QCD is also described using the Feynmanian mathematical apparatus (Fig. 6).

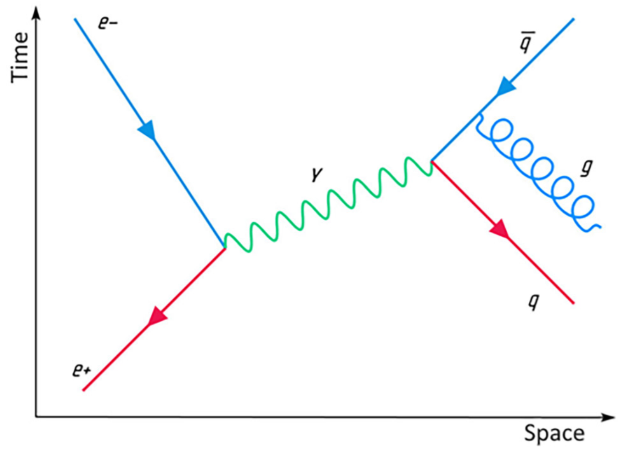

Figure 6. Feynman visualisation of QCD processes (one of the simplest cases): annihilation of an electron and a positron to form a quark from an antiquarian and a photon to emit a gluon
Source: [19]

Gluons in QCD have more bosonic variations than predicted by QCD modelling and were experimentally confirmed in 1979 at the *PETRA* facility. In 2000, thanks to the confirmation of the QCD modelling, a fundamentally new type of matter, the quark-gluon plasma, was discovered at CERN [20]. The quantum adaptation of the strong interaction is based on a more complex mathematical formulation than QED and adopts the conditional mathematical concept of charge colour, and introduces such restrictions and conditions characteristic of this type of modelling as the confinement and asymptotic freedom, which were invented in the formulation and development of the mathematical apparatus of lattice QED [21].

A logical step in the quantum adaptation of fundamental interactions is the quantum gravity model. Even A. Einstein worked on this step in his time [22]. However, the corresponding model has not been formed yet, which is primarily due to the lack of understanding of the process of quantisation of the gravitational interaction: the Einstein energy-momentum tensor acquires the properties of a quantum operator, which implies the need to quantise the geometry of spacetime [23].

The success of the gauge model of the electroweak interaction led to the development of the Grand Unified Theory (GUT) in the 1970s, which described the three fundamental interactions without gravity. A significant drawback of the GUT model is the prediction of proton decay in $10^{>32}$ years, which seems unlikely since the age of the Universe is $10^{>10}$ years. Moreover, it has been experimentally established that the duration of proton decay can be even longer than predicted by the GUT model (more than $10^{>34}$ years) [24]. Thus, on the way to creating a unitary theory of the Whole, humanity has gone through several iterations (Fig. 7).

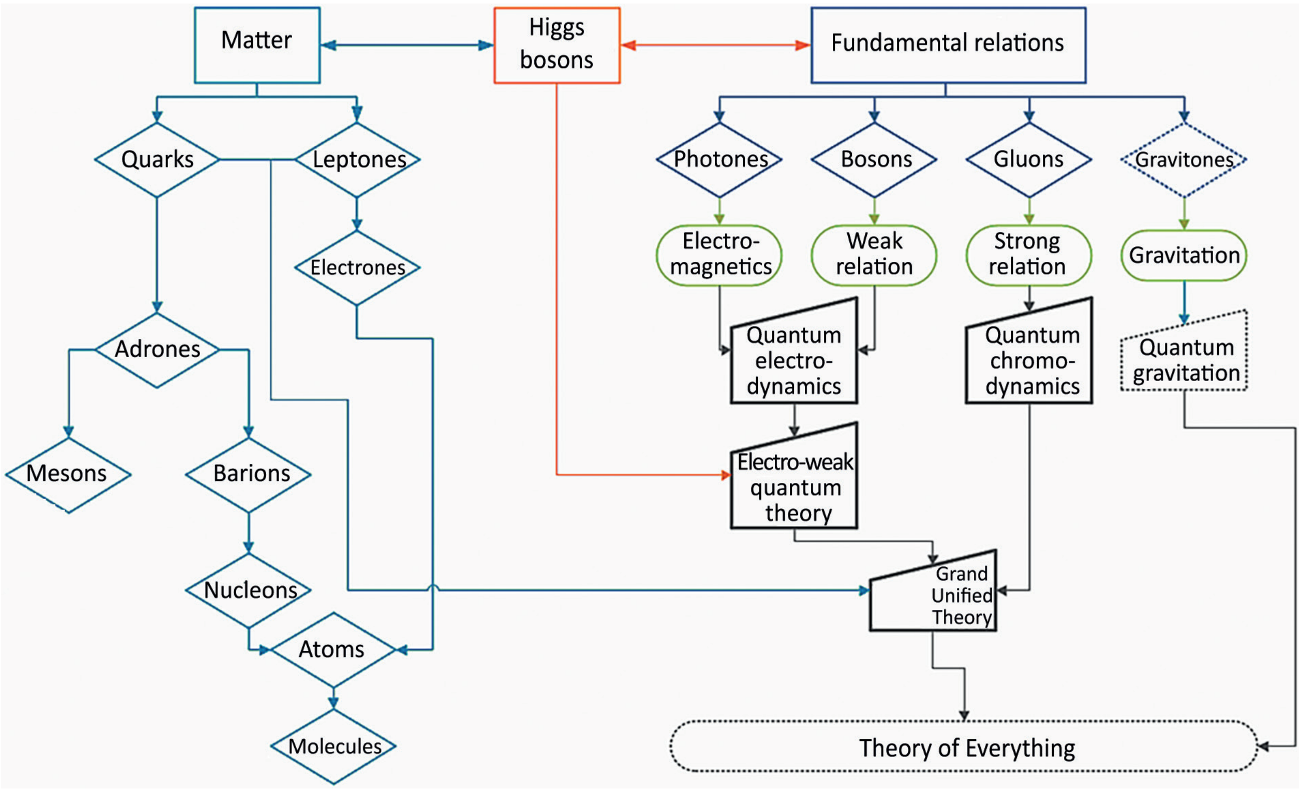

Figure 7. Conceptual diagram of the current state of the Universe modelling with indication of iterations of the development of model-theoretical representations
Note: dotted lines indicate hypothetical structural elements that require the formation of appropriate mathematical and theoretical formulations with subsequent empirical verification
Source: [24]

Experimental confirmation of the existence of the *t*-quark (1995), *b*-quark and tau-neutrino (2000) led to the formulation of a generalised theoretical concept, the Standard Model [13] (Fig. 8). The standard model allowed to systematise the boson-fermion interaction [13] (Fig. 9).

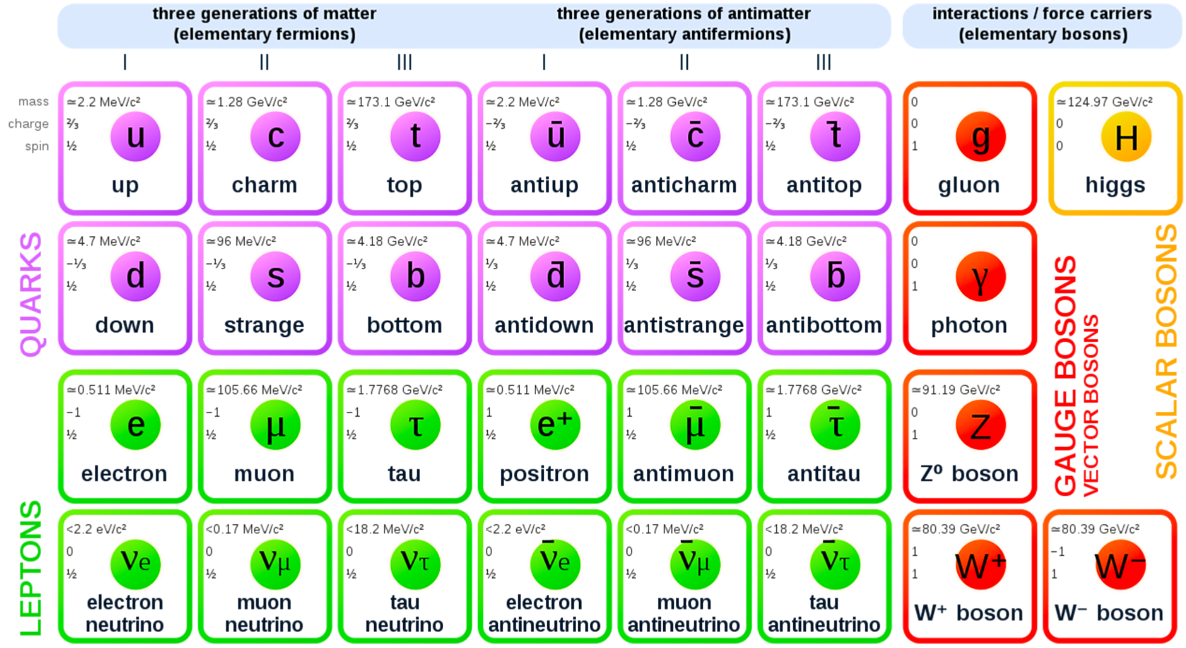

Figure 8. The generally accepted form of the Standard Model

Source: [13]

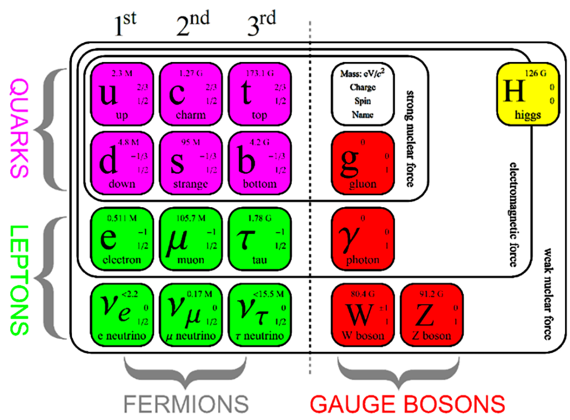

Figure 9. Interaction of bosons and fermions within the Standard Model

Source: [13]

The standard model is formed in compliance with the requirements of invariance of transformations, which form the basis of its mathematical apparatus in the form of local gauge symmetry for the bosonic interaction – formula (2) [25]:

$$SU(3) \times SU(2) \times U(1), \qquad (2)$$

where $SU(3)$ – symmetry group of 8 gluons of the strong interaction (Fig. 8);$SU(2)$ – symmetry group of 3 weak interaction bosons,W^+, W^-, Z^0; $U(1)$ – symmetry group for photons of electromagnetic interaction.

The Standard Model satisfies the conditions of completeness to a limited extent: the existence of gluons (since 1978), bosons W^+, W^-, Z^0 (1983) and H (Higgs boson) (2012) has been experimentally proven, but since 2021, quantum effects have been observed (*LHCb*, *Fermilab*, *CDF*), indicating the need to develop further iterations of modelling in search of a complete model of the Universe (physics beyond the Standard Model) [26].

The Standard Model, among other things (gauge hierarchy, 19 numerical constants, lack of explanations for high-energy physics phenomena, lack of explanations for dark matter and dark energy, etc.), from the point of view of the development of deterministic modelling, has a major drawback – the lack of quantum adaptation of gravitational interaction 13]. The inclusion of gravity in the Standard Model in mathematical modelling leads to the emergence of infinities. Even the application of the renormalisation methods used in QED and QCD does not eliminate the absurdity of mathematical formulations: the Feynmanian apparatus for gravity generates quantum infinities that cannot be eliminated by renormalisation within the framework of general relativity (GR) [13] (Fig. 10).

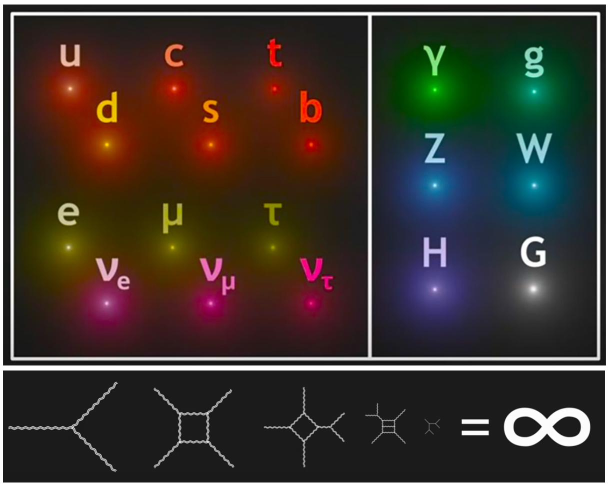

Figure 10. Visualisation of the problems of quantum adaptation of gravitational interaction and its combination with the provisions of the Standard Model

Source: [13]

Following the direction of the Standard Model, to solve the problem of quantum infinities in the mathematical modelling of gravitational interaction, several theoretical formulations have been developed using the principles of supersymmetry, a mathematical model that forms the union of boson-fermion fields by creating hypothetical partners for each of the standardised fundamental particles [27] (Fig. 11).

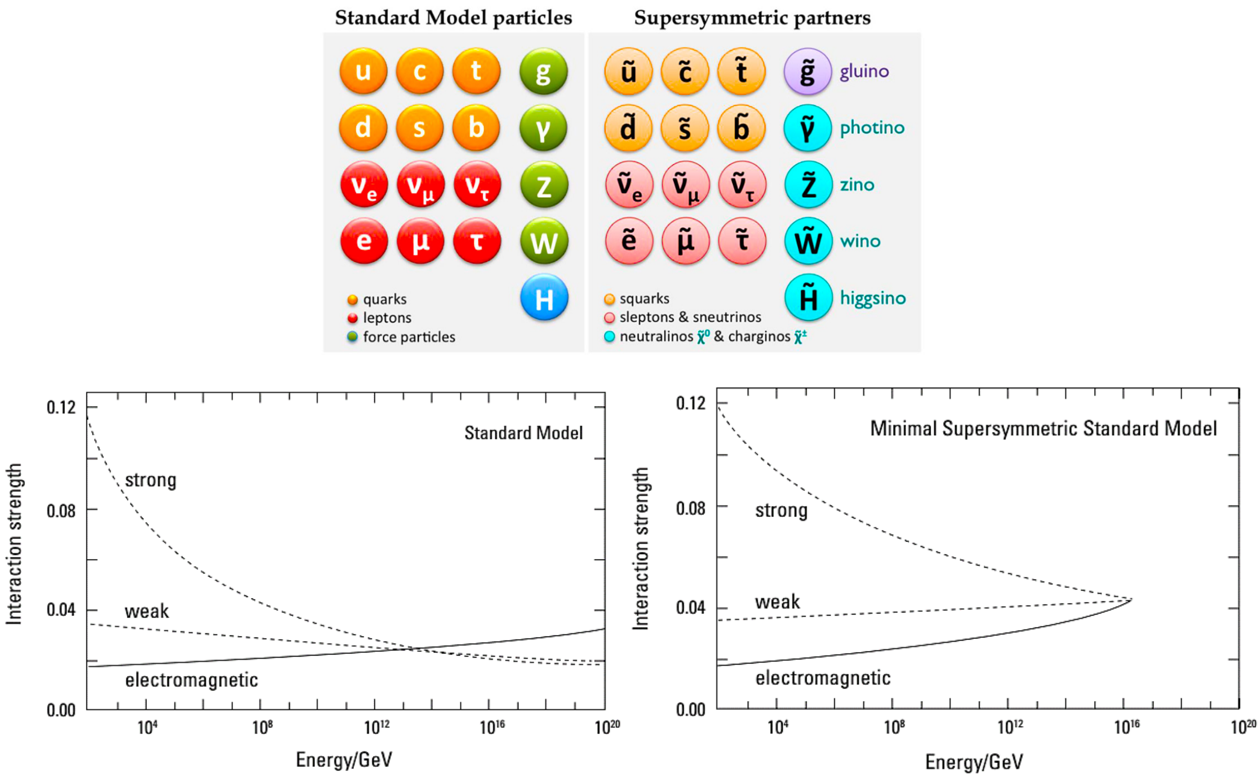

Figure 11. Conceptual diagram of boson-fermion supersymmetry with visualisation of symmetric principles on fundamental interactions (in comparison with the Standard Model)

Source: [27]

In the context of supersymmetric models, a mathematical formulation for supergravity was developed. Supergravity is a mathematical model (a gauge theory of local symmetry) that combines quantum field theories and GR [28]. Supersymmetry and supergravity had the potential to remove quantum infinities, since according to the Feynman rules, positive bosonic infinities annihilated with negative fermionic infinities. The complete calculation and construction of a full-fledged model of supergravity has proved to be an extremely difficult task that has not been solved. Also, no empirical confirmation of the existence of hypothetical supersymmetric boson-fermion partners has been obtained so far [28]. However, the principles of supersymmetry are reflected in a fundamentally new concept of a separate branch of the evolution of the modelling of the Universe – string theory [29]. The main postulate of string theory is that all fundamental particles (bosons and fermions) of the Standard Model (including gravitational interaction quanta) consist of the smallest (currently indivisible) elementary units – quantum strings [3] (Fig. 12). Following the string hypothesis, quantum strings vibrating on the Planck scale form all fundamental particles (fermions) and their interactions (bosons) [4] (Fig. 13).

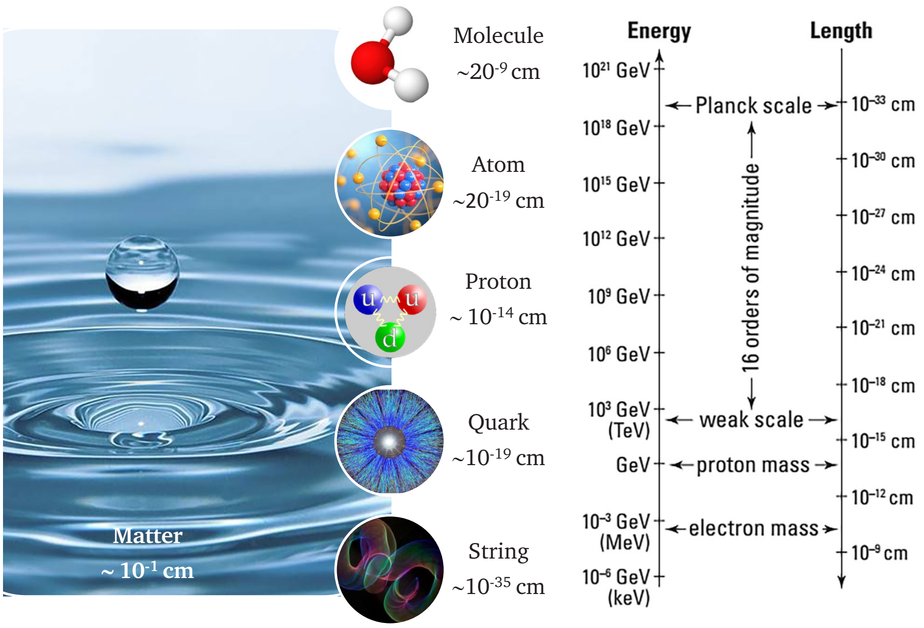

Figure 12. Conceptual scheme for comparing the scale of indivisibility of fundamental particles with the size-energy scale bar

Source: [3]

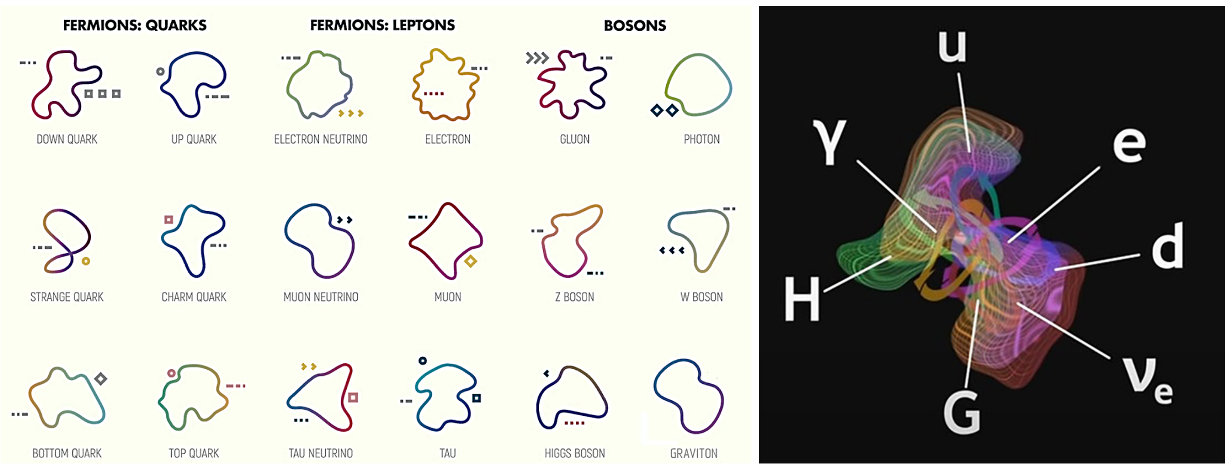

Figure 13. Visualisation of the string level of fundamental particles and fundamental interactions

Source: [4]

String theory combines the theoretical basis of quantum mechanics and Einstein's theory of relativity, and due to the full boson-fermion unification with the involvement of gravity in the model, it has the potential to form the theory of Everything (Fig. 7). A significant advantage of string theory modelling is the absence of the need to apply the renormalisation method and eliminate the problem of quantum infinities [3].

However, despite the mathematical integrity of string modelling, several problems do not allow this theory to satisfy the defined conditions of correspondence. First, it is necessity to use a multidimensional Universe and the corresponding problem of infinite methods of reduction (from 26 to 10) and compactification (from 10 (11) to 4) of dimensions (the so-called "landscape problem" [29]), which in turn leads to the prediction of a multiverse in which different variations of universes with different solutions of multidimensionality compactification are possible, and, accordingly, there is no full description of the mechanism of formation of the low-energy state ("vacuum state") of the observable Universe (also in this case, there are many discussions about the proposed anthropic principle [30]). Secondly, the string theory is inferior in the completeness of the nonperturbative definition to quantum modelling; thirdly, the string theory has no empirical confirmation yet, and the recorded quantisation scales of the gamma-ray burst GRB041219A indicate the need to revise the scale factors of the string model (the quantisation of the radiation was recorded only from the size of 10^{-48}m, which is much smaller than the predicted scale of string formations (Fig. 12)) [3].

The concept of string theory is formed by separate tertiary calculations, which are eventually combined into a generalised model, the *M*-theory [31] (Table 1).

Table 1. Generally accepted systematisation and classification of string modelling

String model type	Dimensionality of the Universe	Supersymmetric multiplicity type (*SUSY generators*)	Chirality	Open strings	Heterotic compacting	Symmetry gauge group	Solving the tachyon condensation problem	Additional info
Bosonic string theory (closed)	26	$N = 0$	–	–	–	–	–	No fermions
Bosonic string theory (open)	26	$N = 0$	–	+	–	$U(1)$	–	No fermions
I type superstring theory	10	$N = 1,0$	+	+	–	$SO(32)$	+	–
IIA type superstring theory	10	$N = 1.1$	–	–	–	$U(1)$	+	Massless nonchiral fermions
IIB type superstring theory	10	$N = 2.0$	+	–	–	–	+	Massless chiral fermions
Heterotic string theory *HO* type	10	$N = 1.0$	+	–	+	$SO(32)$	+	Strings differ in vibrational modes based on the clockwise direction
Heterotic string theory *HE* type	10	$N = 1.0$	+	–	+	$E_8 \times E_8$	+	Strings differ in vibrational modes based on the clockwise direction
Generalised string theory – *M*-theory	11	$N = 1.0$	–	–	–	–	+	A generalised solution of previous superstring models and contains *D*-brane

Source: [31]

The dualities allow combining not only the five main superstring models into a generalised *M*-theory (Fig. 14) but also connecting string modelling with the quantum field theory of supergravity (through the *AdS/CFT* mechanism (Maldacena duality) [32]), which at this stage allows stating the greatest unity of scientific thought in creating a complete model of the Universe (Fig. 15).

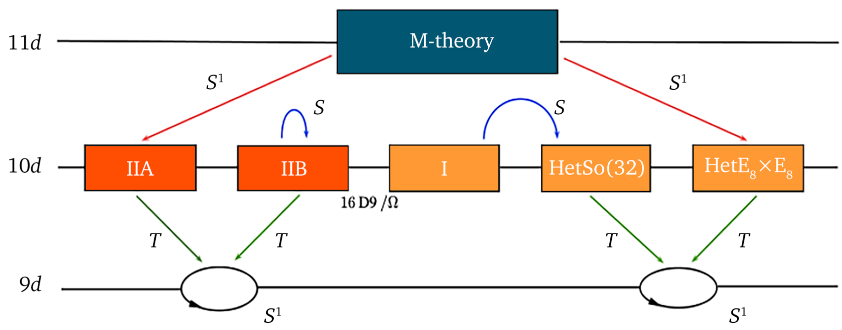

Figure 14. The generally accepted system of dual coupling of superstring models with *M*-theory
Source: [32]

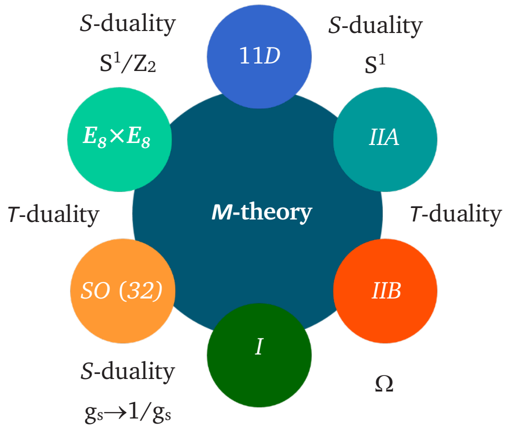

Figure 15. Generalised dual coupling system of superstring models, *M*-theory, and quantum field theory of supergravity (11*D*)
Source: [32]

Therefore, the resulting *M*-theory assumes string and brane formations of different topologies as fundamental parts [33], which can be described using the Feynman mathematical apparatus – Figure 16.

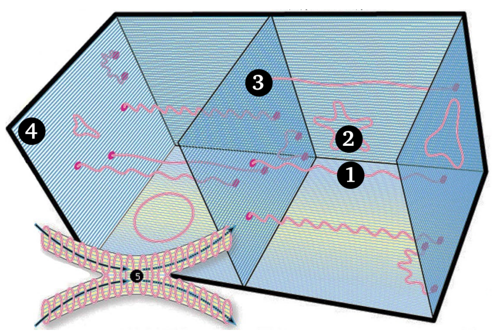

Figure 16. Abstraction of the functioning of the Universe at the level of string-brane formations and interactions within the framework of the generalised unitary *M*-theory
Note 1 – open string formations; 2 – closed string formations; 3 – fixation of open strings; 4 – D-branes; 5 – Feynman mechanism of string interaction
Source: [32]

The use of string-brane formations (Fig. 16) with the corresponding mathematical support (Table 1) and supersymmetry mechanisms allows to provide a model of the full boson-fermion unification, which is de facto the area of contact and coordination of nuclear physics, GR, quantum mechanics and cosmogony of the observable Universe.

Thus, the unitary theoretical positions of the crown of string modelling, the *M*-theory, despite certain contradictions and the lack of technical possibility of empirical testing, have already been successful, proving, if not the correctness of the chosen direction on the way to the theory of Everything, then at least the closeness to the above-mentioned path of development of ideas about the Universe.

After analysing the sources, the following aspects of the relevance of the scientometric landscape of string modelling in the current horizon of bibliometric analysis are stated:

- The development of the theoretical basis of *M*-theory is more intensive compared to string theory itself, but it is more vectorised with clear research directions;
- Among the identified vectors of the current scientific state of string modelling, the most prominent are the holographic principle, six-dimensional branes, brane interpretations, dualities, canonical singularity, etc;

Therefore, the resulting concept of string modelling – *M*-theory – forms the conceptual foundations that explain the functioning of spacetime at the deep Planck level and, although there is no empirical confirmation of string postulates and formulations, it is highly probable that string modelling is the model of the Universe that Einstein hoped to obtain.

Perspectives on string modelling in the quest for a unified theory of Everything

String modelling, as one of the trends in the development of physics outside the Standard Model and de facto not a proven theory, is often criticised by experts, including S.L. Glashow and R.F. Feynman. However, even though there were such prominent physicists in the camp of opponents and critics of string theory, string modelling continued to develop and create common ground with other cosmogonic theories, with quantum adaptations of fundamental interactions and Einstein's principles of relativity.

The paradigm of critical thought regarding the string theory paradigm as a theory of Everything is the thesis that string modelling is only a rough assumption (zero iteration) of quantum adaptation of gravitational interaction to unify it in the Standard Model (as A. Einstein assumed), and not a full-fledged fundamental theory that can explain cosmogony and the existence of the observable Universe (Fig. 7) [2].

In particular, it is worth highlighting the following critical opinions and formulations regarding the relevance of string modelling [34]-[36]:

- based on string theory, it is not possible to obtain a prediction of physical phenomena and processes that could be further tested, and, accordingly, could be either proved or disproved;
- the basic principles of string modelling are not sufficiently clear and fundamental, and do not contain clearly defined criteria, which leads to the generation of sometimes absurd ideas that can be included in the theoretical background;
- there is a significant influence on the development of the theoretical foundations of the opinions and formulations of string physicists-influencers, as opposed to conducting real research;
- string theorists have a significant influence on the social sphere, cultivating ideas about the significant achievement of string modelling, which is not always true since string theory is currently purely conceptual;
- string modelling is quite popular (as mentioned above), which leads to a redistribution of financial flows and academic support to this sector of physics rather than to other theoretical approaches;
- string theory uses complex concepts and mechanisms that not only do not fully (and sometimes not at all) describe the observable universe, but also question recognised physical phenomena and processes;
- the problem of the landscape and falsification of various variations of string theories, as well as numerous possible options for compactifying the multidimensionality of the Universe (it is believed that there are more than 10^{500} such options), which was established in 2003 by the integration of the observed dark energy [37; 38] into string modelling generally calls into question the theoretical basis and fundamentality of string theory, giving rise to such a controversial concept as the anthropic principle [30] (either in a strong or weak formulation), proposed by one of the string influencers L. Susskind.

The criticism of string modelling began in 1998 with the discovery of dark energy, which resulted from the fact that S. Perlmutter, B.P. Schmidt and A. Riess had found that the expansion rate of the Universe was lower earlier, i.e., the 1925 hypothesis of J. Lemaitre that the cosmogonic constant was not stable was confirmed [38].

At present, thanks to the *BOOMERanG, MAXIMA* experiments, the *WMAP* satellite (which observed the microwave anisotropic relic background radiation, which became a tangential proof of the inflationary model of the Universe) and the Planck telescope in the period 2009-2013, it was established that the observed Universe consists of 74% dark matter [39]. The intensity factor of criticism of string modelling was increased by the attempt to explain dark energy within the framework of string theory, which led to the above-mentioned numerous variations of compactification of the multidimensionality of the Universe (and, in fact, to the paradigm of the Multiverse) [40].

Even such ideas as the five-dimensional Randall-Sundrum [41] brane model and the integration of the positive value of the cosmological constant [42] created a perception in the scientific community that these are falsifications to keep attention on string theory. Important figures among those who criticise string theory were L. Smolin and P. Voigt, whose publications significantly intensified the criticism of string theory that spread not only in the scientific world but also publicly [43]. However, even these scientists do not completely exclude string theory, but, as it turned out, strive for a wider range of studies of the Universe, not only string modelling.

String theory, despite its well-developed mathematical formalism, teeters on the edge of science and falsification due to the lack of natural observable evidence, which has led to the formation of two critical principles described below.

Approach 1 – "String theory explains nothing". This position is based on the assertion that over the entire period of development of string modelling, no clear predictions have been made about processes and phenomena in the observable Universe that could be either confirmed or refuted (K. Popper's principle). This critical remark is made in the context of the history of fundamental particle physics, where most elements were predicted and confirmed, which created the fundamentals of nuclear physics and quantum mechanics. Although K. Popper's principle of science falsification does exist and raises the question of the scientific validity of string theory, most scientists disagree with him, because humanity does not currently operate with technologies that would allow high-energy physics experiments. Therefore, there is a high probability that such experiments will be carried out in the future.

However, in this case, the criticism concerns not only string theory in general but most string theorists, who are more interested in reconciling the provisions of string modelling with proven facts and creating interesting mathematical constructions that are largely abstract. It is this basic critical thought that has been cultivated by all string critics from R.F. Feyman to L. Smolin, which is that string modelling has no relation to empiricism and distorts scientific fundamentalism, and most importantly, violates the established approach to research [35]-[37].

Approach 2 – "String theory explains too much". The argumentation of this critical perspective on string modelling is based on the absence of unique predictions, since many theories and mathematical apparatuses of the string landscape describe phenomena and processes with quite different results, which do not give unambiguous statements about the nature of the objects under study, on the contrary, making it impossible to verify research conclusions due to their high variability.

The rapid development of the theory with many unverified results causes the model to lose its relevance as many variations of predictions that cannot be verified significantly worsen the fundamentalism of string theory, even worse than with the first critical principle.

The second critical principle evolves from the principle of Occam's razor: string critics are understandably sceptical of new mathematical constructions and inventions, without which, following string theorists, these models are irrelevant.

One of the solutions to the variability of string modelling predictions is the anthropic principle [30], following which the observable Universe is exactly like this because there are people in it. The anthropic principle (in its strongest formulation) is defended by many factors, without which the existence of life would be impossible (the location of our planet near a single star (about half of the observed stars are binary); the small ellipticity of the orbit, which allows the planet to receive solar radiation relatively evenly; the location of the planet in the circumstellar habitable zone, which ensures the relative stability of the planet's temperature field, etc.). The weak component of the anthropic principle also includes assumptions about the anthropocentricity and creationism of the cosmogony of the observed Universe (in particular, due to its chemical composition (with a predominant amount of carbon as the basis for organic life forms), successful correlations of fundamental interactions (with the corresponding cosmological constant and other constants that are somewhat projective),), the four-dimensionality of the observed Universe (which is associated with gravitational interaction, which, with increasing dimensionality, would lead to instability of matter, which is also interpreted in the successful compactification of dimensions, according to the provisions of string modelling). All of these anthropic assumptions are a violation of the deterministic principles of science and form the opinion in the scientific community that this is a weak defence of string theory. However, considering the prediction of string modelling regarding possible 10^{500} variants of multidimensionality compactification, which leads to the concept of the Multiverse [40], on the contrary, strengthens the deterministic principle of string theory, since it turns out that our Universe is not a unique phenomenon, but only one of many possible variants in which humanity is lucky enough to appear.

Criticism and constant verification of theoretical models and assumptions form the true fundamentalism that is at the heart of civilisational development. Therefore, a critical look at string modelling, which not only sought to rid quantum mechanics of renormalisation methods but also offered potential solutions to quantum gravity in combination with other competing ideas and theories, such as L. Smolin's [44] loop quantum gravity, will allow to form a true model of the universe.

At present, string theory has an elegant mathematical apparatus based on which software and numerical models are possible, but they will still be somewhat abstract, but the expectation of confirmation of supersymmetric partners [27] and gravitational waves [45-47] will significantly strengthen the fundamental nature of string modelling.

Conclusions

Based on the aforesaid, the following conclusions can be drawn. String theory/*M*-theory (in all its variations) is a formalised concept of a model of the Universe with a developed mathematical apparatus that is in dire need of empirical confirmation and fundamental findings to get as close as possible (or refute) to the paradigm of the theory of Everything. The history of the development of string modelling has been going on for more than 50 years (and, considering the first concepts, more than 100 years), but string theory has not come close to the goal of explaining the observable Universe in all its manifestations and interactions. Moreover, the predictions of string modelling have led to the formation of the hypothesis of the Multiverse, in which our Universe is not a unique phenomenon, which, in contrast to the anthropic principle cultivated by the research thought of string theorists, on the contrary, significantly strengthens the deterministic approach to understanding the real picture of the world.

The expected results of high-energy physics experiments to produce supersymmetric boson-fermion partners and detect gravitational waves (*LIGO* and VIRGO detectors) can either refute or confirm the relevance of string modelling. However, while waiting for the empirical data, string theorists have not stood still: as this review shows, the string hypothesis and string mathematics are constantly evolving, focusing on such areas as the holographic principle, six-dimensional branes, brane interpretations, dualities, the canonical singularity, etc.

It is possible that string modelling will prove to be a crude assumption of gravitational interaction quantum adaptation, but this hypothesis has pointed to the possibility of obtaining a generalised Einstein theory of everything. Further research should be accompanied by the study of the mathematical structures of string theory and their reflection on physical phenomena, which can lead to the discovery of new physical laws that will expand the understanding of the Universe.

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Conflict of Interest

None.

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Теорія струн та теорія Всього: огляд досліджень

Абдіміталіп Сатибалдиєв

Кандидат фізико-математичних наук
Харківський національний університет імені В.Н. Каразіна
61022, майдан Свободи, 4, м. Харків, Україна
https://orcid.org/0009-0006-2226-069X

Сирга Бердибекова

Кандидат педагогічних наук
Ошський технологічний університет ім. М.М. Адишева
714018, вул. Ісанова 81, м. Ош, Киргизстан
https://orcid.org/0009-0004-1619-3537

Анарбек Аттокуров

Аспірант
Ошський технологічний університет ім. М.М. Адишева
714018, вул. Ісанова 81, м. Ош, Киргизстан
https://orcid.org/0009-0009-0012-2271

Жанаргул Ігамбердієва

Аспірант
Ошський технологічний університет ім. М.М. Адишева
714018, вул. Ісанова 81, м. Ош, Киргизстан
https://orcid.org/0009-0000-3795-9408

Анотація

Актуальність. Моделювання є основним інструментом для розуміння навколишнього світу, процесів і явищ. Моделі, якими використовується людство в сучасний час, фактично є фрагментарними (дискретними) із певними варіаціями корелятивних узагальнень. Тому людство постійно шукає математичні формулювання, які могли б охопити повну картину Всесвіту.

Мета. Метою дослідження є аналіз еволюції теоретичної та модельної основи фізичної картини світу з ідентифікацією перспективних дослідницьких векторів, що мають потенціал формувати широкі узагальнені моделі Всесвіту, тобто теорію Всього.

Методологія. Для досягнення мети були використані методи систематизації та узагальнення, метааналізу та метасинтезу. Оскільки це дослідження є оглядом і призначене для систематизації та поглиблення знань, воно побудоване на нетрадиційній структурі.

Результати. Описано поточну модель наукового ландшафту, на основі якої були визначені рухливі вектори розвитку теоретичної основи теорії Всесвіту, що дозволило зробити висновок про поточний стан системи фізичного моделювання як основного інструменту цивілізаційного розвитку людства. Дослідження дозволяє встановити, що на даному етапі розвитку ідей про фізичну картину світу М-теорія є потенційною моделлю теорії Всього.

Висновки. Практична значущість результатів дослідження вказує на потенційну математичну та теоретичну концепцію (серед існуючих теорій та моделей), яка є адекватною сучасним уявленням про космогонію, явища та структуру Всесвіту та дозволяє залучити більше уваги до певного напряму наукових досліджень, не лише серед професійної спільноти, але і серед загальної громадськості.

Ключові слова: стандартна модель; квантова хромодинаміка; квантова електродинаміка; квантова гравітація; велика єдина теорія; М-теорія