

# Planck Scale Physics, Gravi-Weak Unification and the Higgs Inflation

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## Abstract

Starting with a theory of the discrete space-time at the Planck scale, we developed a Gravi-Weak Unification (GWU) - a  $Spin(4,4)$ -invariant model unified gravity with weak  $SU(2)$  gauge and Higgs fields in the visible and invisible sectors of the Universe. Considering the Gravi-Weak symmetry breaking, we showed that the obtained sub-algebras contain the self-dual left-handed gravity in the OW, and the anti-self-dual right-handed gravity in the MW. Finally, at the low energy limit, we have only the Standard Model (SM) and the Einstein-Hilbert's gravity. The Froggatt-Nielsen's prediction of the top-quark and Higgs masses was given in the assumption that there exist two degenerate vacua in the SM. This prediction was improved by the next order calculations. We have developed a model of the Higgs Inflation using the GWU action. According to this inflationary model, a scalar field (inflaton) starts trapped from the "false vacuum" of the Universe at the Higgs field's VEV  $v_2 \sim 10^{18}$  GeV. The interaction between the ordinary and mirror Higgs fields  $\phi$  and  $\tilde{\phi}$  generates a Hybrid model by A. Linde of the Higgs Inflation in our Universe.

## Contents:

1. Introduction.
2. Discrete space-time of the Universe at the Planck scale.
  - a) Sidharth's theory of the discrete space-time.
  - b) Random Dynamics and Multiple Point Principle.
3. Plebanski's formulation of General Relativity.
4. Gravi-Weak Unification in the visible sector of the Universe.
5. Mirror world with broken mirror parity.
  - a) Communications between visible and hidden worlds.
  - b) Gravi-Weak action in the invisible (mirror) sector of the Universe.
6.  $U(4)$ -group of fermions.
7. Multiple Point Model and the prediction of the top and Higgs Masses.
8. The Higgs Inflation model with the mirror Higgs boson.
  - a) The GWU action and the self-consistent Higgs Inflation model.
9. Summary and Conclusions.

# 1 Introduction

In this investigation we start with a theory of the discrete space-time by B.G. Sidharth [1–4], existing at the very small (Planck length) distances. Using the results of non-commutativity, the author has shown that in our Universe the cosmological constant (or dark energy density) is almost zero in initial stage of the Universe and so far.

Random Dynamics (RD), suggested by H.B. Nielsen [5, 6] and his collaborators [7–12], is also related with a discrete space-time. RD assumes that at the very small Planck scale distances the fundamental law of the Nature is randomly chosen from a large set of different theories. We assume that such an initial theory, randomly chosen at the Planck scale, is a theory with a group of symmetry:

$$G = G_{(GW)} \times U(4), \quad (1)$$

where  $G_{(GW)}$  is a group of Gravi-Weak Unification:

$$G_{(GW)} = SO(4, 4) \sim Spin(4, 4), \quad (2)$$

and  $U(4)$  is a group of fermions. Previously gravi-weak and gravi-electro-weak unified models were suggested in Ref. [13–15]. The gravi-GUT unification was developed in [16–19]. In Ref. [20] a model of unification of gravity with the weak  $SU(2)$  gauge and Higgs fields was constructed, in accordance with Ref. [21]. However, in contrast to Ref. [21], we assume the existence of the hidden sector of the Universe, when this hidden world is a Mirror World (MW) with broken Mirror Parity (MP) (see Refs. [22–26] and reviews [27–30]). In the present paper we give arguments that MW is not identical to the visible Ordinary World (OW). We consider an extended  $\mathfrak{g} = \mathfrak{spin}(4, 4)_L$ -invariant Plebanski action in the visible Universe, and  $\mathfrak{g} = \mathfrak{spin}(4, 4)_R$ -invariant Plebanski action in the MW. Then we show that the Gravi-Weak Unification symmetry breaking leads to the following sub-algebras:  $\mathfrak{g}_1 = \mathfrak{sl}(2, C)_L^{(grav)} \oplus \mathfrak{su}(2)_L$  – in the ordinary world, and  $\tilde{\mathfrak{g}}_1 = \tilde{\mathfrak{sl}}(2, C)_R^{(grav)} \oplus \tilde{\mathfrak{su}}(2)_R$  – in the hidden world. These sub-algebras contain the self-dual left-handed gravity in the OW, and the anti-self-dual right-handed gravity in the MW. Finally, at low energies, we obtain the Standard Model (SM) group of symmetry and the Einstein-Hilbert’s gravity. In this approach we construct a model of the Inflation, in which the inflaton  $\sigma$ , being a scalar field, during inflation decays into the two Higgs doublets of the SM:  $\sigma \rightarrow \phi^\dagger \phi$ , and then the interaction between the ordinary and mirror Higgs boson fields develops the Hybrid model of the Inflation [32].

## 2 Discrete space-time of the Universe at the Planck scale

At present time the physicists are keenly and persistently searching for some fundamental theory at the Planck scale, at very small distances, much smaller than we can study directly experimentally (with present accelerators). Trying to look insight the Nature and considering the physical processes at small distances, physicists have made attempts to explain the well known low-energy Standard Model (SM) results as a consequence of the Planck scale physics.

Here we have two possibilities:

- 1) At the very small (Planck length) distances our space-time is continuous and there exists a fundamental theory maybe with a very high symmetry.
- 2) At the very small distances our space-time is discrete, and this discreteness influences on the Planck scale physics and beyond it.

In this talk we review, discuss and classify some attempts (exactly, only few examples) to guess such a fundamental theory, which could be the fundamental Theory of the Everything (TOE).

We shall first look at how we might classify such theories.

It is one very important classification separation: whether in the space-time we have all points (continuum), or we have only certain points, rather than all of them. Here, of course, we refer to lattice-like theories as the ones with only some points of space existing, while the continuum space-time represents all Grand Unification Theories (GUTs), superstring theory, General Relativity (GR), supersymmetry, etc. As an example of a continuum space-time having all points, can be considered a theory with the Euclidean geometry in the modern axiomatic formulation (Hilbert's axiomatic representation).

There are many ways to vary in details of how a theory could have only discrete points. The assumption that (3+1)- dimensional space-time is discrete on the fundamental level is an initial (basic) point of view of the present investigation: we take the discreteness as existing, not as the lattice computation trick (as in QCD, say). In the simplest case we can imagine our (3 + 1) space-time as a regular hypercubic lattice with a parameter  $\lambda_{Pl}$ , where  $\lambda_{Pl}$  is the Planck length. But of course we do not know (at least, on the level of our today knowledge), what lattice-like structure (random lattice, or graphene, or any crystal, or foam, or string lattice, etc.) is realized in the description of physical processes at the very small distances.

Modern Fuzzy Space-time models, Loop Quantum Gravity (see for example [33]) and a few other approaches start from the Planck scale as a minimum scale of the Universe. This is also the starting point of the alternative theory, which was developed by B.G. Sidharth in his book [1] and in the large number of his papers (see Refs. [2–4]). It has been considered that the space-time is fuzzy, more generally non-differentiable, and is presented by a non-commutative geometry. The concept of non-commutativity leads to an essential predictions, described in the book [1] and used in the present paper.

Random Dynamics (RD), suggested and developed by H.B. Nielsen and his collaborators [5–12], also is a theory of physical processes proceeding at small distances of order of the Planck length. RD tries to derive the laws of physics known today by the use of almost no assumptions.

Previously the efforts to construct a fundamental theory had led to the Grand Unified Theories (GUTs), especially Supersymmetric SUSY GUTs, which had an aim to give an unified self-consistent description of electroweak and strong interactions by one simple group:  $SU(5)$ ,  $SU(6)$ ,  $SO(10)$ ,  $E_6$ ,  $E_8$ , etc.

The group of Theory of the Everything (TOE) was suggested in Refs. [16]. But at present time the experiment does not indicate any manifestation of these theories.

The next step to search the fundamental theory was a set of theories describing the extended objects: strings, superstrings and  $M$ -theories. They came into existence due to the necessity of unification of electroweak and strong interactions with gravity.

RD is an alternative to these theories. The above mentioned theories are based on some fixed axioms. If namely one of these axioms is changed a little bit, then the theory also is changed and often becomes not even consistent. In RD we have the opposite case. RD is based on the very general assumptions, which take place at the fundamental scale.

Theory of Scale Relativity (SR) [34] is also related with a discrete space-time. This theory assumes that the resolution of experimental measurements plays in quantum mechanics an important role. Suggesting to consider the non-differentiable space-time, L. Nottale built the microphysical world on the concept of the fractal space-time. This non-differentiability implies an explicit dependence of space-time on scale. The principle of relativity was applied not only to motion, but also to scale transformation, because the resolution measurements must be taken into account in definition of the coordinate system.

The resolution of the measurement apparatus plays in quantum physics a completely new role with respect to the classical, since the result of measurements depends on it as a consequence of Heisenberg's relations.

The resolution characterizes the system under consideration. Complete information about the measurement position and time can be obtained, when not only space-time coordinate  $(t, x, y, z)$ , but also resolutions  $(\Delta t, \Delta x, \Delta y, \Delta z)$  are taken into account. As a result, we expect that the space-time to be described by a metric:

$$g_{\mu\nu} = g_{\mu\nu}(t, x, y, z; \Delta t, \Delta x, \Delta y, \Delta z).$$

In connection with a theory of the discrete space-time, we can mention the model by H. Kleinert [35], in which he has shown that there exists a close analogy of geometry of space-time in GR with a structure of a crystal with defects. Kleinert's model considers the translational defects – dislocations, and the rotational defects – disclinations – in the 3- and 4-dimensional crystals. Ref. [36] presents the relation between the Kleinert's model of a crystal and the Plebanski's formulation of gravity. It was shown that the tetrads in gravitational theory are dislocation gauge fields, and the connections are the disclination ones, the curvature is the field strength of connections, and the torsion is the field strength of tetrads.

In this investigation we start with a theory of the discrete space-time by B.G. Sidharth [1].

## 2.1 Sidharth's theory of the discrete space-time and the predictions of non-commutativity

The concept of the discrete space-time (item 2) is a base of the theory, which was developed by B.G. Sidharth in his book [1] and in his papers, for example, in Refs. [2–4].

B.G. Sidharth was first (1997 year) - before the discovery of S. Perlmutter's et al. [37] in 1998 year, - who has shown that a cosmological constant is very small:

$$\Lambda \sim H_0^2,$$

where  $H_0$  is the Hubble rate. Then the Dark Energy (DE) density is also very small:

$$\rho_{DE} \sim 10^{-48} \text{ GeV}^4,$$

what provided the accelerating expansion of our Universe after the Big Bang.

B.G. Sidharth deduced the cosmological constant and dark energy density from the following points of view.

Modern Quantum Gravity (Loop Quantum Gravity [33], etc.) deal with a non-differentiable space-time manifold. In such an approach there exists a minimal space-time cut off, which leads to the non-commutative geometry, a feature shared by the Fuzzy Space-Time also [1, 38–41].

A starting point of the book [1] is the well known fact that in random walk, the average distance  $l$  covered at a stretch is given by

$$l = R/\sqrt{N}, \quad (3)$$

where  $R$  is the dimension of the system and  $N$  is the total number of steps.

The Eq. (3) is true in the Universe itself with  $R_{un}$  being the radius of the Universe  $\sim 10^{28}cm$ ;  $N_{un}$  is the number of elementary particles in the Universe ( $N_{un} \sim 10^{80}$ ), and  $l$  is the Compton wavelength of the typical elementary particle with mass  $m$  ( $l = m/\hbar c$ ) ( $l \sim 10^{-10}cm$  for electron).

A similar equation for the Compton time exists in terms of the age ( $T_{un}$ ) of the Universe:

$$T_{un} = \sqrt{N_{un}}\tau, \quad (4)$$

where  $\tau$  is a minimal time interval (chronon).

Eqs.(3) and (4) arise quite naturally in a cosmological scheme based on fluctuations.

If we imagine that the Universe is a collection of the Planck mass oscillators, then the number of these oscillators is:

$$N_{un}^{Pl} \sim 10^{120}. \quad (5)$$

If the space-time is fuzzy, more generally non-differentiable, then it has to be described by a non-commutative geometry with the coordinates obeying the following commutation relations:

$$[dx^\mu, dx^\nu] \approx \beta^{\mu\nu} l^2 \neq 0. \quad (6)$$

Eq. (6) is true for any minimal cut off  $l$ .

Previously the following commutation relation was considered by H.S. Snyder [38]:

$$[x, p] = \hbar[1 + (\frac{l}{\hbar})^2 p^2], \text{ etc.}, \quad (7)$$

which shows that effectively 4-momentum  $p$  is replaced by

$$p \rightarrow p(1 + \frac{l^2}{\hbar^2} p^2)^{-1}, \quad (8)$$

and the energy-momentum formula now becomes as:

$$E^2 = m^2 + p^2(1 + \frac{l^2}{\hbar^2} p^2)^{-2}, \quad (9)$$

or

$$E^2 \approx m^2 + p^2 - \gamma \frac{l^2}{\hbar^2} p^4, \quad (10)$$

where  $\gamma \sim 2$ .

In such a theory the usual energy momentum dispersion relations are modified [3, 4].

In the above equations  $l$  stands for a minimal (fundamental) length, which could be the Planck length, or more generally Compton wavelength. It is necessary to note, that if we neglect order of  $l^2$  terms, then we return to the usual quantum theory, or quantum field theory. Writing Eq. (10) as

$$E = E' - E'', \quad (11)$$

where  $E'$  is the usual (old) expression for energy, and  $E''$  is the new additional term in modification [4],  $E''$  can be easily verified as

$$E'' = mc^2. \quad (12)$$

In Eq. (12) the mass  $m$  is the mass of the field of bosons.

Furthermore it was shown, that (10) is valid only for boson fields, whereas for fermions the extra term comes with a positive sign [2–4]. In general, we can write:

$$E = E' + E'', \quad (13)$$

where  $E'' = -m_b c^2$  – for boson fields, and  $E'' = +m_f c^2$  – for fermion fields (with mass  $m_b, m_f$ , respectively).

These formulas help to identify the DE density, what was first realized by B.G. Sidharth in Ref. [2].

DE density is the density of the quantum vacuum energy of the Universe. Quantum vacuum, described by Zero Point Fields (ZPF) contributions, is the lowest state of any Quantum Field Theory (QFT), and due to Heisenberg's principle has an infinite value, which is "renormalizable".

Quantum vacuum of the Universe can be a source of cosmic repulsion (see [43] and [42]). However, a difficulty in this approach has been that the value of the cosmological constant turns out to be huge, far beyond what is observed by astrophysical measurements. This has been called "the cosmological constant problem" [44].

The mysterious ZPF contributions, or quantum vacuum energy density (dark energy DE), has been experimentally confirmed by astrophysical measurements. It is given by the following value [45–47]:

$$\rho_{DE} \approx (2.3 \times 10^{-3} eV)^4. \quad (14)$$

The value of cosmological constant  $\Lambda$  is related with  $\rho_{DE}$  by the following way:

$$\Lambda = 8\pi G_N \rho_{DE} = \rho_{DE} / (M_{Pl}^{(red.)})^2, \quad (15)$$

where  $G_N$  is the Newton's gravitational constant, and  $M_{Pl}^{red.}$  is the reduced Planck mass.

Using the non-commutative theory of the discrete space-time, B.G. Sidharth predicted in [1, 2] the value of cosmological constant  $\Lambda$ :

$$\Lambda \simeq H_0^2, \quad (16)$$

where  $H_0$  is the Hubble rate (see [45–47]):

$$H_0 \simeq 1.5 \times 10^{-42} \text{ GeV}. \quad (17)$$

The very interesting predictions of the non-commutativity lead to the physically meaningful relations, including a rationale for the Dirac equation and the underlying Clifford algebra (see [42]).

B.G. Sidharth also predicted the light neutrino mass and tried to extract cosmological constant from the Fermi energy of the cold primordial neutrino background [48].

In connection with a theory of the non-commutativity, it is useful to see [49].

We have essentially used the results of [1] in our Higgs inflation model.

## 2.2 Random Dynamics and Multiple Point Principle

Random Dynamics (RD) was suggested and developed in Refs. [5–11] (see also a review [12]) as a theory of physical processes proceeding at small distances of order of the Planck length.

In Random Dynamics dream (speculation) it is hoped that the physics at very small distances is almost unimportant for what the effective laws to be observed by physicists working with energies per particle up to only a few TeV. So one could crudely say: Random Dynamics does NOT know the physics at small distances. It also does not matter is the hope. But if one has in mind that the true mathematical definition of the even uncountable set of real numbers is a bit tricky, one might say that we can hardly believe that the most fundamental physics should be based on manifolds truly.

Based on the very general assumptions at the fundamental level, the RD argues: the fundamental laws of the Nature are so complicated that it is preferable to think that at very small distances there are no laws at all, our space-time is discrete and the physical processes are described randomly. Then the fundamental law of the Nature is one, which was randomly chosen from a large set of sufficiently complicated theories, and this one leads to the laws observed in the low-energy limit of our experiment.

The lattice model of gauge theories is the most convenient formalism for the realization of the RD ideas.

In lattice Monte Carlo calculations with lattice theories with several action terms coming with each its coefficient (coupling), say traces of different representations of the plaquette variables  $U(\square)$ , one finds phase transitions and even say a triple point. There can then even be phases some invariant subgroup such as say  $Z_N$  of  $SU(N)$  could have confinement at the lattice scale, while the full group might first be confining at a much longer space scale.

Long ago [50] (see also [51]) it was used the assumption that the coefficients in the lattice action were just being adjusted to be at the triple or higher point - Multiple Critical Point (MCP) - in the phase diagram of a theory, to fit finestructure constants in the Antigrand model [52, 53]. The Anti-GUT model, in which each family of quarks and leptons have their own Standard Model group were inspired by some random dynamics thinking.

The a priori mysterious assumption that the coefficients in the lattice gauge theory action should be just at the critical point, where several phases meet, gave rise to that D.L. Bennett and H.B. Nielsen [50] invented the idea of "Multiple Point Principle" (MPP), which claims that coupling constants get adjusted to bring the vacuum into multiple point where several phases, several types of vacua, can coexist in the sense of having the same

energy density.

At first, this MPP seems not to be a consequence of random dynamics thinking, but by a somewhat round about argumentation one can however claim that indeed random dynamics leads to the multiple point principle, which postulates: all vacua which might exist in the Nature (as minima of the effective potential) should have zero, or approximately zero cosmological constant.

One relatively recent claim in the RD is that even if the action were complex, rather than real as usually assumed, it would approximately not be seen in the usual equations of motion and only some predictions about the initial state, or rather about what really happens, would reveal the imaginary part of the action (or equivalently the anti-Hermitian part of the Hamiltonian). If one use this result to assume that there fundamentally is an imaginary part also of the action, this leads to an extremization principle that this imaginary part of the action should be minimized - as may be crudely seen by thinking of the Wentzel-Dirac-Feynman path way integral, in which the integrand goes exponentially down numerically with increasing imaginary part of the action. If it were even speculated, that somehow the coupling constant in the effective theory could also be varied in the search for minimal imaginary part of the action, then it could very easily happen that we got several degenerate vacua, i.e. we could then very likely get the multiple point principle [11].

Finally, we conclude that the Multiple Point Model (MPM) [50, 51] postulates: *there are many vacua in the Universe with the same energy density, or cosmological constant, and all cosmological constants are zero, or approximately zero.*

For example, N. Arkani-Hamed [54] referred to the modern cosmological theory, which assumes the existence of a lot of degenerate vacua in the Universe.

In Ref. [55] the existence of different vacua of our Universe was explained by the MPP. It was shown that these vacua are regulated by the baryon charge and all coexisting vacua exhibits the baryon asymmetry. The present baryon asymmetry of the Universe was discussed.

MPM is a base for the new model of the Higgs inflation developed in the present paper.

### 3 Plebanski's formulation of General Relativity

Previously we have constructed a model unifying gravity with some, e.g. weak SU(2) gauge and the "Higgs" scalar fields - so called Gravi-Weak Unification (GWU) model [20]. We developed our GWU model in accordance with a general model of unification of gravity, gauge and Higgs fields, suggested in Ref. [21]. Constructing the GWU-model, we have used an extension of the Plebanski's 4-dimensional gravitational theory [56], in which the fundamental fields are two-forms containing tetrads and spin connections, and in addition, certain auxiliary fields.

Theory of General Relativity (GR) was formulated by Einstein as dynamics of the metrics  $g_{\mu\nu}$ . Later, Plebanski [56], Ashtekar [57] and other authors [58, 59] presented GR in a self-dual approach, in which the true configuration variable is a self-dual connection corresponding to the gauging of the local Lorentz group,  $SO(1, 3)$ , or the spin group,  $Spin(1, 3)$ .

In the Plebanski's formulation of the 4-dimensional theory of gravity [56–59], the gravitational action is the product of two 2-forms, which are constructed from the connections  $A^{IJ}$  and tetrads (or frames)  $e^I$  considered as independent dynamical variables. Both  $A^{IJ}$  and  $e^I$  are 1-forms:

$$A^{IJ} = A_{\mu}^{IJ} dx^{\mu} \quad \text{and} \quad e^I = e_{\mu}^I dx^{\mu}. \quad (18)$$

Also 1-form

$$A = \frac{1}{2} A^{IJ} \gamma_{IJ} \quad (19)$$

is used, in which the generators  $\gamma_{IJ}$  are products of generators of the Clifford algebra  $Cl(1, 3)$ :

$$\gamma_{IJ} = \gamma_I \gamma_J, \quad (20)$$

where  $\gamma_I$  is the Dirac matrix.

Indices  $I, J = 0, 1, 2, 3$  belong to the space-time with Minkowski's metrics  $\eta^{IJ} = \text{diag}(1, -1, -1, -1)$ , which is considered as a flat space, tangential to the curved space with the metrics  $g_{\mu\nu}$ . In this case connection belongs to the local Lorentz group  $SO(1, 3)$ , or to the spin group  $Spin(1, 3)$ .

In general case of unifications of gravity with the  $SO(N)$ , or  $SU(N)$ , gauge and Higgs fields, the gauge algebra is  $\mathfrak{g} = \mathfrak{spin}(p, q)$ , where  $p = q = 1 + N$  and we have  $I, J = 1, 2, \dots, p+q$ . In our model of unification of gravity with the weak  $SU(2)$  interactions we considered a group of symmetry with the Lie algebra  $\mathfrak{spin}(4, 4)$  (the group  $Spin(4, 4)$  is isomorphic to  $SO(4, 4)$ -group). In this model, indices  $I, J$  run over all  $8 \times 8$  values:  $I, J = 1, 2, \dots, 7, 8$ .

For the purpose of construction of the action for any unification theory, the following 2-forms are also considered:

$$B^{IJ} = e^I \wedge e^J = \frac{1}{2} e_{\mu}^I e_{\nu}^J dx^{\mu} \wedge dx^{\nu}, \quad F^{IJ} = \frac{1}{2} F_{\mu\nu}^{IJ} dx^{\mu} \wedge dx^{\nu}, \quad (21)$$

where

$$F_{\mu\nu}^{IJ} = \partial_{\mu} A_{\nu}^{IJ} - \partial_{\nu} A_{\mu}^{IJ} + [A_{\mu}, A_{\nu}]^{IJ} \quad (22)$$

determines the Riemann-Cartan curvature:

$$R_{\kappa\lambda\mu\nu} = e_{\kappa}^I e_{\lambda}^J F_{\mu\nu}^{IJ}. \quad (23)$$

Also 2-forms  $B$  and  $F$  are considered :

$$B = \frac{1}{2} B^{IJ} \gamma_{IJ}, \quad F = \frac{1}{2} F^{IJ} \gamma_{IJ}, \quad F = dA + \frac{1}{2} [A, A]. \quad (24)$$

The well-known in literature Plebanski's  $BF$ -theory is submitted by the following gravitational action with nonzero cosmological constant  $\Lambda$ :

$$I_{(GR)} = \frac{1}{\kappa^2} \int \epsilon^{IJKL} \left( B^{IJ} \wedge F^{KL} + \frac{\Lambda}{4} B^{IJ} \wedge B^{KL} \right), \quad (25)$$

where  $\kappa^2 = 8\pi G_N$ ,  $G_N$  is the Newton's gravitational constant, and  $M_{Pl}^{red.} = 1/\sqrt{8\pi G_N}$  is the reduced Planck mass.

Considering the dual tensors:

$$F_{\mu\nu}^* \equiv \frac{1}{2\sqrt{-g}}\epsilon_{\mu\nu}^{\rho\sigma}F_{\rho\sigma}, \quad A^{*IJ} = \frac{1}{2}\epsilon^{IJKL}A^{KL}, \quad (26)$$

we can determine self-dual (+) and anti-self-dual (-) components of the tensor  $A^{IJ}$ :

$$A^{(\pm)IJ} = (\mathcal{P}^\pm A)^{IJ} = \frac{1}{2}(A^{IJ} \pm iA^{*IJ}). \quad (27)$$

Two projectors on the spaces of the so-called self- and anti-self-dual tensors

$$\mathcal{P}^\pm = \frac{1}{2}(\delta_{KL}^{IJ} \pm i\epsilon_{KL}^{IJ})$$

carry out the following homomorphism:

$$\mathfrak{so}(\mathbf{1}, \mathbf{3}) = \mathfrak{sl}(\mathbf{2}, \mathbf{C})_{\mathbf{R}} \oplus \mathfrak{sl}(\mathbf{2}, \mathbf{C})_{\mathbf{L}}, \quad (28)$$

where  $R, L$  mean Right and Left, respectively.

As a result, Eq.(28) gives that the non-zero components of connections are only:

$$A^{(\pm)i} = \pm 2A^{(\pm)0i}, \quad (29)$$

where  $I = 0, i$ , and  $i = 1, 2, 3$ .

Instead of the (anti-)self-duality, the terms of the left-handed (+), or  $L$ , and right-handed (-), or  $R$ , components are used.

Plebanski [56] and the authors of Refs. [57–59] suggested to consider a gravitational action in the visible O-world as a left-handed  $\mathfrak{sl}(2, C)_L^{(grav)}$ -invariant action, which contains only self-dual fields  $F = F^{(+i)}$  and  $\Sigma = \Sigma^{(+i)}$  ( $i=1,2,3$ ):

$$I_{(grav)}(\Sigma, A, \psi) = \frac{1}{\kappa^2} \int \left[ \Sigma^i \wedge F^i + (\Psi^{-1})_{ij} \Sigma^i \wedge \Sigma^j \right] \quad (30)$$

with

$$(\Psi^{-1})_{ij} = \psi_{ij} - \frac{\Lambda}{6}\delta_{ij}. \quad (31)$$

Here  $\Sigma^i = 2B^{0i}$ , and  $\Psi_{ij}$  are auxiliary fields defining a gauge, which provides an equivalence of Eq. (30) to the Einstein-Hilbert gravitational action:

$$I_{(EG)} = \frac{1}{\kappa^2} \int d^4x \left( \frac{R}{2} - \Lambda \right), \quad (32)$$

where  $R$  is a scalar curvature, and  $\Lambda$  is the Einstein cosmological constant.

It was assumed in Refs. [56–59] that the anti-self-dual right-handed gravitational world is absent in the Nature ( $\Sigma^{(-)} = F^{(-)} = 0$ ), and our world, in which we live, is a self-dual left-handed gravitational world described by the action (30).

Following the ideas of Ref. [60], we distinguish the two worlds of the Universe, visible and invisible, and consider the two sectors of gravity: left-handed gravity and right-handed gravity.

If there exists in the Nature a duplication of worlds with opposite chiralities - Ordinary and Mirror - we can consider the left-handed gravity in the Ordinary world and the right-handed gravity in the Mirror world. The anti-self-dual right-handed gravitational action of the mirror world MW is given by the following integral:

$$I_{(MW)}^{(grav)}(\Sigma^{(-)}, A^{(-)}, \psi') = \frac{1}{\kappa'^2} \int [\Sigma^{(-)i} \wedge F^{(-)i} + (\Psi'^{-1})_{ij} \Sigma^{(-)i} \wedge \Sigma^{(-)j}]. \quad (33)$$

In Eqs. (30) and (33) we have:

$$\Sigma^{(\pm)i} = e^0 \wedge e^i \pm i \frac{1}{2} \epsilon_{jk}^i e^j \wedge e^k. \quad (34)$$

A correct gauge was provided by Plebanski, when he introduced in the gravitational action the Lagrange multipliers  $\psi_{ij}$  - an auxiliary fields, symmetric and traceless. These auxiliary fields provide a correct number of constraints.

Plebanski considered the action (30) with the following constraints:

$$\Sigma^i \wedge \Sigma^j - \frac{1}{3} \delta^{ij} \Sigma^k \wedge \Sigma_k = 0, \quad (35)$$

and

$$\Sigma^i \wedge \Sigma^{(-)j} = 0. \quad (36)$$

The variables  $\Sigma_{\mu\nu}^i$  have 18 degrees of freedom. The five conditions (35) leave 13 degrees of freedom, and the condition (36) leaves 10 degrees of freedom, which coincides with a number of degrees of freedom given by the metric tensor  $g_{\mu\nu}$ . This circumstance confirms the equivalence of the actions (30) and (32). And now there exist the following Lie algebra describing the GR:

$$\mathfrak{so}(1, 3) = \mathfrak{sl}(2, C)_L \oplus \mathfrak{sl}(2, C)_R. \quad (37)$$

But later, in Ref. [61], we assumed that the mixing of  $g_{\mu\nu}^{L,R}$  can be so strong that the left-handed gravity coincides with the right-handed gravity: the left-handed and right-handed connections are equal, that is,  $A_L = A_R$ . In this case  $g_{\mu\nu}^L = g_{\mu\nu}^R$ , and the left-handed and right-handed gravity equally interact with the visible and mirror matters.

The same approach was considered in the present paper.

## 4 Gravi-Weak Unification model

On a way of unification of the gravitational and weak interactions we considered in Ref. [20] an extended  $\mathfrak{g} = \mathfrak{spin}(4, 4)$ -invariant Plebanski's action:

$$I(A, B, \Phi) = \frac{1}{g_{uni}} \int_{\mathbf{M}} \left\langle BF + B\Phi B + \frac{1}{3} B\Phi\Phi B \right\rangle, \quad (38)$$

where  $\langle \dots \rangle$  means a wedge product,  $g_{uni}$  is an unification parameter, and  $\Phi_{IJKL}$  are auxiliary fields. Here  $I, J, K, L = 1, 2, \dots, 7, 8$ .

Having considered the equations of motion, obtained by means of the action (38), and having chosen a possible class of solutions, we can present the following action for the Gravi-Weak Unification (GWU) - see details in Refs. [20, 21]:

$$I(A, \Phi) = \frac{1}{8g_{uni}} \int_{\mathbf{M}} \langle \Phi F F \rangle, \quad (39)$$

where

$$\langle \Phi F F \rangle = \frac{d^4 x}{32} \epsilon^{\mu\nu\rho\sigma} \Phi_{\mu\nu}{}^{\varphi\chi IJ}{}_{KL} F_{\varphi\chi IJ} F_{\rho\sigma}{}^{KL}, \quad (40)$$

and

$$\Phi_{\mu\nu}{}^{\rho\sigma ab}{}_{cd} = (e_\mu^f)(e_\nu^g)\epsilon_{fg}{}^{kl}(e_k^\rho)(e_l^\sigma)\delta_{cd}^{ab}. \quad (41)$$

A spontaneous symmetry breaking of our new action that produces the dynamics of gravity, weak  $SU(2)$  gauge and Higgs fields, leads to the conservation of the following sub-algebra:

$$\mathfrak{g}_1 = \mathfrak{sl}(2, C)_L^{(grav)} \oplus \mathfrak{su}(2)_L.$$

Considering indices  $a, b \in \{0, 1, 2, 3\}$  as corresponding to  $I, J = 1, 2, 3, 4$ , and indices  $m, n$  as corresponding to indices  $I, J = 5, 6, 7, 8$ , we can present a spontaneous violation of the Gravi-Weak Unification symmetry in terms of the 2-forms:

$$A = \frac{1}{2}\omega + \frac{1}{4}E + A_W, \quad (42)$$

where  $\omega = \omega^{ab}\gamma_{ab}$  is a gravitational spin-connection, which corresponds to the sub-algebra  $\mathfrak{sl}(2, C)_L^{(grav)}$ . The connection  $E = E^{am}\gamma_{am}$  corresponds to the non-diagonal components of the  $8 \times 8$  matrix  $A^{IJ}$ , described by the following way (see [21]):

$$E = e\varphi = e_\mu^a \gamma_a \varphi^m \gamma_m dx^\mu. \quad (43)$$

The connection  $A_W = \frac{1}{2}A^{mn}\gamma_{mn}$  gives:  $A_W = \frac{1}{2}A_W^i \tau_i$ , which corresponds to the sub-algebra  $\mathfrak{su}(2)_L$  of the weak interaction ( $\tau_i$  are the Pauli matrices with  $i = 1, 2, 3$ ).

Assuming that we have only scalar field  $\varphi^m = (\varphi, \varphi^i)$ , we can consider a symmetry breakdown of the Gravi-Weak Unification, leading to the following OW-action [20]:

$$I_{(OW)}(e, \varphi, A, A_W) = \frac{3}{8g_{uni}} \int_{\mathbf{M}} d^4 x |e| \left( \frac{1}{16} |\varphi|^2 R - \frac{3}{32} |\varphi|^4 + \frac{1}{16} R_{ab}{}^{cd} R^{ab}{}_{cd} - \frac{1}{2} \mathcal{D}_a \varphi^\dagger \mathcal{D}^a \varphi - \frac{1}{4} F_{Wab}^i F_W^{i ab} \right). \quad (44)$$

In Eq. (44) we have the Riemann scalar curvature  $R$ ;  $|\varphi|^2 = \varphi^\dagger \varphi$  is a squared scalar field, which from the beginning is not the Higgs field of the Standard Model;  $\mathcal{D}\varphi = d\varphi + [A_W, \varphi]$  is a covariant derivative of the scalar field, and  $F_W = dA_W + [A_W, A_W]$  is a curvature of the gauge field  $A_W$ . The third member of the action (44) is a topological term in the Gauss-Bone theory of gravity (see for example [62, 63]).

Lagrangian in the action (44) leads to the nonzero vacuum expectation value (VEV) of the scalar field:  $v = \langle \varphi \rangle = \varphi_0$ , which corresponds to a local minimum of the effective potential  $V_{eff}(\varphi)$  at  $v^2 = R_0/3$ , where  $R_0 > 0$  is a constant de Sitter space-time background curvature [21].

According to (44), the Newton gravitational constant  $G_N$  is defined by the expression:

$$8\pi G_N = (M_{Pl}^{(red.)})^{-2} = \frac{64g_{uni}}{3v^2}, \quad (45)$$

a bare cosmological constant is equal to

$$\Lambda_0 = \frac{3}{4}v^2, \quad (46)$$

and

$$g_W^2 = 8g_{uni}/3. \quad (47)$$

The coupling constant  $g_W$  is a bare coupling constant of the weak interaction, which also coincides with a value of the constant  $g_2 = g_W$  at the Planck scale. Considering the running  $\alpha_2^{-1}(\mu)$ , where  $\alpha_2 = g_2^2/4\pi$ , we can carry out an extrapolation of this rate to the Planck scale, what leads to the following estimations [64]:

$$\alpha_2(M_{Pl}) \sim 1/50, \quad g_{uni} \sim 0.1. \quad (48)$$

Having substituted in Eq.(45) the values of  $g_{uni} \simeq 0.1$  and  $G_N = 1/8\pi(M_{Pl}^{red.})^2$ , where  $M_{Pl}^{red.} \approx 2.43 \cdot 10^{18}$  GeV, it is easy to obtain the VEV's value  $v$ , which in this case is located near the Planck scale:

$$v = v_2 \approx 3.5 \cdot 10^{18} \text{ GeV}. \quad (49)$$

Such a result takes place, if the Universe at the early stage stayed in the "false vacuum", in which the VEV of the Higgs field is huge:  $v = v_2 \sim 10^{18} \text{ GeV}$ . The exit from this state could be carried out only by means of the existence of the second scalar field. In the present paper we assume that the second scalar field, participating into the Inflation, is the mirror Higgs field, which arises from the interaction between the Higgs fields of the visible and invisible sectors of the Universe.

## 5 Mirror world with broken mirror parity

In contrast to the article [21], in this paper we assume the existence in the Nature of the invisible (hidden) Mirror World (MW) parallel to the visible Ordinary World (OW).

Such a hypothesis was suggested in Refs. [65, 66].

The Mirror World (MW) is a mirror copy of the Ordinary World (OW) and contains the same particles and types of interactions as our visible world, but with the opposite chirality. Lee and Yang [65] were first to suggest such a duplication of the worlds, which restores the left-right symmetry of the Nature. The term "Mirror Matter" was introduced by Kobzarev, Okun and Pomeranchuk [66], who first suggested to consider MW as a hidden (invisible) sector of the Universe, which interacts with the ordinary (visible) world only via gravity, or another (presumably scalar) very weak interaction.

In the present paper we consider the hidden sector of the Universe as a Mirror World (MW) with broken Mirror Parity (MP) [22–26]. If the ordinary and mirror worlds are identical, then O- and M-particles should have the same cosmological densities. But this

is immediately in conflict with recent astrophysical measurements [45–47]. Astrophysical and cosmological observations have revealed the existence of the Dark Matter (DM), which constitutes about 25% of the total energy density of the Universe. This is five times larger than all the visible matter,  $\Omega_{DM} : \Omega_M \simeq 5 : 1$ . Mirror particles have been suggested as candidates for the inferred dark matter in the Universe [25, 28] (see also [31]). Therefore, the mirror parity (MP) is not conserved, and the OW and MW are not identical.

In the Refs. [22–26] it was suggested that the VEVs of the Higgs doublets  $\phi$  and  $\tilde{\phi}$  are not equal:

$$\langle \phi \rangle = v, \quad \langle \tilde{\phi} \rangle = \tilde{v}, \quad \text{and} \quad v \neq \tilde{v}. \quad (50)$$

The parameter characterizing the violation of the MP is

$$\zeta = \tilde{v}/v \gg 1. \quad (51)$$

The parameter  $\zeta$  was introduced and estimated in Refs. [67, 68]. The estimation gave:

$$\zeta > 30, \quad \zeta \sim 100. \quad (52)$$

Then the masses of mirror fermions and massive bosons are scaled up by the factor  $\zeta$  with respect to the masses of their OW-counterparts:

$$\tilde{m}_{\tilde{q}, \tilde{l}} = \zeta m_{q, l}, \quad \tilde{M}_{\tilde{W}, \tilde{Z}, \tilde{\phi}} = \zeta M_{W, Z, \phi}, \quad (53)$$

while photons and gluons remain massless in both worlds.

## 5.1 Communications between visible and hidden worlds

The dynamics of the two worlds of the Universe, visible and hidden, is governed by the following action:

$$I = \int d^4x |e| \left[ L_{(grav)} + L_{SM} + \tilde{L}_{\tilde{SM}} + L_{(mix)} \right], \quad (54)$$

where  $L_{(grav)}$  is the gravitational Lagrangian,  $L_{SM}$  and  $\tilde{L}_{\tilde{SM}}$  are the SM Lagrangians in the OW and MW, respectively.

$L_{(mix)}$  is the Lagrangian describing all mixing terms giving small contributions to physical processes: mirror particles have not been seen so far, and the communication between visible and hidden worlds is hard.

In Ref. [69] it was assumed that along with gravitational interaction between OW and MW worlds, there also exists the interaction between the initial Higgs field  $\phi$  and the mirror Higgs field  $\tilde{\phi}$ :

$$V_{int} = \alpha_h (\phi^\dagger \phi) (\tilde{\phi}^\dagger \tilde{\phi}), \quad (55)$$

where  $\phi$  ( $\tilde{\phi}$ ) is the SM ( $\tilde{SM}$ ) Higgs doublet. This interaction exists in  $L_{mix}$ , and the coupling constant  $\alpha_h$  is assumed as very small.

## 5.2 Gravi-Weak action in the invisible (mirror) sector of the Universe

The action  $I_{(MW)}$  in the mirror world is represented by the same integral (44), in which we have to make the replacement of all OW-fields by their mirror counterparts:

$$e, \phi, A, A_W, R \rightarrow \tilde{e}, \tilde{\phi}, \tilde{A}, \tilde{A}_W, \tilde{R}.$$

However:

$$\widetilde{g_{uni}} = g_{uni},$$

because we assume that at the early stage of the evolution of the Universe, mirror parity was NOT broken.

## 6 U(4)-group of fermions

Constructing the unification of the Gravity and Standard Model (SM) gauge groups by using algebraic spinors of the standard four-dimensional Clifford algebra with a left-right symmetry, we imagine the creation of the SM families at the Planck scale as it was suggested in the theory [1] and in the RD [5, 6].

We assume that at the early stage of evolution of the Universe (say, in  $\sim 10^{-43}$  sec after the Big Bang) the direct product of the gauge groups of GWU and internal symmetry  $U(4)$  randomly emerges:

$$G_{(GW)} \times U(4), \quad (56)$$

which further was broken due to the following breaking chains:

$$G_{(GW)} \rightarrow SL(2, C)^{(grav)} \times SU(2)^{(weak)}, \quad (57)$$

and

$$U(4) \rightarrow SU(4) \times U(1)_{(B-L)} \rightarrow SU(3) \times U(1)_Y \times U(1)_{(B-L)}. \quad (58)$$

Below the see-saw scale ( $M_R \sim 10^{12}$  GeV) we obtain the following group of symmetry:

$$SL(2, C)^{(grav)} \times SU(3)_{(color)} \times SU(2)^{(weak)} \times U(1)_Y, \quad (59)$$

or

$$SL(2, C)^{(grav)} \times G_{(SM)}. \quad (60)$$

Spinors appear in multiplets of gauge groups.

We can consider the 1-form connection,  $A = \frac{1}{2}A^{IJ}\gamma_{IJ}$ , as an independent physical variable describing the geometry of the d-dimensional space-time. The curvature

$$F = dA + \frac{1}{2}[A, A]$$

and

$$B = \frac{1}{2}B^{IJ}\gamma_{IJ}$$

are  $\mathfrak{spin}(p, q)$ -valued 2-form fields. The generators  $\gamma_{IJ} = \gamma_I \gamma_J$  of the  $\mathfrak{spin}(p, q)$ -algebra have indices running over all  $(p + q) \times (p + q)$  values:  $I, J = 1, 2, \dots, p + q$ .

In Ref. [20], in correspondence with Ref. [21], we have developed the Gravi-Weak Unification model starting with the  $\mathfrak{g} = \mathfrak{spin}(4, 4)$ -invariant extended Plebanski's action (44).

The standard four-dimensional Clifford algebra  $Cl_{1,3}$  is given by Dirac gamma matrices,  $\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$ , in Weyl representation, with  $\eta_{\mu\nu} = \text{diag}(-1, 1, 1, 1)$  and  $\gamma_5 = \text{diag}(1, 1, -1, -1)$ . For  $Cl_{1,3}$  we use the basis

$$\{\gamma_{A=1,\dots,16}\} = \{1_4, \gamma_0, \gamma_i, \gamma_0\gamma_i, -\gamma_i\gamma_j, \gamma_5\gamma_0, \gamma_5\gamma_i, \gamma_5\},$$

with  $i=1,2,3$ . This is also the algebra  $\mathfrak{gl}(4, C)$  of all  $4 \times 4$  matrices.

The aim to set quantum numbers of fermions in families of the SM gave the traditional way to embed the SM family into Grand-Unification groups (like  $SU(5)$ ,  $SO(10)$ ,  $E_6$ , etc.) All these approaches consider the gauge groups as internal symmetries. Fermions appear in multiplets of the internal groups, forming a direct product with the space-time Lorentz group.

However, there exists a different way: to resort to the algebraic spinor theory (see for example Ref. [14]), and to set fermions in multiplets of the Clifford algebra, which is isomorphic to the algebra of inhomogeneous differential forms. These spinors still satisfy the Dirac equation. They are not in the minimal representation of the Lorentz group: they are generic elements of the Clifford algebra – objects of dimension  $2^d$ . These multiplets naturally can contain more particles, than the usual description gives, and can accommodate various sets of quantum numbers, including the SM ones. As a result, this approach leads to a promising way to unify gravity with gauge interactions.

Usual spinors  $\psi$  are column objects transforming under Lorentz transformations, while algebraic spinors are objects of the Clifford algebra:  $\Psi = \psi^A \gamma_A$ , which are represented by  $4 \times 4$  complex matrices  $\Psi = \{\psi_{ab}\}$ , with  $a,b=1,2,3,4$ .

These objects are transformed at the left under the algebra-valued transformations. Such transformations act on each column separately, therefore the four columns inside the algebraic spinor represent four invariant subspaces. Thus, an algebraic spinor contains four Dirac spinors. These objects belong to another  $\mathfrak{gl}(4, C)$ -algebra that can accommodate an internal symmetry up to a rank 4, for example,  $U(4)$ .

Considering the left and right chirality objects, we introduce the left and right complex algebraic spinors  $\Psi_{L,R}$ . They again are represented by  $4 \times 4$  complex matrices. Summarizing,  $\Psi_{L,R}$  belongs to  $U(4)_{L,R}$  group, and  $\Psi_L$  contains four isospin doublets of Weyl spinors, which we can identify with the left-handed SM family. It is very suggestive to represent  $\Psi_L$  with lepton and colored quark indices:

$$\Psi_L = \begin{pmatrix} \nu_{L1} & u_{L1,r} & u_{L1,g} & u_{L1,b} \\ \nu_{L2} & u_{L2,r} & u_{L2,g} & u_{L2,b} \\ e_{L1} & d_{L1,r} & d_{L1,g} & d_{L1,b} \\ e_{L2} & d_{L2,r} & d_{L2,g} & d_{L2,b} \end{pmatrix}. \quad (61)$$

In the present paper the SM families of ordinary and mirror worlds (OW and MW) are described in just by a left-right symmetric couple of such spinors:  $\Psi_L$  and  $\Psi_R$ .

Considering the left chirality in  $OW$ , we need a breaking of the  $\mathfrak{gl}(4, C)_L$  to  $\mathfrak{g}_1 = \mathfrak{sl}(2, C)_L^{(grav)} \oplus \mathfrak{su}(2)_L$ .

The transformations belonging to  $\mathfrak{gl}(4, C)_L$  should be restricted to be compact, because non-compact internal symmetries always contain ghosts. This minimal requirement leads from  $\mathfrak{gl}(4, C)$  to its maximal compact group  $U(4)$ , i.e. a group that unifies color and  $(B - L)$ -quantum number by treating lepton number as the fourth color. The representation (61) of  $\Psi_L$  explicitly shows this.

In the broken phase of the GWU, the symmetry in the OW would thus be:

$$SU(2)_L^{(grav)} \times SU(2)_L \times U(4)_L.$$

Then, the right chirality of the MW would give rise to a second copy of these:

$$SU(2)_R^{(grav)} \times SU(2)_R \times U(4)_R.$$

And we have a duplication of worlds.

These groups can be linked to the SM groups by standard breaking chains:

$$U(4) \rightarrow SU(4) \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{(B-L)} \times U(1)_Y,$$

after introducing appropriate Higgs fields needed for the symmetry breaking.

Now it is useful to show explicitly the generators of  $\mathfrak{sl}(2, C)^{(grav)}$  and  $\mathfrak{su}(2)^{(weak)}$ :

$$\mathfrak{sl}(2, C)^{(grav)} : \quad \{\rho_i\} = \{\sigma_i \otimes 1_2\},$$

and

$$\mathfrak{su}(2)^{(weak)} : \quad \{\tau_i\} = \{1_2 \otimes \sigma_i\}. \quad (62)$$

The gauging of symmetries is realized by introducing a covariant derivative with Clifford-algebra valued vector fields:

$$\partial_\mu \rightarrow D_\mu^{L,R} = \partial_\mu + V_\mu^{L,R} + \tilde{V}_\mu^{L,R}, \quad (63)$$

where  $\tilde{V}_\mu^{L,R}$  are just the gauge fields in  $\mathfrak{u}(4)_{L,R}$ -Clifford algebra notation, and the fields  $V_\mu^{L,R}$  unify gravity and weak-isospin.

The  $V_\mu^{L,R}$  can be parametrized in terms of the complex gauge fields  $\omega^L, \bar{\omega}^R, W^{L,R}$ :

$$\begin{aligned} V_\mu^L &= i\omega_\mu^i \rho_i + iW_\mu^{Li} \tau_i, \\ V_\mu^R &= i\bar{\omega}_\mu^i \rho_i + iW_\mu^{Ri} \tau_i, \end{aligned} \quad (64)$$

where  $\omega_\mu^i, \bar{\omega}_\mu^i$  reproduce the self-dual and anti-self-dual spin connections of gravity.

Now we can build kinetic terms for left and right fermions (tr is the trace in  $4 \times 4$  representation):

$$L_{kin} = tr[\Psi_L^\dagger \partial^\mu \Gamma_\mu^L \Psi_L] + tr[\Psi_R^\dagger \partial^\mu \Gamma_\mu^R \Psi_R], \quad (65)$$

where:

$$\Gamma_\mu^{L,R} = \{\pm 1_2, \sigma_i\} \otimes 1_2. \quad (66)$$

## 7 Multiple Point Model and the prediction of the top and Higgs Masses

Recently discovered Higgs boson [71,72] showed an intriguing property: among the many different values of the Higgs mass, which were available, the Nature has chosen one that allows us to think that the SM is valid up to the Planck scale, apart from the existence of some right-handed heavy Majorana neutrinos at a see-saw scale ( $\sim 10^{12} - 10^{14}$  GeV). Of course, this scenario suffers from the hierarchy problem of why the ratio of the Planck scale to the Electroweak (EW) scale is so huge (see [76]). The mechanism for fine-tuning of coupling constants of the SM was suggested in Refs. [73–76] which give an explanation, why the ratio of these two scales should be of the order of  $10^{17}$ , as observed. This is based on the so-called Multiple Point Principle [50].

Some time ago, in Ref. [51], the MPP was applied to the SM by the consideration of the two degenerate vacua: a vacuum at the Planck scale with a Higgs field vacuum expectation value (VEV):  $v_2 \sim 10^{18}$  GeV, and EW vacuum having VEV:  $v_1 = 246$  GeV. Consequently the top quark and Higgs boson couplings were fine-tuned to lie at a point on the SM vacuum stability curve [77–82]. This gave the following MPP prediction by C.D. Froggatt and H.B. Nilsen (see [51]) for the top quark and the Higgs boson masses:

$$m_t = 173 \pm 5 \text{ GeV}, \quad m_H = 135 \pm 9 \text{ GeV}. \quad (67)$$

Later, the prediction for the mass of the Higgs boson was improved by the calculation of the two-loop radiative corrections to the effective Higgs potential [76, 83–86]. The predictions:  $125 \text{ GeV} \lesssim m_H \lesssim 143 \text{ GeV}$  in Ref. [76], and  $129 \pm 2 \text{ GeV}$  in Ref. [85] – provided the possibility of the theoretical explanation of the value  $M_H \approx 126 \text{ GeV}$  observed at the LHC. The authors of the recent paper [86] have shown that the most interesting aspect of the measured value of  $M_H$  is its near-criticality. They have thoroughly studied the condition of near-criticality in terms of the SM parameters at the high (Planck) scale. They extrapolated the SM parameters up to large energies with full 3-loop NNLO RGE precision. All these results mean that the radiative corrections to the Higgs effective potential lead to the true value of the Higgs mass existing in the Nature.

Using the top quark pole mass  $m_t = 173.1 \pm 0.7 \text{ GeV}$  as input leads (see [85]) to an updated MPP prediction for the Higgs mass of  $m_H = 129.4 \pm 1.8 \text{ GeV}$ . This is very close to the observed Higgs mass [71,72]:  $M_H \approx 126 \text{ GeV}$ . The result is rather sensitive to the top quark pole mass: a change of  $\Delta m_t = \pm 1 \text{ GeV}$  gives a change in the predicted Higgs mass of  $\Delta m_H = \pm 2 \text{ GeV}$ .

We see that in the assumption of the validity of the SM at very high Planck-mass scales, the measured value of the Higgs mass lies on, or is very close to the vacuum stability curve. Of course, vacuum stability curve could be a pure coincidence. However, we take the attitude that it is not accidental and requires an explanation. This implies two points:

1. The SM should not be modified so much by new physics on the energy range between the EW scale and the Planck scale, where the second vacuum exists, that the renormalization group running of the Higgs quartic coupling  $\lambda(\mu)$  is significantly altered.
2. There must for some reason exist in the Nature a physical principle forcing one vacuum to be so closely degenerate with another one that it is barely stable, or just metastable [87].

Such a principle is, of course, the above-mentioned MPP. MPP is really a mechanism for fine-tuning couplings.

In order to fine-tune the SM couplings so as to generate the large ratio of the Planck scale to the EW-scale using MPP, it is necessary for them to produce a third vacuum in the SM with zero energy density, i.e. to consider the triple point in the phase diagram of our theory [73–76]. In such a speculative picture this new vacuum is formed at the EW scale by a Bose condensation of a strongly bound state of 6 top and 6 anti-top quarks [74, 76, 88–90].

The behavior of the Higgs self-coupling  $\lambda$  is quite peculiar: it decreases with energy to eventually arrive to a minimum at the Planck scale values and then starts to increase there after. Within the experimental and theoretical uncertainties the Higgs coupling  $\lambda$  may stay positive all way up till the Planck scale, but it may also cross zero at some scale  $\mu_0$ . If that happens, our Universe becomes unstable.

The largest uncertainty in couplings comes from the determination of the top Yukawa coupling. Smaller uncertainties are associated to the determination of the Higgs boson mass and the QCD coupling  $\alpha_s$  (see Refs. [76, 83–86]).

Calculations of the lifetime of the SM vacuum are extremely sensitive to the Planck scale physics. The authors of Refs. [91–93] showed that if the SM is valid up to the Planck scale, then the Higgs potential becomes unstable at  $\sim 10^{11}$  GeV. There are two reasons of this instability. In typical tunnelling calculations, the value of the field at the center of the critical bubble is much larger than the point of the instability. In the SM case, this turns out to be numerically within an order of magnitude of the Planck scale.

The measurements of the Higgs mass and top Yukawa coupling indicate that we live in a very special Universe: at the edge of the absolute stability of the EW vacuum. If fully stable, the SM can be extended all the way up to the inflationary scale and the Higgs field, non-minimally coupled to gravity with strength  $\xi$ , can be responsible for the inflation (see Refs. [94–96]).

## 8 The Higgs Inflation model from the ”false vacuum” and the mirror Higgs boson

The most interesting property of the Universe is the relation between the particle physics and cosmology: between the elementary particles theory and the structure of the Universe.

The compatibility of the modern astrophysical data with vacuum stability (or instability) is one of the most important problem for invoking new physics beyond the SM. In particular, it was suggested in Refs. [94–96] that the Higgs inflation scenario, in which the Higgs field is non-minimally coupled to gravity with strength  $\xi$ , cannot take place if the Higgs self-coupling  $\lambda(\mu)$  (here  $\mu$  is an energy scale) becomes negative at some  $\mu_0$  below the inflationary scale.

In our model, presented here, we assume that at the early stage of the evolution of the Universe, the discrete space-time randomly emerged the group of symmetry  $G = G_{(GW)} \times U(4)$  (via the SUSY GUT group or not), where  $G_{(GW)}$  is the Gravi-Weak Unification group considered in Section 4. In subsequent evolution of the Universe the temperature decreases

and the group  $G_{(GW)}$  undergoes the breakdown to the symmetry given by Eq.(57). As a result, the obtained Lagrangian (exactly the effective potential  $V_{eff}(\varphi)$ ) shows that the vacuum with the VEV  $v = v_2$  of the scalar field  $\varphi$  (so called "second vacuum") appears at large field values  $\sim 10^{18}$  GeV. Following to the MPM scenario (see Section 7), the Higgs effective potential has the next minimum at the EW scale, and the vacuum with the VEV equal to  $v_1 = 246$  GeV (so called "first vacuum") corresponds to the vacuum, in which we live now.

The Higgs inflation scenario is heavily based on the standard vacuum stability analysis. In particular, it requires that a new physics shows up only at the Planck scale  $M_{Pl}$ , and that the SM lives at the edge of the stability region, where

$$\lambda(M_{Pl}) \sim 0 \quad \text{and} \quad \beta(\lambda(M_{Pl})) \sim 0. \quad (68)$$

Here  $\beta(\lambda)$  is the beta-function of the renormalization group equation (RGE) for the Higgs self-coupling constant  $\lambda$ . We see, however, that the new physics interactions at the Planck scale can strongly change this situation.

The realization of the conditions (68) requires such a fine tuning that even a small grain of new physics at the Planck scale can totally destroy the picture. In our model such a fine tuning is MPP, considered in Section 7.

We believe that our model makes a chance for the realization of the Higgs inflation scenario, showing the relation between low and high energy parameters.

The possibility that the SM is valid up to the Planck scale,  $M_{Pl}$ , is nowadays largely explored. For example, many papers were devoted to the scenarios of the Higgs inflation, using the above mentioned assumptions (see for example Refs. [91–99], etc.).

In the present paper we develop an alternative possibility (different with all previous considerations), using an additional mirror scalar field  $\tilde{\varphi}$ , which is very weakly coupled with the usual Higgs field.

We start with a local minimum of the Higgs potential at the field value VEV  $v = v_2 \sim 10^{18}$  GeV, as it was predicted by our GWU model (see Section 4). This minimum exists for a narrow band of the top quark and Higgs mass values. Not only such a local minimum exists, but within the allowed parameter range in the top-Higgs masses, this minimum has the right value of the energy density, which gives rise to the correct amplitude of density perturbations.

The existence of the "false vacuum" ( $v = v_2 \sim 10^{18}$  GeV) in the Higgs potential, which is a source of the exponential expansion in the early Universe, gives not only a combined prediction of the top-Higgs masses, but also the ratio of tensor to scalar perturbations (rate  $r$ ) from the Inflation.

The possibility of achieving a transition from the exponential expansion to a hot radiation era is provided by adding an extra scalar in the gravitational sector of the theory, which slows down the expansion of the Universe.

The height of the potential at the time at which density perturbations are produced is given by the SM Higgs field. The combined predictions on  $m_H$ ,  $m_t$  and  $r$  are generic and independent on the way, what exit from Inflation is realized.

In fact, we present here an alternative model, which provides a graceful exit from the Inflation and gives rise to a radiation era.

In order to achieve enough Inflation, we have the scalar field  $\varphi$  trapped at the value  $\varphi_0$  (of order  $\sim 10^{18}$  GeV) with a suppressed tunnelling rate ( $\Gamma \ll H_0^4$ , where  $\Gamma$  is the tunnelling probability per unit time and value, and  $H_0$  is the Hubble rate).

Then it is necessary, after at least 50-60 e-folds, to trigger a phase transition through an additional scalar field. In our GWU-model, this is a mirror scalar field  $\tilde{\varphi}$ , which plays a role of a clock, so that  $\varphi$  is not stuck at  $\varphi_0$  anymore, and exits through the classical rolls (not through tunnelling, which is extremely small).

When this happens, the field  $\varphi$  can roll down fast to smaller values, ending thus Inflation. Here it is necessary to emphasize, that in our GWU-model the field  $\varphi$  is not a Higgs doublet field of  $SU(2)_L$ , as in the SM, but it is an adjoint field of the  $SU(2)_L$ -group of the weak interactions as in Refs. [?, 21]. We assume, that this field  $\varphi$  decays during the Inflation into the two SM Higgs doublet fields  $\phi$  very quickly, and as a result, the Higgs field  $\phi$  continues the Inflation. At the end, this field eventually oscillates around zero and dissipate energy, producing thus a hot plasma, and finally relax at its true minimum at the usual value  $\phi_1 = 246$  GeV, corresponding to the vacuum, in which we live now.

Then we choose the following behavior:  $\Gamma$  is time-depended, but  $H_0$  stays roughly constant. The Higgs field  $\phi$  interacts directly with an additional mirror Higgs doublet  $\tilde{\phi}$ , as it was suggested in Ref. [69]: the Foot-Kobakhidze-Volkas formula is (55). The authors of Ref. [69] assumed the SM Higgs doublets.

The field  $\tilde{\phi}$  has a time of evolution and modifies the shape of the barrier in the potential  $V_{eff}(\phi)$ : the bottom rises up and then disappears giving the chance to the inflaton ( $\phi$ ) to roll down toward the first (EW) vacuum.

This so-called Hybrid Inflation scenario was first suggested by A. Linde in his paper Ref. [32].

We see, that "waterfall" field  $\phi$  is trapped at the almost zero value and can start evolve, when another field  $\tilde{\phi}$  reaches the almost zero value  $\simeq H_0$ . Inflation stops, when  $\tilde{\phi}$  reaches some value  $\tilde{\phi}_{(end)} = \tilde{\phi}_E$ .

Such a picture introduces an explicit coupling between the Higgs field  $\phi$  and extra (mirror) field  $\tilde{\phi}$ . This is an explicit coupling constant  $\alpha_h$  in Eq. (55).

Of course, this picture changes the RGE themselves. However, the coupling constant  $\alpha_h$  needs to be very weak, and the mass  $\tilde{\phi}$  very large, - then the contribution to the RGE is very small (practically zero), leaving the connection between low-energy parameters and the "false vacuum" values unchanged.

## 8.1 The Planck scale GWU action in the ordinary world

In Section 4 we obtained the GWU action given by Eq. (44). The gravitational part of the action is:

$$\begin{aligned} I_{(OW)}(e, \varphi, A, A_W) &= \frac{3}{8g_{uni}} \int_{\mathbf{M}} d^4x |e| \left( \frac{1}{16} |\varphi|^2 R - \frac{3}{32} |\varphi|^4 + \dots \right) \\ &= \frac{3}{64g_{uni}} \int_{\mathbf{M}} d^4x |e| \left( \frac{1}{2} |\varphi|^2 R - \frac{3}{4} |\varphi|^4 + \dots \right). \end{aligned} \quad (69)$$

Considering the background value  $R \simeq R_0$ , we can find a minimum of the potential:

$$V_{eff}(\varphi) \sim -\frac{1}{2}|\varphi|^2 R_0 + \frac{3}{4}|\varphi|^4 \quad (70)$$

at  $\varphi_0 = \langle \varphi \rangle = v$ . Here  $v^2 = R_0/3$ . Then according to (45), we obtain:

$$I_{(OW)}(e, \varphi, A, A_W) = \int_{\mathbf{M}} d^4x \sqrt{-g} \left( \frac{M_{Pl}^{red}}{v} \right)^2 \left( \frac{1}{2}|\varphi|^2 R - \frac{3}{4}|\varphi|^4 + \dots \right). \quad (71)$$

In the action (71) the Lagrangian includes the non-minimal coupling with gravity [94–96].

We see that the field  $\varphi$  is not stuck at  $\varphi_0$  anymore, but it can be represented as

$$\varphi = \varphi_0 - \sigma = v - \sigma, \quad (72)$$

where the scalar field  $\sigma$  is an inflaton. Here we see that in the minimum, when  $\varphi = v$ , the inflaton field is zero ( $\sigma = 0$ ) and then it increases with falling of the field  $\varphi$ .

Considering the expansion of the Lagrangian around the background value  $R \simeq R_0$  in powers of the small value  $\sigma/v$ , and leaving only the first-power terms, we can present the gravitational part of the action as:

$$I_{(grav OW)} = \int_M d^4x \sqrt{-g} (M_{Pl}^{red})^2 \left( \frac{1}{2} R_0 |1 + \sigma/v|^2 - \Lambda_0 |1 + \sigma/v|^4 + \dots \right). \quad (73)$$

Here  $\Lambda_0 = \frac{3}{4}v^2 = R_0/4$ . Using the last relations, we obtain:

$$I_{(grav OW)} = \int_M d^4x \sqrt{-g} (M_{Pl}^{red})^2 \left( \Lambda_0 - \frac{m^2}{2} |\sigma|^2 + \dots \right), \quad (74)$$

where  $m^2 = 6$  is the bare mass of the inflaton in units  $M_{Pl}^{red} = 1$ .

In the Einstein-Hilbert action the vacuum energy is:

$$\rho_{vac} = (M_{Pl}^{red})^2 \Lambda. \quad (75)$$

In our case (74) the vacuum energy density is negative:

$$\rho_0 = - (M_{Pl}^{red})^2 \Lambda_0. \quad (76)$$

However, assuming the existence of the discrete space-time of the Universe at the Planck scale and using the prediction of the non-commutativity suggested by B.G. Sidharth [1,2], we obtain that the gravitational part of the GWU action has the vacuum energy density equal to zero or almost zero.

Indeed, the total cosmological constant and the total vacuum density of the Universe contain also the vacuum fluctuations of fermions and other SM boson fields:

$$\Lambda \equiv \Lambda_{eff} = \Lambda^{ZMD} - \Lambda_0 - \Lambda_s^{(NC)} + \Lambda_f^{(NC)}, \quad (77)$$

where  $\Lambda^{ZMD}$  is zero modes degrees of freedom of all fields existing in the Universe, and  $\Lambda_{s,f}^{(NC)}$  are boson and fermion contributions of non-commutativity. If according to the theory by B.G. Sidharth [1], we have:

$$\rho_{vac}^{(0)} = (M_{Pl}^{red})^2 \Lambda^{(0)} = (M_{Pl}^{red})^2 (\Lambda^{ZMD} - \Lambda_0 - \Lambda_s^{(NC)}) \approx 0, \quad (78)$$

then Eq. (74) contains the cosmological constant  $\Lambda^{(0)} \approx 0$ . In Eqs. (77) and (78) the bosonic (scalar) contribution of the non-commutativity is:

$$\rho_{(scalar)}^{(NC)} = m_s^4 \quad (\text{in units : } \hbar = c = 1), \quad (79)$$

which is given by the mass  $m_s$  of the primordial scalar field  $\varphi$ . Then the discrete spacetime at the very small distances is a lattice (or has a lattice-like structure) with a parameter

$$a = \lambda_s = \frac{1}{m_s}.$$

This is a scalar length:

$$a = \lambda_s \sim 10^{-19} \text{ GeV}^{-1},$$

which coincides with the Planck length:

$$\lambda_{Pl} = \frac{1}{M_{Pl}} \approx 10^{-19} \text{ GeV}^{-1}.$$

The assumption:

$$\Lambda^{(0)} = \Lambda^{ZMD} - \Lambda_0 - \Lambda_s^{(NC)} \approx 0 \quad (80)$$

means that the Gravi-Weak Unification model contains the cosmological constant equal to zero or almost zero.

B.G. Sidharth gave in Ref. [48] the estimation:

$$\rho_{DE} = (M_{Pl}^{red})^2 \Lambda_f^{(NC)}, \quad (81)$$

considering the non-commutative contribution of light primordial neutrinos as a dominant contribution to  $\rho_{DE}$ , which coincides with astrophysical measurements [45–47]:

$$\rho_{DE} \approx (2.3 \times 10^{-3} \text{ eV})^4. \quad (82)$$

Returning to the Inflation model, we rewrite the action (74) as:

$$I_{(grav \text{ OW})} = \int_M d^4x \sqrt{-g} (M_{Pl}^{red})^2 \left( -\Lambda - \frac{m^2}{2} |\sigma|^2 + \dots \right), \quad (83)$$

where the positive cosmological constant is:

$$\Lambda = \Lambda^{(0)} + \Lambda_f^{(NC)}, \quad (84)$$

which is not zero, but very small. The tiny  $\Lambda$ , corresponding to Eq. (82) given by astrophysical measurements, is a problem of the forthcoming investigations.

We considered the gravitational action in the ordinary world OW. However, it is quite possible that the mirror world MW exists in the Nature together with the ordinary world.

## 8.2 The Planck scale GWU action of the Universe with ordinary and mirror worlds

In this Subsection we present the GWU gravitational action for both worlds (OW and MW) near their local minima at the Planck scale.

Taking into account the interaction of the ordinary and mirror scalar bosons  $\varphi$  and  $\tilde{\varphi}$ , given by equation analogous to Eq. (55) [69]:

$$V_{int} = \alpha_h(\varphi^\dagger\varphi)(\tilde{\varphi}^\dagger\tilde{\varphi}), \quad (85)$$

we obtain:

$$\begin{aligned} I_{(grav)} = & \int_M d^4x \sqrt{-g} \left[ \left( \frac{M_{Pl}^{red}}{v} \right)^2 \left( \frac{1}{2}|\varphi|^2 R - \frac{3}{4}|\varphi|^4 - \alpha_h|\varphi|^2|\tilde{\varphi}|^2 + \dots \right) + \dots \right] \\ & + \int_M d^4x \sqrt{-g} \left[ \left( \frac{\tilde{M}_{Pl}^{red}}{\tilde{v}} \right)^2 \left( \frac{1}{2}|\tilde{\varphi}|^2 \tilde{R} - \frac{3}{4}|\tilde{\varphi}|^4 - \alpha_h|\varphi|^2|\tilde{\varphi}|^2 + \dots \right) + \dots \right]. \quad (86) \end{aligned}$$

Considering the Planck scale Higgs potential, corresponding to the action (86), we have:

$$\begin{aligned} V(\varphi, \tilde{\varphi}) \simeq & \left( \frac{M_{Pl}^{red}}{v} \right)^2 \left( -\frac{1}{2}|\varphi|^2 R_0 + \frac{3}{4}|\varphi|^4 + \alpha_h|\varphi|^2|\tilde{\varphi}|^2 \right) \\ & + \left( \frac{\tilde{M}_{Pl}^{red}}{\tilde{v}} \right)^2 \left( -\frac{1}{2}|\tilde{\varphi}|^2 \tilde{R}_0 + \frac{3}{4}|\tilde{\varphi}|^4 + \alpha_h|\varphi|^2|\tilde{\varphi}|^2 \right). \quad (87) \end{aligned}$$

According to (45), we have:

$$\left( \frac{M_{Pl}^{red}}{v} \right)^2 = \left( \frac{\tilde{M}_{Pl}^{red}}{\tilde{v}} \right)^2, \quad (88)$$

and the local minima at  $\varphi_0 = v$  and  $\tilde{\varphi}_0 = \tilde{v}$  are given by the following conditions:

$$\frac{\partial V(\varphi, \tilde{\varphi})}{\partial |\varphi|^2} \Big|_{|\varphi|=v} = \left( \frac{M_{Pl}^{red}}{v} \right)^2 \left( -\frac{1}{2}R_0 + \frac{3}{2}v^2 + 2\alpha_h|\tilde{\varphi}|^2 \right) = 0, \quad (89)$$

$$\frac{\partial V(\varphi, \tilde{\varphi})}{\partial |\tilde{\varphi}|^2} \Big|_{|\tilde{\varphi}|=\tilde{v}} = \left( \frac{M_{Pl}^{red}}{v} \right)^2 \left( -\frac{1}{2}\tilde{R}_0 + \frac{3}{2}\tilde{v}^2 + 2\alpha_h|\varphi|^2 \right) = 0, \quad (90)$$

which give the following solutions:

$$v^2 \simeq \frac{R_0}{3} - \frac{4}{3}\alpha_h|\tilde{\varphi}|^2, \quad (91)$$

$$\tilde{v}^2 \simeq \frac{\tilde{R}_0}{3} - \frac{4}{3}\alpha_h|\varphi|^2, \quad (92)$$

and

$$V(\varphi = v, \tilde{\varphi} = \tilde{v}) = -\frac{1}{4}[(M_{Pl}^{red})^2 R_0 + (\tilde{M}_{Pl}^{red})^2 \tilde{R}_0] = -(M_{Pl}^{red})^2 \Lambda_0 - (\tilde{M}_{Pl}^{red})^2 \tilde{\Lambda}_0. \quad (93)$$

According to (45), we have:

$$\tilde{M}_{Pl}^{red} = \zeta M_{Pl}^{red} \quad \text{and} \quad \tilde{\Lambda}_0 = \zeta^2 \Lambda_0,$$

and finally we obtain:

$$V(\varphi = v, \tilde{\varphi} = \tilde{v}) = -(1 + \zeta^4)(M_{Pl}^{red})^2 \Lambda_0, \quad (94)$$

what gives the negative vacuum energy density. However, as we have discussed in Subsection 8.1, the cosmological constant is not given by Eq. (94). It must be replaced by the cosmological constant  $\Lambda$ , which is related with the potential (94) and the Dark Energy density (82) by the following way:

$$V(\varphi = v, \tilde{\varphi} = \tilde{v}) = (M_{Pl}^{red})^2 \Lambda = \rho_{DE}. \quad (95)$$

Using the notation:

$$\varphi = v - \sigma \quad \text{and} \quad \tilde{\varphi} = \tilde{v} - \tilde{\sigma}, \quad (96)$$

and neglecting the terms containing  $\alpha_h$  as very small, it is not difficult to see that the potential near the Planck scale is:

$$V(\varphi, \tilde{\varphi}) = (M_{Pl}^{red})^2 \left( \Lambda + \frac{m^2}{2} |\sigma|^2 + \frac{\tilde{m}^2}{2} |\tilde{\sigma}|^2 + \dots \right), \quad (97)$$

where  $m^2 \simeq 6$  and  $\tilde{m}^2 \simeq 6\zeta^2$  (compare with (82)).

The local minimum of the potential (97) at  $\varphi_0 = v$ , when  $\sigma = 0$ , and  $\tilde{\varphi}_0 \neq \tilde{v}$  ( $\tilde{\sigma} \neq 0$ ) gives:

$$V(v, \tilde{\varphi}) = (M_{Pl}^{red})^2 \left( \Lambda + \frac{\tilde{m}^2}{2} |\tilde{\sigma}|^2 + \dots \right). \quad (98)$$

The last equation (98) shows that the potential  $V(v)$  grows with growth of  $\tilde{\sigma}$ , i.e. with falling of the field  $\tilde{\varphi}$ . It means that a barrier of potential grows and at some value  $\tilde{\sigma} = \tilde{\sigma}|_{in}$  potential begins its inflationary falling. Here it is necessary to comment that the position of the minimum also is displaced towards smaller  $\varphi$  (bigger  $\sigma$ ), according to the formula (91).

Our next step is an assumption that during the inflation  $\sigma$  decays into the two Higgs doublets of the SM:

$$\sigma \rightarrow \phi^\dagger + \phi. \quad (99)$$

As a result, we have:

$$\sigma = a_d |\phi|^2, \quad (100)$$

where  $\phi$  is the Higgs doublet field of the Standard Model. The Higgs field  $\phi$  also interacts directly with field  $\tilde{\phi}$ , according to the interaction (55) given by Ref. [69]. It has a time evolution and modifies the shape of the barrier so that at some value  $\tilde{\phi}_E$  can roll down the field  $\varphi$ . This possibility, which we consider in our paper, is given by the so-called Hybrid

Inflation scenarios [32]. Here we assume that the field  $\phi$  begins the inflation at the value  $\phi|_{in} \simeq H_0$ .

Using the relations given by GWU, we obtain near the local “false vacuum” the following gravitational potential:

$$V(\phi, \tilde{\phi}) \simeq \Lambda + \lambda|\phi|^4 + \tilde{\lambda}|\tilde{\phi}|^4 + a_h|\phi|^2|\tilde{\phi}|^2, \quad (101)$$

where  $\lambda = 3a_d$  and  $\tilde{\lambda} = 3\tilde{a}_d$  are self-couplings of the Higgs doublet fields  $\phi$  and  $\tilde{\phi}$ , respectively.

### 8.3 The GWU action and the self-consistent Higgs Inflation model

Returning to the problem of the Inflation, we see that the action of the GWU theory has to be written near the Planck scale as:

$$I_{grav} \simeq - \int_M d^4x \sqrt{-g} (M_{Pl}^{red})^2 \left( \Lambda + \lambda|\phi|^4 + \tilde{\lambda}|\tilde{\phi}|^4 + a_h|\phi|^2|\tilde{\phi}|^2 + \dots \right), \quad (102)$$

where the cosmological constant  $\Lambda$  is almost zero (has an extremely tiny value).

The next step is to see the evolution of the Inflation in our model, based on the GWU, with two Higgs fields,  $\phi$  and mirror  $\tilde{\phi}$ .

In the present investigation we considered only the result of such an Inflation, which corresponds to the assumption of the MPP, that cosmological constant is zero, or almost zero, at both vacua: at the “first vacuum” with VEV  $v_1 = 246$  GeV and at the “second vacuum” with VEV  $v = v_2 \sim 10^{18}$  GeV. If so, we have the following conditions of the MPP (see section 7):

$$V_{eff}(\phi_{min1}) = V_{eff}(\phi_{min2}) = 0, \quad (103)$$

$$V'_{eff}(\phi_{min1}) = V'_{eff}(\phi_{min2}) = 0. \quad (104)$$

Considering the total Universe as two worlds, ordinary OW and mirror MW, we present the following expression for the total effective Higgs potential, which is far from the Planck scale:

$$V_{eff} = -\mu^2|\phi|^2 + \lambda(\phi)|\phi|^4 - \tilde{\mu}^2|\tilde{\phi}|^2 + \tilde{\lambda}(\tilde{\phi})|\tilde{\phi}|^4 + \alpha_h(\phi, \tilde{\phi})|\phi|^2|\tilde{\phi}|^2, \quad (105)$$

where  $\alpha(\phi, \tilde{\phi})$  is a coupling constant of the interaction of the ordinary Higgs field  $\phi$  with mirror Higgs field  $\tilde{\phi}$ .

According to the MPP, at the critical point of the phase diagram of our theory, corresponding the “second vacuum”, we have:

$$\mu = \tilde{\mu} = 0, \quad \lambda(\phi_0) \simeq 0, \quad \tilde{\lambda}(\tilde{\phi}_0) \simeq 0, \quad (106)$$

and then

$$\alpha_h(\phi_0, \tilde{\phi}_0) = 0, \quad \text{if} \quad V_{eff}^{crit}(v_2) = 0. \quad (107)$$

At the critical point, corresponding to the first EW vacuum  $v_1 = 246$  GeV, we also have  $V_{eff}^{crit}(v_1) = 0$ , according to the MPP prediction of the existence of degenerate vacua in the Universe.

Then we can present the full scalar Higgs potential by the following expression:

$$V_{eff}(\phi, \tilde{\phi}) = \lambda(|\phi|^2 - v_1^2)^2 + \tilde{\lambda}(|\tilde{\phi}|^2 - \tilde{v}_1^2)^2 + \alpha_h(\phi, \tilde{\phi})(|\tilde{\phi}|^2 - \tilde{v}_1^2)|\phi|^2, \quad (108)$$

where we have shifted the interaction term:

$$V_{int} = \alpha_h(\phi, \tilde{\phi})(|\tilde{\phi}|^2 - \tilde{v}_1^2)|\phi|^2 \quad (109)$$

in such a way that the interaction term vanishes, when  $\tilde{\phi} = \tilde{\phi}_0 = \tilde{v}_1$ , recovering the usual Standard Model.

At the end of the Inflation we have:  $\tilde{\phi} = \tilde{\phi}_E$ , and the first vacuum value of  $V_{eff}$  is given by:

$$V_{eff}(v_1, \tilde{\phi}_E) = \tilde{\lambda}(|\tilde{\phi}_E|^2 - \tilde{v}_1^2)^2 + \alpha_h(v_1, \tilde{\phi}_E)(|\tilde{\phi}_E|^2 - \tilde{v}_1^2)v_1^2 = 0, \quad (110)$$

and

$$\begin{aligned} V'_{eff}(v_1, \tilde{\phi}_E) &= \left. \frac{\partial V_{eff}}{\partial |\tilde{\phi}|^2} \right|_{\substack{\phi = v_1 \\ \tilde{\phi} = \tilde{\phi}_E}} \\ &= \alpha_h(v_1, \tilde{\phi}_E)(|\tilde{\phi}_E|^2 - \tilde{v}_1^2) = 0. \end{aligned} \quad (111)$$

This means that the end of the Inflation occurs at the value:

$$\tilde{\phi}_E = \tilde{v}_1 = \zeta v_1, \quad (112)$$

which coincides with the VEV  $\langle \tilde{\phi} \rangle$  of the field  $\tilde{\phi}$  at the first vacuum in the mirror world MW. Thus,

$$V_{eff}(\phi, \tilde{\phi}_E) = \lambda(|\phi|^2 - v_1^2), \quad (113)$$

which means the Standard Model.

As it is well-known, the total number of e-folds is given by the following expression (see for example Ref. [98]):

$$N^* = \frac{1}{s_{end}^2} \int_{s_0}^{s_{end}} \frac{ds}{(V'_s/V_s)}, \quad (114)$$

where  $s \equiv |\tilde{\phi}|$  and  $s_0 = s_{in}$ . Then

$$\begin{aligned} V_s &= \lambda(s^2 - \tilde{v}_1^2) + \alpha_h(v_1, s)(s^2 - \tilde{v}_1^2)v_1^2, \\ V'_s &= \frac{\partial V_s}{\partial s} = 2s \frac{\partial V_s}{\partial s^2}, \end{aligned} \quad (115)$$

and

$$\frac{V'_s}{V_s} = 2s \frac{2\tilde{\lambda}(s^2 - \tilde{v}_1^2) + \alpha_h(v_1, s)v_1^2}{\lambda(s^2 - \tilde{v}_1^2)^2 + \alpha_h(v_1, s)(s^2 - \tilde{v}_1^2)v_1^2}. \quad (116)$$

Then Eq. (98) gives:

$$N^* = \frac{1}{2s_{end}^2} \int_{s_0}^{s_{end}} \frac{\lambda(s^2 - s_{end}^2)^2 + \alpha_h(s^2 - s_{end}^2)v_1^2 ds}{2\lambda(s^2 - s_{end}^2) + \alpha_h v_1^2} \frac{1}{s}, \quad (117)$$

where  $s = |\tilde{\phi}|$ ,  $s_{end} = |\tilde{\phi}_{end}| = \zeta v_1$ ;  $\lambda = \tilde{\lambda}$  (property of the MW).  
As a result, we obtain:

$$8N^* = \left(1 + \frac{\alpha_h}{\lambda}\gamma - 2\gamma\right)^2, \quad (118)$$

where  $\gamma = \ln(s_{end}/s_0)$  with initial value  $s_{in} = s_0$ .

Using cosmological measurements [47], we have:

$$N^* \simeq 50 - 60. \quad (119)$$

According to Refs. [67, 68],  $\zeta \sim 100$ , and for  $N^* \simeq 50$  we predict the following estimation:

$$\frac{\alpha_h}{2\lambda} - 1 \simeq \frac{10}{\ln \zeta + \gamma_1}. \quad (120)$$

Here  $\gamma_1 = \ln(v_1/s_0)$ .

In cosmology:  $s_0 \simeq H_0$ , where  $H_0 \simeq 1.5 \times 10^{-42}$  GeV is the initial Hubble rate, and it is not difficult to estimate that:

$$\frac{\alpha_h}{2\lambda} \sim 1. \quad (121)$$

Finally we obtain:

$$\alpha_h(v_1, \tilde{v}_1) \sim 2\lambda(v_1). \quad (122)$$

Using this information, we conclude that the interaction of the Higgs and mirror Higgs bosons (see (55)) near the first vacua is of order of the self-interaction of the ordinary Higgs bosons near the first EW-vacuum. We also conclude that our theory really can correspond to  $\zeta \sim 100$ , as it was estimated by Z. Berezhiani and his collaborators (see Refs. [67, 68]).

We conclude that the Higgs Inflation scenario developed in this investigation is self-consistent with our theory based on the Gravi-Weak Unification, MPM and the discrete space-time Sidharth's theory at the Planck scale.

Now it is obvious that all previous investigations of the Higgs field Inflation do not coincide with our model of the Inflation. It is quite necessary to take into account seriously the interaction between ordinary and mirror Higgs fields. Thus, it is not obvious that the Higgs field Inflation from the "false vacuum" at the Planck scale to the EW vacuum of the Standard Model is in a disagreement with the MPM predictions of the top-Higgs masses and modern cosmological parameters' prediction, as it was shown in Ref. [98], etc.

The theory developed in this investigation predicts the absence of supersymmetry in the Nature at all, or predicts an essentially large supersymmetry's breaking scale ( $M_{SUSY} > 10^{18}$  GeV), what is not within the reach of the LHC experiments. We hope that the future LHC results will shed light on this problem.

In connection with the present investigation, it is necessary to mention the recent Ref. [100], in which it was shown that the RG evolutions of the corresponding Higgs self-interaction ( $\lambda(t)$ ) and Yukawa coupling ( $y(t)$ ) lead to the free-field stable point:

$$\lambda(M_{Pl}) = \dot{\lambda}(M_{Pl}) = 0$$

in the pure scalar sector at the Planck scale, what means that the SM is a low-energy limit of the conceivable theory at the Planck scale, which can be at least conformal, or even

superconformal one. This circumstance is phenomenologically motivated by the actual properties of the SM. In this scenario, the Higgs sector could emerge as a Goldstone boson, associated with a spontaneous breaking of the high-energy conformal invariance. This would simultaneously resolve the hierarchy and Landau pole problems in the scalar sector and would provide a nearly flat potential with two almost degenerate vacua at the EW and Planck scale.

## 9 Summary and Conclusions

1. We suggested to consider the theory of a discrete space-time by B.G. Sidharth as a theory of the Planck scale physics, existing at the early stage of the evolution of our Universe. We have used the Sidharth's predictions of the non-commutativity to have almost zero cosmological constant (c.c.). Previously B.G.Sidharth was first who has shown that c.c. is  $\Lambda \sim H_0^2$ , where  $H_0$  is the Hubble rate, and the Dark Energy density is very small ( $\sim 10^{-48} \text{ GeV}^4$ ), what provided the accelerating expansion of our Universe after the Big Bang. This result of almost zero c.c. was applied to our Gravi-Weak Unification (GWU) model.
2. Using the Plebanski's formulation of gravity, we constructed the Gravi-Weak Unification model, which is invariant under the  $G_{(GWU)} = Spin(4, 4)$ -group, isomorphic to the  $SO(4, 4)$ -group. Gravi-Weak Unification is a model unifying gravity with the weak  $SU(2)$  gauge and Higgs fields.
3. We considered also the ideas of the Random Dynamics, developed by H.B. Nielsen and his collaborators, with aim to explain, why the Nature has chosen at the early stage the symmetry  $G = G_{(GWU)} \times U(4)$ , where  $U(4)$  is a group of fermions. Random Dynamics also assumes a discrete space-time (with lattice-like structure), and leads to the Multiple Point Principle (MPP), which postulates that the Nature has the Multiple Critical Point (MCP). The MPP-model (MPM) predicts the existence of several degenerate vacua in the Universe, all having zero or almost zero cosmological constants.
4. In contrast to other theories of unification, we accepted an assumption of the existence of visible and invisible (hidden) sectors of the Universe. We gave arguments that modern astrophysical and cosmological measurements lead to a model of the Mirror World with a broken Mirror Parity (MP), in which the Higgs VEVs of the visible and invisible worlds are not equal:  $\langle \phi \rangle = v$ ,  $\langle \tilde{\phi} \rangle = \tilde{v}$  and  $v \neq \tilde{v}$ . We considered a parameter characterizing the violation of the MP:  $\zeta = \tilde{v}/v \gg 1$ , using the result:  $\zeta \sim 100$  obtained by Z. Berezhiani and his collaborators.
5. In our model we showed that the action for gravitational and  $SU(2)$  Yang–Mills and Higgs fields, constructed in the ordinary world (OW), has a modified duplication for the hidden (mirror) world (MW) of the Universe.
6. Considering the Gravi-Weak symmetry breaking, we have obtained the following sub-algebras:  $\mathfrak{g}_1 = \mathfrak{sl}(2, C)_L^{(grav)} \oplus \mathfrak{su}(2)_L$  – in the ordinary world, and  $\tilde{\mathfrak{g}}_1 = \tilde{\mathfrak{sl}}(2, C)_R^{(grav)} \oplus$

$\tilde{\mathfrak{su}}(2)_R$  – in the hidden world. These sub-algebras contain the self-dual left-handed gravity in the OW, and the anti-self-dual right-handed gravity in the MW. We showed, that finally at low energies we have the Standard Model and the Einstein-Hilbert’s gravity.

7. We reviewed the Multiple Point Model (MPM) by D.L. Bennett and H.B.Nielsen. We showed that the existence of two vacua into the SM: the first one – at the Electroweak scale ( $v_1 \simeq 246$  GeV), and the second one – at the Planck scale ( $v_2 \sim 10^{18}$  GeV), was confirmed by calculations of the Higgs effective potential in the 2-loop and 3-loop approximations. The Froggatt-Nielsen’s prediction of the top-quark and Higgs masses was given in the assumption that there exist two degenerate vacua into the SM. It was shown that this prediction was improved by the next order calculations.
8. We have developed a model of the Higgs Inflation using the GWU action, which contains a non-minimal coupling of the Higgs field with gravity, suggested by F. Bezrukov and M. Shaposhnikov. According to this model, a scalar field  $\sigma$ , being an inflaton, starts trapped from the ”false vacuum” of the Universe at the value of the Higgs field’s VEV  $v = v_2 \sim 10^{18}$  GeV. Then during the Inflation  $\sigma$  decays into the two Higgs doublets of the  $\tilde{\text{SM}}$ :  $\sigma \rightarrow \phi^\dagger \phi$ . The interaction between the ordinary and mirror Higgs fields  $\phi$  and  $\tilde{\phi}$  generates a Hybrid model of the Higgs Inflation in the Universe. Such an interaction leads to the emergence of the SM vacua at the EW scales: with the Higgs boson VEVs  $v_1 \approx 246$  GeV – in the OW, and  $\tilde{v}_1 = \zeta v_1$  – in the MW. Our model of the Higgs Inflation is in agreement with the predictions of the top-Higgs masses,  $\zeta \sim 100$  and modern cosmological parameters  $N^*$ ,  $A_s$  and  $r$ .
9. The GWU theory developed in this investigation predicts the absence of the supersymmetry at least before  $10^{18}$  GeV.

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