Mirror world and superstring-inspired hidden sector of the Universe, dark matter and dark energy

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We develop a concept of parallel existence of the ordinary (O) and hidden (H) worlds. We compare two cases: (1) when the hidden sector of the Universe is a mirror counterpart of the ordinary world, and (2) when it is a superstring-inspired shadow world described, in contrast to the mirror world, by a symmetry group (or by a chain of groups), which does not coincide with the ordinary world symmetry group. We construct a cosmological model assuming the existence of the superstring-inspired E_6 unification, broken at the early stage of the Universe to $SO(10) \times U(1)_Z$—in the O-world, and to $SU(6)' \times SU(2)'_\theta$—in the H-world. As a result, we obtain the low-energy symmetry group $G'_{\rm SM} \times SU(2)'_\theta$ in the shadow world, instead of the standard model group $G_{\rm SM}$ existing in the O-world. The additional non-Abelian $SU(2)'_\theta$ group with massless gauge fields, ''thetons,'' is responsible for dark energy. Considering a quintessence model of cosmology with an inflaton σ and an axion a_θ, which is a pseudo Nambu-Goldstone boson induced by the $SU(2)'_\theta$-group anomaly, we explain the origin of dark energy, dark matter and ordinary matter. In the present model we review all cosmological epochs (inflation, reheating, recombination and nucleosynthesis), and give our version of the baryogenesis. The cosmological constant problem is also briefly discussed.

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I. INTRODUCTION

In this paper we consider the hypothesis that there may exist in the Universe the ordinary (O) and hidden (H) worlds, assuming the existence of the mirror (M) or superstring-inspired shadow (H) counterpart of our observable O-world. Constructing a new cosmological model with superstring-inspired E_6 unification in the four-dimensional space, which is broken at the early stage of the Universe to $SO(10) \times U(1)_Z$—in the O-world, and to $SU(6)' \times SU(2)'_\theta$—in the H-world, we try to explain the origin of the dark energy (DE), dark matter (DM) and ordinary matter (OM), in accordance with energy densities given by recent cosmological observations. The model describes the inflation, reheating, baryogenesis and nucleosynthesis epochs of our Universe, confirming the ΛCDM model of our accelerating Universe with a tiny value of the cosmological constant (CC), Λ.

The study is based on Refs. [1,2] and presents a development of the ideas considered previously in Ref. [3]. However, in the present work we give a new interpretation of the possible accelerating expansion of the Universe, as far as inflation and baryogenesis.

A. Recent results of cosmological and astrophysical observations

Modern models for DE and DM are based on precise measurements in cosmological and astrophysical observations [4–6].

For the present epoch, the Hubble parameter $H = H_0$ is given by the following value [4]:

$$H_0 = 1.5 \times 10^{-42}\ \mathrm{GeV}, \tag{1}$$

and the critical density of the Universe is

$$\rho_c = 3H^2/8\pi G = (2.5 \times 10^{-12}\ \mathrm{GeV})^4, \tag{2}$$

where G is the gravitational constant.

Cosmological measurements give the following density ratios of the total Universe [4]:

$$\Omega = \Omega_r + \Omega_m + \Omega_\Lambda \approx 1, \tag{3}$$

where $\Omega_r \ll 1$ is a relativistic (radiation) density ratio, and

$$\Omega_\Lambda = \Omega_{\rm DE} \approx 75\% \tag{4}$$

for the mysterious DE, which is responsible for the acceleration of the Universe. The total matter density is

$$\Omega_m \approx \Omega_M + \Omega_{\rm DM} \approx 25\%, \tag{5}$$

with

$$\Omega_M \approx \Omega_B \approx 4\% \tag{6}$$

for (visible) ordinary matter and baryons, while

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$$\Omega_{\mathrm{DM}} \approx 21\% \tag{7}$$

for the DM). These results give

$$\Omega_{\mathrm{DM}}/\Omega_B \approx 5. \tag{8}$$

The ΛCDM-cosmological model [7] predicts that the cosmological constant CC is

$$\Lambda = 8\pi G \rho_{\mathrm{vac}}^{(\mathrm{eff})}, \tag{9}$$

where the value $\rho_{\mathrm{vac}}^{(\mathrm{eff})}$ is the effective vacuum energy density of the Universe, which coincides with ρ_{DE}. Using Eqs. (2) and (4), we can calculate the dark energy density:

$$\rho_{\mathrm{DE}} = \rho_{\mathrm{vac}}^{(\mathrm{eff})} \simeq 0.75\rho_c \simeq (2.3 \times 10^{-3}\ \mathrm{eV})^4. \tag{10}$$

This is a result of recent cosmological observations [6], which also fit the equation of state for DE: $w = p/\rho$ with the following constant value of w:

$$w = -1.05 \pm 0.13(\text{statistical}) \pm 0.09(\text{systematic}). \tag{11}$$

In the units $\kappa = 1$, where $\kappa^2 = 8\pi G$, we have the cosmological constant:

$$\Lambda = \rho_{\mathrm{DE}} \simeq (2.3 \times 10^{-3}\ \mathrm{eV})^4, \tag{12}$$

which is extremely small.

This result is consistent with the present model of accelerating Universe [7] (see also the reviews [8]), dominated by a tiny cosmological constant Λ, $w = -1$ and cold dark matter—this is the so-called ΛCDM scenario.

B. Main assumptions of the present model

Our model is based on the following assumptions:

(i) The grand unified theory (GUT) is inspired by the superstring theory [9–11], which predicts E_6 unification in the four-dimensional space [11], occurring at the high energy scale $M_{E_6} \approx 10^{18}$ GeV.

(ii) There exists a mirror world [12,13], which is a duplication of our ordinary world, or a shadow hidden world (see Ref. [14]). The H-world is not identical with the O-world, having different symmetry groups.

(iii) DE and DM are described by the mirror world with broken mirror parity (MP) [see Refs. [15–21]], or by the superstring-inspired shadow H-world considered in Refs. [1–3].

(iv) We assume that E_6 unification restores mirror parity at high energies $\approx 10^{18}$ GeV (and at the early stage of the Universe). Then the mirror world exists at the scale $M'_{E6} = M_{E6} \approx 10^{18}$ GeV, and the symmetry group of the Universe is $E_6 \times E'_6$.

The paper is organized as follows: In the next section we introduce the E_6 unification in the four-dimensional space-time inspired by superstring theory and the breaking of this unification in different ways. In Sec. III, we present the hypothesis of the existence in Nature of a mirror world parallel to the visible ordinary world. We discuss their particle content, the mirror world with broken mirror parity and the seesaw scale in the ordinary and mirror worlds. In Sec. IV we introduce the hidden sector as a superstring-inspired shadow world, with the low-energy symmetry group $G' = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y$, as compared to $G_{\mathrm{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$ in the O-world. The group G' has an additional non-Abelian group $SU(2)'$ with gauge fields, "thetons," which are neutral massless vector particles. These thetons have a macroscopic confinement radius $1/\Lambda'_\theta$, where $\Lambda'_\theta \sim 10^{-3}$ eV. The breaking mechanism of the E6 unification is presented in Sec. V. It has been shown that this breaking is realized by the Higgs fields H_{27} belonging to the 27-plet of E_6—in the O-world, and by H351 belonging to the 351-plet of E'_6—in the H-world. We discuss the problem of walls avoiding an unacceptable wall dominance. Sections VI, VII, and VIII are devoted to the problem of cosmological constant. We show that the cancellation between the "bare" cosmological constant, and the vacuum energy stress, $8\pi G_{\rho\mathrm{vac}}$, described only by the SM contributions of the ordinary and hidden worlds, explains the small value of dark energy density $\rho_{\mathrm{DE}} = \simeq (2.3 \times 10^{-3}\,\mathrm{eV})^4$ by the condensates of—fields. Inflationary, reheating and radiation epochs of our Universe are reviewed in Secs. IX and X. The inflationary potential is described by the Coleman-Weinberg potential. The ordinary and hidden sectors of the Universe have different cosmological evolutions and never have to be in equilibrium with each other. The big bang nucleosynthesis (BBN), considered in Sec. XI, gives the constraint $T' < T$, where $T(T')$ is the O-(H-)temperature of the Universe. The difference between the O- and H-worlds is described in terms of two macroscopic parameters: $x \equiv T'/T$ and $\beta \equiv \Omega'_B/\Omega_B$. In Sec. XII we describe the dark matter assuming that the shadow baryons and shadow helium atoms are the best candidates for DM. We explain the result of astrophysical observations: $\Omega_{\mathrm{DM}}/\Omega_M \simeq 5$. In Sec. XIII we consider the scenario of baryogenesis of Ref. [2], in the present context.

II. SUPERSTRING THEORY AND E_6 UNIFICATION

A. Superstring theory

Superstring theory [9–11] is a paramount candidate for the unification of all fundamental gauge interactions with gravity. Superstrings are free of gravitational and Yang-Mills anomalies if the gauge group of symmetry is $SO(32)$ or $E_8 \times E_8$. The "heterotic" superstring theory $E_8 \times E'_8$ was suggested as a more realistic model for unification of all fundamental gauge interactions with gravity [10]. However, this ten-dimensional theory can undergo spontaneous compactification. The integration over six compactified dimensions of the E_8 superstring theory leads to the effective theory with the E_6 unification in the four-dimensional space [11].

Superstring theory has led to the speculation that there may exist another form of matter—hidden "shadow matter''—in the Universe, which only interacts with ordinary matter via gravity or gravitational-strength interactions [14]. The shadow world, in contrast to the mirror world [12,13], can be described by another group of symmetry (or by a chain of groups of symmetry), which is different from the ordinary world symmetry group. According to the (super)string theory, the two worlds, ordinary and shadow, can be viewed as parallel branes in a higher dimensional space, where the O-particles are localized on one brane and the H-particles—on another brane, and gravity propagates in the bulk.

In our model we have assumed that at very high energies there exists the E_6 unification predicted by superstring theory.

B. E_6 unification

Three 27-plets of E_6 contain three families of quarks and leptons, including right-handed neutrinos N_a^c (where $a =$ 1, 2, 3 is the index of generations). The description of generations is briefly discussed in Ref. [22], but here we omit generation subscripts, for simplification.

Matter fields (quarks, leptons and scalar fields) of the fundamental 27-representation of the E_6 group decompose under $SU(5) \times U(1)_X$ subgroup as follows (see Ref. [23]):

$$27 \to (10, 1) + (\bar{5}, 2) + (5, -2) + (\bar{5}, -3) + (1, 5) + (1, 0). \tag{13}$$

The first and second numbers in the brackets in Eq. (13) correspond to the dimensions of the $SU(5)$ representations and to the $U(1)_X$ charges, respectively. These representations decompose under the groups with the breaking

$$SU(5) \times U(1)_X \to SU(3)_C \times SU(2)_L \times U(1)_Z \times U(1)_X. \tag{14}$$

We consider the following $U(1)_Z \times U(1)_X$ charges of matter fields: $Z = \sqrt{\frac{5}{3}} Q^Z$, $X = \sqrt{40} Q^X$.

The standard model (SM) family which contains the doublets of left-handed quarks Q and leptons L, right-handed up and down quarks u^c, d^c, and also right-handed charged lepton e^c, belongs to the $(10, 1) + (\bar{5}, 2)$ representations of $SU(5) \times U(1)_X$. Then, for the decomposition (14), we have the following assignments of particles:

$$\begin{aligned} (10, 1) \to Q = \begin{pmatrix} u \\ d \end{pmatrix} &\sim \left(3, 2, \frac{1}{6}, 1\right), \\ u^{\mathbf{c}} &\sim \left(\bar{3}, 1, -\frac{2}{3}, 1\right), \\ e^{\mathbf{c}} &\sim (1, 1, 1, 1). \end{aligned} \tag{15}$$

$$(\bar{5}, 2) \to d^{\mathbf{c}} \sim \left(\bar{3}, 1, \frac{1}{3}, 2\right), \quad L = \begin{pmatrix} e \\ \nu \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, 2\right), \tag{16}$$

$$(1, 5) \to S \sim (1, 1, 0, 5). \tag{17}$$

The remaining representations in (14) decompose as follows:

$$(5, -2) \to D \sim \left(3, 1, -\frac{1}{3}, -2\right), \quad h = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix} \sim \left(1, 2, \frac{1}{2}, -2\right), \tag{18}$$

$$(\bar{5}, -3) \to D^{\mathbf{c}} \sim \left(\bar{3}, 1, \frac{1}{3}, -3\right), \quad h^{\mathbf{c}} = \begin{pmatrix} h^0 \\ h^- \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, -3\right). \tag{19}$$

To the representation (1,5) is assigned the SM-singlet field S, which carries nonzero $U(1)_X$ charge. The light Higgs doublets are accompanied by the heavy color triplets of exotic quarks (''diquarks'') $D, D^{\mathbf{c}}$ which are absent in the SM (see Ref. [23]).

The right-handed heavy neutrino is a singlet field N^c represented by (1,0):

$$(1, 0) \to N^{\mathbf{c}} \sim (1, 1, 0, 0). \tag{20}$$

C. Breaking of the E_6 unification

It is well known (see, for example, Ref. [24]) that there exist three schemes of breaking the E_6 group:

(i)

$$E_6 \to SU(3)_1 \times SU(3)_2 \times SU(3)_3, \tag{21}$$

(ii)

$$E_6 \to SO(10) \times U(1), \tag{22}$$

(iii)

$$E_6 \to SU(6) \times SU(2). \tag{23}$$

The first case was considered in the first paper of Ref. [1], where we have investigated the possibility of the breaking:

$$E_6 \to SU(3)_C \times SU(3)_L \times SU(3)_R \tag{24}$$

in both O- and M-worlds, with broken mirror parity. The model has the merit of an attractive simplicity. However, in such a model we are unable to explain the tiny CC (12) given by astrophysical measurements, because in the case (24) we have in both worlds the low-energy limit of the SM, which forbids a large confinement radius (i.e. small energy scale) of any interaction.

It is quite impossible to obtain the same E_6 unification in the O- and M-worlds with the same breakings ii) or iii) in both worlds if mirror parity MP is broken. In this case, we are forced to assume different breakings of the E_6 unification in the O- and H-worlds:

$$E_6 \to SO(10) \times U(1) \qquad \text{in the O-world},$$

$$E_6' \to SU(6)' \times SU(2)' \qquad \text{in the H-world},$$

explaining the small value of the CC, Λ, by condensation of fields belonging to the additional $SU(2)'$ gauge group which exists only in the H-world and has a large confinement radius.

The breaking mechanism of the E_6 unification is given in Ref. [25]. The vacuum expectation values (VEVs) of the Higgs fields H_{27} and H_{351} belonging to 27- and 351-plets of the E_6 group can appear in the case (22) for the O-world only with nonzero 27-component:

$$\langle H_{351}\rangle = 0, \qquad v = \langle H_{27}\rangle \neq 0. \tag{25}$$

In the case (23) for the H-world we have

$$\langle H_{27}\rangle = 0, \qquad V = \langle H_{351}\rangle \neq 0. \tag{26}$$

The 27 representation of E_6 is decomposed into 1 + 16 + 10 under the $SO(10)$ subgroup and the 27 Higgs field, H_{27}, is expressed in "vector" notation as

$$H_{27} \equiv \begin{pmatrix} H_0 \\ H_\alpha \\ H_M \end{pmatrix}, \tag{27}$$

where the subscripts 0, $\alpha = 1, 2, \ldots, 16$ and $M = 1, 2, \ldots, 10$ stand for singlet, the 16- and the 10-representations of $SO(10)$, respectively. Then

$$\langle H_{27}\rangle = \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}. \tag{28}$$

Taking into account that the 351-plet of E_6 is constructed from 27×27 symmetrically, we see that the trace part of H_{351} is a singlet under the maximal little groups. Therefore, in a suitable basis, we can construct the VEV $\langle H_{351}\rangle$ for the case of the maximal little group $SU(2) \times SU(6)$. A singlet under this group which we get from a symmetric product of 27×27 comes from the component $(1, 15) \times (1, 15)$ and hence

$$\langle H_{351}\rangle = \begin{pmatrix} V \otimes 1_{15} & \\ & 0 \otimes 1_{15} \end{pmatrix}. \tag{29}$$

According to the assumptions of Ref. [1], in the ordinary world there exists the following chain of symmetry groups from the GUT scale of the E_6 unification up to the SM scale:

$$\begin{aligned} E_6 &\to SO(10) \times U(1)_Z \to SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \\ &\to [SU(3)_C \times SU(2)_L \times U(1)_Y]_{\rm SUSY} \to SU(3)_C \times SU(2)_L \times U(1)_Y. \end{aligned} \tag{30}$$

In the shadow H-world, we have the following chain:

$$\begin{aligned} E_6' &\to SU(6)' \times SU(2)_\theta' \to SU(4)_C' \times SU(2)_L' \times SU(2)_\theta' \times U(1)_Z' \to SU(3)_C' \times SU(2)_L' \times SU(2)_\theta' \times U(1)_X' \times U(1)_Z' \\ &\to [SU(3)_C' \times SU(2)_L' \times SU(2)_\theta' \times U(1)_Y']_{\rm SUSY} \to SU(3)_C' \times SU(2)_L' \times SU(2)_\theta' \times U(1)_Y'. \end{aligned} \tag{31}$$

In general, this is not an unambiguous choice of the $E_6(E_6')$ breaking chains.

III. E_6 UNIFICATION IN ORDINARY AND MIRROR WORLD

The results of Refs. [15–21] are based on the hypothesis of the existence in Nature of a mirror world parallel to the visible ordinary world. The authors have described the O- and M-worlds at low energies by a minimal symmetry $G_{\rm SM} \times G_{\rm SM}'$, where

$$G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

stands for the observable SM, while

$$G_{\rm SM}' = SU(3)_C' \times SU(2)_L' \times U(1)_Y'$$

is its mirror gauge group counterpart. The M-particles are singlets of $G_{\rm SM}$ and the O-particles are singlets of $G_{\rm SM}'$. *These different O- and M-worlds are coupled only by gravity, or possibly by another very weak interaction*. In general, we can consider a supersymmetric theory when $G \times G'$ contains the grand unification groups $SU(5) \times SU(5)'$, $SO(10) \times SO(10)'$, $E_6 \times E_6'$, etc.

A. Particle content in the ordinary and mirror worlds

The M-world is a mirror copy of the O-world and contains the same particles and types of interactions as our visible world. The observable elementary particles of our O-world have the left-handed (V-A) weak interactions, which violate P-parity. If a hidden mirror M-world exists, then mirror particles participate in the right-handed ($V + A$) weak interactions and have the opposite chirality.

Lee and Yang were the first [12] to suggest such a duplication of the worlds, which restores the left-right symmetry of Nature. They introduced a concept of right-handed particles, but their R-world was not hidden. The term "mirror matter" was introduced by Kobzarev, Okun and Pomeranchuk [13]. They suggested the "mirror world" as the hidden sector of our Universe, which interacts with the ordinary (visible) world only via gravity or another very weak interaction. They have investigated a variety of phenomenological implications of such parallel worlds (for recent comprehensive reviews on mirror particles and mirror matter, see Ref. [26]).

Including the Higgs bosons Φ, we have the following SM content of the O-world:

$$L - \text{set: } (u, d, e, \nu, \tilde{u}, \tilde{d}, \tilde{e}, \tilde{N})_L, \Phi_u, \Phi_d;$$
$$\tilde{R} - \text{set: } (\tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}, u, d, e, N)_R, \tilde{\Phi}_u, \tilde{\Phi}_d;$$

with the antiparticle fields: $\tilde{\Phi}_{u,d} = \Phi^*_{u,d}$, $\tilde{\psi}_R = C\gamma_0\psi^*_L$ and $\tilde{\psi}_L = C\gamma_0\psi^*_R$.

Considering the minimal symmetry $G_{\rm SM} \times G'_{\rm SM}$, we have the following particle content in the M-sector:

$$L' - \text{set: } (u', d', e', \nu', \tilde{u}', \tilde{d}', \tilde{e}', \tilde{N}')_L, \Phi'_u, \Phi'_d;$$
$$\tilde{R}' - \text{set: } (\tilde{u}', \tilde{d}', \tilde{e}', \tilde{\nu}', u', d', e', N')_R, \tilde{\Phi}'_u, \tilde{\Phi}'_d.$$

B. Mirror world with broken mirror parity

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. Mirror parity is not conserved, and the ordinary and mirror worlds are not identical. Then the VEVs of the Higgs doublets ϕ and ϕ' are not equal:

$$\langle\phi\rangle = v, \qquad \langle\phi'\rangle = v' \quad \text{and} \quad v \neq v'. \tag{32}$$

Introducing the parameter characterizing the violation of MP,

$$\zeta = \frac{v'}{v} \gg 1, \tag{33}$$

we have the estimate of Refs. [15–21]:

$$\zeta \sim 100.$$

Then the masses of fermions and massive bosons in the mirror world are scaled up by the factor ζ with respect to the masses of their counterparts in the ordinary world:

$$m'_{q',l'} = \zeta m_{q,l}, \tag{34}$$

$$M'_{W',Z',\Phi'} = \zeta M_{W,Z,\Phi}, \tag{35}$$

while photons and gluons remain massless in both worlds.

Let us consider now the expressions for the running of the inverse coupling constants,

$$\alpha_i^{-1}(\mu) = \frac{b_i}{2\pi}\ln\frac{\mu}{\Lambda_i}, \qquad \text{in the O-world;} \tag{36}$$

$$\alpha_i'^{-1}(\mu) = \frac{b'_i}{2\pi}\ln\frac{\mu}{\Lambda'_i}, \qquad \text{in the M-world.} \tag{37}$$

Here $i = 1, 2, 3$ correspond to $U(1), SU(2)$ and $SU(3)$ groups of the SM (or SM′). A big difference between the electroweak scales v and v' will not cause the same difference between the scales Λ_i and Λ'_i. Hence,

$$\Lambda'_i = \xi\Lambda_i, \tag{38}$$

where $\xi > 1$.

C. Seesaw scale in the ordinary and mirror worlds

In the language of neutrino physics, the O-neutrinos ν_e, ν_μ, ν_τ are active neutrinos, while the M-neutrinos $\nu'_e, \nu'_\mu, \nu'_\tau$ are sterile neutrinos. The model [15–21] provides a simple explanation of why sterile neutrinos could be light, and could have significant mixing with the active neutrinos.

If MP is conserved ($\zeta = 1$), then the neutrinos of the two sectors are strongly mixed. But it seems that the situation with the present experimental and cosmological limits on the active-sterile neutrino mixing do not confirm this hypothesis. If instead MP is spontaneously broken, and $\zeta \gg 1$, then the active-sterile mixing angles should be small:

$$\theta_{\nu\nu'} \sim \frac{1}{\zeta}. \tag{39}$$

As a result, we have the following relation between the masses of the light left-handed neutrinos:

$$m'_\nu \approx \zeta^2 m_\nu. \tag{40}$$

In the context of the SM, in addition to the fermions with nonzero gauge charges, one introduces also the gauge singlets, the so-called right-handed neutrinos N_a with large Majorana mass terms. According to Refs. [15–21], they have equal masses in the O- and M-worlds:

$$M'_{\nu,a} = M_{\nu,a}. \tag{41}$$

Let us consider now the usual seesaw mechanism. Heavy right-handed neutrinos are created at the seesaw scales M_R in the O-world and M'_R in the M-, or H-world. From the Lagrangian, considering the Yukawa couplings identical in the two sectors, it follows that

$$m_\nu = \frac{v^2}{M_R}, \qquad m'_\nu = \frac{v'^2}{M'_R} \tag{42}$$

and we immediately obtain the relations (40), with

$$M'_R = M_R. \tag{43}$$

Then we see that even in the model with broken mirror parity, we have the same seesaw scales in the O- and M-(H-)worlds.

IV. SHADOW WORLD AND θ PARTICLES

In the first paper of Ref. [1] was presented an example of the gauge coupling constant evolutions from the SM up to the E_6-unification scale in the ordinary and mirror worlds with broken mirror parity, assuming that the E_6 group of symmetry undergoes the breaking: $E_6 \to SU(3)_C \times SU(3)_L \times SU(3)_R$ in both worlds (O and M) and gives the SM group of symmetry at lower energies. Of course, such a Universe could exist, but it is difficult to find a simple explanation why the observable CC has such a tiny value (12), since such a model does not have an extremely large radius of confinement for any gauge interaction. Thus, it is impossible to conceive a vacuum with extremely small energy density.

In the present paper we consider the idea of the existence of θ particles, developed by Okun [27]. In those works it was suggested the hypothesis that in Nature there exists the symmetry group

$$SU(3)_C \times SU(2)_L \times SU(2)_\theta \times U(1)_Y, \tag{44}$$

i.e. with an additional non-Abelian $SU(2)_\theta$ group whose gauge fields are neutral, massless vector particles—thetons. These thetons have a macroscopic confinement radius $1/\Lambda_\theta$. Later, in Ref. [3], it was assumed that if any $SU(2)$ group with the scale $\Lambda_2 \sim 10^{-3}$ eV exists, then it is possible to explain the small value (12) of the observable CC. The latter idea was taken up in Ref. [1].

In the present context we assume the existence of the low-energy symmetry group (44) in the shadow world, but not in the ordinary world, as a natural consequence of different schemes of the E_6 breaking in the O- and H-worlds. θ-particles are absent in the ordinary world, because their existence is in disagreement with all experiments. However, they can exist in the H-world:

$$G' = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y. \tag{45}$$

By analogy with the theory developed in [27], we consider shadow thetons $\Theta'^{i}{}_{\mu\nu}$, $i = 1, 2, 3$, which belong to the adjoint representation of the group $SU(2)'_\theta$, three generations of shadow θ-quarks q'_θ and shadow leptons l'_θ, and the necessary θ scalars ϕ'_θ for the corresponding breakings. Shadow thetons have macroscopic confinement radius $1/\Lambda'_\theta$, and we assume that

$$\Lambda'_\theta \sim 10^{-3} \text{ eV}. \tag{46}$$

Matter fields of the fundamental 27-representation of the E'_6 group decompose under $SU(2)'_\theta \times SU(6)'$ subgroup as follows: $27 = (2, 6) + (1, 15)$, where

$$(2, 6) \to q' = \begin{pmatrix} q'_{\theta,A}|_{I_\theta=+1/2} \\ q'_{\theta,A}|_{I_\theta=-1/2} \end{pmatrix}, \tag{47}$$

$$(1, 15) \to D', D'^c \tag{48}$$

$$h' = \begin{pmatrix} h'^{+} \\ h'^{0} \end{pmatrix}, \tag{49}$$

$$h'^{\mathbf{c}} = \begin{pmatrix} h'^{0} \\ h'^{-} \end{pmatrix}, \tag{50}$$

$$q'^{c}{}_a, N'^c, S'. \tag{51}$$

Here $A = 1, \ldots, 6$; $a = 1, 2, 3$ are color indices and I_θ is a θ isospin; $\theta -$ quarks are $q'_{\theta,A}$, while usual shadow quarks $q'^{c}{}_a$, the right-handed neutrino N'^c and the scalar S' are $SU(2)'_\theta$ singlets.

V. INFLATION, E_6 UNIFICATION AND THE PROBLEM OF WALLS IN THE UNIVERSE

The simplest model of inflation is based on the superpotential

$$W = \lambda\varphi(\Phi^2 - \mu^2), \tag{52}$$

containing the inflaton field given by φ and the Higgs field Φ, where λ is a coupling constant of order 1 and μ is a dimensional parameter of the order of the GUT scale (see, for example, [28]). The supersymmetric vacuum is located at $\varphi = 0$, $\Phi = \mu$, while for the field values $\Phi = 0$, $|\varphi| > \mu$ the tree level potential has a flat valley with the energy density $V = \lambda^2\mu^4$. When the supersymmetry is broken by the nonvanishing F-term, the flat direction is lifted by radiative corrections and the inflaton potential acquires a slope appropriate for the slow roll conditions.

This so-called hybrid inflation model leads to the choice of the initial conditions [17]. Namely, at the end of the Planck epoch the singlet scalar field φ should have an initial value $\varphi = f \sim 10^{18}$ GeV (E_6-GUT scale), while the field Φ must be zero with high accuracy over a region much larger than the initial horizon size $\sim M_{Pl}$. In other words, the initial field configuration should be located right on the bottom of the inflaton valley and the energy density starts with $V = \lambda^2\mu^4 \ll M^4_{Pl}$.

If E'_6 is the mirror counterpart of E_6, then we have Z_2 symmetry, i.e. a discrete group connected with the mirror parity. In general, the spontaneous breaking of a discrete group leads to phenomenologically unacceptable walls of huge energy per area (see Fig. 1).

Then we have the following properties for the energy densities of radiation, DM, M and wall:

$$\rho_r \propto \frac{1}{a(t)^4}, \qquad \rho_{M,\mathrm{DM}} \propto \frac{1}{a(t)^3}, \qquad \rho_{\mathrm{wall}} \propto \frac{1}{a(t)},$$

where $a(t)$ is a scale factor with cosmic time t in the Friedmann-Lemaítre-Robertson-Walker metric describing

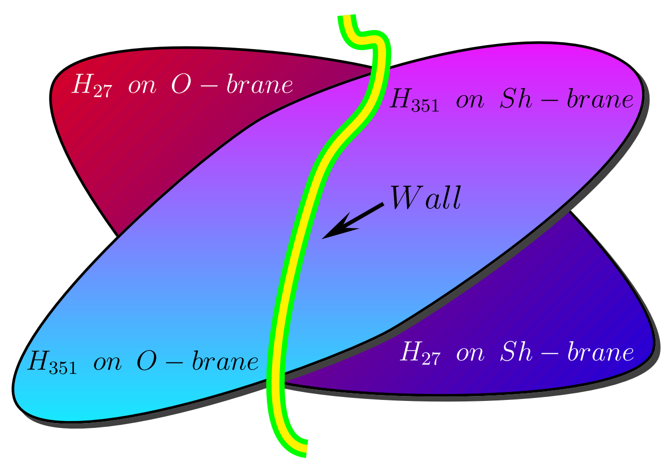

FIG. 1 (color online). The E'_6 is the mirror counterpart of E_6. The spontaneous breaking of a discrete group Z_2 connected with the mirror parity leads to phenomenologically unacceptable wall with huge energy per area.

our Universe. For large Universe, we have $\rho_{\rm wall} \gg \rho_{M,{\rm DM}}, \rho_r$ In our case of the hidden world, the shadow superpotential is

$$W' = \lambda' \varphi' (\Phi'^2 - \mu'^2), \tag{53}$$

where $\Phi' = H_{351}$ and $\langle H_{351} \rangle = \mu'$. Then the initial energy density in the H-world is $V' = \lambda'^2 \mu'^4 \ll M_{Pl}^4$. To avoid this phenomenologically unacceptable wall dominance we cannot assume symmetry under Z_2 and thus $V = V'$ is not automatic. Instead, it is necessary to assume the following fine-tuning:

$$V = V' \colon \lambda^2 \mu^4 = \lambda'^2 \mu'^4, \tag{54}$$

which helps to obtain the initial conditions for the GUT-scales and GUT-coupling constants: $M_{E_6} = M'_{E_6'}$ and $g_{E_6} = g'_{E_6'}$.

VI. THE COSMOLOGICAL CONSTANT PROBLEM

The cosmological constant (CC) was first introduced by Einstein in 1917 [29] with the aim to admit a static cosmological solution in his new general theory of relativity. The introduction of the cosmological constant λ, the bare cosmological constant, was accomplished by the addition to the original field equations:

$$G^{\mu\nu} = R^{\mu\nu} - \tfrac{1}{2} R g^{\mu\nu} = 8\pi G T^{\mu\nu} \tag{55}$$

of the divergence-free term $-\lambda g_{\mu\nu}$:

$$G^{\mu\nu} = 8\pi G T^{\mu\nu} - \lambda g^{\mu\nu}, \tag{56}$$

where $R_{\mu\nu}$ is the Ricci curvature of $g_{\mu\nu}$, and $T_{\mu\nu}$ is the energy-momentum tensor of matter.

Later it was realized (see [30,31]) that quantum fluctuations result in a vacuum energy, $\rho_{\rm vac}$: any mode contributes $\frac{1}{2}\hbar\omega$ to the vacuum energy, and the expected value of the energy-momentum tensor of matter is

$$\langle T^{\mu\nu} \rangle = T_m^{\mu\nu} - \rho_{\rm vac} g^{\mu\nu}, \tag{57}$$

where $T_m^{\mu\nu}$ vanishes in vacuum. The quantum expectation of the energy-momentum tensor, $\langle T^{\mu\nu} \rangle$, acts as a source for the Einstein tensor, and we have

$$G^{\mu\nu} = 8\pi G T_m^{\mu\nu} - \Lambda g^{\mu\nu}, \tag{58}$$

where Λ is the effective cosmological constant provided by the contribution of the vacuum energy, ρ_{vac}. We would expect that the effective vacuum energy,

$$\rho_{\rm vac}^{\rm (eff)} = \frac{\lambda}{8\pi G} + \rho_{\rm vac} = \frac{\Lambda}{8\pi G}, \tag{59}$$

to be not smaller than $\rho_{\rm vac}$. Even if the bare cosmological constant is assumed to vanish ($\lambda = 0$), the effective cosmological constant is not equal to zero. Requiring that $\Lambda = 0$ means that there must be an exact cancellation between the bare cosmological constant, λ, and the vacuum energy stress, $8\pi G \rho_{\rm vac}$:

$$\Lambda = 0 \quad \to \quad \lambda + 8\pi G \rho_{\rm vac} = 0. \tag{60}$$

When the spontaneous symmetry breaking was widely discussed in the standard model, Veltman commented that the vacuum energy arising in spontaneous symmetry breaking gives an additional contribution to the CC [32].

If we assume that the field theory is only valid up to some energy scale $M_{\rm cutoff}$, then there is a contribution to $\rho_{\rm vac}$ of $O(M_{\rm cutoff}^4)$. Collider experiments have established that the SM is accurate up to energy scales $M_{\rm cutoff} \gtrsim O(M_{EW})$, where $M_{EW} \approx 246$ GeV is the electroweak scale. We would therefore expect $\rho_{\rm vac}$ to be at least $O(M_{EW}^4)$.

In the absence of any new physics between the electroweak and the Planck scale, $M_{Pl} \approx 1.2 \times 10^{19}$ GeV, where quantum fluctuations in the gravitational field can no longer be safely neglected, we would expect $\rho_{\rm vac} \sim O(M_{Pl}^4)$. If supersymmetry were an unbroken symmetry of Nature, the quantum contributions to the vacuum energy would all exactly cancel, leaving $\rho_{\rm vac} = 0$ and $\Lambda = \lambda$. However, our Universe is not supersymmetric today, and so supersymmetry (SUSY) must have been broken at some energy scale $M_{\rm SUSY}$, where 1 TeV $\lesssim M_{\rm SUSY} \lesssim M_{Pl}$. We note that the SUSY breaking is necessary in our superstring, and thereby SUSY-based, model. Thus, we would expect $\rho_{\rm vac} \sim O(M_{\rm SUSY}^4)$. Our model of quantum cosmology also has to take into account extra dimensions and branes, spontaneous breaking of compactification.

Previously, in Ref. [33] and also in Ref. [34], it was shown that supergravity models which ensure the vanishing of the vacuum energy density near the physical vacuum lead to a natural realization of the multiple point model [35] (see also the reviews [36]) describing the degenerate vacua with zero Λ.

The expansion rate of our Universe is sensitive to $\rho_{vac}^{\rm (eff)}$, or equivalently Λ. The result of astrophysical measurements is given by Eq. (12), which has established that $(\rho_{\rm vac}^{\rm (eff)})^{1/4} \simeq 2.3 \times 10^{-3}$ eV. This implies that $\rho_{\rm vac}^{\rm (eff)}$ is some 10^{60}–10^{120} times smaller than the expected contribution from quantum fluctuations, and gives rise to the cosmological constant problem: *Why is the measured effective vacuum energy or cosmological constant so much smaller than the expected contributions to it from quantum fluctuations?*

VII. A PROPOSAL FOR SOLVING THE CC PROBLEM

Here we follow the ideas of Ref. [37], which gives a possible way to solve the CC problem.

In quantum mechanics we consider the probability amplitudes: the initial state $|i\rangle$ transforming to a final state $|f\rangle$. In this spirit, using the Euclidian action S_E, only with the Ricci scalar R and the cosmological constant Λ, Baum and Hawking [38] have calculated the path integral in the Euclidian space-time which gives the following expression:

$$e^{-S_E} = e^{3\pi M_{Pl}/\Lambda}. \tag{61}$$

So, $\Lambda = 0$ dominates the action integral, which is interpreted as the probability for $\Lambda = 0$ being close to 1.

The essence of the new approach [37] is that the bare cosmological constant λ, considered in Sec. VI, is promoted from a parameter to a field. The minimization of the action with respect to λ then yields an additional field equation, which determines the value of the effective cosmological constant, Λ. In the classical history it dominates the partition function of the Universe, Z.

If we take the total action of the Universe defined on a manifold $\mathcal{M}$, and with effective cosmological constant Λ, to be $S_{\rm tot}(g_{\mu\nu}, \Psi^a, \Lambda; \mathcal{M})$, where Ψ^a are the matter fields and $g_{\mu\nu}$ is the metric field, then we define $S_{\rm class}(\Lambda; \mathcal{M})$ to be the value of $S_{\rm tot}(g_{\mu\nu}, \Psi^a, \Lambda; \mathcal{M})$ evaluated with $g_{\mu\nu}$ and Ψ^a obeying their classical field equations for fixed boundary initial conditions, and obtain the field equation for the effective cosmological constant, Λ, given by

$$\frac{dS_{\rm class}(\Lambda; \mathcal{M})}{d\Lambda} = 0. \tag{62}$$

With a given $\mathcal{M}$, Eq. (62) can be viewed as a consistency equation which relates the configuration of metric and matter variables in $\mathcal{M}$ to λ. Equation (62) can be viewed as a consistency condition on the configuration of the effective cosmological constant, Λ, the matter, Ψ^a, and the metric, $g_{\mu\nu}$, in $\mathcal{M}$. The consistency condition provided by Eq. (62) will be violated for the vast majority of potential configurations $\{g_{\mu\nu}, \Psi^a, \Lambda\}$. If observations determine a set of $\{g_{\mu\nu}, \Psi^a, \Lambda\}$ for which Eq. (62) is violated then this proposal would be falsified. At the same time, if the observed configuration is consistent with Eq. (62) within observational limits, then the present proposal would, for the time being, have passed an important empirical test and remain a plausible solution to the CC problems. If $\Lambda \approx 0$ dominates the action integral, then we have an approximate cancellation between the bare cosmological constant and the vacuum energy stress:

$$\Lambda \approx 0 \to \lambda \approx -8\pi G \rho_{\rm vac}. \tag{63}$$

The proposal [37] for solving the cosmological constant problem is similar in certain respects to other multiverse models such as the string landscape, when Λ takes different values in different vacua parts of the multiverse. Despite this similarity, this proposal differs from the multiverse/landscape models. It is also agnostic with respect to the modified theory of gravity and the number of space-time dimensions.

VIII. DARK ENERGY

A. Quintessence model of cosmology

Quintessence is described by a complex scalar field φ minimally coupled to gravity. In the context of the general relativity (GR), gravity is a universal force described by the space-time metric $g_{\mu\nu}$, and the dynamics of the two worlds, ordinary and hidden, is governed by the following action:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R + \lambda + (\nabla\varphi)^2 - V(\varphi) + \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}\right], \tag{64}$$

where

$$(\nabla\varphi)^2 = g^{\mu\nu}\partial_\mu\varphi^\dagger\partial_\nu\varphi, \tag{65}$$

and $V(\varphi)$ is the potential of the field φ, $\kappa^2 = 8\pi G = M_{Pl}^{-2}$, M_{Pl} is the reduced Planck mass, R is the space-time curvature, λ is the 'bare' cosmological constant, $\mathcal{L}(\mathcal{L}')$ is the Lagrangian of the O-(H-) sector, and $\mathcal{L}_{\rm mix}$ is the Lagrangian of photon-photon$'$, neutrino-neutrino$'$, etc. mixing (see [20]).

When both E_6 and E_6' symmetry groups are broken, at the same seesaw scales $M_R = M_R'$, down to $G_{\rm SM}$ and $G_{\rm SM}' \times SU(2)_\theta'$ subgroups, respectively, then we have

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa},\\ \mathcal{L}' &= \mathcal{L}_\theta' + \mathcal{L}_{\rm gauge}' + \mathcal{L}_{\rm Higgs}' + \mathcal{L}_{\rm Yukawa}',\end{aligned} \tag{66}$$

where all parts of Lagrangians $\mathcal{L}$ and $\mathcal{L}'$ are self-explanatory.

The two sectors mean that at least below the scales $M_R = M_R'$ the degrees of freedoms (the fields) can be classified into fields from the O-sector and fields from the H-sector. We could thus consider the energy density due to zero point fluctuations in the H-fields as contributing to $\rho_{\rm vac}^{(H)}$ while the O-fields contribute to $\rho_{\rm vac}^{(O)}$. Here we see that

$$\rho_{\rm vac}^{(O)} = \rho_{\rm vac}^{(\rm SM)}, \tag{67}$$

and

$$\rho_{\rm vac}^{(H)} = \rho_{\rm vac}^{(\rm SM')} + \rho_{\rm vac}^{(\theta)}. \tag{68}$$

Taking into account the fine-tuning considered in Sec. V, we can assume that the SUSY breaking scales are identical in the O- and H-worlds: $M_{\rm SUSY} = M_{\rm SUSY}'$. Then

$$\rho_{\rm vac}^{(\rm SM)} = \rho_{\rm vac}^{(\rm SM')} \sim O(M_{\rm SUSY}^4), \tag{69}$$

and

$$\rho_{\rm vac}^{(H)} = \rho_{\rm vac}^{(O)} + \rho_{\rm vac}^{(\theta)}. \tag{70}$$

In the framework of our cosmological model we calculate the dark energy density relating the value $\rho_{\rm DE}$ only with the $SU(2)_\theta'$ gauge group contributions. This explains the smallness of the dark energy density given by astrophysical measurements. This phenomenon is not obvious and should be explained.

If we neglect the weak connection between O- and H-worlds via gravity, then we can approximately consider them as independently existing in the Universe, and each sector can be described by its own action with "bare" cosmological constant λ_0:

$$S_O = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R + \lambda_0 + (\nabla\varphi)^2 - V(\varphi) + \mathcal{L}\right], \quad (71)$$

and

$$S_H = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R + \lambda_0 + (\nabla\varphi')^2 - V(\varphi') + \mathcal{L}' + \mathcal{L}'_\theta\right]. \quad (72)$$

According to the proposal [37], the most probable configuration is the extremum given by Eq. (62) for the ordinary world:

$$\lambda_0 + 8\pi G\rho_{\rm vac}^{(O)} = 0. \quad (73)$$

Then

$$\rho_{\rm vac}^{(O,{\rm eff})} = 0 \quad (74)$$

and

$$\rho_{\rm vac}^{(H,{\rm eff})} = \rho_{\rm vac}^{(\theta)}. \quad (75)$$

Finally, we obtain

$$\rho_{\rm vac}^{({\rm eff})} = \rho_{\rm vac}^{(H,{\rm eff})} = \rho_{\rm vac}^{(\theta)}. \quad (76)$$

Here, the effective cosmological constant, Λ, is not zero:

$$\Lambda = 8\pi G\rho_{\rm vac}^{(\theta)}, \quad (77)$$

and the effective vacuum energy density is equal to the DE density:

$$\rho_{\rm DE} = \rho_{\rm vac}^{({\rm eff})} = \rho_{\rm vac}^{(\theta)}. \quad (78)$$

This speculative consideration explains a tiny value of the DE density calculated in the next subsection.

B. Inflaton, axion and DE density

We assume that there exists an axial $U(1)_A$ global symmetry in our theory, which is spontaneously broken at the scale f by a singlet complex scalar field φ:

$$\varphi = (f + \sigma)\exp(ia_{ax}/f). \quad (79)$$

We assume that the VEV $\langle\varphi\rangle = f$ is of the order of the E_6-unification scale: $f \sim 10^{18}$ GeV. The real part σ of the field φ is the inflaton, while the boson a_{ax} (imaginary part of the singlet scalar fields φ) is an axion and could be identified with the massless Nambu-Goldstone (NG) boson if the corresponding $U(1)_A$ symmetry is not explicitly broken by the gauge anomaly. However, in the hidden world the explicit breaking of the global $U(1)_A$ by $SU(2)'_\theta$ instantons inverts a_{ax} into a pseudo Nambu-Goldstone (PNG) boson a_θ. Therefore, in the H-world we have

$$\varphi' = (f + \sigma')\exp(ia_\theta/f). \quad (80)$$

The flat Friedmann-Lemaître-Robertson-Walker spacetime gives the following field equation for the axion a_θ (see reviews [8]):

$$\frac{d^2a_\theta}{dt^2} + 3H\frac{da_\theta}{dt} + V'(a_\theta) = 0. \quad (81)$$

where H is the Hubble parameter.

The singlet complex scalar field φ reproduces a Peccei-Quinn (PQ) model [39]. Near the vacuum, a PNG mode a_θ gives rise to the following PQ axion potential:

$$V_{\rm PQ}(a_\theta) \approx (\Lambda'_\theta)^4(1 - \cos(a_\theta/f)). \quad (82)$$

This axion potential exhibits minima at

$$V_{\rm PQ}|_{\rm min} = 0, \quad (83)$$

where

$$\cos(a_\theta/f) = 1, \ \text{i.e.}\ (a_\theta)_{\rm min} = 2\pi nf, \quad n = 0, 1, \ldots \quad (84)$$

For small fields a_θ we expand the effective PQ potential near the minimum:

$$V_{PQ}(a_\theta) \approx \frac{(\Lambda'_\theta)^4}{2f^2}(a_\theta)^2 + \ldots = \frac{1}{2}m^2(a_\theta)^2 + \ldots \quad (85)$$

and hence the PNG axion mass squared is given by

$$m^2 \sim (\Lambda'_\theta)^4/f^2. \quad (86)$$

Solving Eq. (81) for a_θ we can use the axion potential:

$$V(a_\theta) = V_{\rm PQ}(a_\theta), \quad (87)$$

which gives

$$V'(a_\theta) = \frac{(\Lambda'_\theta)^4}{f}\sin(a_\theta/f). \quad (88)$$

If now $\sin(a_\theta/f) = 0$, then $\dot{a}_\theta = 0$, and $V_{\rm PQ}(a_\theta) = 0$, because $\cos(a_\theta/f) = 1$, according to Eqs. (82) and (83).

The minimum of the total θ potential is

$$V_\theta|_{\rm min} = V_{\rm PQ}(a_\theta)|_{\rm min} + V_{\theta\text{-condensate}}, \quad (89)$$

where the first term is zero, according to Eq. (83), and

$$V_{\theta\text{-condensate}} = (\Lambda'_\theta)^4. \quad (90)$$

In this case, when $a_\theta = $ const and $\dot{a}_\theta = 0$, the contribution of axions to the energy density of the H-sector is equal to zero. Finally, we obtain

$$\rho_{\rm vac}^{({\rm eff})} = \rho_{\rm vac}^{(\theta)} = |\dot{a}_\theta|^2 + V_\theta|_{\rm min} = (\Lambda'_\theta)^4. \quad (91)$$

The DE density is equal to the value

$$\rho_{\rm DE} = \rho_{\rm vac}^{({\rm eff})} = (\Lambda'_\theta)^4. \quad (92)$$

Taking into account the result (12) of recent astrophysical observations, we obtain the estimate of the $SU(2)'_\theta$ group's gauge scale:

$$\Lambda'_\theta \simeq 2.3 \times 10^{-3}\ \text{eV}. \quad (93)$$

If $\Lambda'_\theta \sim 10^{-3}$ eV and $f \sim 10^{18}$ GeV, we can estimate the θ-axion mass from Eq. (86):

$$m \sim \Lambda_\theta'^2/f \sim 10^{-42}\ \text{GeV}, \tag{94}$$

which is extremely small. But according to Eqs. (89)–(92), these light axions do not give the contribution to $\rho_{\rm DE}$. It is given only by the condensate of θ fields.

Then it is well known (see reviews [8]) that the equation of state for θ fields is

$$w_\theta = \frac{\dot{a}_\theta^2 - 2V_\theta}{\dot{a}_\theta^2 + 2V_\theta}, \tag{95}$$

and we have (with $\dot{a}_\theta = 0$):

$$w = w_\theta = -1, \tag{96}$$

in accordance with the astrophysical observation (11).

IX. INFLATION IN THE ORDINARY AND SHADOW WORLDS

The results of Wilkinson Microwave Anisotropy Probe [5] lead to a severe constraint on inflationary models giving the value of the spectral index:

$$n_s = 0.95 \pm 0.02. \tag{97}$$

The modern inflationary models give an exact scale-invariant spectrum with $n_s = 1$ (see [6,40]). By this reason, any model describing the early inflationary era has to take into account this constraint: the inflationary potential, describing the early inflationary universe, has to give the desired spectral index n_s.

For compactness of notation, here and in the following we denote the ordinary world rates by the nonprimed symbols and mirror-hidden world ones by the primed symbols. The superscript $(')$ means that the equations where it is used are valid both for the O-, as well as for the H-world.

The scalar field φ produces the following Coleman-Weinberg potential [41]:

$$V_{CW} = A(\varphi^\dagger\varphi)^2\left(\log\left(\frac{\varphi^\dagger\varphi}{f^2}\right)^2 - 1\right) + Af^4. \tag{98}$$

Then for the inflaton $\sigma^{(')}$ we can consider the following inflationary potential in the zero temperature limit [42]:

$$V_{infl}^{(')} = A^{(')}(\sigma^{(')} + f)^4\left(\log\left(\frac{\sigma^{(')} + f}{f}\right)^4 - 1\right) + A^{(')}f^4. \tag{99}$$

Taking into account the finite temperature effects, we have

$$V_{infl,T^{(')}}^{(')} = V_{infl}^{(')} + \beta_T^{(')}(T^{(')})^2(\sigma^{(')} + f)^2, \tag{100}$$

where $\beta_T^{(')}$ is a constant.

At high temperature, the field σ is trapped at the $U(1)_A$ symmetric minimum $\langle\sigma\rangle = -f$ (i.e. $\langle\varphi\rangle = 0$). When the Universe cools down and reaches a sufficiently low temperature, then a new minimum appears at the $U(1)_A$-symmetry breaking value $\langle\sigma\rangle = 0$ (i.e. $\langle\varphi\rangle = f$). The critical temperature T_C corresponds to such a value of temperature when the two above minima become degenerate:

$$T_C = f\sqrt{\frac{A}{\beta_T}}e^{-(1/4)}. \tag{101}$$

Then the Universe cools down further and reaches the Hawking temperature:

$$T_{\rm Hawking} = \frac{H}{2\pi} \approx \frac{1}{2\pi}\sqrt{\frac{8\pi}{3M_{Pl}^2}V_{infl}|_{\sigma=-f}} = \sqrt{\frac{A}{3\pi}}\frac{f^2}{M_{Pl}}, \tag{102}$$

where H is the Hubble parameter at that epoch. The first order phase transition occurs and σ starts its slow-rolling towards the true minimum of the inflationary potential and gets this minimum at the end of inflation. We have a similar development in the hidden sector of the Universe.

But these two sectors, ordinary and hidden, have different cosmological evolutions. In particular, they never have to be in equilibrium with each other: the BBN constraints require that the H-sector have smaller temperature than the O-sector: $T' < T$ (see Ref. [21]).

X. REHEATING AND RADIATION

During reheating the exponential expansion, which was developed by inflation, ceases and the potential energy of the inflaton field decays into a hot relativistic plasma of particles. At this point, the Universe is dominated by radiation and then quarks and leptons are formed.

All the difference between the ordinary and shadow worlds can be described in terms of two macroscopic (free) parameters of the model:

$$x \equiv \frac{T'}{T}, \qquad \beta \equiv \frac{\Omega_B'}{\Omega_B}, \tag{103}$$

where $T(T')$ is the O-(H-) photon temperature in the present Universe, and $\Omega_B(\Omega_B')$ is the O-(H-)baryon fraction.

In subsection I A we have presented the energy density ratio which is a sum of relativistic (radiation) component Ω_r, nonrelativistic (matter) component Ω_m and the vacuum energy density Ω_Λ. The recent observational data indicate that the Universe is almost flat giving Eq. (3), in a perfect accordance with the inflationary paradigm.

The relativistic fraction is represented by photons and neutrinos. The contribution of the H-degrees of freedom to the observable Hubble expansion rate, which are equivalent to an effective number of extra neutrinos $\Delta N_\nu = 6.14 \cdot x^4$, is small enough: $\Delta N_\nu = 0.05$ for $x = 0.3$ (see [21]). In our model,

$$\omega_r = \Omega_r h^2 = 4.2 \cdot 10^{-5}(1 + x^4), \qquad h = \frac{H}{H_0}, \tag{104}$$

where the contribution of H-species is negligible due to the BBN constraint: $x^4 \ll 1$.

Recent cosmological observations [6] show that for redshifts $(1 + z) \gg 1$ we have

$$H(z) = H_0[\Omega_r(1 + z)^4 + \Omega_m(1 + z)^3]. \tag{105}$$

Therefore, the radiation is dominant at the early epochs of the Universe, but it is negligible at the present epoch: $\Omega_r^{(0)} \ll 1$.

Any inflationary model has to describe how the SM-particles were generated at the end of inflation. The inflaton, which is a singlet of E_6, can decay, and the subsequent thermalization of the decay products can generate the SM-particles. The inflaton σ produces gauge bosons: photons, gluons, $W^{\pm}$, Z, and matter fields: quarks, leptons and the Higgs bosons, while the inflaton field σ' produces H-world particles: shadow photons and gluons, thetons, W', Z', θ-quarks q_θ, θ-leptons l_θ, shadow quarks q' and leptons l', scalar bosons ϕ_θ and shadow Higgs fields ϕ'. In shadow world we end up with a thermal bath of SM$'$ and θ particles. However, we assume that the density of θ particles is not too essential in cosmological evolution due to small θ-coupling constants.

According to Ref. [21], at the end of inflation the O- and H-sectors are reheated in a nonsymmetric way ($T_R > T'_R$). After reheating (at $T < T_R$) the exchange processes between O- and H-worlds are too slow, by reason of very weak interaction between the two sectors. As a result, it is impossible to establish equilibrium between them. Thus, both worlds evolve adiabatically and the temperature asymmetry ($T'/T < 1$) is approximately constant in all epochs from the end of inflation until the present epoch. Therefore, the cosmology of the early H-world is very different from the ordinary one when we consider such crucial epochs as baryogenesis and nucleosynthesis. Any of these epochs is related to an instant when the rate of the relevant particle process, $\Gamma(T)$, becomes equal to the Hubble expansion rate $H(T)$. In the H-world these events take place earlier and the processes freeze out at larger T than in the ordinary world.

XI. BIG BANG NUCLEOSYNTHESIS

At the end of cosmic inflation the Universe was filled with a quark-gluon plasma. This plasma cools down until *the hadron epoch*, when hadrons (including baryons) can form. Then neutrinos decouple and begin travelling freely through space. This cosmic neutrino background is analogous to the CMB which was emitted much later. After the hadron epoch the majority of hadrons and antihadrons annihilate each other, leaving leptons and antileptons dominating the mass of the Universe. Here we reach *the lepton epoch*. Then the temperature of the Universe continues to fall until the end of the lepton/antilepton pairs creation. Also most of the leptons/antileptons are eliminated by annihilation processes. At the end of the lepton epoch the Universe undergoes *the photon epoch* when the energy of the Universe is dominated by photons, which still essentially interact with charged protons, electrons and eventually nuclei.

The temperature of the Universe again continues to fall. It falls to the point when atomic nuclei begin to form. Protons and neutrons combine into atomic nuclei by nuclear fusion process. However, this nucleosynthesis stops at the end of the nuclear fusion. At this time, the densities of nonrelativistic matter (atomic nuclei) and relativistic radiation (photons) are equal.

The BBN epoch in the H-world proceeds differently from the ordinary one and predicts different abundances of primordial elements. This shadow BBN is analogous to the mirror BBN scenario considered in Refs. [19–21].

The difference of the temperatures ($T' < T$) gives that the number density of H-photons is much smaller than for O-photons:

$$\frac{n'_\gamma}{n_\gamma} = x^3 \ll 1. \tag{106}$$

The primordial abundances of light elements depend on the baryon to photon number density ratio: $\eta = n_B/n_\gamma$. The result of Wilkinson Microwave Anisotropy Probe [5] gives: $\eta \simeq 6 \cdot 10^{-10}$, in accordance with the observational data.

The Universe expansion rate at the ordinary BBN epoch (with $T \sim 1$ MeV) is determined by the O-matter density itself. As far as $T' \ll T$, for the ordinary observer it is difficult to detect the contribution of the H-sector, which is equivalent to $\Delta N_\nu \approx 6.14x^4$ and negligible for $x \ll 1$ [21]. As for the BBN epoch in the shadow world, for the H-observer the contribution of the O-sector is equivalent to $\Delta N'_\nu \approx 6.14x^{-4}$, which is dramatically large. Therefore, the observer in H-world, which measures the abundances of shadow light elements, should immediately detect the discrepancy between the Universe expansion rate and H-matter density at the shadow BBN epoch (with $T' \sim 1$ MeV): the O-matter density is invisible for the H-observer.

During the structure formation, the most important moments are connected with the matter-radiation equality (MRE), plasma recombination and matter-radiation decoupling (MRD) epochs.

From Eq. (105) we see that MRE is given by the following relation:

$$1 + z_{eq} = \frac{\Omega_m}{\Omega_r}. \tag{107}$$

The estimate of Ref. [19] gives

$$1 + z_{eq} = 2.4 \cdot 10^4 \frac{\omega_m}{1 + x^4}, \tag{108}$$

where $\omega_m = \Omega_m h^2$. The shadow relativistic component is negligible for $x \ll 1$.

Recombination

The MRD takes place when most of the electrons and protons recombine into neutral hydrogen and free electron density strongly diminishes. During the recombination, the photon scattering rate drops below the Hubble expansion rate. In the O-world the MRD takes place in the matter dominant period at the temperature $T_{\rm dec} \simeq 0.26$ eV, corresponding to the redshift

$$1 + z_{\rm dec} = \frac{T_{\rm dec}}{T_{\rm today}} \simeq 1100. \tag{109}$$

In the H-world we have the MRD temperature $T'_{\rm dec} \simeq T_{\rm dec}$ and

$$1 + z'_{\rm dec} \simeq x^{-1}(1 + z_{\rm dec}) \simeq \frac{1100}{x}. \tag{110}$$

This means that in the H-world MRD occurs earlier than in the O-world. According to Ref. [19],

$$x_{\rm dec} = \frac{1 + z_{\rm dec}}{1 + z_{eq}} \simeq \frac{4.59 \cdot 10^{-2}}{\omega_m}, \tag{111}$$

and H-photon decoupling epoch coincides with the MRE epoch. Equation (111) gives a critical value for temperature, which plays a very important role in cosmology: for $x < x_{eq}$, the H-photons would decouple already during the radiation dominated period.

Thus, at the end of recombination, most of the atoms in the Universe are neutral, photons travel freely and the Universe becomes transparent. The observable CMB is a picture of the Universe at the end of this epoch.

XII. BARYON DENSITY AND DARK MATTER

Shadow baryons (and shadow helium), which are invisible to ordinary photons, are the best candidates for dark matter (DM).

Here we give an approximate estimate of baryon masses in the O- and H-worlds. Most part of the mass of nucleons (proton and neutron) is provided by the dynamical (constituent) quark masses m_q forming the nucleon. The dynamical quark mass is

$$m_q \simeq m_0 + \Lambda_{\rm QCD}, \tag{112}$$

where $m_0 \sim 10$ MeV is the current mass of light quarks u, d, and $\Lambda_{\rm QCD} \simeq 300$ MeV. Then the nucleon mass M_B can be estimated as

$$M_B \simeq 3m_q \simeq 1 \text{ GeV}. \tag{113}$$

As to shadow current quark mass m'_0 (see subsection III B), we have

$$m'_0 \simeq \zeta m_0 \sim 1 \text{ GeV}, \tag{114}$$

for $\zeta \sim 100$. This estimate gives the shadow nucleon mass M'_B equal to

$$M'_B \simeq 3(m'_0 + \Lambda'_{\rm QCD}). \tag{115}$$

Taking into account Eq. (38) and the estimate $\xi \simeq 1.5$ given by Ref. [20] (see also Ref. [1]), we obtain $\Lambda'_{\rm QCD} \simeq 450$ MeV, and

$$M'_B \simeq 3(1 + 0.45) \text{ GeV} \simeq 4.35 \text{ GeV}. \tag{116}$$

Here we should point out that in our model baryons of shadow world are formed not only by quark system qqq, but also by $q_{\theta,\vartheta}q_\theta^\vartheta q$, where $\vartheta = 1, 2$ is the index of the $SU(2)'_\theta$ group. The last system gives the quark-diquark structure of shadow baryons. However, they do not give essential contributions to baryon density, by reason of small θ-charges.

Since the H-sector is cooler than the ordinary one, then we have $n'_B \gtrsim n_B$ by the estimate of Ref. [21], and

$$\rho'_B = n'_B M'_B > \rho_B = n_B M_B. \tag{117}$$

Now we can explain the relation (8), especially if we take into account the shadow helium mass fraction (see Ref. [21]).

Finally, we predict that the energy density of the hidden sector is

$$\rho' = \rho_{\rm DE} + \rho_{\rm DM} = \rho_{\rm DE} + \rho'_B + \rho_{\rm CDM}, \tag{118}$$

where $\rho_{\rm DE}$ is given by (10), $\rho'_B = n'_B M'_B \approx 0.17\rho_c$ and $\rho_{\rm CDM} \approx 0.04\rho_c$ presumably contains shadow helium.

The energy density of the O-world is

$$\rho_M = \rho_B + \rho_{\rm nuclear}, \tag{119}$$

where $\rho_B = n_B M_B \approx 0.04\rho_c$ and the contribution of ordinary helium and other atoms is much smaller. Then it is possible to explain the observable result [see Eq. (8)]:

$$\frac{\Omega_{\rm DM}}{\Omega_M} \simeq \frac{\rho_{\rm DM}}{\rho_M} \simeq \frac{\rho'_B + \rho_{\rm CDM}}{\rho_B + \rho_{\rm nuclear}} \simeq \frac{0.17 + 0.04}{0.04} \simeq 5. \tag{120}$$

XIII. BARYOGENESIS

In Ref. [2] we have a presented baryogenesis mechanism in our cosmological model with superstring-inspired E_6 unification. In this model, the B-L asymmetry is produced by the conversion of ordinary leptons into particles of the hidden sector.

After the nonsymmetric reheating with $T_R > T'_R$, the exchange processes between O- and H-worlds are too slow, by reason of the very weak interaction between the two sectors. As a result, it is impossible to establish equilibrium between them, so that both worlds evolve adiabatically and the temperature asymmetry ($T'/T < 1$) is approximately constant in all epochs from the end of the inflation until the present epoch.

The equilibrium between two sectors of massless particles with the same temperature is not broken by the cosmological expansion, and the baryon asymmetry (and any charge asymmetry) cannot be generated in the Universe. However, if there are two components in the plasma with different temperatures, then the equilibrium is explicitly broken as long as the temperatures are not equal. In our case of observed and hidden sectors, the equilibrium never occurs due to their essentially different temperatures. In this case, baryon asymmetry may be generated even by scattering of massless particles.

In the Bento-Berezhiani model of baryogenesis [18] the heavy Majorana neutrinos play the role of messengers between ordinary and mirror worlds. Their model considers the group of symmetry $G_{\rm SM} \times G_{\rm SM'}$, i.e. the standard model and its mirror counterpart. Heavy Majorana neutrinos N are singlets of $G_{\rm SM}$ and $G_{\rm SM'}$ and this is the explanation, why they can be messengers between ordinary and mirror worlds.

In our model with E_6 unification, the N-neutrinos belong to the 27-plet of E_6 and E'_6, and they are not singlet particles. But after the breaking

$$E_6 \to SO(10)\times U(1)_Z \to SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_X\times U(1)_Z \quad (121)$$

in the O-world, and

$$E'_6 \to\to SU(6)'\times SU(2)'_\theta \to SU(3)'_C\times SU(2)'_L\times SU(2)'_\theta\times U(1)'_X\times U(1)'_Z \quad (122)$$

in the H-world, heavy Majorana neutrinos N_a become singlets of the subgroups $SU(3)_C \times SU(2)_L \times U(1)_X \times U(1)_Z$ and $SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z$, according to Eq. (20). Therefore, in our model [1], after the breaking of $SO(10)$ and $SU(6)'$ and below seesaw scale ($\mu < M_R = M'_R \sim 10^{10-15}$ GeV), when we have the symmetry groups $G_{\rm SM}$ and $G_{\rm SM'} \times SU(2)'_\theta$, the heavy Majorana neutrinos N_a again can play the role of messengers between the O- and H-worlds.

Baryon B and lepton L numbers are not conserved quantum numbers. They are directly related to the seesaw mechanism for light neutrino masses. B-L is generated in the decays of heavy Majorana neutrinos, N, into leptons l (or antileptons $\bar{l}$) and the Higgs bosons ϕ (which are the standard Higgs doublets):

$$N \to l\phi, \bar{l}\,\bar{\phi}. \quad (123)$$

In this context, the three necessary Sakharov conditions [43] are realized in the following way:

(1) B-L and L are violated by the heavy neutrino Majorana masses.

(2) The out-of-equilibrium condition is satisfied due to the delayed decay(s) of the Majorana neutrinos, when the decay rate $\Gamma(N)$ is smaller than the Hubble rate H: $\Gamma(N) < H$, i.e. the lifetime is larger than the age of the Universe at the time when N_a becomes nonrelativistic.

(3) CP violation (C is trivially violated due to the chiral nature of the fermion weak eigenstates) originates as a result of the complex $lN\phi$ Yukawa couplings producing asymmetric decay rates:

$$\Gamma(N \to l\phi) \neq \Gamma(N \to \bar{l}\,\bar{\phi}), \quad (124)$$

so that leptons and antileptons are produced in different amounts and the B-L asymmetry is generated.

XIV. SUMMARY AND CONCLUSIONS

In this paper we have developed the hypothesis of parallel existence of the ordinary and hidden sectors of the Universe. We have constructed a new cosmological model with the superstring-inspired E_6 unification in the four-dimensional space. We have assumed that this unification was broken at the early stage of the Universe to $SO(10) \times U(1)_Z$ in the O-world, and to $SU(6)' \times SU(2)'_\theta$ in the H-world. We have investigated the breaking mechanism of the E_6 unification. In the O-world this breaking is realized by the Higgs field H_{27} belonging to the 27-plet, while in the hidden sector the breaking of the E'_6 unification occurs due to the Higgs field H_{351} belonging to the 351-plet of the E'_6. The corresponding VEVs are $v = \langle H_{27}\rangle$ and $V = \langle H_{351}\rangle$. From the beginning, we have assumed that E'_6 is the mirror counterpart of the E_6. Then the discrete symmetry Z_2 (connected with the mirror parity MP) leads to a phenomenologically unacceptable wall. Using the simplest model of inflation with the superpotential $W = \lambda\varphi(\Phi^2 - \mu^2)$, where the field φ is the inflaton and Φ is the Higgs field, λ is a coupling constant and μ is a dimensional parameter of the order of the GUT scale $\sim 10^{18}$ GeV, we avoid this unacceptable wall dominance assuming the following fine-tuning: $V = V'$, what gives $\lambda^2\mu^4 = \lambda'^2\mu'^4$. Here $V^{(\prime)} = \lambda^{(\prime)2}\mu^{(\prime)4}$ is the energy density of the tree level potential.

According to our assumptions, there exist the following chains of symmetry breakings:

(i) in the O-world,

$$E_6 \to SO(10)\times U(1)_Z \to SU(4)_C\times SU(2)_L\times SU(2)_R\times U(1)_Z \to SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_X\times U(1)_Z \to [SU(3)_C\times SU(2)_L\times U(1)_Y]_{\rm SUSY} \to SU(3)_C\times SU(2)_L\times U(1)_Y,$$

(ii) in the H-world,

$$E'_6 \to SU(6)'\times SU(2)'_\theta \to SU(4)'_C\times SU(2)'_L\times SU(2)'_\theta\times U(1)'_Z \to SU(3)'_C\times SU(2)'_L\times SU(2)'_\theta\times U(1)'_X\times U(1)'_Z \to [SU(3)'_C\times SU(2)'_L\times SU(2)'_\theta\times U(1)'_Y]_{\rm SUSY} \to SU(3)'_C\times SU(2)'_L\times SU(2)'_\theta\times U(1)'_Y.$$

In contrast to the results of Refs. [15–21], based on the concept of the parallel existence in Nature of the mirror (M-) and ordinary (O-) worlds described by a minimal symmetry $G_{SM} \times G'_{SM}$, we assume the existence of the low-energy symmetry group $G' = SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y$ in the H-world and the SM symmetry group in the O-world. This is a natural consequence of different schemes of the E_6-breaking in the O- and H-worlds considered in subsection II C. In comparison with $G_{\rm SM}$, the group G' has an additional non-Abelian $SU(2)'_\theta$ group whose gauge fields are massless vector particles, 'thetons'. These 'thetons' have a macroscopic confinement radius, $1/\Lambda'_\theta$. The estimate given by Ref. [1] confirms the scale $\Lambda'_\theta \sim 10^{-3}$ eV. Assuming the cancellation between the bare cosmological constant, λ, and the vacuum energy stress, $8\pi G\rho_{\rm vac}$, described only by the SM contributions of the O- and H-worlds (see Secs. VI, VII, and VIII), we explain the small value of $\rho_{\rm DE}$, i.e. the observable tiny cosmological constant, only as a result of the θ-fields condensation: $\rho_{\rm DE} = \rho^{\rm (eff)}_{\rm vac} = (\Lambda'_\theta)^4 \simeq (2.3 \times 10^{-3}\ {\rm eV})^4$.

Taking into account the modern inflationary models with spectral index $n_s \simeq 1$, we have considered the inflationary potentials in zero temperature limit and also at the finite temperature T. With this aim, we have used the Coleman-Weinberg potential (98) for the singlet scalar field φ. We have considered in both O- and H-worlds the first order phase transition when the inflaton starts its slow-rolling towards the true minimum of the inflationary potential at $\sigma^{(\prime)} = 0$, and reaches this minimum at the end of inflation.

We have discussed how the SM-particles were generated at the end of inflation: the inflaton decays, and the subsequent thermalization of these decay products generates the SM-particles. The inflaton σ produces gauge bosons: photons, gluons, $W^\pm$, Z, and matter fields: quarks, leptons and the Higgs bosons, while the inflaton σ' produces hidden particles: shadow photons, gluons and thetons, W', Z', θ-quarks q_θ, θ leptons l_θ, shadow quarks q' and shadow leptons l', scalar bosons ϕ_θ and shadow Higgs fields ϕ'.

The O- and H-sectors have different cosmological evolutions: they are never in equilibrium with each other. The BBN constraints require that the H-sector must have smaller temperature than the O-sector: $T' < T$ [21]. The difference between the O- and H-worlds is described in terms of two macroscopic parameters: $x \equiv T'/T$ and $\beta \equiv \Omega'_B/\Omega_B$, where $T(T')$ is the O-(H-)photon temperature of the Universe at present, and $\Omega_B(\Omega'_B)$ is the O-(H-)baryons fraction.

We have considered the reheating and radiation in Sec. X and big bang nucleosynthesis in Sec. XI. During reheating the exponential expansion, developed by inflation, ceases and the potential energy of the inflaton field decays into a hot relativistic plasma of particles. The relativistic fraction is represented by photons and neutrinos. The radiation is dominant at the early epochs of the Universe, but it is negligible at the present epoch: $\Omega_r^{(0)} \ll 1$.

The contribution of the H-degrees of freedom to the observable Hubble expansion rate, which are equivalent to an effective number of extra neutrinos $\Delta N_\nu = 6.14 \cdot x^4$, is small enough. In our model: $\omega_r = \Omega_r h^2 = 4.2 \cdot 10^{-5} \times (1 + x^4)$ $(h = H/H_0)$, where the contribution of the H-species is negligible due to the BBN constraint, $x^4 \ll 1$.

At the end of inflation the O- and H-sectors are reheated in a nonsymmetric way: $T_R > T'_R$. After reheating, at $T < T_R$, the exchange processes between the O- and H-worlds are too slow (due to the very weak interaction between two sectors), and it is difficult to establish equilibrium between them. As a result, the temperature asymmetry $(T'/T < 1)$ is approximately constant from the end of inflation until the present epoch.

We have seen that the cosmological evolutions of the early O- and H-worlds are very different, in particular, when we consider such crucial epochs as baryogenesis and nucleosynthesis. The BBN epoch proceeds differently in the O- and H-worlds and predicts different abundances of primordial elements. For example, due to the condition $T' < T$, the density of H-photons number is much smaller than for O-photons: $n'_\gamma/n_\gamma = x^3 \ll 1$.

The structure formation in the Universe is connected with the plasma recombination and MRD epochs. Also the MRE is important, being given by the relation $1 + z_{eq} = \Omega_m/\Omega_r \simeq 2.4 \cdot 10^4 \cdot \Omega_m h^2/(1 + x^4)$. During the MRD epoch, most of the electrons and protons recombine into neutral hydrogen and the free electron density essentially diminishes. The MRD temperature is $T_{\rm dec} \simeq 0.26$ eV, what corresponds to the redshift $1 + z_{\rm dec} = T_{\rm dec}/T_{\rm today} \simeq 1100$. In the H-world we have the MRD temperature $T'_{\rm dec} \simeq T_{\rm dec}$ and $1 + z'_{\rm dec} \simeq x^{-1}(1 + z_{\rm dec}) \simeq 1100/x$, which means that in the H-world MRD occurs earlier than in the O-world.

During the recombination epoch the photon scattering rate drops below the Hubble expansion rate. The H-photon decoupling epoch coincides with the MRE epoch. At the end of recombination, the atoms in the Universe are neutral, photons travel freely and the Universe becomes transparent. The observed CMB gives a picture of the Universe at the end of this epoch.

In Sec. XII we have estimated ρ_M and $\rho_{\rm DM}$ in the framework of our cosmological model. We assume that shadow baryons and shadow helium, invisible for ordinary photons, give the main contribution to dark matter (DM). We explain the observable result: $\Omega_{\rm DM}/\Omega_M \simeq \rho_{\rm DM}/\rho_M \simeq 5$.

Section XIII is devoted to the baryogenesis mechanism presented in Ref. [2]. In our cosmological model with superstring-inspired E_6 unification, the B-L asymmetry is produced by the conversion of ordinary leptons into particles of the hidden sector. After the nonsymmetric reheating with $T_R > T'_R$, it is impossible to establish an equilibrium between the O- and H-sectors, and baryon asymmetry may be generated even by the scattering of massless particles. In our model with E_6 unification existing at the early stage of the Universe, after the breaking of $E_6(E'_6)$, heavy Majorana neutrinos N_a become singlets of the subgroups $SU(3)_C \times SU(2)_L \times U(1)_X \times U(1)_Z$ and $SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z$, and can play the role of messengers between the O- and H-worlds. B-L quantum number is generated in the decays of heavy Majorana neutrinos, N, into leptons l (or antileptons $\bar{l}$) and the Higgs bosons ϕ: $N \to l\phi, \bar{l}\,\bar{\phi}$. The three necessary Sakharov conditions [43] are realized in our model of baryogenesis.

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